SIMULATION OF THE LOSSES BY DECAY IN THE DECAY RING FOR THE BETA-BEAMS

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1. INTRODUCTION

The aim of the "beta-beams" is to accelerate and store high intensities of highly energetic β radioactive ions until they decay [1]. The problem is that the ions decay during all the acceleration process and the decay products will hit the walls of the PS, SPS and of the decay ring. The activation must be studied in the whole complex [2] (PS, SPS and the decay ring). However, since the stored intensity is the biggest in the decay ring, its design must take into account the power deposition problem very early. In this note, we will focus on the evaluation and the location of this kind of losses in the decay ring. We will see that this determines the dipole length.

When an ion decays, its rigidity changes. Indeed, whereas its momentum change is negligible, its charge number has changed. If Z_0, Z_1, $(B\rho)_0$, $(B\rho)_1$ are respectively the charge number and the rigidity of the source ion and of the product ion, p their momentum, we have :

$(B\rho)_0 = \frac{p}{Z_0 e}$ and $(B\rho)_1 = \frac{p}{Z_1 e}$.

Thus, $\delta = \frac{\Delta(B\rho)}{(B\rho)_0} = \frac{Z_0}{Z_1} - 1$

The deviation due to δ is analogous to the one due to a momentum difference.

For instance, for $^{6}He^{2+}$ (which decays into $^{6}Li^{3+}$), δ = -1/3 and $^{18}Ne^{10+}$ (which decays into $^{18}F^{9+}$), δ = +1/9. This difference is so high that the product ions will quickly be lost when they enter a dipole. Therefore, it is not possible to extract the decay products from the arc. We can only have a design with beam stoppers in the arc in order to limit the depositions in the magnetic elements. To evaluate our design, we added a module to the BETA code giving the amount of the losses on the ring walls. But it does not take into account the effects of the interaction of the decay products with the chamber: we can only predict the peaks of deposition. After hitting the wall, the decay products are supposed to be lost in the chamber. Before putting stoppers, it was necessary to have the right length for the dipoles in order to avoid the depositions there.

2. DIPOLE LENGTH

The central trajectory of an ion stays the same after its decay in a straight section until it enters a dipole. It is strongly deviated besides. In [2], the calculation assumes a uniform repartition of the losses in the arc. But, in reality, the products of the decays in a drift will give a peak after crossing a bend magnet. As the dipoles are the most sensitive elements to the quenching, we must avoid mostly the depositions there. The aim of this paragraph is to calculate the domain of variation of the bend angle as a function of the bend radius and of the chamber sizes in first order. The dispersion function in a dipole is given by: $\rho(1-\cos(\theta))$ with ρ the bend radius and θ the bend angle. The length L of the dipole is equal to $\rho\theta$. The dispersion in the dipole as a function of the path length is then $\rho\left(1-\cos\left(\frac{L}{\rho}\right)\right)$. The deviation for the decay product from a radioactive ion is $\rho\delta\left(1-\cos\left(\frac{L}{\rho}\right)\right)$ (Figure 1).

