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Existing and upcoming particle accelerators in India

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November 2017

Abstract

In this report, brief information of existing and upcoming particle accelerators in India has been compiled for scientist, engineers and students in India and abroad to have idea on status of particle accelerators in India. Attempt has been made to include detail operating parameters, thrust research areas, limitations and additional facilities, its availability to users across the country and abroad. This report may serve as an important document in the future to propose state of art facilities and particle accelerators in different parts of country. However, the present report does not contain any information on accelerators in the past that are no longer in operation or already decommissioned.

Contents

	Page No.
1. Introduction	1-2
2. Existing Particle Accelerators in India	
2.1 Bhabha Atomic Research Centre	
2.1.1 Folded Tandem Ion Accelerator(FOTIA)	3-5
2.1.2 14 MeV neutron generator	6-7
2.1.3 10 MeV electron RF LINAC	8-9
2.1.4 3 MeV electron Accelerator	10-11
2.1.5 16.5 Medical cyclotron	12-13
2.2 Guru Ghasidas Vishwavidyalaya	
2.2.1. 3 MV Tandetron Accelerator	14-16
2.3 Indian Institute of Technology, Kanpur	
2.3.1 1.7 MV Tandetron Accelerator	17-18
2.4 Indira Gandhi Centre for Atomic Research	
2.4.1. 1.7 MV Tandetron Accelerator	19-20
2.5 Institute of Physics	
2.5.1 3 MV Pelletron Accelerator	21-23
2.6 Inter University Accelerator Centre	
2.6.1 15 UD Pelletron Accelerator	24-27
2.7 Mangalore University	
2.7.1 Microtron Accelerator	28-29
2.8 National Centre for Compositional Characterisation of Materials (CCCM), Hyderabad	
2.8.1 3 MV Tandetron Accelerator	30-31
2.9 Panjab University	
2.9.1 Low energy cyclotron	32-33
2.10 Raja Ramanna Centre for Advanced Technology	
2.10.1 Synchrotron Radiation Source INDUS-I	34-37
2.10.2 Synchrotron Radiation Source INDUS-II	38-41
2.11 S.P. Pune University	
2.11.1 14 MeV Neutron Generator	42-44
2.11.2 6.5 MeV Race-Track Microtron	45-48
2.12 Tata Institute of Fundamental Research	
2.12.1 14 UD Pelletron Accelerator	49-53
2.13 Variable Energy Cyclotron Centre	
2.13.1 224 cm Variable energy cyclotron (K-130)	54-55
3. Upcoming Particle Accelerators in India	
3.1 Bhabha Atomic Research Centre	
3.1.1 Low Energy High Intensity Proton Accelerator (LEHIPA)	56-60
3.2 Institute for Plasma Research, Ahmedabad	
3.2.1 High intensity 14 MeV Neutron generator	61-62
3.3 Saha Institute of Nuclear Physics	
3.3.1 FRENA (3 MV Tandem Accelerator)	63-64
3.4 Variable Energy Cyclotron Centre	
3.4.1 Radioactive Ion Beam Facility	65-66
3.4.2 K-500 Superconducting Cyclotron	67-69
3.4.3 DAE's Medical Cyclotron(MC-30)	70-71
4. Summary and Conclusions	72
5. Acknowledgement	73

1. Introduction

Particle accelerators produce beams of charged particles for research and applications. They play a major role in the field of basic and applied sciences, in our understanding of nature and the universe. In India, development of particle accelerators started in the year 1950, with the successful installation of 1 MeV proton accelerator using Cockcroft-Walton generator at TIFR, Mumbai, which was followed by a 38 inch Cyclotron commissioned at Saha Institute of Nuclear Physics, Kolkata in 1960. Accelerator based neutron generators using D-T reaction was also commissioned at SINP, Kolkata in the year 1957, and similar accelerator was indigenously developed at BARC in the early 1970's which were used for neutron physics research. In the early 60's, there were several DC accelerators set up at different institutions and Universities across the country viz Bose Institute at Kolkata, Banaras Hindu University, Aligarh Muslim University, Andhra University, IGCAR Kalpakkam, BARC, Mumbai. A 2 MV Van de Graff accelerator was also set up at IIT, Kanpur for neutron induced fission studies. A 5.5 MV Van de Graff generator was also installed at BARC in 1961, which was again retrofitted as Folded Tandem Ion Accelerator for delivering ions with A~40 and energy ~ 60 MeV, and commissioned in 2000. In the early 70's, a Cyclotron facility capable of delivering 5 MeV proton was set up at Punjab University which was gifted by University of Rochester, USA. A 224 cm Variable Energy Cyclotron (VEC) also started operating since 1978 at VECC, Kolkata. In the early 80's, Race-track Microtrons and 14 MeV neutron generators were also commissioned at Pune University.

In 1988, 14 UD Pelletron accelerator was commissioned at TIFR, Mumbai coupled to a LINAC booster again commissioned in 2007. In 1991, 15 UD Pelletron accelerator also started operating at Inter University Accelerator Centre (IUAC), New Delhi. In 1992, 3 MV Pelletron accelerator was installed at Institute of Physics, Bhubhaneswar. In 1995, a variable energy microtron developed by CAT, Indore was also commissioned at Mangalore University. In the same year, 3 MV Tandetron accelerator was also commissioned at National Centre for Compositional Characterization of Materials. A 3 MV Tandetron Accelerator has recently been installed at Guru Ghasidas Vishwavidyalaya, Bilaspur. Two more 1.7 MV Tandetron Accelerators were also installed recently at IIT Kanpur and IGCAR, Kalpakkam. The first synchrotron radiation source in India Indus-1 was commissioned in 1999, capable of delivering electron beam up to 450 MeV. Then Indus-2 capable of delivering electron beam with energy up to 2.5 GeV was commissioned in 2005.

There are also upcoming particle accelerators in the country. Low Energy High Intensity Proton Accelerator (LEHIPA) which is being developed at BARC, Mumbai consist of 50 keV Electron Cyclotron Resonance (ECR) ion source that is accelerated further by 3 MeV Radio Frequency Quadrupole (RFQ) and 20 MeV Drift Tube Linac (DTL). The LEHIPA of 40-50 MeV proton beam using DTL will be coupled to Couple Cavity Linac (CCDTL) to get 100 MeV proton beams that will be further accelerated to 1 GeV by elliptical Super Conducting (SC) Cavity. LEHIPA is mainly designed for ADS program. The Institute for Plasma Research is also developing high intensity neutron source using D-T reaction for fusion neutronics related research, with neutron flux 10^{12} n/s. A 3 MV Tandetron accelerator is also being installed in SINP, Kolkata dedicated for nuclear astrophysics experiments. FRENA will be used for low energy nuclear astrophysics related to fusion of heavy ions like ^{12}C, ^{16}O, ^{20}Ne. The facility is also planned for low energy neutron source using ^{7}Li(p,n)^{7}Be reaction to investigate the s-process nucleosynthesis and to study specific reactions in the H and He-burning phases of stars and the p-process reactions. At VECC, Kolkata, there are also ongoing developments on Radioactive Ion Beam facility. Recently radioactive ion beams (RIB) of ^{14}O(71 sec), ^{42}K(12.4 hrs),^{43}K (22.2 hrs) and ^{41}Ar (1.8 hrs) have been successfully produced at VECC, using a novel gas-jet recoil transport coupled Electron Cyclotron Resonance (ECR) ion- source technique. The RIB of ^{14}O has been further accelerated through the RFQ linac to 1.4 MeV. Stable isotope beams such as ^{12}C, ^{16}O, ^{14}N, ^{40}Ar, ^{39}K, ^{56}Fe are also accelerated and are being used for material science experiments. The option of using electron linac for production of neutron-rich RIB through photo- fission route and acceleration of RIB using linacs up to about 6-7 MeV/u is under consideration. Finally, it is proposed to inject the 6-7 MeV/u RI as well as stable beams into a Separated Sector Cyclotron for further acceleration to about 100 MeV/u. A K-500 superconducting cyclotron being developed at VECC, Kolkata is also expected to be commissioned soon. Apart from existing 16.5 MeV Medical Cyclotron facility at RMC, and upcoming 30 MeV Medical Cyclotron, Kolkata which are included in this report, there are also three 11 MeV Medical Cyclotrons, six 16.5 MeV Medical Cyclotrons and two 18 MeV Medical Cyclotrons across the country which are dedicated for medical isotope productions and for medical sciences.

The present report consists of existing and upcoming particle accelerators in India. Attempt is also made to report detail operating parameters and beam specifications. One of the motivation of the present study is to investigate the number of existing and upcoming accelerators utilized or to be utilized for neutron physics as their thrust areas, and detail analysis in this regard will be discussed in Summary and Conclusions.

2. Existing Particle Accelerators in India

2.1 Bhabha Atomic Research Centre, Mumbai

2.1.1 Folded Tandem Ion Accelerator (FOTIA):

1. Name and address of the Institute:
Nuclear Physics Division, BARC, Mumbai 4000 85, India

2. Person incharge of the Facility:
P.V. Bhagwat (Pramod@tifr.res.in) Head, Ion Accelerator Development Division, NPD, BARC
A. Agarwal, Officer in Charge, FOTIA, NPD, BARC

3. Type of Accelerator:
Folded Tandem Ion Accelerator (FOTIA), the accelerator is indigenously developed.

4. Beam details:

Beam Species	Max. Energy	Max. current/Intensity
^{7}Li, ^{12}C, ^{16}O and ^{19}F and other heavy ion beams upto A=40	66 MeV	< 100 nA
Proton	Upto 6 MeV	200 nA
Neutron	Below 5 MeV using $^{7}Li(p,n)$ and $^{9}Be(p,n)$	10^{6}-10^{7} n/sec/cm^{2}

5. Approximate/expected date of installation/commission: April 2000

6. Pulsed or D.C. operation: Continous Beam

7. Is the facility utilized for neutron physics experiments?
The facility has been and is being used to carry out neutron induced cross section measurement using quasi-monoenergetic neutrons from $^{7}Li(p,n)^{7}Be$ reaction.

Figure 1: FOTIA experimental hall showing the neutron production head where Lithium sample is mounted.

8. Is the facility available for outside user?:

The facility is mainly devoted for DAE scientists. Few Universities in collaboration with BARC scientists also utilized the facility.

9. Major experimental facilities available:

Multipurpose scattering chamber
Scintillator detectors for neutrons (NE213)
Charged particle detectors
PIXE (Particle Induced X-ray Emission)
RBS (Rutherford BackScattering)
PIGE (Particle Induced Gamma Emission)

10. Type of experiments being carried out:

FOTIA is in operation and has been used both for basic and applied research. The main areas of research are:

i) Prompt fission neutron spectra in fast neutron induced fission reaction with incident energy range of neutron from 2 to 3 MeV for 232Th and 238U,
ii) Application of particle induced gamma-ray emission for non-destructive determination of fluorine in barium borosilicate glass samples
iii) Elemental analysis studies using the Rutherford backscattering (RBS) technique.
iv) Studies on effects of breakup and transfer channels on elastic scattering and fusion cross-sections in heavy ion induced reactions around the Coulomb barrier.
v) Neutron capture cross-section measurements for various target elements in the energy range below 5 MeV.
vi) ERDA (Energy Recoil Detection Analysis)
vii) NRA (Nuclear Reaction Analysis)
viii) RNR (Resonant Nuclear Reaction)

11. Program Advisory Committee/experiment proposals: No.

12. Picture/Schematic:

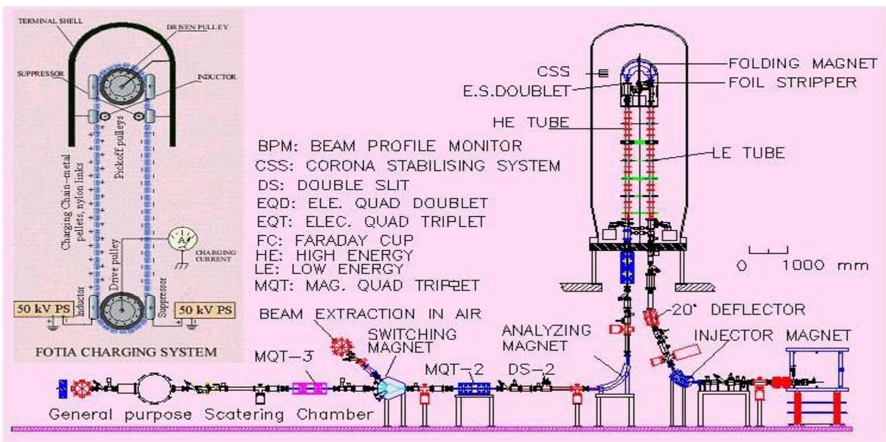

Figure 2: Schematic of Folded Tandem Ion Accelerator at NPD, BARC, Mumbai.

Figure 3: Folded Tandem Ion Accelerator at NPD, BARC, Mumbai.

13. Sources of information:

A. Agarwal, S.Santra et. al., “Status report on the folded tandem ion accelerator at BARC”, Pramana, 59 (2002) 739–744

Proceedings of DAE-BRNS Indian Particle Accelerator Conference, IUAC, New Delhi, Feb 15-18, 2011(http://www.iuac.res.in/event/InPAC11/proceedings/InPAC2011%20Proceedings/I-20/SKGupta.pdf)

2.1.2. 14 MeV Neutron Generator:

1. Name and address of the Institute:

Purnima Laboratory, Neutron & X-Ray Physics Division, BARC, Mumbai 400085, India

2. Person in charge of the Facility: Dr. Amar Sinha (image@barc.gov.in)
Saroj Bishnoi (saroj@barc.gov.in)

3. Type of Accelerator:
14 MeV Neutron Generator (Cock-Croft Walton Type)

3.1: Nuclear Reaction: $^{2}H_{1} + {}^{3}H_{2} \rightarrow n + {}^{4}He_{2} + Q[\,17.4\text{ MeV}]$
$^{2}H_{1} + {}^{2}H_{1} \rightarrow n + {}^{3}He_{2} + Q[\,3.3\text{ MeV}]$

3.2: Name of the Company or Supplier:
The 14 MeV Neutron Generator was completely indigenously designed, fabricated and installed.

4. Beam details:

Beam Specifications	Max. Energy	Max. Current/Intensity
Proton or Deuteron	30 keV - 300 keV	1 mA
Neutron	~14.1 MeV (at 90^0) using D-T ~2.45 MeV using D-D	5×10^{10} n/sec

5. Approximate/expected date of installation/commission: Early 1970's

6. Pulsed or DC operation: DC as well as Pulsed with pulsed width 100-200 ns using beam chopper.

7. Is the facility utilized for neutron physics experiments?
The facility has been utilized mainly for generating 14 MeV neutrons using D-T reaction, 2.45 MeV neutrons using D-D reactions.

8. Is the facility available for outside user?
The facility is mainly devoted for DAE personnel, although few University students in collaboration with BARC scientist had performed few experiments.

9. Major experimental facilities available:
HPGe detector, NaI (Tl) detector; BGO detector; Data Acquisition system, Transportable neutron generator, compact single gap neutron generator.

10. Type of experiments being carried out:

Many experiments have been conducted with this neutron generator by various divisions in BARC. The facility has also been used for experiments of Coincidence and Time of Flight

(TOF) measurements using APT technique in collaboration with Padova University, Italy and neutron radiography for VSSC, Thiruvananthapuram. The facility has also been used for elemental analysis, ADSS benchmarking experiments, neutron radiography, detector response study, nuclear data generation etc.

11. Program Advisory Committee/experiment proposals: No

12. Future Plans:

The neutron generator will be coupled with India's first sub-critical system.

13. Picture/Schematic:

Figure 4: 14 MeV neutron generator at Purnima Laboratory, BARC, Mumbai

14. Sources of information:

Tarun Patel and Dr. Amar Sinha, "Development of low energy deuteron accelerator based dc and pulsed neutron generators", BARC Newsletter, Founder's day special issue October 2013, Page no: 146-149.

