Commissioning of HIRFL-CSR and its Electron Coolers

Institute of Modern Physics
Chinese Academy Of Sciences

Xiaodong Yang

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Function of Cooler in HIRFL-CSR

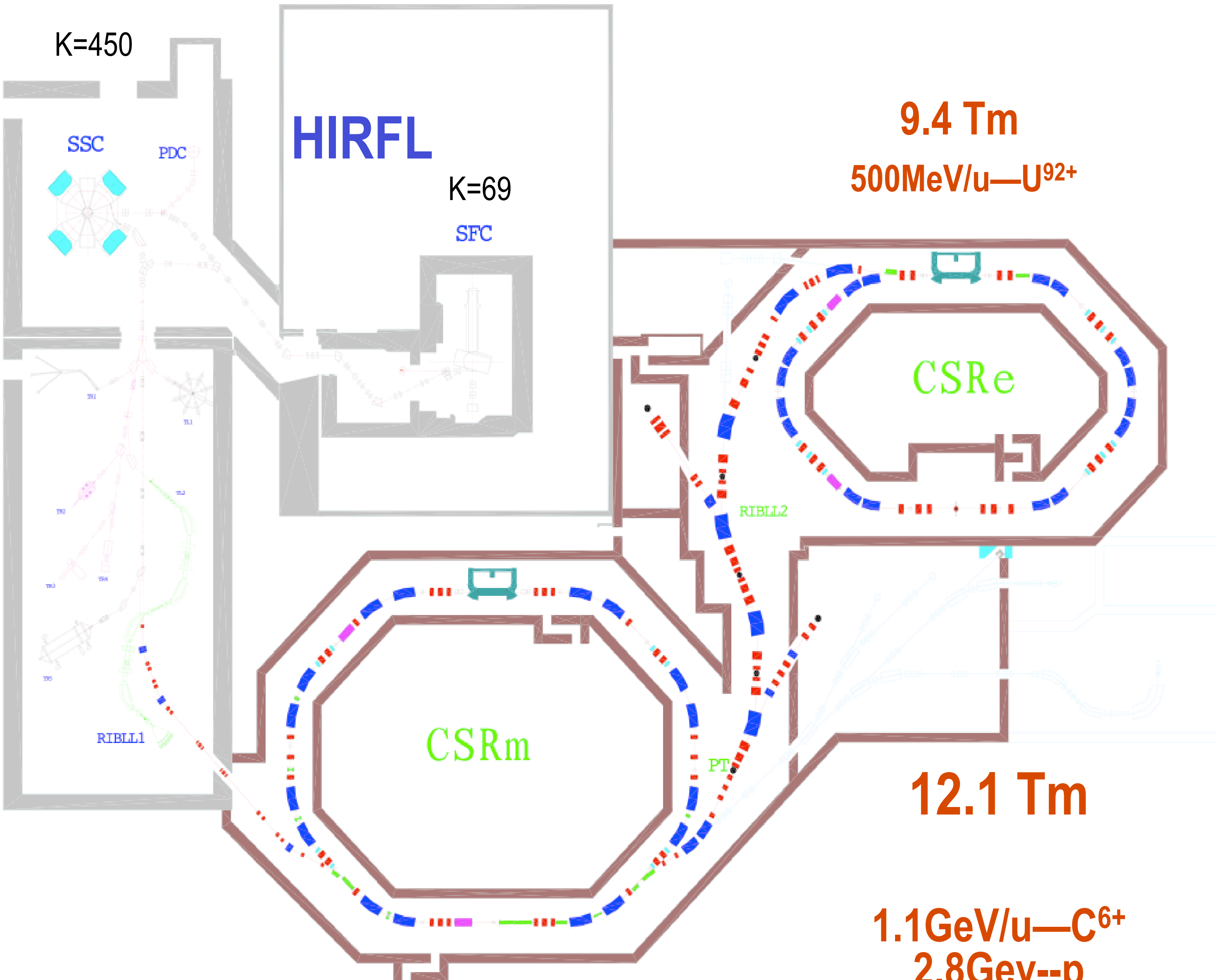
Main Ring

Heavy Ion Beam Accumulation

Experimental Ring

High Precision
High Resolution

HIRFL-CSR Layout



Physics Program of CSR

RIB physics
(With Radioactive Ion Beams)

Researches of hot nuclei
(With high-energy beams)

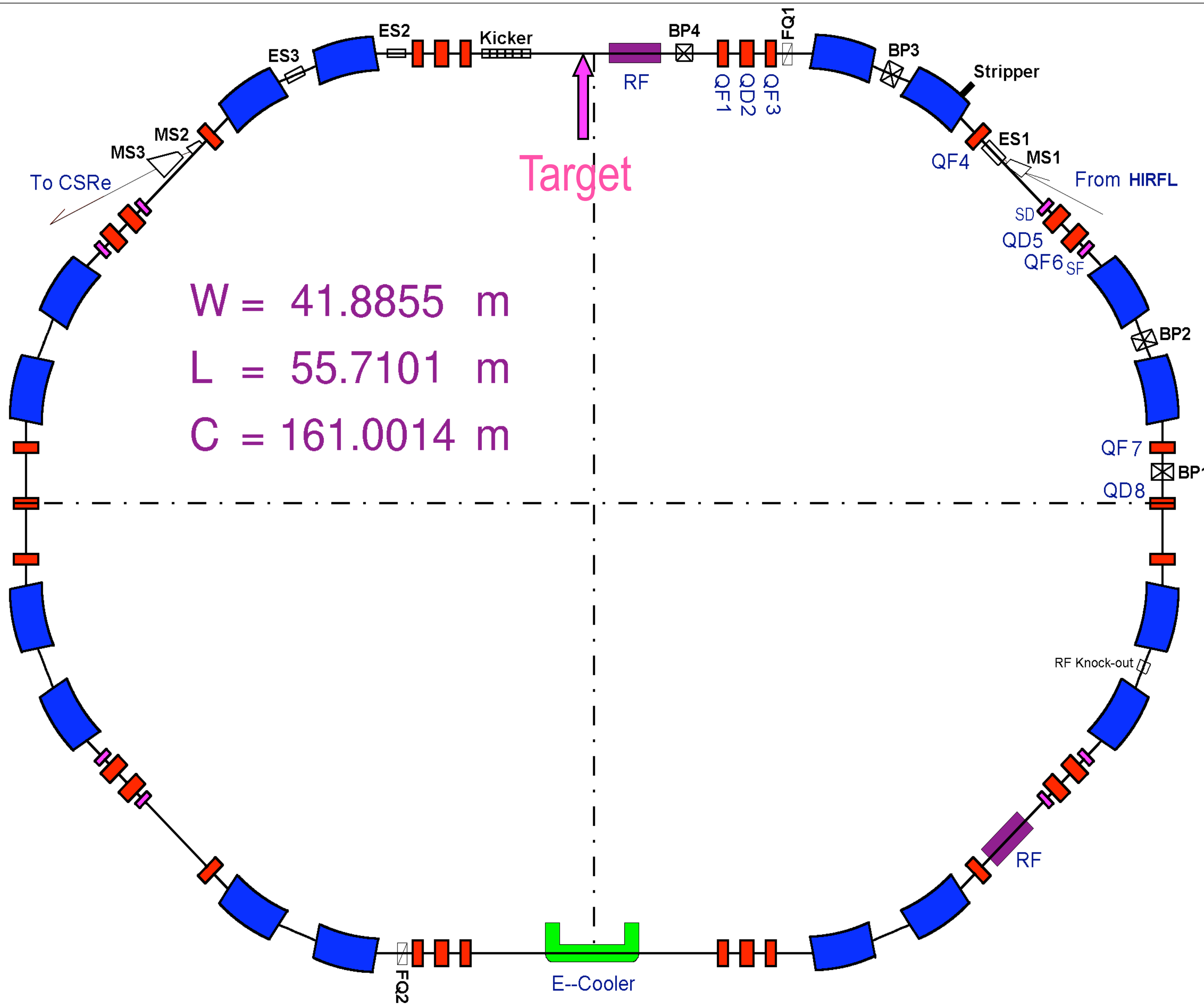
Atomic physics
(With highly charged heavy ions)

Related applications

CSR major parameters

	CSRm	CSRe
Circumference (m)	161.0014	128.8011
Average radius (m)	$8R_{SSC}=34R_{SFC}=25.62416$	$4/5R_{CSRm}=20.499328$
Geometry	Race-track	Race-track
Max. energy (MeV/u)	2800 (p) 1100 (C^{6+}) 500 (U^{72+})	2000 (p) 750 (C^{6+}) 500 (U^{92+})
Bρ (Tm)	0.81/12.05	0.50/9.40
B(T)	0.10/1.60	0.08/1.60
Ramping rate (T/s)	0.05 ~ 0.4	-0.1 ~ -0.2
Repeating circle (s)	~17 (~10s for Accumulation)	
Acceptance	Fast-extraction mode	Normal mode
A_h (π mm-mrad)	200 (Δp/p = ±0.3 %)	**150** (Δp/p =±0.5%)
A_v (π mm-mrad)	40	**75**
Δp/p (%)	1.4 (ε_h= 50 π mm-mrad)	**2.6** (ε_h= 10 π mm-mrad)

	CSRm		CSRe
E-cooler			
Electron energy (KeV)	35		300
Eff. cooling length (m)	3.4		3.4
RF system	Accel.	Accum.	Deceleration
Harmonic number	1	16, 32,64	1
f_{min}/f_{max} (MHz)	0.24/1.81	6.0 / 14.0	0.4 / 2.0
Voltages (n × kV)	1 × 7.0	1 × 20.0	2 × 10.0
Vacuum (mbar)	(3.0×10^{-11})		



