

15th International Workshop on

COOL25

Beam Cooling and
Related Topics



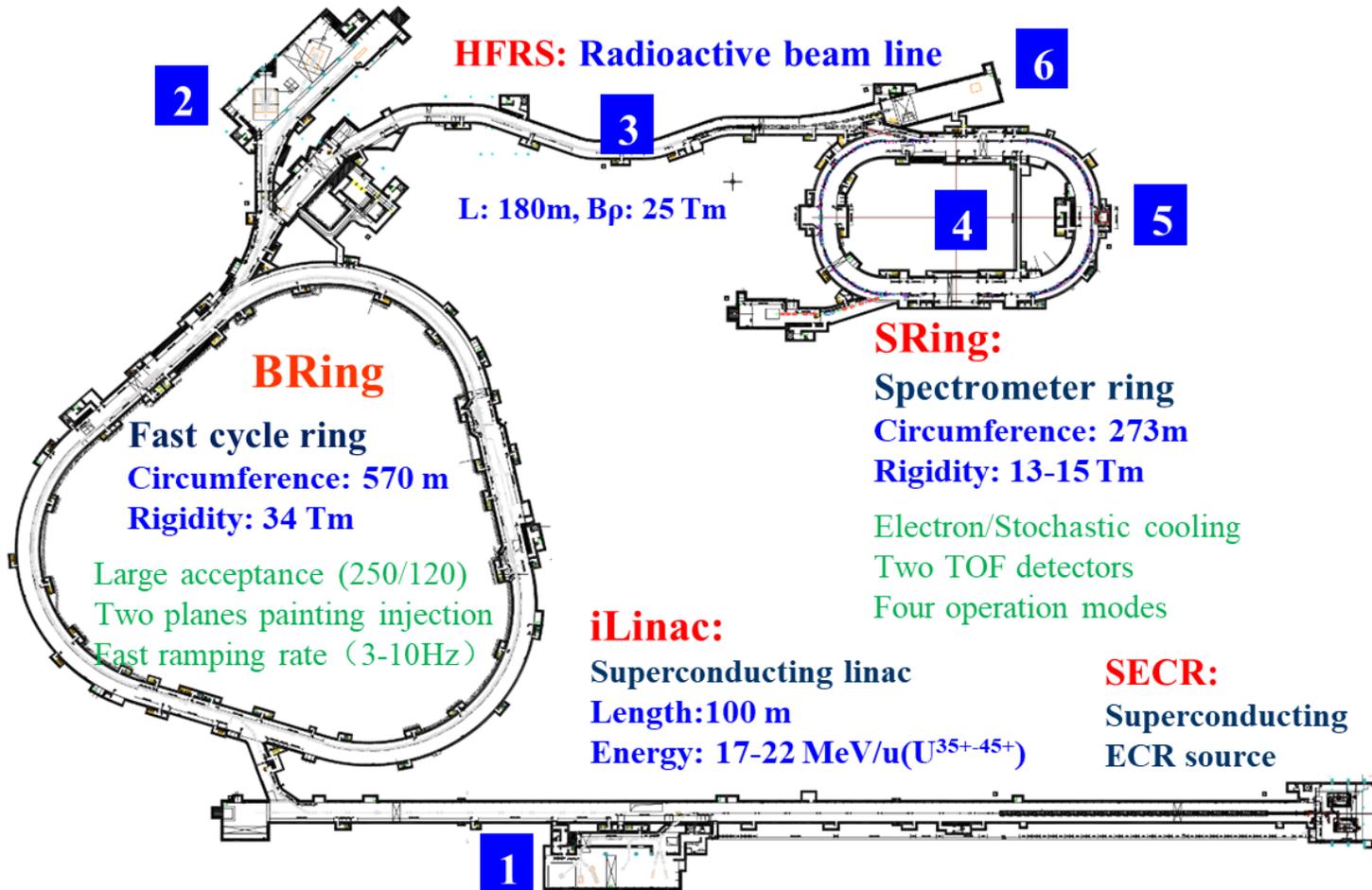
Longitudinal beam stacking in storage ring using pulsed e-cooling

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- Accumulation of RIBs or high-charged particles is required for various experiments in storage rings, such as in FAIR, NICA and HIAF project.

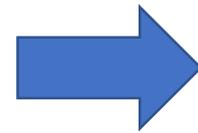
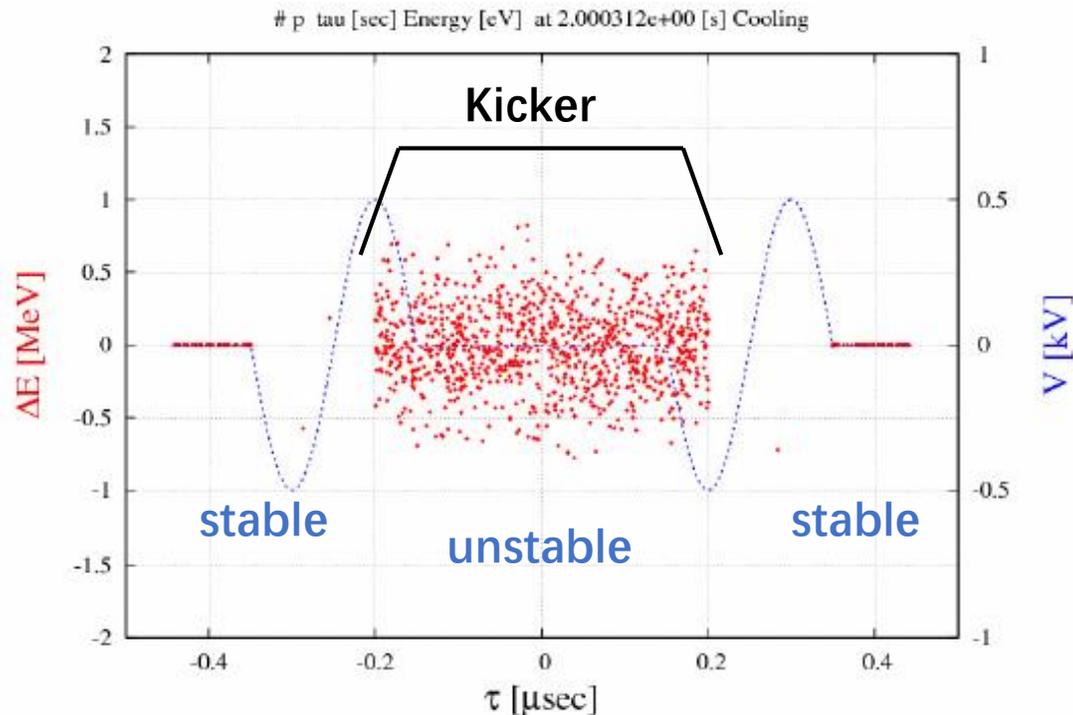


Experimental terminals

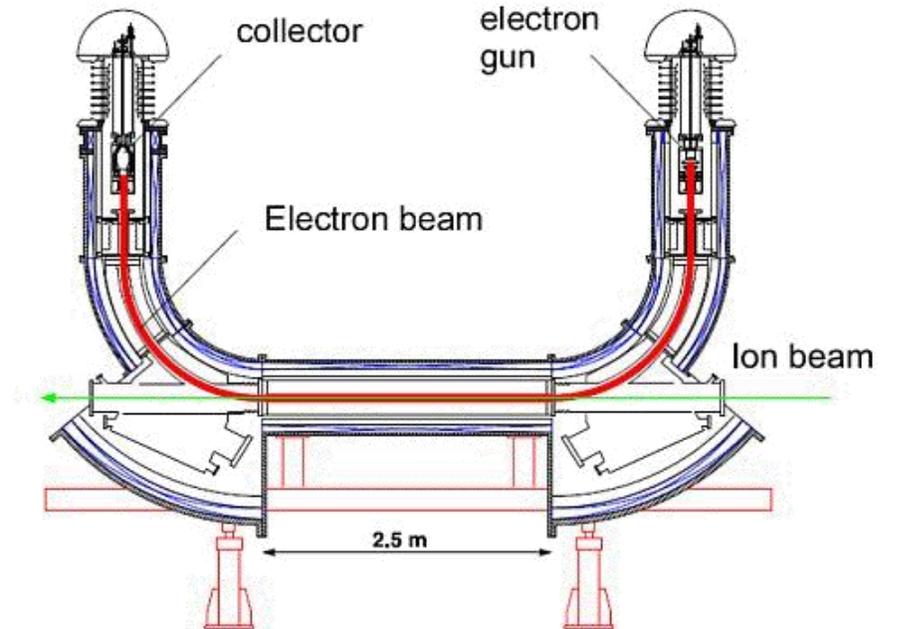
- ① Low energy nuclear structure terminal
- ② High energy experimental terminal
- ③ High energy fragment separator HFRS
- ④ High precision spectrometer ring SRing
- ⑤ Electron ion recombination terminal
- ⑥ Radioactive ion beam physics terminal

- Accumulation of RIBs or high-charged particles is required for various experiments in storage rings, such as in FAIR, NICA and HIAF project.
- Around 2000s, the barrier bucket concept has been used and studied in a number of synchrotrons at Fermilab, BNL, KEK and CERN.

