CONCEPTUAL DESIGN OF AN ELECTRON-NUCLEUS SCATTERING FACILITY AT GSI.

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Abstract

This report presents results of the feasibility study of the electron-nucleus collider, which is under consideration as a possible part of the future extension of the existing fragment beam facility FRS at GSI [1, 2]. It shall be used for experimental investigations of charge radii and charge distributions of nuclei far off stability, i.e. neutron rich and neutron deficient radioactive nuclei.

1 INTRODUCTION

The envisaged equipment consists of an electron storage ring operated at energies, variable between 200 and 500 MeV, and an ion storage ring NESR [3], which is planed to be operated at a set of discrete energies, variable between 200 MeV/u and 740 MeV/u. The electron ring is planned to be fed with electrons at full energy. They would be accelerated in a pulsed 500 MeV linac.

The ion ring is intended to be supplied with the precooled fragment beams from a dedicated Collector Ring CR, capable to cool the secondary beams stochastically to primary beam quality within approximately 100 ms [5].

2 ELECTRON LINAC

Our approach to the linac design is similar to the design of the positron part of VEPP-5 injector complex [4]. This is a normal-conducting S-band 500 MeV linac, capable routinely accelerate a single bunch of electrons with the intensity of up to $2 \cdot 10^{10}$ particles. The only feature, which distinguish our approach from a conventional linac design, is the use of 4 isochronous 180° turns, which provide a step-by-step energy variation in the energy range between 125 MeV up to 500 MeV.

3 INTERACTION REGION OPTICS

In the proposed interaction region optical scheme both beams are flat at the collision point, in spite of equal horizontal and vertical emittances. This is due to a large enough difference between the horizontal and the vertical values of the β-functions at the interaction point (IP). The value of the horizontal β-function is chosen in the range of $100 \div 200$ cm and the vertical β-function is equal to $15 \div 20$ cm.

One problem, which inevitably arises due to significant difference between electron and ion velocities, is the synchronization of particles rotation in two so different rings. The ratio of revolution frequencies obviously should be integer. Beam-beam effects require for this ratio to be as small as possible. We think, that the acceptable value for this ratio is $n = 5$ for the highest ion's energy 740 MeV/u.

mElectron and ion beams collide at zero angle. The electron ring can be placed outside as well as inside of the ion ring circumference.

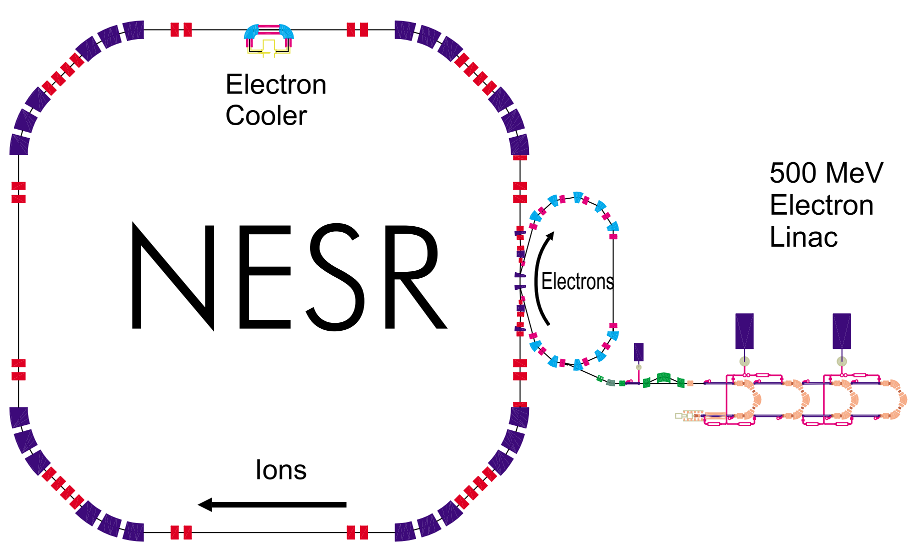

Figure 1: General layout of the e-A collider

Opposite to the interaction region of the electron ring a long dispersion-free drift section is foreseen, which, in general, can be used for many purposes, for instance, for the accomodation of SASE-laser, undulators, high-field wigglers or Siberian Snake.

In one of the straight section of the ion ring an electron cooling device will be placed, which will provide an extensive cooling rates of both transversal and the longitudinal ion emittances.

4 ELECTRON RING

In the first version of the electron ring 15° separation magnet is positioned very close to the IP, namely in 50 cm. The main advantage of this optical structure is that ion and electron beams are separated very quickly after they have collide and, therefore, the most largest number of bunches can be stored in both rings, say 24 electron bunches and 120 ion bunches.