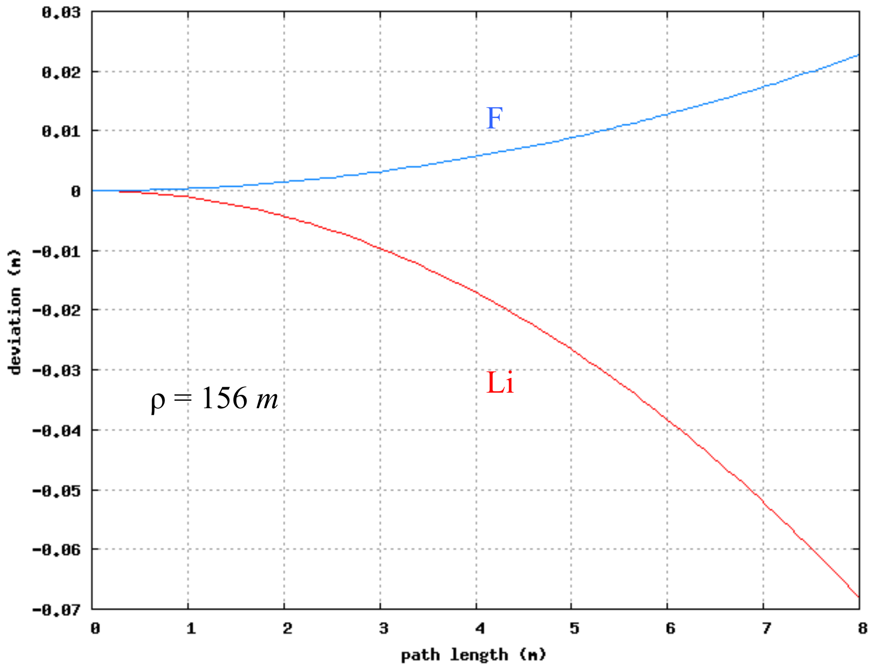


Figure 1 : Deviation of the decay products vs dipole length for the decay products $^{6}Li^{3+}$ and $^{18}F^{9+}$

The dipole has two degrees of freedom: its angle and its radius. We are going to fix the bend radius and calculate the bounds for the angle.

If we want to be sure that the accumulated beam does not hit the chamber, we must have $\rho|\delta|(1-\cos(\theta))+X_{beam}<X_{bend}$ with a half-aperture of X_{bend} for the dipole and a half beam size of X_{beam}. The solution is $\theta_{\max}=\arccos\left(1-\frac{X_{bend}-X_{beam}}{\rho|\delta|}\right)$.

Moreover, the dipole has to be long enough to avoid the depositions on the next magnetic elements. After a L_{SD} long drift, the deviation is $\rho|\delta|\left(1-\cos(\theta)+\frac{L_{SD}}{\rho}\sin(\theta)\right)$. We must have $\rho|\delta|\left(1-\cos(\theta)+\frac{L_{SD}}{\rho}\sin(\theta)\right)-X_{beam}>X_{chamber}$ with a half-aperture of $X_{chamber}$ for the chamber.

The solution is

$$\theta_{\min}=-\arccos\left(1/\sqrt{1+\left(\frac{L_{SD}}{\rho}\right)^2}\right)+\arccos\left(\left(1-\frac{X_{chamber}+X_{beam}}{\rho|\delta|}\right)\bigg/\sqrt{1+\left(\frac{L_{SD}}{\rho}\right)^2}\right)$$

The beam size in the regular lattices is around ±2 cm. We use half-apertures of 6 cm for the dipoles and 4 cm for the chamber. At $\gamma = 100$, the magnetic rigidity for $^{6}He^{2+}$ is 932 T.m. The bend radius is then 156 m for a 6 T field. We use 2 m long drifts. After calculation, if we consider $^6He^{2+}$, the maximum angle for the bend length is about Pi/80 (which corresponds to a 6.13 m length) and the minimum angle is around Pi/89 (which corresponds to a 5.5 m length). Therefore, the dipole length must be between 5.5 m and 6.12 m to avoid the deposition in the dipole and in the next magnet element (Figure 2).

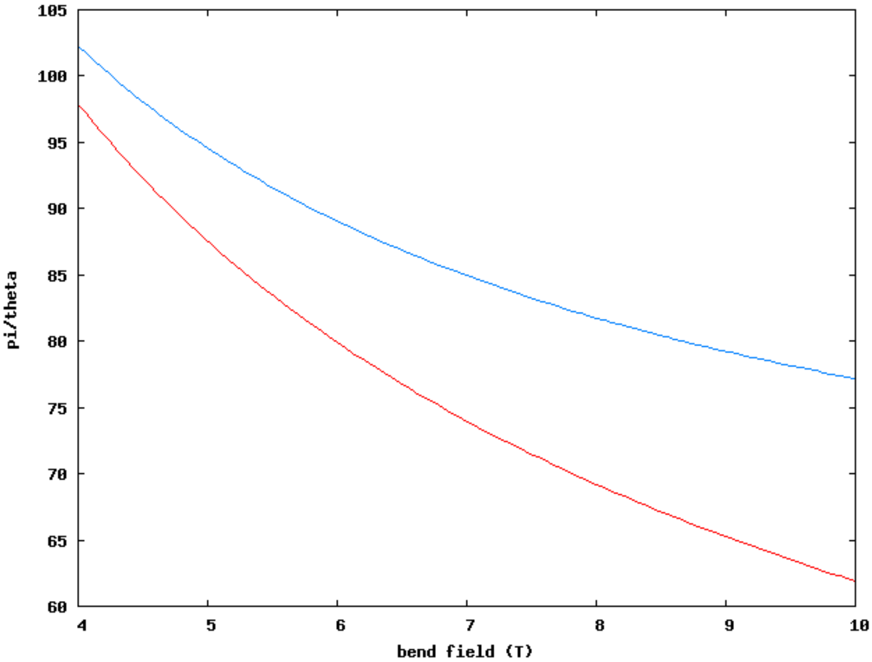


Figure 2 : π/θ vs dipole field to avoid peaks in the magnetic elements
In blue, maximum value. In red, minimum value.

