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Decay losses along the accelerator chain of the EURISOL Beta-beam baseline design

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Abstract

The Beta-beam is based on the acceleration and storage of radioactive ions. Due to the large number of ions required and their relatively short lifetime, beam losses due to decay are a major concern. This note presents an estimation of the decay losses for the Beta-beam along the accelerator chain that comprises the CERN PS and SPS machines. For illustration purposes, the power deposition in the accelerators is compared to the nominal CNGS proton operation.

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1 Introduction

The neutrino Beta-beam concept is based on the acceleration of radioactive ions, which emit neutrinos or anti-neutrinos due to beta-decay [1]. The Beta-beam task within the EURISOL design study (DS) [2] investigates the accelerator chain using part of the existing infrastructure at CERN.

Isotopes are produced by a primary proton beam impinging on a target. These drift into an ECR, where they are partly or fully stripped. Post-acceleration is done by a LINAC and an Rapid Cycling Synchrotron (RCS), which both need to be designed. Further acceleration is achieved using the existing PS and SPS machines. The isotopes are finally stored in a decay ring for the production of the desired neutrino beam. Details of the current scheme are described in Ref. [3].

One of the major issues of the accelerator chain are beam losses caused by particle decay. The beta-decay of unstable isotopes changes the charge-to-mass ratio resulting in a different magnetic rigidity, leading to beam loss. The demand for an unprecedented number of ions to be stored in the decay ring results in important losses during accumulation and acceleration. In view of using the existing PS and SPS machines, this is a big challenge as these machines are slow cycling, causing high decay loss especially at low gamma. This note takes into account only the beam losses due to radioactive decay computed for the baseline scenario of the Beta-beam [3]. The loss figures obtained are compared with the nominal CNGS operation for the purpose of illustration. Other beam losses (due to space charge, intra-beam scattering, beam transfer and handling) will add to the decay losses considered here.

2 Isotope decay and power loss

^{6}He and ^{18}Ne are the isotopes of choice for the Beta-beam. Their half-lives at rest are $t_{1/2}(^{6}He) = 0.81\,\mathrm{s}$ and $t_{1/2}(^{18}Ne) = 1.67\,\mathrm{s}$. The parent particle population as a function of time during accumulation, acceleration and storage decreases like

$$\frac{d}{dt}N(t) = -\frac{ln(2)}{t_{1/2}\,\gamma(t)}N(t) \tag{1}$$

where $\gamma(t)$ is the usual relativistic parameter. The decay products are ^{6}Li for ^{6}He and ^{18}F for ^{18}Ne, with a decay branching ratio of unity in both cases. With the ions fully stripped (atomic number A, charge Q, momentum p), the magnetic rigidity

$$B\rho = \frac{A}{Q}p \tag{2}$$

changes the charge-to-mass ratio by a factor 1.5 for the ^{6}He decay and by about 10% for the ^{18}Ne decay. This causes the daugther particles to be lost, more or less equally distributed over the circumference of the machine. For simplicity we assume the kinetic energy of the lost particles to be the contribution to the energy deposition in the surrounding machine: At high gamma the difference in total and kinetic energy of a particle is marginal. At low energies, the electromagnetic cascade is dominant. The kinetic energy of the particles lost from the beam will be deposited in the vicinity of the beam line, mainly in magnetic elements and shielding. The energy lost from the beam per cycle is calculated as

$$E_{loss/cycle} = \int^{t_{cycle}} \frac{dN}{dt} * T(t)\, dt \tag{3}$$

where T is the kinetic energy and t_{cycle} is the cycle time of the Beta-beam complex. A representative number, which can be compared with other accelerator cases, is the time-averaged power loss per unit circumference of the machine:

$$P_{loss}/l = \frac{E_{loss}/cycle}{t_{cycle} * circumference_{machine}} \tag{4}$$

Faced with the complications of accelerating radioactive ions, it is of particular interest to compare the decay losses with the well-known case of beam losses for proton acceleration. For comparison it is assumed that the total energy deposition caused by an ion with mass number A is similar to that of A single protons in the momentum range above $100\,\mathrm{MeV/u}$ [4]. This assumption is not valid when looking into the details (e.g., cascade profiles). Still, for total energy balance of particle loss and energy deposition, the above argument holds.