BB system + beam cooling



Pulsed e-cooler



□ Barrier voltage of pulsed e-beam

- Assuming a pulsed e-beam with the current varies linearly at the edges. So the longitudinal electric field due to space charge is

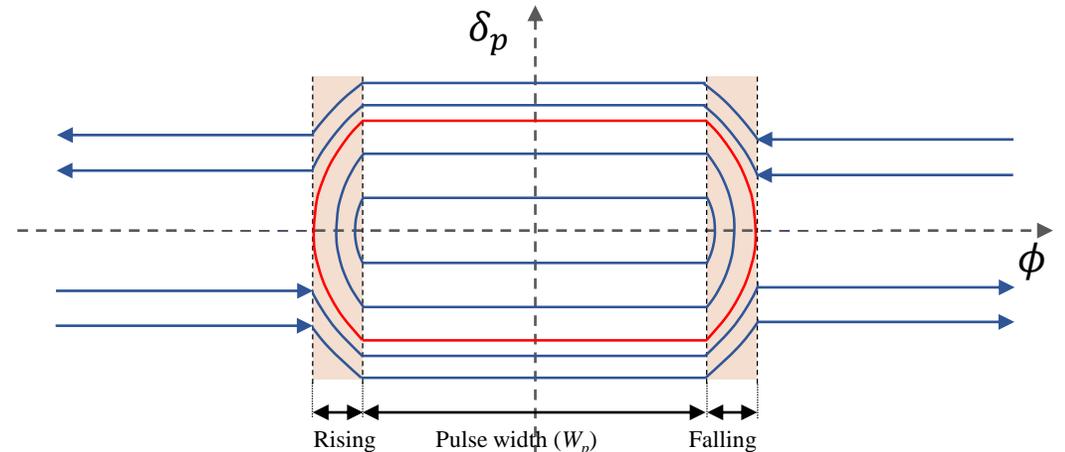
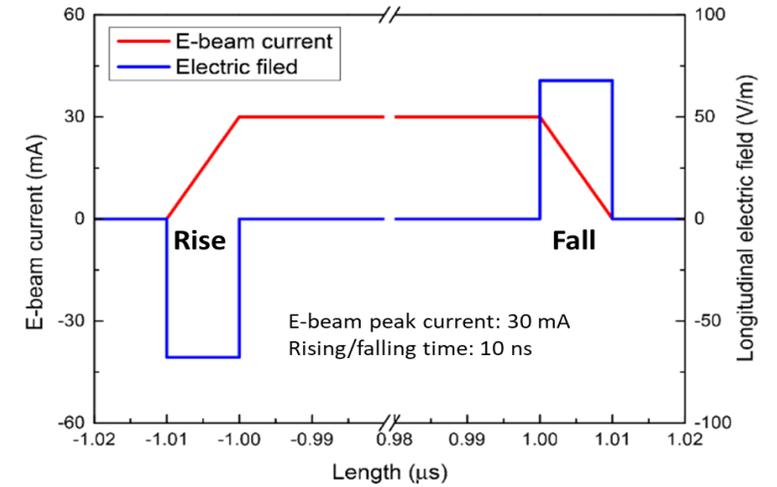
$$E_z(\varphi) = -\frac{1}{\beta\gamma^2} \frac{1}{4\pi\epsilon_0 c} \left[2 \ln\left(\frac{b}{R_e}\right) + 1 \right] \frac{\partial I_e(\varphi)}{\partial \varphi} \quad \frac{\partial I_e(\varphi)}{\partial \varphi} = k = \frac{I_e}{\Delta\phi_B}$$

- The barrier voltage is determined by the electric field E_z and the length of the cooler L_{cooler}

$$V_{BB} = |E_z| \times L_{\text{cooler}} \quad V(\varphi) = \begin{cases} 0, & -\pi < \varphi \leq -(\Delta\phi_B + \frac{1}{2}\Delta\phi) \\ -V_{BB} + V_{SC}, & -(\Delta\phi_B + \frac{1}{2}\Delta\phi) < \varphi \leq -\frac{1}{2}\Delta\phi \\ 0, & -\frac{1}{2}\Delta\phi < \varphi \leq \frac{1}{2}\Delta\phi \\ V_{BB} - V_{SC}, & \frac{1}{2}\Delta\phi < \varphi \leq (\Delta\phi_B + \frac{1}{2}\Delta\phi) \\ 0, & (\Delta\phi_B + \frac{1}{2}\Delta\phi) < \varphi \leq \pi \end{cases}$$

V_{SC} : space charge of i-beam

- This method requires that the stable area coincides with the cooling region, which means it only works for heavy ion beams below transition energy ($\eta < 0$).



□ Barrier voltage of pulsed e-beam

- Particle motion in longitudinal phase space

$$\frac{d\phi}{dt} = \eta \frac{2\pi}{T_0} \frac{1}{\beta^2} \frac{\Delta E}{E_0}$$

$$\frac{d\Delta E}{dt} = \frac{ZeV(\phi)}{T_0} + [\lambda_{IBS} - \lambda_{cool}(\phi)]\Delta E$$

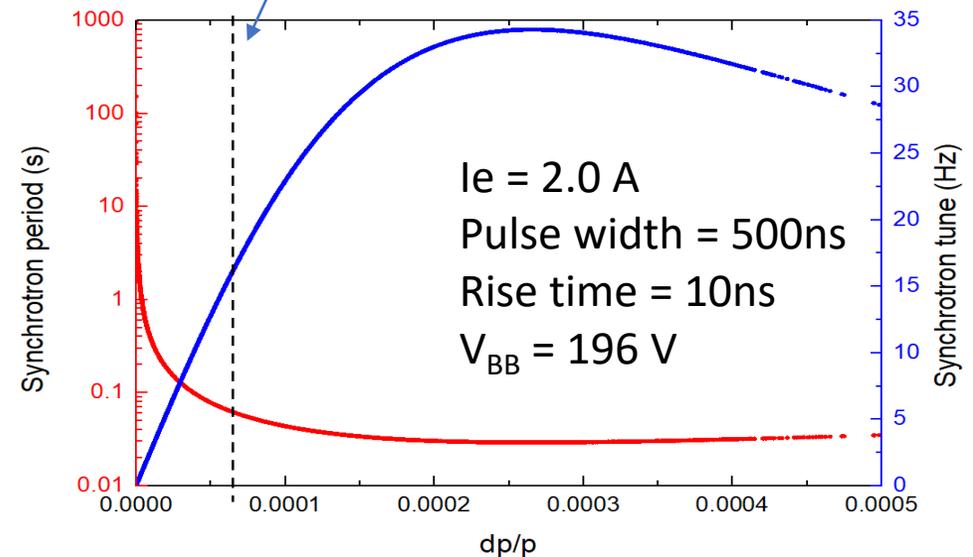
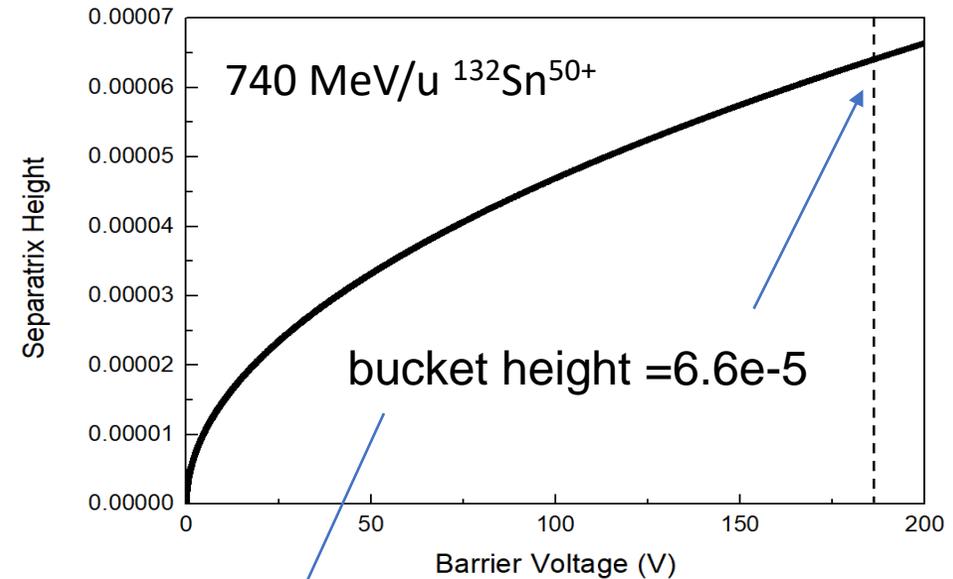
- Bucket height

$$\left(\frac{\delta p}{p}\right)_B = \sqrt{\frac{ZeV_{BB}\Delta\phi_B}{\pi\eta\beta^2\gamma Am_0c^2}} = \sqrt{\frac{ZegI_eL_{cooler}}{2\pi\epsilon_0A|\eta|\beta^3\gamma^3 Cm_0c^3}}$$

geometric factor: $g = 2 \ln(b/R_e) + 1$

- Synchrotron oscillation period

$$T_s = T_0 \frac{1}{\eta} \left(\frac{\delta p}{p_0}\right)^{-1} \frac{\Delta\phi}{\pi} + 4T_0 \frac{A\gamma\beta^2 m_0c^2}{ZeV_B} \frac{\delta p}{p_0}$$

