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Possible ways of increasing the number of (anti-) neutrinos from the EURISOL beta-beam facility

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Introduction

In the note on Parameter and Intensity Values (Version 1, April 2005) [1] for the EURISOL beta-beam facility the accelerator complex is based on the use of the existing PS and SPS accelerators at CERN.

I will in this note explore different possibilities to increase the rate compared to the baseline scenario described in ref. [1]. The results are shown as trend curves for the annual rate of neutrino along one of the straight sections in the decay ring. Trend curves can help identify the right parameter space for a machine design but they do not on themselves guarantee that a realistic solution for machine design can be found. The work has been done respecting the major constraints of using the existing PS and SPS. In addition, I have also limited myself to use of the existing decay ring design by Jacques Payet and Atoine Chance even though I have assumed that the γ can be changed without major changes. For the stacking I have assumed that we can merge 15 ^{6}He bunches and 40 ^{18}Ne incoming bunches in the decay ring without major losses. The situation is better for ^{18}Ne which due to a more advantageous mass-to-charge ratio will see an almost three times larger acceptance of the decay ring bunch permitting 40 merges [2]. All parameters for the EURISOL DS baseline in May 2005 are documented in the appendix of ref. [1].

Annual rate

For the purpose of this note the target values for the annual rate of neutrinos out of the beta-beam decay ring are taken as 2.9×10^{18} antineutrinos from ^{6}He and 1.1 10^{18} neutrinos from ^{18}Ne for a canonical year of 10^{7} s. This annual rate origins from [3,4] where it was also assumed that 6He and 18Ne could be run in parallel in the same storage ring. This would have resulted in a total rate over 10 years running of 29×10^{18} antineutrinos from ^{6}He and 11 10^{18} neutrinos from ^{18}Ne. For the EURISOL beta-beam design study it has been decided to not consider the parallel running as an option. Consequently, the total rate for 10 years running would for the given annual rate be a factor of two lower than in [3,4].

The annual rate along one straight section of the decay ring can be expressed as,

$$Annual\_rate = \left(1 - 2^{-\left(\frac{mergesratio \times spsrepetitiontime}{\gamma_{top} t_{half}}\right)}\right) \times \frac{spsout \times straightfrac}{spsrepetiontime} \times 10^{7}$$

where the *mergesratio* is the number of merges that can be done in the decay ring without major losses from the process itself, *spsrepetitiontime* is the period for the fills in the decay ring, γ_{top} the γ factor of the decay ring, t_{half} the half life at rest for the ions, *spsou*t the total number of ions injected into the decay ring for each fill and *straightfraction* the fraction of the decay ring length for the straight section generating the neutrino beam.

Ion production

The production of ^{6}He and ^{18}Ne was investigated in ref. [5] in 2001. To reach the nominal annual rate without any changes to the baseline scenario described in note [1] the production would have to be increased. In table 1 the assumed possible production is compared to a theoretical required production.

	Nominal production rate from ref. [5]	Required production rate	Missing factor
6He	2 10^13	3.3 10^13	1.64
18Ne	8 10^11	2.1 10^13	26.25

Table 1

The assumed possible production is compared to a theoretical required production.

For the theoretically required production rate the number of ^{6}He and ^{18}Ne ions in each stage of the beta-beam base-line design can be calculated using the intensities.nb notebook from ref [1] and 40 merges in the decay ring for ^{18}Ne [2].

6He

Source rate	3.28×10^{13}
ECR	1.92×10^{12}
RCS inj	9.55×10^{11}
RCS	9.36×10^{11}
PS inj	1.12×10^{13}
PS	9.45×10^{12}
SPS	8.92×10^{12}
Decay Ring	9.53×10^{13}

18Ne

Source rate	2.1×10^{13}
ECR	3.73×10^{11}
RCS inj	1.86×10^{11}
RCS	1.85×10^{11}
PS inj	2.65×10^{12}
PS	2.51×10^{12}
SPS	2.48×10^{12}
Decay Ring	7.28×10^{13}

Gamma dependence

The annual rate will depend on the γ of the decay ring due to the required acceleration time in the SPS and the increased life time of the decay ring. For given rf voltage, the longitudinal acceptance scales as the square root of γ (neglecting minor η and relativistic β dependences). This has in Mathematica notation been included as:

```
Clear[mergesratio];
(* 18Ne: merges=40 and 6He: merges=15 *)
mergesratio := merges Sqrt[topgamma/100]
```

The acceleration time in the SPS has a minimum length depending on hardware limitations and is also increasing in steps of 1.2 seconds due to the basic timing period of the CERN accelerator complex. In figure 1 and figure 2 the γ dependence of ^{18}Ne and ^{6}He is shown respectively. The maximum γ that can be reached for ^{6}He is 150 and for ^{18}Ne 250.