2.1.3 10 MeV electron RF LINAC

1. Name and address of the Institute:
Electron Beam Centre, BARC, Kharghar, Navi Mumbai, India

2. Person in charge of the Facility:
M. Kumar (mukesh_kishu@yahoo.com)
Accelerator & Pulse Power Division, BARC

3. Type of Accelerator:
10 MeV electron RF LINAC

3.1. Name of the Company or Supplier:
The 10 MeV electron LINAC is designed and constructed by BARC in collaboration with SAMEER.

4. Beam details:

Beam Particles	Electrons
Operating Beam Energy	8- 10 MeV
Beam current (Average)	33 mA
R.F. Peak Power	6 MW [Pulsed]
Type of Oscillator	Klystron
Working Frequency	2856 MHz
Repetition Rate	310 Hz
Pulse Width	10 μs
Maximum Gun Voltage	50 KV
Operating Vacuum	1×10^{-7} Torr

5. Approximate/expected date of installation/commission: 2000

6. Pulsed or D.C. operation: Pulsed

7. Is the facility utilized for neutron physics experiments? : No.

8. Is the facility available for outside user?
DAE scientists have used the facility and few university professors for photon induced nuclear cross section measeurements.

9. Type of experiments being carried out:
Irradiation of environment friendly waste disposal of PCB, for food processing, irradiation of polymer blend samples, irradiation of power diodes to reduce reverse recovery time,

photon induced fission cross sections and nuclear cross section measurements for structural materials etc.

10. Program Advisory Committee/experiment proposals: No

11. Picture/Schematic:

Figure 5: 10 MeV electron LINA facility at Electron Beam Centre, BARC, Kharghar, Mumbai.

12. Sources of information:

R.C.Sethi et. al., "10 MeV, 10 kW Industrial RF electron LINAC for material processing", Proceedings of the Indian Particle Accelerator Conference, Kolkata, March 1-5, 2005 (InPAC 2005), p-122.

M.Kumar et. al., "Utilization of 10 MeV RF electron linear accelerator for research and industrial applications",IJPAP, 50 (2012) 802-804

R. Crasta, H. Naik, S.V. Suryanarayana, Ganesh Sanjeev, P. M. Prajapati, M. Kumar, T .N. Nathaniel, V.T. Nimje, K.C. Mittal, "Measurement of Photo-neutron reaction Cross- Section of 93Nb at end point bremsstrahlung energy of 10 MeV", Proceedings of the DAE Symp. on Nucl. Phys. 56 (2011) 1032 Available online at www.sympnp.org/proceedings.

2.1.4 3 MeV electron accelerator

1. Name and address of the Institute:
Electron Beam Centre,BARC, Kharghar, Navi Mumbai, India

2. Person in charge of the Facility:
M. Kumar (mukesh_kishu@yahoo.com)
Accelerator & Pulse Power Division, BARC

3. Type of Accelerator:
3 MeV, 30 kW DC electron accelerator

4. Beam details:

Beam Particles	Electrons
Operating Beam Energy	1 - 3 MeV
Maximum Gun Voltage	5 KV
Maximum Current	0 - 10 mA

5. Approximate/expected date of installation/commission: After 2000

6. Pulsed or D.C. operation: DC

7. Is the facility utilized for neutron physics experiments? : No.

8. Is the facility available for outside user? : Yes

9. Type of experiments being carried out:
Irradiation of environment friendly waste disposal of PCB,
for food processing,
irradiation of polymer blend samples,
irradiation of power diodes to reduce reverse recovery time.

10. Program Advisory Committee/experiment proposals: No

11. Picture/Schematic:

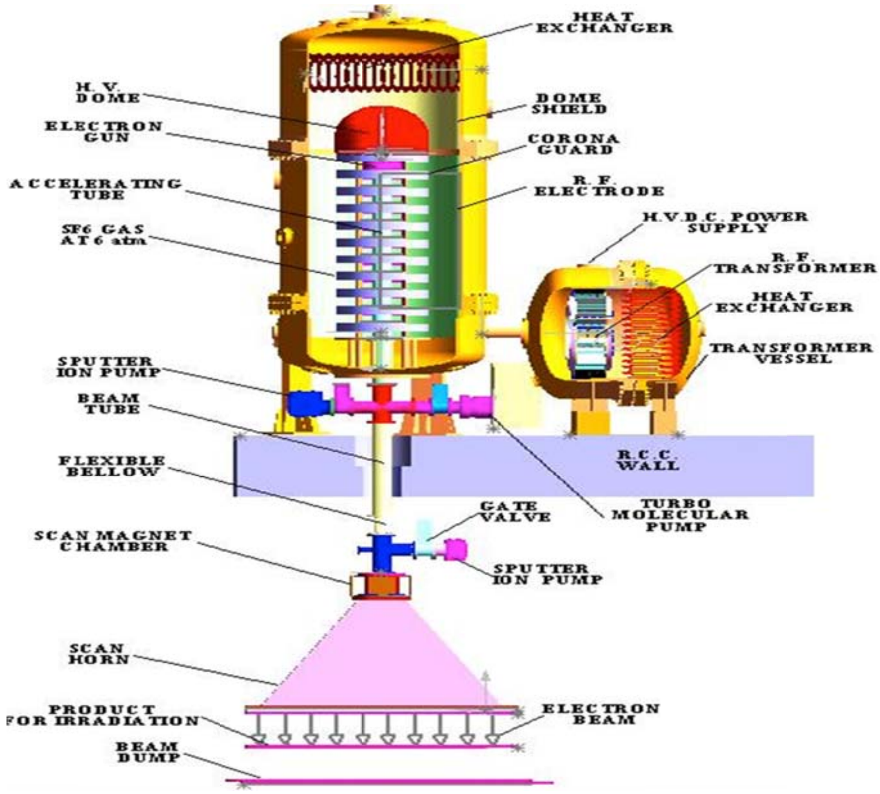

Figure 6: 3 MeV electron accelerator at Electron Beam Centre, BARC, Kharghar, Mumbai.

12. Sources of information:

K.C. Mittal, "Status of industrial electron linac development programme at BARC, india", Proceedings of Indian Particle Accelerators Conference 2011 (http://www.iuac.res.in/event/InPAC11/proceedings/InPAC2011%20Proceedings/I-20/KCMittal.pdf)

K. Nanu et al., "Development of 3 MeV, 30 kw DC electron accelerator at EBC, kharghar", THPMA043 ,APAC 2007, Raja Ramanna Centre for Advanced Technology(RRCAT), Indore, India https://accelconf.web.cern.ch/accelconf/a07/PAPERS/THPMA043.PDF

2.1.5 16.5 MeV Medical cyclotron

1. Name and address of the Institute:

Radiation Medicine Centre, BARC, Annex Building, Tata Hospital Campus, Jerbai Wadia Road, Dadar East, Mumbai, Maharashtra 400012

2. Person incharge of the Facility:

Dr. Sharmila Banerjee (sharmila@barc.gov.in) Senior General Manager, Medical Cyclotron Facility, RMC, Rarel, Mumbai-400 012

3. Type of Accelerator:

16.5 Medical cyclotron **(GE)**

4. Beam details:

Beam Parameters	Max. Energy(MeV)	Max. Current(μA) Variable CUrrent
H^-	16.5 (fixed)	75 (Single beam) 40 (Double beam)
D^-	4 (fixed)	60 (Single beam) 30 (Double beam)
Radionuclides that can be produced	18F, 11C, 13N & 15O	

6. Approximate/expected date of installation/commission: 2002

7. Is the facility utilized for neutron physics experiments? :

The facility is devoted for radioisotope production for medical sciences.

8. Is the facility available for outside user? : No

9. Major experimental facilities available:

Cyclotron, 16.5MeV proton & 4 MeV deuteron, Automated [18F]FDG synthesizer, Gas Processing Unit for preparation of [15O]H2O and [11C]CH3 I , PET

10. Type of experiments being carried out:

Isotope Production and PET.

11. Program Advisory Committee/experiment proposals: No.

12. Picture/Schematic:

Figure 7: 16.5 MeV Medical Cyclotron at RMC, Mumbai

15. Sources of information:

M.G.R. Rajan, Saikat Nandy, N. Lakshminarayanan, B.K. Sharma, Arpit Mitra, Amit Kumar, Shrinibas Nayak, Kanchan Kushwaha, Arjun G, R. Chinagandham, Yuvraj N., "BARC Medical Cyclotron Facility: Performance and Achievements in the First Decade after Commissioning", BARC Newsletter Issue No. 329 (2012) 41-47

P.V.Bhagwat, "Safety aspects in particle accelerators", Paper presented in 33rd Safety and Occupational Professionals Meet IPR, 23-25th November 2016 (http://www.ipr.res.in/33rd-DAE-Meet/documents/Safety-aspects-particle%20accelerator.pdf)

See also: http://www-pub.iaea.org/mtcd/publications/pdf/p1251-cd/presentations/a5_bhagwat.pdf
http://www.britatom.gov.in/htmldocs/mcf.html

2.2 Guru Ghasidas Vishwavidyalaya

2.2.1 3 MV Tandetron Accelerator, Guru Ghasidas Vishwavidyalaya, India

1. Name and address of the Institute:

National Centre for Accelerator based Research, Department of Pure and Applied Physics, Guru Ghasidas Vishwavidyalaya, Bilaspur-495009, India

2. Person incharge of the Facility:

Dr. P. K. Bajpai (bajpai.pk1@gmail.com) Professor and Head, Deparment of Pure and Applied Physics, GGV, Bilaspur, India

3. Type of Accelerator:

3 MV Tandem Accelerator (Pelletron 9SDH- 4)

4. Beam/Machine details:

At terminal voltage of 3 MV, following beam parameters are expected. Beams are negative ions.

Beam	Max. Beam Energy (MeV)	Max. Beam Current(μA)
^{1}H	6	50
^{4}He	9	10
^{7}Li	12	1.50
^{10}B	18	0.020
^{12}C	21	0.018
^{14}N	18	0.050
^{15}N	15	0.352
^{16}O	27	0.14
^{19}F	24	0.024
^{23}Na	18	0.0050
^{28}Si	27	0.88
^{31}P	18	5
^{58}Ni	36	0.044
^{90}Zr	21	0.018
^{197}Au	39	0.0264

5. Pulsed or D.C. operation: Not Specified

6. Approximate/expected date of installation/commission: November 2014

7. Is the facility utilized for neutron physics experiments? :

The high proton beam current available ~ 50□Amp at 6 MeV will be used for ^{7}Li(p, n) reaction for generating quasi-mono energetic source of neutrons to produce high neutron flux. The expected neutron flux is ~ 4.5x10^9 neutrons/cm^2/sec as it has high proton beam current of ~50□Amp.

8. Is the facility available for outside user? :

The facility is available to research institutions and universities in the country. For last two years the centre is providing beam time to various external users and so far more than twenty experiments have been successfully conducted.

9. Major experimental facilities available:

The accelerated positive ions from the pelletron can be delivered to one of three beam lines (i) MeV ion implanter at the end of the -10□□beam line and (ii) an RC43 RBS End Station equipped with detectors for PIXE, NRA, ERDA and channeling for ion beam analysis as well as ion irradiation facilities at the 20□□port of the analyzing magnet. A third beam line at the 0□□port of the injector magnet will be used for low energy high current proton beam for neutron generation.

10. Type of experiments being/to be carried out:

Nuclear Physics, Material Science Nanotechnology, Environmental Sciences, Life Sciences, Biotechnology, and Radiation Biology. It includes ion beam analysis techniques such as RBS, PIXE, NRA, RDA, and low (keV) and high energy (MeV) range ion implantation. Further, this facility will provide plat-form for low energy nuclear physics community for extensive studies in the areas related to nuclear astrophysics, neutron-induced reactions, measurements of neutron scattering cross sections, sub-barrier fusion reactions.

11. Program Advisory Committee/experiment proposals: No.

12. Picture/Schematic:

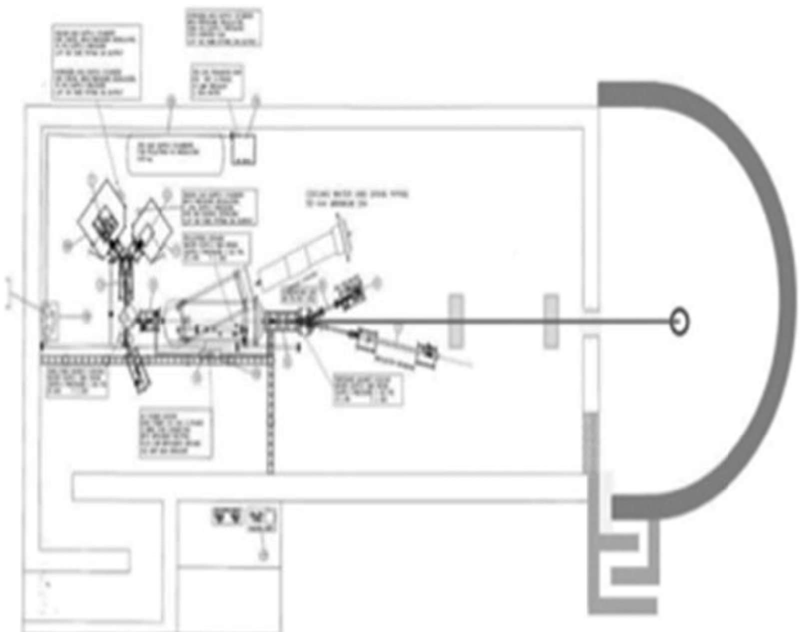

Figure 8: Planned facility for neutron generation using 3MV pelletron accelerator, GGU, Bilaspur

Figure 9: 3 MV Tandetron Accelerator at GGU, Bilaspur

15. Sources of information:

P. K. Bajpai, T. Trivedi, Shiv. P. Patel, C. Mallik and L.Chaturvedi, “National Centre for Accelerator based Research at GGV Bilaspur: Emerging facility for Neutron Generation”, Proceedings of the DAE Symp. on Nucl. Phys. 58 (2013) 962.

Private Communication with Dr. P.K. Bajpai, GGV, Bilaspur.

2.3 Indian Institute of Technology, Kanpur

2.3.1 1.7 MV Tandetron Accelerator, IIT Kanpur, India

1. Name and address of the Institute:
Indian Institute of Technology, Kanpur, Kalyanpur, Kanpur, Uttar Pradesh 208016, India

2. Person incharge of the Facility:
Dr. Aditya H. Kelkar (akelkar@iitk.ac.in)

3. Type of Accelerator:
3.1 **1.7 MV Tandem Accelerator**

3.2 **Name of Supplier:** High Voltage Engineering Europa (HVEE), Netherlands

4. Beam/Machine details:
The terminal voltage is in the range of 100 KV – 1.7 MV with high voltage stability of 30 V. The accelerator is equipped with a dual source injector system, which includes (i) a negative sputter ion source Model 860C for producing ions of heavy elements and (ii) a duoplasmatron ion source model 358 for producing ions of H and He.

Beam	Max. Beam Current(μA)
^{1}H	25
^{4}He	2
^{11}B	20
^{16}O	80
^{28}Si	140
^{31}P	35
^{58}Ni	10
^{63}Cu	15
^{197}Au	50

5. Pulsed or D.C. operation: DC

6. Approximate/expected date of installation/commission: August 2016

7. Is the facility utilized for neutron physics experiments? :
The facility can be utilized for neutron source using 7Li(p,n)7Be reaction. However, the facility is not yet utilized for neutron source.

8. Is the facility available for outside user? :
The facility will is available to research institutions and universities in the country.

9. Major experimental facilities available:

Thermal deposition system (Make: Consolidated Vacuum Corporation, New York)

For electrical measurements: Keithley source meter 6430 :
Vacuum and air annealing set up [upto 1400^{0}C]
He leak detector
Deionised Water Plant
SPIN Coater

10. Type of experiments being carried out:

RBS and Channelling
Proton beam writing (focussing protons down to ~ 400 nm)
Ionoluminescence
PIXE
ERDA - Forward Scattering

11. Program Advisory Committee/experiment proposals: Yes (Please see https://www.iitk.ac.in/ibc/)

12. Picture/Schematic:

Figure 10: 1.7 MV tandetron accelerator at IIT, Kanpur.