To sum up, the chamber dimensions strongly determine the bounds for the dipole parameters. Since deviation of the decay products is much stronger for $^6He^{2+}$ than for $^{18}Ne^{10+}$, the dipole length is optimized for $^6He^{2+}$.

3. SIMULATION OF THE LOSSES IN THE RING

We have quantified the losses in the arcs at the first order to locate the deposition peaks and to know where we need to insert beam stoppers. The principle is described below.

We divide each element of the structure in small pieces, which gives NB elements. We initialize an array of which each entry corresponds to an element. For each element *i* (*i* going from 1 to NB), we make the structure begin there. Besides, we cut the envelope in N_{sigma} envelopes centered on the closed orbit (Figure 3). Each envelope *j* corresponds to a number n_j of standard deviations σ for the beam distribution f_σ. We transport the beam and we locate the elements Max_i^j and Min_i^j where the extremities of the envelope *j* (corresponding to $n_j\sigma$) hit the chamber. Since the power of the particles comprised between the beam envelopes at $n_1\sigma$ and $n_2\sigma$ is given by the formula $P'L_i \int_{n_1\sigma}^{n_2\sigma} f_\sigma(x)dx$ where *P'* is the power lost per meter, L_i the length of the element *i*, we are able to calculate the power comprised between the extremities of two following envelopes. We assume that the deposition is uniform between them. Thus, to have a power lost per meter, we have to divide by the length of the deposition area. Besides, we add each one of these contributions in the array to have the total deposited power in each element.

We have to precise that our simulation does not take into account the contributions due to multipolar effects (sextupolar , octupolar effects…). For example, the sextupolar kick is not visible in our simulation. It is necessary to use another code to study the blow-up. Recently, we are in collaboration with Dr Jones from TRIUMF to better locate the losses in the ring thanks to his code ACCSIM [3] which realizes quite good tracking simulations. It takes into account the interactions with the matter (possibilities to use FLUKA or GEANT4) and the sextupolar kicks.

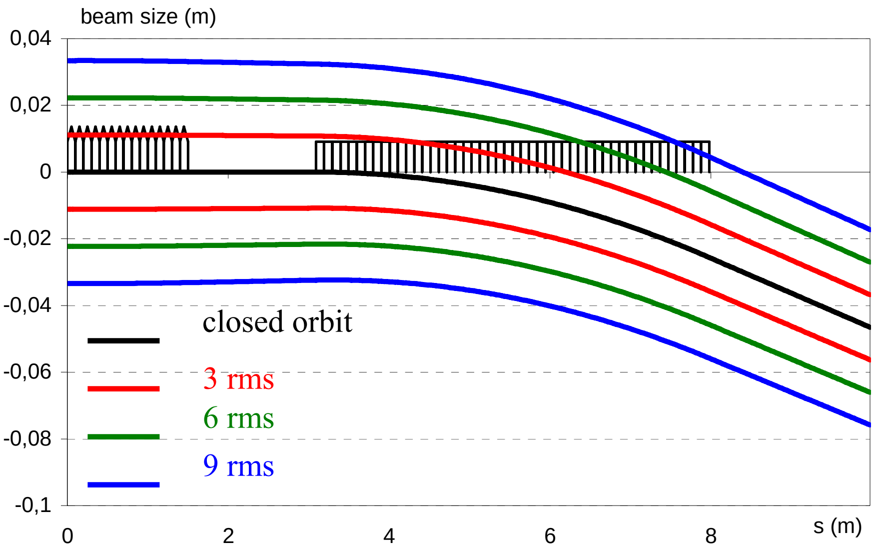


Figure 3 : Beam size of the ions after decaying in the first element for different numbers of rms

4. RESULTS

The number of ions stored in the decay ring as a function of time is:

$N_{stored}(t) = N_0 2^{\frac{-t}{\gamma\tau_{1/2}}}$ with N_0 the stored number of ions just after the merging

