Siberian Branch of Russian Academy of Science
BUDKER INSTITUTE OF NUCLEAR PHYSICS

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RF SYSTEMS FOR A HIGH-INTENSITY HEAVY ION SYNCHROTRON WITH STRONG BUNCH COMPRESSION

(Part II)

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Abstract

The second Part of the Design Study Report on the high intensity heavy ion beam bunch compression complex describes concepts and preliminary designs of the radio-frequency systems which will enable injections of necessary amount of bunches, acceleration of ions and subsequent compression of the beam in a single short bunch. The main objectives for this study was inspecting of possible basic limitations on such a design (e.g. what should be the structure of the RF-system, what kind of RF-items should be used and what phenomena limit basic parameters of these items). In our design we studied first the cases which enable the simplest operation modes of the bunch compressor. In particular we adopted that the frequency of injected bunches in the ring is the same as that in the preceding linac (36 MHz).

In the present design the RF system of the bunch compression synchrotron consists of two main parts. One enables injections of ion bunches and their subsequent acceleration from the energy 10 MeV/u till the energy 125 MeV/u, while the other enables the bunch compression.

During the acceleration the RF-frequency changes from 36 MHz to about 117 MHz. These frequency variations can be achieved using ferrite loaded RF-cavities. Particular design parameters of cavities were chosen using benchmark tests of the ferrites in the desired frequency range. The amplitude of the RF-voltage in a cavity is limited by the density of the power dissipated in the ferrite and does exceeds 12 kV/cavity. Total amount of the required cavities is 250. The acceleration time is 0.2 s. As it was shown in the first part of the report, at least two identical accelerating RF-stations separated by equal segments of the orbit circumference are necessary to enable simultaneous stability of incoherent and dipole coherent synchrotron oscillations. For the closed orbit perimeter equal to 1200 m, the harmonic number of the accelerating RF-field should be 994.

The bunch compression will be performed using a special RF-system which generating the sawtooth form dependence of the RF-voltage on the ion position in the bunch. We assume that the beam filling pattern contains a 10% gap free of bunches. Correspondingly, the useful slope of the saw should take 10% of the closed orbit circumference. In this report we studied two possibilities. One is based on employment of five first harmonics of the revolution frequency to form the desired sawtooth shape of RF-voltage. In the other, this sawtooth shaped voltage should be created using the inductive type accelerating devices. Presently, we consider the last case as a more favorable.

Contents

1 Introduction

We report here results of the conceptual design studies for RF systems in the future GSI synchrotron [1] which will enable operation with intense beam of the U^{4+}-ions in the kinetic energy range W = 10 MeV/u till W=125 MeV/u. The ion beam intensity is up to 10^{13} ions in the beam. In the bunch compression mode operation should enable the reduction of the bunch length down to 10 ns at an ion energy of 125 MeV/u ($2\sigma_s \simeq 1.41$ m). Initial beam parameters for our calculations correspond to the preliminary synchrotron parameter sets as they are described in Ref.[1]. We assume that a new injector linear accelerator in GSI will provide, e.g. for U^{4+}-ions the following parameters:

ion energy	W	MeV/u	10
beam current	I	emA	15
bunch repetition frequency	f_b	MHz	36
beam pulse duration		ms	up to 1
transverse beam emittances (normalized)	$\epsilon_{x,z}$	mmmrad	1
longitudinal bunch emittance	ϵ_s	(keV/u)·ns	3

In the high intensity operation mode the beam is obtained in the synchrotron using up to 20-turn injection. The longitudinal emittance of injected bunches is small (ϵ_s=3 [(keV/u)·ns]). On the other hand intensity of a single injected bunch is already so high that its longitudinal phase space forces should be compensated by adequate RF voltage. As is described in Ref.[1], the accumulation of the intense beam will occur displacing new bunch deposits in the transverse phase space. In the longitudinal phase space the bunches of subsequent turns will be injected in the same RF bucket. Correspondingly, to keep the accumulated bunch length constant the amplitude of the RF voltage during the injection period (up to 0.5 ms) will increase linearly.

The RF system of the bunch compressor described here consists of two parts. The first one is an RF system for the acceleration. Its main objectives are the beam management in the longitudinal phase space during injection and subsequent acceleration of the beam from injection energy 10 MeV/u up to the final energy of 125 MeV/u. The accelerating RF systems should meet the requirements listed in the Table 1. If the guiding magnetic

Table 1: Initial parameter list for the accelerating system design

Ion injection energy, Emin, MeV/u	10
Number of Uranium ions, N	10^{13}
Uranium ions charge, e	$4e^{+}$
Bunch repetition rate, fmin, MHz.	36
Revolution frequency at injection, Fmin, kHz	36
Number of injected bunches	750
Circumference of the accelerator, m	1200
RF system harmonic number, q	994
Final ion energy, MeV/u	125
Final revolution frequency , kHz	117
Pressure of accelerator vacuum chamber, Torr	10^{-11}

field of the synchrotron increases linearly in time (from $B_{\min}$ to $B_{\max}$ during the time interval δt)

$$B(t) = B_{\min} + \frac{B_{\max} - B_{\min}}{\delta t} t.$$

the accelerating voltage V and synchronous phase ϕ_s are constant and provided that $\delta t = 0.3$ s, correspond to $V_{RF} = 2.83$ MV and $\phi = 0.156$ rad. As it is shown in Ref.[1], in a space charge dominated beam the values of the voltage amplitude and of the synchronous phase are calculated using the matching conditions in the longitudinal phase space for the required acceleration gain, minimizing increase in the bunch length due to space charge fields in the bunch. The second RF system for the bunch-compression produces the energy modulation in the beam which is required for its subsequent shortening. This system produces the sawtooth shaped RF signal on the accelerating gaps. In this report we examine for bunch compression two possibilities. A sawtooth RF system is using the first 5 harmonics of the revolution frequency. As we shall see, with a necessary feedback system this system can work well, if the accelerated beam train has a 20 % gap in the beam filling pattern. Another device discussed uses an inductive type of acceleration units. This device enables the operations with bunch trains having only 10 % gap in the beam filling pattern. The total beam current in the synchrotron is about 1.6 A after acceleration and this value increase approximately by a factor of 1000 during the bunch compression. If the beam will pass the acceleration and the bunch compression RF systems simultaneously, its transformations will be affected by strong beam loading effects. These problems are eliminated, if according to Ref.[1], the ring will be a racetrack with two long straight sections, and one of these straight section will split in three beam lines (see in Fig.1). Passing the beam to different beam lines we avoid the interference in the action on the beam of the different synchrotron RF systems.

2 Accelerating RF system

During the acceleration cycle the working frequency of the RF system should vary from $f_{\min}$ =36MHz to $f_{\max}$=117MHz. For this frequency range the 60HH ferrite can be used in RF cavities.

RF voltage of an accelerating caivity is often limited by the power density in ferrite. For many accelerating RF caivities the specific power density in ferrite is in the range of 0.17 - 0.25 W/cm^3 [6],[7] The research of ferrite properties and cavity numerical simulation have shown that at an acceleration rate of 36 kV/m, an acceleration time of 0.2 s. and a repetition frequency of 0.5 Hz the average power dissipation in ferrite is equal to 0.12 W/cm^3. If it is presumed that the power dissipation in ferrite is proportional to the density of magnetic flux B^4, then the cavity voltage can be increased by 20%. It is not a noticeable rise and the final maximum RF voltage of the cavity will be set only after testing of a fullscale pilot RF cavity.

The RF cavity design allows for baking out the part of vacuum chamber inside the cavity. Prior to baking out the vacuum chamber the magnet yoke should be removed and the coil should be shifted away. Then the cooling water should be evacuated from cavities and ferrites are to be dried. During baking out procedure vacuum chamber and ferrite are heated to temperatures of 300-350^{o}C. It is known that ultrasonic water saturation doesn't make significant change in the ferrite parameters (10-15%) (see, for example, in Ref[2]). Metal-ceramic joint made with thermo diffusion welding doesn't pose any problems for application of water cooling, too. All this circumstances certainly stand for water cooling for this design of RF cavity.

2.1 RF cavity for acceleration system

The cavity design and its outside dimensions are shown in Fig.2. Since the maximum accelerating voltage per cavity is 12 kV, the required maximum amplitude of the RF-voltage during the injection and acceleration period (3 MV) can be obtained using 250 of such cavities. These cavities will be placed in the accelerating line of the bypass (Injection orbit in the Fig. 1) During acceleration the cavity frequency is varied in the range of 36 - 117 MHz changing the value of the biasing magnetic field of the cavity. The magnetic system of the cavity consists of the solenoid and of the yoke. It creates a periodic magnetic

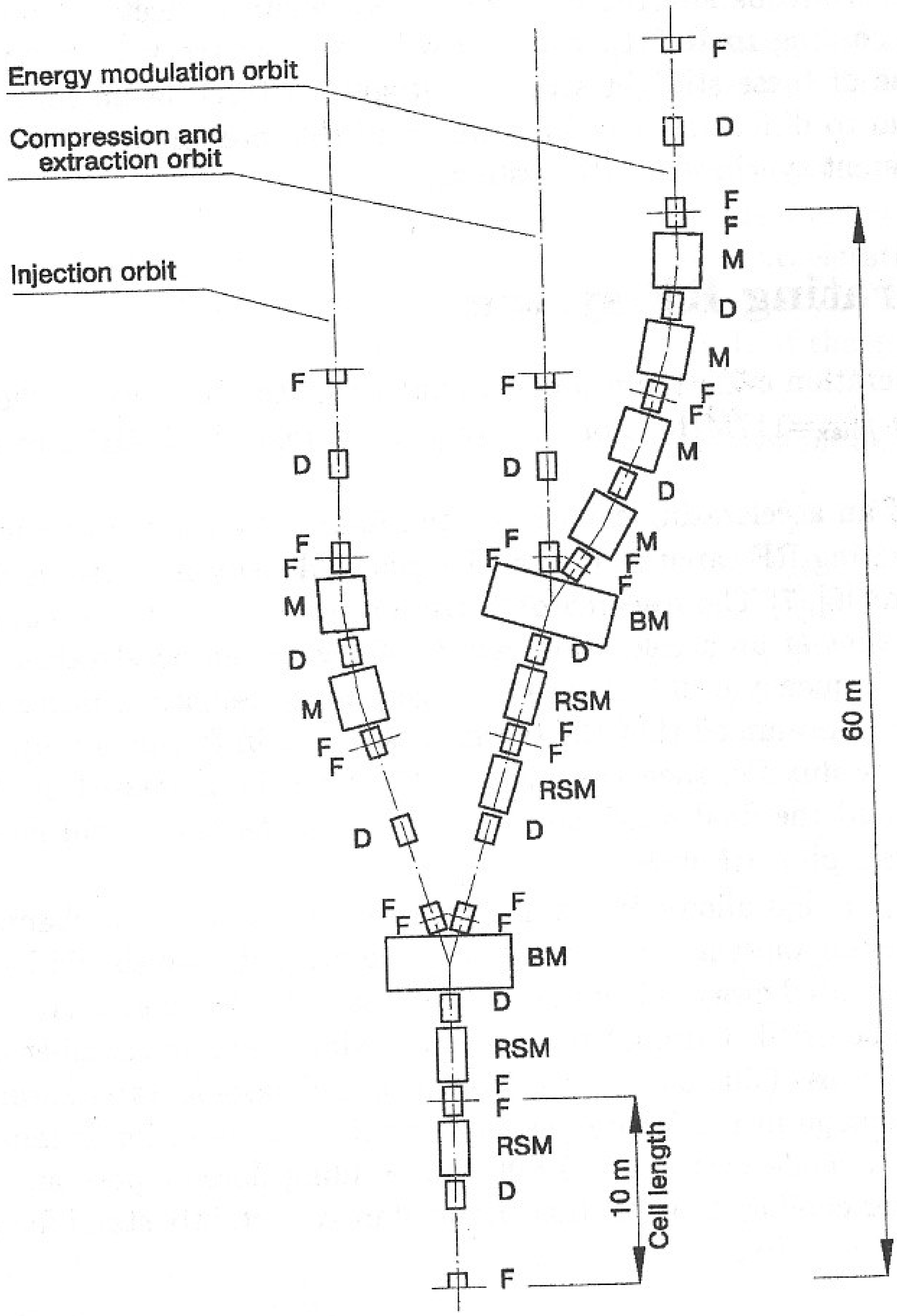


Figure 1: Schematic layout of the bypass insertion: F, D - lenses, RSM - switching magnets, BM - two-aperture bending magnet, M - bending magnet (standard for arc cells of the synchrotron).

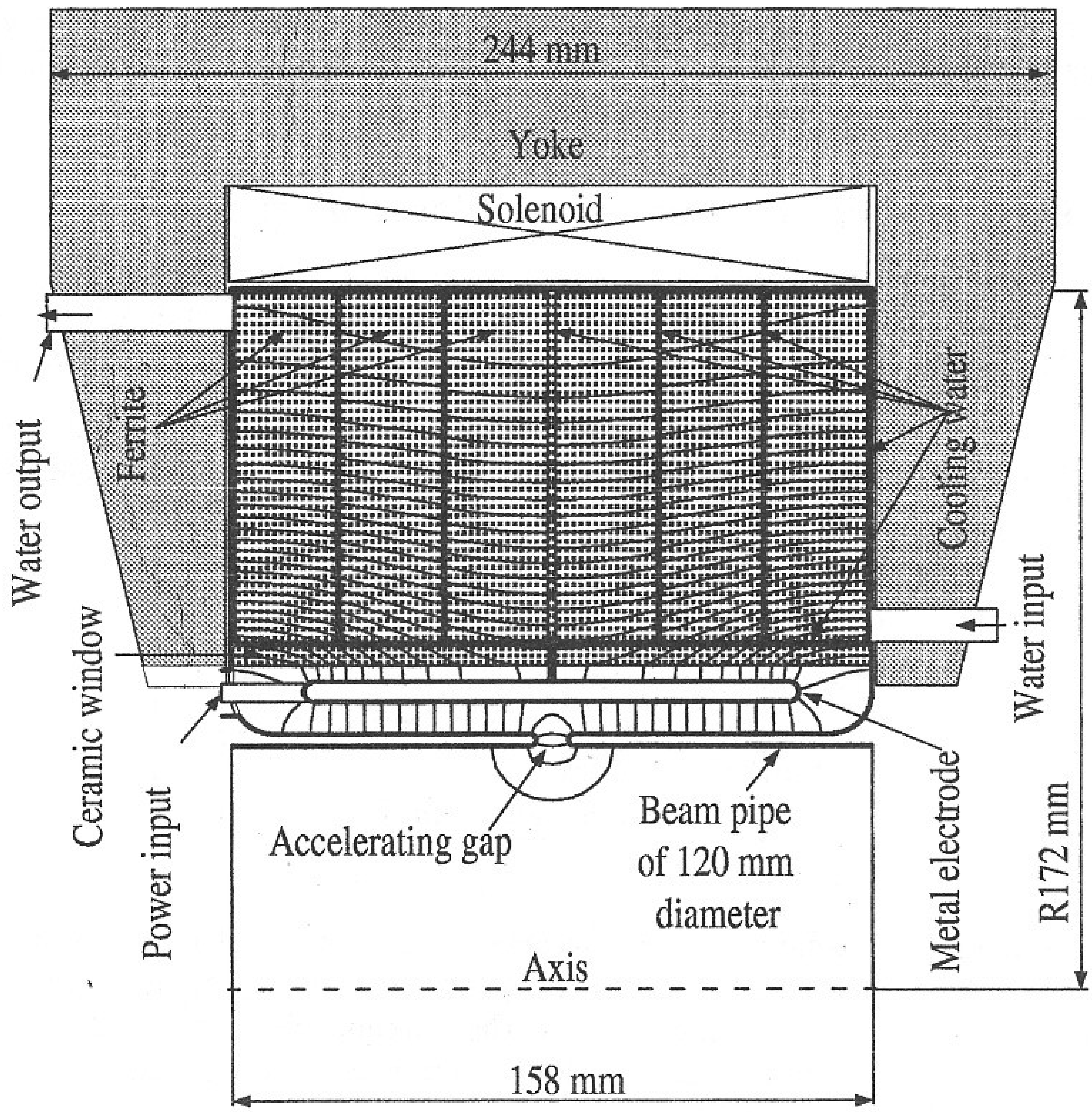


Figure 2: Sketch of the acceleration system RF-cavity with RF electrical field lines and outside dimensions.

field with the repetition frequency of 0.5 Hz in the cavity ferrite. During the acceleration cycle ($\Delta t = 0.2$ s) the value of this field increases from 1790 to 5870 Gauss. The biasing magnetic fields of adjacent cavities can be set to have opposite directions, so that the influence of the magnetic field on the ion trajectories can be reduced.