CSRm Lattice Layout

Main Parameters Table of HIRFL-CSR

		CSRm	CSRe
Ion Energy/MeV/u		8-50	10-450
Electron Energy/keV		4.39-27.43	5.5-247.87
Ring Length/m		161.0	128.8
Cooling section Length/m		4.0	4.0
βFunction/m	Horizontal β_h	10.0	12.5
	Vertical β_h	17.0	16.0
Dispersion/m		0	0
Magnetic Strenghth/T		<0.15	<0.15
Max Electron Current/A		3	3
Initial Emittance (πmmmrad)	Horizontal ε_h	150	30
	Vertical ε_v	20	30
Initial Momentum Spread $\Delta P/P$		$\pm 5\times 10^{-3}$	$\pm 5\times 10^{-3}$
Final Emittance (πmmmrad)	Horizontal ε_h	20	1
	Vertical ε_v	20	1
Final Momentum Spread $\Delta P/P$		$\pm 5\times 10^{-4}$	$\pm 1\times 10^{-6}$

Some topics discussed

- Collection of electron beam
- Adiabatic expansion of electron beam
- Influence of magnetic field imperfection
- Motion of electron beam in toroid

Parameters related to the cooling time ---lattice function

- βFunction
- Dispersion
- Initial Emittance and Momentum Spread

Parameters related to cooling time ---Ion beam

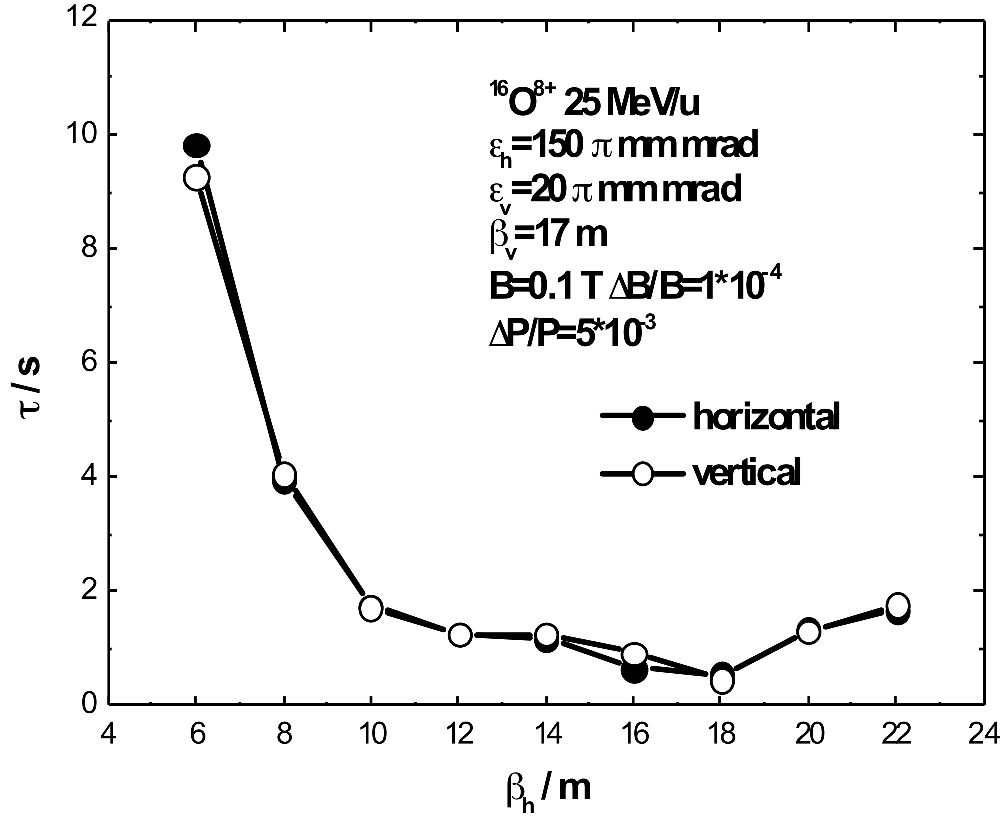
- Ion Energy
- Species of Ion
- Charge State
- Ion Beam Current

Parameters related to Cooling Time
---Electron Beam

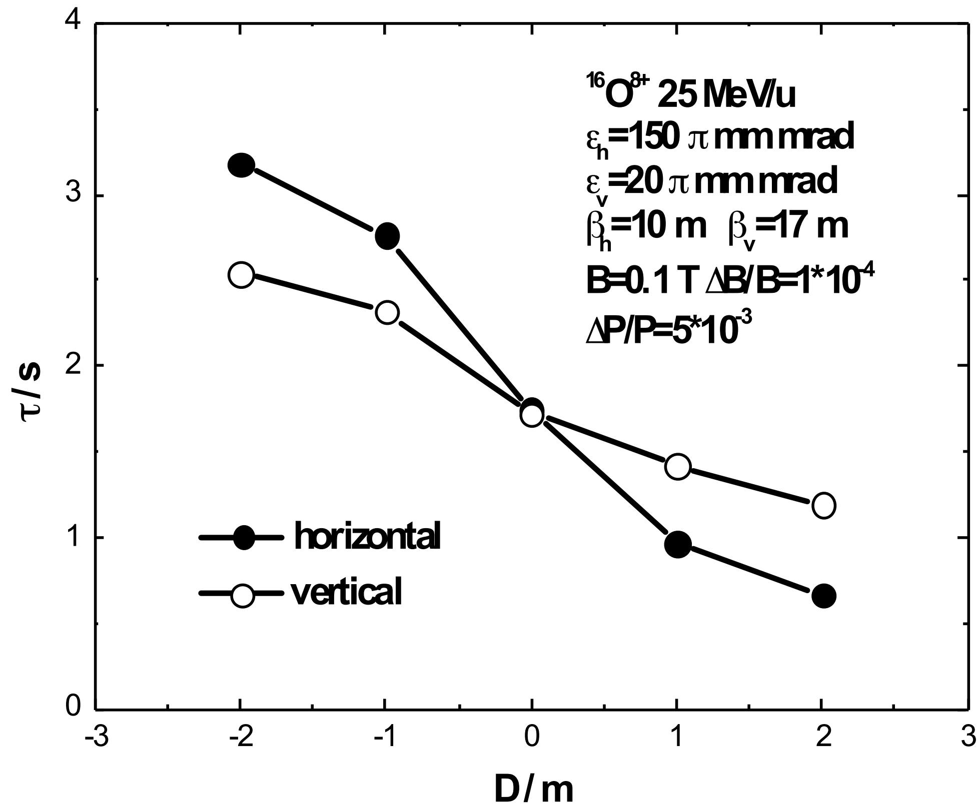
- Density of Electron
- Electron Beam Current
- Radius of Electron Beam
- Transverse Temperature of Electron Beam

Parameters related to Cooling Time ---Electron cooling Device

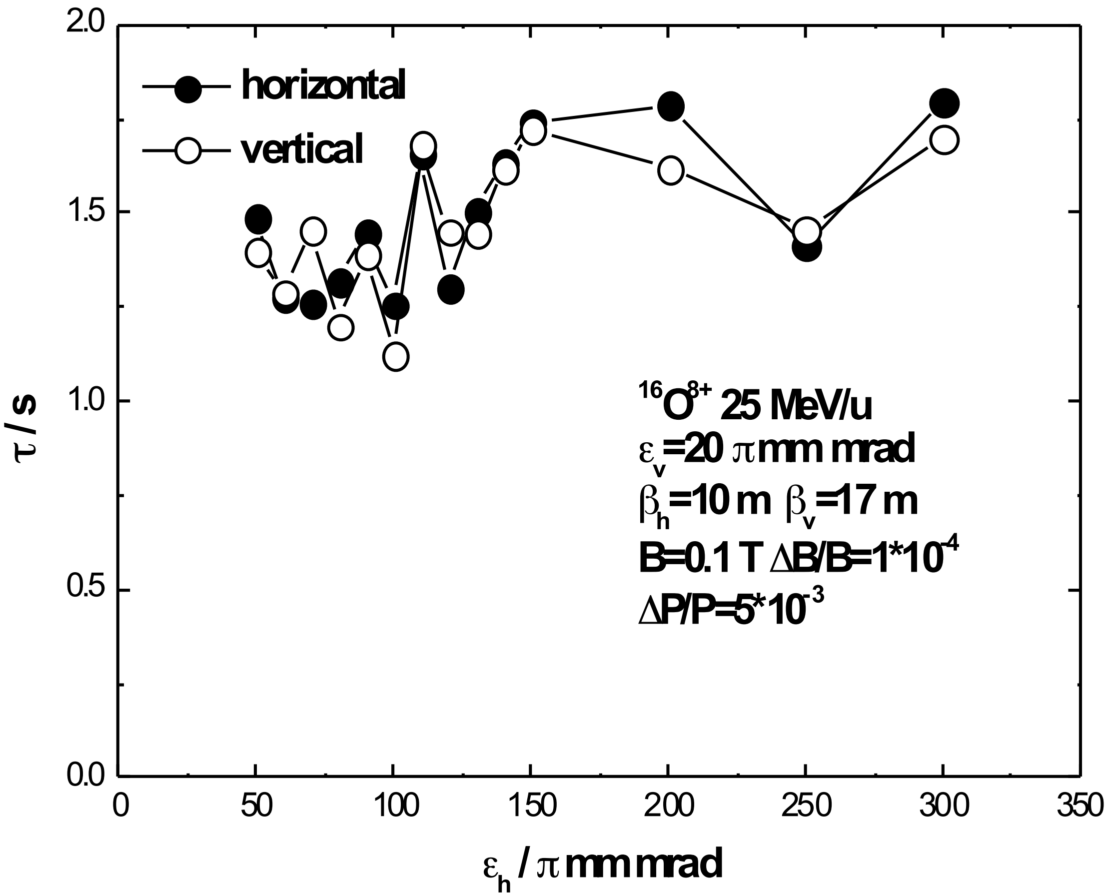
- Effective Cooling Length
- Magnetic Field Strength
- Parallelism of Magnetic Field in Cooling section



