A NEW LATTICE FOR THE BETA-BEAM DECAY RING TO REDUCE THE HEAD-TAIL EFFECTS *

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Abstract

The beta-beam concept relies on the production, by beta decay of radioactive ions of a very high flux, of an electron neutrino and anti-neutrino beam towards a distant detector. In this aim, the radioactive isotopes are stored in a long racetrack-shaped ring, called the decay ring, where they orbit until they decay or are lost. The intensities to store in the decay ring to obtain the required neutrino fluxes are very high (several amperes in average). Therefore, collective effects occur. Among them, the head tail effect, caused by transversal resonance impedance, is one of the main issues: the beam was shown to be unstable with the previous decay ring lattice. The transition gamma was reduced to mitigate this problem. For this purpose the lattice was changed by removing the injection from the arc to put it in a chicane which is added in one of the long straight sections. After presenting the limitation due to head tail effects, we will present the modification in the lattice and their impact on the dynamic aperture in the decay ring. Then the improvement on the beta-beam performance with respect to the lower transition gamma will be shown.

INTRODUCTION

The Beta-Beam concept [1] is one of the proposed next generation neutrino oscillation facilities and relies on the β-decay of radioactive ions. After production and acceleration in the PS and SPS up to $\gamma = 100$, the ions $^6\mathrm{He}^{2+}$ and $^{18}\mathrm{Ne}^{10+}$ are stored in a horse-racetrack shaped storage ring: the Decay Ring (DR). One of its straight sections is aimed at an oscillation experiment and the decaying ions create a highly pure (anti) electron neutrino beam. The aimed annual (anti) neutrino flux of (2.9e18) 1.1e18 from (β^-) β^+ decaying (^{6}He) ^{18}Ne ions gives good sensitivities if the Duty Factor (DF) is smaller than 1% in the DR [2]. The DR is 6911.5 m long and will host 20 ion bunches. The number ^{18}Ne (^{6}He) per bunch has to be $3.4 \cdot 10^{12}$ ($4.5 \cdot 10^{12}$) in the DR to reach the nominal (anti) neutrino fluxes. Each bunch is then 2 m long, which enables to keep the DF below 1%. Hosting the nominal number of ions in as small bunches as needed in the DR implies seemingly insurmountable low transverse broadband impedance [3]. Although an approximation, the "Coasting Beam Equation" given in Eq. (1) gives the upper limit $N^{\mathrm{th}}_{b_{x,y}}$ for the number of ions in the bunch as a function of the beam and lattice parameters [4]. The limit depends clearly on the slipping factor η.

$$N^{\mathrm{th}}_{b_{x,y}} = \frac{32\sqrt{2}}{3} \frac{R|\eta|\epsilon_l^{2\sigma} f_r}{\langle\beta_{x,y}\rangle Z^2\beta^2 c R_\perp} \tag{1}$$

where Z is the charge number, A the mass number, R the machine radius, $\epsilon_l^{2\sigma}$ the longitudinal emittance at 2σ, f_r the resonance angular frequency and $R_\perp$ the transversal wall impedance.

In order to push the intensity limit, the idea was then to increase the momentum compaction of the DR by changing its lattice. This report focuses on the adopted solution for the new lattice and the optical properties. The considerations about the other ways to mitigate the head tail effects are developed in [5].

AN INJECTION CHICANE

The momentum compaction α_P is given by the Eq. (2).

$$\alpha_P = \frac{1}{\gamma_T^2} = \frac{1}{\mathcal{C}} \oint \frac{D_x(s)\, ds}{\rho} \tag{2}$$

$\mathcal{C}$ is the ring circumference, D_x the horizontal dispersion and ρ the curvature radius.

In the reference design given in [6], the DR is made of two identical arcs and of two long straight sections. In the long straight section which is not aimed at the detector, a momentum collimation section is inserted to remove the particles which may hit the septum blade after merging. The region which mainly contributes to the momentum compaction is the arcs. The immediate way to increase the momentum compaction could be to increase the average dispersion in the arcs. Nevertheless, a larger dispersion implies larger apertures for the dipoles. Moreover, the arcs are subjects to different constraints such as being 2π insertions, having a low-β and high dispersion at the injection, being matched to the straight sections, which leaves few degrees of freedom to increase the dispersion.

