Electron Cooling System for HIAF Project in China

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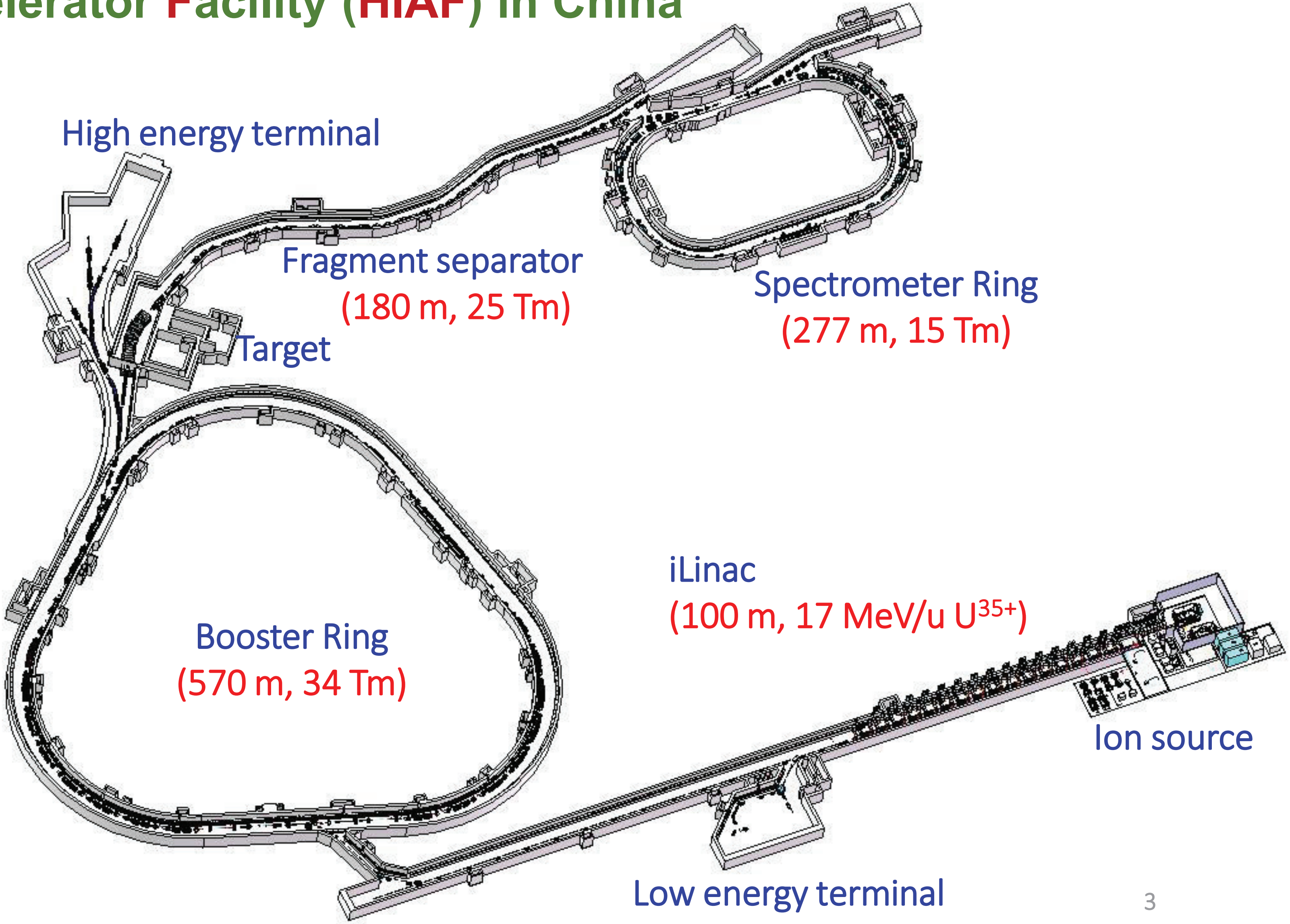
Outline

I. The HIAF project introduction
II. Why an electron cooler is needed for HIAF
III. Typical cooling process simulation
IV. Cooler design and status
V. Conclusion and outlook

High Intensity heavy-ion Accelerator Facility (HIAF) in China

- An accelerator complex for nuclear & atomic experiments (mass measurement, DR)
- Based on the experience of CSR (synchrotron) and ADS (Linac)
- Focusing on the radioactive ion beam production
- 7 years construction (start from 2018/12/23)



Beam Parameters

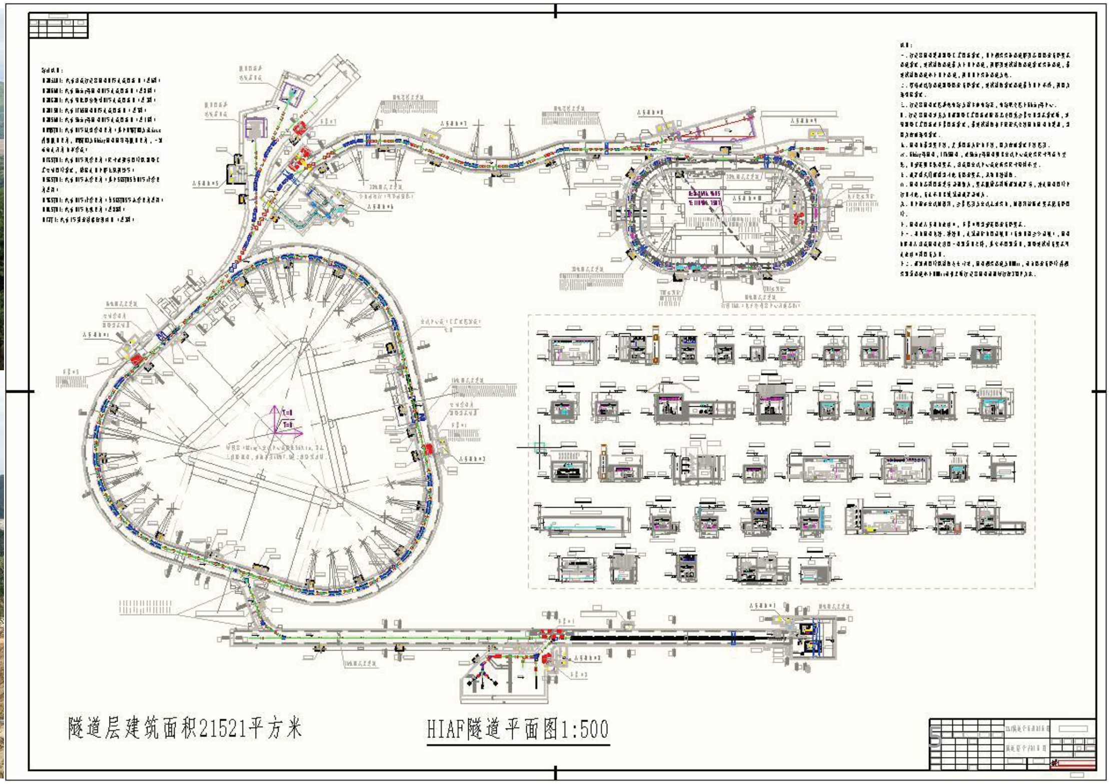
Ion beam		Energy (GeV/u)	Current (ppp)
Metallic elements	$^{18}O^{6+}$	2.6	1.0×10^{11}
	$^{78}Kr^{19+}$	1.7	7.5×10^{10}
Nonmetallic elements	$^{209}Bi^{31+}$	0.85	3.0×10^{10}
	$^{238}U^{35+}$	0.8	3.0×10^{10}

Compare with HIRFL-CSR Lanzhou:

- **Primary beam intensity increases by $\times10^3$**
- **Secondary beam intensity increase by $\times 10^4$**

Current Status

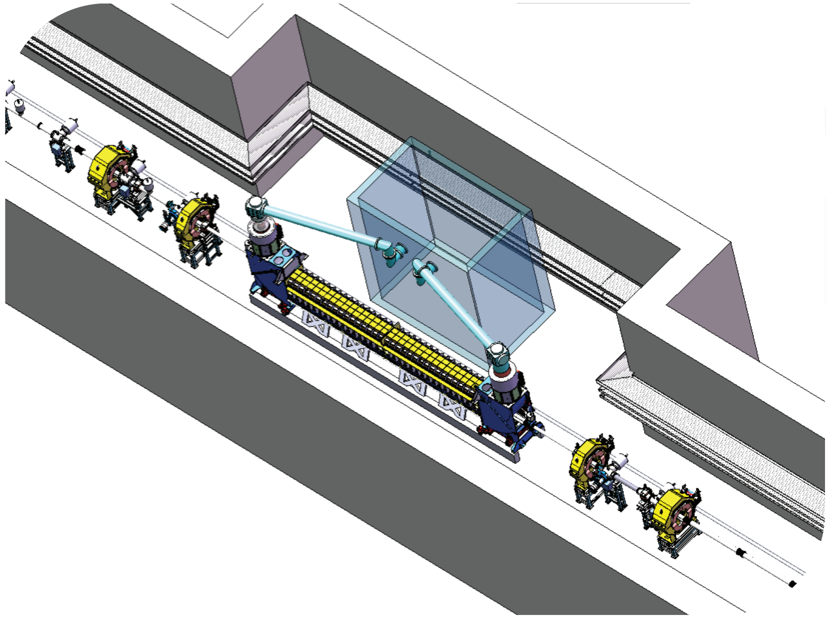
- The accelerator design work is finished and fixed
- The tunnel construction will be started in February 2020
- Prototypes of dipole and its power supply, RF cavity…

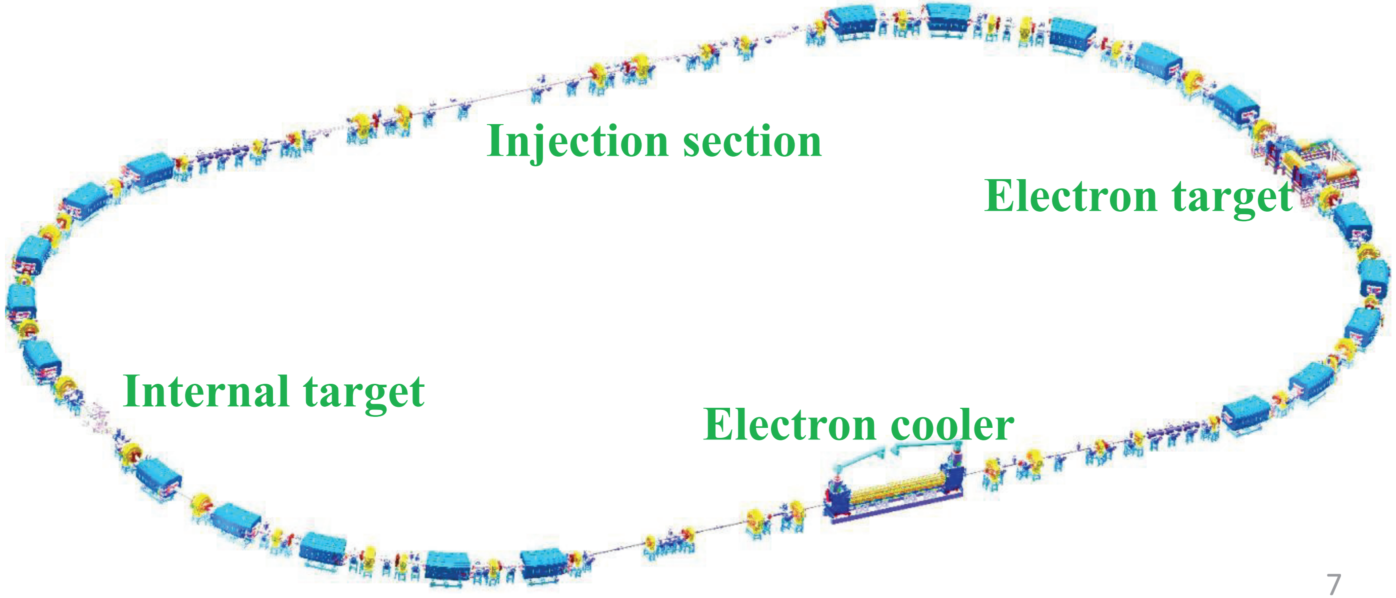


New Campus in 2025

Spectrometer Ring (SRing)

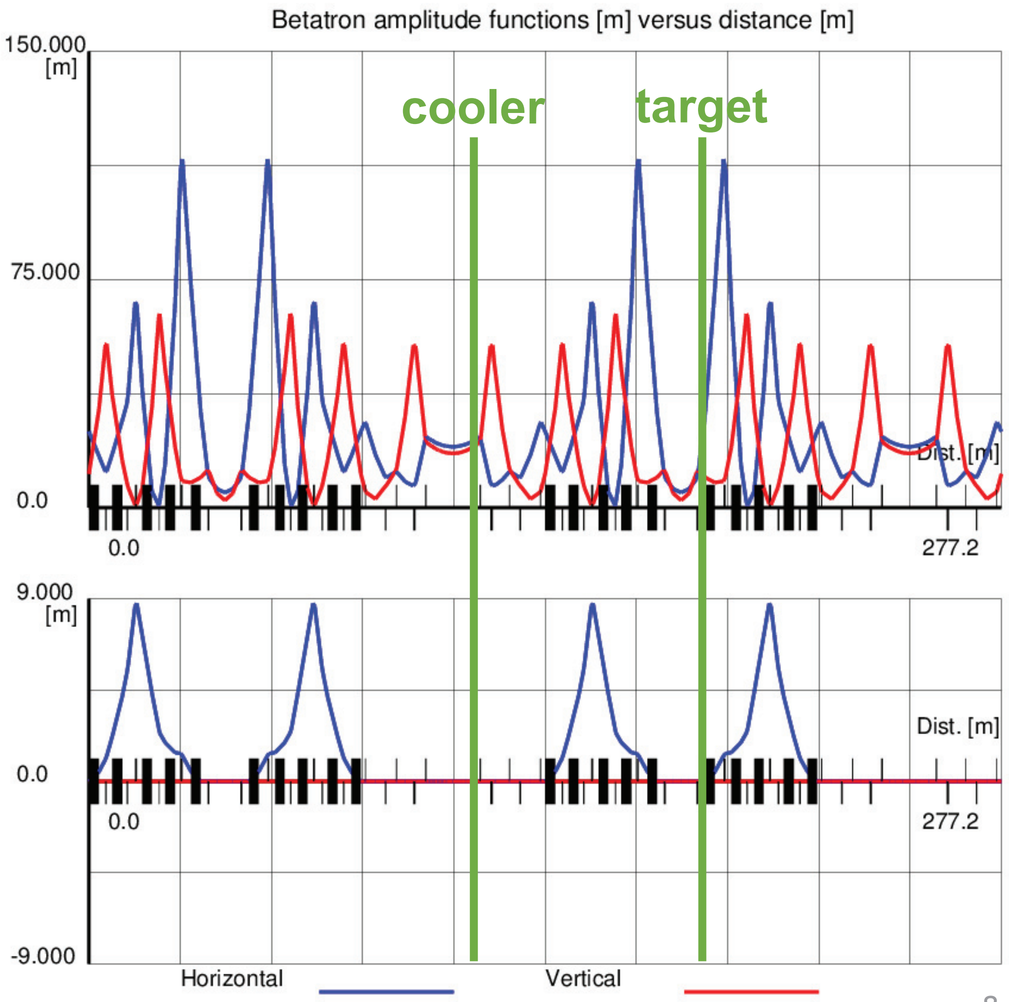
- SRing is a platform for nuclear & atomic experiments
- Electron cooling is used to improve the quality of highly-charged, low-energy heavy ion beam for internal target experiments
- It is also used for the electron-ion recombination measurements together with the electron target
- Cooling of long-lived radioactive isotopes with stochastic cooling system





