BEAM EXTRACTION IN PAMELA NS-FFAG

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Abstract

PAMELA is a design project of particle therapy facility using NS-FFAG. The remarkable feature of PAMELA for a fixed field accelerator is variability of extraction beam energy. The feature is expected to improve beam quality for treatment. To realise the energy variable extraction, vertical extraction is employed in PAMELA.

OVERVIEW OF PAMELA

PAMELA is a design study of particle therapy facility using non-scaling FFAG(NS-FFAG) [1]. Employing fixed field accelerator enables rapid change of particles from proton to carbon ions and provide a high repetition rate. In addition, thanks to the small orbit excursion for a fixed field accelerator [1, 2], PAMELA has possibility of extract beam with arbitrary energy over the energy range of treatment. The small but finite orbit excursion requires a large aperture, strong field magnet for the main magnet. A new type of superconducting combined function magnet realises such field [3].

The variable energy extraction is a unique feature for a fixed field accelerator and is expected to improve beam quality in the treatment. Furthermore, the ability will put PAMELA in an unique position among fixed field accelerators as a real alternative of medium energy synchrotron with high beam intensity.

The ring parameters of PAMELA are summarised in Table 1.

Table 1: Main Parameters of PAMELA Ring

particle	proton	carbon
Energy(ink/ext)	31/250(MeV)	68/400(MeV/u)
Radius	6.251m	9.2m
Maximum field	3.6T	3.5T
Straight section	1.3m	1.2m
Orbit Excursion	0.17m	0.21m
No. of cells	12	12
Magnet	FDF triplet SC	FDF triplet SC

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EXTRACTION SYSTEM REQUIREMENT

As a fixed field accelerator, variability of extraction energy is one of the key challenges of PAMELA. Ordinary fixed field accelerators including FFAG and cyclotron have considerably large orbit excursion. Horizontal extraction, which is employed by existing FFAGs and cyclotron, has three difficulties in changing the extraction energy. Those are (1) large inductance and strong field of kicker magnet, (2) beam distortion caused by nonlinear detuning, and (3) matching with extraction channel.

In PAMELA proton ring, the entire orbit excursion is about 18cm. To cover the excursion with a kicker, it needs aperture of more than 20cm. In addition, an orbit separation of more than 10cm needs to be generated by kicker for the treatment energy range, 70MeV$\sim$250MeV. Such a large aperture and orbit separation result in huge inductance and pulse voltage of the kicker. In addition, the non-linear field of FFAG has inevitable detuning of betatron motion, and the detuning sets the upper limit of orbit separation. According to the tracking simulation, the maximum obtainable orbit separation is about 8cm in PAMELA proton ring.

In addition, even if a sufficient orbit separation is obtained in the horizontal extraction, the correction of angular dispersion at septum, which is inevitably generated due to the horizontal orbit excursion, is non-trivial issue. At the moment, no doable option of beam transport system that can manage such large angular dispersion was found.

Due to the above reasons, PAMELA employed vertical beam extraction.

VERTICAL EXTRACTION

In PAMELA, extracted beam size is assumed to be less than 10πmm $\cdot$rad. Considering vertical beta function of proton ring, $\sim$1m, the extracted beam size is typically less than 4mm. Assuming septum of 1cm thick and margin of 5mm in both sizes of septum, the required orbit separation should be more than 28mm. In the design, orbit separation of 30mm is set as the target number. The orbit separation generated by kicker at septum,Δx, is expressed as

$$\Delta x = \Delta x' \sqrt{\beta_1 \beta_2} \sin\phi \quad (1)$$

,where $\Delta x'$,β_1, β_2 and ϕ mean angular kick by kicker, beta function at kicker, beta function at septum, and phase advance over the two points. Using the vertical phase advance per cell,$\sim$0.26, and beta function at the straight section, $\sim$1m, a bending power of 0.06T $\cdot$m is required in order to generate the target orbit separation for 250MeV proton. The kicker and septum are installed in adjacent straight sections in the setup. The requirement for kicker is summarised in Table 2.

