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Electron Cooling Experiments in CSR

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Lanzhou

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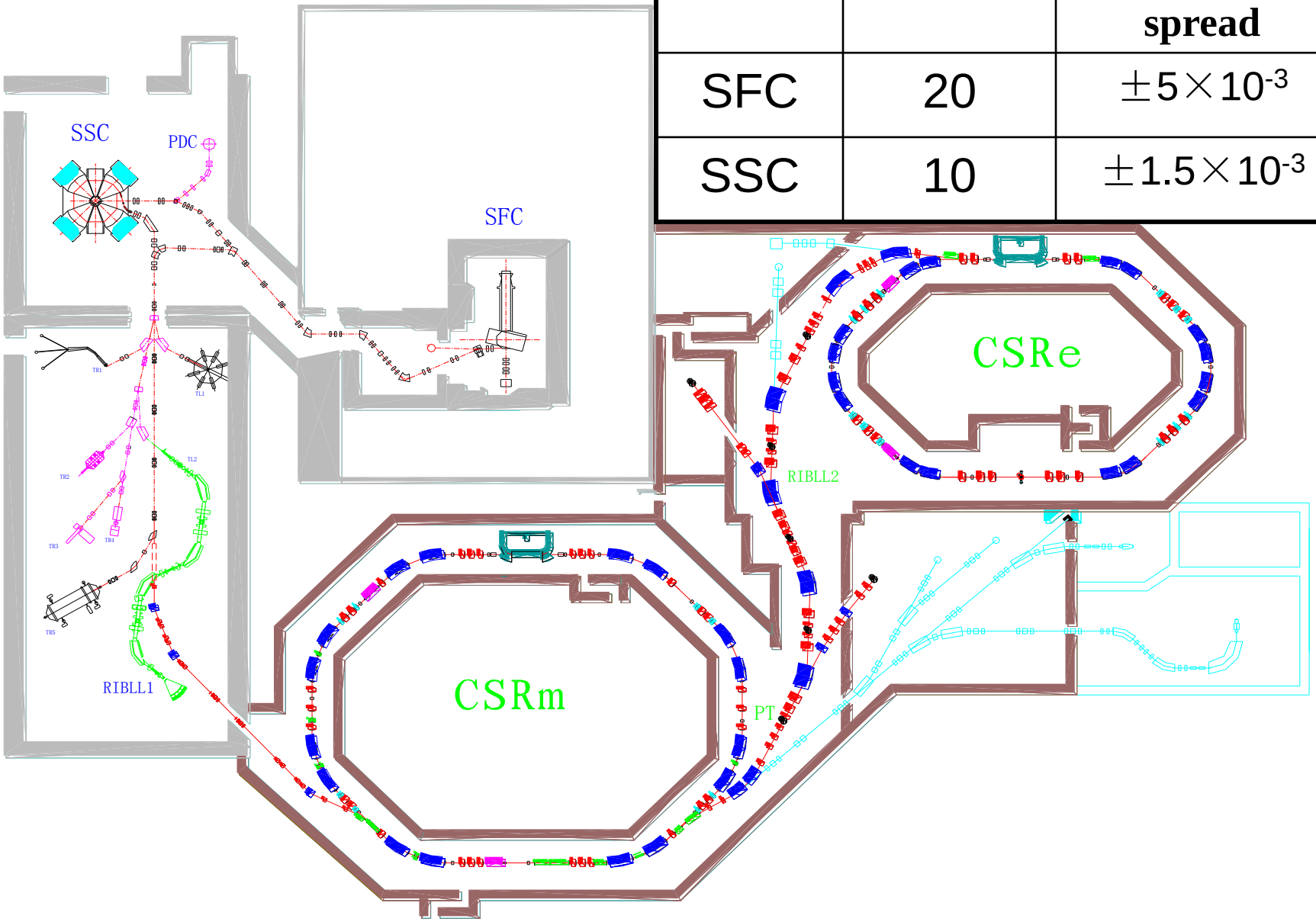
- CSR introduction
- Electron Cooling Devices
- Ion Beam Accumulation in CSRm
- Ion Beam Cooling in CSRe
- The influence of magnetic field in toroid on the longitudinal cooling force and time
- Upgrade of Cooler in CSRm

HIRFL-CSR Layout

	Emittance	Momentum spread
SFC	20	$\pm 5 \times 10^{-3}$
SSC	10	$\pm 1.5 \times 10^{-3}$



Main parameters of CSR

	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)

CSR Cooling Devices

Milestones about CSR Coolers

- 1996 Dubna COOL96 get the help from Igor Meshkov
- 1999 Novosibirsk, Contract
- 2002-9-25 35kV Cooler test finished in BINP
- 2003-3-15 35 kV Cooler test finished in IMP
- **2003-9-15 300kV Cooler test finished in BINP**
- **2004-5-6 300kV Cooler test finished in BINP**
- 2006-12-7 First cooling observed in CSRm
- 2006-12-27 First beam accumulation in CSRm
- **2009-4-20 First beam Cooling in CSRe**

Xiaodong Yang visited Dubna JINR in 1996

Delegation from IMP visited Novosibirsk BINP in 1999

HIRFL-CSR
Electron Cooling Devices

CSRm

Accumulation of heavy ion

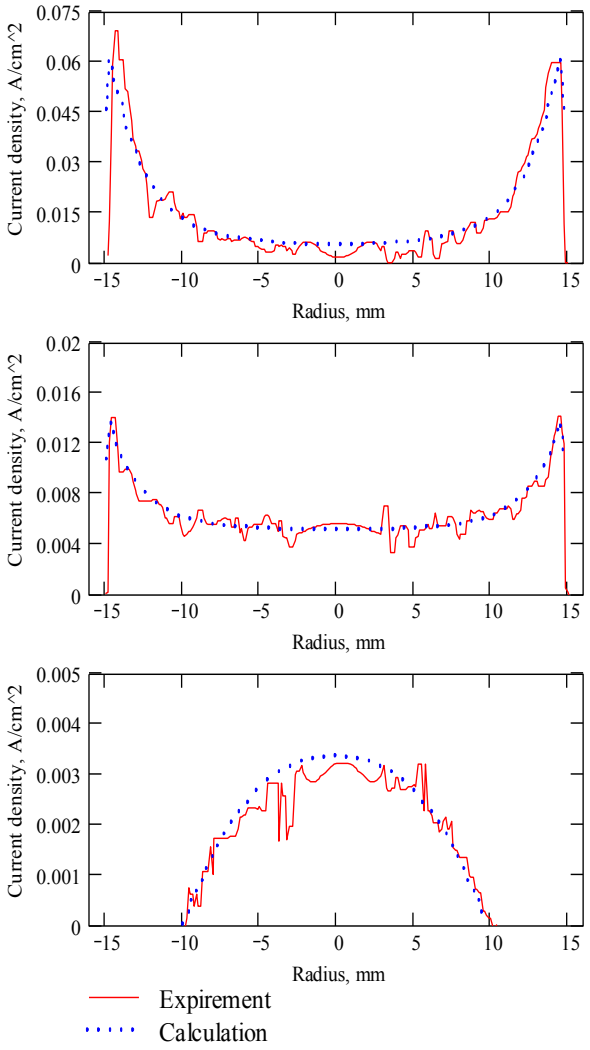
(Increase the phase space intensity)

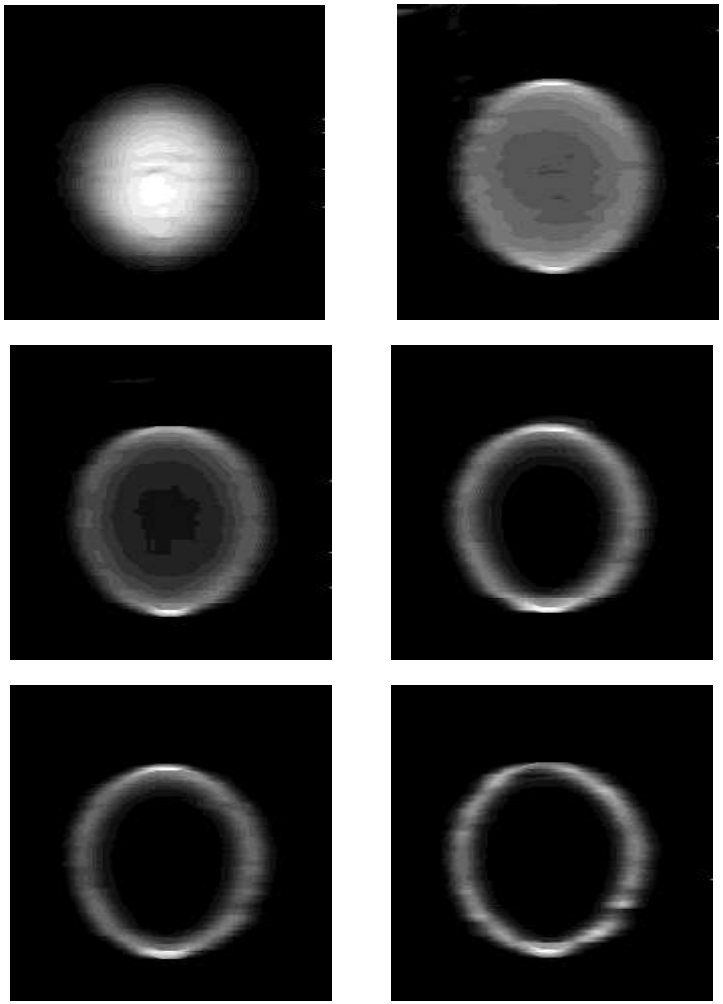
CSRe

1. **Provide high precision, high resolution heavy ion beam**
2. **Improve the quality of ion beam**
3. **Counteract scattering due to gas target**

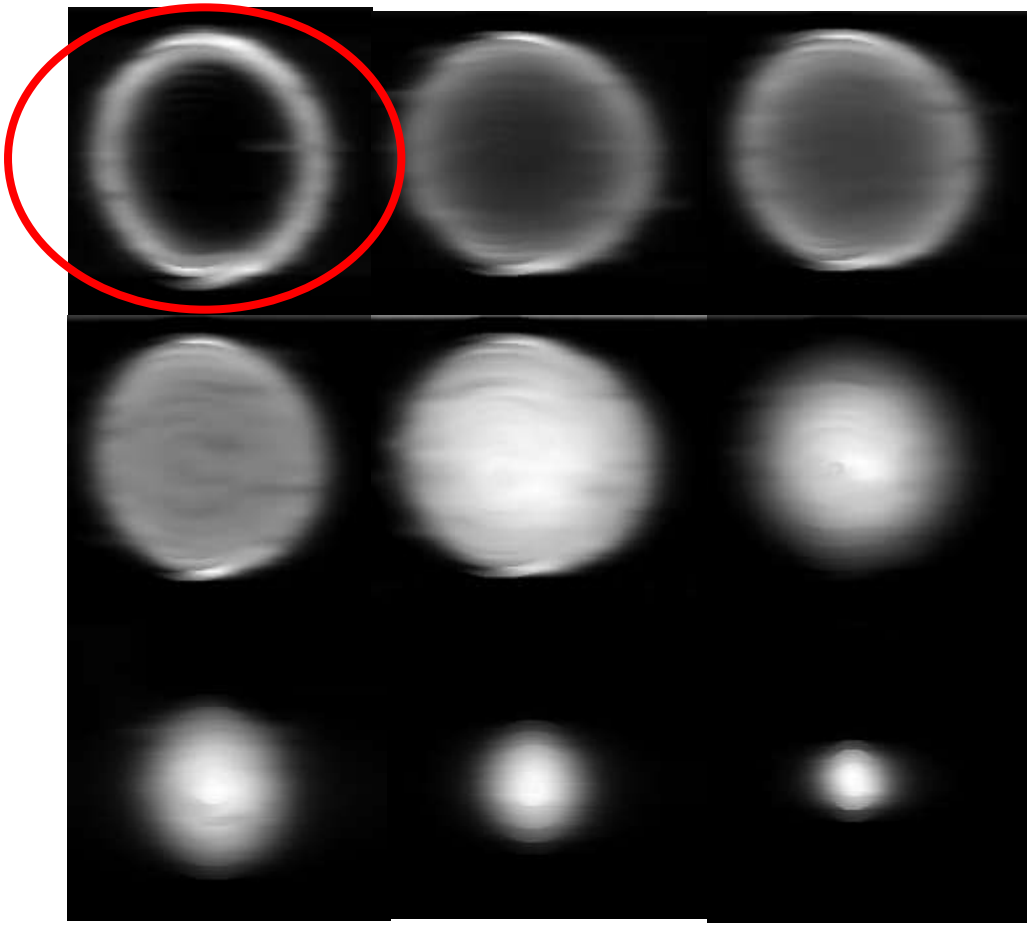
	CSRm		CSRe
E-cooler			
Electron energy (KeV)	35		300
Eff. cooling length (m)	3.4		3.4
RF system	Accel.	Accum.	Deceleration
Harmonic number	1	16, 32,64	1
f_{min}/f_{max} (MHz)	0.24/1.81	6.0 / 14.0	0.4 / 2.0
Voltages (n × kV)	1 × 7.0	1 × 20.0	2 × 10.0
Vacuum (mbar)	(3.0×10^{-11})		

Electron beam profile





Hollow electron beam



Distribution of electron beam

CSRm Electron cooling device

Parameters of cooler in CSRm

- Electron energy 4-35kV
- Cathode diameter 29.0mm
- Maximum electron current 3.0A
- Magn. expansion factor 1-4
- Vacuum pressure $\leq 3 \times 10^{-11}$mbar
- Gun magnetic field 1250Gauss
- Cooling section field 375Gauss
- D electron beam in cooling section 53mm

