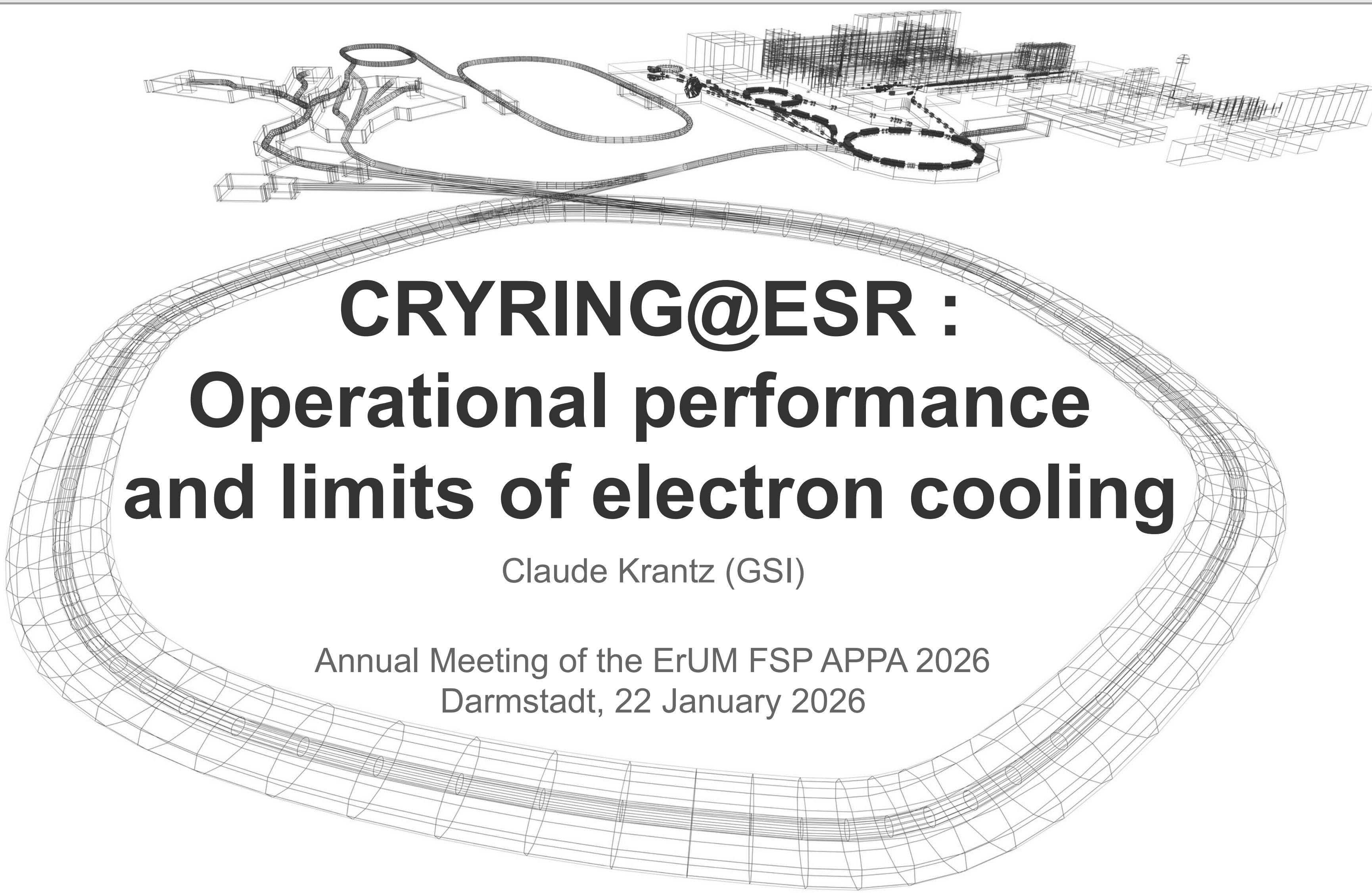
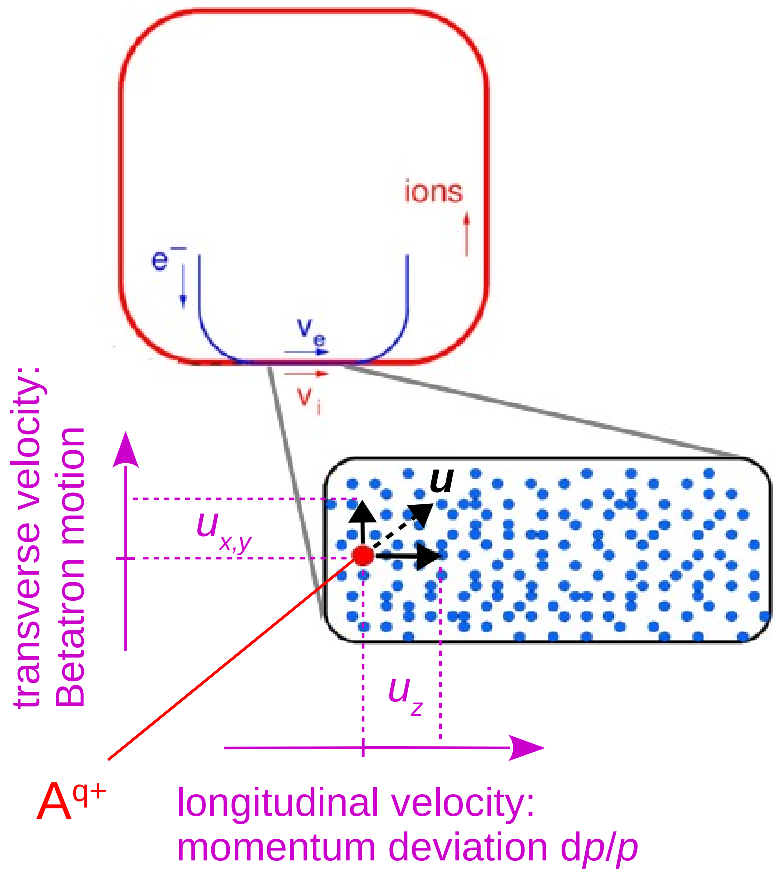


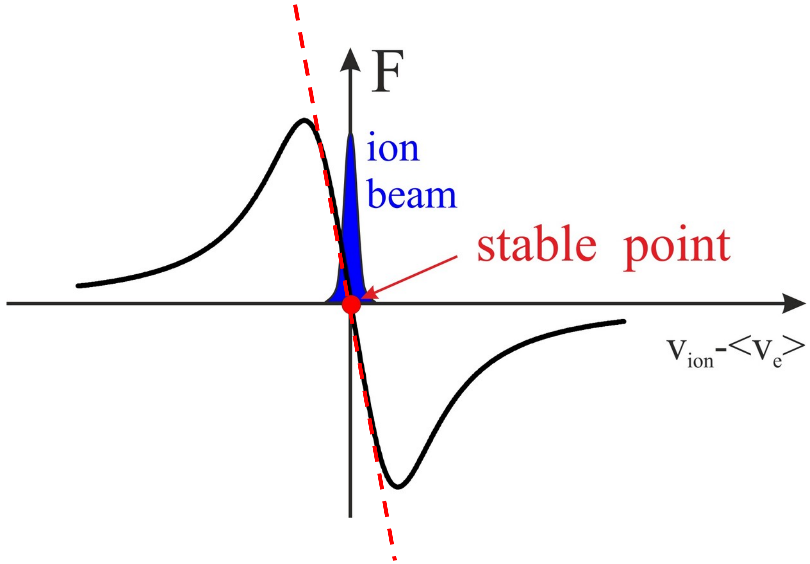
CRYRING@ESR : Operational performance and limits of electron cooling

Claude Krantz (GSI)