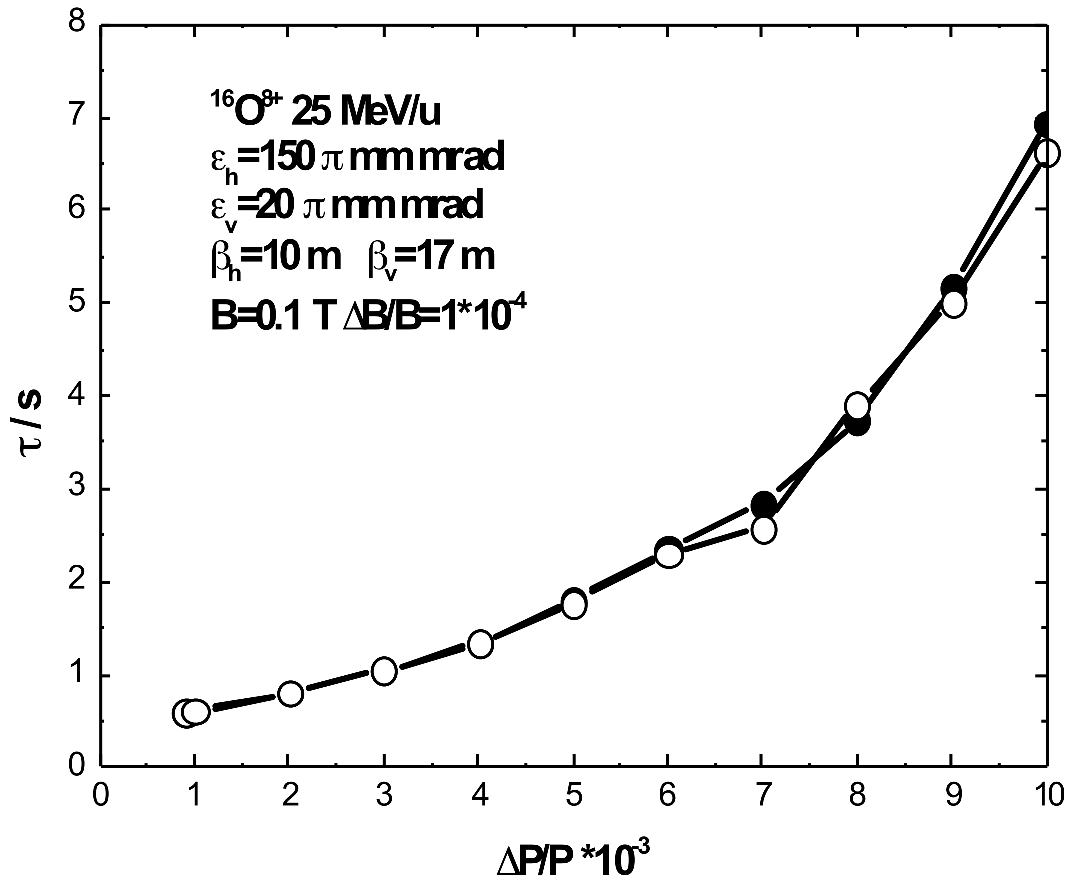
Cooling time as a function of Betatron function



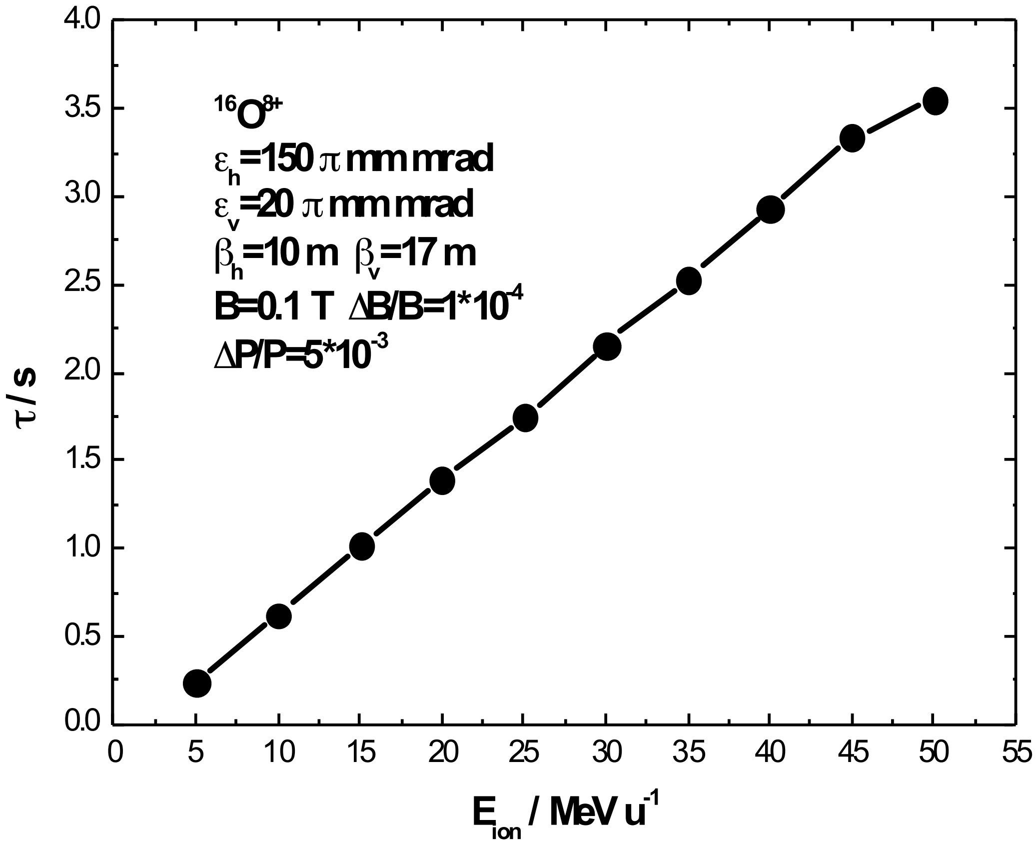
Cooling time as a function of dispersion in the cooler location



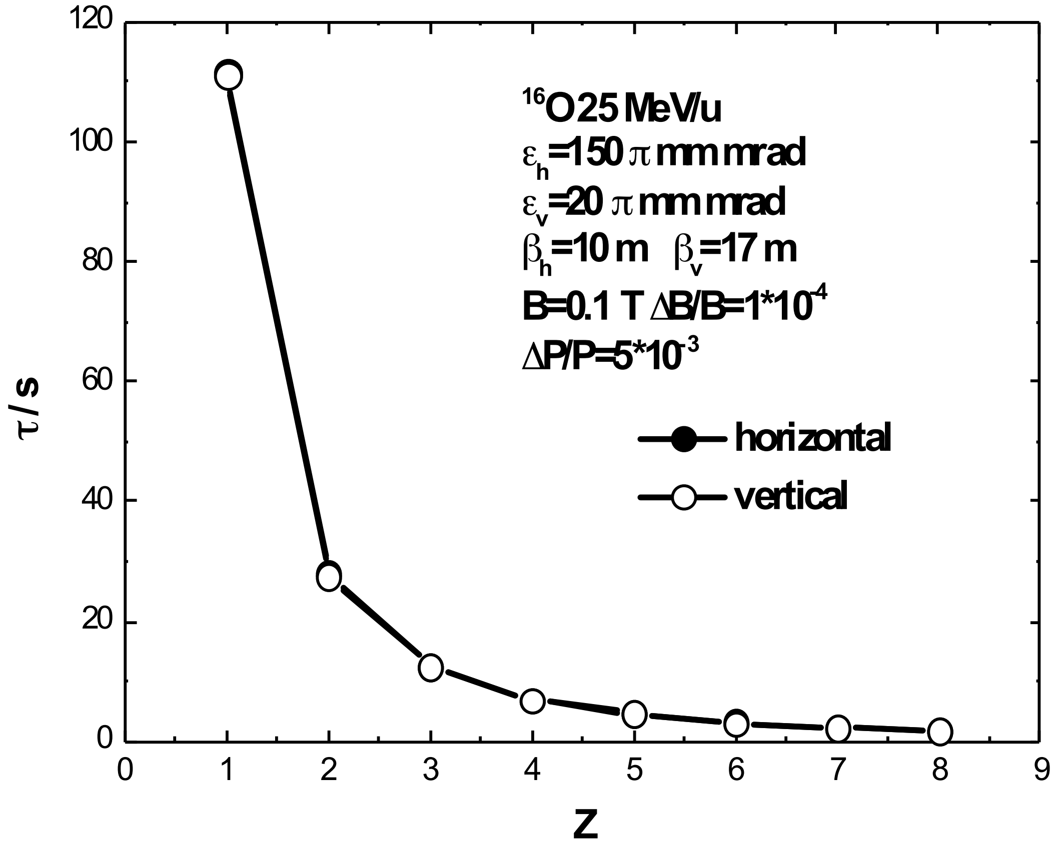
Cooling time as a function of initial emittance