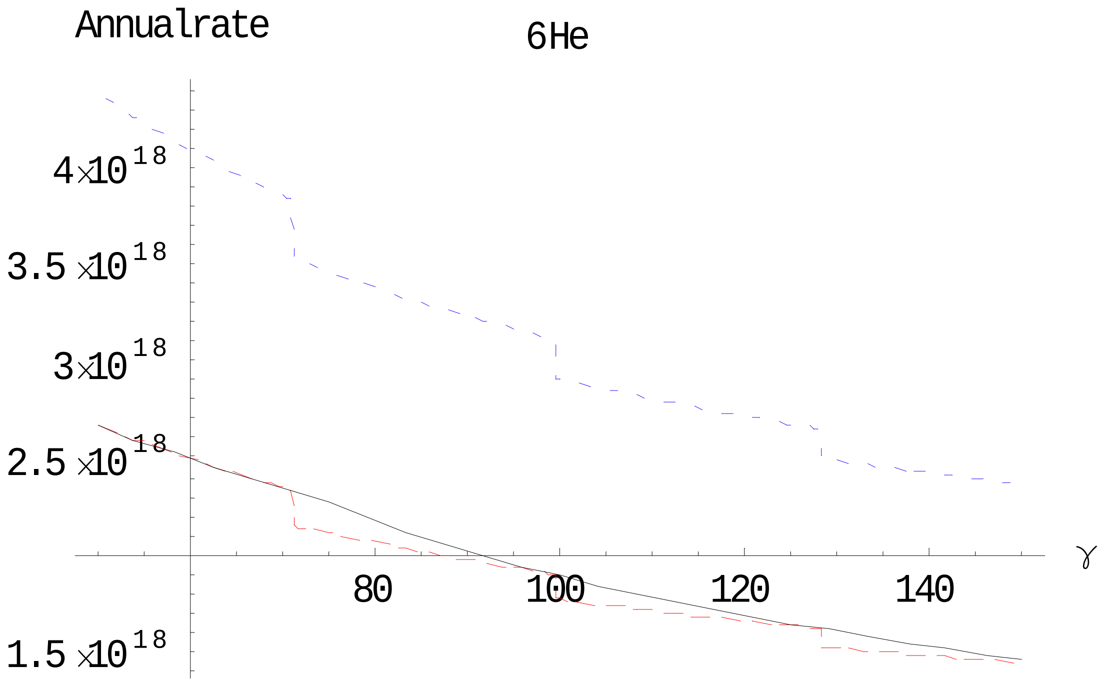

Figure1: The annual rate of anti-neutrinos from 6He as a function of γ. The red dashed line shows the annual rate with the given source rate respecting a basic period of 1.2 seconds of the CERN accelerator complex. The solid line shows the same dependence

but with a “smooth” choice of acceleration time for PS and SPS. The top blue dotted curve shows the γ dependence for 6He with the annual rate at γ=100 taken as the target value of 2.9 10^{18} anti-neutrinos per year.