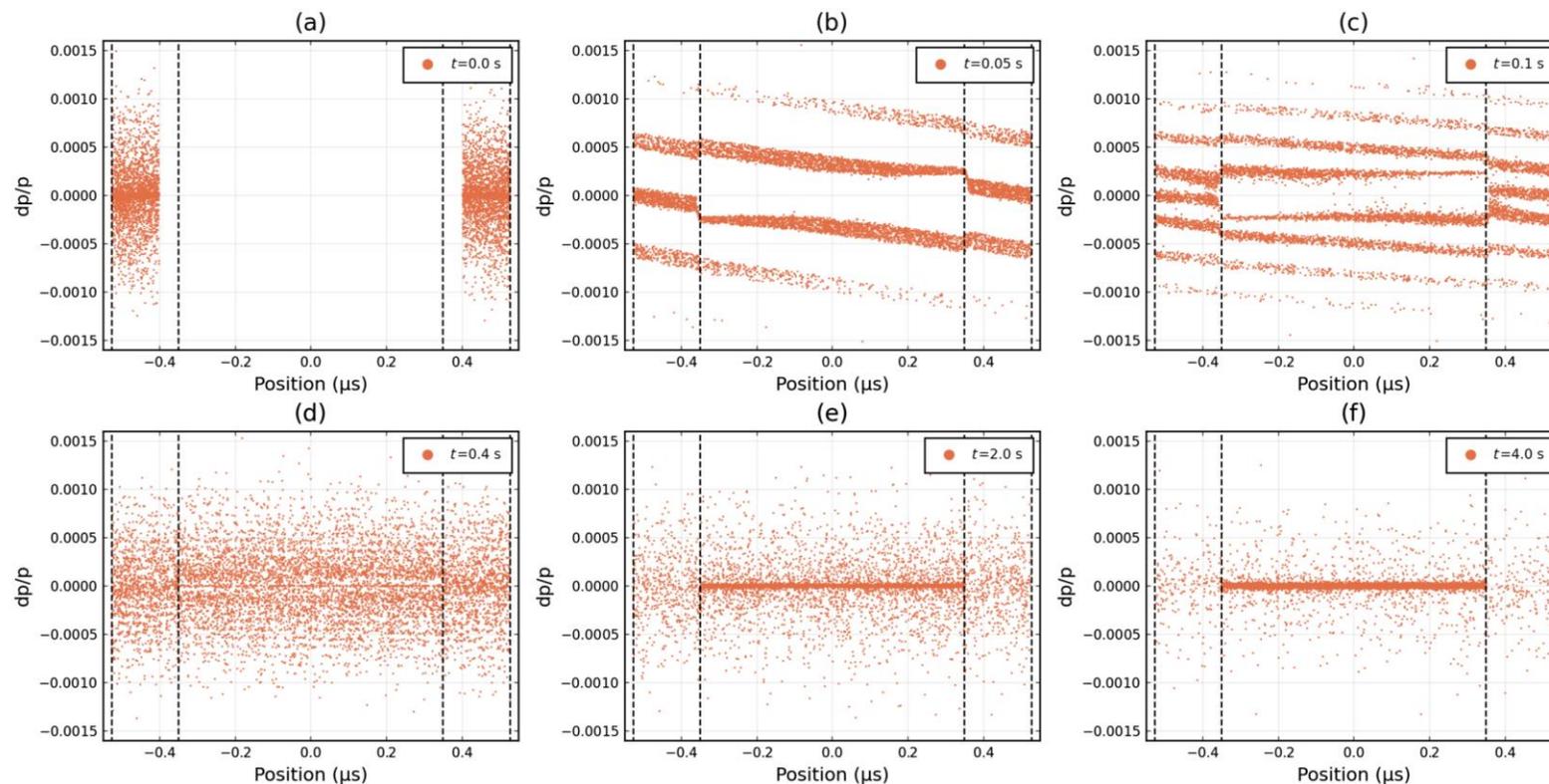


□ Beam injection and cooling

- The injected ion would be finally cooled into the stable region, and confined by the barrier voltage.
- The simulation includes **BB voltage, IBS and ion space charge (longitudinal)**.

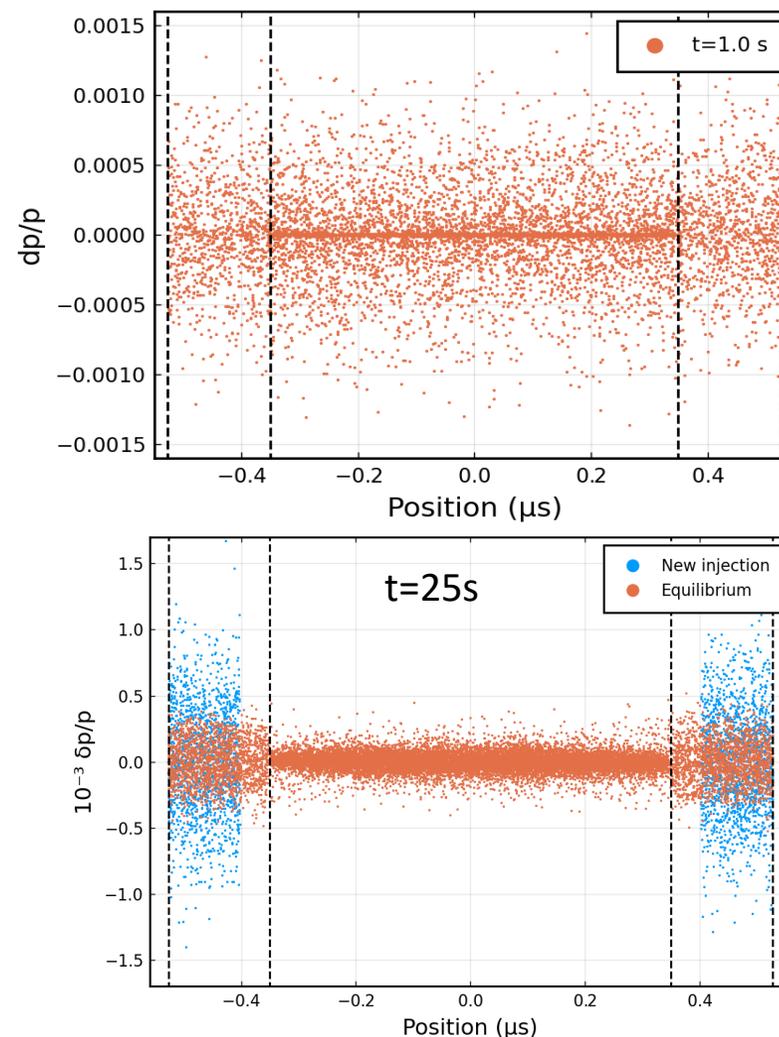
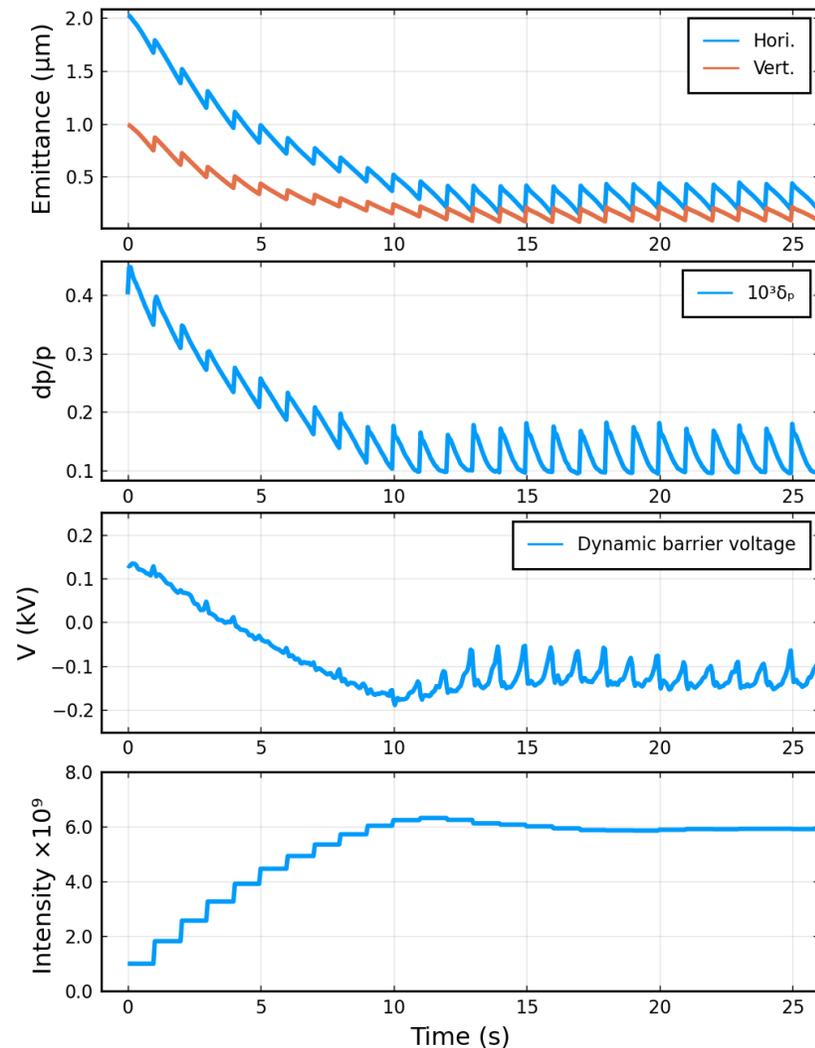
Beam parameters in SRing of HIAF

