THE BETA-BEAM DECAY RING DESIGN

A. Chancé, J. Payet, CEA/DSM/DAPNIA, Saclay, France

Abstract

The aim of the beta-beams is to produce highly energetic beams of pure electron neutrino and anti-neutrino, coming from β-decays of the $^{18}Ne^{10+}$ and $^{6}He^{2+}$, both at $\gamma = 100$, directed towards experimental halls situated in the Fréjus tunnel [1], [2], [3]. The high intensity ion beams are stored in a ring until the ions decay. Consequently, all the injected ions will be lost anywhere in the ring, generating a high level of irradiation. Since they come from the SPS, the ring circumference has to be a multiple of the SPS one. The straight sections must be as long as possible in order to maximize the useful neutrino flux. The straight section length is chosen to be about 36% of the circumference length, which imposes 1-km-long arcs. The bend field in the arcs is then achievable. The arc has been chosen as a 2π phase advance insertion, which improves the optical properties (dynamic aperture and momentum acceptance) and allows the easy determination of the working point by the optics of the straight sections.

DECAY RING SCHEME

The ring circumference is the same as the SPS one: 6911 m for synchronism reasons. The straight section length is 2462 m, which corresponds to 36% of the circumference. Each arc is then 994 m long. Half of the arcs is filled with dipoles. The bending radius of the dipoles is then equal to 156 m, which corresponds to a magnetic field of 6 T for $^{6}He^{2+}$ and 3.6 T for $^{18}Ne^{10+}$.

One of the two long straight sections is aligned with the detector and is used as the neutrino source whereas the other is used for the momentum collimation [4]. The two arcs of the decay ring are identical and can be cut in 4 functional parts:

- A regular FODO lattice in the arc
- A matching section to adapt the optical functions of the straight section with the FODO lattices
- An insertion for the injection in the arc
- A matching section to adapt the FODO lattices with the insertion

The arc is a 2π phase advance insertion, which makes easy the determination of the working point by the optics of the straight sections. The arc is designed for $^{6}He^{2+}$ and $^{18}Ne^{10+}$ at $\gamma = 100$.

STRAIGHT SECTIONS

The straight sections are constituted of 14 172-m-long FODO lattices. Since one of the two straight sections is the neutrino source for the detector which is 130 km far away, the maximum angle for the ions in the straight section has to be small compared to the emission cone angle of the neutrinos given by $1/\gamma$ with γ the relativistic factor. The maximum value for the Twiss parameters γ_x and γ_y is $1.3.10^{-2}$ m^{-1} [5]. The emittance at 4 σ is 3.5 π mm.mrad for $^{18}Ne^{10+}$. The relative enlargement of the neutrino emission cone is then equal to 2.1 %.

REGULAR FODO LATTICE

To transport the beam along the arc, we use FODO lattices except in the section dedicated to the injection. There are 10 38.7-m-long regular FODO periods in each arc. To limit the apertures needed for the dipoles, the dispersion and the optical function β_x have to be quite small. To have a compact ring, a small bending radius is needed. The dipole is split in two pieces to enable the insertion of a beam stopper in between, which will absorb the decay products [4][6]. The bending radius of a dipole in the decay ring is 155.56 m for an angle of π/86 rad [4]. The optical functions of the arc are presented in Figure 1. The strongest gradient in the arc is reached for the focusing quadrupole of the FODO lattice: its value is around 45 T/m.

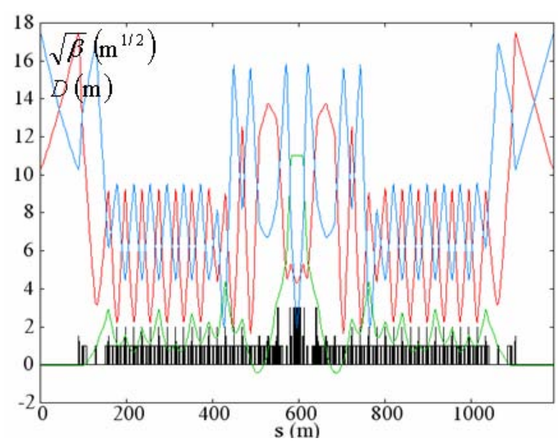

Figure 1: Optical functions in the arc. In red horizontal β function, in blue the vertical one, in green horizontal dispersion.

MATCHING SECTION BETWEEN THE ARC AND THE STRAIGHT SECTION

The relative difference of the magnetic rigidity between an ion and its decay product is -1/3 for $^{6}He^{2+}$ (which gives $^{6}Li^{3+}$) and 1/9 for $^{18}Ne^{10+}$ (which gives $^{18}F^{9+}$). The focusing is weak in the whole section. Consequently, wherever an ion decays in the straight section, its decay product will be transported until the first dipole in the arc and be lost behind. This represents 36% of the total amount of decay. The deposited power in the chamber at the arc entry is then huge: several tens of kilowatts. To avoid that, the matching section is specially designed to allow extracting the decay products $^{6}Li^{3+}$ and $^{18}F^{9+}$ from the ring (Figure 2). It has to begin with a dipole to separate the decay products from the reference beam. Behind, a long drift is needed to improve the separation. If we assume the magnet transverse half size is 0.3 m, a 12-m-long extraction septum of 0.5 T will be necessary to extract the Fluorine opposite the Lithium.

