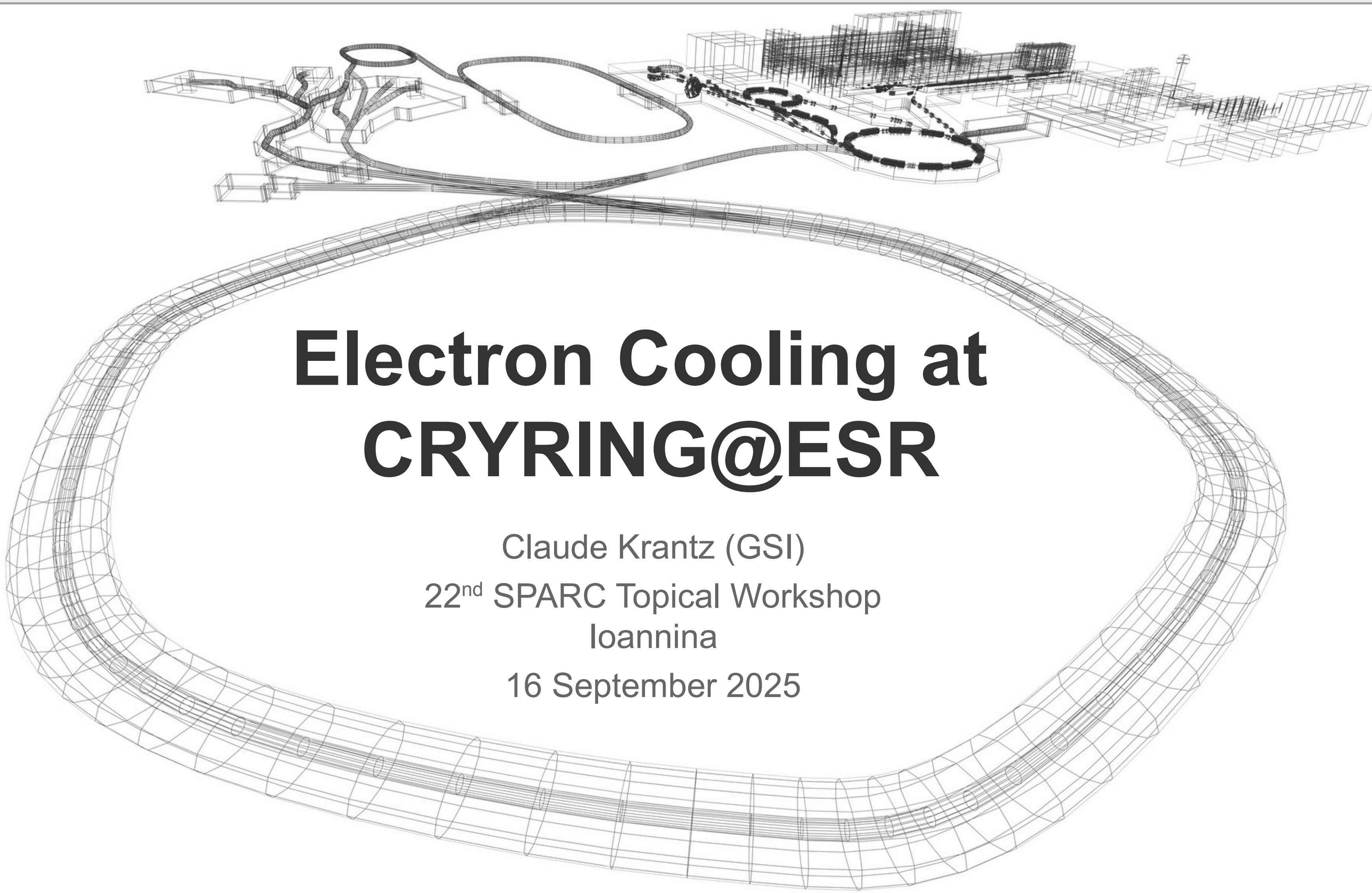


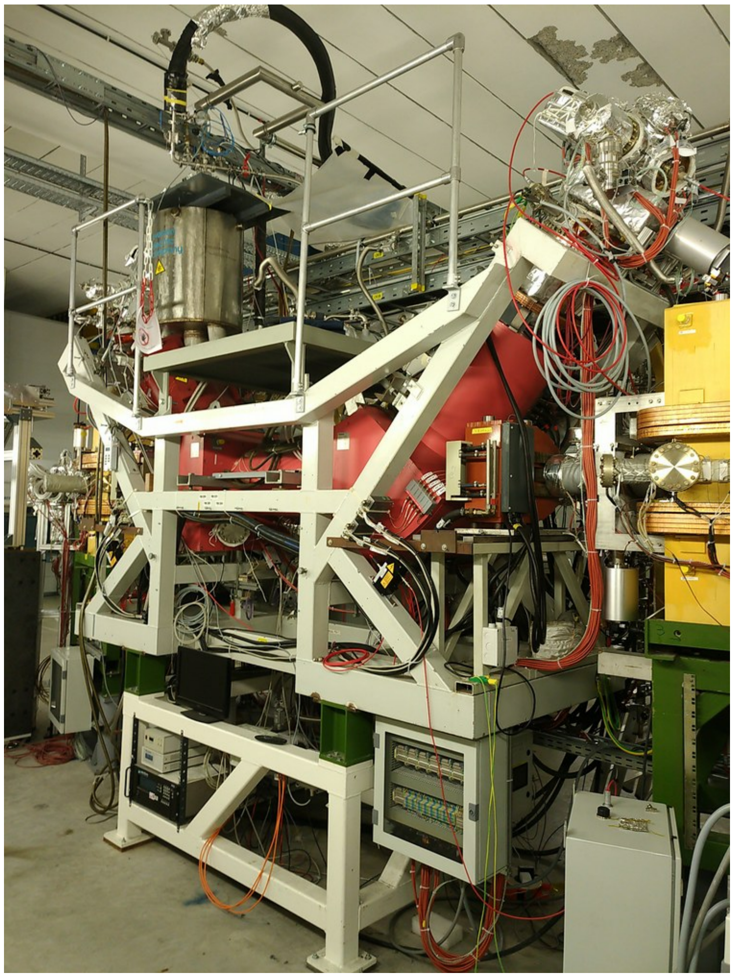
Electron Cooling at CRYRING@ESR

Claude Krantz (GSI)

22^{nd} SPARC Topical Workshop
Ioannina

16 September 2025

Electron Cooling at CRYRING@ESR



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.

Electron Cooling at CRYRING@ESR

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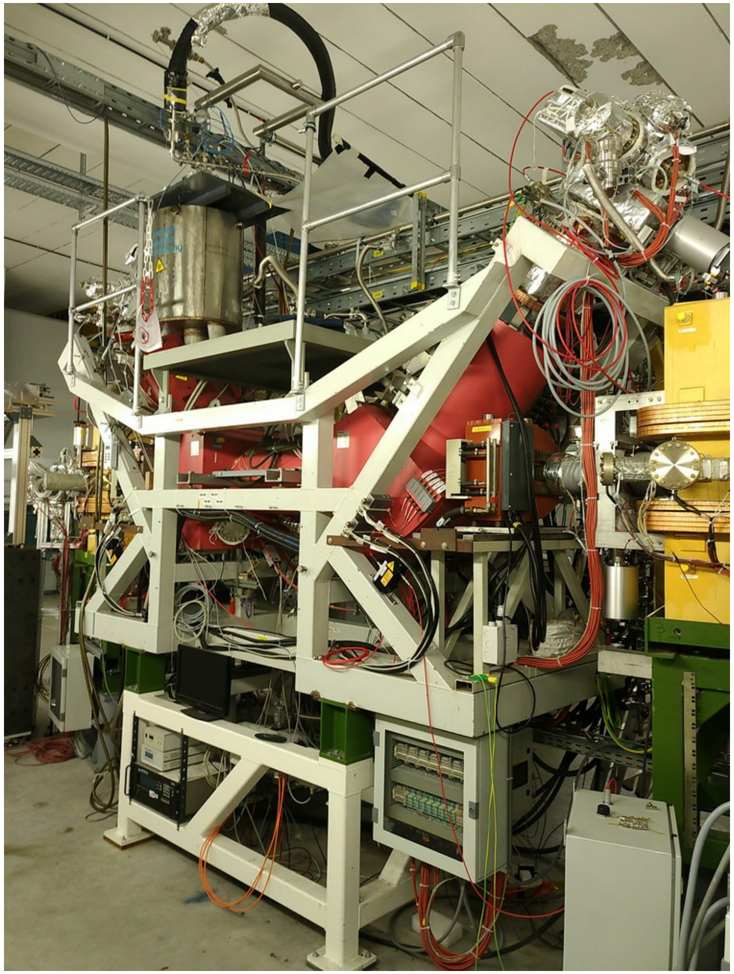
Electron Cooling at CRYRING@ESR



