BEAM EXTRACTION IN PAMELA NS-FFAG*

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Abstract

PAMELA (Particle Accelerator for MEdicaL Application) is a design study of particle therapy facility using NS-FFAG. PAMELA lattice realizes stable betatron tune with relatively small orbit excursion for a field accelerator with the help of newly developed combined function magnet. The combined function magnet provide an ability to flexibly change the operating point. The challenge of the beam extraction in PAMELA is the variability of extraction energy. The small orbit excursion of PAMELA helps to realize it. To tackle the problem, PAMELA employed vertical extraction with large gap kicker magnet. In addition to the fast extraction, PAMELA has a possibility of resonant extraction with a help of its ability to change the tune footprint. This feature opens up wide range of applications for PAMELA lattice such as ADSR.

OVERVIEW OF PAMELA

PAMELA is a design study of particle therapy facility using NS-FFAG(Non-Scaling Fixed Field Alternating Gradient)[1]. Employing fixed field accelerator enables rapid change of particles from proton to carbon ions and provide a high repetition rate operation. The pulsed beam of FFAG is considered to be fit well to the spot scanning treatment, which is the next generation treatment scheme for particle therapy.

The small but finite orbit excursion requires a large aperture, strong field magnet for the main magnet. Unlike a scaling FFAG, PAMELA employs truncated multipole field as Eq.1

$$\left(\frac{B}{B_0}\right) = \left(\frac{R}{R_0}\right)^k \rightarrow 1 + \sum_{n=1} \alpha(k,n) \left(\frac{\Delta r}{R_0}\right)^n \qquad (1)$$

where Δr, $\alpha(k,n)$ are the deviation from magnet centre, $r - R_0$, expansion factor of the , respectively.

A new type of superconducting combined function magnet realises such field[3]. The magnet has an ability to change the multipole field component individually. The truncated multipole field configuration and the variability of multipole field configuration provide operational flexibility which makes it possible to change not only the average tune but overall tune footprint. One application of such tune footprint trimming is presented in the later section of the paper. In addition, thanks to the small orbit excursion ($\sim$ 17cm for proton lattice, $\sim$ 21cm for carbon) for a fixed field accelerator[1, 2], PAMELA has a possibility to extract beam with arbitrary energy over the entire energy range for treatment. The variable energy extraction and flexible tuneability of operation point are unique features for a fixed field accelerator and are expected to improve beam quality in the treatment. The ring parameters of PAMELA are summarised in Table 1.

* Work supported by the COMFORM collaboration under EPSRC grant number EP/E0332869/1

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Table 1: Main Parameters of PAMELA Ring

particle	proton	carbon
Energy(inj)	31(MeV)	68(MeV/u)
Energy(ext)	70∼250(MeV)	140∼400(MeV/u)
Mean 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

EXTRACTION SYSTEM REQUIREMENT

For a fixed field accelerator, energy variable beam extraction 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 in 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 17cm. To cover the excursion with a kicker, it needs aperture of more than 20cm. In horizontal extraction in PAMELA, an orbit separation of more than 10cm needs to be generated in maximum to cover the entire treatment energy range, 70MeV∼250MeV. Such a large aperture and orbit separation result in huge inductance and huge pulse voltage of the kicker. Analytically, inductance of dipole magnet is expressed as $L = w \cdot l/g$, where $w,\ l,\ g$ mean width, length and gap hight of kicker. The formula tells that for a fixed magnet volume, a kicker with larger width and smaller gap height has larger inductance compared to one with smaller width and larger gap hight. In addition, the non-linear field of FFAG has intrinsic nonlinear detuning of betatron motion, and the detuning sets the upper limit of available orbit separation. According to the tracking simulation, the maximum obtainable orbit separation is about 8cm in PAMELA proton ring.

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. On the other hand, in the vertical extraction, required orbit separation is constant and smaller(¡3cm). Due to the above reasons, PAMELA employed vertical beam extraction.