3 The cycle of accumulation and acceleration

The acceleration cycle for the Beta-beam baseline accelerator complex [3] is shown in Figure 1 for ^{6}He and in Figure 2 for ^{18}Ne. Source, post-accelerator and RCS are operated at $10\,\mathrm{Hz}$. 20 RCS bunches of either ^{6}He or ^{18}Ne are accumulated at injection energy in the PS over $1.9\,\mathrm{s}$. The beam is then accelerated in PS and SPS to $\gamma = 100$ for ^{6}He and ^{18}Ne. The magnet cycles of the RCS, PS and SPS are superimposed. The black, solid line indicates the repetition of post acceleration at $10\,\mathrm{Hz}$, followed by the acceleration of the accumulated bunches through the PS and the SPS. The advantageous charge-to-mass ratio of ^{18}Ne results in a shorter overall cycle: 20 new bunches are sent from the SPS to the decay ring every 6 seconds for ^{6}He and every 3.6 seconds for ^{18}Ne.

During the long accumulation in the PS at low gamma and the following acceleration at low gamma, the intensity of the bunches decreases remarkably. E.g.,

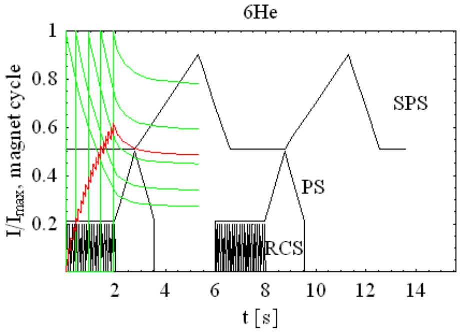

Figure 1: *Cycle of the Beta-beam complex accelerating ^{6}He. For illustration purposes the single bunch intensities (green) are indicated for the 1st, 5th, 10th, 15th and 20th bunch.*

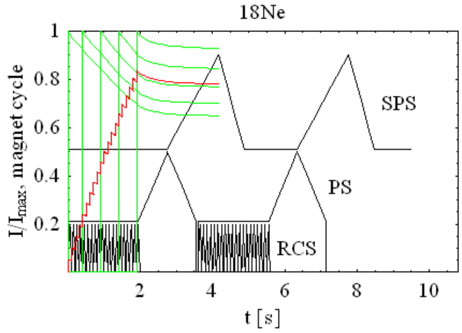

Figure 2: *cycle of the Beta-beam complex accelerating ^{18}Ne. For illustration purposes the single bunch intensities (green) are indicated for the 1st, 5th, 10th, 15th and 20th bunch.*

the first bunch injected into the PS has a remaining intensity at the end of the PS accumulation of about 35% for ^{6}He and of about 70% for ^{18}Ne (eq. 1). The bunches injected later remain with accordingly higher intensity at the end of PS accumulation. This is illustrated with green lines showing single bunch intensities. All intensities are normalized to the equivalent maximum intensity: a single bunch has its highest intensity just at the end of accumulation in the RCS. The total intensity is indicated by the red line, normalized to the total number of ions injected into the RCS taking into account the multiturn efficiency[1].

The bunches ejected from the SPS are merged with the already circulating bunches in the decay ring. To achieve bunches in the decay ring with more balanced intensities, one could permute the positions of the injected bunches in the PS from cycle to cycle. This scenario has not yet been studied in detail concerning machines requirements and timing. However, this would not change the scenario of decay losses presented here.

4 Beam losses

4.1 Decay losses of the Beta-beam

Figures 3 and 5 show the decay losses as a function of time. The figures here are based on a top-down evaluation of the particle intensities, which makes them

[1] $\mathrm{norm} = \mathrm{rcsbatches} * \mathrm{I}_{\mathrm{ECR\ out}}/\mathrm{batch} * \mathrm{rcsefficiency}$ [3]

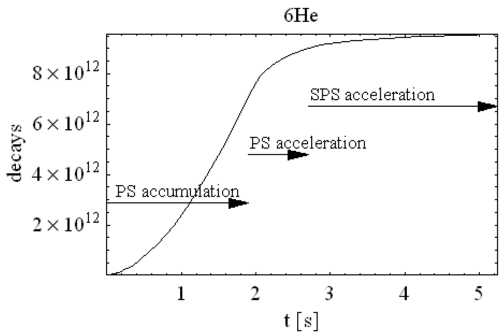

Figure 3: *Cumulative ^{6}He decays during acceleration. The major part occurs during accumulation and acceleration in the PS, which takes place in the time interval* $0 \leq t \leq 2.7\,\mathrm{s}$.