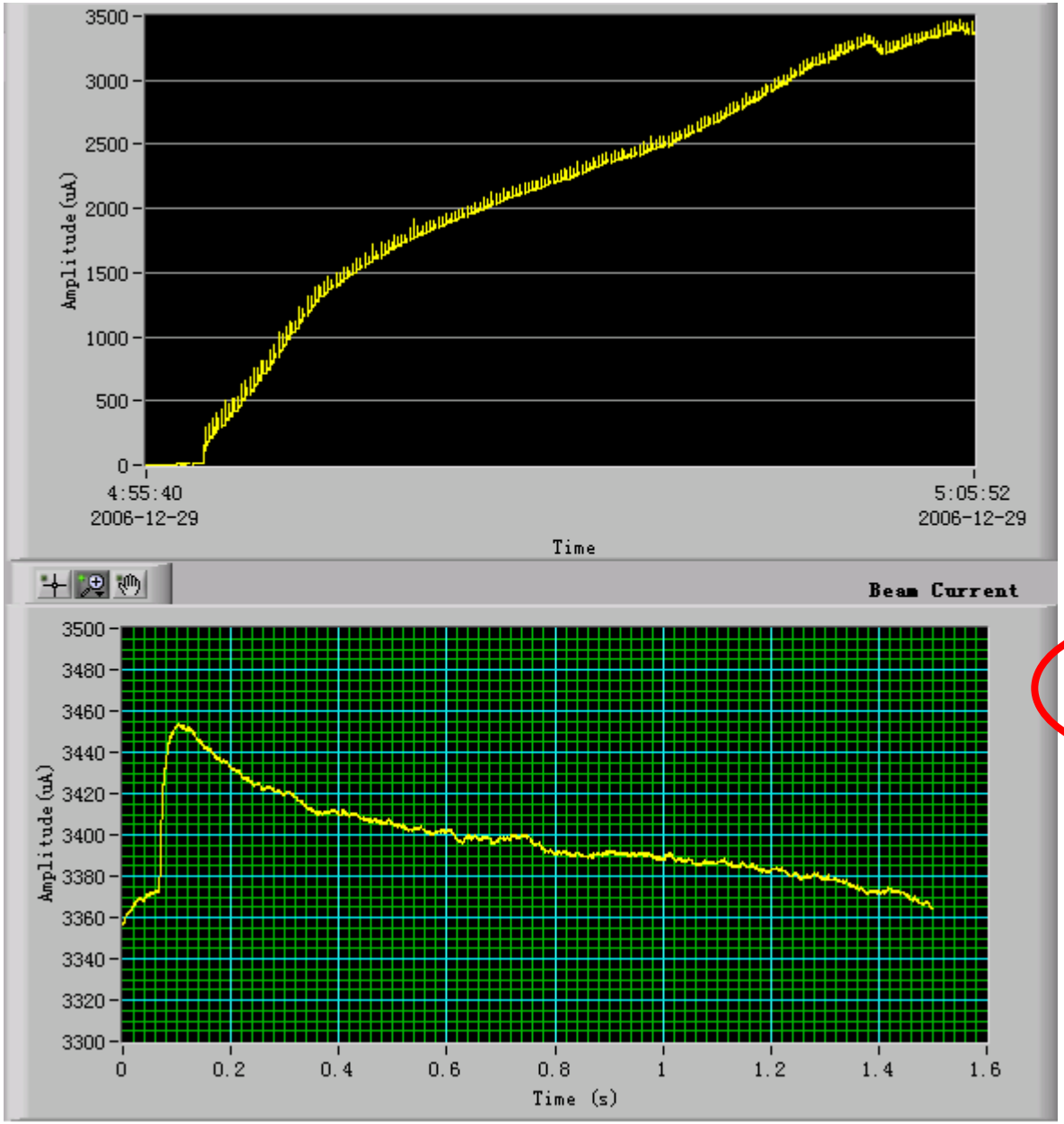
CSRe Electron Cooling device

Parameters of CSRe electron cooler

Item	value
Maximum electron energy	**300keV**
Maximum electron beam current	**3A**
Gun perveance	**29μP**
Cathode diameter	**29mm**
Current collection efficiency	⩾99. 99%
Maximum magnetic field in Gun section	**0.5T**
Maximum magnetic field in cooling section	**0.15T**
Field parallelism in cooling section	**$4*10^{-5}$**
Effective length of cooling section	**3.4m**
Vacuum pressure	$\leqslant 3*10^{-11}$mbar