VERTICAL EXTRACTION

In PAMELA, extracted beam size is assumed to be less than 10πmm·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 sides of septum, the required orbit separation should be more than 28mm. In the design, orbit separation of 30mm is set as the target number. 'One-kicker One-septum' configuration is the baseline option of beam extraction in PAMELA. In the configuration, the orbit separation at septum generated by kicker,Δx, is expressed as

$$\Delta x = \Delta x' \sqrt{\beta_1 \beta_2} \sin \phi \tag{2}$$

where $\Delta x'$,β_1, β_2 and ϕ mean kick angle by kicker, beta function at kicker, beta function at septum, and phase advance between kicker and septum, respectively. 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·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 Figure 1. Orbit separation of more than 30mm 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 below 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.

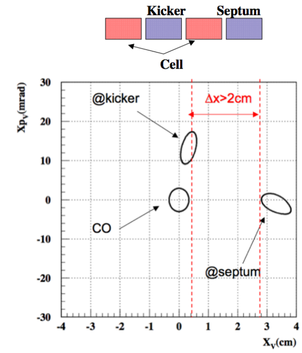

Figure 1: Phase space motion in extraction process of PAMELA proton ring (E_{ext}: 250MeV).

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 dimension at the end of the septum section. Septum field and length required to pass the cryostat is shown in Figure 2. Due to the drift space, the shorter and stronger septum is, the more efficient in terms of bending power. Considering the balance of field strength and realistic length of magnet, septum field and length were set as 1.5T, 0.7m, respectively.

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

The gap hight of 14cm requires septum current of more than 150k A·turn. Such a huge current requires a superconducting septum. To accommodate the energy variability with the superconducting septum, the horizontal field distribution should have a field gradient so that the septum field at certain point matched with the beam momentum at the point. The field shape is actually the same as the main

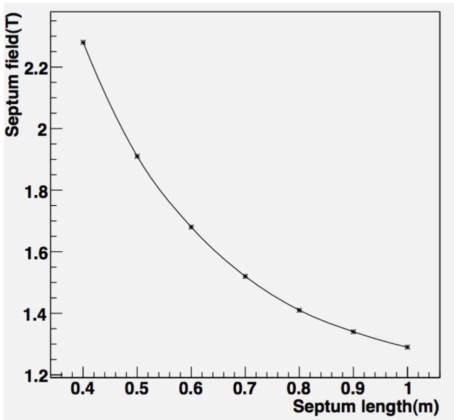

Figure 2: Septum length and field strength required for PAMELA proton ring.

magnet. Figure 3 show TOSCA model of the gradient field septum and the horizontal field distribution over the aperture.

One problem is the field leakage from the septum. Due to the strong field and large aperture, field strength of stray field are about 15mT.m for proton ring and 40mT.m for carbon ring, respectively. The stray fields have almost comparable strength with those of extraction kicker. Therefore, the COD caused by the stray field should be managed. One remedy is to cancel COD using bump orbit. In PAMELA, the phase advance per cell is around 0.75 for horizontal and 0.25 for vertical. Thus, installing the identical magnet of the septum magnet over two magnet cell composes π bump orbit for both direction. Employing vertical injection and installing the identical septum for injection can cancel out influence of the stray field to the circulating beam, though it is certainly overkill for the injection. For the correction, the operation point tuneability of PAMELA is advantageous.

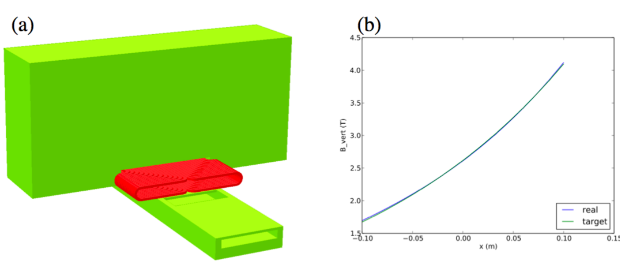

Figure 3: Superconducting combined function septum for PAMELA (a) Schematic view of design model, (b) Horizontal field as a function of horizontal position in septum.