Annual Meeting of the ErUM FSP APPA 2026
Darmstadt, 22 January 2026

Electron cooling

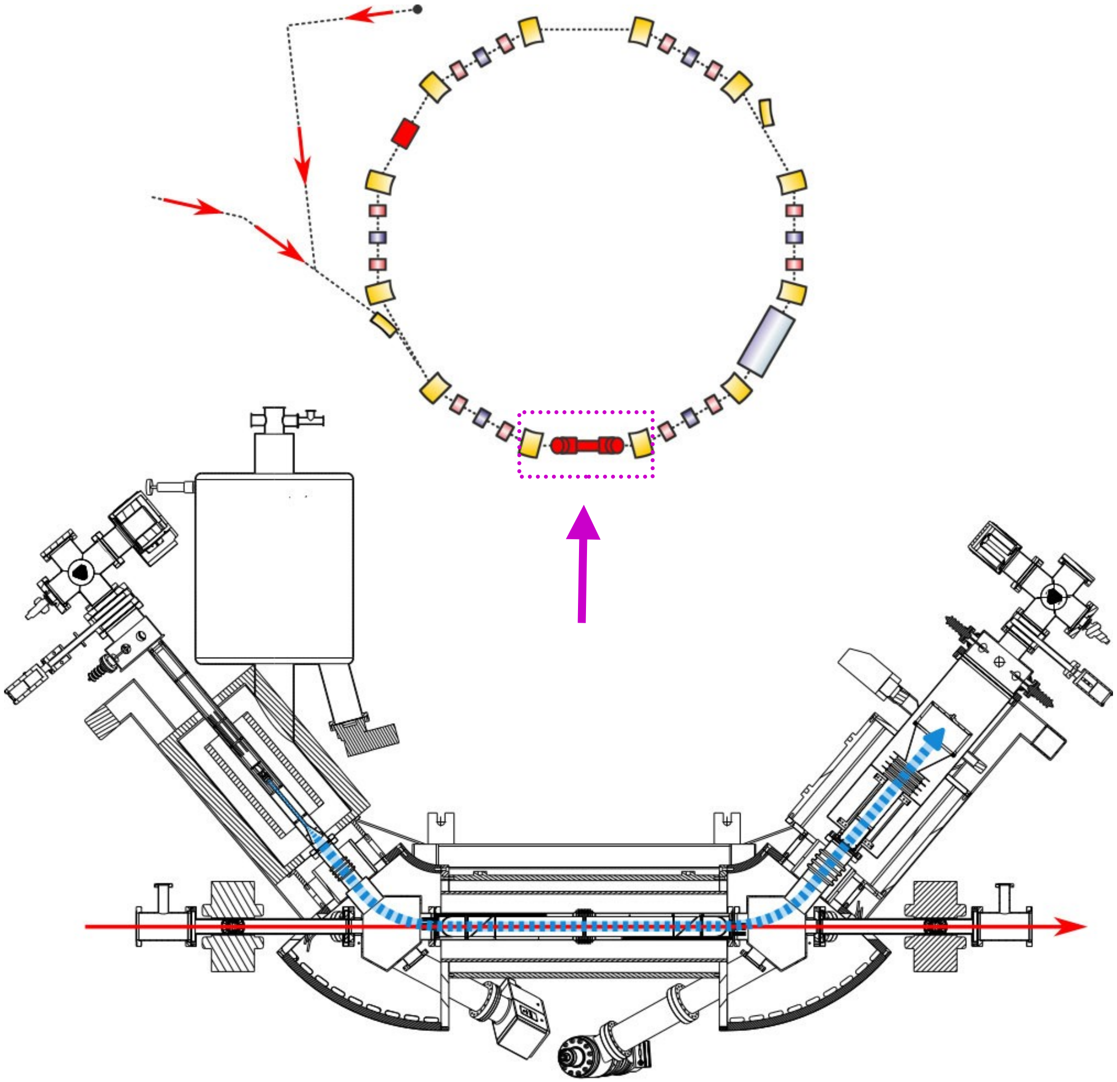


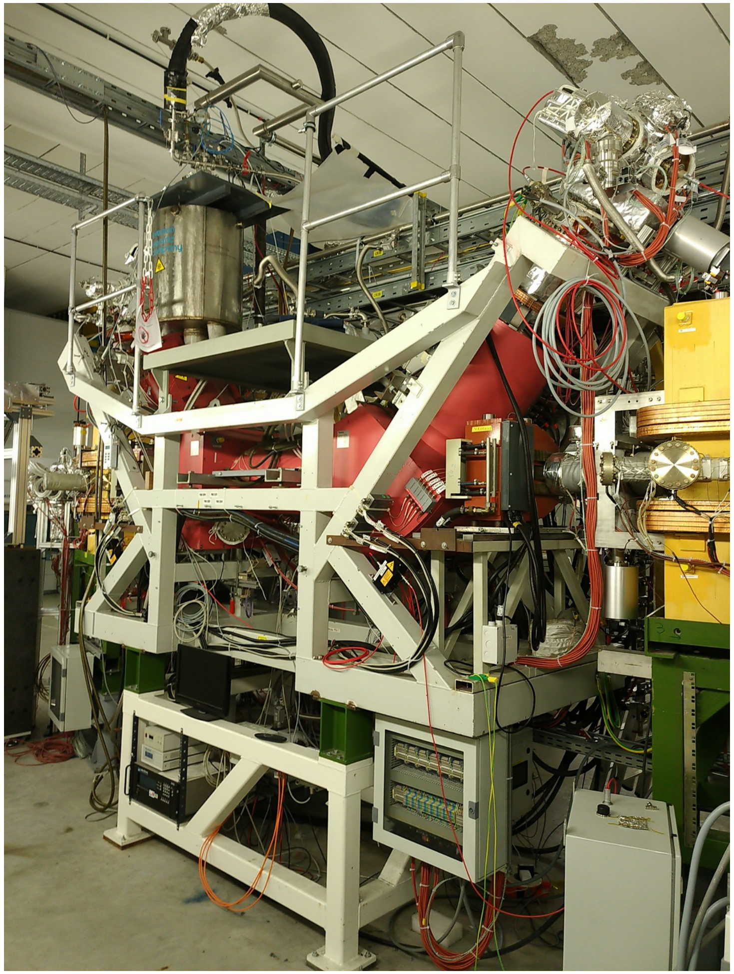


cooling
rate:

$$\tau_{\text{cool}}^{-1} \propto \frac{q_{\text{ion}}^2}{m_{\text{ion}}} \times \frac{n_e}{T_e^{3/2}}$$

The CRYRING@ESR electron cooler

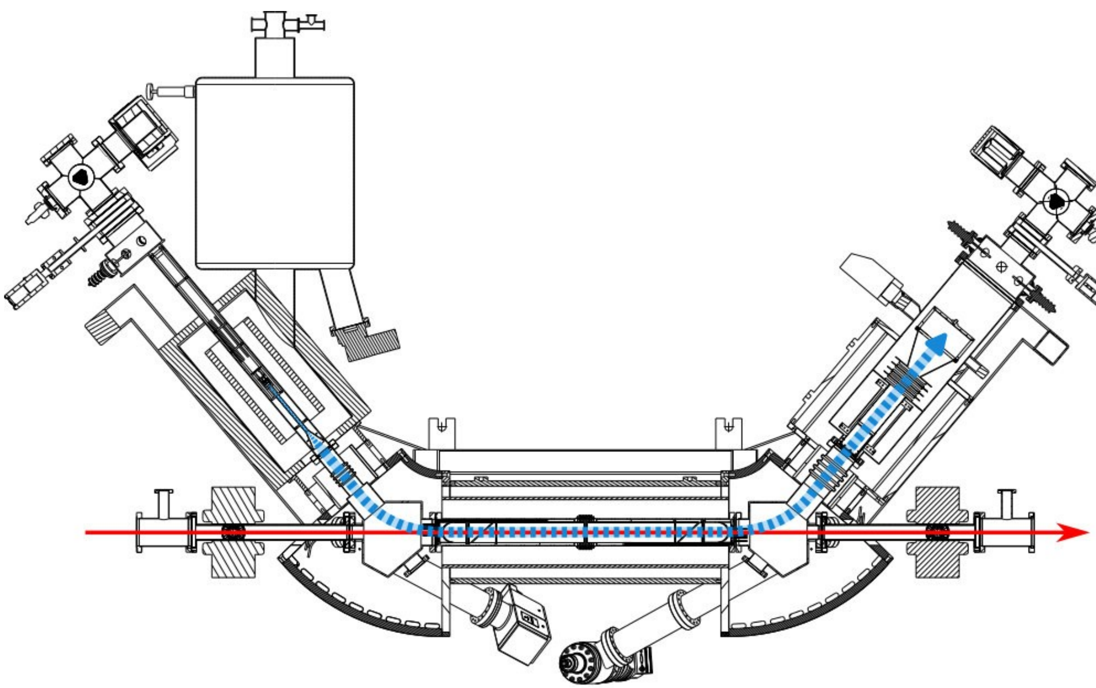




The CRYRING@ESR electron cooler in 2025

The CRYRING@ESR electron cooler

	rated max.	typical max.	CRYRING $B\varrho$ limit: D^+	CRYRING $B\varrho$ limit: $^{238}U^{92+}$
U_{cool}	7500 V	~6600 V		
E_{ion}/A	13.6 MeV/u	~12.0 MeV/u	25.6 MeV/u	14.8 MeV/u

