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A LOW ENERGY ACCUMULATION STAGE FOR A BETA-BEAM FACILITY

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Abstract

The EU supported EURISOL Design Study encompasses a beta-beam facility for neutrino physics. Intense electron (anti-)neutrino beams are in such a machine generated through the decay of radioactive ions in a high energy storage ring. The two main candidate isotopes for the generation of a neutrino and an antineutrino beam are 6He and 18Ne. The intensities required are hard to reach, in particular for the neon case. A possible solution to increase the intensity is to use an accumulator ring with an electron cooler. Critical parameters such as cooling times and current limitations due to space charge and tune shifts are presently being optimized. We will in this presentation give an overview of the low energy accumulation stage and review recent work on this option.

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The EU supported EURISOL Design Study encompasses a beta-beam facility for neutrino physics. Intense electron (anti-)neutrino beams are in such a machine generated through the decay of radioactive ions in a high energy storage ring. The two main candidate isotopes for the generation of a neutrino and an anti-neutrino beam are ^{6}He and ^{18}Ne. The intensities required are hard to reach, in particular for the neon case. A possible solution to increase the intensity is to use an accumulator ring with an electron cooler. Critical parameters such as cooling times and current limitations due to space charge and tune shifts are presently being optimized. We will in this presentation give an overview of the low energy accumulation stage and review recent work on this option.

INTRODUCTION

In the study of a beta-beam facility within the EURISOL Design Study [1] ^{6}He and ^{18}Ne have been chosen as suitable isotopes to generate electron neutrino and antineutrino beams. The half-lives of ^{6}He and ^{18}Ne are 0.80 s and 1.67 s. The study aims for a flux of 10^{18} anti-neutrinos (from ^{6}He) and neutrinos (from ^{18}Ne) per year. A major problem is to achieve the number of stored ^{18}Ne ions required to reach the intensity of the neutrino beam needed by the proposed experiments [2]. Thus, we have studied what can be gained by including a storage ring with electron cooling which is used to accumulate ions at a relatively low energy (100 MeV/u). To match the repetition frequency of the beam pulses coming from the linac, 10 Hz, the cooling time has to be short, of the order of 0.1 s. Also the limitations due to space charge induced tune shifts have to be considered.

COOLING AND ACCUMULATION

The design of the beta-beam facility that we have used in this work is based on the current version, no. 2, of the base line scenario [3]. A schematic view of the facility is shown in Fig. 1. The accumulation ring we have studied would be placed between the linac and the RCS. The accelerator chain after the accumulation ring has been kept identical to version 2. Each beam pulse from the linac is injected into the accumulation ring with multi-turn injection. Continuous, fast electron cooling compresses the ion beam in all dimensions in phase space and makes it possible to increase the number of stored ions by accumulating several pulses from the linac, at the rate of 10 Hz, before the ions are extracted and further

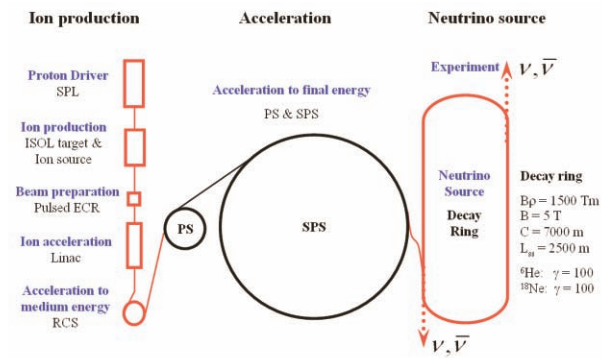

Figure 1: Layout of a beta-beams facility.

accelerated in the RCS and the following accelerators to the final energy. No acceleration is planned in our ring. The energy of the ions after the linac, in the base line scenario we use, is 100 MeV/u, which gives an electron energy of 55 keV. It would be easier to achieve the short cooling time at a lower energy, but the limitations due to space charge would become more severe. In this work we have only studied the design of a ring at 100 MeV/u. However, the possibility to store the ions at a lower energy in the cooler ring is not excluded, but would require further changes in the base line scenario.

Electron cooling

The electron cooling is performed by merging an electron beam with the ion beam in one straight section. It is fast for already cold ions but slower when electron and ion velocities differ, since

$$1/\text{cooling time} \sim I_e/\Theta^3$$

where Θ is the angle between ions and electrons. Thus cooling is fastest in the center of the beam but in our case only the cooling of the outer part of the beam is important. The cooling time (the time it takes to cool to 1/e) does not depend on ion current, and normally cooling is much faster longitudinally than transversely. Practically one has achieved up to 1 A electron current.