15. Sources of information:

High Voltage Engineering Europa Netherland Brochure: HVEE Brochure

1.7 MV hc Tandetron Accelerator Lab (https://www.iitk.ac.in/ibc/index.htm)

2.4 Indira Gandhi Centre for Atomic Research, Kalpakkam, Tamilnadu, India

2.4.1 1.7 MV Tandetron Accelerator, IGCAR, Kalpakkam,India

1. Name and address of the Institute:

Indira Gandhi Centre for Atomic Research, Kalpakkam, Tamil Nadu 603102

2. Person incharge of the Facility:

Dr. A.K. Bhaduri, Director, IGCAR

3. Type of Accelerator:

1.7 MV Tandem Accelerator

4. Beam/Machine details:

Terminal Voltage	Upto 1.7 MV
Ions of almost all elements in the periodic table	0.3 MeV to 1.7(1+q) MeV
Beam Current	few μA

5. Pulsed or D.C. operation: DC

6. Approximate/expected date of installation/commission: Recent

7. Is the facility utilized for neutron physics experiments? :

The facility has never been used for neutron physics experiments as per literature survey.

8. Is the facility available for outside user? :

The facility is available to research institutions and limited universities in the country.

9. Major experimental facilities available:

Multipurpose Scattering Chamber
Beam lines for RBS/Channeling, PIXE, Implantation

10. Type of experiments being carried out:

Ion beam characterization work RBS technique
Ion Implantation RBS, PIXE, ERDA, NRA, Channeling
Radiation enhanced diffusion and segregation

11. Program Advisory Committee/experiment proposals: No

12. Picture/Schematic:

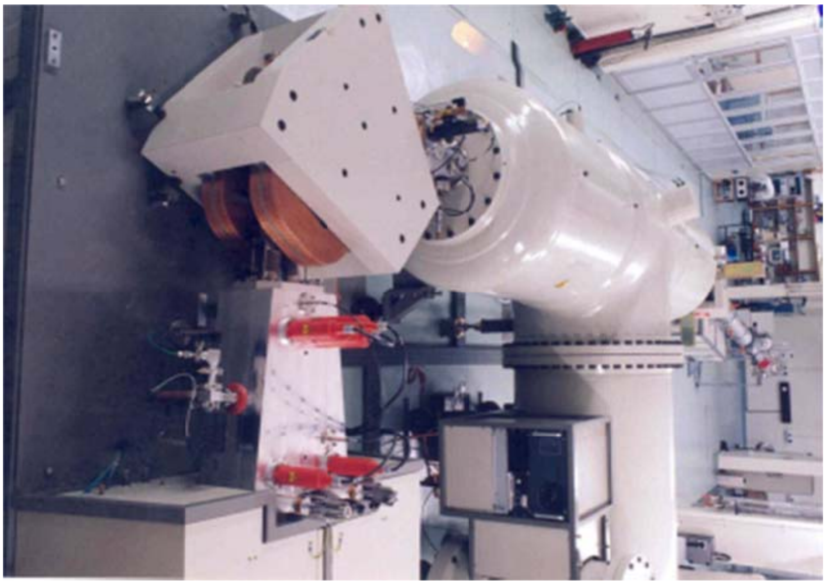

Figure 11: 1.7 MV Tandetron Accelerator at IGCAR, Kalpakkam

13. Sources of information:

R. Ravisankar et al, "Gamma-ray spectroscopic and PIXE analysis of beach rock samples of south east coast of Tamilnadu, India" *Int. J. PIXE* **17**, 193 (2007).

See also http://www.iopb.res.in/~alumni/Sundaravel.pdf

2.5 Institute of Physics, Bhubhaneswar

2.5.1 3 MV Pelletron Accelerator, IOP, Bhubhaneswar , India

1. Name and address of the Institute:

Institute of Physics, Sachivalaya Marg, Bhubaneswar, Odisha 751005, India

2. Person incharge of the Facility:

Prof. Sudhakar Panda (panda@iopb.res.in), Director, IOP, Bhubhaneswar
Prof. S.Sahoo (sahoo@iopb.res.in), Professor in charge, IOP, Bhubhaneswar

3. Type of Accelerator:

3 MV tandem type Pelletron Accelerator (NEC model 9SDH-2), MCSNICS ion source

4. Beam/Machine details:

Terminal Voltage	0.5 – 3 MV
Positive Ion beam energy of H, He, Li,C,Si,Cu,Ag,Au	1-12 MeV
Beam Current	The beam currents on target range from a few nano-Amperes to a few tens of nano-Amperes.

5. Approximate/expected date of installation/commission: 1992

6. Is the facility utilized for neutron physics experiments? :

The facility has never been used for neutron physics experiments as per our literature survey.

7. Is the facility available for outside user? :

The facility is available to research institutions and universities in the country.

8. Major experimental facilities available:

Multipurpose Scattering Chamber
HPGe Detectors
Beam lines for RBS/Channeling, ERDA (End Station from NEC), PIXE, Implantation, and AMS
50 keV Low Energy Ion implanter – SNICS ion source
Focused Ion Beam (FIB) (Zeiss-make): 2 keV – 30 keV (in combination with FEGSEM) Low Energy Broad Beam Ion Source (Tectra GmbH-make): 50 eV – 2 keV for ion etching work (ion source coupled with Prevac-make chamber)

9. Type of experiments being carried out:

The accelerator facility is being used for studies that require IBA techniques such as RBS, ion-channeling, PIXE etc. The facility is also being used for ion-implantation and irradiation studies. Accelerator Mass Spectrometry of radiocarbon is another important feature of IBL.

The main focus of the research has been on ion beam modification and analysis of materials. Some of the major physics issues, which are being addressed include The following: Thin film growth related phenomena, ion beam mixing, defects and diffusion in semiconductors, magnetism in thin films, ion beam synthesis and modification of nanostructures, irradiation response of nano-dimensional noble metal islands, and surface nanostructuring by ion beams. The facility has also been used for measurements of Fusion cross sections for 6,7Li + 24Mg reactions at energies below and above the barrier.

10. Program Advisory Committee/experiment proposals:

Yes. Beam schedule is prepared monthly and circulated to the users on 1st of every month. Alphatross ion-source is used for RBS runs.

11. Future Plans:

Upgradation of irradiation chamber that will be equipped with a load lock chamber and a 5-axes sample manipulator with low- and high-temperature sample holders.

Plan to facilitate theon-line heavy ion induced RBS and ERDA techniques in the process of developing a new ECRIS based low-to-medium energy ion beam facility. This facility will be able to provide ion beams at a wide range of energies (a few tens of keV to a few MeV) for experiments in condensed matter physics and nanoscience.

12. Picture/Schematic:

Figure 12: 3 MV Pelletron accelerator at IOP, Bhubhaneswar

Figure 13: Scattering chamber and detectors at IOP, Bhubhaneswar

15. Sources of information:

G.V. Ravi Prasad, D.P. Mahapatra, A.M. Punithavelu, B.L.K. Somayajulu, K. Gopalan, "Status of the AMS project at IOP Bhubaneswar", Nuclear Instruments and Methods in Physics Research B 172 (2000) 66-69

D.P.Mahapatra, B.L.K.Somayajulu, K.Gopalan, "Development of AMS facility at Institute of Physics(IOP) Bhubhaneswar", Indian Journal of Pure & Applied Physics, 39(2001)29-31

M.Ray, A.Mukherjee, M.K.Pradhan,Ritesh Kshetri, M.Saha Sarkar, R.Palit, I.Majumdar, P.K.Joshi, H.C.Jain, "Fusion cross sections for 6,7Li + 24Mg reactions at energies below and above the barrier", Physical Review C 78 (2008) 064617

2.6 Inter University Accelerator Centre (IUAC)

2.6.1 15 UD Pelletron Accelerator

1. Name and address of the Institute:

Inter-University Accelerator Centre(IUAC), New Delhi 110067, India

2. Person incharge of the Facility:

Dr. D. Kanjilal(dk@iuac.res.in), Director, IUAC

3. Type of Accelerator:

15 UD Pelletron with superconducting LINAC booster

4. Beam details:

Beam Species	Max. Energy	Max. current/Intensity
^{1}H, $^{6,7}Li$, ^{9}Be, $^{10,11}B$, $^{12,13}C$, ^{14}N, $^{16,18}O$, ^{19}F, ^{24}Mg, ^{27}Al, $^{28,29,30}Si$, ^{31}P, $^{32,34}S$, $^{35,37}Cl$, ^{40}Ca, ^{45}Sc, $^{46,48,50}Ti$, ^{51}V, $^{56,57}Fe$, ^{58}Ni, ^{63}Cu, ^{64}Zn, ^{74}Ge, $^{107,109}Ag$, ^{120}Sn, ^{127}I, ^{159}Tb, ^{181}Ta, ^{197}Au, ^{208}Pb	8-10 MeV/A	1 -10 pnA depending upon the ion

5. Approximate/expected date of installation/commission: 1991

6. Pulsed or D.C. operation: DC as well as pulsed with repetition rate of 250 ns.

The Pelletron of IUAC produces DC as well as pulsed ion beams of several of elements having energy up to 15 MV per charge state. Pulsed beams with time width in the range 1ns(for protons) to 2 ns(for heavier ions) at 12 MHz repetition rate.

7. Is the facility utilized for neutron physics experiments? :

The facility has never been used as neutron source for neutron physics experiments as per the literature survey done by the authors.

8. Is the facility available for outside user? :

Yes, the facility is available for researchers across the country.

9. Major experimental facilities available:

Indian National gamma Array (INGA): 24 Clover Detector array with a total photo-peak detection efficiency of ~5%

Gamma Detector Array (GDA): 12 Compton suppressed HPGe detectors setup
Heavy Ion Reaction Analyzer (HIRA): One of few recoil mass spectrometers (RMS) in the world and first of its kind in Asia dedicated to the study of heavy ion induced nuclear reaction dynamics.
Hybrid Recoil mass Analyzer (HYRA)
General Purpose Scattering Chamber (GPSC): A1.5 m diameter scattering chamber equipped with rotating arms and in-vacuum target transfer system.
National Array of Neutron Detectors (NAND): About100 organic liquid scintillators of 5" diameter and 5" thickness for fission fragment in coincidence with neutrons studies.
Accelerator Mass Spectrometry (AMS): The IUAC AMS facilty comprises of Multicathode SNICS source, re-circulating gas stripper, offset Faraday cup, Wien Filter, AMS chamber, insertable Faraday cup, Gas Cell absorber and Multi-Anode Gas Ionization Chamber (MAGIC). The AMS facility for 10Be measurements is in operation and recently 26Al measurements from standard samples have also been added.

10. Type of experiments being carried out:

The research activities at the Centre can be grouped in the areas of Nuclear reactions near Coulomb barrier, High spin spectroscopy, Spectroscopy of highly charged ions, Interaction of swift heavy ions with materials, Materials characterization, Materials Modification, Device fabrication, Radiation Biology, Accelerator Mass spectroscopy etc.

In nuclear physics, the major emphasis in reaction dynamics studies has been to explore the role of nuclear structure effects in the sub- and near barrier fusion process. Experiments have been carried out to isolate the target deformation effects and understand how they alter the observed spin distribution. The role of transfer channels in enhancing fusion cross section has been investigated both experimentally and theoretically. Measurement of precise fusion cross-sections has been conducted to obtain a reliable barrier distribution for heavy nuclei. A modified neutron flow model has been developed for understanding the fusion systematics in the barrier region. For heavy nuclei, the dynamical effects of fission delay have been investigated through a measurement of the spin distribution of fusion evaporation residue. Data from GDR and particle emission have been used to investigate nuclear shapes and level densities at high spin. For the study of nuclear spectroscopy, the emphasis has mainly been on the study of high spin structure of transitional nuclei and nuclei near shell closure. The systematics of high spin levels in nuclei in the mass region ~ 75, ~90, ~120, ~130 and ~ 160 have been carried out in the last few years to investigate the interplay of single particle, vibrational and rotational degrees of freedom and the co-existence of these structures. Measurements of quadrupole moments of several nuclei have been carried out using the DSAM, RDM and hyperfine interaction studies. The current emphasis is on complete nuclear spectroscopy using information from $\gamma-\gamma$, e-γ and life time measurements. The nuclear physics programme touches almost all current thrust areas of nuclear structure and nuclear dynamics at energies around or slightly above the interaction barrier of the projectile-target systems. Regarding detector systems, the future availability of HYRA in combination with INGA would offer a world-class competitive tool for exotic nuclear structure studies.

11. Program Advisory Committee/experiment proposals:

Yes, Accelerator User Committee (AUC) is responsible for allocating projects and experiments.

13. Future Plans:

The High Current Injector (HCI) project was envisaged to overcome the low current limitation of the Pelletron Accelerator and to provide varieties of ion species like Nobel gases etc. which are not possible with existing Pelletron Accelerator. The high current from HCI will not only reduce the number of shifts needed for carrying out the experiments but will also enable users to carry out very low cross section nuclear reactions studies which are not possible using beams from Pelletron due to its low current limitations. The HCI would use a Radio Frequency Quadrupole (RFQ), Drift Tube Linac (DTL) and low beta superconducting cavities to accelerate heavy ions having A/q ≤ 6, from the high temperature superconducting electron cyclotron resonance ion source (HTS-ECRIS called PKDELIS) to the existing superconducting linear accelerator (SC LINAC). The DTL has been designed to accelerate ions from 180 keV/u to 1.8 MeV/u, using six Interdigital-H (IH) type RF resonators operating at 97 MHz.

14. Picture/Schematic:

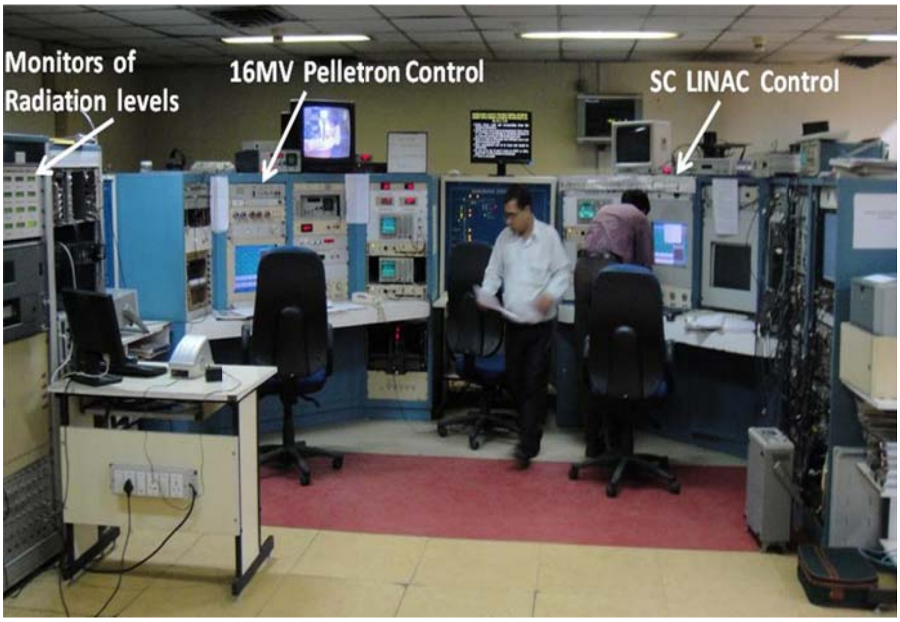

Figure 14: Control room of 15 UD Pelletron Facility at IUAC, New Delhi

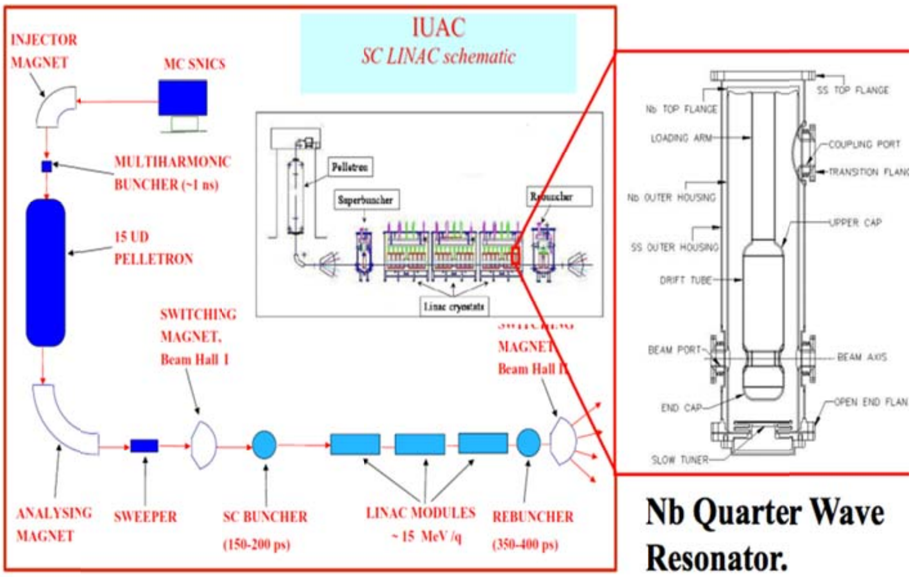

Figure 15: Schematic of 15 UD Pelletron LINAC Facility at IUAC, New Delhi.