γ the relativistic factor

$\tau_{1/2}$ the half-time

The kinetic energy of the stored beam is: $T_{stored}(t) = (\gamma - 1)E_0 I_0 2^{\frac{-t}{\gamma\tau_{1/2}}}$ with E_0 the rest energy of an ion

The lost power by decay is then: $P_{stored}(t) = \frac{\gamma - 1}{\gamma} \frac{E_0 N_0 Ln(2)}{\tau_{1/2}} 2^{\frac{-t}{\gamma\tau_{1/2}}}$

The maximum lost power by decay is: $P_{\max} = \frac{\gamma - 1}{\gamma} \frac{E_0 N_0 Ln(2)}{\tau_{1/2}}$

For the current values, in the top down approach to reach the neutrino fluxes given in [3], we have the Table 1 below.

Table 1 : Beam parameters

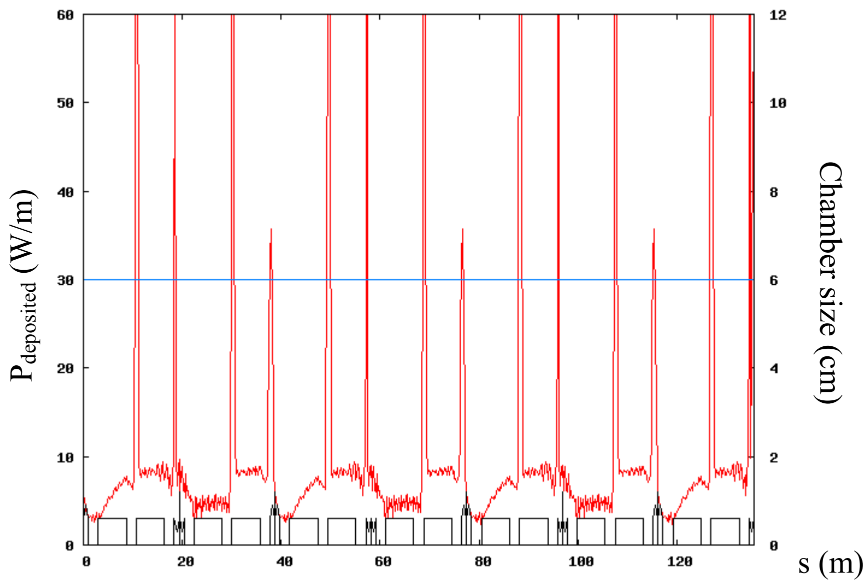
	^{6}He	^{18}Ne
gamma	100	100
rigidity (T.m)	932	559
E_0 of an ion at rest (GeV)	5.61	16.8
Stored intensity	$9.66\ 10^{13}$	$7.42\ 10^{13}$
Stored beam energy (kJ)	8674	19925
Lost power (stored beam) (kW)	74.2	82.7
Lost power (stored beam) (W/m)	10.7	12

The lost powers by $^{6}He^{2+}$ and by $^{18}Ne^{10+}$ are around 11 W/m so we cannot neglect one of them. We assume that the transverse distribution is Gaussian. If we do the simulation for the regular FODO lattice in the ring [5] of which the parameters are in the Table 2, we have the Figure 4.

Table 2 : Parameters of the magnetic elements for the regular FODO lattice in the ring

QUADRUPOLES		
function	length (m)	strength (m^{-2})
QP1	2	$-3.16\ 10^{-2}$
QP2	2	$4.85\ 10^{-2}$
BEND		
bend angle (rad)	bend radius (m)	
Pi/86	156	

The rms emittance value that we used was 0.11 π mm.mrad [5].