Accumulation ring

We have made a preliminary design of a cooler ring to be able to make some realistic cooling calculations. A schematic layout is shown in Fig. 2. The ring is symmetric with two superperiods, each quarter of the ring has two gradient dipoles and five quadrupoles in four families. The lattice functions are shown in Fig. 3.

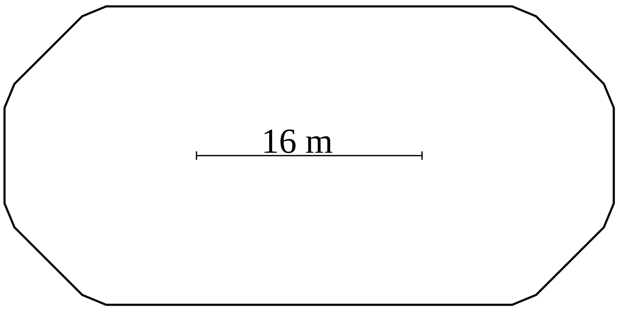

Figure 2: Layout of an accumulator ring.

To obtain fast cooling one needs as long a cooler as possible. This is easiest done by having a racetrack-shaped ring, where one of the long straight sections would be used for an electron cooler and the other for injection and extraction.

Next, large β-functions in the cooler give fast cooling since

$$1/\text{cooling time} \sim 1/\Theta^3 \sim (\beta/\varepsilon)^{1.5}.$$

As can be seen in Fig. 3, this ring has $\beta_x \approx 12$ m and $\beta_y \approx 15$ m in the cooler.

Simulations of cooling

We have simulated electron cooling with a tracking program with a 3D cooling force and electron beam space charge [4]. Intrabeam scattering is not included, so the central part of the beam will be unrealistically cooled. However, the cooling of the outer part of the beam should be correct. Since the decreasing size of the beam is what makes it possible to accumulate further beam pulses into the ring, the results of the simulations are useful to evaluate if the cooling is fast enough for accumulation.

Both the design of the ring and the cooler simulations are in a preliminary stage, but with a 14 m long electron cooler (13% of the circumference) a cooling time in the order of 0.1 s seems achievable for neon, but the electron current has to be high, which might be difficult to realize.

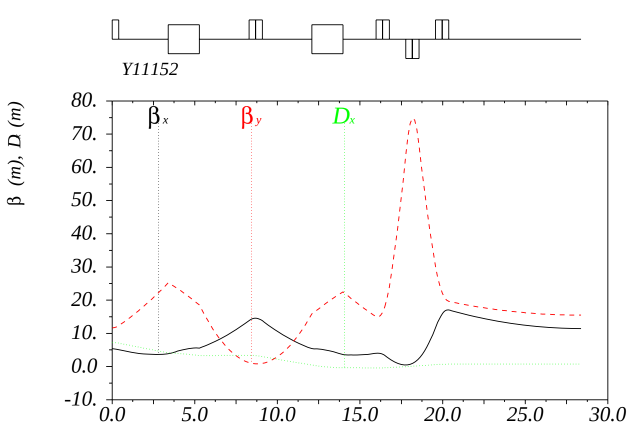

Figure 3: Lattice functions for one fourth of the accumulator ring, calculated with MAD-8

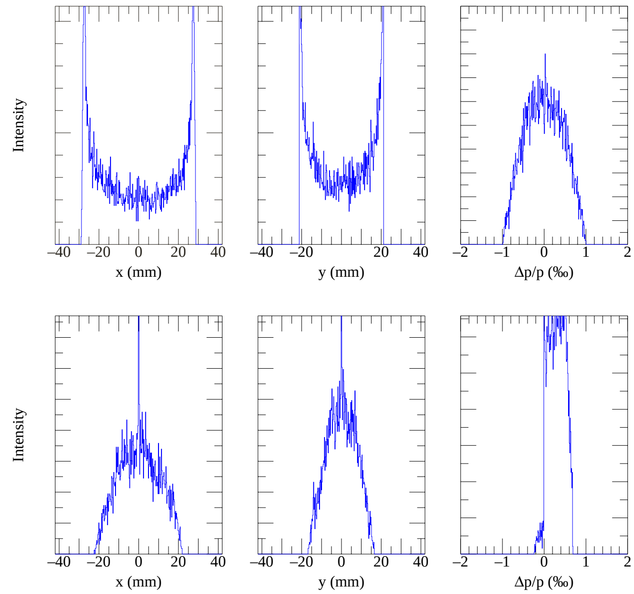

Figure 4: Simulation of horizontal, vertical, and longitudinal profiles of an $^{18}Ne^{10+}$ beam before (above) and after (below) 0.1 s cooling. Initially all ions have the same emittances, ε_x=65 π mm mrad and ε_y=30 π mm mrad. Intrabeam scattering is not included so after cooling the central peak becomes unrealistically high.

