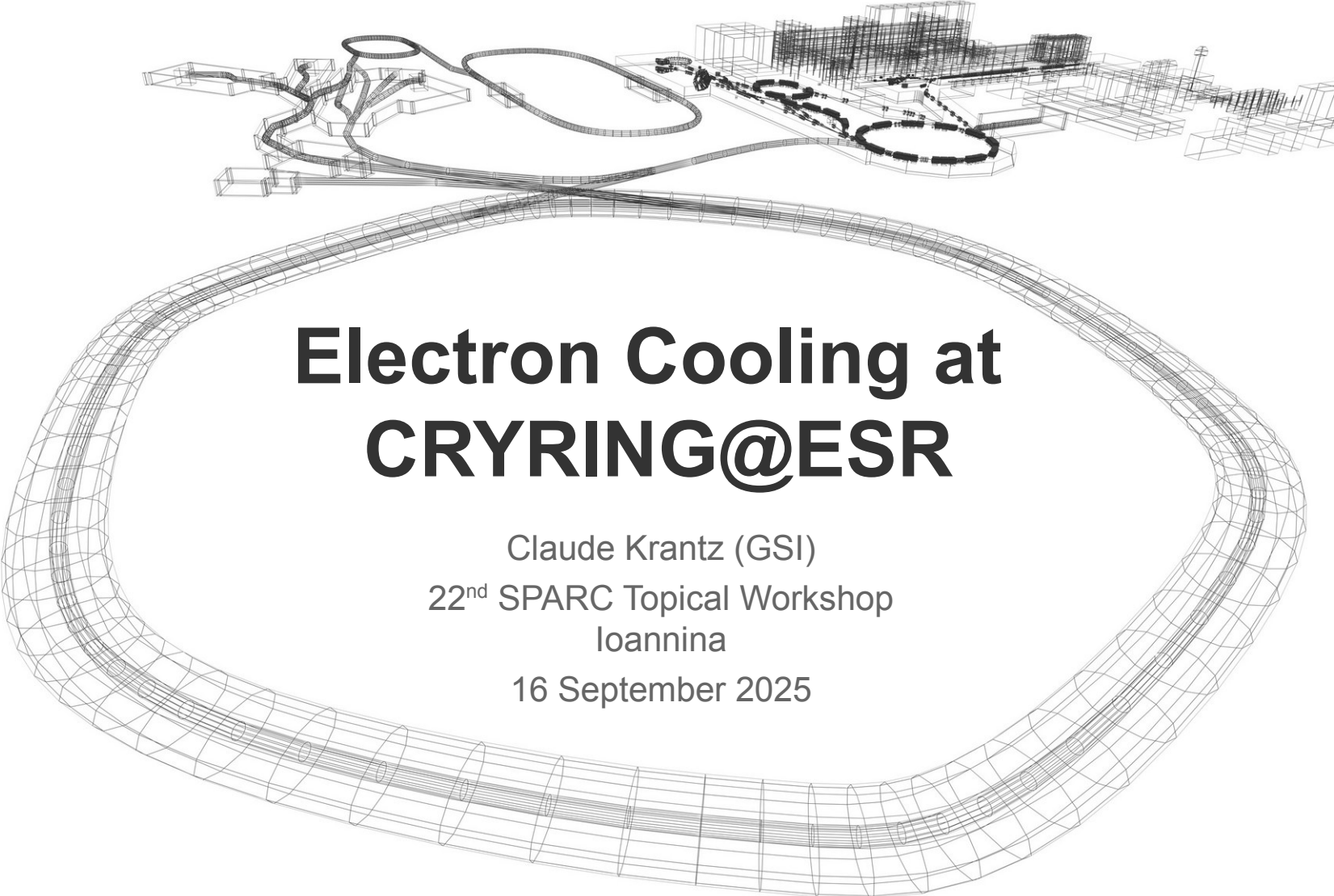
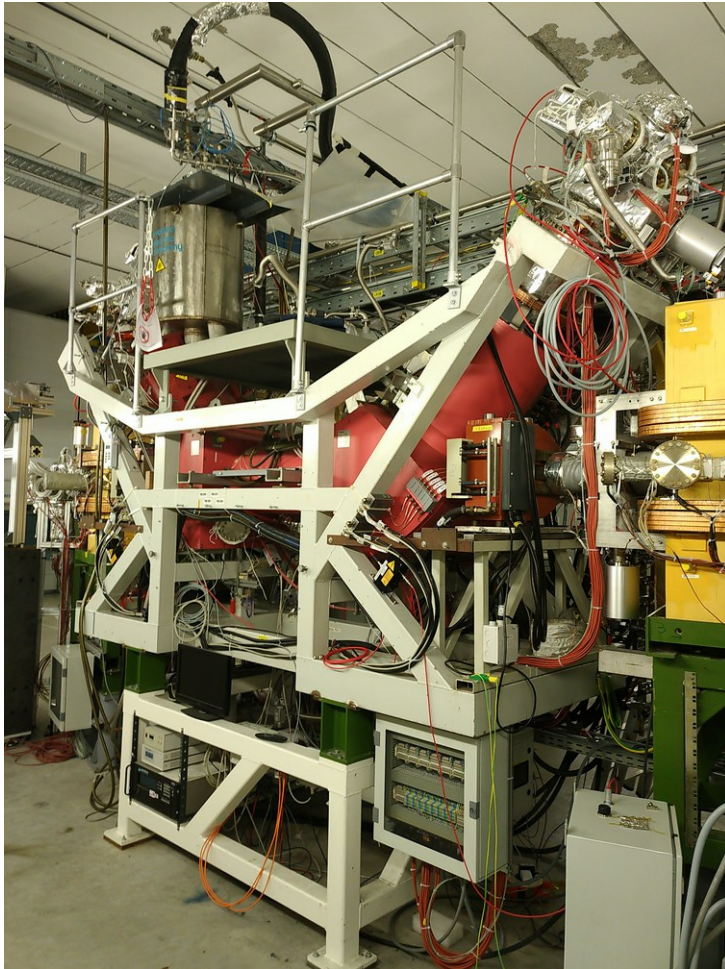


A detailed wireframe model of a particle accelerator, likely the FAIR facility. It features a large, oval-shaped main ring with a complex internal structure, and several smaller, more intricate sections at the top. The model is rendered in a light gray wireframe style, showing the various components and their arrangement.

Electron Cooling at CRYRING@ESR

Claude Krantz (GSI)
22nd SPARC Topical Workshop
Ioannina
16 September 2025



The CRYRING@ESR electron cooler in 2025

Physica Scripta. Vol. 48, 405–412, 1993

Electron Cooling at CRYRING

H. Danared

Manne Siegbahn Institute of Physics, S-104 05, Stockholm, Sweden

Received March 25, 1993; accepted in revised form May 17, 1993

Abstract

The design of the CRYRING electron cooler, including magnets, electron gun and collector, and the vacuum system, is described. Light and heavy atomic ions and molecular ions have been cooled at ion energies between 0.29 and 10.9 MeV per nucleon. Experiments in atomic and molecular physics have been performed using the cooler both for beam cooling and as an electron target. Measurements of longitudinal drag forces and resulting estimates of transverse and longitudinal electron temperature are presented.



Cooler installed
in May 1992 !!

Cooling demonstrated ...

... for many ions !

... at many energies !

... for target experiments !

... for electron temperatures !

