EURISOL DS/TASK12/TN-05-01
1 June 2005

The EURISOL Beta-beam Facility

Parameter and Intensity Values, Version 1, April 2005

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Abstract

The flux out of the Beta-beam facility [1] is determined by the number of ions that can be produced, by the number remaining after acceleration and by the total accumulated in the decay ring. We present a "bottom-up" analysis of the ion intensities along the accelerator chain and of the neutrino and antineutrino flux out of the decay ring, starting with the rate at which atoms are transported out of the target.

Beta-beam baseline

A full description of the Beta-beam can be found in e.g. [2,3]. Here, we only repeat the main elements of the baseline scenario, with emphasis on the actual parameters used for the intensity calculations. This note documents intensities and certain parameters for the EURISOL Beta-beam conceptual design as it stands at the time of the first Task Meeting (14 April 2005). The design will evolve with the objective of reaching the target values set by the user community. All such developments will be documented in future EURISOL DS Beta-beam notes.

Production

In the Beta-beam baseline it is assumed that we can produce and transport 2×10^{13} ^{6}He atoms/s and 8×10^{11} ^{18}Ne atoms/s out of the target with a proton driver beam current of 100 μA impinging on the target at 2.2 GeV. These numbers are based on an evaluation of suitable isotopes and their production rates at ISOL facilities and have been presented as part of the Beta-beam contribution to NuFact02. The full write-up of this presentation could not be published as part of the proceedings, but it exists as a CERN internal note [4].

ECR source

Efficient bunching and stripping of the high intensity beam are achieved using a high-frequency ECR source [5]. We assume the efficiency of such a source to be 100% for ^{6}He, with all ions being extracted in the 2+ charge state, but only 30% for ^{18}Ne ions due to only one (e.g., 6+) of several charge states being extracted. We further assume that the ECR operates at 16 Hz with an accumulation time of 60 ms, that the source is at a potential of 50 kV relative to the linac, and that the ions are ejected in 50 μs long bunches with a physical transverse emittance of around 50 π.mm.mrad.

Linac and rapid cycling synchrotron

The linac accelerates the ions to 100 MeV/nucleon, after which they are multi-turn injected into a rapid cycling synchrotron (RCS). We assume an injection efficiency of

50%. Both ion species are accelerated to a magnetic rigidity of 8 Tm in a time dictated by the 16 Hz repetition rate of the ECR source. Each cycle provides a single bunch.

PS accumulation and acceleration to high energy

The PS waits for 16 shots from the RCS then accelerates the 16 bunches to a magnetic rigidity of 86.7 Tm. Merging takes place at top energy to form 8 bunches that are ejected in a single turn to the SPS. There they are accelerated to γ=100 and ejected, again by single-turn extraction, into the decay ring. The cycle time of the SPS is a multiple of the 1.2 s basic period of the CERN machines. The extra acceleration required for the ^{6}He results in a 6 s cycle compared with only 3.6 s for ^{18}Ne.

Decay ring

The 8 incoming bunches are combined with the 8 circulating ones of the stack by an asymmetric merging process in the decay ring. The number of times this process can be repeated is constrained by the 1 eVs longitudinal emittance of each bunch delivered by the SPS. Simulations for ^{6}He show that such bunches can be stacked up to 15 times. The situation should be better for ^{18}Ne due a more advantageous charge-to-mass ratio, but the necessary simulations have not yet been performed and, therefore, the same merging factor is conservatively assumed.

The total duration (at its shortest) of the 8 bunches in the ^{6}He simulations is roughly 50 ns. Since the revolution period of the decay ring is 23 μs, this corresponds to a so-called duty cycle of around 2×10^{-3}.

The annual integrated flux of potentially useful neutrinos and antineutrinos emanating from the decay ring is linearly dependent on the relative length of the straight section that points towards the detector. This is taken to be 36% of the decay ring circumference [6].

Results

The parameters given in the Appendix to this note result in the following numbers of ions at each stage of the CERN Beta-beam facility. The decay losses are properly accounted for, but the transfer efficiencies between the different machines are assumed to be 100% except for the multi-turn injection into the RCS. The source rate is given (in atoms/s) at the entrance to the ECR, while the decay ring figure is the maximum number of stored ions immediately after injection from the SPS.

