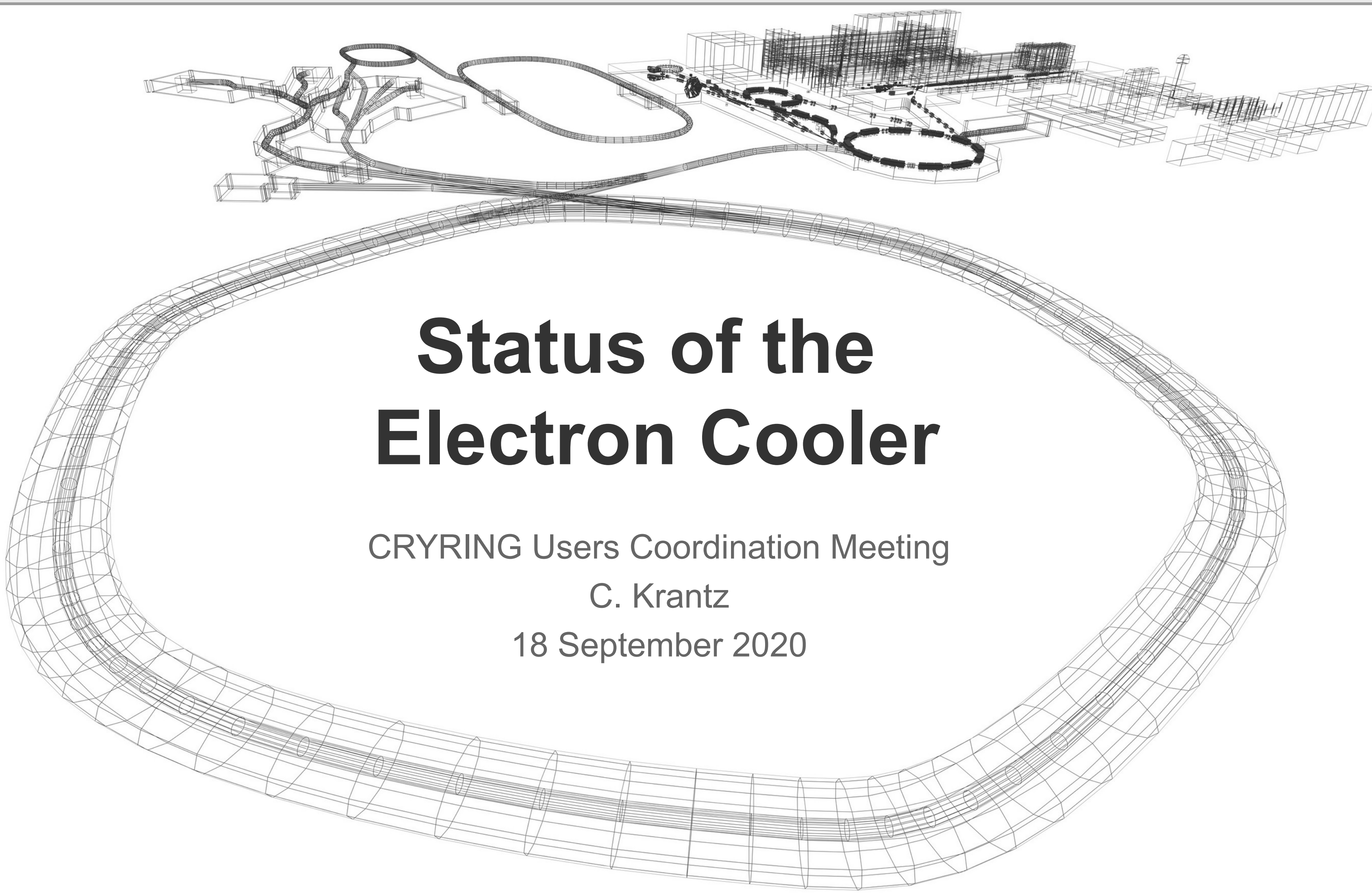


Status of the Electron Cooler

CRYRING Users Coordination Meeting

C. Krantz

18 September 2020

Status of the CRYRING@ESR electron cooler

Recent technical improvements

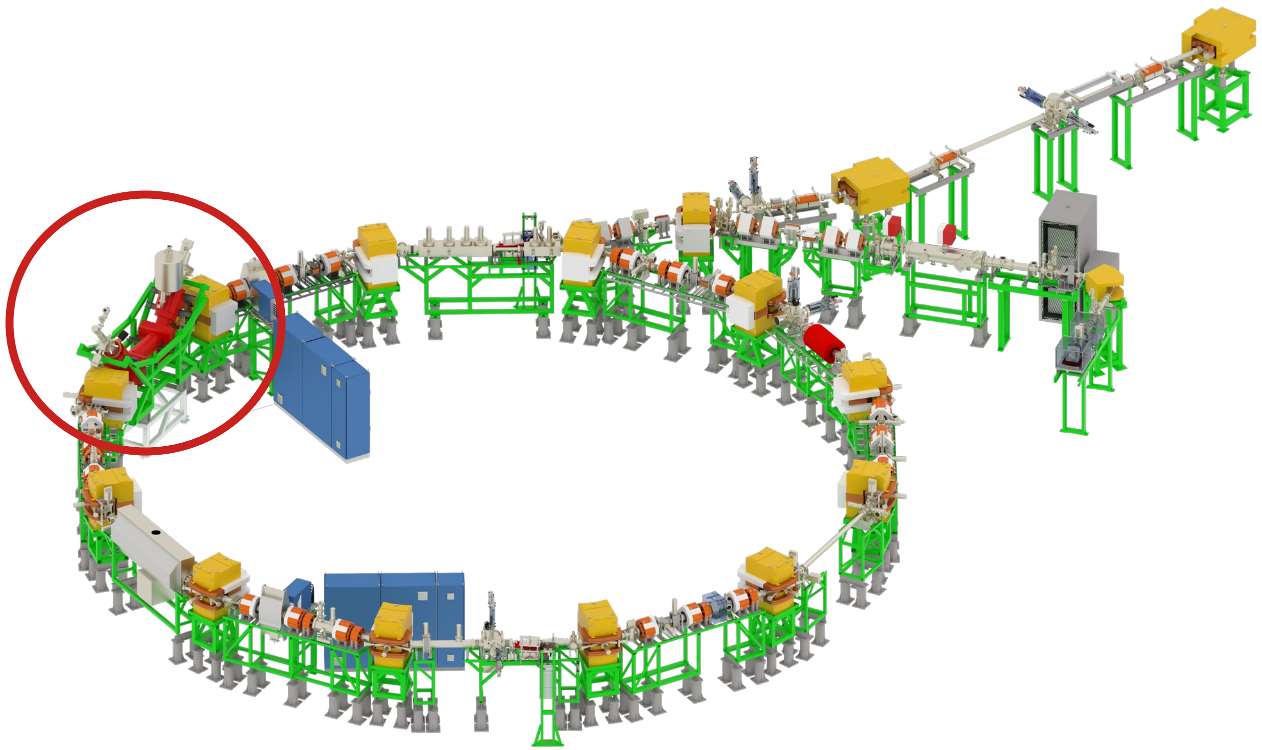
- LHe system
- e-gun

Commissioning

- e-beam transport
- e-target operation

Outlook

- Machine experiments
- Possible HW upgrades



The CRYRING electron cooler

18 years of successful operation and successive improvements at MSL.

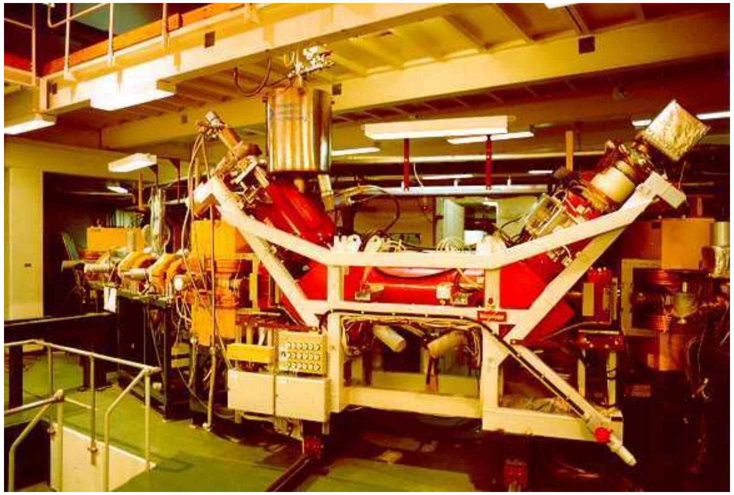
→ Pioneered strong expansion of e-beam

$$T_{trans} = T_{cath} \frac{B_{cooler}}{B_{gun}}$$

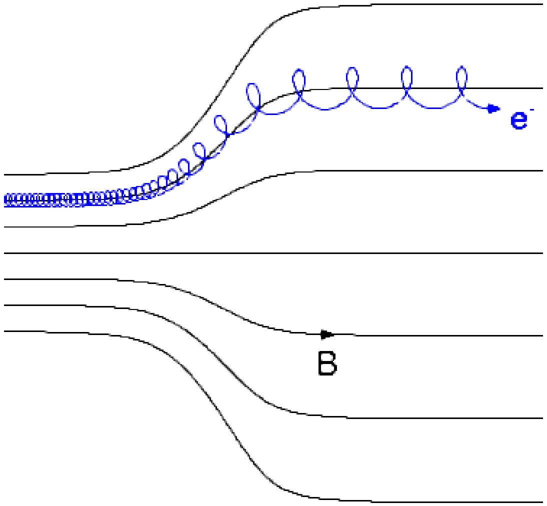
with s.c. gun solenoid: $B_{gun} / B_{cooler} = 100$

Device contributed significantly to our understanding of electron cooling.

(… besides enabling countless experiments on atomic and molecular physics.)



msi.se



The CRYRING electron cooler

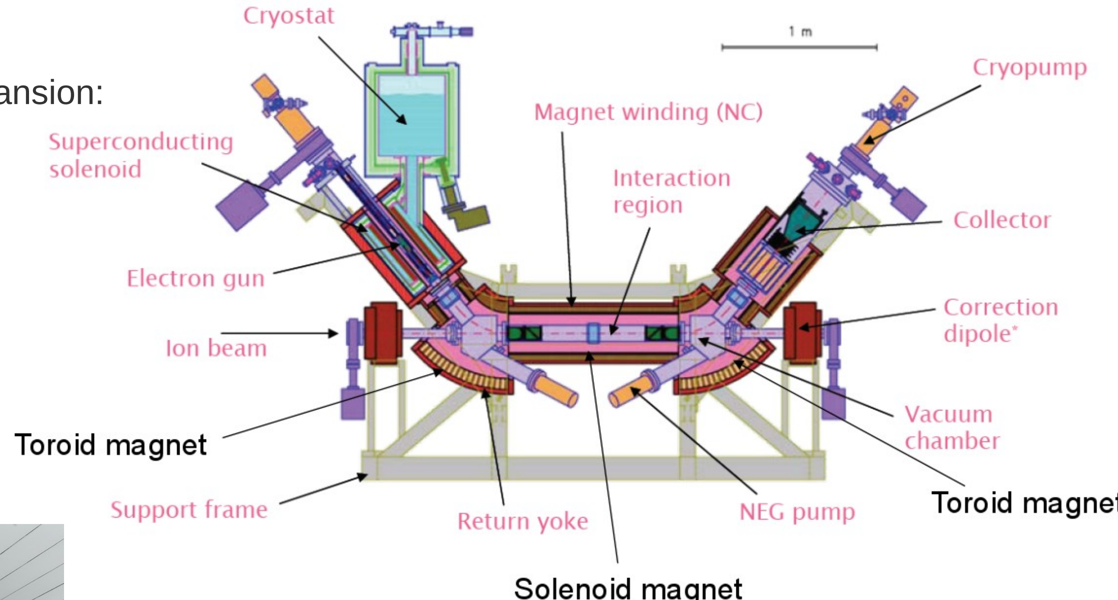
Transverse electron temperature at max. expansion:

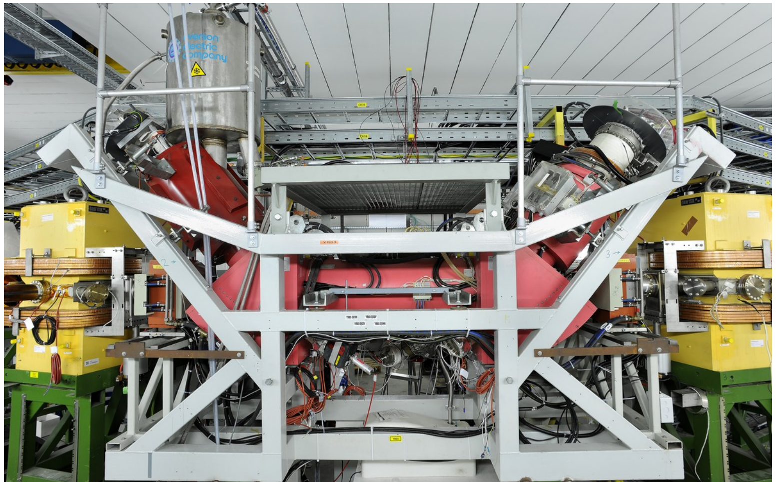
Theory:

T_{cath} ~ 100 meV/k_B (1200 K) → $T_\perp$ ~ 1 meV/k_B

Various MSL experiments:

$T_\perp$ = 1.5 … 3 meV/k_B





electron energy	≤ 8 keV (~14.6 MeV/u)
electron current	≤ 110 mA
cathode diameter	4 mm
mag. expansion factor	≤ 100 (≤ 3 T → 0.03 T)
e-beam diameter	≤ 40 mm
cooler solenoid length	≈ 1.1 m (~ 2% C_{ring})
vacuum	~ 10^{-11} mbar

(Very) brief history of the cooler

1992	–	First cooled beam at MSL (May): D^+
1993	–	Upgrade to expansion-10 e-gun (n.c. gun solenoid)
1997	–	Upgrade to expansion-100 e-gun (s.c. solenoid)
2009	–	End of operation at MSL
2012	–	Start of CRYRING@ESR project
2014/15	–	Re-assembly at GSI/FAIR, various repairs
2018	–	First cooled beam at GSI/FAIR (2 Nov., 13:30): D^+ @ 0.29 MeV/u
2019	–	Improvements of LHe system
2020	–	Reliable operation with new LHe system, first cooling of ESR-injected beams, first e-target experiments (DR).

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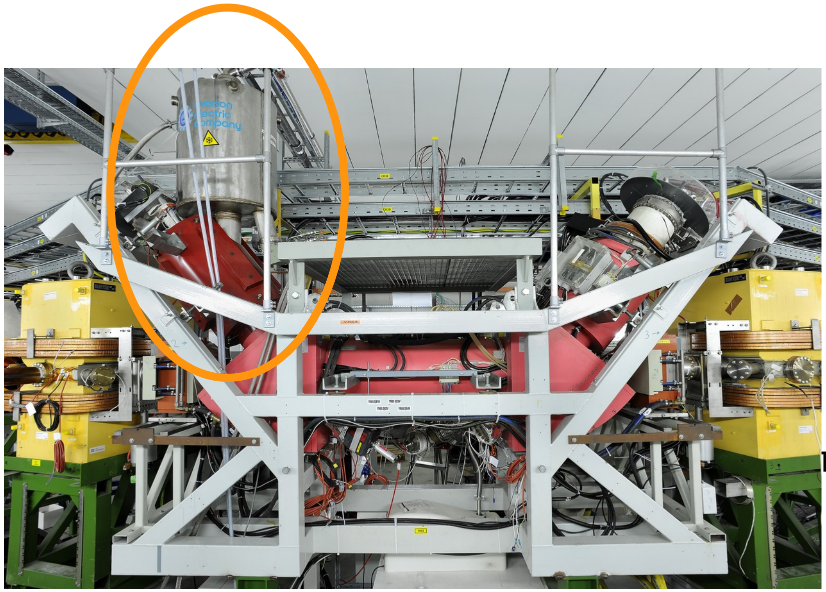
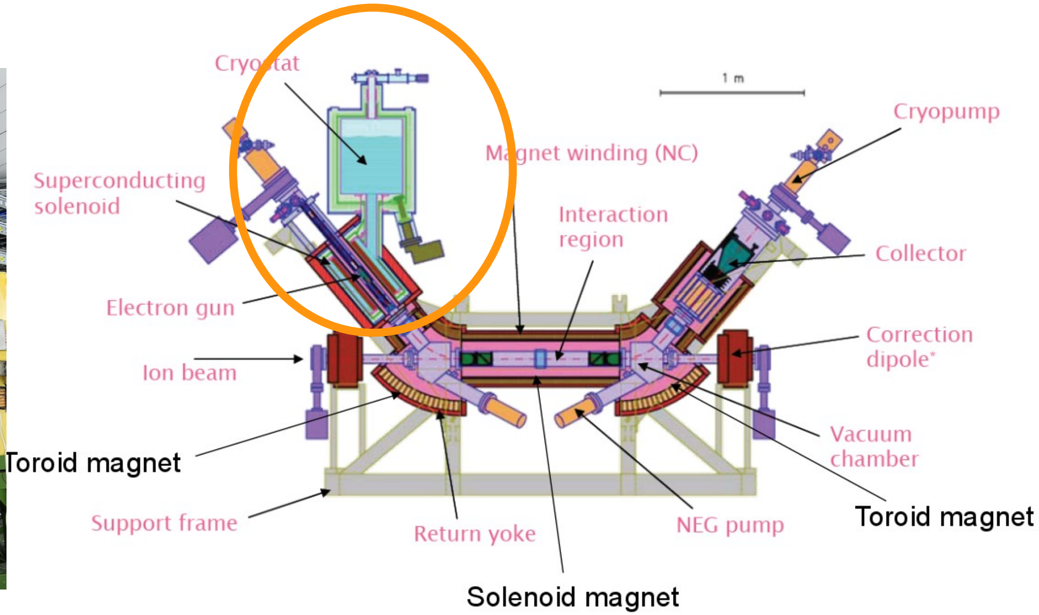
LHe system upgrade

2018: Installation of fixed-line LHe supply from liquefier facility.
→ Cooling down worked, re-filling not. :-(





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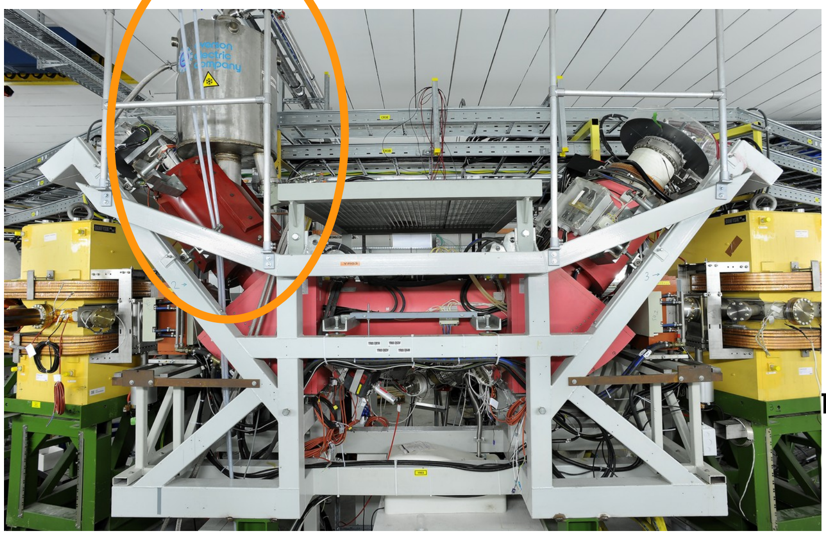
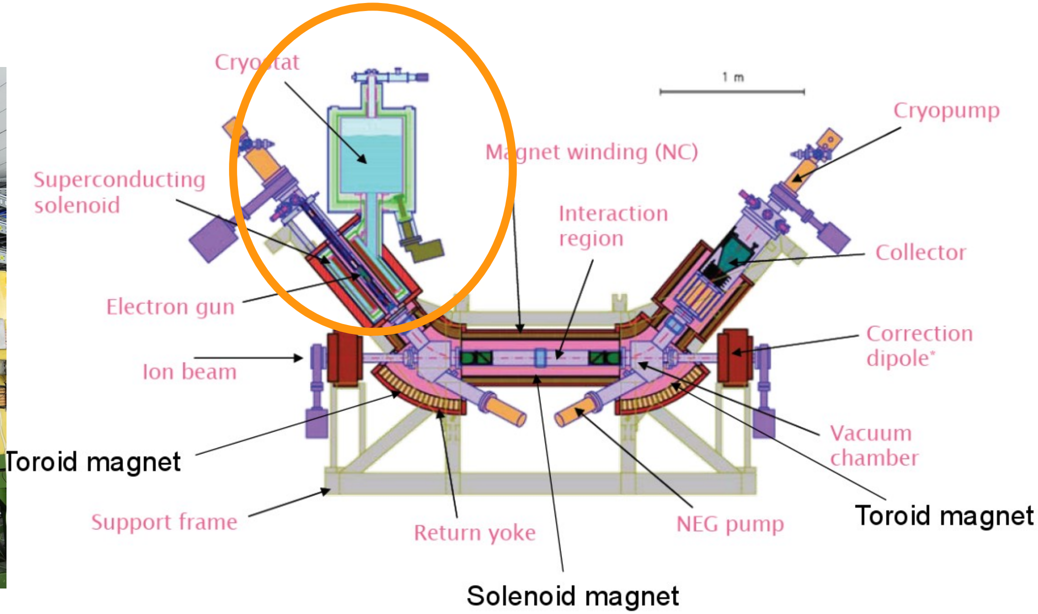