15. Sources of information:

1. Walter Henning and Wim van Oers, "A Worldwide Perspective Of Research And Research Facilities in Nuclear Physics by the IUPAP Working Group 9", IUPAP Report 41, 2014.

2. Information Brochure of IUAC, New Delhi, http://www.iuac.res.in/aboutus/info/infobro.pdf

3. http://www.iuac.res.in/event/ijschool/16/DKanjilal.pdf

4. Ruchi Mahajan et. al., "Neutron multiplicity measurements for 48Ti+144,154Sm systems", Proceedings of the DAE-BRNS Symp. on Nucl. Phys. 60 (2015) 498.

2.7 Mangalore University

2.7.1 Variable energy Microtron

1. Name and address of the Institute:
Mangalore University, Mangalagangotri, Mangalore, Karnataka 574199, India

2. Person incharge of the Facility: Prof. Ganesh Sanjeev **(**ganeshsanjeev@rediffmail.com**)**

3. Type of Accelerator:
Variable energy Microtron

4. Beam details:

Beam Species	Max. Energy	Max. Current/Intensity
Electron	8/12 MeV	50 mA

5. Approximate/expected date of installation/commission: 1995

6. Pulsed or D.C. operation: Pulsed beam with pulsed width 2.5 μs and pulse rate 250 Hz.

7. Is the facility utilized for neutron physics experiments? :
The bremsstrahlung photons from the Microtron are made to fall on cylindrical beryllium discs of appropriate dimension to get fast neutrons. The fast neutrons are thermalised using high density polyethylene (HDPE), borated wood and borated rubber. Accelerator based pulsed neutron sources can provide neutrons of thermal energies (0.025eV) to several MeV. A neutron yield of 10^9 n/sec was obtained theoretically for beryllium thickness of 6cm at 50 Hz PRR.

8. Is the facility available for outside user? :
The facility is mainly devoted for graduate and Ph.D programmes in the Mangalore University.

9. Major experimental facilities available:
Fission chamber and SSNTD facility
Ag wrapped GM tubes for Neutron detection
41.2% relative efficiency HpGe Detector
30% relative efficiency HpGe Detector
3” X 3” Flat and 5” x 5” well type NaI(Tl) Spectrometers
High sensitive ionisation chamber based radiation survey meters (Victoreen & Ludlum) with range of 1 R/h to a few R/h

10. Type of experiments being carried out:
The research areas include Radiation Dosimetry Studies Chemical Dosimeters - Fricke, FBX, Alanine & Glutamine TL dosimeter - CaSO4:Dy, Clinical Dosimetry Comparison / Calibration Studies, Semiconductor Irradiation Studies Power Diodes, Schottky diodes, Transistors, MOSFETs, Solar Cells etc. Photofission Studies Cross-section, Angular Distribution of fission fragments, Radiation Biophysics Chromosome Aberration, Micronucleus Induction in human blood lymphocytes, Cell Survival and Gene Conversion, Relative Biological Effectiveness, Radiation Processing Coffee seed, Onion, Potato, Spices, Seeds of non-conventional legumes –

canavalia, Mucuna Pruriens seeds, Vanilla beans, Bakery items, ayurvedic & siddha medicines, etc have been carried out. Apart from that, Irradiation studies on Polymer, Hydrogel, Thin films, Nano particles, Ferroelectric materials, Crystals – NLO, TGS and other organic crystals, etc have also been performed. The facility is also utilized for Photon & Neutron based studies - Activation Experiments.

11. Program Advisory Committee/experiment proposals: No

13. Future Plans:

Up-gradation of the existing accelerator facility with higher beam power to cater to the needs of the Microtron Users is planned with the support of BRNS. Detailed neutron based studies on various aspects would be taken up.

14. Picture/Schematic:

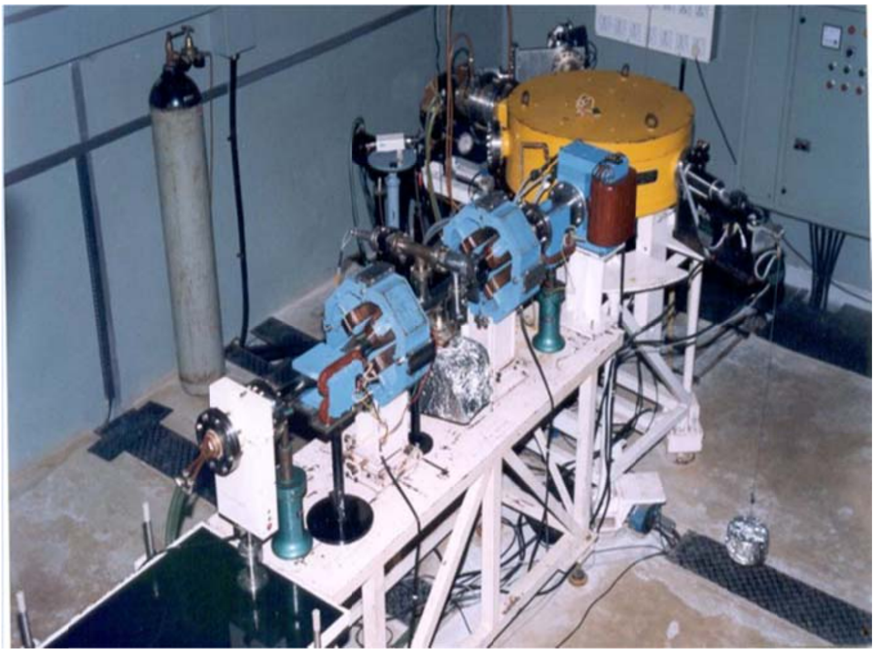

Figure 16: 8 MeV Microtron at Mangalore University, India

15. Sources of information:

Presentation of Prof. Ganesh Sanjeev, the link is given below (http://indico.vecc.gov.in/indico/getFile.py/access?resId=41&materialId=30&confId=9)

2.8 National Centre for Compositional Characterisation of Materials (CCCM), Hyderabad

2.8.1 3 MV Tandetron Accelerator, NCCCM, Hyderabad, India

1. Name and address of the Institute:

National Centre for Compositional Characterisation of Materials (CCCM), NFC, Moula Ali, Secunderabad, Telangana 500062

2. Person incharge of the Facility:

Dr. Sunil Jai Kumar (suniljai@barc.gov.in), Head, NCCCM, Hyderabad

3. Type of Accelerator:

3 MV Tandetron Accelerator

4. Beam/Machine details:

Terminal Voltage	Upto 3 MV, beam stability is +-300 V
Proton Li, B, Al, Mg beams are also produced	2-3 MeV and maximum current is 5 μA

5. Pulsed or D.C. operation: DC

6. Approximate/expected date of installation/commission: 1995

7. Is the facility utilized for neutron physics experiments? :

The facility has never been used for neutron physics experiments as per our literature survey.

8. Is the facility available for outside user? :

The facility is available to research institutions and universities in the country.

9. Major experimental facilities available:

Multipurpose Scattering Chamber
HPGe Detectors
Semiconductor detectors Ge(Li) etc
Beam lines for RBS/Channeling, PIXE,PIGE , Implantation
X-Ray Photoelectron Spectroscopy system

10. Type of experiments being carried out:

It is being used for a number of analytical experiments, including depth profiling of hydrogen and fluorine, nitrogen, using nuclear resonance reaction analysis, determination of low Z elements, compositional analysis of hard coatings, analysis of porous silicon and compositional analysis of several alloys and composite materials, compositional analysis and thickness determination by RBS, elemental analysis of bulk material by PIXE and PIGE, Determination of boron concentration in borosilicate glass, boron carbide and graphite samples, Element Analysis of Medicinal Plants etc.

11. Program Advisory Committee/experiment proposals:
The Program Advisory Committee looks after the proposals.

12. Picture/Schematic:

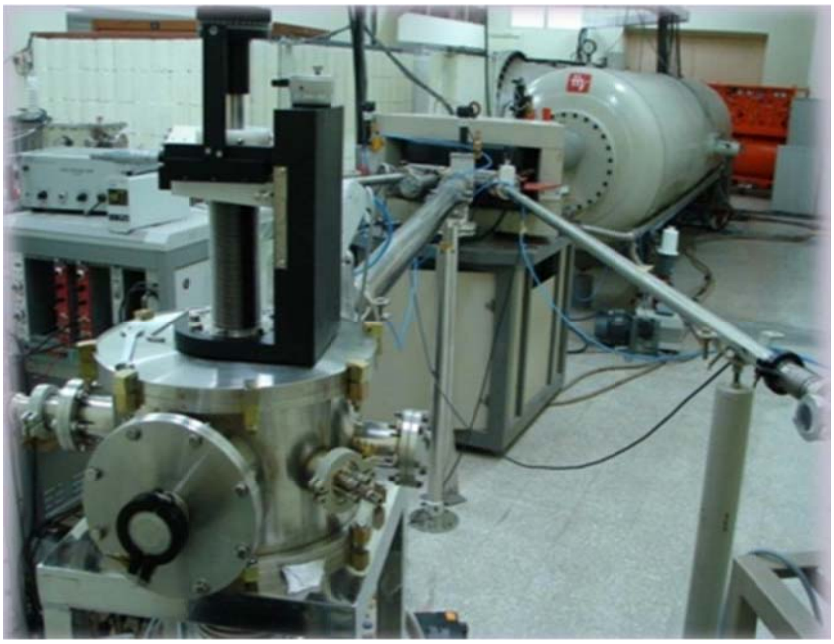

Figure 17: 3 MV Tandetron Accelerator at NCCCM, Hyderabad

15. Sources of information:

S.Kumar, S.Vikram Kumar, G.L.N.Reddy, V.Kain, J.V.Ramana, V.S.Raju,"Depth profiling of nitrogen using 429 keV and 897 keV resonances in the 15N(p,ag)12C reaction.
Nuclear Instrumentation Methods B 240 (2005) 704

Also see http://shodhganga.inflibnet.ac.in/bitstream/10603/139639/6/06_chapter%203.pdf

2.9 Panjab University

2.9.1 Low Energy Cyclotron

1. Name and address of the Institute:
Panjab University, Sector 14, Chandigarh, 160014, India

2. Person incharge of the Facility:
Prof. B.R. Behera (bivash@pu.ac.in)

3. Type of Accelerator:
The low-energy cyclotron at Panjab University, Chandigarh was installed with the renovated components of the variable energy cyclotron from University of Rochester, New York, USA. This machine is a single Dee classical cyclotron with a variable frequency in the range of 10–20 MHz. The maximum magnetic field of main magnet can be used up to 14 k Gauss.

4. Beam/Machine details:

Beam	Energy
Proton	2-3 MeV

5. Pulsed or D.C. operation: DC

6. Approximate/expected date of installation/commission: early 1970's

7. Is the facility utilized for neutron physics experiments? :
As per our literature survey and from the EXFOR Database, the facility has never been used for neutron physics experiments.

8. Is the facility available for outside user? :
The facility is available to research institutions and universities in the country.

9. Major experimental facilities available:
Multipurpose Scattering Chamber
HPGe Detectors
Beam lines for RBS/Channeling, PIXE,PIGE , Implantation

10. Type of experiments being carried out:
Elemental Analysis by PIXE and PIGE techniques
Coulomb Excitation
Lifetime Measurements using RDM & DSAM techniques
Systematics of Mechanism of Heavy Ion induced reactions
Nuclear Reaction Dynamics
Proton Induced Modifications in Materials

11. Program Advisory Committee/experiment proposals: No

12. Picture/Schematic:

Figure 17: Scattering chamber area at low energy cyclotron, Panjab University

15. Sources of information:

http://physics.puchd.ac.in/cyclotron/

http://physics.puchd.ac.in/singhkp/research-lab.html

Private Communication with Dr. A.Tyagi, Banaras Hindu University, India

2.10 Raja Ramanna Centre for Advanced Technology, Indore, India

2.10.1 Synchrotron Radiation Source Indus-1

1. Name and address of the Institute:

Raja Ramanna Centre for Advanced Technology, Indore-452013, Madhya Pradesh, India

2. Person incharge of the Facility:

Dr. P.A. Naik (panaik@rrcat.gov.in) Director, RRCAT, Indore
Shri A.C. Thakurta (thakurta@rrcat.gov.in), Director, Electron Acceleration Group, RRCAT, Indore

3. Type of Accelerator:

Synchrotron Radiation Source Indus-1, India's first Synchrotron Radiation Source, Indigenously developed.

4. Beam/Machine details:

The synchrotron radiation source Indus-1 thus consists of a 20 MeV microtron, a 450 MeV synchrotron and a storage ring Indus-1. The layout of the Indus facility is shown in Figure 1. The electrons are generated and accelerated to 20 MeV in the microtron. After extracting the beam from the microtron, the beam is transported to the synchrotron through transfer line-1 (TL-1). A long pulse of 1 ms is injected into the synchrotron; the energy of the electrons is increased from 20 MeV to 450 MeV. After acceleration to 450 MeV , the electrons are extracted from the synchrotron and then transported to the storage ring Indus-1 through the transfer line-2 (TL-2). This process of production, acceleration and injection is carried out every second till the stored current is 100 mA in the storage ring Indus-1. In the storage ring, the electron beam keeps circulating for a few hours emitting synchrotron radiation continuously in the dipole (bending) magnets. The beam life time at 100mA is 75 minutes at present. The parameters of Indus- 1 are shown in Table-1.

Energy	450 MeV
Current	100 mA (achieved 200 mA)
Bending Field	1.5 T
Circumference	18.96m
Operating point	1.69, 1.31
Beam Emittance εx	$1.5x10^{-7}$ mrad
□□□□□□□□□□□□□□□□□□□□□ □□□□□□□□εz	$1.5x10^{-8}$ mrad

Beam Size σx σz	0.28 mm 0.07 mm
Energy spread	3.85×10^{-4}
Momentum compaction	0.235
Chromaticities (ξx,z)-1.9,-0.3 (measured -2.6,+3.1)	
Revolution frequency	15.82 MHz
Harmonic number	2
Power loss	0.36kW ; 0.05kW

Indus-1 and Indus-2 have a common injection system which consists of a microtron and a booster synchrotron. The microtron injector developed at CAT is a classical type microtron which gives 20 MeV electron beam with a current of 30mA in pulses of 1 to 2 μs duration at a repetition rate of 1 to 3 Hz.

5. Pulsed or D.C. operation: Pulsed

6. Approximate/expected date of installation/commission: May 1999

7. Is the facility utilized for neutron physics experiments? :

The facility has never been used for neutron physics experiments as per our literature survey.

8. Is the facility available for outside user? :

The facility is available to research institutions and universities in the country.

9. Major experimental facilities available:

High Resolution VUV Spectroscopy Beamline
Angle integrated Photoelectron Spectroscopy Beamline (AI PES)
Angle Resolved Photoelectron Spectroscopy Beamline (AR PES)
Soft X-ray Reflectivity Beamline
Photo Physics Beamline
IR Spectroscopy Beamline

10. Type of experiments being carried out:

Electronic excitations up to and beyond the first ionization potential.
Change in geometry and vibrational frequencies of excited states.
Valence/Rydberg nature of excited states and assignment of Rydberg series using quantum defect analysis.
Assignment of vibrational progressions arising from fundamental/ combination modes accompanying the valence /Rydberg transitions including hot band contributions arising from low lying vibrational/ torsional modes.