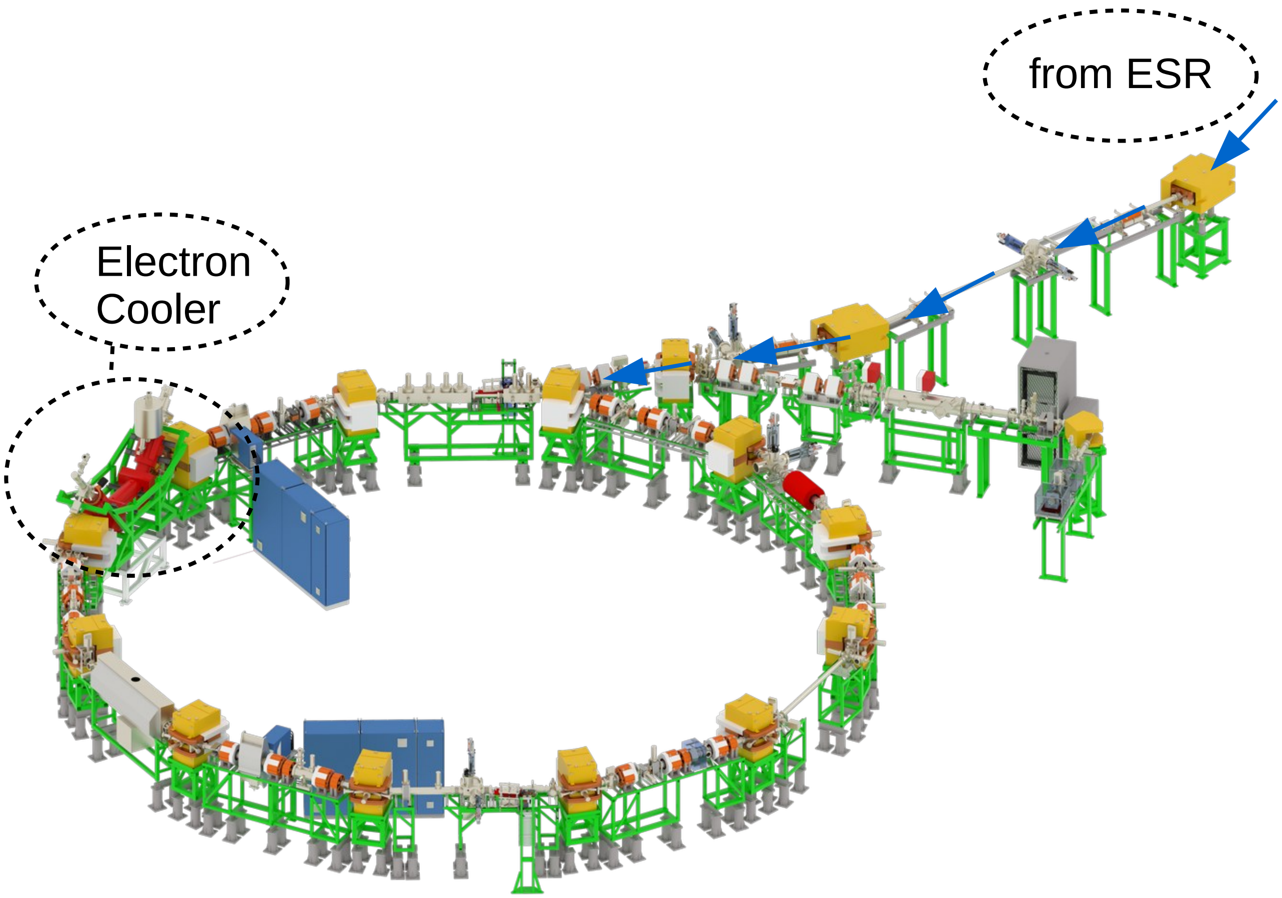
The CRYRING@ESR electron cooler in 2025

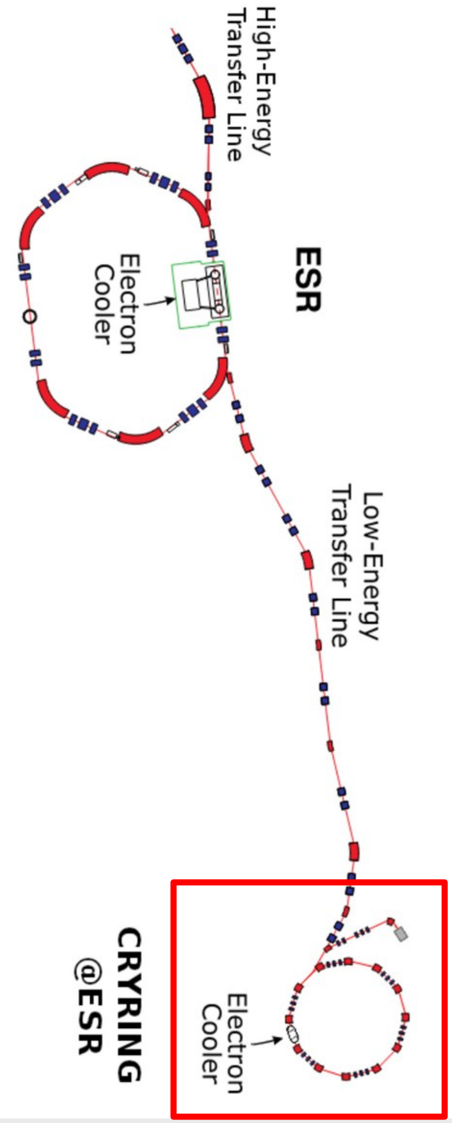
Outline

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

Electron Cooler Performance

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

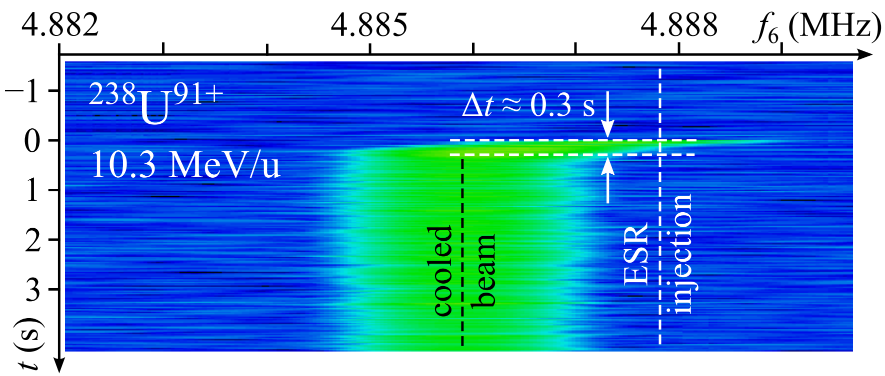




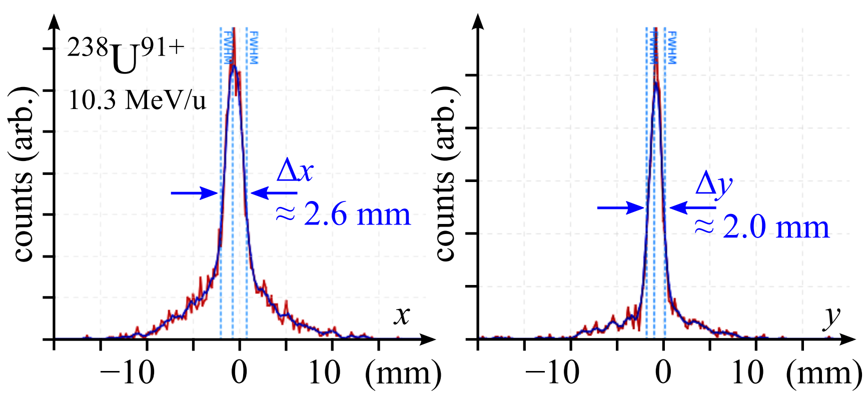
Electron Cooler Performance

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

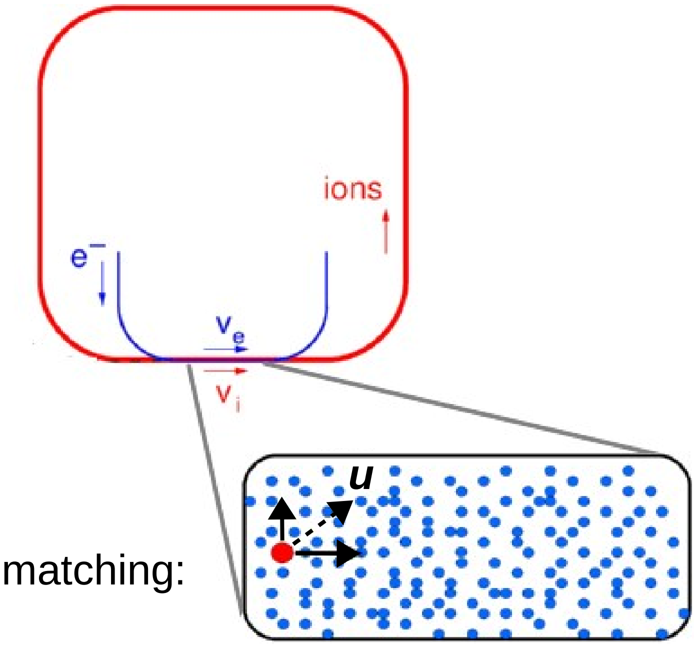
Longitudinal cooling ~ 0.1 s