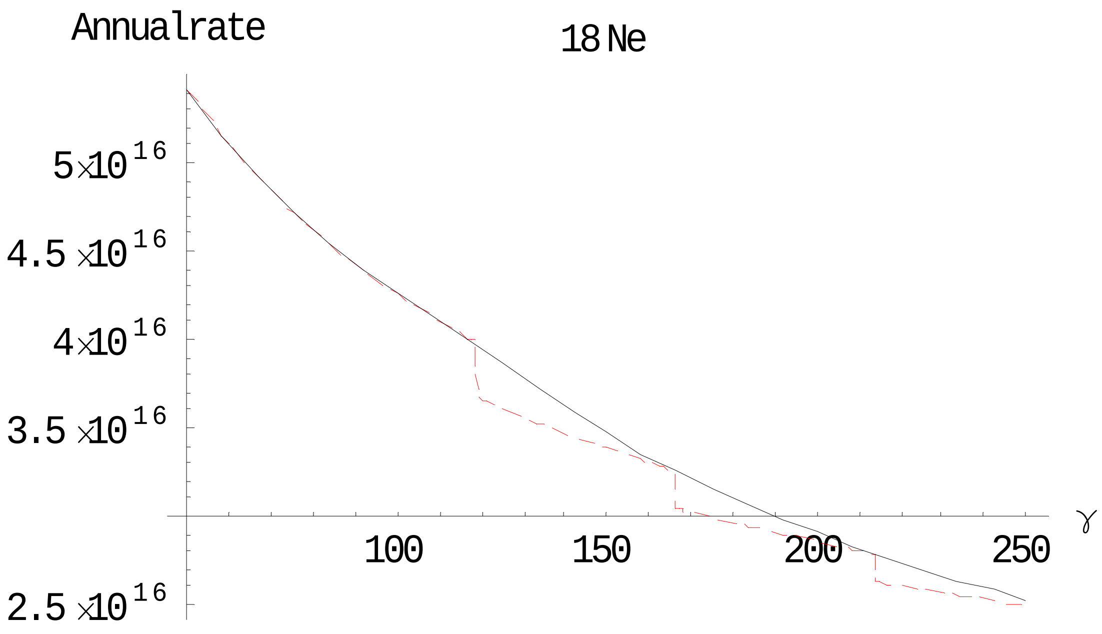

Figure2: The annual rate of neutrinos from ^{18}Ne as a function of γ. The red dashed line shows the annual rate with the given source rate respecting a basic period of 1.2 seconds of the CERN accelerator complex. The solid line shows the same dependence but with a “smooth” choice of acceleration time for PS and SPS.

Duty cycle dependence

At least in theory, the available longitudinal acceptance for stacking in the decay ring can be increased by increasing the number of bunches in the decay ring. This will increase the duty cycle as the duty cycle is set by the total length in time of all bunches in the decay ring divided by the revolution time.

The present limits of 15 merges for ^{6}He and 40 merges for ^{18}Ne is set by the available longitudinal emittance in the baseline design of ref. [1,2]. For both ^{6}He and ^{18}Ne this will truncate the stacking well before decay rate equals the stacking rate. In the formula for the annual rate the first factor is the result of this truncation. The nominal duty cycle in the beta-beam baseline is 2.2 10^{-3} for 8 bunches (50 ns total length) of either ^{6}He or ^{18}Ne at a Lorenz γ factor of 100. Figure 3 and 4 shows the annual rate as a function of number of bunches in the decay ring. All other parameters have been taken from the baseline design [1,2]. The duty cycle can be estimated for the given range of gammas in this note as

