

Matched Electron Cooling

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Abstract

Electron cooling of an ion beam is considered in a ring with coupled optics matched with the solenoid of a cooling section. Betatron motion of ions is then represented as a superposition of the two independent circular modes of the two uncorrelated uncoupled canonical emittances, similar to the drift and cyclotron modes of an electron beam in a solenoid. Then cooling of the ion cyclotron mode is not limited by the ion space charge. Cooling of the drift mode is attained by use of dispersion of both beams introduced to the solenoid section. Ion optics organized in this way allows one to drastically diminish the space charge impact on the 4D emittance at beam stacking in a booster and cooling in a collider ring, thus enhancing the cooling rate. Equilibrium due to the IBS is estimated. We also evaluate the gain in luminosity by means of a round to flat beam transformation around the Interaction Point.

Outline

- Introduction: Magnetized Electron Cooling
- Circular Modes Rings (CMR)
- Space charge and cooling in CMR
- CMR with electron cooling
- Cooling of the cyclotron mode
- Dispersive cooling for drift mode
- IBS impact
- Use of CMR
- Resume

ERL-based Circulated Magnetized HEEC

- Canonical emittances (norm) in solenoid:**

Cyclotron emittance: $\varepsilon_c = \frac{T_c}{eB} = \frac{eBr_c^2}{2mc^2}$;

Drift emittance: $\varepsilon_d = \frac{eBa_0^2}{2mc^2}$;

$$\varepsilon_{4D} = \varepsilon_c \cdot \varepsilon_d = \frac{T_c}{4mc^2} a_0^2 = \frac{1}{4} \left(\frac{p_{\perp 0}}{mc} a_0 \right)^2 \equiv \varepsilon_0^2$$

$$r_c = \frac{p_{\perp}}{eB} \sim (5 - 15) \mu m ; \quad a_0 \sim (1 - 3) mm$$

$$\varepsilon_c \sim (.01 - .1) \mu m ; \quad \varepsilon_d \sim (10^2 - 10^3) \mu m$$

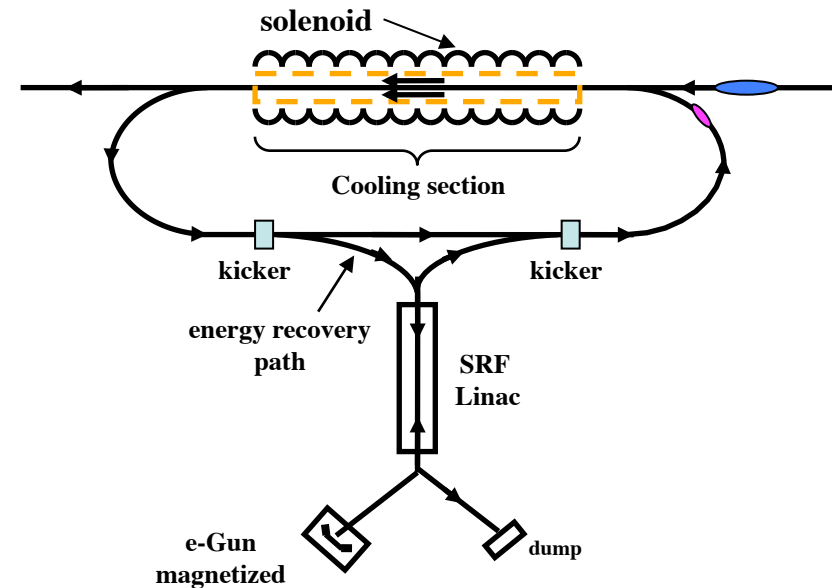
$$Br_c^2 = inv \quad Ba_0^2 = inv ;$$

- Reduction of Laslett' detune:**

At non-magnetized cathode: $\Delta v_0 = \frac{Nr_e \Pi_c}{4\pi\sqrt{2\pi}\gamma^2 \varepsilon_0 \sigma_z}$

Magnetized round beam (rotation drift in SpCh field):

$$\Delta v_d = \frac{Nr_e \Pi_c}{4\pi\sqrt{2\pi}\gamma^2 \varepsilon_d \sigma_z} = \Delta v_0 \sqrt{\frac{\varepsilon_c}{\varepsilon_d}} = \Delta v_0 \frac{r_c}{a_0}$$