Spectrometer Ring lattice & parameters

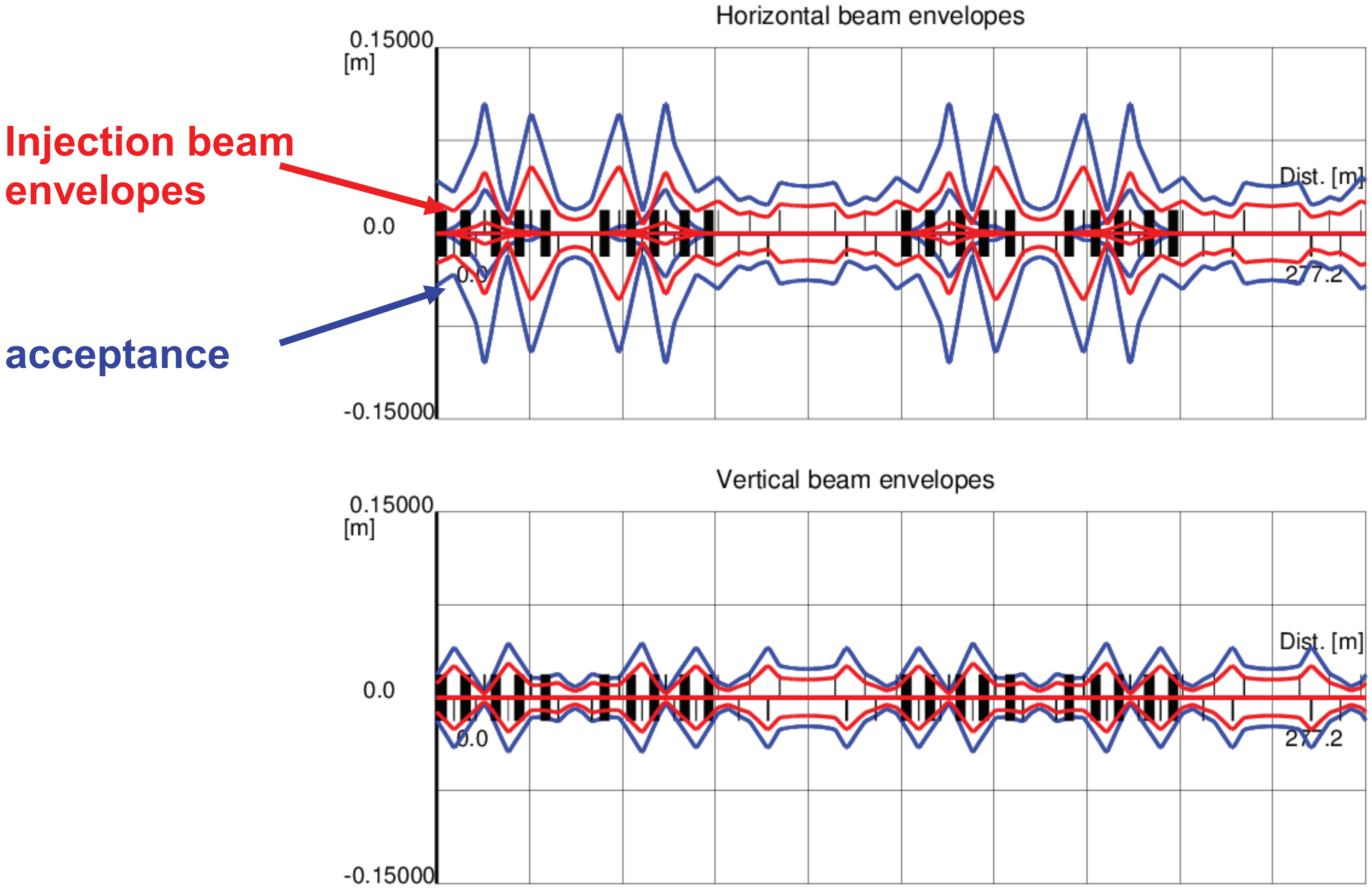
Parameters	value
Circumference	277.3 m
Magnetic rigidity	2 – 15.8 Tm
Deceleration rate	0.3 T/s
Operation circle	10 -120 s
Bending radius	9.5 m
γ_{tr}(internal target mode)	4.52
Tune	4.21 / 5.23
Chromaticity	-11.41 / -9.95
β_{max}	116.56 / 64.72 m
β_x/β_y at target	5.00/2.44 m



Spectrometer Ring acceptance

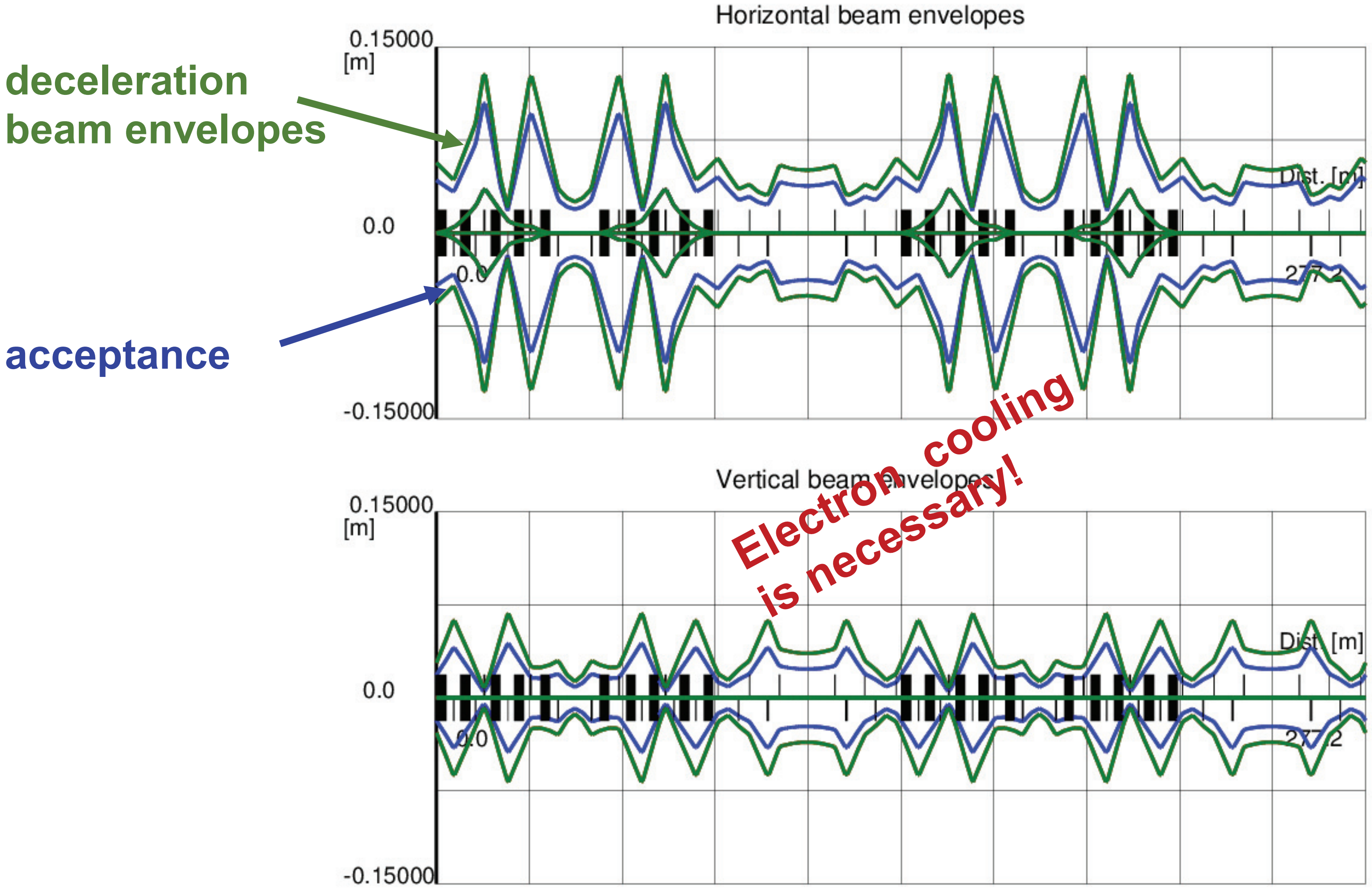
Modes	Transverse	dp/p
Isochronous γ=1.43	30 / 30 π.mm.mrad	0.2%
Isochronous γ=1.67	30 / 30 π.mm.mrad	0.25%
Isochronous γ=1.84	30 / 30 π.mm.mrad	0.3%
Normal mode (for long-lived isotopes)	120 / 30 π.mm.mrad	1.1%
Internal target mode (for stable ions, include deceleration)	**72 / 30 π.mm.mrad**	**0.8%**

Beam envelopes at the top energy 800 MeV/u



Note: Linear optics

Beam envelopes at the experimental energy 30 MeV/u (without cooling)

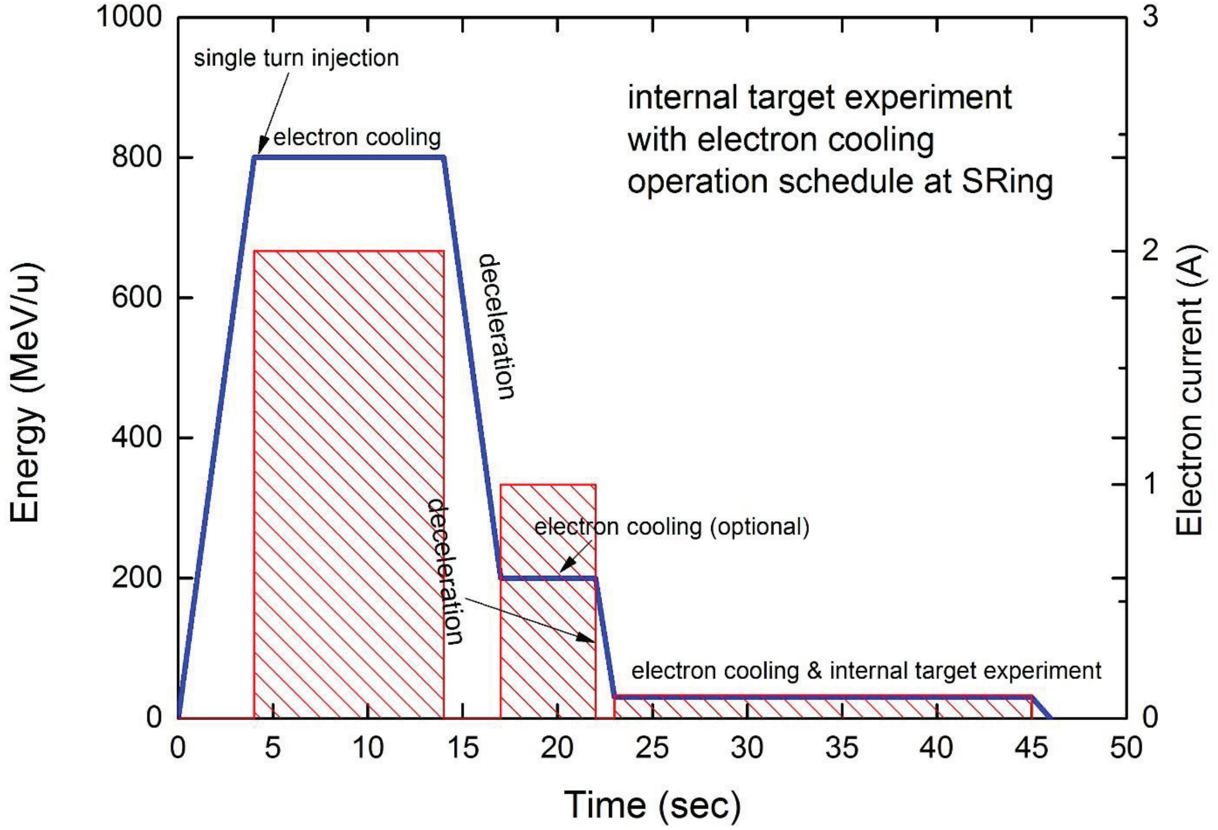


Note: Linear optics

The deceleration beam size would be larger than the acceptance without cooling

2. Why an electron cooler is needed

SRing electron cooler operation scheme



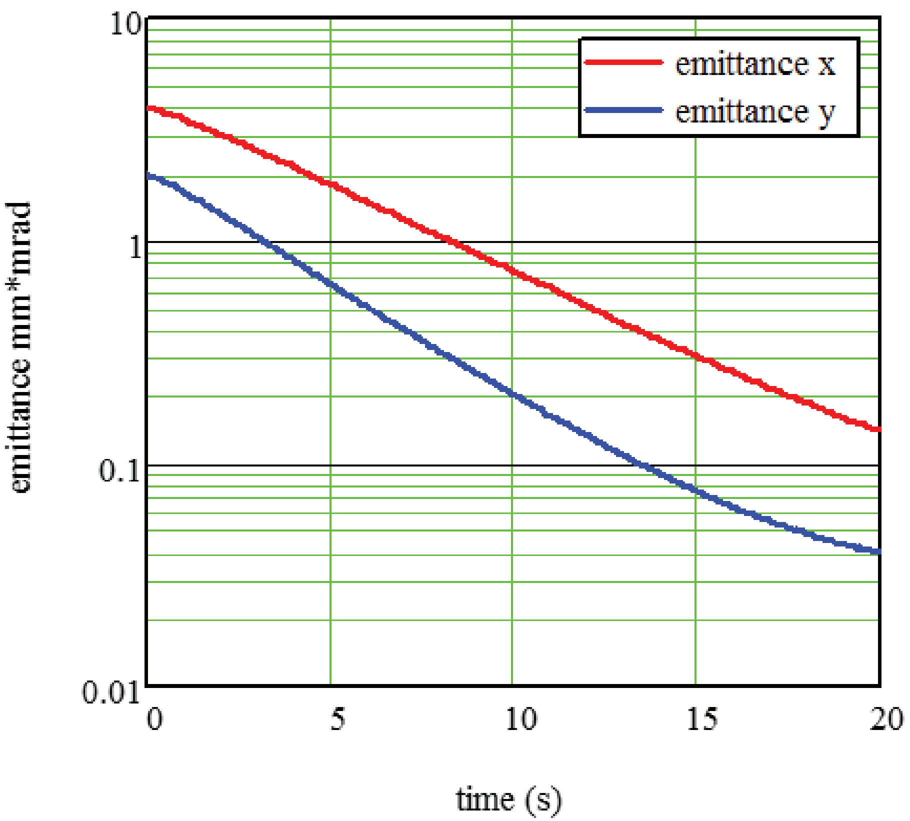
- ☐ Cooling at the injection energies (**improve the beam quality** for deceleration)
- ☐ Cooling at the experimental energies (suppress **heating**, compensation **energy loss**)
- ☐ Cooling at intermediate energies (for **optimization** of the deceleration)