Beam profiles after 1 s



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

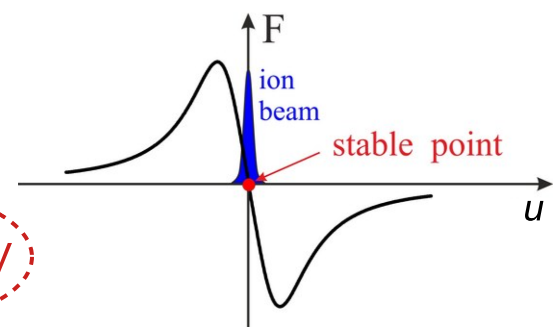


Velocity matching:

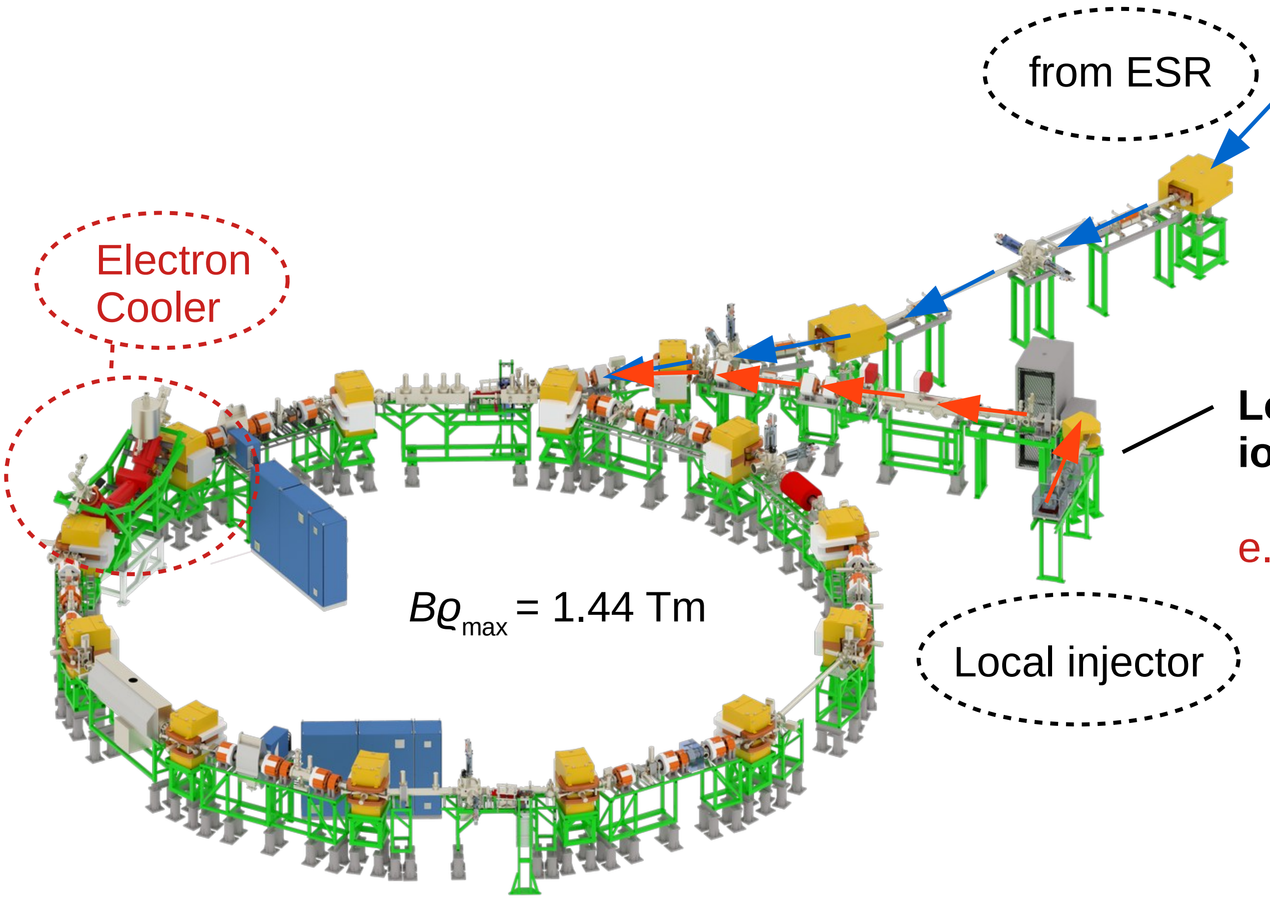
$$E_e = \frac{m_e}{m_i} \cdot E_i$$

$E_i \approx$ 10 MeV/u

$\rightarrow$ $E_e \approx$ 5500 eV



Electron Cooler Performance



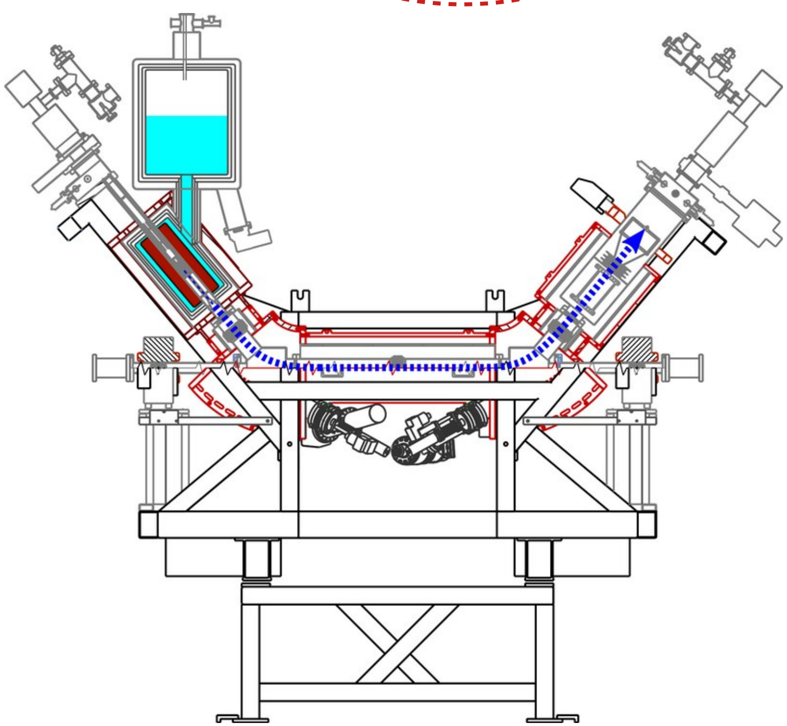
Low- or singly charged ions:

e.g. $^{20}Ne^{2+}$ (0.800 MeV/u)
$^{12}C^{+}$ (0.330 MeV/u)
$^{24}Mg^{+}$ (0.168 MeV/u)
$^{25}Mg^{+}$ (0.155 MeV/u)
…

