IONIZATION COOLING IN A LOW-ENERGY ION RING WITH INTERNAL TARGET FOR BETA-BEAMS PRODUCTION

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Abstract

A compact ring with an internal target for the production of ^{8}Li or ^{8}B as neutrino or antineutrino emitters has been proposed in [1], to enhance the flux of radioactive isotopes for a beta-beam facility. The circulating beam is expected to survive for thousands of turns and, according to this scheme, the ionization cooling provided by the target itself and a suitable RF system will be enough to keep the beam transverse and longitudinal emittances under control. The ionization cooling potential for a preliminary ring design is here investigated by means of tracking simulations and analytical considerations, keeping in mind that a correct modeling of the beam-target interactions is fundamental for these studies. Technological issues for such a ring and possible show-stoppers are also briefly discussed.

INTRODUCTION

Ionization cooling [2] is recently receiving large attentions for the fast cooling of muons for a Neutrino Factory or a Muon Collider [3]. It is based on the principle that a beam traversing a material looses energy and only its longitudinal component is recovered in the RF cavities, with the net effect of a transverse emittance shrinking. Longitudinal ionization cooling is achieved at expenses of the transverse one by introducing coupling via the dispersion and by using a wedge-shaped absorber in a high dispersive region.

Ref. [1] proposes ionization cooling to cure the blow-up in a compact storage ring with an internal gas jet target, to produce radioactive isotopes for Beta-Beams facilities [4]. The nuclear reactions to produce the pure electron neutrino or anti-neutrino emitters are respectively ^{6}Li(^{3}He,n)^{8}B and ^{7}Li(p,n)^{8}Li. The ions are injected (in cw mode) at the target position via a charge-exchange methods and, at the energies of interest, the circulating beam is fully stripped. The reaction products will be emitted at an angle of about 10^o and a special collection device will stop and transport them to an ECR source by a diffusion/effusion process.

The paper is not considering the particle production and collection mechanisms, but is focusing on the implication for the stored beam, which needs to survive for at least 10^4 turns, corresponding to the production rate characteristic time for the target thickness proposed in [1].

The challenge of applying ionization cooling for low-energy ions resides in the strongly negative slope of the Bethe-Bloch formula [5] for the 25 MeV energy of interest. In particular, $(\partial E_{loss}/\partial p) < 0$ means that for an increase of particle momentum, the energy losses in the material becomes weaker, thus causing extra heating in the longitudinal plane [6]. Tracking simulations have been set-up by adapting the code SixTrack [8, 9] to the specific needs of the Production Ring and the results compared with analytical predictions.

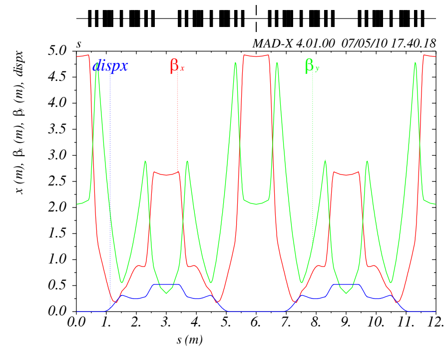

Figure 1: Production Ring Twiss Parameters

PRODUCTION RING PARAMETERS

The optics of the 12 m long production ring for the 25 MeV ^{7}Li ions is shown in Fig. 1 and the design is well documented in the work by [7]. The ring has a two-fold symmetry: two of the straight sections have zero dispersion, in order to accommodate the RF cavity(ies), the other two, instead, have an horizontal dispersion of 50 cm, as required by the specifications for the production target, which will be installed in one of them. Table 1 summarizes the ring parameters. The lattice, which has still to be optimized, was used to set up tracking simulations and for a preliminary investigation of the parameters that one should consider to minimize the blow-up.

Table 1: Production Ring Parameters

Particle		^{7}Li
Energy	E_c	25 MeV
Relativistic gamma	γ_r	1.00383
Beam rigidity	$B\rho$	0.636 T m
Transition γ	γ_t	3.58
Tune	$Q_{x,y}$	2.58, 1.63
Natural chromaticity	$Q'_{x,y}$	-3.67, -3.58
β @ target	$\beta^*_{x,y}$	2.62 m, 0.35 m
Dispersion @ target	$D^*_{x,y}$	0.523 m, 0 m
Target thickness	t_0	0.27 mg/cm^2
	n_t	10^{19} atoms/cm^2
Energy losses @ target	E_{BB}	~ 0.30 MeV

INTERACTION WITH THE TARGET AND SIMULATIONS

The Code Modifications

Sixtrack [8] is widely used at CERN mainly for dynamic aperture studies and for collimation. It is a fully 6D, symplectic, single-particle tracking code and can read the lattice directly form a MADX-PTC special output file, including higher order multipole components. The collimation version [9] adds the possibility to track an initial particle distribution and follows the the interaction with matter in the collimators.