^{6}He:

Source rate	$2.\times10^{13}$
ECR	1.17×10^{12}
RCS inj	5.83×10^{11}
RCS	5.71×10^{11}
PS inj	6.85×10^{12}
PS	5.8×10^{12}
SPS	5.48×10^{12}
Decay Ring	5.88×10^{13}

^{18}Ne:

Source rate	$8.\times10^{11}$
ECR	1.42×10^{10}
RCS inj	7.1×10^{9}
RCS	7.04×10^{9}
PS inj	1.01×10^{11}
PS	9.58×10^{10}
SPS	9.45×10^{10}
Decay Ring	1.19×10^{12}

This corresponds to a total integrated flux in a ten-year run (5 years of ^{6}He plus 5 years of ^{18}Ne) of 8.82×10^{18} antineutrinos and 9.49×10^{16} neutrinos.

There is little consensus on target values for the integrated flux out of the decay ring, nor is γ=100 for both ion species well-established. However, the desired order of magnitude is 10^{18} decays in a canonical year of 10^{7} s [7]. (We do not consider running with ^{6}He and ^{18}Ne ions simultaneously.)

Conclusions

The integrated fluxes achievable in the present scenario have been evaluated in a consistent "bottom-up" approach. The results for neutrinos coming from the decay of ^{18}Ne do not match the expected order of magnitude.

References

[1] P. Zucchelli, "A novel concept for a neutrino factory: the beta-beam", Phys. Let. B, 532 (2002) 166-172.

[2] M. Benedikt, S. Hancock and M. Lindroos, "Baseline design for a beta-beam neutrino facility", in Proc. European Particle Accelerator Conf., Lucerne (2004).

[3] M. Lindroos and the beta-beam working group, "The acceleration and storage of radioactive ions for a beta-beam facility", in Proc. RNB-6, Argonne, 2003, Nuclear Physics A, 746 (2004) 361.

[4] 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.

[5] http://moriond.in2p3.fr/radio/radioprogramme.html

[6] A. Chancé and J. Payet, "Studies of the injection system in the decay ring of a beta-beam neutrino source", in Proc. Particle Accelerator Conf., Knoxville (2005).

[7] J. Bouchez, M. Lindroos and M. Mezzetto, "Beta-beams: present design and expected performances", in Proc. 5th International Workshop on Neutrino Factories and Superbeams, New York (2003).