Another solution, which was chosen, is to put a chicane in the long straight section which is not directed towards the detector. A layout of the chicane is given on Figure 1. The chicane is symmetric and made of dipoles with opposite curvatures. By changing the sign of the dispersion with the one of the dipole field, it is possible to increase the value of the integrate by keeping the same circumference. In Reference [6],the injection region was located in the arcs because the presence of dipoles makes this region naturally

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dispersive. By using matching quadrupoles, it was possible to make the injection without adding extra elements. With this new scheme, the injection insertion can be moved to this chicane. The big advantage is to make the arcs much simpler and more compact. They become a succession of FODO lattices separated from the long straight sections by a matching section used as a dispersion suppressor too. The drawback is to increase the number of elements in the DR: 216 dipoles are necessary against 176 before.

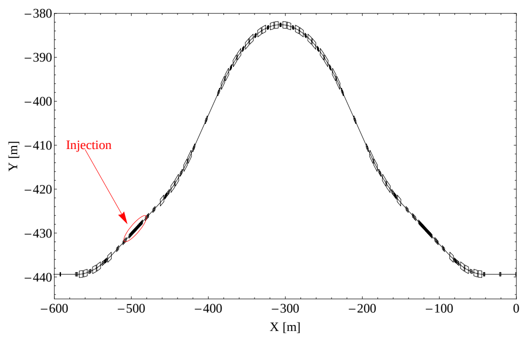

Figure 1: Layout of the injection chicane.

NEW LATTICE

The arcs are now made of regular FODO lattices. The phase advance per period is $\pi/2$ rad in both planes. Since the sextupoles are located near the quadrupoles, they can compensate each other every two period. Since the arcs are 2π insertions, the tune of the ring is given by the long straight sections. The presence of the injection chicane and the collimation section makes the two long straight sections different. Nevertheless, to make these two sections more similar, the fractional part of the phase advance is the same for both.

The betatron functions, calculated with BETA[7], in the whole ring and a zoom in the injection chicane are shown on Figure 2 and Figure 3. To enable the off-momentum injection (explained more precisely in [6]), the dispersion must be high with low betatron functions at the injection point. The optical functions at the injection point are $\beta_x = 22$ m, $\beta_y = 7.3$ m and $D_x = 11$ m, which is similar to the previous values. The parameters of the lattice and of the elements are summed up in Table 1 and Table 2. With this new lattice, the momentum compaction goes from 0.15% to 0.29%. The slipping factor η is then doubled, which means that the intensity limit is doubled too (see Eq. (1)). It could be possible to increase the slipping factor again by adding another chicane but it implies a cost increase (more dipoles).

DYNAMIC APERTURE

The chromaticity of the DR was canceled by using two sextupole families located at the middle of the quadrupoles in the arcs. The phase advance of $\pi/2$ per period in the

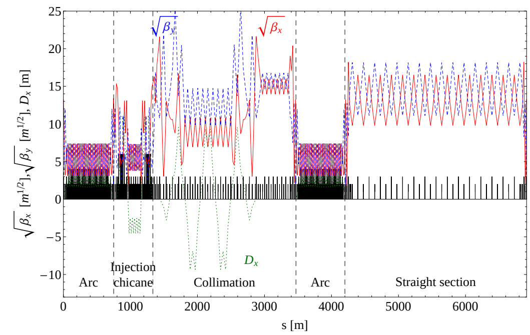

Figure 2: Horizontal betatron function (red full line), vertical betatron function (blue dashed line) and horizontal dispersion (green dotted line) in the whole DR.

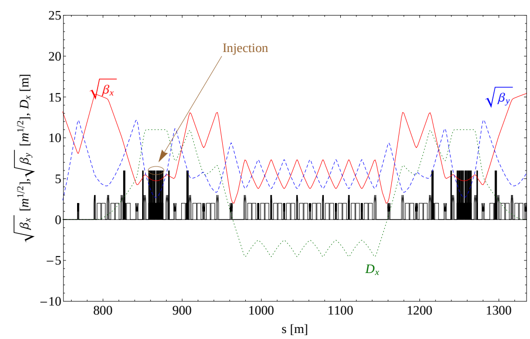

Figure 3: Horizontal betatron function (red full line), vertical betatron function (blue dashed line) and horizontal dispersion (green dotted line) in the injection chicane.

arcs enables to cancel the non linearities brought by the sextupoles (the transfer matrix of two periods is $-\mathbf{1}$ where $\mathbf{1}$ is the identity matrix). The dynamic aperture was calculated for 10,000 turns at the injection point for different values of δ: -0.25%, 0 and 0.25%. The rms beam sizes are then $\sigma_x = 1.83$ mm and $\sigma_y = 0.76$ mm. The dynamic aperture is shown on Figure 4. The dynamic aperture is larger than 20σ in both planes for the energy range of the beam, which is sufficient to keep the beam stable.