- E-gun cathode immersed in solenoid
- Optical matching between bends and solenoids
- **Circulator-cooler** ring makes up to 100 time reduction of the required beam current from injector/ERL
- **Fast kicker** operated at 15 MHz repetition rate and 2 GHz frequency bandwidth are required (**obertonal SRF concept** in development at JLab; **beam-beam kicker** SBIR proposal will be submitted (Fermilab & JLab))

Magnetized e-beam transport

- At cathode immersed in solenoid, the gun generates almost parallel (laminar) beam (Larmor circles due to temperature and aberrations are very small compared to beam size)
- Such beam state is then transplanted to the solenoid in cooling section (preserving the magnetic flux across the beam area)
- MB can be emitted from solenoid and transported through ERL as round-rotated in the axial or quadrupole optics, arcs, and injected through a matching insertion into the cooling solenoid
- The solenoid field can be controlled to make e-beam size matching properly the ion beam size.

Strong reduction of e-beam divergence and misalignments impacts to cooling rates (magnetized EC) – thanks to freezing of electron transverse motion in solenoid

Cooling rates in a magnetized e-beam

- Strong reduction of e-beam divergence (both the original and acquired because of the transport aberrations) and misalignments impacts to cooling rates – thanks to freezing of electron transverse motion in solenoid
- Short term (instantaneous) rate:

$$\tau_c^{-1} = \frac{4\pi Z^2 e^4 n_e}{\gamma^2 A m_p m_e} < \left[\frac{\ln(r_c/\rho_{min})}{u^3} + \frac{\ln(\rho_{max}/r_c)}{u_d^3} \right] >$$

$$\frac{\vec{u}}{c} = \gamma(\vec{\theta}_i - \vec{\theta}_e), \frac{\gamma_i - \gamma_e}{\gamma}; \quad \frac{\vec{u}_d}{c} = \gamma(\vec{\theta}_i - \vec{\theta}_{ed}), \frac{\gamma_i - \gamma_e}{\gamma}$$

$$\frac{Ze^2}{\rho_{min}} = m_e u^2; \quad \rho_{max} = u_d \cdot \min\left(\frac{l_c}{\gamma c}; \frac{1}{\omega_e}\right); \quad \omega_e = (4\pi n_e e^2 / \gamma m_e)^{1/2}$$

- Long term rate (averaged over many ion revolutions):

$$(\tau_c^{-1})_{max} = \frac{\pi^2 Z^2 r_p r_e \dot{N}_e}{A \gamma I_x I_y I_z} \cdot \frac{\Delta\gamma_i}{\sqrt{(\Delta\gamma_i)^2 + (\Delta\gamma_e)^2}} \cdot \frac{S_i}{S_e} \cdot \frac{l_c}{\Pi_i} \cdot (\ln)_{ad}$$

$$S_i \leq S_e$$

$$\sigma_{zi} \geq \sigma_{ze}$$

Advantages of the magnetized EC

- Magnetized gun generates (in space superposition) two invariant **Circular Modes (CM)** of the e-beam of two very unequal transverse sizes:
 - *Drift mode* of a huge canonical emittance (3-5 hundred of μm) associated with beam size at cathode
 - *Cyclotron mode* of a small canonical emittance associated with Larmor circles of electrons (very small compared with the beam radii)
- Space charge does not limit emittance of the cyclotron mode.
- Huge *drift emittance* results in:
 - Strong reduction *Laslett detune* in cooling section and in whole the e-ring
 - Strong (if not complete) suppression of CSR in arcs (by a large longitudinal slip in arcs due the drift emittance and dispersion)

CM optics for Ion Beam?

By the way, there is the following serious issue of the MEIC design:

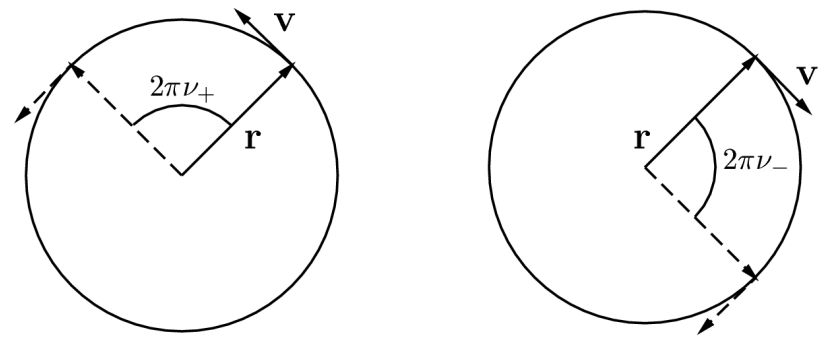
- **Space charge** of short ion bunches of MEIC does limit luminosity of the collider in the “low” energies region

**Observation of features of a magnetized e-beam transport
provokes a question:**

CM optics for Ion Beam?

