中国科学院近代物理研究所
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High energy electron cooling at HIAF

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2026/04/01, Huizhou

Outline

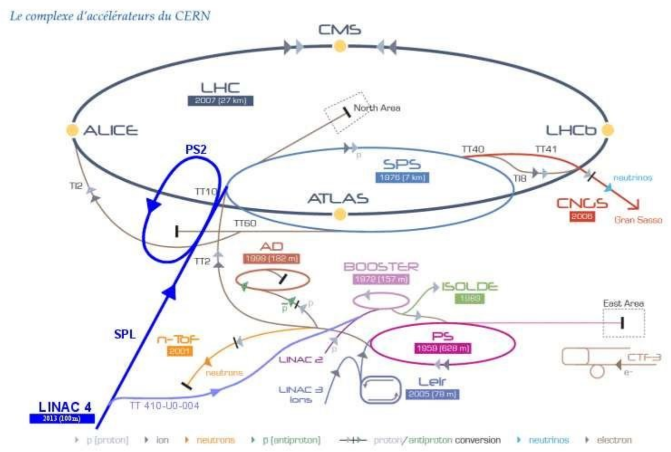
1. Background and motivation
2. Beam cooling methods for ~10GeV/u ions
3. Plan for the HIAF e-cooling
4. Conclusion

➢ Background and motivation

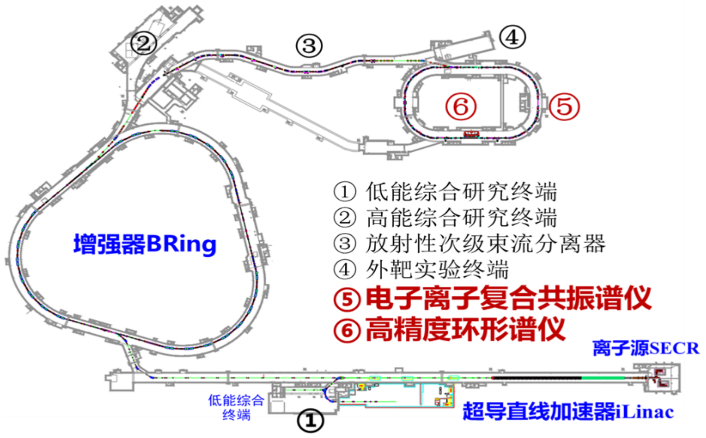
Beam cooling at high energies is desired for future accelerators

- 4.5 MeV cooler made a great contribution on Tevatron luminosity (2005 ~ 2011)
- 2 MeV cooler tested @ COSY and would be a part of HESR @ FAIR future
- 2.6 MeV LEReC operated @ RHIC ion-ion collision (first ever in colliders, RF accelerator)
- Next generation beam cooling for EIC

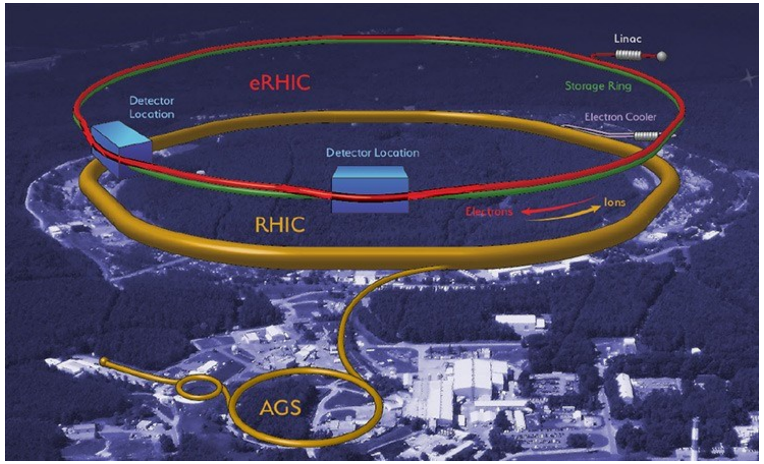
Energy frontier



Intensity frontier



Precision frontier

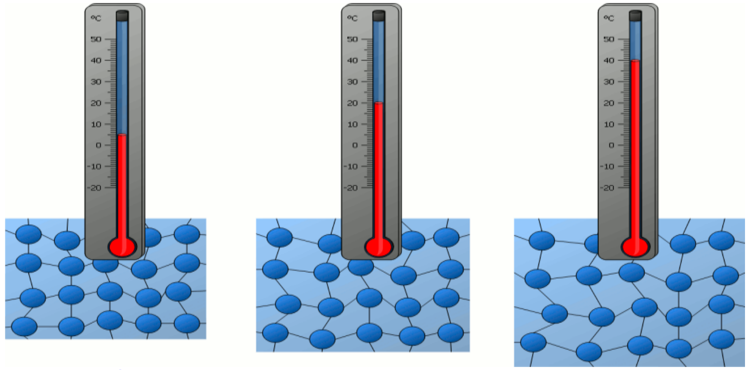


What is beam cooling?

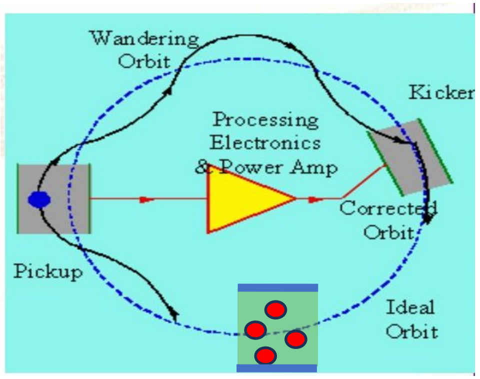
- Cooling is a reduction of the 6D phase space volume occupied by the beam

Longitudinal beam temperature: $$kT_s = m_0 c^2 \beta^2 \left(\frac{\triangle p}{p}\right)^2$$

Transverse beam temperature: $$kT_{x,y} = m_0 c^2 \beta^2 \gamma^2 \left(\frac{\varepsilon_{x,y}}{\beta_{x,y}}\right)$$



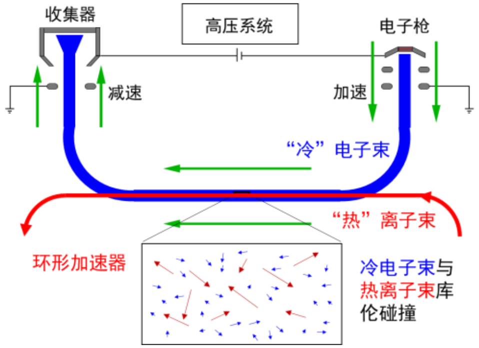
- Two methods employed for beam cooling:



Stochastic cooling

$$\tau \propto \frac{2N}{W}$$

Less particles, faster cooling rate



Electron cooling

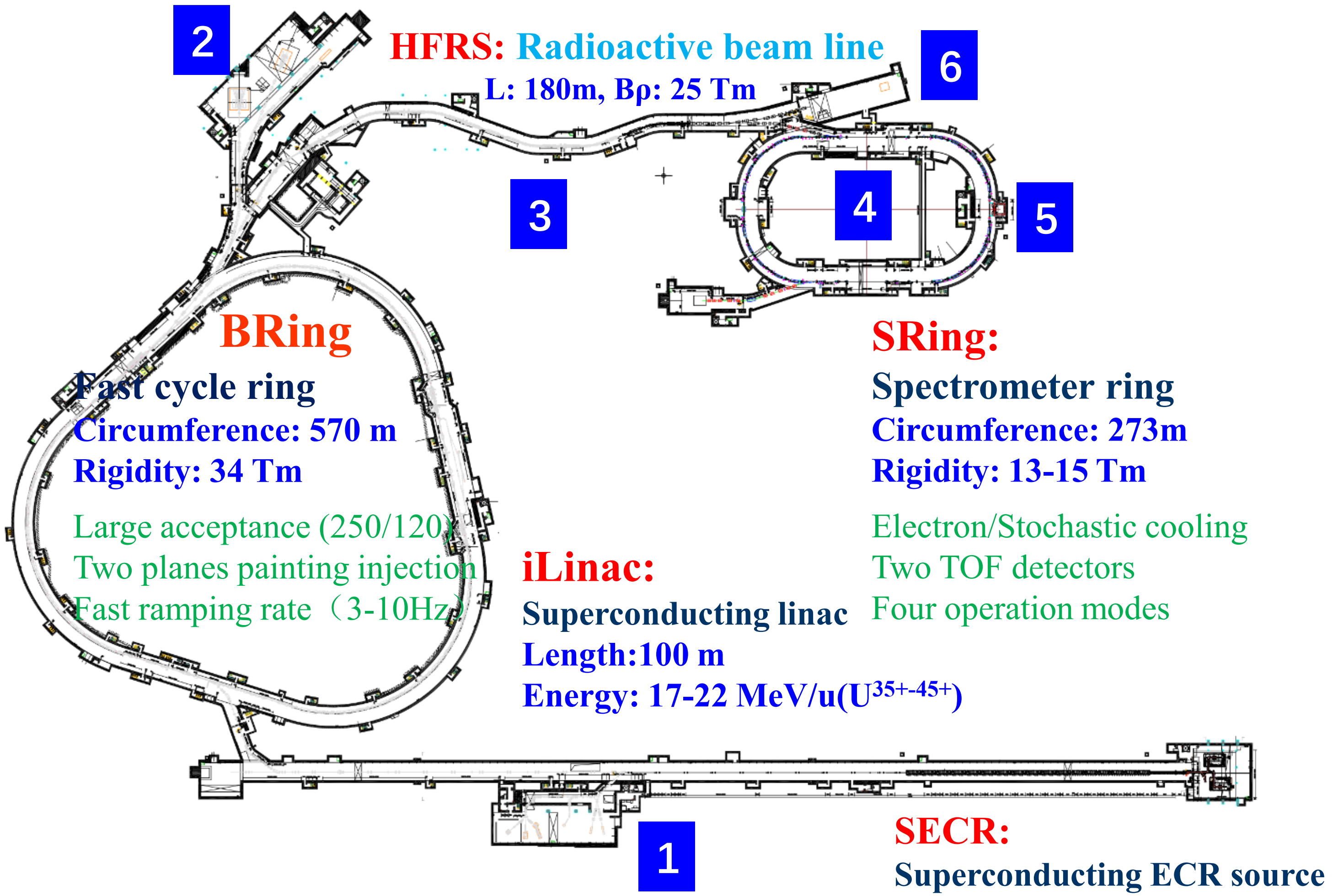
$$\tau \propto \gamma^2$$

Lower energies, faster cooling rate

➢ Background and motivation

HIAF: aimed to provide the highest intensity (pulsed) heavy ion beams in the world

- HIAF=4th SECR + superconducting Linac + Fast ramping rate synchrotron + Terminals



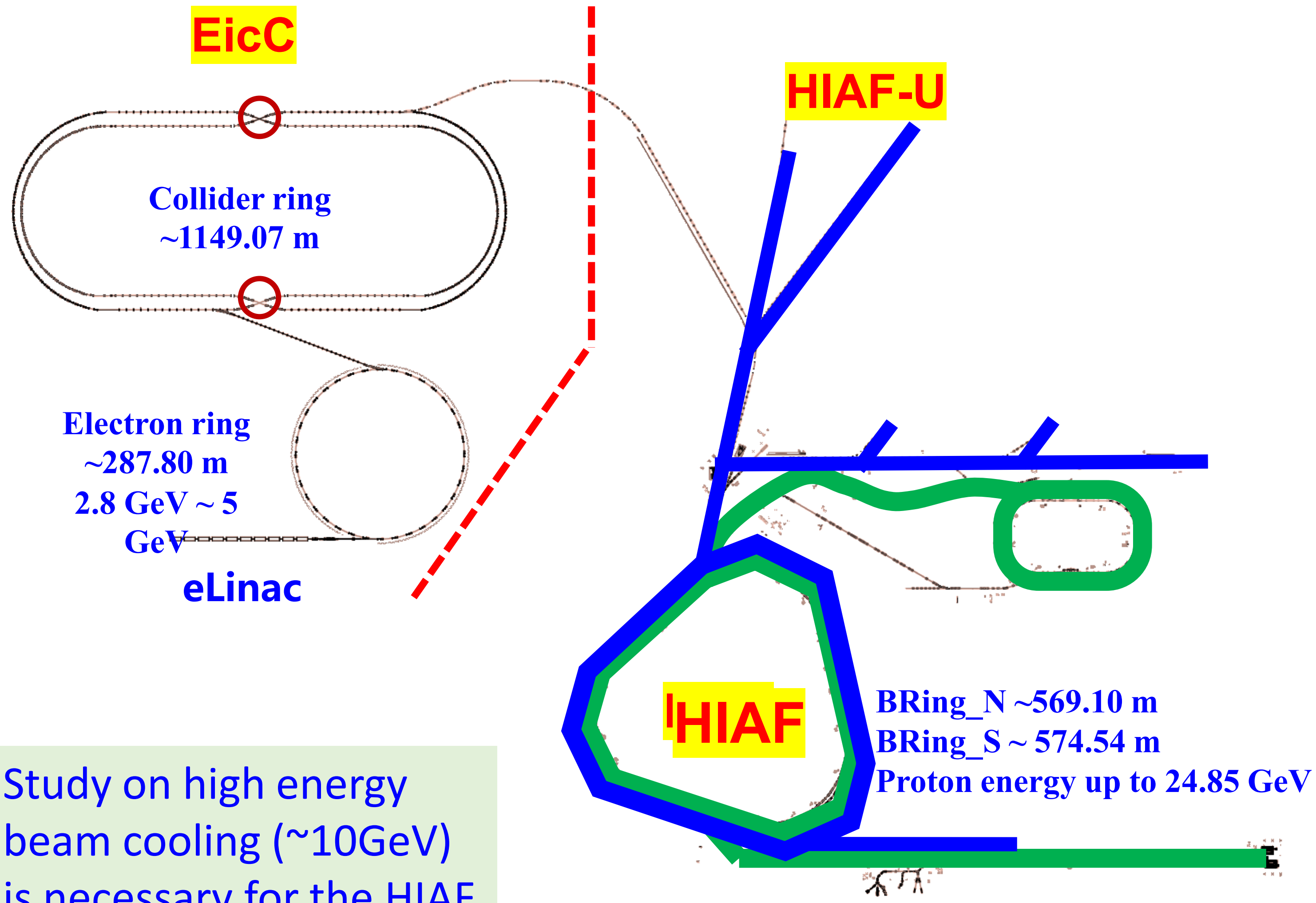
- Low energy nuclear structure terminal
- High energy experimental terminal
- High energy fragment separator HFRS
- High precision spectrometer ring SRing
- Electron ion recombination terminal
- Radioactive ion beam physics terminal

➢ Background and motivation

HIAF upgrade plan

- Increase the injection energy, build superconducting synchrotron to improve the magnetic rigidity up to 86 Tm
- Design the electron accelerator and build an electron ion collider