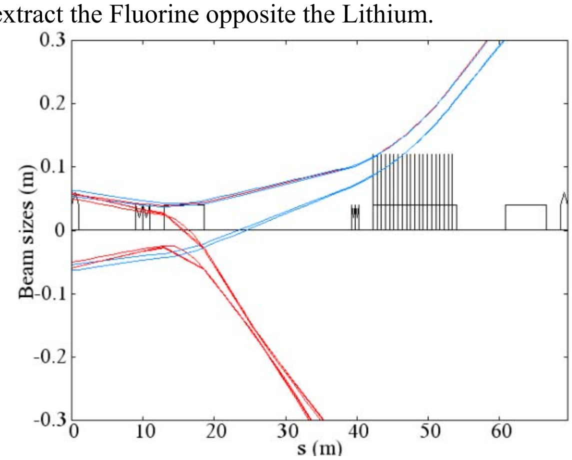

Figure 2: Extraction of the decay products coming from the long straight section. In red Lithium beam, in blue Fluorine beam.

INSERTION FOR THE INJECTION

Since the injection is « off-momentum » [7] [8], it is realized in a high horizontal dispersion area. We note Δ the relative momentum difference between the stored and injected beams and we use the parameters and the notations given in Table 1. The stored beam is assumed collimated at δ_m in energy then its size is $\delta_m.D_x$. The beam size of the injected beam is given by $\sqrt{n_i^2 \beta_x \varepsilon_x + (\delta_i D_x)^2}$. The distance between the central axis of the stored beam and of the injected one is equal to $\Delta.D_x$. We have then:

$$\Delta.D_x = \delta_m D_x + e_S + \sqrt{n_i^2 \beta_x \varepsilon_x + (\delta_i D_x)^2}$$

To minimize the value of Δ necessary for the injection, β_x must be as low and D_x as high as possible. The injection section is thus an insertion at low β_x and high D_x. At the injection point, β_x and β_y are focused by a doublet of quadrupoles to obtain a waist here. The injection septum magnet is 18 m long and inserted in a 25-m-long drift. Its magnetic field is 1 T.

With the parameters given in Table 1, the relative momentum difference is $\Delta \approx 5.10^{-3}$. In the baseline, the cavity voltage is 20 MV and the frequency is 40 MHz [9]. The transition gamma of the ring is 27. For $^{6}He^{2+}$ and $^{18}Ne^{10+}$, the RF system accepts a relative momentum difference Δ up to respectively 6.1 10^{-3} and 7.9 10^{-3}. Therefore, the injected beam is accepted by the RF system. We obtain then the optical functions of the Figure 3 and the beam sizes of the Figure 4.

Table 1: Beam parameters at the injection point.

β_x	23 m
horizontal dispersion D_x	10.9 m
momentum spread of the stored beam (full) δ_m	2.5 10^{-3}
momentum spread of the injected beam (full) δ_i	0.4 10^{-3}
rms horizontal emittance ε_x	0.22 π mm.mrad
number n_i of rms (injected beam)	5
number n_m of rms (stored beam)	7
septum thickness e_S (with its guard)	15 mm

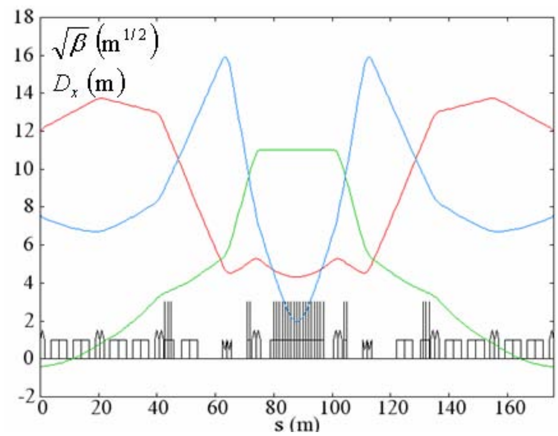

Figure 3: Optical functions in the injection section. In red horizontal β function, in blue the vertical one, in green horizontal dispersion.

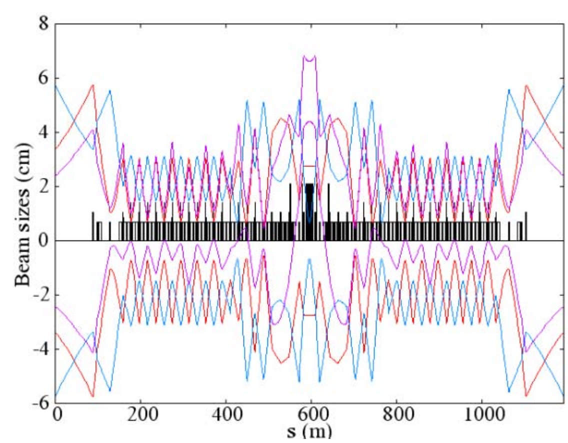

Figure 4: Sizes of the stored beam (red) at 7 σ and of the injected beam (purple) at 5 σ at first order. In blue envelope of the stored beam in the vertical plane.