Nevertheless, if the initial position of a particle is in the stability region, it does not imply that its trajectory is elliptical in the phase space. Therefore, we have tracked a set of particles for 10,000 turns with SixTrack[8]. On Figure 5 and Figure 6, we have respectively shown the trajectories of particles with the initial coordinate $x = n\sigma_x$ (the other coordinates are set to zero) in the horizontal phase space and with the initial coordinate $y = n\sigma_y$ (the other coordinates are set to zero) in the vertical phase space. The trajectories of the particles stay clearly elliptical up to 10σ in both planes, which show that the non linearities brought by the sextupoles are well canceled.

CONCLUSION

Enlarging the momentum compaction was made possible by adding a chicane in one of the long straight sections. The injection was moved from the arcs to this chicane, which implies extra dipoles. The advantage of this new lattice is to make the arcs much simpler. The second order properties are not damaged with a dynamic aperture larger than 20σ and a linear motion up to 10σ.

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Table 1: Parameters of the Decay Ring.

Description	Units	Value
Total length $\mathcal{C}$	m	6911.5
Machine radius	m	1100
Eff. Straight. Sec.	%	39
Relativistic gamma	-	100
Magnetic rigidity (He^{2+})	T.m	938
Hor. rms emittance ϵ_x	πmm.mrad	0.15
Vert. rms emittance ϵ_y	πmm.mrad	0.08
Horizontal tune Q_x	-	22.23
Vertical tune Q_y	-	19.16
Nat. hor. chromaticity ξ_x	-	-1.538
Nat. vert. chromaticity ξ_y	-	-1.577
$\langle\beta_x\rangle$	m	124.7
$\langle\beta_y\rangle$	m	160.4
$\langle D_x\rangle$	m	0.72
Momentum compaction α_P	%	0.29
Transition gamma	-	18.6

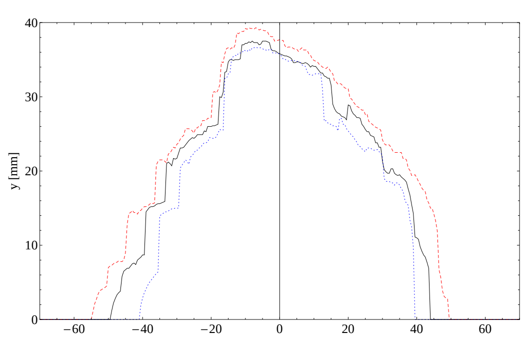

Figure 4: Dynamic aperture at the center of the injection insertion for 10,000 turns at $\delta = 0, 0.25, -0.25\%$ (black full line, red dashed line and blue dotted line).

Table 2: Parameters of the Magnetic Elements.

Element Type	Parameter	Units	Value
Dipoles	Total number	-	216
	Nb in the chicane	-	40
	Length	m	4.675
	Angle	rad	$\pi/84$
	Radius	m	125
	Max. Field	T	7.46
Quadrupoles	Total number	-	221
	Max. Strength	m^{-2}	0.067
	Max. Gradient	T/m	62.85
Sextupoles	Total number	-	74
	Nb families	-	2
	Max. Strength $S_m L$	m^{-2}	0.074
	Max. Grad. $H_m L$	T/m	69.3

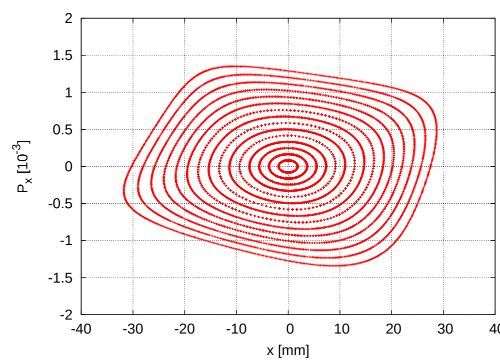

Figure 5: Tracking of a particle with the initial horizontal position $n\sigma_x$ at the injection point, the other positions are set to zero and n goes from 1 to 15 with an increment of 1.

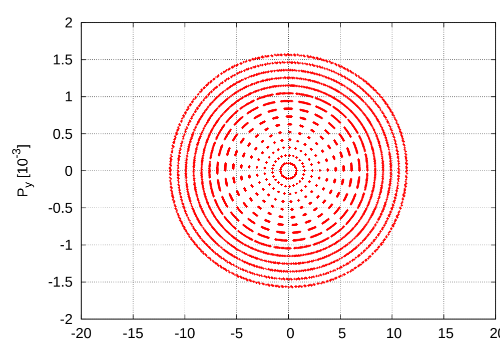

Figure 6: Tracking of a particle with the initial vertical position $n\sigma_y$ at the injection point, the other positions are set to zero and n varies from 1 to 15 with an increment of 1.