In the second version of the electron ring lattice a magnet free space is equal to ± 2.0 m from the IP. Electron ring final focus quads are placed in the common with the ion ring straight section. The separation magnet is behind these two quads. As disadvantage we shall consider a large distance from IP to the final focus quads of the ion ring and, correspondingly, large β-functions values in these quads.

The remaining part of the half-arc in both versions is comprised by 5 elementary cells, each containing the 33° magnet, the quad doublet and the drift 120 cm long. Half-arc is ended by a dispersion free long straight section, which is quite suitable for housing there different insertions.

The harmonic number of the electron ring RF system was chosen to be $h = 24$, which corresponds to the operational frequency $f_{RF} = 53.043$ MHz. Such a choice was dictated partly by the need to be able to achieve the design bunch length $\sigma_s = 4$ cm, and partly by the need to have enough freedom in choice of number of circulating bunches: 1, 2, 3, 4, 6, 8, 12 or 24 bunches.

In order to ensure the longitudinal and also the transverse beam stability, the cavity can be made either with proper HOM frequency adjustment, or with HOM damping by absorbing loads.

5 ION RING INTERACTION REGION

Achieving of high luminosity of the e-A collider implies an operation in the mode of low β-functions at the interaction point, therefore, the NESR optics should be essentially modified for this kind of operation.

A detailed optics study has shown, that more or less easy it is possible to achieve of 15 ± 20 cm for the value of a vertical β-function and 100 ± 150 cm for the horizontal β-function.

Main parameters of both rings for the most heavy ions with Z=92, A=238 (A/Z=2.587), with velocity $\beta_i = 0.8303$ and kinetic energy T=740 MeV/u (this corresponds to the rigidity of 11.976 T·m) are listed in the Table 1.

Table 1: General parameters of the electron-nucleus collider for the case of A=238, Z=92 and $\beta_i = 0.8303$

	Units	Electron ring	Ion ring
Circumference	m	45.215	187.717
Energy	$GeV, GeV/u$	0.500	0.740
Revolution frequency	MHz	6.63	1.326
Betatron tunes, ν_x, ν_z		3.8, 2.8	3.8, 3.8
Compaction factor, α		0.056	0.036
Bending radius	m	1.25	8.125
Number of bunches		8	40
Bunch to bunch spacing	m	5.65	4.7
Bunch population		$5 \cdot 10^{10}$	$0.92 \cdot 10^{7}$
Beam currents	mA	425	7.2
Energy losses/turn	keV	4.423	
Total radiated power	kW	1.88	
Damping time, τ	ms	34	20
Beam emittances, $\varepsilon_{x,z}$	$\mu m \cdot mrad$	50	50
Beta functions at IP, $\beta_{x,z}$	cm	100, 15	100, 15
Beam size at IP, $\sigma_{x,z}$	μm	220, 87	220, 87
Beam divergence at IP, $\sigma_{x',z'}$	$mrad$	0.22, 0.58	0.22, 0.58
Momentum spread, $\sigma_{\Delta p/p}$		.00036	.0004
Bunch length, σ_s	cm	4	15
Beam-beam parameters, $\xi_{x,z}$		0.005, 0.002	0.046, 0.018
Laslett tune shift, $\Delta\nu$			0.1
Luminosity	$cm^{-2}s^{-1}$	$1 \cdot 10^{28}$	

6 LUMINOSITY CONSIDERATIONS

In general, the luminosity in a collider is given by the equation:

$$L = F_i n_i \frac{N_{eb} N_{ib}}{4\pi \sigma_x \sigma_z} \tag{1}$$

where F_i is an ion revolution frequency, n_i is a number of ion bunches (we recall, that $F_i n_i = F_e n_e$) , σ_x is the horizontal beam size at collision point and σ_z is the vertical, N_{eb} and N_{ib} are the bunch populations for electrons and ions.

The most important limitation arises from the **beam-beam effect**, which is characterized by the ions tune-shifts:

$$\begin{aligned} \xi_{ix} &= \frac{Z}{A} \cdot \frac{N_{eb} r_p \beta_x}{2\pi \gamma_i \beta_i (\sigma_x + \sigma_z)\sigma_x} \\ \xi_{iz} &= \frac{Z}{A} \cdot \frac{N_{eb} r_p \beta_z}{2\pi \gamma_i \beta_i (\sigma_x + \sigma_z)\sigma_z} \end{aligned} \tag{2}$$

where r_p is the classical proton radius, γ_i and β_i are the ion relativistic factors.

With a strong electron cooling we can expect that a threshold in the ion beam-beam tune shift may reach $\xi_{ix} = 0.05$ — a typical value for electron-positron colliders. One can see, that the beam-beam limited luminosity is proportional to $F_i n_i N_{ib}$, otherwise it is proportional to the ion revolution frequency and the total number of ions $N = n_i \cdot N_{ib}$ in all n_i bunches, see the red solid line on the Fig.2.