The production target has been implemented in the code as a special collimator element and the interaction with matter modeled by simple analytical formulas. The energy lost by a particle traversing a target is a random value from a Gaussian distribution with the mean given by the Bethe-Bloch formula [5] and the rms spread (energy straggling) is read from Table 1 in [1] and assumed proportional to the target thickness. For the Multiple Coulomb Scattering (MCS), the following formula is used:

$$\theta_c = \frac{14.1MeV}{\beta cp} z \sqrt{\frac{t}{\chi_0}} \left[1 + 0.038 \ln \frac{t}{\chi_0}\right] \quad (1)$$

Since Sixtrack can only deal with protons, it is necessary to convert the proton energy to the ^{7}Li ions' before and back again after the target [7] and to have an equivalent proton beam with the same rigidity $(B\rho)$ and the same momentum $\Delta p_{RF}/p$ recovered at the RF-cavity. This leads to an equivalent proton energy of $\sim$ 19 MeV and an energy recovered of $\Delta E_{RF} \sim 0.22$ MeV for the reference particle. RF voltage and synchrotron phase, for an harmonic number $h = 1$, have been set to $V = 860.6$ keV and $\phi_s = 15^o$, from considerations of bucket height, but can be further tuned.

Furthermore, a few beam diagnostics have been included in SixTrack, e.g. the possibility to have the turn by turn rms emittance evolution in the three plane.

Simulations with a Rectangular Target

Figure 2 shows the transverse and longitudinal beam blow-up in the case of a rectangular-section target (zero wedge angle). Important beam losses happen when the momentum spread (dp/p) becomes larger then a few 10^{-2} and before one can already note changes in the slope of the transverse emittances evolution. This is due to the large, non-corrected natural chromaticity which leads to values of $\Delta Q \sim 0.4$ for a $dp/p \sim 10^{-2}$ and induces resonance crossing and losses. Including sextupoles in the lattice needs to be carefully studied since they can excite additional resonances.

The Choice of Wedge-angle

A wedge-shaped target in a dispersive region is used to transfer the cooling from the horizontal to the longitudinal

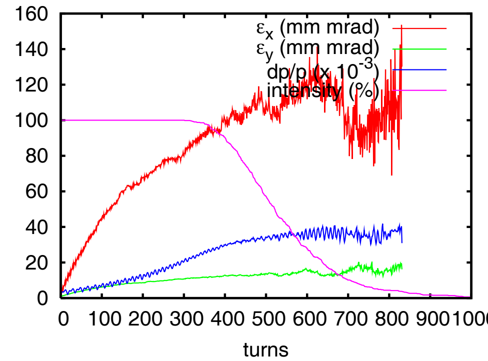

Figure 2: Emittance blow-up in case of zero wedge angle

plane. By linearizing the Bethe-Bloch formula, with respect to the target thickness variation Δt and the particle energy offset ΔE_c, one obtains:

$$E_{BB}(t, E_c) \approx \left.\frac{dE}{ds}\right|_{E_{c0}} t_0 + \left.\frac{dE}{ds}\right|_{E_{c0}} \Delta t + \left.\frac{\partial\left(\frac{dE}{ds}\right)}{\partial E_c}\right|_{E_{c0}} t_0\, \Delta E_c$$

The first term is the mean energy lost by a beam of nominal energy E_{c0}, traversing a target of uniform thickness t_0, and is recovered in the RF-cavity for the synchronous particle. The second and third terms both depend on the particle momentum offset $(\Delta p/p)$, since it is $\Delta E_c = E_c(\gamma + 1)/\gamma(\Delta p/p)$ and $\Delta t = 2\rho \tan(\theta/2)\Delta x$, where ρ is the target density, θ is the angle of the wedge and $\Delta x = D^*(\Delta p/p)$ is the horizontal offset at the target induced by the dispersion. By playing with the dispersion and the wedge-angle it is possible to compensate for the difference in mean loss value due to different particle energy and, in particular, to fully compensate for the losses dependence on the momentum offset if:

$$D^* \tan\frac{\theta}{2} = \frac{1}{2\rho}\left(\frac{dE}{ds}\right)^{-1}_{E_{c0}} \frac{\gamma+1}{\gamma} \frac{\partial}{\partial E_c}\left.\left(\frac{dE}{ds}\right)\right|_{E_{c0}} t_0\, E_c$$

For our simulations, the wedge-angle has been chosen equal to 6^o, as a compromise between the blow-up in horizontal and in longitudinal plane. In particular, if one choses the angle necessary to keep a constant dp/p ($\sim 15^o$), the blow-up in the horizontal plane would be too large and would lead to immediate losses. Figure 3 shows the beam intensity, transverse emittances and longitudinal blow-up as a function of the wedge angle.