Ion beam	
Species	$^{238}\text{U}^{92+}$
Energy (MeV/u)	800
Number of particles per injection	1×10^9
rms emittance (x/y) (μm)	2.0/1.0
rms momentum spread	4.0×10^{-4}
Injected beam length (μs)	0.25
Revolution time (μs)	1.054
Electron beam	
Current (A)	1.0
Radius (cm)	2.0
Pulse length (μs)	0.7
Rising/falling time (ns)	10.0
V_{BB} (Volt)	120.2
Bucket height	0.5×10^{-4}
Transverse temperature (eV)	0.5
Longitudinal temperature (eV)	1.2×10^{-3}
Magnetic field (Gs)	1500
Magnetic field straightness	5.0×10^{-5}



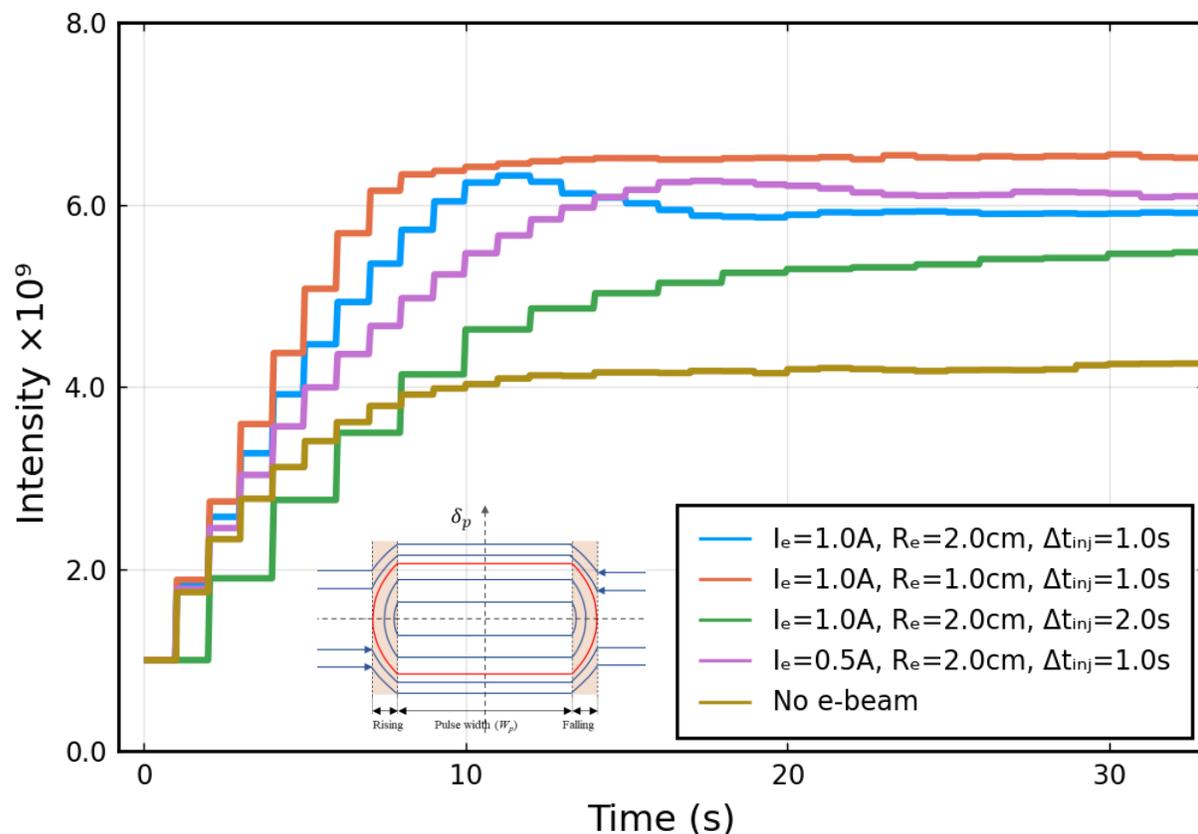
□ Beam accumulation

- The beam equilibrium momentum spread is the result of cooling and IBS effects, which is one of the main limitations of the beam stacking performance.
- Another limitation is the space charge effect of the ion beam, a high charge intensity can seriously affect the dynamic barrier voltage and even cancel out the stable region.



□ Beam accumulation optimization

- Considering space charge, the dynamic bucket height and factors such as injection cycle, IBS, and cooling efficiency make the stacking process complex, requiring careful parameter optimization.



Ion	Z	A	E_0 (MeV/u)	$\sqrt{Z^3/A}$	Est. $N_{stacking}$
U	92	238	800	57.2	1.00
Sn	50	132	740	30.8	1.87
Sn	50	104	740	34.7	1.66
Xe	54	131	900	34.7	1.64
Kr	36	84	950	23.6	2.41
Kr	36	84	600	23.6	2.48
Ar	18	40	1000	12.1	4.71
C	6	12	600	4.2	13.8
C	6	12	1500	4.2	14.3

Estimation of the stacking performance (IBS&Cooling)

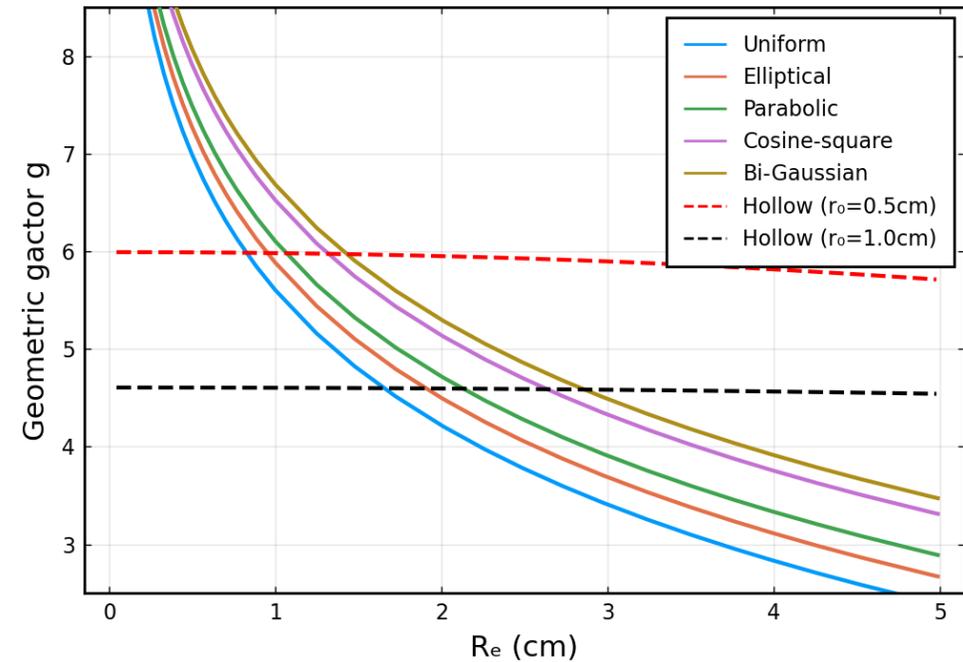
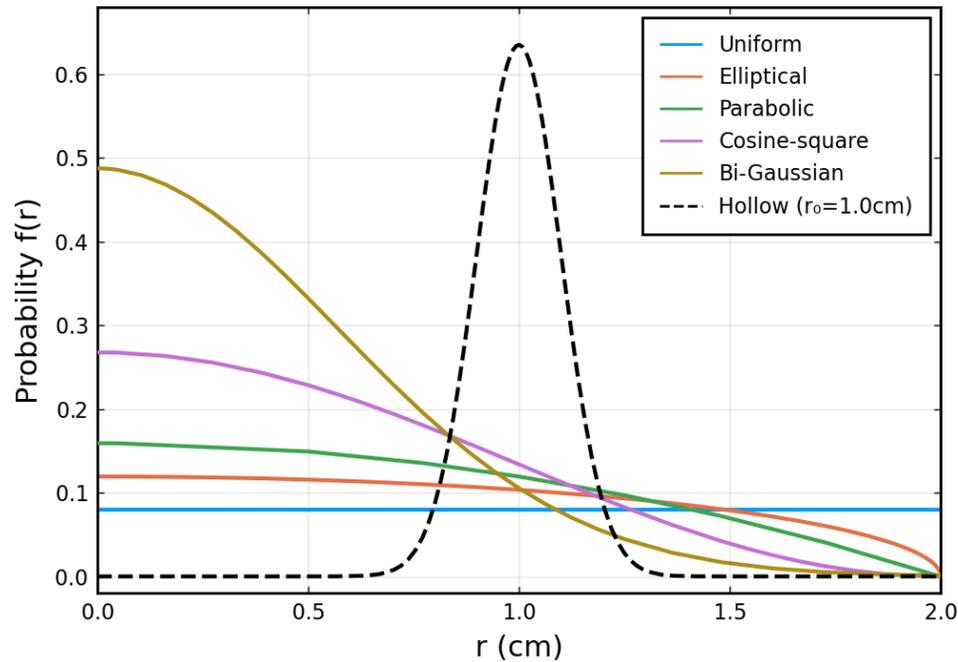
$$N \propto \sqrt{\frac{gAn_e^3a^2}{|\eta|Z^3\gamma^3}}$$