$$Dutyfactor = \frac{N_{bunches}}{8} \times 0.0022$$

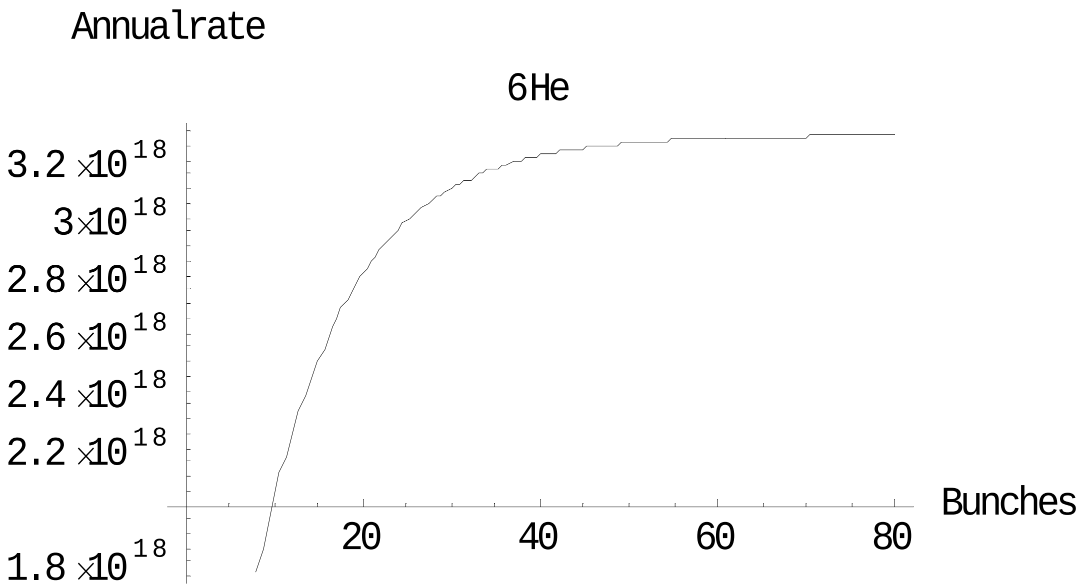

Figure 3: The annual rate of anti-neutrinos from the decay of ^{6}He as a function of number of bunches. The curve starts to the left with 8 bunches at the nominal duty cycle of 2.2 10^{-3} and saturates when the decay rate equals the stacking rate.

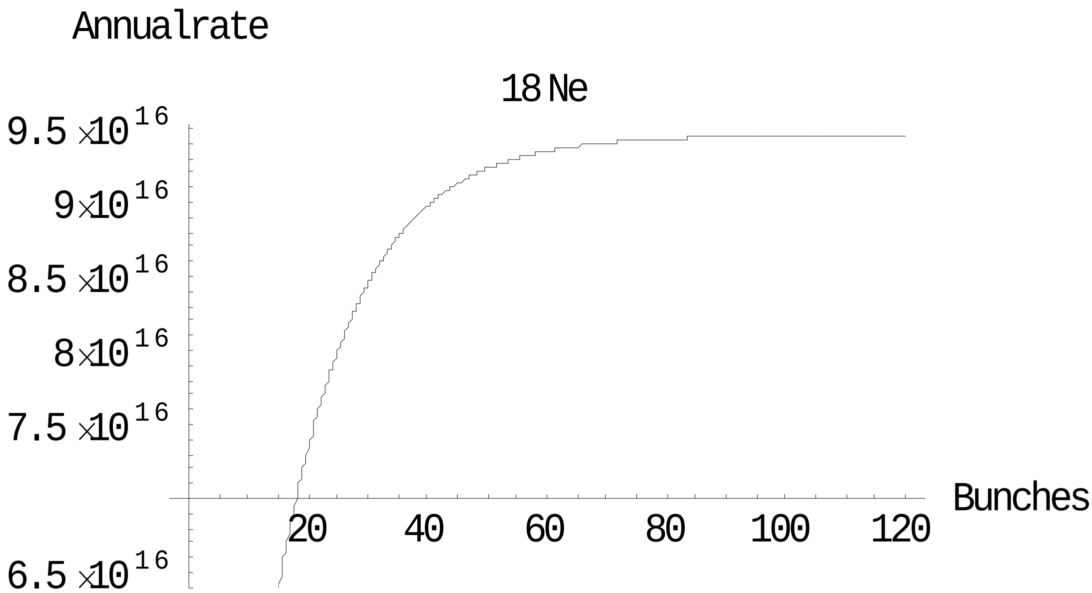

Figure 4: The annual rate of anti-neutrinos from the decay of ^{18}Ne as a function of number of bunches. The curve starts to the left with 8 bunches at the nominal duty cycle of 2.2 10^{-3} and saturates when the decay rate equals the stacking rate.

Accumulation time

In the beta-beam base-line [1] the ions are produced for one second and thereafter accelerate during several seconds to a γ of 100. During the acceleration no ions are produced. In theory, ions could be produced continuously as long as they can be stored while waiting for acceleration. There is optimum set by the life-time of the ion and the required acceleration time as can be seen in the trend curves in figure 5 and 6. The accumulation is in these calculations done at PS injection energy in a new radiation hard and separate storage ring. The storage ring will require a cooling system to reduce the longitudinal emittance of the stored ions. At PS injection the total longitudinal emittance of the ions must not exceed the emittance of the baseline beam to avoid setting new constraints on the following stages. In particular, it is very important for the stacking process. It would be more efficient to store the ions at a higher energy (life-time) but with the present limit on the PS acceleration time this can not be efficiently explored.

