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RF-SYSTEM DESIGN
OF PROTON SYNCHROTRON
FOR HADRON THERAPY

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Introduction

The RF - system must supply 2 kV peak voltage in the frequency range from 1.29 to 4.81 MHz. The highest ramp velocity is 30MHz/s. The length of the cavity is below 1 m (the typical size in accelerator technology).The system parameters are illustrated in fig. 1a,b. The work mode of the RF-system is divided into three stages: adiabatic trapping, acceleration of the beam and preparation of the beam.
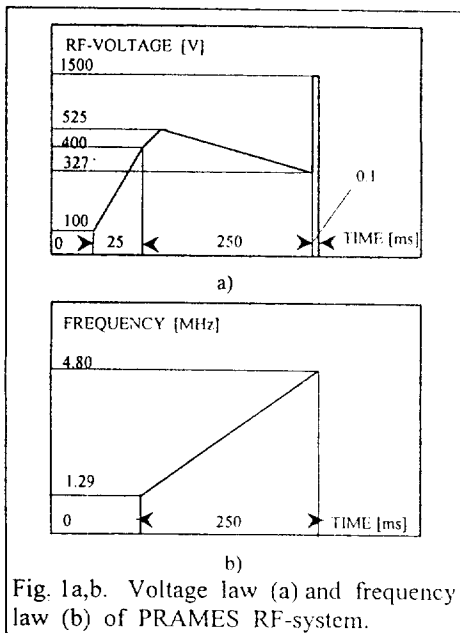

Fig. 1a,b. Voltage law (a) and frequency law (b) of PRAMES RF-system.

RF-system configuration.

The parameters of some similar systems developed earlier for proton synchrotrons are presented in Table 1[1÷8]. A ferrite loaded RF-cavity with a quarter or half of wavelength is used as acceleration structure in all systems. The design of the RF-systems can be of two types:

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-RF-systems with untunable RF-cavities (or so called broad band RF-cavities) [6,7,8];

-RF - systems with tunable RF-cavities[1,2,3,4,5].

For the untunable RF-cavity a power loss in the magnetic material has an important meaning in obtaining a wide operating frequency range. This effect makes it difficult to get a high accelerating voltage (above 1.5 kV) for the RF-cavity of the Kyoto University [6,7] The RF-cavity of the Toshiba cor. [8] is a new concept of the untunable RF-cavity. The gap voltage is equal to 5 kV in the frequency range from 1 to 8 MHz. The new ferrite SY-20 developed by the TDK company is used in this RF-cavity. This ferrite has a very high quality factor (μQf). It reduces the RF-power losses in the ferrite by several times and leads to the gap voltage increase. This type of the RF-cavity meets the requirements to the PRAMES RF- system. But the choice to use this very type of the RF-cavity will depend on the cost of the ferrite.

The resonance frequency of the tunable RF-cavity is changed by the bias magnetic field in the ferrite. The bias magnetic field is produced by the bias winding placed directly on the ferrite rings (the RF-cavity with the internal bias winding) or by the external quadrupole magnet. The quadrupole biasing magnet is placed on the outer conductor beyond the cavity. Application of the RF- cavity with the external quadrupole magnet is determined by the frequency range width. The basic requirements of PRAMES RF-system are similar to the parameters of the CELSIUS RF-system [1,2] For comparison the main parameters of these RF- systems are shown in table 2. The CELSIUS RF- system design can be considered as a prototype for the PRAMES RF-system.

In general the configuration of the PRAMES RF-system is an accelerating station with a single RF-cavity. The cavity is a ferrite loaded coaxial structure with the internal bias winding. The bias winding is connected to a controlled source able to generate the current in the winding up to several hundred Amperes. The RF-cavity is driven by a power amplifier.

Table 1. Parameters of the developed RF - systems

	CELSIUS Uppsala	TSR Heidelberg	CIS IUCF Indiana University	CPAF CT Kyoto University	CPAS CT Toshiba cor.
Length of the ring [m]		55.4	17.4	~23	
Peak RF voltage [kV]	1.6	5.0	0.5	1.0	5.0
Frequency range [MHz]	1.0÷5.0	0.45÷12.0	1.0÷10.0	1.5÷10.0	1.0÷8.0
Frequency ratio	5.0	26.7	10.0	6.7	8.0
Type of the RF cavity	$\lambda/4$ -ferrite loaded - tuned	$\lambda/4$ -ferrite loaded - tuned	$\lambda/4$ -ferrite loaded - tuned	$2\times\lambda/4$- ferrite loaded - untuned	$2\times\lambda/4$ - ferrite loaded - untuned
Ferrite material	8C12 PHILIPS μ = 900	8C12 PHILIPS μ = 900	8C12 PHILIPS μ = 900	HITACHI METALS Ltd. μ= 1000;100	SY - 20 TDK co.
Dimensions of ferrite rings [mm]	500/300/25	498/270/25	498/270/25	500/280/25	
Number of ferrite rings	16	20	10	8	
Length of the cavity [m]	~ 1		0.7	0.4	1.9
Type of the biasing field supply	Internal winding	External quadrupole magnet	External quadrupole magnet	No	No
Number of the turn	2	5	50	-	-
Bias current [A]	1500	150	20	-	-
Cooling	Water	Water	Air	Air	Water

Table 2. Comparison the main parameters of RF- systems

			CELSIUS	PRAMES
1	Peak RF - voltage	kV	1.6	2.0
2	Frequency range	MHz	1.0 ÷ 5.0	1.2 ÷5.0
3	Frequency ratio		5	4.8

Choice of magnetic material

The cavity and amplifier characteristics depend on the magnetic material qualities. Ferrite materials are used in the accelerator technology as magnetic material for the RF - cavities.

