DESIGN OF THE MEBT FOR THE PAMELA MEDICAL FFAG

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Abstract

The PAMELA medical FFAG complex under design in the UK, aims to operate with both proton and carbon beams for hadron therapy. Medium energy beam transfer (MEBT) of PAMELA consists of the proton beam line coming out of the injector cyclotron, carbon beam transfer from the independent carbon 6+ injector Linac, switching dipole (SD) when both beam merge and transfer line toward the PAMELA NS-FFAG. The MEBT layout and design, which needs to incorporate the beam chopper for the intensity modulation, are discussed. The careful matching of optical functions between various components in the MEBT and beam dynamics simulations are presented.

INTRODUCTION

General Layout

PAMELA would be the first non-scaling fixed field alternating gradient machine (NS-FFAG) for proton and carbon. The general layout of *PAMELA* is discussed in [1-3] and is shown in figure 1.

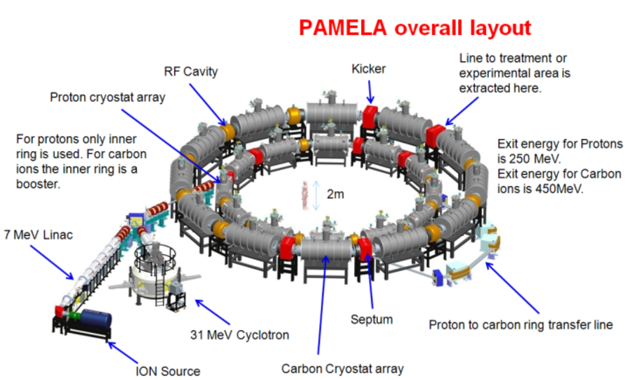

Figure 1: Schematic drawing of the beam injection into FFAG in the *PAMELA* project

Expected injection requirements for proton and carbon 6^+ beams into the FFAG rings of *PAMELA* are approximately 31 and 8 MeV/u energy, respectively. These values are carried over from the design parameters of the lattice under investigation [2]. To achieve the same magnetic rigidity and to allow staged building and commissioning with protons and for the faster switching between ion species, protons and carbons will be produced in separate sources [1-3]. The carbon particles will be transported from the ion source into a pre-accelerator via a Low Energy Beam Transport (LEBT), accelerated, and from there injected into *PAMELA* through a Medium Energy Beam Transport (MEBT), where the particles should meet the energy requirements as noted above. Part of the carbon MEBT, after a switching dipole, is shared with protons, which are delivered into the MEBT via a cyclotron. The general injection layout based on a cyclotron for proton and a Linac for carbon is shown in figure 2. There are two options for pre-accelerating carbon ions for PAMELA, either accelerating carbon with the charge state 4^+ from the ion source and stripping after the pre-accelerator or directly accelerating carbon 6^+ ions all the way from the ion source.

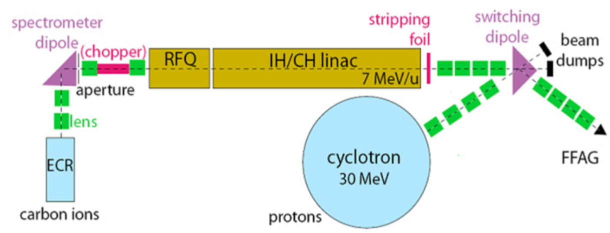

Figure 2: Schematic drawing of the beam injection into FFAG in the *PAMELA* project.

MEBT

A switching dipole will combine the two different beam lines into a single MEBT that would transport the ions up to the injection point into *PAMELA*. The MEBT also prepares the beam structure to match the FFAG injection requirements so that the loss of current at injection is reduced as much as possible.

The switching dipole will bend the carbon and the proton beams with different angles, according to the ratio of the magnetic field integral and the magnetic rigidity.

The magnetic rigidity of carbon and proton for *PAMELA* should be the same. The length of the SD should also be kept fixed. But, depending on the different magnetic fields that the SD should present for carbon and protons, they will bend at different angles so that they both enter the same beam line after the SD. For 31 MeV proton beam the equivalent magnetic rigidity would approximately be $B\rho = 0.811\,\mathrm{Tm}$. Supposing an rbend switching dipole for a 30 degree separation between the beam lines before the SD, the required magnetic field for particles with more bending after the SD would be twice as large as the other one.