Parameter	electron	proton
Circumference (m)	1151.20	1149.81
Kinetic energy (GeV)	3.5	19.08
CM energy (GeV)	**16.76**	
Polarization	80%	70%
Bunch intensity (x10[11])	0.44	**0.27**
$\varepsilon_x, \varepsilon_y$ (nm·rad, rms)	12.5/3.75	**25/12.5**
Bunch length (cm, rms)	0.75	**8**
Luminosity ($cm^{-2}s^{-1}$)	**1.13×10^{33}**	



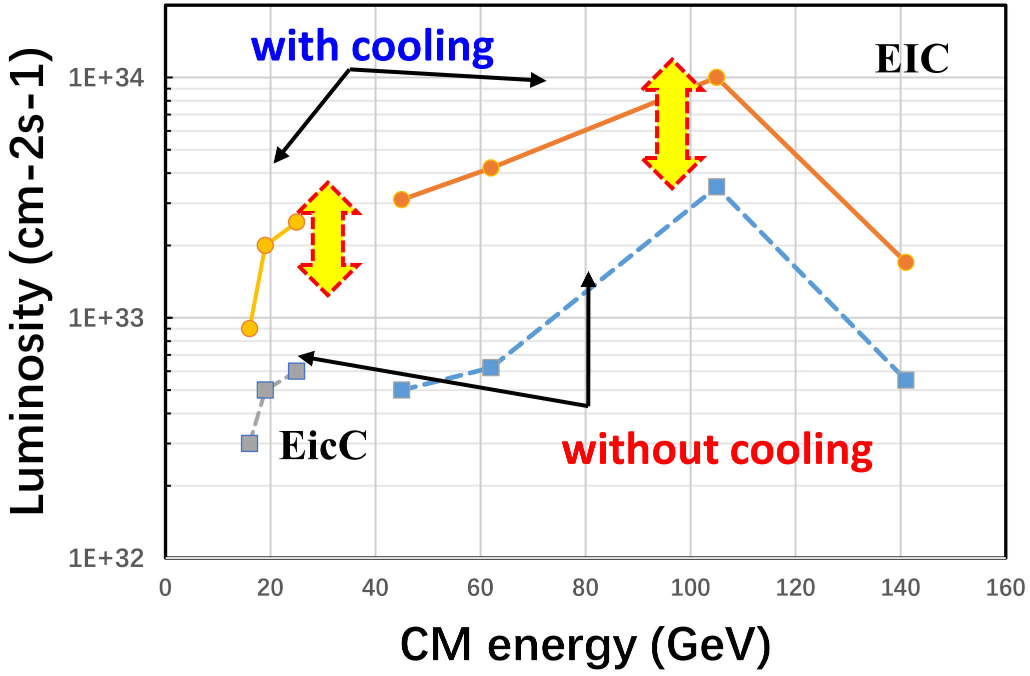
Study on high energy beam cooling (~10GeV) is necessary for the HIAF upgrade plan

➢ Background and motivation

Electron cooling @ ~10 GeV heavy ion beam

- Recycler e-cooler shown us ~10 GeV beams can be cooled by electron beam (with DC accelerator)
- LEReC told us Linac accelerator can be used for electron cooling facility

$$L = \frac{N_p N_e f_c}{2\pi \sqrt{\sigma_{p,x}^2 + \sigma_{e,x}^2}\sqrt{\sigma_{p,y}^2 + \sigma_{e,y}^2}}$$



U.S. DEPARTMENT OF ENERGY | Office of Science

Technical Challenges for EIC

EIC will be one of the most complex collider accelerators ever to be built. It will push the envelope in many fronts including high degrees of beam polarizations, high luminosity, beam cooling, beam dynamics, crab cavities for both beams, and an interaction region with complex magnets.

Required Accelerator R&D Advances for EIC (list from the Jones panel report)

- Hadron cooling techniques
- Polarized electron sources
- Ring magnet demonstrations
- Interaction region magnet design and prototyping
- Machine-detector interfaces
- Superconducting RF technology
- Large scale cryogenics technology

DOE Support to EIC Accelerator R&D and FOA Landscape
---M.Farkhhondeh, 2018

Background and motivation

Electron cooling @ ~10 GeV heavy ion beam

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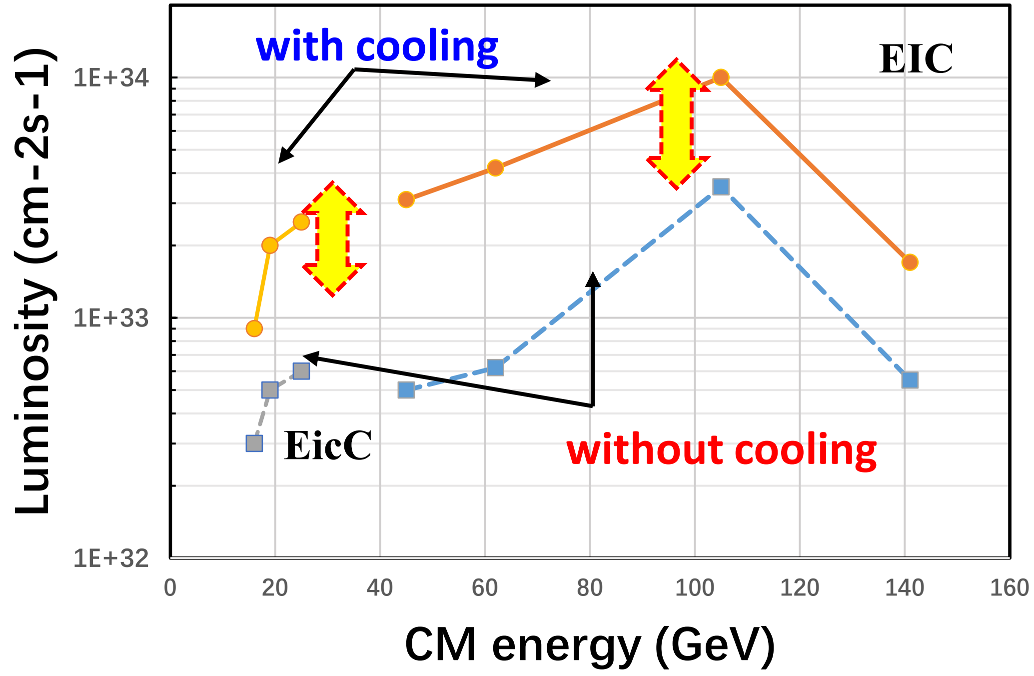
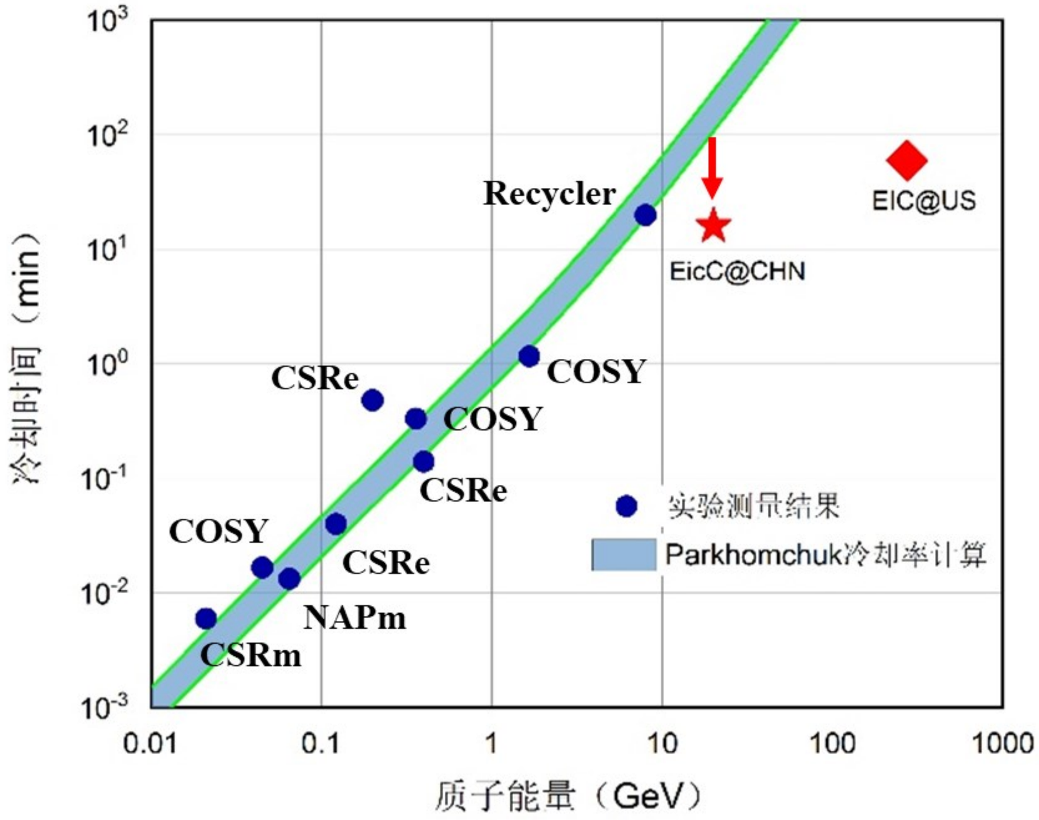
- LEReC told us Linac accelerator can be used for electron cooling facility

$$\frac{1}{T_c} = 4 r_e r_p n_e \eta_c c \frac{1}{\gamma^2}\left(\frac{1}{\beta^2\gamma^2\theta_\perp^2 + \beta^2\theta_\parallel^2 + \theta_{eff}^2}\right)^{\frac{3}{2}} \frac{Z^2}{A} \ln\xi$$



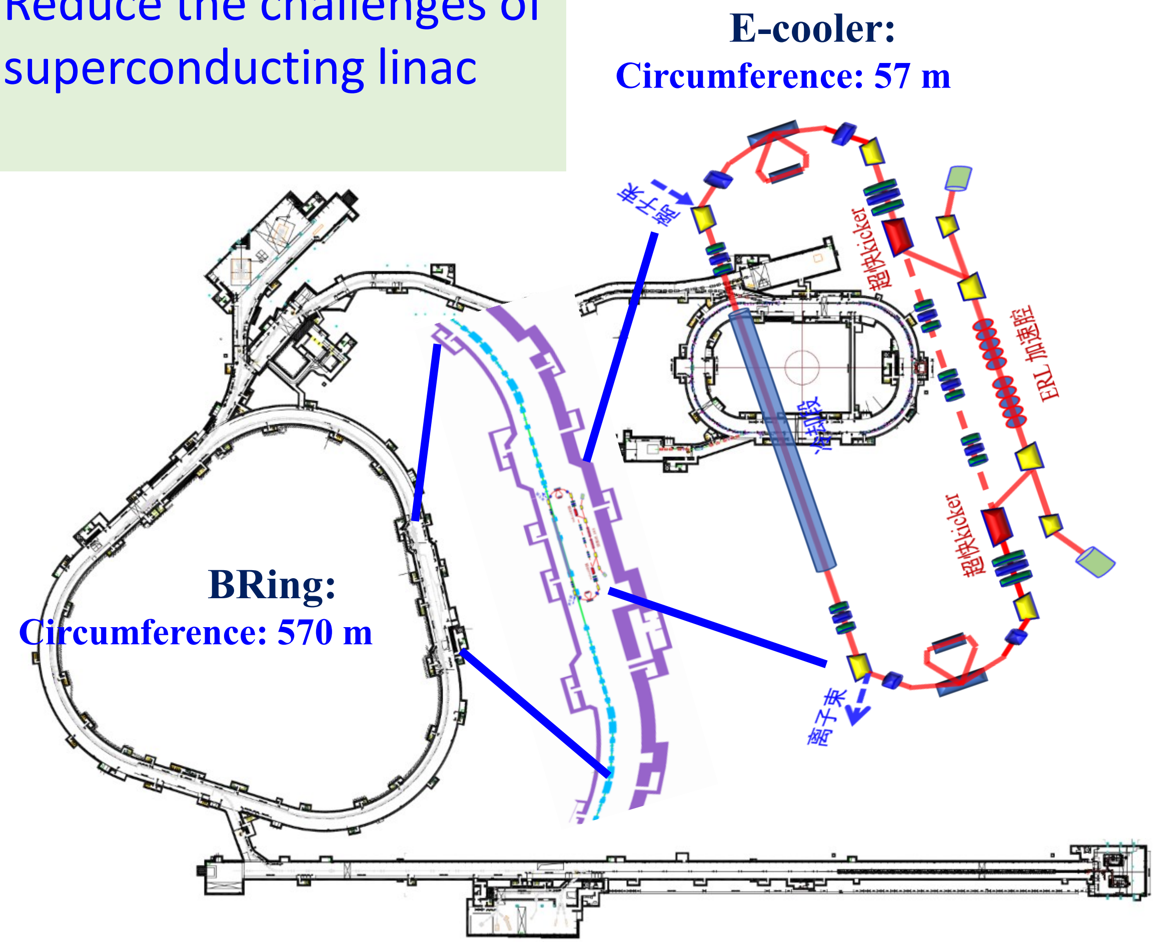


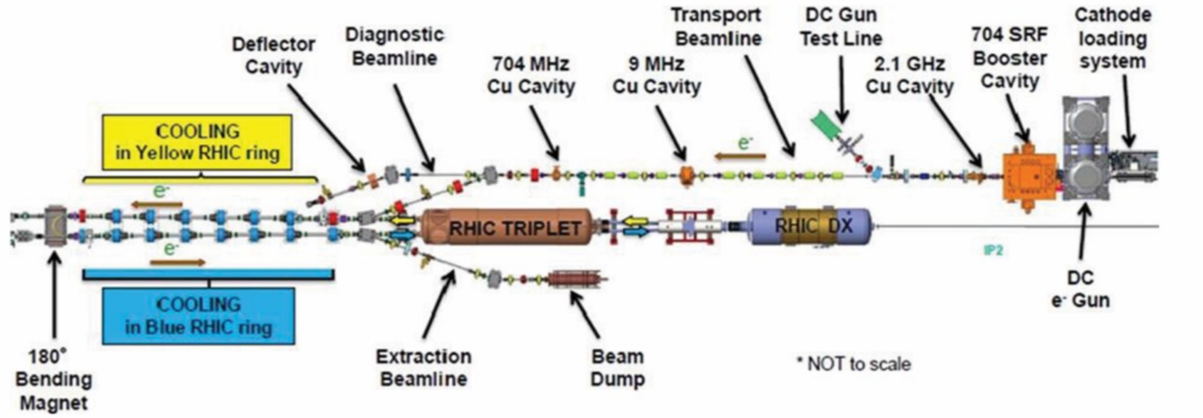
➢ Beam cooling method for ~10 GeV/u ions