The cavity is cooled by water which flows in the gaps shown in the figure. The ceramic window consists of two parts. Between them a metal (copper) electrode is soldered. The electrode is a part of RF capacitance of the cavity and closes the ceramic window against the beam vacuum channel. The RF power feeding to the cavity is made through a conducting link to this electrode. Side and cylindrical walls of the cavity body are manufactured from 1 mm sheets of stainless steel. The cavity body is supported by the magnetic system frame.

2.2 RF characteristics of the accelerating mode

The cavity properties were calculated using the program CLANS [1]. These calculations used the RF properties of ceramics, cooling water and cavity metals which are listed in Table 2 The ferrite properties required for these calculations were measured using an RF

Table 2: The RF properties of cavity materials at accelerating frequencies.

Copper resistivity at 60^0C, μOhm·cm	1.89
Stainless steel resistivity, μOhm·cm	73.7
Permeability μ' of the ferrite	11
Ceramic permittivity ε'	12
Dielectric losses in ceramic, $tan(\delta)$	0.001
permittivity ε' of water	81
Dielectric losses in water, $tan(\delta)$	0.01

setup described in the Chapter 3. RF characteristics of the accelerating cavity mode were calculated for five frequencies at 12 kV RF voltage. RF characteristics of the accelerating cavity mode and properties of the ferrite at these frequencies are shown in Table 3. The complete length of one cavity with additional units is $\simeq 0.4$ m so that the total length of the accelerating RF system is 100 m.

The calculations showed that the maximum RF magnetic field (B_{max}) differs from its minimum value (B_{min}) not more than by a factor of 20%. It is taken into account, that tan(δ) is constant for all ferrite volume and corresponds to an average value of a field $B_{av} = (B_{max} + B_{min})/2$.

2.3 RF characteristics of higher order modes

Higher order modes (HOM) were calculated using the program CLANS [3]. The measured ferrite properties at frequencies of 100 - 1000 MHz at a small signal in the magnetic field of 1000 - 3200 Gauss were used. The frequency 1080 MHz is a critical frequency namely the TM_{01} mode for a circular waveguide of a diameter of 200 mm (vacuum chamber of that

Table 3: RF properties of the accelerating cavity mode and ferrite properties in accelerating frequency range.

External magnetic field , Gs	1796	2105	2547	3354	5865
Resonance frequency, MHz	35.87	48.002	64.2	85.37	112.8
Quality factor [Q]	88.1	129	192	293	436
Shunt impedance [Z_0], kOhm	7.59	8.36	9.38	10.9	12.6
Total power, kWt	9.48	8.61	7.68	6.59	5.71
Specific ferrite losses, Wt/cm3*	1.57	1.19	1.01	0.81	0.72
Ferrite magnetic permeability	23.82	13.2	7.33	4.07	2.26
Tangent of magnetic losses, tan(δ)	.0104	.0068	.0036	.0025	.0014

part of the accelerator, where the cavities are located). The results of the calculation for W=10 MeV/u and W=125 MeV/u are shown in Tables 3, 4. If W=10 MeV/u, the HOM impedances (except the 113 MHz mode) are less than 1 Ohm. HOM cavity impedances $Z(f)$ at W=10 MeV/u and W=125 MeV/u are shown in Fig.3 For the first 6 modes these

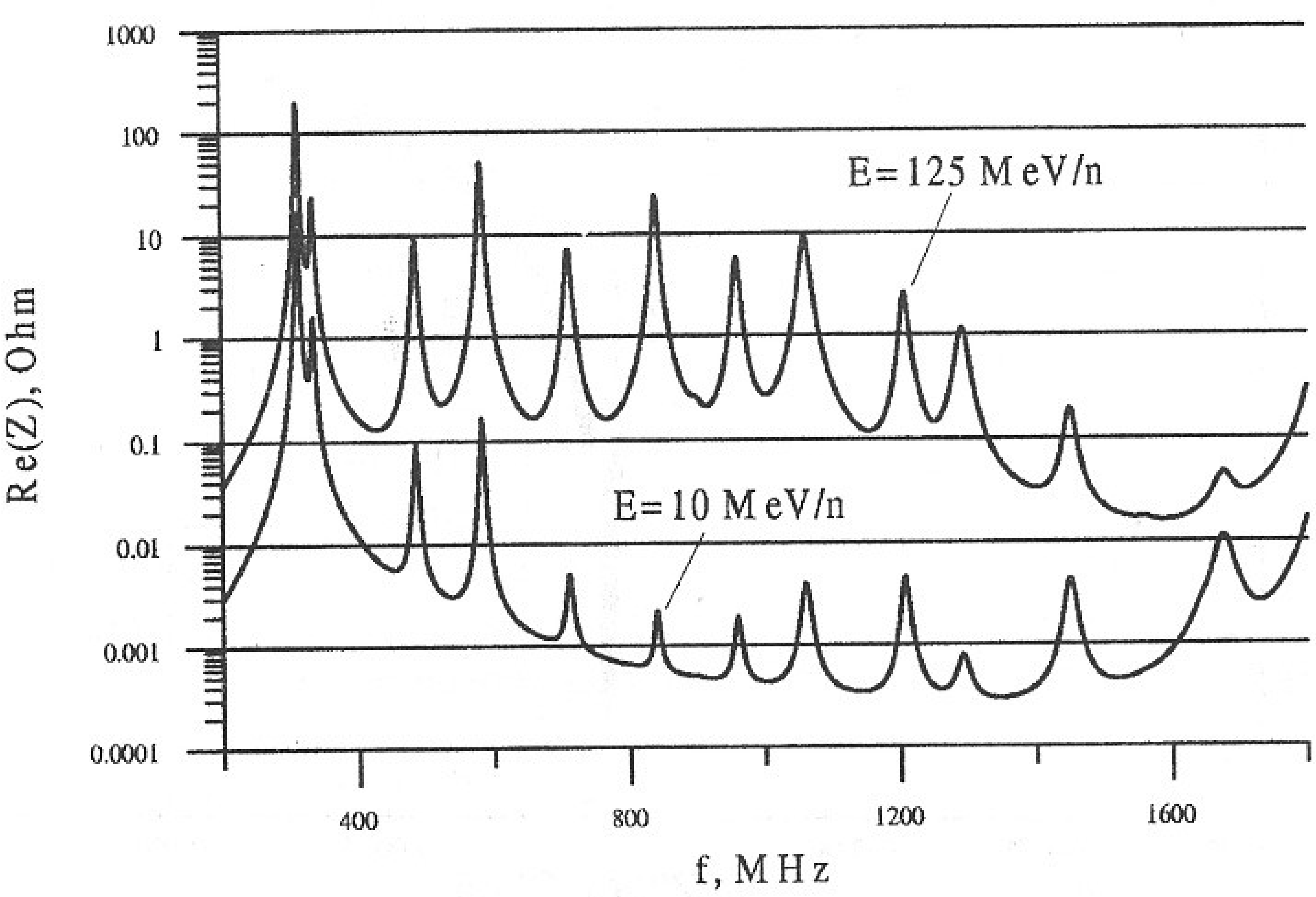


Figure 3: HOM spectrum of the cavity at initial (W=10 MeV/u) and at the final (W=125 MeV/u) ion energies.

values are listed in Table 4.

The strength of the interaction of coherent oscillations of the beam with surrounding electrodes is determined by the specific coupling impedance, which is

$$\frac{Z(f)}{n} = \frac{f_0}{f} Z(f).$$

Table 4: Characteristics of the HOM at (W=10 MeV/u; left part) and at (W=125 MeV/u; right part).

k	f_k, MHz	Z_0, Ohm	Q	f_k, MHz	Z_0, Ohm	Q
1	113.11	63.57	25.9	366.36	76.3	111.0
2	205.13	1.357	86.3	394.6	2.282	86.6
3				582.5	0.282	107.5
4				668.79	10.33	136.9
5				854.88	0.1769	117.2
6				958.18	1.872	157.57

As is seen from Figs.4 and 5, for the designed accelerating cavities these values are

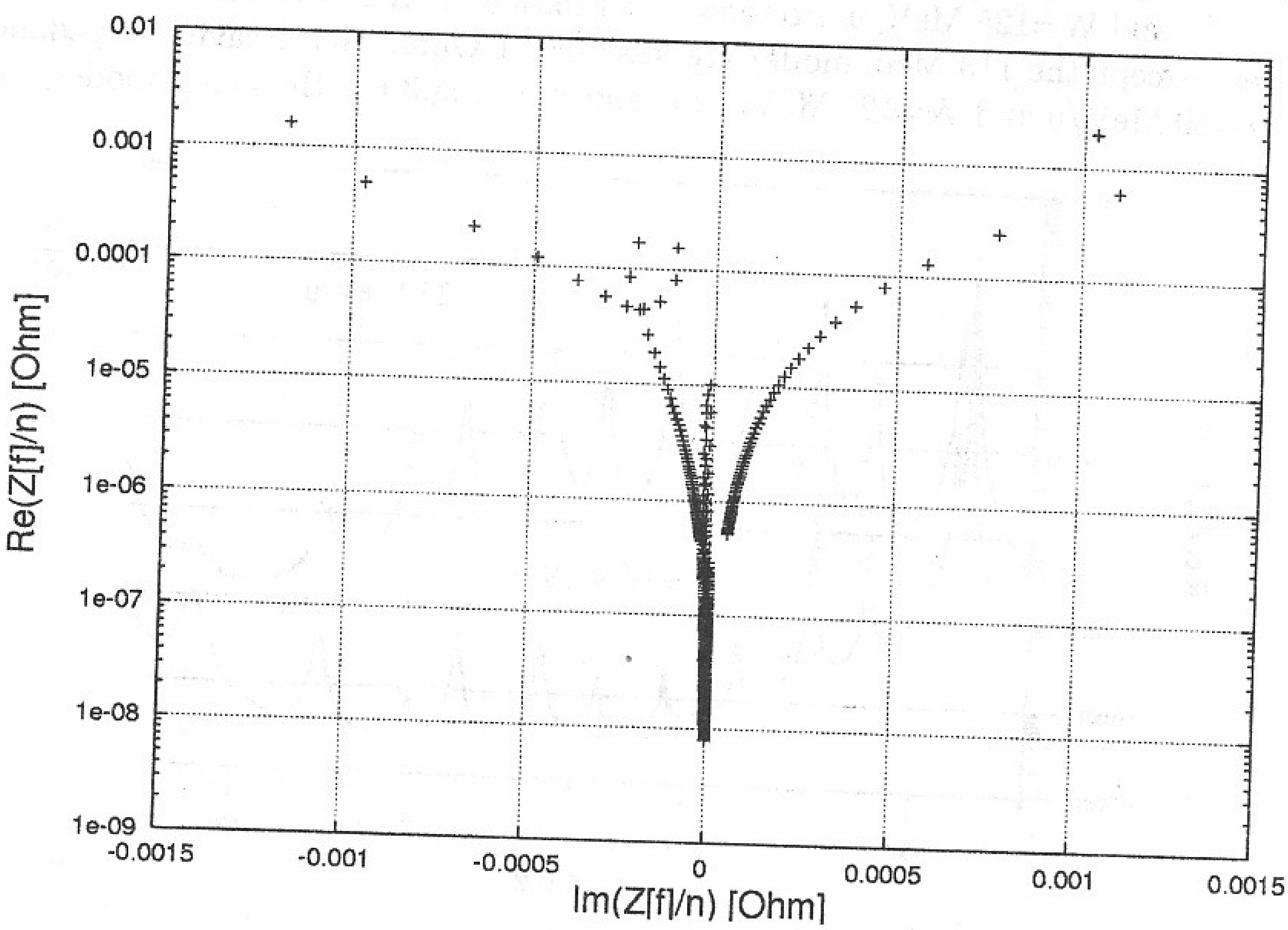


Figure 4: HOM spectrum of the cavity in terms of Z/n. Ion energy 10 MeV/u.

negligible small as compared to the coupling impedance of the ideally conductive vacuum chamber of the synchrotron ($Z/n \simeq 170$ Ohm)

$$\frac{Z}{n} = \frac{30}{\gamma^2(v/c)}\left[2\ln\left(\frac{l_\perp}{a}\right)+1\right] \simeq 170\,[\mathrm{Ohm}], \quad W = 125[\mathrm{MeV/u}].$$

Here, $l_\perp$ is the radius of the vacuum chamber and a the beam radius.

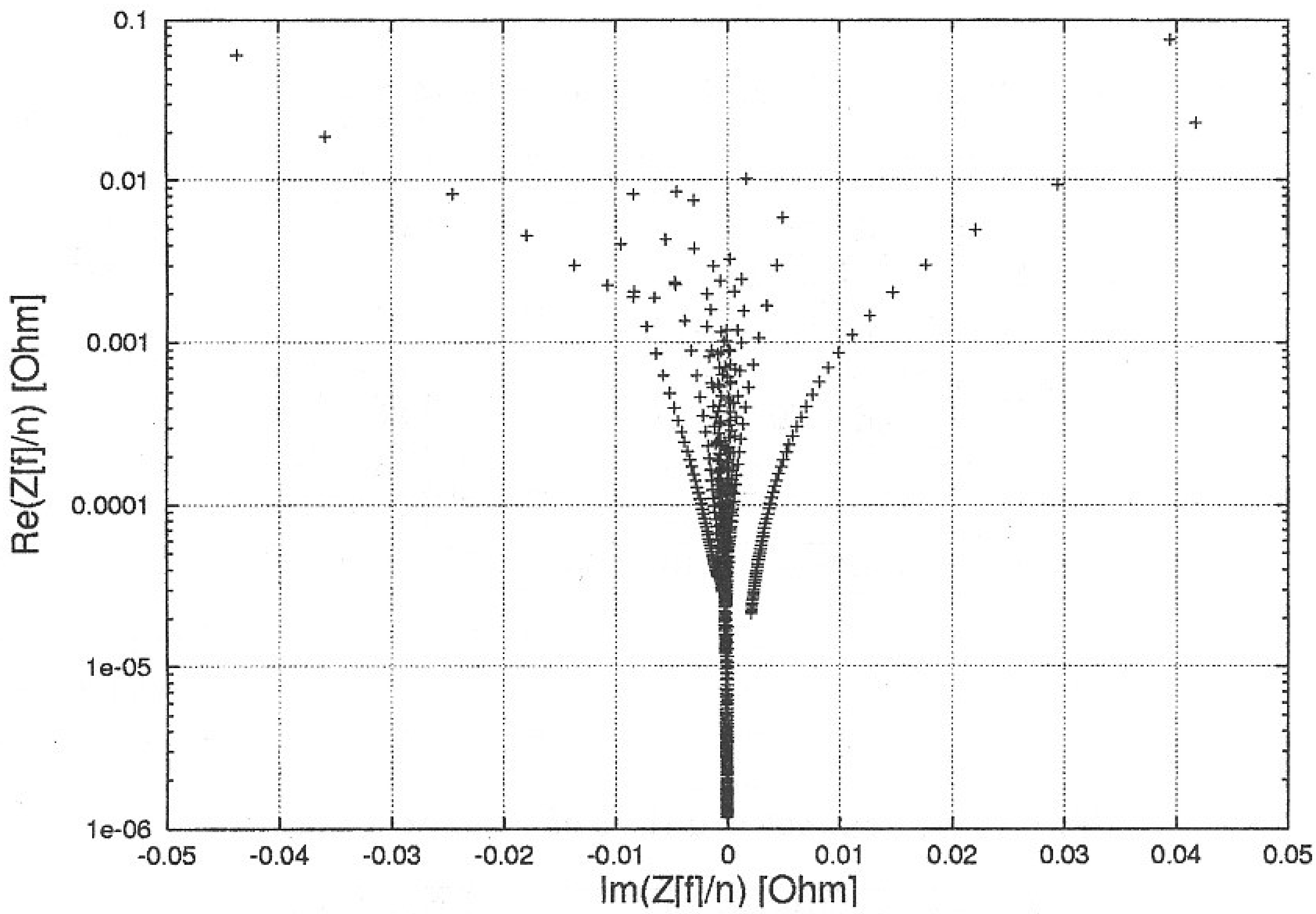


Figure 5: HOM spectrum of the cavity in terms of Z/n. Ion energy 125 MeV/u.