Physica Scripta. Vol. 48, 405–412, 1993

Electron Cooling at CRYRING

H. Danared

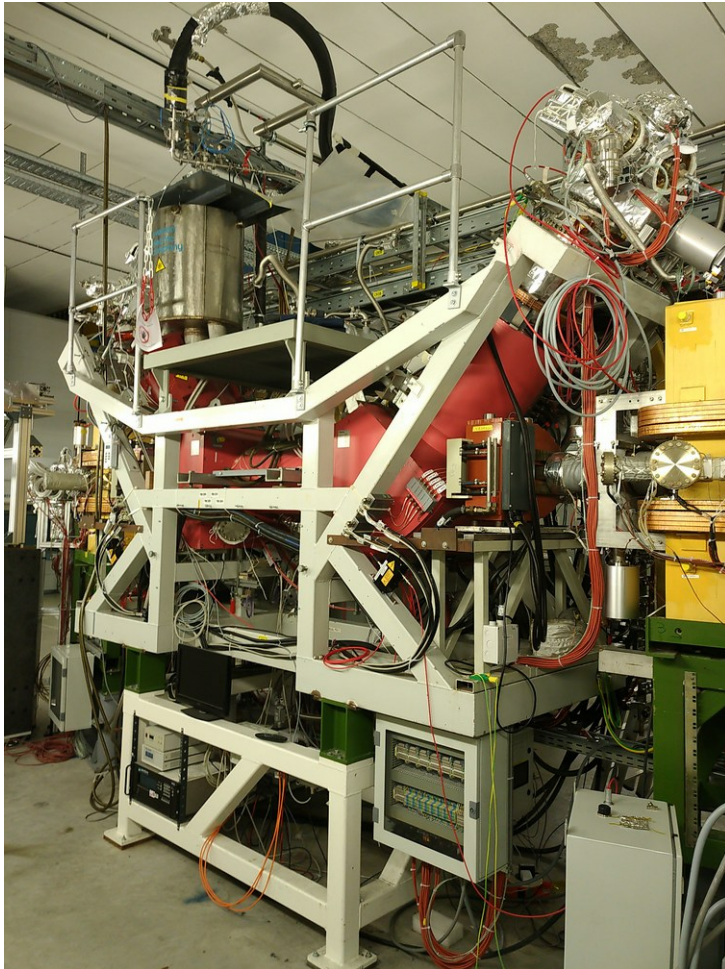
Manne Siegbahn Institute of Physics, S-104 05, Stockholm, Sweden

Received March 25, 1993; accepted in revised form May 17, 1993

Abstract

The design of the CRYRING electron cooler, including magnets, electron gun and collector, and the vacuum system, is described. Light and heavy atomic ions and molecular ions have been cooled at ion energies between 0.29 and 10.9 MeV per nucleon. Experiments in atomic and molecular physics have been performed using the cooler both for beam cooling and as an electron target. Measurements of longitudinal drag forces and resulting estimates of transverse and longitudinal electron temperature are presented.

The CRYRING@ESR electron cooler in 2025



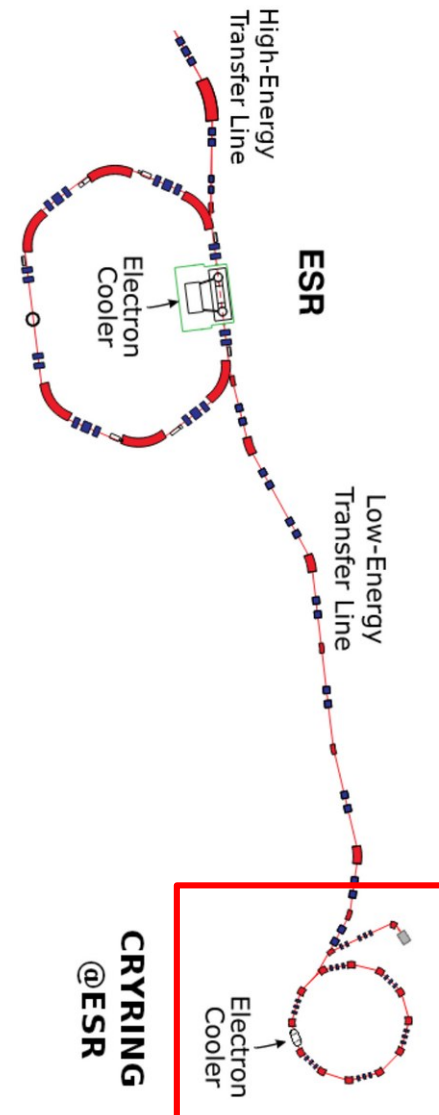
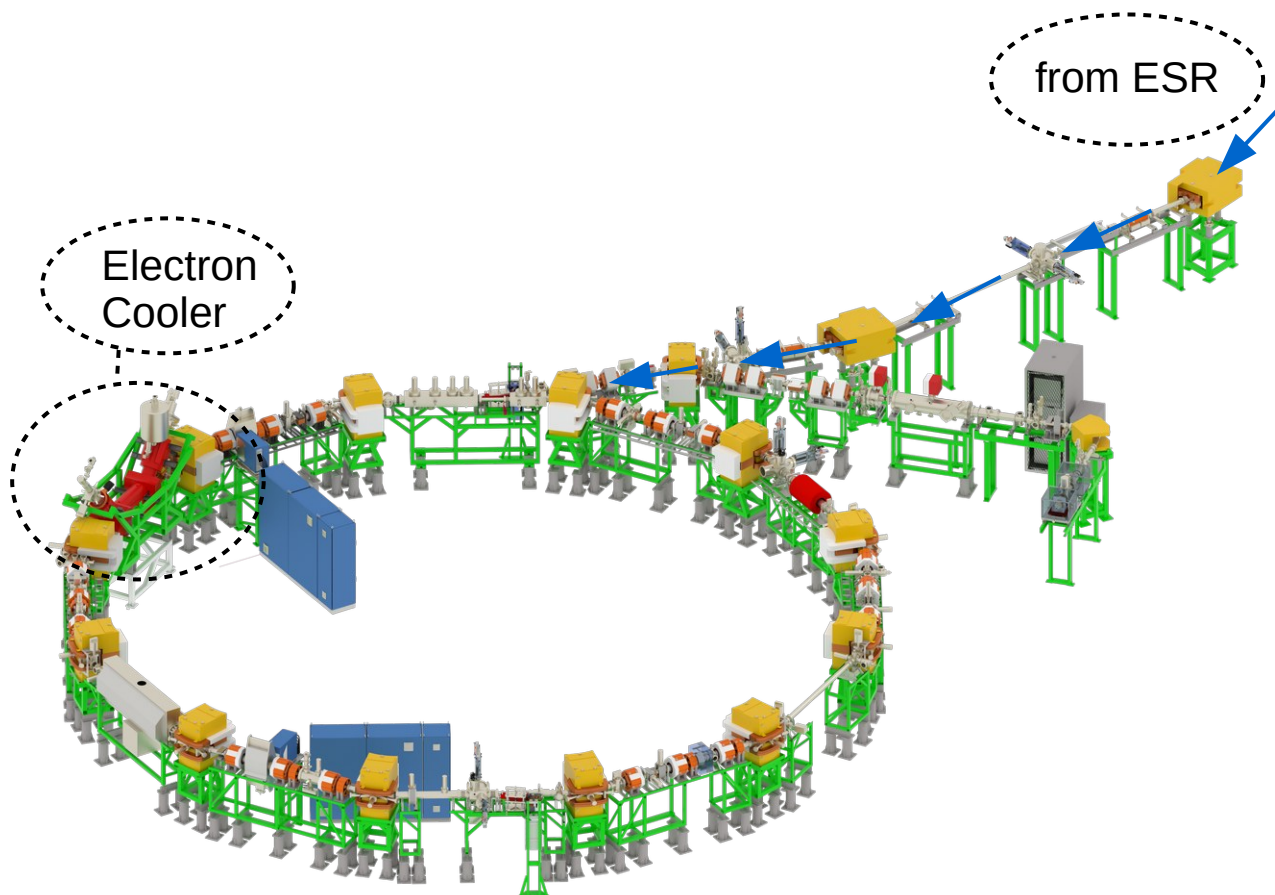
The CRYRING@ESR electron cooler in 2025

Outline

- Electron cooler performance
- Hardware upgrades
- Improved e-target operation
- Remaining challenges

Electron Cooler Performance

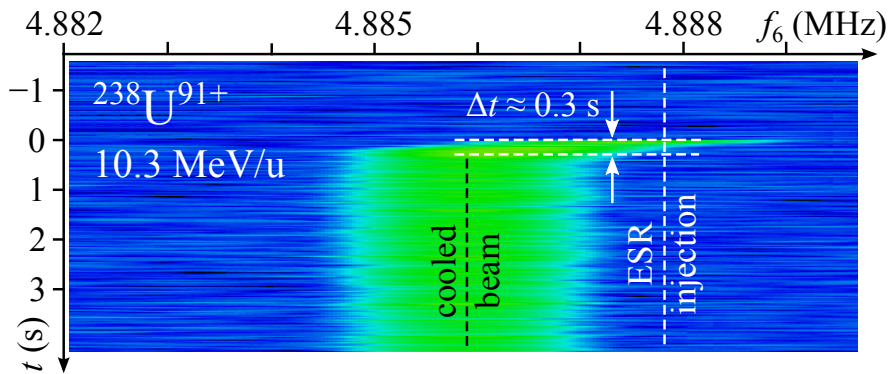
Highly-charged ions:
e.g. $^{298}\text{U}^{91+}$ @ 10 MeV/u



