THE RF MODULATOR

FOR THE RFMASS EXPERIMENT

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Summary : The RF modulator is the crucial part of the Radio-Frequency Mass-Spectrometer. The required specifications are presented here in the frame work of atomic mass measurements of far from stability nuclei at the ISOLDE/CERN facility.

1. Principle of the RF modulator.

For the purpose of mass measurement at ISOLDE, the trajectory in the radio-frequency mass spectrometer (RFMS) is quite similar to the case of the mass measurement of antiproton at LEAR except the slit size. However, the frequency has to be lowered because of the lower cyclotron frequency of heavier ions, and the principle of the resonant cavities has to be given up in order to get a wide band device which can be operated over a wide frequency range in order to cover the mass range from A = 7 to A = 250 A (1 mass unit ≈ 1 GeV/c^2). The RF modulator presented here is based on a set of 3 parallel plates acting as a plane capacitor. It is made of a central electrode fed with the RF power surrounded by 2 grounded plates (figure 1). Each of these plates have 2 openings in order to let the beam go through, the upper one is for modulation and the lower one for demodulation. The rectangular slits are 0.4 mm wide and 5 mm high, later on, a height of 10 mm will be used so as to increase the geometrical acceptance of the spectrometer. The longitudinal geometry of the modulator is based upon 2 parameters : the gap length (g) and the drift length (d) which correspond, at a first approximation, respectively to the insulator thickness and to the central plate thickness. The geometry has to be optimized in order to get the kinetic energy modulation as large as possible for a given RF voltage V_{RF}

2. Typical characteristics of the RFMS.

In order to make mass measurements within a precision of 5.10^{-7}, it is required that the mass resolving power is close to 10^5. So long as the isochronism quality is good enough ($\Delta\tau/\tau \leq 1/R$), the resolving power is given by $R = m/\Delta m \approx 2\pi n D_m / w$ where the integer n is the harmonic number which links the RF frequency to the cyclotron frequency according to $f_{RF} = (n+1/2)f_c$. ${}_m$ is the amplitude of the modulation of the diameter of the trajectory and w the width of the slits (inlet, modulation, demodulation and exit slits). Using n = 1500, ${}_m$ = 5 mm and w = 0.4 mm, we obtain R = 1.2 10^5. As the diameter of the trajectory is 1 m, ${}_m$ = 5 mm corresponds to a kinetic energy modulation of 1%. The kinetic energy of the ions from ISOLDE is 60 keV, then, we need an energy modulation of ΔE = 600 eV.

3. Features of the RF modulator.

The RF voltage applied to the central electrode is $V = V_0 \sin\varphi, \varphi = \omega t$. In first approximation, we assume that the electric field is homogeneous in the gaps ; φ_0 is the RF phase when the particle is

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coming into the first gap, φ_g and φ_d the variation of phase during the flight across the gaps and the drift. The variation of kinetic energy at the exit of the first gap is :

$$\Delta \mathbf{E_1} = \frac{\mathbf{qV_0}}{\varphi_\mathbf{g}} \times \left[\sin\left(\varphi_\mathbf{g} + \varphi_\mathbf{0}\right) - \sin \varphi_\mathbf{0} \right]$$

and, at the exit of the second gap is :

$$\Delta \mathbf{E_2} = \frac{\mathbf{qV_0}}{\varphi_\mathbf{g}} \times \left[\sin\left(2\varphi_\mathbf{g} + \varphi_\mathbf{d} + \varphi_\mathbf{0}\right) - \sin\left(\varphi_\mathbf{g} + \varphi_\mathbf{d} + \varphi_\mathbf{0}\right) \right].$$

φ_g and φ_d are related to the velocity **v** of the particles and to the frequency as $\varphi_g = \omega g / v$ et $\varphi_d = \omega d / v$. In order to obtain the largest possible value for $\Delta E = \Delta E_1 + \Delta E_2$, we have to choose g as small as possible and d very close to $\mathbf{d} = \beta\lambda(\mathbf{k} + \mathbf{1/2}) - \mathbf{g}$, where $\beta = \frac{v}{c}$ and $\lambda = c / f_{RF}$ is the wave length of the RF. The integer k has to be as small as possible in order to get rid of deterioration of the isochronism quality. For the purpose to keep the homogeneity of the RF field in the gaps, and also for an easier machining, the gap g will be kept larger than 0.4 mm.