2.4 RF power amplifier for the accelerating system.

Each channel of the power amplifier consists of a broadband driver and an output stage using tetrode GU-92A with grounded grids. This tetrode is produced by SED company, St.Petersburg, Russia. The anode of the tube is directly connected to the central conductor of the cavity through a capacitor. The design amplitude of the RF voltage at the anode is 6 kV. The maximum output power of the stage - 8 kW during 0.2 s. General and limiting values are shown in the Tables 5–7. For higher reliability of the output stage the filament voltage given in the Table 6 is reduced.

3 Measurement of ferrite parameters for RF cavities.

The described designs of the accelerating cavities substantially used the particular properties of the ferrites in the conditions specific for the synchrotron operations. As we already mentioned, in all cases we assumed that the ferrite of 60HH-type will be used in accelerating cavities. This ferrite is produced by Russian company "Domen", Saint.-Petersburg. However, the ferrite parameters had to be measured in the range of 36 – 1000 MHz for low and high RF magnetic flux.

3.1 Measurement at high RF magnetic flux.

A ferrite ring of 60HH was used in the measurement. The outside diameter of the ring was D = 30 mm, internal diameter d = 15 mm, height of the ring h = 10 mm. This ferrite ring was placed into a coaxial line the internal dimensions of which were equal to those of the ring. The coaxial line had a short circuit at one side, the other side had the capacitance load of 590 pF, so it was a resonator.

This resonator was placed into an oven with walls temperature of 30°C. The resonator case had an electric heater, which was controlled so that the case temperature was kept constant at 60°C. If some RF power was dissipated inside resonator, then the power supplied by heater could be reduce by the same value in order to keep the case temperature constant. A change of the heater power was measured. The resonator voltage was measured by a calibrated amplitude detector.

This oven was placed in the biasing magnetic field. The force lines of the field were parallel to the ferrite ring axis. With this resonator it was only possible to measure only magnetic losses. Dielectric losses were presumed to be small compared with the magnetic ones. The obtained measurement data are sufficient for estimation of possibility to use this ferrite in the accelerating system of the machine and were used to calculate parameters of the accelerating RF system in the operating frequency range of 36 - 117 MHz. The summary is shown in Fig.6, Fig.7.

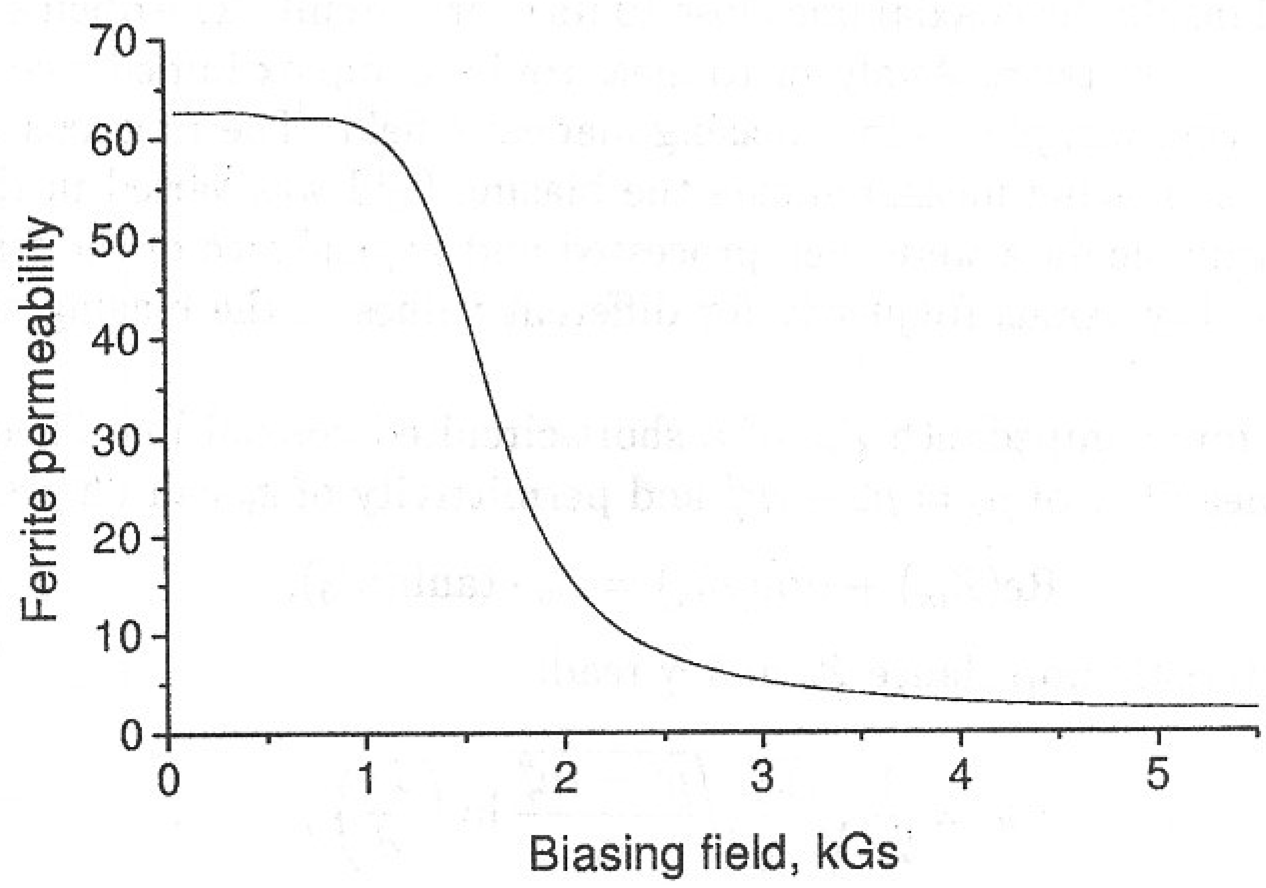


Figure 6: Real part of the ferrite permeability versus biasing magnetic field.

3.2 Measurement at low RF magnetic flux.

Measurements of the ferrite parameters at small RF field were made using P4-37 Network Analyzer in a frequency range of 30 - 1000 MHz at various levels of a biasing magnetic

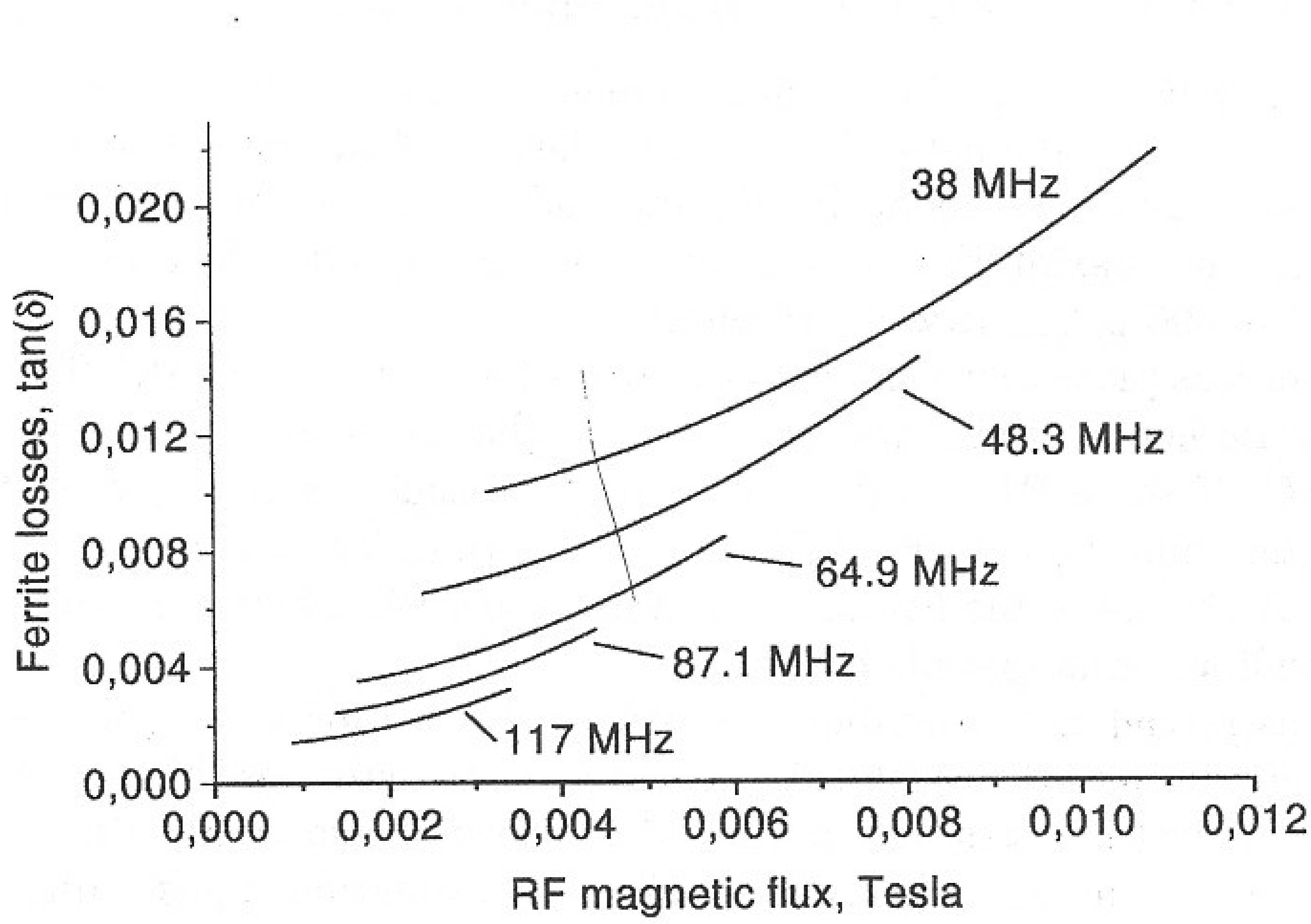


Figure 7: Tangent of the ferrite losses versus RF magnetic flux for different frequencies.

field. A short-circuited coaxial line was used for the measurements. A ring made of 60HH ferrite was placed inside the coaxial line close to its short circuit. The open end of the line was connected to the Network Analyzer to measure its complex impedance. The coaxial line with a ferrite ring was placed in a biasing magnetic field. The ring axis was set along the field force lines. During measurements the biasing field was varied in the range of 0 - 5.8 kGs. The available data were then processed and dependence of the ferrite complex magnetic permeability versus frequency for different values of the biasing magnetic field was obtained.

The complex input impedance Z_{in} of a short-circuited coaxial line filled with ferrite which has a permeability of $\mu_r = \mu_r' - i\mu_r''$ and permittivity of ε_r can be presented as:

$$\mathrm{Re}(Z_{in}) + i\mathrm{Im}(Z_{in}) = Z_0 \cdot \tanh(\gamma l_0), \tag{1}$$

where the characteristic impedance Z_0 and γ read:

$$Z_0 = \frac{1}{2\pi}\sqrt{\frac{\mu_0}{\varepsilon_0}}\sqrt{\frac{\mu_r' - i\mu_r''}{\varepsilon_r}}\ln\left(\frac{D}{d}\right), \tag{2}$$

$$\gamma = \omega\sqrt{\mu_0\varepsilon_0}\sqrt{(\mu_r' - i\mu_r'')\varepsilon_r}. \tag{3}$$

In Eqs.(2) and (3) the value $\sqrt{\mu_0/\varepsilon_0} = 377$ Ohm is the impedance of empty space, while $1/\sqrt{\mu_0\varepsilon_0} = 3 \cdot 10^8$ m/s is a speed of light, D, d, l_0 are the ferrite ring dimensions. For a given Z_{in} and ω the values μ_r' and μ_r'' were found as the roots of Eq.(1). The ferrite permittivity $\varepsilon_r = 12.4$ was measured at low frequency of 1 MHz. The obtained results were used to calculate the impedance of accelerating RF system beyond the operational frequency range up to 1 GHz.

Three examples of the obtained data are shown in Fig.8, Fig.9 and Fig.10.

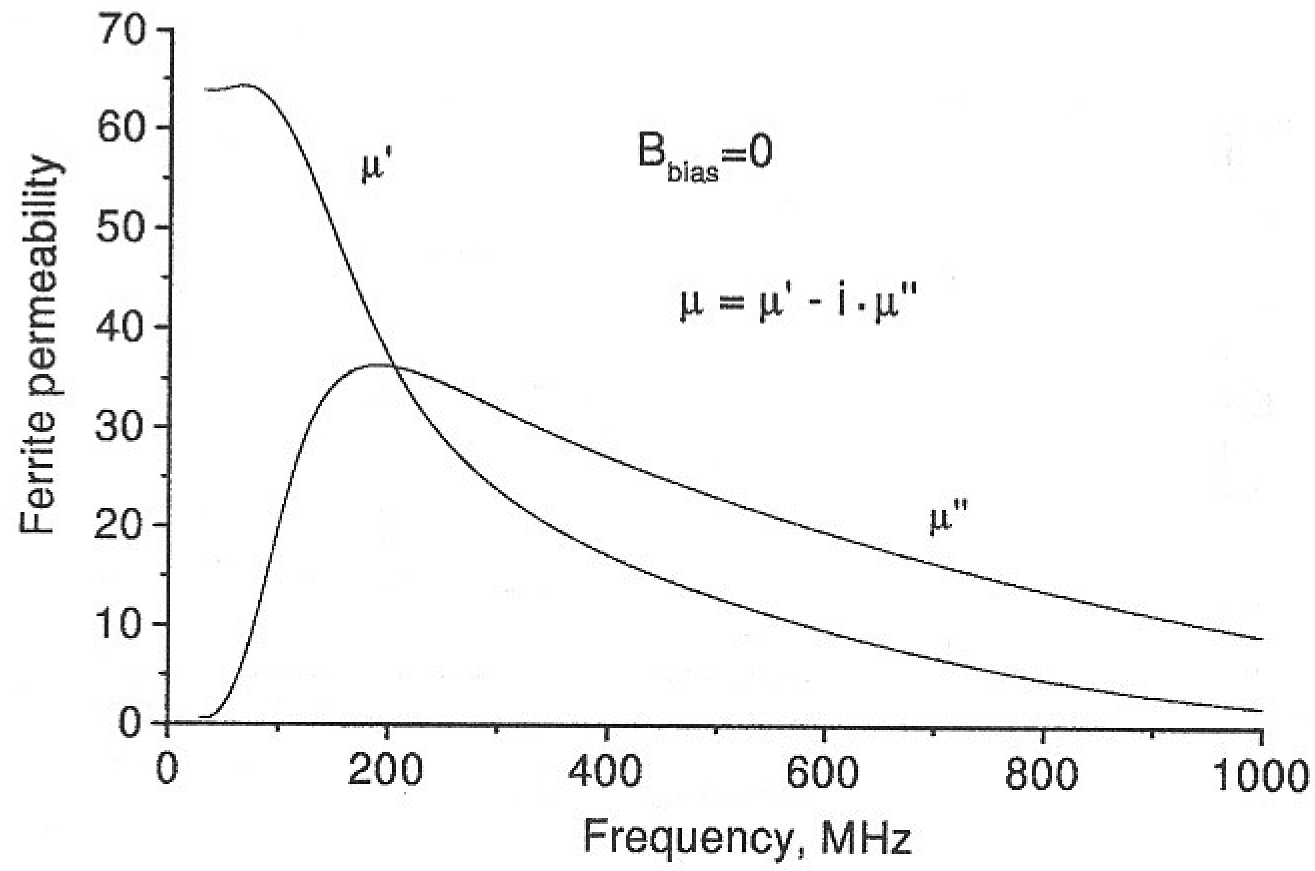


Figure 8: Dependence of the real and imaginary parts of the ferrite permeability versus frequency at zero biasing.