□ Beam accumulation optimization

- Barrier voltage: energy, e-beam pulse width and the geometric factor
- E-beam distribution can be used to optimize the accumulation performance

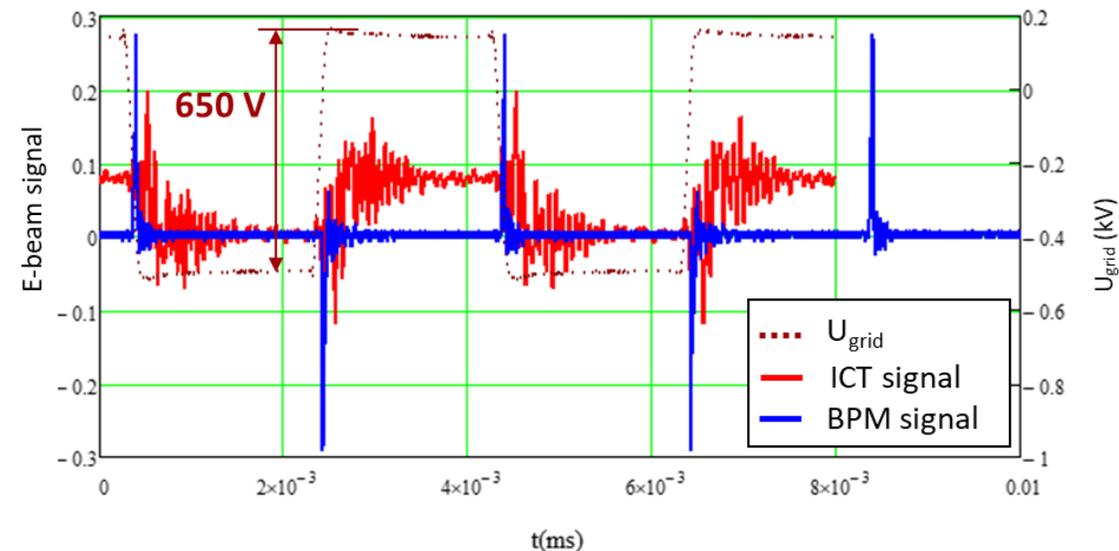
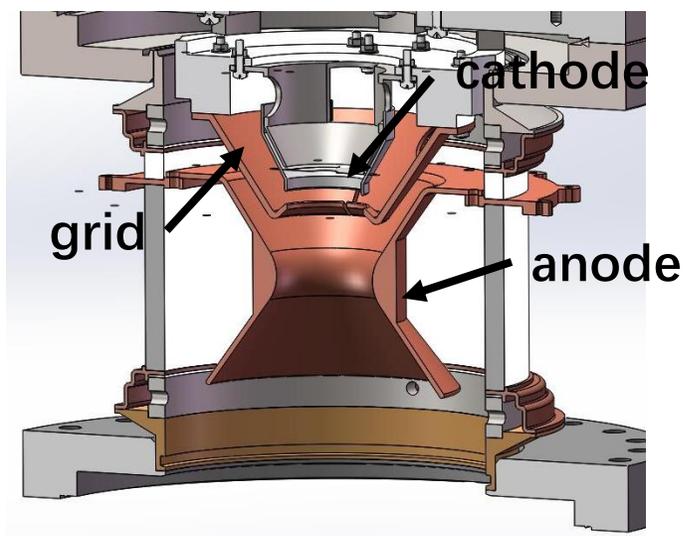
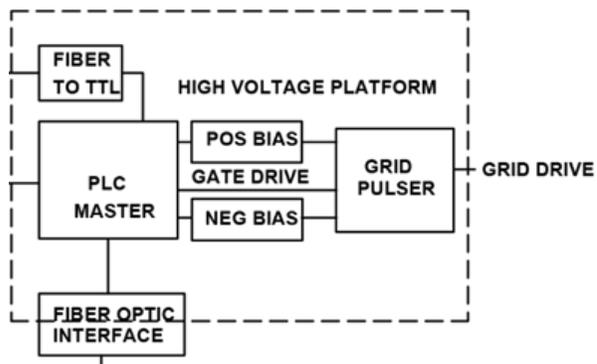
$$E_z(\varphi) = -\frac{1}{\beta\gamma^2} \frac{1}{4\pi\epsilon_0 c} \left[2 \ln\left(\frac{b}{R_e}\right) + 1 \right] \frac{\partial I_e(\varphi)}{\partial \varphi}$$

$$g = \int_r^b \frac{2}{x} \int_0^x 2\pi r f(r) dr dx \simeq \int_0^b \frac{2}{x} \int_0^x 2\pi r f(r) dr dx$$



□ EC35 @HIRFL CSRm

- The pulse generator is applied to provide a voltage on the grid to switch on/off the electron beam.



- Pulsed electron beam can be measured by BPMs (blue) and ICT (red) in front of the collector.

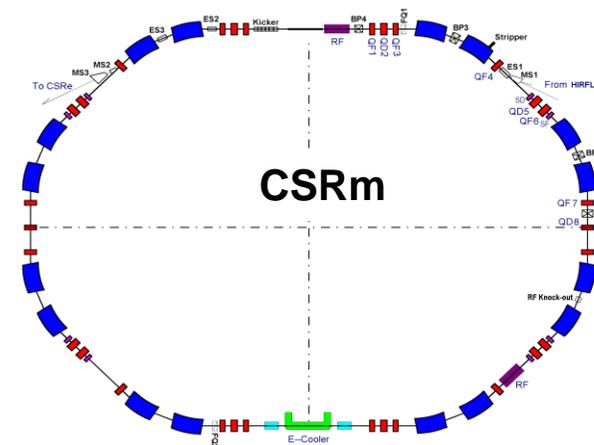
- L.J. Mao, COOL2017, TUP15
- M.W. Bruker, Phys. Rev. Accel. Beams 24, 012801 (2021)