Table 2: Requirements for Extraction Kicker System

Rise time(ns)	100
Flat top(ns)	>150
Beam size(π mm mrad)	10
Max length (m)	1
Orbit separation(cm)	3
Bending power(T.m)	0.06
Minimum aperture[H/V](cm)	19/2

With the specifications, the beam motion in the phase space in the extraction process is shown in Fig. 1. More than 30mm of orbit separation is generated with the kicker specified in Table 2. The obtained orbit separation is consistent with that of analytical model. The hardware parameters for such kicker system is summarised in Table 3. The peak voltage of kicker is manageable level with present technology. However, the large peak current caused by large gap hight needs careful design and development of power supply. The development of kicker system is one of the R&D items of hardware development.

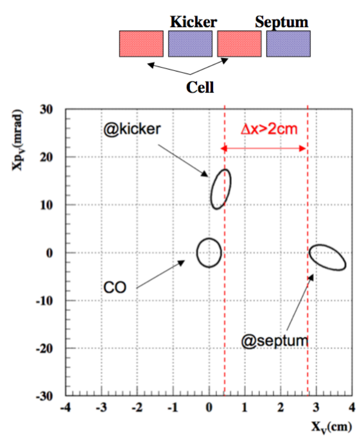

Figure 1: Phase space motion in extraction process of PAMELA proton ring (E_{ext}:250MeV).

Table 3: Specifications of extraction kicker for proton ring

Aperture[W/G/L](cm)	20/3/100
Inductance(μH)	0.2
Peak current (A)	10000
PS voltage (KV)	40

ORBIT AFTER SEPTUM AND CONNECTION TO BEAM TRANSPORT

The outer radius of the cryostat of the PAMELA main magnet is 40cm. Thus, the extraction septum needs to generate an orbit separation of the size at the end of the septum section. Septum field and length required to pass the cryostat is shown in Fig. 2. Due to the drift space, the shorter and stronger septum is more efficient in terms of bending power. Considering the balance of field strength and realistic length of magnet, at the moment septum field and length were set as 1.5T, 0.7m, respectively. The large gap hight of 14cm requires septum current of more than 150k A·turn. Such current requirement would require a superconducting septum.

Table 4: Requirements of Extraction Septum System for Proton Ring

Field strength	1.5T
Septum length	0.7m
Space for conductor	1cm
orbit separation at flange	0.4m
Horizontal aperture	14cm

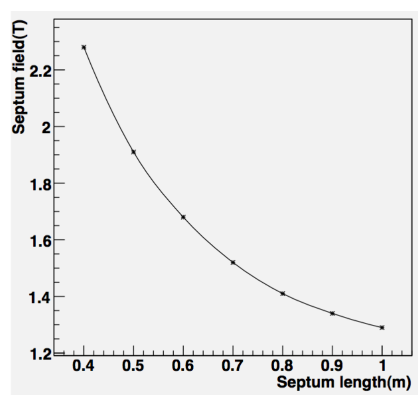

Figure 2: Septum length and field strength required for PAMELA proton ring

In vertical extraction, in order to connect to the transport line, orbit needs to be bend back horizontally. To realise it, it is a natural and simple approach to form a dispersion matching section, where a pair of bending magnet of opposite polarity is employed. At the dispersion matching section, horizontal orbit separation is the same as that of ring. Then, the beam is connected directly to beam transport channel. For the beam transport channel, there can be considered two options. One is an achromatic transport channel using FFAG optics [5], and the other is a conventional beam transport and delivery system. The advantage of the FFAG transport is the ability to transport wide range of momentum with a fixed field. Due to the ability, PAMELA