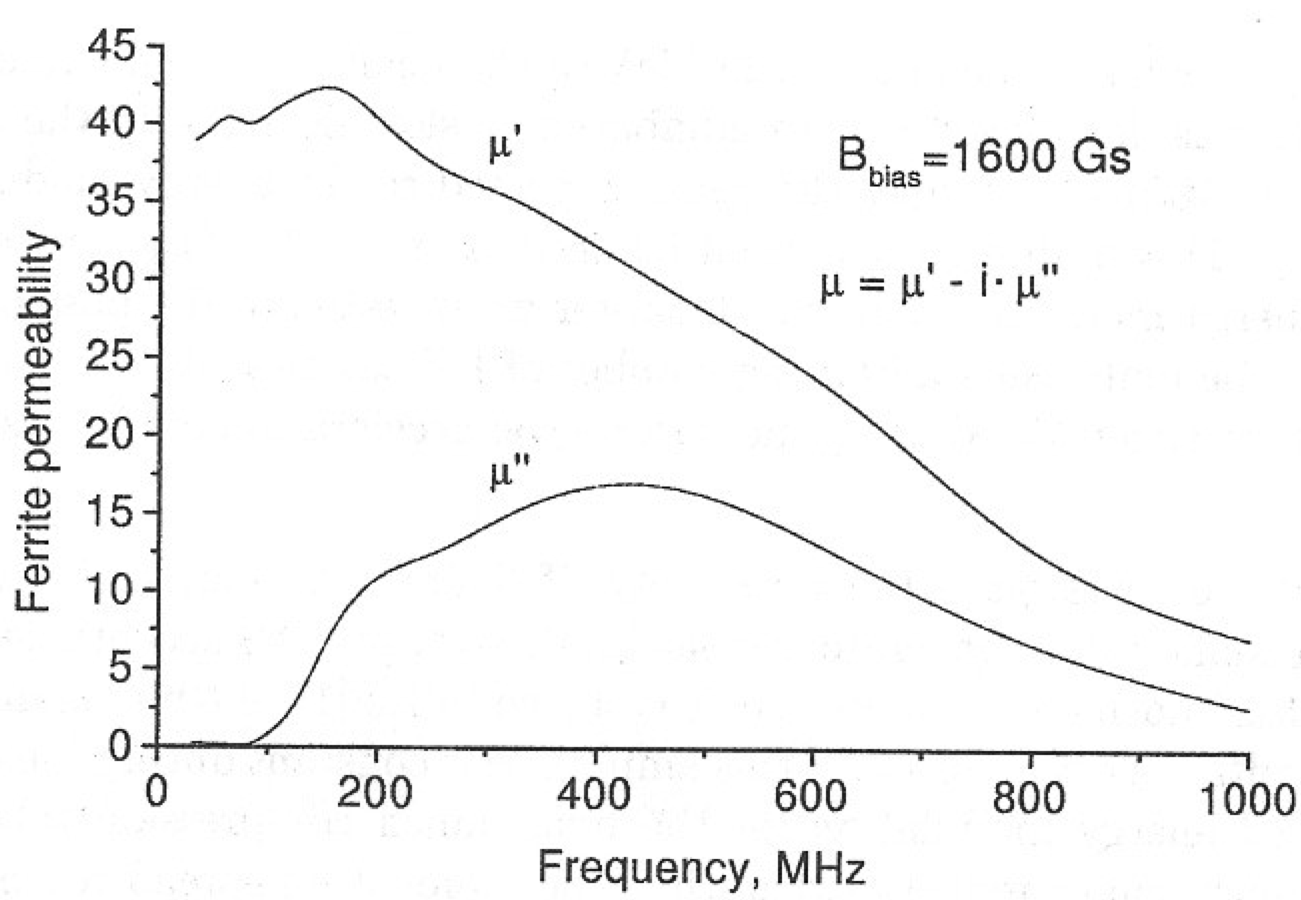


Figure 9: Dependence of the real and imaginary parts of the ferrite permeability versus frequency at a biasing field of 1600 Gs.

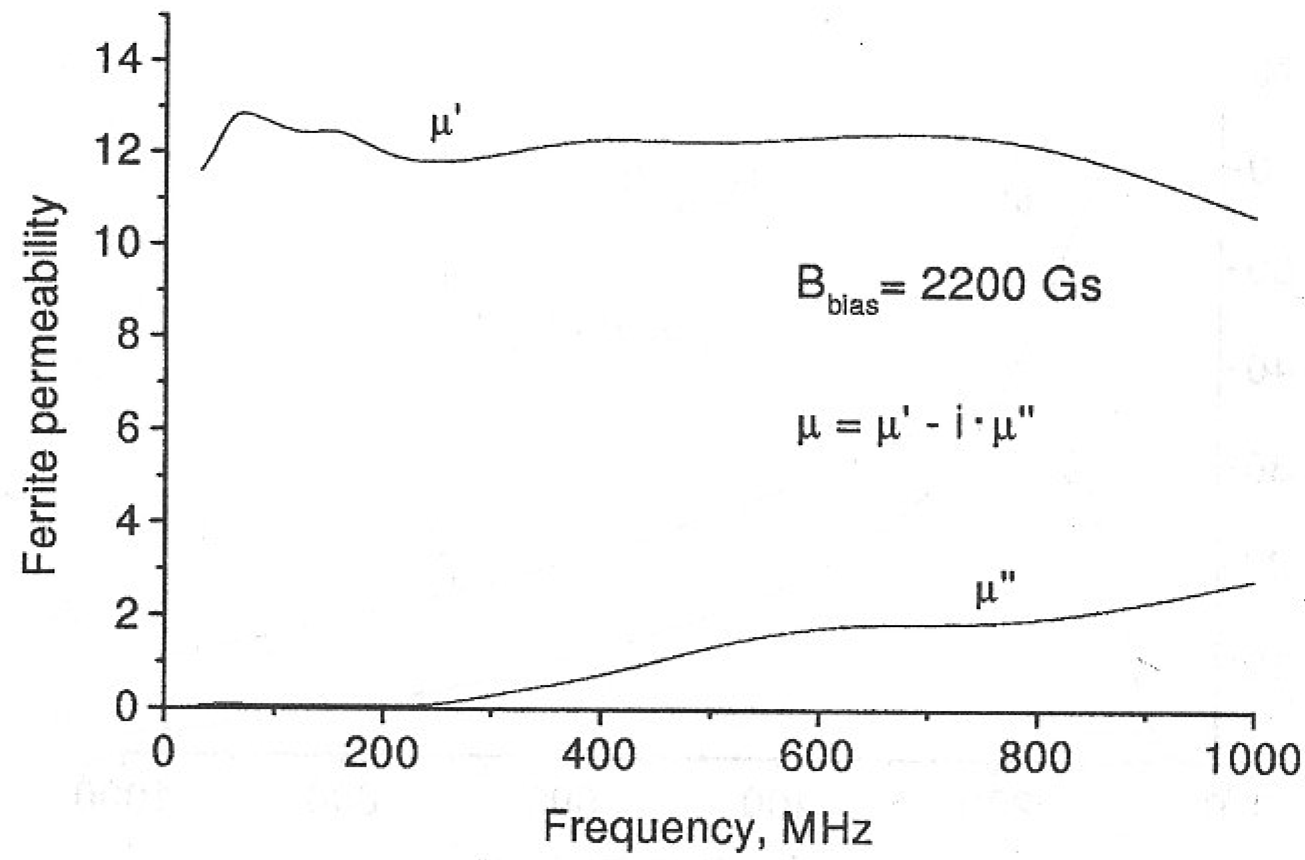


Figure 10: Dependence of the real and imaginary parts of the ferrite permeability versus frequency at a biasing field of 2200 Gs.

4 RF system for the longitudinal bunch compression.

After accelerating ions up to the energy 125 MeV/u the beam enters the bunch compression mode. First, it is debunched due to adiabatically slow decrease in the accelerating voltage amplitude. After debunching the beam is passed to the energy modulation orbit of the bypass (Fig. 1) containing the special RF system generating the sawtooth-shaped voltage for the energy modulation. In this Chapter we investigate the possibility, if such an RF system can be built using a limiting number of RF cavities. A different possibility when such a voltage is generated using induction type acceleration device was studied in Ref.[1].

In this report we investigate the possibility, if 5 first harmonics of the revolution frequency can be sufficient to generate the sawtooth voltage with acceptable parameters for the longitudinal bunch compression. As it is shown in Ref[1], the maximum amplitude of the sawtooth voltage $V_0 = 1380$ kV. If this amplitude is constant during the compression cycle, the required energy modulation for the final bunch compression takes 76 turns. After that the bunch length reduces twice while the momentum spread reaches the value of $\delta p/p = 0.62$ %. After 76 turns the beam is passed again in the RF-free line of the bypass for the final compression. The compressed beam is extracted into a channel where the target is installed. The goal is to decrease the bunch length at the target till 10 ns (about 1 m), or shorter (see in Ref.[1]). The RF system consists of 3 identical sections. Each section creates a sawtooth voltage of 460 kV. We describe one of such a section.

4.1 Technical requirements for the sawtooth voltage and parameters of RF system.

The parameters of the sawtooth voltage are chosen to reach the bunch length of 10 ns near the target. First, let us estimate the requirements for the sawtooth voltage stability. A change of the voltage amplitude will cause a shift δL of the minimum bunch size position off the target. This shift due to a relative change of the sawtooth voltage amplitude $\delta V_0/V_0$ can be estimated as:

$$\frac{\delta V_0}{V_0} = \frac{8}{\pi}\frac{\delta L}{L_0},$$

where L_0 is the initial beam length before compression. Taking, for example, $\delta L =$ 1m, and $L_0 = 960$m, we obtain $\delta V_0\ /V_0 = 0.26$ %.

Deviation of the sawtooth voltage from the linear dependence on the synchrotron phase results in increase in the minimum attainable size of the bunch after compression. The sawtooth voltage is formed by summation of voltages of the revolution frequency harmonics and some additional compensating voltage. As we already mentioned in the described device the harmonics with numbers 1, 2, 3, 4 and 5 are used. The resulting form

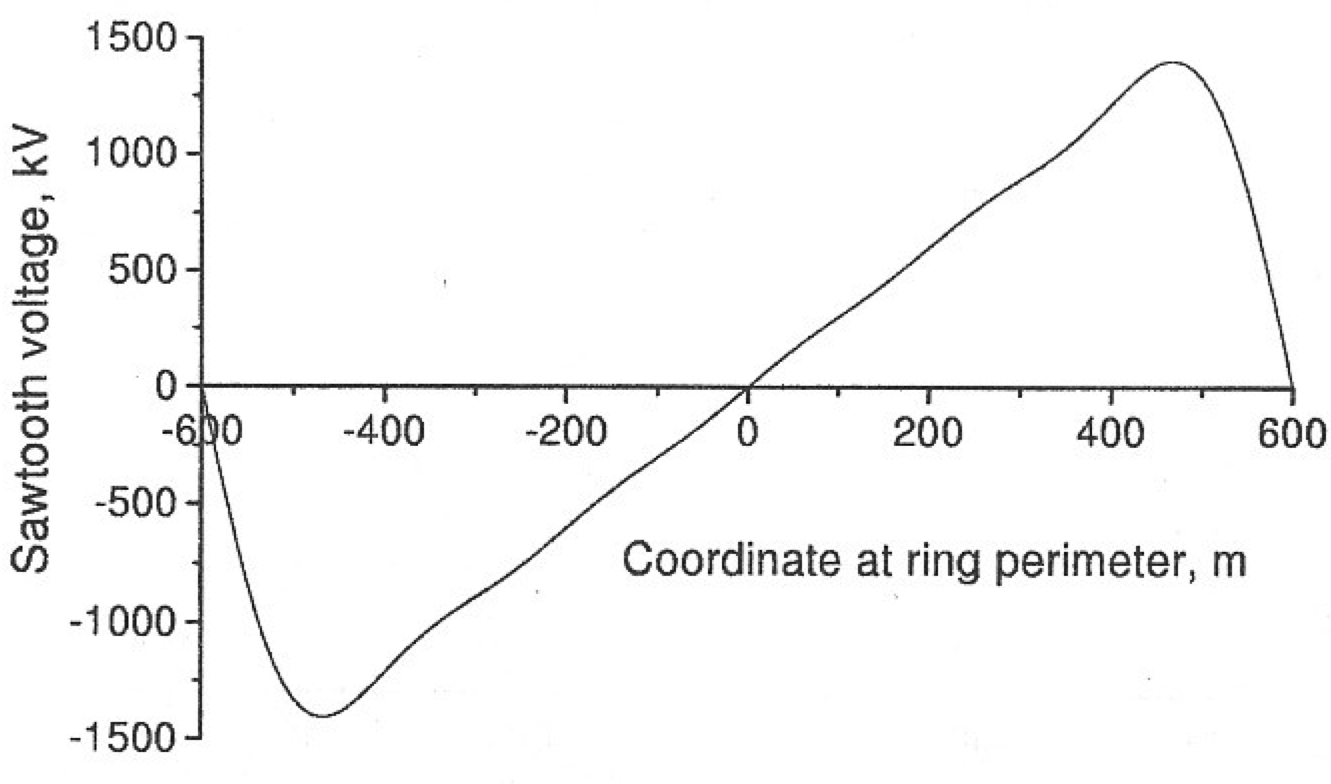


Figure 11: Sawtooth voltage which is formed by summation of five harmonics of the beam revolution frequency. The usable part of the sawtooth voltage is in interval between coordinates - 470 m and + 470 m of the accelerator perimeter.

of the voltage, which is obtained only from harmonic is shown on Fig.11. Amplitudes and the phases of harmonics voltage are chosen to ensure the best linearity. But even in this case the deviation from linear dependence exceeds 14 kV (Fig.12). Computer simulations show that the shift of the minimum bunch size position caused by this nonlinearity is in the range of ± 4m (Fig.7). Effects of the bunch space charge forces were not taken in account

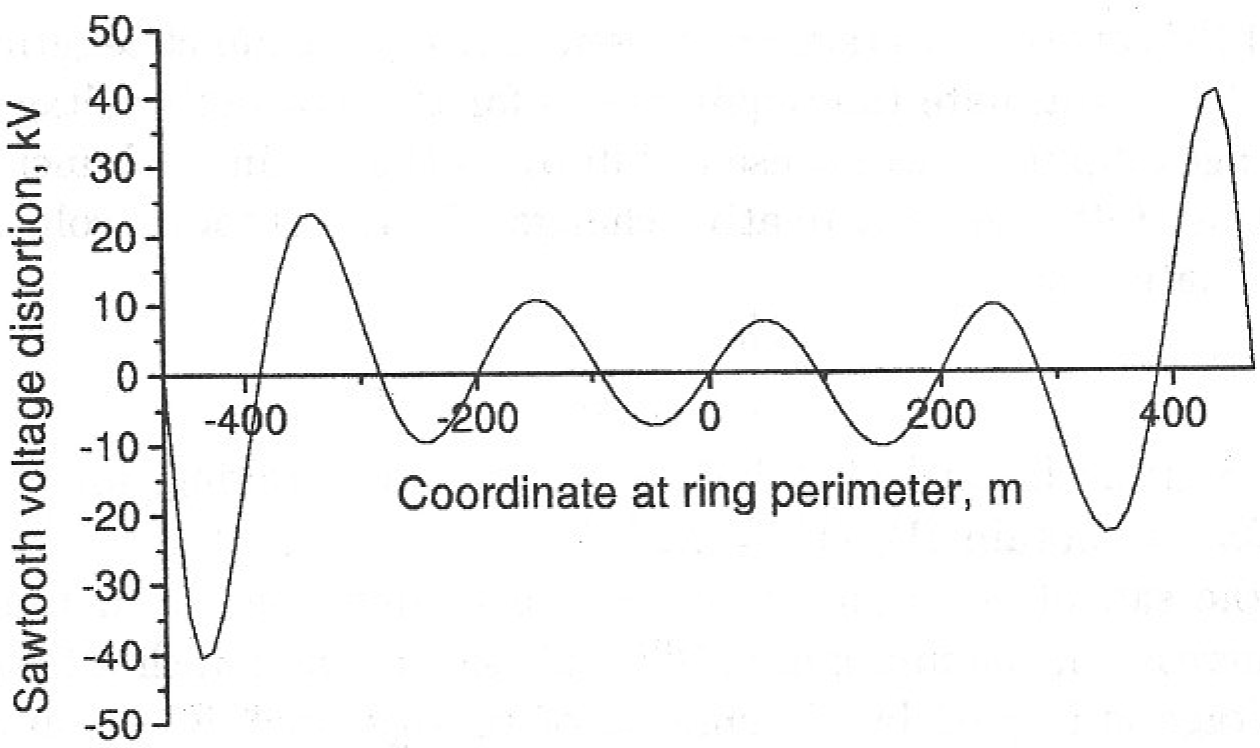


Figure 12: Deviation of the sawtooth voltage from linear form versus perimeter coordinate, m.