HIAF high energy electron cooling study plan

- A long section in BRing, design and test a electron cooling idea: **Linac-ring combination**

Reduce the challenges of superconducting linac



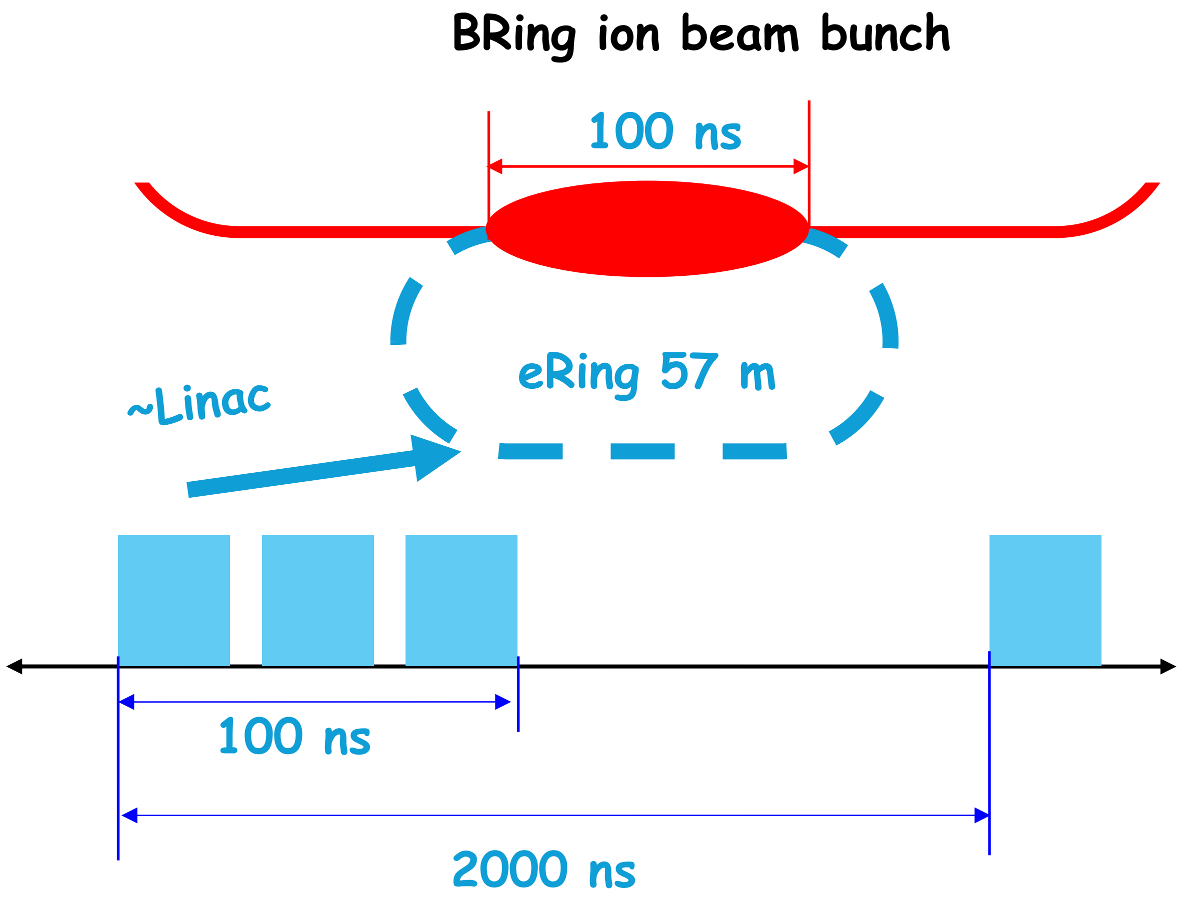


Electron beam requirement for cooling			
Kinetic energy, MeV	1.6	2	2.6
Pulse duration at the cathode, psec	40	40	40
Bunch duration in cool. sect, psec	400	400	20
Electron bunch (704MHz) charge, pC	130	170	200
Bunches per macrobunch (9 MHz)	30	30	24-30
Charge in macrobunch, nC	4	5	5-6
RMS normalized emittance, um	< 2.5	< 2.5	< 2.5
Average current, mA	36	47	45-55

➢ Beam cooling method for ~10 GeV/u ions

How to reduce the requirement of Linac for high energy cooler

- A long section in BRing, design and test a electron cooling idea: **Linac-ring combination**



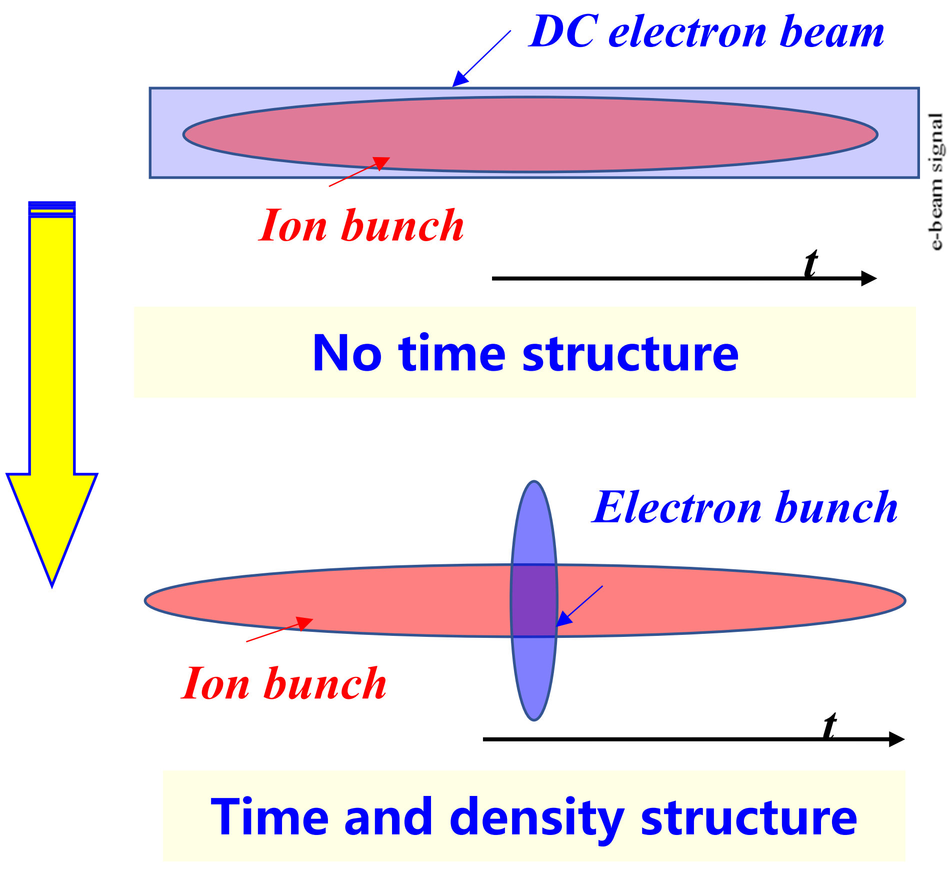
Parameters	value
proton bunch length	100 ns in total
revolution frequency	0.5 MHz
e-beam peak current	100 mA
RMS normalized emittance	**< 2 umrad**
RMS energy spread	**< 5e-4**

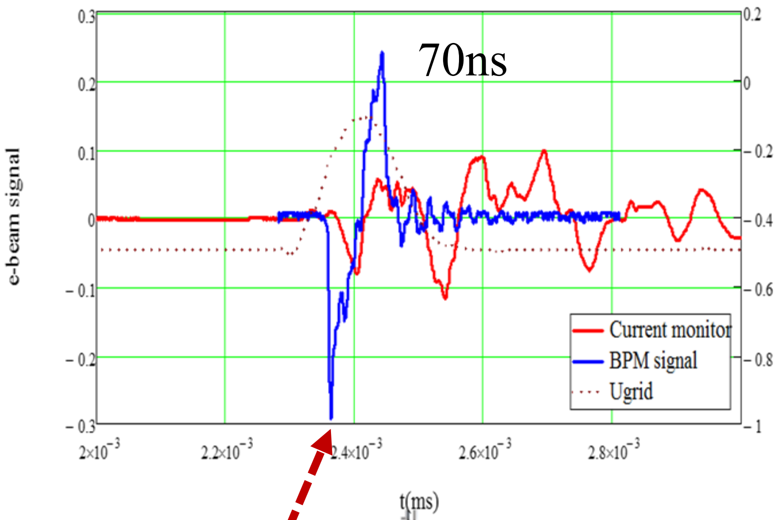
Use the electron beam for several times, reduce the power of the linac

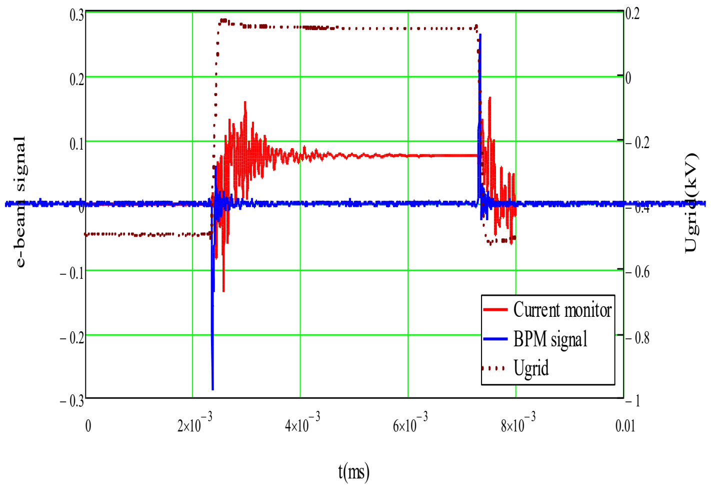
➢ Beam cooling method for ~10 GeV/u ions

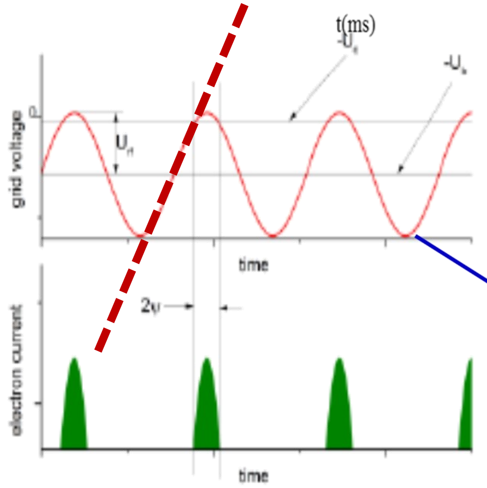
Cooling with bunched electron beam

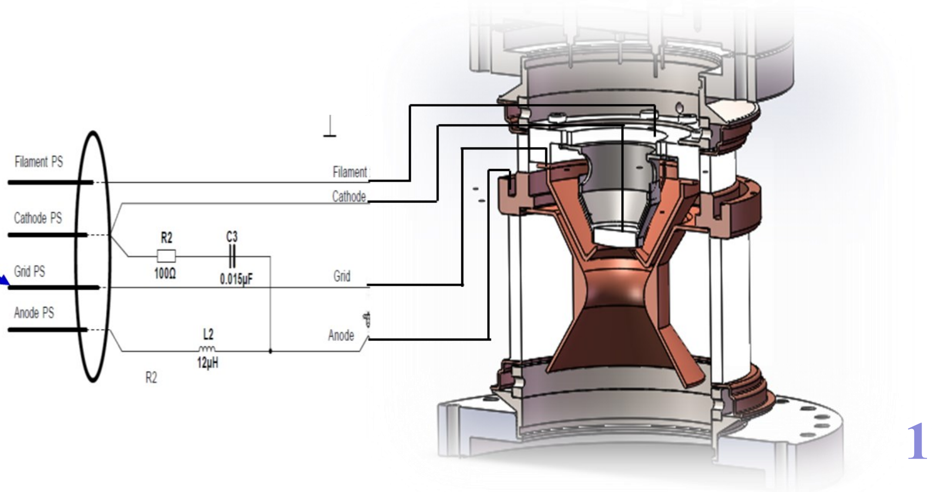
- Test the influence of bunched electron beam cooling @ HIRFL CSR







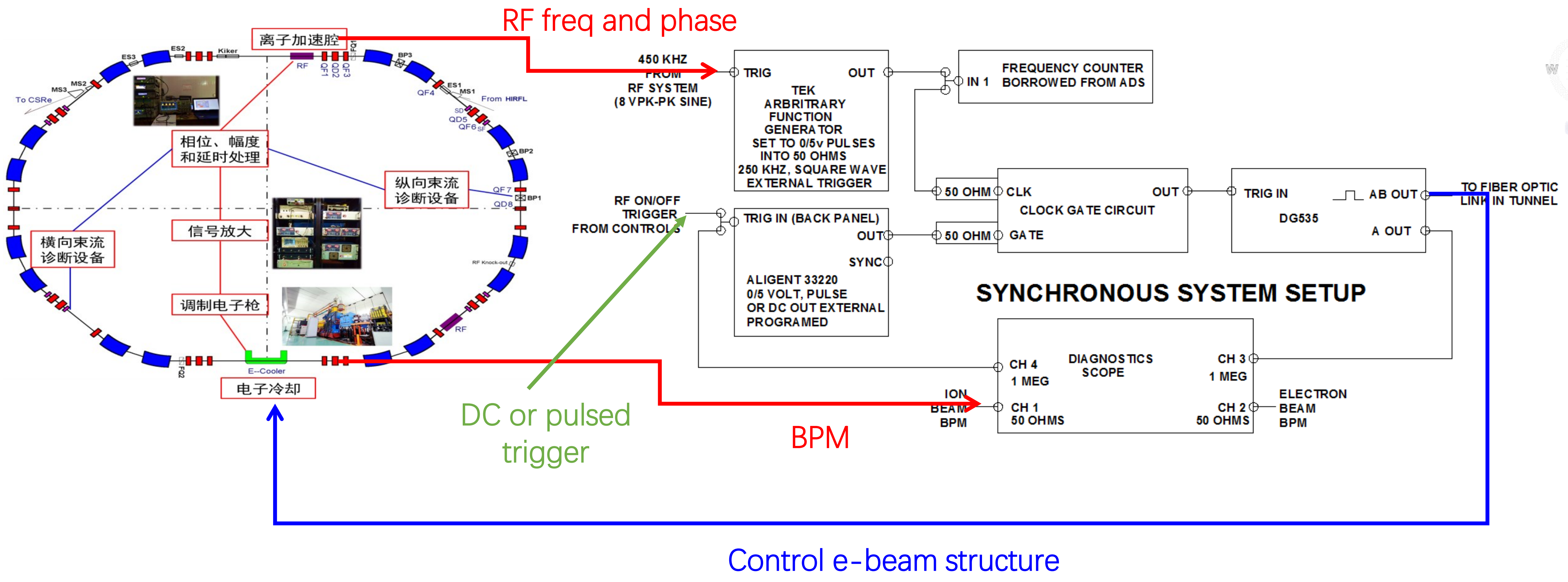




➢ Beam cooling method for ~10 GeV/u ions

Cooling with bunched electron beam

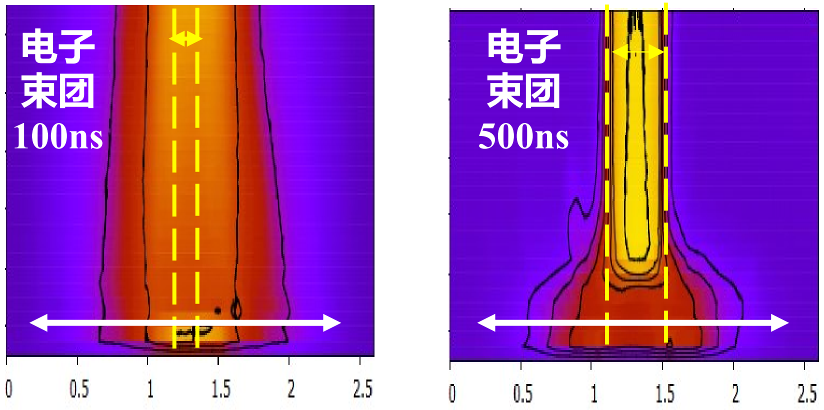
- Timing system to make a synchronization with electron and ion beam