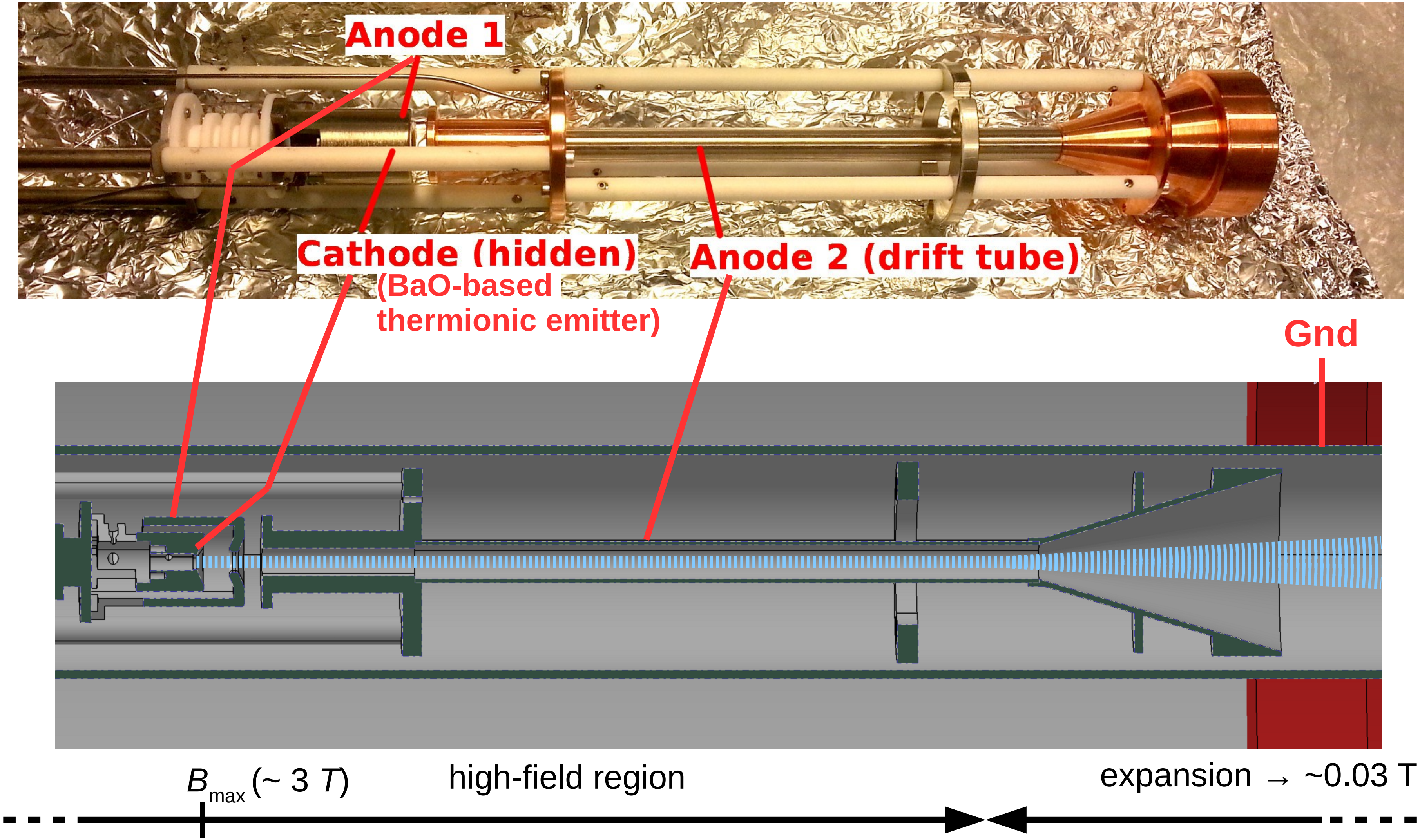


2019: Several improvements of cryo-system + LHe line (partly trial+error):
Bypass for transfer-line pre-cooling, insulation, cryostat connection …

Jan 2020: Reliable LHe refilling procedure established! (→ J. Roßbach + Cryodep.)

Feb. – May: Uninterrupted operation of the superconducting gun solenoid. :-)
(Cooler can operate during refills.)

Electron gun



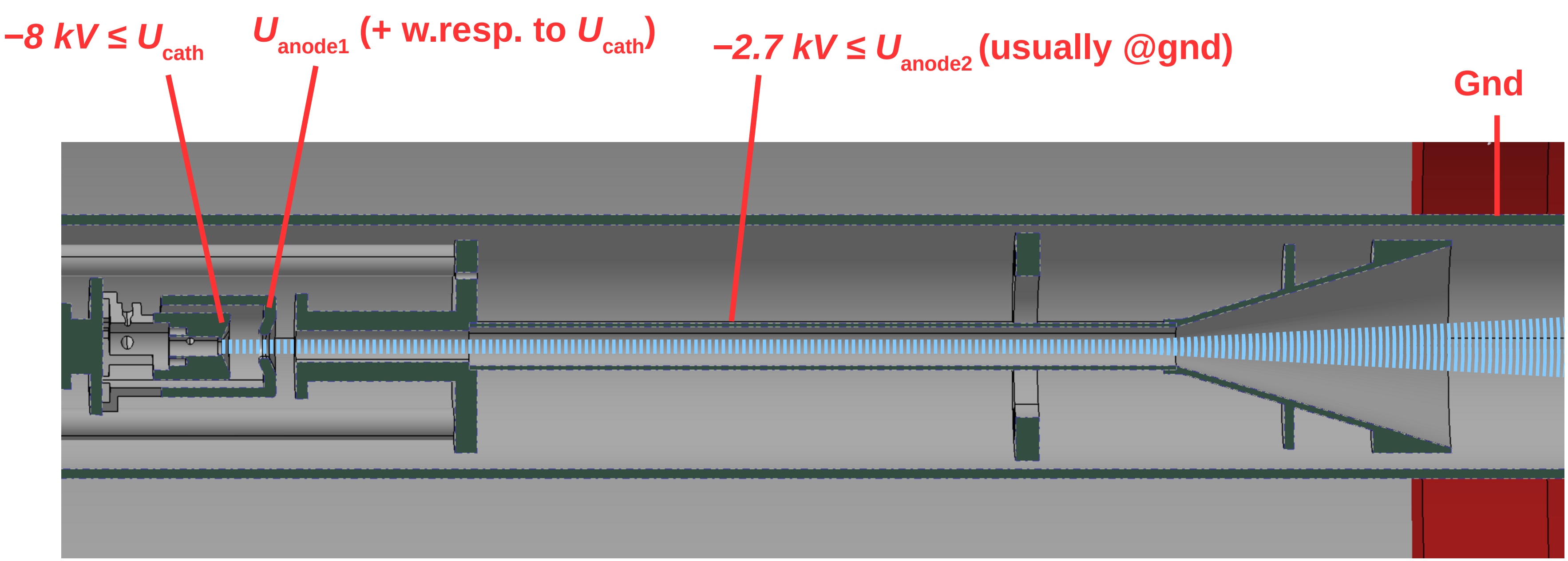
Electron gun

Max. voltages limited by small size of e-gun (sparking):

* Electron energy ≤ 8 keV

* $U_{extr.} = | U_{anode1} - U_{cath} | \leq 1600$ V according to MSL documentation → $I_e \leq 110$ mA.

* „Delayed acceleration“ using Anode-2 possible at low energy (up to ~ 3 keV) only.



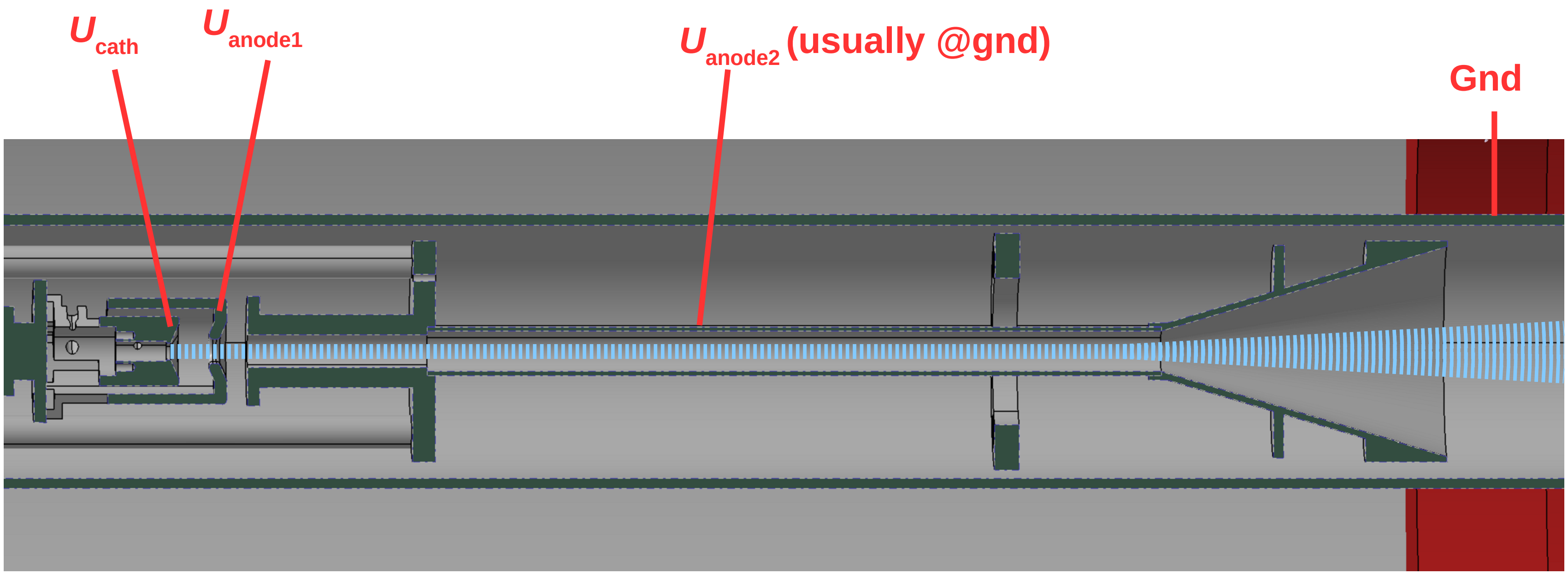
Electron gun

Because of imperfect screening: Anode 2 (usually @ gnd.) contributes to $U_{extr.}$:

* Beam current depends (weakly) on energy.

* Setting | U_{cath} – U_{anode1} | = 0 V did not fully prevent electron extraction at high energy.

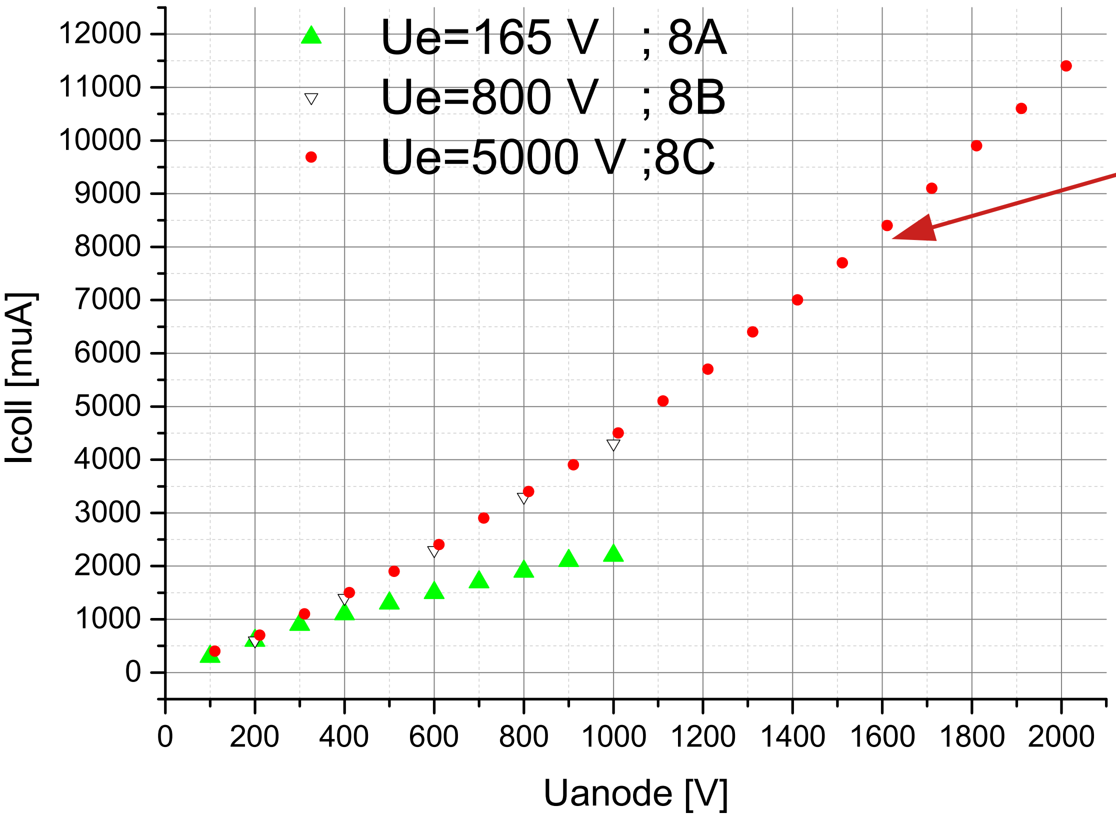
→ Since May 2020: U_{cath} – 100 V applied to Anode1 to reliably switch-off the cooler beam.