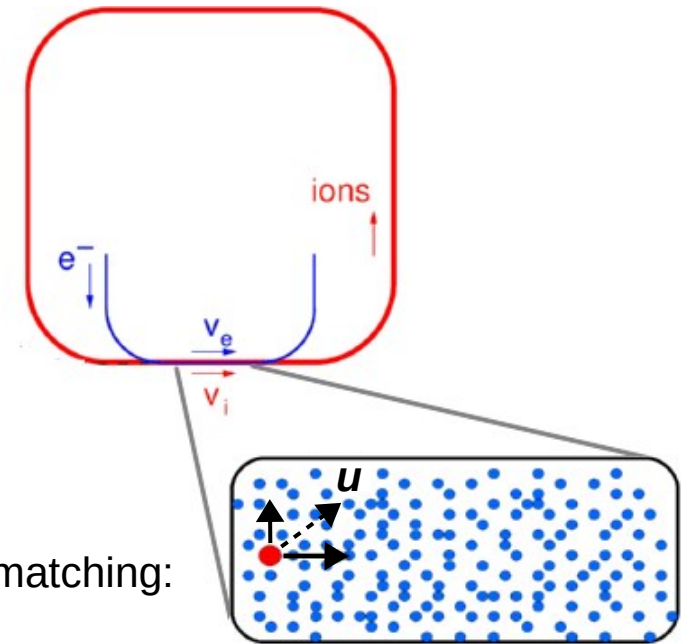
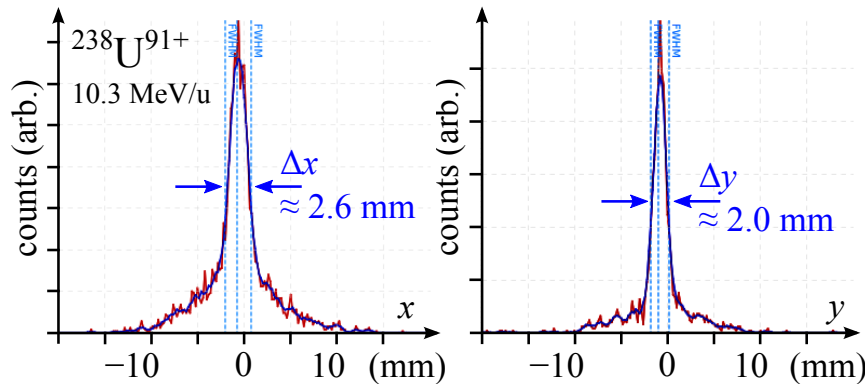
Electron Cooler Performance

Highly-charged ions:
e.g. $^{298}\text{U}^{91+}$ @ 10 MeV/u

Longitudinal cooling ~ 0.1 s



Beam profiles after 1 s

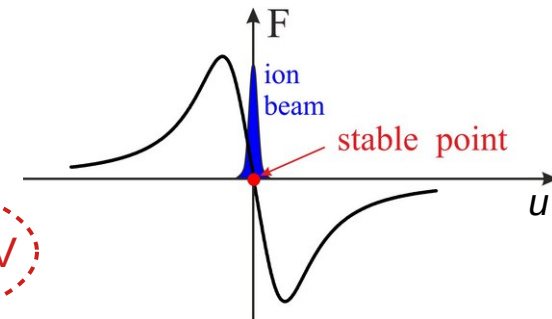


Velocity matching:

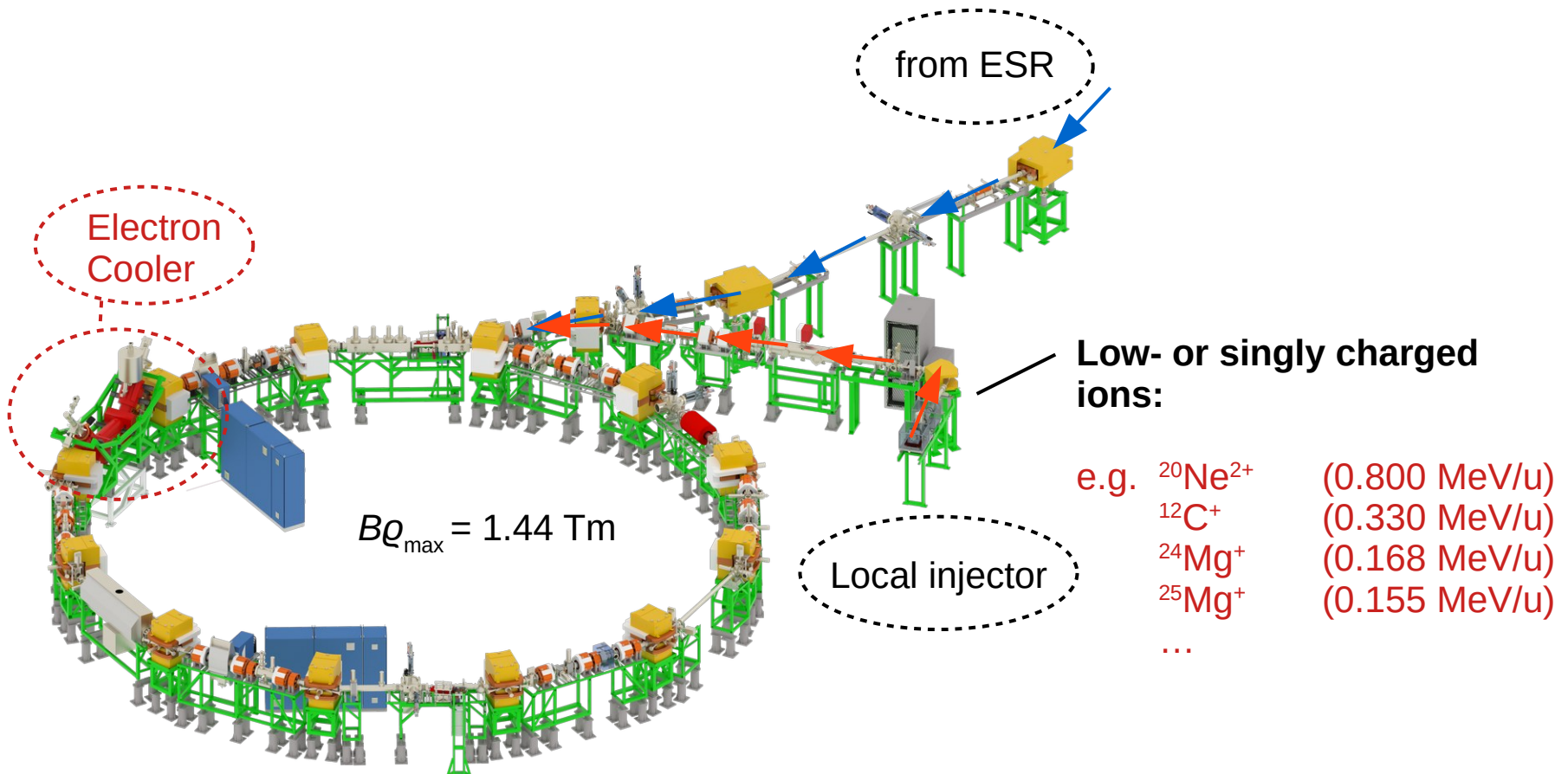
$$E_e = \frac{m_e}{m_i} \cdot E_i$$

$$E_i \approx 10 \text{ MeV/u}$$

$$\rightarrow E_e \approx 5500 \text{ eV}$$

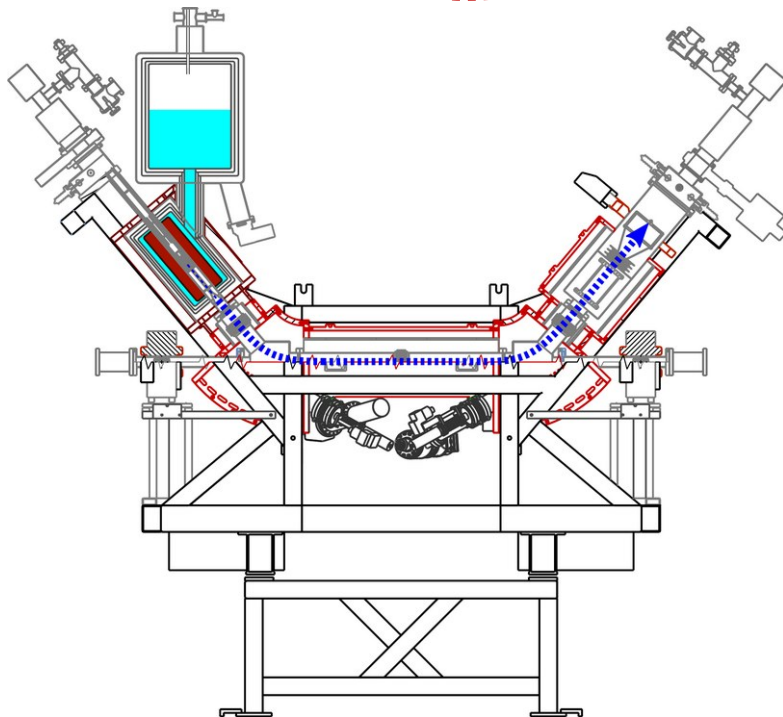


Electron Cooler Performance



e.g. $^{25}\text{Mg}^+$: $E_i \approx 155 \text{ keV/u}$

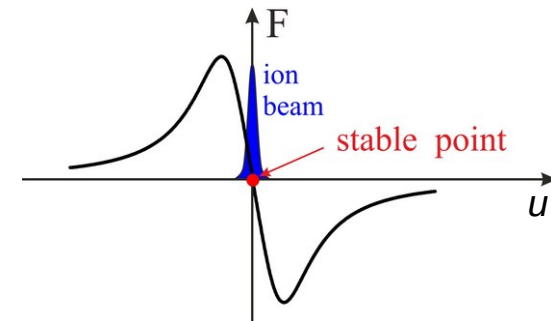
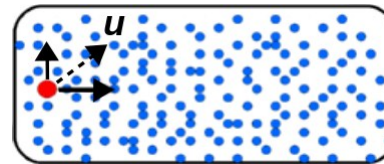
→ $E_e \approx 85 \text{ eV}$



Singly/weakly charged ions:

low cooler voltages ... $E_e = \frac{m_e}{m_i} \cdot E_i \approx e U_{cool}$

... and low e-currents. $I_e \sim U_{cool}^{3/2}$



Rate for low-energy e-cooling:

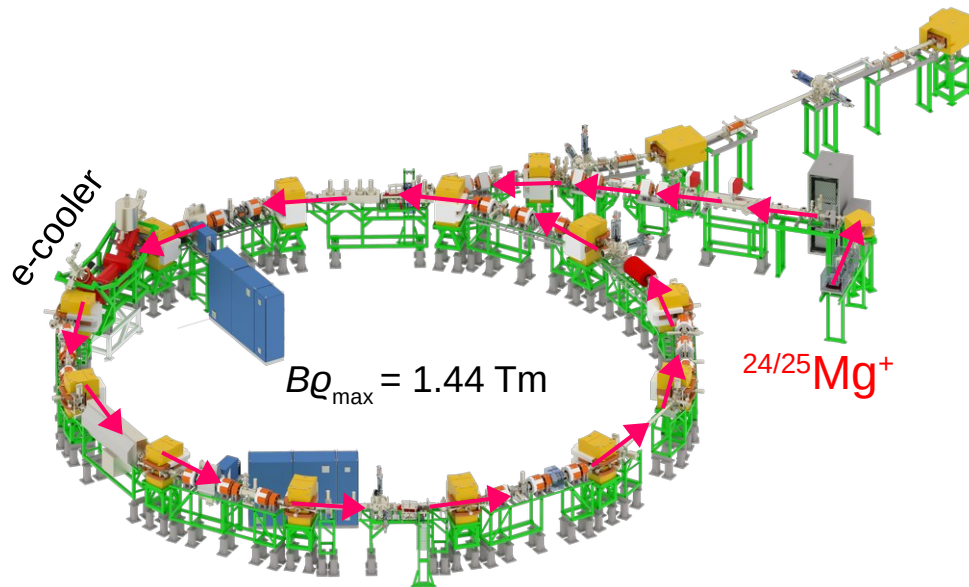
$$\frac{1}{\tau_{cool}} \sim \frac{q_i^2 \cdot U_{cool}}{m_i}$$

Electron Cooler Performance

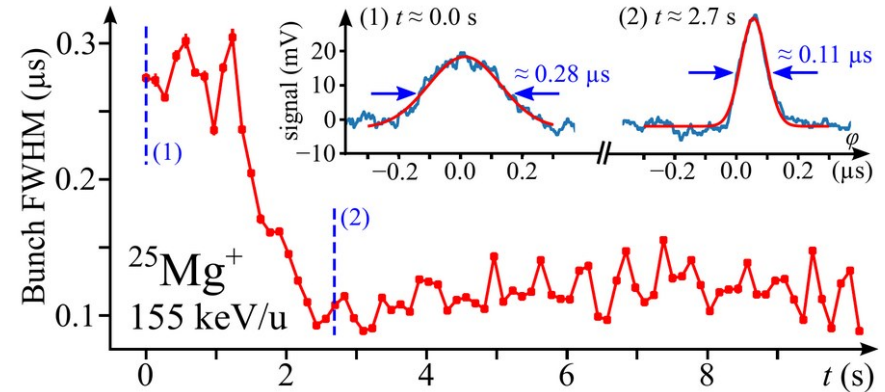
$^{24}\text{Mg}^+$ and $^{25}\text{Mg}^+$ @ 0.168 and 0.155 MeV/u

$E_e = 92 \text{ eV} / 85 \text{ eV}$

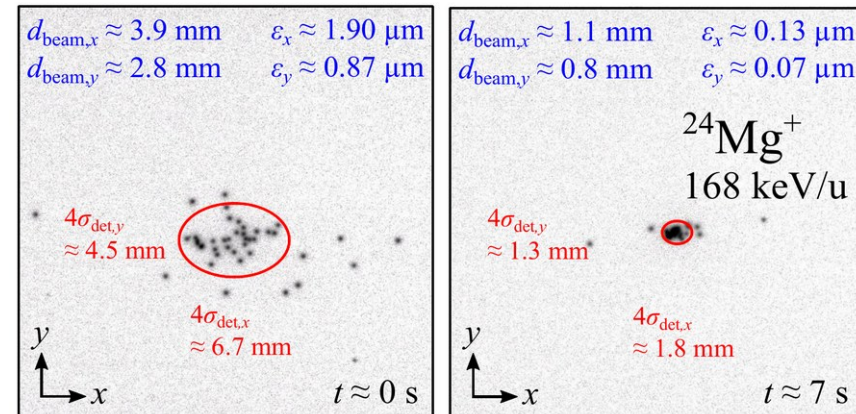
$I_e = 1.7 \text{ mA}$



Longitudinal cooling (bunched)



Transverse cooling (neutral imaging)