4. RFMS simulations.

The aim is to find the best adaptation of the geometry of the modulator over the useful mass range from A = 7 to 250. A selection of the typical parameters of the RFMS are summarized in table 1. They are calculated using a multi-particle simulation code SRFISOLMASS (19/10/93 version) which is very close to the real spectrometer except the homogeneity of the magnetic field which is supposed to be perfect. It is able to give the mass resolving power and the transmission for a given set of parameters ; particularly, the effect on the line shape of different modulation and demodulation amplitudes might be shown.

- In the table 1, the first line corresponds to the PBARMASS experiment at LEAR, it exhibits a good agreement with the experimental parameters (with resonant cavities, the length of the drift is different and the mass resolving power had to be multiplied by a factor of 6 because of the energy filters).

Table 1.

A	E (keV)	B (T)	VRF (kV)	Amp. (mm)	fc (Hz)	fRF (MHz)	β	βλ/2 (mm)	g/d/g (mm)	n	R/1000
1	200	0.1288	1.17	5	1977155.	2966.7	2.07e-2		0.5/1.5/0.5	1500	244
1	60	0.0705	0.35	5	1083055.	1625.1	1.13e-2	1.05	0.5/0.5/0.5	1500	127
5	60	0.1577	0.35	5	484375.	726.8	5.08e3	1.05	0.5/0.5/0.5	1500	127
10	60	0.2230	0.35	5	342507.	513.9	3.59e-3	1.05	0.5/0.5/0.5	1500	124
20	60	0.3154	0.35	5	242189.	363.4	2.54e-3	1.05	0.5/0.5/0.5	1500	130
40	60	0.4461	0.35	5	171254.	257.0	1.79e-3	1.05	0.5/0.5/0.5	1500	129
60	60	0.5463	0.35	5	139828.	209.8	1.47e-3	1.05	0.5/0.5/0.5	1500	126
80	60	0.6309	0.35	5	121095.	181.7	1.28e-3	1.05	0.5/0.5/0.5	1500	126
100	60	0.7053	0.35	5	108311.	162.5	1.14e-3	1.05	0.5/0.5/0.5	1500	125
150	50	0.7886	0.29	5	80730.	121.1	8.5e-4	1.05	0.5/0.5/0.5	1500	125
200	37	0.7833	0.22	5	60143.	90.25	6.3e-4	1.05	0.5/0.5/0.5	1500	123
250	30	0.7886	0.175	5	48438.	72.68	5.1e-4	1.05	0.5/0.5/0.5	1500	125

With the present system, the whole mass range is covered using only a single modulator (g = 0.5 mm, d = 0.5 mm) but it has to be fed with a very broad band RF power amplifier which is not realistic.

- Before to pay attention to the required band width of the system and to the impedance matching, a set of modulators with several geometry's is optimized in order to cover the whole mass range. To lower the cost of the RF power amplifier and to make easier the impedance matching, it seems convenient to restrict the frequency span to 1 octave : 250 MHz up to 500 MHz. Using 4 geometry's allowing for a good overlap of the mass ranges (Table 2), and running the modes k= 1 (3β λ/2) and k = 2 (5βλ/2), makes it possible to get a resolving power larger than 10^5.

Table 2.