Figure 4 shows that, after 1000 turns, 70% of the beam is lost in the machine because it hits the horizontal aperture (which is set to ± 10 cm), to be compared to the expected production rate, which generates a decrease of the circulating beam with a rate of $\tau^{-1} \approx 10^{-4}\nu_0$. This results is not surprising, since the horizontal beta function at the target position is about 8 times larger than the vertical one.

Analytical estimations for the transverse equilibrium emittances [6] lead to $\varepsilon_x = \frac{1}{2}\langle\theta_c^2\rangle (dp/p)^{-1}\beta_x = 82.3\mu m$ in the horizontal plane and $11\mu m$ in the vertical, values

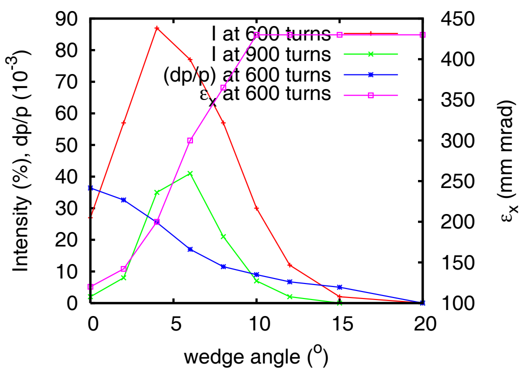

Figure 3: Intensity, horizontal emittance and momentum spread after 600 turns as a function of the wedge angle. The intensity after 900 turn is also reported.

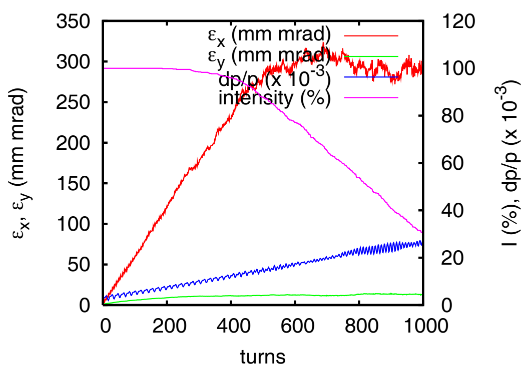

Figure 4: Beam blow-up in the 3 planes, in case of a 6^o wedge angle

which are confirmed in the simulations with zero wedge angle. The lattice should still be optimized and x-y coupling [6] will probably need to be introduced as well.

Losses due to single large-scattering events [10] and to Intra-Beam Scattering also needs to be included in the computations.

CONCLUSIONS AND TECHNOLOGICAL CHALLENGES DISCUSSION

Tracking simulations of ionization cooling in the low energy Production Ring for Beta Beams are now fully in place and benchmarked with analytical formulas. Next steps would be to optimize the lattice, in particular reducing the horizontal beta at the target position and correcting the natural chromaticity.

In parallel with these studies, the feasibility of the production ring is evaluated. The most crucial issue is the requirement in [1] of having a 10^{19}atoms/cm^2 thick gas jet target in the accelerator vacuum environment, which is needed for producing a sufficiently high beta-emitters flux, important for neutrino physics. Existing cluster jet targets reach about 10^{15}atoms/cm^2 [11]. Possible solutions have been investigated. Increasing the injected beam intensity is not feasible, since the proposed ^{7}Li source is already at the limit of the available operational currents ($< 100\mu A$). Living with a poor vacuum in the machine, which could be a solution as long as the residual gas is thin compared to the target, causes problems to the RF cavity. Indeed, since a voltage of about $300keV$ ($Z_{Li} = 3$) is needed at a few MHz, the solution would be to use a capacitive-loaded cavity [12], which needs to be conditioned and operated under vacuum. Working with a lower density would mean having a lower ion productions, but also a better lifetime and therefore a higher intensity circulating in the machine. More detailed studies are needed, especially since we would be in the regime of "thin" targets, with a few collision per traversal, in which the description in terms of Multiple Coulomb Scattering angle and energy straggling are not valid any longer [10], but the possibility to gain a factor 10^4 is very optimistic. We are also considering the direct kinematic option [6], i.e. having a deuterium beam circulating and hitting a lithium target. Issues linked to the heating of the foil or instabilities of the jet, if a liquid target is chosen, will have to be addressed, as well as the unfavorable kinematics leading to small velocities and exit angles of the produced ions.

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