HIGH FIELD GRADIENT RF SYSTEM FOR A SPIRAL FFAG, RACCAM

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Abstract

A high field-gradient RF system for a spiral FFAG is described. It uses wideband Magnetic Alloy (MA) cavities to cover the frequency 1.86 to 7.5 MHz. The beam will be accelerated with a high repetition rate of >100 Hz to satisfy hadron therapy requirements. The cavity has a wide 80 cm aperture in horizontal direction to allow a large excursion for beam acceleration. Less than 40 cm long it can be installed in a very short straight section.

RACCAM

The Project, RACCAM[1], aims at basic research on FFAGs, including the demonstration of the potential for medical application and for future muon acceleration. The RACCAM chose a spiral shape for the magnet design instead of a radial sector-type magnet, which has been already demonstrated in medium-energy FFAGs in Japan[2]. The advantage of spiral magnets is to make a FFAG compact because the beam is focused by the spiral edge and the negative bending angle for a magnet is not necessary. However, the allowed space for RF systems is limited and orientation with some tilted angle to the beam direction may be needed.

RF PARAMETERS

A very unique feature of the RACCAM-FFAG accelerator is very fast cycling, so it can deliver high dose rate. It allows bunch-to-bunch energy variation, which gives access to 3-D tumor motion tracking. The RACCAM RF system parameters for both minimum and maximum extraction energy are listed in Table 1.

Table 1: Main RF parameters

		Min. Energy	Max. Energy
Injection Energy	MeV	5.5	15
Extraction Energy	MeV	70	180
Momentum compaction, α		1/6	1/6
RF harmonic number, H		1	1
RF voltage, peak	kV	6	6
Synchronous phase	deg	30	30
RF frequency	MHz	1.8593-5.0758	3.0339-7.5432
Acceleration time	ms	9.74 (4.87)	5.44 (2.72)
Number of cavities		1 (2)	1 (2)

RF SYSTEM

In this paper, we use the larger MA cores[3] of the PRISM project[4,5] as a reference. The core size and impedance fit the requirements for the RACCAM-FFAG. Two RF cavities are necessary to demonstrate up to 200 Hz repetition rate. One cavity is used for 100 Hz operation and the other is prepared as a back-up. Each RF cavity will be installed with a small tilted angle in a narrow space between the spiral magnets, as shown in Fig. 1. The length of each RF cavity is 38 cm. Fringing field from the spiral magnets should not affect to the MA cores which have a large permeability. The field clamps will be installed beside magnets and the magnetic field around the cavity will be below 100 Gauss. Because the beam orbits at injection and at extraction are not parallel, the acceleration gap in the cavity has a curved shape to reduce the transverse kicks by the acceleration field.

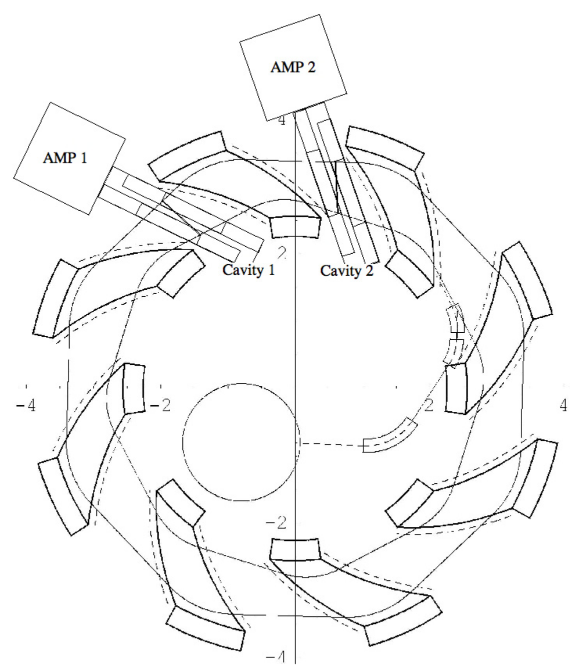

Fig. 1. Schematics of RACCAM FFAG. An H^- cyclotron will be used as injector. The cyclotron extraction energy is variable from 5 to 15 MeV. The extraction energy from the FFAG will be changed in 1 sec. for slice-to-slice scanning, synchronized extraction kick is foreseen for 3D motion tracking. The FFAG consists of 10 spiral magnets. The dashed lines beside the magnets indicate the field clamp to reduce the fringing field which may cause the degradation of cavity impedance by

saturation of the magnetic field in cores. The orbit excursion is 67 cm.

