PAMELA: DEVELOPMENT OF THE RF SYSTEM FOR A NON-RELATIVISTIC NON-SCALING FFAG

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Abstract

The PAMELA project(Particle Accelerator For MEdical Applications) currently consists of the design of a particle therapy facility. The project, which is in the design phase, contains Non-Scaling FFAG, particle accelerator capable of rapid beam acceleration, giving a pulse repetition rate of 1kHz, far beyond that of a conventional synchrotron. To realise the repetition rate, a key component of the accelerator is the rf accelerating system. The combination of a high energy gain per turn and a high repetition rate is a significant challenge. In this paper, options for the rf system of the proton ring and the status of development are presented.

OVERVIEW OF PAMELA

The PAMELA particle therapy facility includes non-scaling FFAG(NS-FFAG)[1]. Using fixed field accelerator enables rapid change of particles from proton to carbon ions and the achievement of high pulse repetition rate. In addition, due to the small orbit excursion for a fixed field accelerator[1, 2], variable energy beam extraction is possible. The small orbit excursion is accomplished through the use of a new type of superconducting combined function magnet[3]. The variable energy extraction is a unique feature for a fixed field accelerator and contributes to improved beam quality in the treatment. The parameters of the proton ring of PAMELA are summarised in Table 1.

Table 1: PAMELA Accelerator Parameter (Proton Ring)

particle	proton
Energy(ink/ext)	31MeV/250 MeV
Radius	6.251m
Maximum field	4T
Straight section	1.7m
Orbit Excursion	0.17m
Extraction	fast extraction (vertical)
β range	0.251∼0.614
No. of cells	12
p_{ext}/p_{inj}	3

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RF SYSTEM REQUIREMENT

The requirements of rf system from medical, dynamical and geometrical viewpoints are discussed.

The planned irradiation scheme in PAMELA is spot scanning, which irradiates individual small volume, 'voxel', by pencil beam. In spot scanning, a uniform dose field is formed by modulating beam intensity, so called Intensity modulated particle therapy(IMPT). The design goal for PAMELA is a painting speed of 100 voxel/sec. To accommodate IMPT with pulsed beam structure of FFAG, beam provided to each voxel should be subdivided into small beam fraction and deliver it until the dose reaches the prescription. To achieve the goal, with the necessary irradiation accuracy the beam pulse repetition rate must approach 1kHz[4]. Additional intensity control may be achieved by modulation of the injected beam intensity. The energy range of PAMELA proton ring is 31∼250MeV necessitating an energy gain of 100keV/turn.

The present baseline design has a relatively large tune variation with beam energy and the beam is expected to cross a half integer resonance [2] during acceleration. The required accelerating rate to pass through resonance satisfactory has been calculated analytically, and the validity of the analysis was confirmed using tracking simulation[5]. The required energy gain to overcome the resonance blow-up in PAMELA is 50keV, which is lower than that required for the 1kHz repetition rate. Thus, the overall requirement for the energy gain is 100keV/turn.

The lattice has twelve fold symmetry and two of the long straight section are required for the single turn injection and two single turn extraction. Thus, up to eight straights may be used for rf. The geometric constraints on the rf are the length of long straight section of 1.7m and the aperture needs to take into account the orbit excursion of 0.17m and beam size. To leave room for beam diagnostics and vacuum pumps, the cavities should ideally be less than 1.2m in length and provide a horizontal aperture of more than 0.2m.

The requirements of PAMELA rf accelerating system are summarised in Table 2.

Table 2: Requirements of PAMELA Rf System

Frequency for h=1(inj/ext$_{\max}$)	1.94/4.62MHz
Repetition rate	1kHz
Energy gain/turn	100keV
Number of cavity	Up to 8
Length	<1.2m
Aperture	>20cm

RF OPTIONS

Several acceleration schemes were considered including harmonic number jumping scheme, schemes to allow simultaneous acceleration of different momenta beam trains. However, only three of the rf options considered are mentioned here.

- Induction cavity
- Broadband MA(Magnetic Alloy) cavity
- Ferrite loaded rf cavity

The advantage of the induction cavity is the ability to apply an arbitrary accelerating wave. The feature makes it possible to accelerate long bunch trains[8]. In addition, the low impedance is advantageous for competing beam loading effects. Thus, it is suitable for the acceleration of a high current beam. However, it requires a complicated and high power control system, and as PAMELA has a very low beam current, the advantages of the induction cavity are are not ideally suited to PAMELA.

The advantages of MA are higher $\mu \dot{Q} \dot{f}$ value and higher saturating field compared to conventional ferrite. The feature enables MA cavity to achieve higher field gradient than ferrite loaded cavities[7]. The low Q feature of the cavity makes it possible to eliminate the bias current circuit of conventional ferrite cavity, resulting in a simpler system. The broad bandwidth also provides the ability to mix multiple frequencies simultaneously and perhaps to accelerate multiple bunches of different momenta[9]. However, the present extraction scheme of PAMELA does not allow multi-beam acceleration. In addition,the wide frequency range required leads to a very low Q for such cavities and thus to high rf power requirements. Also cavity cooling for high repetition rate of 1kHz becomes a problem.