Electron gun: Perveance

Initially, extracted electron current was low compared to experience from MSL.

Child-Langmuir law: $I = P\,U^{3/2}$



2018 – 2019 measurements:

$P \sim 0.2\,..\,0.5\cdot10^{-3}$ mA $V^{-3/2}$

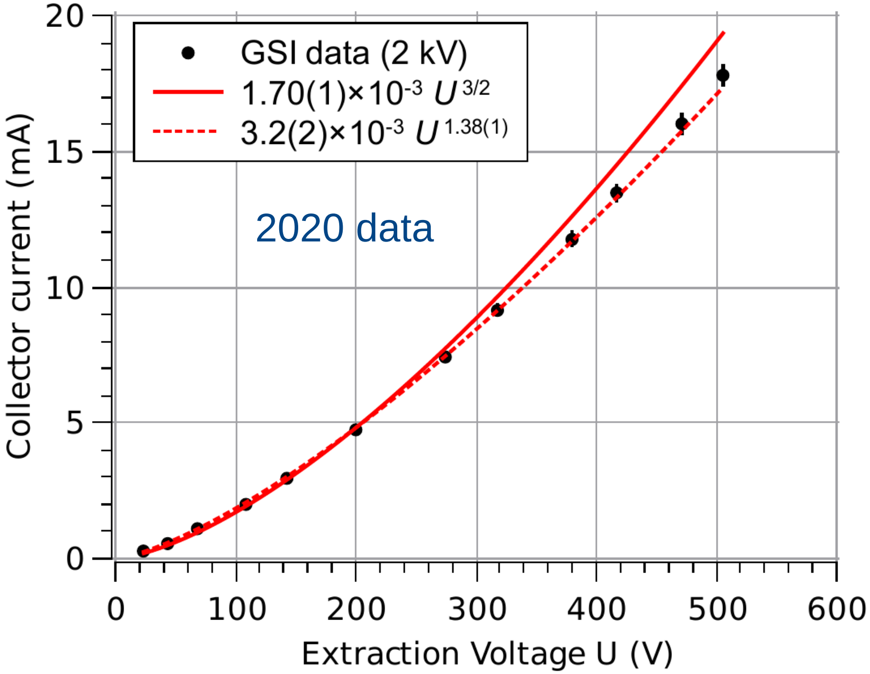
[MSL ref. val: $1.7\cdot10^{-3}$ mA $V^{-3/2}$]

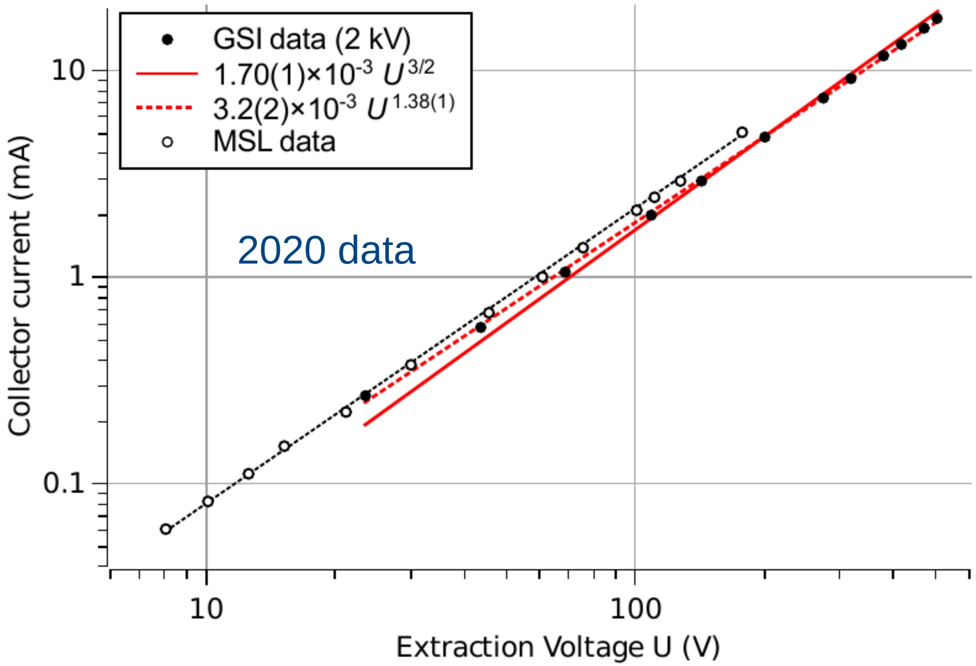
Electron gun: Perveance

→ Fixed end 2019

Probably by better (longitudinal) matching of cathode position and magnetic field maximum.

(Side effect of a vacuum incident followed by cathode replacement)





Electron gun: Alignment

Strong expansion requires careful alignment of e-gun to magnetic axis.

Expansion: $$d_{beam} = d_{cath} \sqrt{\frac{B_{gun}}{B_{cooler}}}$$

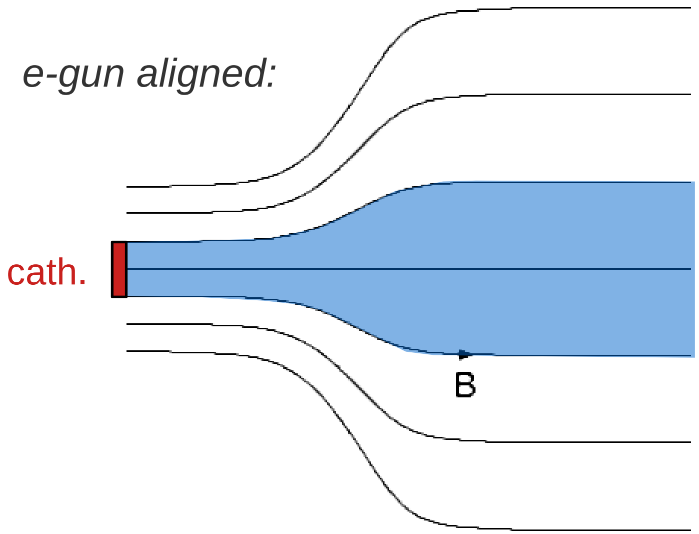
If misaligned by Δr_{mis}: $$\Delta r_{beam} = \Delta r_{mis} \sqrt{\frac{B_{gun}}{B_{cooler}}}$$

with $B_{gun}/B_{cooler} = 100$:

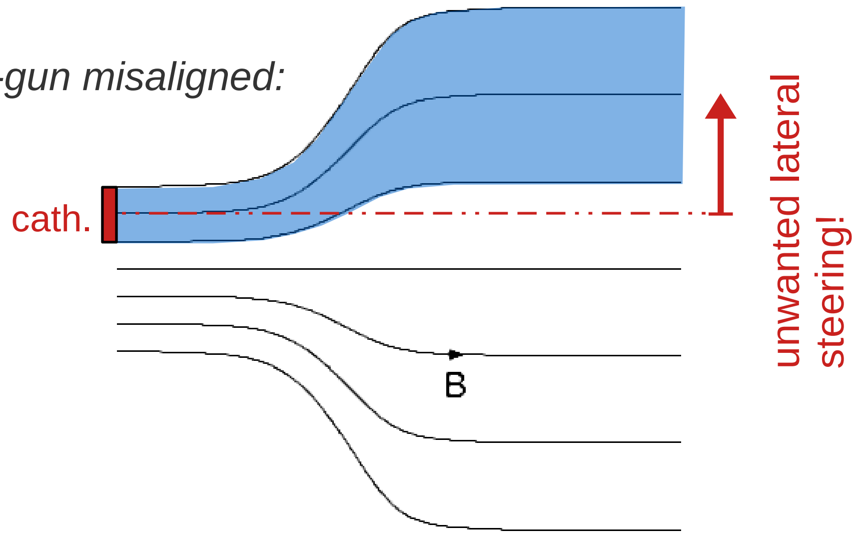
$\Delta r_{mis} = 1$ mm → $\Delta r_{beam} = 10$ mm

At usual $B_{cooler} = 0.03$ T, steerer coils can correct only by ±12 mm!

e-gun aligned:



e-gun misaligned:

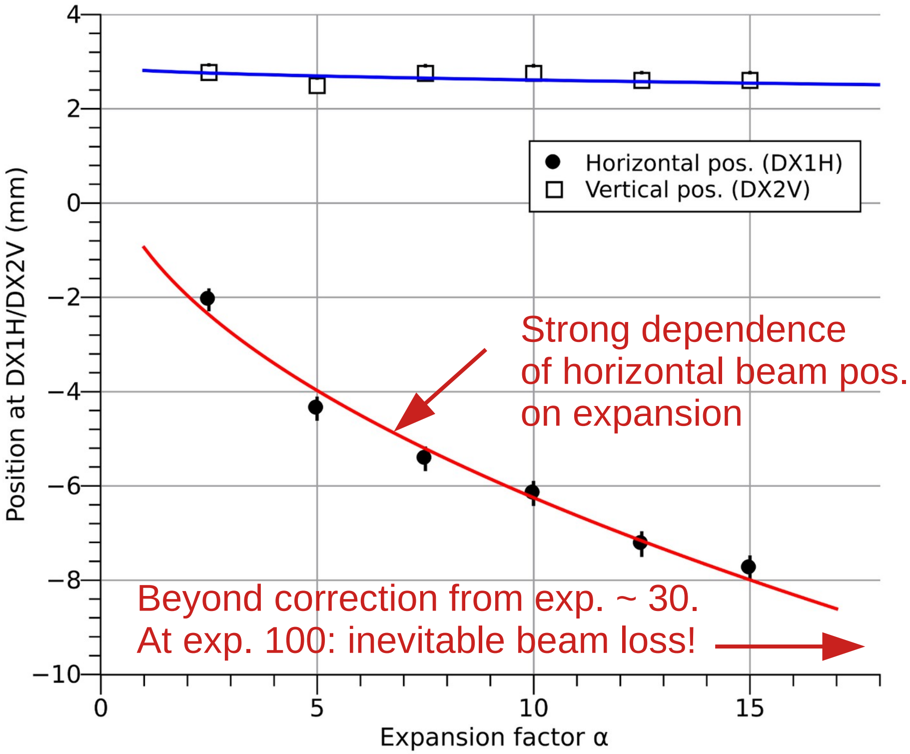


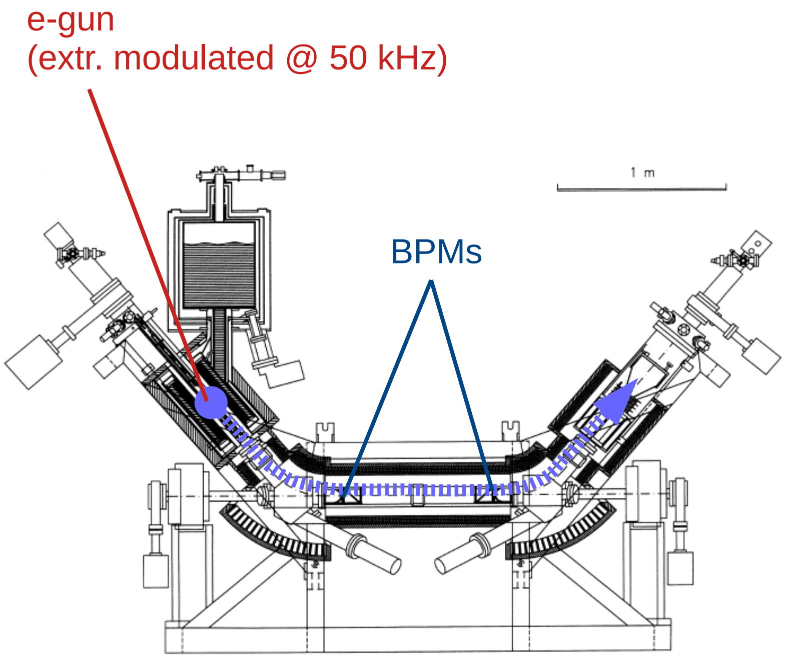
Electron gun: Alignment

April 2020 – Various observations suggested lateral gun misalignment:

* *e-current loss at high expansion,*
* *overlap with ion beam required extreme (horizontal) steerer settings*

Mai 2020 – Direct measurement: lateral e-beam position vs. expansion.