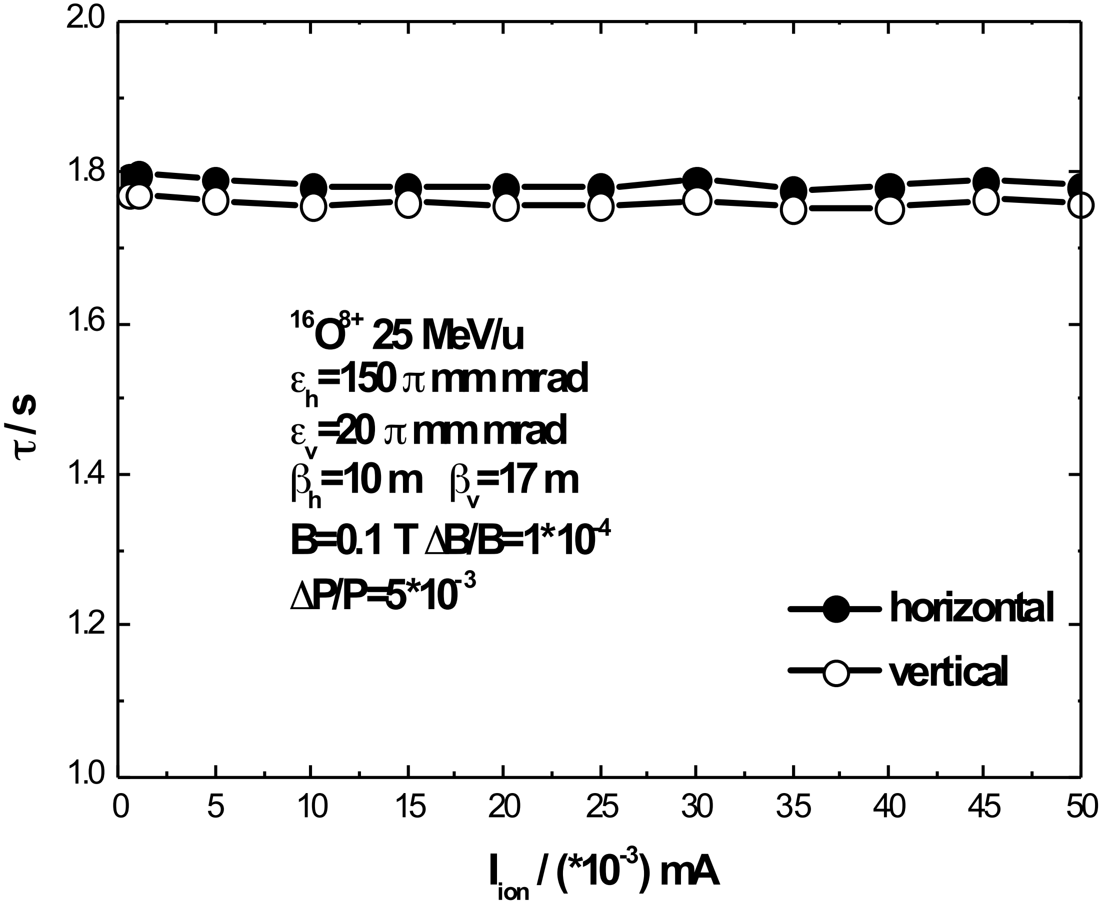
Cooling time as a function of initial momentum spread



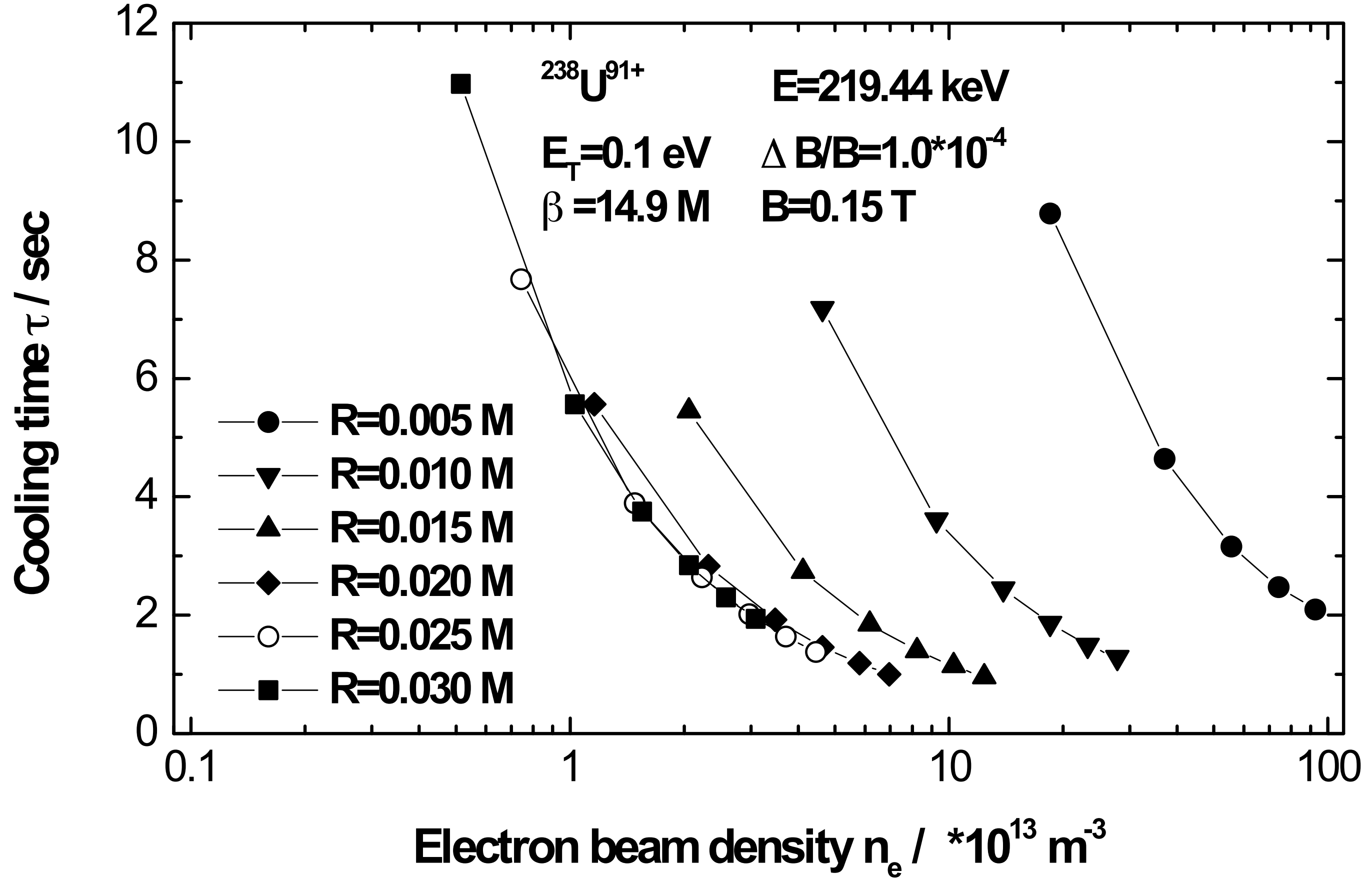
Cooling time as a function of ion energy



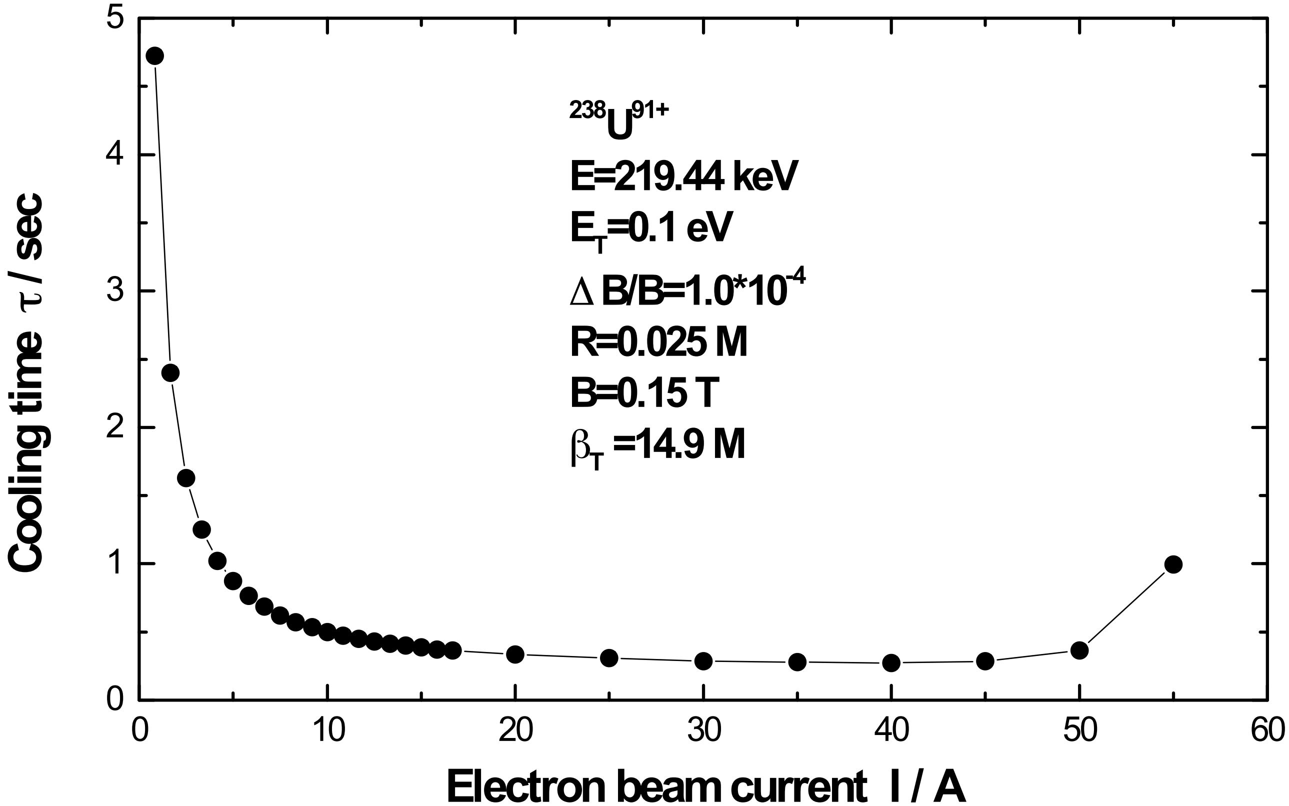
Cooling time as a function of charge state