➢ Beam cooling method for ~10 GeV/u ions

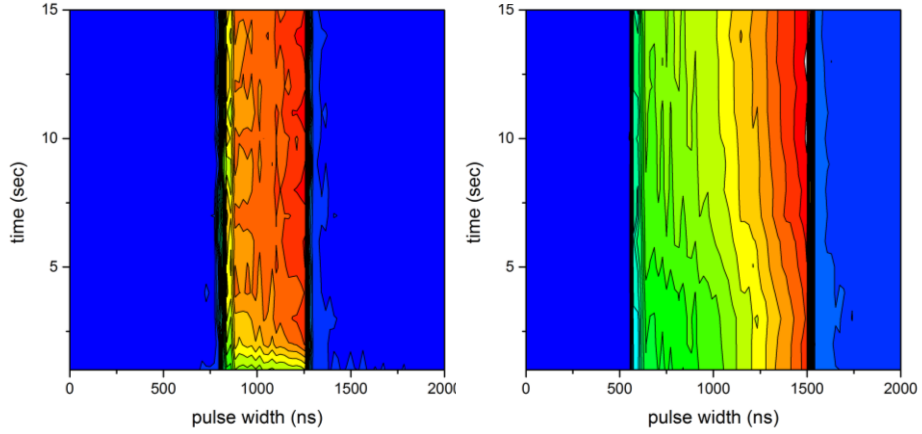
Coasting and bunched ion beam cooled by pulsed electron beam

With RF



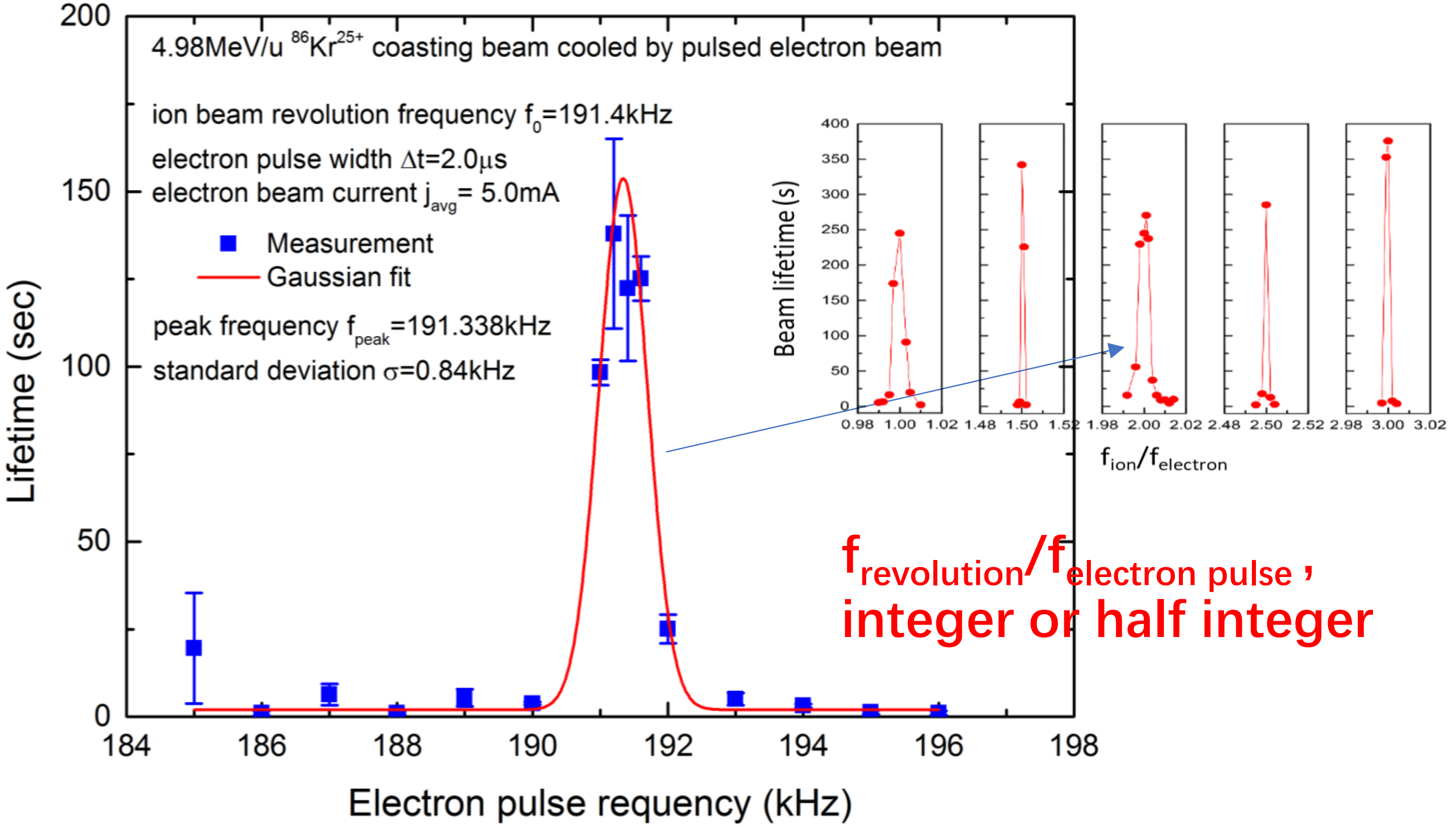
Ion bunch length μs

Without RF



500ns 1000ns

synchronization

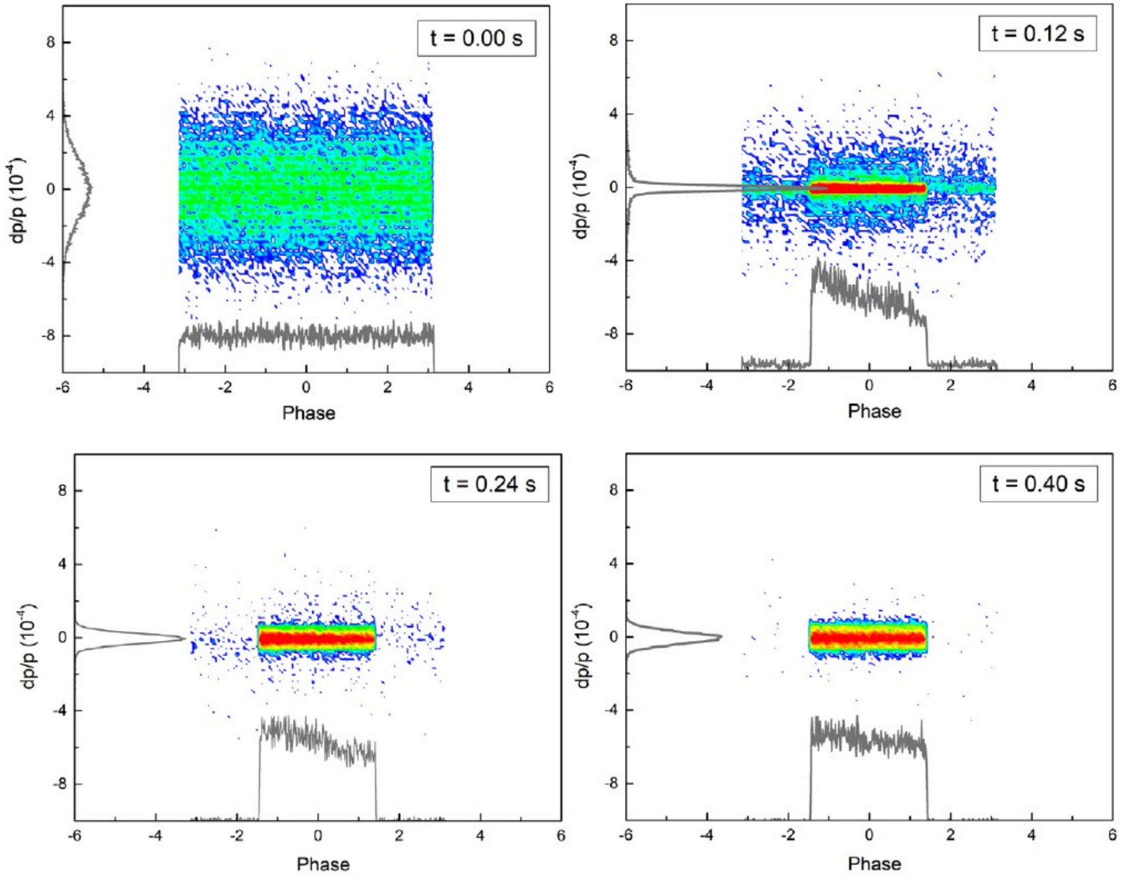


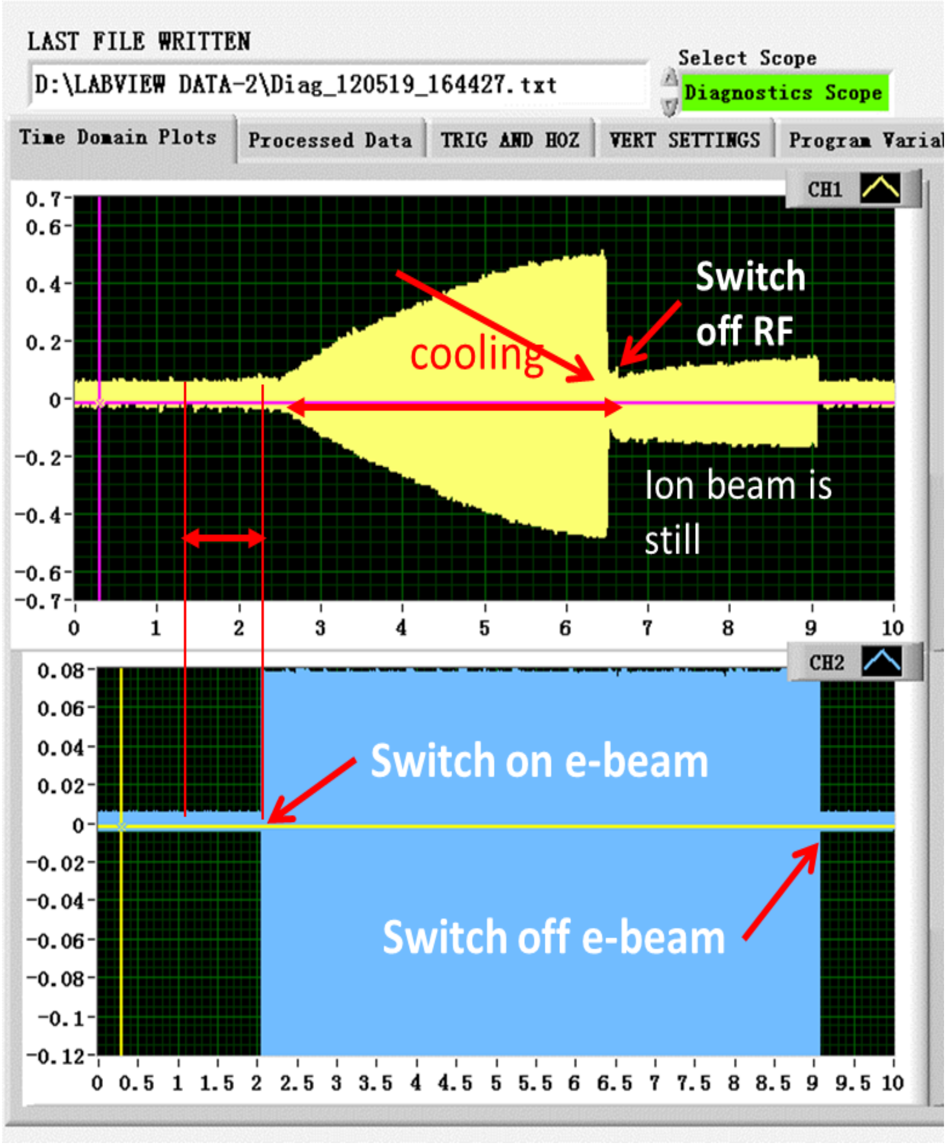
➢ Beam cooling method for ~10 GeV/u ions

