INJECTION OF PROTON AND CARBON 6^+ INTO THE NON-SCALING FFAG

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Abstract

For the PAMELA medical non-scaling FFAG, carbon 6+ as well as proton particles are required. The general injection layout based on a cyclotron for proton and a Linac for carbon is considered. 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. For both options solution has been investigated. Simulations of beam dynamics for both particle species are presented. The resulting schemes based on either the single turn or multi-turn injection into the first FFAG ring is discussed.

INTRODUCTION

Several different scenarios for the front end of *PAMELA* have been investigated [1]. In accordance with the lattice under investigation expected injection requirements for proton and carbon 6^+ beams into the FFAG rings of *PAMELA* are approximately 31 and 8 MeV/u energy, respectively [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. 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 is shared with protons, which are delivered into the MEBT via a cyclotron. There are two options for pre-accelerating carbon for PAMELA, either accelerating carbon 4^+ ions from the ion source and stripping after the pre-accelerator or accelerating carbon 6^+ ions all the way from the ion source. For both options a solution has been investigated (see Figure. 1). A 30 MeV proton beam is equivalent to 3.3 MeV/u carbon 4^+ and 7.5 MeV/u carbon 6^+ from the perspective of magnetic rigidity. A Linac for carbon and cyclotron for protons seems to be the only effective solution. A common Linac for both is also excluded as a Linac defines a velocity profile for all species. We should also mention that a very short Linac / re-buncher, less than a meter in length, may be required after the cyclotron to adapt the cyclotron beam output into the bunch structure required for the FFAG accelerator and to increase the energy from 30 MeV to 30.97 MeV as required by FFAG lattice design.

Also note that 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. In the case of high current proton sources and in our proposal, the ion source is positioned inside the cyclotron and will be delivered with the cyclotron, but care must be taken for carbon sources. Carbon 4^+ sources can produce currents of 200 μA, but carbon 6^+ ion currents are closer to 1 μA.

While the carbon 6^+ accelerator would be more compact and efficient and the current could be sufficient for a rapid cycling machine as proposed for *PAMELA*, in case of technical difficulties, preventing us from reaching a cycling rate of 1 kHz, the fall back option under investigation is to use carbon 4^+ injection and a stripping foil which will produce a higher peak current of carbon 6^+ for injection. To achieve the beam current design parameter in the nano-Ampere range, possible losses through the rest of the accelerator chain must be strictly avoided. Since the FFAG design requires carbon 6^+, carbon 4^+ must be stripped to the higher charge state. This is only possible through a stripping foil for sufficiently high energies of carbon 4^+. Thus, carbon 4^+ ions should be accelerated in the pre-accelerator and then we can increase their charge state to carbon 6^+ ions before injecting into FFAG rings. We need the same magnetic rigidity for protons and carbon 6^+ as injected into the FFAG. The planned scenario for injection is illustrated in Figure 1, where a schematic including the LEBT, pre–accelerator and MEBT is shown. We propose to use a commercially available proton cyclotron with kinetic energy about 30 MeV, followed by a short Linac for bunching and final injection energy as the first stage.

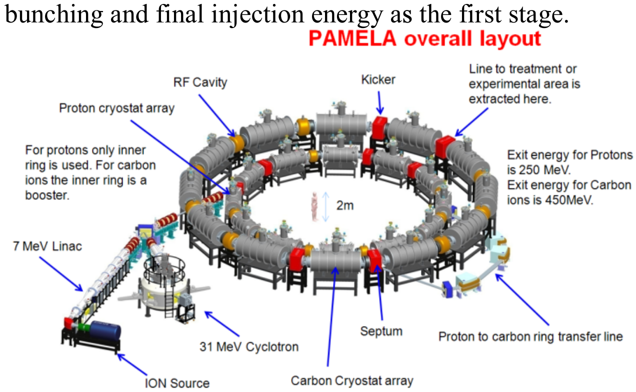

Figure 1: Schematic drawing of the beam injection into FFAG in the *PAMELA* project.

In the second stage, we utilise an electron cyclotron resonance (ECR) ion source to produce 8-10 keV/u carbon 4+ beams. As $C4^+$ is mixed with C^{3+} and C^{5+}, we

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have to employ a spectrometer dipole for mass/charge separation. An aperture then can remove C^{3+} and C^{5+} ions. We also use an RFQ to accelerate the C^{4+} up to 400 keV/u and we then put an IH/CH, (Interdigital H mode/ Crossbar H mode structure) Linac for further acceleration. By this point the energy of the C^{4+} is about 7.5 MeV/u and if we now use a stripping foil to strip C^{4+} to C^{6+} it would meet the FFAG requirements. Note that stripping from 4^+ to 6^+ at low energies before the RFQ is impossible and even immediately after RFQ where the nominal energy of the beam has reached 400 keV/u is still too inefficient as the beam would get stuck in the foil. Therefore, we should utilize a stripping foil after the IH/CH structure where the beam has acquired enough energy to pass the foil and we can get carbon 6^+ from carbon 4^+ with high efficiency. Alternatively, we can accelerate carbon 6^+ ions all the way from the ion source. In this case, we should make use of an aperture to single out carbon 6^+ from carbon 3^+, 4^+ and carbon 5^+. No stripping foil would be needed.