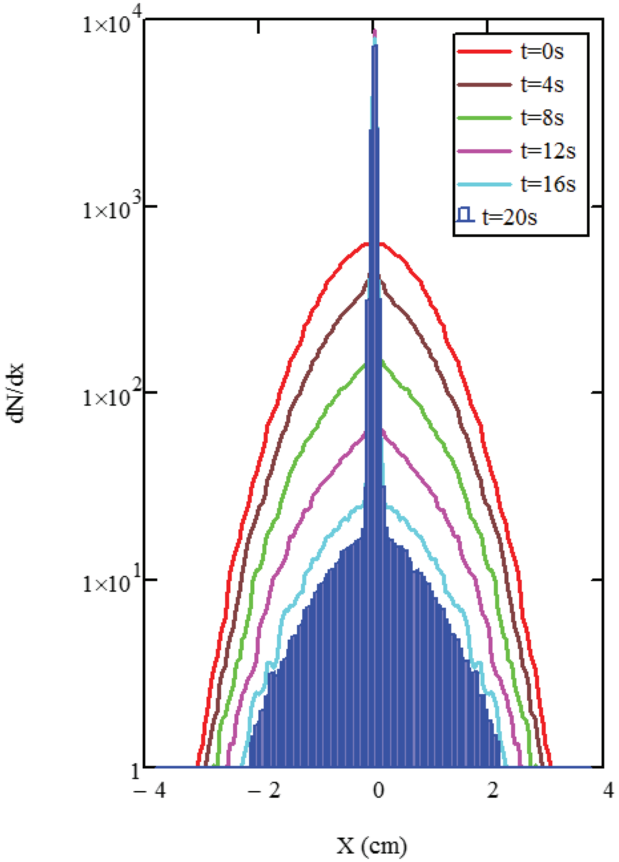
Stable ions: cooling of U^{92+} ion beam

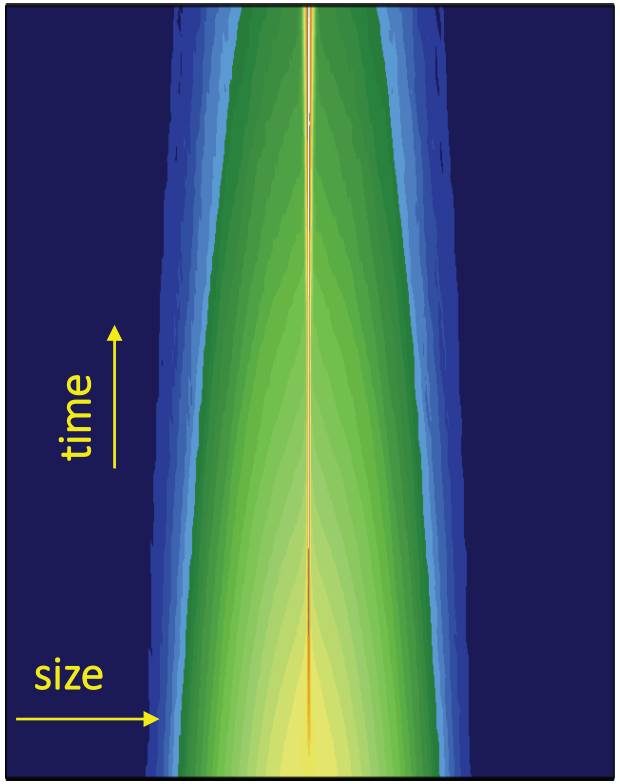
Particle	$^{238}U^{92+}$	
Ion energy	**800 MeV/u**	**30 MeV/u**
Particle number in the ring	1×10^{9}	1×10^{9}
Initial emittance H/V（RMS）	**4.0/2.0 π.mm.mrad**	**6.0 π.mm.mrad**
Initial momentum spread（RMS）	**8.0×10^{-4}**	**4.0×10^{-4}**
Electron energy	438.8 keV	16.4 keV
Electron current	**2.0 A**	**0.1 A**
Electron beam radius	30 mm	
Effective cooling length	7.4 m (2.6% of the ring)	
Longitudinal magnetic field at the cooling section	0.15 T	
Magnetic field homogeneity	**1×10^{-4}**	
Betatron function at cooler	9.9/9.7 m (H/V)	
Electron beam temperature (transverse/ longitudinal)	0.5 eV / 3.0×10^{-5} eV	0.1 eV / 2.0×10^{-5} eV
Target thickness	**------**	**1.0×10^{14} cm^{-2}s^{-1}**

Stable ions: cooling of U^{92+} ion beam @ 800 MeV/u

- ✓ At the injection (top) energy (800MeV/u), electron cooling is not fast
- ✓ It is planed to reduce the emittance less than 1.0 π.mm.mrad with 10 sec.







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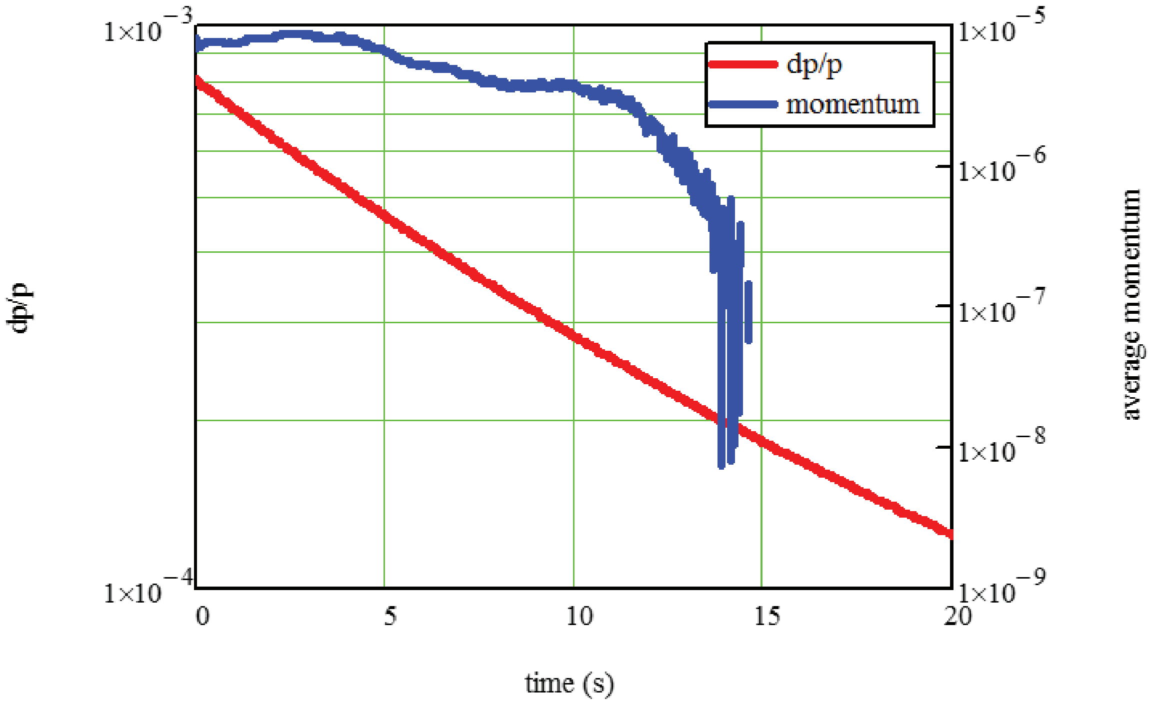
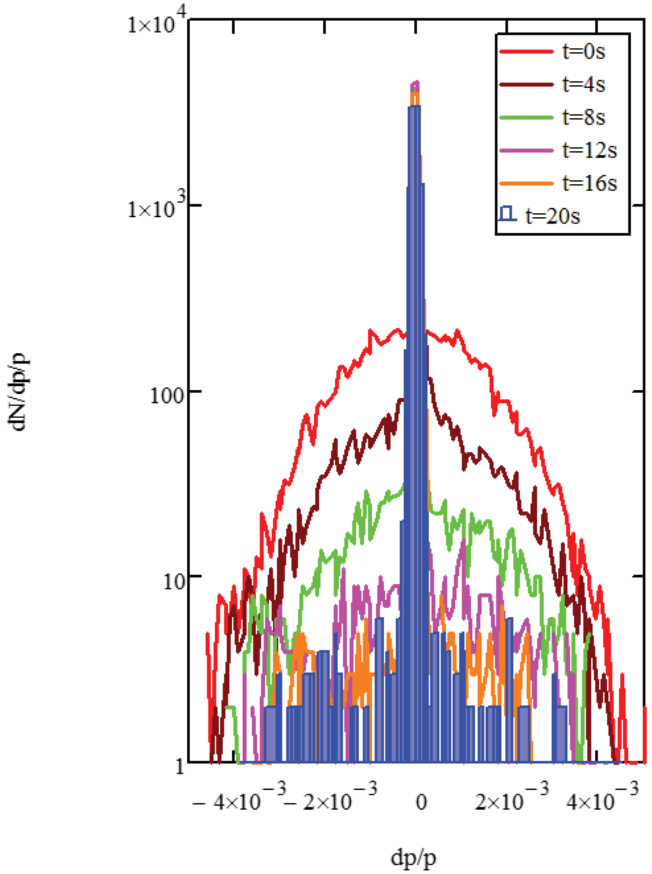
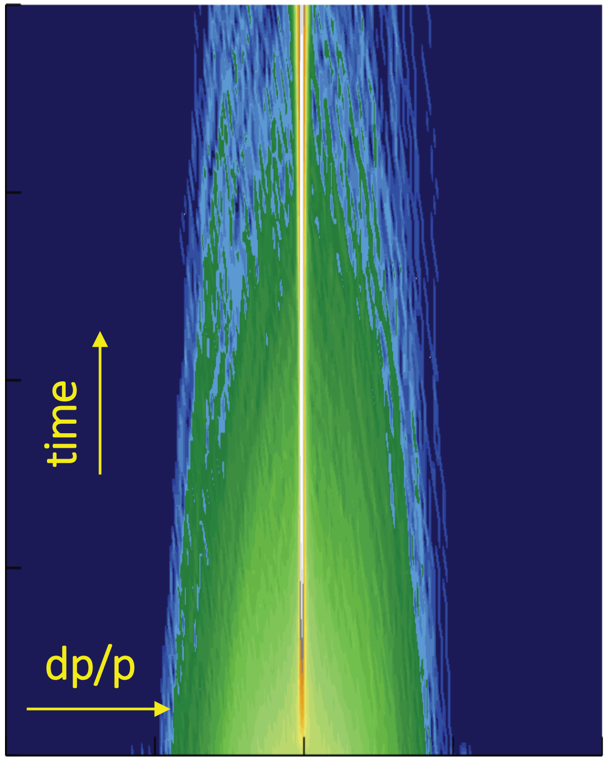
- ✓ At the injection (top) energy (800MeV/u), electron cooling is not fast
- ✓ It is planed to reduce the emittance less than 1.0 π.mm.mrad with 10 sec.
- ✓ A decreasing of the momentum spread would be good for the RF design



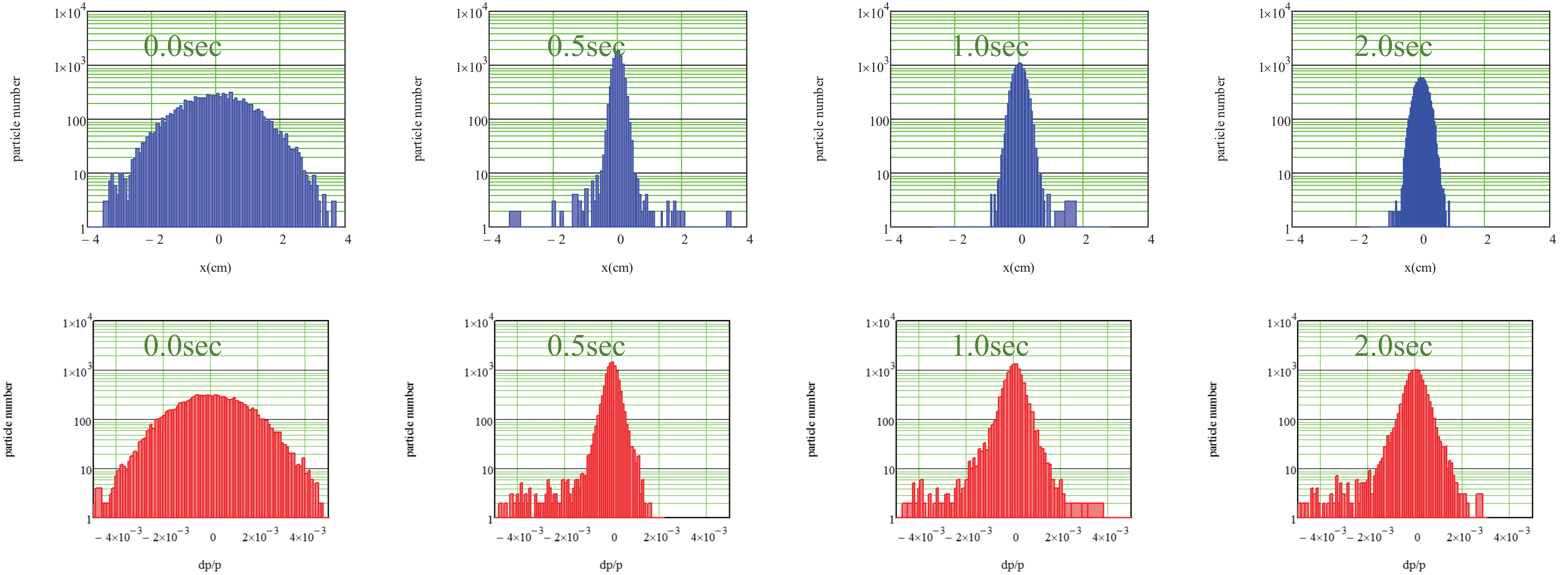




3. Typical cooling process simulation

Stable ions: cooling of U^{92+} ion beam @ 30 MeV/u

- ✓ **Cooling is fast at the low energies**
- ✓ **Suppress the heating and compensate the energy loss**