The second process, which becomes important in the case of very intense ion beam, is a **space-charge effect**.

Electromagnetic fields of an ion bunch defocus an ion particle, with the resulting space charge tune-shift $\Delta\nu$ being equal to:

$$\Delta\nu = \frac{Z^2}{A} \cdot \frac{N_{ib} r_p}{\gamma_i^3 \beta_i^2 \varepsilon} \cdot \frac{R}{2\sqrt{2\pi}\sigma_s} \qquad (3)$$

where σ_s is the ion bunch length and ε is the transverse emittance.

With a powerful electron cooling all three emittances will shrink until the space-charge tune-shift will reach its highest possible value of about $0.1 \div 0.15$.

If the space charge limited ion beam emittance is large than the electron one, then luminosity is equal to:

$$\begin{aligned} L_{\Delta\nu} &= F_e n_e \cdot \frac{A}{Z^2} \cdot \frac{N_{eb} \Delta\nu \gamma_i^3 \beta_i^2}{4\pi r_p \sqrt{\beta_x \beta_z}} \cdot \frac{2\sqrt{2\pi}\sigma_s}{R} \qquad (4) \\ \xi_{xi} &= \frac{1}{Z} \cdot \frac{N_{eb}}{N_{ib}} \cdot \frac{\Delta\nu \gamma_i^2 \beta_i}{2\pi \left(1 + \frac{\sigma_z}{\sigma_x}\right) \sqrt{\beta_x \beta_z}} \cdot \frac{2\sqrt{2\pi}\sigma_s}{R} \end{aligned}$$

So, the space charge limited luminosity does not depend on the number of ions. It saturates at a level, determined by the equation (4). This is shown on the Fig.2 for three different ion species by the three horizontal lines on the height, which is proportional to the factor A/Z^2 and to a number of bunches. On the Fig.2 we plot these three saturation levels in the assumption, that number of ion bunches is equal to $n_i = 120$ and that number of electron bunches is equal to $n_e = 24$. This corresponds to the distance to first parasitic crossing $L_p = 85.5cm$.

7 ELECTRON COOLING

Electron cooling plays an extremely important role, providing the stacking of short lived ion species as well as suppression of strong beam-beam effects and fighting against of intrabeam scattering [7]. The cooling times in the order of 100 ms are needed for these purposes.

8 CONCLUSION

The discussed above the electron-nucleus scattering facility can provide the luminosity ranging from $1 \cdot 10^{26}$ cm^{-2}s^{-1} up to $3 \cdot 10^{29}$ cm^{-2}s^{-1}, depending on the nuclei specie, yields, life time, stacking factor and so on.

Preservation of the longitudinal polarization of the electron beam can be provided by installing of a Siberian Snake in a special long straight section of the electron ring.

The choice of a certain detector scheme may strongly influence on lattices of both rings, therefore in the next step main efforts should be concentrated on the design of a high momentum resolution magnetic spectrometer for the scattered electrons.

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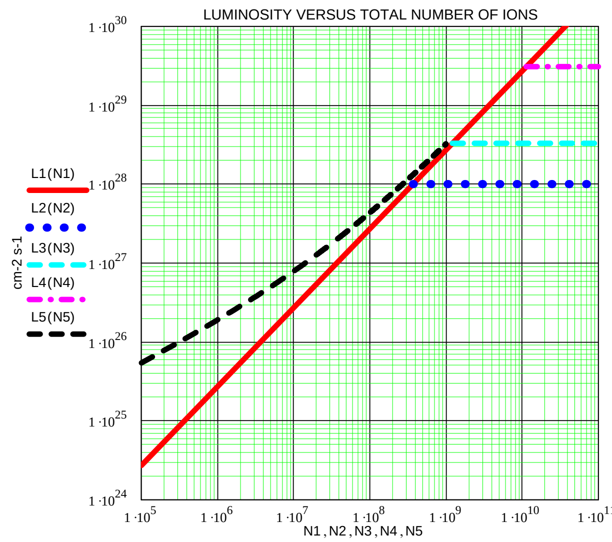

Figure 2: Luminosity dependence on the total number of ions. The red line corresponds to the beam-beam limitation with $\xi_{ix} = 0.045$. The black dashed line shows the additional luminosity benefit, which can be achieved with a small number of ions in the operation mode with the significantly reduced ion beam emittance with respect to the electron one. In this case the electron beam density is assumed to be about 10 times higher at $N = 10^5$ and gradually falls down to a normal value at $N = 10^9$. Three upper horizontal lines correspond to a limitation due to the space charge effect for different ion species, namely for Z=3 (dashed-dotted purple), Z=28 (dashed green), Z=92 (dotted blue). In all cases we admit $A/Z = 2.587$, $N_{eb} = 5 \cdot 10^{10}$, $n_i = 40$ and $n_e = 8$.

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