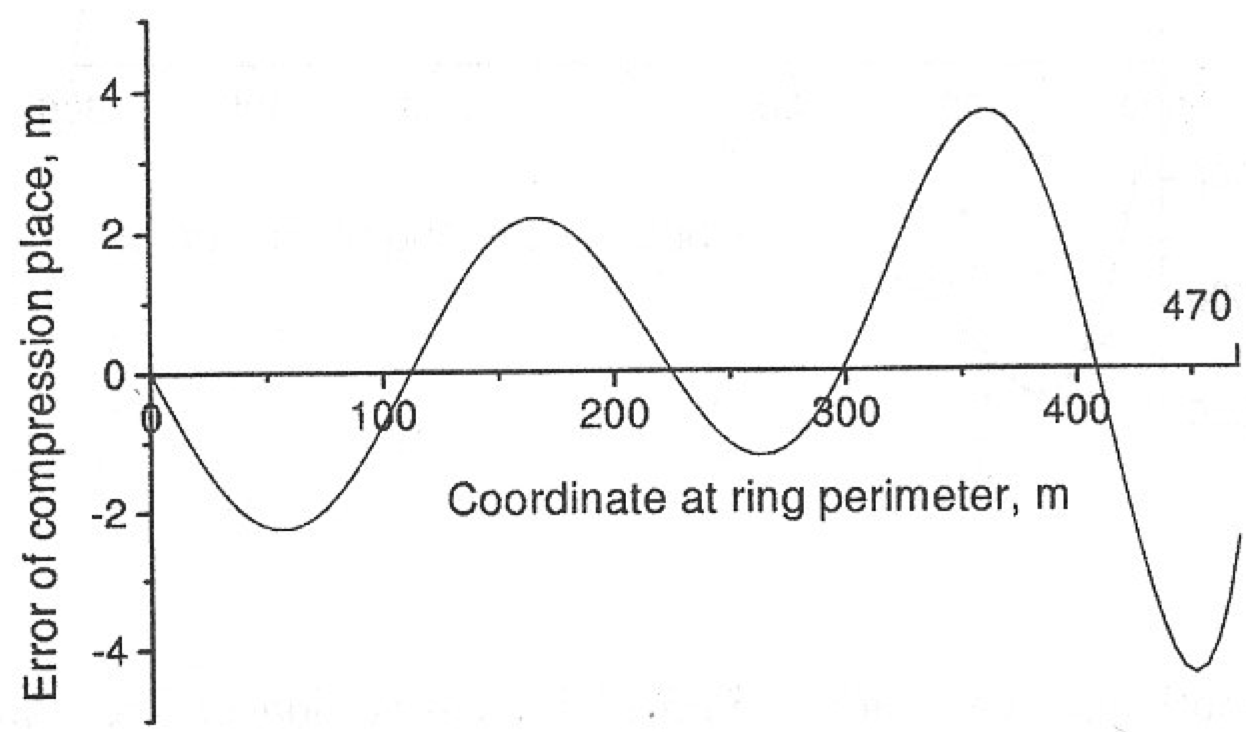


Figure 13: The shift δL of the minimum bunch size position in meters versus the initial particles coordinate at the perimeter of the accelerator before compression. Compensation is absent. Zero coordinate is at the zero point of the sawtooth voltage.

in these simulations. For compensation of the nonlinearity an additional accelerating gap will be installed in the straight section of the accelerator, where the accelerating voltage will be equal to the difference between the ideal sawtooth voltage and the voltage, which is obtained from harmonic only.

During operation of the RF system the beam is compressed to a half of its initial length. So, the current, for example of the 1-st harmonic of a beam current which is flowing through a gap of accelerating cavity increases up to $I_m = 1$A. The induced voltage at the cavities gap results in nonlinear distortion of the sawtooth voltage shape. The resulted distortion should not exceed a value of $\simeq 0.1\%$ of the voltage amplitude. Therefore, the output impedance of the RF system should not exceed

$$0.001\frac{V_0}{I_m} \simeq 460[\text{Ohm}].$$

In order to reduce the output impedance of RF system to this value a feedback loops should be used.

4.2 Cavities.

Each of the cavities may be represented as a short-circuited piece of a coaxial line with a capacitance load at the open end. For reduction of geometrical length and matching of electrical parameters of the cavity the internal volume of a coaxial line is filled by ferrites. The current design of the cavities assumes employment of the ferrites of Russian production 3000HH and 2000HH. These ferrites are produced in Sanct.-Petersburg by the company DOMAIN. For the required frequency range they have lowest losses at high value of magnetic flux and are recommended for application in these conditions (see, for example, in Ref.[4]) The RF voltage created on the gap of each cavity is 20 kV. The required total RF voltage for one of 3 sections and the cavities parameters for all harmonic numbers are given in the Table 8.The schematic drawing of the cavity is shown in Fig.14.

For production convenience all capacitances installed in the cavities are identical and the capacitance value is equal to 33000 pF. Each of the ferrite rings in a cavity is made of 8 sectors with fixed gaps between sectors. This provides for lower manufacture expenses. The gaps along the ring perimeter allow to make the radial magnetic flux distribution more uniform. The gap size in ferrite rings is chosen so as to ensure the required resonance frequency of the cavity with a given capacitance. A fine tuning of the cavity is made by an external biasing magnetic field. (the tuner magnet is not shown in Fig.14). The average power dissipation in the cavity does not exceed 50 W, therefore, cooling of the cavity is not required. The design of the compensating RF cavity is similar to a cavity in Fig.14. Ferrite ring sectors are put tightly, without any gaps. Three such cavities are required for compensation of the sawtooth nonlinearity. Main parameters of the cavity are given below in the Table 9.

The vacuum chamber inside the cavity has a winding of a insulated heating element for baking out the chamber. The inner conductor of the cavity has a water cooling and is thermally isolated from vacuum chamber to prevent its overheating during the baking out process.

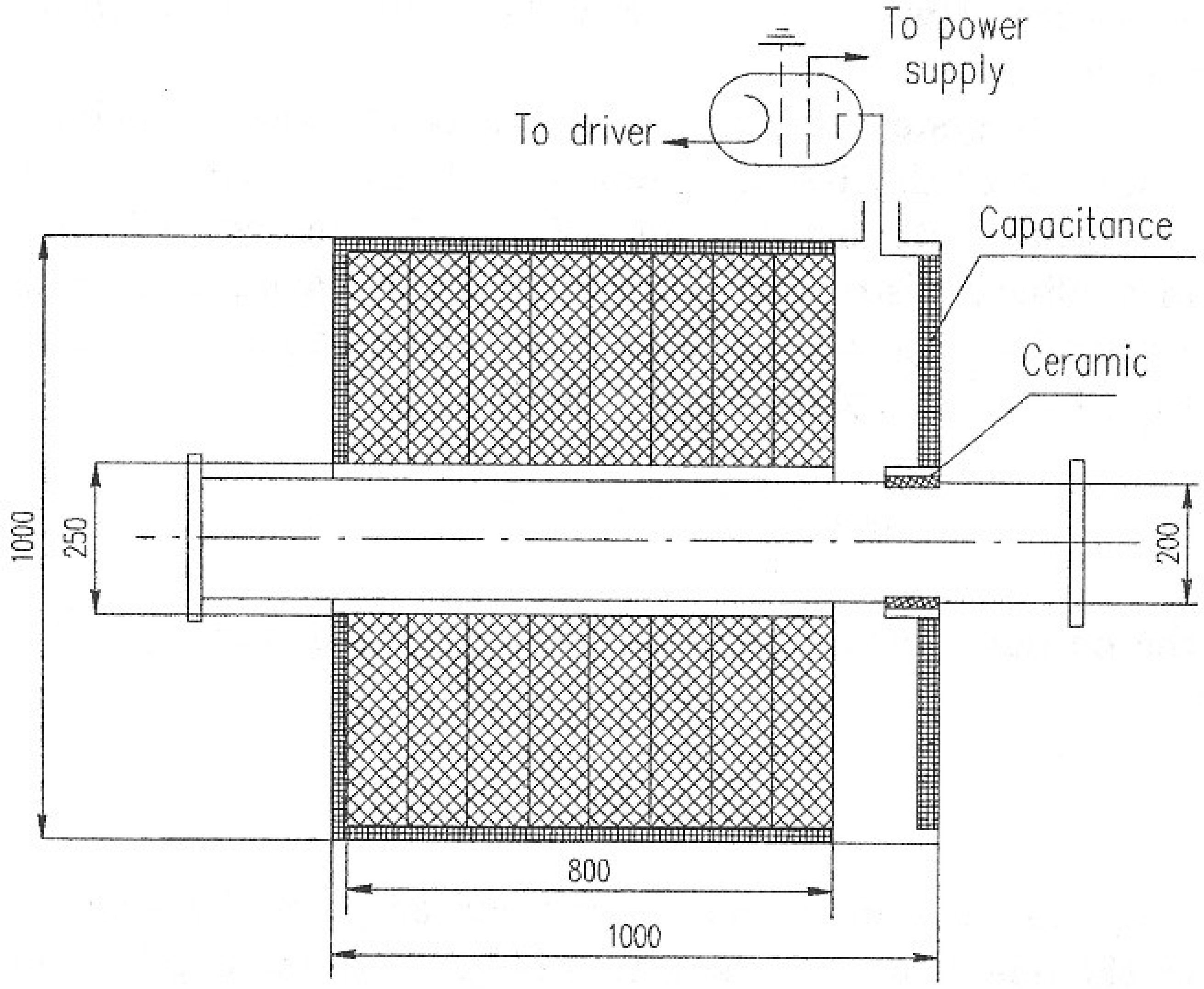


Figure 14: Schematic drawing of a cavity for the sawtooth voltage device.

Table 8: Main parameters of RF cavity: Total amplitude of RF voltage is given for one section out of 3. Ferrite type is 3000HM for the first harmonic and 2000HM for all others.

Frequency, kHz	117	234	351	468	585
Harmonic number	1	2	3	4	5
RF voltage, kV	1094	474	243	118	43.8
Number of cavities	55	24	12	6	3
Maximum gap voltage kV	20	20	20	20	20
RF magnetic flux in ferrite, Gs	900	450	450	450	450
Cavity shunt impedance, Ohm	2400	2620	2450	2200	2200
Q-value	58	127	178	213	268
Pulse RF power in a cavity, kW	83	76	81	91	90.6
Ferrite cavity length, m	0.8	0.8	0.54	0.40	0.32
Ferrite permeability	3000	2000	2000	2000	2000
RMS power in a cavity, W	41	38	40	45	45

The total number of cavities for this bunch compression RF system is 103 (compensating cavities included). The total length of this RF system is determined by an average length of one cavity 1.1 m. So the total length of a straight section in the ring required for placing of the RF system is 113 m.

Table 9: Main parameters of the compensating cavity

Maximum gap voltage, kV	15
Cavity capacitance value, pF	1000
Inductance of ferrite line, μH	700
Ferrite permeability	3000
Length of ferrite set, m	1.0
Resonance frequency, kHz	190

4.2.1 Design of the capacitance for the cavities of the sawtooth device.

One possible design of capacitance for these cavities is presented in Fig.15 and Fig.16. Each capacitance consists of a sequence of layers of metal electrodes (Fig.15, item 1) and layers of dielectric (Fig.15 , item 2), ring-shaped dielectric inserts (Fig.15 , item 3), ceramic windows (Fig.15 , item 4) and laps from conducting ceramics (Fig.15 , item 5). The dielectric layer can be made from two layers of a capton film. The thickness of one layer of the film is equal to 50 microns. The electrodes are made of stainless steel. The losses in stainless steel at high frequencies suppress resonances of higher order modes in thin dielectric layers. Dielectric inserts can be made from silicon rubber. Conducting ceramic laps enables to decrease the quality factor of the higher order modes which exist in a cavity formed by vacuum and air areas adjacent to ceramic window. Sophisticated shape of the laps makes the longitudinal electric field distribution on the ceramic window surface along each segment more uniform. Also the laps separate the ceramic windows from the beam pipe.

Such a capacity design provides uniform distribution of the electrical field in the capacitance. At a voltage across the accelerating gap of U = 20 kV, the electric field on the dielectric insert surface (in air) is $\mathcal{E}$ = 2.7 kV/cm.

Calculations of parameters of an higher order mode existing in the area adjacent to the ceramic window were carried out using the CLANS codes. Fig.17 represents the calculated geometry and picture of electrical field lines. The parameters of this mode are listed in the Table 10.

