INJECTION LAYOUT FOR PAMELA

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Abstract

For the *PAMELA* project, the injection layout for both protons as well as carbon 6^+ ions is discussed. The injection system would consist of a 30 MeV cyclotron for protons and a chain of elements for carbon ions such as ECR ion source, bending magnets and focusing solenoids; RFQ, IH/CH structures and a stripping foil. The charge particle simulation for both protons and carbon ions passing through the elements has been carried out via General Particle Tracer (GPT) software.

INTRODUCTION

Several different scenarios for the front end of *PAMELA* have been investigated [1]. Expected injection requirements for proton and carbon 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 second ring in the KST [2] three ring lattice and are also valid for the lattice under investigation [3]. For faster switching between ion species, protons and carbon will be produced in separate sources. The particles will be transported from the ion sources into a pre-accelerator via a Low Energy Beam Transport (LEBT), and from there they are injected into *PAMELA* through a Medium Energy Beam Transport (MEBT), where the particles should meet the energy requirements as noted above. High current proton sources are easily found, 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^+ current could be sufficient for a rapid cycling machine as proposed for *PAMELA*, the safe 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 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.

METHOD AND RESULTS

The planned scenario for injection is illustrated in Figure 1, where a schematic of the proposed injection system including the LEBT, pre–accelerator and MEBT is shown. Here, we propose to use a commercially available proton cyclotron with kinetic energy about 30~31 MeV, followed by a short Linac as the first stage.

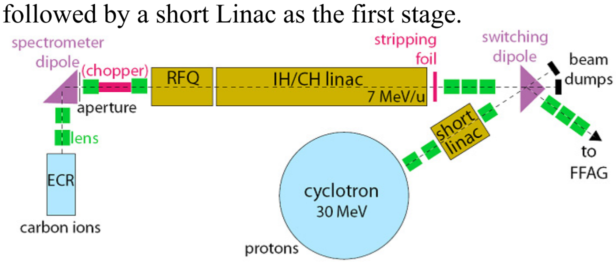

Figure 1: Schematic drawing of the beam injection into FFAG in the *PAMELA* project.

In the second stage, we utilize an electron cyclotron resonance (ECR) ion source to produce 8-10 keV/u carbon 4^+ beams. As C^{4+} is mixed with C^{3+} and C^{5+}, we have to employ a spectrometer dipole for mass/charge separation. An aperture then can block 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 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.

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. As a final remark, we should also mention that a very short Linac / rebuncher, less than a meter in length, may be required after the cyclotron to increase the energy from 30 MeV to 30.97 MeV as required by FFAG lattice design and to adapt the cyclotron beam output into the bunch structure required for the FFAG accelerator. 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.

Other Options

An extension of the current 30 MeV proton cyclotron is possible, such that it can also accelerate carbon ions. In this case this multi-particle machine could accelerate

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carbon 4^+ up to 3.3 MeV/u and carbon 6^+ up to 7.5 MeV/u. Therefore, the latter case can meet FFAG requirement too as we can inject both proton and carbon 6^+ directly from the same cyclotron into FFAG. Of course, it is assumed that this new machine would be able to accelerate all three species. If, for technical deficiency, it could merely accelerate protons and carbon 4^+ with 30 and 3.3 MeV/u, respectively, then again we can get the right charge state to carbon 6^+ using an immediate stripping foil, but with the same carbon 4^+ energy (3.3 MeV/u). This means the energy obtained for FFAG is reduced by a factor of 3.3/7.5. As a result, we would again need a Linac structure to reach the required energy for carbon 6^+. On the other hand, if we first accelerate carbon 4^+ through the Linac and use a stripping foil at the end, we would get higher efficiency from the stripping foil. But setting the magnetic rigidity of carbon 4^+ and carbon 6^+ equal to each other, the acceleration is only 4/9 efficient from energy aspect and 2/3 from velocity aspect due to the velocity profile of Linacs, so this option also has some drawbacks. A detailed investigation is needed to find which method optimises the total efficiency, but in any case we inevitably should put it aside as, while protons are directly injected into FFAG from the cyclotron, we have to take a very long path starting from the same cyclotron and reaching the FFAG for carbons.