Study of vibronic coupling, charge transfer excitations and Renner-Teller effects.
Comparative studies of excited electronic state structure in isotopically substituted, iso-electronic and substituent molecules.
Quantum chemical calculations for vibrational frequencies and excited state energies of molecules using GAMESS and Gaussian.
PES studies of GaP on silicon and germanium wafers
Resonant Photoemission studies of Mo-Re alloy syatem
PES studies of oxide thin films,(ISUD, RRCAT)
Resonant photoemission studies of Fe, Al and Fe-Al alloy
PES studies of FeSi3 (MSD, BARC)
PES studies of TiO2 (IGCAR)
PES studies of ZnO on LiAlO2 and GaP wafer
Thermal stability studies of ion beam sputter deposited C/B4C x-ray multilayer mirror
Stability and normal incidence reflectivity of W/B4C multilayer mirror near the boron K absorption edge.
Cleaning of Carbon Layer from the Gold Films Using a Pulsed Nd:YAG Laser.
Study on effective cleaning of gold layer from fused silica mirrors using nanosecond-pulsed
Quantitative determination of higher harmonic contents in the soft x-ray spectra of toroidal grating monochromator using a reflection multilayer.
Network compaction and surface deformation in the hydrogenated silicon nitride film
Smoothening of tungsten–carbon interfaces and change in interface asymmetry on heat treatment
Study of optical response near the absorption edge
Growth kinetics and compositional analysis of silicon rich a-SiNx:H film: A soft X-ray reflectivity study.
Study of polished zinc sulphide surface
Probing porosity at buried interfaces using soft x-ray resonant reflectivity.

11. Program Advisory Committee/experiment proposals: Yes, National Advisory Committee, International Advisory Committee

12. Picture/Schematic:

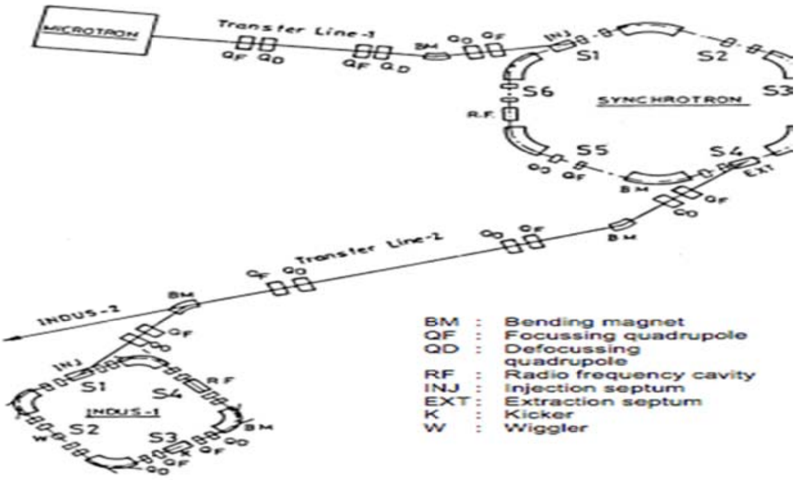

Figure 18: Layout of Indus-1 sunchrotron radiation facility, RRCAT, Indore.

Figure 19: Storage ring of Indus-1, RRCAT, Indore

13. Sources of information:

D. D. Bhawalkar, "India's first synchrotron radiation source Indus-1: A historical perspective", Current Science 82(3), (2002) 279

D.D. Bhawalkar, A.S.Rajarao, "Recent and future accelerator activities in India", Proceedings of the second Asian particle accelerator conference, Beijing china 2001

See also http://www.rrcat.gov.in/technology/accel/srul/indus1beamline/

2.10.2 Synchrotron Radiation Source Indus-2

1. Name and address of the Institute:

Raja Ramanna Centre for Advanced Technology, Indore-452013, Madhya Pradesh, India

2. Person incharge of the Facility:

Dr. P.A. Naik (panaik@rrcat.gov.in) Director, RRCAT, Indore
Shri A.C. Thakurta (thakurta@rrcat.gov.in), Director, Electron Acceleration Group, RRCAT, Indore

3. Type of Accelerator:

Synchrotron Radiation Source Indus-2, Indigenously developed.

4. Beam/Machine details:

Indus-2 is a 2.5 GeV storage ring. It operates 24x7.

Maximum Energy	2.5 GeV
Lattice Type	Expanded Chasman Green
Superperiods	8
Circumference	172.4743 m
Maximum Current	300 mA
Beam Emittance εx	5.81×10^{-8} mrad
εy	5.81×10^{-9} mrad
A vailable Straight Section for insertion devices	5
Maximum Straight length available for insertion devices	4.5 m
Beam Size σx σz	0.234 mm 0.237 mm
Beam envelope vacuum	$<1 \times 10^{-9}$ mbar
Beam life time	24 Hrs
RF Frequency	505.812 MHz
Critical Wavelength	1.98 Å Bending Magnet
	0.596 Å (High Field Wiggler)

Indus-1 and Indus-2 have a common injection system which consists of a microtron and a booster synchrotron. The microtron injector developed at CAT is a classical type microtron which gives 20 MeV electron beam with a current of 30mA in pulses of 1 to 2 μs duration at a repetition rate of 1 to 3 Hz.

5. Pulsed or D.C. operation: Pulsed

6. Approximate/expected date of installation/commission: December 2005

7. Is the facility utilized for neutron physics experiments? :

The facility has never been used for neutron physics experiments as per our literature survey.

8. Is the facility available for outside user? :

The facility is available to research institutions and universities in the country.

9. Major experimental facilities available:

High Resolution VUV Spectroscopy Beamline
Angle integrated Photoelectron Spectroscopy Beamline(AI PES)
Angle Resolved Photoelectron Spectroscopy Beamline (AR PES)
Soft X-ray Reflectivity Beamline
Photo Physics Beamline
IR Spectroscopy Beamline

10. Type of experiments being carried out:

Electronic excitations up to and beyond the first ionization potential.
Change in geometry and vibrational frequencies of excited states.
Valence/Rydberg nature of excited states and assignment of Rydberg series using quantum defect analysis.
Assignment of vibrational progressions arising from fundamental/ combination modes accompanying the valence /Rydberg transitions including hot band contributions arising from low lying vibrational/ torsional modes.
Study of vibronic coupling, charge transfer excitations and Renner-Teller effects.
Comparative studies of excited electronic state structure in isotopically substituted, iso-electronic and substituent molecules.
Quantum chemical calculations for vibrational frequencies and excited state energies of molecules using GAMESS and Gaussian.
PES studies of GaP on silicon and germanium wafers
Resonant Photoemission studies of Mo-Re alloy syatem
PES studies of oxide thin films,(ISUD, RRCAT)
Resonant photoemission studies of Fe, Al and Fe-Al alloy
PES studies of FeSi3 (MSD, BARC)
PES studies of TiO2(IGCAR)
PES studies of ZnO on LiAlO2 and GaP wafer
Thermal stability studies of ion beam sputter deposited C/B4C x-ray multilayer mirror
Stability and normal incidence reflectivity of W/B4C multilayer mirror near the boron K absorption edge.
Cleaning of Carbon Layer from the Gold Films Using a Pulsed Nd:YAG Laser.
Study on effective cleaning of gold layer from fused silica mirrors using nanosecond-pulsed

Quantitative determination of higher harmonic contents in the soft x-ray spectra of toroidal grating monochromator using a reflection multilayer.
Network compaction and surface deformation in the hydrogenated silicon nitride film
Smoothening of tungsten–carbon interfaces and change in interface asymmetry on heat treatment
Study of optical response near the absorption edge
Growth kinetics and compositional analysis of silicon rich a-SiNx:H film: A soft X-ray reflectivity study.
Study of polished zinc sulphide surface
Probing porosity at buried interfaces using soft x-ray resonant reflectivity.

11. Program Advisory Committee/experiment proposals: Yes, National Advisory Committee, International Advisory Committee

12. Picture/Schematic:

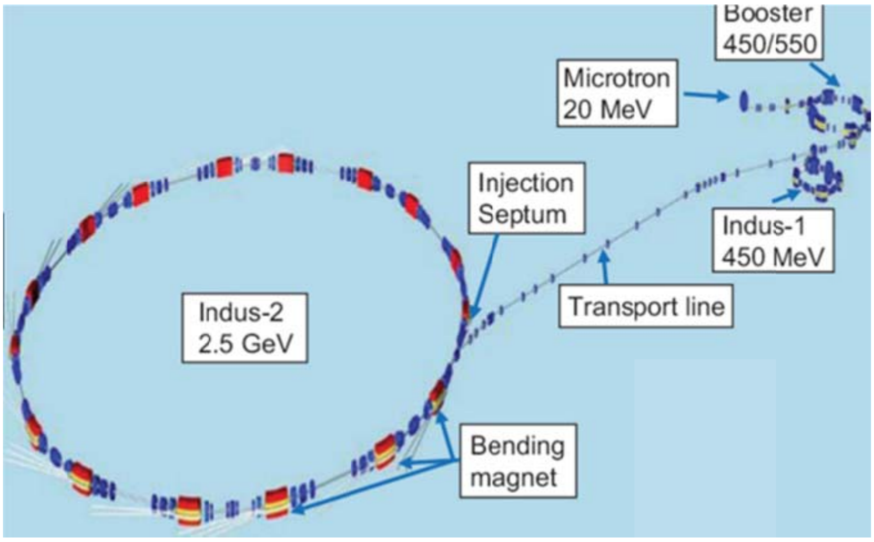

Figure 20: Layout of Indus-2 synchrotron radiation facility, RRCAT, Indore.

Figure 21: Indus-2 ring, RRCAT, Indore

13. Sources of information:

S K Deb, Gurnam Singh and P D Gupta, "Indus-2 Synchrotron Radiation Source: current status and utilization", Journal of Physics: Conference Series 425(2013) 072009

D.D. Bhawalkar, A.S.Rajarao, "Recent and future accelerator activities in India", Proceedings of the second Asian particle accelerator conference, Beijing china 2001

See also http://www.rrcat.gov.in/technology/accel/srul/indus1beamline/

2.11 Savitribai Phule Pune University, Pune

2.11.1 14 MeV Neutron Generator:

1. Name and address of the Institute:

Department of Physics.
S. P. Pune University, Ganeshkhind, Pune 411007, India

2. Person in charge of the Facility:

Dr. S. D. Dhole: Professor of Physic (sanjay@unipune.ac.in)

2.1. Other involved Faculty:

(i) Dr. S. S. Dahiwale: Asst.Professor. (ssd@physics.unipune.ac.in).

(ii) Prof. V. N. Bhoraskar[Retd] (vnb@unipune.ac.in)
Distinguished Professor.

3. Type of Accelerator:

14 MeV Neutron Generator (Cock-Croft Walton Type)

3.1: Nuclear Reaction: $^{2}H_{1} + {}^{3}H_{2} \rightarrow n + {}^{4}He_{2} + Q[\,17.4\ MeV]$

3.2: Name of the Company or Supplier:

The 14 MeV Neutron Generator was completely designed, fabricated and installed in the Pune University workshop using indigenously available components.

4. Beam details:

Beam Specifications	Max. Energy	Max. Current/Intensity
Deuteron	30 keV - 200 keV	150 μA
Neutron	13.27MeV(at 160^0) – 15.13MeV(at 0^0) using D-T	10^7-10^8 n/sec/cm^2

5. Approximate/expected date of installation/commission: 1980

6. Pulsed or D.C. operation: Continuous beam

7. Is the facility utilized for neutron physics experiments? :

The facility has been utilized mainly for generating 14 MeV neutrons using D-T reaction. The neutrons are used for the studies of (i) Cross Sections of neutron induced reactions for nuclear data (ii) Elemental Analysis by off-line gamma-ray measurements, (iii) Elemental analysis by Prompt Gamma- ray measurements.

8. Is the facility available for outside user? :

The facility is mainly devoted for graduate and Ph.D. programs in the S.P. Pune University. In addition, for collaborative work with other institutions.

9. Major experimental facilities available:

HPGe detector: 1.8 keV energy resolution and 30% relative efficiency.
NaI (Tl) detector; BGO detector; Silicon Surface Barrier detectors
Data Acquisition software such as Maestro, Genie2k.P.C. based M.C.A.
General purpose scattering chamber; Radiation Monitors; Radioisotope storage room.

10. Type of experiments being carried out:

The 14 MeV neutrons with flux ~ 10^8 n/cm^2-sec is mainly used for research work in the fields of nuclear reactions, elemental analysis, neutron irradiation effects on semiconductor devices, etc. Many neutron induced cross sections for (n, g), (n, p), (n, a), (n, 2n) reactions for reactor applications have been measured. Neutron induced double-differential cross sections measurements for outgoing alpha particles for few elements had also been performed. The facility and the neutron source have also been utilized for experiments related to prompt gamma measurements for detection of explosive class materials. Furthermore, the accelerator with a deuteron beam in the keV energy range has also been used for charged particle induced cross section measurements for light elements important for astrophysics.

11. Program Advisory Committee/experiment proposals: No

12. Future Plans:

Under DAE-BRNS grant, the facility is being renovated for nuclear data physics experiments.

13. Picture/Schematic:

Figure 22: 14 MeV neutron generator at Savitribai Phule Pune University, India

Figure 23: Control system of 14 MeV Neutron Generator along with HPGe detector and other electronic systems.

2.11.2 6.5 MeV Electron Accelerator: Race-Track Microtron.

1. Name and address of the Institute:

Department of Physics.
Savitribai Phule Pune University, Ganeshkhind, Pune 411007, India

2. Person in charge of the Facility:

Dr. S. D. Dhole: Professor of Physics (sanjay@unipune.ac.in)

2.1. Other involved Faculty: (i) Dr. S. S. Dahiwale: Asst.Professor. (ssd@physics.unipune.ac.in).

(ii) Prof. V.N.Bhoraskar[Retd] Distinguished Professor. (vnb@unipune.ac.in)

3. Type of Accelerator:

6.5 MeV Electron Accelerator: Race-Track Microtron. [Originally 8 MeV].

This Race-Track Microtron was made in the university workshop. However, a number of components such as microwave system, waveguides, Electron gun cathodes and filaments, thyratrons, high voltage components, were obtained from the Berkeley University, USA, at the time of installation during 1978-1982.

4. Beam details and Specifications:

Beam Particles	Electrons
Operating Beam Energy	0.5-1 MeV and 6.5 – 8 MeV
Beam Current (Average)	~ 1 µAmp
Beam Current (Peak Pulse)	10 mA [Pulse width~ 1.8 µSec.
Number of Orbits	Eight [Race-Track shape]
R.F. Peak Power	1 MW[Pulsed]
Maximum Pulse Rate	50 pps
Type of Oscillator	Magnetron (MG 5236A)
Working Frequency	2780 MHz
Pulse Width	1.6µs to 2.0 µs
Beam Diameter (Without Scattering)	Variable from 1mm to 6 mm
Main Chamber	50.8 cm O.D. X 7.6 cm height
Cavity type	Right Circular Cylinder TE010 mode
Magnet Type	Four Sector[Electro-Magnet]
Gun Current	120 mA [Pulsed]

Maximum Gun Voltage	25 KV
Magnetic field strength at Gap	Variable :1000 to 3000 Gauss
Operating Vacuum	1×10^{-6} Torr

5. Approximate/expected date of installation/commission: 1978-1982.

6. Pulsed or D.C. operation: Pulsed Beam of duration ~ 2 μSec: 50 PPS.

7. Is the facility utilized for electron beam physics experiments?

The facility is being used for producing 6.5 MeV electrons and 1 MeV electrons [rarely used]. The electron beam of 6.5 MeV is used regularly for research and teaching.

8. Is the facility available for outside user:

The facility is mainly used for the teaching of M.Sc. Physics and research programs of M. Phil and Ph.D. degree courses of the Department of Physics, Savitribai Phule Pune University.