Circular Modes Transport (CMT) & Rings (CMR)

- Design beam transport around a ring creating two circular modes (CM) of two naturally opposite helicities.
- Each of two individual CMs will look at a point of the orbit as a round (more generally, elliptical) turn by turn rotating pencil beam with some phase advance.



Circular modes

- CMs may occupy all the beam transport (ring or line)
but also:
- CMs can be created from (annihilated to) *planar modes* in a region of a ring or line applying ***round to flat transformations*** (RFT)
- CMs can be *magnetized* by *cooling solenoid*

Ion space charge with CMs

- Laslett detune of two CM modes is intrinsic-equate:

$$\Delta\nu_{\downarrow 1} = \Delta\nu_{\downarrow 2} = \Delta\psi / 2\pi = I_{\downarrow peak} / I_{\downarrow A} \cdot Z_{m\downarrow e} / A_{m\downarrow p} \cdot \Pi / 4\pi\gamma^{\uparrow 2} \beta_{\downarrow L} (\varepsilon_{\downarrow 1} + \varepsilon_{\downarrow 2}) ; \quad (I_{\downarrow A} \equiv 17 \text{ KA}; \quad \beta_{\downarrow L} \equiv v/c)$$

- Similar to magnetized e-beam, beam space charge can be “settled” just into one of two CMs, leaving other “empty” i.e. having a very low emittance:

$$\varepsilon_{\downarrow 1} \Rightarrow Z_{m\downarrow e} / A_{m\downarrow p} \cdot \Pi_{\downarrow i} / 4\pi\gamma^{\uparrow 2} \beta_{\downarrow L} \Delta\nu_{\downarrow i} ; \quad \varepsilon_{\downarrow 2} \ll$$

- On the background of large CM, the small one manifests in a low “temperature” of the round-rotating beam

Beam Cooling with CMs

- Cooling of small CM will not be stopped by the SpCh
- Applicable to stochastic cooling
- What about electron cooling?
- Applicable to EC in principle as well, but cooling rate can be limited by rotation of the “large” CM
- Can we eliminate this rotation in cooling section?
- Yes, we can

“Magnetized” Ion Beam

or

CMs matched with solenoid

- One of two CMs can be matched with the *drift motion* of solenoid
- Consequently, other CM becomes matched with the *cyclotron motion* of ions in the solenoid
- Matching requires expansion of beta-function in the enter/exit areas to that of the solenoid:

$$\beta \Rightarrow \beta_{\downarrow s} = 2\gamma\beta_{\downarrow L} A m_{\downarrow p} c^2 / ZeB$$

- Ratio of beams' sizes in solenoid: $\sigma_{\downarrow id} = \sqrt{A \varepsilon_{\downarrow id} / ZeB m_{\downarrow p} c^2} = \sqrt{A/Z m_{\downarrow p} \varepsilon_{\downarrow id} / m_{\downarrow e} \varepsilon_{\downarrow ed} \sigma_{\downarrow ed}}$

Cyclotron and longitudinal cooling

- In a homogeneous e-beam one can cool the CyM and energy spread
- However, ion beam size may exceed the e-beam size (at least for initial ion beam)
- *Scanning e-beam* is solution for this issue

