LOSS MANAGEMENT IN THE BETA-BEAM DECAY RING

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Abstract

The aim of the beta-beams is to produce pure electron neutrino and anti-neutrino highly energetic beams, coming from β-decay of the $^{18}Ne^{10+}$ and $^{6}He^{2+}$, both at $\gamma = 100$, directed towards experimental halls situated in the Fréjus tunnel [1], [2]. The high intensity ion beams are stored in a ring, until the ions decay. Consequently, all the injected particles will be lost anywhere around the ring generating a high level of irradiation. In order to keep a constant neutrino flux, the losses due to the decay of the radioactive ions are compensated with regular injections. The new ion beam is then merged with the stored beam with a specific RF program [3]. We have to consider two sources of losses:

- The β-decay products: their magnetic rigidity being different from the reference one, they are bent differently and lost.
- The losses during the injection merging process.

The first one needs a particular ring design in order to insert appropriate beam stoppers at the right place. The second one needs a specific collimation system which allows beam longitudinal halo cleaning between two successive injections.

LOSSES CONSIDERED

We distinguish only two sources of losses for the stored beam in the decay ring. The losses due to instabilities or other effects are not considered here. The first source comes from the decay of the radioactive ions. When an ion decays, its charge number changes whereas its kinetic energy stays about the same. If δ is the relative magnetic rigidity difference between the two particles then the deviation due to δ is analogous to the one due to a momentum difference. For $^{6}He^{2+}$ (which decays into $^{6}Li^{3+}$), δ is equal to δ_{Li} = -1/3 and for $^{18}Ne^{10+}$ (which decays into $^{18}F^{9+}$) to δ_F = +1/9. This difference is so high that the product ions will be quickly lost when they enter a dipole. Therefore, the decay products cannot be extracted from the arc. We use then beam stoppers in the arc to limit the depositions in the magnetic elements. To evaluate our design, a module was added to the BETA code [8] giving the amount of the losses on the walls [4].

The second source of losses is the blow up of the stored beam in the longitudinal phase space between two injections due to the Liouville theorem [5]. After around 15 injections for $^{6}He^{2+}$ and 20 for $^{18}Ne^{10+}$, the ions are not accepted in momentum at the injection septum blade anymore. Since the lifetime of $^{6}He^{2+}$ and $^{18}Ne^{10+}$ at $\gamma = 100$ is around one minute, a large part of the injected ions will be lost before decaying. In the top-down approach to reach the nominal physics request [2], we have the beam parameters given in the Table 1. The collimated energy is here just an estimation. The stored beam distribution must be studied, which will improve the calculation of the amount of the losses along the ring. Anyway, the energy to collimate is too large to use a single stage collimation system. A multistage collimation section is then needed, which was developed in numerous studies, for example in the LHC case [7].

Table 1: Beam parameters.

	$^{6}He^{2+}$	$^{18}Ne^{10+}$
γ	100	100
E_0 of an ion at rest (GeV)	5.61	16.8
Magnetic rigidity (T.m)	935	559
Stored ion number	$9.66\ 10^{13}$	$7.42\ 10^{13}$
Lost power by decay (W/m)	10.8	12
Energy to collimate between 2 injections (MJ)	≈ 0.4	≈ 0.9

DIPOLE LENGTH

At first order, only the dipoles introduce some dispersion in the ring. Therefore, the products of the decays are not separated before a dipole. They are then deviated and will produce a deposition peak somewhere in the ring. The aim is to determine which chamber geometry avoids locating this peak in the magnetic elements. Absorbers are inserted in the ring at a distance L=0.5m from the dipole. Their length is fixed to L_{abs}=1m.

The deviation for the decay product from a radioactive ion is in a dipole $\rho\delta(1\text{-}\cos(\theta))$ with ρ the bending radius and θ the dipole angle. For the accumulated Lithium beam not to hit the walls of the dipole, its length must be adjusted. We must have:

$$\rho|\delta_{Li}|(1-\cos(\theta)) + L|\delta_{Li}|\sin(\theta) + X_{beam} < X_{dipole}$$

with a half-aperture of X_{dipole} for the dipole and a half beam size of X_{beam}. Moreover, the dipole has to be long enough to have the Lithium beam hit the absorber behind. Therefore, we must have:

$$\rho|\delta_{Li}|(1-\cos(\theta)) + (L + L_{abs})|\delta_{Li}|\sin(\theta) - X_{beam} > X_{abs}$$

with the absorber at X_{abs} from the axis.

The Fluorine beam is less deviated than the Lithium beam (Figure 1). It is not absorbed by the first absorber. For it not to hit the dipole behind, we must have:

$$|\delta_F|(2\rho\sin(\theta) + (2L + L_{abs})\cos(\theta))\sin(\theta) + X_{beam} < X_{dipole}$$

The horizontal rms emittance is 0.11 and 0.22 π mm.mrad respectively for $^{6}He^{2+}$and $^{18}Ne^{10+}$. The beam size at 4 σ in the regular lattices is then around ±1.3 cm and ±1.8 cm for $^{6}He^{2+}$ and $^{18}Ne^{10+}$. The absorbers are at X_{abs} = 4 cm from the machine axis. The bending radius is 156 m, which gives a magnetic field of 6 T for $^{6}He^{2+}$. The half-aperture of the dipoles X_{dipole} is assumed equal to

8 cm. After calculation, the dipole angle must be between $\pi/80$ and $\pi/86$ to avoid the deposition in the magnetic elements. To respect the periodicity of the lattices, the dipole angle must be $\pi/86$. In that case, Figure 1 shows that the decay products from $^6He^{2+}$ are then absorbed by the first absorber and the ones from $^{18}Ne^{10+}$ by the second one.