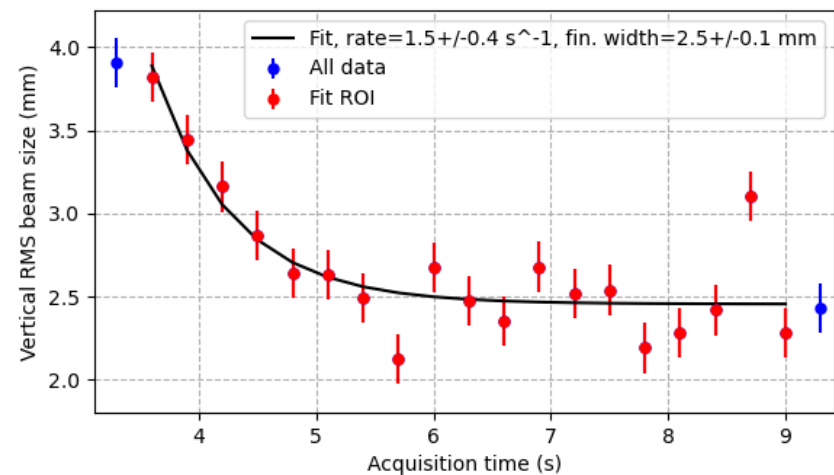
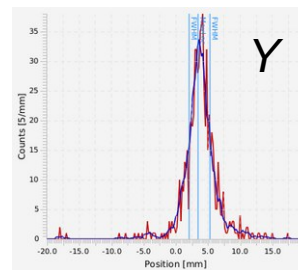
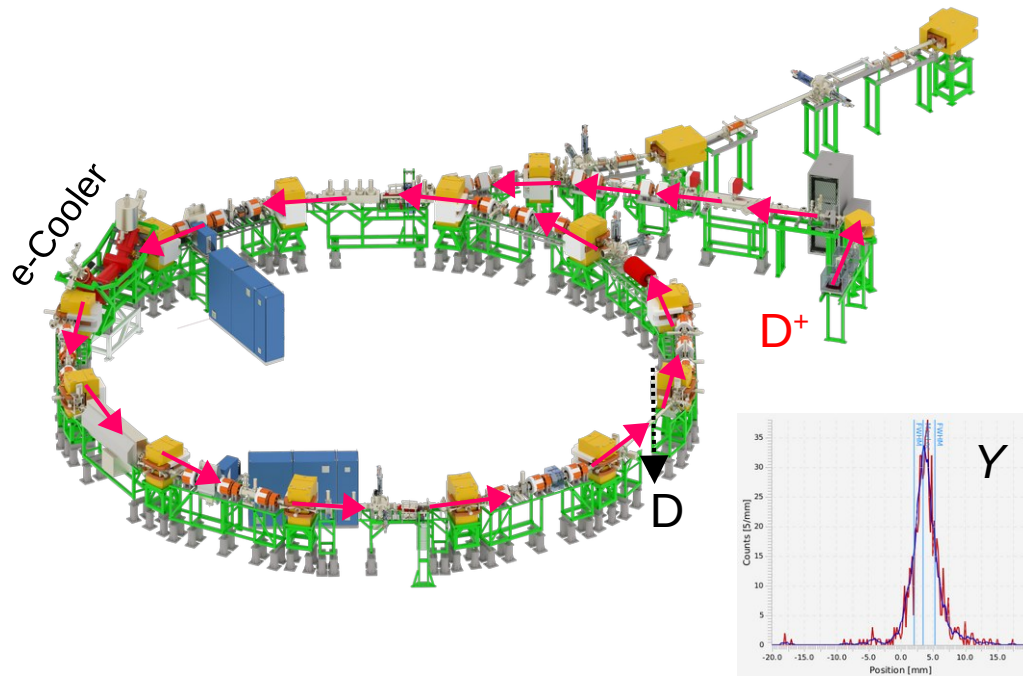
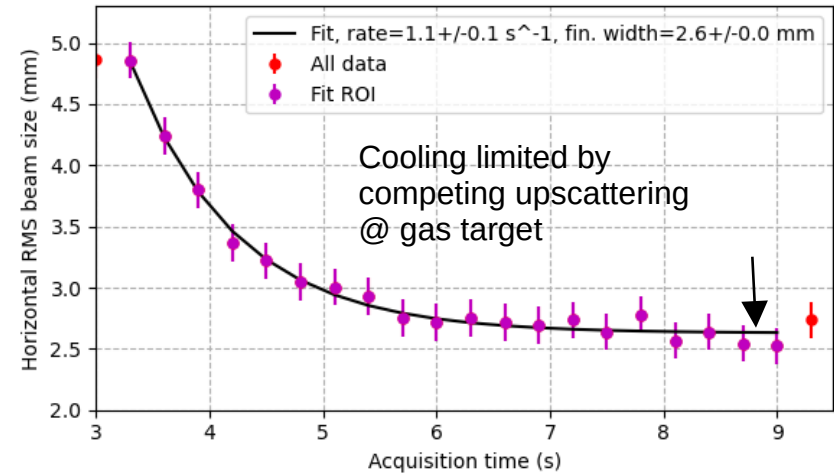
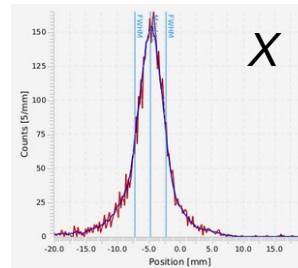
Krantz et al., Proc. IPAC 2021 (2021)

Electron Cooler Performance

Ultralow D^+ @ 0.092 MeV/u

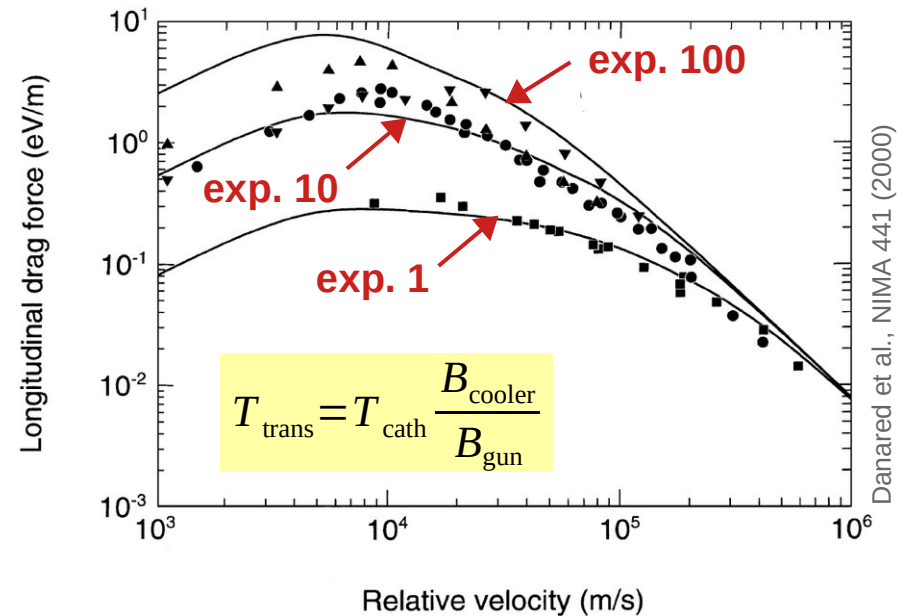
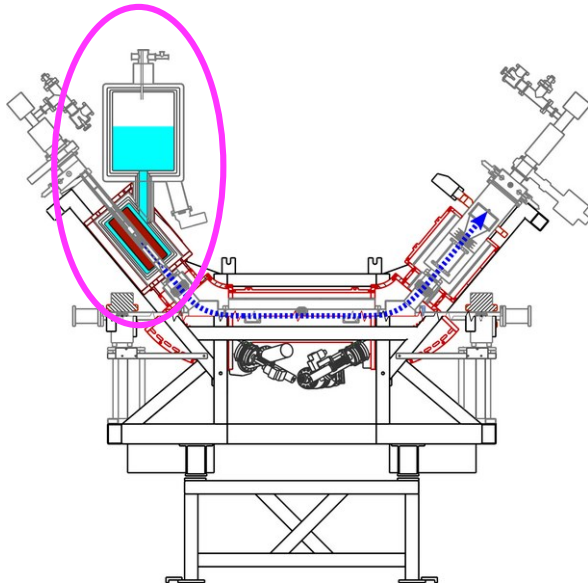
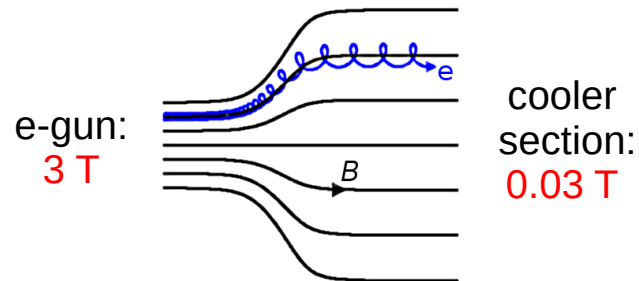
$$E_e = 50 \text{ eV}$$

$$I_e = 0.5 \text{ mA}$$

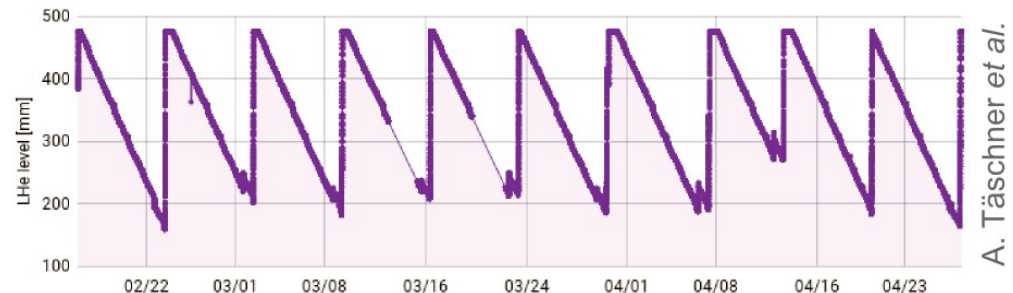


Hardware Upgrades: Cryogenics

Outstanding feature: 100 x adiabatic expansion

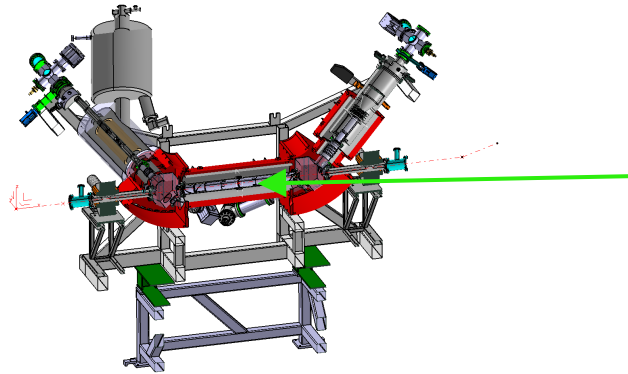


2018 ... 2020: Connected s.c. solenoid to closed-loop LHe plant.