Dispersive cooling of the drift mode

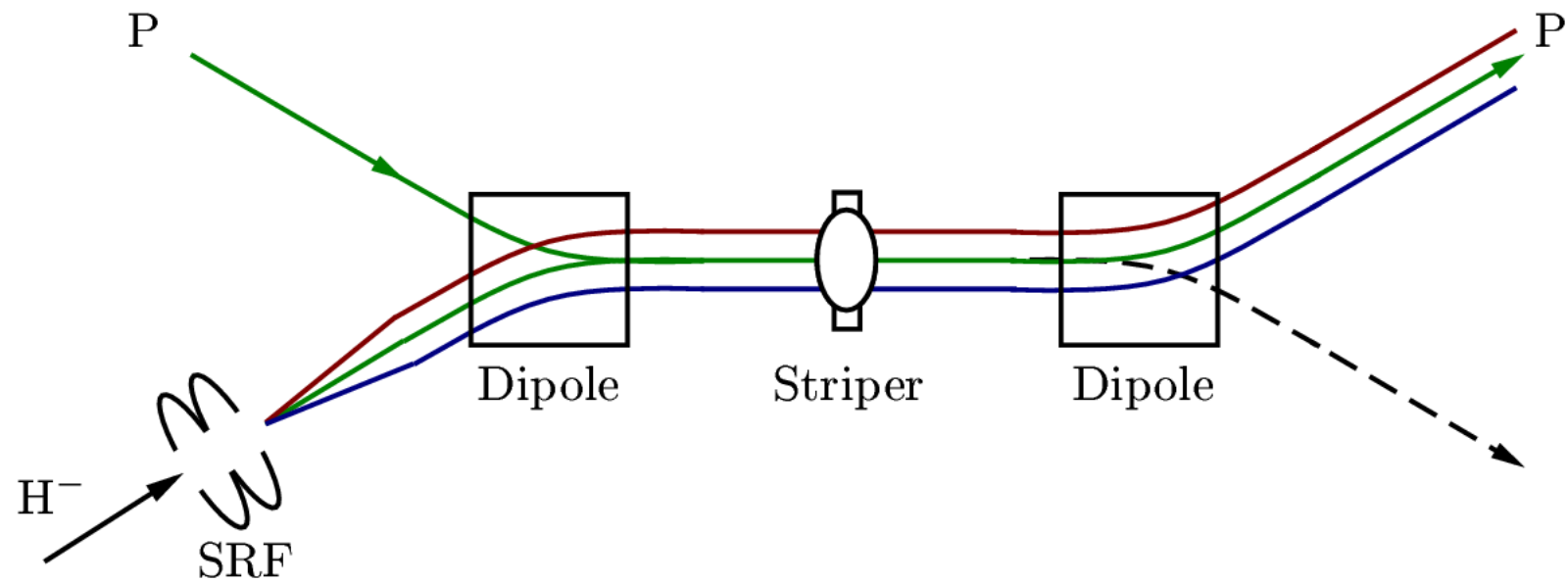
- To attain the drift cooling, introduce dispersion of appropriate magnitude and sign for both beams in solenoid
- Comment on organizing i-beam dispersion:
while zooming the ion beta-function to match solenoid, one can avoid undesirable growth of the dispersion, by a specific design of the dipole/quadruple lattice of the zooming section
- Possible alternative to e-dispersion:
 - Make scanning of e-beam *gradient-inhomogeneous*

IBS in CM rings

- *Cyclotron cooling* can be stopped by IBS in ion beam around the CM ring
- Below the *transition energy* (TE) (approximately...), IBS heating is due to *alteration of beam focusing*
- Above TE, IBS heating is mainly due to the “*negative longitudinal mass*”

Use of CM and Matched EC

RF-painting for stacking in one CM



Shortening the initial cooling time

- At optimal organization of EC (including the dispersive cooling), cooling time is determined by the 6D normalized emittance of ion beam (beam extension is not necessary but can be applied when advantageous)
- So, when having one CM emittance small, one receives a significant reduction of the cooling time (cooling after injection to collider ring; and initial cooling at top energy)

Potential to overcome the SpCh limitation of EIC luminosity

- While maintaining a round-rotating cooled beam state around the ring, one can transform *round beam to flat* to the IP (since the e-beam is flat), in this way **gaining luminosity over the SC limit of the ring.**

Easing the IR design

- Having flat or one-CM-round beam in IR is easing significantly the *achromatic IR* design
- Allows one to reduce limitations of *dynamical aperture* due to the non-linear fields of achromatic IR

Resume

- CM transport of ion beams look suggesting a significant reduction of space charge limitations to beam emittance, cooling rates, dynamic aperture and luminosity of medium energy EIC
- A contr-active effect of CMs might be an increase of IBS impact due to the introduced 2D coupling with particle energy
- CMs' Pros & Cons should be studied comprehensively

Thank you for your attention!