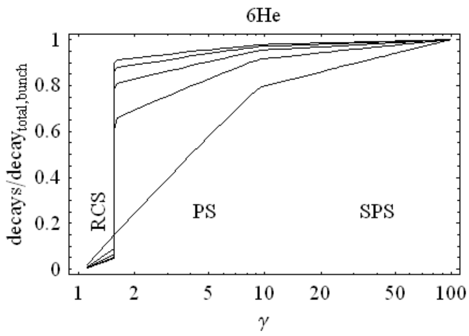

Figure 4: *Relative ^{6}He decays before entering the storage ring as a function of the relativistic gamma for five different bunches (top to bottom: 1st, 5th, 10th, 15th, 20th).*

different to the intensities given in Ref. [3]. The top-down approach is based on the assumption of the nominal rates of $2.9 * 10^{18}$ anti-neutrinos/year from ^{6}He decay or $1.1 * 10^{18}$ neutrinos from ^{18}Ne decay per straight section [10]. The top-down intensities in the notation of Ref. [3] are given in Table 1.

	^{6}He	^{18}Ne	unit
RCS inj	$9.26 * 10^{11}$	$2.73 * 10^{11}$	$\mathrm{ions/cycle_{RCS}}$
RCS out	$8.98 * 10^{11}$	$2.69 * 10^{11}$	$\mathrm{ions/cycle_{RCS}}$
PS inj	$1.12 * 10^{13}$	$4.53 * 10^{12}$	ions/cycle[2]
PS out	$9.53 * 10^{12}$	$4.31 * 10^{12}$	ions/cycle
SPS out	$9.0 * 10^{12}$	$4.26 * 10^{12}$	ions/cycle
Decay ring	$9.66 * 10^{13}$	$7.42 * 10^{13}$	ions[3]

Table 1: *Number of ions at each stage of the Beta-beam facility in the top-down approach.*

All decay losses in the PS amount to $\approx 90\%$ of the total decays up to injection into the decay ring for both isotope types. During the first $1.9\,\mathrm{s}$ the RCS is cycling at the same time as the PS is accumulating. The corresponding losses are displayed together in Figures 3 and 5. However, as the duration for which the beam

[2]at the end of accumulation
[3]stored ions, maximum just after merging

stays in the RCS is an order of magnitude smaller than in the PS, the majority of losses occurs in the PS, as indicated in Table 2.
Figure 4 and Figure 6 show the relative decay losses for single bunches. The PS operates in the gamma range [1.54;9.33] for ^{6}He and [2.21;15.5] for ^{18}Ne. The major part of the losses occur in the PS machine for both isotopes due to the long accumulation time of $\approx 2\,\mathrm{s}$.

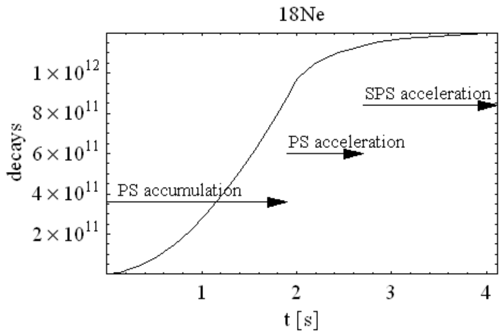

Figure 5: *Cumulative ^{18}Ne decays during acceleration. The picture is similar as the one of ^{6}He (Figure 3), but the total number of decays is almost one order of magnitude smaller.*

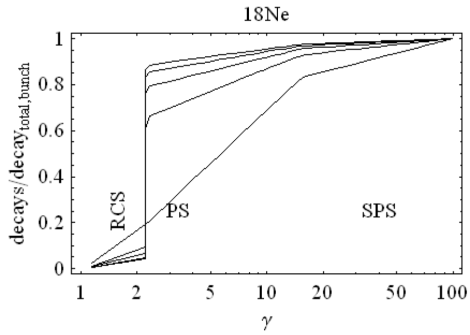

Figure 6: *Relative ^{18}Ne decays before entering the storage ring as a function of the relativistic gamma for five different bunches (top to bottom: 1st, 5th, 10th, 15th, 20th).*

loss [ions/s]	RCS	PS	SPS		Total
^{6}He	$0.1 * 10^{12}$	$1.4 * 10^{12}$	$0.09 * 10^{12}$		$1.59 * 10^{12}$
^{18}Ne	$0.2 * 10^{11}$	$3 * 10^{11}$	$0.2 * 10^{11}$		$3.3 * 10^{11}$