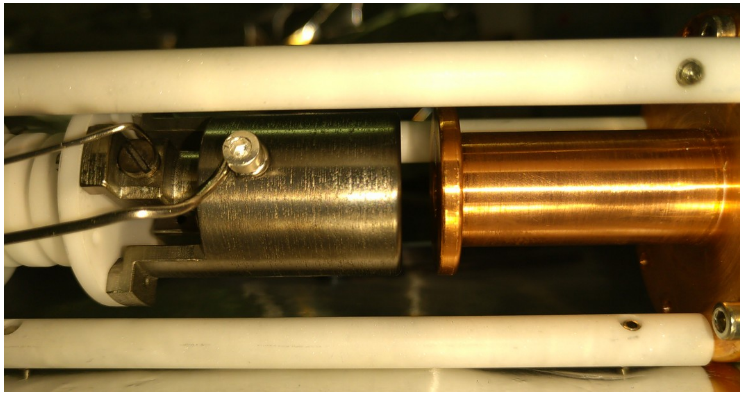


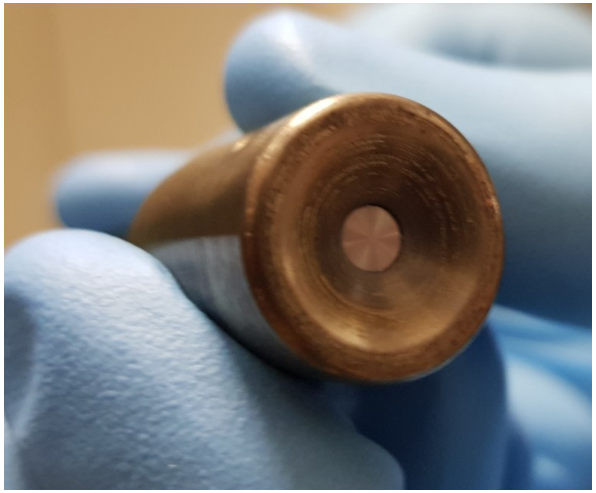
For ESR-injected beams cooler terminal voltage is typically the limiting factor for E_{ion}.

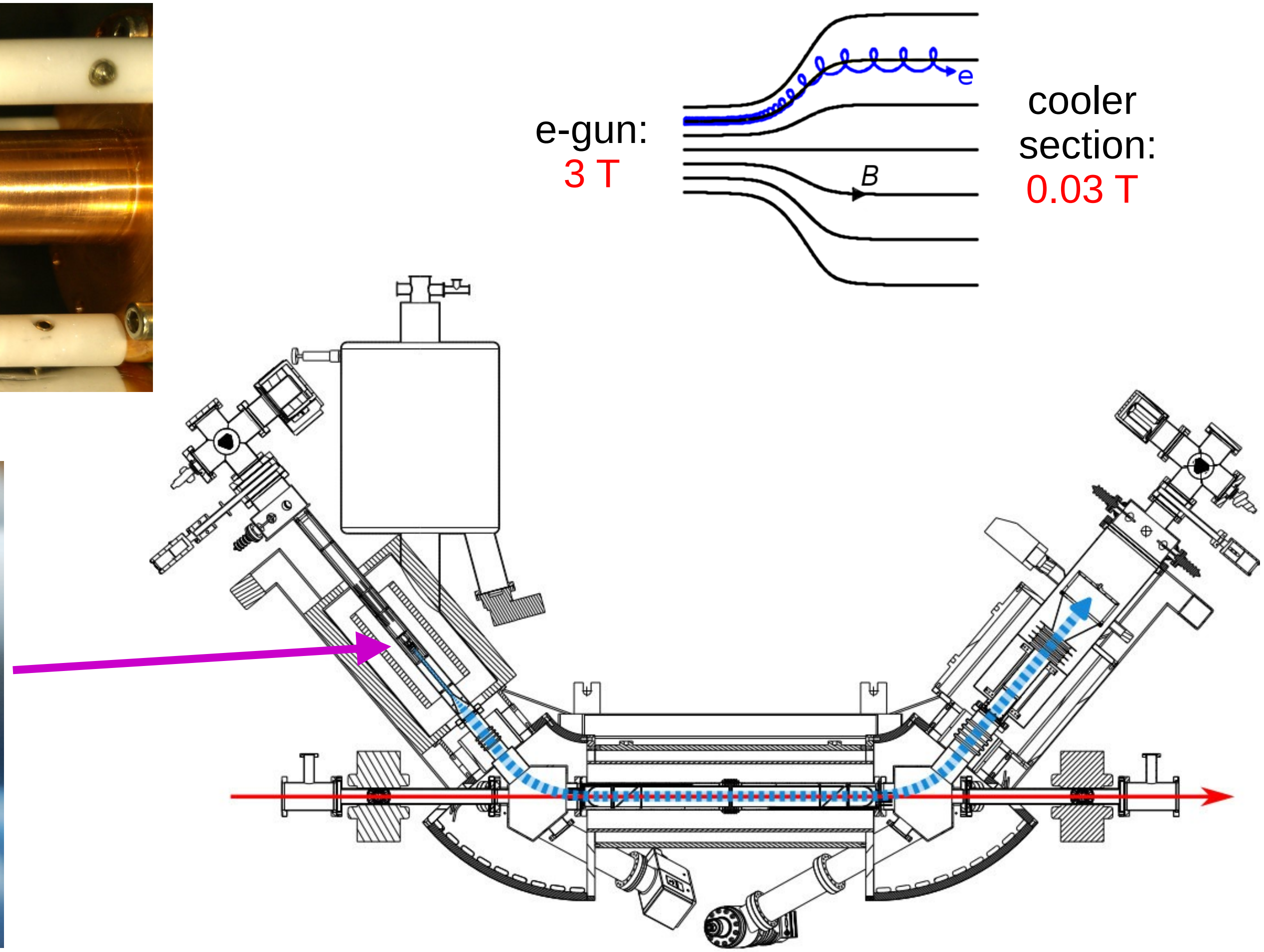
$$\beta_e \stackrel{!}{=} \beta_{ion}$$

The CRYRING@ESR electron cooler

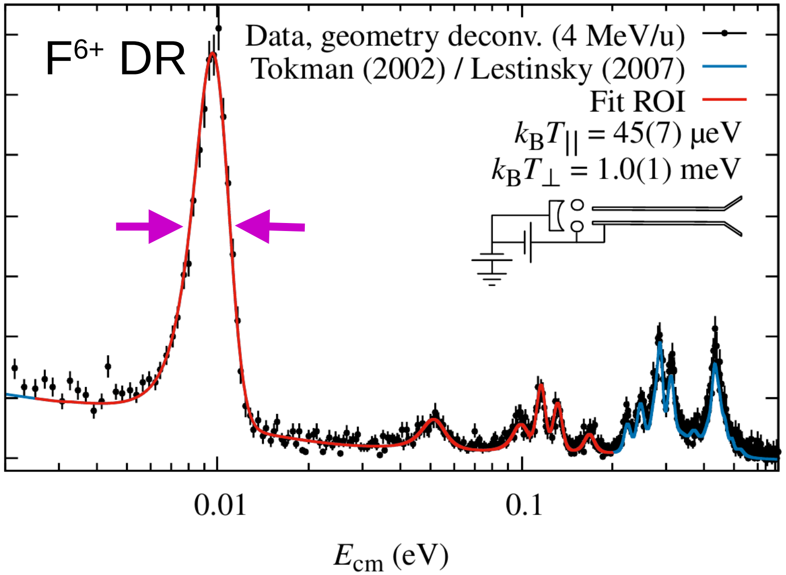
To allow for **100x magnetic expansion** e-gun is *tiny*! ⌀ 4 mm → ⌀ 40 mm





