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Accumulation in a ring at low energy for the beta-beam

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Introduction

In the first study of a Beta-beam facility at CERN [1] a choice was made for ^{6}He and ^{18}Ne as suitable isotopes to generate an electron (anti-) neutrino beam. An alternative to ^{18}Ne is ^{19}Ne which is closer to stability and easier to produce. However, the half life of ^{19}Ne is a factor of ten larger, so a high number of stored ions is needed to reach the required annual rate of neutrinos. This is a major problem as the present choice of isotopes already requires operation close to the tune shift and space charge limits of the existing PS and SPS accelerators. An additional limitation might be the Intra-Beam Scattering (IBS) in the coasting bunched beam during accumulation stages in the PS and/or SPS and during the storage in the decay ring. However, the long half life also opens the possibility to accumulate ions at low energy before the main accelerator chain. This, together with the better production yields, will increase the annual rate for neutrinos at the end of the straight section, and it can bring the beta-beam facility closer to the high set goals of oscillation physicists [2] as well as add some operational margin.

Scenario

To simplify comparison we have chosen Version 2 of the baseline scenario [3] as a starting point. The RCS (after the linac at 100 MeV/u) is modified to include an electron cooler in a straight section and the possibility to store ions at injection energy for long times. The beam is injected with classical multi-turn injection during continuous electron cooling to permit stacking of several pulses from the ECR before further acceleration of the accumulated ions. The accelerator chain after the accumulation ring has been kept identical to Version 2. We have compared two options for the intermediate storage of bunches, the first option with storage of up to 20 bunches in the PS (Version 2) and the second with storage of the 20 bunches one by one in the SPS.

Cooling and Accumulation

The ions are injected into the cooler and accumulator ring which would replace the RCS or be a modification of it. For convenience, we still call it the RCS. The ions in this ring are continuously cooled by an electron cooler. The cooling compresses the beam in all dimensions in phase space, which makes it possible to inject more pulses from the linac into the ring. If the RCS injection energy is kept at 100 MeV/u, the cooler voltage needs to be 55 kV. Considering only the electron cooling, it might be advantageous to inject the ions in RCS at a lower energy. The required cooling times has to be of the same order as the time between the injected beam pulses, i.e. 0.1 s, which seems to be achievable with an electron current of 1-2 A, but this has to be further investigated. It might be difficult to obtain this short cooling time transversally and higher electron current might be needed as well as special arrangements, such as a hollow electron beam, which is used in the new LEIR cooler.

After each period of accumulation the ions are accelerated in the RCS and then stored either in PS or in SPS while another accumulation period starts in the RCS. 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.

Also for ions with shorter half lives the intensity can be increased by accumulating them in RCS, but of course much fewer pulses can be accumulated in such a case before the intensity is saturated. As a rule-of-thumb the intensity levels off after about three half-lives.

Results ^{19}Ne

The (anti-) neutrino annual rate is the figure of merit for the Beta-beam facility. In figure 1 the annual rate is plotted as a function of number of accumulated ECR bunches, with the exception of production rate and the gamma of the decay ring all other input data are taken from the published Version 2 of the beta-beam facility. The gamma for the decay ring has been set to 150 to compensate for the lower Q-value of ^{19}Ne (compared to ^{18}Ne). The production rate for ^{19}Ne has been assumed to be a factor of 20 above the production rate for ^{18}Ne [4].

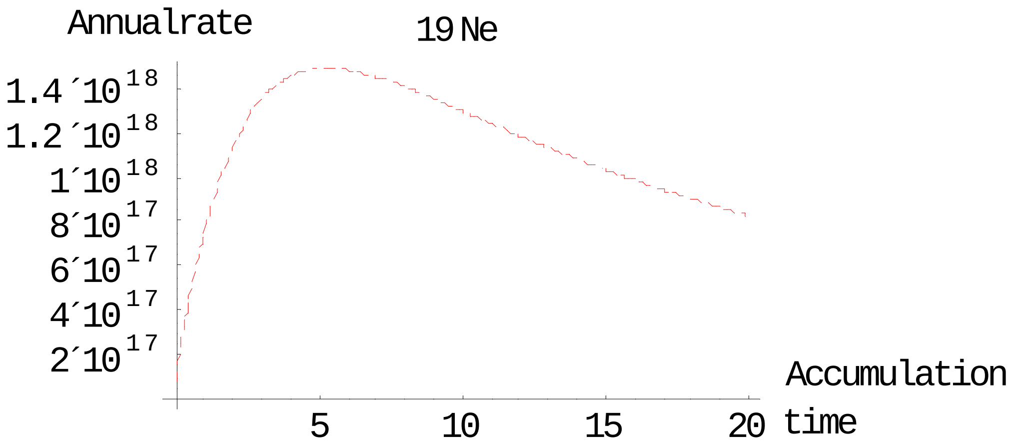

Figure 1. The annual neutrino rate as a function of number of ECR bunches accumulated before the RCS. The maximum annual rate for this version of the beta-beam facility is reached for 5.5 seconds accumulation (corresponding to 55 ECR bunches injected) before the RCS. All other parameters are taken from Version 2 of