A	E (keV)	B (T)	VRF (kV)	Amp. (mm)	fc (Hz)	fRF (MHz)	β	#βλ/2 (mm)	g/d/g (mm)	n	R/1000
7	60	0.1866	0.35	5.0	204688.	499.6	4.29e-3	3.87	0.5/3.36/0.5	1220	106
16	60	0.2821	0.35	5.0	270776.	330.5	2.84e-3	3.87	0.5/3.36/0.5	1220	106
28	60	0.3732	0.35	5.0	409373.	249.8	2.14e-3	3.87	0.5/3.36/0.5	1220	106
23	60	0.3383	0.35	4.5	225843.	499.7	2.37e-3	2.13	0.5/1.63/0.5	2212	157
50	60	0.4987	0.35	4.5	153174.	338.9	1.61e-3	2.13	0.5/1.63/0.5	2212	160
92	60	0.6765	0.35	4.5	112922.	249.8	1.18e-3	2.13	0.5/1.63/0.5	2212	163
84	60	0.6464	0.35	3.5	118177.	499.9	1.24e-3	1.86	0.4/1.46/0.4	4230	199
150	50	0.7885	0.35	4.0	80730.	341.5	8.5e-4	1.86	0.4/1.46/0.4	4230	245
200	37	0.7833	0.32	5.0	60143.	254.4	6.3e-4	1.86	0.4/1.46/0.4	4230	314
170	44	0.7875	0.35	3.5	71137.	367.1	7.5e-4	1.53	0.4/1.13/0.4	5160	238
210	35	0.7806	0.35	4.2	57085.	294.6	6.0e-4	1.53	0.4/1.13/0.4	5160	310
250	30	.7886	0.35	5.0	48438.	250.1	5.1e-4	1.53	0.4/1.13/0.4	5162	382

To summarize, this last combination of 4 modulators is realistic and the mass range could be covered as it follows :

	A	g/d/g (mm)
Mod. I	**7 - 28**	**0.5 / 3.36 / 0.5**
Mod. II	**23 - 92**	**0.5 / 1.63 / 0.5**
Mod. III	**84 - 200**	**0.4 / 1.46 / 0.4**
Mod. IV	**170 - 250**	**0.4 / 1.13 / 0.4**

5. RF field homogeneity.

The principle of the radio-frequency spectrometer is relying upon the condition that modulation and demodulation amplitudes are equal. As a consequence, the RF field has to be homogeneous over the whole height of the slits and to have the same amplitude in the modulation and demodulation slits. The figures 2 to 5 exhibit the effect on the line shape of the inequality of the amplitudes :

Figures	demodulation amp /modulation amp.	R
2	1.00	$1.57\ 10^5$
3	1.01	$1.57\ 10^5$
4	1.10	$1.22\ 10^5$
5	1.50	$0.50\ 10^5$

As a consequence, the inhomogeneity of the electric field and the inequality of amplitudes should stay below 10% in order to keep the resolving power around 10^5.

6. Bandwidth and frequency range

Even though, the frequency scan is usually narrow, wide RF scans has to be done over several consecutive harmonic numbers to make possible a check of the resonance peak equidistance. For a 5 harmonic scan lasting approximately 1 second, the RF amplitude must be constant at 1% over 1 MHz at 500 MHz ($\Delta f/f \approx 2\ 10^{-3}$) and 2 MHz at 250 MHz ($\Delta f/f \approx 8\ 10^{-3}$). Practically, during one day or more, the RF system will be tuned at the center of this frequency domain to make comparison between 2 masses A (known) and B (unknown). Then, the system will be tuned at a different frequency selected in the domain 250 - 500 MHz to move towards another mass region. As a consequence, the RF system (figure 6) should be tunable over this frequency domain (figure 7).

The required RF voltage is 350 V (700 V peak to peak). It has to be reachable from 250 to 500 MHz, using a tunable transformer and a manually tunable impedance matching section. In order to get a flat characteristic over a wide band (2 MHz) the power line between the RF amplifier and the modulator should have a characteristic impedance of 50 ohms.

7. Technical features

In order to dissipate the heat from approximately 1 kW of RF power, the dissipative elements have to be water-cooled. To get rid of RF pertubational effects outside the spectrometer, the RF line and the modulator housing has to be as tight as possible for RF radiation.