Coasting beam cooling

Grouping effect:

ion beam pulse with the same length of e-beam



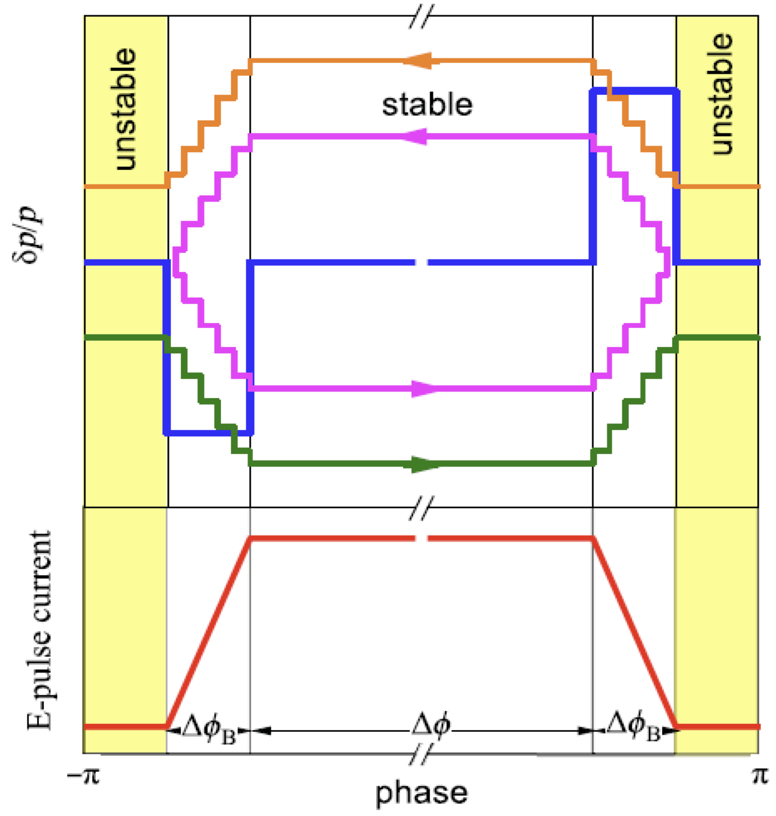


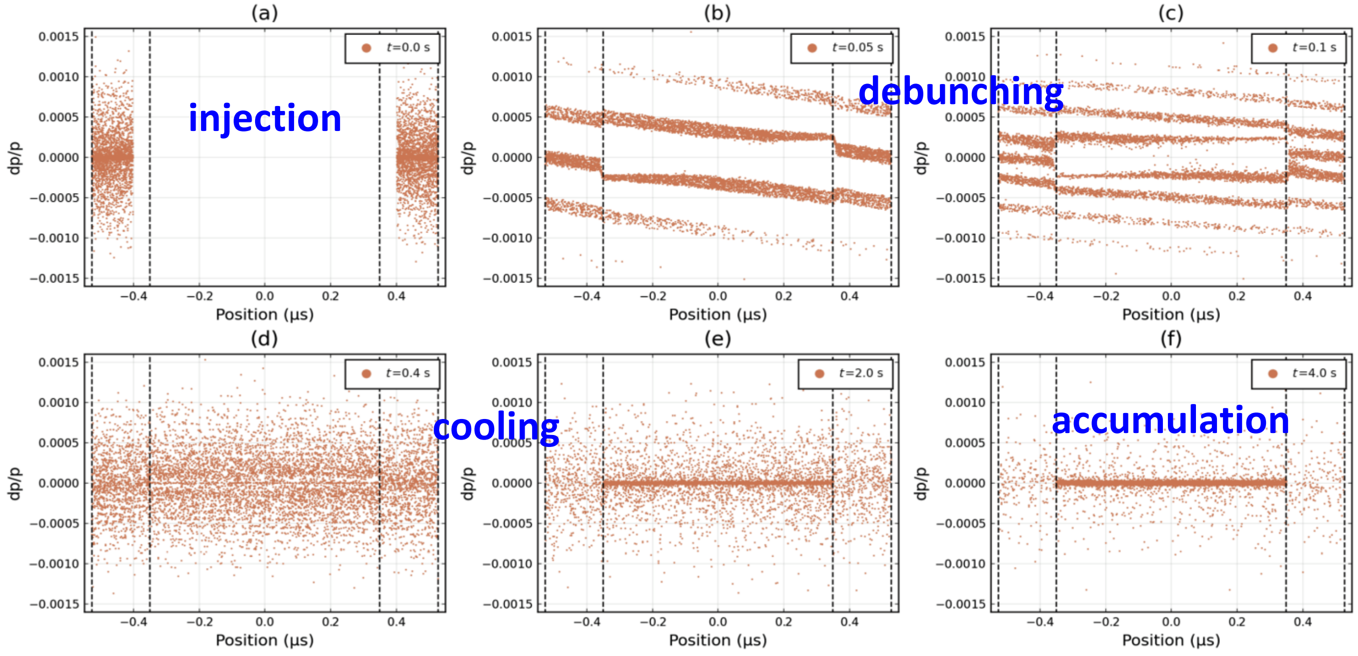
Nuclear Inst. And Methods in Phys. Research, A 902 (2018) 219-227

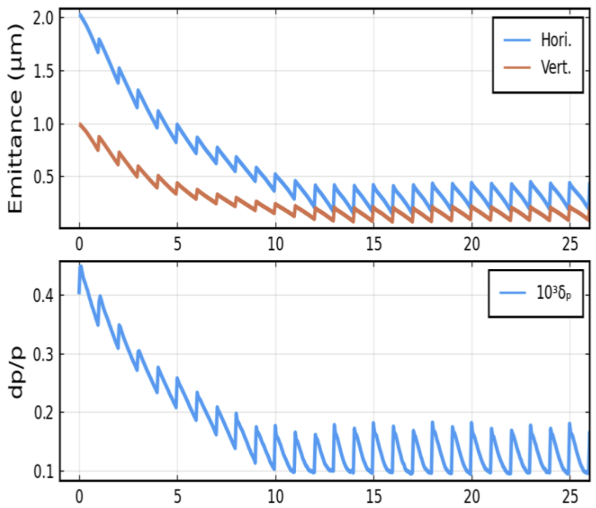
➢ Beam cooling method for ~10 GeV/u ions

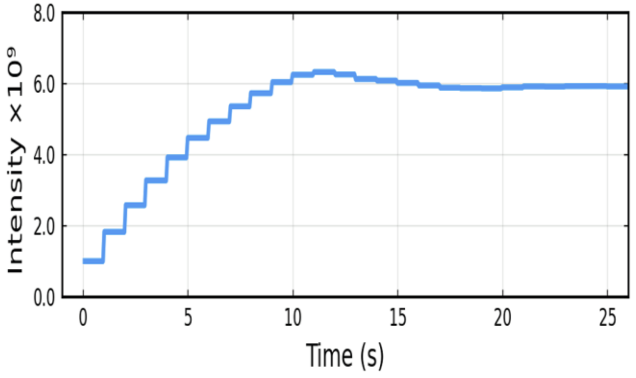
Beam stacking with pulsed e-cooling

- Very similar to the beam stacking process with cooling and barrier bucket cavity









—L.Mao, PRAB 26, 030103, 2023

➢ Beam cooling method for ~10 GeV/u ions

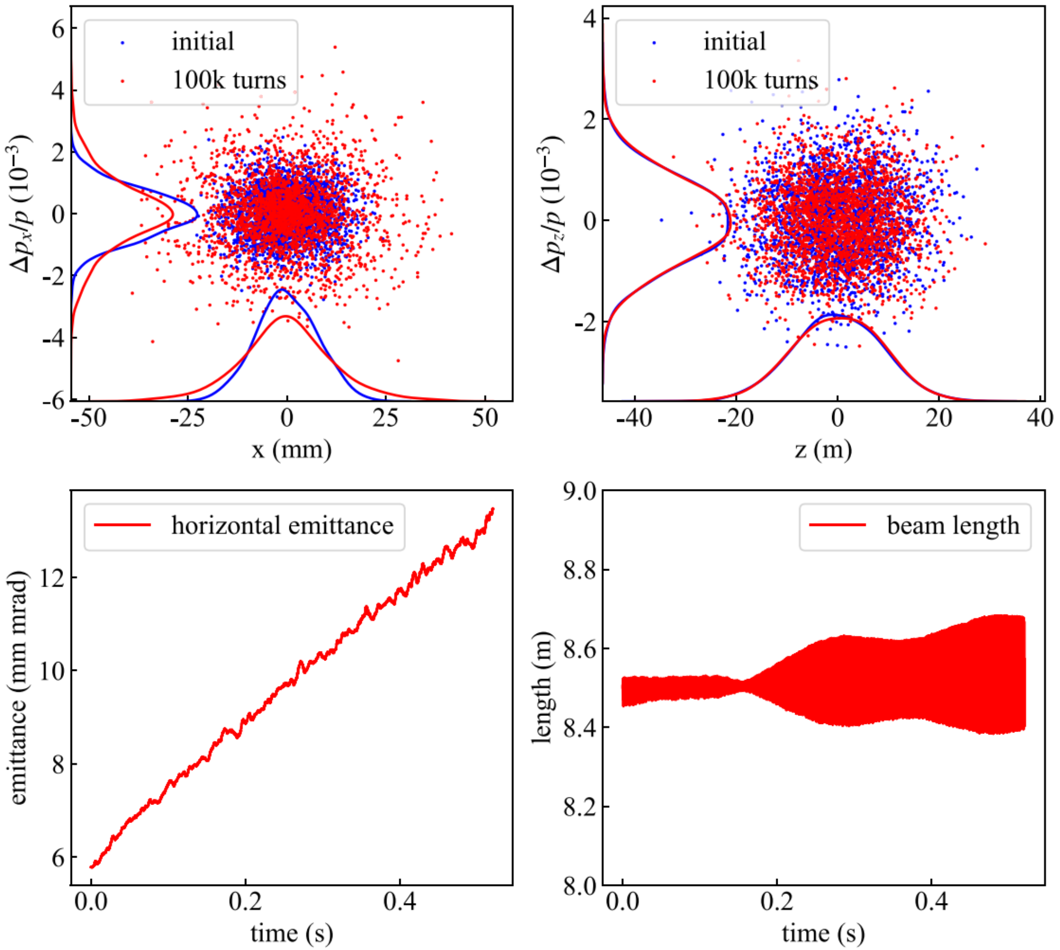
instabilities

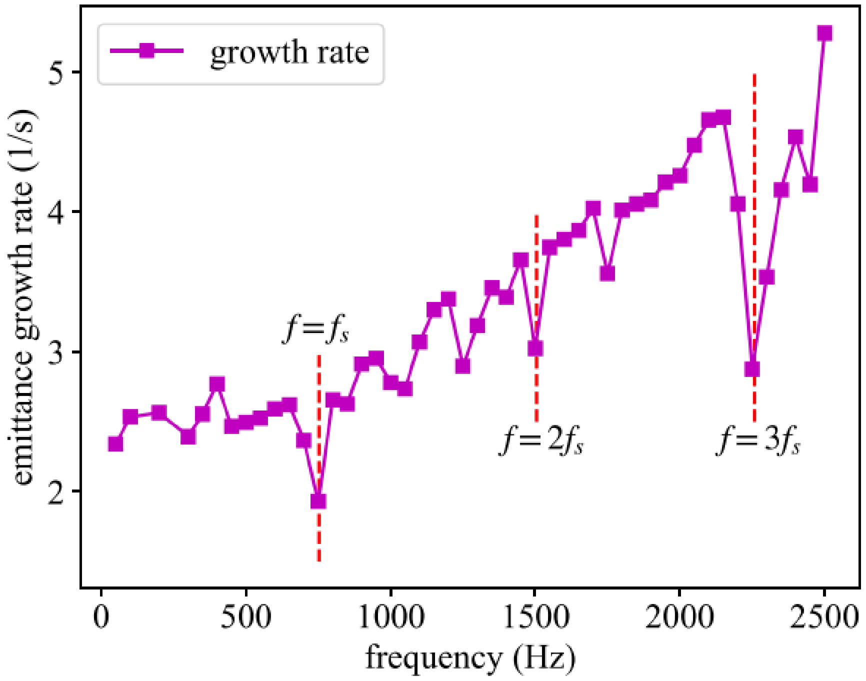
- Emittance growth caused by transverse oscillation due to space charge effect

$$F_{SC}=\begin{cases}\dfrac{-ZeI_e r}{2\pi\varepsilon_0\beta\gamma^2 ca^2}, r\le a\\ \dfrac{-ZeI_e}{2\pi\varepsilon_0\beta\gamma^2 cr}, r>a\end{cases}$$

$$2\tilde{Q}\pm k\nu_e=K \qquad \nu_e=1\pm\frac{f_e}{f_{rev}}$$

$$E_z=-\frac{g}{4\pi\varepsilon_0\beta c\gamma^2}\frac{dI_e(z)}{dz}$$





Beam cooling method for ~10 GeV/u ions

Learn from LEReC

- 100 meters of beamlines with the DC gun, high power fiber laser, 5 RF systems, many magnets and beam instrumentation

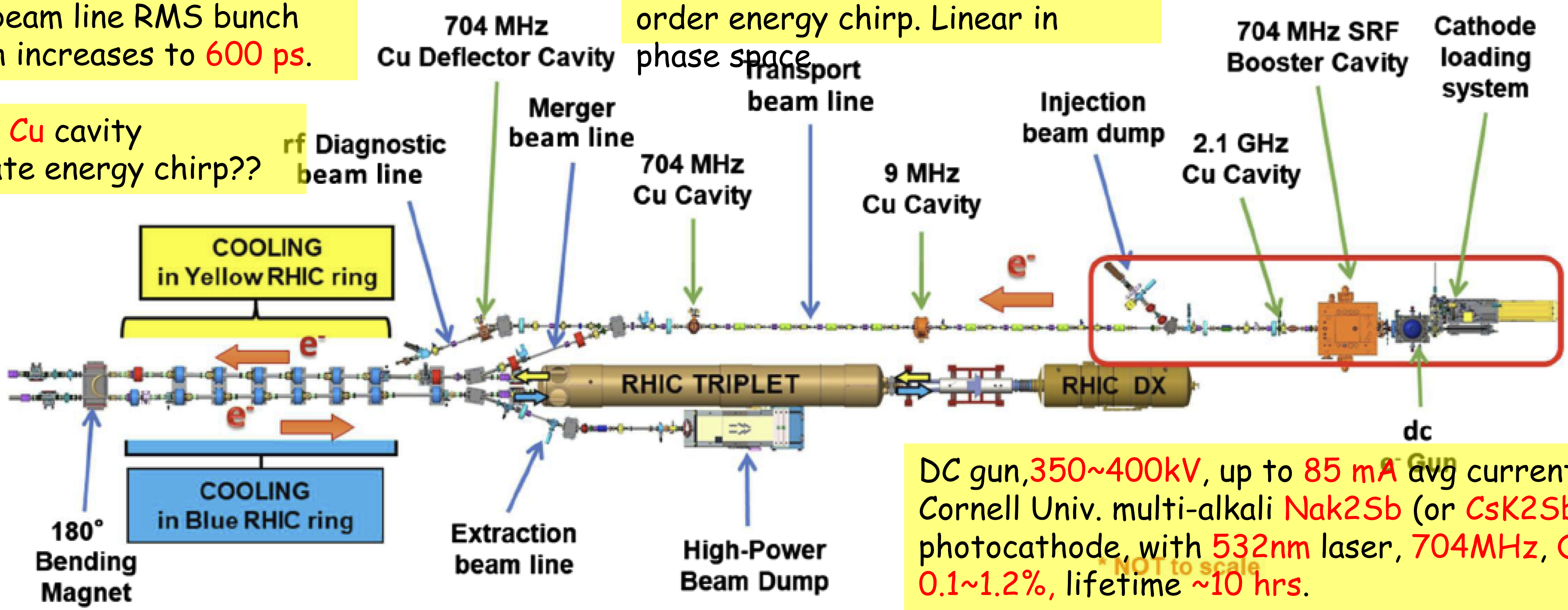
9 MHz cavity remove bunch to bunch energy variation. Beam loading effect??