In vertical extraction, in order to connect to the transport line, orbit needs to be bend back vertically. To realise it, it is a natural and simple approach to implement a dispersion matching section, where a pair of bending magnet of opposite polarity is employed. Upstream one is the extraction septum. At the dispersion matching section, horizontal orbit excursion is the same as that of the ring. Then, the beam is connected directly to beam transport channel.

For the extraction 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 without changing the setting of transport line. Due to the ability, PAMELA employs FFAG transport as the primary option for beam transport. The second option, conventional beam transport line requires finite transient time to match the setting of transport line to the beam momentum. Energy step size in actual operation of spot scanning would be typically 2$\sim$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 a practical option in PAMELA.

With the configuration of PAMELA, the conventional approach needs another dispersion matching section to match the horizontal orbit excursion to the optical axis of conventional transport line. It is schematically shown in Figure 4. Figure 4 shows the beta function along the dispersion matching channel.[1] This shows that the beam can be surely transported over the treatment energy range of proton. The possibility that PAMELA can employ dual option for transport line means it can take a staging approach for development of the beam delivery system. With the approach, the development of ring and FFAG transport system can be separated, which minimizes the R&D risk in the development stage.

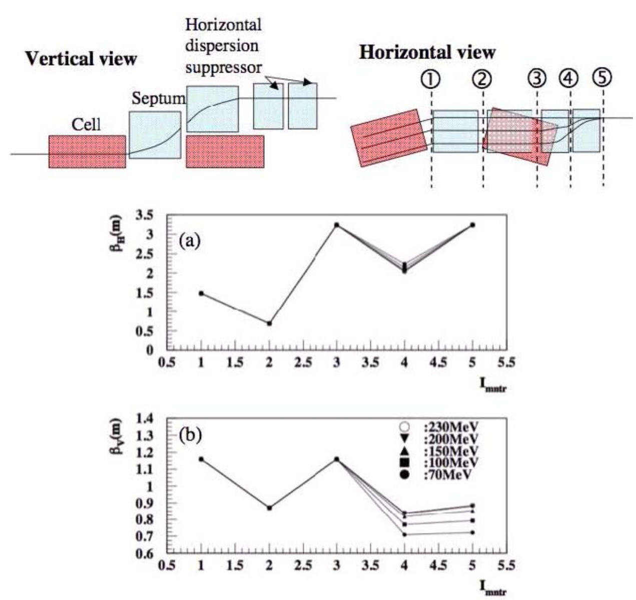

Figure 4: Beta function in extraction and matching section (a): β_H, (b): β_V.

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

POSSIBILITY OF RESONANT EXTRACTION

In PAMELA, by trimming multipole field and relative field strength, it can change not only the average tune but also the overall tune footprint[6]. The feature gives PAMELA another option of beam extraction, resonant extraction.

With the multipole trimming, it is possible to form a tune footprint so that vertical tune increase or decrease as beam energy increases with keeping the total tune drift below 0.5. Typical results of tune footprint trimming are shown in Figure 5