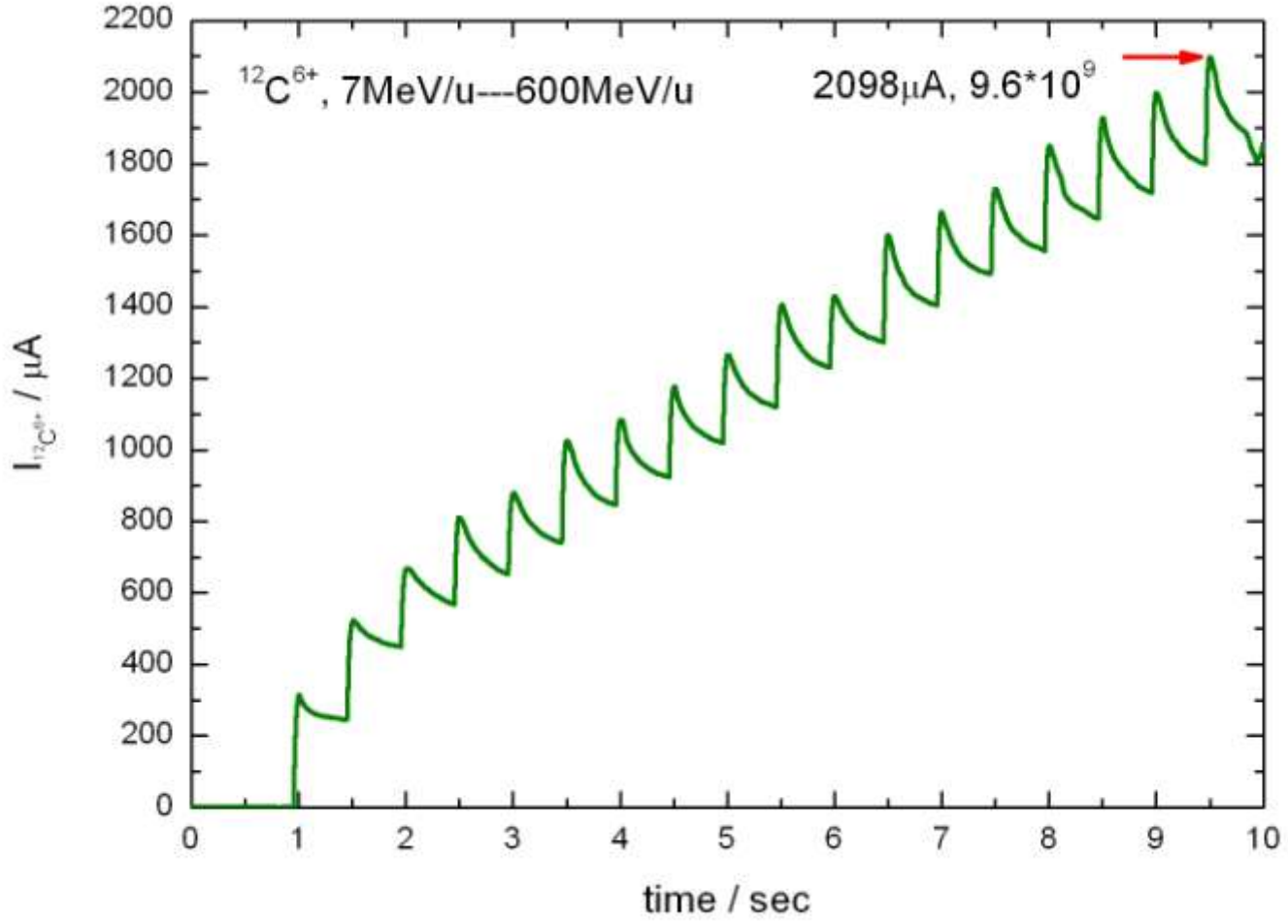
CSRm Results

Beam Accumulation

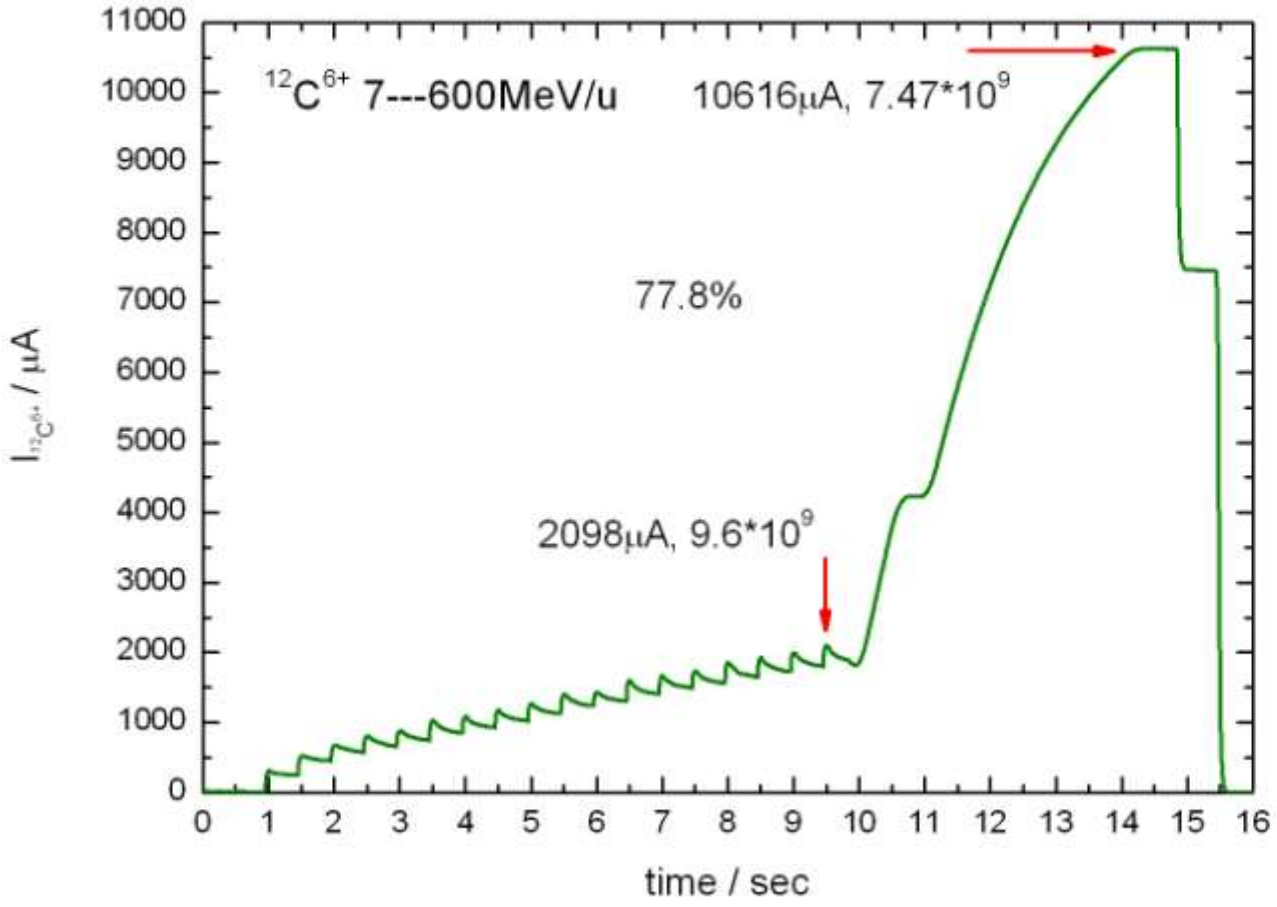


$1.59*10^{10}$

Beam accumulation in 10minutes in 2006

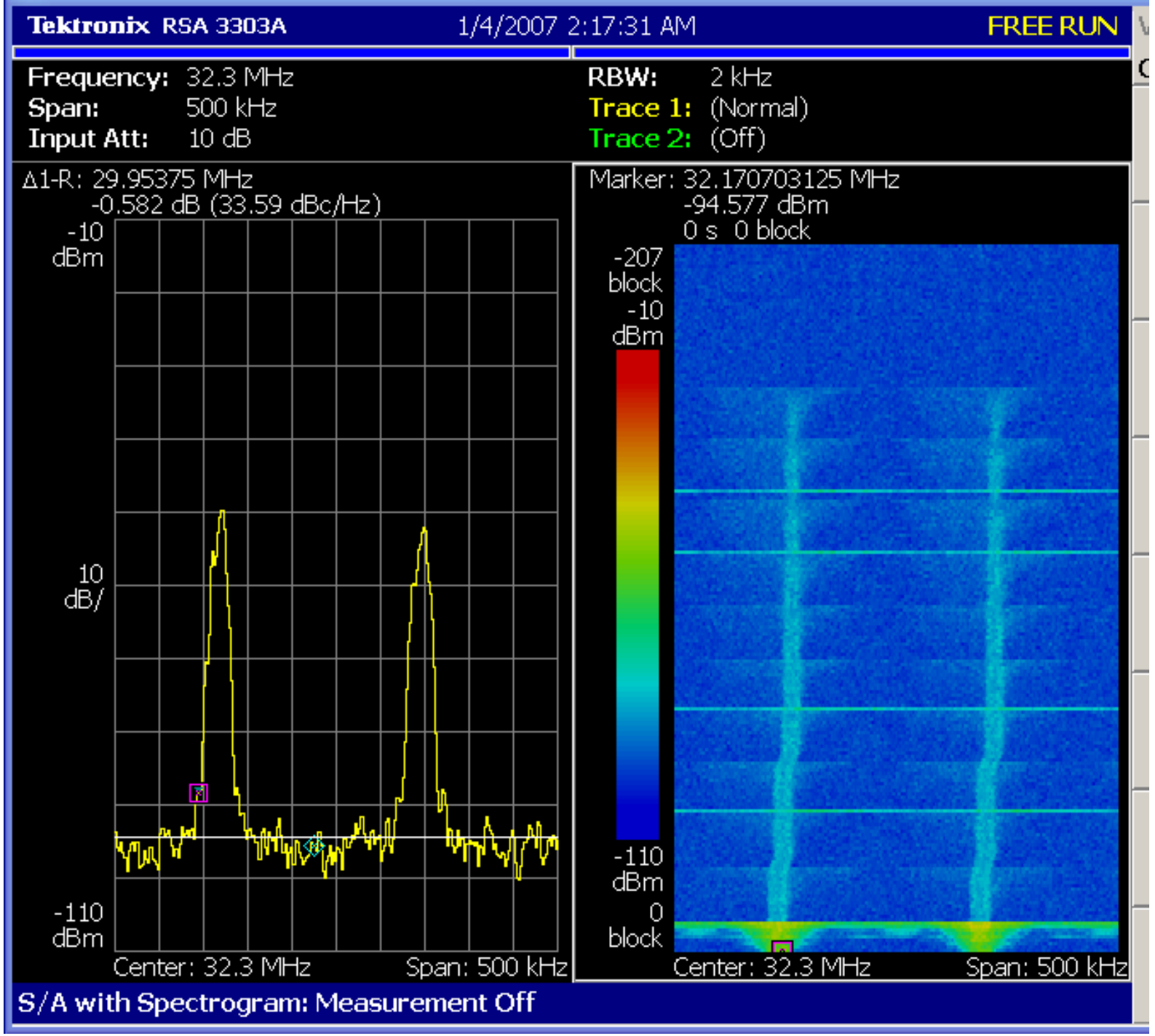


$^{12}C^{6+}$ Accumulation in 10 sec

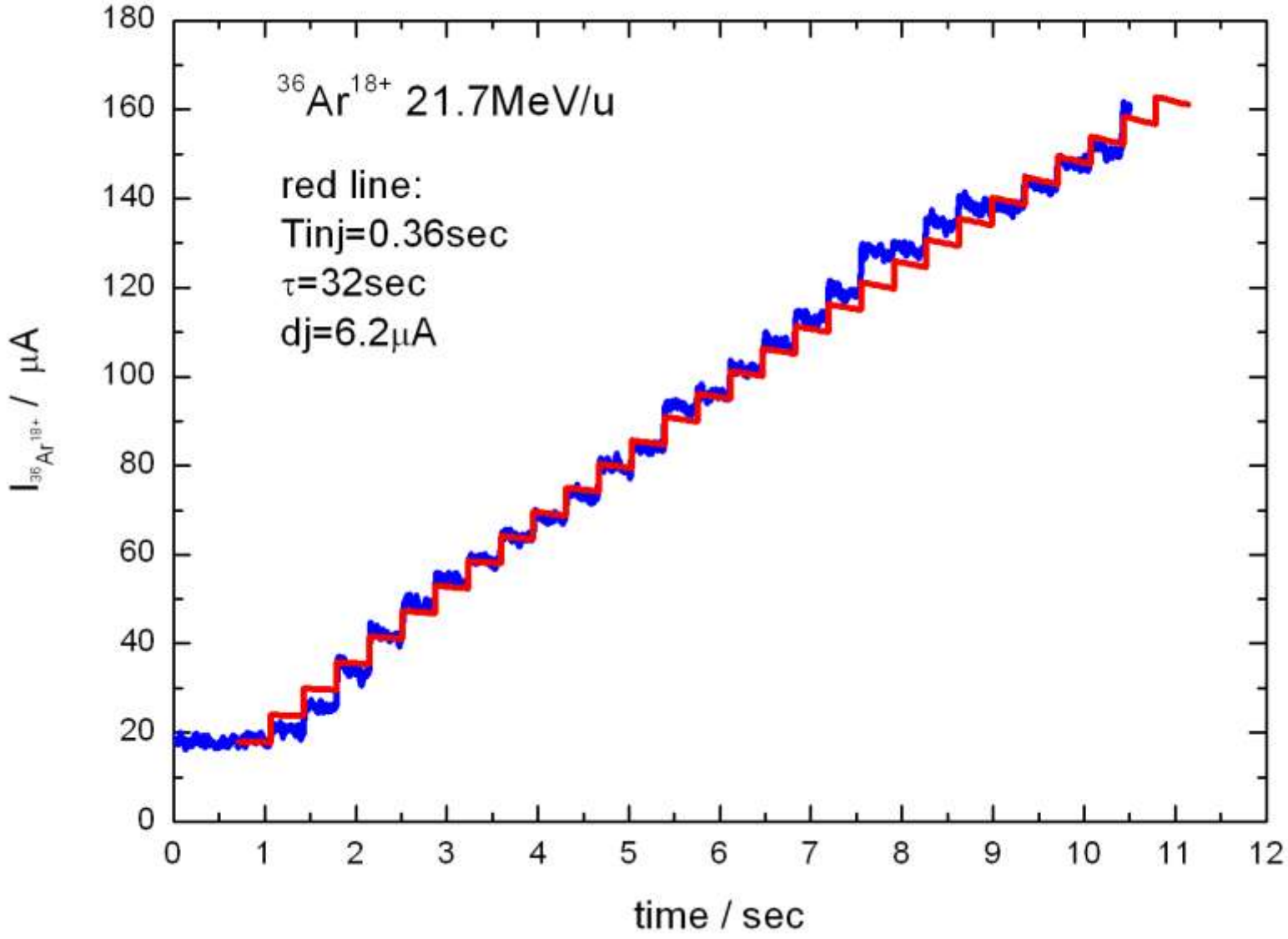


$^{12}C^{6+}$ 7MeV/u---600MeV/u

Accumulation, Cooling and Acceleration



Beam accumulation in CSRm



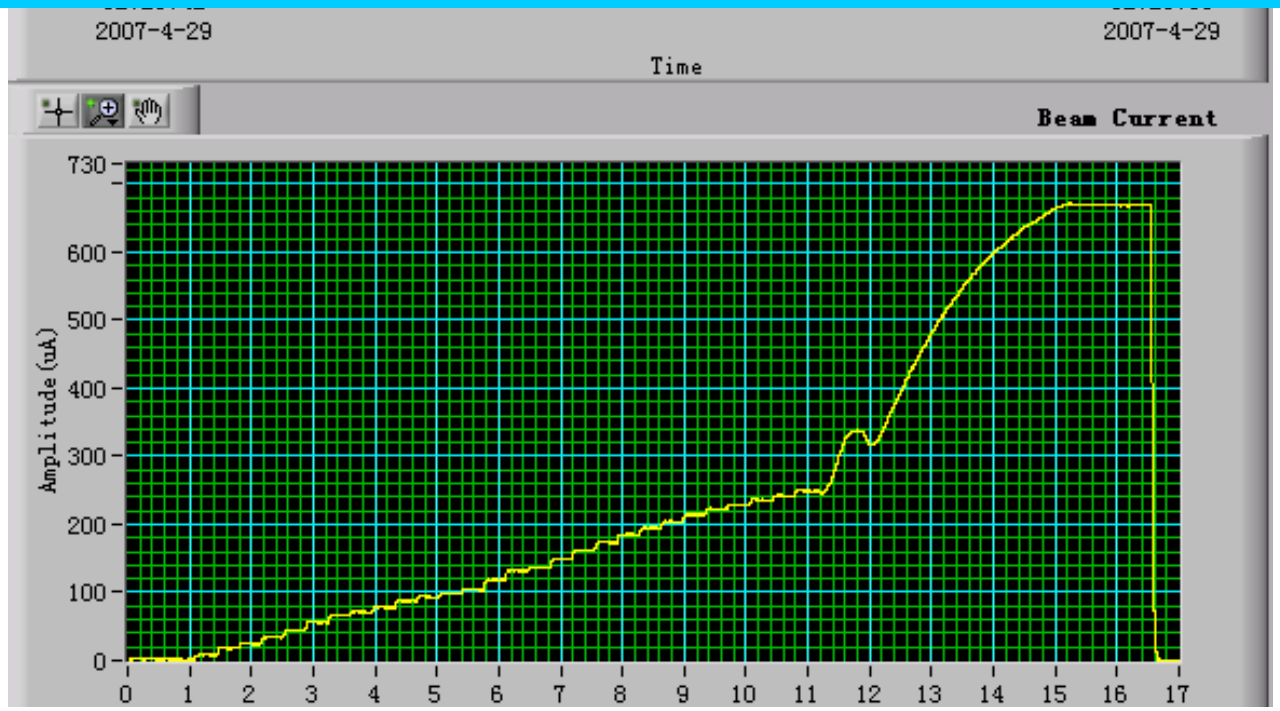
Repeated Multiturn injection SSC ε=10πmmmrad

NIM-A441(2000) 175-182

Accumulation rate=the increase of circulating current per unit of time divided by the current in the injection line to the synchrotron

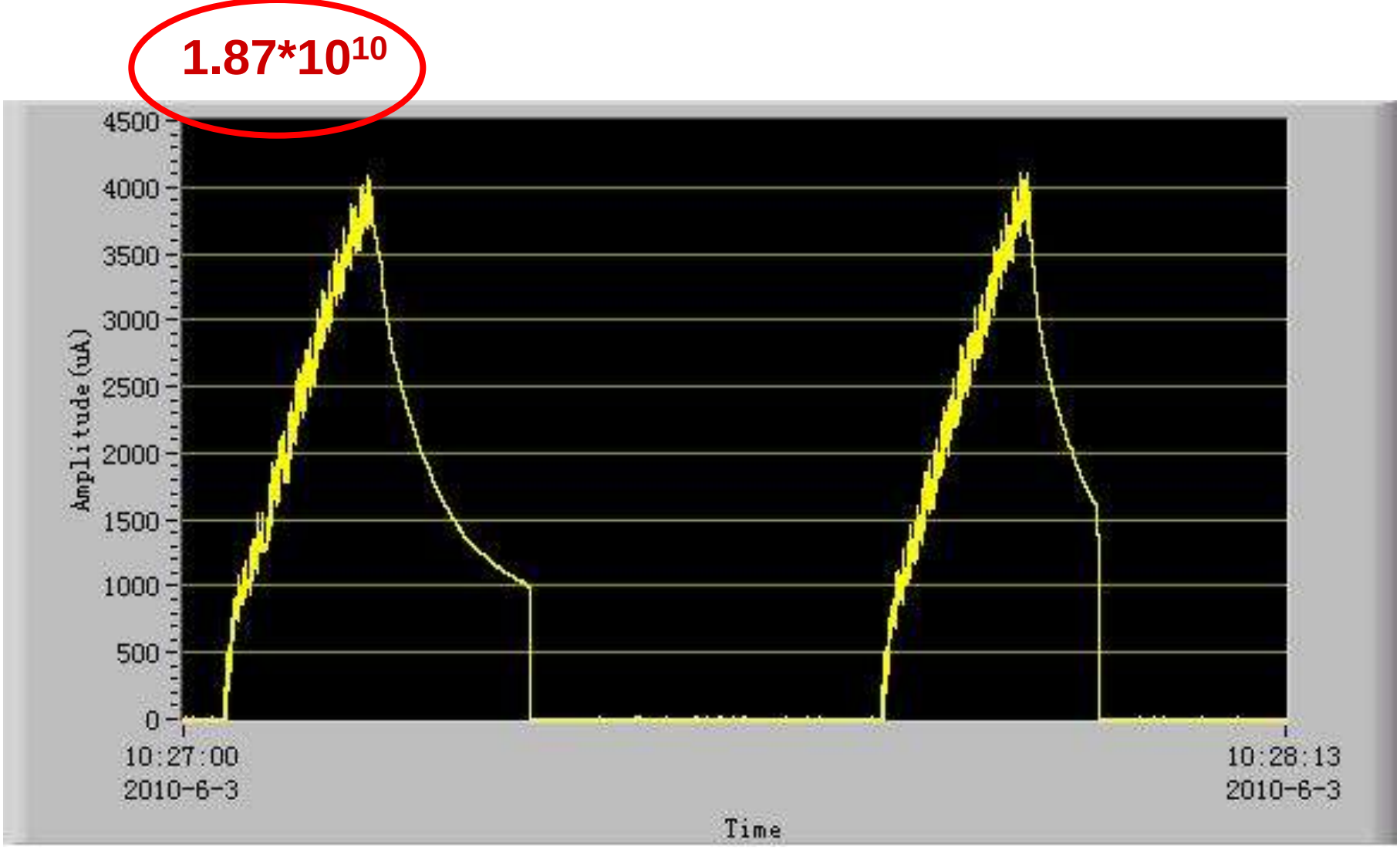
Accumulation rate=250μA/10second/4μA=6

It seems slightly bigger than the maximal value 5 in Figure 4 and 5 of the reference!



250μA
in 10 seconds

Best result of $^{36}Ar^{18+}$ accumulation and acceleration to 600MeV/u



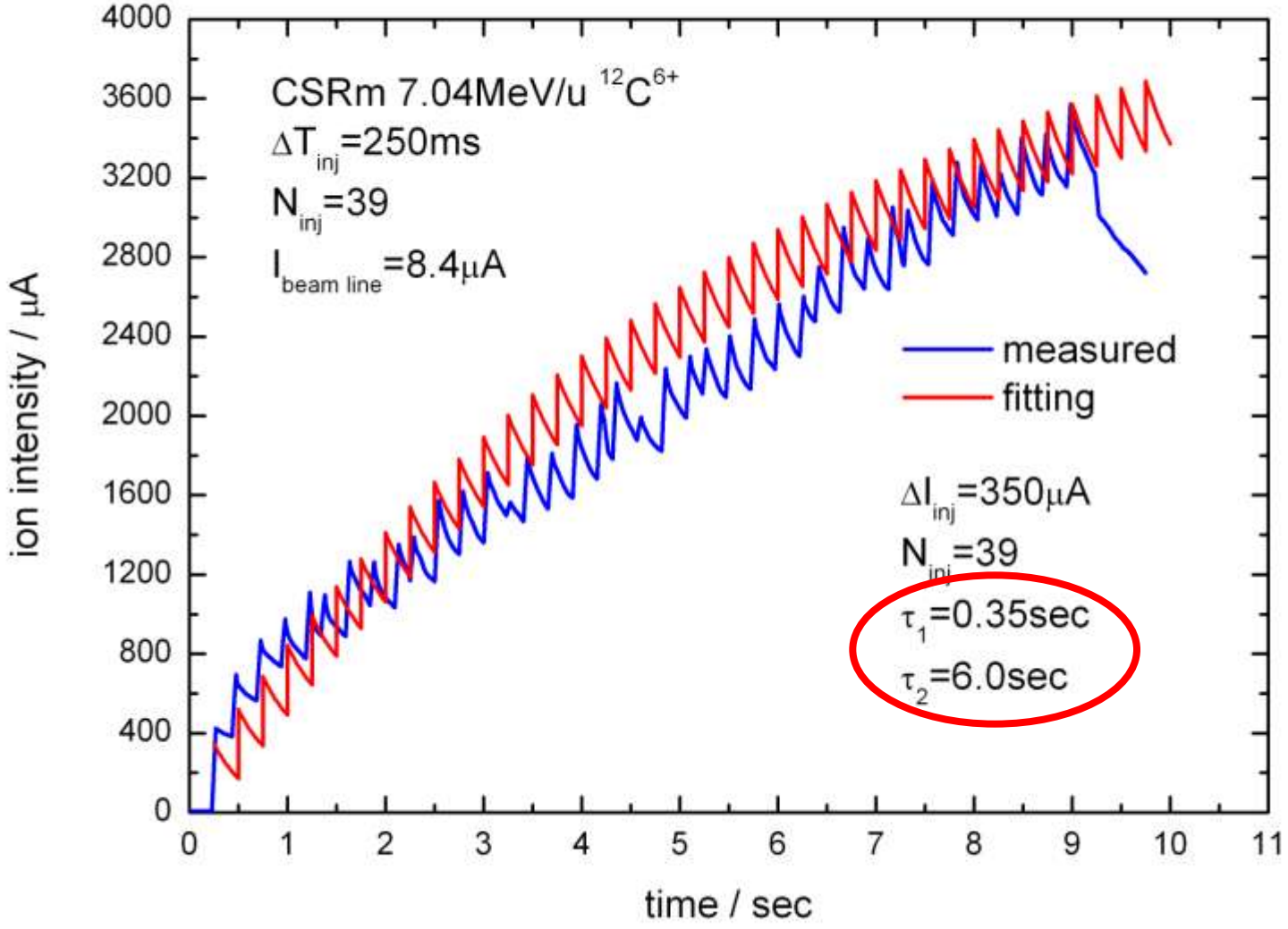
$^{12}C^{6+}$ Accumulation in 10 sec in CSRm in 2010