The MA core has a racetrack shape. Although the aperture of the MA core is 1 m (H) X 0.3 m (V), the aperture of the beam pipe is 0.83 m (H) X 0.13 m (V) because of the cavity structure. The cavity consists of two water tanks and a beam pipe. Two MA cores are installed in each water tank and cooled by demineralised water directly[6]. The MA cores are coated by epoxy resin to protect from corrosion by water. The cross section of the cavity is shown in Fig. 2.

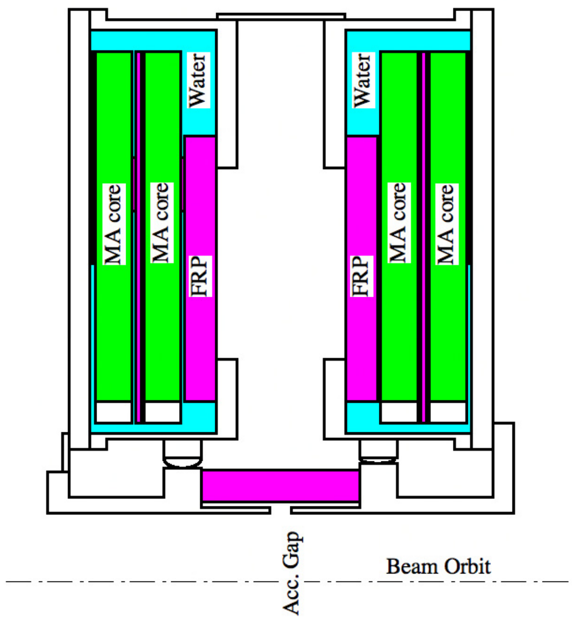

Fig. 2. The vertical cross section of the cavity. Two MA cores are installed in each water tank. The water tank consists of the materials FRP (Fiber Reinforced Plastics) and stainless steel. The acceleration gap has a curved shape to fit the beam orbits. The FRP cylinder around the gap will be used for the vacuum instead of a ceramic pipe. The high power RF will be fed by two bus bars from the tube amplifier, which is located near the cavity.

The cavity impedance is calculated using the impedance of PRISM cores. In case of MA cavity, which does not use a tuning circuit to sweep the resonant frequency, the cavity bandwidth is affected by capacitances of cavity structure and vacuum tubes at high frequency. To reduce the effects from the capacitance of vacuum tubes, each acceleration gap is connected to the corresponding tubes by bus bars. And, it is considered to use 4CW30,000 or RS1084 which have only about 20 - 40 pF output capacitance and reasonable output power to drive the cavity. Main sources of capacitance in the RF system are from cavity structure (few ten pF), cooling water in water tanks (about 10 pF) and vacuum tubes (several ten pF). A total capacitance of 100-150 pF is estimated. Figure 3 shows the expected impedance curve of the RACCAM cavity. When the total capacitance is 150 pF, the cavity impedance at 7 MHz is below 200 Ω and it is rather difficult to obtain the required voltage. An additional inductor[7] may work to cancel a part of the capacitance effect. Such scheme has been already used for J-PARC RCS cavities. The inductor will be installed in the amplifier.

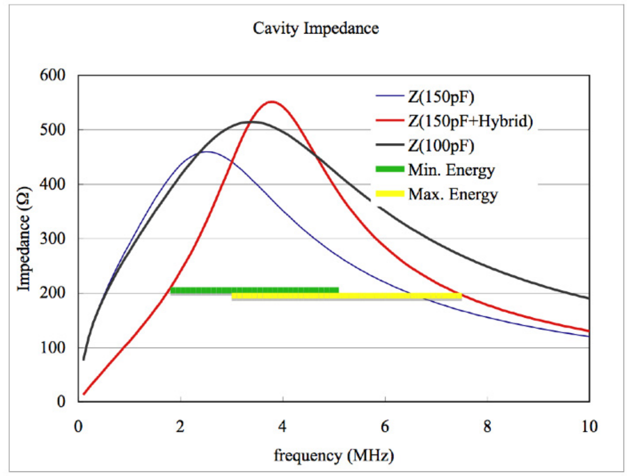

Fig. 3. Expected cavity impedance calculated based on measurements of PRISM cores. The black line is the impedance when the floated capacitance is normal (100 pF). The blue line shows the case when the capacitance is 50 pF larger than the normal case. In this case, the compensation inductance may help to increase the impedance around 7 MHz, as shown by a red line.