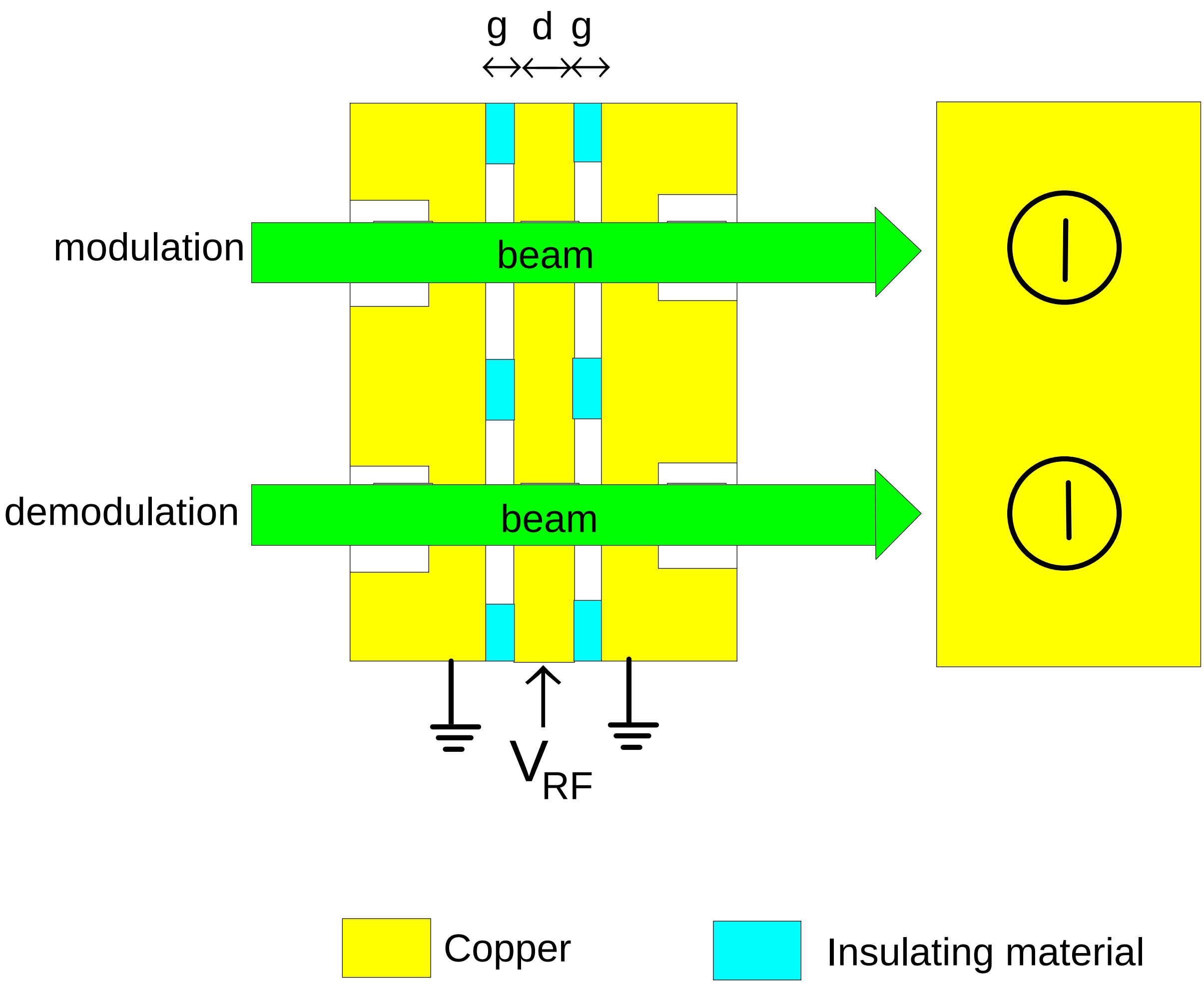

Figure 1. Schematic view of the RF modulator

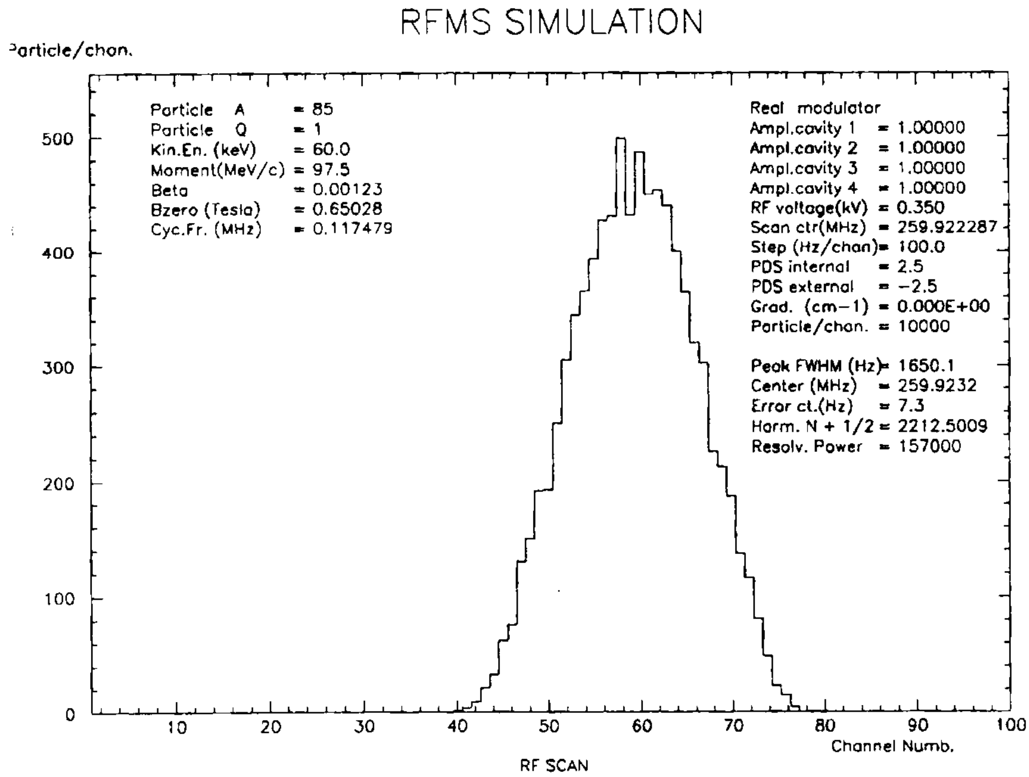

Figure 2. Resonance peak for demodulation