CSRm Accumulation results

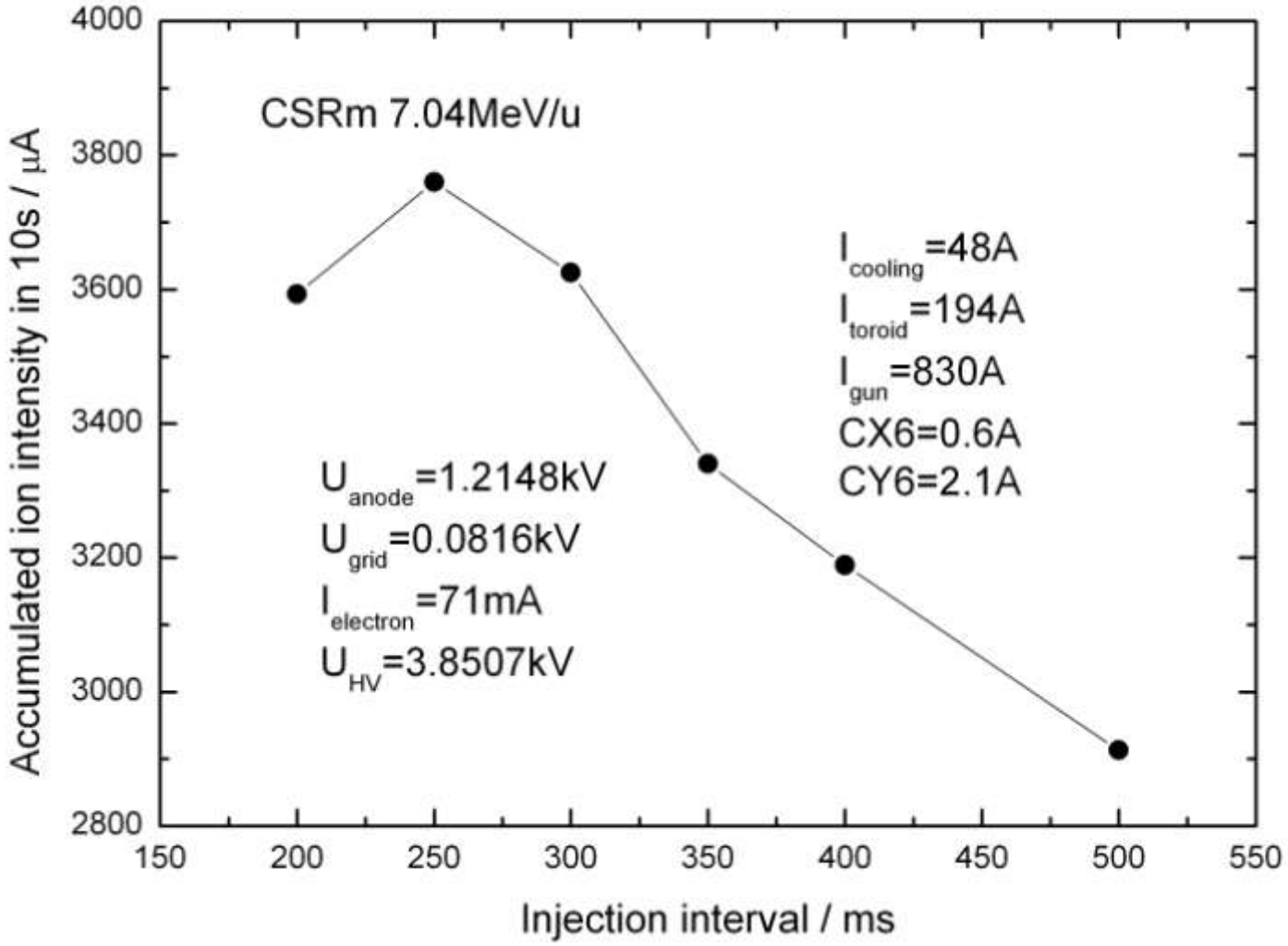
Ion	E (MeV/u)	Mode	foil ($\mu g/cm^{2}$)	$T_{injection}$ (Sec)	I_{inject} (μA)	I_{single} (μA) max	I_{10sec} (μA) max	Long time (μA)	Lifetime in EB (sec)
$^{12}C^{6+}$	7.09	Strip	15	1	10~12	167	700	3500	255(70mA)
$^{12}C^{4+}$	7.10	MI		1	4.4~6	20	105	120	27.7(124mA)
$^{36}Ar^{18+}$	21.7	MI	350	0.35	4	6	250	435	554.7(97mA)
$^{129}Xe^{27+}$	2.9	MI		0.35	3	6.5	70	70	12(70mA)
$^{12}C^{5+}$	8.26	MI		0.9	3	11	70	90	16(151mA)
$^{78}Kr^{28+}$	4.04	MI	30	0.2	2.4	5	80	70	4.5(172mA)

CSRm Momentum spread

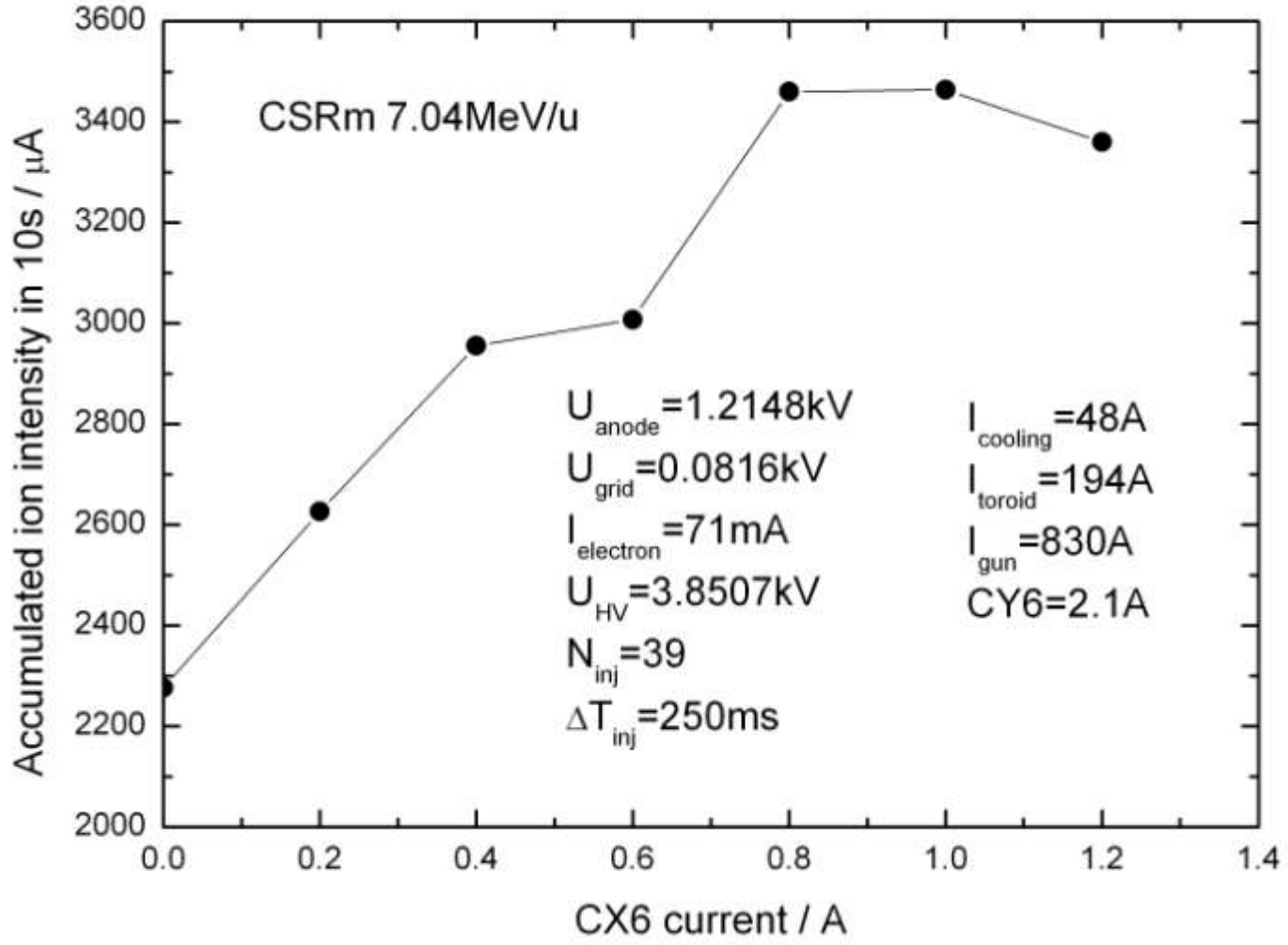
Ion	E (MeV/u)	Mode	ΔP/P injection	ΔP/P After accumulation	ΔP/P After acceleration
$^{12}C^{6+}$	7.09---1000	Strip	1.46×10^{-3}	3.94×10^{-3}	3.6×10^{-4}
$^{12}C^{4+}$	7.10---300	MI			
$^{36}Ar^{18+}$	21.7-1000	MI	6.98×10^{-4}	3.16×10^{-4}	2.5×10^{-4}
$^{129}Xe^{27+}$	2.9---235	MI		2.35×10^{-4}	1.84×10^{-4}
$^{12}C^{5+}$	8.26---100	MI		2.3×10^{-4}	1.3×10^{-4}
$^{78}Kr^{28+}$	4.04---205	MI		3.5×10^{-4}	1.4×10^{-4}



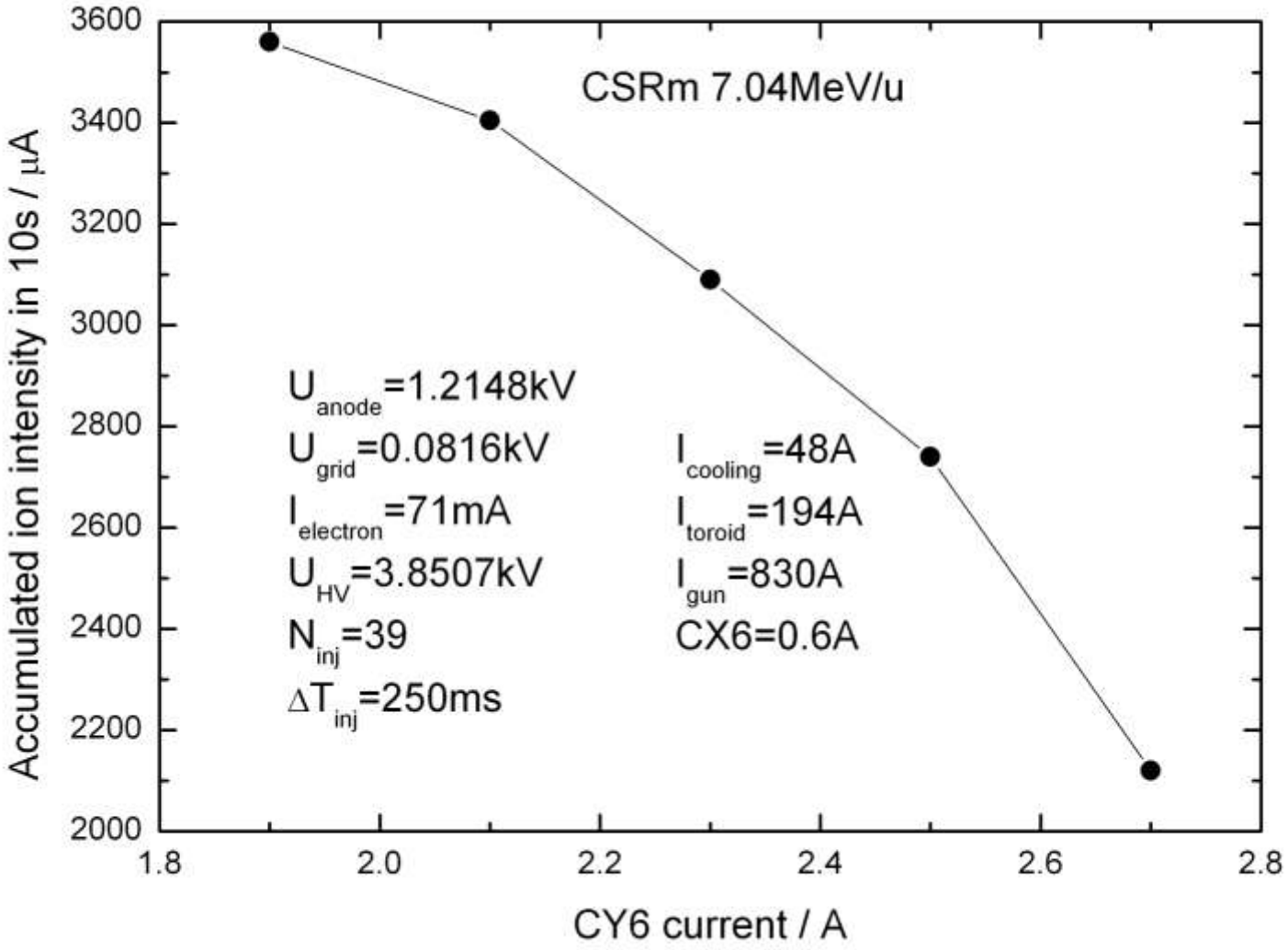
Two components fitting comparing with experimental data



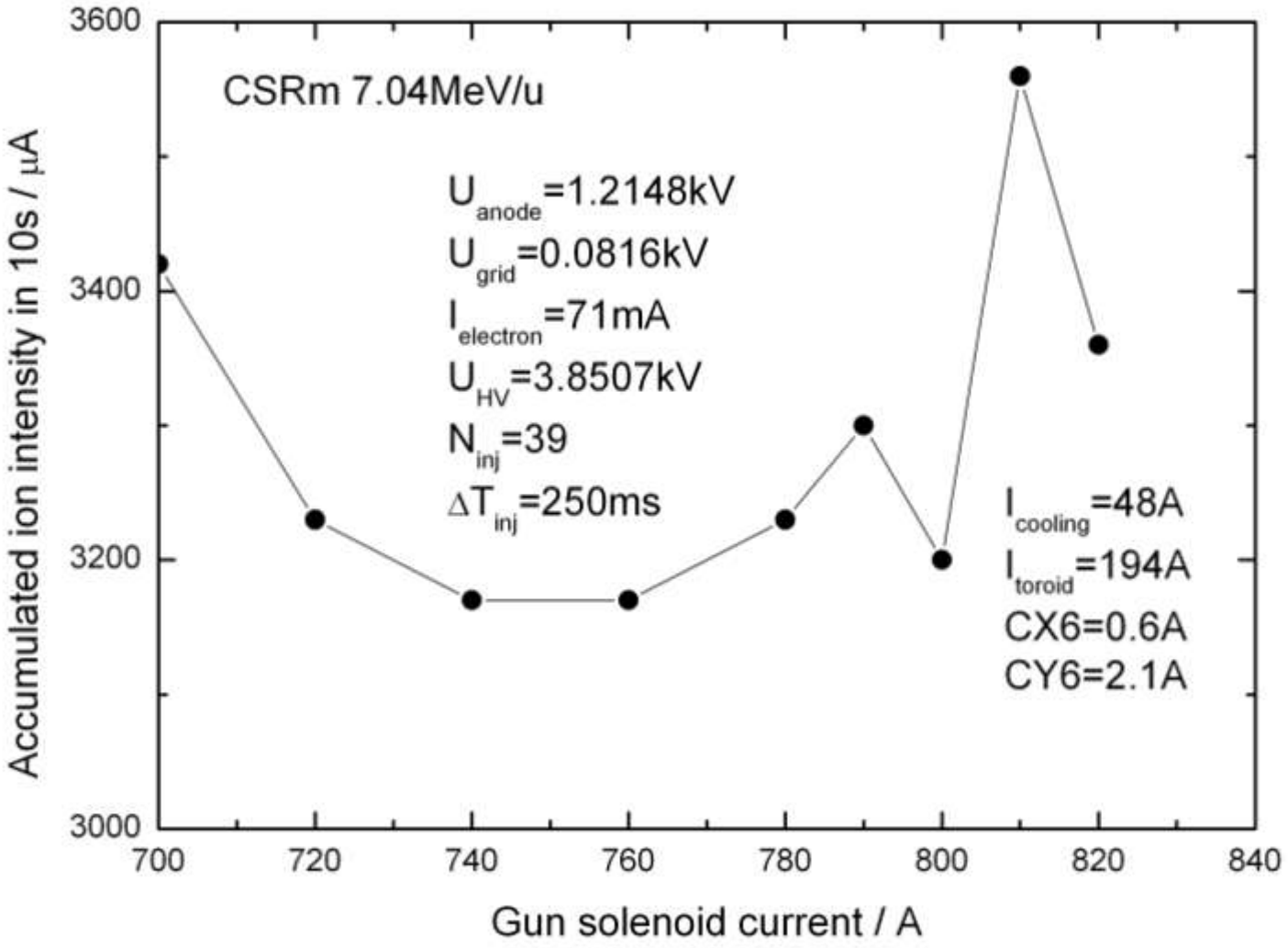
Accumulated ion intensity in 10s as a function of injection interval