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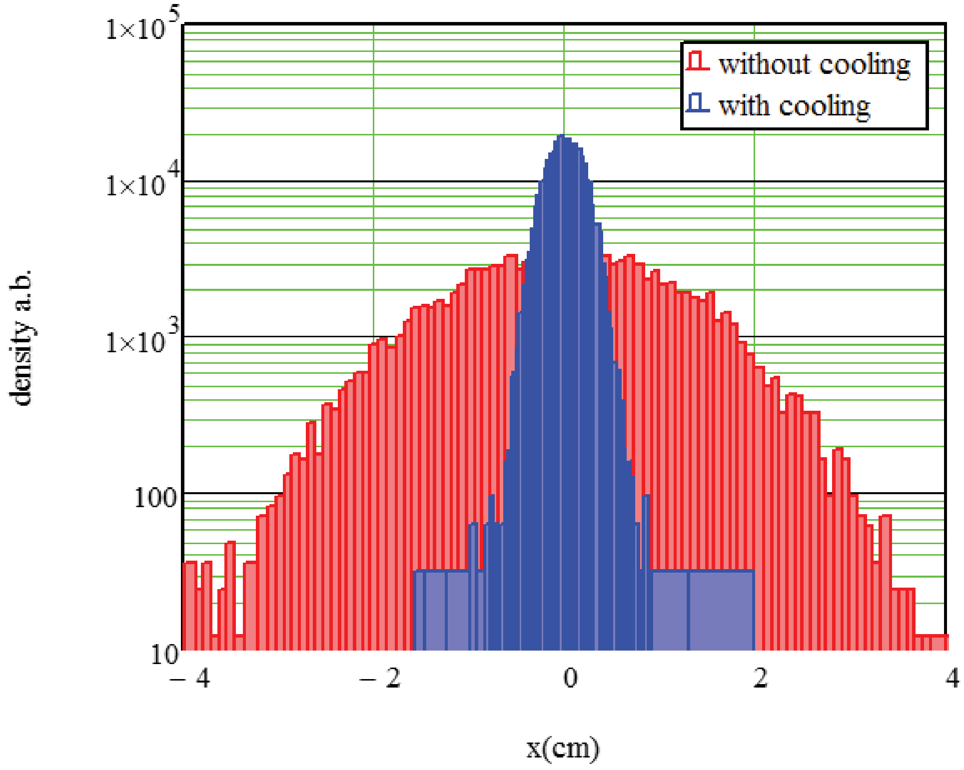
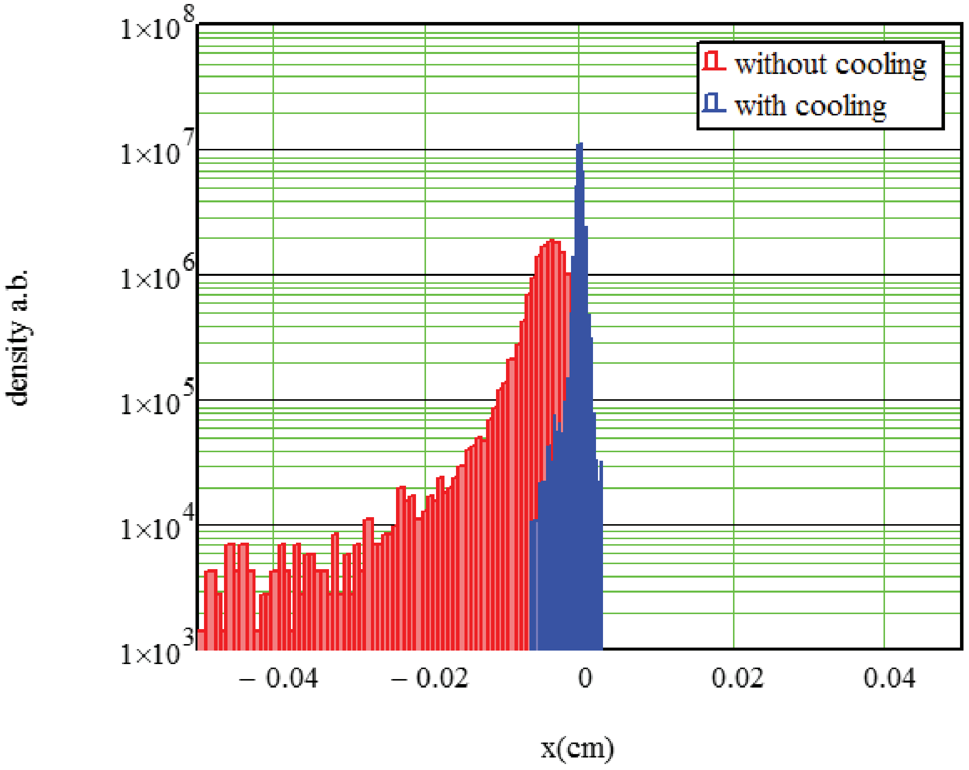




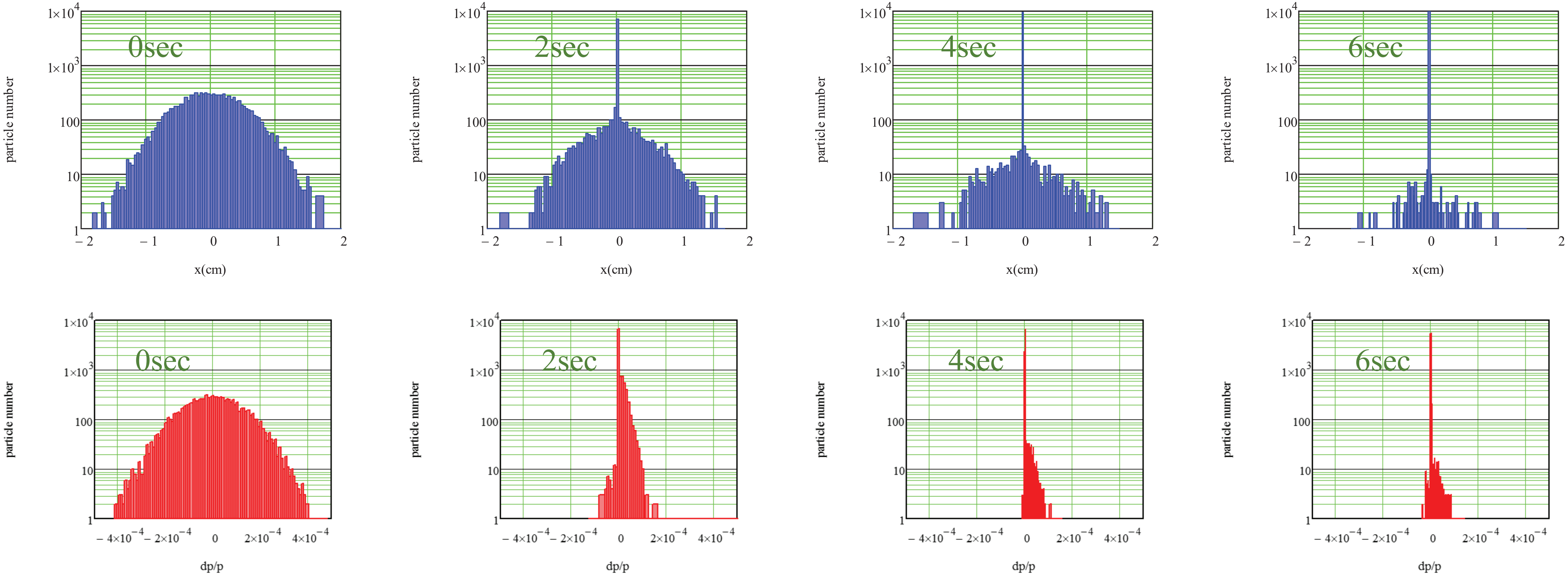
Beam distribution after 2 seconds with & without electron cooling

Isotopes: cooling of Sn^{50+} ion beam

Particle	$^{132}Sn^{50+}$
Ion energy	**740 MeV/u**
Particle number in the ring	1×10^5
Initial emittance H/V（RMS）	**1.25/1.25 π.mm.mrad**
Initial momentum spread（RMS）	**6.0×10^{-5}**
Electron energy	405.9 keV
Electron current	**2.0 A**
Electron beam radius	30 mm
Effective cooling length	7.4 m (2.6% of the ring)
Longitudinal magnetic field at the cooling section	0.15 T
Magnetic field homogeneity	**1×10^{-4}**
Betatron function at cooler	9.9/9.7 m (H/V)
Electron beam temperature (transverse/ longitudinal)	0.5 eV / 3.0×10^{-5} eV

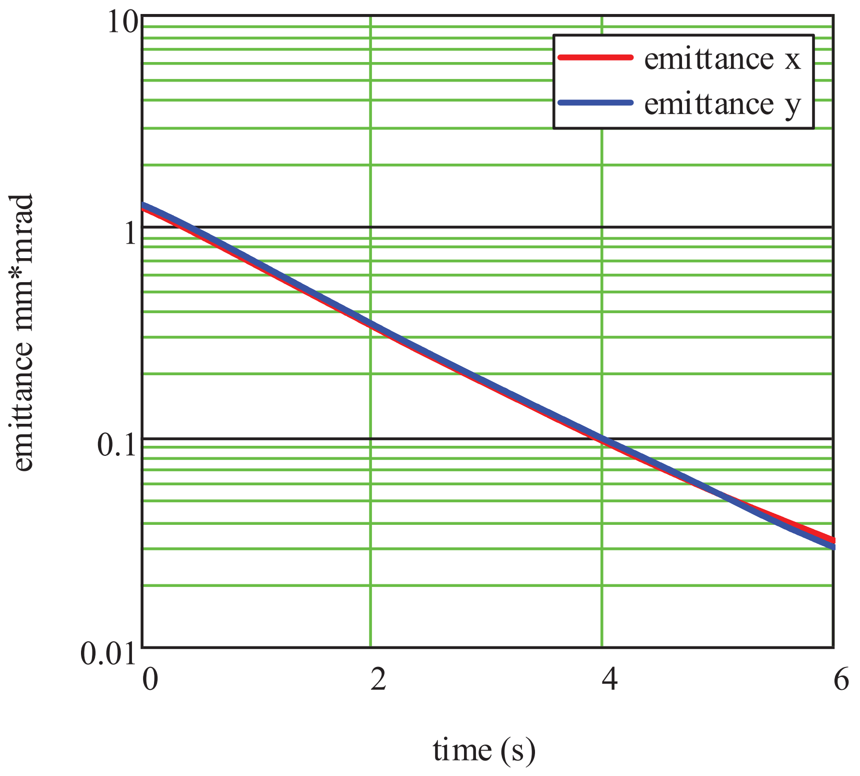
Isotopes: cooling of Sn^{50+} ion beam

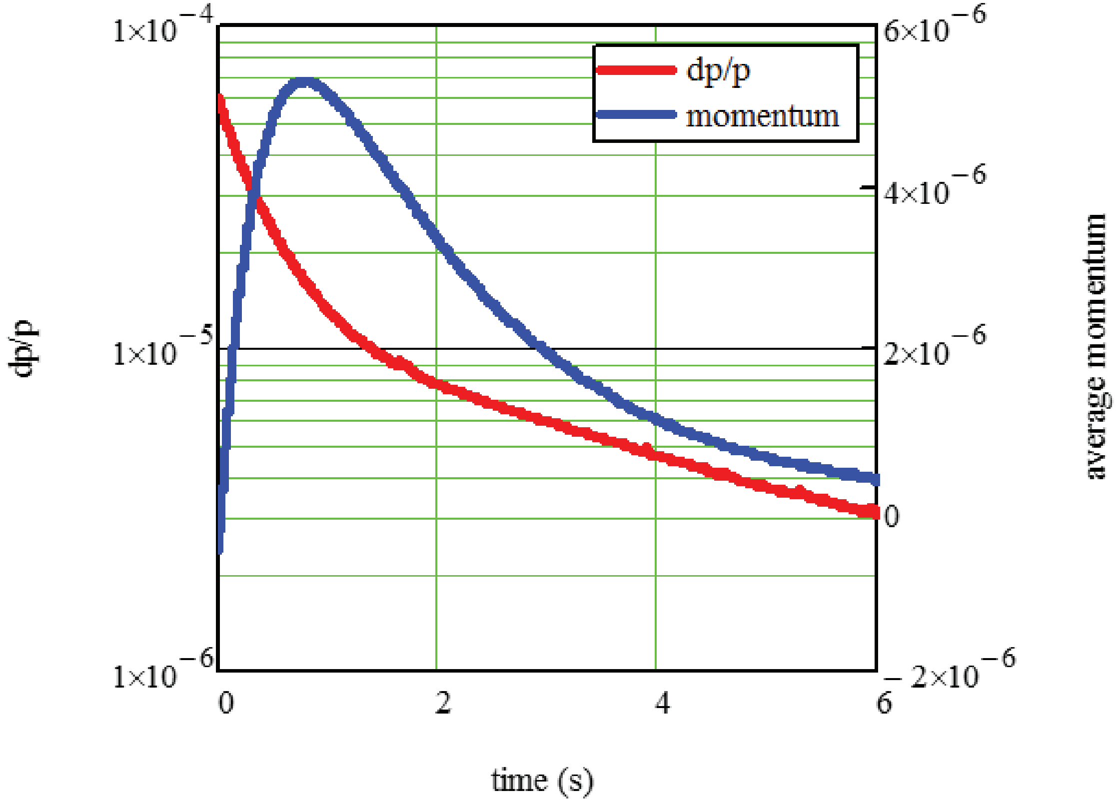
✓ **With the help of stochastic cooling system, a small initial beam emittance and momentum spread is obtained. It is good for electron cooling**