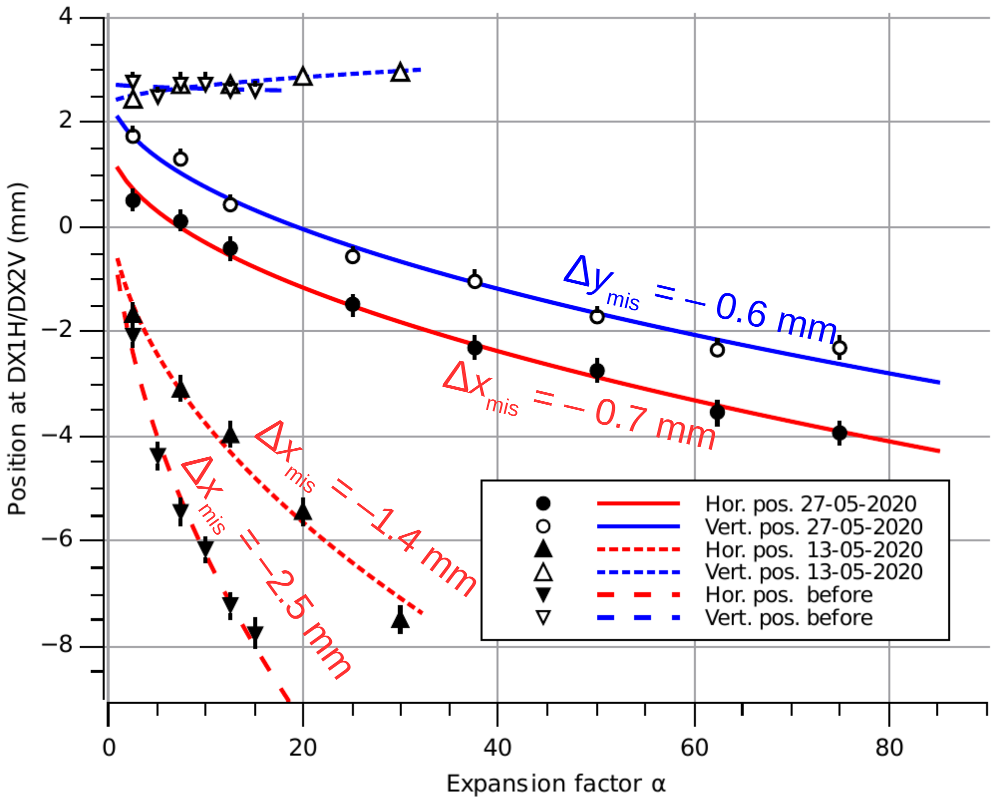




Electron gun: Alignment

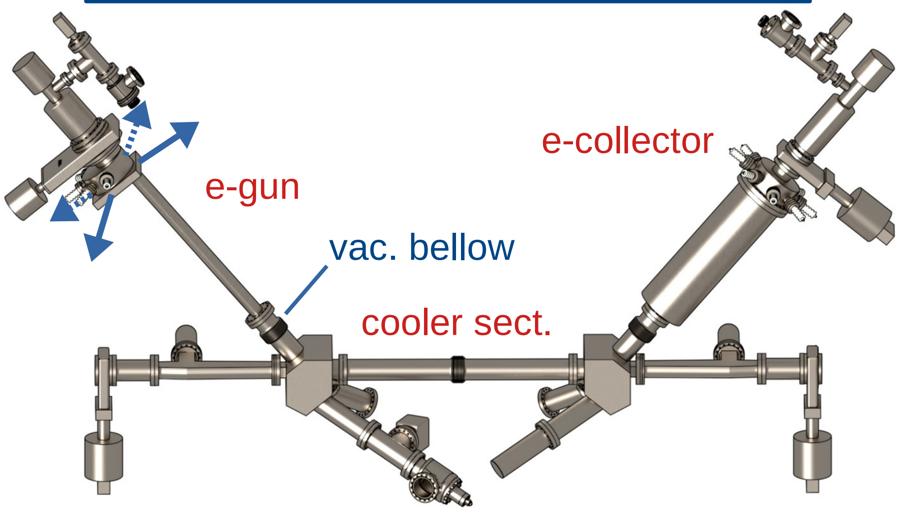
May 2020 – Beam-based re-alignment of e-gun (2x).

Result is not perfect ...
… but beam transport and alignment work up to expansion 100. :-)



Limited by adjustment mechanics
+ decoupling bellow.

Proper solution requires disassembly
→ *postponed for now*.

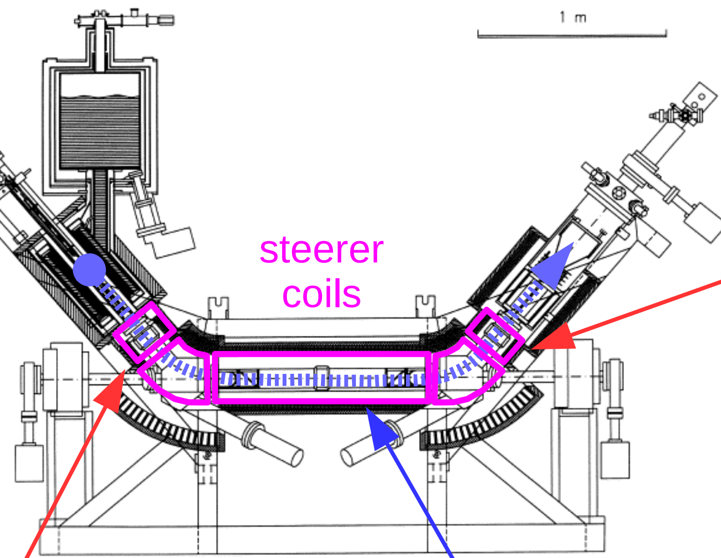


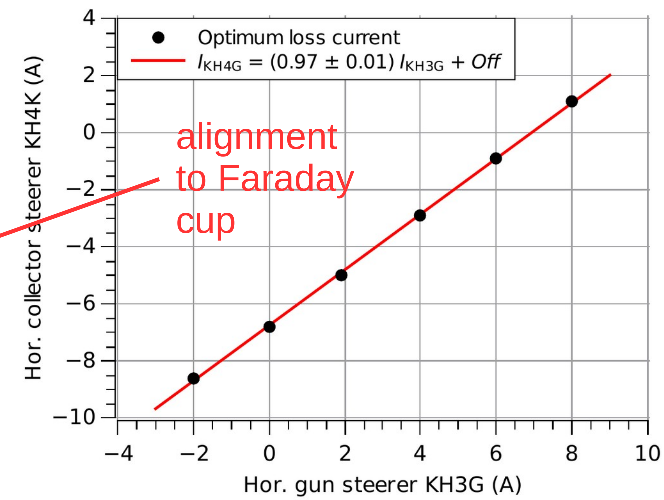
Magnetic electron beam transport

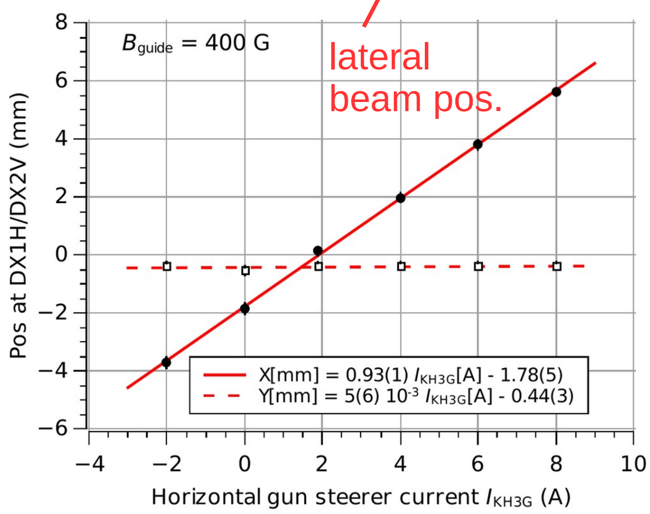
May 2020

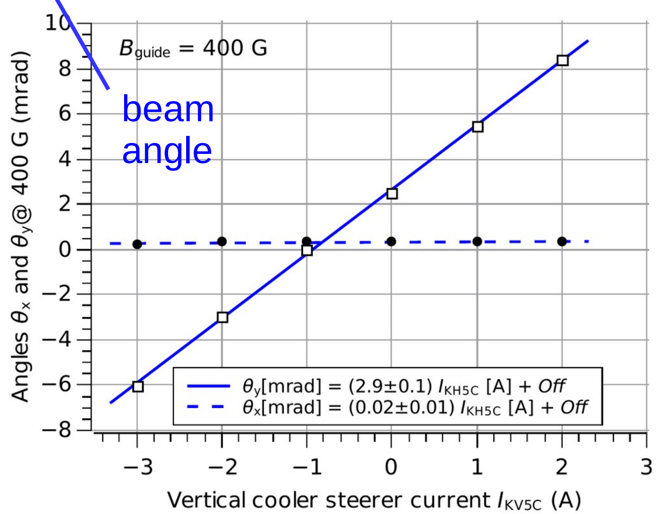
Analysed magnetic e-beam transport.

Valuable data for efficient operation of the cooler.





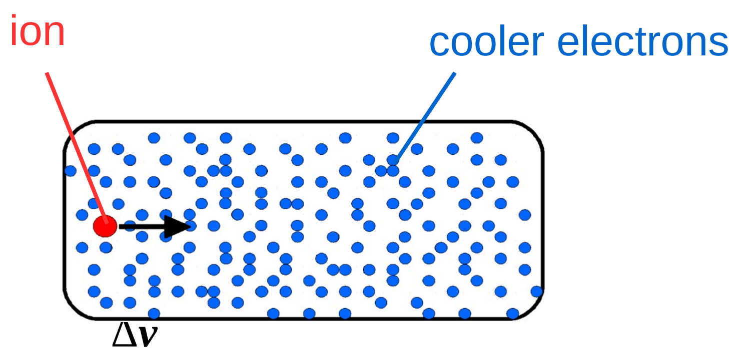




Electron-target operation

Electron cooling:

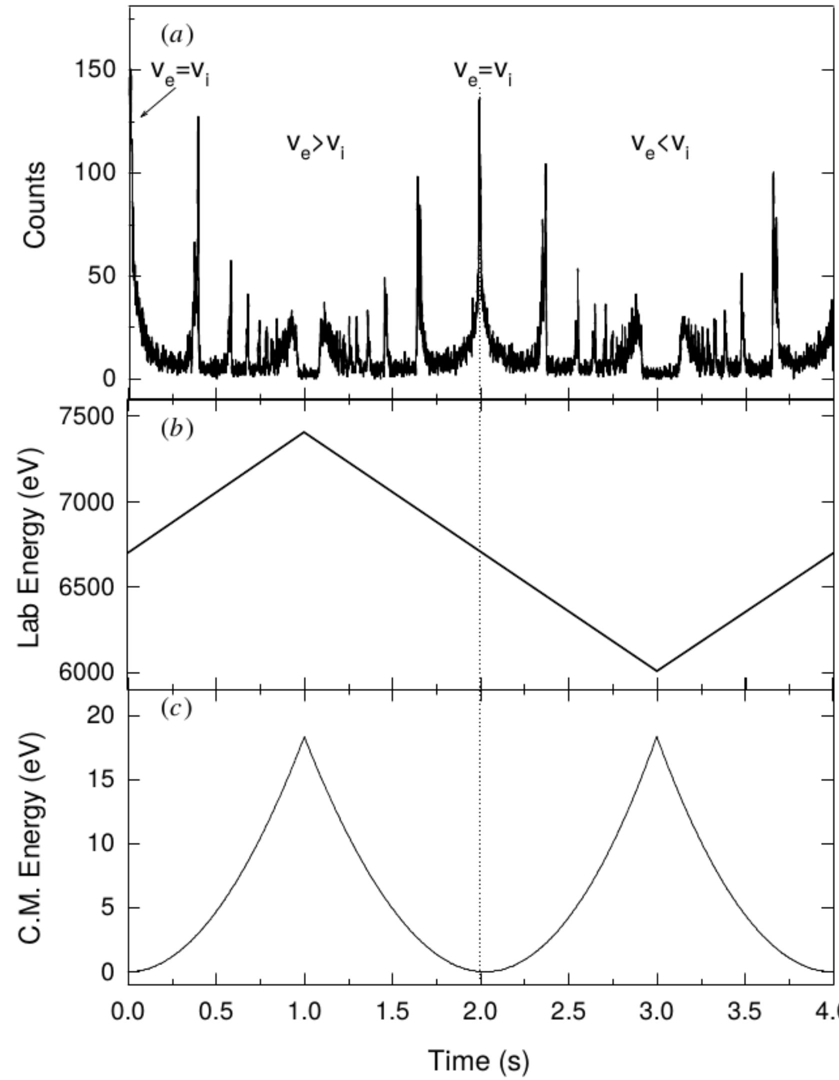
→ $\Delta v = |\, \langle v_e \rangle - v_{ion} \,| \approx 0$ m/s



Electron-Target operation:

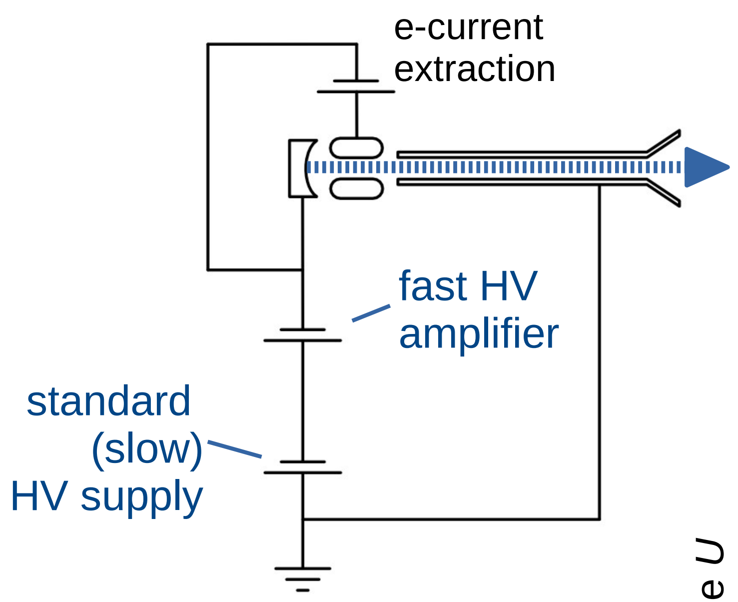
Set e-gun voltage such that $\langle v_e \rangle \neq v_{ion}$

$$E_{coll} \approx \frac{1}{2} m_e \Delta v^2 \approx \left(\sqrt{E_e} - \sqrt{\frac{m_e}{m_{ion}} E_{ion}} \right)^2$$