In the amplifier, two tetrodes are used for push-pull operation. The tetrodes operate with grounded cathode scheme and the RF signal drives the control grid. Usually, the anode choke circuits may cause a series resonance around 7 MHz. The choke should be designed to avoid causing resonances at the acceleration frequency.

Based on the impedance measurement of the PRISM RF system, which uses 100 kW-class tubes, the power loss was calculated. Maximum power density in cores will be 0.52 W/cc, which is half of that in the J-PARC RCS cavity.

Table 2: Cavity parameters

Number of cavities		2
Size of Cavity	m	2(H) X 1.2 (V) X 0.38 (L)
Beam Pipe	m	0.83(H) X 0.13(V)
Core material		Magnetic Alloy
Size of core	m	1.7 (H) X 1.0 (V) X 0.03 (L)
Number of cores in cavity		4
Cavity Impedance	Ω	400
Power loss	kW	45
Power Density in core	W/cc	0.32 (average), 0.54 (Max.)

FURTHER STUDY

Another FFAG design is under investigation [1]. In the new design, spiral angle of the FFAG magnets is larger and length of straight section becomes shorter than the original design described in the previous section. Two sets of single-end MA cavity which has 20 cm in length are considered. The cavity consists of single water tank shown in Fig.2. Although the waveform of gap voltage may be distorted when the tube amplifier is operated with the class B. The distortion will be cancelled using another cavity which is located at the other straight section. Two system will be operated like push-pull scheme. In this case, the total RF voltage will be 6 kV. There is another idea to use this distortion effectively. Figure 4(c) shows expected gap voltage for single-end MA cavity. When the beam emittance is small, the beam bunch will be accelerated although the distortion will reduce the bucket size. The distortion will affect significantly when the beam is being captured before acceleration. During the beam capture to acceleration process, it is necessary to reduce the voltage distortion. It may be necessary to reduce the gap voltage during the capture process to minimize the voltage distortion as shown Fig. 4(b). Tracking simulation is also needed.

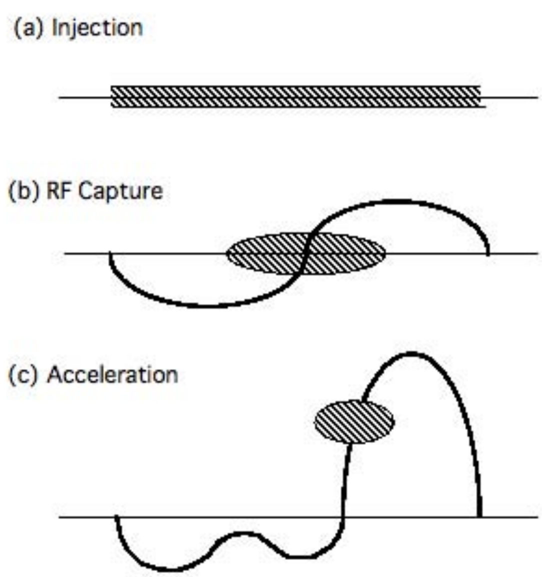

Fig. 4. Beam acceleration with distorted RF voltage. A coasting beam (a) from a cyclotron will be captured by RF voltage with less distortion as the capture voltage is low (b). During acceleration, the tube amplifier is operated with the class B and the gap voltage will be distorted by the second harmonic component of tube current (c). Although the size of RF bucket is reduced, the beam bunch will be accelerated if the beam emittance is small.

It might be required to enlarge the horizontal aperture of cavity to fit a large orbit excursion. It may reduce the cavity impedance and available gap voltage. Engineering design study is necessary for the precise calculation.

SUMMARY

A high field-gradient RF system for RACCAM FFAG is described. The cavities are designed to fit the narrow spaces between the spiral magnets. The field clamps will be installed beside the magnets to reduce the fringing field around the cavities. The MA cavities will be driven by high power amplifier using tetrodes. The power consumption in the cavities and power tubes are calculated. The maximum power density in the MA cores is 0.52 W/cc and it is possible to cool by an established scheme using a direct water cooling. A single-end MA cavity design is also described for another FFAG lattice.

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