Alternatively, it might be considered an option to modify the structure of the second FFAG ring to accelerate the proton ions from 70 MeV up to 250 MeV while accelerating carbon 6^+ from 17.5 MeV/u up to 68 MeV/u. This results in less resonance crossing. We have considered the idea of a new multi-particle cyclotron that would be able to extract 70 MeV alpha particles (${}_2^4He^{2+}$), or equivalently 17.5 per nucleon helium beam, and is accordingly also able to extract 17.5 MeV/u for ${}^{12}C^{6+}$. If we keep the current parameters of the present lattice, (30 MeV protons and 7.8 MeV carbon 6^+), this machine with 70 MeV injection energy for protons and 17.5 MeV/u for carbon 6^+ is not a solution to our needs. But if this new machine can also accelerate carbon 4^+ with 7.8 MeV/u then we can use a stripping foil immediately after to strip carbon 4^+ to carbon 6^+ with 7.8 MeV/u which we need according to FFAG design. The real problem with this scenario is that we would need another cyclotron for delivering a 30 MeV proton beam. This means two cyclotrons, one 7.8 MeV/u carbon 4^+ (equivalent to a 70 MeV proton machine) and the other a 30 MeV proton machine, which would not be economical.

LEBT

A Low energy beam transport line (LEBT) will transport the particles from the source to the RFQ. For carbon, the layout consists of 4 solenoids for transversal focussing and a spectrometer dipole to select the required charge state and remove the others. Different charge states will bend at different radii of curvature in the dipole and therefore will be focused to different locations by a magnetic lens. An aperture after the spectrometer dipole ensures that only the ions in the necessary charge state are allowed to enter the pre-accelerator. 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 particle dynamics of the carbon beam was studied using the General Particle Tracer (GPT) from *Pulsar Physics,* [4]. The results covering the transfer line from the ion source up to the RFQ are shown in the Figures 2 and 3.

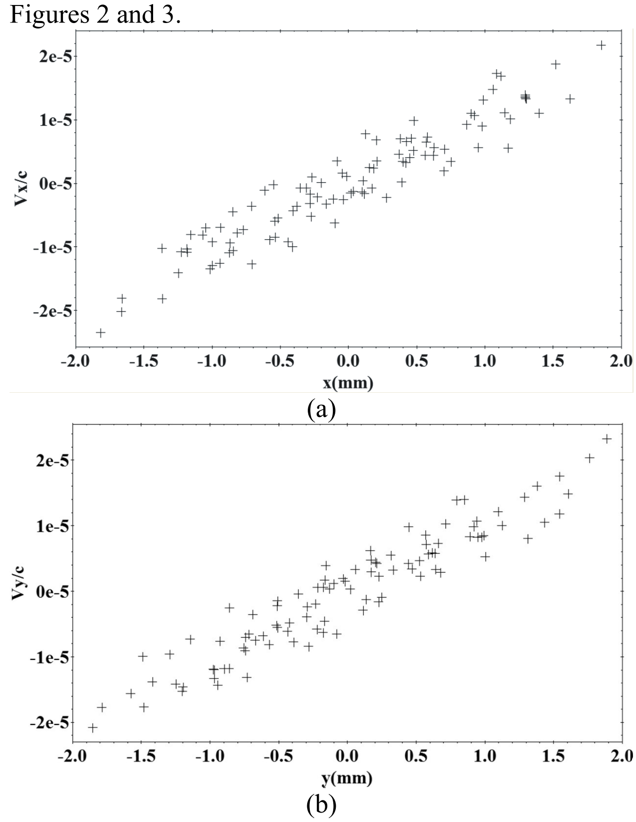


Figure 2: Initial (a) horizontal and (b) vertical phase space distributions of 100 sample particles starting from ion source.

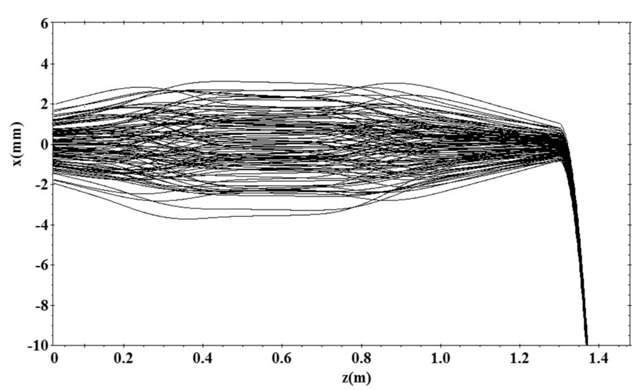


Figure 3: Two solenoids each 0.25 m long are positioned at 0.30 and 0.85 m from the ion source. The first solenoid runs the particles parallel and the second one focuses them. Each solenoid consists of 50000 Amp turns, with inner and outer radius of 0.05 and 0.10 m, respectively.