Table 2: *Ion losses due to particle decay during a Beta-beam cycle in the various machines. The table displays losses from the point of injection into the RCS, not taking into account the RCS injection inefficiency (50%) mentioned in [7], which is not a decay loss mechanism.*

4.2 Proton losses during CNGS operation

The nominal CNGS scenario foresees an annual total of $4.5 * 10^{19}$ protons on target [5]. Assuming the SPS delivers a beam of $4.4 * 10^{13}$ protons per cycle,

Machine / process	Intensity/cycle [protons]	Transmission	Losses/cycle [protons]
target T40	$4.40 * 10^{13}$		
to target (fast extraction)		$\approx$ 100 %	
SPS at 400 GeV	$4.40 * 10^{13}$		
SPS transition (21GeV)		92%	$1.9 * 10^{12}$
SPS injection (13GeV)		96%	$1.9 * 10^{12}$
TT2/TT10	$4.78 * 10^{13}$		
PS extraction (13 GeV)		90%	$5.3 * 10^{12}$
PS 13 GeV	$5.31 * 10^{13}$		
PS transition (6.1 GeV)		92%	$1.15 * 10^{12}$
PS injection (1.4 GeV)		94%	$1.15 * 10^{12}$
PSB extraction/recombination		96%	$2.3 * 10^{12}$
PSB 1.4 GeV	$5.78 * 10^{13}$		

Table 3: *Beam loss inventory for nominal CNGS operation [6]. The intensities and losses are given for both PS batches together.*

$1.02 * 10^6$ SPS cycles with a repetition time of $6\,\mathrm{s}$ are needed per year. An estimate of CNGS beam losses was obtained scaling from the 1998 SPS fixed target beam (for the neutrino experiments CHORUS and NOMAD) [6]. This was a similar proton beam operation, where a quasi loss-free performance is expected (fast extraction) for CNGS. The corresponding intensities and beam losses in the different machines are quoted in Table 3. During CNGS operation, two PS batches are accelerated within one SPS super-cycle of $6.0\,\mathrm{s}$. Table 3 summarizes the losses, separated according according to machine. The corresponding kinetic energies are also indicated. The losses mentioned for PS extraction are those occurring on the extraction septum and are therefore counted as PS machine losses.

4.3 Annual losses

The Beta-beam scenario assumes an operation period of $10^7\,\mathrm{s}$ per year. CNGS will run for about $6 * 10^6\,\mathrm{s}$ per year to deliver the nominal $4.5 * 10^{19}$ protons on target. Table 4 summarizes the integrated intensities and losses for each scheme. Additionally, it displays the Beta-beam losses as the number of nucleons lost, which can be compared with the number of protons lost during CNGS operation. For vacuum considerations, the comparison of the flux of ions (nuclei) is important especially in the low energy range where, for the Beta-beam scenario, the highest ion losses occur. The dependence of the desorption effect on the primary ion energy is weak [9]. Investigating the machines with a relatively high rate of ions

machine		CNGS [6]	Beta-beam		ratio
		protons	^{6}He	^{18}Ne	
RCS	nucleon loss	-	$5.4*10^{18}$	$3.6*10^{18}$	-
	ion loss		$0.9*10^{18}$	$0.2*10^{18}$	
PS	nucleon loss	$7.8*10^{18}$	$84.6*10^{18}$	$54*10^{18}$	11 (7)
	ion loss		$14.1*10^{18}$	$3*10^{18}$	
SPS	nucleon loss	$3.9*10^{18}$	$5.4*10^{18}$	$1.8*10^{18}$	1.4 (0.5)
	ion loss		$0.9*10^{18}$	$0.1*10^{18}$	
Total	nucleon loss	$8.6*10^{18}$	$95.4*10^{18}$	$59.4*10^{18}$	11 (7)
	ion loss		$15.9*10^{18}$	$3.3*10^{18}$	
	nucleon @ γ_{top}	$4.5*10^{19}$	$9.05*10^{19}$	$1.95*10^{19}$	2 (0.4)
	ions @ γ_{top}		$1.51*10^{19}$	$1.1*10^{19}$	

Table 4: *Comparison of integrated beam losses of nominal CNGS operation and of the Beta-beam scenario during a physics year. The ratio is defined as the nucleon losses of the Beta-beam scenario compared to the ones of CNGS, for ^{6}He and for ^{18}Ne (bracketed).*

lost per unit length (Table 5) is of high importance.