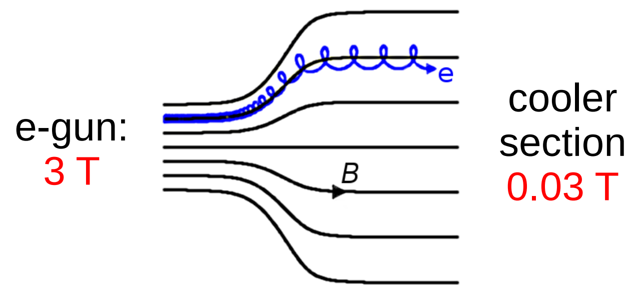


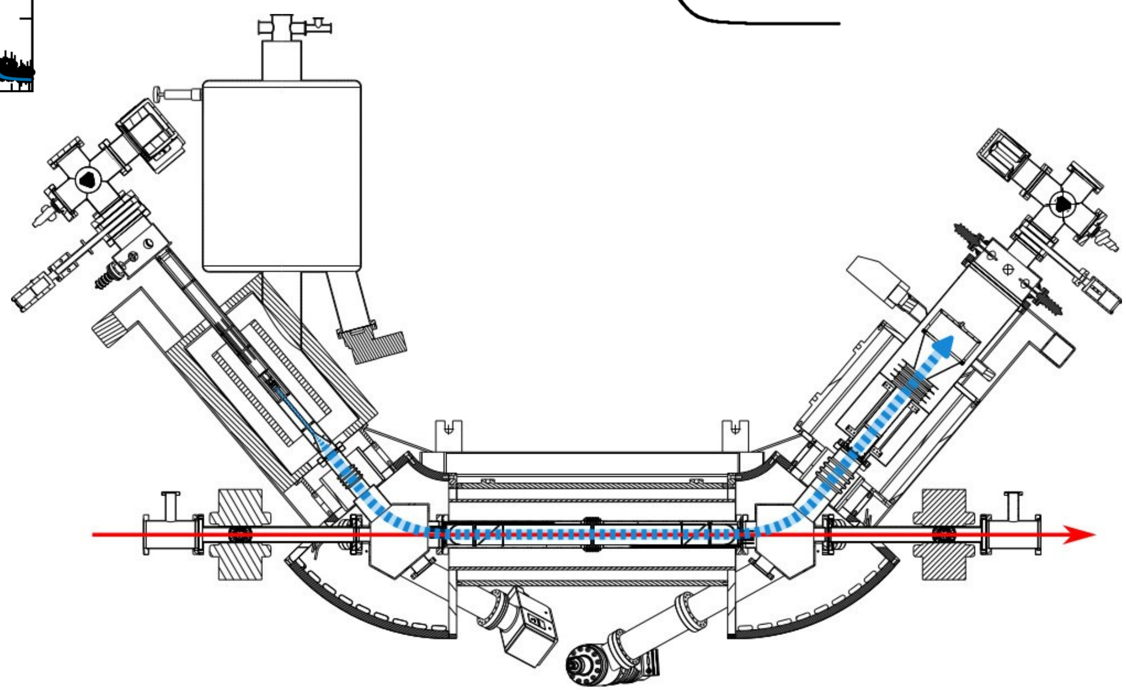
The CRYRING@ESR electron cooler



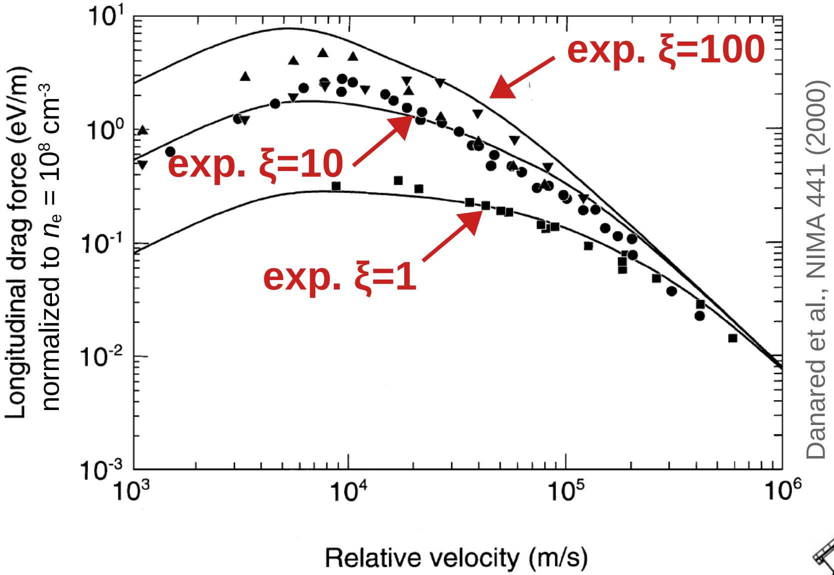
Krantz et al., t.b.p.

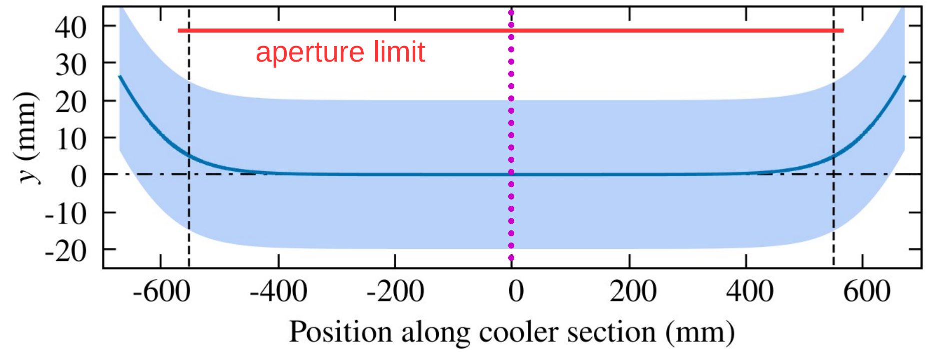
$T_{cath.} \approx 100$ meV/k_B → $T_{e,\perp} \approx 1$ meV/k_B

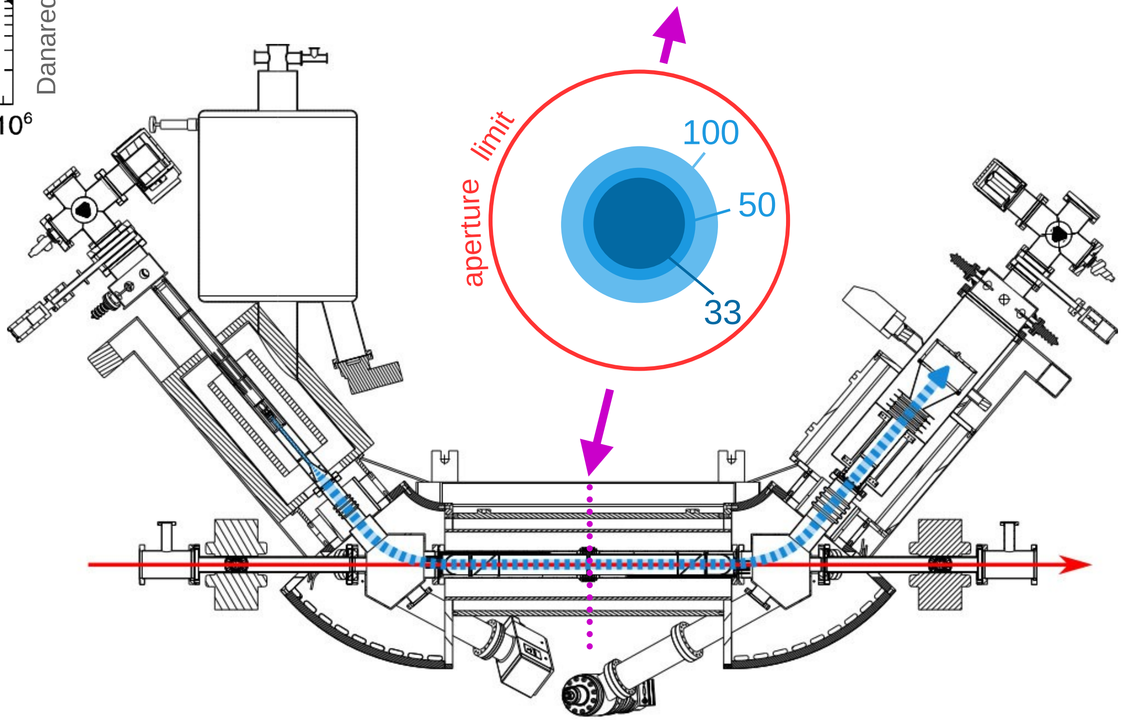




The CRYRING@ESR electron cooler







cooling rate:

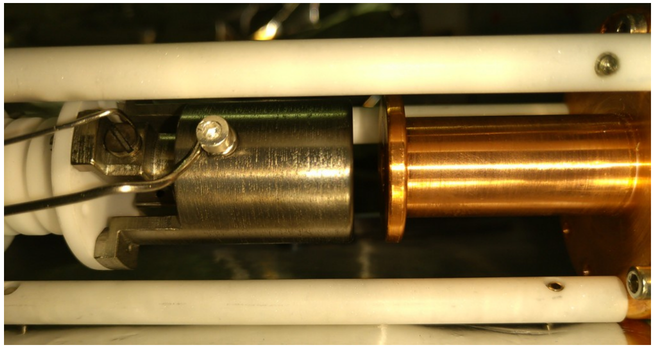
$$\tau_{\text{cool}}^{-1} \propto \frac{q_{\text{ion}}^2}{m_{\text{ion}}} \times \frac{n_e}{T_e^{3/2}}$$