Injection Scenarios

For injecting protons into the FFAG, different scenarios have been considered. In one scenario, a vertical injection is considered. The cyclotron and the proton beam line before the SD should position lower than the FFAG. Using a vertical dipole after the SD the beam can be oriented towards the FFAG, which is located about a few meters higher than the ground. Using another vertical dipole and also the septum the beam can be injected into the ring. The latter two elements would also counteract the vertical dispersion produced by the former vertical dipole. In this scenario it is clear that several sets of quadrupoles, would be needed in order to introduce the vertical dispersion matching to zero after injection into the FFAG ring. This requires 2pi phase advance and makes this matching section relatively long. In the second scenario, the FFAG and the cyclotron will be located on the same platform. The beam after the SD can cross the FFAG ring from outside through one straight section (i.e. ring pipe). Now the bema from inside of the FFAG can be horizontally injected into the ring. Note that contrary to the conventional synchrotrons, because of the orbit excursions in FFAGs, the beam injection into the ring should be performed from inside the ring. In figure 3, we have shown one MEBT layout, in which the cyclotron is located inside the FFAG ring.

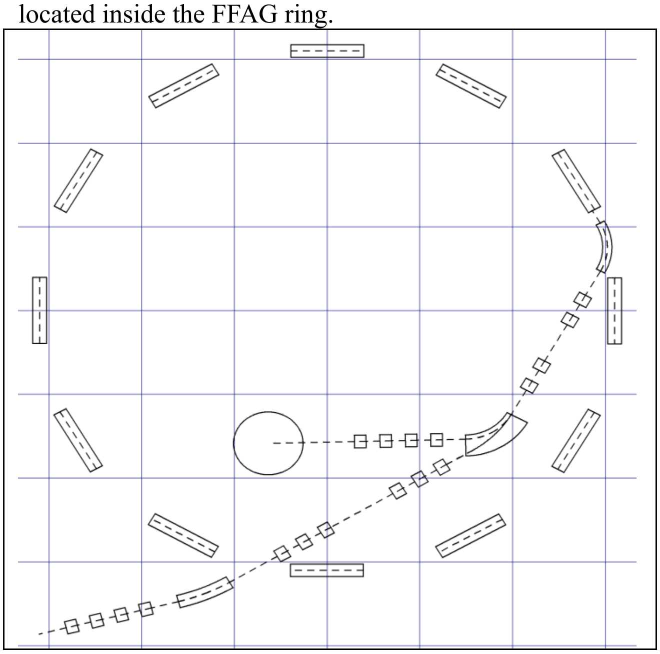

Figure 3: MEBT injection layout for *PAMELA*, based on a cyclotron inside the FFAG ring.

Principles of the MEBT Design

Proton beam requirements are summarized in table 1. As noted earlier, a switching dipole is needed to combine the proton and carbon beam lines. The dipole gives rise to an extra dispersion and one needs bending magnets to compensate the dispersion. In order to obtain enough flexibility in performing matching of optical functions, 8 quadrupole magnets are needed - 4 located downstream and 4 upstream the switching dipole. Long drift section is introduced in the common proton/carbon part of the MEBT, where the potential chopper could be located.

Table 1: Proton Beam Parameter for *PAMELA*

Parameter	**Value**
Radius of the ring	$R_0 = 6.251m$
Circumference	$C = 39.276m$
Relativistic beta at Injection	$v = 75.24 \times 10^6 m/s$
Revolution time	$T_{revoultion} = 0.522\mu s$
Pulse time	$T_{pulse} \approx \frac{T_{revoultion}}{2} = 261ns$
Harmonic number	$h = 10$
RF period	$T_{RF} = 0.052\mu s$
RF frequency	$f_{RF} = 19MHz$
$I_{mean} = I_{dc} = I_{average}$	10^{11} particle/second
Repetition rate	$f_{rep} = 1000Hz$
Duration of each cycle	$1ms$
Injected particles in each cycle	10^8
Pulse particle current	$\approx 3800 \times 10^{11}$
$Df = \frac{T_{pulse}}{T_{repetition}}$	$\frac{261ns}{1ms} = 261*10^{-6}$
Pulse particle current	$I_{pulse} = \frac{I_{mean}}{Df} \approx 3800 \times 10^{11}$
Pulse electrical current	$60.8\mu A$

Horizontal dispersion matching is realised by choosing the phase advance between SD and the septum. As the exact value of dispersion function at extraction from the cyclotron is not known at the time of preparing this paper zero value was assumed, but this system should have enough degrees of freedom to match other values. As the MEBT is designed such that only the magnetic field in the switching dipole will be changed, when the proton/carbon operation modes will be flipped, the dispersion matching in the carbon line requires additional bending magnet. Separate set of quadrupoles are used to perform the beam matching from the linac: 4 quadrupoles upstream the matching dipole and 6 quadrupole magnets separated into 2 triplets between the dipole and the switching dipole . It is worth noting that in order to obtain sufficient room in case of locating the cyclotron inside the FFAG ring far enough to avoid the superposition of magnetic fields, the bending angle of the SD needs to be quite large (about 60 degree). This will produce substantial dispersion, which needs to matched to the value in the FFAG ring.