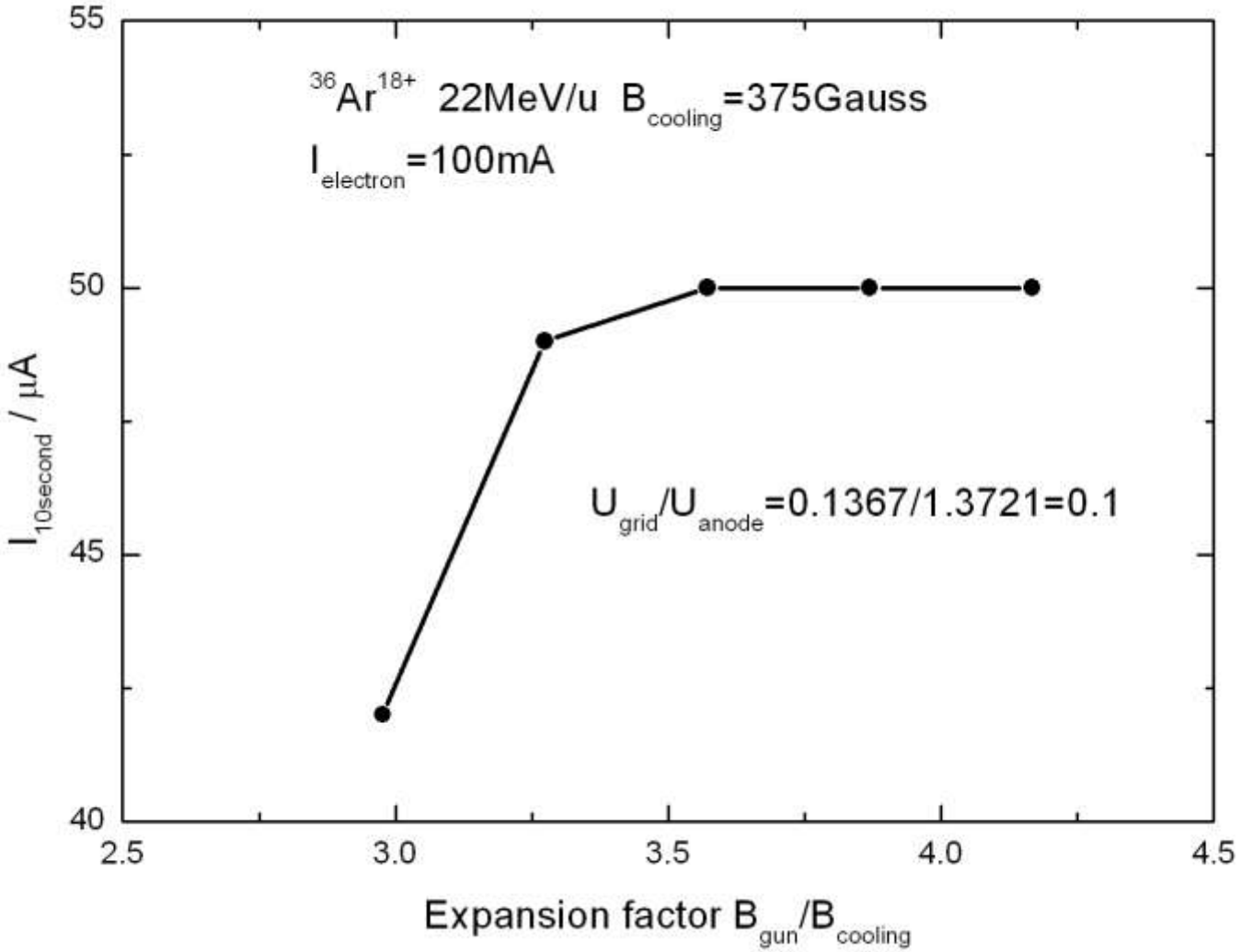
Accumulated ion intensity in 10s as a function of CX6 current

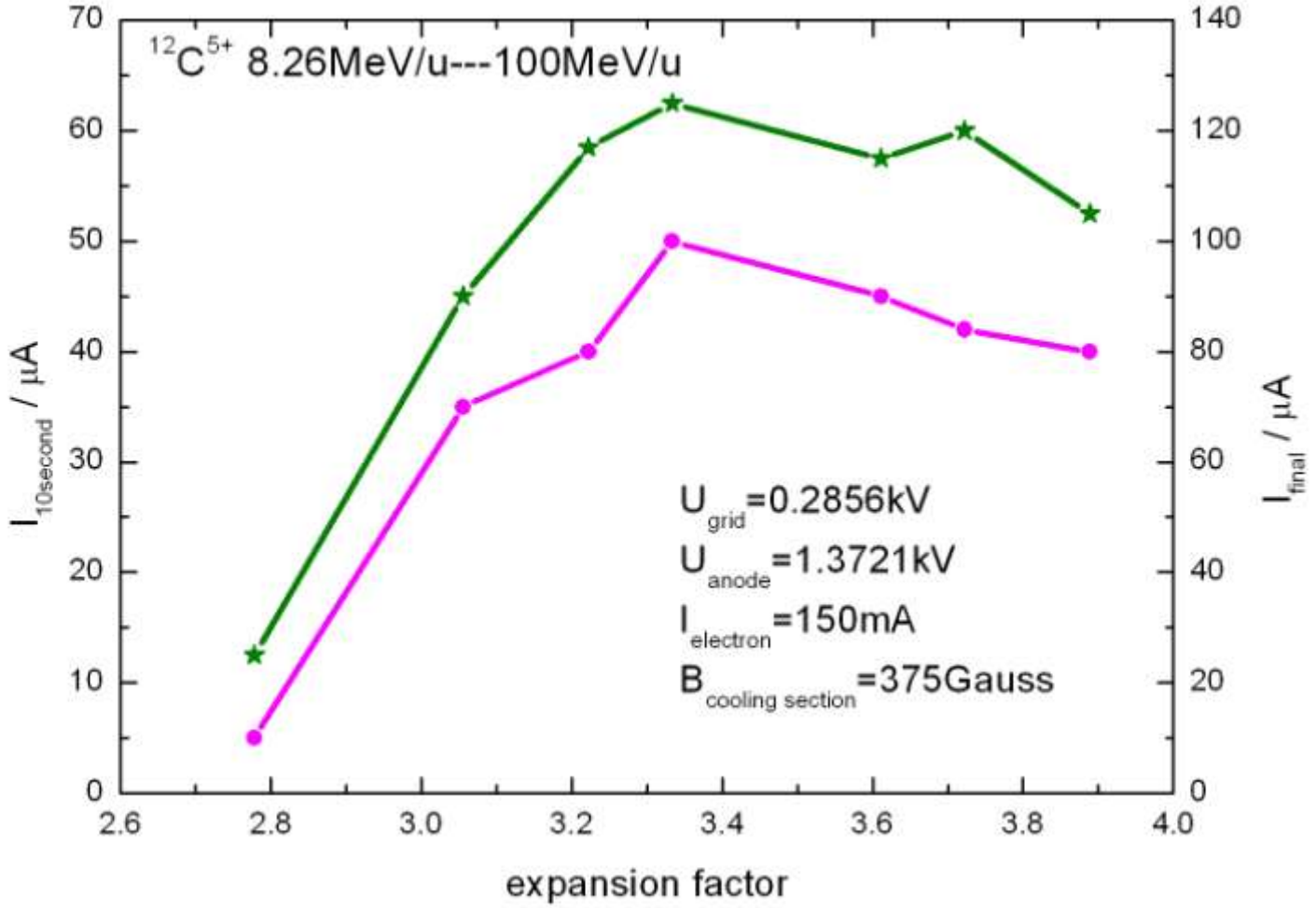


Accumulated ion intensity in 10s as a function of CY6 current



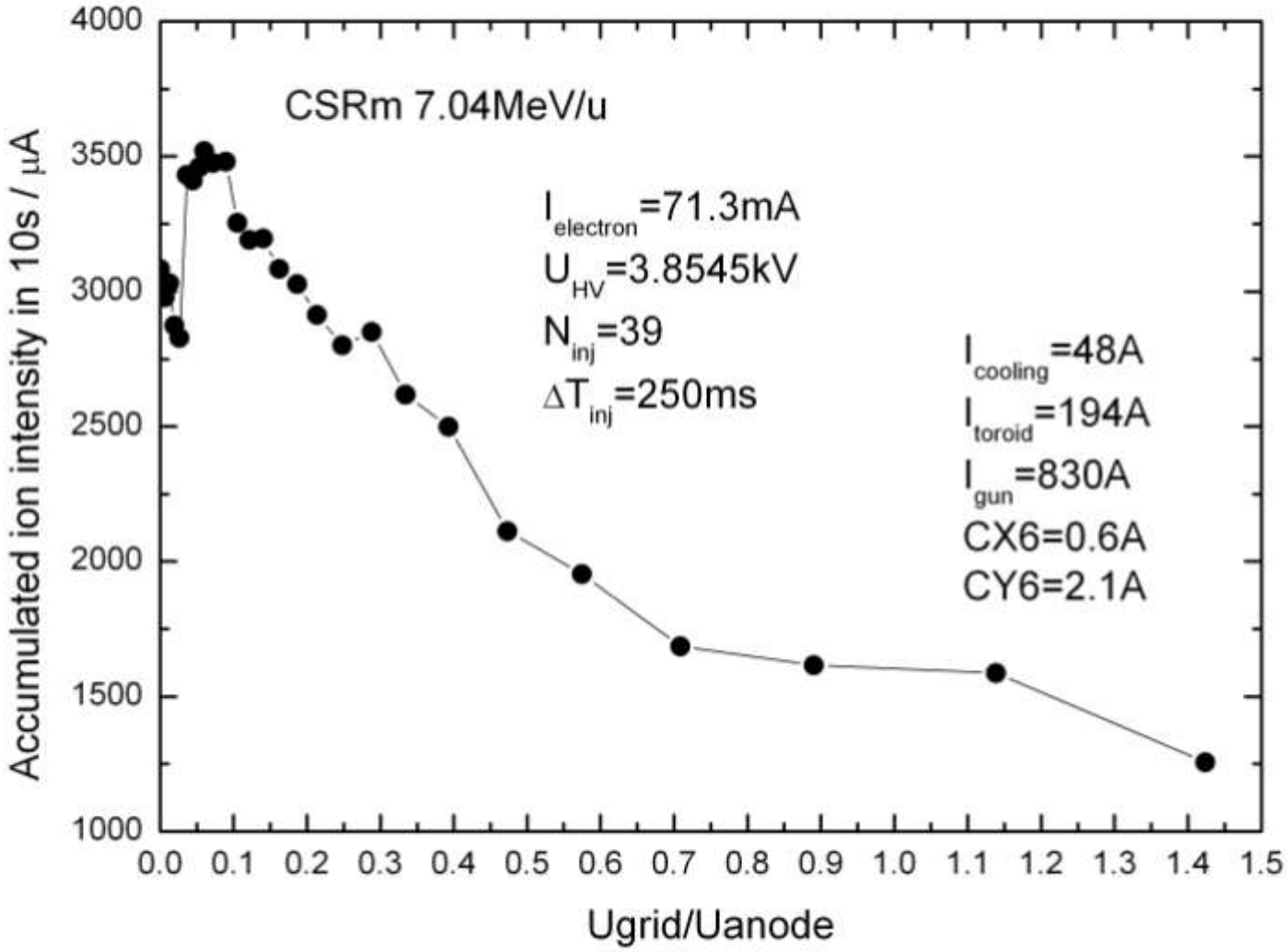
Accumulated ion intensity in 10s as a function of Gun solenoid current


$^{36}Ar^{18+}$ 22MeV/u $B_{cooling}$=375Gauss
$I_{electron}$=100mA
U_{grid}/U_{anode}=0.1367/1.3721=0.1
$I_{10second}$ / μA
Expansion factor $B_{gun}/B_{cooling}$
55
50
45
40
2.5
3.0
3.5
4.0
4.5