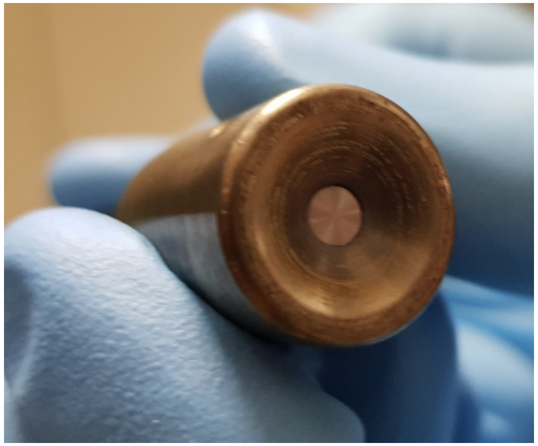
$T_{e,\perp} \sim \xi^{-1}$

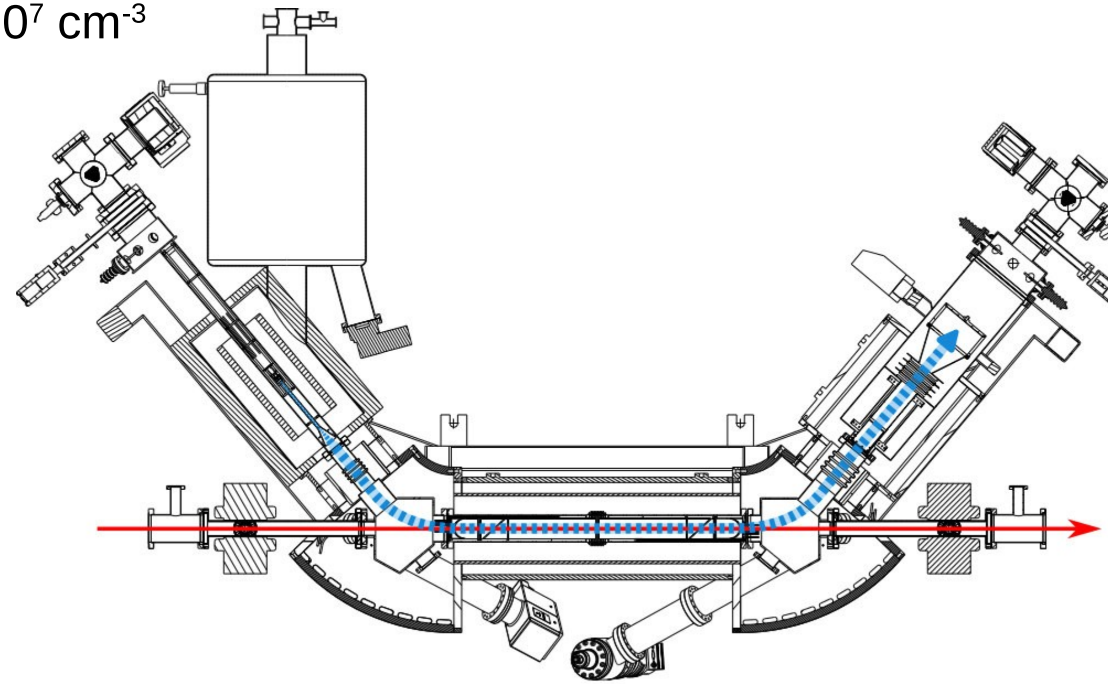
BUT: $n_e \sim \xi^{-1}$

The CRYRING@ESR electron cooler

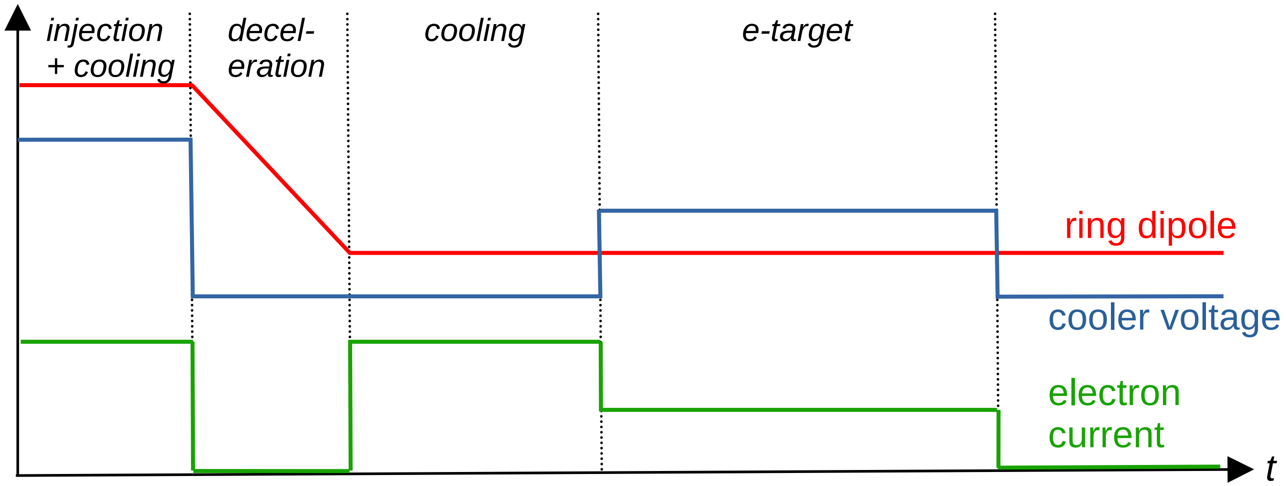
	rated max. sparking limit	typical max. @ 900°C
I_e	110 mA	50...60 mA
$U_{extract}$	1600 V	900...1000 V
n_e ξ=50, 10 MeV/u	2.5×10^7 cm^{-3}	1.3×10^7 cm^{-3}

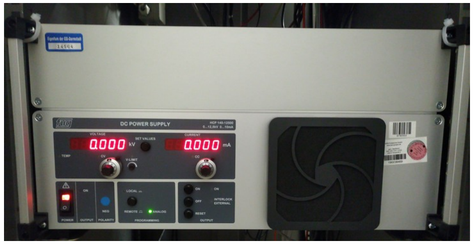






The CRYRING@ESR electron cooler





Quite flexible operation using **accelerator controls**

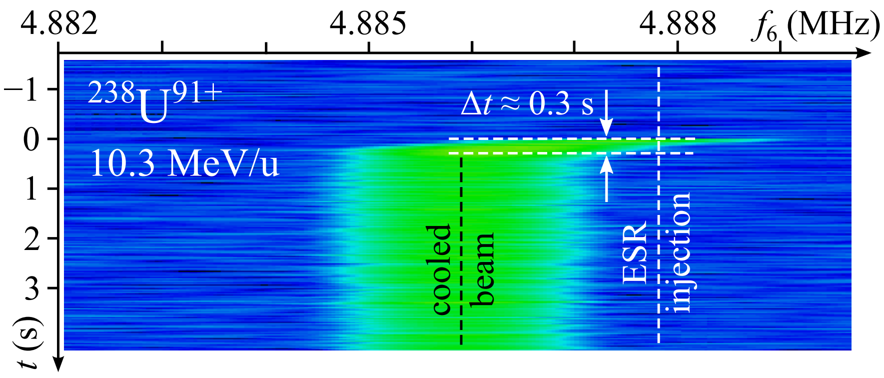
New **high-precision HV supply** (< 10 ppm)

High-precision (~ 1 ppm) **voltage dividers** (Uni Münster)

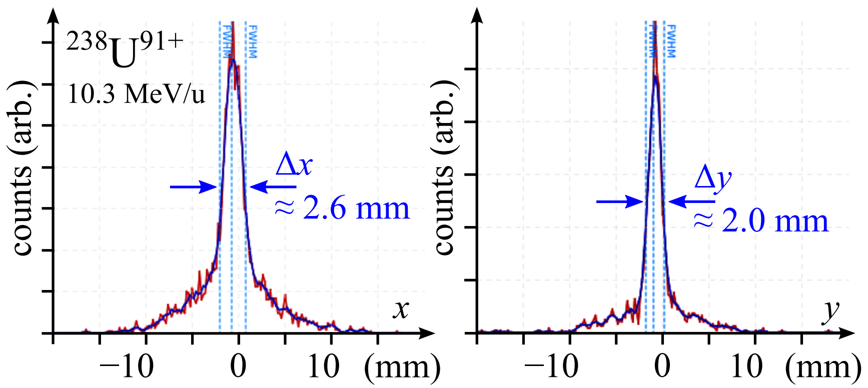
V. Hannen et al.