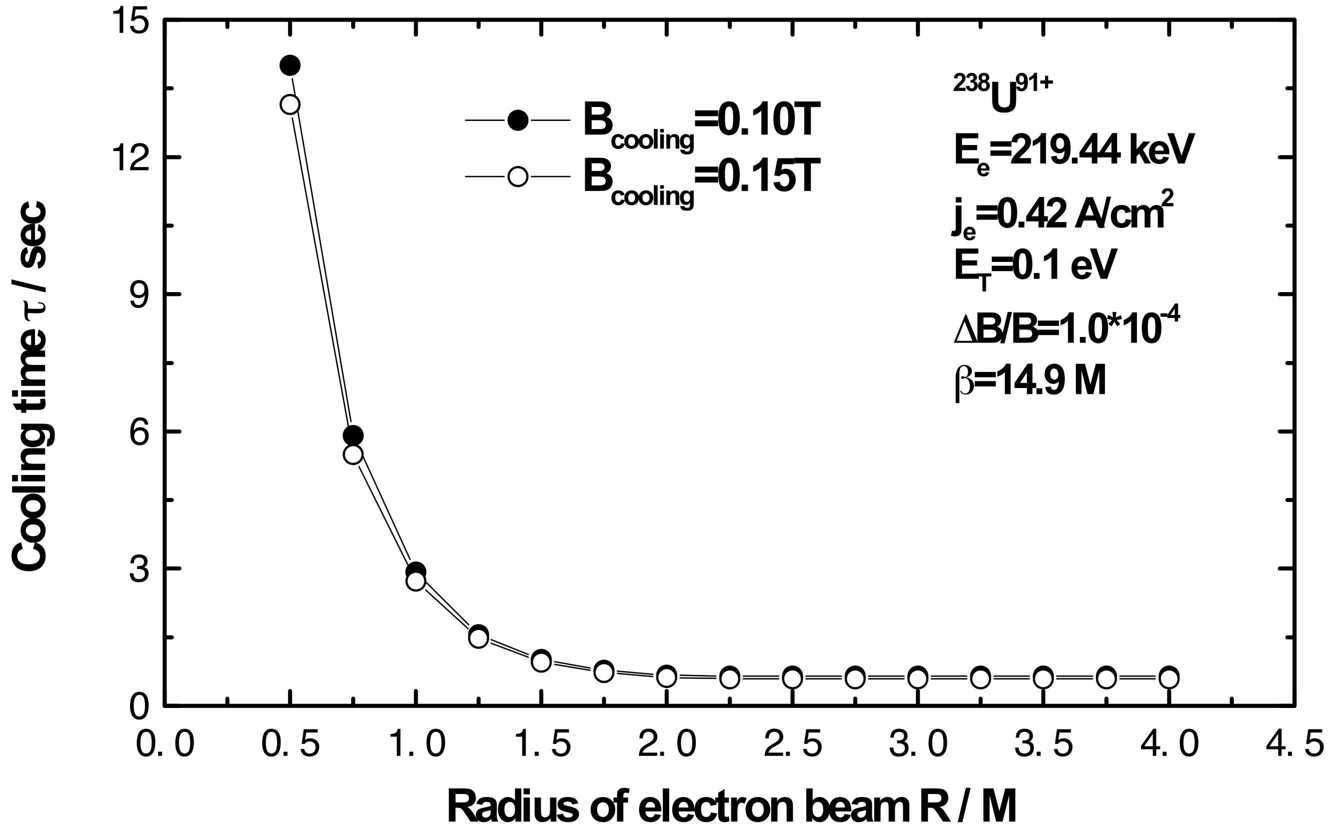
Cooling time as a function of injection ion beam current



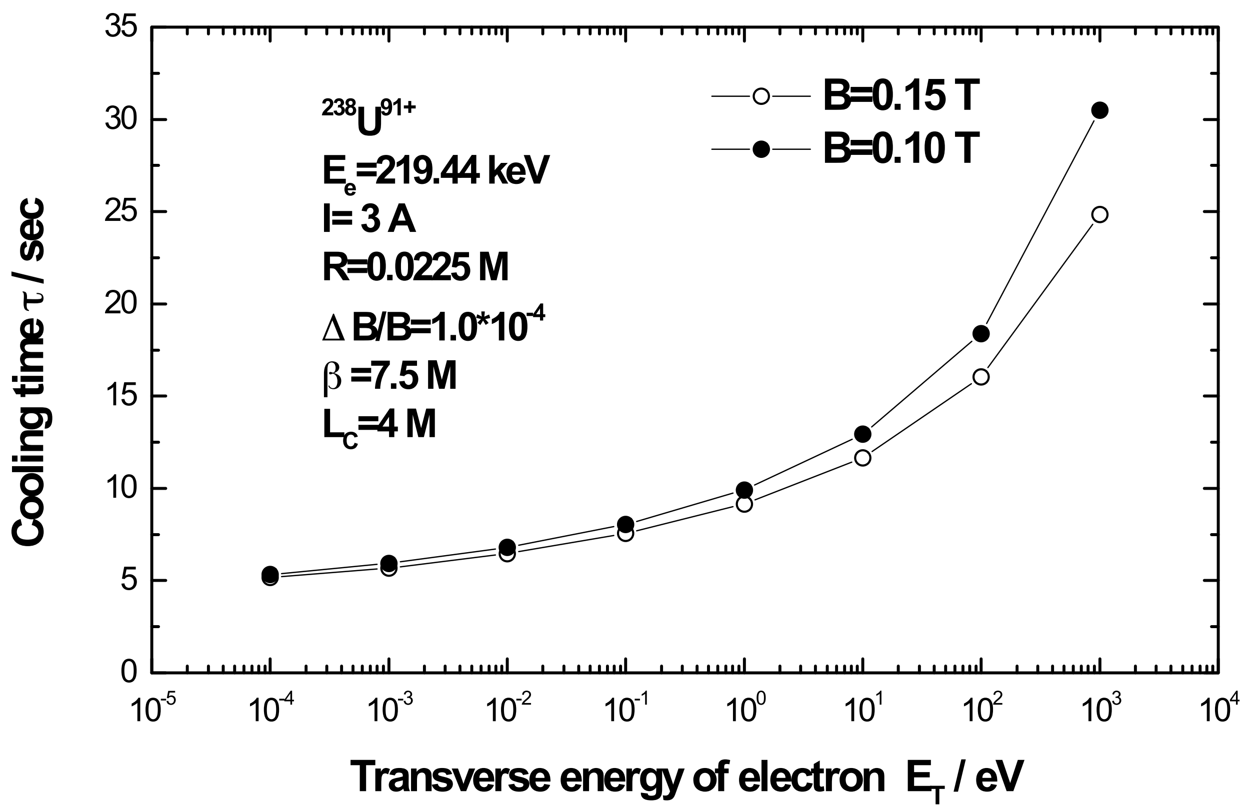
Cooling time as a function of electron density at different radius