Considering the above issues, the options of induction cavity and MA cavity were dropped as the first candidate and effort concentrated on the design of a ferrite loaded rf cavity.

FERRITE LOADED RF CAVITY

The power dissipation of a rf cavity is expressed as

$$P = \frac{V^2}{2\omega Q L} \tag{1}$$

where V, ω, Q, and L mean rf gap voltage,angular frequency of rf, Q-value of cavity and inductance of cavity. In terms of power dissipation, high Q cavity operated with high frequency is desirable.

The current design of the PAMELA rf cavity is similar to an ISIS rf cavity[6], but the operating frequency is increased substantially to 19.5∼46.3MHz using harmonic 10. This enables a two gap cavity to fit comfortably within the lattice straight sections and to support gap voltage of up to 15kV peak. The total length of the cavity is 1.1m flange to flange. A schematic of the cavity is shown in Figure 1. The current design is based on the use of Ferroxcube 4D2(Figure 2, but the several ferrites will be investigated to select the most suitable. Although a static Q of ∼100 appears achievable at 19MHz this value will be strongly affected by the rapid change of frequency required by the accelerator. Based of the Ferroxcube 4D2 the available voltage, shunt impedance and power dissipation were calculated assuming the static ferrite values. Table 3 shows the summary. The dynamics properties of small samples of ferrite will be measured to provide more realistic data and to check the overall feasibility of the design.

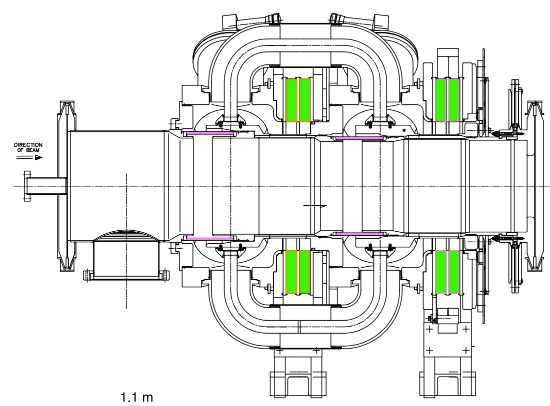

Figure 1: Side-view of planned ferrite loaded rf cavity for PAMELA.

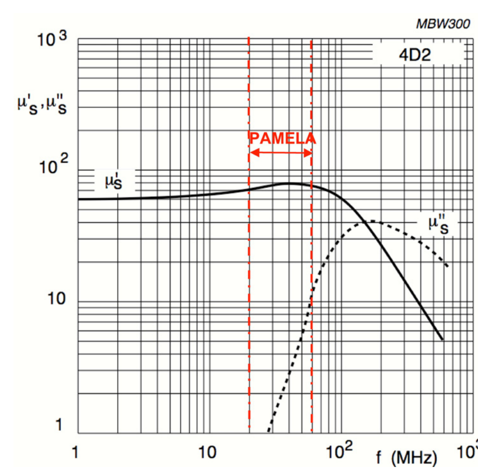

Figure 2: Frequency dependence of permeability of Ferroxcube 4d2[10]. $\mu'_s \mu''_s$ mean real part and imaginary part of complex permeability, respectively.

Table 3: Expected Performance of PAMELA RF Cavity

Frequency (MHz)	Shunt impedance(Ω) for Q=100	Power/gap(kW) @$15kV_p$
20.0	5883	19.1
21.6	5449	20.6
23.6	4978	22.6
26.4	4457	25.2
30.4	3867	29.1
37.1	3168	35.5
52.0	2263	49.7

STATUS OF DEVELOPMENT AND FUTURE PLAN

Though the ferrite loaded rf cavity itself has a long history of development and is becoming a well established technology, the high repetition cycle and high field gradient of the PAMELA rf cavity require careful investigation to establish its feasibility and to obtain the lowest rf power for the facility. For example, the high loss effect and dynamics loss effect of ferrite, which are observed in high power, high rate frequency modulation operation, will deteriorate cavity Q-value. The expected bandwidth of $\sim$ 100kHz to amplitude and phase modulation may result in non-negligible phase error in trying to achieve the 1kHz repetition rate. Longitudinal biasing of the ferrite may lead to higher Q.

A staged R&D program is planned to investigate these problems. As the first stage, the measurement of ferrite properties will be carried out over one year. After measuring the ferrite properties and establishing its suitability as rf core material, a proposal will be made for a full scale design.

SUMMARY

The PAMELA rf acceleration system requires a high repetition rate of 1kHz, with a high accelerating voltage more than 15kV/gap. A ferrite loaded rf cavity is selected as the first approach. To establish its feasibility, R&D program is now underway. Once a suitable material is found, construction of a test rf cavity will be proposed.

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