Appendix

Mathematica package in text form:

```
Off[General::spell1];

c = 299792458;

(* All energies are in eV; "Tpern" = kinetic energy per nucleon. *)
setmachines := (
  bp = 1.2; (* 1.2s basic period. *)
  quantize[t_] := bp (IntegerPart[t/bp] +
Ceiling[FractionalPart[t/bp]]);
  ecrejTpern := 50 10^3 q/nnumber;
  ecraccumulationtime = 60 10^-3;
  rcsinjTpern = 100 10^6;
  rcsaccumulationtime = 50 10^-6;
  rcsefficiency = 0.5;
  bunchingtime = 5 10^-3;
  rcsaccelerationtime := (rcscycletime - bunchingtime)/2;
  rcsBrhomax = 8; (* 300MeV/nucleon 6He equivalent. *)
  rcscycletime = 1/16;
  rcsbatches = 16;
  psinjTpern := Sqrt[(rcsBrhomax c q/nnumber)^2 + Epern^2] - Epern;
  psaccumulationtime := (rcsbatches-1) rcscycletime;
  psaccelerationtime = 0.8;
  psBrhomax = 86.7;
  pscycletime := quantize[psaccumulationtime + 2.0 psaccelerationtime
+ 0.1];
  psbatches = 1;
  spsinjTpern := Sqrt[(psBrhomax c q/nnumber)^2 + Epern^2] - Epern;
  spsaccumulationtime := (psbatches-1) pscycletime;
  spsaccelerationtime := (topTpern - spsinjTpern) *
    nnumber/(q 100 10^9); (* 100GeV/s proton equivalent. *)
  topgamma = 100;
  topTpern := Epern (topgamma - 1);
  spscycletime := quantize[spsaccumulationtime + 1.5
spsaccelerationtime + 1.0];
  spsrepetitiontime := Max[pscycletime, spscycletime];
  straightfraction = 0.36;
)

set6He := (
  name = "6He"; nnumber = 6; q = 2;
  Erest = 5.606 10^9; (* Rest mass in eV/c^2. *)
  Epern := Erest/nnumber;
  thalf = 0.81; (* Half-life at rest. *)
  sourcerate = 2 10^13; (* Effective rate, includes 40% efficiency. *)
  ecrefficiency = 1;
  setmachines;
  mergesratio = 15;
)

set18Ne := (
  name = "18Ne"; nnumber = 18; q = 10;
  Erest = 16.767 10^9; (* Rest mass in eV/c^2. *)
  Epern := Erest/nnumber;
  thalf = 1.67; (* Half-life at rest. *)
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```
  sourcerate = 8 10^11; (* Effective rate, includes 40% efficiency. *)
  ecrefficiency = 0.3; (* Single charge state. *)
  setmachines;
  mergesratio = 15;
)

ecraccumulation := (ClearAll[n];
  gamma[t_] := 1 + ecrejTpern / Epern;
  decayrate[t_] := Log[2] n[t] / (gamma[t] thalf);
  eqns = {D[n[t], t] == sourcerate - decayrate[t], n[0]==0};
  n[t_] = ecrefficiency n[t] /. DSolve[eqns, n[t], t] //First;
  nout0 = n[ecraccumulationtime]
)

rcsbunching := (ClearAll[n];
  gamma[t_] := 1 + rcsinjTpern / Epern;
  decayrate[t_] := Log[2] n[t] / (gamma[t] thalf);
  eqns = {D[n[t], t] == -decayrate[t], n[0]==nout0};
  n[t_] = rcsefficiency n[t] /. DSolve[eqns, n[t], t] //First;
  nout1 = n[bunchingtime]
)

rcsacceleration := (ClearAll[n];
  rcsTpern[t_] := rcsinjTpern +
    (psinjTpern - rcsinjTpern) (1 - Cos[Pi t/rcsaccelerationtime])/2;
  gamma[t_] := 1 + rcsTpern[t] / Epern;
  decayrate[t_] := Log[2] n[t] / (gamma[t] thalf);
  eqns = {D[n[t], t] == -decayrate[t], n[0]==nout1};
  n[t_] = n[t] /. DSolve[eqns, n[t], t] //First;
  nout2 = n[rcsaccelerationtime]
)
rcsout := (ecraccumulation; rcsbunching; rcsacceleration)

psaccumulation := (ClearAll[n];
  gamma[t_] := 1 + psinjTpern / Epern;
  decayrate[t_] := Log[2] n[t] / (gamma[t] thalf);
  eqns = {D[n[t], t] == -decayrate[t], n[0]==nout2};
  nsinglebatch[t_] = n[t] /. DSolve[eqns, n[t], t] //First;
  n[t_] = Sum[UnitStep[t-t0] nsinglebatch[t-t0],
    {t0, 0,psaccumulationtime,rcscycletime}];
  nout3 = n[psaccumulationtime]
)

psacceleration := (ClearAll[n];
  psTpern[t_] := psinjTpern +
    (spsinjTpern - psinjTpern) t/psaccelerationtime;
  gamma[t_] := 1 + psTpern[t] / Epern;
  decayrate[t_] := Log[2] n[t] / (gamma[t] thalf);
  eqns = {D[n[t], t] == -decayrate[t], n[0]==nout3};
  n[t_] = n[t] /. DSolve[eqns, n[t], t] //First;
  nout4 = n[psaccelerationtime]
)
psout := (rcsout; psaccumulation; psacceleration)

spsaccumulation := (ClearAll[n];
  nout5 = nout4
)

spsacceleration := (ClearAll[n];
  spsTpern[t_] := spsinjTpern +
    (topTpern - spsinjTpern) t/spsaccelerationtime;
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```
  gamma[t_] := 1 + spsTpern[t] / Epern;
  decayrate[t_] := Log[2] n[t] / (gamma[t] thalf);
  eqns = {D[n[t], t] == -decayrate[t], n[0]==nout5};
  n[t_] = n[t] /. DSolve[eqns, n[t], t] //First;
  nout6 = n[spsaccelerationtime]
)
spsout := (psout; spsaccumulation; spsacceleration)

decayringaccumulation := (ClearAll[n];
  gamma[t_] := 1 + topTpern / Epern;
  decayrate[t_] := Log[2] n[t] / (gamma[t] thalf);
  eqns = {D[n[t], t] == -decayrate[t], n[0]==nout6};
  nsinglebatch[t_] = n[t] /. DSolve[eqns, n[t], t] //First;
  n[t_] = Sum[UnitStep[t-t0]
UnitStep[t0+mergesratio*spsrepetitiontime-t] *
    nsinglebatch[t-t0], {t0, 0,t,spsrepetitiontime}];
  nout7 = n[(mergesratio-1)spsrepetitiontime]
)
fullchain := (spsout; decayringaccumulation)

annualrate := (1 - 2^-(mergesratio spsrepetitiontime/(topgamma
thalf))) *
  spsout straightfraction 10^7/spsrepetitiontime
```