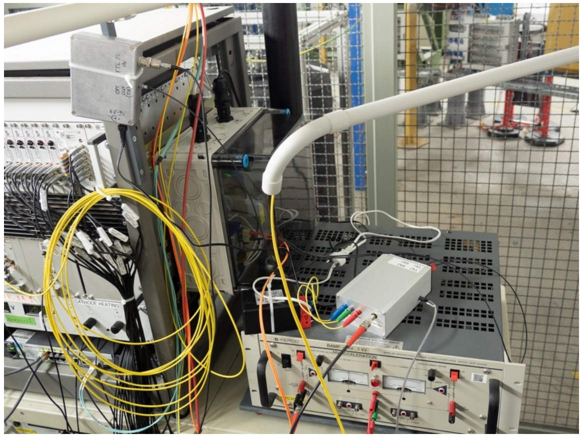


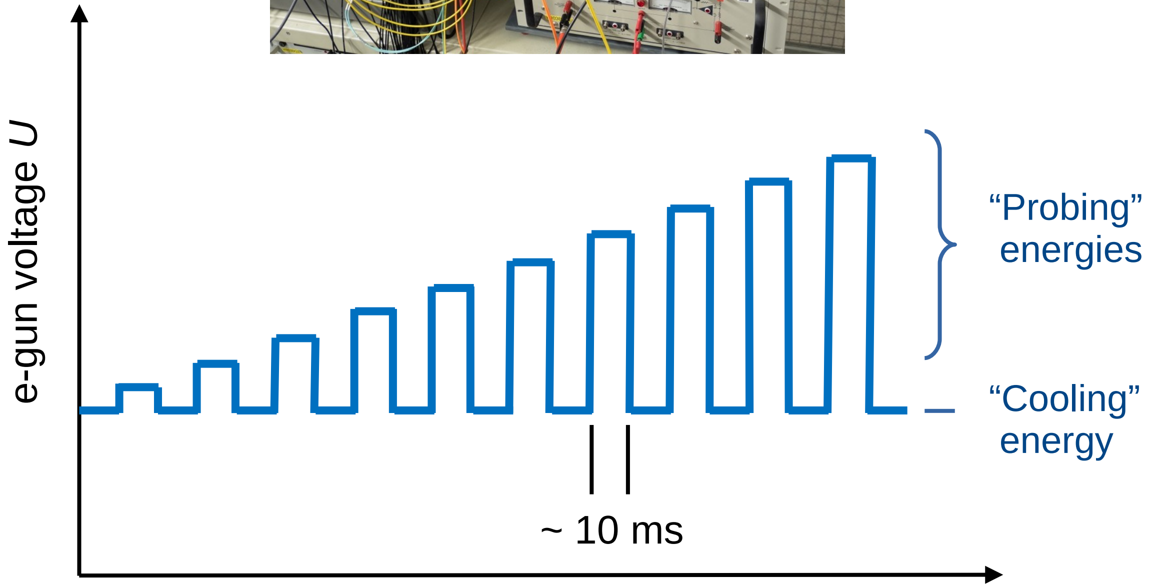
Zong, J. Phys. B 31 (1998) 3729

Electron-target operation



C. Brandau et al., Uni GI

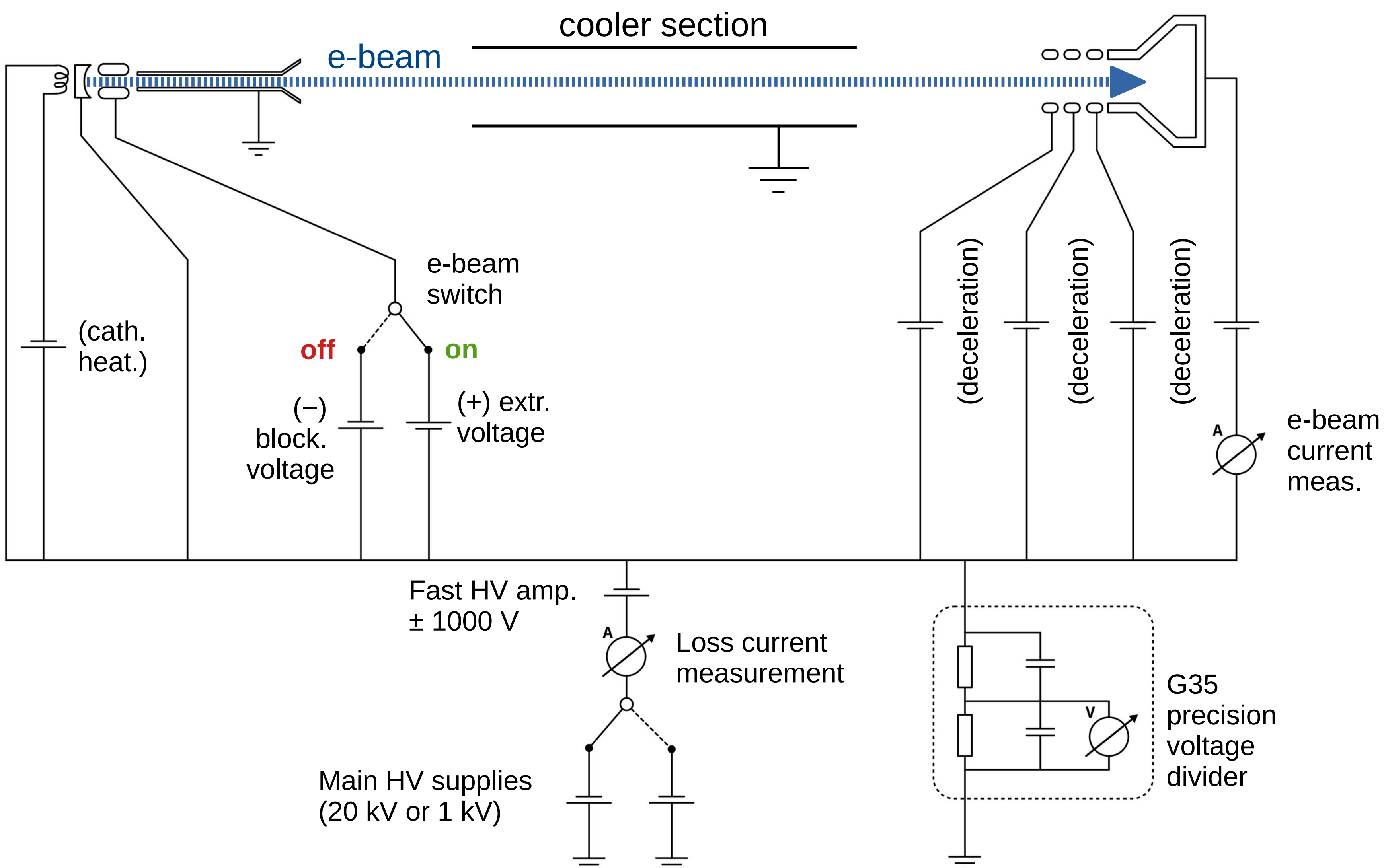




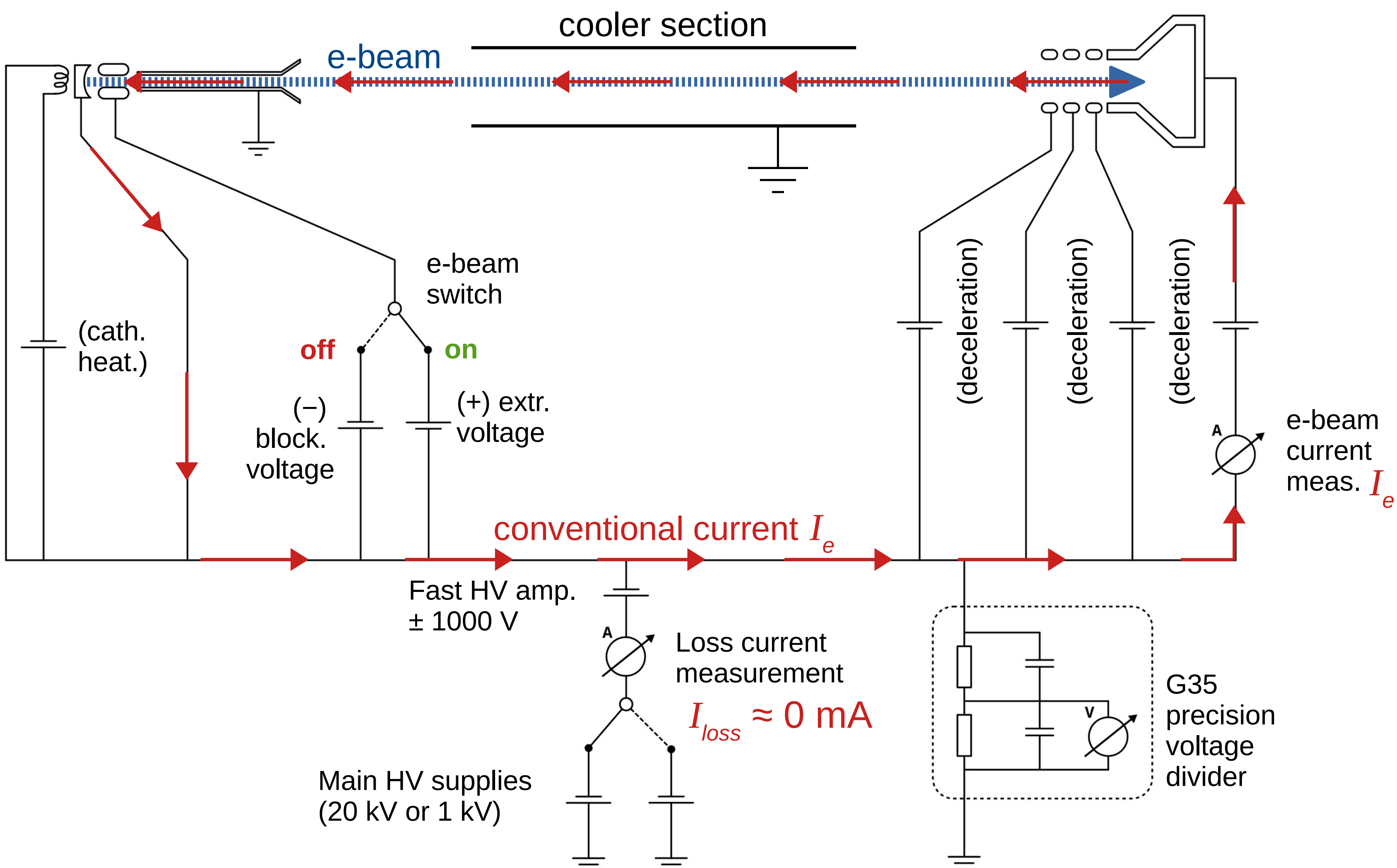
Prevent *dragging* of v_{ion} by fast switching between "cooling" and "probing" voltages.

(→ *"Wobbling"*)