Isotopes: cooling of Sn^{50+} ion beam

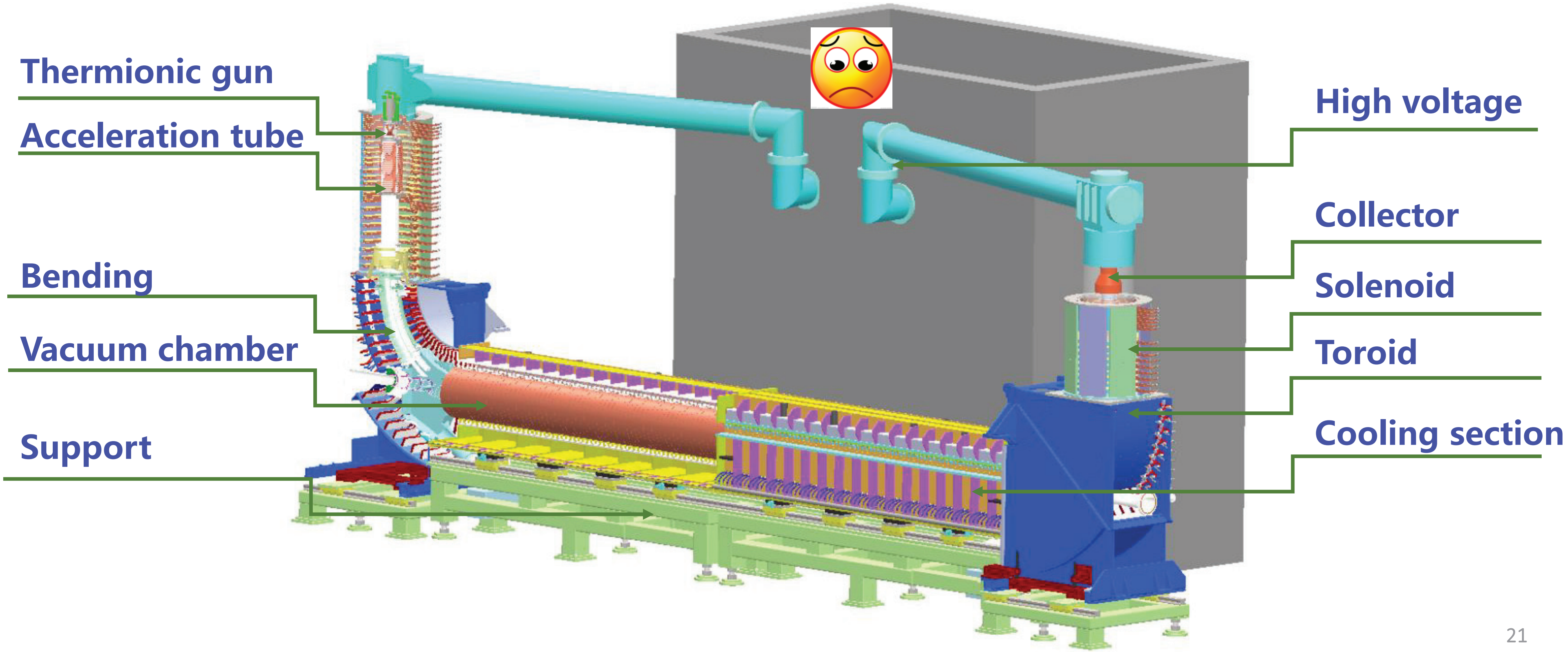
- ✓ With the help of stochastic cooling system, a small initial beam emittance and momentum spread is obtained. It is good for electron cooling
- ✓ Final emittance is less than 0.1 π.mm.mrad, momentum spread is less than 10^{-5}





A classical DC magnetized electron beam cooling device

Based on the present 300 keV coolers designed by BINP at CSR

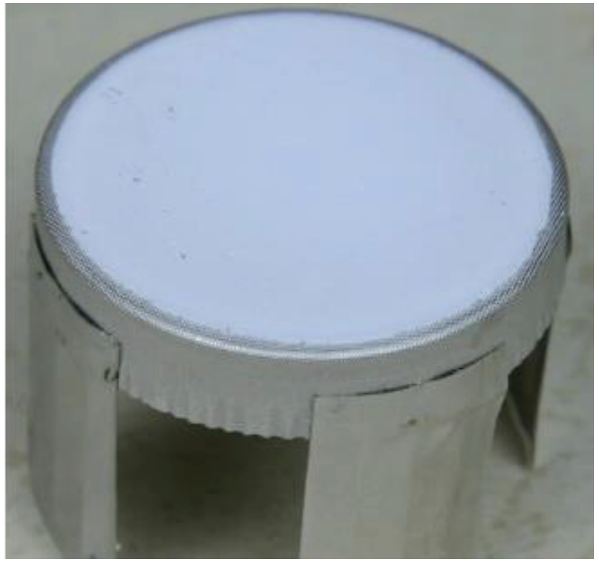


SRing cooler technical parameters

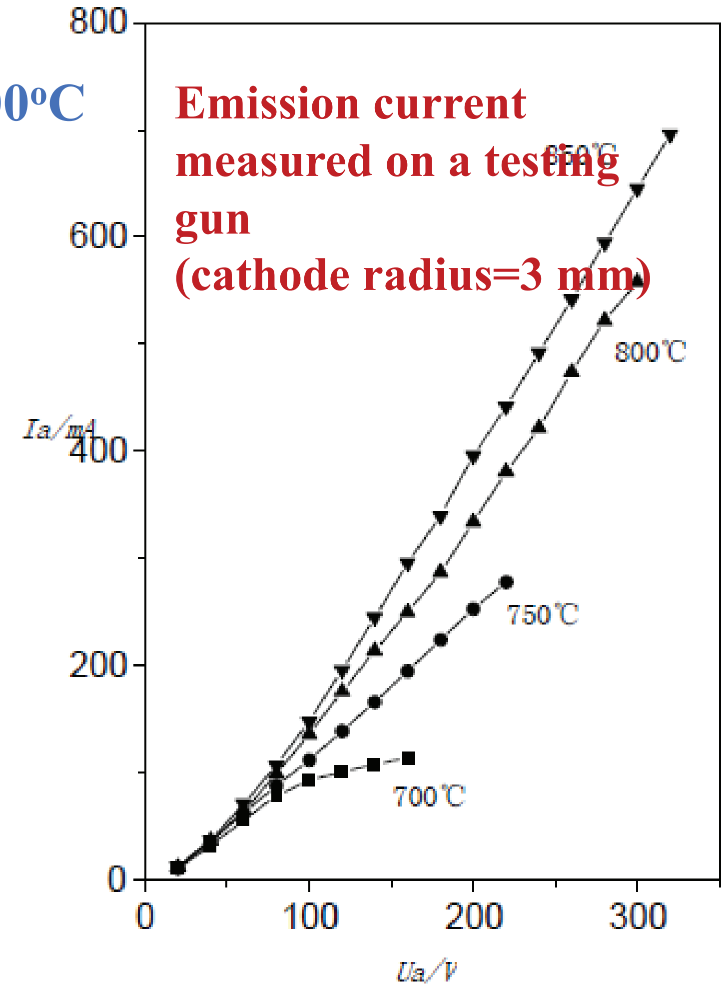
Maximum electron energy	450 keV
Total length of the straight section	16.0m
Total length of the cooler	11.2 m
Height of the cooler	5.0 m
Effective cooling length	7.4 m（2.6% of circumference）
Cathode radius	15 mm
Cathode temperature	0.1 eV
High voltage ripple(pp max. @ 450 kV)	5.0×10^{-5}(???)
Magnetic field homogeneity	1.0×10^{-4}
Maximum electron current	2.0 A
Vacuum condition	$<2.0\times10^{-11}$ mbar

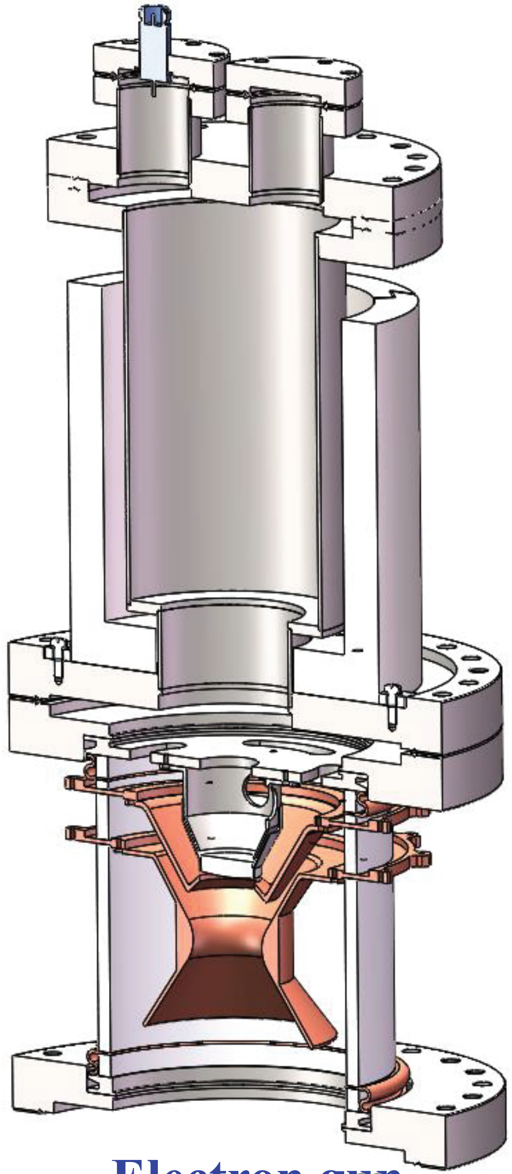
✓ Thermionic electron gun

- An ion pump will be installed on the top of the gun
- A Ni sponge oxide cathode was developed
- the emission current density >0.5 A/cm^2 @ 700^{o}C



Cathode

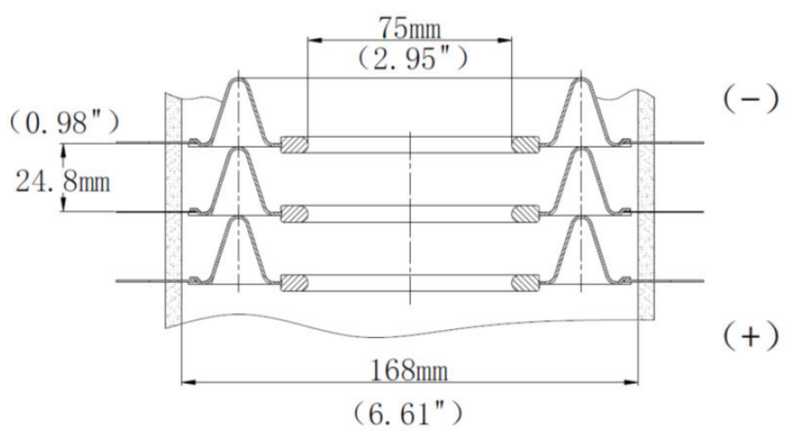


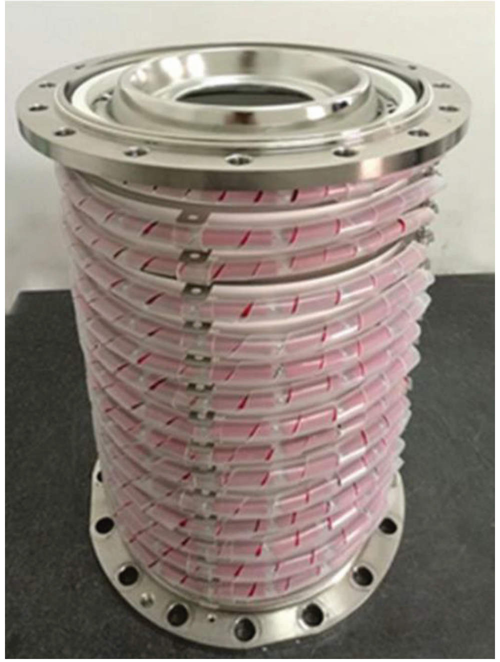


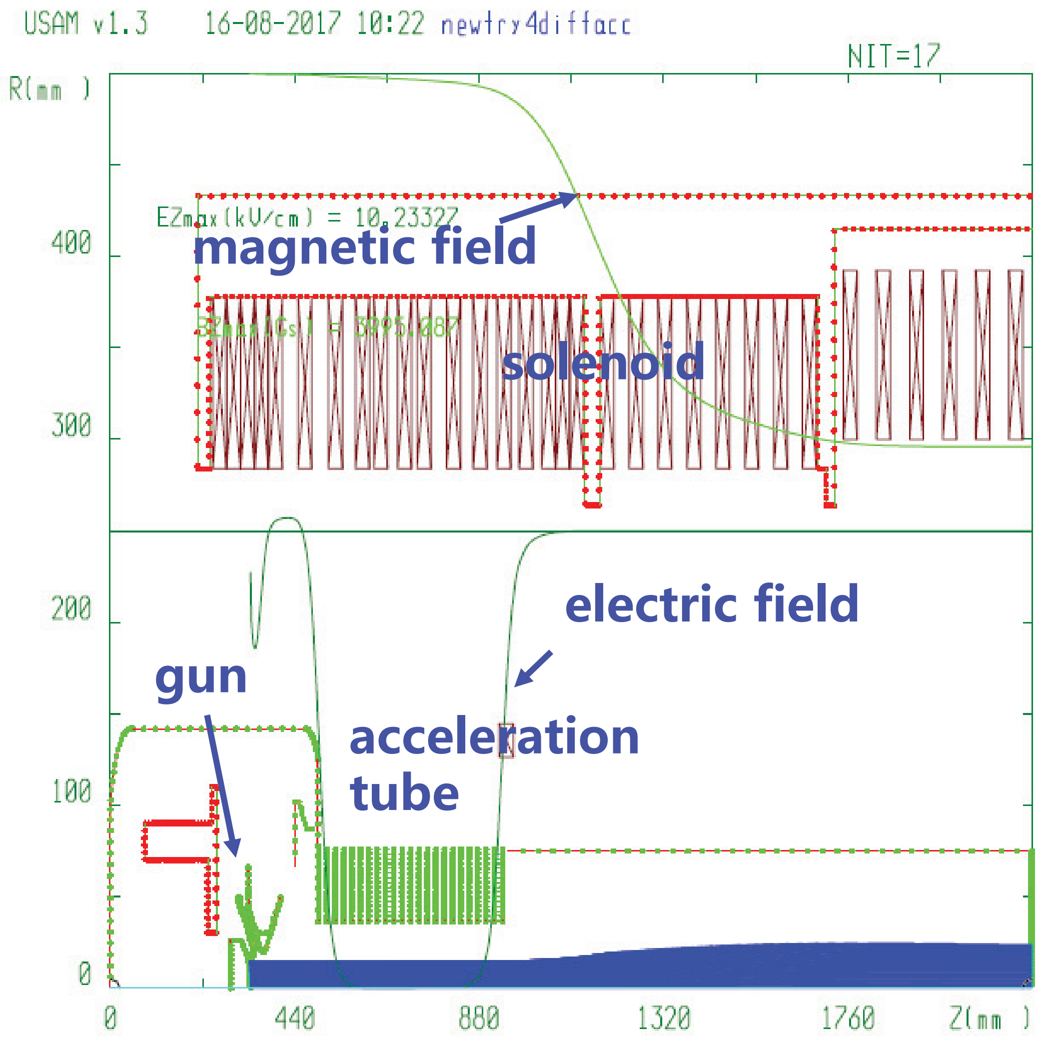
Electron gun

✓ Gun and acceleration tube

- Gun and acceleration tube are installed in a same solenoid with the maximum magnetic field of 4.0 kGs
- Acceleration electrical gradient is less than 10 kV/cm
- The strong magnetic field is used to reduce the electron temperature out of the acceleration tube
- The electron temperature after acceleration (450 keV) is **0.1 eV**