Electron Cooler Performance

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

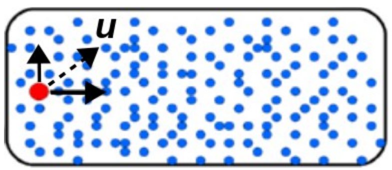
→ $E_e \approx 85$ eV

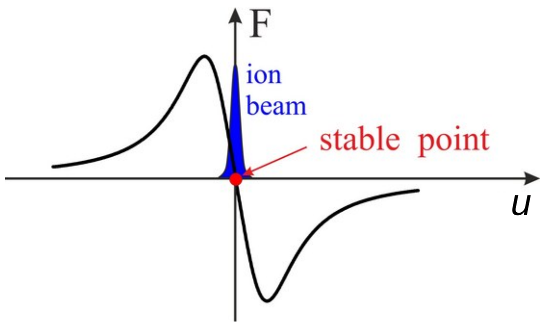


Singly/weakly charged ions:

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

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





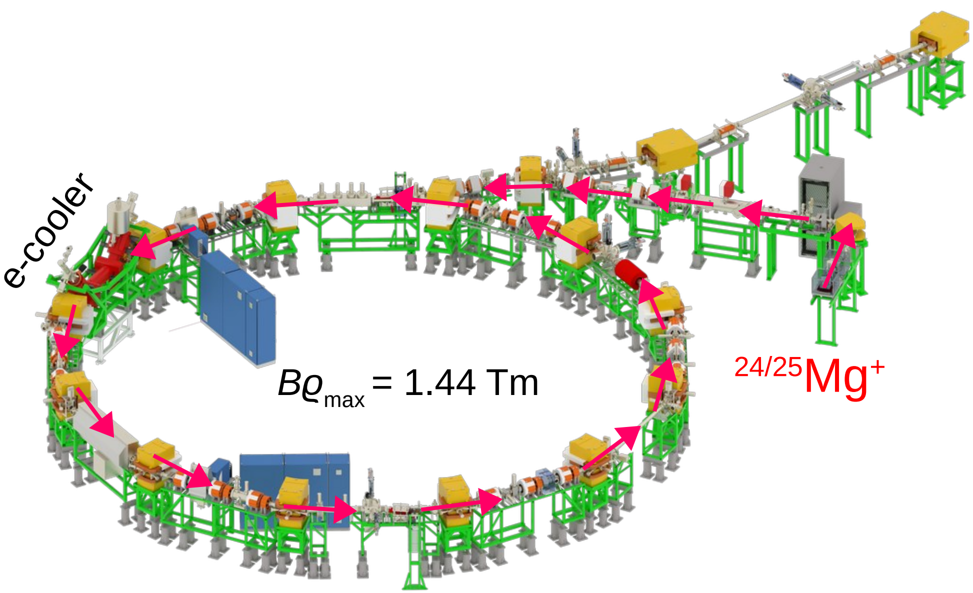
Rate for **low-energy e-cooling**:

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

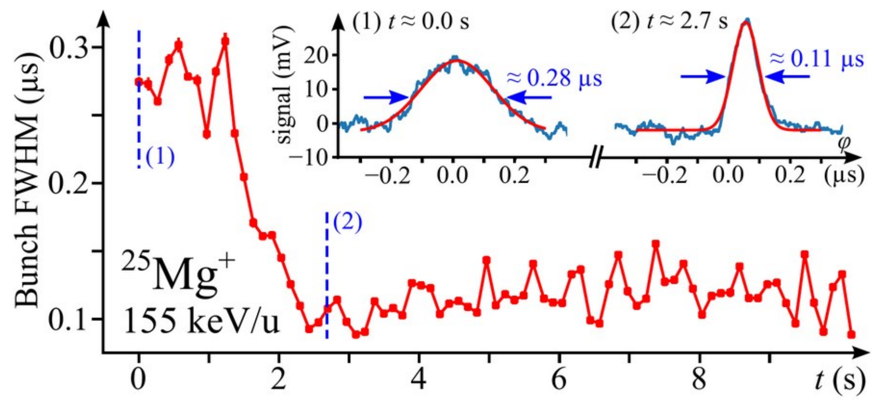
Electron Cooler Performance

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

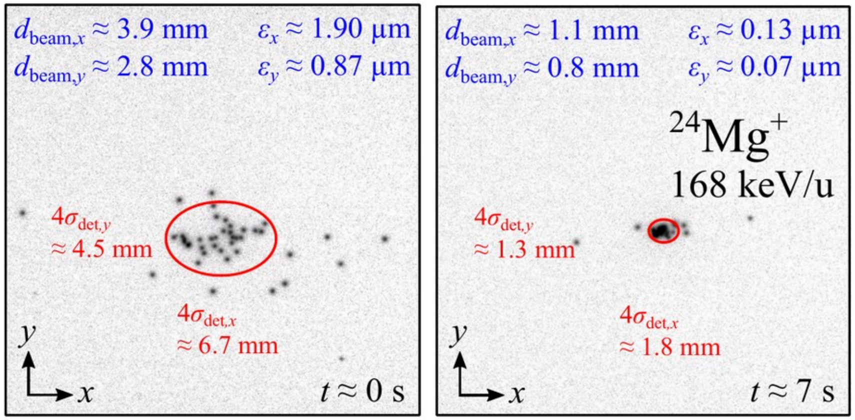
E_e = 92 eV / 85 eV
I_e = 1.7 mA



Longitudinal cooling (bunched)



Transverse cooling (neutral imaging)

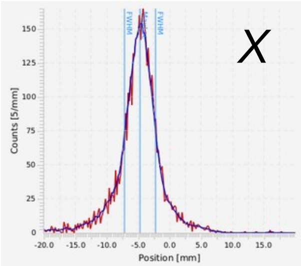


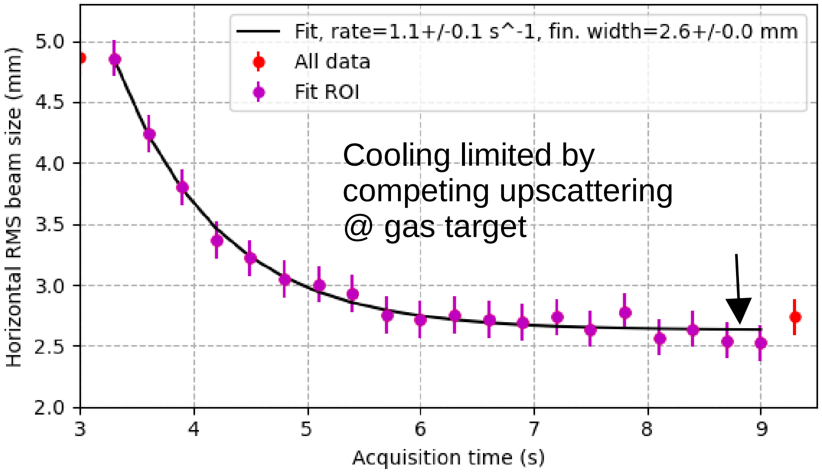
Krantz et al., Proc. IPAC 2021 (2021)