and modulation amplitudes ratio of : 1.00.

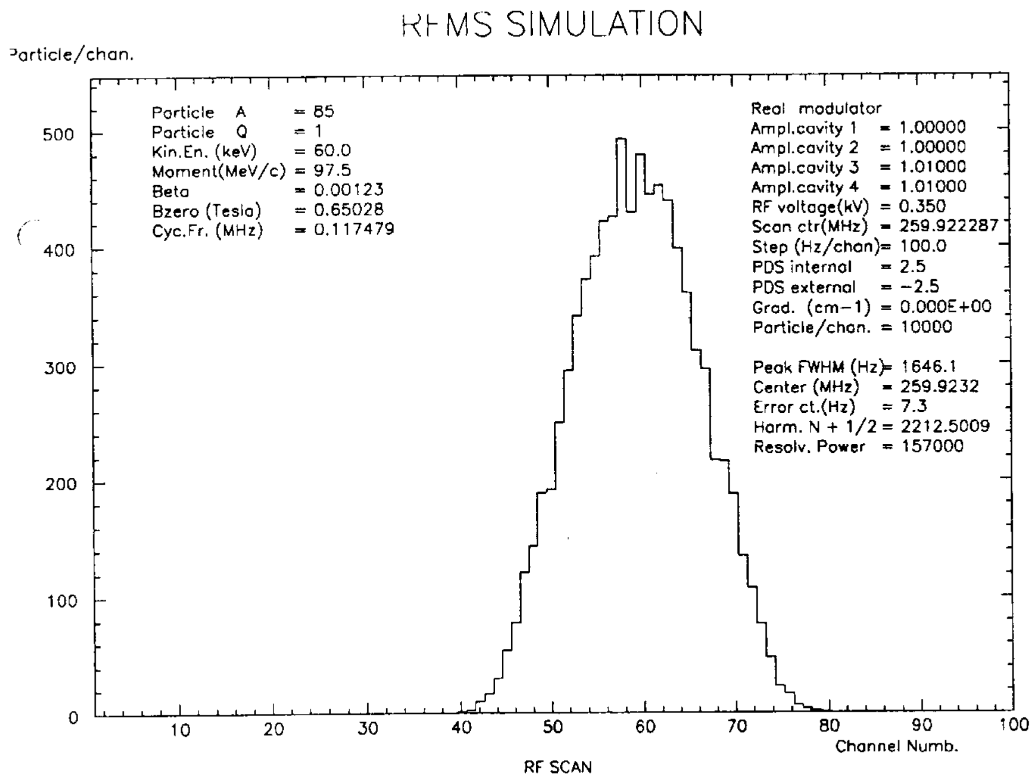

Figure 3. Resonance peak for demodulation and modulation amplitudes ratio of : 1.01.