the beta-beam design study [3] and consequently 20 bunches are stored in the PS before acceleration in SPS and injection into the decay ring.

In table 1 the number of ions in each stage of the facility is given for the optimum solution of 5.5 seconds accumulation (cooresponding to 55 ECR bunches injected) before the RCS. All other parameters are taken from Version 2 of the beta-beam design study [3] and consequently 20 bunches are stored in the PS before acceleration in SPS and injection into the decay ring.

Source rate	1.6×10^{13}
ECR	4.67×10^{11}
RCS accu	1.17×10^{13}
RCS inj	1.17×10^{13}
RCS	1.16×10^{13}
PS inj	1.03×10^{14}
PS	1.02×10^{14}
SPS	1.02×10^{14}
Decay Ring	1.57×10^{15}

Table 1: Number of ions for the scenario in figure 1 for each stage of the facility for 55 ECR bunches accumulated before the RCS.

For the optimum value of 55 ECR bunches, accumulation in the RCS will require a long waiting time for the PS at 1124 MeV/u with a time separation of 5.5 second between injected pulses. This opens the possibility of storing the ions in the SPS (at injection energy) rather than in the PS. The annual rate as a function of number of ECR bunches is shown in figure 2 and the number of ions in each stage of the facility is given in table 2 for 120 ECR bunches. To keep the duty factor the same as for Version 2, 20 bunches are accumulated in the SPS.

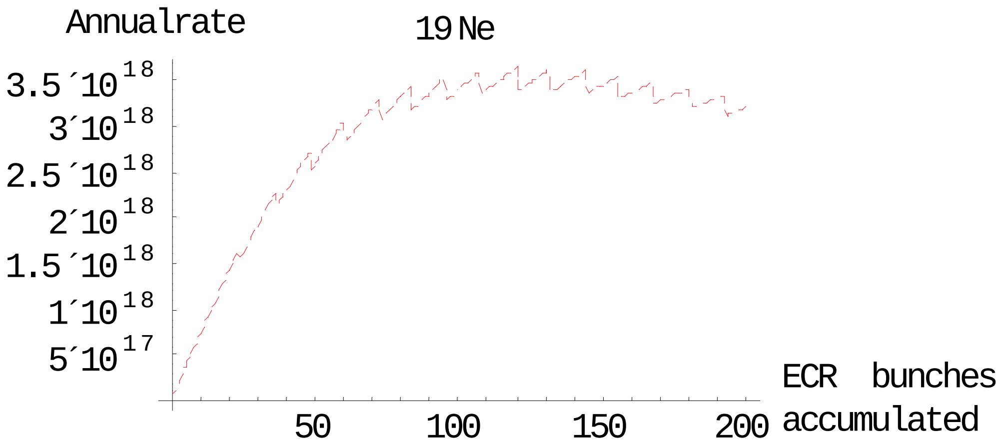

Figure 2: The annual rate of neutrinos as a function of number of ECR bunches accumulated before the RCS and further acceleration. For this version of the beta-beam facility 20 bunches of ions are stored in the SPS (rather than in the PS as in Version 2 [3]) at injection energy before acceleration and injection into the decay ring.

Source rate	1.6´ 10^{13}
ECR	4.67´ 10^{11}
RCS accu	2.28´ 10^{13}
RCS inj	2.28´ 10^{13}
RCS	2.27´ 10^{13}
PS inj	2.27´ 10^{13}
PS	2.26´ 10^{13}
SPS	3.37´ 10^{14}
Decay Ring	3.92´ 10^{15}

Table 2: Number of ions for the scenario in figure 2 for each stage of the facility for 120 ECR bunches accumulated before acceleration in the RCS. A total of 20 bunches are stored in the SPS at injection energy before acceleration and transfer to the decay ring.

