# Issues of Electron Cooling

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# Outline

- Friction force
- Magnetized cooling
- Misalignment impact
- Cooling rates
- Longitudinal sweep cooling
- Dispersive cooling
- Transverse sweep cooling
- Counter ERL
- Drift merger
- Meyer magnets arcs
- Conclusion

# Friction force

- $\vec{F} = -\frac{4\pi n_e Z^2 e^4}{A m_e} < [\frac{\vec{u}}{u^3} \ln(\frac{r_c}{\rho_{min}}) + \frac{\vec{u}_d}{(u_d)^3} \ln\left(\frac{\rho_{max}}{r_c}\right)] >$
- $2\pi r_c = \lambda_c \theta_e$

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

$$\frac{Ze^2}{\rho_{min}} = m_e u^2;$$

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

$$\rho_{max} = u_d \cdot \min\left(\frac{l_c}{\gamma c}; \frac{1}{\omega_e}\right);$$

- **Phenomenon of "fast cooling":**

In strong solenoid, electron Larmor cycles $r_c$ are very small compared to beam size $a$, then efficiency of heat energy exchange at collisions is not limited by spread of electron transverse velocities:

$$\vec{F} = -\frac{4\pi n_e Z^2 e^4}{A m_e} < \frac{\vec{u}_d}{(u_d)^3} \ln\left(\frac{\rho_{max}}{r_c}\right) >$$

# Misalignments

- ***Issue*: control the coherent angle of electrons relative the ion** beam
- ***Short waves*** range is not crucial (reduction of the adiabatic log)
- ***Long waves*** range can be controlled by BPMs and compensated (?)
- ***Electron drift*** in space charge field (reduction of ad. log)

# Optimized Electron Cooling

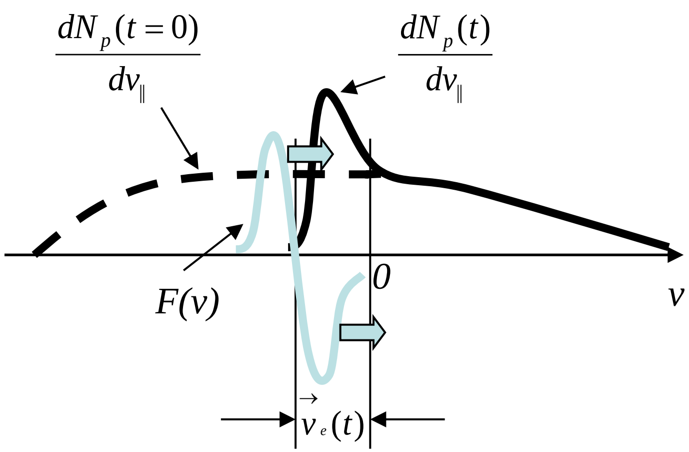
- ***Magnetized cooling (general principle)***

  **In a strong solenoid, cooling rate has only few sensibility to electron Larmor oscillations and misalignments**

- ***Sweep-cooling***

  The initial ion beam has a large energy spread .

  **Use *sweep cooling* to gain *a large reduction* of the longitudinal cooling time**




- ***Dispersive cooling***

  **In a high energy ion beam, longitudinal cooling rate is large compared to the transverse one.**

  **By organizing dispersion of ion bam and transverse gradient of the longitudinal friction force, one can redistribute (equalize) cooling decrements, thus gaining the transverse cooling rate.**