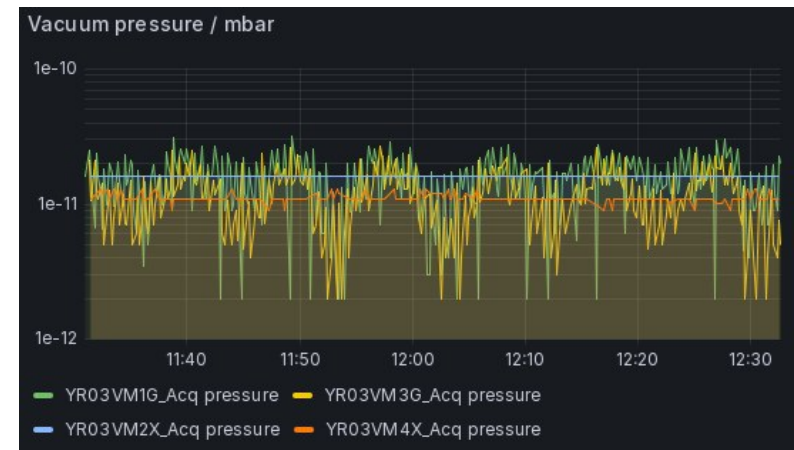


Hardware Upgrades: Vacuum

2021: cooler developed vacuum problems. Reason: **broken bakeout jacket**

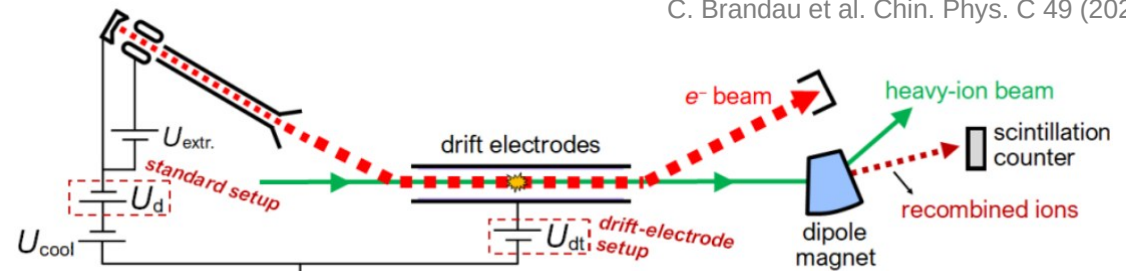
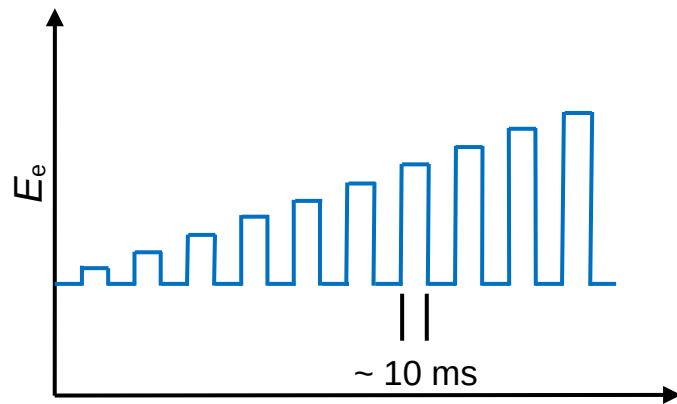


2022/23: Full disassembly of e-cooler.
Replacement of **jackets, pumps, gauges.**



2025: Vacuum $\sim 1 \cdot 10^{-11}$ mbar with e-beam on.

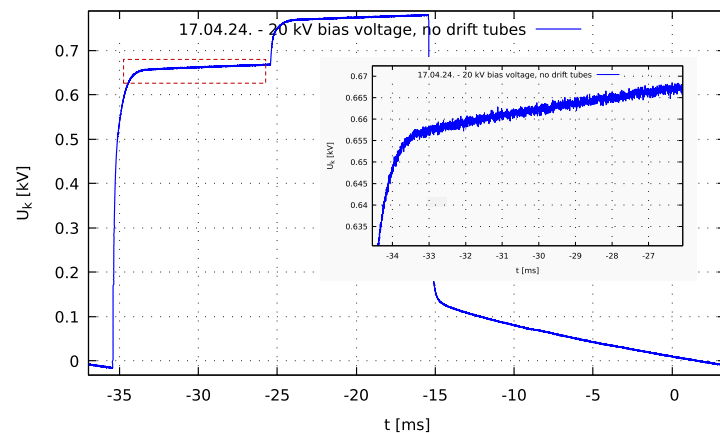
Hardware Upgrades: e-Target Operation



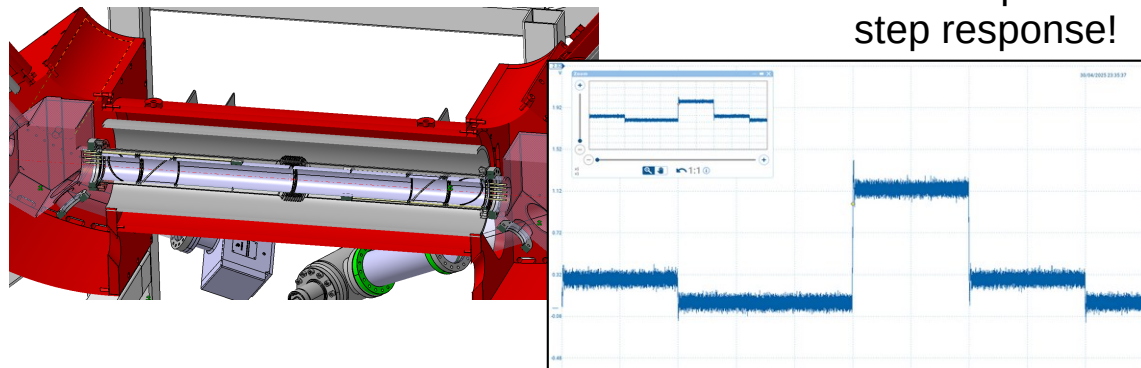
A. Koutsostathis et al., Proc. of HNPS 2024
C. Brandau et al. Chin. Phys. C 49 (2025)