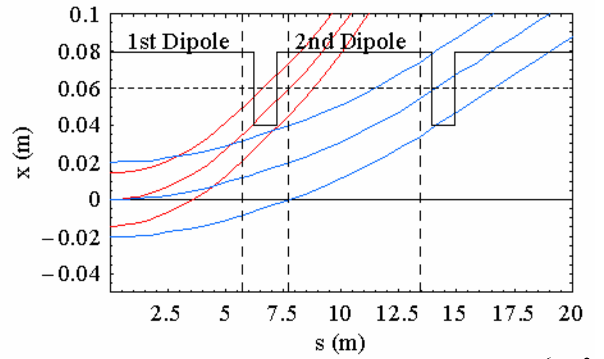

Figure 1: Deviation of the decay products. In red, $^6He^{2+}$, in blue $^{18}Ne^{10+}$, in black chamber size.

SIMULATION OF THE DECAY LOSSES IN THE RING

To evaluate the deposition peaks, the losses in the arcs have been calculated at first order. The daughter particle is assumed to have the same coordinates as the mother particle in the 6D phase space. Only the charge and then the magnetic rigidity are changed. The simulation does not take into account the contributions due to multipolar effects and the decay products are supposed to be completely absorbed by the stoppers [4]. To improve the simulation, the interactions of the ions with the absorbers will have to be studied.

The average powers lost by $^6He^{2+}$ and by $^{18}Ne^{10+}$ are around 11 W/m so none of them can be neglected and both species must be taken into account. Figure 2 shows the deposition in the FODO lattice for the parameters given in Table 1 and a Gaussian transverse distribution.

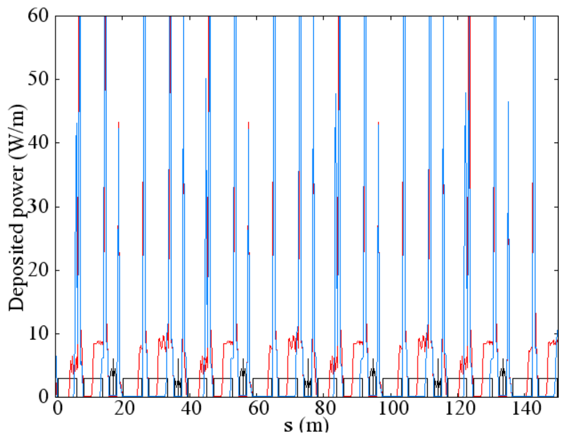

Figure 2: Deposited power by the decay products in the regular FODO lattice with a half-aperture of 8 cm for the magnetic elements and of 4 cm for the drifts. In red, losses for $^6He^{2+}$, in blue, losses for $^{18}Ne^{10+}$.

Figure 2 shows that the losses in the magnetic elements can be limited by putting absorbers in the ring. Whereas the deposition in the dipoles is negligible in the $^{18}Ne^{10+}$ case, it is not for $^6He^{2+}$. The interactions of the decay products with the absorbers must be studied since secondary particles may interact with the dipole behind and provoke quenches there: the absorber may not be long enough to stop completely the coming ions. The effect of the insertion of beam stoppers into the decay ring on the transverse impedance must be estimated too.

OPTICS OF THE COLLIMATION SECTION

To remove the longitudinal halo due to the merging, a momentum collimation section is necessary. Therefore, a high normalized dispersion is needed at the primary collimator, which is realized by doing a dispersion bump with four dipoles in one of the two long straight sections. To improve the optical properties like the dynamic aperture, the straight section dedicated to the collimation is made symmetrical (Figure 3). The removed high energies prevent from using superconducting magnets near the collimation section. Therefore, the dipoles and the quadrupoles are warm in the whole collimation section: the bend radius of each dipole is 580 m for an angle of 20 mrad. For $^6He^{2+}$, the magnetic field is then 1.6 T.

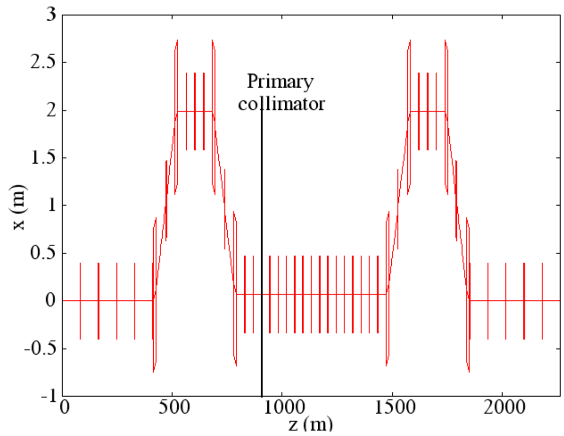

Figure 3: Layout of the collimation section.