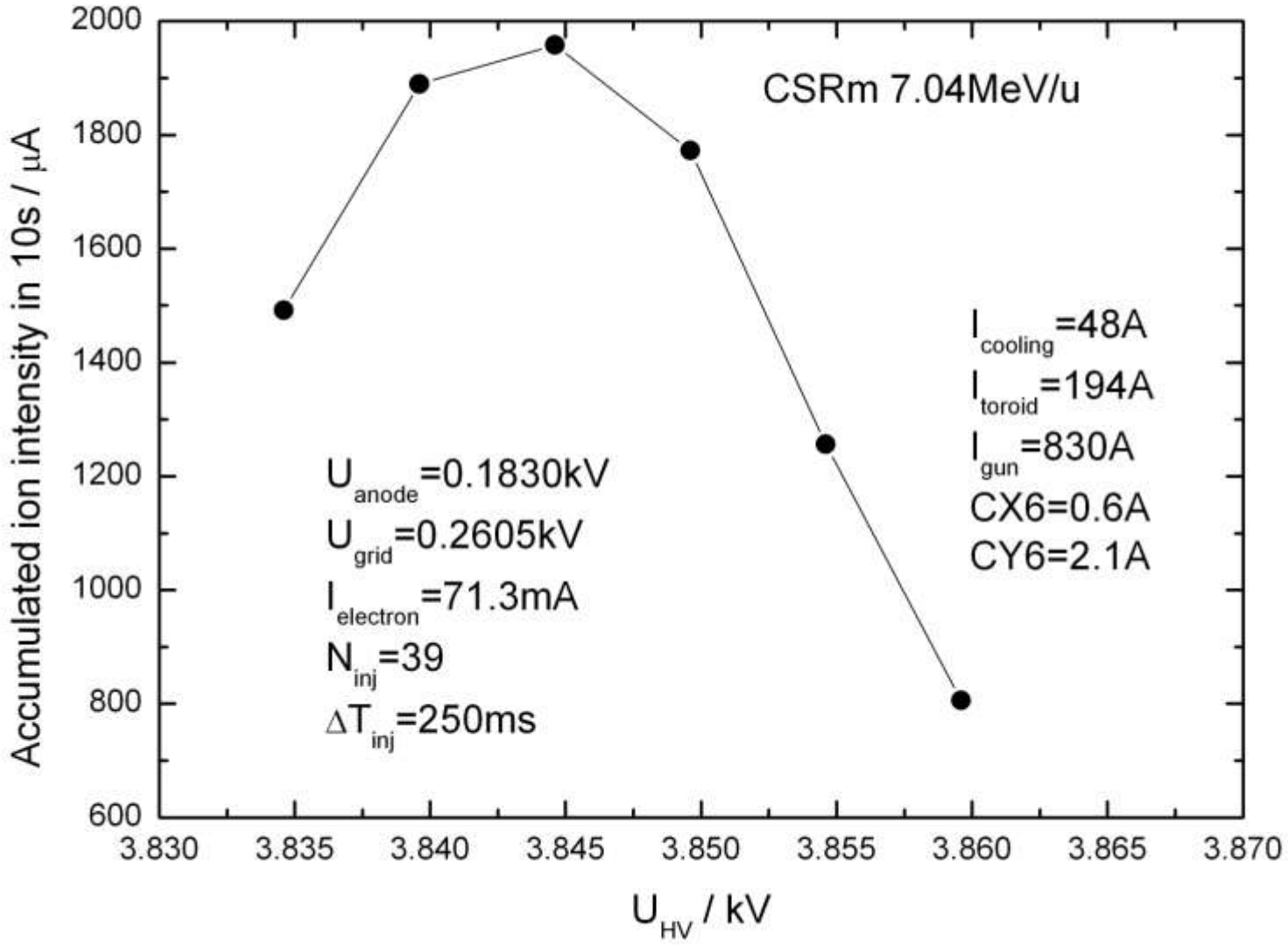


Expansion factor

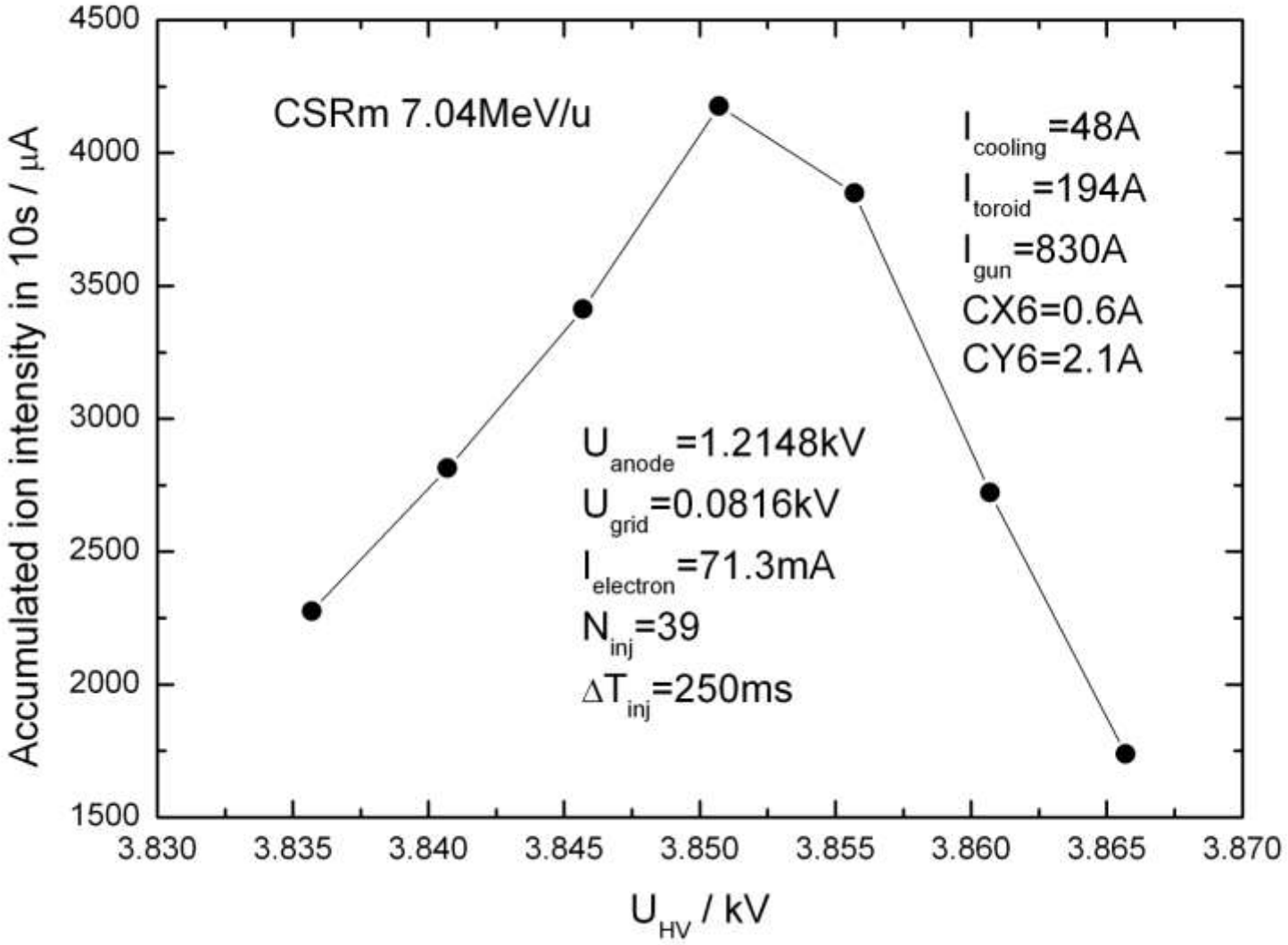
The electron beam current was fixed.
The density change due to expansion has not taken into account



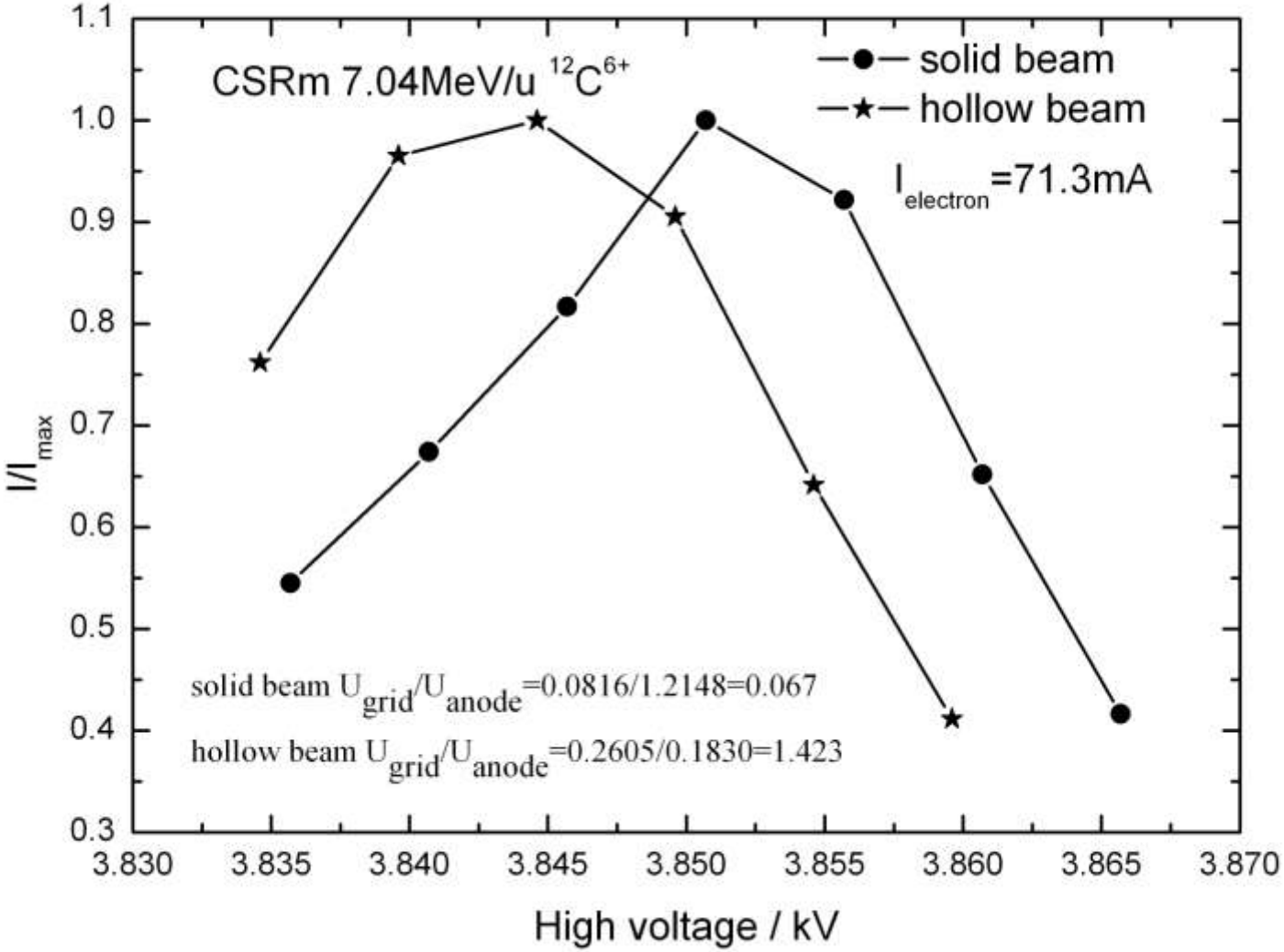
Accumulated ion intensity in 10s as a function of Ugrid/Uanode
The electron beam current and energy were kept fixed.



Accumulated ion intensity in 10s as a function of electron energy In the case of hollow electron beam



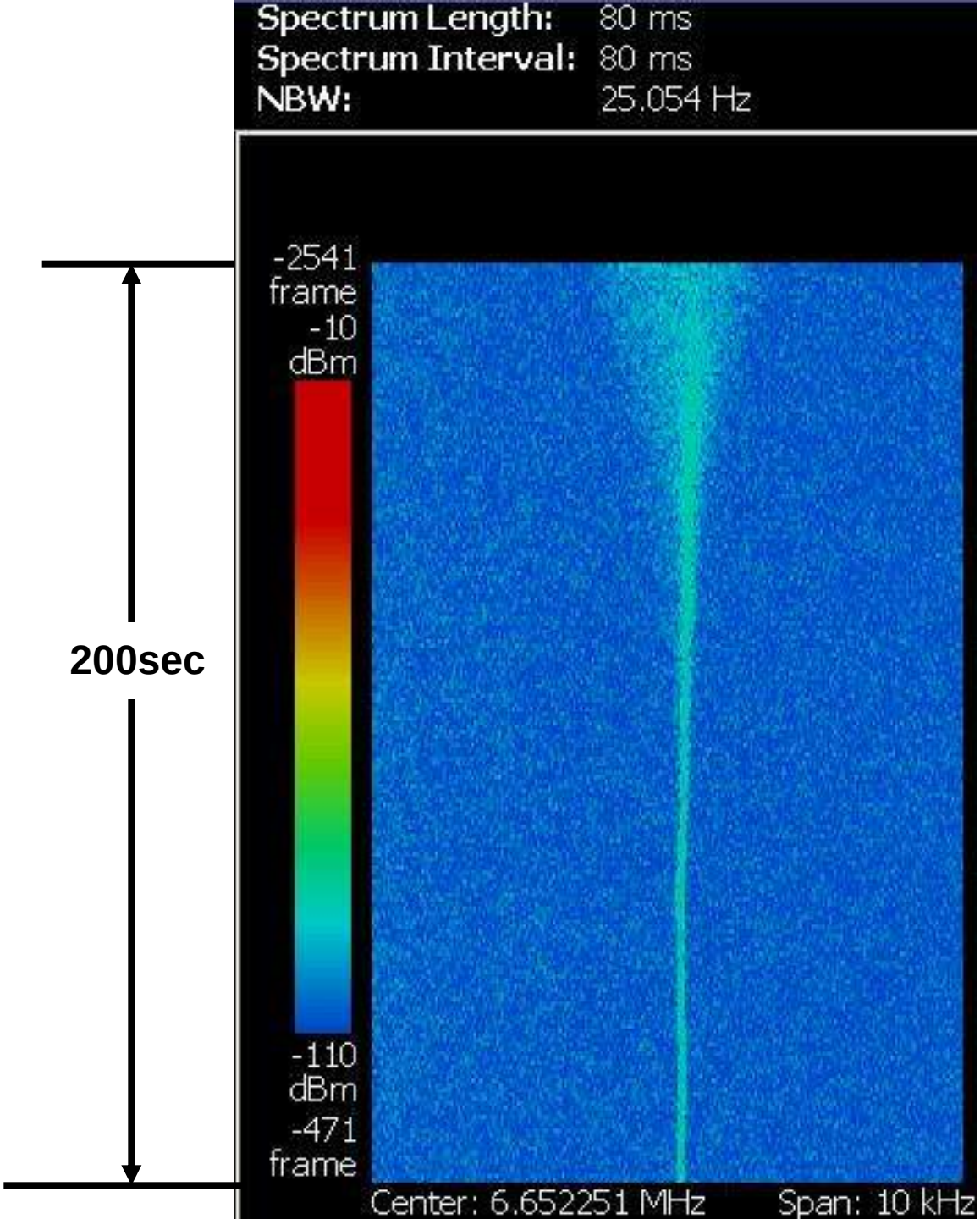
Accumulated ion intensity in 10s as a function of electron energy In the case of solid electron beam



Accumulated ion intensity in 10s as a function of electron energy In the case of hollow and solid electron beam

CSRe results

Beam Cooling

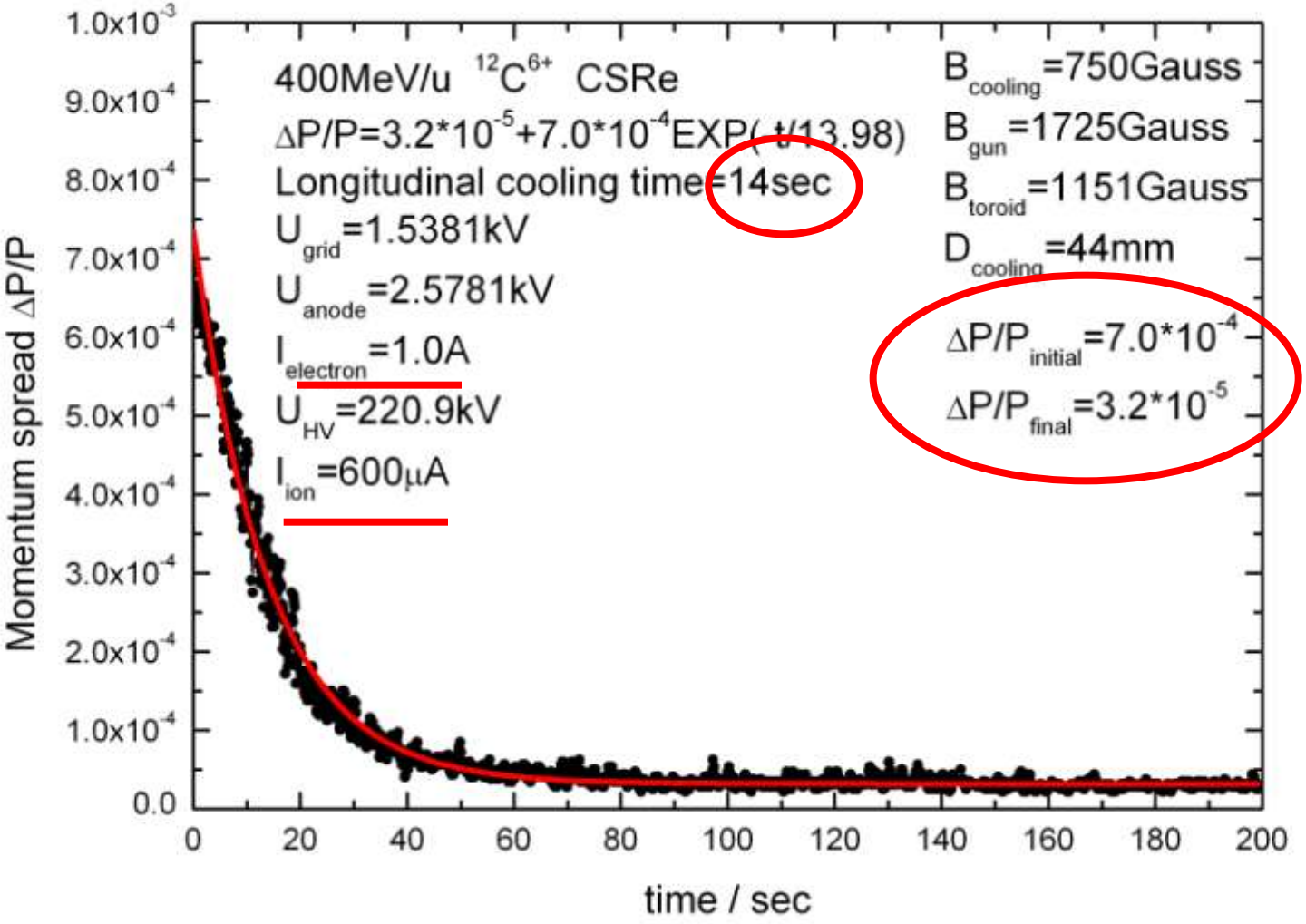


Schottky signal after fine tune the ion beam and electron beam.