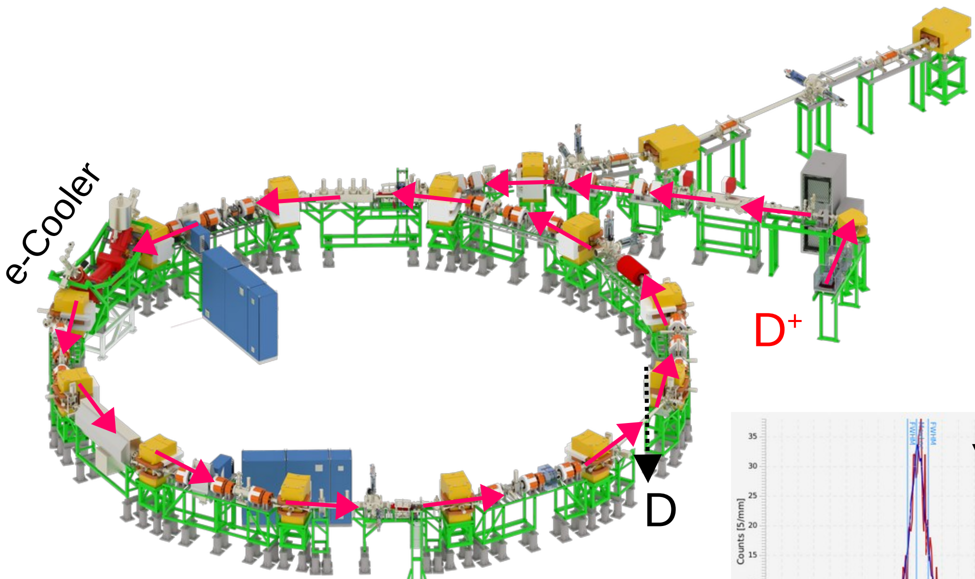
Electron Cooler Performance

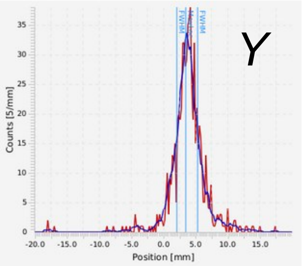
Ultraslow D⁺ @ 0.092 MeV/u

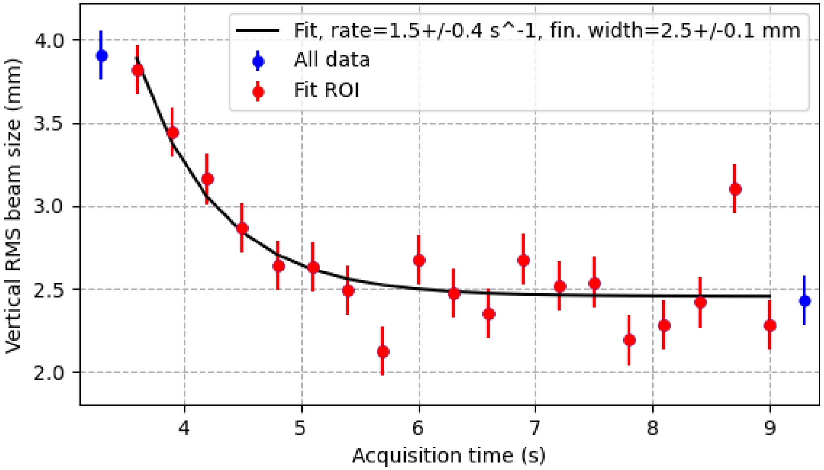
E_e = 50 eV
I_e = 0.5 mA





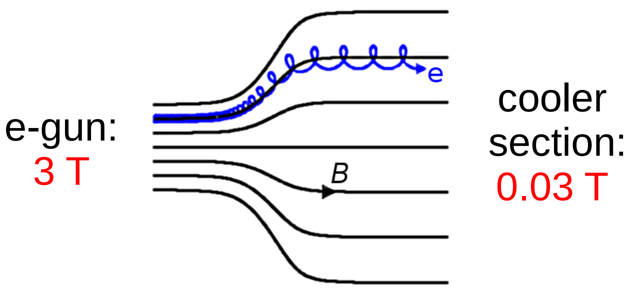


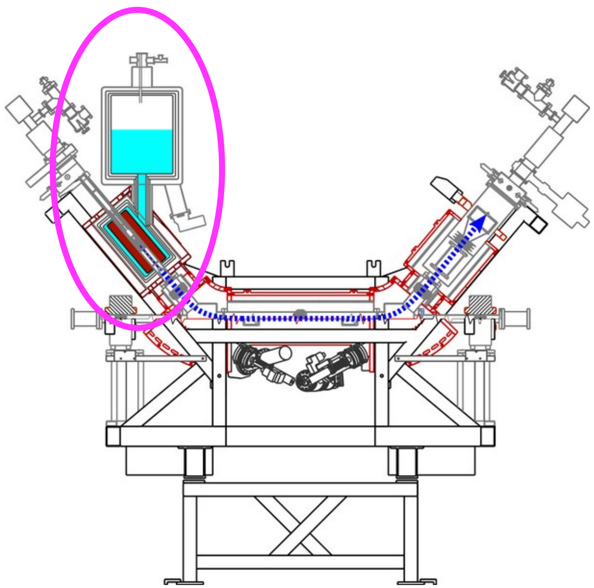


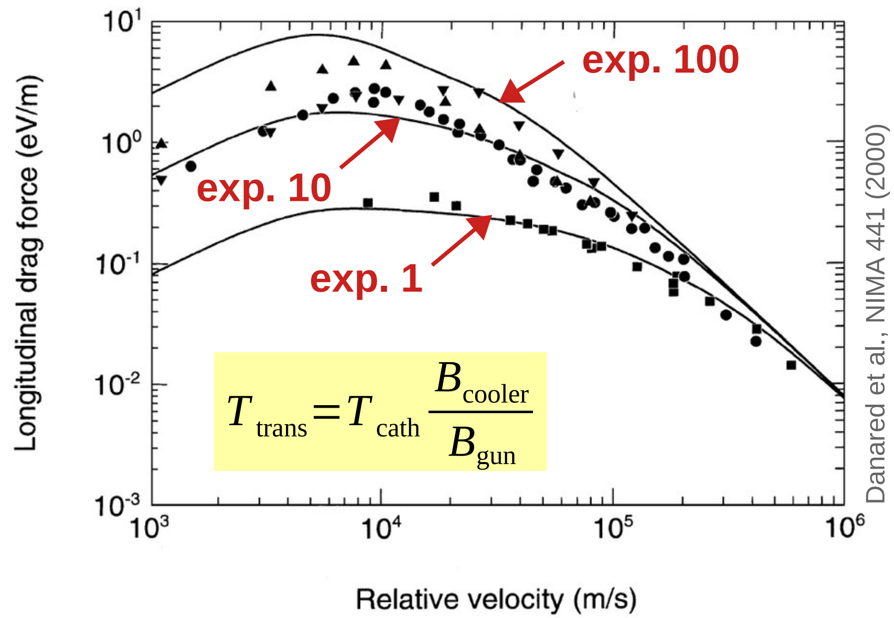


Hardware Upgrades: Cryogenics

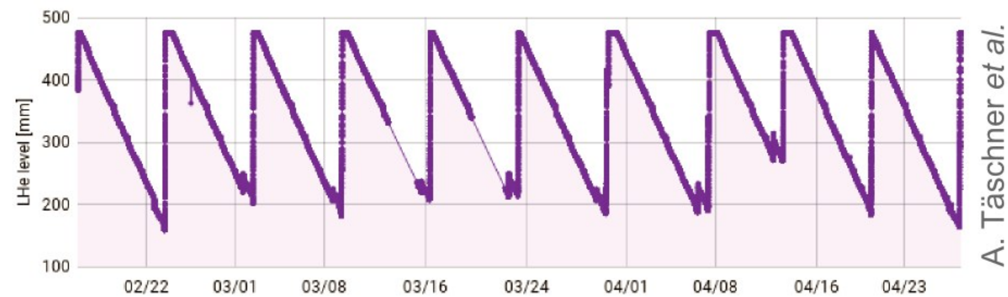
Outstanding feature: 100 x adiabatic expansion





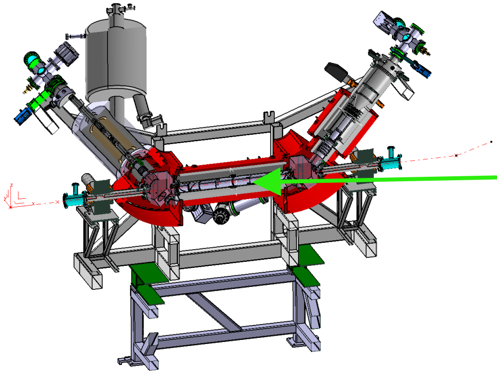


2018 … 2020: Connected s.c. solenoid to closed-loop LHe plant.