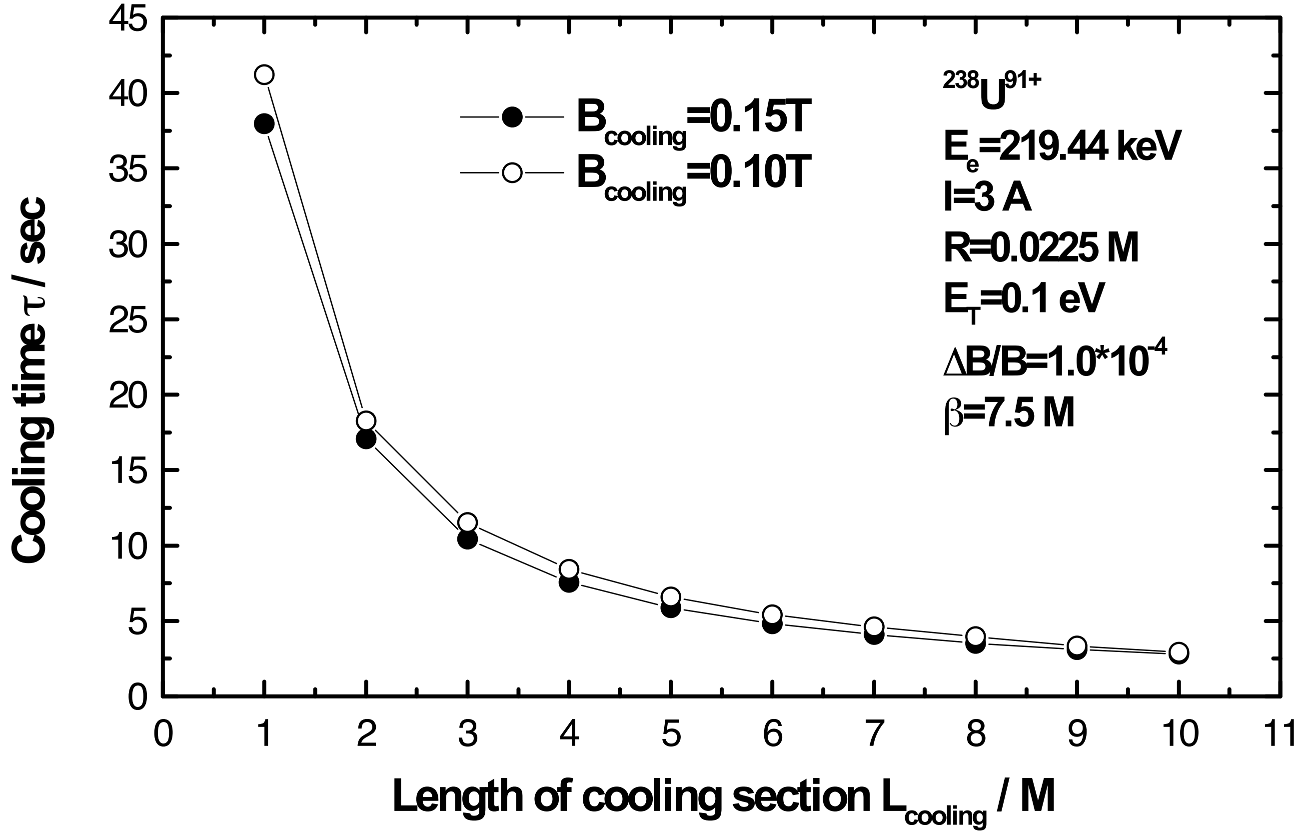
Cooling time as a function of electron beam current at fixed radius



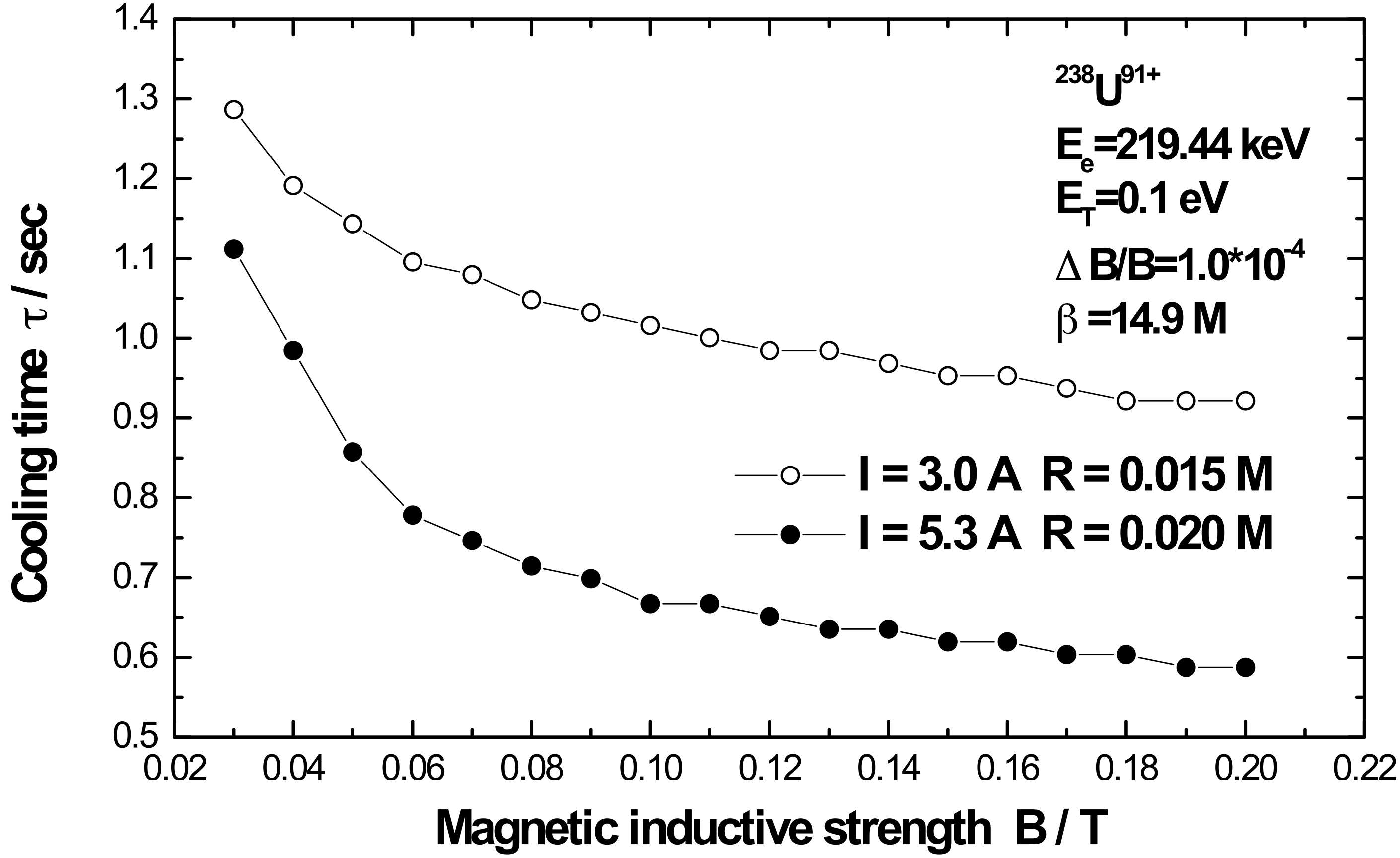
Cooling time as a function of radius of electron beam at fixed density



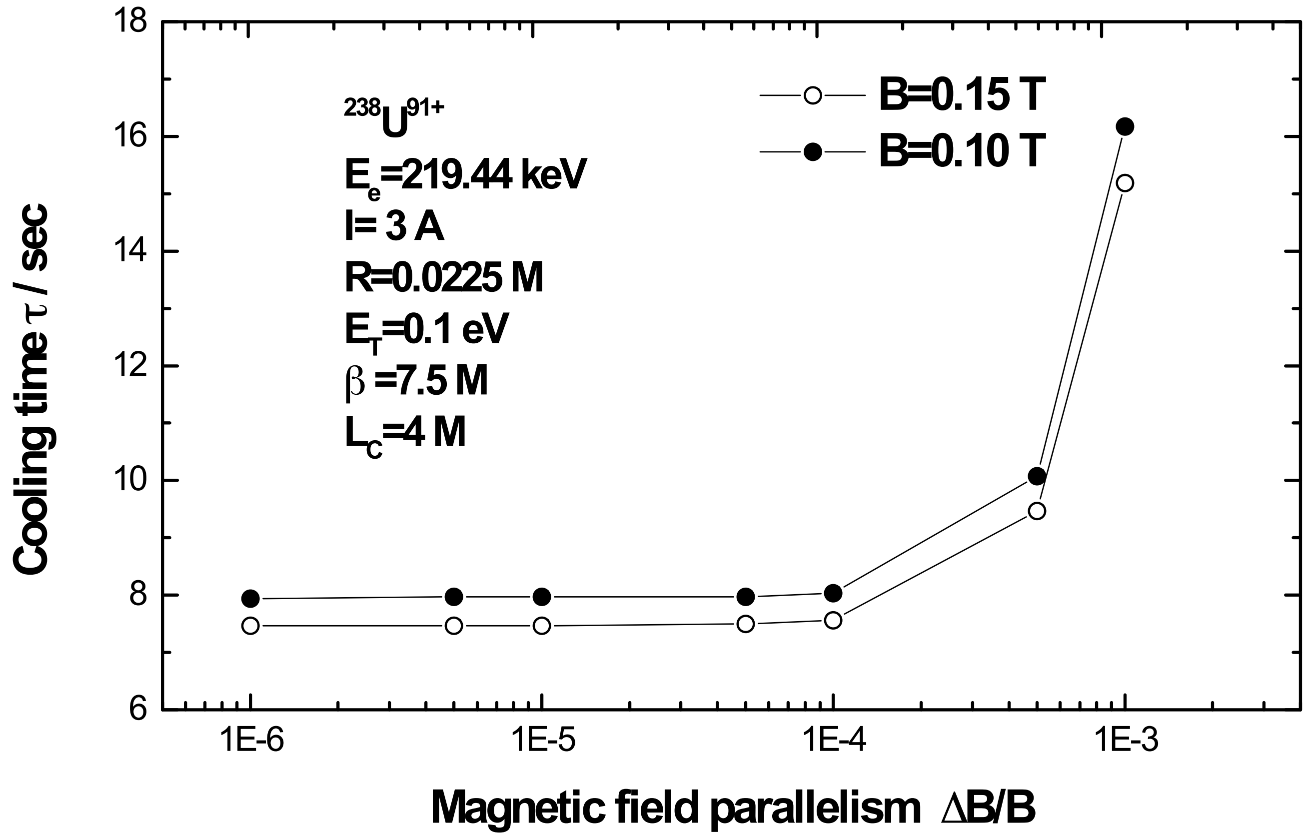
Cooling time as a function of transverse energy of electron