2023: Installed **drift electrodes** in cooler section

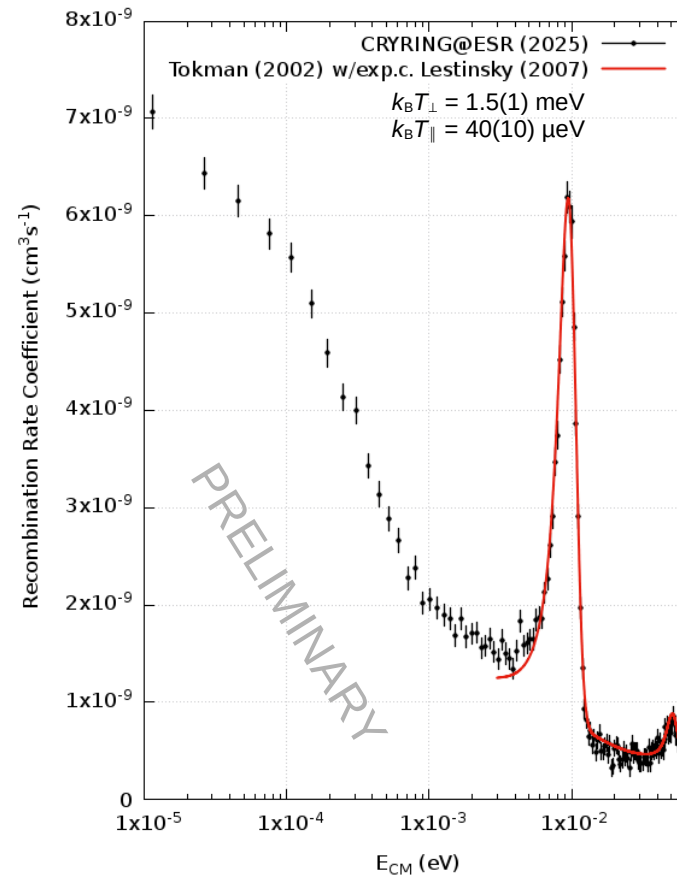
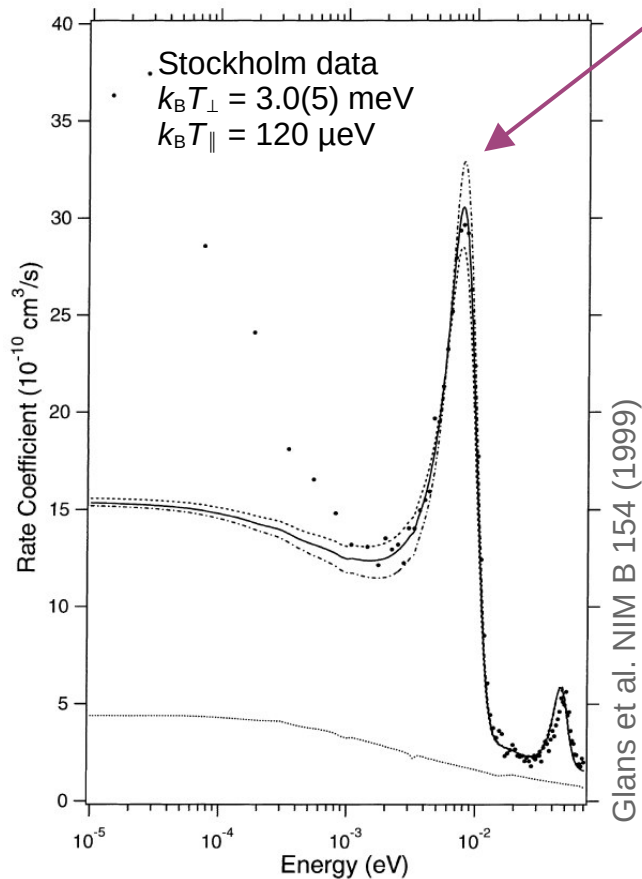
Application of meas. ramp to cooler terminal lead to **instabilities** ...



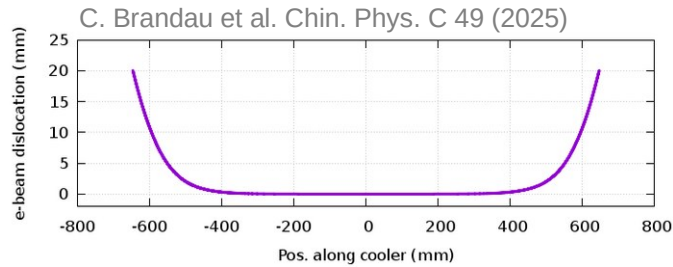
2025: much improved step response!



Dielectronic Recombination of F^{6+}

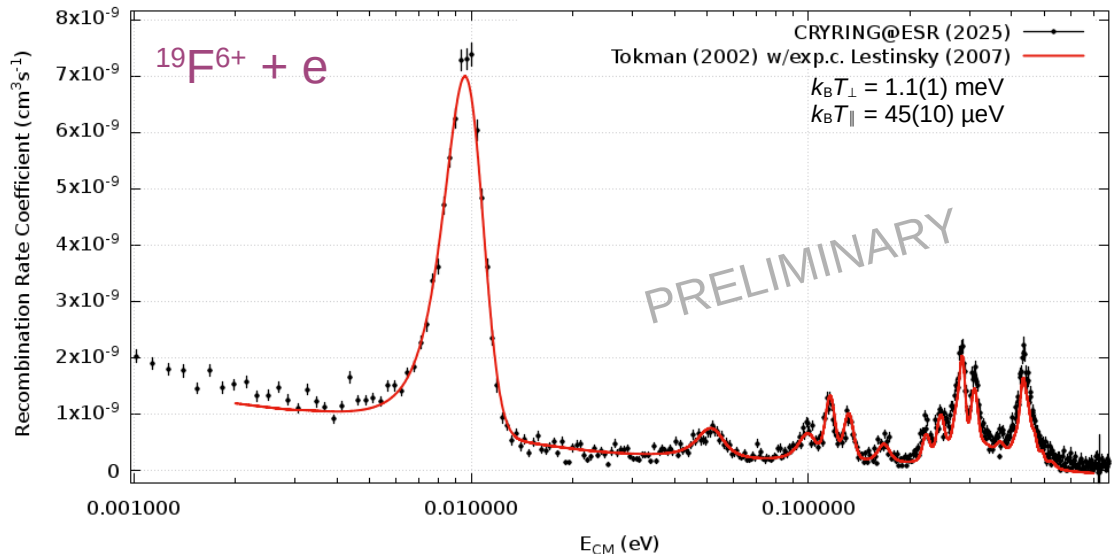
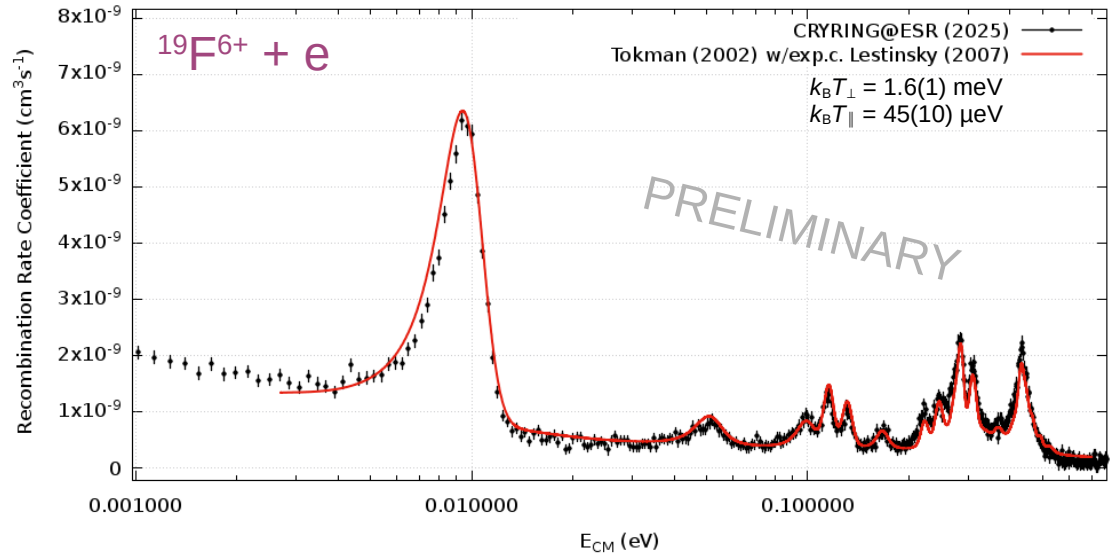
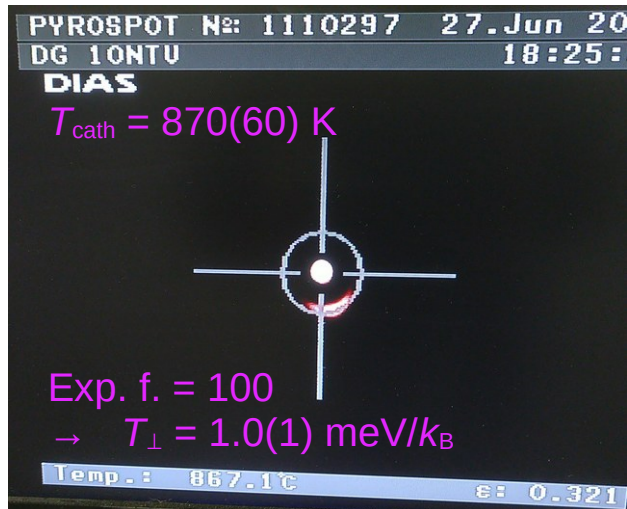