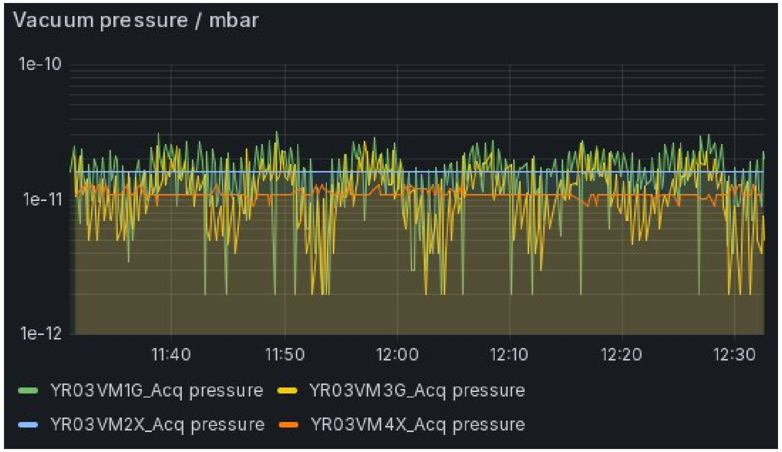


Hardware Upgrades: Vacuum

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



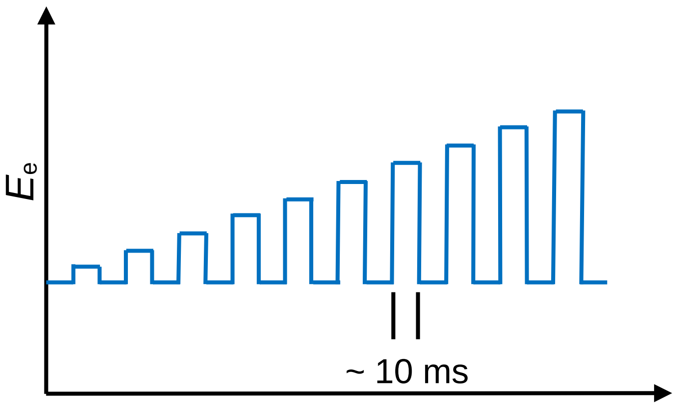
2022/23: Full disassembly of e-cooler.
Replacement of **jackets, pumps, gauges**.

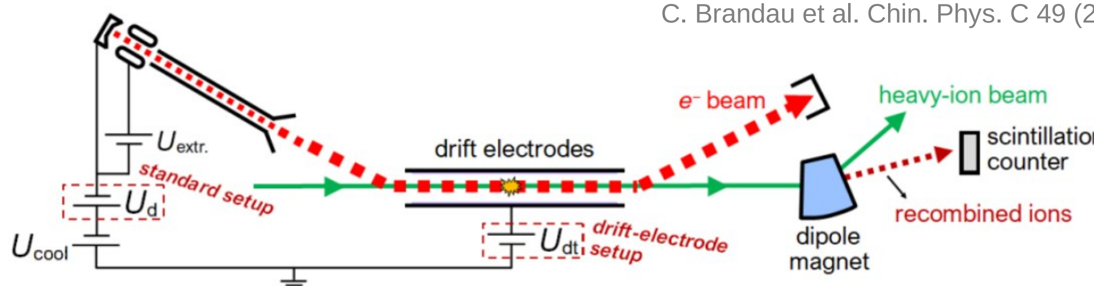


2025: Vacuum ~$1\cdot10^{-11}$ mbar with e-beam on.

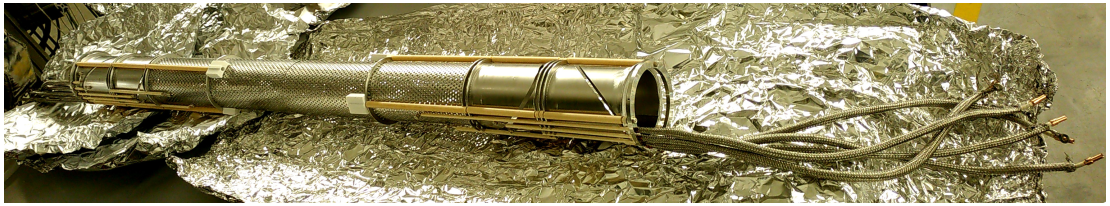
Hardware Upgrades: e-Target Operation

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

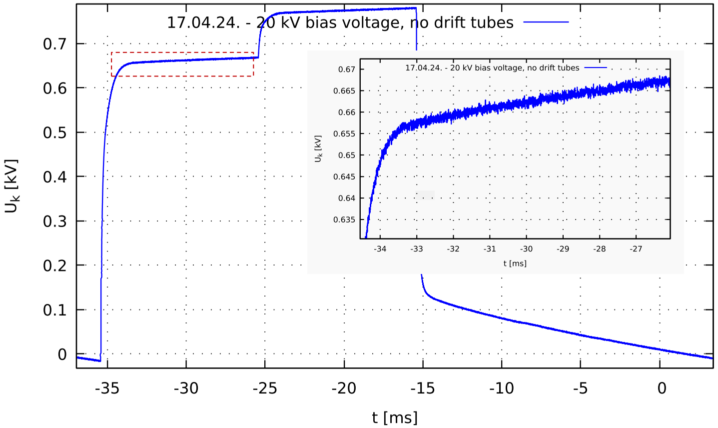


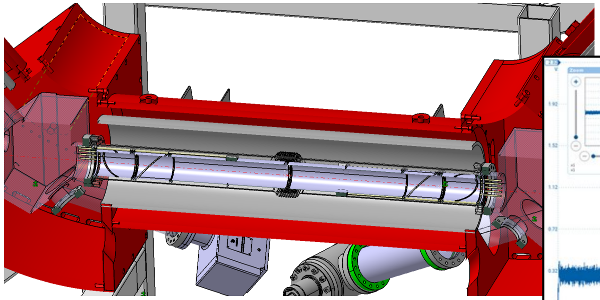


2023: Installed **drift electrodes** in cooler section

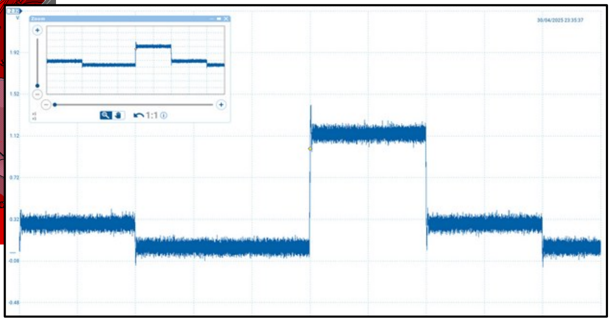


Application of meas. ramp to cooler terminal lead to **instabilities** ...