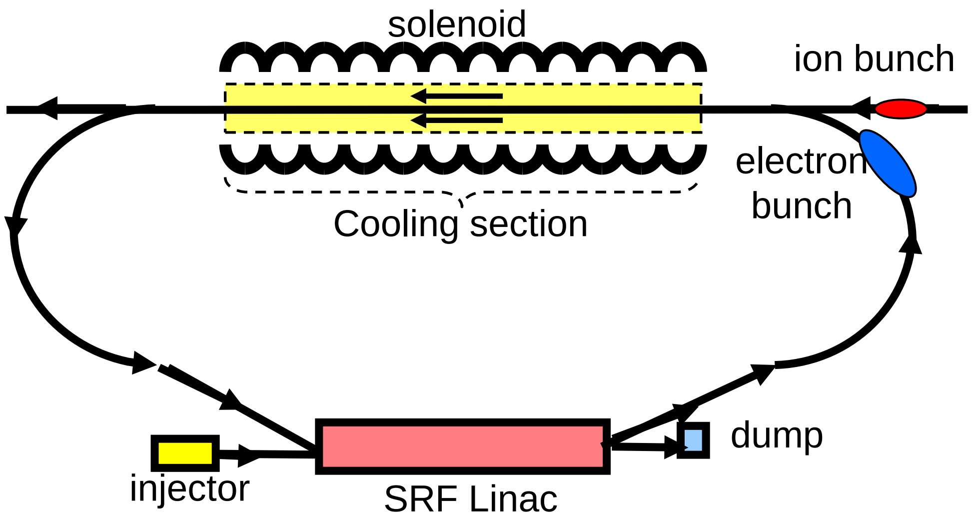
- ***Enhancing all cooling rates by the transverse space-sweep a thin e-beam***

  **- Combines dispersive mechanism with transverse sweep-cooling**

  **/ suggests a large reduction of the cooling time!/**

- ***Cooling with flat beams:*** **making magnetized e-beam flat in the cooling solenoid, to match flat i-beam (due to IBS)**

# Thoughts on ERL

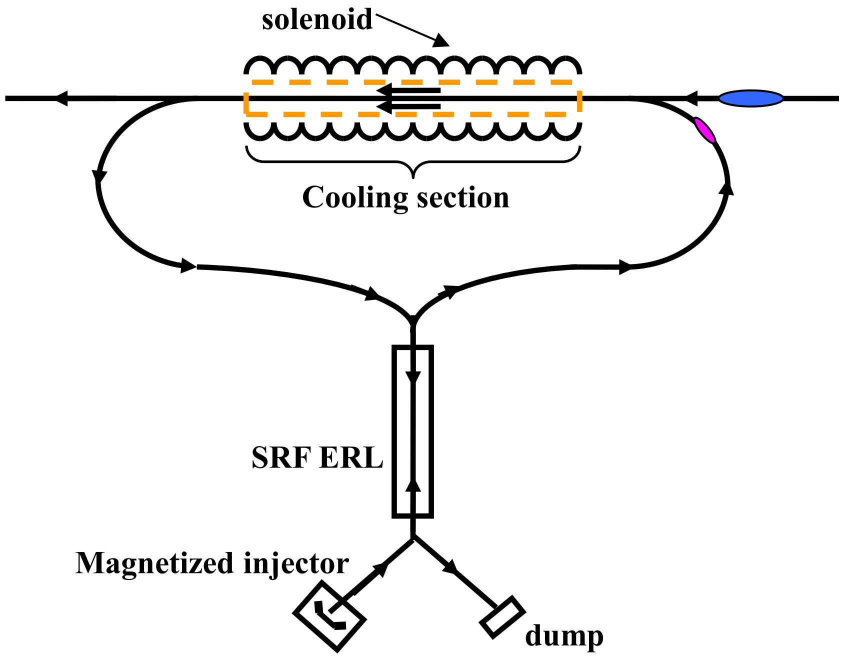



<u>Issues:</u>

- High current source (1 A challenge for a Ph-gun)
- High non-recovered beam power (5 MeV pre-acceleration before merger)
- Merger (difficult at low energy of ion/cooling beam)
- High current BBU

# Counter ERL

## /solution for merge ? /




- Magnetized (2KG) grid-operated DC gun: 300 KV, 200 mA; 1ns, 1.6 nC, 238 MHz
- Magnetized Compressor-preaccelerator : 5 MeV, 2 cm bunches
- 5 to 55-140 MeV, 476 MHz SRF ERL
- Post-ERL 3× 476 MHz SRF monochromator
- Encountering ER beam

# Head-on counter ERL

## /Impact, tolerances and corrections/

- *Single transverse kick:* $(\delta p_r)_{max} = 2\frac{Ne^2}{ac}$
- Excited Larmor: $r_L = c\frac{\delta p_r}{eB}$; $\frac{(r_L)max}{a} = \frac{Nr_e}{\varepsilon_d}$ ; $r_e = 2.8 \times 10^{-13} cm$
- An example: $N = 1.2 \times 10^{10}$; $a = 5mm$; $B = 0.1T \longrightarrow \varepsilon_d = 0.08\ cm$

Then:

$$\frac{(r_L)max}{a} \approx 4 \times 10^{-2}$$

- Contribution to optics: $\delta \nu_{tr} = \frac{(r_L)max}{a} = 4 \times 10^{-2}$

At **constant density** across the beam area, $\delta \nu_{tr}$ can be accounted in matching with the cooling solenoid.