Cooling process using pulsed e-beam

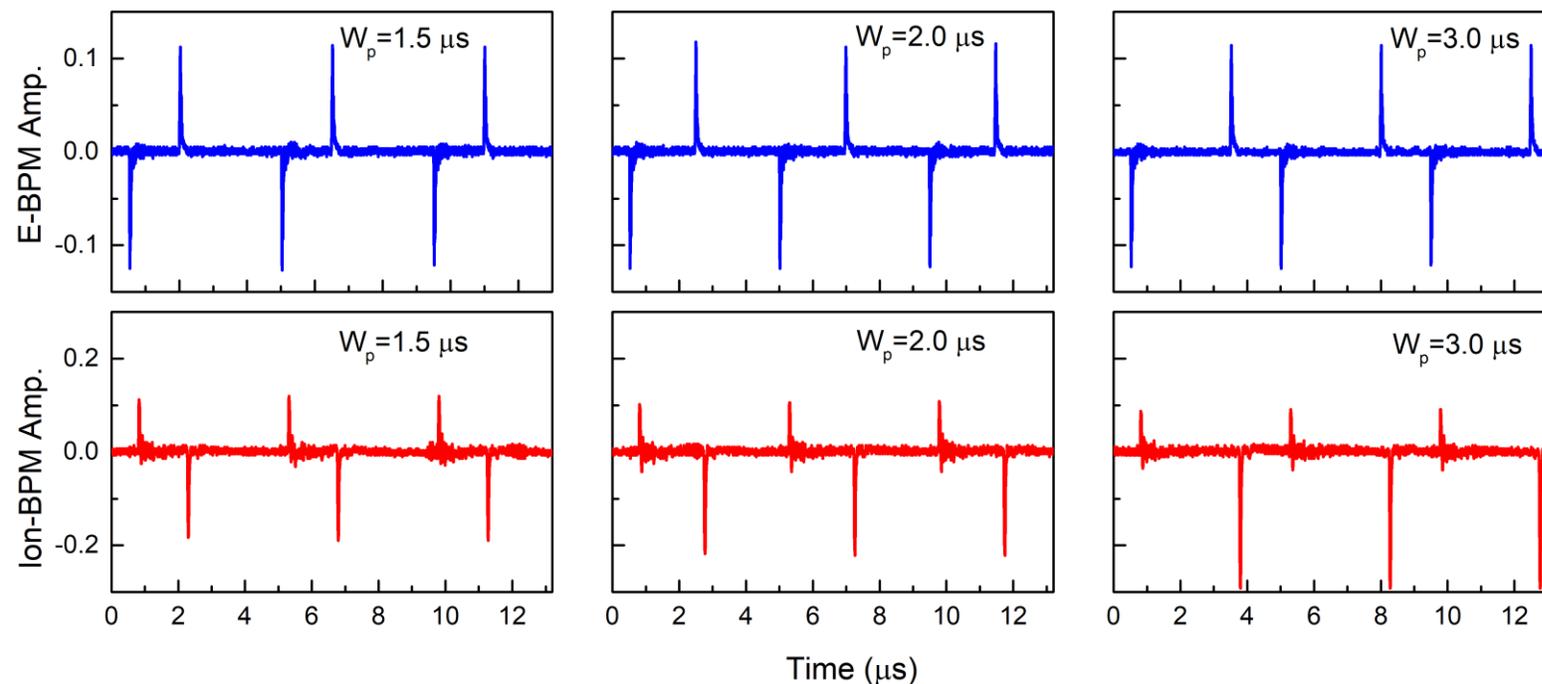


Experiment @HIRFL-CSRm

- Grouping effect** – The coasting ion beam was been cooled to a pulse and the pulse width is same with the electron beam.



7.0 MeV/u C ⁶⁺	Coasting
Particle number	5.0×10^8
Emittance (RMS)	*/*
dp/p (RMS)	2.0×10^{-4}
Bunch length (RMS)	*
RF voltage	*
h	*
E-beam current (peak)	30 mA
E-beam diameter	~30 mm
Pulse width	0.5-3.0 μ s
Rising/falling time	10 ns

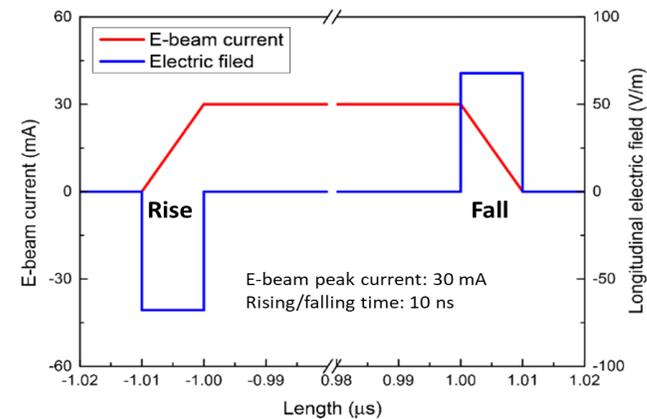


Cooling process using pulsed e-beam

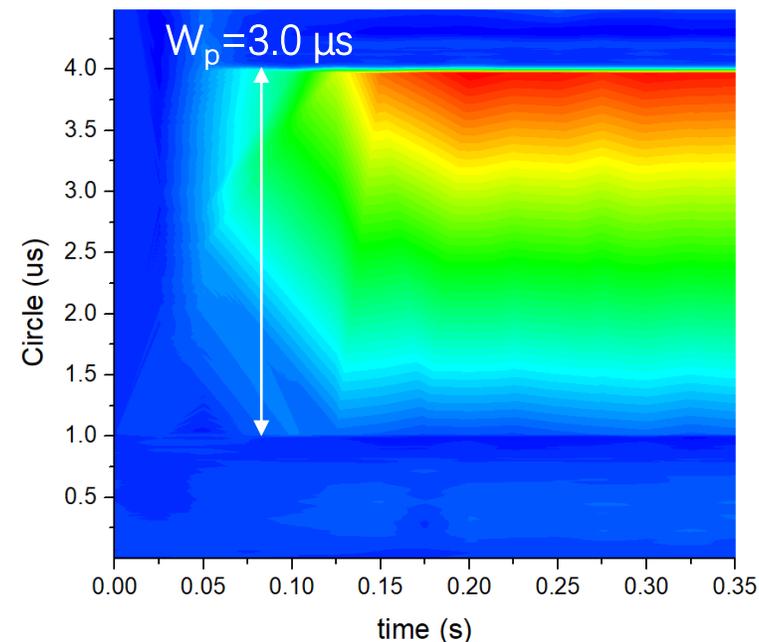
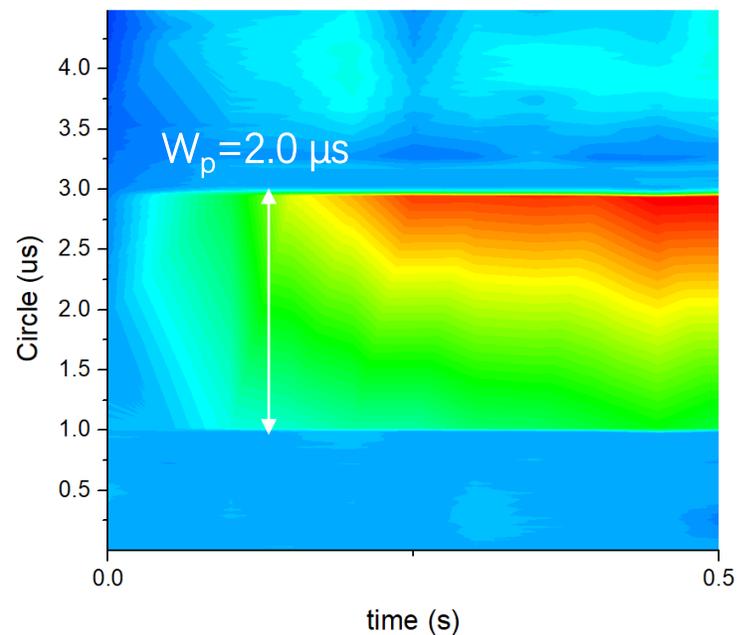
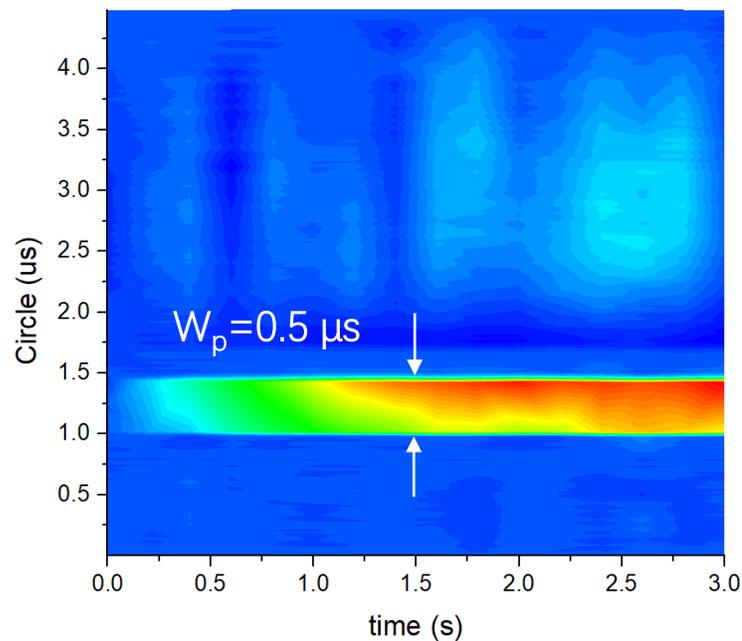


□ Experiment @HIRFL-CSRm

- Longitudinal beam profile of the ion beam is slowly grouped to a pulse during the cooling process
- Nonuniform intensity distribution of the ion beam has been identified.