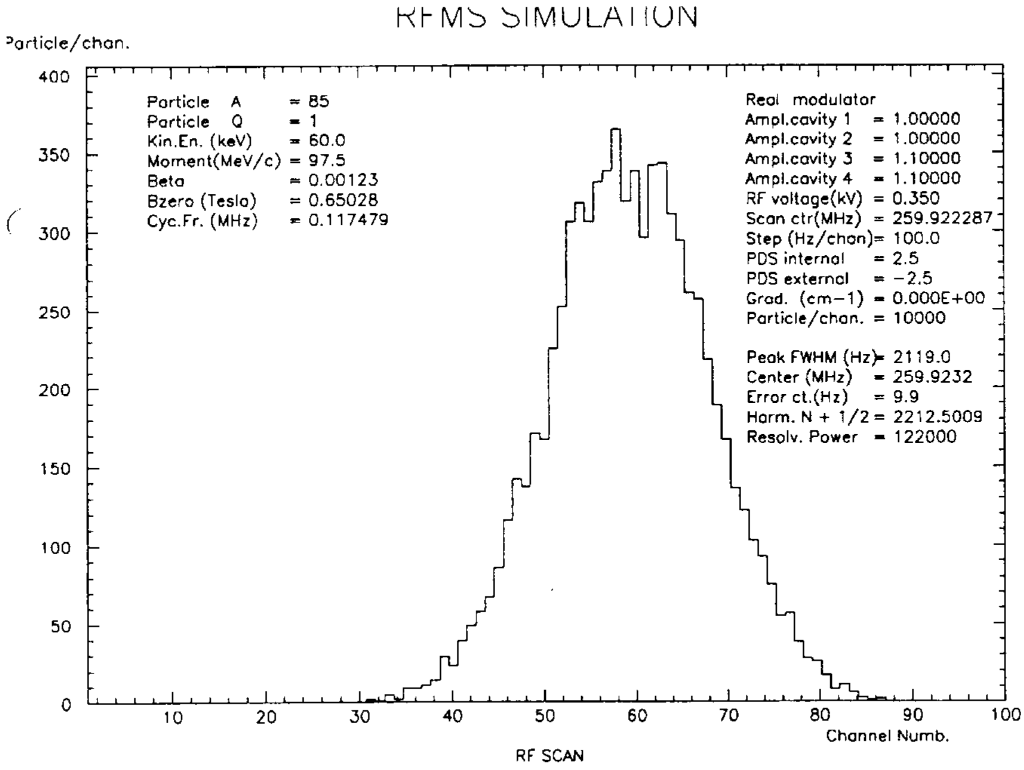

Figure 4. Resonance peak for demodulation and modulation amplitudes ratio of : 1.10.