9. Major experimental facilities available:

(a) Low energy electron beam (0-20 keV)
(b) Radiation environment system (electron, proton ion and UV radiation)
(c) Design of 6 MeV Accelerator Based Pulsed Neutron Source
(d) HPGe detector: 1.8 keV energy resolution and 30% relative efficiency.
(e) NaI(Tl) detector
(f) BGO detector
(g) Few Silicon Surface Barrier detectors
(h) Data Acquisition software such as Maestro, Genie2k.
(i) General purpose scattering chamber
(j) Thermo luminescence Dosimetry Systems

10. Type of experiments being carried out:

The 6.5 MeV electrons with flux ~8x 10^{12} e^{-}/sec over a spot of 3 mm diameter. The electrons are being used for different types of experiments; some of are listed below;

(a) Radiation damage in semiconductor materials and devices.
(b) Irradiation effects of 1 MeV and 6 MeV electrons on the space quality (i) MOS devices (ii) electrical components (iii) polymers (iv) glass materials (v) functional oxides, (vi) space quality materials and (vii) tailoring the switching characteristics of thyristors and diodes, etc.
(c) Generation and characterization of bremsstrahlung radiation (e, γ) using targets of high Z-elements such as tungsten, molybdenum, tantalum,
(d) Production of pulsed (2 μsec) neutrons through (γ, n) reaction using beryllium target.
(e) Radiation enhanced diffusion of elements such as boron, fluorine, silver, gold etc. in polymers and glass materials.
(f) In situ synthesis and decoration of metal nanoparticles and semiconductor nanoparticles on dielectric spheres by 6.5 MeV electron irradiation.
(g) Measurement of cross sections of nuclear reactions for formation of metastable state through photo- neutrons produced through Be(γ, n) reaction.
(h) Tailoring of switching characteristics of thyristors and silicon diodes by electron irradiation.

11. Program Advisory Committee/experiment proposals: No

12. Future Plans:

Under DST-SERB grant, the facility is being renovated for generation and characterization of bremsstrahlung radiation (e, γ) from various targets (tungsten, Pb, Au, Ta, etc.) physics experiments.

13. Schematic and Pictures of Microtron Accelerator with Control Panel:

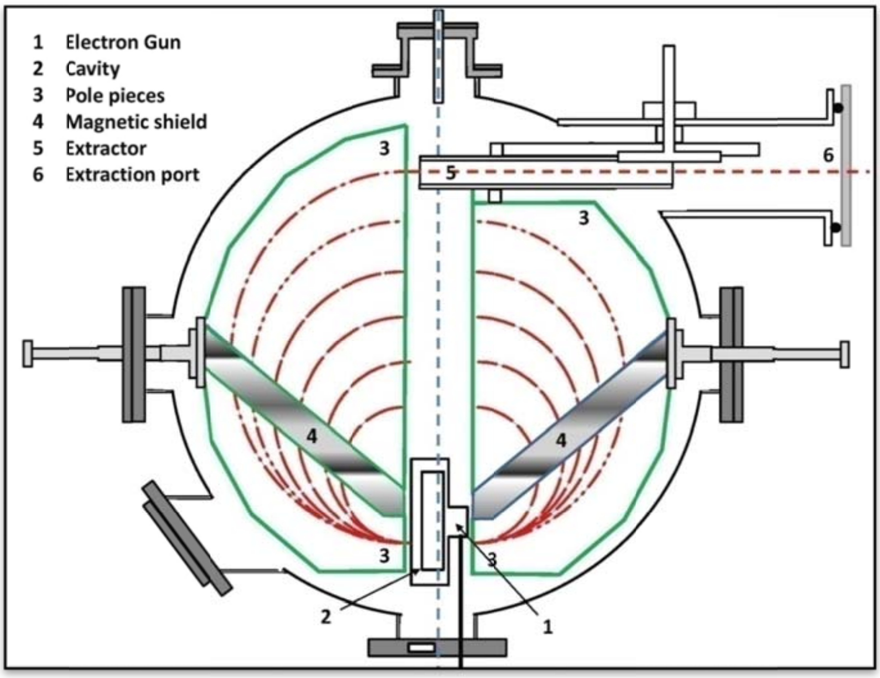

Figure 24: Schematic diagram of the 6 MeV Race-Track Microtron

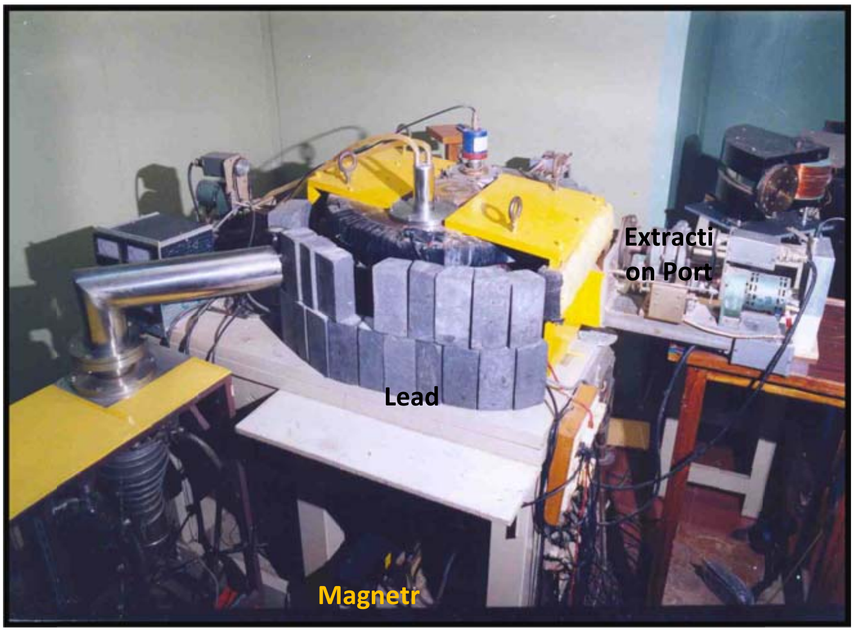

Figure 25: A view of the 6 MeV Race-track Microtron.

Figure 26: A View of control system of the Race-Track Microtron.

14. Sources of information:

Private Communication with Prof. S. D. Dhole and Prof. V. N. Bhoraskar.

2.11 Tata Institute of Fundamental Research(TIFR)

2.11.1 14 UD Pelletron Accelerator

1. Name and address of the Institute:

Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, Mumbai 400005 India

2. Person incharge of the Facility:

Dr. Alok Saxena(aloks@barc.gov.in)
Prof. R.G.Pillay(pillay@tifr.res.in)

3. Type of Accelerator:

14 UD Pelletron with LINAC booster

4. Beam details:

Beam Species	Max. Energy	Max. current/Intensity
^{6,7}Li, ^{10,11}B, ^{12,13}C, ^{14}N, ^{16,18}O, ^{19}F, ^{24}Mg, ^{27}Al, ^{28,30}Si, ^{31}P, ^{32,34}S, ^{35,37}Cl	Upto 8-10 MeV/A	1-5 pnA
Proton	Upto 24 MeV	200 nA
Neutron	Using ^{7}Li(p,n) and ^{9}Be(p,n)	10^{7}-10^{8} n/sec/cm^{2}

Heavier beams like Iodine, Silver are available through Pelletron. Alpha beam and additional negative ion beams are made available on request. Alpha beam are also available using *Alphatross* source.

5. Approximate/expected date of installation/commission:

30th December 1988(Pelletron), 28th November 2007(LINAC Booster)

6. Pulsed or D.C. operation:

In addition to continuous beams, pulsed beams of ~1 ns width separated by about 100 ns to 1.6 □s.

7. Is the facility utilized for neutron physics experiments? :

The facility has 6 M irradiation set up for neutron physics experiments using ^{7}Li(p,n) and ^{9}Be(p,n) quasi-monoenergetic neutron sources.

Figure 27: 6 M irradiation set up for neutron physics experiments

8. Is the facility available for outside user? :

TIFR and DAE scientists mainly use the facility with few collaborators from universities.

9. Major experimental facilities available:

Clover Detector Array for discrete gamma ray spectroscopy with auxiliary detectors.

150cm dia Scattering Chamber, with two independently rotatable arms permitting detector rotation and target ladder adjustment from remote without beam interruption using Programmable Logic Controller, for charged particle spectroscopy and fission studies.

BaF_2/$LaBr_3$ array for high energy gamma ray studies with BGO/NaI(Tl) multiplicity filter

Charged Particle Array based on Si pad (Delta-E)and CsI(E) detectors

Neutron Detectors Array of 18 Liquid Scintillation detectors and Annular parallel plate avalanche counter having 12 segmented signal read out with angular coverage from 5 degree to 11 degree, for Time of Flight Technique based compound nucleus residue tagging

MWPC and Si-strip detectors for angular distribution measurements of particles
7.0T superconducting magnet for hyperfine interaction studies

Electron spectrometer and X ray detector for atomic physics studies with gas and foil targets

Irradiation setups

High current proton and neutron irradiation facility

Low background offline counting facility

10. Type of experiments being carried out:

Nuclear reactions (elastic, inelastic, transfer, fusion and fission reactions)
Nuclear structure & spectroscopy

Nuclear data generation relevant to nuclear reactors as well as IAEA coordinated research programs on advanced nuclear reactors, nuclear astrophysics, application of nuclear physics in elemental analysis using PIGE (Particle Induced Gamma Emission)

Atomic &Cluster physics

Condensed Matter Physics &Material Science

Radiochemical studies

Accelerator mass spectrometry, production of track-etch membranes

Low flux secondary neutron production for irradiation studies

Low flux proton irradiation damage studies relevant to space bound devices, materials and yield improvement in wheat & rice seeds

Application of thin layer activation technique for wear and corrosion rate measurement.

11. Program Advisory Committee/experiment proposals:

The Pelletron Linac Programme Implementation Committee (PLPIC) screens the experimental proposals and monitors utilization of the accelerator.

13. Future Plans:

High voltage upgrade of Pelletron tandem accelerator to sustain operation up to 14 MV by replacing the existing accelerating tubes with new generation high gradient accelerating tubes in phased manner without significantly affecting user utilization.

Fabrication & installation of low beta niobium cavities in the first two modules of Superconducting LINAC Booster to enhance the mass range of accelerated ions.Development of digital LLRF control for the superconducting cavities.

A state of the art ECR ion source capable of delivering Uranium ions of charge state 34+ with good intensity. A prototype RFQ will be coupled to this, which is at an advanced stage of completion. It is proposed to build low and high beta SC modules to ECR and RFQ to realise a heavy ion facility, which will be located at BARC.

14. Picture/Schematic:

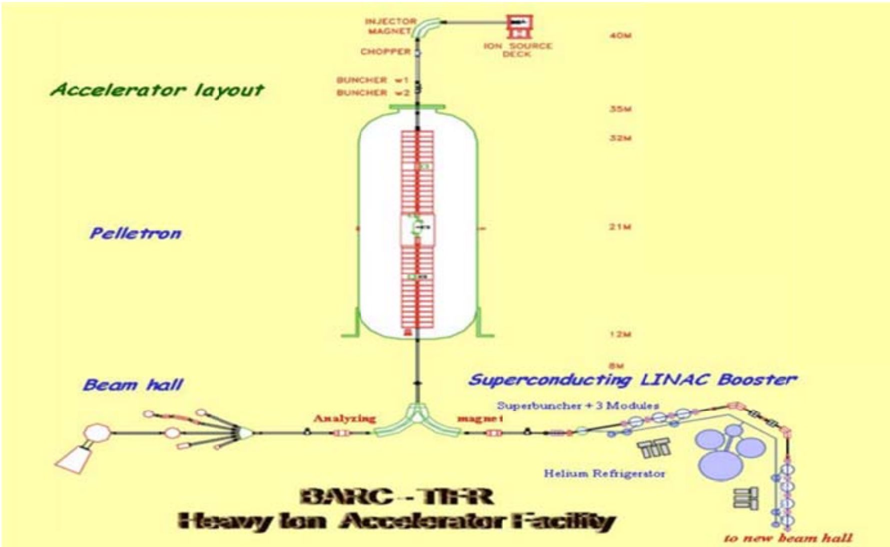

Figure 28: Schematic of Pelletron LINAC facility, TIFR Mumbai.

Figure 29: Hall 1 of Pelletron LINAC Facility showing general purpose scattering chamber, TIFR, Mumbai

Figure 30: Hall 1 of Pelletron LINAC Facility showing general purpose scattering chamber, TIFR, Mumbai

15. Sources of information:

R.G. Pillay, V.M. Datar, "BARC – TIFR Pelletron-LINAC Facility", Internal Report for Silver Jubilee (1988 – 2013), http://www.tifr.res.in/~pell/plf25_2013.pdf

Walter Henning and Wim van Oers, "A Worldwide Perspective Of Research And Research Facilities in Nuclear Physics by the IUPAP Working Group 9", IUPAP Report 41, 2014.

Private Communication with Dr. Alok Saxena, Head, NPD, BARC, Mumbai.

2.13 Variable Energy Cyclotron Centre (VECC), Kolkata, India

2.13.1 224 cm Variable Energy Cyclotron (VEC)

1. Name and address of the Institute:
Variable Energy Cyclotron Centre(VECC)
1/AF, Bidhan Nagar Kolkata-700 064
India

2. Person incharge of the Facility:
Shri Amitava Roy (amitav@vecc.gov.in) Acting Director, VECC, Kolkata
Dr. Arup Bandyopadhyay (arup@vecc.gov.in), Head, Accelerator Physics Group, VECC, Kolkata

3. Type of Accelerator:
224 cm Variable Energy Cyclotron (VEC), AVF cyclotron with K=130

4. Beam details: : Extracted and Delivered to the users for experiments. Presently available maximum energies are given in the parenthesis.

Beam Species	Max. Energy (MeV)	Max. current/Intensity (nA)
Proton	7-20 (15)	10000 (Ch 1)
Alpha	26 – 80 (60)	4000 – 5000 (Ch 1), upto 20 (ch 2/ch 3)
Nitrogen	122	135 (extracted)
Oxygen	180	410 (extracted)
Neon	200	310 (extracted)
Argon	350	150 (extracted)

5. Approximate/expected date of installation/commission: 1978

6. Pulsed or DC operation: Repetition rate ~ 100 – 200 ns (Depending on the RF operating frequency)

7. Is the facility utilized for neutron physics experiments? :
As per the EXFOR Database record, the facility has not been used as a neutron source for neutron scattering or as a neutron generator.

8. Is the facility available for outside user? :
The facility is a national facility.

9. Major experimental facilities available:
Various Irradiation chambers
90 cm scattering Chamber for charged particle spectroscopy
VENUS, VENTURE Detector arrays for gamma spectroscopy, hosts INGA facility
High efficiency LAMBDA detector array for high energy gamma ray measurements
Double and Single sided Si strip detectors, backed by CsI(Tl) for Charged particle.
ToF Neutron detectors
Gas detectors (MWPC)

10. Type of experiments being carried out:

The cyclotron provided experimental facility for nuclear physics community. It has also been used for nuclear chemistry, condensed matter physics, isotope production etc.

11. Program Advisory Committee/experiment proposals:

The VEC Users' Committee screens the experimental proposals allocates beam time to users.

12. Future Plans:

Another campaign of Heavy ion acceleration is planned in immediate future.

13. Picture/Schematic:

Figure 31: The 224 cm Variable Energy Cyclotron at VECC, Kolkata

15. Sources of information:

Walter Henning and Wim van Oers, "A Worldwide Perspective Of Research And Research Facilities in Nuclear Physics by the IUPAP Working Group 9", IUPAP Report 41, 2014.

Few information have also been obtained from http://www.vecc.gov.in/pages/display/55-Organization-Chart.

Private Communication with Dr. Gopal Mukherjee, VECC.

3. Upcoming Particle Accelerators in India

3.1 Bhabha Atomic Research Centre

3.1.1 Low Energy High Intensity Proton Accelerator (LEHIPA)

1. Name and address of the Institute:

Nuclear Physics Division, BARC, Mumbai, India

2. Person incharge of the Facility:

Dr. Alok Saxena, Head, NPD, BARC (aloks279@gmail.com)
(aloks@barc.gov.in)

3. Type of Accelerator:

50 keV Electron Cyclotron Resonance (ECR) ion source that is accelerated further by 3 MeV Radio Frequency Quadrupole (RFQ) and 20 MeV Drift Tube Linac (DTL).