- Frequent non-resonant kicks can be accounted, as well
- Larmor-phased compensation of the head-on kicks can be considered if needed
- **A potential problem**: counter-scattered electrons may hurt the SRF cavities

# Miss-counter ERL

## space charge dynamics

- *Single transverse kick:* $c\delta\vec{p} = 2Ne^2 \frac{\vec{h}+\vec{r}}{(\vec{h}+\vec{r})^2}$
- *Expansion on* $r/h$
- *Linear terms can be accounted in linear optics*
- *Excited quadratic terms*

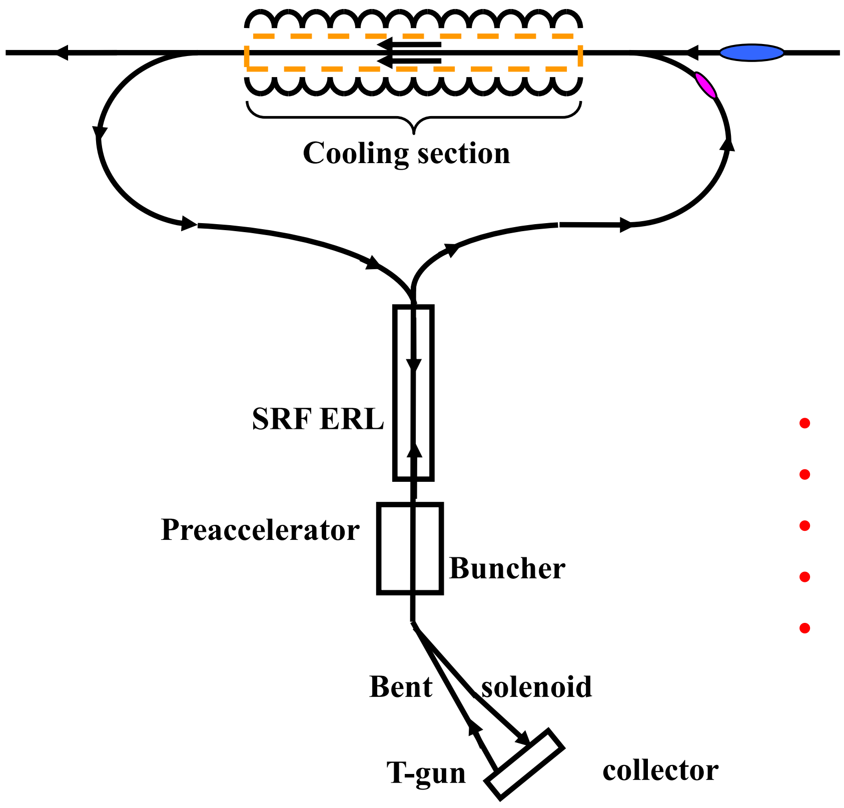
$$\frac{r_L}{a} = \frac{Nr_e}{\varepsilon_d}\left(\frac{a}{h}\right)^3\left(\frac{r}{a}\right)^2;$$

- An example: $N = 1.2 \times 10^{10}$; $a = 3mm$; $B = 0.2T$ $\longrightarrow$ $\varepsilon_d = 0.05\ cm$
  $h = 1cm$; Then:

$$\frac{r_L}{a} \approx 2 \times 10^{-3}\left(\frac{r}{a}\right)^2$$

- Constant density across the beam area is not needed
- Integrated Larmor kick can be auto-compensated !
- $(p_\perp)' - i\Omega_L p_\perp = F$; $p_\perp = e^{i\Psi}\int e^{-i\Psi(s)}F(s)ds$; $\sum e^{-i\Psi_k} \Longrightarrow 0$