Other options have been considered for the injection layout. One is based on injecting both proton and carbon 6^+ from one single multi-particle cyclotron. This machine would be able to accelerate protons up to 30 MeV and equivalently carbon 6^+ up to 7.5 MeV/u which therefore can meet the FFAG requirements. The other option also based on using one single multi-particle cyclotron with ability to accelerate protons up to 70 MeV and equivalently carbon 6^+ up to 17.5 MeV/u, which would result in less resonance crossing, but it needs modification of the current FFAG lattice. Alternatively, it would accelerate carbon 4^+ up to 7.8 MeV/u which using a striping foil could deliver carbon 6^+ to meet the requirement of the current lattice. In the latter a second 30 MeV cyclotron for carbon would also be needed for the current lattice which would not be economical. The detailed discussions are given in [1].

ION SOURCE PARAMETERS

We have selected an Electron Cyclotron Resonance Ion Source (ECRIS) for the carbon for its high beam quality and beam current stability. Depending on the injection scheme, a super-nanogun type ECR ion source or hyper-nanogun type can be employed for a multi-turn or a single-turn injection scheme, respectively [3]. For a single-turn injection scheme a super-nanogun ECR with a superconducting magnet can alternatively be used. Since PAMELA takes advantage of a high repetition rate of 1000 Hz, therefore, a single-turn injection can be assumed, but a multi-turn injection is not excluded in case the delivered beam from the injector falls short of the requirement. This is in contrast to other FFAG projects like RACCAM, in which due to a lower repetition rate (100 Hz) a multi-turn injection approach has been applied to produce the necessary current. A typical ECR ion source produces an 8 keV/u C^{+4} beam via an external extracting voltage say ~24 kV. The choice of the extracting voltage results from the requirement imposed by the Child-Longmuir law, which is a proportionality relation between the current density and the extracting voltage at a distance *d* from the source, and to avoid technical difficulties occurring for higher voltage . For the required carbon currents, the limit given by the Child-Longmuir law exceeds the current requirements by more than two orders of magnitude. The total energy is 8*12=96 keV. The voltage again can be calculated as 96/4=24 KV.

This external voltage would also extract C^{+3}, C^{+4} and also C^{+5} with the energies 6,8 and 12 keV/u. It is clear that Carbon 6^+ has higher kinetic energy using the same extracting voltage. Applying the same extracting voltage, here 24 kV, to all species, the energy of the Carbon 6^+ particles exceeds those of Carbon 5^+ and Carbon 4^+. In the phase space plane they show higher values of the longitudinal velocity in one snap shot (See figure 2). Typical beam radius and divergence for carbon injection from an ECRIS are 2 mm and 50 mrad, respectively, while the emittance of the beam amounts to 0.25 pi mm-mrad. Of course, the beam parameters strongly depend on the RFQ acceptance. As a remark we here state that the pulse duration amounts5 to 506 ns approximately. The design frequency of the RFQ is about 200 MHz [5]. Therefore, the bunch distance inside the RFQ is 1/ $(200*10^6)$ =5ns. If we consider 1/6 of the RF period for the acceleration (i.e. 60 out of 360 degrees), the bunch length would be 506/6=0.8 ns accordingly. The number of bunches in the train can be approximately estimated to be506/5~100.

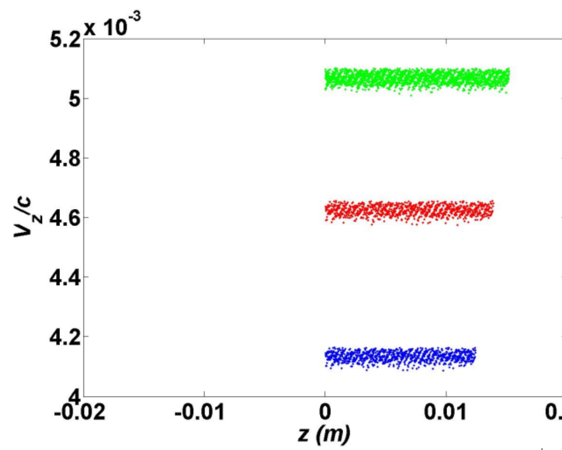

Figure 2: Longitudinal velocities of Carbon 6^+ (top), Carbon 5^+ (middle), and Carbon 4^+ (bottom), immediately after the Electron Cyclotron Resonance Ions source (ECRIS).