Further only the ferrite 8C12 (PHILIPS) will be considered. Specially for accelerators the PHILIPS firm produces ferrite rings T/498/270/25 8C12 [9]. Their main properties are given in Table 3.

Table 3.

1	Outer diameter	mm	498
2	Inner diameter	mm	270
3	Thickness	mm	25
4	Initial μ		900
5	Remanent μ		600
6	Dielectric constant ε		~ 10
7	Quality factor, 1 MHz:		
	$B_{rf} = 10$ mT		7.5
	$B_{rf} = 20$ mT		5.0
8	Frequency range	MHz	$1 \div 10$
9	Curie point	° C	≥ 125
10	Mass	kg	17

RF - cavity

The sizes of the cross - section of the RF-cavity loaded by the ferrite rings are defined by the sizes of the ferrite rings, the bias winding and the vacuum chamber of the accelerator . The vacuum chamber is an ellipse with axes of 138 and 70 mm.

The ferrite length of the cavity is proportional to the gap voltage. For the initial frequency of 1.2 MHz with the 100 Gauss induction, the length of the ferrite part of the cavity is 0.42m. It means that we can place 12 ferrite rings. The total length of the cavity is 0.82m including the bias field windings and the ceramic gap.

The cavity is composed from one quarter - wave - length coaxial line loaded with the ferrite material (Fig.2).
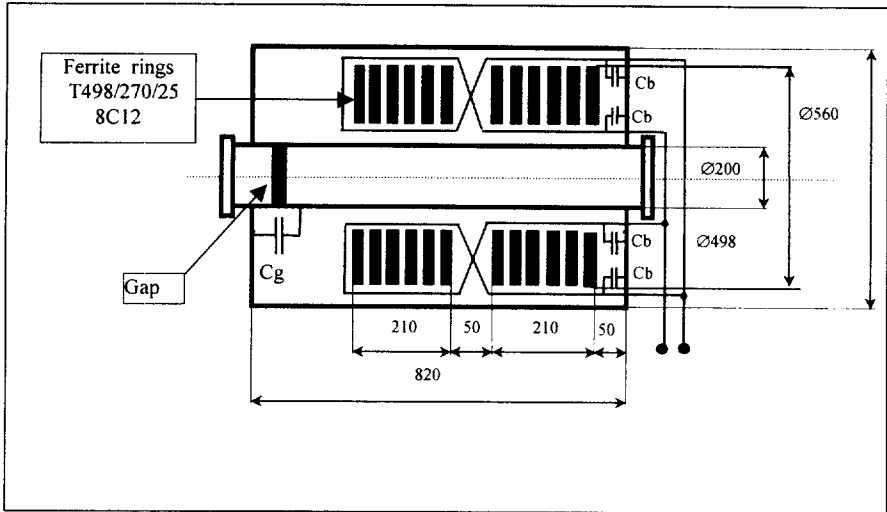

Fig.2

The RF - cavity schematic diagram

The space between the inner and outer conductors of the cavity is filled with the ferrite rings. The ferrite rings are stacked axially with spacing for the cooling air. The magnetic bias field is created by internal bias winding installed directly on the ferrite rings. Twelve rings are divided into two blocks and the winding is fixed as a figure of eight. The 800 A current is needed to reach the maximum frequency of 5.0 MHz. The RF - power loss in the ferrite is 2 kW.

The RF - cavity parameters are summarized in Table 4.

Table 4. Parameters of the RF-cavity

Electrical

1	Peak RF - voltage	kV	2.0
2	Frequency range	MHz	1.2÷5.0
3	Frequency ratio (Kf)		4.17
4	Electrical length	degree	13
5	Tuning capacitor	pF	680
6	RF - power	W	2000
7	Bias current	A	800
8	RF - induction	T	0.01
9	Ferrite material		8C12 PHILIPS
10	Number of ferrite rings		12
11	Dimensions of ferrite ring	mm	498/270/25

Design

12	Outer diameter of cavity	mm	560
13	Inner diameter of cavity	mm	200
14	Ferrite length	mm	420
15	Cavity length	mm	820

Power amplifier

The amplifier chain is composed of the 6 kW final stage, a 1.0 kW driver and a linear amplifier with the control gain. The air cooled tetrode (for example, Gu-90 B) is used for the power final amplifier. This RF - tube operate with the anode voltage of 6.5 kV and maximum power of 6 kW working in class AB. The driver and the linear amplifier compose a broadband transistorized amplifier.