Electron cooler performance

Longitudinal cooling ~ 0.1 s



Beam profiles after 1 s



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

Highly-charged ions:

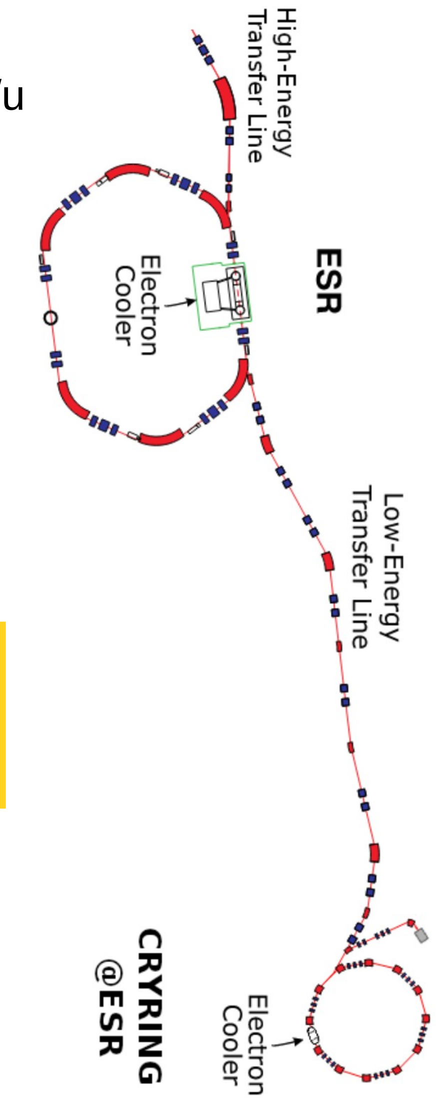
e.g. $^{298}U^{91+}$ @ 10 MeV/u

$$\beta_e \overset{!}{=} \beta_{ion}$$

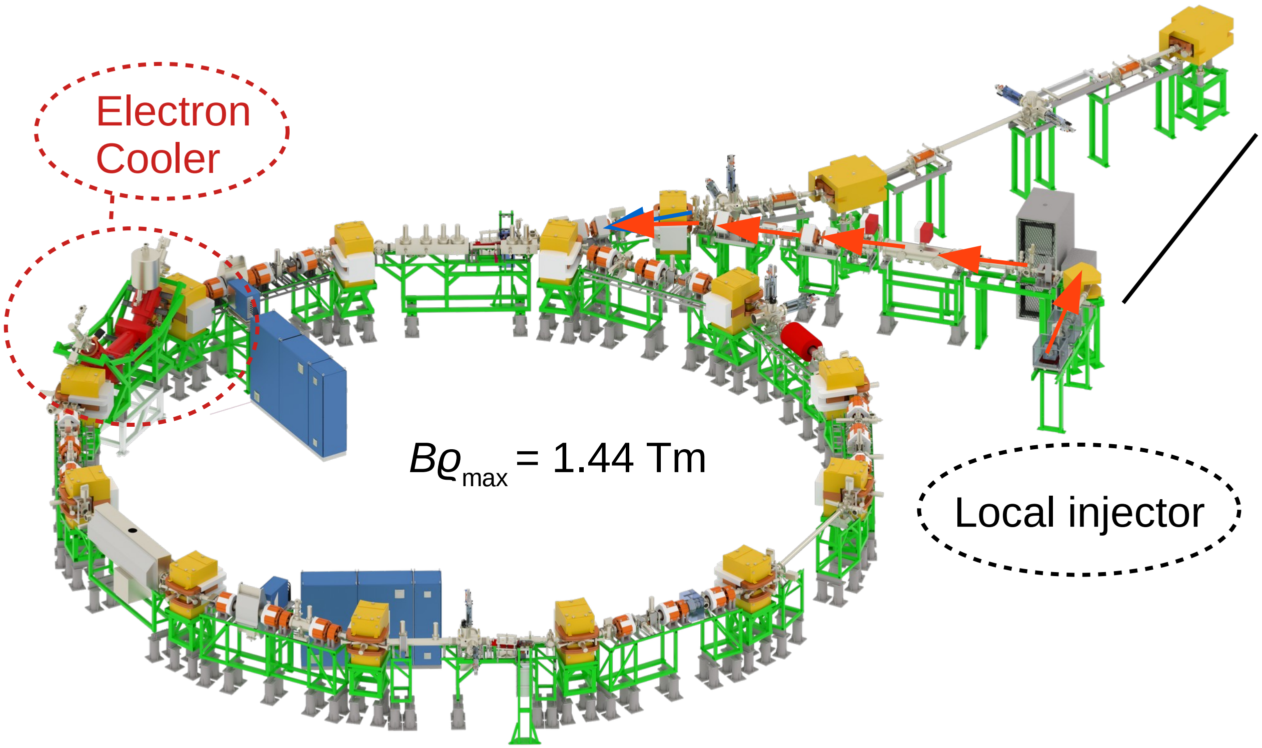
$E_i \approx 10$ MeV/u

$\rightarrow E_e \approx 5500$ eV

$$\tau_{cool}^{-1} \propto \frac{q_{ion}^2}{m_{ion}} \times \frac{n_e}{T_e^{3/2}}$$



Electron cooler performance



Low- or singly charged ions:

$^{16}O^{2+}$	1.56 MeV/u →	870 V
$^{20}Ne^{2+}$	0.80 MeV/u →	450 V
$^{12}C^{+}$	0.33 MeV/u →	190 V
$^{24}Mg^{+}$	0.17 MeV/u →	100 V
$^{25}Mg^{+}$	0.16 MeV/u →	93 V
…		

<u>low</u> cooler voltage ($\beta_e = \beta_{ion}$) $$E_e = \frac{m_e}{m_i} \cdot E_i \approx e\,U_{cool}$$

e-current s.-c. limited ("perveance"): $$I_e \sim U_{cool}^{3/2}$$

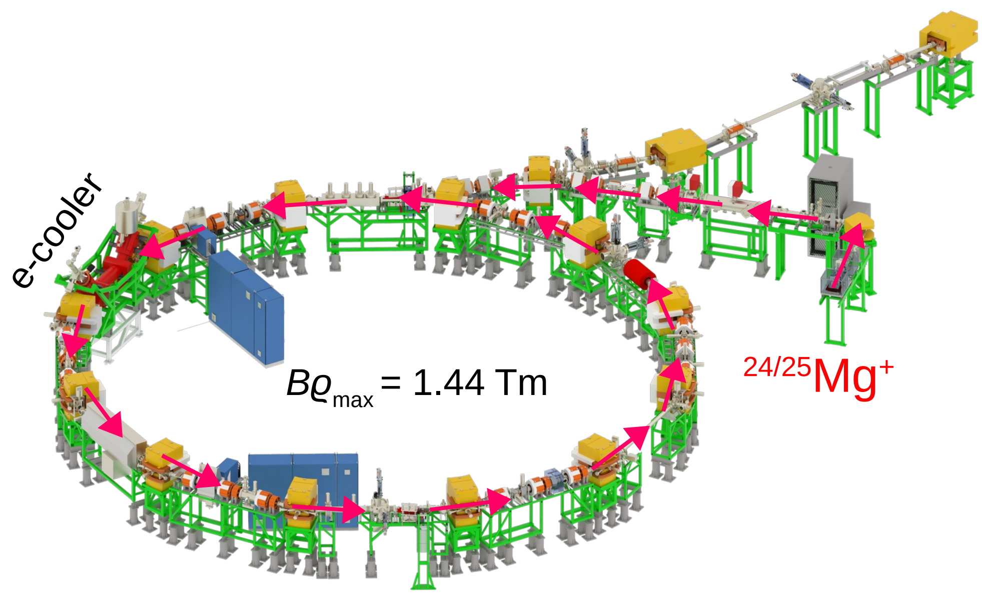
Rate for **low-energy e-cooling**:

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

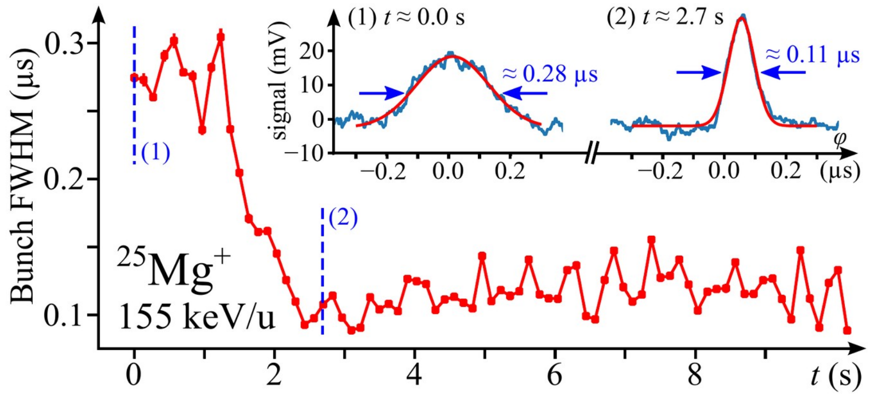
Electron cooler performance

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

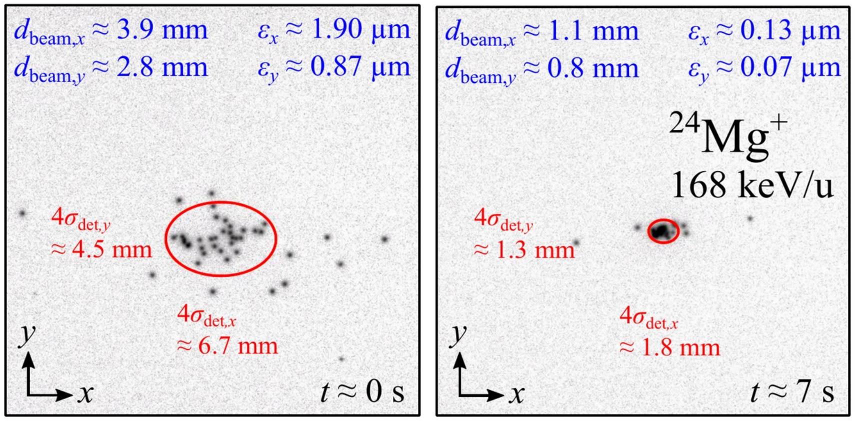
E_e = 92 eV / 85 eV
I_e = 1.7 mA



Longitudinal cooling (bunched)



Transverse cooling (neutral imaging)

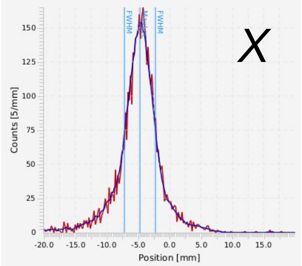


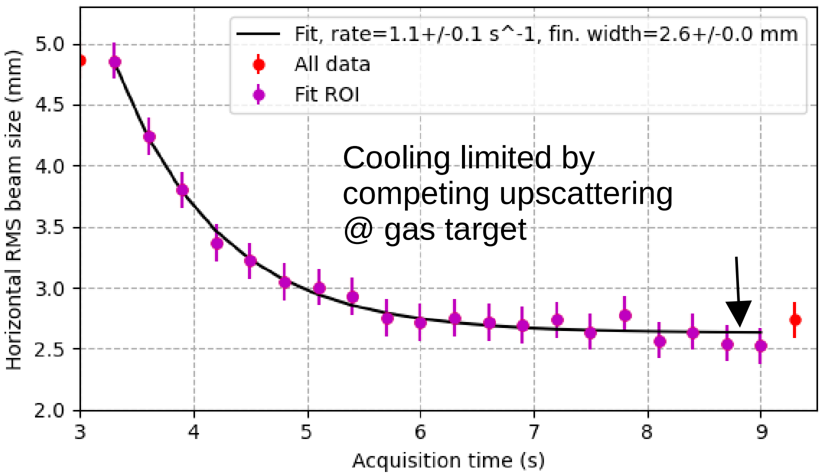
Krantz et al., Proc. IPAC 2021 (2021)