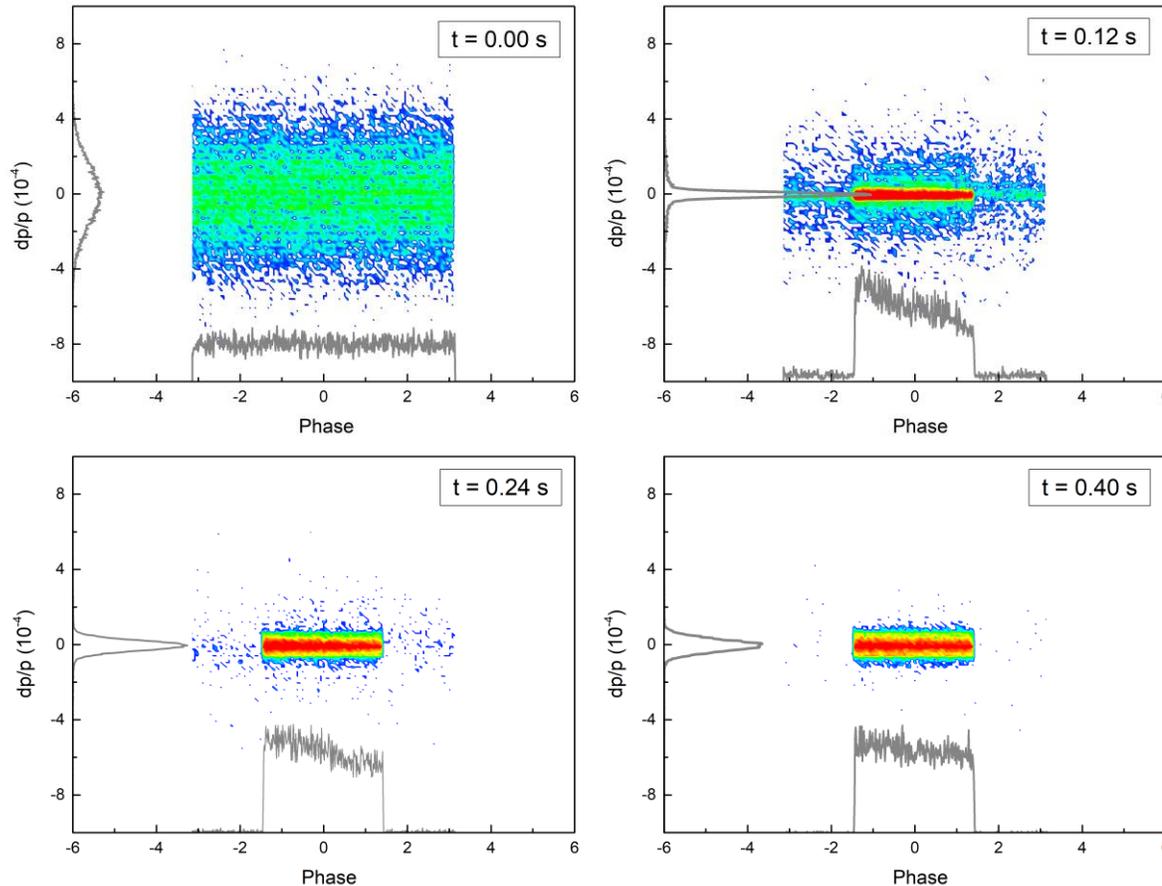


- $E=67.8$ V/m
- $V_{BB}=230.5$ V
- **Bucket height = $2.0e-4$**



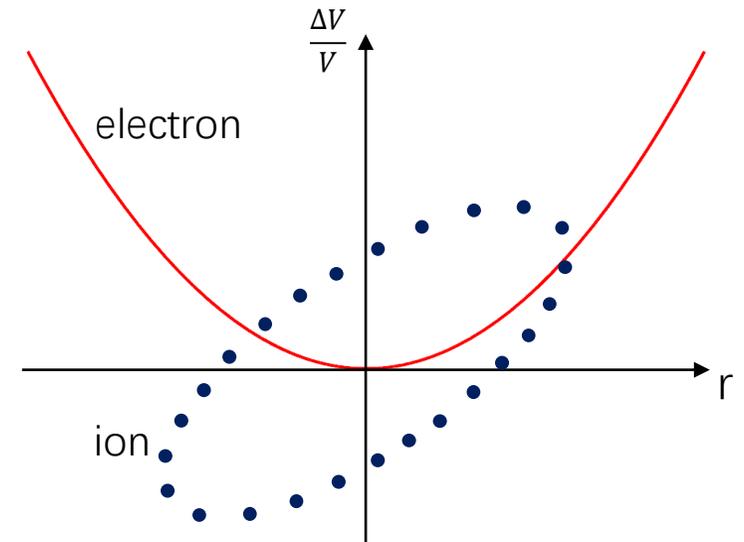
Simulation

$W_p = 2.0 \mu\text{s}$



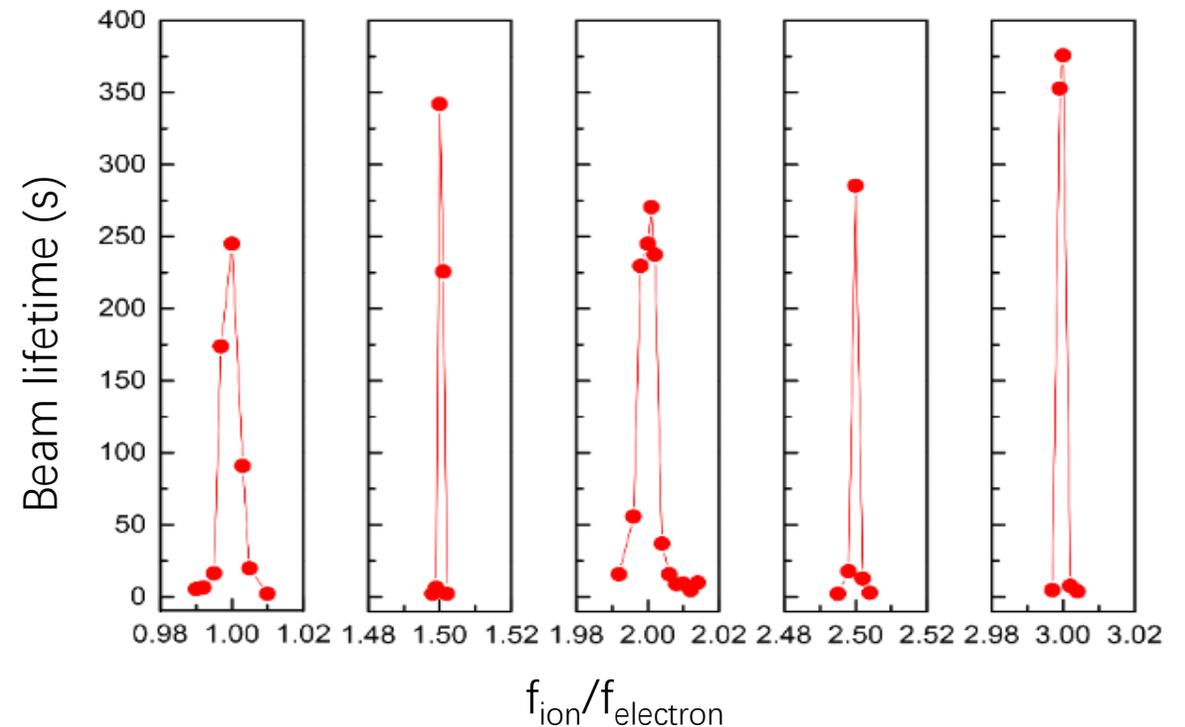
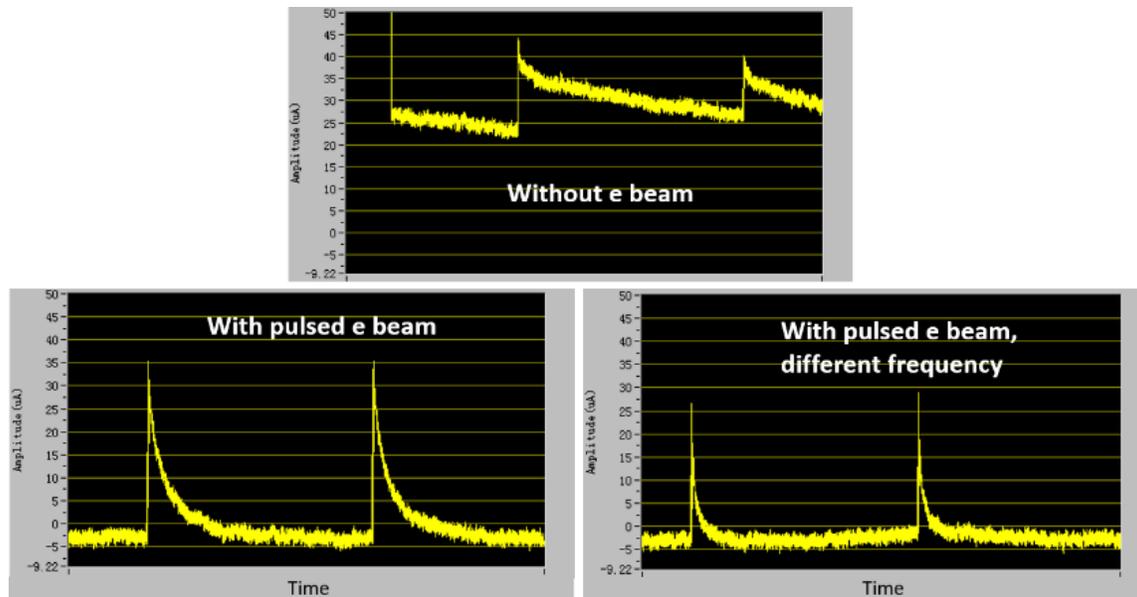
- Non-uniform distribution – the ions with a certain radius will be cooled to the positive momentum region in phase space

E-beam velocity deviation



□ Lifetime issue

- **Beam lifetime** – The beam lifetime was strongly affected by the repetition frequency of pulsed e-beam. The frequency of e-beam should be integer or half integer of the ion beam revolution period for a stable beam.