Cooling time as a function of length of cooling section



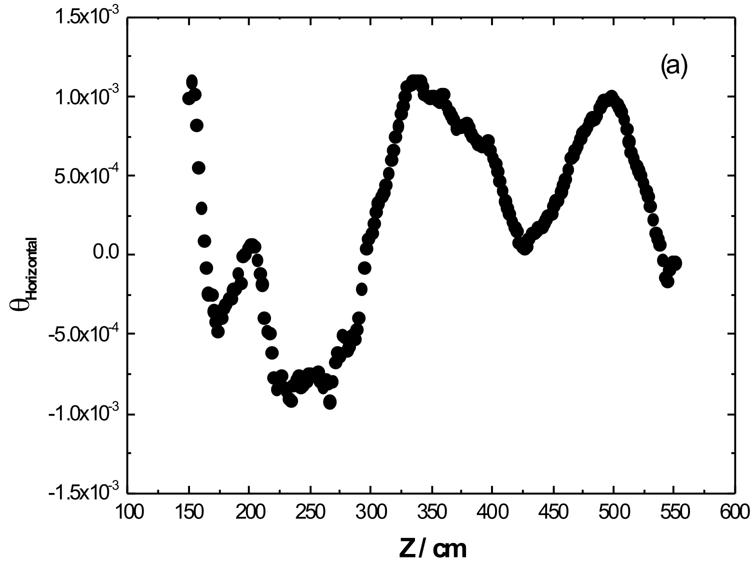
Cooling time as a function of magnetic inductive strength in cooler

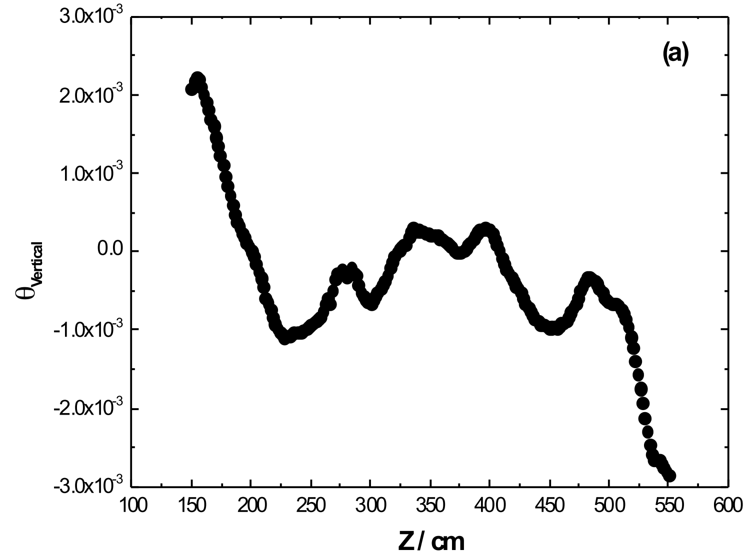


Cooling time as a function of magnetic field parallelism

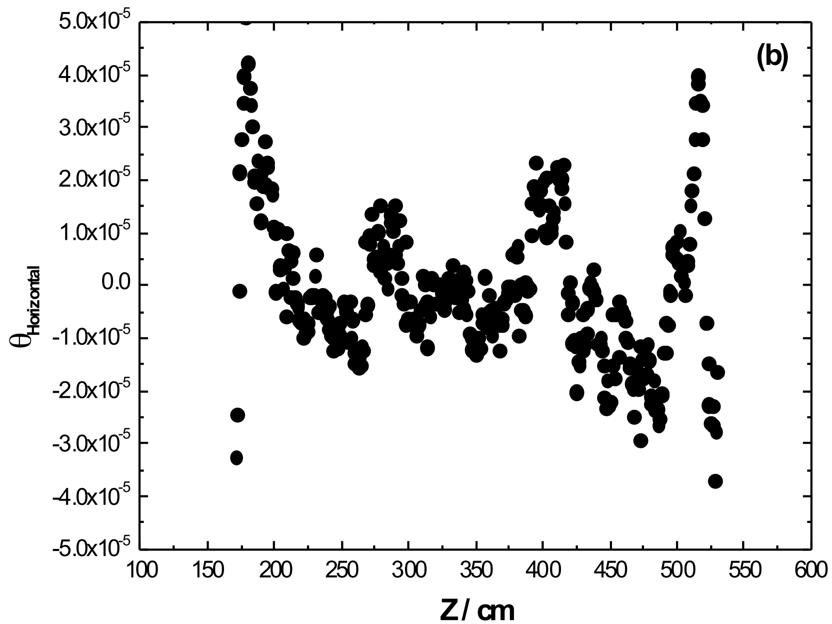
Previous results of commissioning

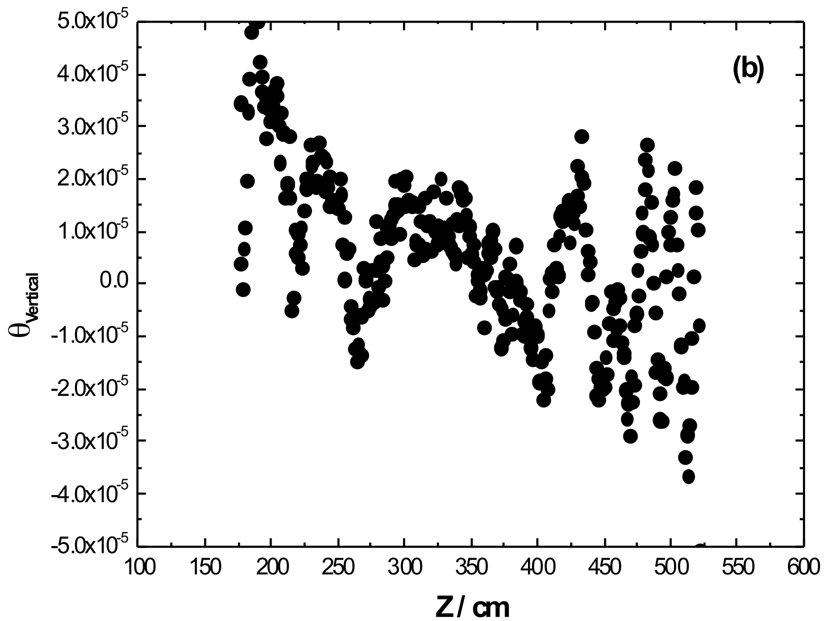
- Hollow beam
- High parallelism magnetic field in cooling section
- Electrostatic bending