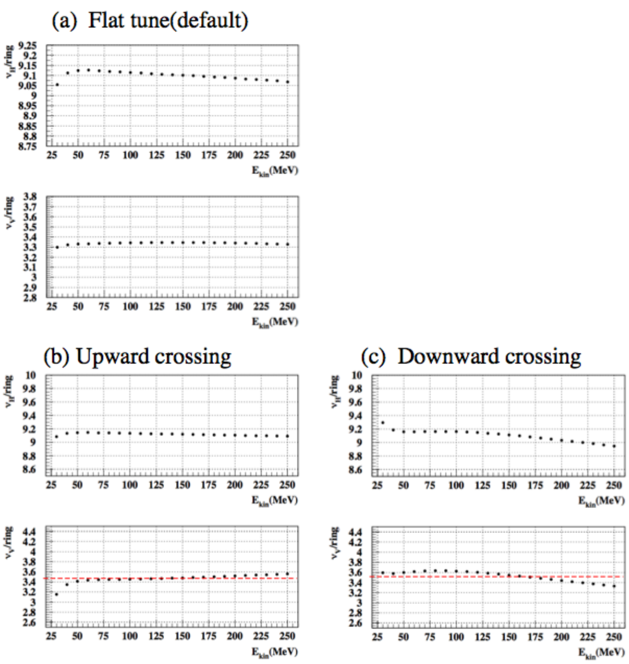

Figure 5: Tune footprint with multi-pole trimming, (a) Flat tune(default), (b) Upward drift, (c) Downward drift.

With such tune drift, the half integer resonance can be used for beam extraction, since half integer resonance can be driven by beam acceleration in a lattice with a tune drift. Fixed field nature of FFAG fits well with it.

In a scaling FFAG, by changing the relative field strength of focusing bending magnet and defocusing bending magnet, which is so called F/D ratio, the vertical tune can be changed freely without significant change of horizontal tune. With lattice parameters of PAMELA, change of F/D ratio of 1% can vary the vertical ring tune over 0.5. Thus, the tiny change of F/R ratio can vary the resonance crossing energy over the entire energy range of PAMELA. It means that energy variable extraction is possible in PAMELA not only in fast extraction but resonant extraction.

Beam motion in half integer resonance was discussed in [7] and it has a directional dependence of resonance crossing. In results, the beam motion shows a significant difference ac coding to the direction of resonance crossing. Figure 6 and Figure 7 shows typical beam motion in upward and downward half integer crossing. To excite the resonance, quadrupole field components of the defocusing magnet of the lattice are varied to match the harmonics of the excited resonance.

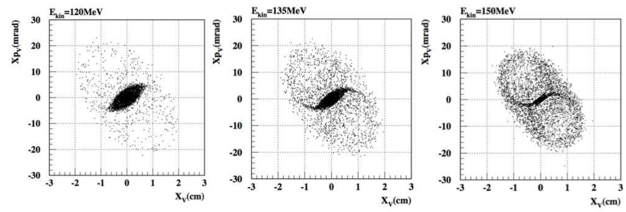

Figure 6: Vertical beam motion in upward half integer resonance crossing.

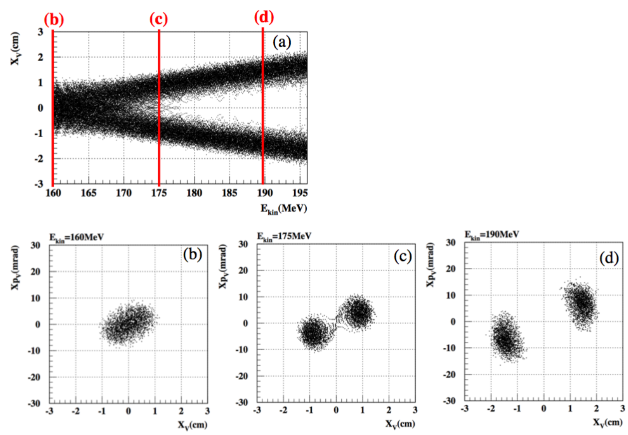

Figure 7: Vertical beam motion in downward half integer resonance crossing (a) vertical beam position at the centre of straight section during resonance crossing, (b) ∼(d) are the slices in typical energies.

With the nonlinear field of scaling FFAG, it has intrinsic nonlinear detuning, with which betatron tune increases as the betatron amplitude increases. Under the nonlinear detuning, the upward crossing is not suitable for a real beam extraction due to its sensitiveness to beam size and external perturbation. It can be easily understood considering the fact that beam with larger amplitude experiences resonance earlier in upward resonance crossing. On the other hand, the downward crossing is robust against such external factors. In this viewpoint, the downward crossing is the practical choice for the acceleration-driven resonant extraction in PAMELA type FFAG lattice.