LEBT

A Low energy beam transport line (LEBT) will be utilized to transport the particles from the source to the RFQ. For carbon, the layout consists of 4 solenoids (rectangular coils) for transversal focussing and a spectrometer dipole to select the required charge state and remove the others. The particle dynamics of the carbon beam was studied using the General Particle Tracer (GPT) from *Pulsar Physics,* [4]. At the current stage simulations have been done using built-in elements of GPT. It is planned to use a realistic field map for the elements later. Two solenoids each 0.25 m long are positioned at approximately 0.325 and 0.875m from the ion source. The first solenoid runs the particles parallel and the second one focuses them. After the charge to mass separation by the spectrometer, we position two more solenoids to focus the beam into the RFQ. The parameters of the rectangular coils are 5 and 10 cm inner and outer radius for the first two solenoids with 25 length, and 3 and 8 cm inner and outer radii for the last two solenoids with again 25 cm length. The spectrometer dipole bends the beam downward. Different charge states will bend at different radii of curvature in the dipole. The radius of the dipole is 0.25 meters. We may require the beam to enter and exit the dipole normal to the magnet faces. But, due to the weak focusing effect of the dipole, we have a focusing in one plane, but not in the other plane. Consequently, at the cost of having less total horizontal focusing, we should, introduce an effective vertical edge focusing through the pole face rotation angles at the entrance and at the exit of the dipole. Angles of incidence and exit pole faces are taken to be 0.25 rad, for both.

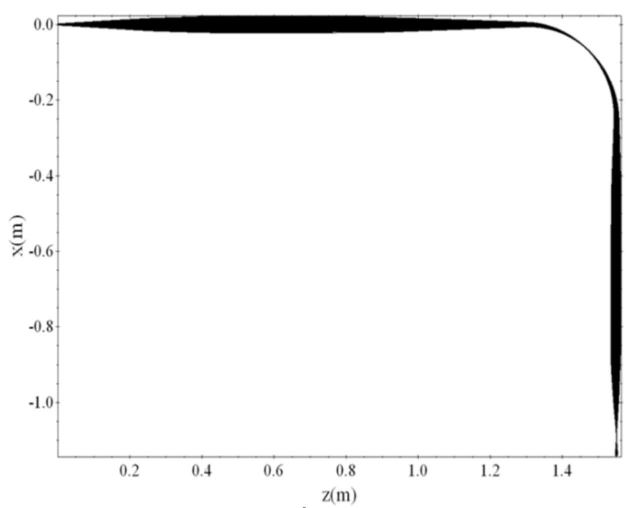

Figure 3: Trajectories of C^{6+} particles from the ECR ion source toward RFQ entrance.

An aperture (10 mm in radius) after the spectrometer dipole ensures that only the ions in the necessary charge state are allowed to enter the pre-accelerator. We also need an aperture before the spectrometer dipole (10 mm in radius) to partially remove carbon 4^+ and carbon 5^+.

In figure 3, Trajectories of 2000 C^{6+} particles from the ECR ion source toward RFQ entrance are simulated. In figure 4 we have shown the trajectories of 2000 C^{6+}, 1000 C^{5+} and 1000 C^{4+} particles from the ECR ion source toward RFQ entrance. A spectrometer dipole bends the beams downward. Different charge states will have different radii of curvature while passing through the spectrometer dipole. An aperture immediately after the spectrometer dipole can remove the unnecessary species, such as C^{5+} and C^{4+} beams, as is shown in the figure, and let only the desired species (C^{6+}) through the rest of the Linac.

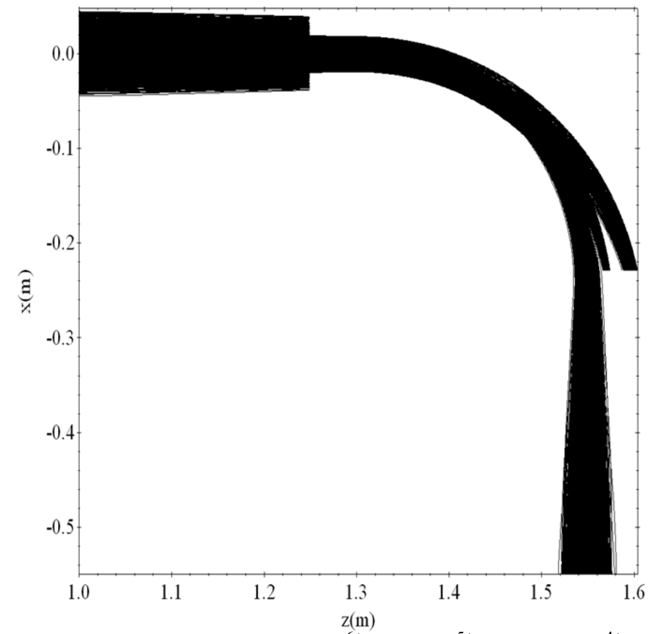

Figure 4: Trajectories of 2000 C^{6+}, 1000 C^{5+} and 1000 C^{4+} toward RFQ entrance.

Without the first aperture the trajectories of carbon 6^+ and carbon 5^+ would be quite mixed up so that the second aperture after the dipole would not separate them properly. The final section of the LEBT line may include a chopper for beam injecting into *PAMELA*, together with two lenses that act, firstly, to ensure that the beam through the chopper is parallel and, secondly, to focus the beam into the RFQ, as the RFQ requires a convergent beam to yield a reasonable transmission. The beam dynamic simulation for the RFQ and also MEBT are presented in other articles [5, 6]. As RFQs do not work efficiently at high velocities an IH/CH drift tube Linac should be also employed [7].

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