Dual-structure features for heavy ion and light particles at NICA collider

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Introduction

For successful collider experiments, it is essential to maintain a sufficient beam lifetime. Additionally, it is crucial to solve transition energy issue in order to achieve the desired beam emittance required for high luminosity.
The dual magneto-optical structure opens up the prospect of accelerating both heavy ions, such as gold, and light particles like protons and deuterons.

Beam Lifetime

The lifetime of the beam luminosity in a collider experiment is achieved through the reduction of intra-beam scattering effects, coupled with the application of stochastic and electron beam cooling techniques. This approach assumes particular significance when dealing with high-intensity ion beams.

$$\begin{aligned} \frac{d\varepsilon}{dt} &= \underbrace{-\frac{1}{\tau_{tr}} \cdot \varepsilon}_{\text{cooling}} + \underbrace{\left(\frac{d\varepsilon}{dt}\right)_{IBS}}_{\text{heating}} \\ \frac{d\delta^2}{dt} &= \underbrace{-\frac{1}{\tau_{\text{long}}} \cdot \delta^2}_{\text{cooling}} + \underbrace{\left(\frac{d\delta^2}{dt}\right)_{\text{IBS}}}_{\text{heating}} \end{aligned} \tag{1}$$

ε – transverse emittance, $\tau_{tr}, \tau_{\text{long}}$ – transverse/longitudinal cooling time, δ – momentum spread.

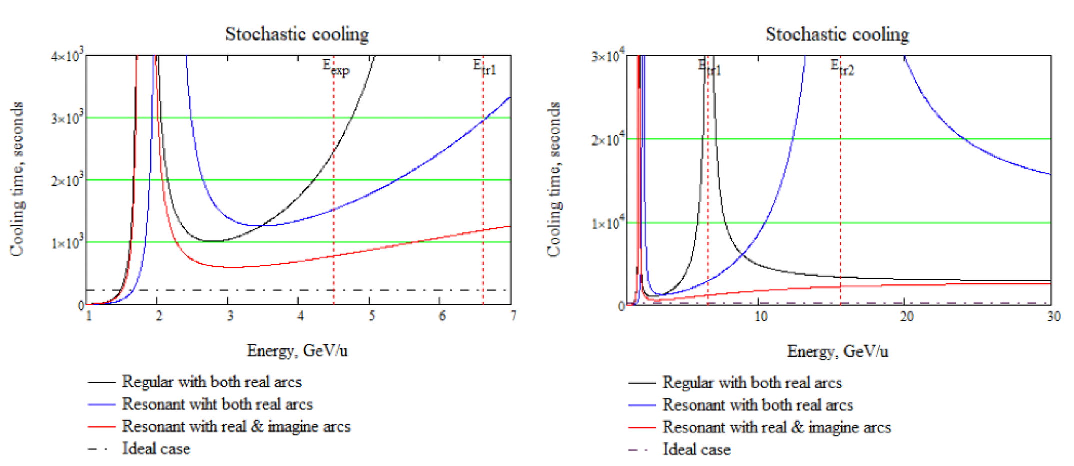
Stochastic Cooling

The cooling rate can be determined [1]:

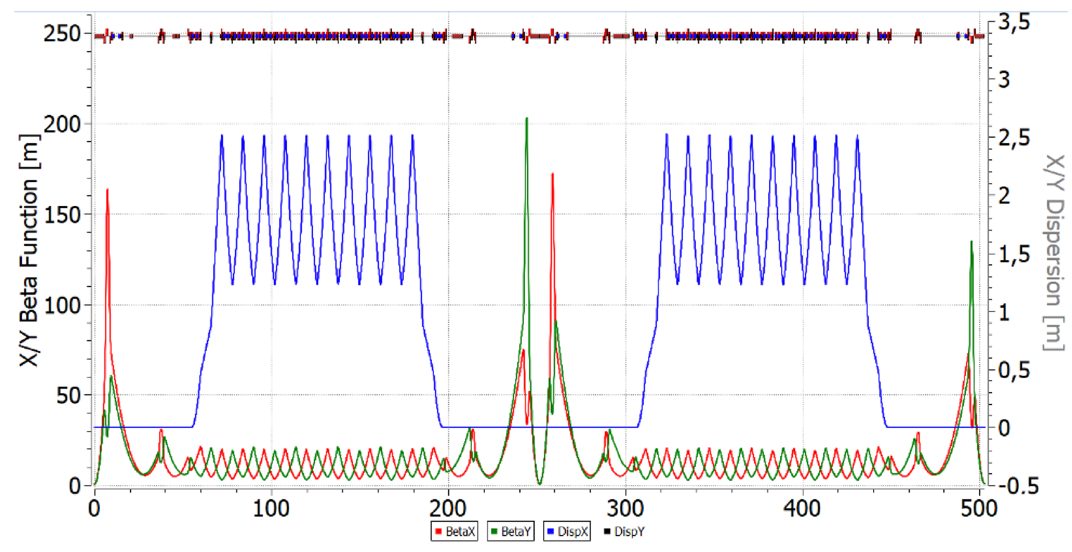
$$\frac{1}{\tau_{tr,l}} = \frac{W}{N} [\underbrace{2g\cos\theta\left(1 - 1/M_{pk}^2\right)}_{\substack{\text{coherent}\\ \text{effect(cooling)}}} - \underbrace{g^2\left(M_{kp} + U\right)}_{\substack{\text{incoherent}\\ \text{effect(heating)}}}] \tag{2}$$

The mixing coefficients are defined as

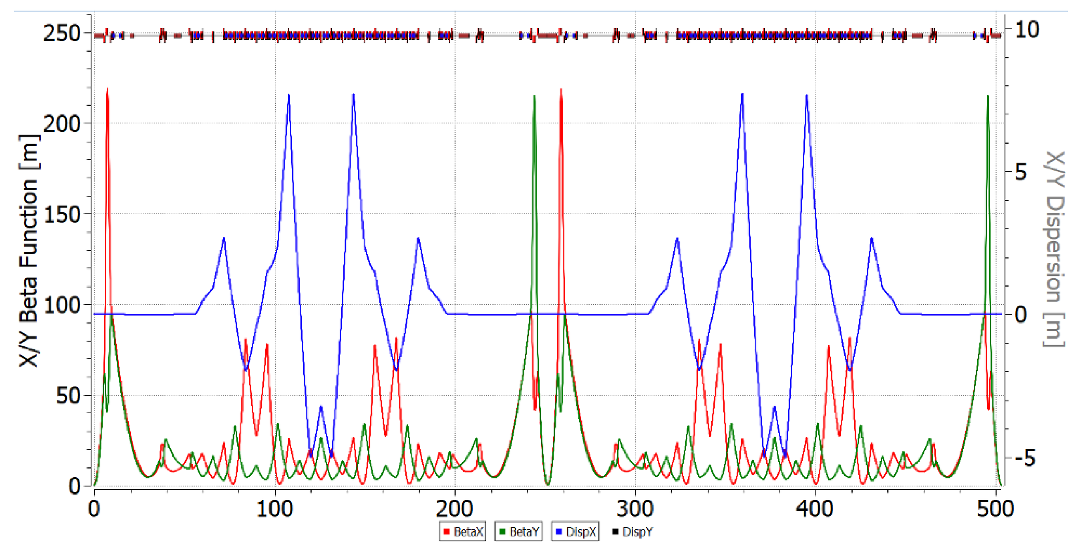
$$\begin{aligned} M_{pk} &= \frac{1}{2\left(f_{\max} + f_{\min}\right)\eta_{pk} T_{pk} \frac{\Delta p}{p}}, \\ M_{kp} &= \frac{1}{2\left(f_{\max} - f_{\min}\right)\eta_{kp} T_{kp} \frac{\Delta p}{p}} \end{aligned} \tag{3}$$