4.2.2 RF Power amplifier.

All RF power amplifiers will employ tetrode tubes GU - 53A. These tubes are produced by Sveltlana company in Sanct.-Petersburg Russia. Limiting values of the tube are shown in the Table 11. All tetrodes use the common grid configuration. Anodes are coupled to a cavity gap directly at operation frequency. The pulse mode of operation is used with a

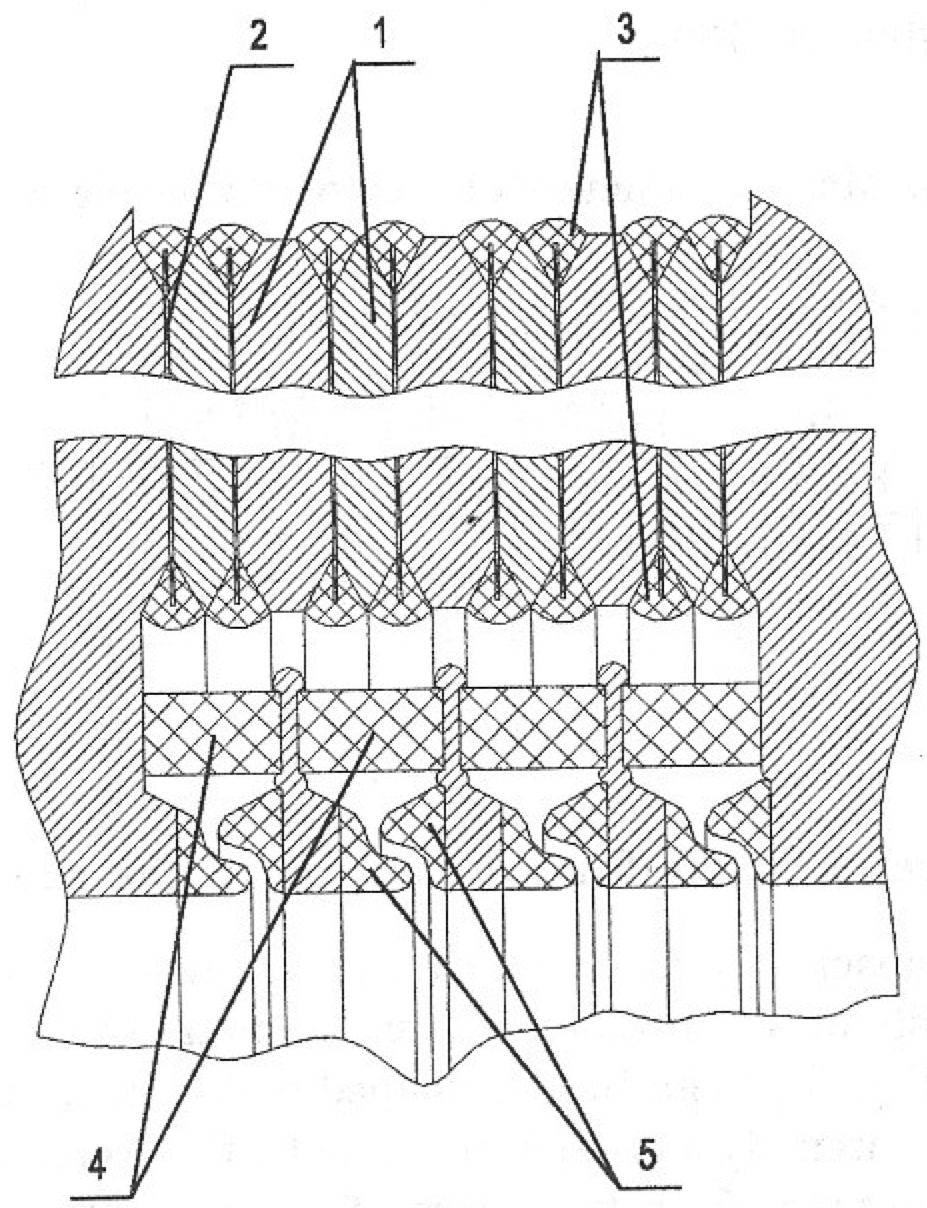


Figure 15: Design of capacitance for harmonics cavity. 1 - metal electrode; 2 - layer of dielectric; 3 - ring-shaped dielectric insert; 4 - segment of ceramic window; 5 - laps from conducting ceramics.

Table 10: Parameters of the high order mode

Frequency, MHz	741.796
Quality factor	9.8860
Transit time factor	.8028
Effective impedance, OHM	4.061
Shunt impedance, OHM	40.15

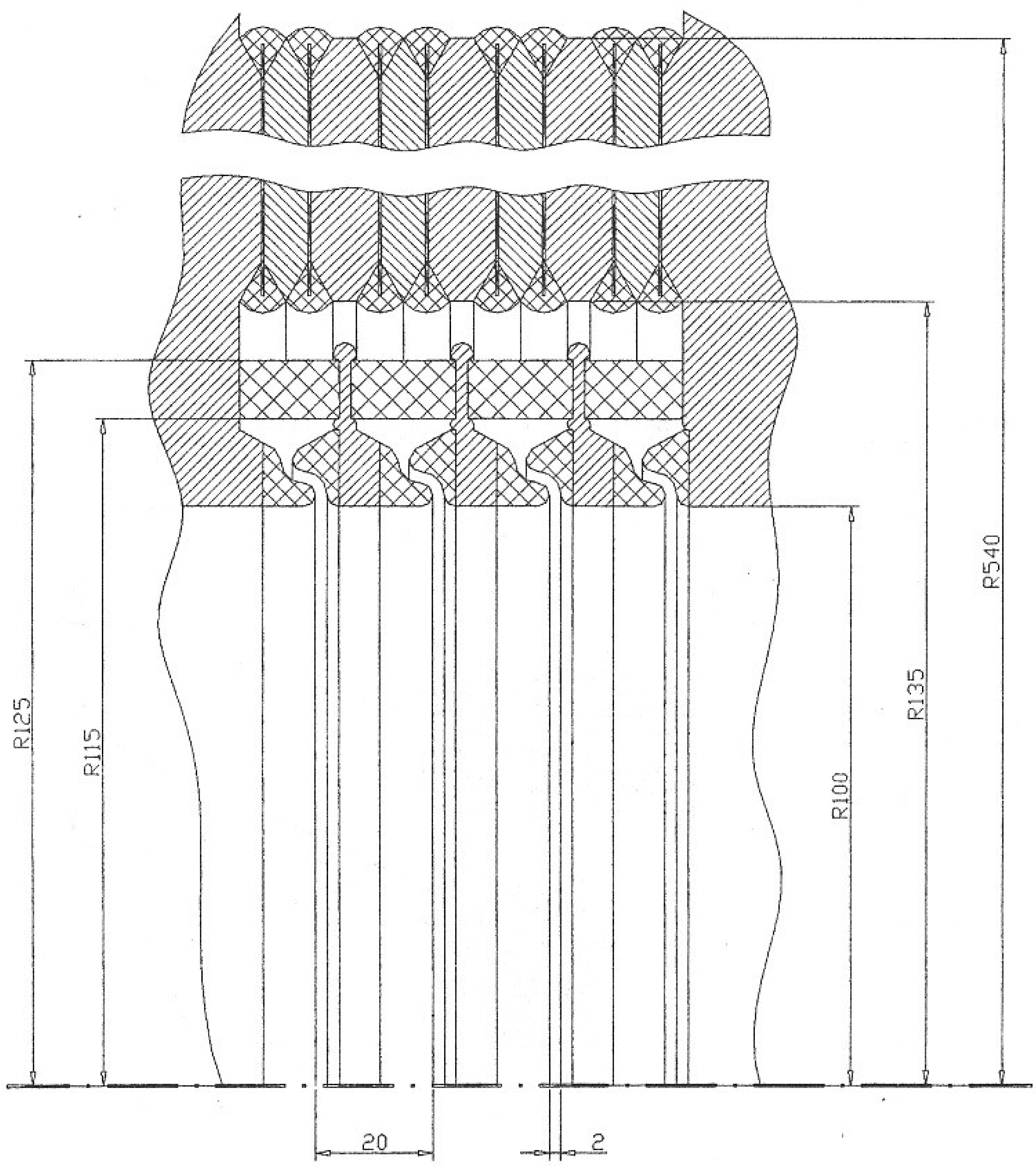


Figure 16: Design of capacitance for harmonics cavity All dimensions are in mm.

Table 11: Limiting values of tetrode GU-53A

Anode voltage in a pulse mode, kV	32
Filament voltage, V	14
Filament current, A	245
Anode dissipation, kW	40
Frequency, MHz	75
Anode current in pulse mode, A	200
Maximum envelope temperature, ^oC	150

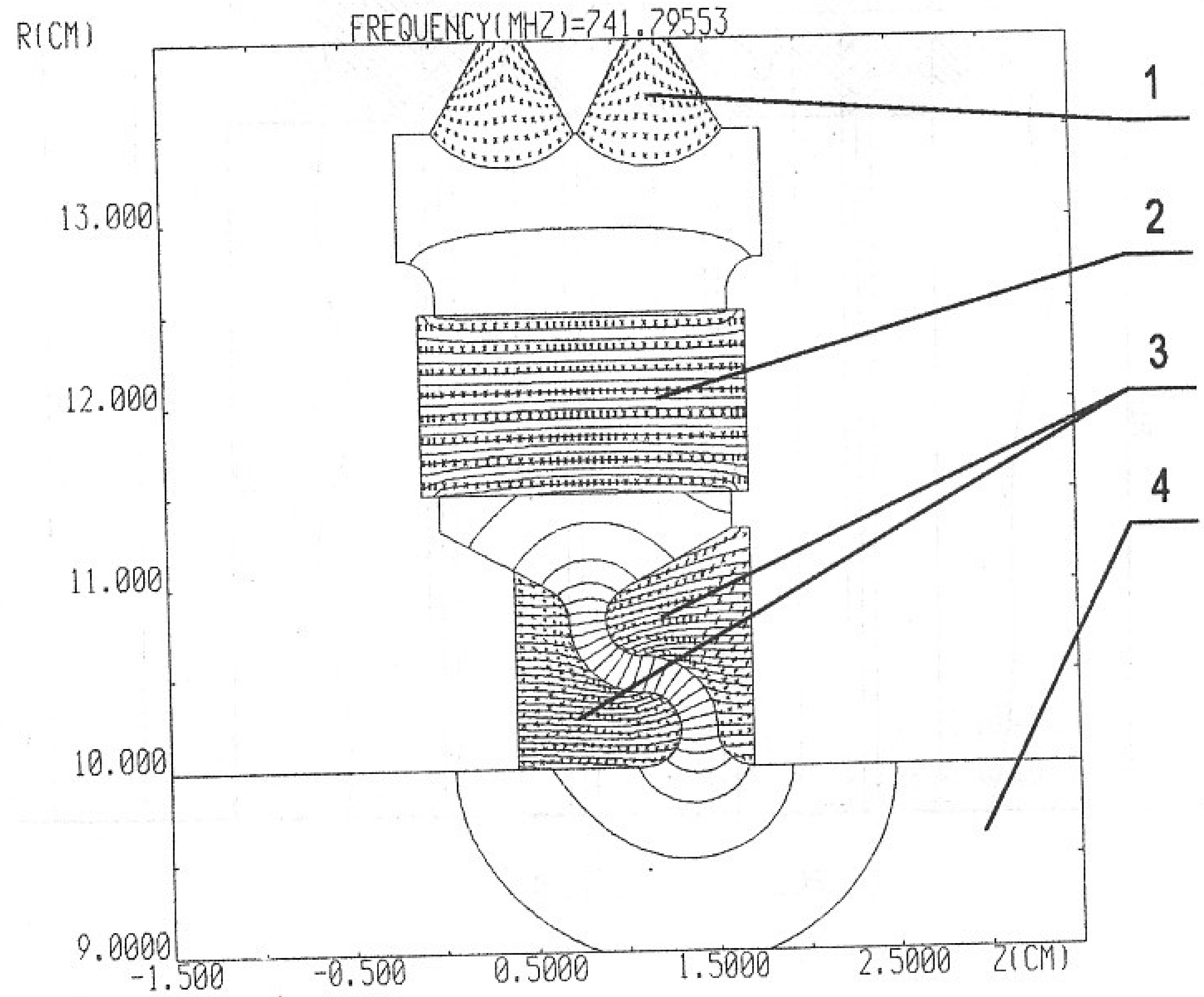


Figure 17: Electrical field lines for higher order mode. 1 - dielectric with dielectric permittivity $\varepsilon = 4$; 2 - dielectric with $\varepsilon = 9.5$; 3 - dielectric with $\varepsilon = 16$ and dielectric loss parameter $tan(\delta) = 0.76$; 4 - circular waveguide with diameter D = 200 mm.

duty factor of 1/1500. The factor is determined by the acceleration cycle of 2s, and the pulse length of 1.3 ms. All tubes are operating under A class condition. Characteristic parameters of the amplifier which operates at the harmonic number of the revolution frequency are given in the Table 12. Block-diagram of one channel is shown in Fig.18.

Table 12: Some characteristic parameters of the power amplifier.

Anode DC voltage, kV	25
DC anode current during pulse, A	10
Power gain in the stage	90
Maximum output power, kW	100

The reference voltage source generates signals of harmonic of the revolution frequency.

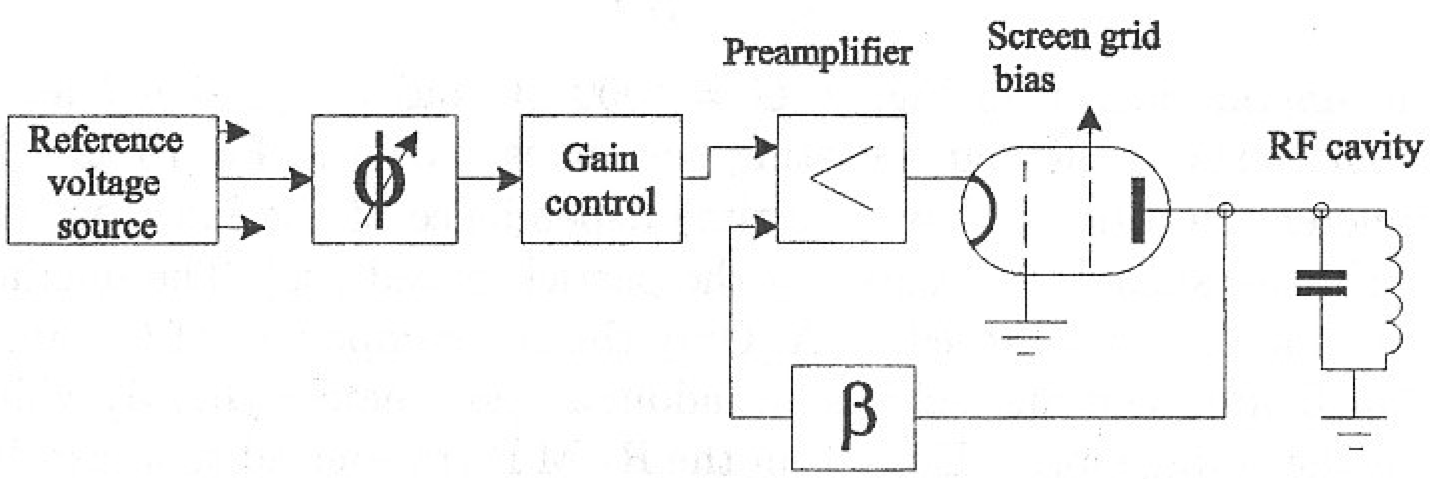


Figure 18: Block-diagaram of one channel of the sawtooth voltage device.

One of the signal passes through the phase shifter, the amplifier with gain control and comes to the preamplifier input. There is a feedback loop to reduce the output impedance of the channel for the beam current. The loop gain is determined by the β value. The output impedance Z of the stage for the beam reads:

$$Z = \frac{Z_0}{1 + K\beta}$$

Here is Z_0 the output impedance of the stage without the feedback loop, $K\beta$ is an open loop gain. It is possible to make the open loop gain in this configuration as high as 100. In this case the output impedance of one cavity for a beam will be reduced to 12 Ohm. A detailed analysis of the feedback loop will be given in the Section 4.3.

There is another way to reduce the voltage at the cavity gap induced by a beam current. For this purpose a third signal from a beam position monitor (BPM) comes to the preamplifier input. The signal from BPM is filtered so as to have only the harmonic of the operational frequency of the channel. Phase and amplitude of the signal are set so that the beam current through the cavity gap is compensated. In that case the requirements to a feedback loop are less strict.

All these measures allow to reduce the output impedance in the region of the operational frequency to a value of $\sim$ 1200 Ohm. The compensating cavities increase the output impedance by several percents. For higher frequencies beyond the operational range up to 1 GHz low output impedance is provided by appropriate design of the cavity capacitance and its vacuum part.

The compensating channel must create a voltage form identical to that in Fig.12. Three compensating cavities are required to be installed. Each cavity provides for 15 kV of RF amplitude maximum. The output stage of the RF generator uses the same tetrode tube GU-53A. The signal spectrum generated across the cavity gap is in the region of the 5-th harmonic of the revolution frequency and higher. Since the resonance frequency of the cavity 190 kHz is much lower, the required AC component of the tetrode current I_a can be estimated using

$$I_a = C\frac{dV_d}{dt} + \frac{1}{L}\int V_d dt,$$

where V_d is a function shown in Fig.12, C = 1000 pF and L = 700 μH are the cavity parameters. The form of the compensating current is shown in Fig.19 as a function of the ring perimeter. In order to have the time dependence of the function, the value of perimeter coordinate should be divided by the particle speed (βc). The maximum anode current of one tube does not exceed 50 A. Only the AC component of the anode current is shown in this figure. The channel has a random access memory (RAM) which contains information of the voltage form. Data from the RAM is transferred to a fast digit/analog converter (DAC) and output signal from the DAC comes to the preamplifier input. It is advisable to install a slow feedback loop to compensate for the amplifier nonlinearity and gain instability. A form of the cavity voltage is memorized every cycle and compared to the required one. The RAM information is corrected properly before the next cycle.