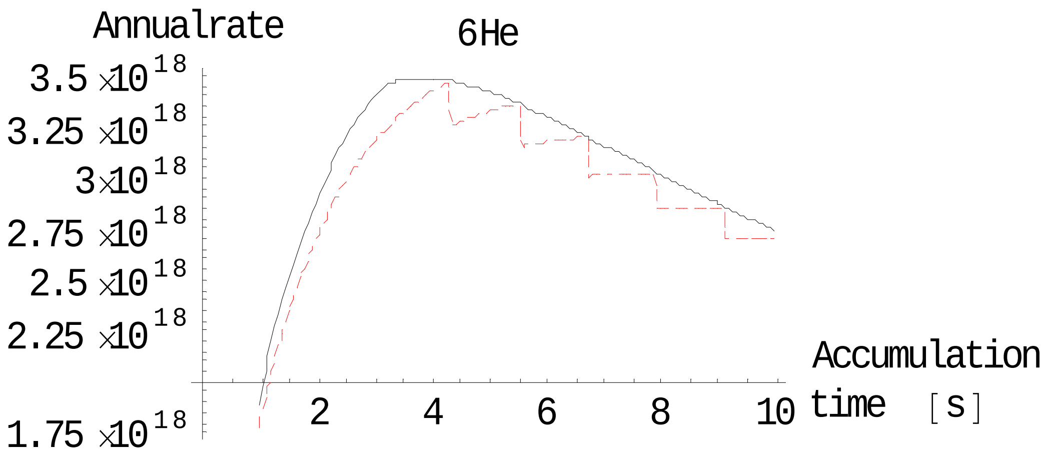

Figure 5: The annual rate of anti-neutrinos from ^{6}He as a function of the accumulation time at PS injection energy. The red dashed line shows the annual rate respecting a basic period of 1.2 seconds of the CERN accelerator complex. The solid line shows the same dependence but with a “smooth” choice of acceleration time for PS and SPS. All other parameters have been taken from the baseline design [1,2]

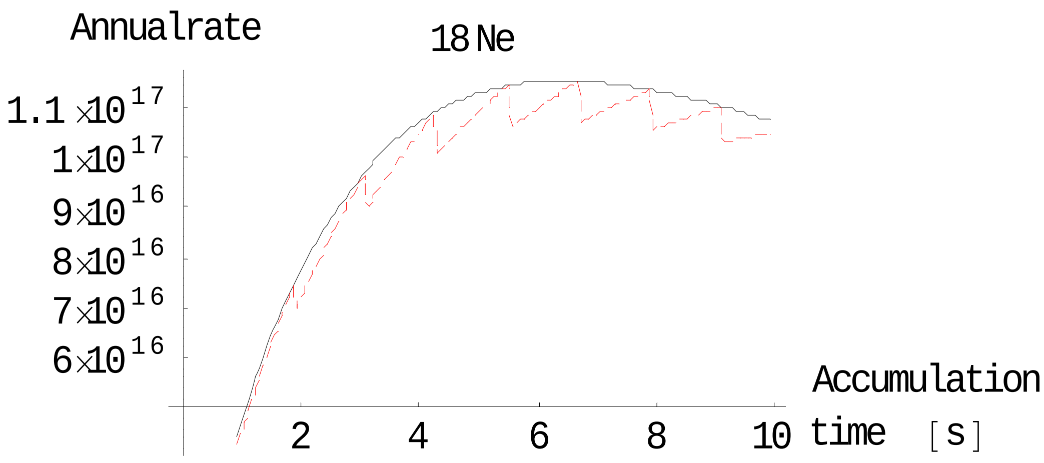

Figure 6: The annual rate of neutrinos from ^{18}Ne as a function of the accumulation time at PS injection energy. The red dashed line shows the annual rate respecting a basic period of 1.2 seconds of the CERN accelerator complex. The solid line shows the same dependence but with a “smooth” choice of acceleration time for PS and SPS. All other parameters have been taken from the baseline design [1,2]

Combining a higher gamma with a higher duty cycle

The duty cycle of the beta-beam facility has to be low to suppress the background in the detector. At a higher γ this constraint is less severe. The trend curves in figure 7 and 8 show the annual rate as a function of γ for three different duty-cycles, 2.2 10^{-3}, 4.4 10^{-3} and 6.6 10^{-3}. The blue horizontal line shows the annual rate of the baseline [1] facility at a γ of 100.