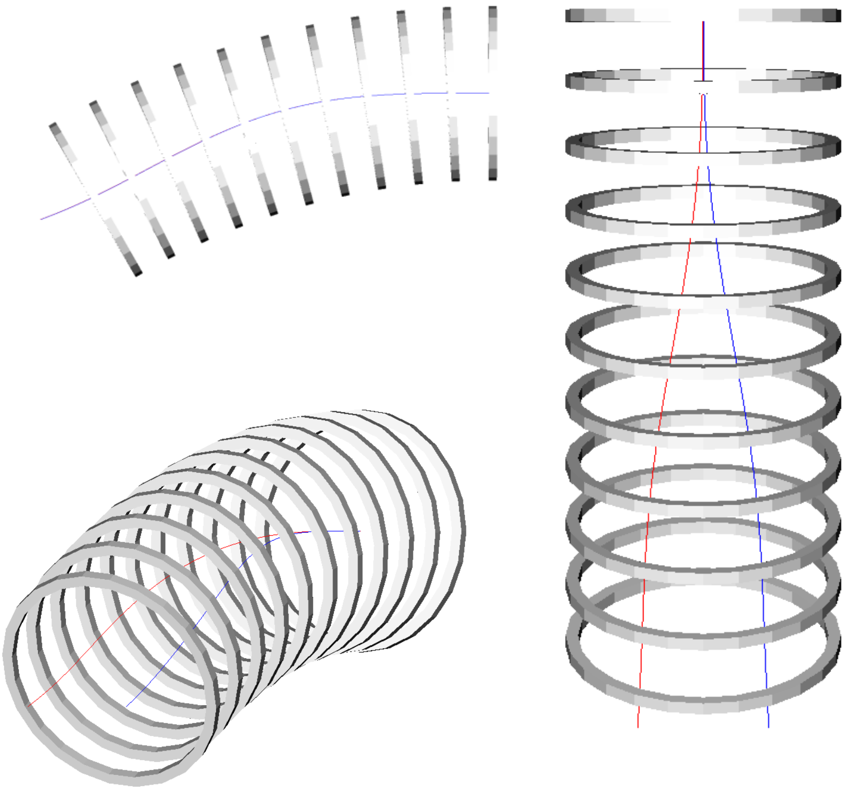
# DRIFT MERGER + DEEP RECOVERY




- Magnetized (2KG) grid-operated gun:
  300 KV, 1-2 A; 1-2 ns, 2-4 nC, 238 MHz
- Magnetized Compressor-preaccelerator :
  5 MeV, 238 to 476 MHz; 2 cm bunches
- SRF ERL 5 to 25 -170 MeV, 476 MHz
- Post-ERL beam monochromator 3× 476 MHz
- Encountering ER beam
- Deep ER including DC gun voltage part

- Split of two orbits by drift in bent solenoid
- Recovered pre-accelerator
- Recovered DC gun
- Very low energy & power dump (collector)
- Very low active beam power!

# Counter orbits split in bent solenoid



$$\frac{(v_z)^2}{R} = \frac{F_x}{\gamma m} \; ; \qquad F_x = \frac{e}{c} v_y B$$

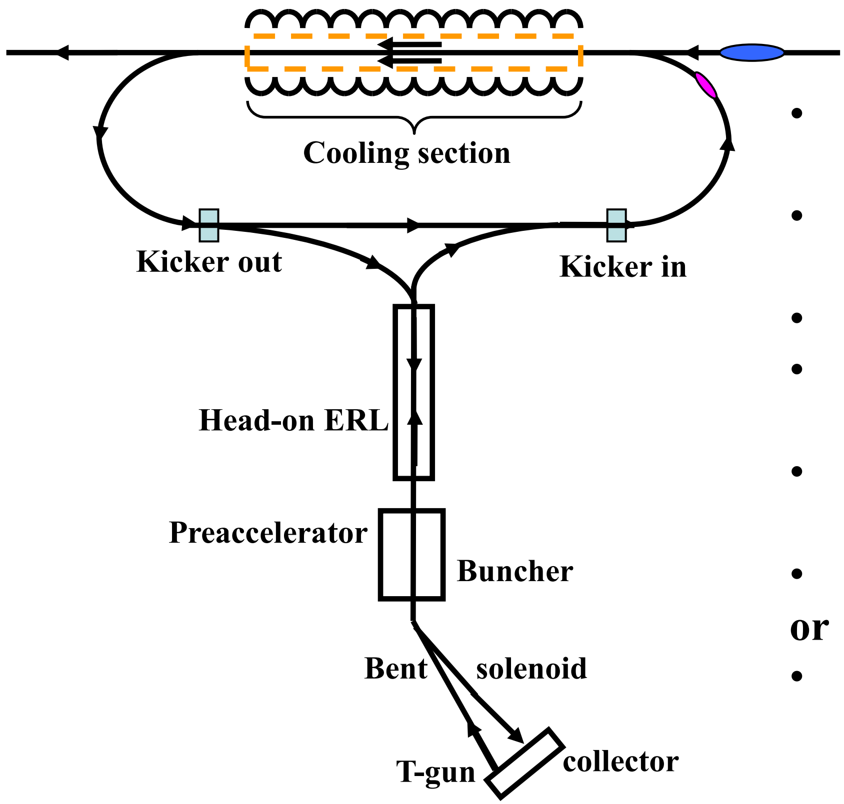
$$v_y = \frac{\gamma m c (v_z)^2}{eBR}$$