Gamma dependence of the annual rate

The gamma dependency of the annual rate for the set of parameters used to generate table 1 and 2 is shown in figure 3.

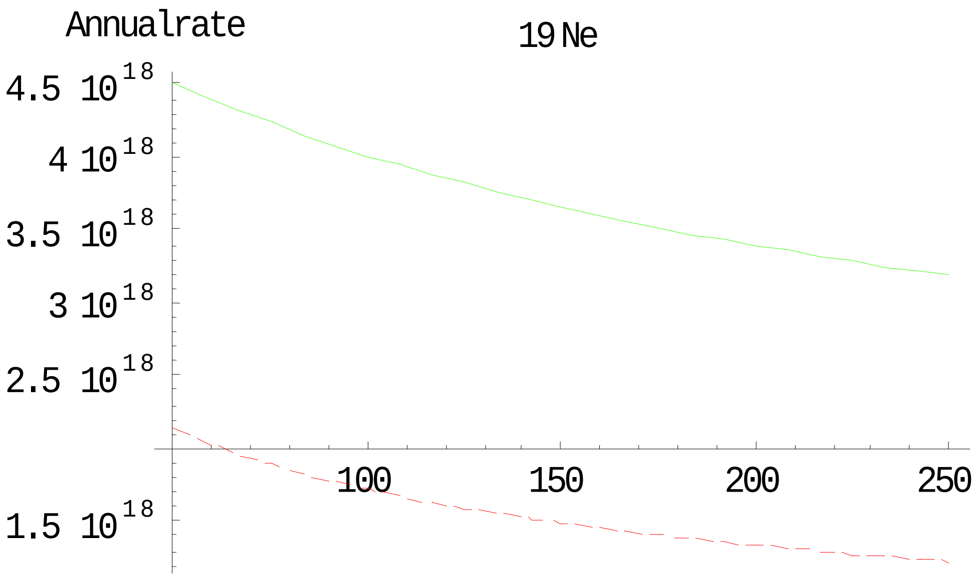

Figure 3: The annual neutrino rate as a function of gamma (decay ring). The dashed red curve towards the bottom of the graph shows the gamma dependence for intermediate storage is the PS (all parameters except gamma are identical to table 1) and the green curve towards the top shows the dependence for storage in the SPS (all parameters except gamma are identical to table 2).

Results for other isotopes

Some gain can be also be made for the original isotopes, ^{6}He and ^{18}Ne, with an accumulation stage before the decay ring. In table 3 the number of ^{6}He ions for each stage of the facility for an annual rate of $5.5\ 10^{18}$ anti-neutrinos is given and in table 4 the number of 18Ne ions for each stage is given for annual rate of $1.6\ 10^{17}$ neutrinos.

Source rate	2.´ 10^{13}
ECR	1.87´ 10^{12}
RCS accu	1.04´ 10^{13}
RCS inj	1.04´ 10^{13}
RCS	1.01´ 10^{13}
PS inj	1.01´ 10^{13}
PS	8.61´ 10^{12}
SPS	2.75´ 10^{13}
Decay Ring	1.9´ 10^{14}

Table 3: Number of ions for an optimized scenario for ^{6}He with 23 ECR batches accumulated in the RCS and a total of only 5 bunches stored in the SPS before acceleration and ejection to the decay ring for each stage of the facility. This scenario results in an annual rate for antineutrinos of $5.5\ 10^{18}$.

Source rate	$8. \times 10^{11}$
ECR	2.29×10^{10}
RCS accu	1.8×10^{11}
RCS inj	1.8×10^{11}
RCS	1.77×10^{11}
PS inj	1.77×10^{11}
PS	1.69×10^{11}
SPS	1.27×10^{12}
Decay Ring	1.12×10^{13}

Table 4: Number of ions for each stage of the facility for an optimized scenario for ^{18}Ne with 23 ECR batches accumulated in the RCS and only 10 bunches stored in the SPS before acceleration and ejection to the decay ring. This scenario results in an annual rate for antineutrinos of $1.6\ 10^{17}$.

Conclusions

The study has shown that an accumulation stage before the RCS is a powerful tool to boost the annual rate of (anti-)neutrinos from a Beta-beam facility, in particular for longer lived isotopes such as ^{19}Ne. However, the resulting large numbers of ions in the subsequent accelerator chain is a problem considering the known space charge and tune shift limits of the PS and SPS. Still, considering possible future improvements or replacement of the PS and the possibility to enhance the annual rate also for the “traditional” Beta-beam isotopes we propose to pursue this study.

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References

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