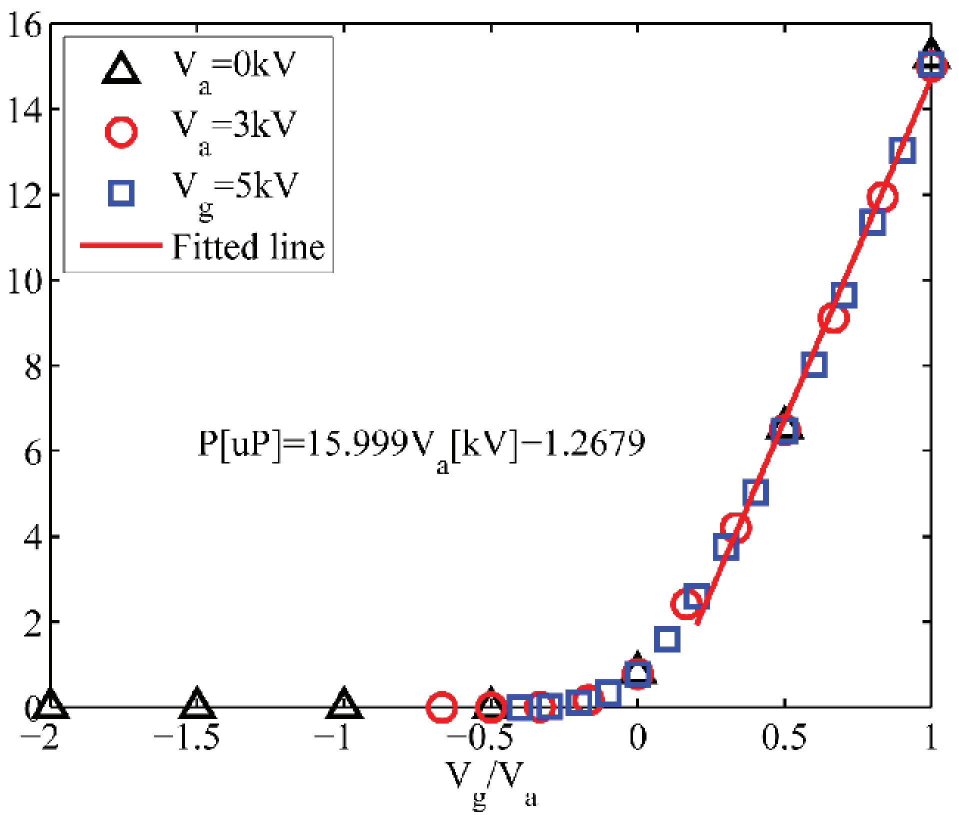


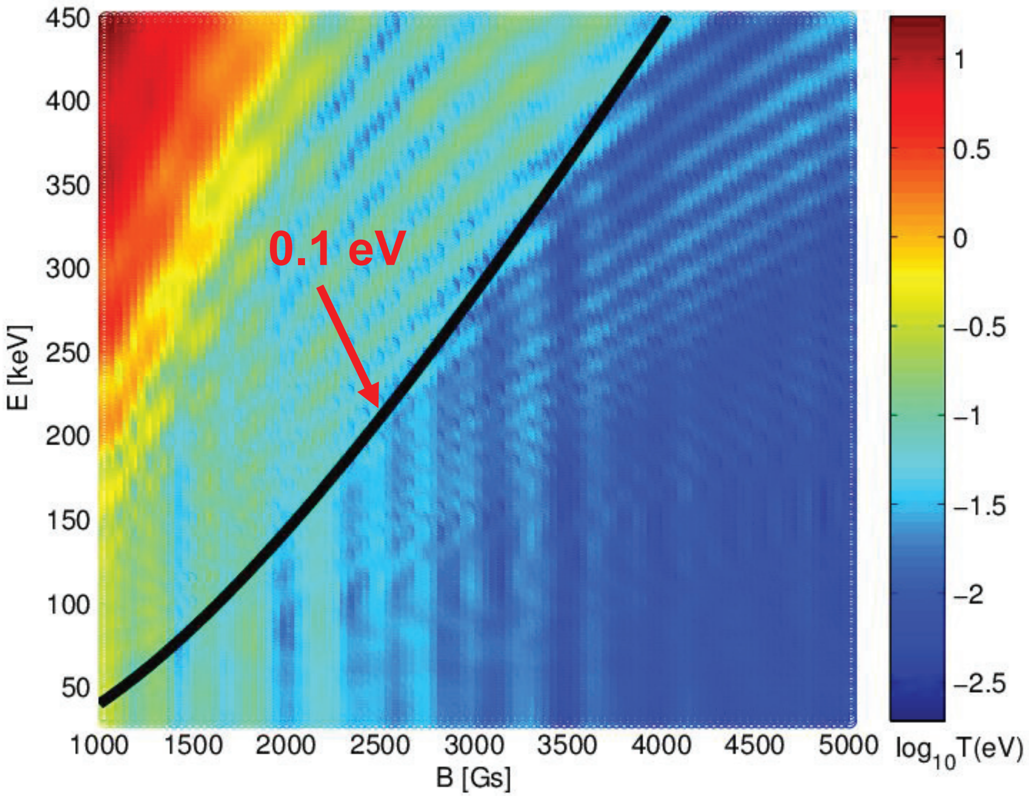




✓ Gun and acceleration tube

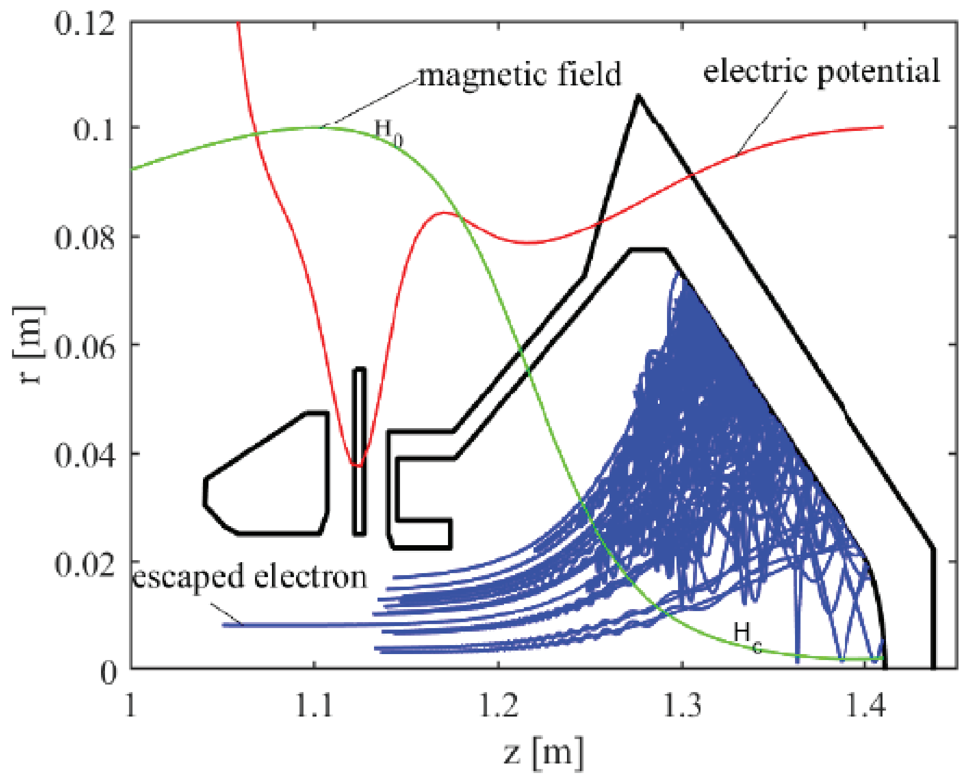
- The maximum electron beam current is **2.0 A**
- The magnetic field in the gun section could be optimized at different energies

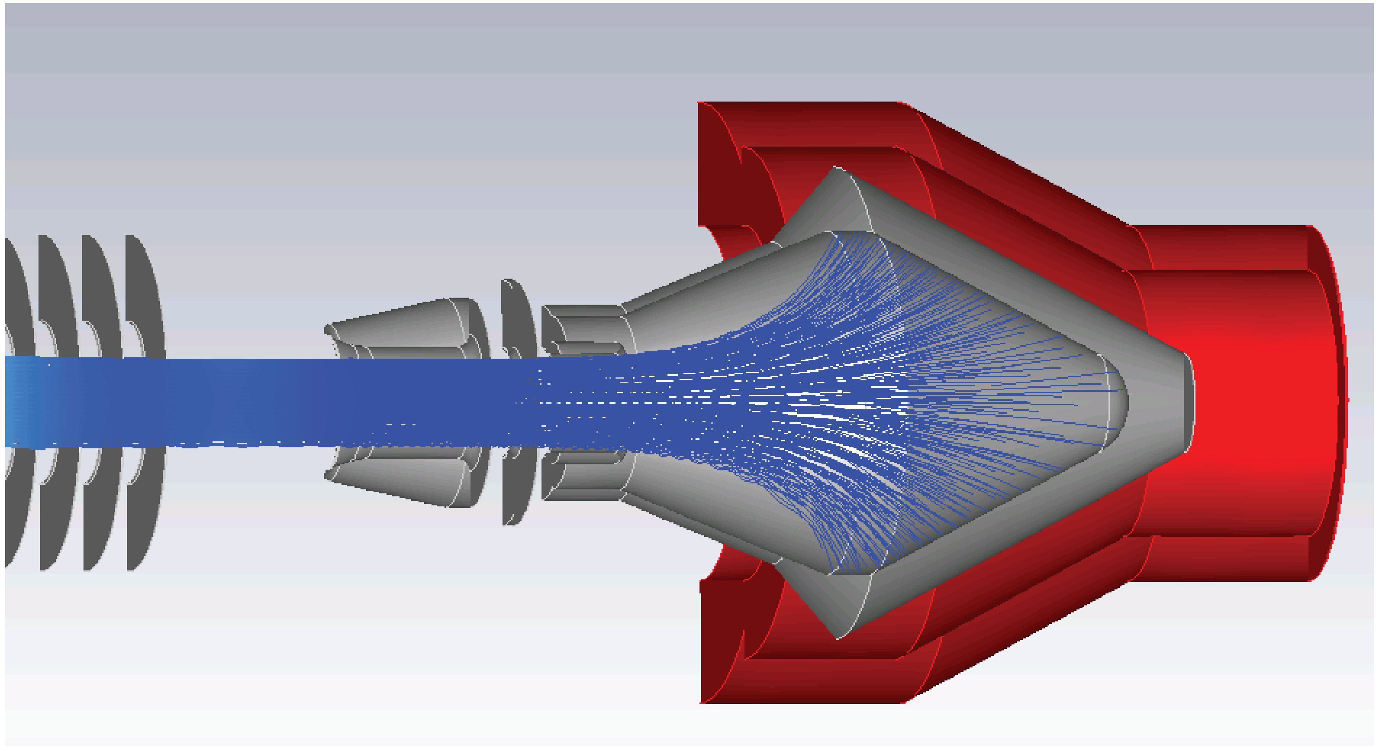




✓ Gun and acceleration tube

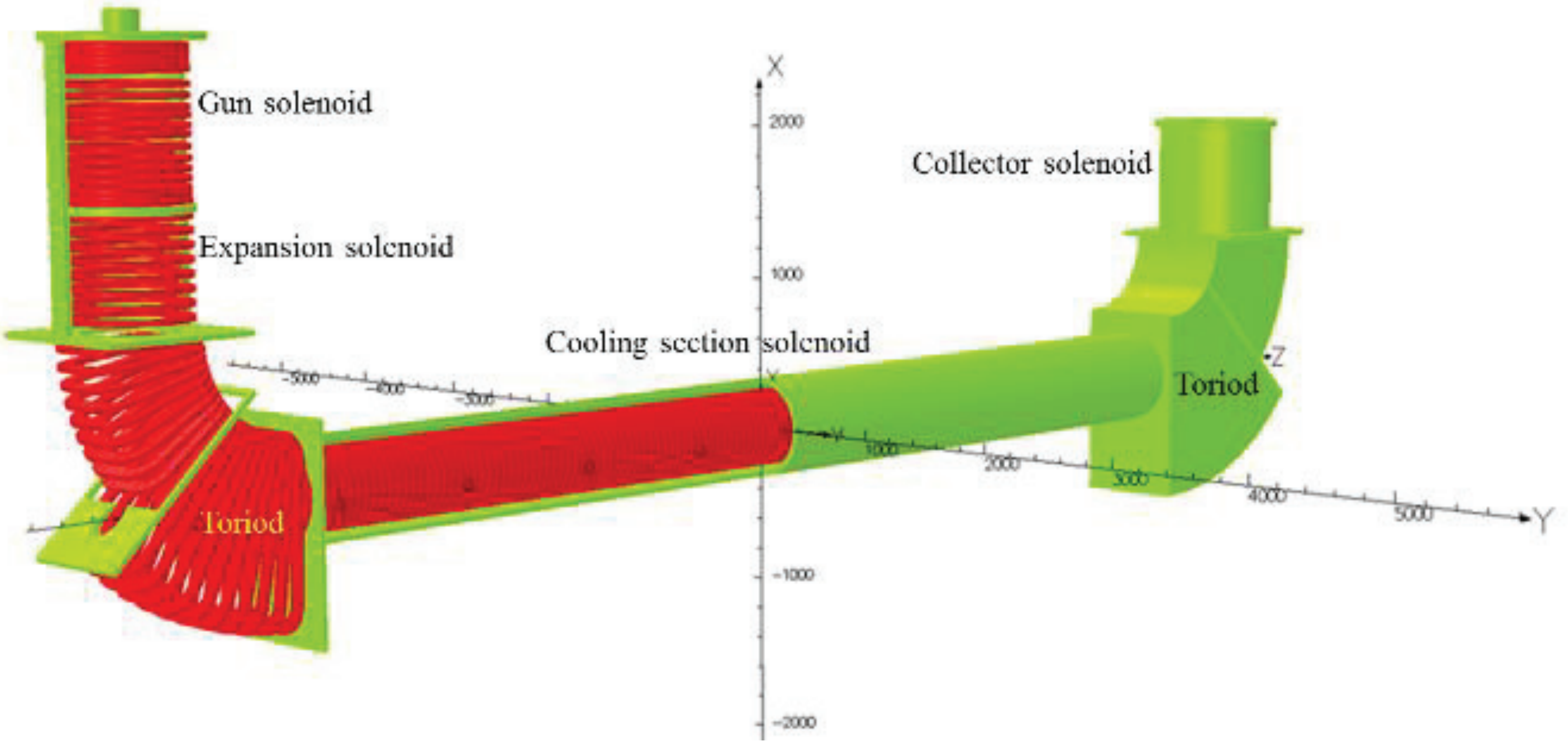
- The maximum magnetic field in the collector is 2.0 kGs
- The collector efficiency is around 1.5×10^{-3}