Warm 2.1 GHz cavity(3rd harmonic) corrects the second order energy chirp. Linear in phase space

704 MHz SRF acceleration, introduce an energy chirp, 80 ps bunch length @ cathode minimizes the length

30m beam line RMS bunch length increases to 600 ps.

704 MHz Cu cavity compensate energy chirp??



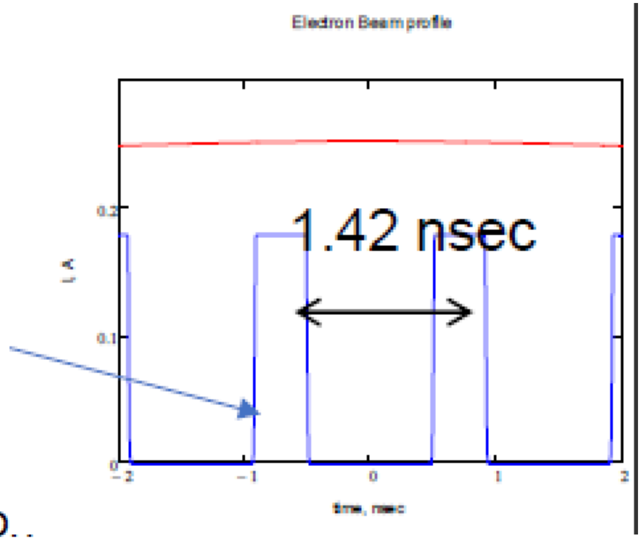
DC gun,350~400kV, up to 85 mA avg current, Cornell Univ. multi-alkali Nak2Sb (or CsK2Sb) photocathode, with 532nm laser, 704MHz, QE 0.1~1.2%, lifetime ~10 hrs.

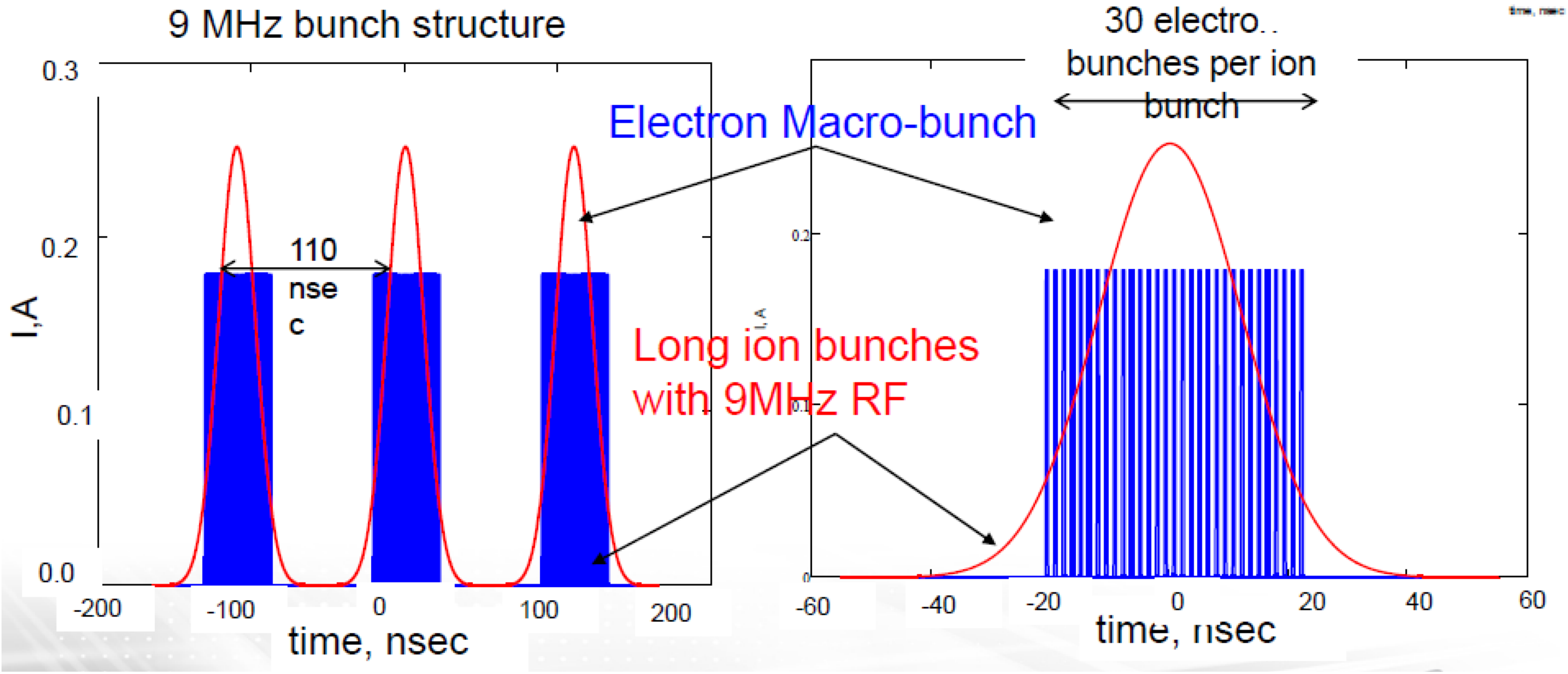
➢ Beam cooling method for ~10 GeV/u ions

Many electron bunches for one ion bunch

- 30 electron bunches are used to cool one ion bunch

- Electron bunches:
- f_SRF=703.5 MHz
- I_peak=180 mA
- FWHM=400 psec

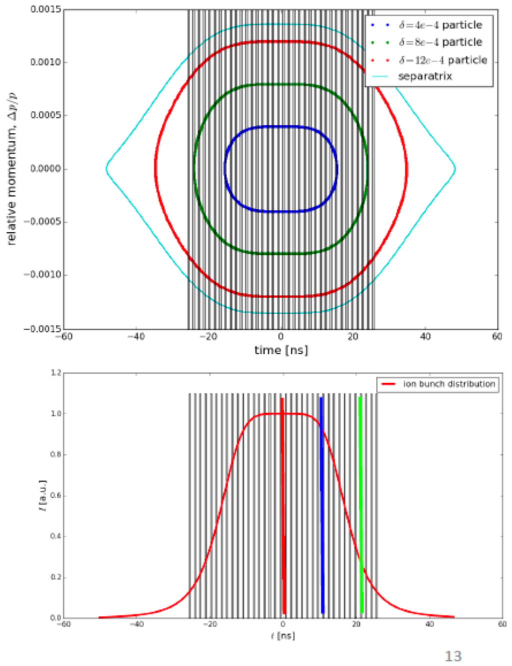


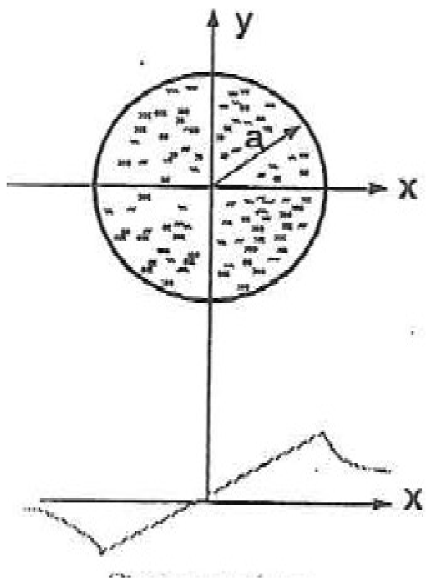


➢ Beam cooling method for ~10 GeV/u ions

Emittance growth from modulated focusing and bunched electron beam @ LEReC

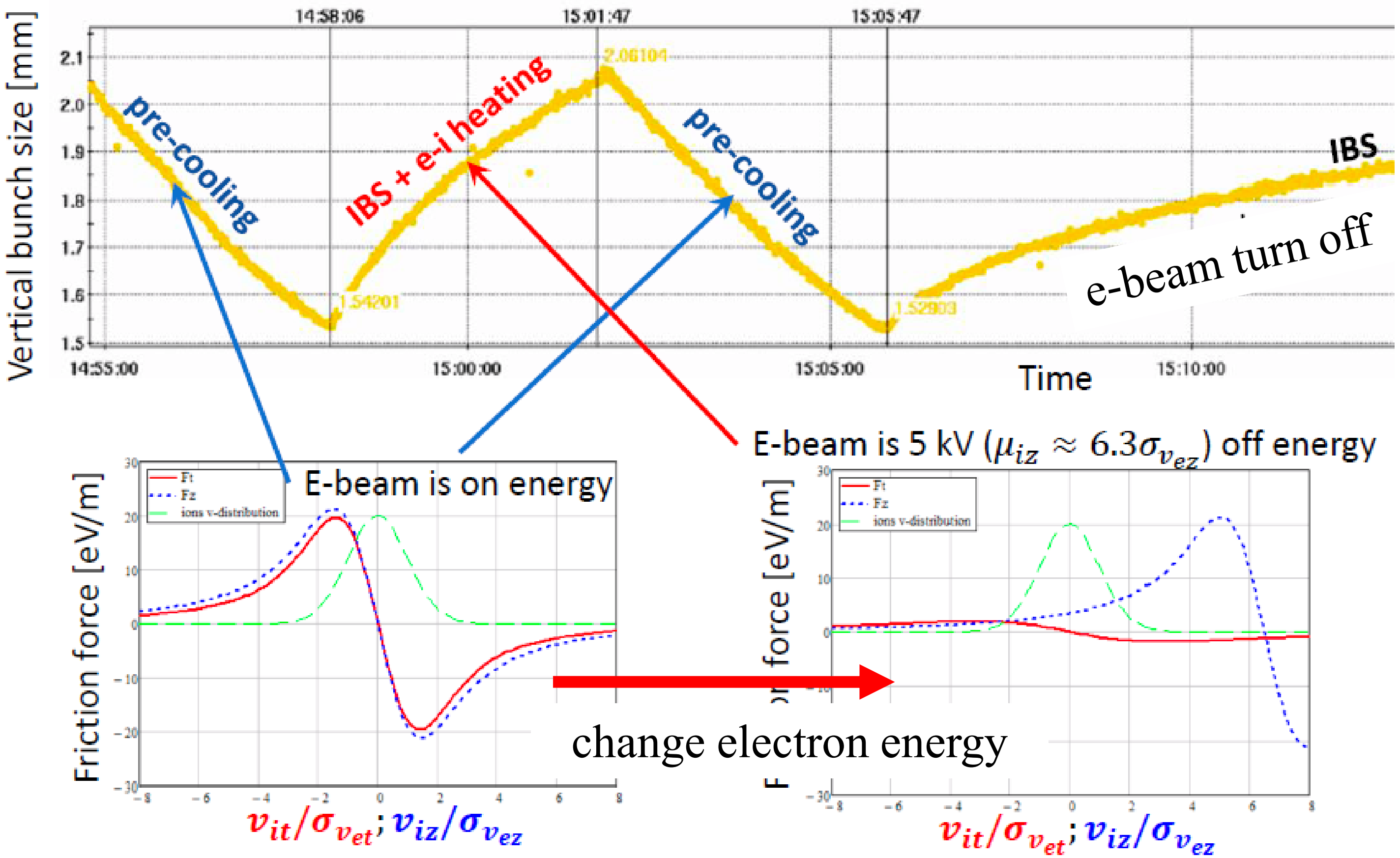
- Transverse space charge field will provide a kicker on the ion
- coupling with synchrotron tune, chromaticity, effected by IBS and cooling





$$F_r = eZ_i\left(E_r - v_s B_\phi\right) = eZ_i \frac{I_e}{2\pi\varepsilon_0 \beta c \gamma^2}\frac{r}{a^2}$$

Mike Blaskiewicz report at BNL in 2015



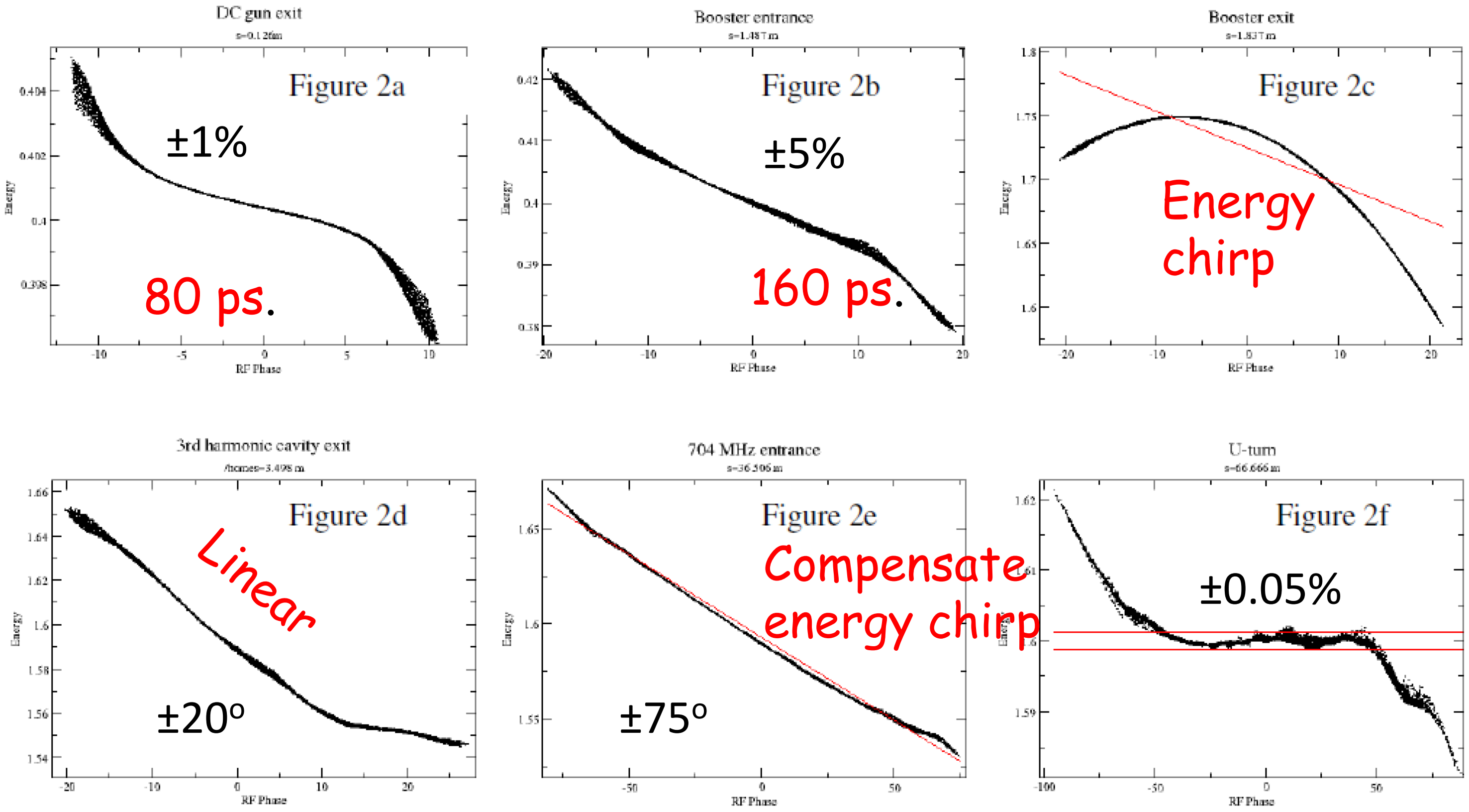
—S.Seletskiy, COOL'23

➢ Beam cooling method for ~10 GeV/u ions

Longitudinal phase space manipulation

- The electron beam must not only be optimized for a **low transverse emittance** but also for a **low energy spread** in order to achieve efficient cooling