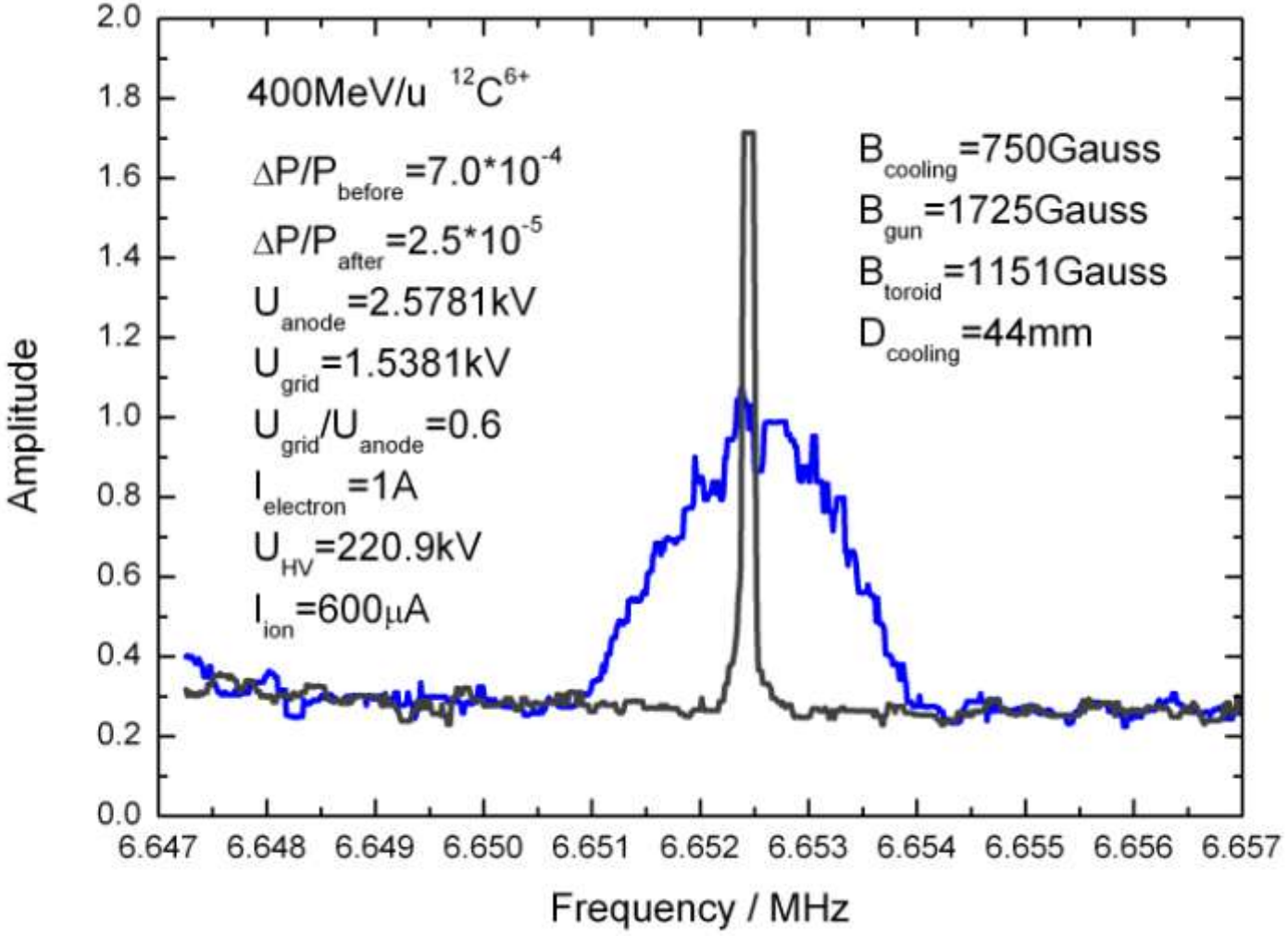
1. Magnetic field in toroid

2. Electron beam current

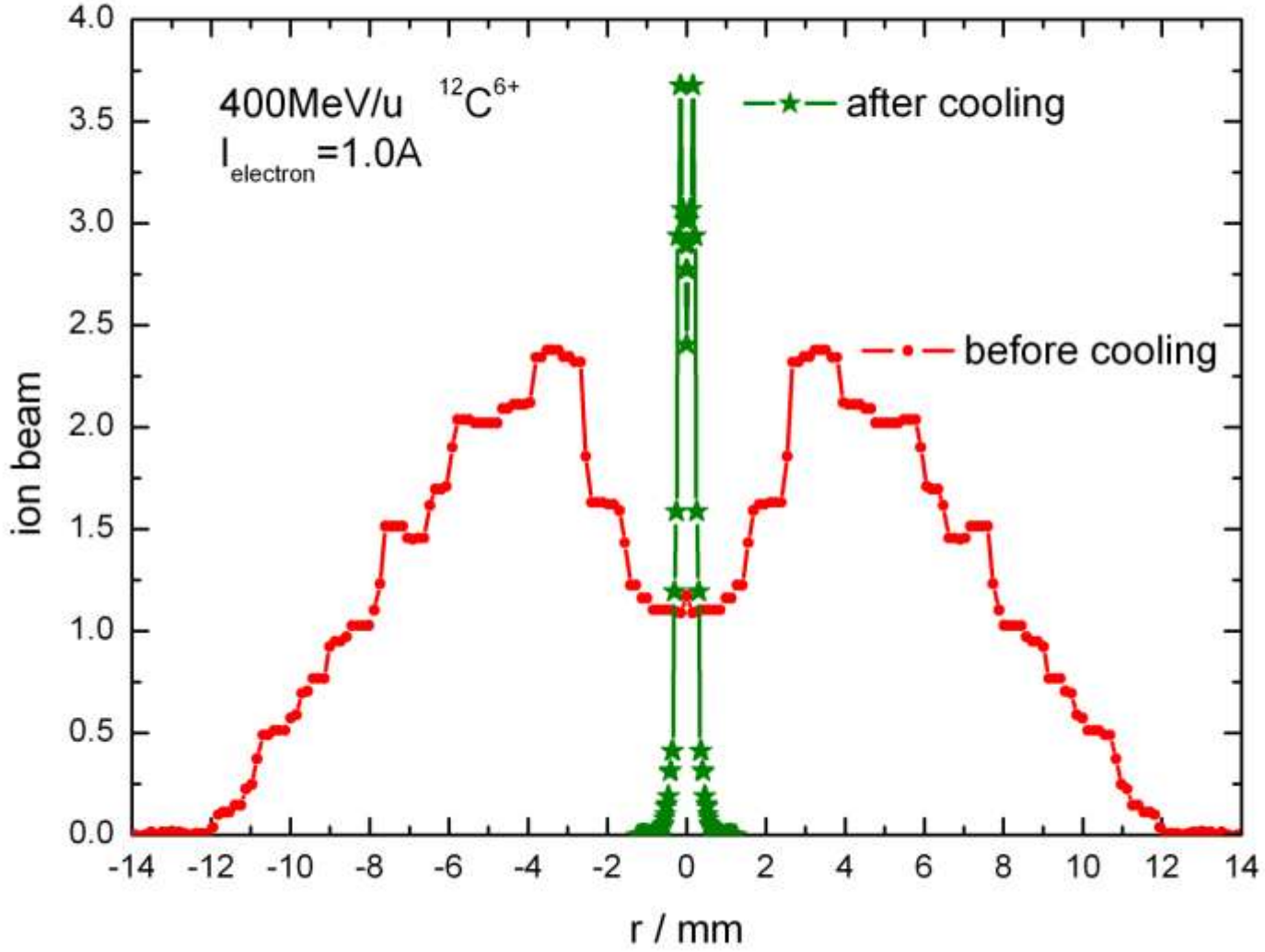
3. angle



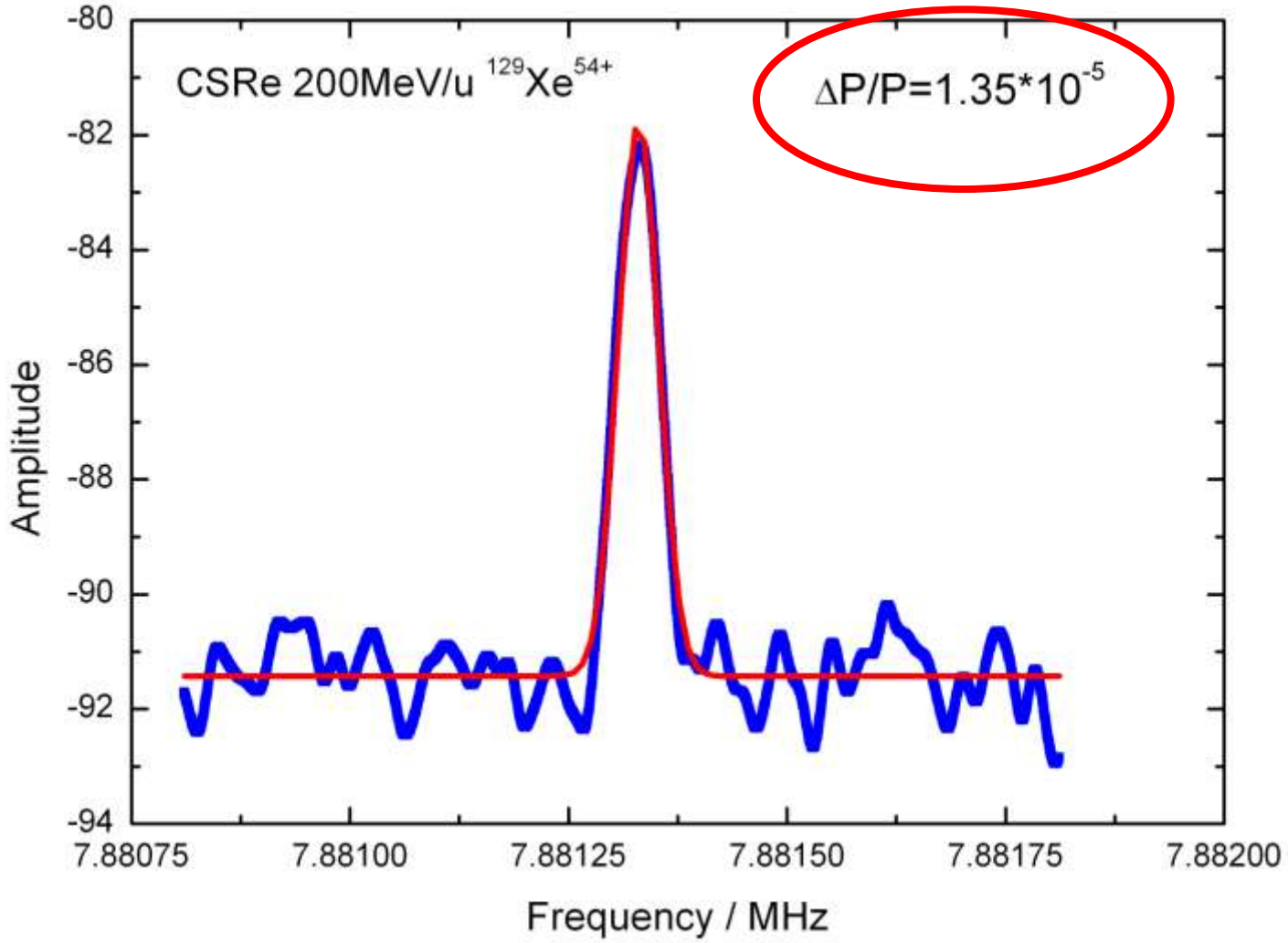
Momentum spread as the function of time



Momentum spread before and after electron cooling

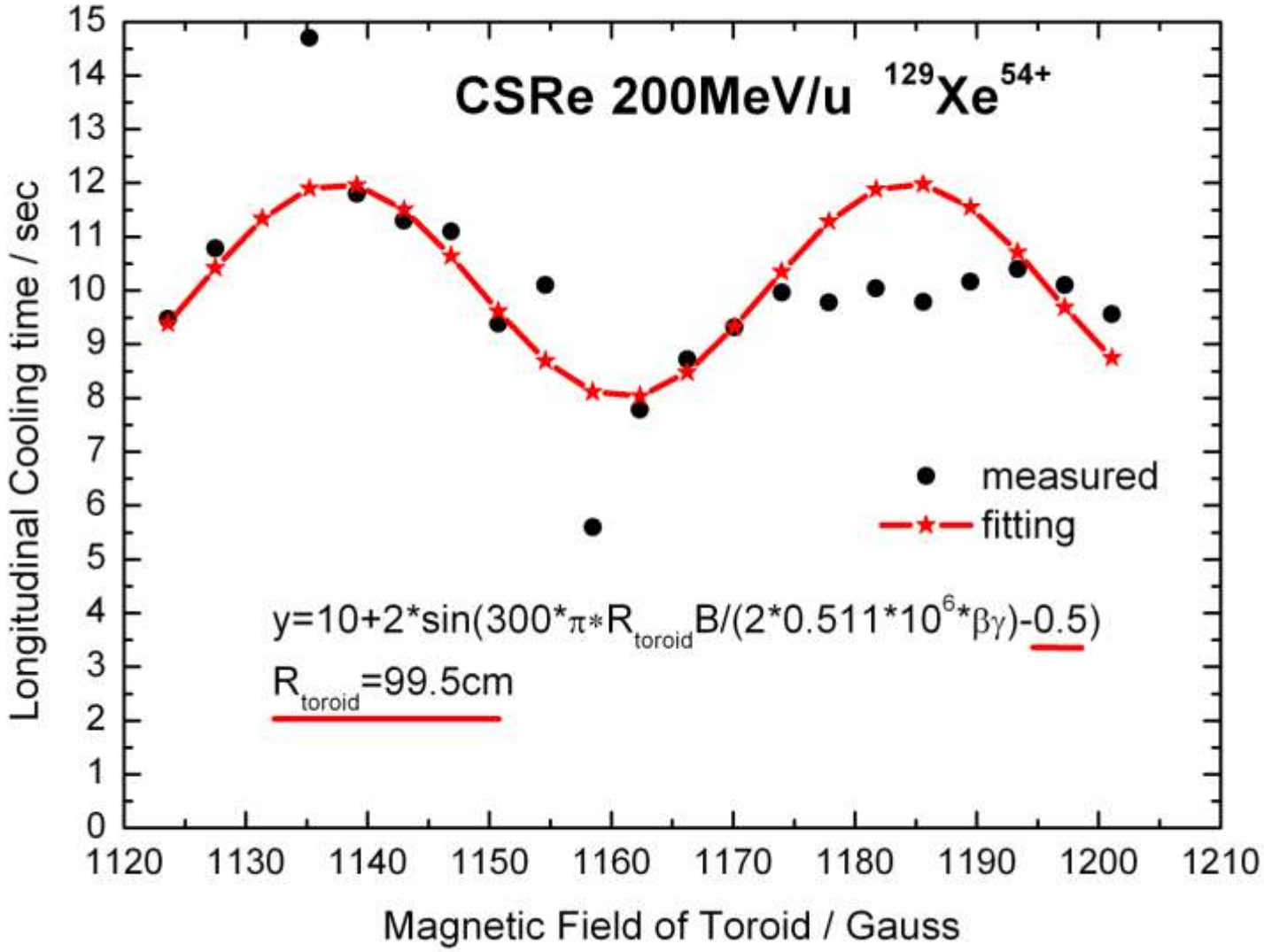


Beam transverse size before and after electron cooling



Measured minimum momentum spread of 200MeV/u $^{129}Xe^{54+}$

The influence of toroid magnetic field on the longitudinal cooling



Longitudinal cooling time as the function of magnetic field of toroid

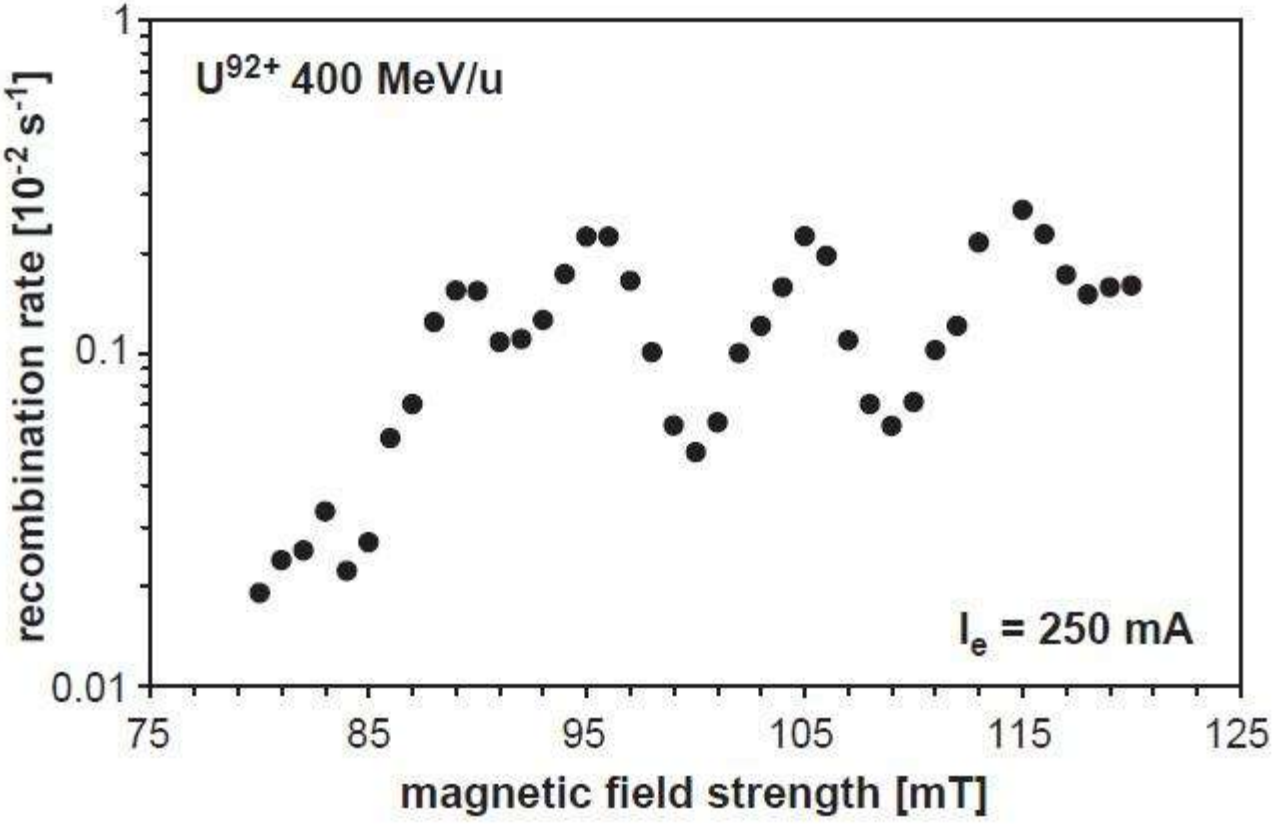
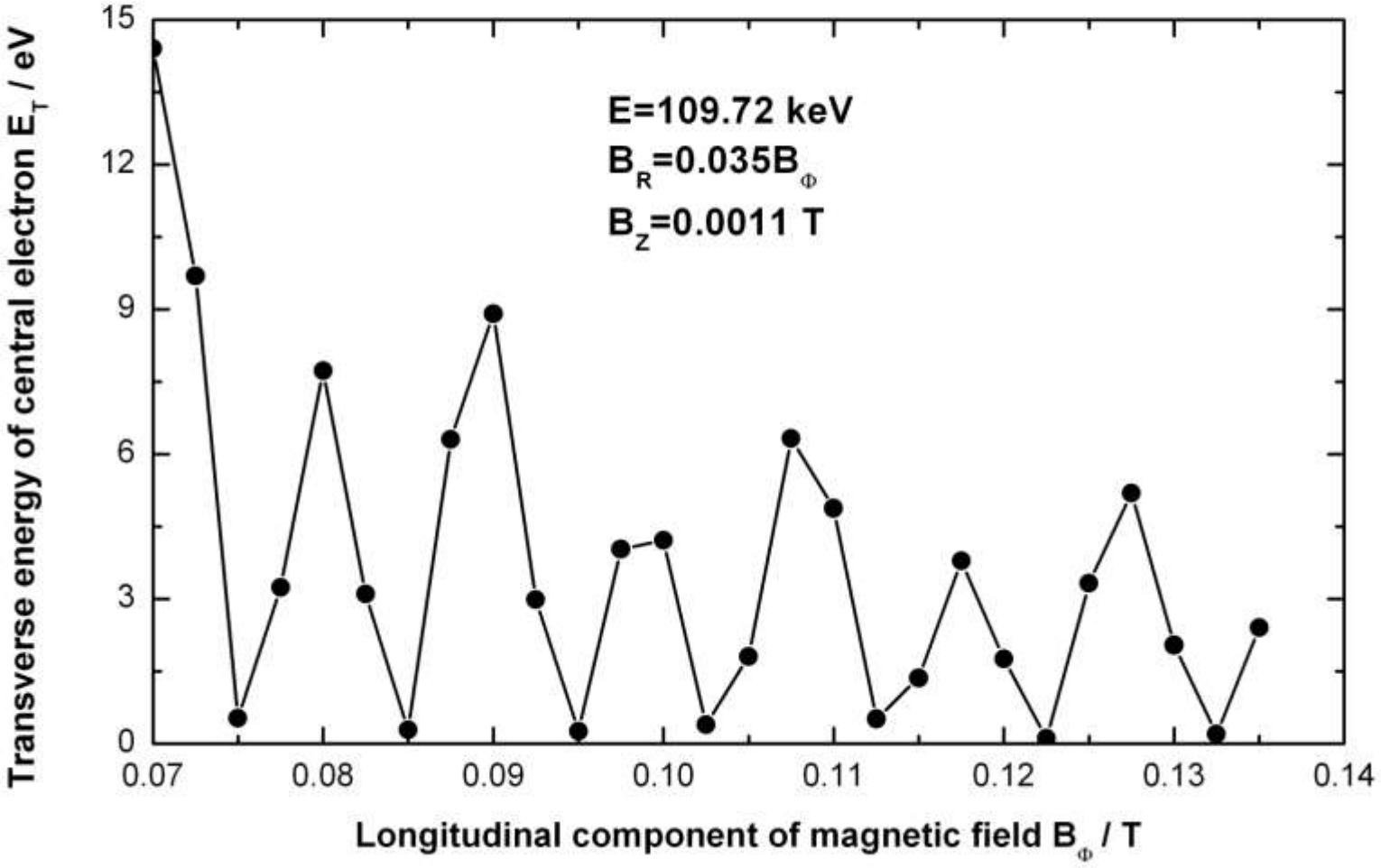
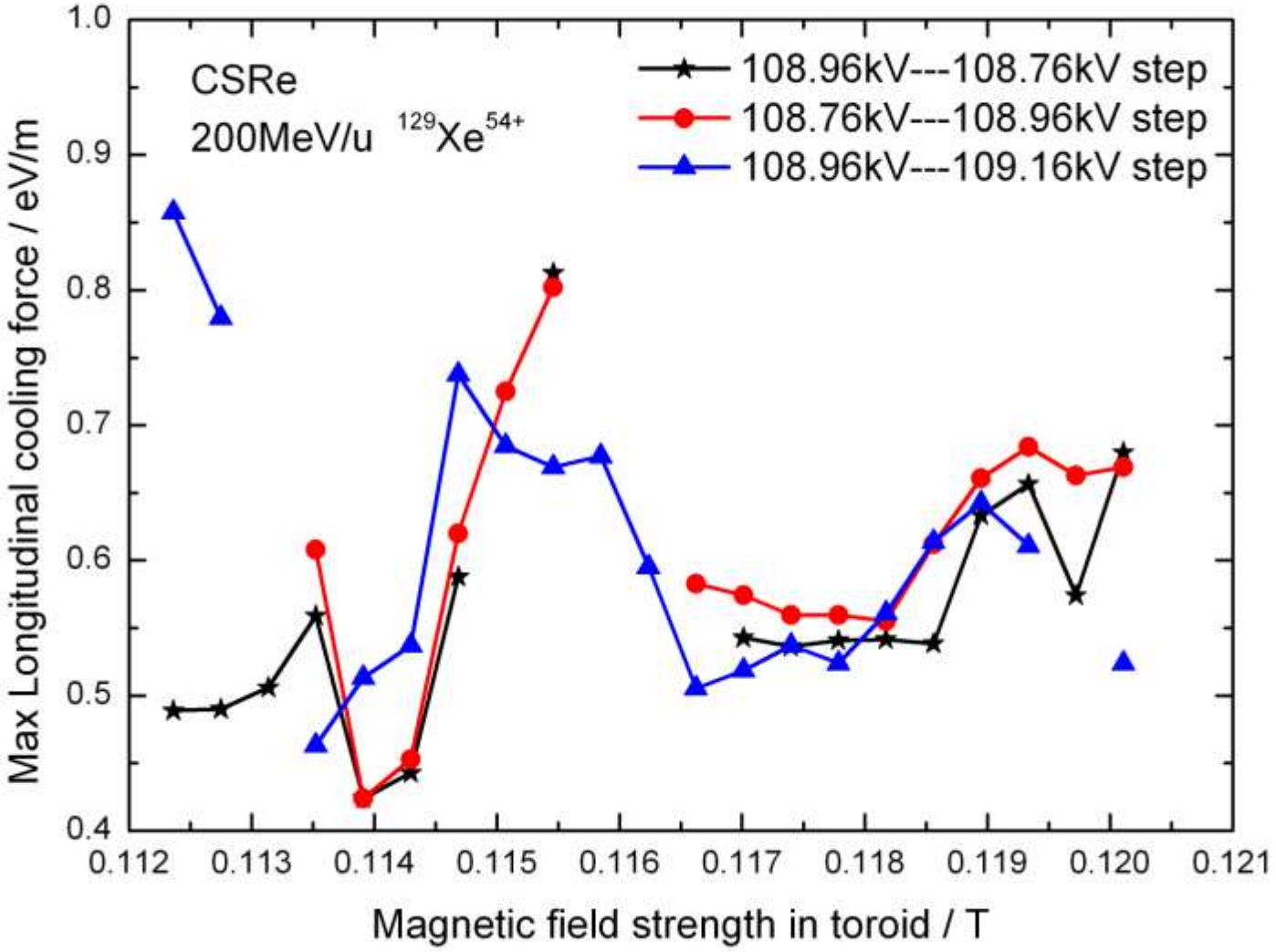


Fig. 2. Recombination rate of U^{92+} at 400 MeV/u as a function of the longitudinal magnetic field strength of the electron cooler.

P. Beller ***NIM*** A532(2004) 427-432

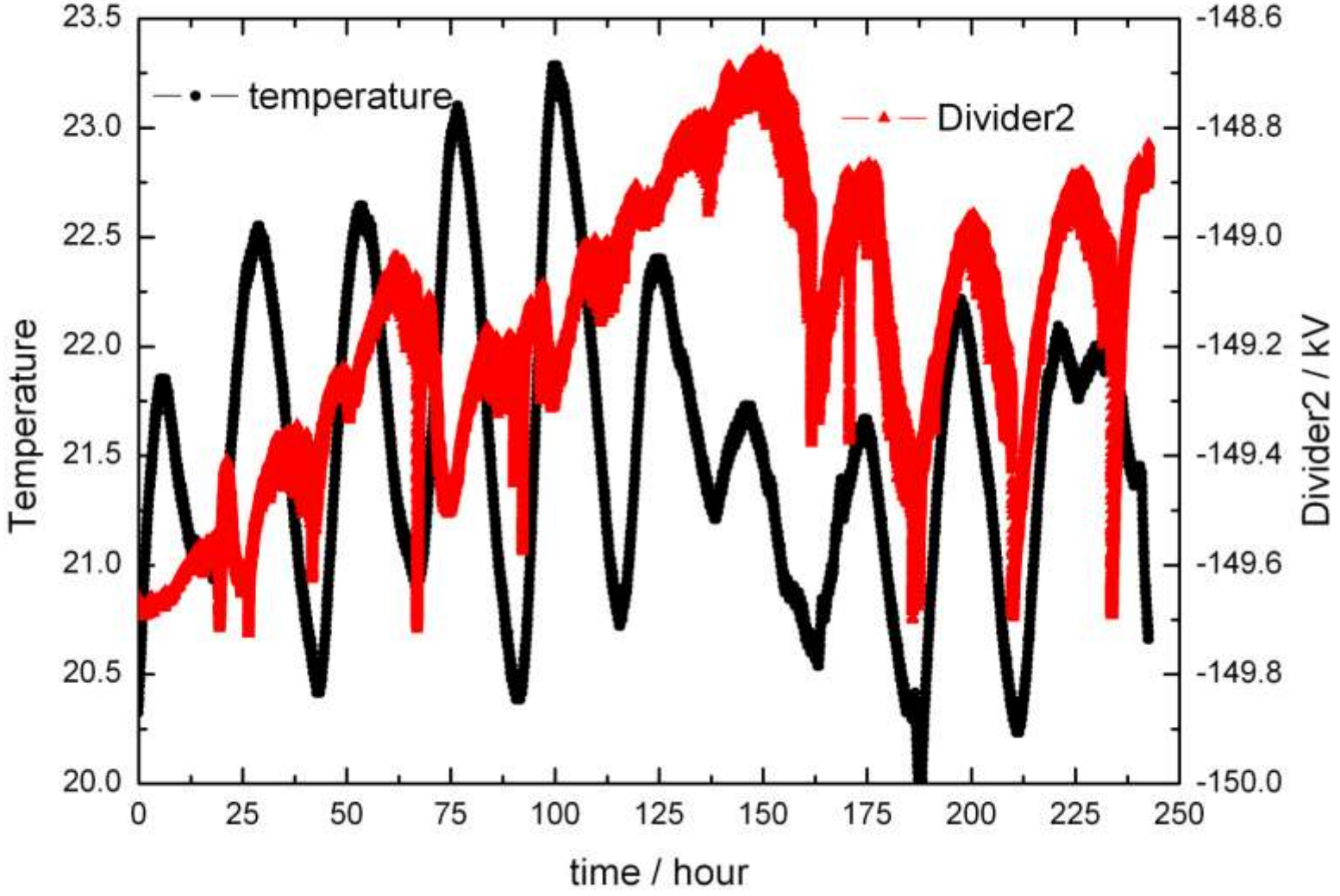


Transverse energy of central electron as the function of longitudinal magnetic field in toroid



Max. longitudinal cooling time as the function of magnetic field of toroid

Upgrade and improvements



Longtime stability of high voltage of CSRe cooler(10days)

Upgrade and improvements

- Electron beam energy modulation system was installed and tested in CSRm cooler.
- Stability of High voltage system for CSRe cooler was suggested.

Summary

- A few species heavy ion beam with different injection energy was cooled, accumulated and accelerated in CSRm
- 400MeV/u $^{12}C^{6+}$ and 200MeV/u $^{129}Xe^{54+}$ was cooled with internal target in CSRe
- Two cooling device come into routine operation
- Coolers were ready for physics experiments
- Electron beam energy modulation system was installed and tested in CSRm cooler

Without the help of Russian Colleagues, no CSR

Thanks for all Russian Colleagues' contribution in CSR project!

Thank You !

www.impcas.ac.cn

Electron cooling pioneers at Novosibirsk in 1974 – left to right: V Parkhomchuk, A Skrinsky, I Meshkov, N Dikansky.

Older and wiser – the same pioneers in 1998: Dikansky, Skrinsky, Parkhomchuk, Meshkov.