At the primary collimator, the normalized dispersion $D_x/\sqrt{\beta_x}$ reaches -1 m$^{1/2}$ with $D_x' = \alpha_x = 0$. The secondary collimators must be put to specific phase advances modulo π after the primary collimator [7]. A FODO lattice has been realized with a phase advance per lattice of $\pi/3$ in the horizontal plane and $\pi/6$ in the vertical plane. Moreover, another constraint is that the phase advances in both long straight sections have the same fractional part. In this way, we keep the same working point as in [6]. The global tune in the decay ring is 22.23 in the horizontal plane and 12.16 in the vertical plane. The optical functions and the beam sizes are plotted with BETA [8] on the Figure 4 and Figure 5. The needed half-aperture in the collimation section is around 9 cm for the magnetic elements. The strongest gradient is 15 T/m for a 1-m-long quadrupole.

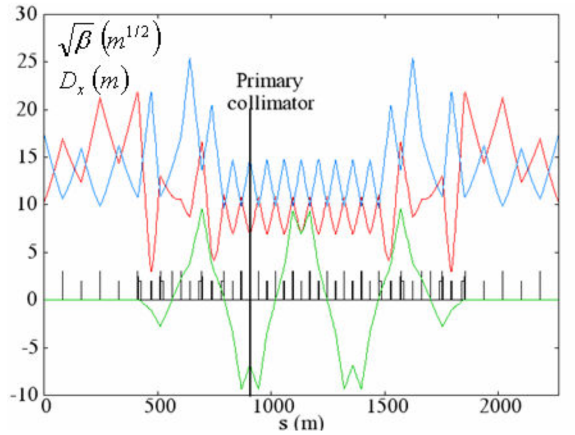

Figure 4: Optical functions in the collimation section. In red β_x, in blue β_y, in green the horizontal dispersion D_x.

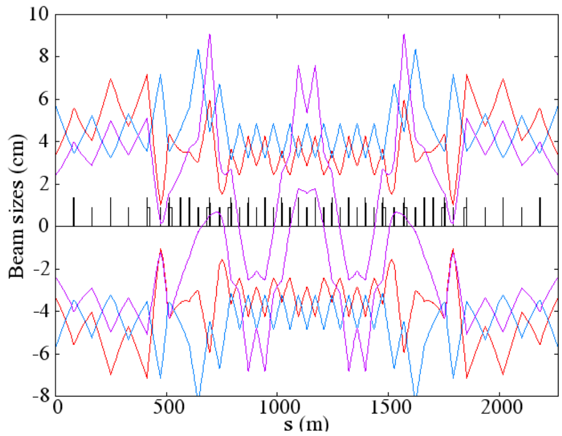

Figure 5: Beam sizes in the collimation section. Stored beam at 7 σ in red in the horizontal plane, in blue in the vertical one, in purple injected beam at 5 σ and at $\delta = 0.5$ % in energy in the horizontal plane.

With the modification of one of the two long straight sections, the superperiod of the decay ring is 1. Therefore, the dynamic aperture is likely to be reduced a lot compared to the one obtained in [6] and the geometric and chromatic aberrations can be too strong to accept the beam. We have corrected the chromaticity and minimized the third order resonance effects with sextupoles in the both arcs. Since the beam size is large in the collimation section, we have not inserted sextupoles there to avoid the strong non linearities due to the geometric aberrations. After compensation, we obtain then the dynamic aperture at the injection point given in Figure 6. The betatron amplitude at 7 σ of the stored $^{18}Ne^{10+}$ beam is 1.6 cm in the horizontal and vertical planes there.

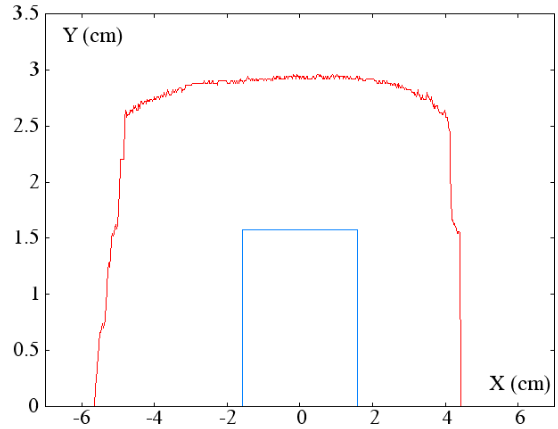

Figure 6: Dynamic aperture at the injection point at the reference energy, in blue beam size at 7 σ.

SUMMARY

We have studied how to mitigate the amount of the decay losses and of the losses due to the merging hitting the magnetic elements. The geometry of the chamber has been modified to minimize the deposition of the decay products into the dipoles at first order. Moreover, to remove the ions which are not accepted in energy anymore after the merging, a momentum collimation section has been inserted into one of the two long straight sections. Despite this insertion, the dynamic aperture is still large enough to accept the whole beam after compensation of the resonances.

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