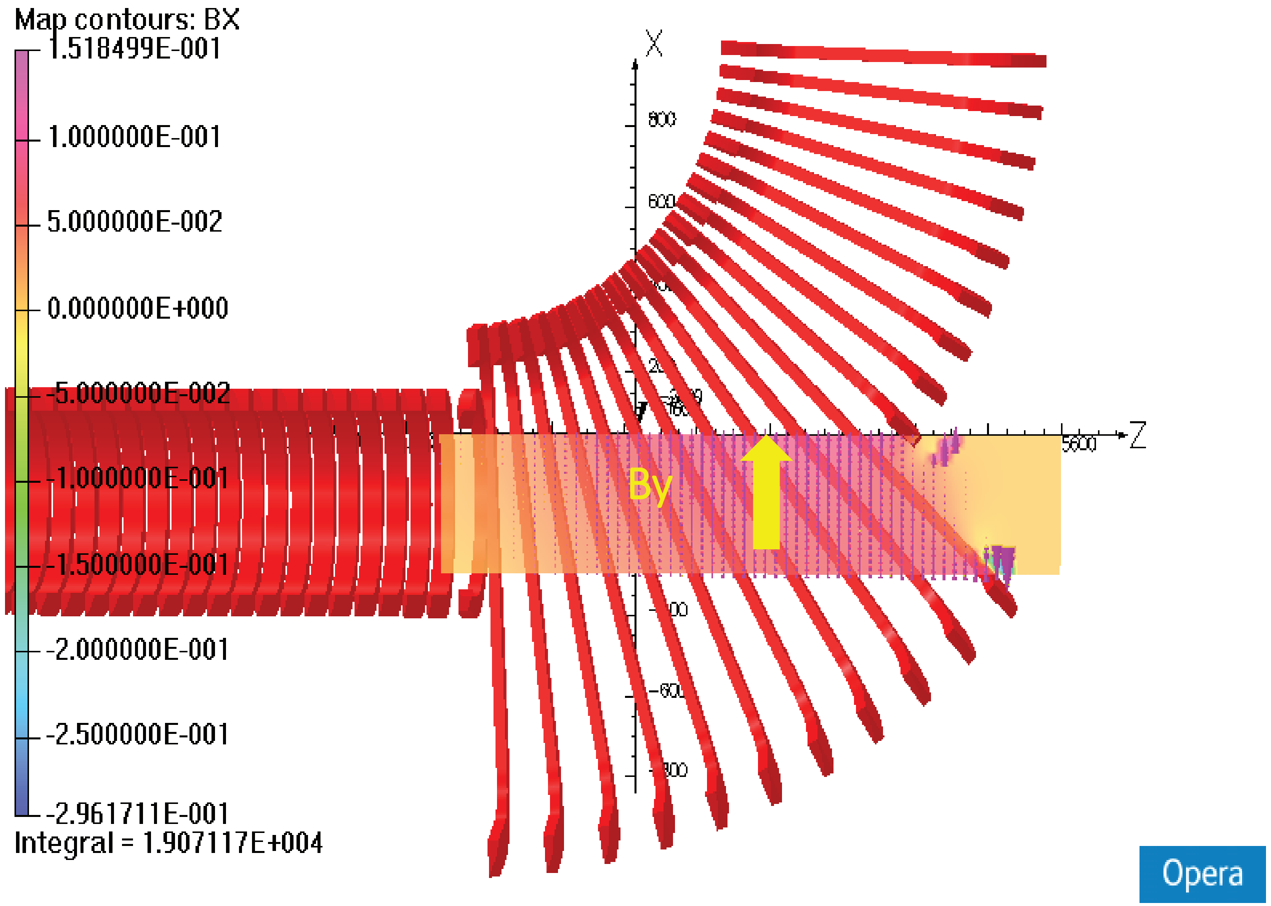
✓ Guiding magnetic field

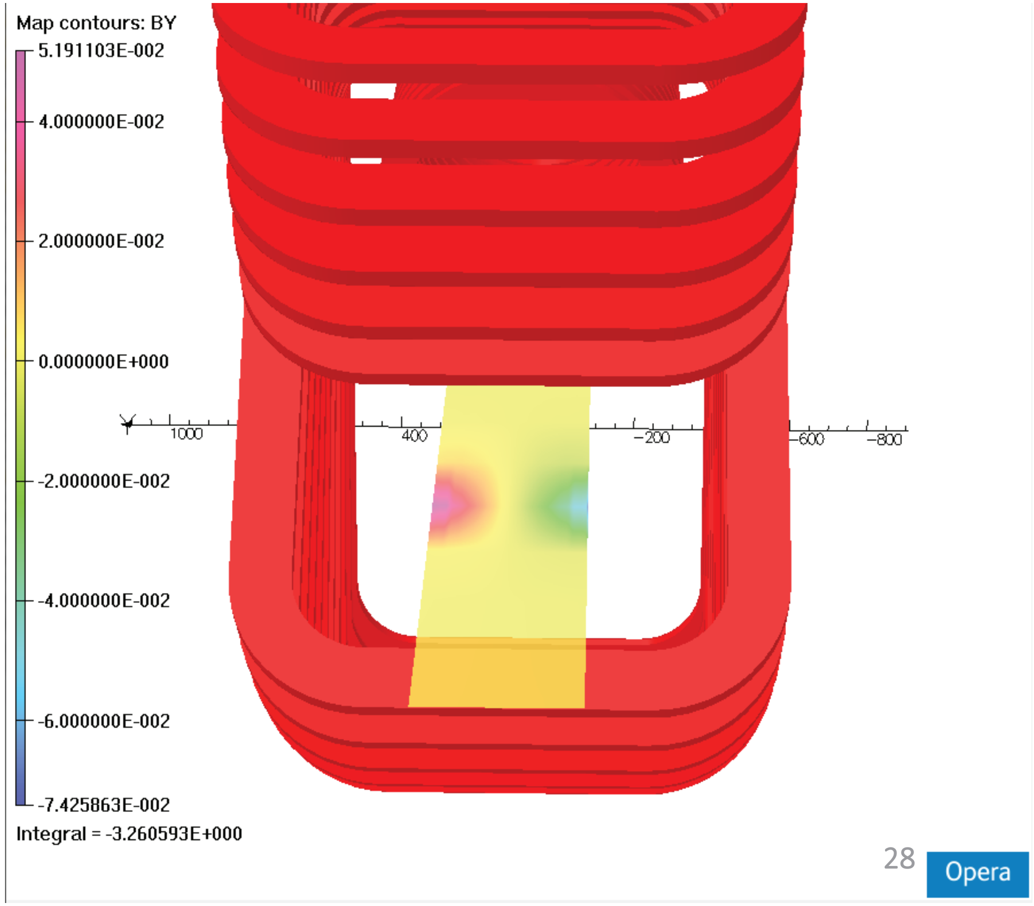
- The guiding magnetic field is built by many pancake coils
- The field calculation was made by OPERA
- The magnetic field homogeneity is $<10^{-4}$



✓ Guiding magnetic field

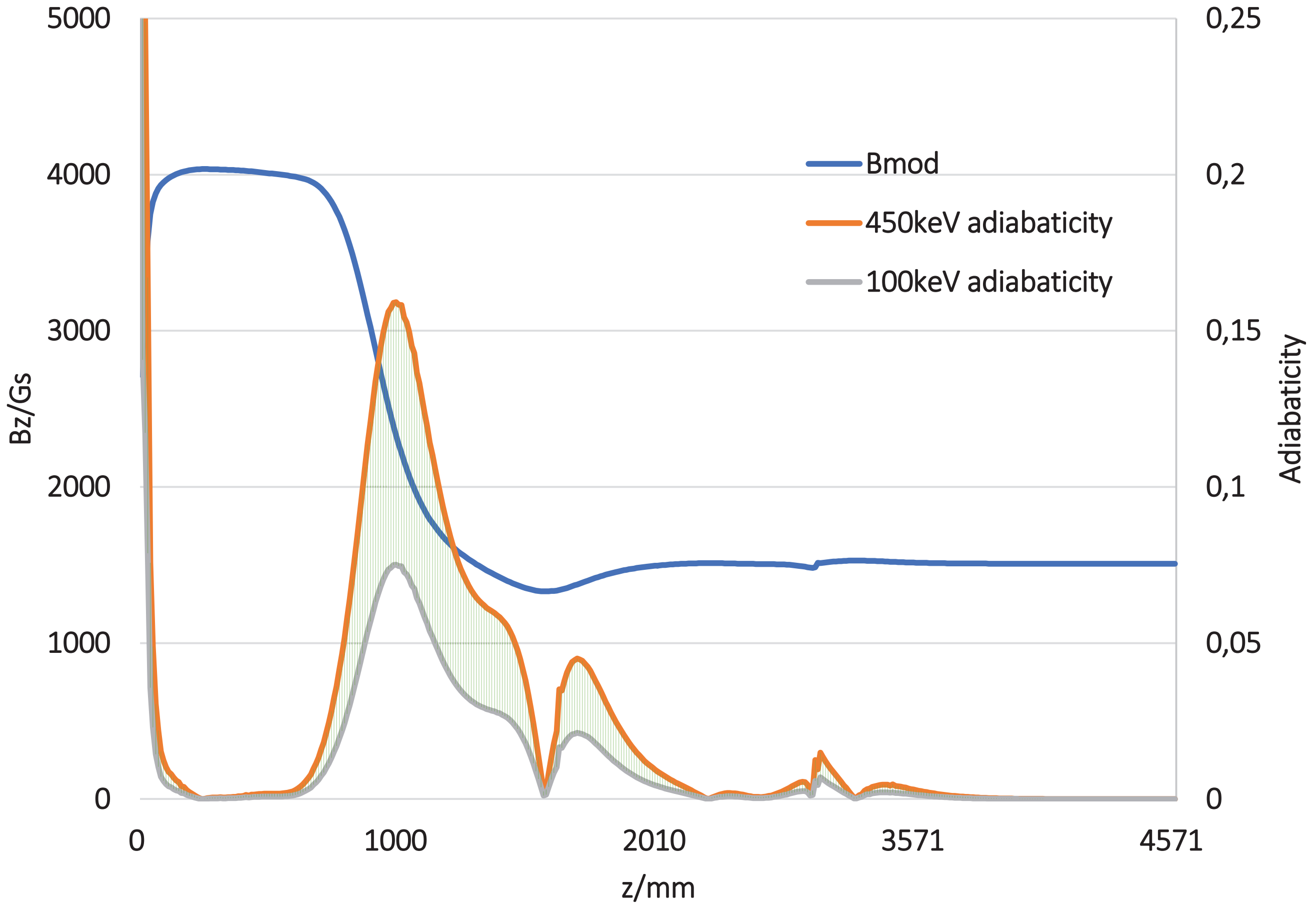
- Transverse magnetic field components in toroids causes a severe horizontal ion beam deflection, local orbit correction is necessary
- Horizontal magnetic field direction