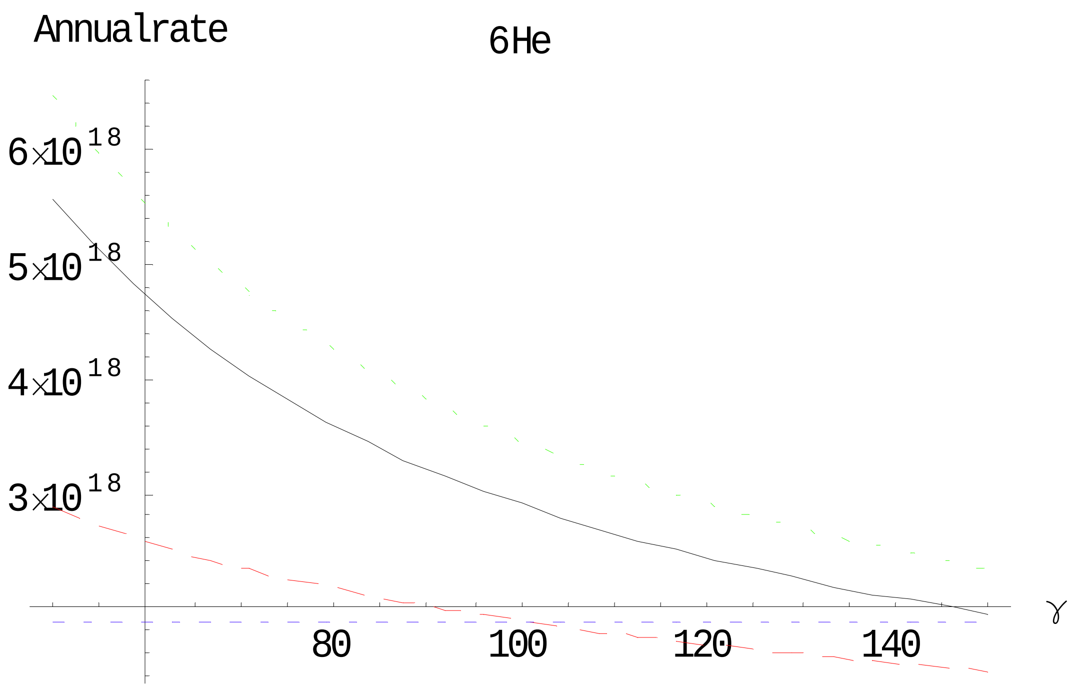

Figure 7: The annual rate of anti-neutrinos from 6He as a function of γ for three different duty cycles. The lower red dashed line is for the nominal duty cycle [1] of 2.2 10^{-3}, the solid middle line for a duty cycle of 4.4 10^{-3} and the green dotted line for a duty cycle of 6.5 10^{-3}. The blue dashed horizontal line shows the annual rate of the baseline facility [1] at γ=100.