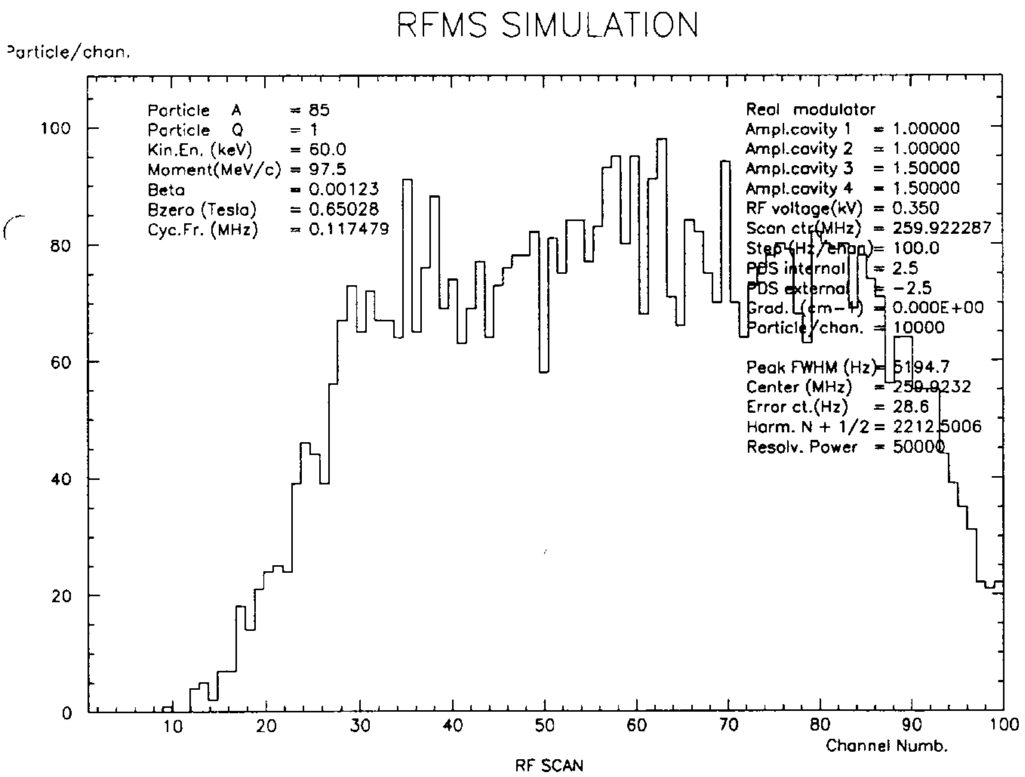

Figure 5. Resonance peak for demodulation and modulation amplitudes ratio of : 1.50.