Energy [MeV]	1.6	2.0	2.6
Bunch Charge for Cooling [pC]	100	120	150
Accelerated bunch Charge [pC]	130	160	200
Bunches per train	30	27	24
Total beam Current [mA]	40	40	44
Normalized Emittance [μ]	< 2.5	< 2.5	< 2.5
Energy spread $\cdot 10^{-4}$	< 5	< 5	< 5



energy spread increase due to space charge effect from gun to booster

acceleration and energy chirp in SRF booster

3^{rd} harmonic RF cavity corrects the second order energy chirp

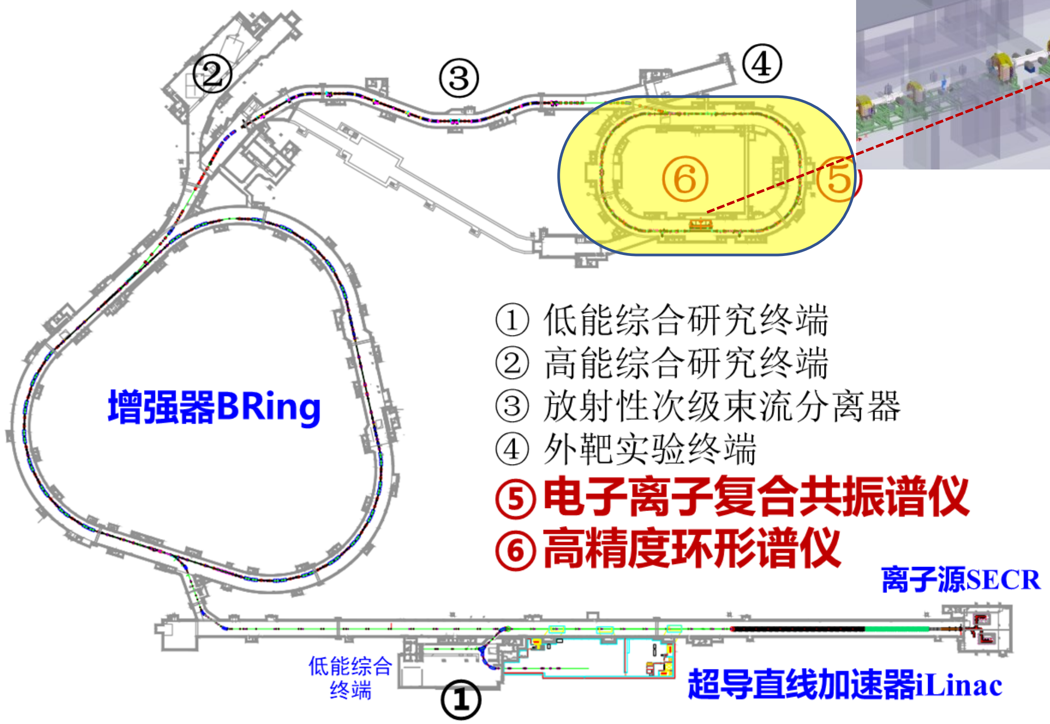
30 meter long transport to increase the bunch length

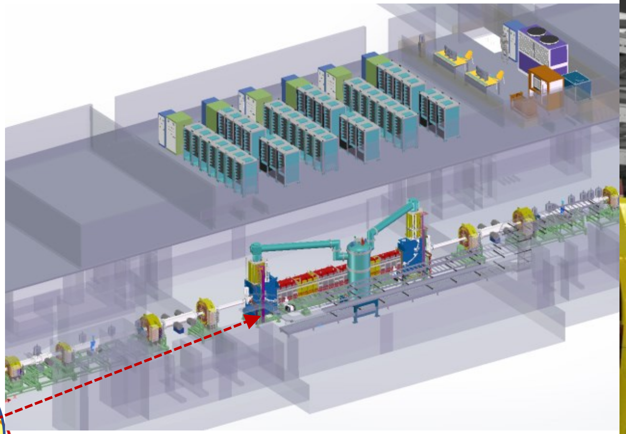
warm RF cavity removes energy chirp

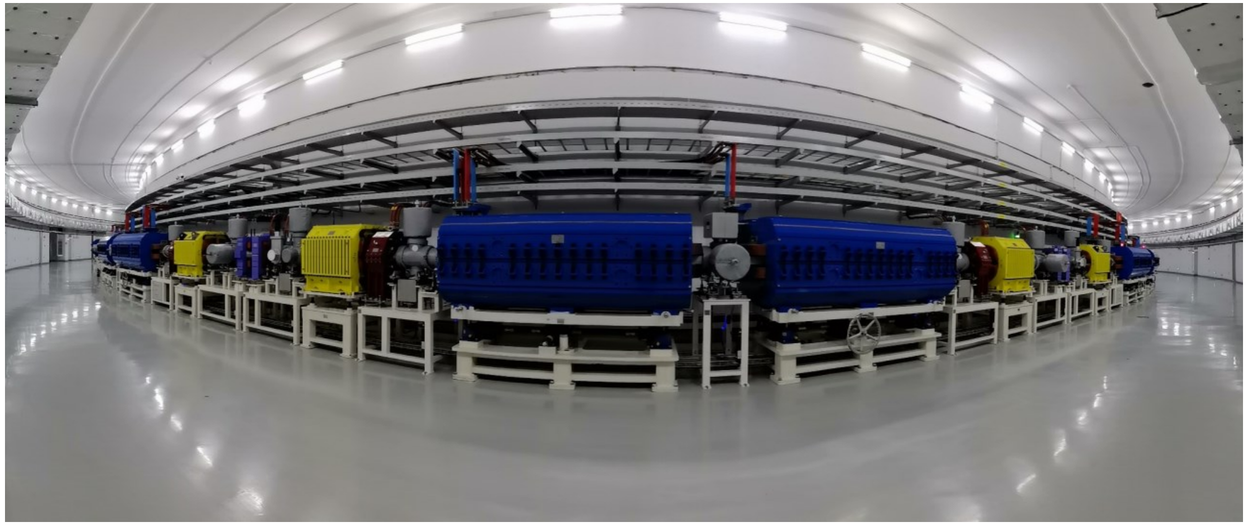
➢ Plan for the HIAF e-cooling

A DC cooler @ SRing

- Compensate the energy loss and emittance growth at internal target experiment



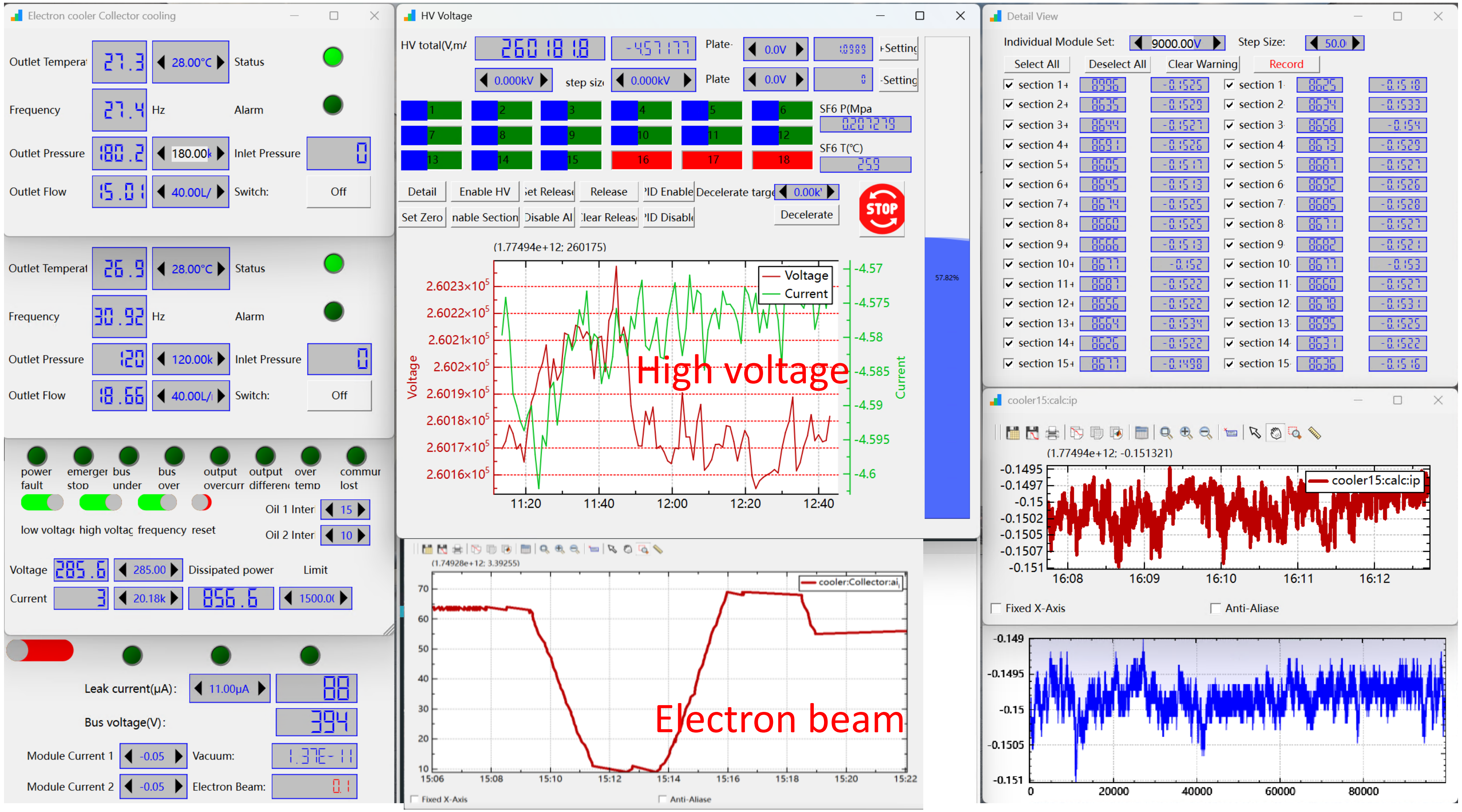




➢ Plan for the HIAF e-cooling

A DC cooler @ SRing

- High voltage system is ready for the cooling test

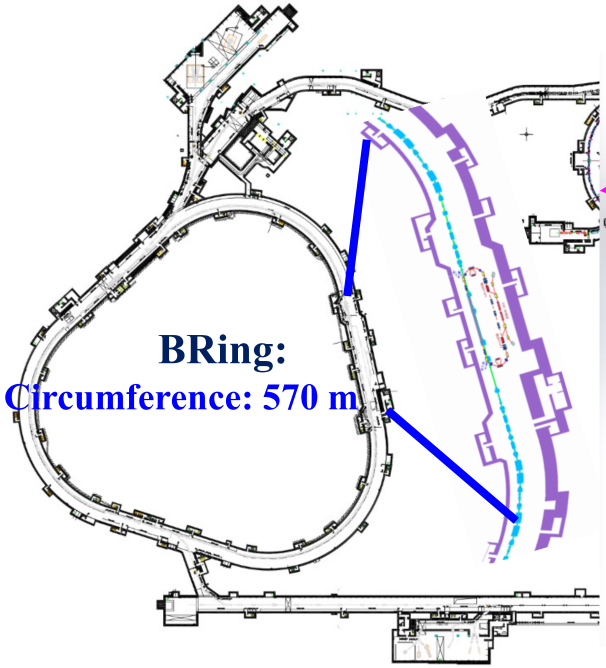


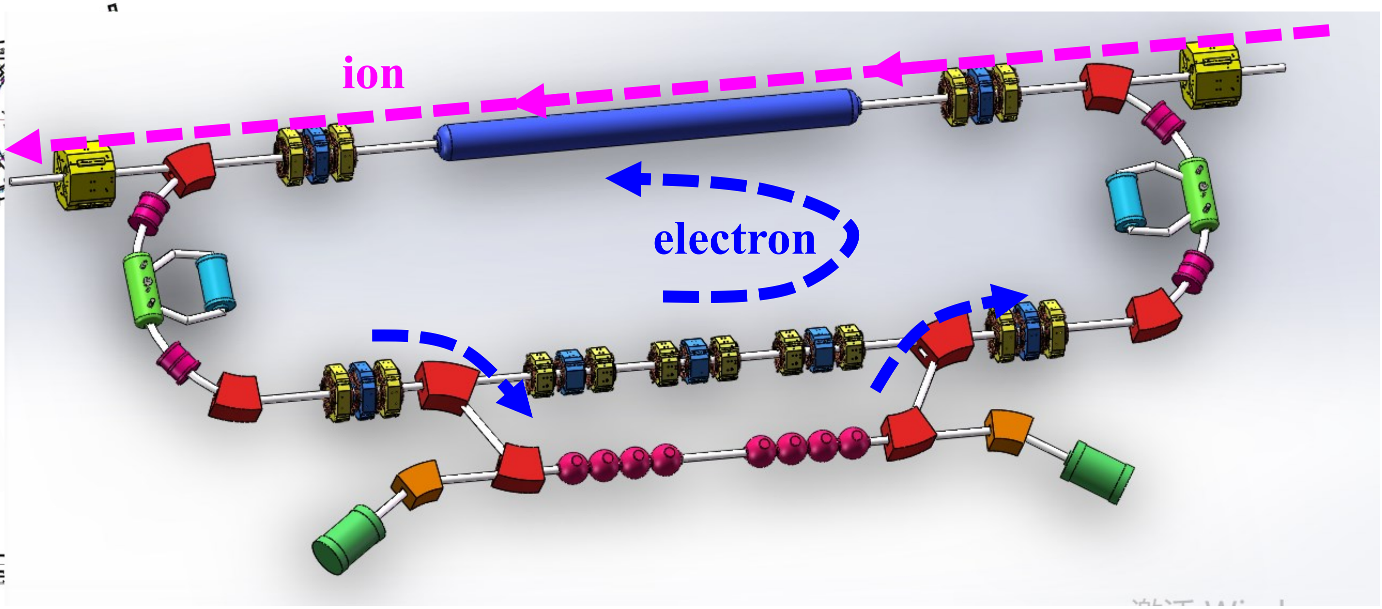
➢ Plan for the HIAF e-cooling

High energy cooler @ BRing

- Use linac and electron storage ring, to reduce the power of linac and dumper
- Electron repetition in storage rings with ~10 Hz or ~100Hz
- S or L band normal conducting linac is selected as an injector of electron ring
- Energy recovery linac could be considered in the future