□ Heating effect

- E-beam space charge drives resonance in transverse direction and causes emittance growth
- However, beam lifetime remains an issue

$$J(M) = J_0(1 + 2g_k^2 M^2)$$

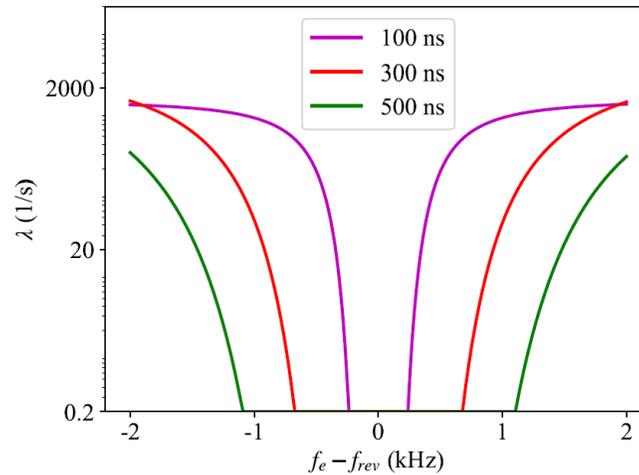
$$g_k = (2\pi)^{3/2} \frac{\sigma_e \Delta v_{peak}}{T_e} \exp\left[-\frac{2(2\tilde{Q} \pm K)^2 \pi^2 \sigma_e^2}{v_e^2 T_e^2}\right]$$

$$\Delta v_{peak} = \frac{N_e}{2\pi\sqrt{2\pi}\sigma_e} \frac{r_0 \beta_{avg}}{\gamma^3 \beta^3 a_e^2} \frac{L_{cool}}{c}$$

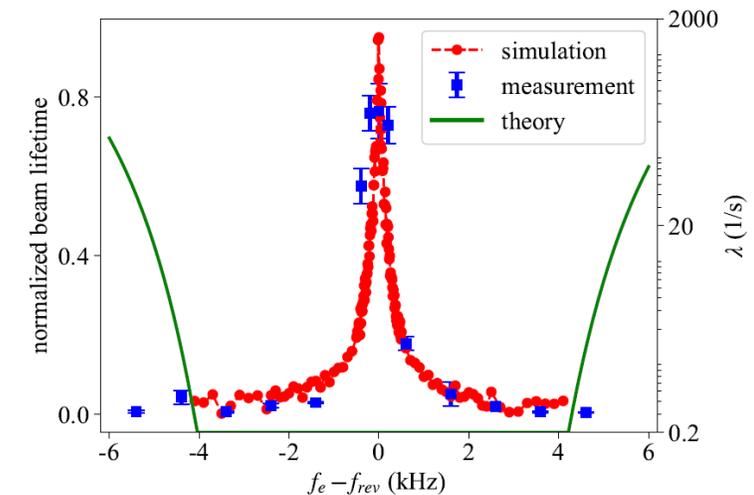
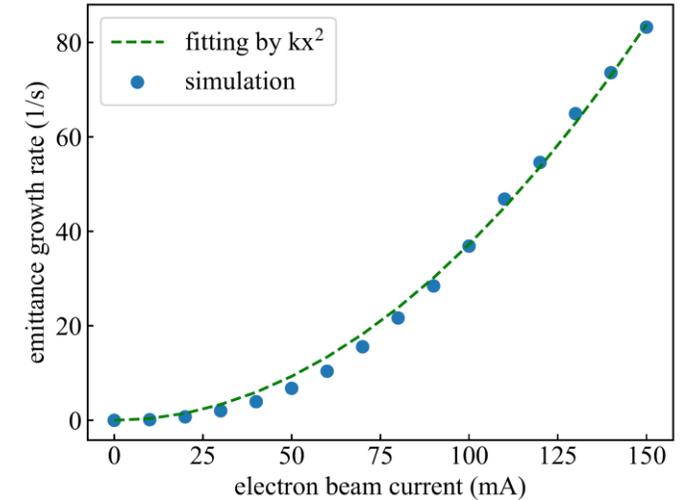
Resonance: $2\tilde{Q} \pm kv_e = K$

Stable region: $S_w = \pm 0.52\sqrt{2}(2\tilde{Q} \pm K)\pi\sigma_e f_{rev} / C$

$$\lambda = \frac{1}{\Delta M \cdot T_{rev}} = \frac{1}{T_{rev}} \sqrt{\frac{2J_0 g_k^2}{\Delta J}}$$

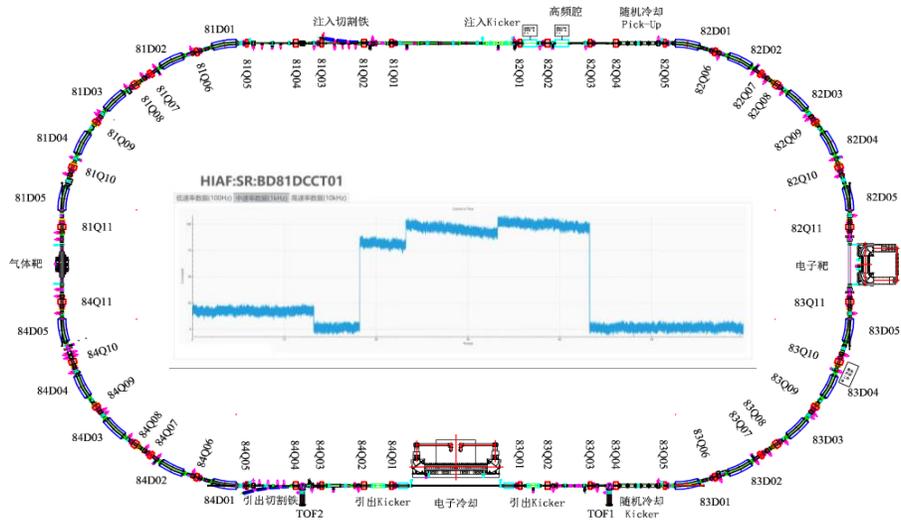


($\Delta v_{peak} = 0.01$, $Q = 3.63$, $K = 7$, $\Delta J/J = 1\%$)



- G. Wang, Tech. Rep No. C-A/AP/536, BNL, 2015.
- F. Ma, Nuclear Inst. and Methods in Physics Research, A 1033 (2022) 166731

□ HIAF SRing



ISO Mode

Ion spiese

RIBs ($A < 238$) : neutron-rich, proton-rich

$^{138}\text{Sn}^{50+}$ (400.5MeV/u) , $^{100}\text{Sn}^{50+}$ (624.1MeV/u)

Normal Mode

Ion spiese

RIBs ($A < 238$) : neutron-rich, proton-rich

$^{132}\text{Sn}^{50+}$ (740MeV/u) , $^{104}\text{Sn}^{50+}$ (740MeV/u)

IT Mode

Ion spiese

Fully stripped: H-like, He-like

$^{40}\text{Ar}^{18+}$, $^{84}\text{Kr}^{36+}$, $^{131}\text{Xe}^{54+}$, $^{238}\text{U}^{92+}$



- We propose a new beam stacking scheme based on pulsed e-beam, in which a barrier voltage and cooling effect can be realized simultaneously.
- Simulation demonstrates that this approach is a promising technique for efficient beam accumulation in storage rings. Many factor will affect the process, optimization and limitation should be carefully addressed.
- Experiment on HIRFL-CSRm have demonstrate the barrier voltage. And the results indicate that heating effect and beam lifetime are critical and should be further studied.
- We expect this stacking method can be applied to accumulate RIBs and high-charged ions in low and medium energy storage rings for high-precision experiments, especially for the SRing of HIAF project.

Thanks for your attention