SECOND ORDER STUDIES

The natural normalized chromaticities in the ring are $\xi_x = -1.67$ and $\xi_y = -2.17$. With $\upsilon_x \sim 20$ and $\upsilon_z \sim 12$, the tune shift for a momentum difference of 5.10^{-3} is then -0.17 and -0.13 in each plane, which makes the chromaticity correction necessary. The phase advance of each arc is exactly 2π: the working point can be chosen to minimize the effect of the third order resonances. A good compromise is $\upsilon_x = 20.23$ and $\upsilon_z = 12.16$.

The chromaticity is corrected with two sextupole families inserted in the FODO lattices. However, Figure 5 shows that the dynamic aperture is too small to accept the whole beam. In fact, the coupling resonances υ_x-2υ_z = -4 and υ_x-υ_z = 8 are the ones that are the most excited. It is necessary to compensate these resonances while controlling the contributions of the other third order resonances. In that aim, five other sextupole families have been added in the matching section between the injection insertion and the FODO lattices. The contribution of the third order resonances has been minimized near the working point. Moreover, we have put constraints on the values of the derivative of the tune as a function of the amplitude to avoid the crossing of low order resonances [10]. The dynamic aperture has then increased sufficiently to accept the whole injected beam (Figure 5).

Moreover, the tune variations with momentum are quite small for the horizontal plane and negligible for the vertical one (Figure 6): the dynamic aperture stays the same for the injected beam. Therefore, the injected and the stored beams are accepted by the decay ring.

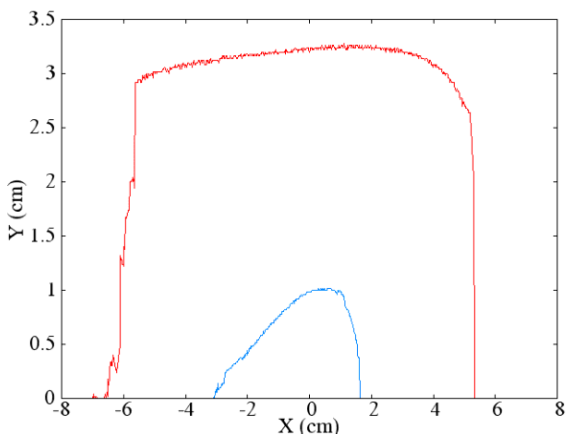

Figure 5: Dynamic aperture at the injection point. In blue, chromaticity correction only, in red chromaticity correction and resonance compensation.

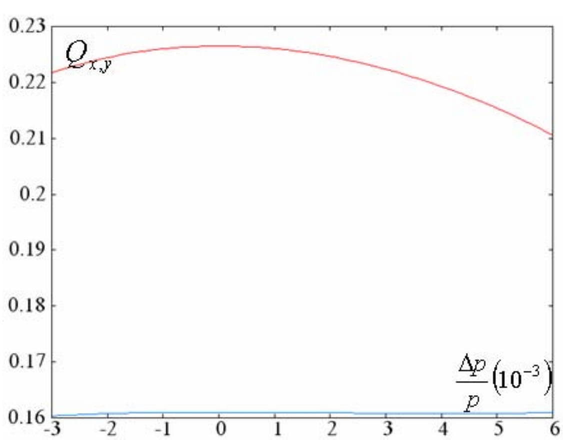

Figure 6: Representation of fractional part of the horizontal tune (in red) and of the vertical tune (in blue) as a function of Δp/p.

In the top down approach [2], the ion population in each 1.65-m-long bunch is respectively 4.83 10^{12} and 3.71 10^{12} for $^{6}He^{2+}$ and $^{18}Ne^{10+}$. If the rms emittances for each species were 0.11 π mm.mrad, the self-field incoherent tune shift would be then respectively -0.02 and -0.14. It is too high for $^{18}Ne^{10+}$. Therefore, the emittance has been enlarged up to 0.22 π mm.mrad for $^{18}Ne^{10+}$. In that case, the tune shift becomes equal to -0.07, which is manageable. So, the space charge effects are not negligible and will have to be taken into account in further studies.

SUMMARY

A design for the decay ring has been realized with BETA [11] at the first and second orders. The different functional parts of the ring have been studied. The arc entry is specially made to extract the decay products from the long straight sections. The Twiss parameters at the septum blade enable to inject a beam at an energy δ=5 ‰ Moreover, sextupoles have been put in the arcs to compensate the third order resonances. The dynamic aperture is then large enough: the decay ring accepts the injected and stored beams at the first and second orders.

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