The final stage is installed under the cavity. The driver is located outside the prohibited accelerator area. They are connected with the 50 Ω coaxial cable. The dc voltages operating on these stages are constant and the RF - envelope is controlled by modulating at a low level stage (linear amplifier).

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Cavity tuning

The ferrite - loaded RF - cavity is tuned by the bias magnetic field in the ferrite. The variation of the bias magnetic field changes the permeability μ, and then the inductance of the cavity changes as well as the resonance frequency. The bias magnetic field is produced by winding, that is connected to a regulated power source. The bias current is varied in the range from 0 to 800 A. The control signal for the RF - cavity tuning comes from a function generator. It is added with the signal from a phase detector and then the summarized signal regulates the power supply. The cavity is tuned automatically by the control loop. This control loop detects the phase difference between the grid and anode of the Gu- 90 B tetrode and keeps it close to 180° during the acceleration cycle. The RF - amplitude information is obtained from the capacitive divider connected to the anode Gu- 90 B tetrode. The RF - envelope is detected, compared to the reference and directed to the input of the gain controlled RF - amplifier. The block diagram of the tuning system is shown in figure 3.

Control system of the RF system

The important problem of the control system is to co-ordinate the work of the magnet system and the RF system (fig.1). The work of the control subsystem (fig.4) of the radio-frequency (RF) system is synchronized with a magnet field and a beam position. The system uses a digital signal processor (DSP) for the beam feedback control and a digital control RF-synthesizer for the frequency ramp [5].
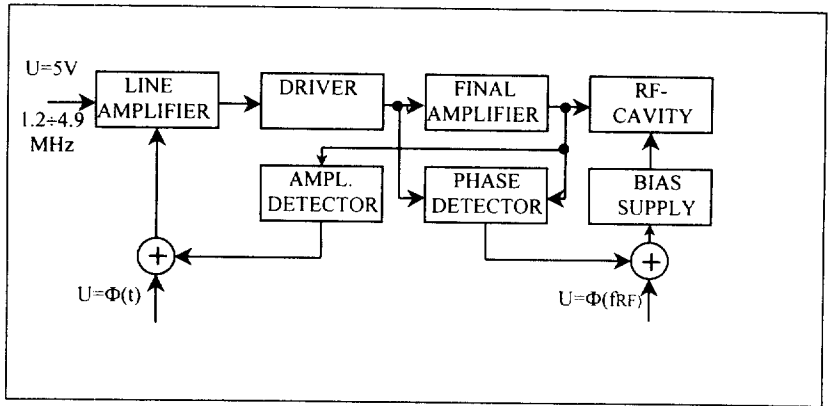
Fig.3

Block diagram of the tuning system.
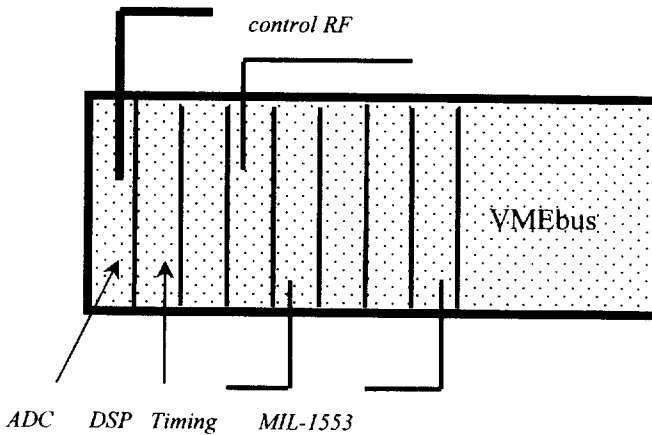
Phase error. radial error, B', RF phase error

Fig.4

The control system of the RF system.

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Проект ускоряющей системы медицинского синхротрона
для протонной терапии

Представлен проект ускоряющей системы для медицинского протонного синхротрона. Рассматриваемый синхротрон должен ускорять протонный пучок с интенсивностью $6{,}25 \cdot 10^{10}$ протонов в импульсе при частоте повторения 1 Гц в диапазоне энергий $60 \div 220$ МэВ. Ускоряющая система состоит из резонатора, наполненного ферритом, усилителя мощности и управляющей системы. Максимальное напряжение на зазоре 2 кВ в диапазоне частот $1 \div 5$ МГц.

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RF-System Design of Proton Synchrotron for Hadron Therapy

A conceptual design of the RF-system for the medical proton synchrotron is presented. The synchrotron will be able to accelerate high-intensity proton beam of $6.25 \cdot 10^{10}$ protons per pulse till the energy of $60 \div 220$ MeV with the repetition rate of 1 Hz. The RF-system consists of a RF-cavity with a magnetic material, a power amplifier, a tuning control system and a beam control system. The RF-system must supply 2 kV peak voltage in the frequency range from 1 to 5 MHz.

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