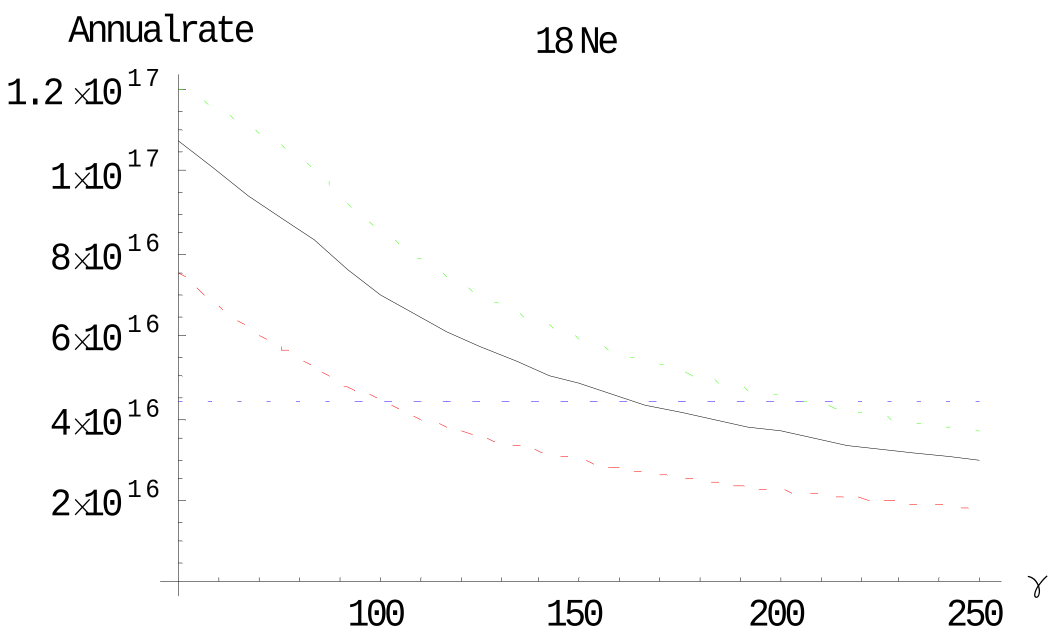

Figure 8: The annual rate of neutrinos from 18Ne as a function of γ for three different duty cycles. The lower red dashed line is for the nominal duty cycle [1] of 2.2 10^{-3}, the solid middle line for a duty cycle of 4.4 10^{-3} and the green dotted line for a duty cycle of 6.5 10^{-3}. The blue dotted line shows the annual rate of the baseline facility [1] at γ=100.

Charge state from ECR

The biggest efficiency loss in the baseline design [1] for ^{18}Ne is after the ECR source were only one charge state of ^{18}Ne can be used for further acceleration. A brute force method to avoid this loss would be to build 3 linacs for parallel acceleration of ions up to 10 MeV/u, strip the ions and funnel them together for further acceleration. Any proposal for a more elegant and less costly solution would be most welcome.

Conclusions

The work demonstrates that the annual rate at a beta-beam facility can be increased compared to the baseline design and still make use of the existing accelerator infrastructure at CERN. The physics reach should now be studied for each of the options so that a common set of parameters for the beta-beam can be agreed upon.

A "best case" scenario for a beta-beam facility at a γ of 100 optimizing on the annual rate would for 6He be and accumulation time in the PS of 4.3125 seconds and a SPS repetition time of 6 seconds at the baseline duty cycle and with the baseline ion production rate. The annual rate could in this case reach 3.45 10^{18} decays in the straight section with 1.13 10^{14} ions in the decay ring.

The number of ^{6}He ions in the different stages of the baseline would be

Source rate	$2.\times10^{13}$
ECR	1.17×10^{12}
RCS inj	5.82×10^{11}
RCS	5.7×10^{11}
PS inj	1.33×10^{13}
PS	1.12×10^{13}
SPS	1.06×10^{13}
Decay Ring	1.13×10^{14}

A "best case" scenario for a beta-beam facility at a γ of 100 optimizing on the annual rate would for ^{18}Ne be and accumulation time in the PS of 5.5625 seconds, a SPS repetition time of 7.2 seconds, three charge states accelerated from the ECR source at the baseline duty cycle and with the baseline ion production rate. The annual rate could in this case reach 3.43 10^{17} decays in the straight section with 2.23 10^{13} ions in the decay ring.

The number of ^{18}Ne ions in the different stages of the baseline would be

Source rate	$8. \times 10^{11}$
ECR	4.27×10^{10}
RCS inj	2.13×10^{10}
RCS	2.11×10^{10}
PS inj	1.05×10^{12}
PS	9.96×10^{11}
SPS	9.83×10^{11}
Decay Ring	2.23×10^{13}

Acknowledgements

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References

[1] M. Benedikt, S. Hancock and M. Lindroos, The EURISOL Beta-beam Facility Parameter and Intensity Values, Version 1, April 2005

[2] S. Hancock, private communication, May, 2005

[3] J. Bouchez, M. Lindroos and M. Mezzetto, Beta-beams: Present design and expected performance, In the proceedings of Nufact 03, New York, 2003 (IOP)

[4] J. Burguet-Castell, D. Casper, J.J. Gomez-Cadenas, P.Hernandez, F.Sanchez Neutrino oscillation physics with a higher gamma beta-beam, hep-ph/0312068

[5] B. Autin, M. Benedikt, M. Grieser, S. Hancock, H. Haseroth, A. Jansson, U. Köster, M. Lindroos, S. Russenschuck and F. Wenander, "The acceleration and storage of radioactive ions for a neutrino factory", PS/OP/Note 2002-181.