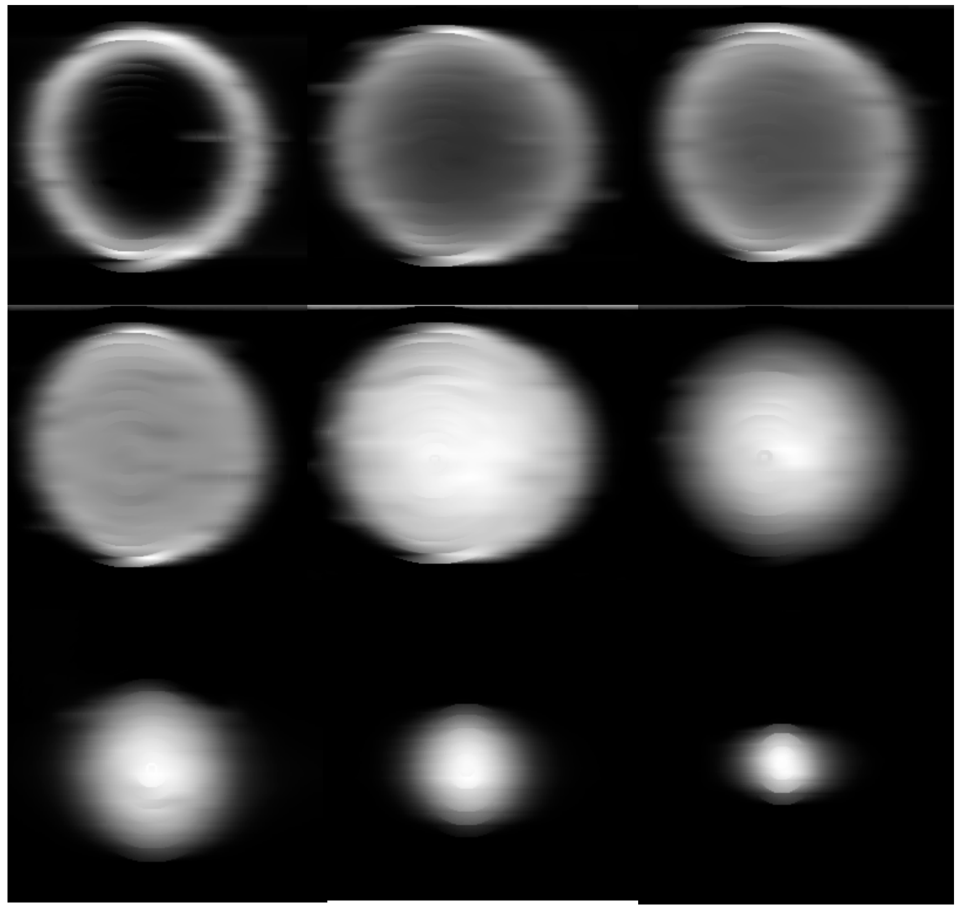


Angle of Magnetic force line with respect to geometric center before adjustment

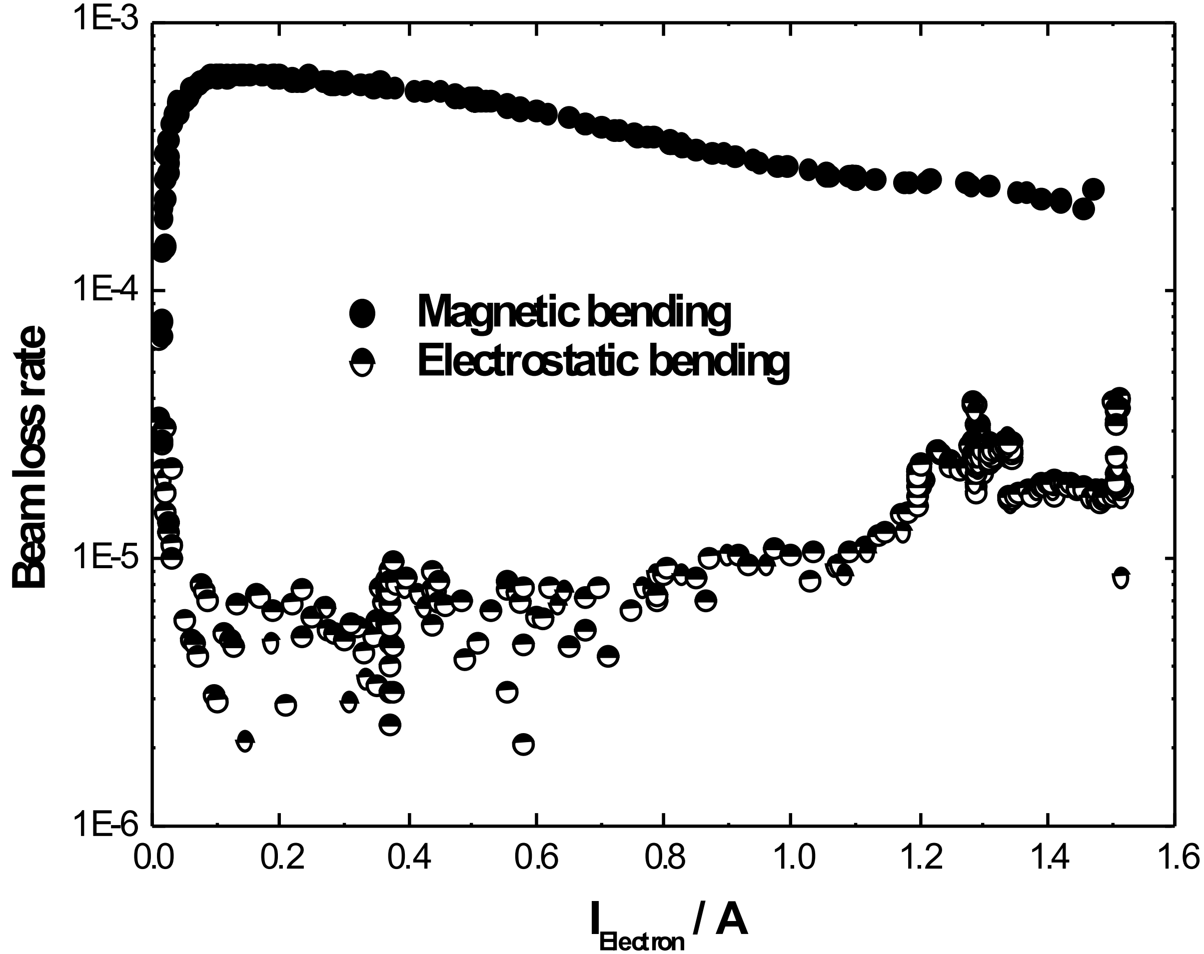




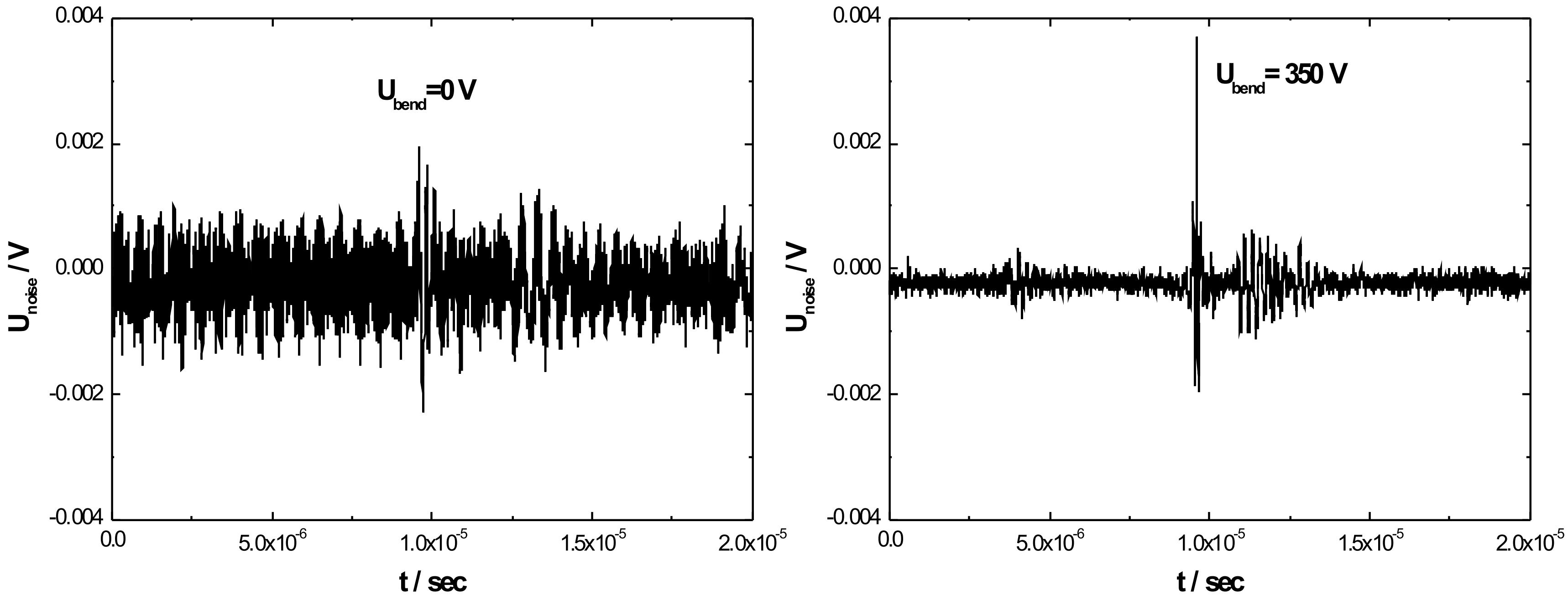
Angle of Magnetic force line with respect to geometric center after adjustment



Electron beam profile



Comparison of different bending



Noise at different bending

Results of commissioning

		CSRm		CSRe	
		Design	test	design	test
Electron energy (keV)		35	30	300	252
Beam current(A)		3	3	3	2.32
parallelism	horizontal	$<1\times10^{-4}$	7.84×10^{-6}	$<1\times10^{-4}$	3.87×10^{-5}
	vertical	$<1\times10^{-4}$	8.04×10^{-6}	$<1\times10^{-4}$	3.89×10^{-5}
Beam loss rate		$<1\times10^{-4}$	$<1\times10^{-4}$	$<1\times10^{-4}$	$<1\times10^{-4}$
Vacuum(mbar)		3×10^{-11}	1×10^{-11}	3×10^{-11}	4×10^{-11}
Stability of HVPS		1×10^{-4}	1×10^{-4}	1×10^{-4}	1×10^{-4}

Stability of magnetic field power supply

	CSRm		CSRe	
	design	test	design	test
200A PS	1.0×10^{-3}	5.9×10^{-4}	1.0×10^{-3}	1.4×10^{-4}
780A PS	1.0×10^{-3}	2.4×10^{-4}	1.0×10^{-3}	2.9×10^{-4}
1200A PS	1.0×10^{-3}	3.8×10^{-4}	1.0×10^{-3}	6.3×10^{-4}
Bending PS	1.0×10^{-3}	5.0×10^{-4}	1.0×10^{-3}	2.7×10^{-4}
CX6 Correction coil PS	1.0×10^{-3}	1.3×10^{-4}	1.0×10^{-3}	
CY6 Correction coil PS	1.0×10^{-3}	1.1×10^{-2}	1.0×10^{-3}	

Conclusion

1. lattice parameters of HIRFL---CSR lie in the optimal range for electron cooling
2. In the CSRm, the ion with higher charge state and lower energy should be chose as injection so that the ion beam will be cooled to required emittance in the shorter time
3. Electron cooling is more powerful when the injected ion beam has smaller initial emittance and momentum spread .

Conclusion

4. If introduce positive dispersion in the cooling section, the cooling time will become shorter than zero dispersion
5. Electron density should approach optimal value in the case of low energy, and as big as possible in the case of high energy
6. The magnetic field should be strong enough and parallelism is better than 1×10^{-4}.

Previous Commission of CSR

- From September 2004, the injection line was tuned with 7 Mev/u C^{4+} beam, the ion beam intensity is about 3 microamperes. The transmission efficiency is about 70%. Three cycles beam were observed in the main ring.

We would like to acknowledge our Russian colleagues.

Sincere honor and respect to the members of international advisory committee.

Thanks!