4.4 Power losses

To some extent, the power losses of the Beta-beam can be compared with those expected for CNGS operation [6]. However, losses are rather uniformly distributed around the circumference of the machines in the case of isotope decay, whereas for a proton operation, most losses occur around injection and extraction located at the relevant beam elements. Table 5 lists the ion losses of the Beta-beam scenario compared with the proton case of CNGS. It should be kept in mind that only decay losses of the Beta-beam scenario are taken into account here, whereas for CNGS, the total loss inventory is taken. Other losses known for stable ion operation have still to be studied and included in the overall beam loss inventory for the Beta-beam scenario.

Given the beam loss inventory as a function of the energy, the power loss density along the accelerator chain (eq. 4) can be calculated (Table 5). The Beta-beam losses and power depositions are deduced from the decay losses mentioned earlier.

The power loss, averaged over the PS circumference of $200\pi\,\mathrm{m}$ and the cycle time, is $2.2\,\mathrm{W/m}$ for the ^{6}He case and $2.8\,\mathrm{W/m}$ for the ^{18}Ne case.

machine		CNGS [6]	Beta-beam	
		protons	^{6}He	^{18}Ne
RCS	loss/cycle [ions]	-	$0.57 * 10^{12}$	$0.7 * 10^{11}$
	loss/cycle/l [ions/m]	-	$3 * 10^9$	$0.35 * 10^9$
	$\mathrm{E_{loss}/cycle[kJ]}$	-	0.2	0.1
	$\mathrm{P_{loss,average}}^4\mathrm{[W/m]}$	-	0.17	0.14
PS	loss/cycle [ions]	$7.6 * 10^{12}$	$8.43 * 10^{12}$	$10.7 * 10^{11}$
	loss/cycle/l [ions/m]	$1.2 * 10^{10}$	$2.7 * 10^{10}$	$0.34 * 10^{10}$
	$\mathrm{E_{loss}/cycle[kJ]}$	12.4	8	6
	$\mathrm{P_{loss,average}[W/m]}$	3.3	2.2	2.8
SPS	loss/cycle [ions]	$3.8 * 10^{12}$	$0.53 * 10^{12}$	$0.6 * 10^{11}$
	loss/cycle/l [ions/m]	$5.4 * 10^8$	$0.8 * 10^8$	$0.1 * 10^8$
	$\mathrm{E_{lost}/cycle[kJ]}$	10.3	16.8	6.1
	$\mathrm{P_{loss,average}[W/m]}$	0.25	0.4	0.25
Total	loss/cycle [ions]	$11.4 * 10^{12}$	$9.53 * 10^{12}$	$1.2 * 10^{12}$
	$\mathrm{E_{lost}/cycle}$ [kJ]	22.7	25	12.2

Table 5: *Comparison of losses along the accelerator chain for CNGS and Beta-beam operation. "Ions" refer to protons in the CNGS case and to the specific isotope of the Beta-beam.*

5 Summary

This note presents the decay losses along the accelerator chain of the Beta-beam based on the design studied within EURISOL DS [3]. The power deposition per unit circumference due to decay losses for the Beta-beam is comparable to the impact of proton losses expected for nominal CNGS operation. The most important power deposition occurs in the PS machine due to the long accumulation time at low gamma and does not exceed $3\,\mathrm{W/m}$. Thus, comparing nominal beta-beam and CNGS operation with an almost equally long operation period per year, machine activation due to beta-decay losses is not a show-stopper but still deserves careful consideration. Other beam loss mechanism (due to space charge, intra-beam scattering, beam transfer and handling) will be subject of a future paper.

[4] circumference of 200 m assumed

6 Acknowledgments

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