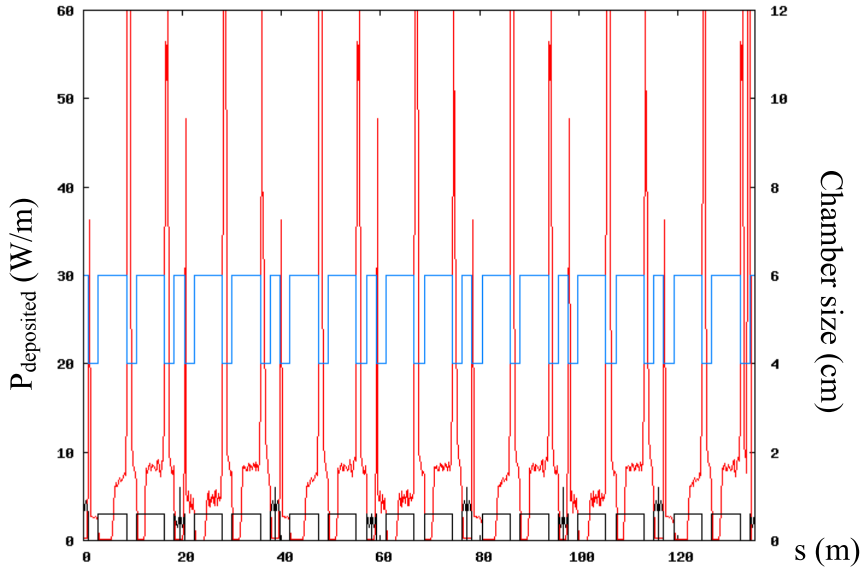


Figure 4 : Losses in the regular FODO lattice for $^{6}He^{2+}$
Above without absorbers, below with absorbers
In red, losses in the regular FODO lattice. The blue line indicates the aperture limit

The Figure 4 proves that it is possible to limit the losses in the magnetic elements by putting beam stoppers in the structure. Without them, we have deposition peaks in the dipoles. It is important to notify that the interactions with the matter are not calculated. The decay products are supposed to be absorbed by the stopper.

On Figure 5, we have plotted the deposition of power per meter in the FODO lattice for $^{18}Ne^{10+}$. We see that a dipole half-aperture of 6 cm is not sufficient and we have deposition peaks at the middle of the dipoles. The dipoles are then likely to quench.

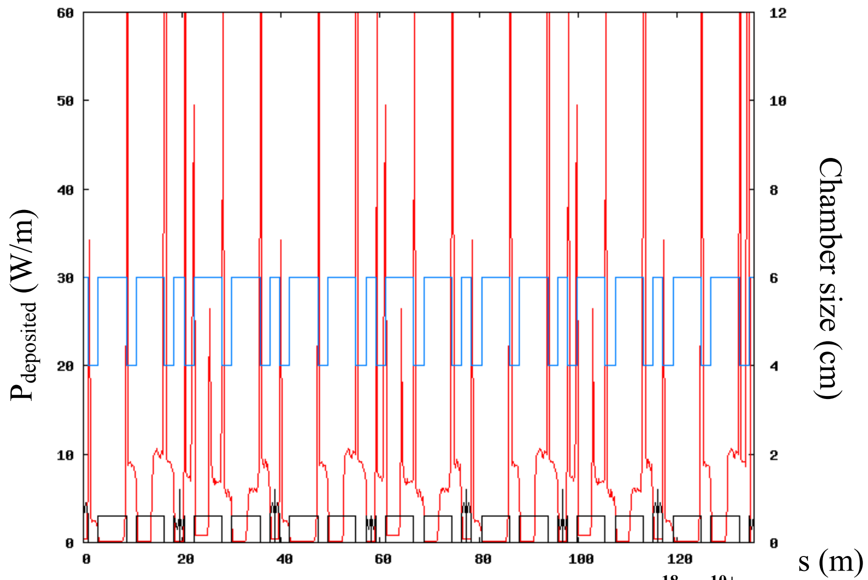


Figure 5 : Losses in the regular FODO lattice for $^{18}Ne^{10+}$
In red, losses in the regular FODO lattice, in blue aperture size

It was predictable if we plot the deviation of the decay products in such a lattice by taking into account the chamber geometry (Figure 6). We clearly see that a half aperture of 6 cm is sufficient for $^{6}He^{2+}$ but not for $^{18}Ne^{10+}$. The decay products hit then the walls of the second magnet at its middle. To avoid that, we can either lengthen the drift or enlarge the dipole aperture. A quick calculation shows that the needed length for the drift would be superior to

10 m with a half aperture of 6 cm. We cannot afford such lengths. So, we must enlarge the dipole half apertures until 8 cm. We obtain then the Figure 7, which shows the deposition of the decay products in the FODO lattice for such a half-aperture in the magnetic elements. The deposition peaks are not located in the dipole anymore in that case.