Putting ESS(Electric Static Septum) outside of circulating beam, beam can be extracted. Figure 8 shows phase space distribution of circulating beam and extracted beam. In the figure, ESS is set 1cm away from the medium plane.

Figure 9 shows a typical distribution of extracted energy and time structure. For the downward crossing, the extraction energy spread can be minimized while keeping the extraction efficiency high enough by optimising the energy at which acceleration stops. It should be mentioned that in the

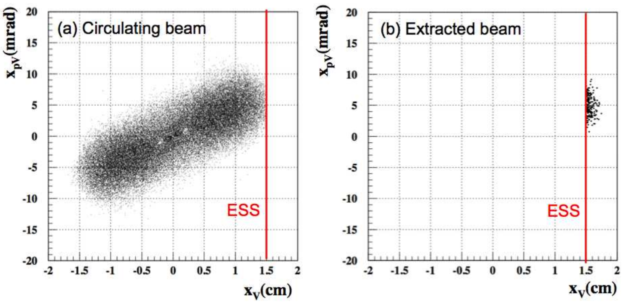

Figure 8: Phase space distribution of circulating and extracted beam in resonant extraction of downward crossing (a) Circular beam (including the beam in splitting process), (b) Extracted beam.

extraction, there is no knob to control the extraction rate. In PAMELA, about 100 turns are needed to extract the entire beam. Thus, exactly speaking, the extraction is multi-turn extraction, not a slow extraction.

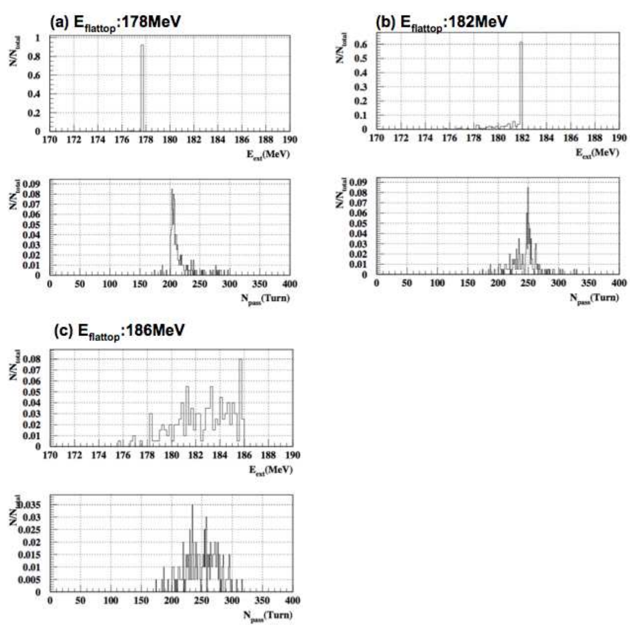

Figure 9: Extracted beam distribution in downward resonance extraction (top: Energy distribution vs. fraction of intensity, bottom: number of turn from a reference turn vs. fraction of intensity).

With the feature, it can be an alternative option of fast beam extraction for the application that its kicker specification is engineeringly hard and that extracted beam structure is not important.

The driver of the resonant extraction is only acceleration, and beam which reaches the extraction energy blows up by itself and extracted. The nature of the multi-turn extraction makes it possible to employ the multi-bunch acceleration [8, 9], which is a promising beam acceleration scheme of FFAG to increase beam intensity without drastic increase of rf power. Combining the multi-turn extraction and multi-bunch acceleration will open up a wide range of application of FFAG not only for particle therapy but also as a high intensity application such as ADSR[10].

SUMMARY

Energy variable beam extraction is one of the major challenge in PAMELA. For the realisation, it employs vertical extraction with wide aperture kicker and combined superconducting septum. The specification of kicker are within engineeringly feasible range, though the uncertainties of inductance and reliability of kicker still remain. For the extraction beam transport, FFAG beam transport line and conventional beam transport can be employed. The tuneability of operation point in PAMELA provides a possibility of energy-variable resonant extraction which is expected to have large variety of application as a versatile medium energy accelerator like proton driver for ADSR.

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