$$\tan \alpha_d = \frac{p_z}{eBR} = \frac{\lambda_L}{2\pi R} \; ;$$

$$y_d(z) = \frac{\lambda_L}{\pi R}(z - z_0)$$

# counter ERL with CCR

## /low current gun + mitigation of BBU/




- Magnetized (2 KG) grid-operated DC gun: 300 KV; 30 - 200 mA; 1-2 ns, 2-4 nC, 238/q MHz
- Magnetized Compressor-preaccelerator : 5 MeV, 2 cm bunches
- 5 to 55 -140 MeV, 476 MHz SRF ERL
- Post-ERL 3× 476 MHz SRF beam monochromator
- Circulator-cooler ring with 2T solenoid: 238 - 952 MHz bunch rep. rate, up to 3A
- SRF kicker 95,2 MHz /q rep.rate

or

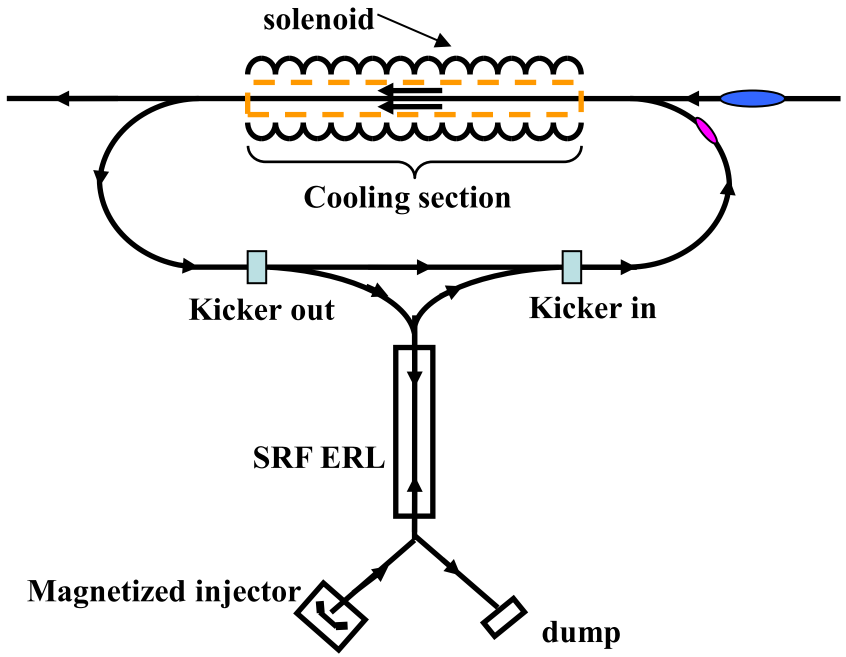
- Beam-beam kicker: pulsed current, 100 - 300 KV high charge/bunch DC source (no RF; DC energy recovery)

**Advantages:**

- Low current source and ERL
- Large reduction of BBU (low current ERL + mitigation by the circulation in CCR)

# Head-on ERL with CCR

## /low current gun + mitigation of BBU/

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- Post-ERL 3× 476 MHz SRF beam monochromator
- Circulator-cooler ring with 2T solenoid: 238 MHz bunch rep. rate, up to 3A
- SRF kicker

or

- Beam-beam kicker: similar pulsed current DC source (high charge/bunch) + DC energy recovery)