Most of the accelerator beam line components were indigenously designed and fabricated, including the high current ECR ion source, low energy beam transport line, RFQ,

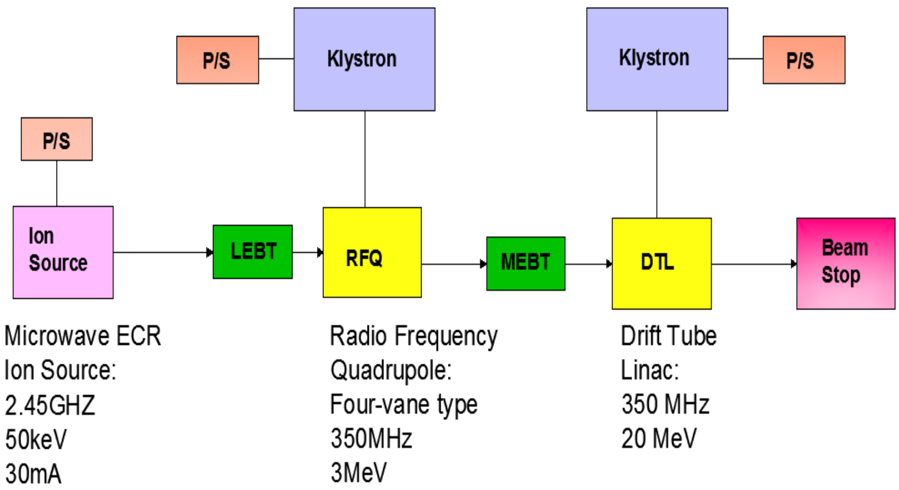

Figure 32: Schematic of LEHIPA, BARC, Mumbai

4. Beam details:

LEHIPA is designed to deliver 20 MeV, 20 mA proton beam. Specifications of ECR Ion source, RFQ and DTL are given below:

Table 1. Specifications of LEHIPA ECR ion source.

Parameters	Values
Particle	Proton
Beam Current	40 mA
Beam Energy	50 keV
RF Power at 2.45 GHz	500 – 1100 W

Table 2. Design parameters of the RFQ.

Parameters	Value	Units
Particle	proton	
I/O energy	0.05/3.00	MeV
Frequency	352.21	MHz
Beam current	30	mA
Vane voltage	68	kV
Focusing strength (B)	5.6	
Average bore radius (R_0)	0.306	cm
Transverse radius of curvature (ρ_t)	0.306	cm
Modulations	1–1.81	
Synchronous phase	-90/-30	deg
Input Trans RMS emittance	0.20	π mm-mrad
Output Trans RMS emittance	0.21	π mm-mrad
Long emittance	0.139	deg-MeV
Accelerated	96	%
Transmission	97	%
Shunt Impedance	52.3	kOhm-m
Length	4	m
Cu power	387	kW
Beam power	89	kW
Total RF power	476	kW

Table 3. Design parameters of the Drift Tube Linac(DTL).

Parameters	Value
Particle	proton
Beam Energy	3 - 50 MeV
Frequency	352.21 MHz
Beam current	30 mA
Tank Diameter	52 cm
Drift Tube Diameter	12 cm
Average bore radius	1 cm

5. Approximate/expected date of installation/commission: Upto 3 MeV installed, higher energies under Development.

6. Pulsed or D.C. operation: DC as well as Pulsed.

7. Is the facility utilized for neutron physics experiments? :

The facility is planned to be used as high intensity neutron source using high current proton beam with 9Be(p,n) reaction.

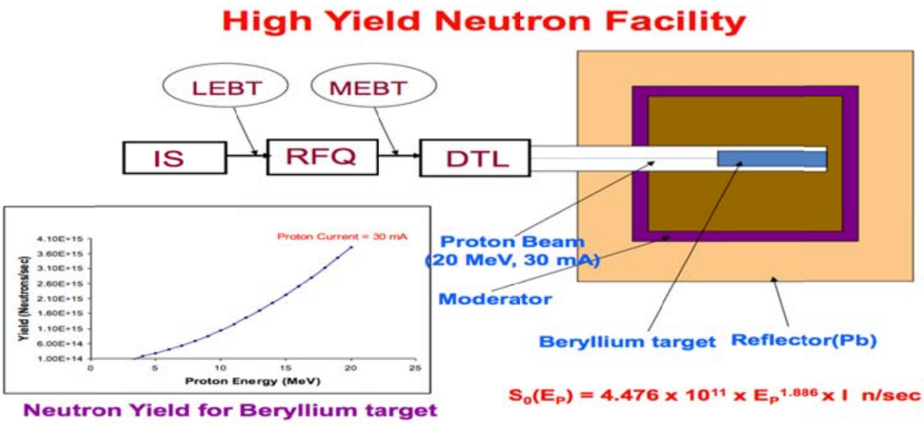

Figure 33: Schematic of High Yield Neutron Facility using LEHIPA, BARC

8. Is the facility available for outside user? :

The facility will be mainly develoted for DAE scientists. Few Universities in collaboration with BARC scientists will also utilize the facility.

9. Major experimental facilities available: Under development

10. Type of experiments to be carried out:

LEHIPA is mainly designed for ADS program, for 1 GeV proton accelerator. However, there is plan to utilize the facility for high yield neutron source using D-T as well as 9Be(p,n) for neutron physics experiments, for 20 MeV proton beam for ADS experiments in HWR critical facility etc.

11. Program Advisory Committee/experiment proposals: No.

12. Future Plan:

The LEHIPA of 40-50 MeV proton beam using DTL will be coupled to Couple Cavity Linac (CCDTL) to get 100 MeV proton beam which will be further accelerated to 1 GeV by elliptical Super Conducting (SC) Cavity.

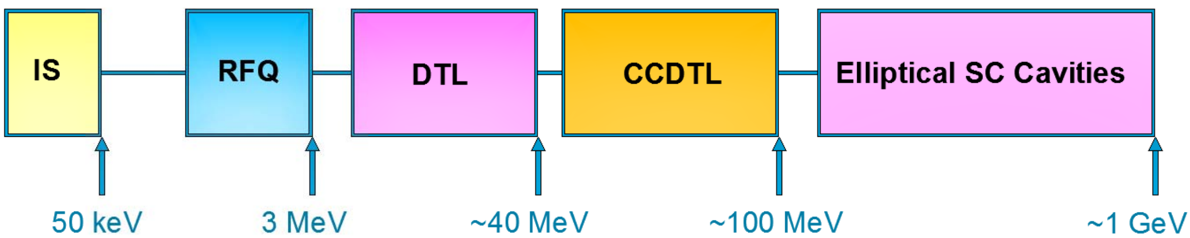

Figure 34: Schematic of 1 GeV proton LINAC

12. Picture/Schematic:

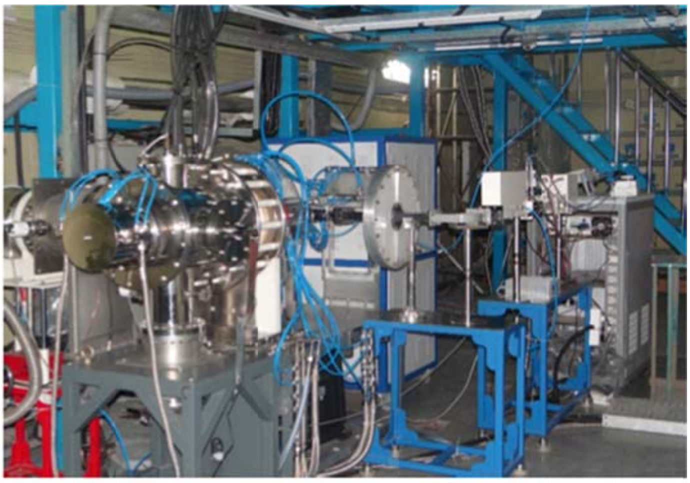

Figure 35: 50 keV ECR Ion Source, LEHIPA, BARC

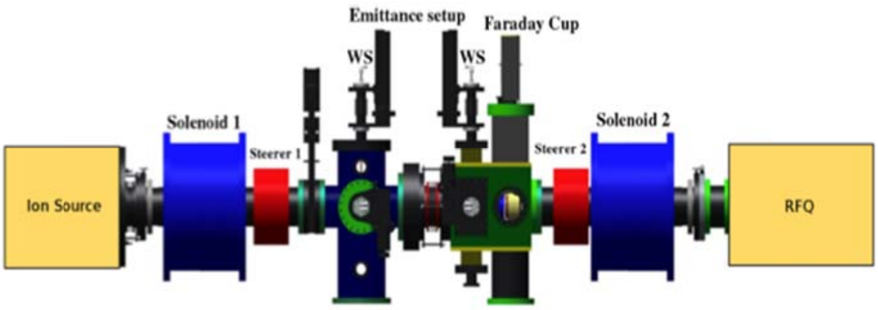

Figure 36: Low energy beam transport line, LEHIPA, BARC

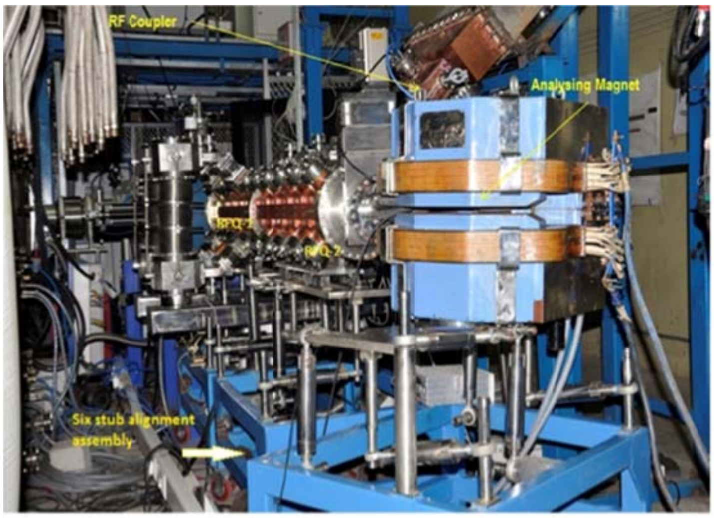

Figure 37: 3 MeV RFQ, LEHIPA, BARC

13. Sources of information:

P. Singh et al., “Accelerator development in India for ADS programme”, Pramana 68 (2007) 331.

P.V. Bhagwat, S. Krishnagopal, J.V. Mathew, S.K. Singh, P. Jain, S.V.L.S. Rao, M. Pande, R. Kumar,P. Roychowdhury, H. Kelwani, B.V. Rama Rao, S.K. Gupta, A. Agarwal, B.M. Kukreti and P. Singh, “Beam acceleration through proton radio frequency quadrupole accelerator in BARC”, JINST 11(2016) T05001

Rajni Pande, Shweta Roy, T. Basak, S.V.L.S. Rao and P. Singh, “Beam dynamics for the 1 gev proton linac for ads”, BARC Newsletter, Founder’s day special issue , Issue No.285 (2007) 140-152

P.Singh, “Complexity of Accelerator Driven System”, A presentation on Indo-Japan Accelerator School, IUAC Feb 17 2015, New Delhi

Srinivas Krishnagopal, “LEHIPA: A High Current Low Energy Accelerator for Nuclear Physics” , Proceedings of the DAE Symp. on Nucl. Phys. 60 (2015) 53

3.2 Institute for Plasma Research, Ahmedabad, India:

3.2.1 High Intensity 14 MeV Neutron Generator

1. Name and address of the Institute:

Fusion Neutronics Laboratory, Institute for Plasma Research, Bhat, Gandhinagar-382428, India

2. Person in charge of the Facility/contact person:
Dr. C.V.S.Rao (modinisrinivas@gmail.com)

3. Type of Accelerator:
14 MeV Neutron Generator (DC Electrostatic Accelerator)

3.1: Nuclear Reaction: $^{2}H_{1} + ^{3}H_{2} \rightarrow n + ^{4}He_{2} + Q[\,17.4\ MeV]$

3.2. Name of the Company or Supplier:
The 14 MeV Neutron Generator is being indigenously designed, fabricated and to be installed.

4. Proposed Beam details:

Type of Machine	DC electrostatic accelerator
Maximum Acceleration Voltage	300 keV
Type of Beam	D^{+} Ion
Ion Current	10 mA
Vacuum Pressure	$1x10^{-6}$ Torr
Tritium Target	200 Ci
Neutron Yield	5-8 x 10^{11} n/sec
Neutron Energy	~13 – 15 MeV

5. Approximate/expected date of installation/commission: ~yet to be commisioned

6. Pulsed or D.C. operation: DC

7. Is the facility utilized for neutron physics experiments? :
The facility has been utilized mainly for generating 14 MeV neutrons using D-T reaction

8. Is the facility available for outside user? :
The facility is mainly devoted for fusion neutronics studies for ITER project.

9. Major experimental facilities available:
Multipurpose target chamber, ECR plasma Ion source, HPGe detector, NaI (Tl) detector; BGO detector; Data Acquisition system, compact neutron generator.

10. Type of experiments being carried out:
Beam test and characterization is going on, and few test experiments using activation technique is being carried for neutron induced cross sections on pure Au, Al, Cu, Zr and In foils

are presented and compare with calculations.

11. Program Advisory Committee/experiment proposals: No

12. Future Plans:

Water cooled rotating tritium target of activity 20 Ci is being developed which is expected to give neutron yield 10^{12} n/s with the deteron beam current of 20 mA.

13. Picture/Schematic:

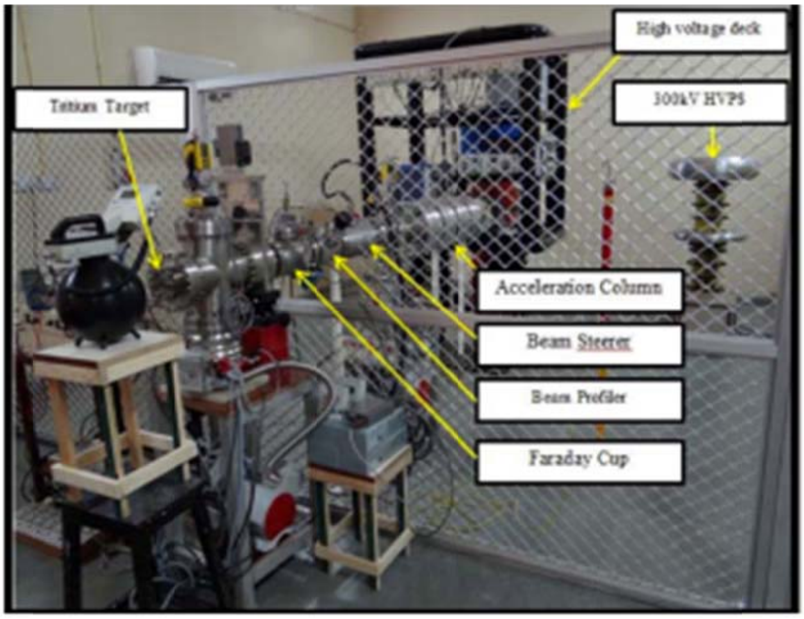

Figure 38: 14 MeV neutron generator at IPR, Gandhinagar, India

14. Sources of information:

B. Chaudhari, S. Vala, M. Abhangi, C.V.S Rao, T.K Basu and B. Sarkar, "Design of Safety Interlock System For Accelerator Based 14-MeV Neutron Generator", Proceedings of the DAE Symp. on Nucl. Phys. 59 (2014) 872

R.Makwana, S.Vala, M.Abhangi, S.Jakhar, C.V.S.Rao, T.K.Basu, "Shielding design of the proposed laboratory for an intense 14 MeV neutron generator", Indian Journal of Pure and Applied Physics, 50(2012) 799-801.