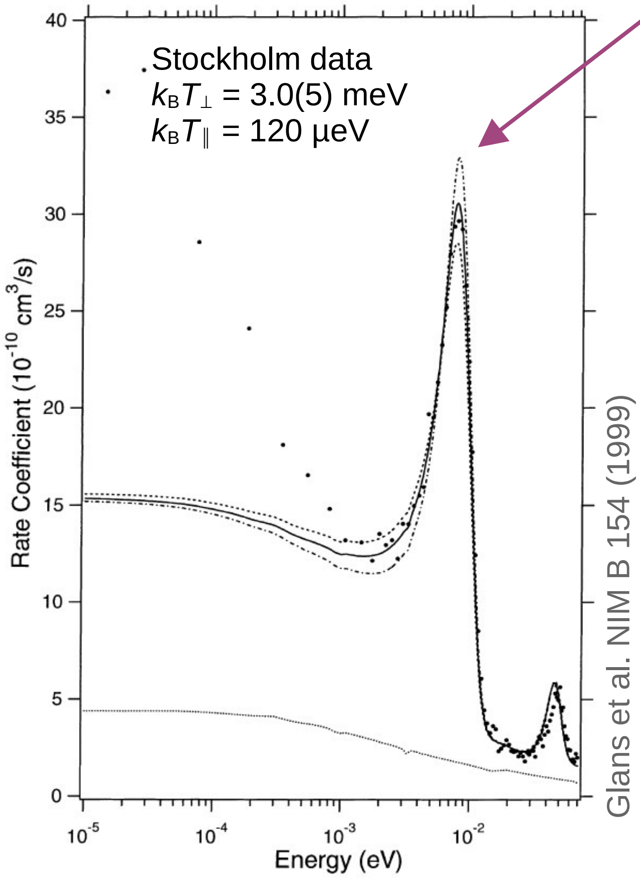
2025: much improved step response!

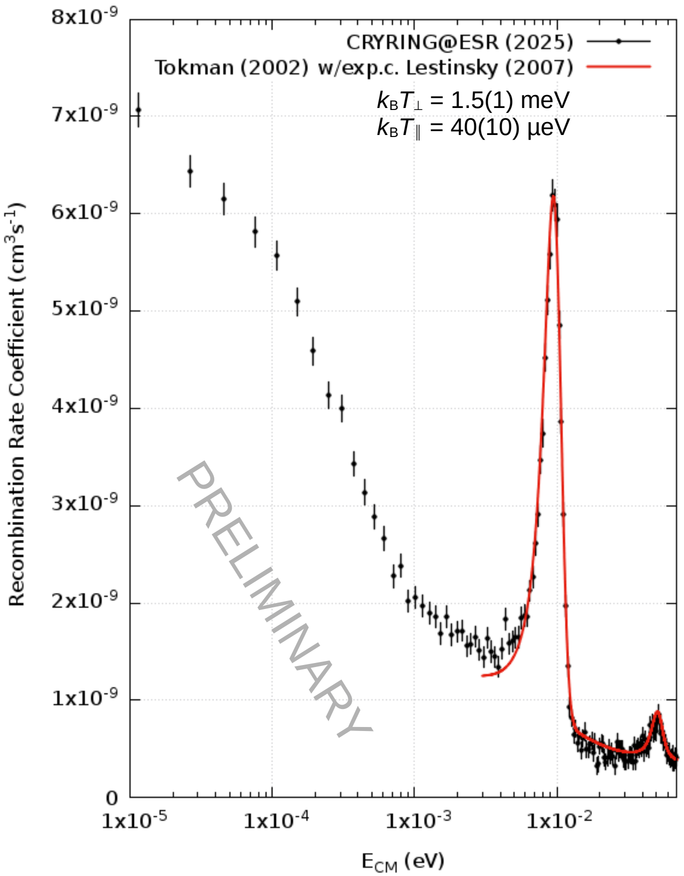


e-Target Operation

Dielectronic Recombination of F^{6+}

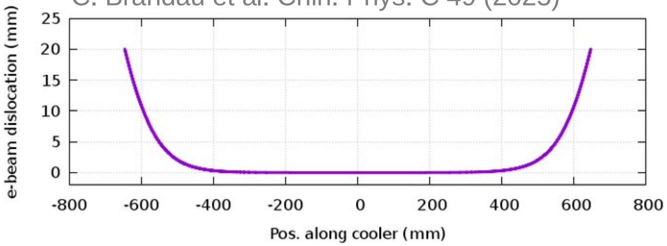
$$^{19}F^{6+} + e \rightarrow {}^{19}F^{5+}\,(2p_{3/2}\,6p_{1/2})_2 \rightarrow {}^{19}F^{5+} + \gamma$$



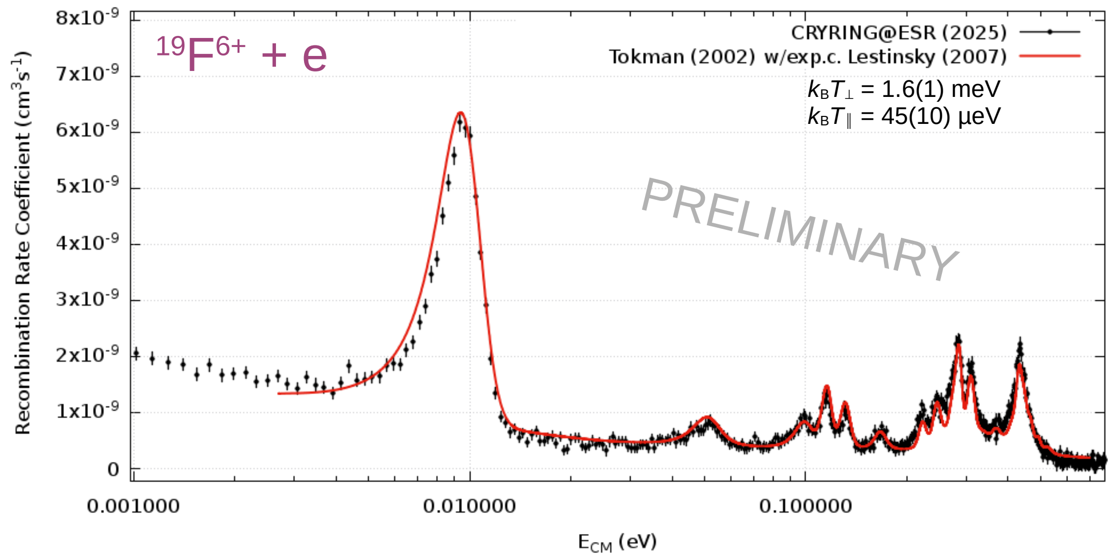


e-Target Operation

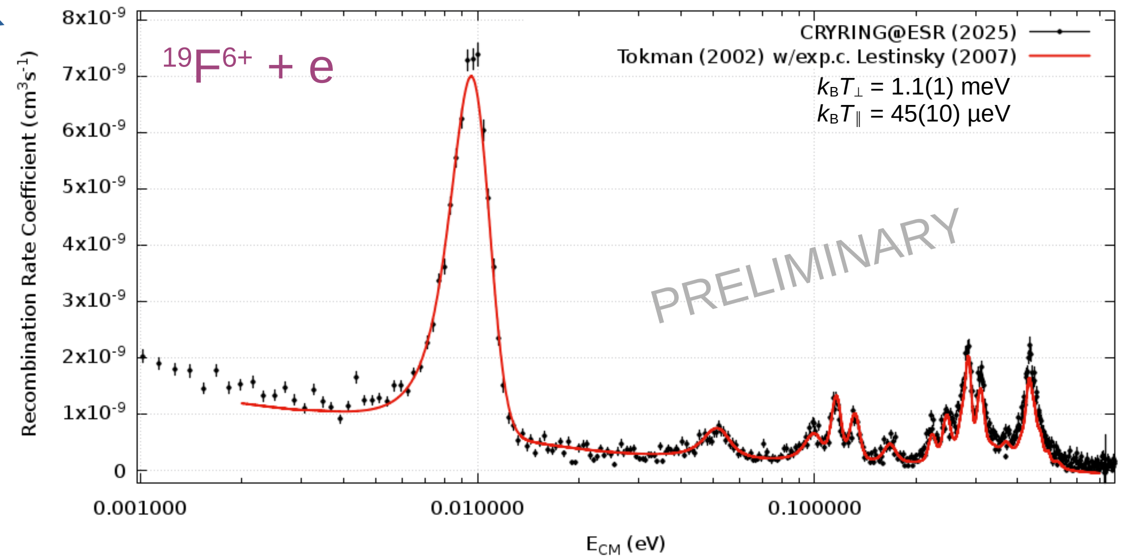
C. Brandau et al. Chin. Phys. C 49 (2025)