e-Target Operation

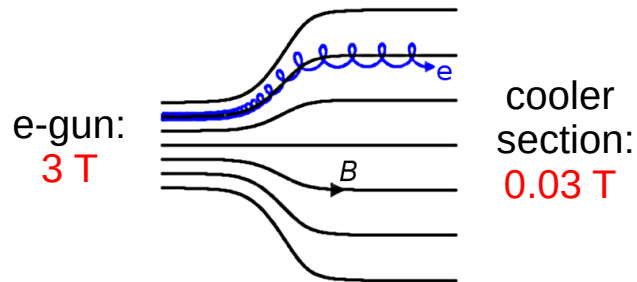


Convolved with
e-beam geometry

Numerically deconvolved



Challenges Remaining

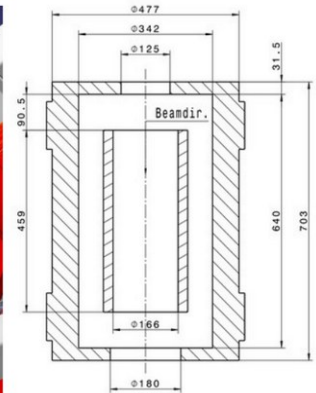
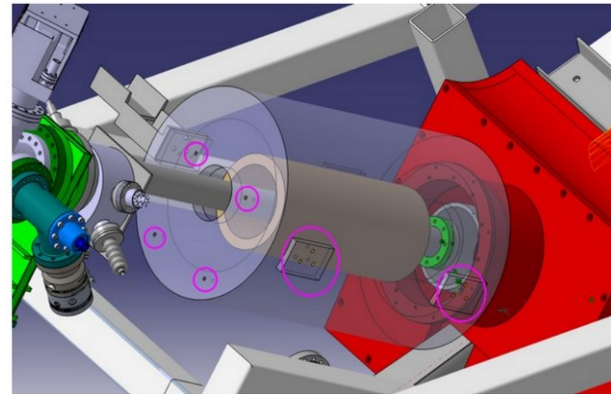
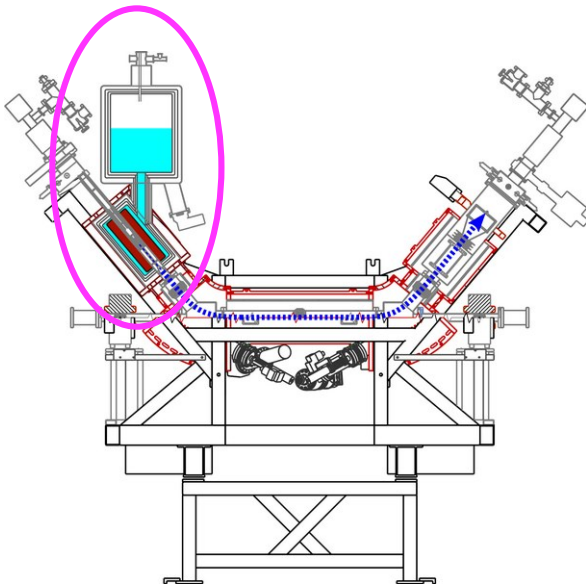


Existing **SCM** is old.

Cryo-system requires intense **maintenance**.

Need to **resupply He** regularly.

2024: *Almost* purchased a new magnet free of liquid cryogen ...



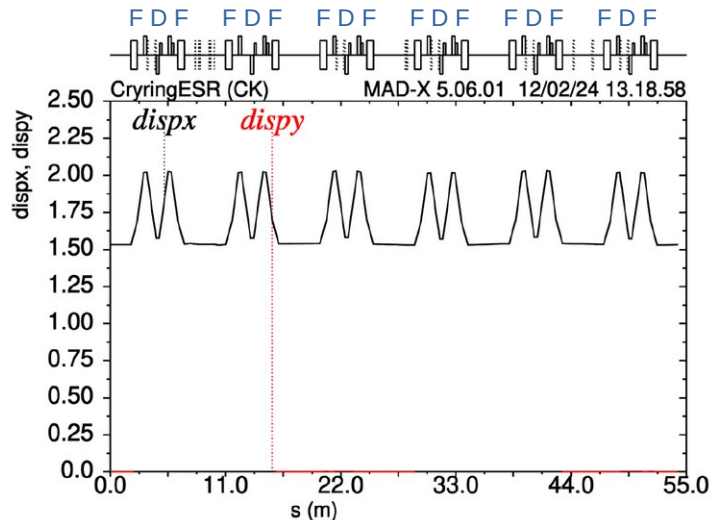
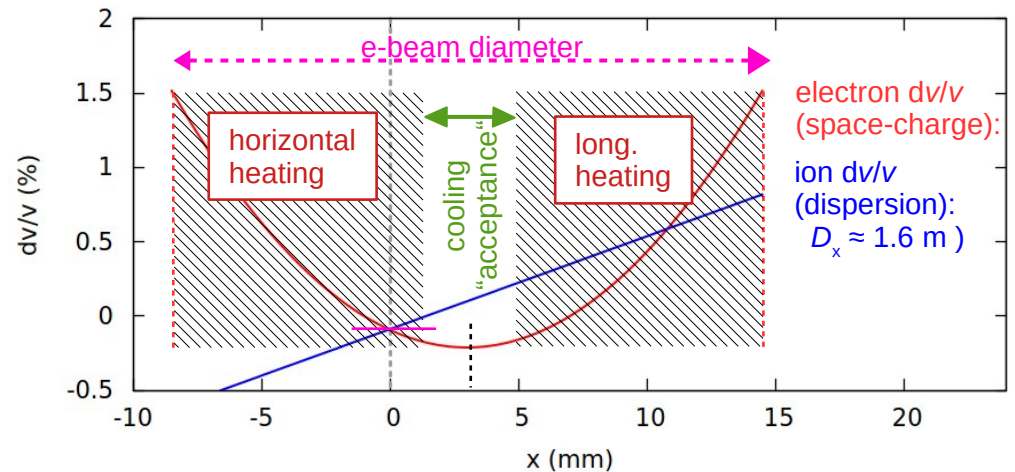
... to be continued!

Challenges Remaining

Low energies (1): Dispersive electron heating

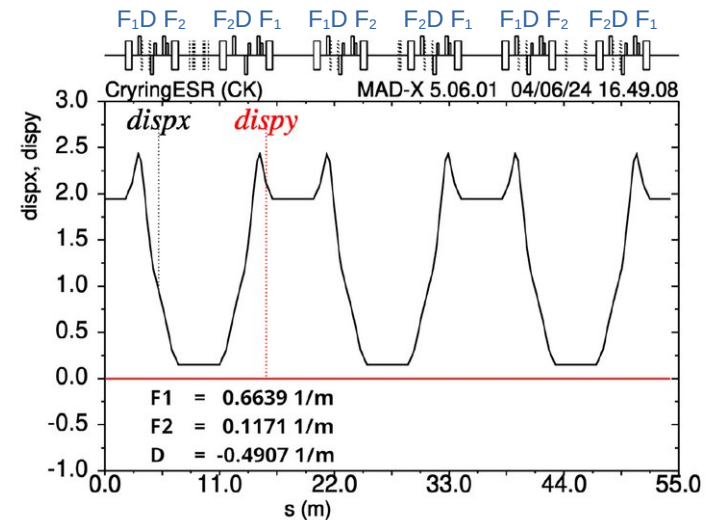
Dispersion vs.
e space-charge:

Edges of e-beam
turn into **ion heaters**!



Solution:

Split quads
into three
families



Challenges Remaining

Low energies (2): What do they mean for the accuracy of E_i ?

true electron accel. voltage		terminal voltage		space-charge potential		cathode workfunction		drift-tube workfunction		fract. heating voltage
$\frac{E_e}{e}$	=	U_{cooler}	-	$U_{S.C.}$	+	$\Phi_{cath.}$	-	Φ_{316L}	+	$f \cdot U_{heat}$
91.4 V	=	100.0 V	-	7.8 V	+	2.0 V	-	4.4 V	+	1.6 V
optimistic (!) error budget: ± 0.6 V		± 0.0001 V		± 0.1 V		± 0.2 V		± 0.2 V		± 0.5 V

Rel. uncertainty
of ion energy $\frac{\Delta E_i}{E_i} = 0.7\%$

c.f. @ ESR

$U_{cooler} \sim 100$ kV

$\Delta U_{tot} \sim 1$ V

$\rightarrow \Delta E_i / E_i \ll 10^{-4} !!$

Thank you!



Z. Andelkovic, C. Brandau, H. Danared, C. Dimopoulou, S. Fedotova,
W. Geithner, V. Hannen, E.-O. Hanu, M. Herber, F. Herfurth, R. Heß, C. K.,
A. Koutsostathis, I. Kraus, M. Lestinsky, M. Looshorn, E. B. Menz,
K. Mohr, W. Nörtershäuser, A. Reiter, J. Roßbach, R. Sánchez,
S. Schippers, C. Schroeder, A. Täschner, S. Trotsenko, G. Vorobyev,
M. Waider, S. Wang, D. Winzen