With the present design, ions with ε_x less than 65 π mm mrad becomes cooled in 0.1 s, as seen in Fig. 4. In the simulations we have used 2.5 A electron current, 29 mm electron beam radius and a 0.05 T longitudinal magnetic field.

Since the transverse cooling rate is approximately proportional to $Q^{1.7}/A$ [4], the cooling time of $^6He^{2+}$ is about five times longer. Thus, it seems to be difficult to obtain a short cooling time transversally for this ion. However, in the base line scenario, the required intensity of the helium ions is reached, so while an increase in the number of ions available would add a welcome safety margin, it is less essential than for the case with the neon ions. If it is desired, a higher electron current would be needed as well as special arrangements, such as a hollow electron beam as is planned to be used in the LEIR cooler

OPTIMIZING THE TOTAL CYCLE

After each period of accumulation the ions are accelerated in the RCS and can then stored before further acceleration either in PS or in SPS while another accumulation period starts in the accumulator ring. The optimum number of ion pulses accumulated and stored in this way is given by the balance of the radioactive decay of the ions (the speed of which depends on the energy at which they are stored) and the rate of intensity increase during accumulation. The optimum scheme also depends on different limitations in all the rings, such as space charge limitations, instabilities, radiation concerns, cycle lengths of PS and SPS etc.

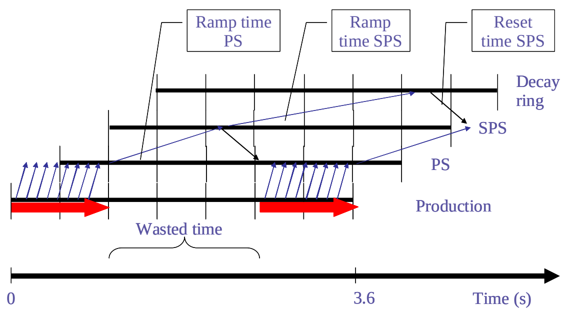

Figure 5: A complete cycle for the baseline beta-beam complex consists of injection into the PS, storage of bunches at PS injection energy, acceleration in the PS and SPS and finally injection into the decay ring.

The time between subsequent injections in the present baseline without an accumulation ring is 6 seconds for ^{6}He and 3.6 seconds for ^{18}Ne. The baseline injection scheme with the first RCS bunch being stored at PS injection energy for up to 2 seconds before acceleration to higher energies does not make use of all ions produced in the target, see figure 5. The here proposed accumulator ring will add considerable flexibility to the injection scheme and permit an efficient use of all produced ions. In figure 6 the annual neutrino rate is plotted as a function of the number of accumulated ECR bunches. The ions are in this calculation kept in the SPS at injection energy (and not in the PS as in the baseline) as the accumulator ring opens the possibility to store ions during a full PS magnetic cycle. Storing ion bunches in the SPS, rather than in the PS, before acceleration and injection into the decay ring results in an additional gain due to the longer half life of the ions at the higher SPS injection energy. The maximum annual rate of neutrinos with 23 accumulated ECR bunches and 10 bunches stored in the SPS is $1.6\cdot10^{17}$ neutrinos for a year of 10^{7} seconds. This is four times better than the base-line scenario and less than a factor of 7 below the target value of $1\cdot10^{18}$ neutrinos. Possible improvement of the production rate could, in combination with an accumulator ring, make it possible to reach the target.

CONCLUSIONS

The study has shown that an accumulation ring equipped with fast electron cooling before the RCS could increase the annual rate of (anti-)neutrinos from a beta-beam facility with a factor of four. Still further increases in the number of ^{18}Ne ions stored are however needed to achieve the neutrino rate required by the proposed experiments.

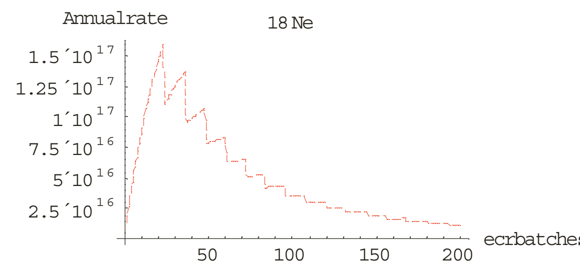

Figure 6: The annual rate of neutrinos along one straight section of the decay ring as a function of number of pulses accumulated in the accumulator ring. A total of ten bunches from the accumulator ring is stored in the SPS before further acceleration and injection into the decay ring. The discontinuities in the curve are due to a requirement that the PS and SPS cycle time must be a multiple of 1.2 seconds.

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