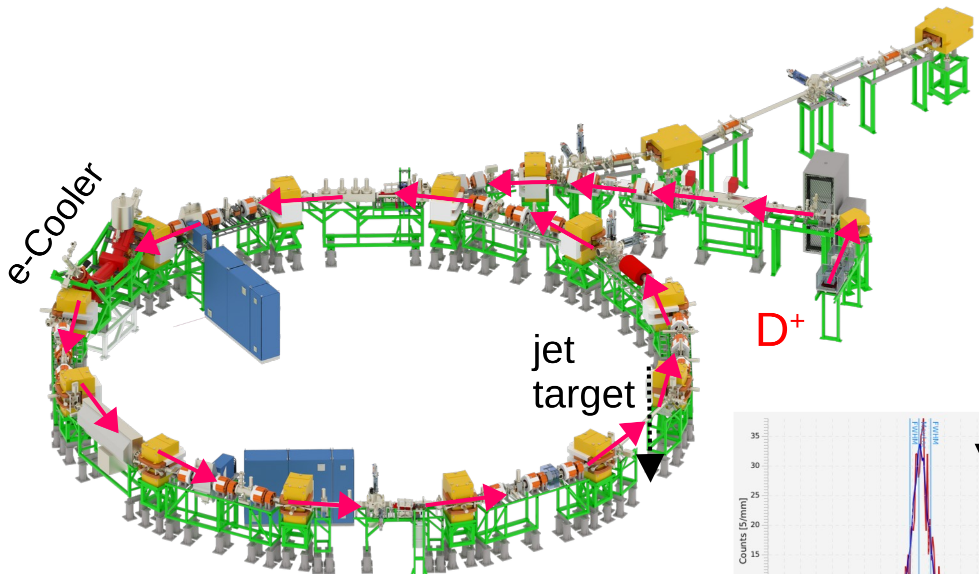
Electron cooler performance

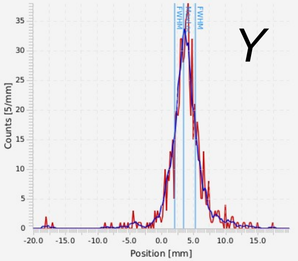
D^{+} @ 0.092 MeV/u

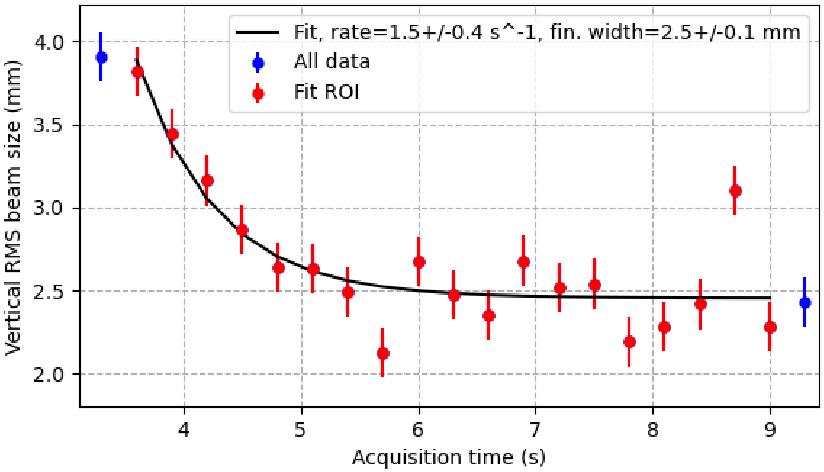
E_e = 50 eV
I_e = 0.5 mA



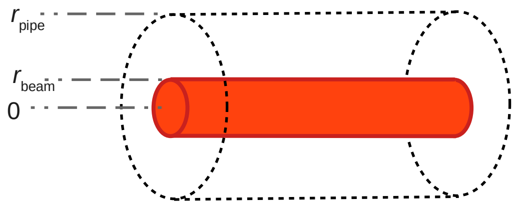




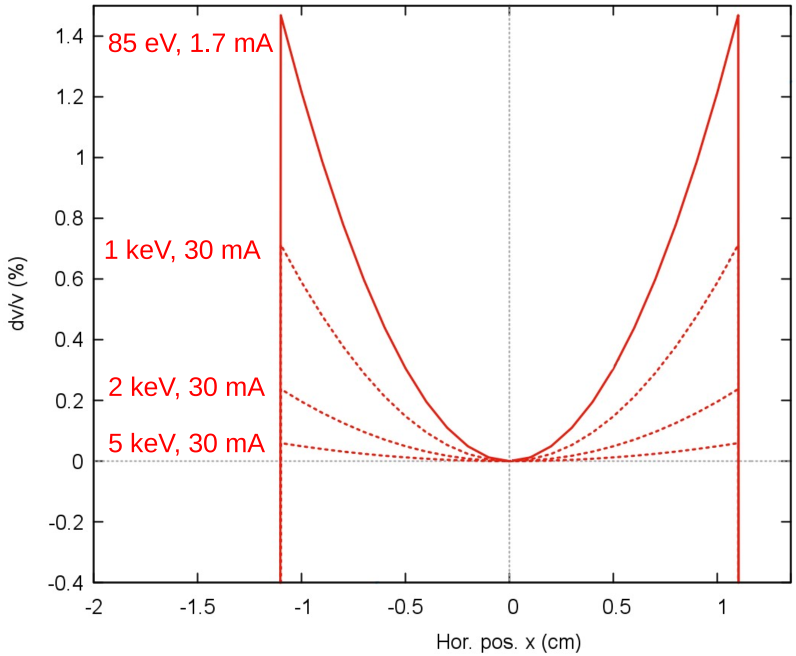


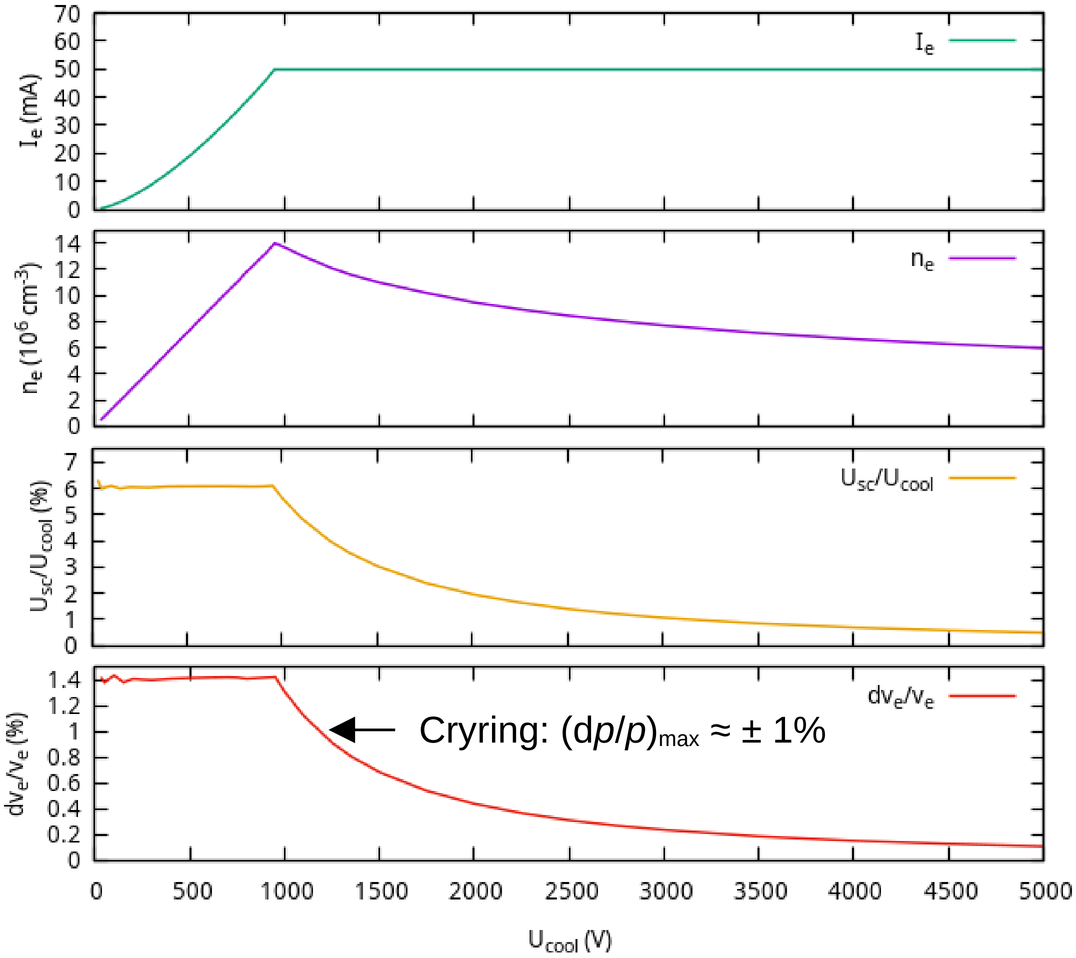


Low-energy challenges



space-charge induced
e velocity profile (ξ = 33)

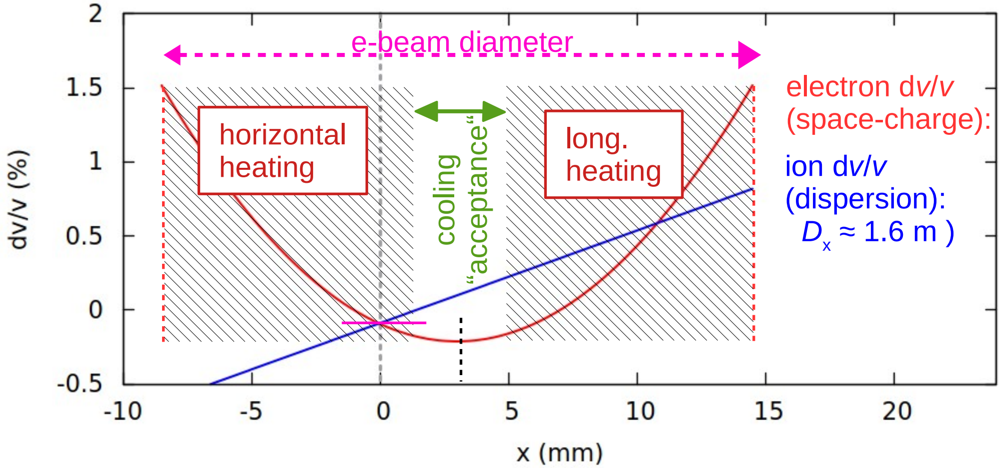


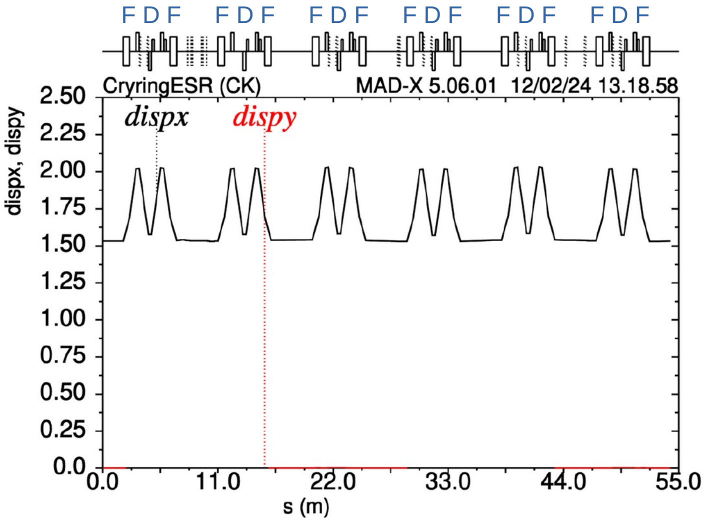


Dispersive electron heating

Dispersion vs. e space-charge:.

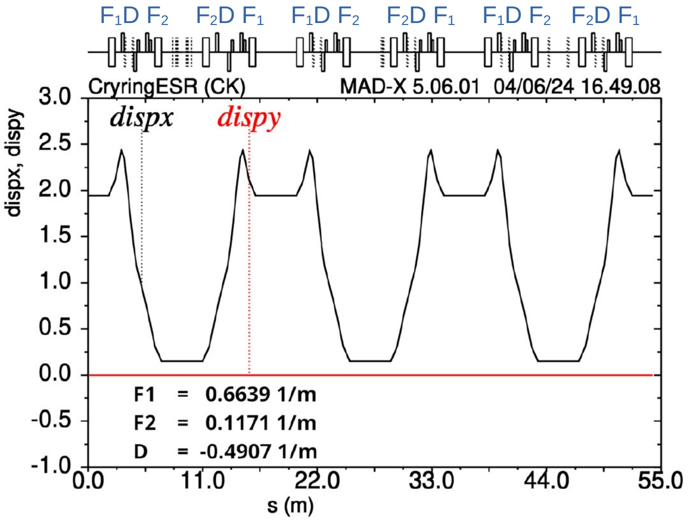
Edges of e-beam turn into **ion heaters**!





possible solution:
(but not here yet)

Split quads into three families



Low-energy challenges

Accuracy of E_e and 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, S. Schippers, C. Schroeder,
A. Täschner, S. Trotsenko, G. Vorobyev, D. Winzen