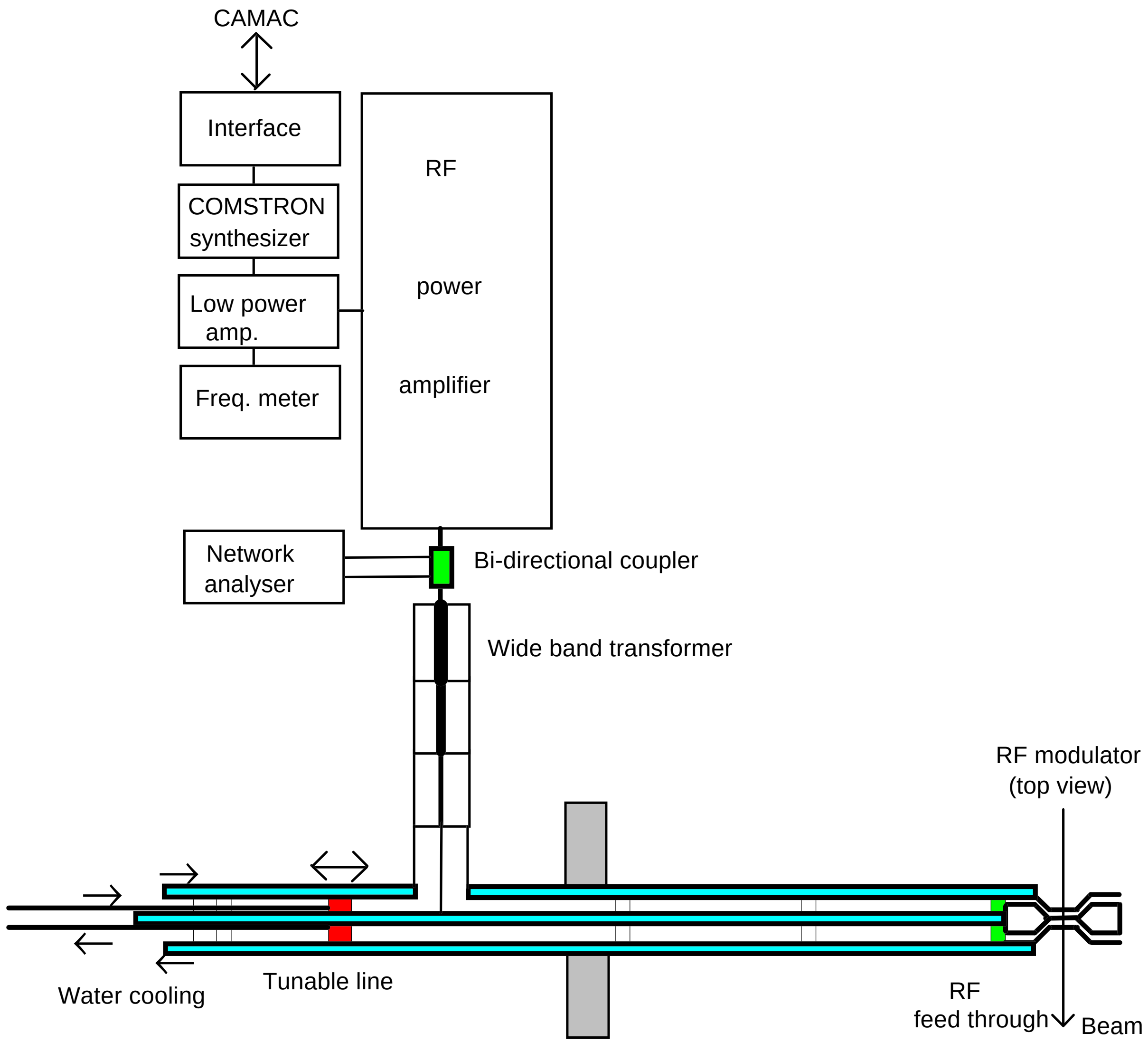

Figure 6. The RF system.

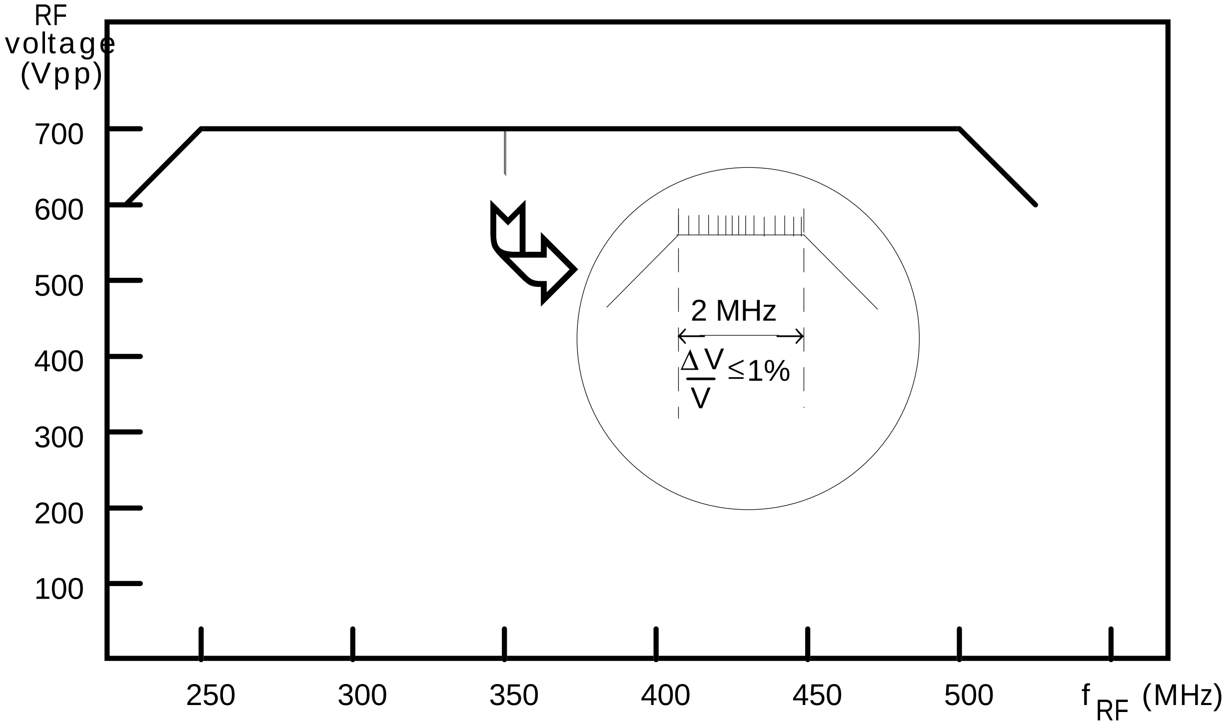

Figure 7. Bandwidth and frequency span. The RF frequency is scanned quickly (less than 1 second) over a width of 2.0 MHz in working band (circle). The position of the band has to be moved in the domain from 250 MHz up to 500 MHz using the tunable impedance matching system.