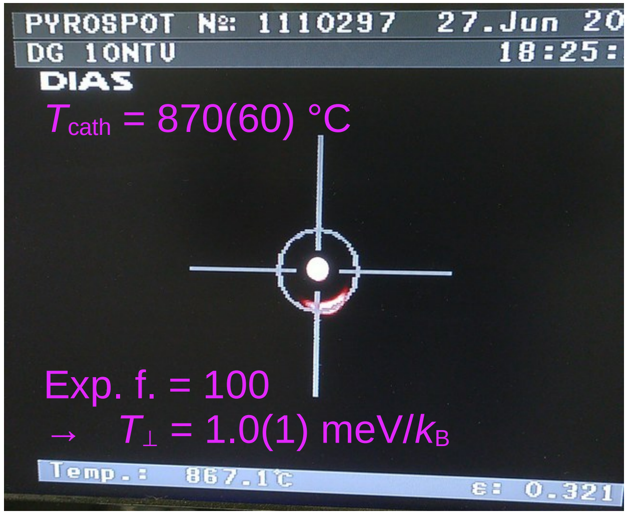


Convolved with
e-beam geometry



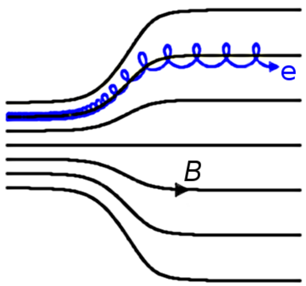
Numerically deconvolved





Challenges Remaining

e-gun:
3 T

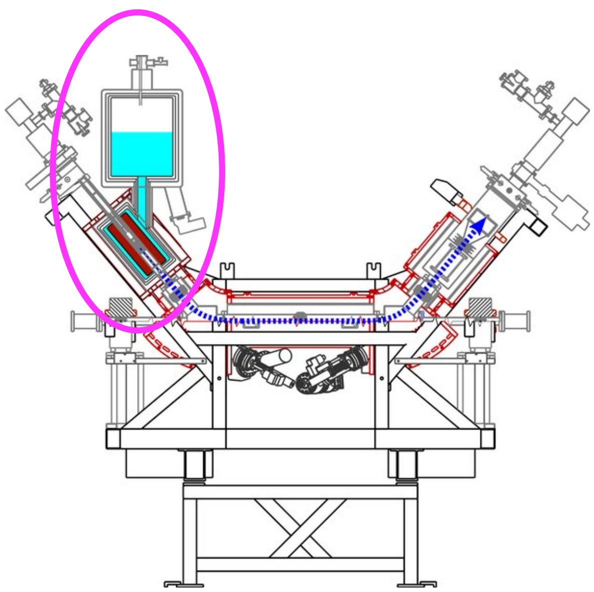


cooler
section:
0.03 T

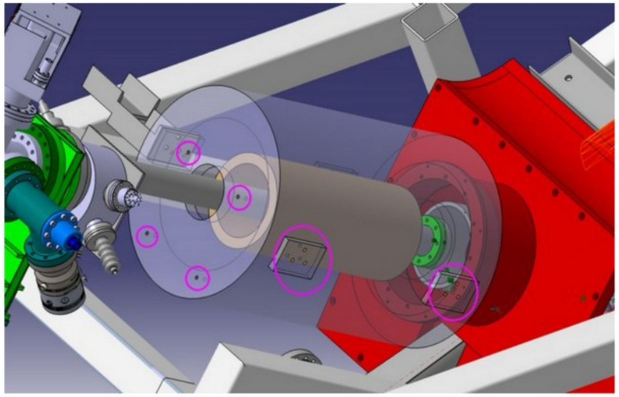
Existing **SCM is old.**

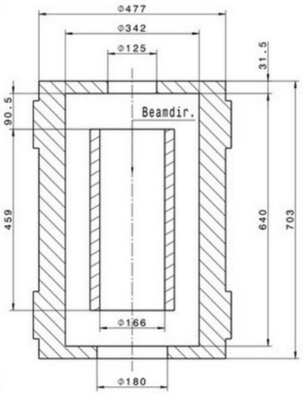
Cryo-system requires intense **maintenance.**

Need to **resupply He** regularly.



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





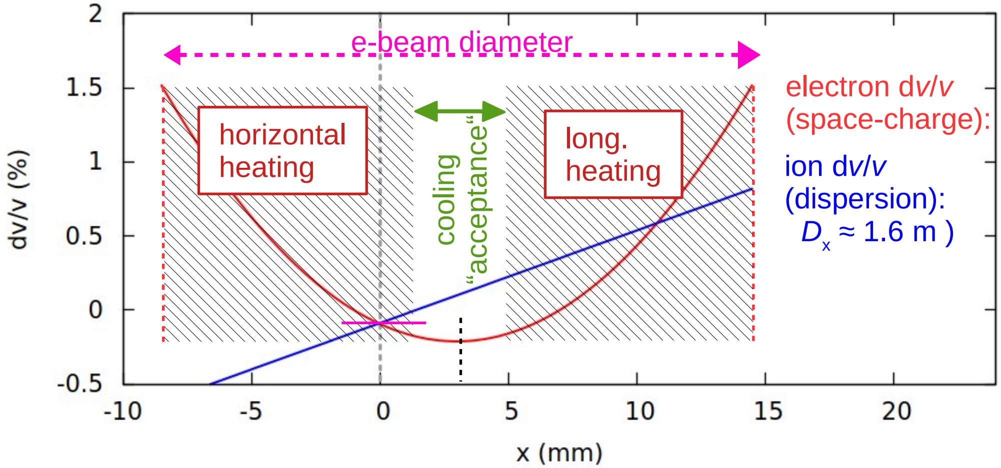
… to be continued!

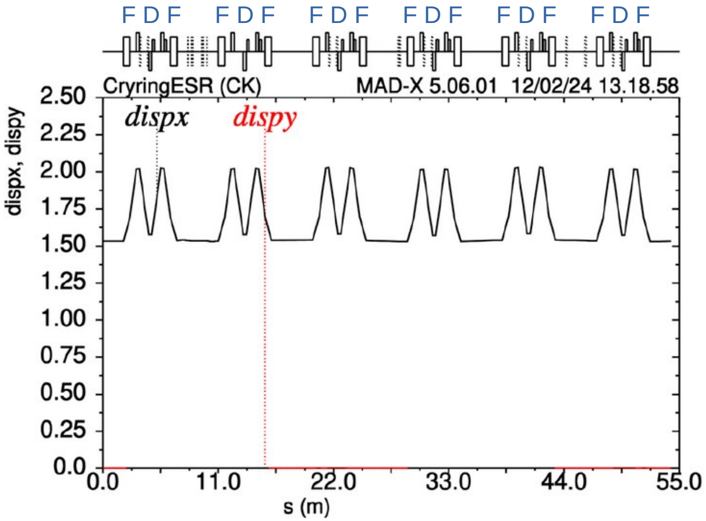
Challenges Remaining

Low energies (1): **Dispersive electron heating**

**Dispersion vs.
e space-charge:**.

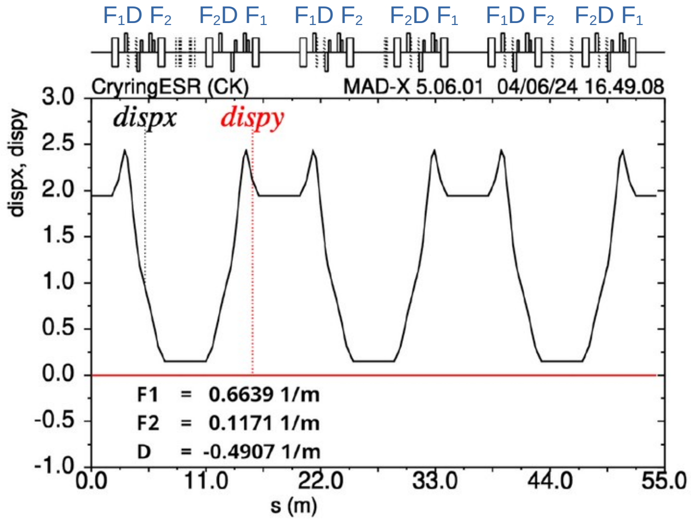
Edges of e-beam
turn into **ion heaters**!





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} ~ 100 kV
ΔU_{tot} ~ 1 V

→ $\Delta E_i / E_i \ll 10^{-4}$!!

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