参数	BRing-cooler
Eneryg	5.5 MeV
Macro charge	**10 nC**
Macro e-bunch	**~ 100 ns**
Energy spread	1×10^{-4}
angle	<100 μrad





➢ Plan for the HIAF e-cooling

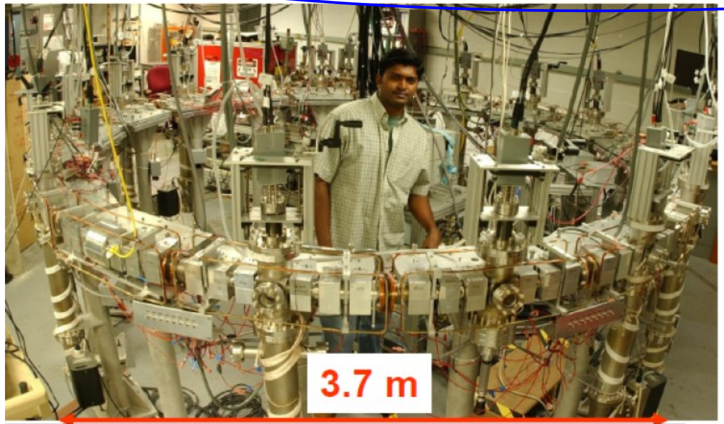
Ultra low energy electron ring

- It is a big challenge to design a ~5 MeV electron storage ring
- Intrabeam scattering, space charge effect, lifetime …

UMER – A Scale Model of a High-Intensity Ring

Mission: Study Space Charge Dynamics over Long Path Lengths

low energy	high current	low-emittance
10 keV	0.5-100 mA	0.3-3 μm



Lap time	=	197 ns, (5.08 MHz)
Pulse Length	=	15 to 145 ns,
Full-Lattice Period	=	0.32 m (std. lattice)
Vacuum Pipe radius	=	25.4 mm

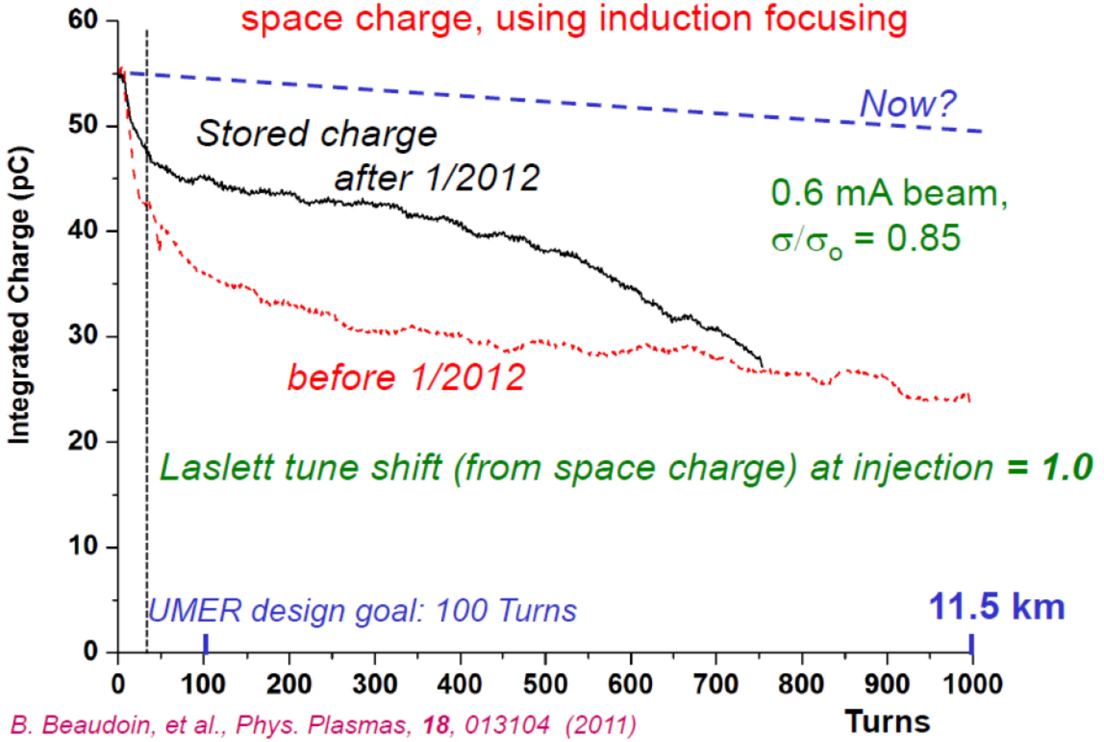
~10^{10} particles or up to 14 nC

- Safe
- Reproducible results
- Available: accelerator and beam physicists are the users
- Flexible: lattice, magnets, apertures

Shown: UMD graduate Charles Thangaraj (2009), now at FNAL

Beam Losses with Longitudinal Containment

Demonstrated long-distance recirculation of a beam with high space charge, using induction focusing



*B. Beaudoin, et al., Phys. Plasmas, **18**, 013104 (2011)*

➢ Plan for the HIAF e-cooling

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- It is a big challenge to design a ~5 MeV electron storage ring
- Intrabeam scattering, space charge effect, lifetime …

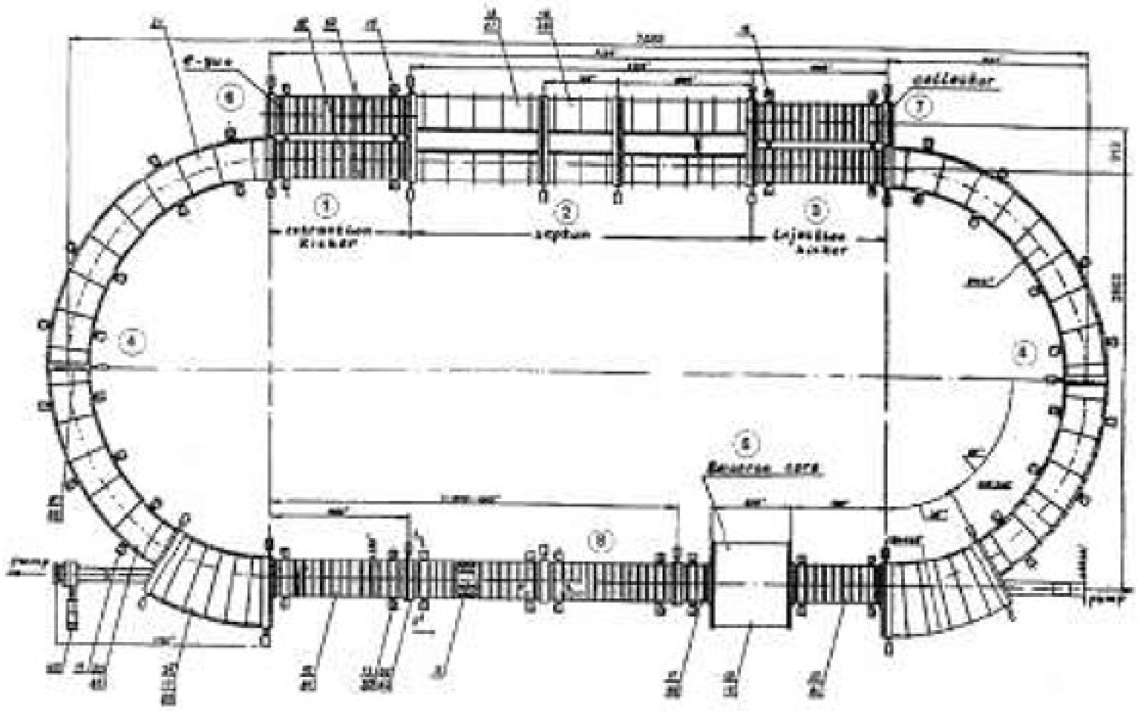


Fig. 1. The Modified Betatron Prototype.

Table 2
General parameters of the MOBY

Circumference (m)	18.28
Electron energy (MeV)	0.01–4.36
Beam current at maximal energy (A)	0.01–0.5
Electron beam radius (cm)	1
Revolution period (ns)	300–50
Longitudinal magnetic field (G)	1000
Bending magnetic field (G)	1.8–110
Major radius of the toroids, (m)	1.45
Gradient of quadrupole field (G/cm)	−4–+4
Inductive accelerating voltage amplitude (V)	50
Acceleration repetition frequency (Hz)	1
Acceleration cycle duration (ms)	10
Residual gas pressure (Torr)	10^{-9}

MOBY designed by JINR

➢ Plan for the HIAF e-cooling

Dispersive cooling

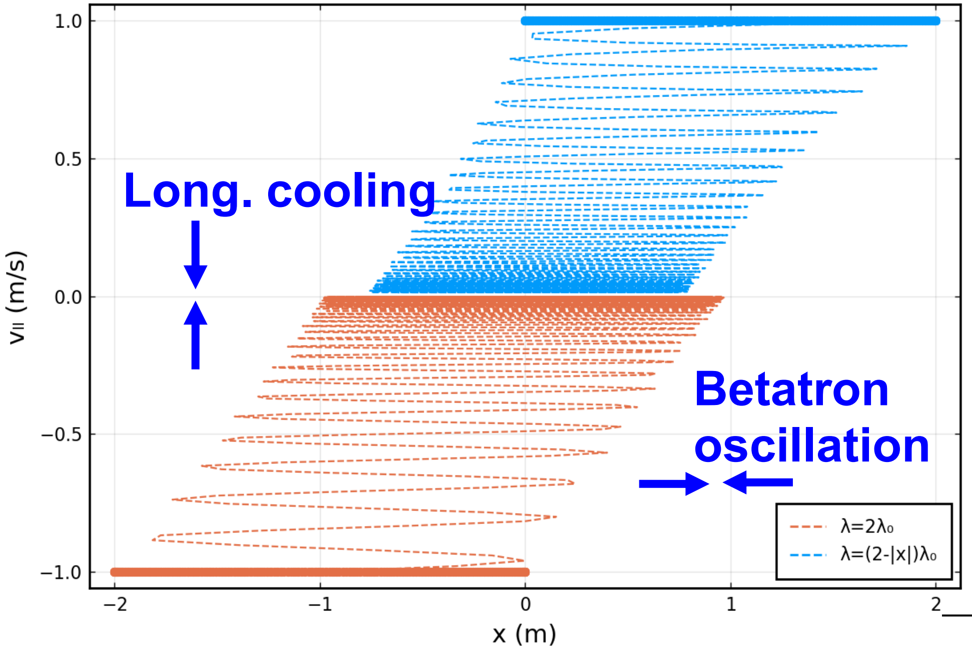
- To get the balance between longitudinal and transverse cooling rate

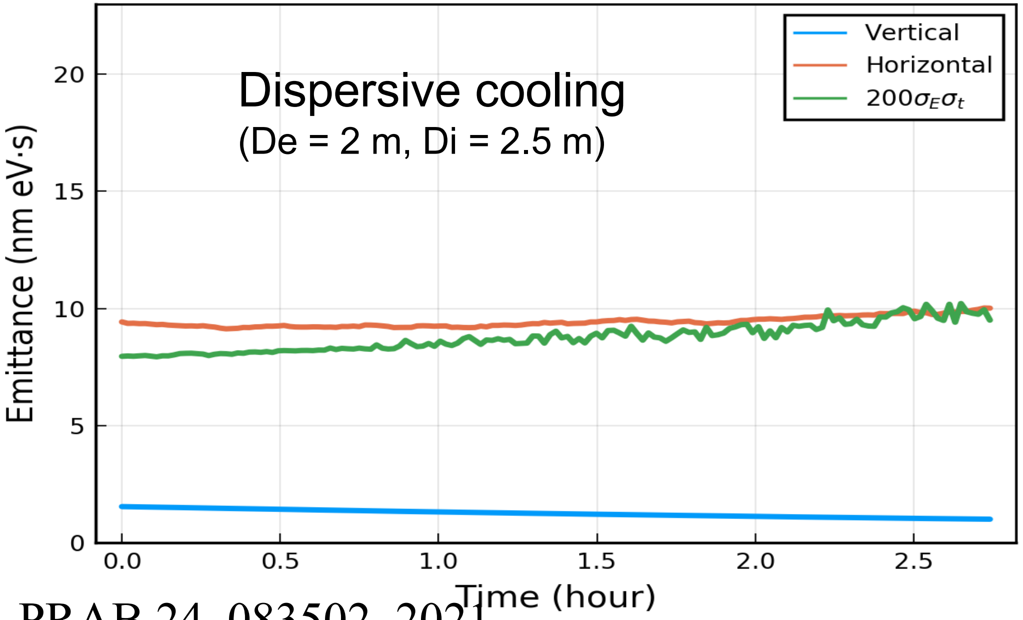
$$p_\perp/mc = \gamma\theta_\perp \gg \sigma_\gamma/\gamma = p_\parallel/mc$$
$$kT_\perp/kT_\parallel \propto \gamma^2$$

$$\langle\Delta\delta^2\rangle = -2C_p\langle n_e\delta^2\rangle + 2C_p\delta_o\langle n_e\delta\rangle + 2C_pK_{sc}x_o\left(x_o\langle n_e\delta\rangle + 2\langle n_e x_\beta\delta\rangle + 2D\langle n_e\delta^2\rangle\right)$$

$$\langle\Delta\epsilon\rangle = -C_x\epsilon_0\langle n_e\rangle + \frac{C_pD}{\beta_x}\langle n_e x_\beta\delta\rangle - \frac{C_pD\delta_o}{\beta_x}\langle n_e x_\beta\rangle - \frac{C_pDK_{sc}x_o}{\beta_x}\left(x_o\langle n_e x_\beta\rangle + 2\langle n_e x_\beta^2\rangle + 2D\langle n_e x_\beta\delta\rangle\right)$$

E-beam density $\boldsymbol{n_e}$ — Energy offset $\boldsymbol{\delta_o}$ — Space charge $\boldsymbol{K_{sc}}$ and displacement $\boldsymbol{x_o}$





—H.Zhao, L.Mao, PRAB 24, 083502, 2021

➢ Conclusion

- We are investigating a high energy electron cooling method in HIAF-Bring, to reduce the emittance and momentum spread of ~10 GeV ion beams
- A combination of linac and storage ring could be a possible way to provide electron beam with ~100 mA, ~1 umrad and ~0.01% energy spread

Thank you for your attention!