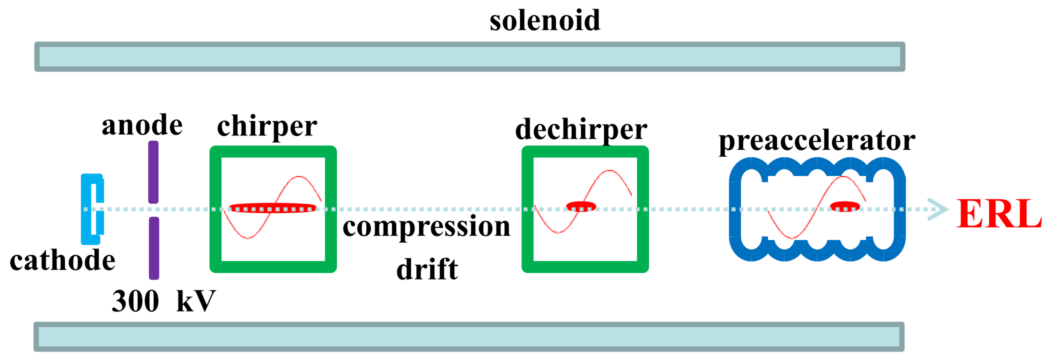
**Advantages:**

- Low current source and ERL
- Large reduction of BBU (low current ERL + mitigation by the circulation in CCR)

# Estimation of Magnetized Injector for ERL

## 1. Magnetized grid-operated DC gun

| | |
|---|---|
| Voltage | 300 KV |
| Impulse duration | 1.4 ns |
| Bunch charge | 4 nC |
| Peak current | 2.8 A |
| Repetition rate MHz | 238 |
| Solenoid field | 2 KGs |
| Beam radii | 3 mm |
| Average current | 1 A |
| SpCh energy gradient | 0.2 KV |
| Tr. emittance, norm. | 12 $\mu M$ |




## 2. Bunch compressor

| | |
|---|---|
| Initial bunch length | 42 cm |
| Chirper frequency | 238 MHz |
| Voltage | 400 KV |
| Velocity chirp | $\pm$ 0.25 |
| Drift length | 4 m |
| Post bunch length | 2 cm |
| Sp.Ch. tr.energy gradient | 18 KV |
| Dechirper frequency | 238 MHz |
| Voltage | 1.6 MV |

## 3. Preaccelerator (NC RF)

| | |
|---|---|
| Frequency | 238 MHz |
| Voltage | 4.2 MV |
| RF energy gradient | $10^{-3}$ |

# ERL for HEEC

## SRF ERL

Short cavities; axial lenses in between

| | |
|---|---|
| Frequency | 476 MHz |
| Integrated voltage, max | 115 MV |
| Bunch length | 1 cm |
| Energy gradient in the beam | $5 \cdot 10^{-3}$ |

## Post-ERL SRF monochromator

| | |
|---|---|
| Frequency | 1428 MGHz |
| Voltage | 12 MV |
| Residual energy gradient | $5 \cdot 10^{-5}$ |

- **An ssue of compression/acceleration**:

  - Impact of transverse RF field to beam cyclotron emittance

  **Preliminary estimations show possibility to maintain beam cyclotron emittance**

  **Could be compensated if necessary (?)**

# Magnetized beam transport

- Inverted cooling solenoid (compensation of coupling in ion ring and impact to ion spin)
- Quadruple CAM invertor for e-beam
- Implementation of the drift mode tune for CCR: use the inverted cooling solenoid to rotate of the drift mode while preserving the x-dispersion (reflection relative the horizontal plane)
- Electron and ion dispersion in cooling section
- Bent Meyer’s magnets for arcs (combined solenoid and bend field)
- Isochronous CCR (compensating bend’s compaction factor)

# Conclusion

- The ***dispersive*** and ***sweep*** cooling should be investigated as possible ways to accelerate Electron Cooling process
- Counter ERL is proposed for study as a conceivable version of solution for high current SRF linac for HEEC that might provide both a robust merge and low active power of the cooling in all energy range of ion facility
- Possible show stopper? Like BBU?
- If so, this issue is an additional argument for that, the circulated (+ counter ERL) cooling should be investigated sooner better than later… .

**THANK YOU FOR YOUR ATTENTION!**