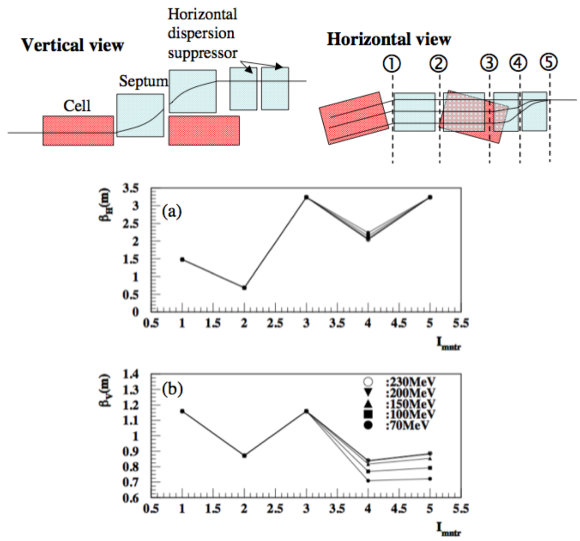

Figure 3: Beta function in extraction and matching section (a):β_H, (b):β_V.

employed FFAG transport as the primary option for beam transport. On the other hand, the second option, conventional beam line, can not change the beam energy rapidly. Conventional transport needs another dispersion matching section to correct horizontal orbit excursion as schematically shown in Fig. 3. In addition, the channel also consist of bending magnet and focusing magnet along the channel. The fields of these elements need to be varied according to the beam energy and inevitably needs some transient time. Energy step size in actual operation in spot scanning would be typically 2∼3 MeV, which corresponds to momentum change of about 1% . Transient time to change the field setting over the energy step would be within 1 second. Thus, if the transient time of 1 second is an acceptable overhead for treatment, conventional beam delivery system can be also employed in PAMELA. Figure 3 shows the beta function along the dispersion matching channel.[1] This shows, over the treatment energy range of proton, the beam can be surely transported.

EXTENSION TO CARBON RING

The proposed lattice of carbon ring for PAMELA has similar length of straight section and phase advance per cell to those of proton ring [4]. With the specifications of PAMELA, carbon beam has rigidity about 2.6 times larger than that of proton beam in maximum. That means the extraction system of carbon ring needs larger bending power of that factor compared to that of proton ring. The required bending power of kicker and septum are about 0.16T.m and 4T.m, respectively. The realisation of such such strong fields are big challenges. Septum of 4T field is the more challenging item in these two. To make a space for septum of such a strong field, two-septum configuration could be a possible approach (Fig. 4). In the option, a weak field septum is installed in the next straight section of kicker. Typical bending power of the first septum is 0.4T.m and the beam is kicked inward. To avoid the beam loss due to inward kick, the septum length of less than 0.5m is desirable with present kicker specifications. Then, with the help of kick by the first septum, the orbit separation more than 7cm can be generated at the second septum. The option can help to ease the requirements of extraction septum. However, the large amplitude betatron motion is strongly influenced by the nonlinear field of FFAG. The careful tracking simulation and dynamics study would be needed.

[1] In FFAG transport option, horizontal dispersion matching section is not needed.

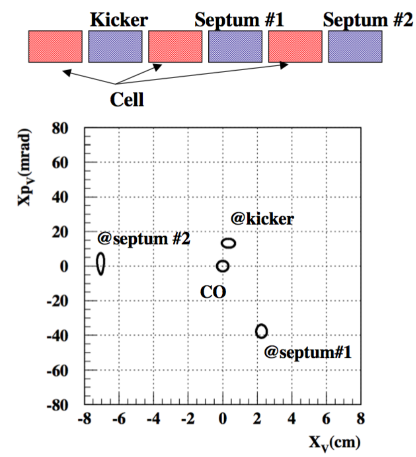

Figure 4: Phase space motion of extracted beam in 2septum option.

SUMMARY

Energy variable beam extraction is one of the major challenge in PAMELA. For the realisation, it employs vertical extraction with wide aperture kicker. The specification are still within engineeringly feasible range, though the uncertainties of inductance and reliability of kicker still remain. To establish the engineering feasibility of the kicker system, submission of hardware R&2 proposal is under planning.

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