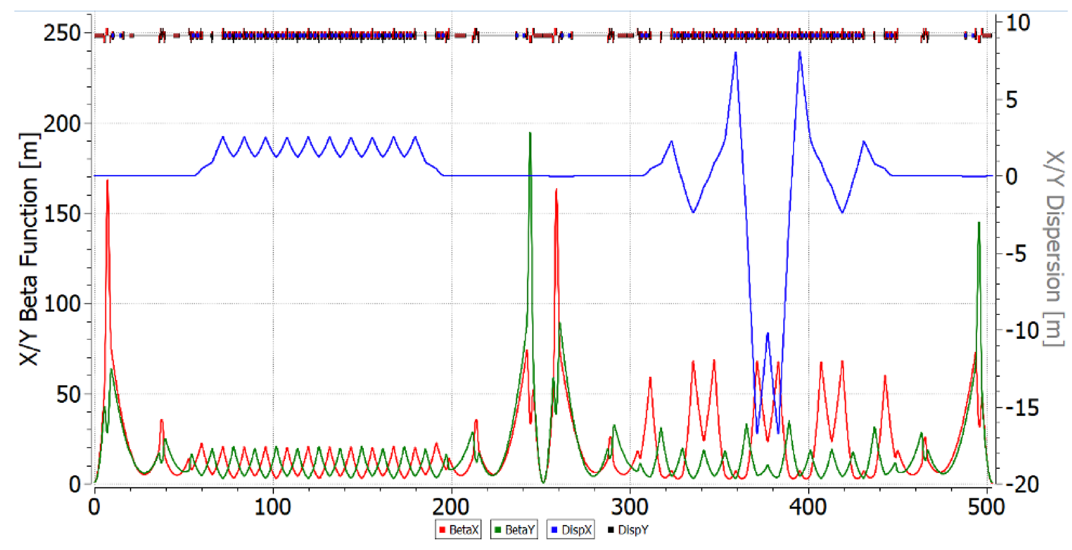
Structures



"Regular". The straight sections remain constant in all structures. Their arrangement doesn't affect the IBS and transition energy. To suppress dispersion in the *"regular"* structure used 'missing magnets' technic [2].



"Resonant". Based on the resonant principle [3] and can be obtained from *"regular"* one by dividing quadrupoles into 2 families. Transition energy can be adjusted to increase it above the experiment energy.



"Combined". In the case of a *"combined"* structure, one arc operates in a *regular* mode,

$$\eta_{pk} = 1/\gamma_{tr}^2 - 1/\gamma^2 \tag{4}$$

while the other employs resonant modulation

$$\eta_{kp} = -1/\gamma_{tr}^2 - 1/\gamma^2 \tag{5}$$

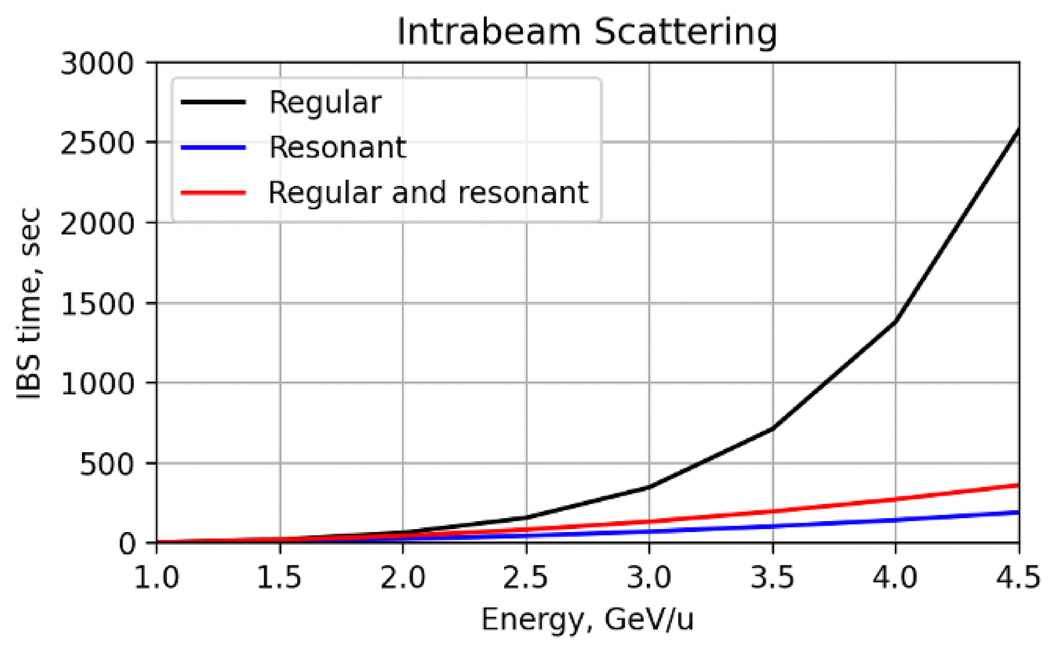
In *"resonant"* optics the second asymptotic is at higher energy compared to the *"regular"*. In *"combined"*, the cooling efficiency is closer to the ideal value in a large energy range from 2.5 to 4.5 GeV, while in *"regular"* optics the cooling rate is almost two times lower at the most optimal point ~ 3 GeV. This behaviour is explained by absence of the second point of asymptotic growth.