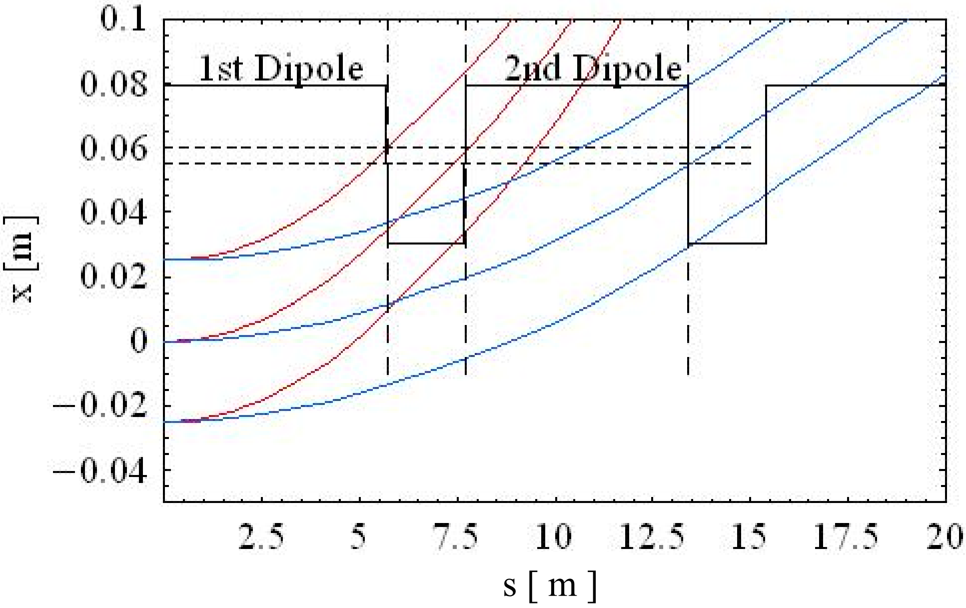


Figure 6 : Deviation of the decay products along the FODO lattice in absolute value
In red $^{6}Li^{3+}$ in blue $^{18}F^{9+}$, the beam size is at 9 σ

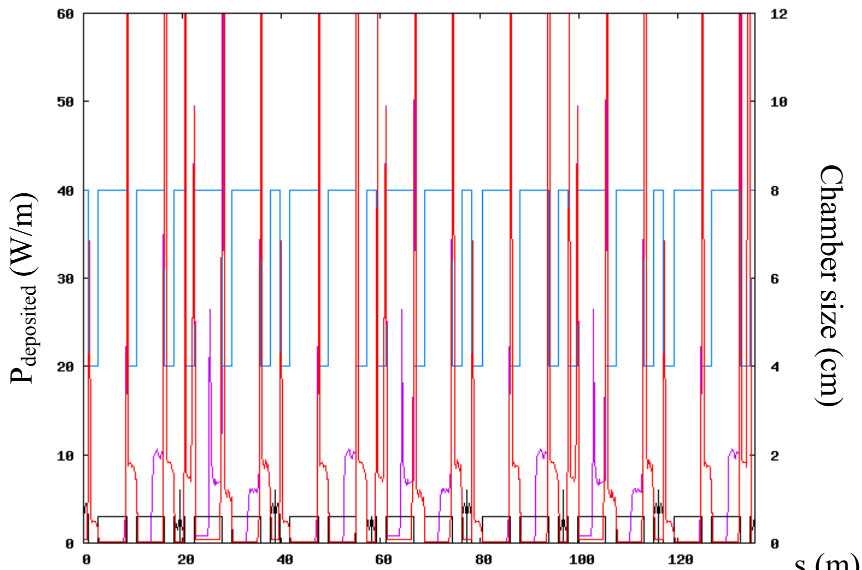


Figure 7 : Losses in the regular FODO lattice for $^{18}Ne^{10+}$ with a half-aperture of 8 cm for the magnetic elements
In red, losses in the regular FODO lattice, in purple losses with a half aperture of 6 cm in the magnetic elements, in blue chamber size

5. SUMMARY

The amount of losses is so high that we have to optimize the design to enable the insertion of beam stoppers in the ring. In the top-down approach, we have to consider at once $^{6}He^{2+}$ and $^{18}Ne^{10+}$. The length of the dipoles is optimized for $^{6}He^{2+}$ and their aperture is enlarged for $^{18}Ne^{10+}$. In order to evaluate our structure, we have written a code which quantifies the depositions in the ring. At the moment, it does not take into account the sextupolar kicks and the interaction with the matter. However, it is quite fast and locates the deposition peaks. We are looking forward to comparing our results with the ones using ACCSIM [4].

6. ACKNOWLEDGEMENTS

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