MADX Investigation

For the layout shown in Fig. 3, the Madx investigation has resulted in the following optical functions for the carbon beam line shown in Fig. 4.

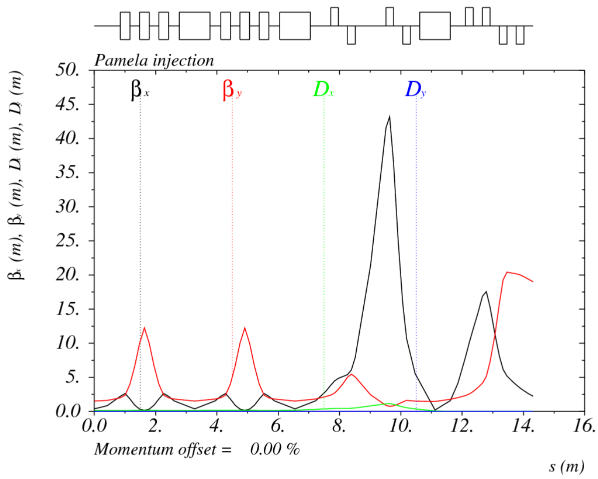

Figure 4: Beta functions for the layout shown in figure 3.

The betatron functions in the carbon operation mode are shown in Fig. 4. Please note, that the inverse matching problem is presented with the FFAG cells located on the left and the matching cell to the carbon Linac is located on the right. On the other hand for the case that cyclotron is located outside of the FFAG, we have devised the transport from the cyclotron into the FFAG again using MADX. Between the 30 MeV cyclotrons and the FFAG we consider a focusing system consisting of usual quadrupoles. In figure 5, we have shown the MADX calculation for beta functions and the dispersions for the proton beam transport from the FFAG ring to the Cyclotron (in the inverse direction). From the left, shown is the two PAMELA triplet cells. Each magnet in the cell is a combined function magnet. Triplet are separated by a one meter sbend septum, and a one meter rbend kicker at the entrance of the FFAG. In this layout, we have considered 4 quadrupoles after and another four before the switching dipole. Each quadrupole is 0.25 meter long. Using the above chain of elements, a matched solution between the cyclotron and the FFAG has been obtained.

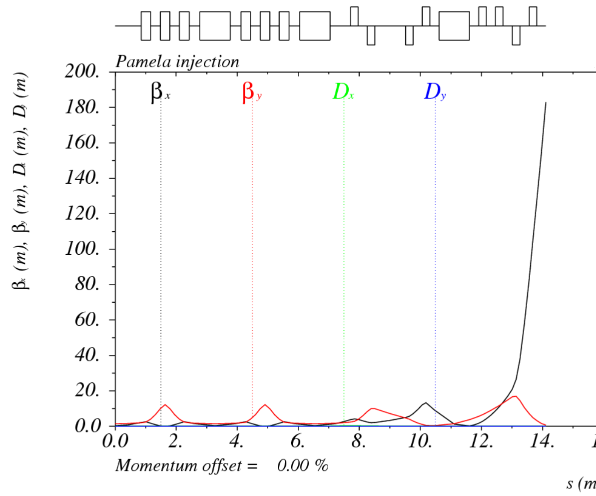

Figure 5. Horizontal and vertical beta functions and dispersions between the cyclotron (right) and the FFAG (left) obtained via MADX.

Single versus Multi-turn Injection

One important issue for beam injection into Pamela is the multi-turn against single-turn injection problem.
Although the high repetition rate (1000 Hz), for Pamela favours a single –turn injection, but due to low carbon 6^+ current from the ion sources, we may need to consider the multi-turn injection scheme. In the latter we would need magnetic and electric septum and also a bumper instead of the usual kickers used in single turn injection schemes due to different rise times.
To adapt the time structure of the beam extracted from the cyclotron to the time structure required for FFAG injection a buncher might be additionally positioned in the MEBT. The carbon pre-acceleration using an RFQ is discussed in [4]. We also need an Interdigital H/ Cross bar H structure to accelerate the carbon up to the design requirements.

CONCLUSIONS

The flexible design of the MEBT to serve for beam delivery in both proton and carbon operation modes was obtained. The only parameters, which needs to be adjusted is the magnetic field in the switching dipole, which would allow for a very short down time during treatment. The beam dynamics studies and final optimisation will be addressed in the future studies.

REFERENCES

[1] M. Aslaninejad *et al.*, Proceedings of PAC09, Vancouver, BC, CA, MO6RFP029,(2009).
[2] K. Peach *et al.*, Proceedings of PAC09, Vancouver, BC, CA, TH4GAC03,(2009).
[3] M. Aslaninejad *et al.*, “Injection of Proton and Carbon 6+ into the Non-scaling FFAG”, these proceedings.
[4] M. J. Easton *et al.*, “RFQ design optimization for PAMELA injector”, these proceedings.