3.3 Saha Institute of Nuclear Physics, Kolkata, India

3.3.1 Facilities for Research in Expt. Nucl. Astrophys.(FRENA), SINP, India

1. Name and address of the Institute:

Saha Institute of Nuclear Physics (SINP)
1/AF, Bidhan Nagar Kolkata-700 064
India

2. Person incharge of the Facility:

Dr. A.K.Mohanty (ajitkumar.mohanty@saha.ac.in), Director, SINP, Kolkata
Prof. A.Goswami (asimananda.goswami@saha.ac.in), Converner, FRENA Project Implementation Committee, SINP, Kolkata

3. Type of Accelerator:

3 MV Tandetron Accelerator

4. Beam/Machine details:

Terminal Voltage Terminal Voltage Stability	0.2 – 3 MV +-300 V(GVM Stabilization) +-100 V(Slit Stabilization)
DC Beam Currents H^+ He^{2+} Heavier Ions	 350-500 μA 70 μA 5-50 μA
Pulsed Operation Pulse width H^+ and D^+ are expected	 2 ns

5. Approximate/expected date of installation/commission: Under Construction

6. Is the facility utilized for neutron physics experiments? :

FRENA facility will be used as high flux low energy neutron source by using $^7Li(p,n)^7Be$ reaction.

7. Is the facility available for outside user? :

The facility will be a national facility available to all research institutions and universities in the country.

8. Major experimental facilities available: Not Available at present

9. Type of experiments to be carried out:

FRENA will be used for low energy nuclear astrophysics related to fusion of heavy ions like ^{12}C,^{16}O,^{20}Ne. The facility is also planned for low energy neutron source using $^7Li(p,n)^7Be$ reaction to investigate the s-process nucleosynthesis and to study specific reactions in the H and He-burning phases of stars and the p-process reactions.

10. Program Advisory Committee/experiment proposals: Not yet formed
11. Future Plans:
12. Picture/Schematic:

Figure 39: 3 MV tandetron accelerator at SINP, Kolkata

15. Sources of information:

A. Goswami, "FRENA: An upcoming facility for experimental Nuclear Astrophysics" Proceedings of the DAE-BRNS Symp. on Nucl. Phys. 61 (2016) 49

Please also visit http://www.saha.ac.in/web/frena-about-frena

3.4 Variable Energy Cyclotron Centre

3.4.1 Radioactive Ion Beam Facility

1. Name and address of the Institute:

Variable Energy Cyclotron Centre(VECC)
1/AF, Bidhan Nagar Kolkata-700 064
India

2. Person incharge of the Facility:

Shri Amitava Roy(amitav@vecc.gov.in) Acting Director, VECC, Kolkata
Dr. Vaishali Naik (vaishali@vecc.gov.in), Head, Radioactive Ion beam Facilities Group, VECC, Kolkata

3. Type of Accelerator:

Primary Accelerator: AVF cyclotron with K=130
ISOL type facility

4. Beam details: Different types of radioactive ion beams are expected.

5. Approximate/expected date of installation/commission: Already in operation in part.

6. Is the facility utilized for neutron physics experiments? :

The facility is not designed for neutron source for neutron physics experiments.

7. Is the facility available for outside user? : The facility will be a national facility.

8. Major experimental facilities available: High resolution Gamma ray detectors, Total absorption gamma ray spectrometer.

9. Type of experiments being carried out:

Recently radioactive ion beams (RIB) of ^{14}O (71 sec), ^{42}K (12.4 hrs), ^{43}K (22.2 hrs) and ^{41}Ar (1.8 hrs) have been successfully produced at VECC, using a novel gas-jet recoil transport coupled Electron Cyclotron Resonance (ECR) ion- source technique. The RIB of ^{14}O has been further accelerated through the RFQ linac to 1.4 MeV. Stable isotope beams such as ^{12}C, ^{16}O, ^{14}N, ^{40}Ar, ^{39}K, ^{56}Fe are also accelerated and are being used for material science experiments.

10. Program Advisory Committee/experiment proposals:

International Advisory Committee for SCC and RIB project & Project Implementation Committees have been over-viewing the projects.

11. Future Plans:

The option of using electron linac for production of neutron-rich RIB through photo-fission route and acceleration of RIB using linacs up to about 6-7 MeV/u is under consideration. Finally, it is proposed to inject the 6-7 MeV/u RI as well as stable beams into a Separated Sector Cyclotron for further acceleration to about 100 MeV/u.

12. Picture/Schematic:

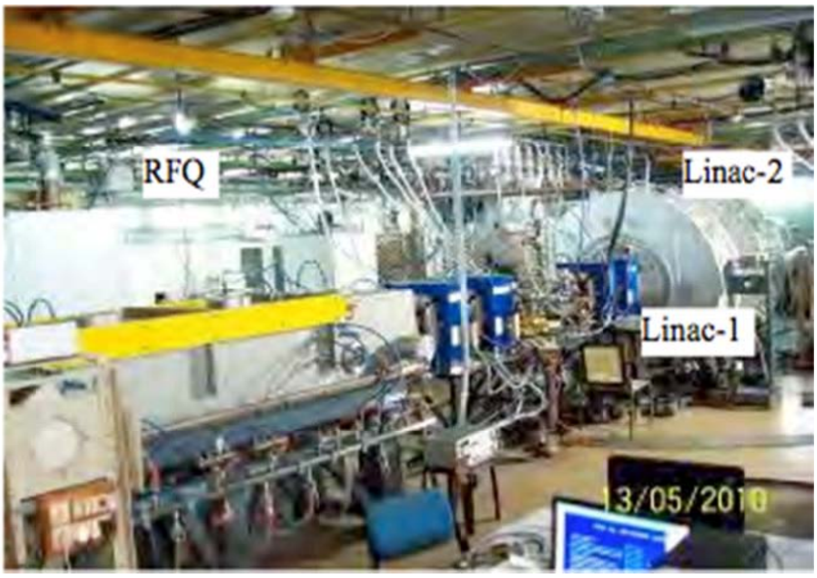

Figure 40: RIB facility being developed at VECC, Kolkata

13. Sources of information:

Walter Henning and Wim van Oers, "A Worldwide Perspective Of Research And Research Facilities in Nuclear Physics by the IUPAP Working Group 9", IUPAP Report 41, 2014.

Few information have also been obtained from http://www.vecc.gov.in/pages/display/55-Organization-Chart.

Private Communication with Dr. Gopal Mukherjee, VECC

3.4.2 K-500 Superconducting Cyclotron

1. Name and address of the Institute:

Variable Energy Cyclotron Centre(VECC)
1/AF, Bidhan Nagar Kolkata-700 064
India

2. Person incharge of the Facility:

Shri Amitava Roy(amitav@vecc.gov.in) Acting Director, VECC, Kolkata
Dr. Arup Bandyopadhyay (arup@vecc.gov.in), Head, Accelerator Physics Group, VECC, Kolkata

3. Type of Accelerator:

K-500 Superconducting Cyclotron

4. Beam details: For Medium and Heavy ions: Maximum available energy will be $500*q^2/A^2$ MeV/A
For lighter ions: Maximum available energy will be 160*q/A MeV/A

5. Approximate/expected date of installation/commission: Under Construction.

6. Is the facility utilized for neutron physics experiments? :

The facility is not designed as neutron source for neutron physics experiments.

8. Is the facility available for outside user? :

The facility will be a national facility.

9. Major experimental facilities available:

A state-of-the-art 3-part cylindrical type Scattering chamber

Charged particle detector array: Each detector in the forward part of the array (covering angular range ~ 5° - 40°) has been planned to be made up of 3 detector elements in telescope configuration. Each detector telescope will consist of (i) thin Si- strip ΔE detector (Size: 5cm x 5cm, thickness: 30 – 50 μm, 16 strips, one-sided), followed by (ii) thick Si-strip ΔE/E detector (Size: 5cm x 5cm, thickness: 500 μm – 1mm, 16 strips, double-sided, X-Y directions), and (iii) 4 CsI(Tl) crystals (Size: 2.5cm x 2.5cm, thickness: 4 – 6cm). Backward part of the array will be consist of ~250 Si+CsI telescopes.

Neutron multiplicity detector: Neutron multiplicity detector is a large tank of Gd- loaded liquid scintillator, read out using PMTs. The neutron detector is planned to be designed in such a way that the charged particle array can be placed within the neutron detector, rendering it possible to measure simultaneously the neutrons as well as charged particles.

High energy gamma detector array: The array will consist of 162 BaF2 detectors (each of size: 3.5cm x 3.5cm x 35cm).

Segmented clover HPGe detectors

Low background counting laboratory.

10. Type of experiments being carried out: Under Development and Construction Stage

11. Program Advisory Committee/experiment proposals:

At present the VEC Users' Committee will be formed.

13. Future Plans:

Ion trap: It is used for trapping low energy ions in magnetic field. Typical field required is ~5T, which is planned to be provided by a superconducting solenoid.

Multidisciplinary research facility: Low temperature irradiation setup. Acoustic emission setup etc.

14. Picture/Schematic:

Figure 41: Superconducting Cyclotron being developed at VECC, Kolkata

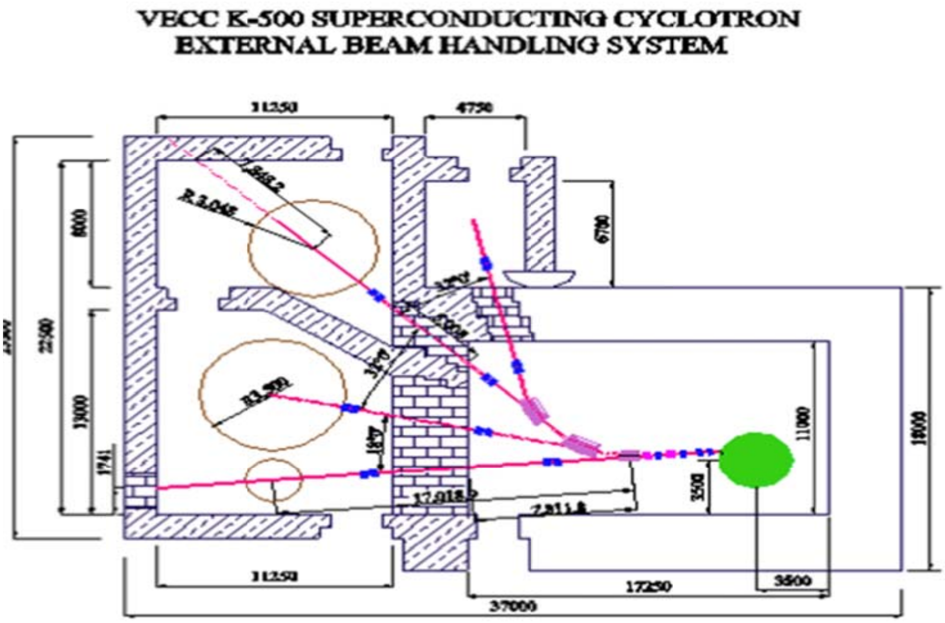

Figure 42: Schematic of K-500 Superconducting Cyclotron external beam handling system.

15. Sources of information:

Walter Henning and Wim van Oers, “A Worldwide Perspective Of Research And Research Facilities in Nuclear Physics by the IUPAP Working Group 9”, IUPAP Report 41, 2014.

Few information have also been obtained from http://www.vecc.gov.in/pages/display/55-Organization-Chart.

Private Communication with Dr. Gopal Mukherjee, VECC

3.4.3 DAE's Medical Cyclotron Facility (30 MeV Medical cyclotron)

1. Name and address of the Institute:

Mouza Chowgaria, Off Eastern Metropolitan Bypass, Kolkata, West Bengal, VECC

2. Person/Institution incharge of the Facility:

Variable Energy Cyclotron Centre(VECC)
1/AF, Bidhan Nagar Kolkata-700 064
India

3. Type of Accelerator:

MC-30 Medical cyclotron

3.1 Supplier: M/s Ion Beam Application, Belgium.

4. Beam details:

Beam Parameters	Max. Energy(MeV)	Max. Current(μA)
Proton	15 – 30	500

5. Approximate/expected date of installation/commission: Under installation

6. Is the facility utilized for neutron physics experiments? :

The facility is devoted for radioisotope production and for medical sciences.

7. Is the facility available for outside user? : No

8. Major experimental facilities available:

Radioactive Waste handling systems,Radiation safety equipment, Clean rooms, Packaging facility, Ultra pure water production system, Laminar flow bench

SPECT: Target electroplating setup for Tl/Zn, Solid Target Irradiation Station, Pneumatic transport system Hotcells with Manipulators, Automated chem. Systems for Tl/Ga, Enriched target recovery systems.
PET Liquid target irradiation system, Irradiated water transfer system, Hotcells for FDG production.

9. Type of experiments to be carried out:

This facility will be used, mainly for the production of radioisotopes & radiopharmaceuticals for diagnostic imaging in Single Photo Emission Computed Tomography and Positron Emission Tomography, besides front line research experiments in the fields of material sciences, radiochemistry, liquid metal target development, etc.

10. Program Advisory Committee/experiment proposals: No.

11. Picture/Schematic:

Figure 43: DAE's Medical Cyclotron at Kolkata

12. Sources of information:

R.K.Bhandari, "Medical Cyclotron facility at Kolkata", Paper presented at Eighteenth International Conference on Cyclotrons and their applications 2007, page no. 87-89. (https://accelconf.web.cern.ch/accelconf/c07/PAPERS/87.pdf)

M.K.Das, "Medical Radioisotope production programme in the forthcoming medical cyclotron facility, Kolkata" IFAD 2012 (http://indico.vecc.gov.in/indico/getFile.py/access?resId=43&materialId=9&confId=10)

P.V.Bhagwat, "Safety aspects in particle accelerators", Paper presented in 33rd Safety and Occupational Professionals Meet IPR, 23-25th November 2016 (http://www.ipr.res.in/33rd-DAE-Meet/documents/Safety-aspects-particle%20accelerator.pdf)

See also: http://sterlingandwilson.com/offerings/electrical/featured-projects/the-medical-cyclotron-kolkata/

4. Summary and Conclusions

The existing and upcoming particle accelerators in India are listed, and their brief operating parameters and descriptions are also provided. The present investigation observes that there are currently two existing 14 MeV neutron generators using D-T reactions in the country, one at S.P. Pune University, and the other at Purnima Laboratory, BARC. These neutrons generators can produce neutron flux around 10^7 n/cm^2/s operated under a continous mode. Apart from these two, Institute for Plasma Research is also developing high intensity neutron source. This facility will utilize ECR ion source that will be capable of generating 14 MeV neutrons, using D-T reaction with a flux of 10^{12} n/cm^2/s in a continous mode of operation. This upcoming facility will be dedicated for fusion neutronics research for ITER project.

FOTIA and 14 UD Pelletron facility have been ulized for neutron source using ^{7}Li(p,n)^{7}Be reaction upto proton energy 6 MeV and 28 MeV respectively. However, due to the continous beam structure, Time of Flight measurement measurement cannot be performed to characterize the beam profile, and experimentalist has to rely on calculated or derived neutron spectrum for data reduction procedure resulting in less accurate experimental results. Since the proton current in these facilities are also low (in the order of few tens of nA), only very limited neutron induced cross sections with high cross sections can be measured.

The 3 MV Tandetron accelerator has recently been installed at GGV, Bilaspur. The high proton beam current available ~ 50 μA at 6 MeV will be used for ^{7}Li(p, n)^{7}Be reaction for generating quasi-mono energetic source of neutrons to produce high neutron flux. The expected neutron flux is ~ $4.5\text{x}10^9$ neutrons/cm^2/sec. However, the facility does not have pulsed beam option and therefore it will have its limitations in its usefulness.

The 3 MV Tandetron accelerator is being installed as FRENA facility at Saha Institute of Nuclear Physics, Kolkata which will be used as high flux low energy neutron source by using ^{7}Li(p,n)^{7}Be reaction. This facility will be able to produce pulsed proton and deuteron beams with 2 ns pulsed width. This facility is dedicated for experimental nuclear astrophysics.

Considering the number of users and looking at the number of particle accelerator facilities and their range of applications, it can be mentioned that India do not have state of art dedicated neutron facilities which can be used for precise measurement of neutron induced cross sections, for performing neutron scattering experiments, and for high energy neutron sources which can be used for measurement of (n,xn) reactions(x=1,2,3…..) etc.

5. Acknowledgement

The authors acknowledge the help and support of scientists across India who contributed information related to particle accelerators existing in their institutes/universities. The help and support of Dr. Naohiko Otsuka, Nuclear Data Section, International Atomic Energy Agency, Vienna in finalizing the report as INDC-IND technical report is also gratefully acknowledged.

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