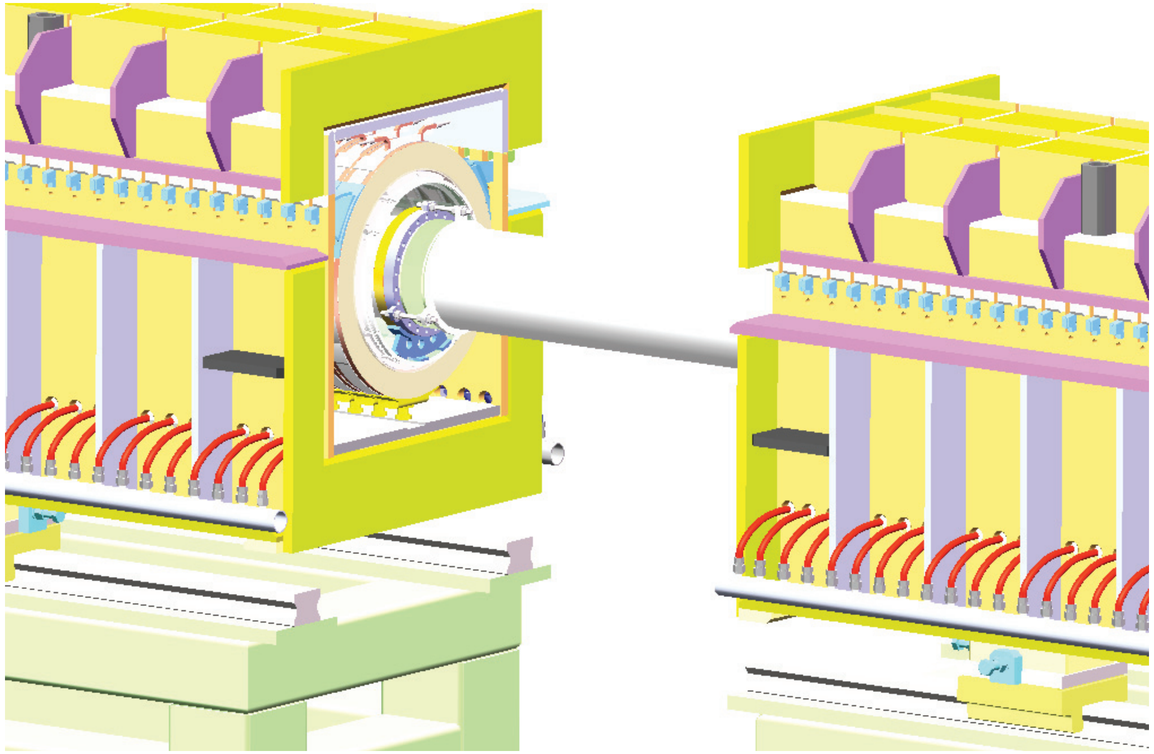
✓ Adiabatic expansion

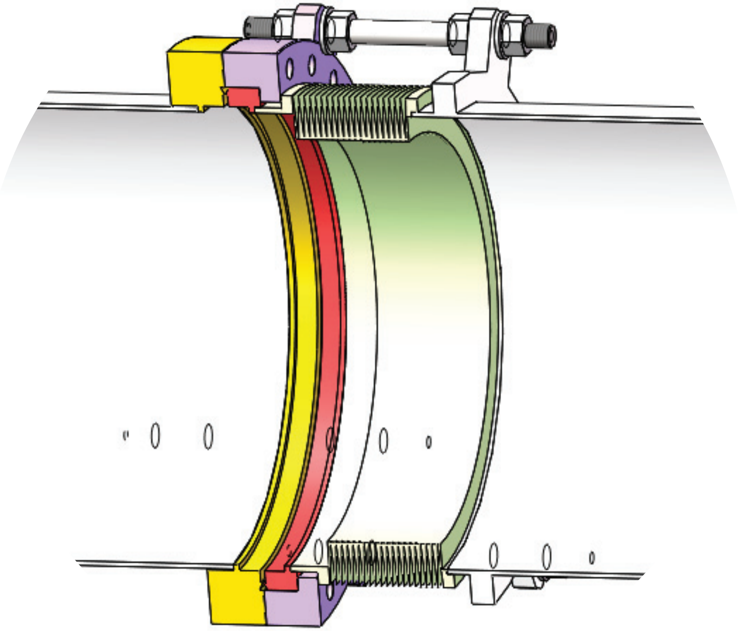
- A solenoid located between gun and toroid is used for transverse adiabatic expansion
- An adiabatic parameter is less than 0.15 for the energy of 450 keV



✓ Connection of cooling solenoid

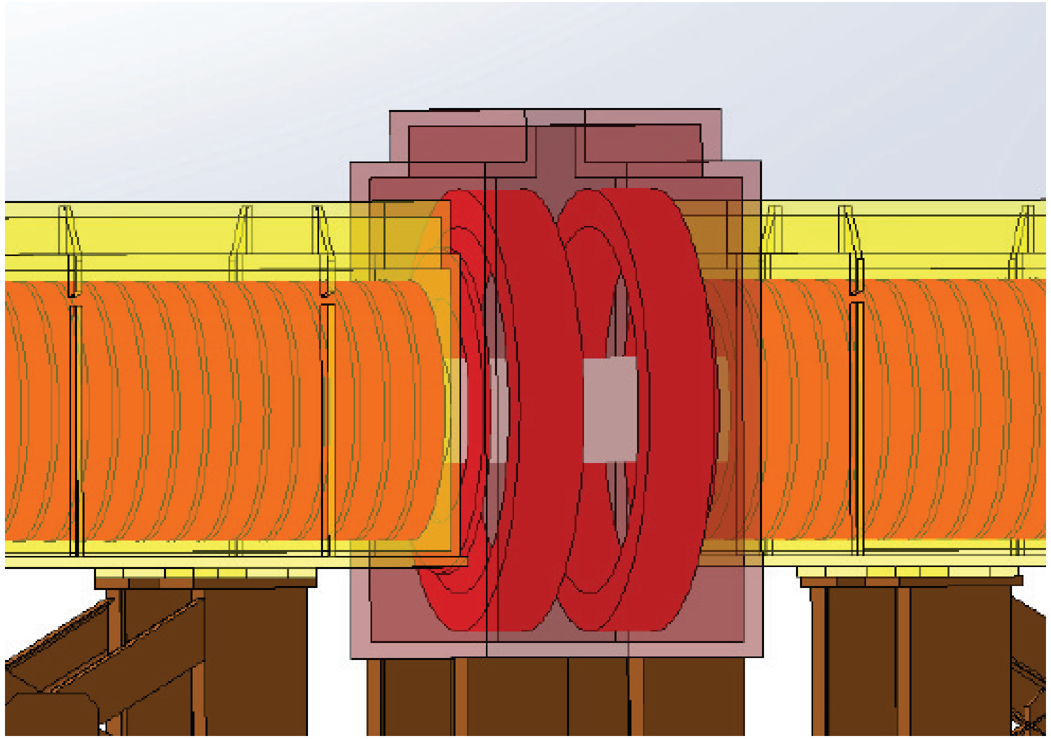
- A mechanical design of the cooling section

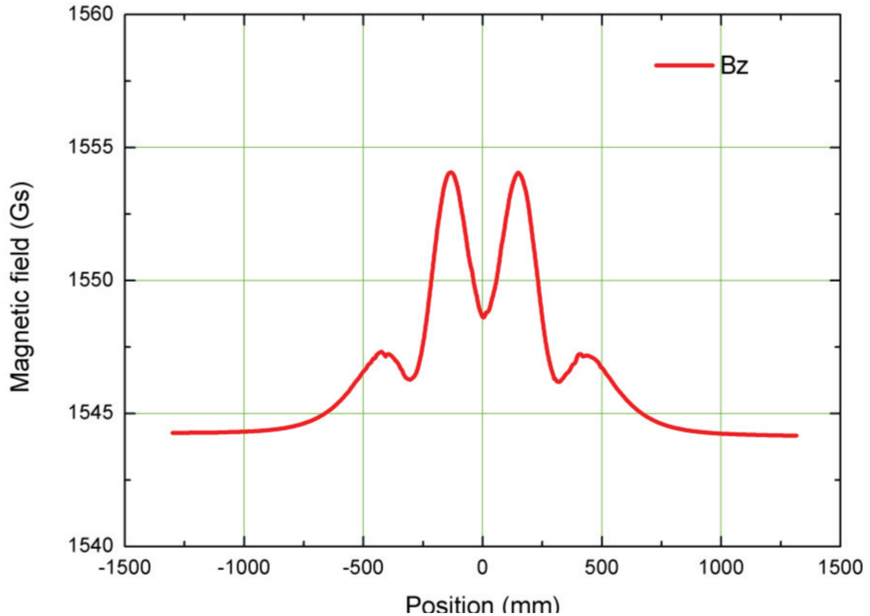


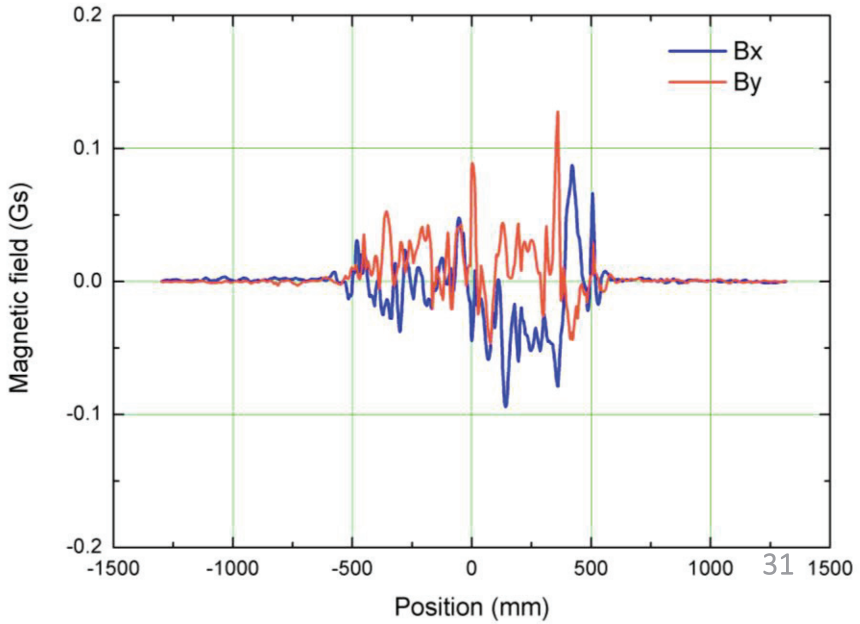


✓ Connection of cooling solenoid

- A 0.5 m connection section is used
- It is also good for the vacuum system
- A magnetic field distortion

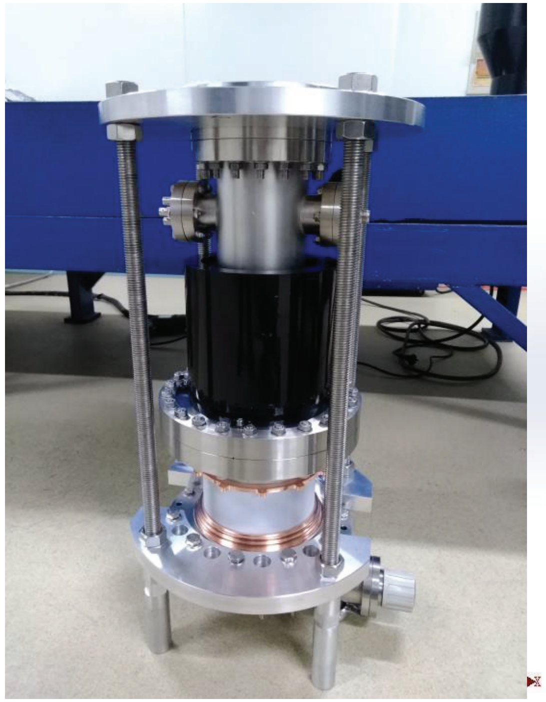


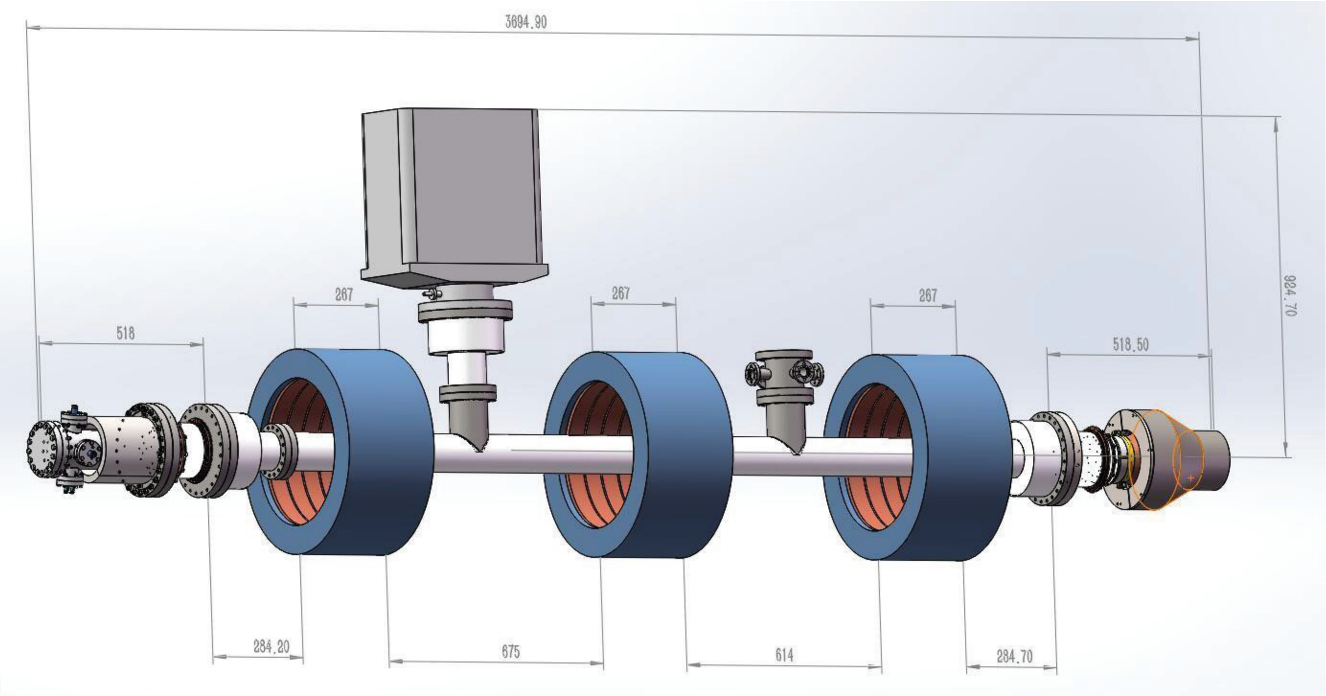


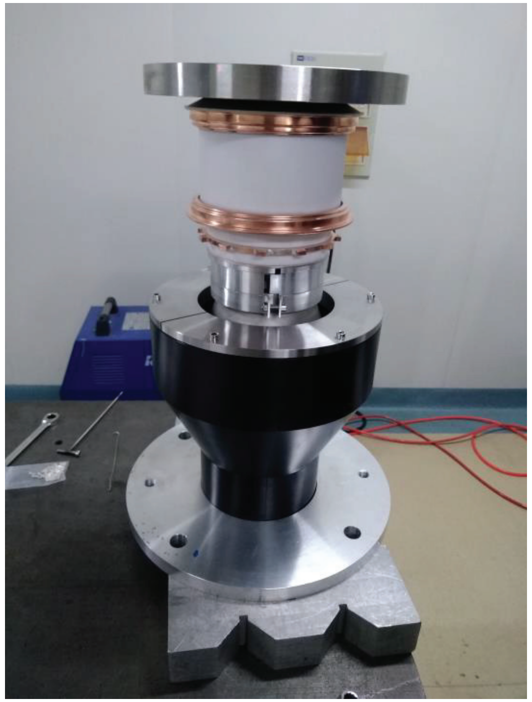


✓ Testbench for the gun and collector

- A testbench is built for the gun, collector and diagnostics tests
- Prototypes of the gun and the collector were already finished







4. Conclusion and outlook

- **A 450 keV magnetized electron cooling device is necessary for the HIAF project, the technical parameters were listed according to the simulation results**
- **The present CSR 300 keV cooler designed by BINP provide us a very good platform**
- **The electron gun, collector and acceleration tube could be provided by some domestic institutes and companies**
- **The high voltage system is still a problem for us**

- Thanks to Dr. Parkhomchuk, Dr. Reva, Mr. Skorobogatov and BINP group for the continuously support on the CSRm cooler devices
- Thanks to Dr. Katayama for the fruitful discussion on the SRing electron cooling simulation.

Thanks for your attention!