4.3 Beam coupled impedance of RF system for the beam compression.

In this Section the output impedance of all cavities, except the compensating cavity, is determined. The following lumped circuit was used to calculate the output impedance of one cavity tuned to the m-th harmonic (Fig.20). The cavity in this lumped circuit is represented by 54 two-port networks connected in series. In the calculations each two-port network is described by an A-matrix (A-parameters).

$$\begin{vmatrix} V_1 \\ I_1 \end{vmatrix} = |A| \cdot \begin{vmatrix} V_2 \\ I_2 \end{vmatrix} = \begin{vmatrix} a_{00} & a_{01} \\ a_{10} & a_{11} \end{vmatrix} \cdot \begin{vmatrix} V_2 \\ I_2 \end{vmatrix}$$

The A-matrix of the two-port network equivalent to the 54 serially connected networks is determined as:

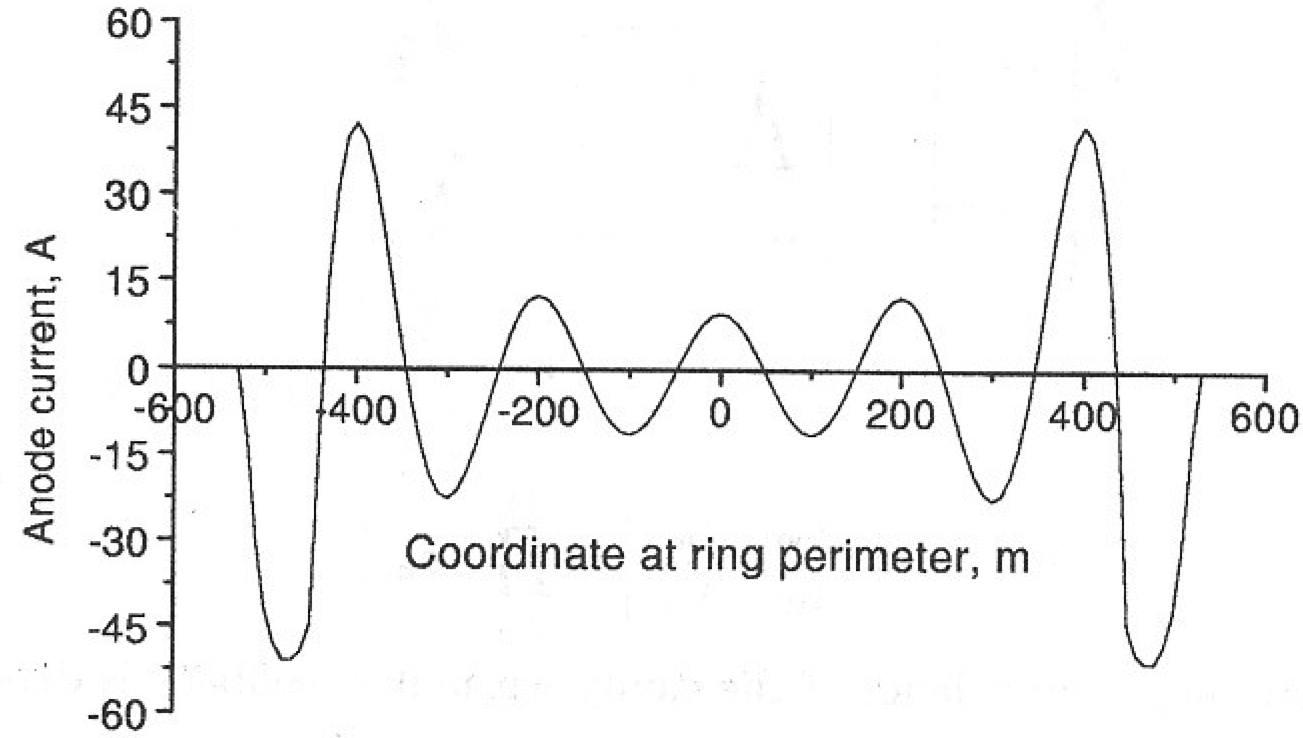


Figure 19: Anode current of the compensating cavity versus coordinate of the ring perimeter.

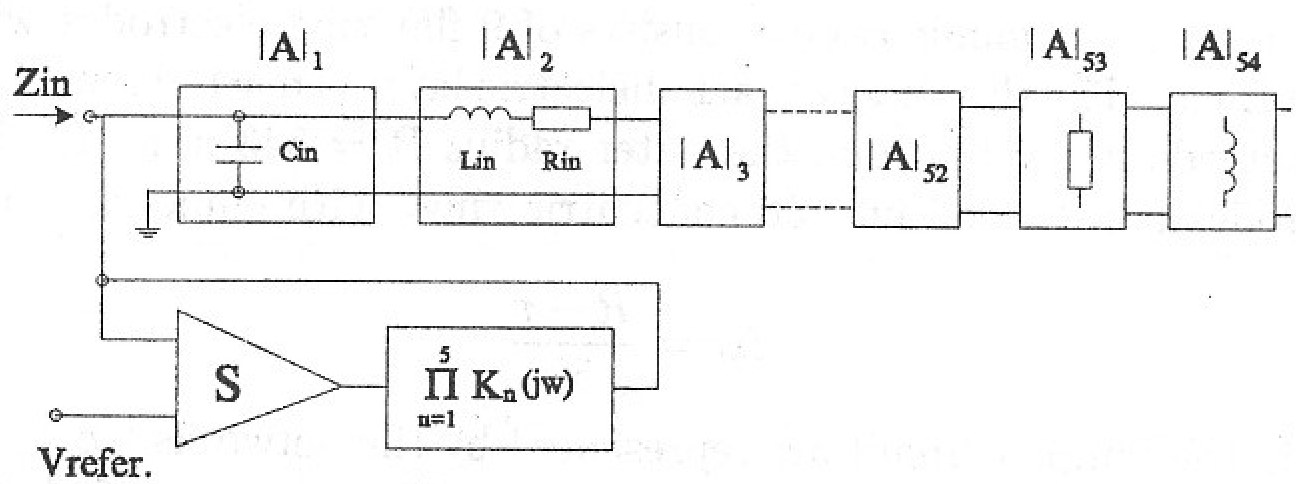
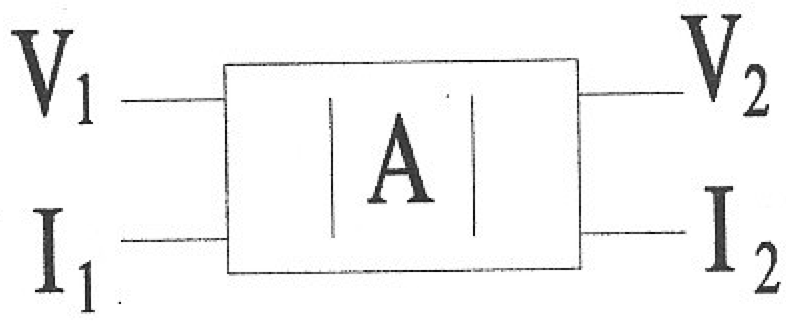


Figure 20: Equivalent circuit of the RF cavity for the compressing RF system. Zin - impedance of the cavity from the beam side. Elements $|A|_1$, $|A|_2$ are equivalent parameters of the vacuum part of the cavity capacitance (see Table 10); $|A|_{53}$, $|A|_{54}$ are cavity shunt impedance and equivalent cavity inductance correspondingly, elements $|A|_3$, $|A|_{52}$ represent the cavity capacitance.



$$| A | = \begin{vmatrix} A_{00} & A_{01} \\ A_{10} & A_{11} \end{vmatrix} = \prod_{k=1}^{54} | a_k |$$

The beam coupled output impedance of the cavity without a feedback is determined as:

$$Z_{in} = \frac{A_{00}}{A_{10}}$$

The results of calculations from the Table 10 were used to find C_{in}, R_{in} and L_{in}. The frequency of this resonant volume is equal to f_{in}= 742 MHz, the quality factor Q is 9.9, the characteristic impedance ρ = 4.06 Ohm, the shunt impedance Z_0=40 Ohm. One cavity has 4 of such volumes. Therefore, the values C_{in}, R_{in} and L_{in} are determined using

$$R_{in} = \frac{4 \cdot R}{Q^2}$$

$$C_{in} = \frac{1}{4 \cdot 2\pi \cdot f_{in} \cdot \rho}$$

$$L_{in} = \frac{4\rho}{2\pi \cdot f_{in}}$$

The capacitor of each harmonic cavity consists of 9 flat ring electrodes with 8 dielectric layers between them. The thickness of each dielectric layer is h =100 μm. The inner radius of the ring electrode is r =150 mm, the outer radius R = 543 mm. In the calculations the ring electrodes are divided into 50 concentric rings with equal radii increments Δr, where:

$$\Delta r = \frac{R - r}{50}$$

The rings in the lumped circuit are represented by the networks $| a |_3 - | a |_{52}$. Each of these networks has the following equivalent circuit (Fig.21), where L_n is the inductance, C_n – capacitance and Z_n is the complex impedance of the skin layer of the n-th ring (n=3 ... 52). The capacitance C_n was determined as:

$$C_n = \frac{\pi \cdot [(r + n \cdot \Delta r)^2 - (r + (n-1) \cdot \Delta r)^2] \cdot \varepsilon \cdot \varepsilon_0}{k \cdot h}$$

$$L_n = \frac{\varepsilon \cdot k}{c_n \cdot v_0^2}$$

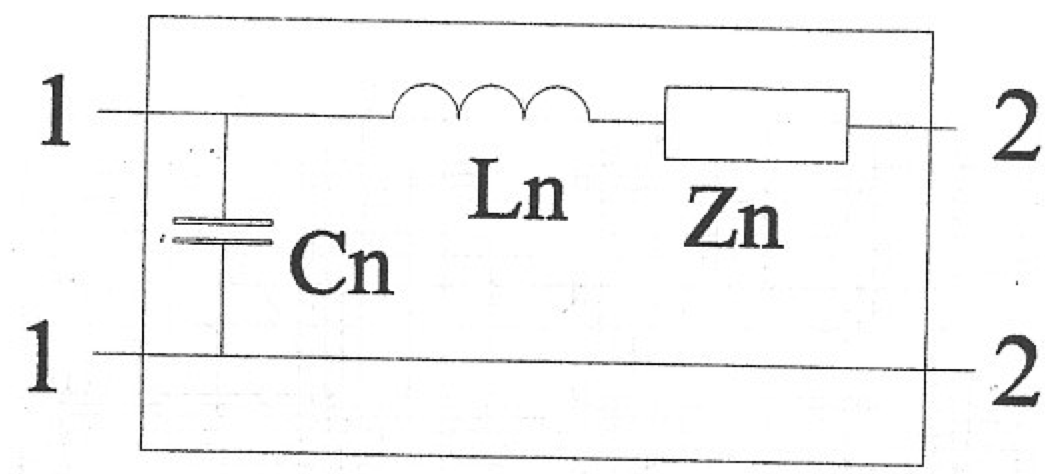


Figure 21: The equivalent circuit of the capacitance ring.

$$Z_n = \frac{2k \cdot \rho \cdot \Delta r}{\delta \cdot 2\pi \cdot (r + (n - 0.5) \cdot \Delta r)} \cdot (1 + j)$$

Where: $v_0 = 3 \cdot 10^8$ m/s, ε is the relative permittivity of capton ($\varepsilon = 3.5$), k is the number of dielectric layers in the capacitor (k=8), ρ is resistivity of stainless steel (the nodes material), δ is the skin depth in stainless steel.

For the quadrupole $\mid A \mid_{53}$ R is the cavity shunt impedance. The value of L is derived from the next formula:

$$L = \frac{1}{(m \cdot 2\pi f_0)^2 \cdot C}$$

f_0 - revolution frequency at the end of acceleration cycle ($f_0 = 117$ kHz), m is the cavity harmonic number, C is the cavity capacitance ($C=33 \cdot 10^{-9}$F). This value is the eighth's part of capacity formed by two circular stainless steel nodes and by 100 mm capton layer.

The cavity shunt impedances R_m, number of cavities K_m, tuned at harmonic number m =1..5 are taken from the Table 8. All these cavities have the impedance Z from the beam side equal to:

$$Z = T^2(f) \sum_{m=1}^{5} k_m \cdot Z_m$$

where T(f) is the transit time factor. This factor is determined by the fact that each cavity has four accelerating gaps. The distance between gaps is δl =2 cm. The running wave of current, moving along the cavity axis with phase velocity equal to the velocity of particles at the end of acceleration cycle v, will produce current on the adjacent gaps with phase shift:

$$T^2(f) = \frac{(\sum_{n=0}^{3} \sin(N \cdot \phi))^2 + (\sum_{n=0}^{3} \cos(N \cdot \phi))^2}{4}$$

where N is the cavity gap number.

The calculations results are shown on Figs.22. For stabilization of the cavity gap

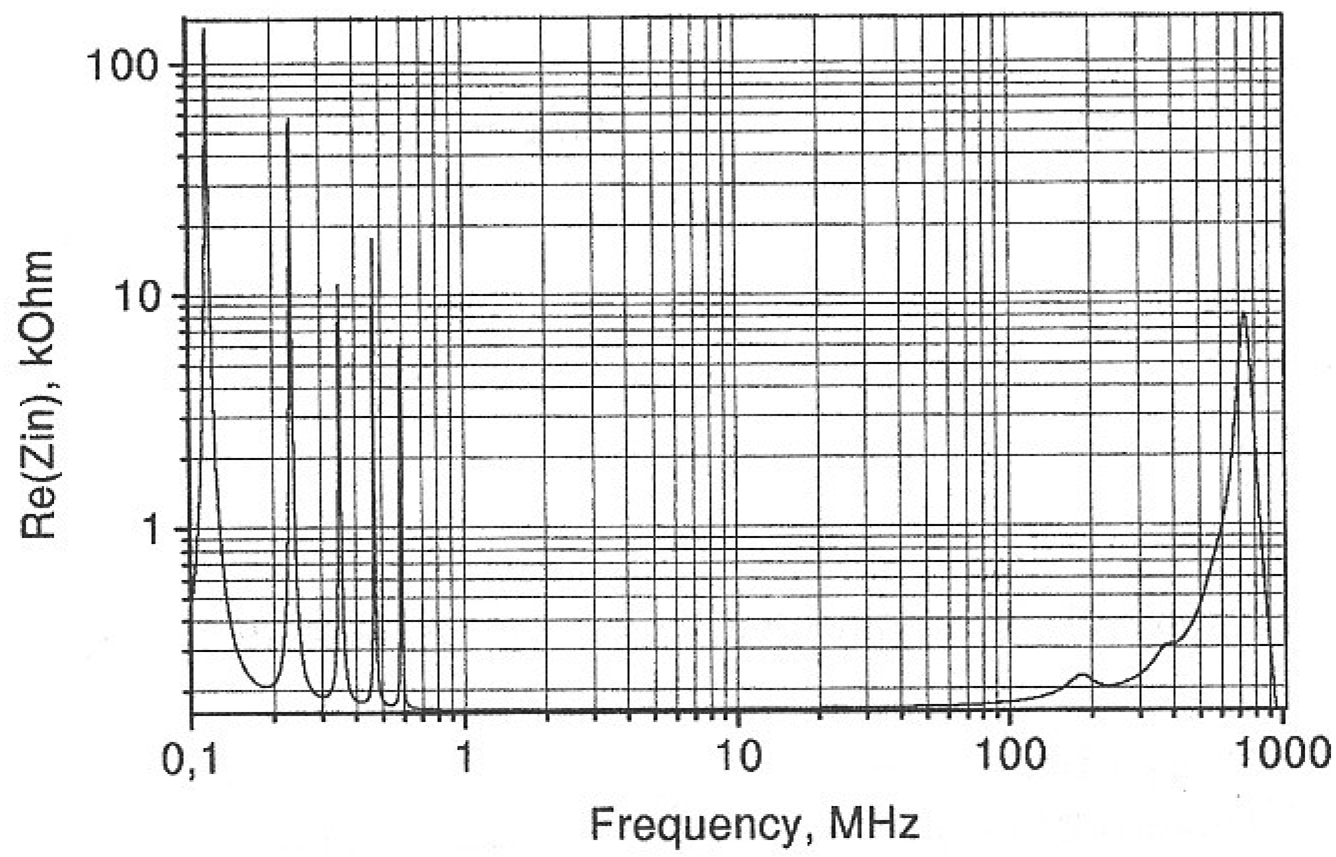


Figure 22: Output impedance of RF system for the beam compression. Feedback loop is open.

voltage and for reducing of the output impedance each power amplifier has a feedback loop. The possibility of creating RF power amplifier to feed the cavity and a feedback loops was considered. The estimations had shown that the open-loop gain $K\beta$ could be represented as:

$$K\beta = S \cdot \prod_{l=1}^{5} k_l(2\pi f)$$

$$k_1 = \frac{j \cdot 2\pi f \cdot \tau_1}{1 + j \cdot 2\pi f \cdot \tau_1}$$

$$k_{2,3,4} = \frac{1}{1 + j \cdot 2\pi f \cdot \tau_{2,3,4}}$$

$$k_5 = e^{j \cdot 2\pi f \cdot \tau_1}$$

Where S=0.075, and the time constants $\tau_1; \tau_2; \tau_3; \tau_4; \tau_5$ are equal respectively: $2.02 \cdot 10^{-4}$; $16 \cdot 10^{-9}$; $32 \cdot 10^{-9}$; $5 \cdot 10^{-9}$; $20 \cdot 10^{-9}$.