In Figure 2 the initial phase space of 100 sample particles is shown. The trajectories of these particles (observed in the coordinate system relative to the ion source at z=0) are drawn in Figure 3. The bending process via the spectrometer dipole is obvious. The beam dynamic simulation for the RFQ is presented in another article [5]. As RFQs do not work efficiently at high velocities, an IH/CH drift tube Linac should be also employed [6]. The details of the Linac will be investigated once the output of the RFQ is determined.

MEBT

So far only transport from Cyclotron into FFAG has been investigated, as the output of the RFQ and Linac are not yet known. The layout consists of 6 quadrupoles and one buncher cavity. Between the 30 MeV cyclotron and the FFAG we should consider a focusing system consisting of usual quadrupoles. 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 results so far show that we need two sets of triplet quadrupoles to establish the focusing of the system, while providing two minimum beam sizes (i.e. two waists) at the location of the buncher and at the entrance of the beam into the FFAG. The simulations results from the GPT codes for the trajectory of 100 sample particles and the initial transverse phase space are shown in the Figures 4 and 5.

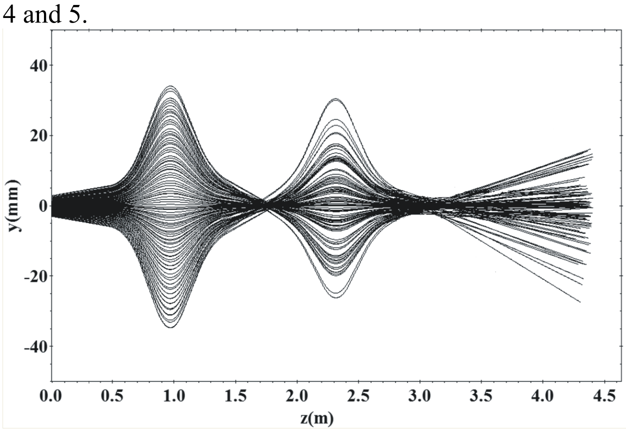
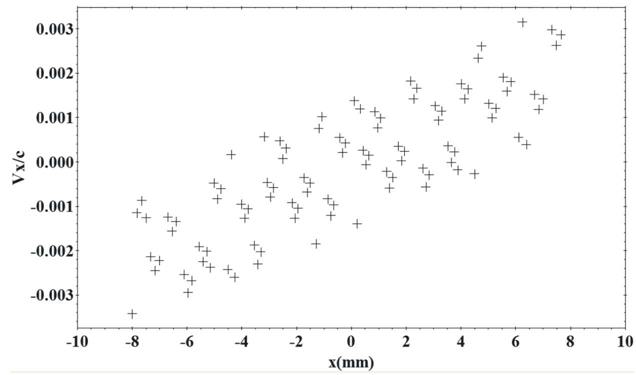
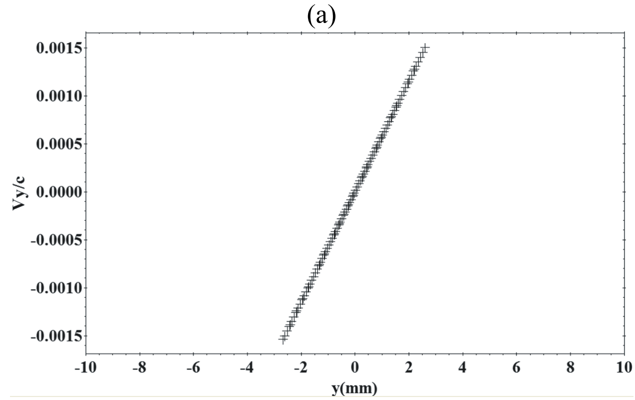


Figure 4: The trajectory of 100 particles in the vertical plane between the cyclotron and the FFAG ring, as obtained by GPT package. Two waists in the middle and at the end of the longitudinal direction correspond to the place where a buncher may locate and the entrance of the FFAG ring.



(a)



(b)

Figure 5: Typical initial (a) horizontal and (b) vertical phase space distribution of 100 sample particles from the cyclotron.

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