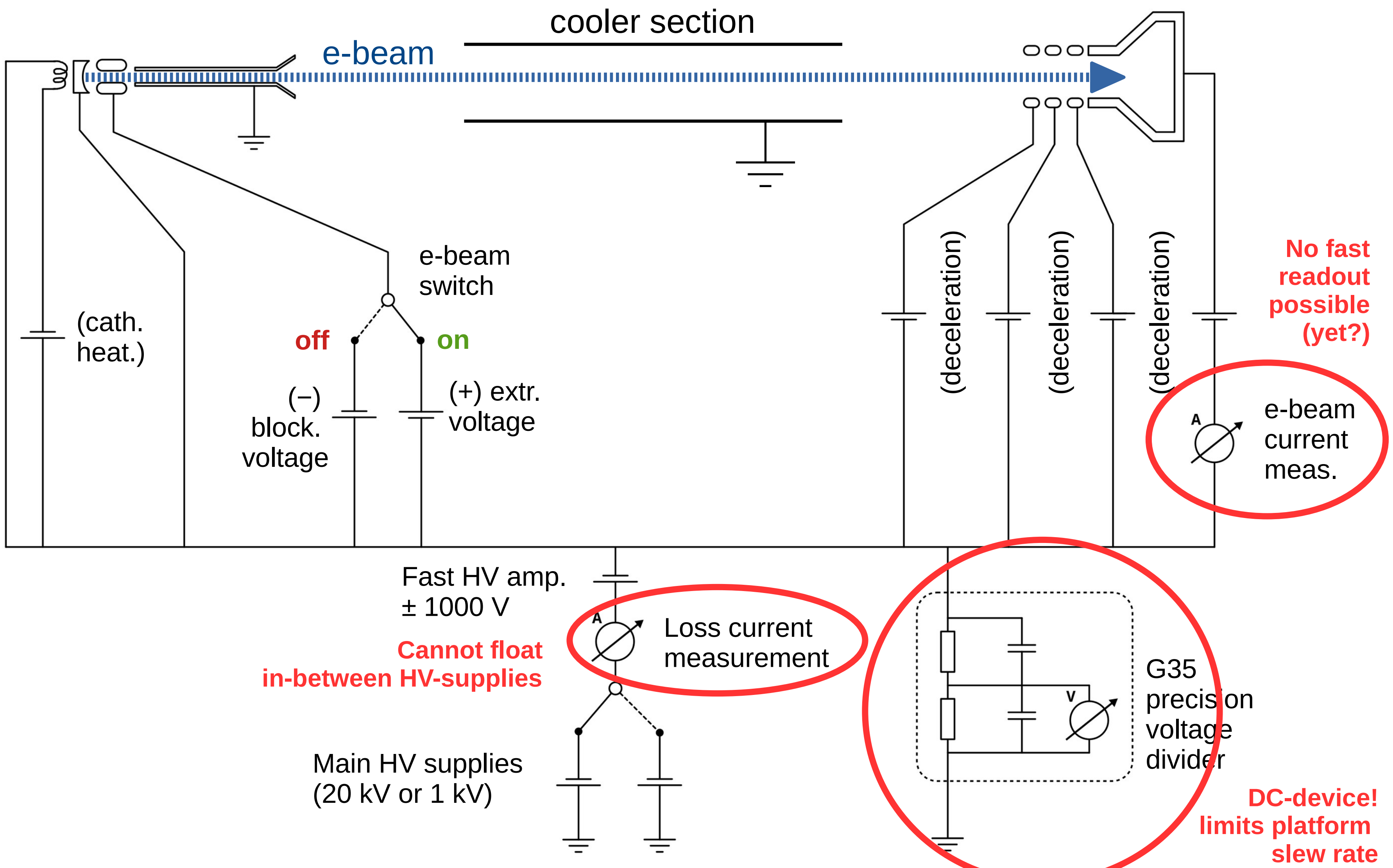
Electron-target operation



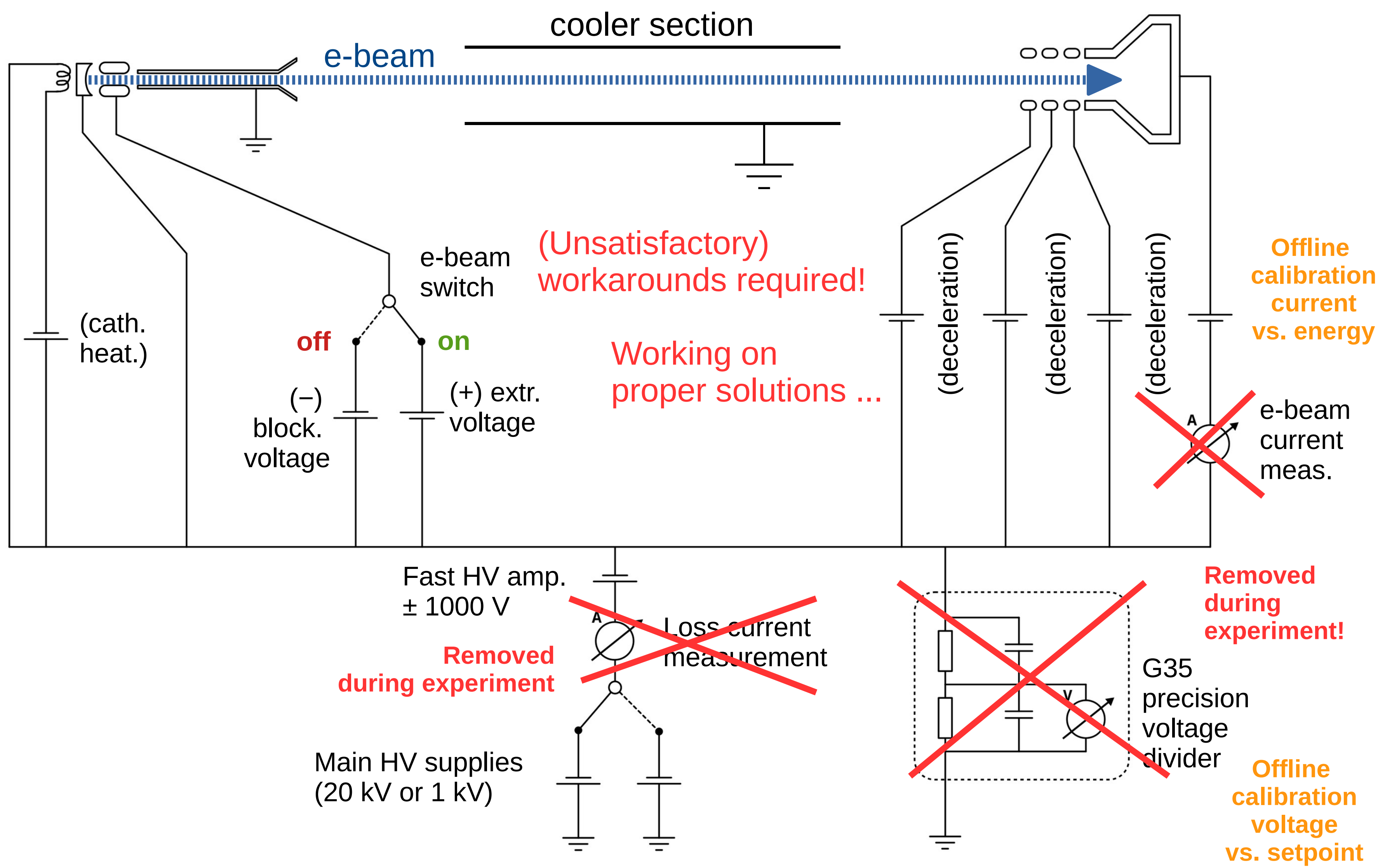
Electron-target operation



Electron-target operation

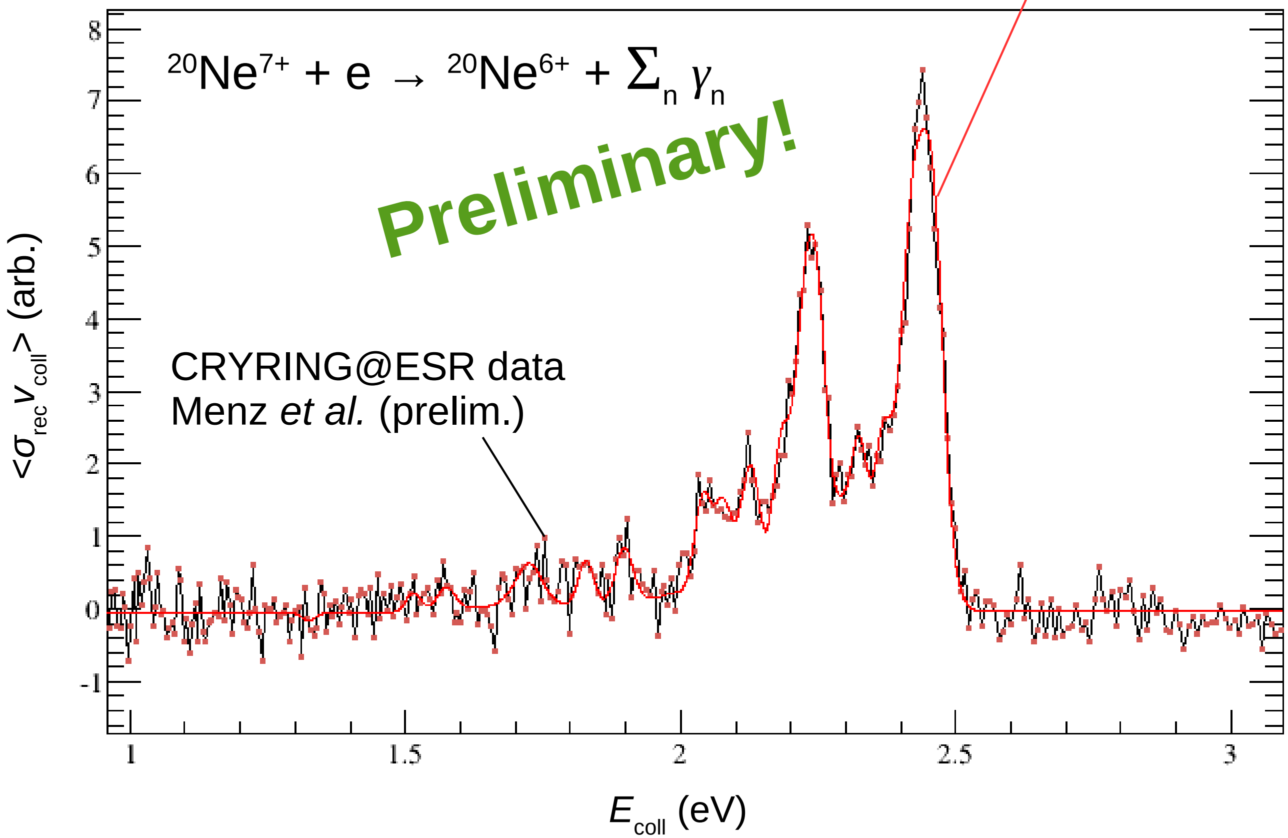


Electron-target operation



Electron-target operation

Artificial (!) line spectrum convolved with $T_\perp = 2.6$ meV/k_B, $T_{||} = 50$ µeV/k_B



→ Resolution seems fine! :-)

(… although not the best ion for *T*-benchmarks …)

Up next:

Comparison to full RMBPT calculation
(74 resonances, E. Lindroth, *Hyperfine Interact. 114, 1998*)

→ E. Menz, in prep.

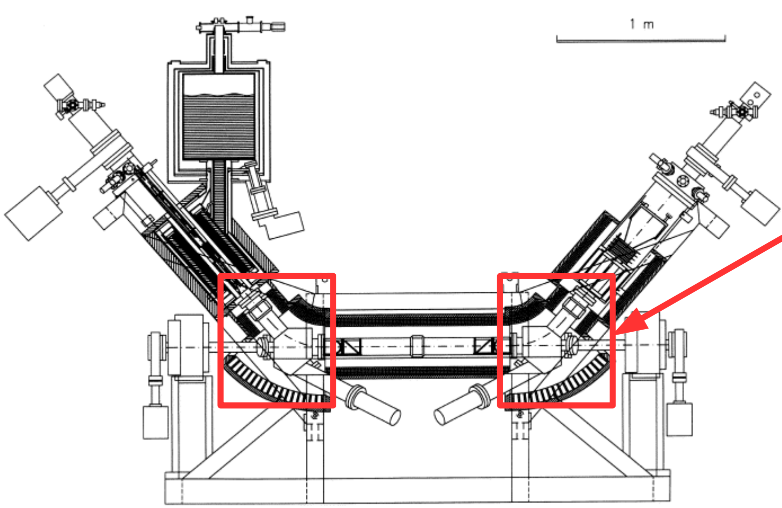
Outlook: Ongoing work

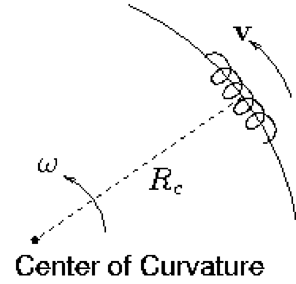
Improve compatibility with “wobbling” operation (electron-target mode)

→ Installing secondary (less-precise-but-faster) **voltage divider** (→ S. Schippers, Uni. Gießen)

→ Looking for solution for **fast e-current measurement**.

→ Integrating fast steerer power-supplies for **toroidal drift compensation** during experiment. (→ C. Brandau, Uni GI)





$$\mathbf{v}_d = \frac{1}{q}\frac{\mathbf{F}_{cf} \wedge \mathbf{B}}{B^2} = \frac{m v_{||}^2}{q B^2}\frac{\mathbf{R}_c \wedge \mathbf{B}}{R_c^2}$$

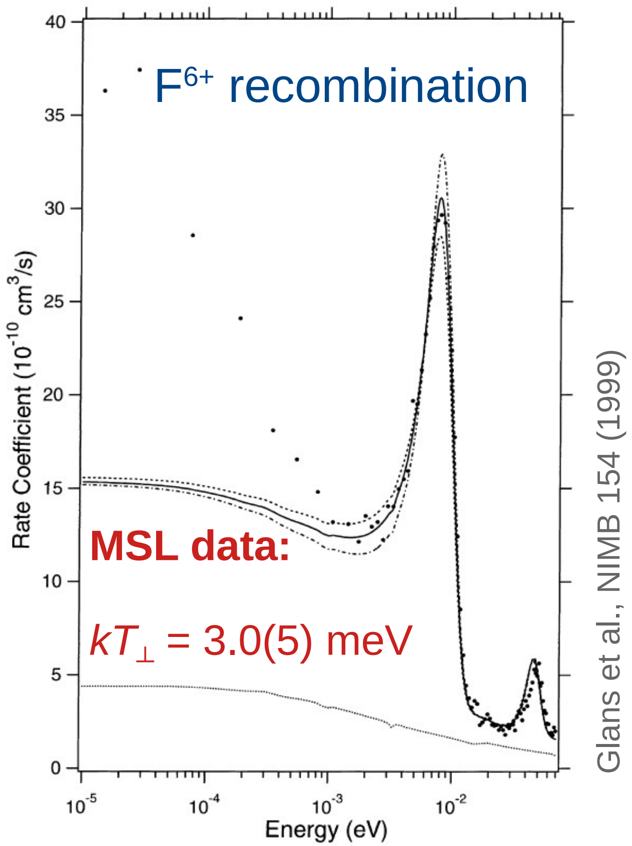
$$\Delta x_{\text{toroid}}[\text{mm}] \approx 0.093 \frac{\sqrt{E_e[\text{keV}]}}{B_{\text{guide}}[\text{T}]}$$

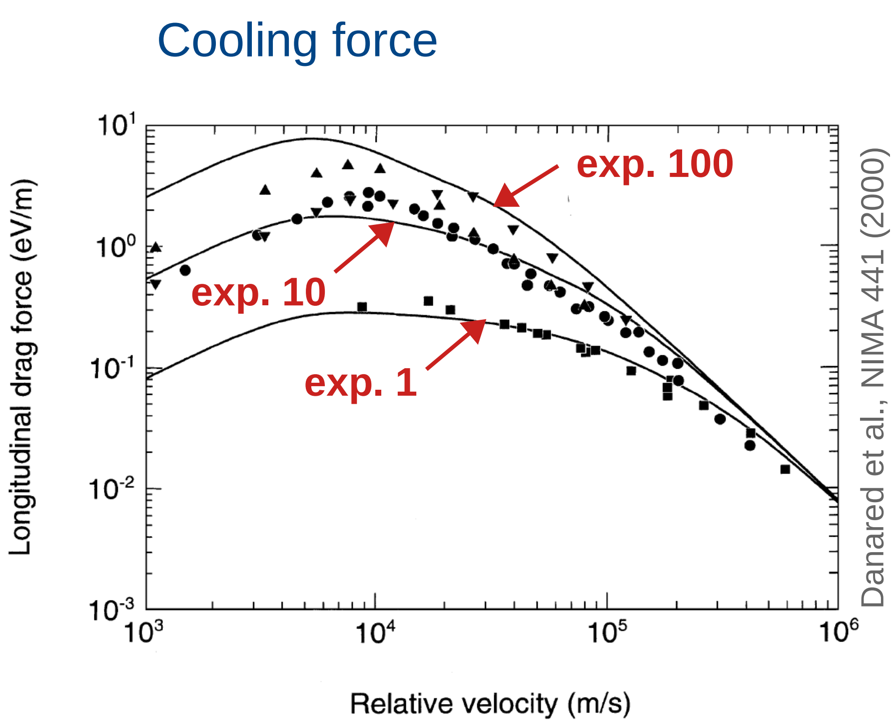
Up to now: only static correction by control system

Outlook: Machine experiments

Goal: Characterise performance of electron cooler, compare to MSL results

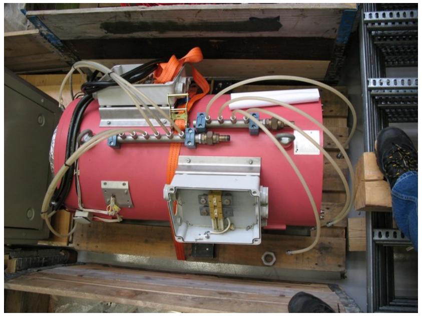
The low $T_\perp$ after expansion is <u>the</u> outstanding feature of the cooler,
→ we need to show that we are on par with past MSL operation.





Outlook: Hardware upgrades

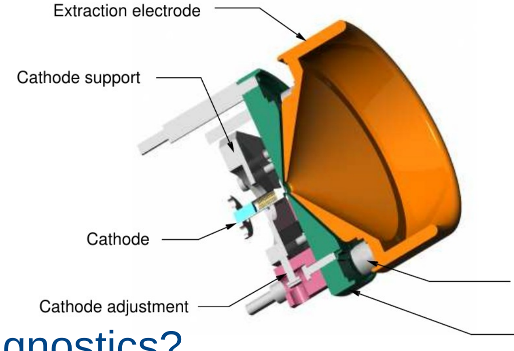
February 2020: Workshop on “The Future of the Electron Cooler”



Various possible hardware upgrade paths identified:

* Re-commission factor-10-expansion gun solenoid (+e-gun)?

→ *Fallback solution in case of terminal failure of s.c. magnet*
→ *(higher current, higher energies possible)*

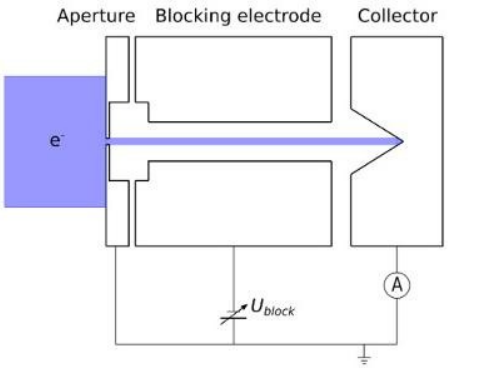


* Re-design e-gun with state-of-the-art features?

→ *Independent control electrode (→ beam profile)*
→ *Slow acceleration*

* Re-design collector section with enhanced beam diagnostics?

→ *Pinhole profile scanner, retarding field analyser*



* Re-design cooler section?

→ *Get rid of aperture-limitation by BPMs?*
→ *Drift-tube for energy variation?*

Thank you!

J. Roßbach, R. Heß, C. Dimopoulou,
M. Bräscher, M. Kelnhofer, C.K.
(Beam Cooling)

J. Krieg
(Storage Rings)

E. Menz, M. Lestinsky
(Atomic Physics)

S. Fuchs, J. P. Willamowski, C. Brandau, S. Schippers
(Univ. Gießen)

F. Herfurth + the CRYRING-Team
(Decelerators)