The close-loop cavity output impedance reads:

$$Z_{k\beta} = T^2(f) \cdot \sum_{m=1}^{5} k_m \cdot \frac{Z_m}{1 + Z_m \cdot k\beta}$$

The calculations results for this case are shown in Fig. 23

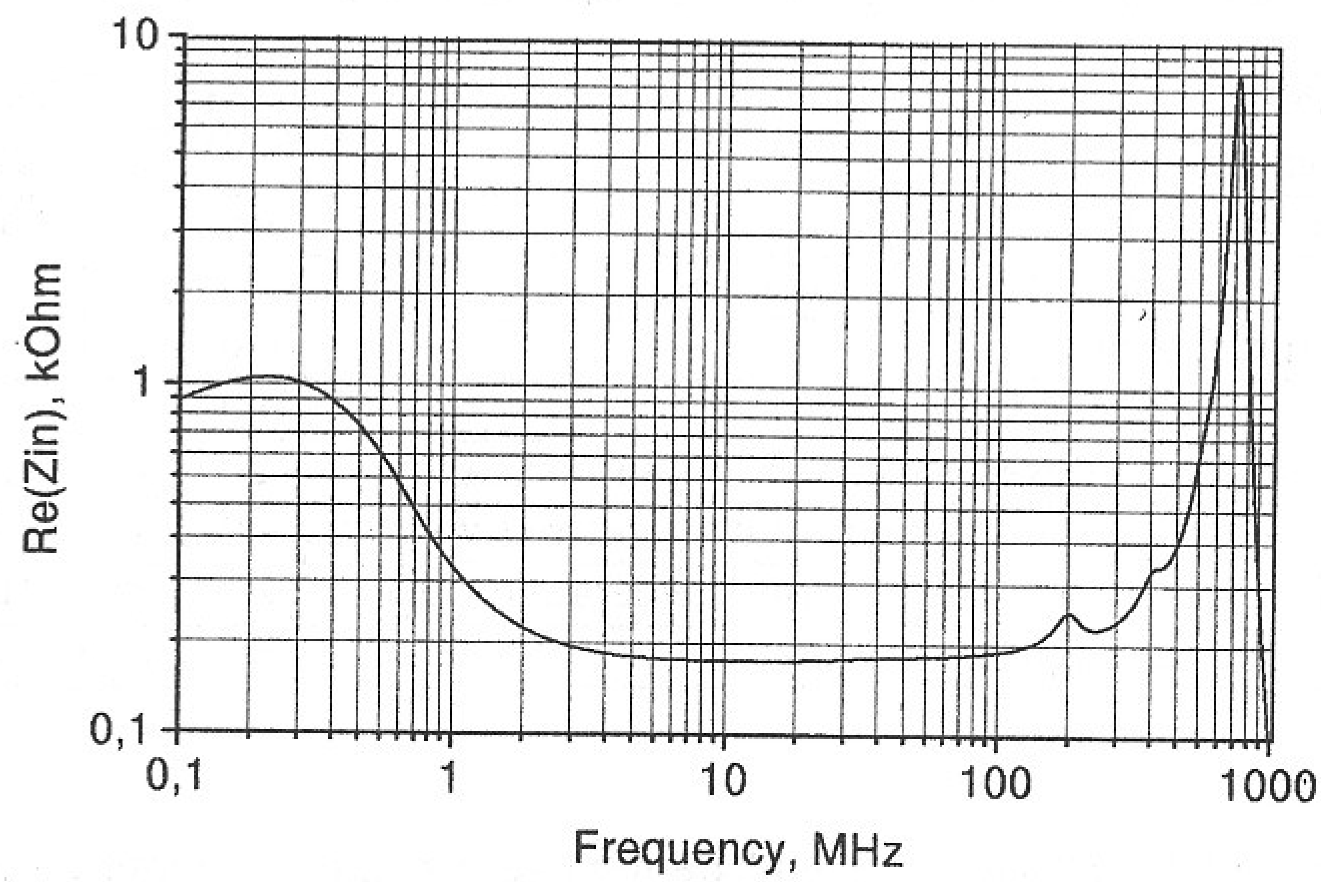


Figure 23: Output impedance of RF system for the beam compression. Feedback loop is on.

4.4 Inductive type sawtooth voltage device

Another and very promising possibility of the generating of the sawtooth compressing voltage provides use of the induction type accelerating devices (see, for example, in Ref.[5]). This acceleration structure should be installed into energy modulation line of the bypass (see in Fig.1). As is shown on Fig. 24, such a structure consists of necessary amount of the identical sections .

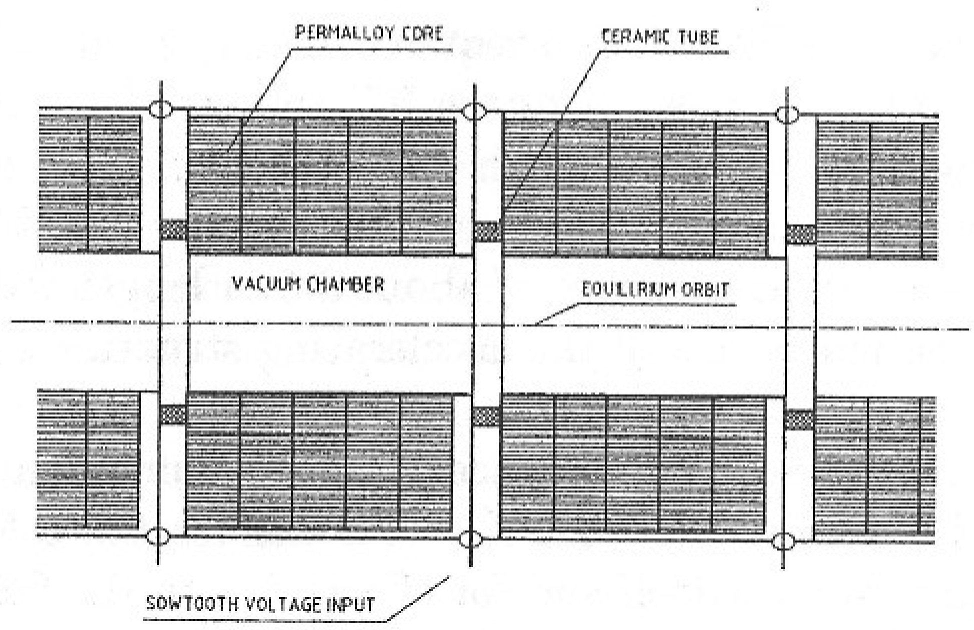


Figure 24: Schematic layout of the induction-type RF-structure generating the sawtooth bunch compression voltage.

Each cell of the unit contains the toroid magnetic core located around the equilibrium orbit. The neighbor sections are separated one from another by the gap with a ceramic tube, which is used as the vacuum seal assembly and as the high voltage insulator.

Table 13: Parameter list of the sawtooth voltage device.

Parameter	Unit	Value
Beam energy	MeV/u	125
Revolution period	μs	8.511
Ratio of saw back laps to period		0,1
Core inner diameter	cm	15
Core radial thickness	cm	10
Induction change-over during period in permalloy	T	± 1.0
Specific longitudinal gradient of accelerating voltage	keV/m	± 80
Specific longitudinal gradient on the ceramic tube	keV/cm	<10
Core magnetizing peak current	kA	< 0.5

One of a permalloy composition could be used as a magnetic material for the cores. Such kind of the cores were already utilized in induction accelerators [5] with rectangular pulses of the duration about 0.5 μs. In this case, the thickness of the permalloy film was of 10–20 μm. Using an extrapolation of these results to our parameter region, we arrive at the parameter set given in the Table 13.

Figure 25 shows one period of the specific sawtooth RF-voltage per one meter of the magnetic cores length and the inductance time diagram in the permalloy during one RF-period.

Every section is fed through some inputs. The sawtooth shape of the RF-voltage is formed using the sawtooth shape of the feeding voltage, which is supplied using coaxial cables.

The single section length could be chosen to fit the desired magnitude of the power supply voltage. As was shown Ref.[1], the required energy modulation is reached in 50 turns, if the beam passes the inductive sawtooth RF-voltage of ± 2.48 MV per turn. This energy gain can be provided, if the sawtooth energy modulation device occupies 30 m of the free space in the energy modulation line of the bypass insertion. If every straight section lattice cell contains two free spaces of about 3.5 m length (total length per cell is 7 m), 6 cells could be enough to install the accelerating structure for the required beam energy modulation.

The deviations from the linear dependence of the compression voltage on the synchrotron phase should be smaller than 0.1 %. This defines the tolerances for both the nonlinearity of the feeding voltage itself and for effects due to RF-fields, which the bunch induces in the unit. The beam debunching before energy modulation will suppress the high frequency beam loading effect. As we saw, during this period an increase in the local bunch current is given by factor between 1.4 and about 2. Since the average reactive part of the coupling impedance of the vacuum chamber with the perfectly conducting walls $[(Z/n)]$ is about 200 Ohm, the total impedance of the sawtooth voltage unit should not exceed this value. For the same reasons, an increasing of the inductive part of the coupling impedance of the unit can be very desirable. Particularly, these problems should be addressed by more detailed engineering work.

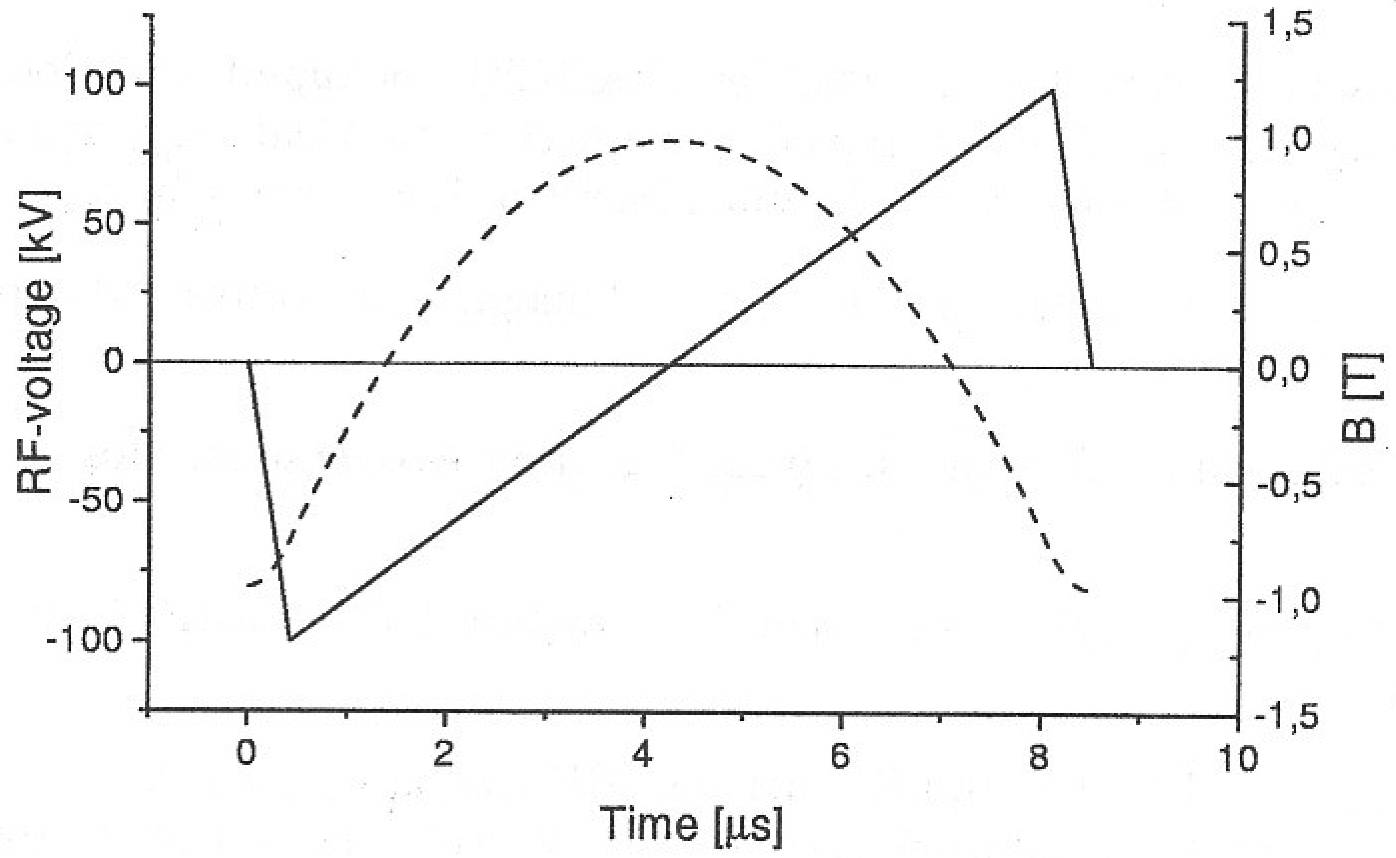


Figure 25: The shape of one period of the specific sawtooth RF-voltage per one meter of the magnetic cores length (solid line) and the inductance time diagram in the permalloy during one RF-period (dashed line).

5 Conclusion

Described calculations and measurements show that the designed RF cavities for accelerating RF system are quite feasable. Low impedances of the higher order modes indicate that interaction with these cavities will very unlikely limit the beam (bunch) performance, even in the case if the bunch will be debunched to a coasting beam. The measurements of the electromagnetic properties of the ferrites, which, or similar, can be (and very likely will be) used for the manufacturing of these cavities, enable reliable calculations of the electromagnetic modes of the cavities.

An employment of the first 5 harmonics of the revolution frequency in line with necessary feedback systems enables generation of the sawtooth voltage for the bunch compression of the bunch train filling 80 % of the closed orbit perimeter. A feedback system reducing deviations of the dependence of the RF voltage on the synchrotron phase from the linear behavior has been designed. The last limitation is eliminated when using induction type acceleration units for the energy modulation prior to bunch compression, when the length of the useful slope of the voltage is 90 % of the orbit perimeter.

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RF systems for a high-intensity heavy ion synchrotron with strong bunch compression

(Part II)

Н. Фомин и др.

ВЧ система синхротрона для ускорения интенсивных пучков тяжелых ионов с сильным сжатием сгустка

(Часть II)

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