Intra-Beam Scattering (IBS)

The selection of an appropriate cooling technique hinges on comparing its characteristic time scales with the rate at which the beam is heated due to intra-beam scattering.

$$\frac{1}{\tau_{IBS}} = \frac{\sqrt{\pi} c Z^2 r_p^2 L_C N}{4 \quad A \cdot C_{\text{orb}}} \frac{\langle \beta_x \rangle}{\beta^3 \gamma^3 \varepsilon_x^{5/2} \left\langle \sqrt{\beta_x} \right\rangle} \left(\left\langle \frac{D_x^2 + \dot{D}_x^2}{\beta_x^2} \right\rangle - \frac{1}{\gamma^2} \right) \tag{6}$$

It should be expected that in optics with a value η close to zero, the heating rate should decrease. Heavy ion beam $^{197}_{79}Au$ of the NICA collider with maximum luminosity $10^{27}\ sm^{-2}s^{-1}$.



It can be concluded that in a *regular* structure, stochastic cooling is able to balance intra-beam scattering in the energy range $W \geq 4.5$ GeV. In *resonant* structures, the IBS time is notably reduced. This is explained by the fact that the structure has a greater ratio $\left\langle \frac{D_x^2 + \dot{D}_x^2}{\beta_x^2} \right\rangle$ between the dispersion and the beam β-function than in the case of a *regular*. Thus, for the case of heavy ions, the configuration should be *regular* and minimally modulated. Electron cooling is used in the *regular* structure to cool the beam lower 4.5 GeV.

Transition Energy

In the context of light nuclei, such as protons and deuterons, the IBS time experiences a significant increase as the charge decreases. Consequently, the issue of intra-beam scattering becomes critical for heavy-ion beam. Owing to the charge-to-mass ratio, the peak energy of the proton beam amounts to approximately 13 GeV. Meanwhile, the transition energy of the *"regular"* structure, which acts as a characteristic of the accelerator magneto-optical structure, stands at 5.7 GeV. Thus, transition energy needs to be overcome. Previously, has been demonstrated that dispersion modulation can increases transition energy or even reaches a complex value in a *"resonant"* structure [4].

CONCLUSION

The dual magneto-optical structure is proposed for accelerating both heavy ion and light particle beams, exemplified by the NICA facility. Shown that the stochastic cooling time in *"resonant"* and *"combined"* structures is significantly shorter than in *"regular"* ones. However, due to modulation of β-function and D dispersion, the time of intra-beam scattering decreases. For this reason, a *"regular"* magneto-optic structure with minimally modulated dispersion and β-function is optimal in the heavy-ion mode. In the case of protons, the problem of overcoming the transition energy is important, for this a *"resonant"* or *"combined"* magneto-optical structure can be used. It does not require a significant adjustment, only the allocation of a separate focusing quadrupole family.

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