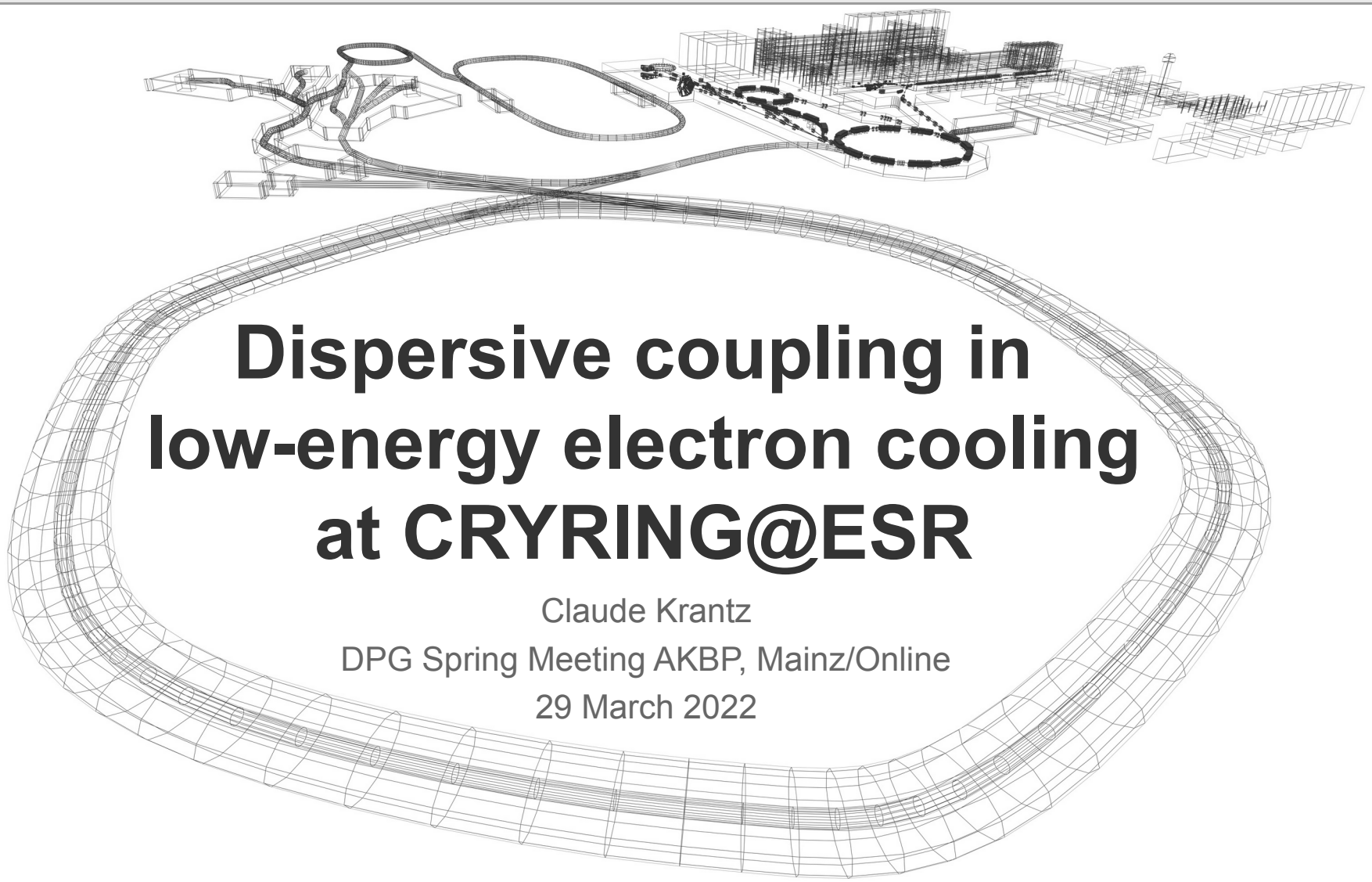


Dispersive coupling in low-energy electron cooling at CRYRING@ESR

Claude Krantz

DPG Spring Meeting AKBP, Mainz/Online

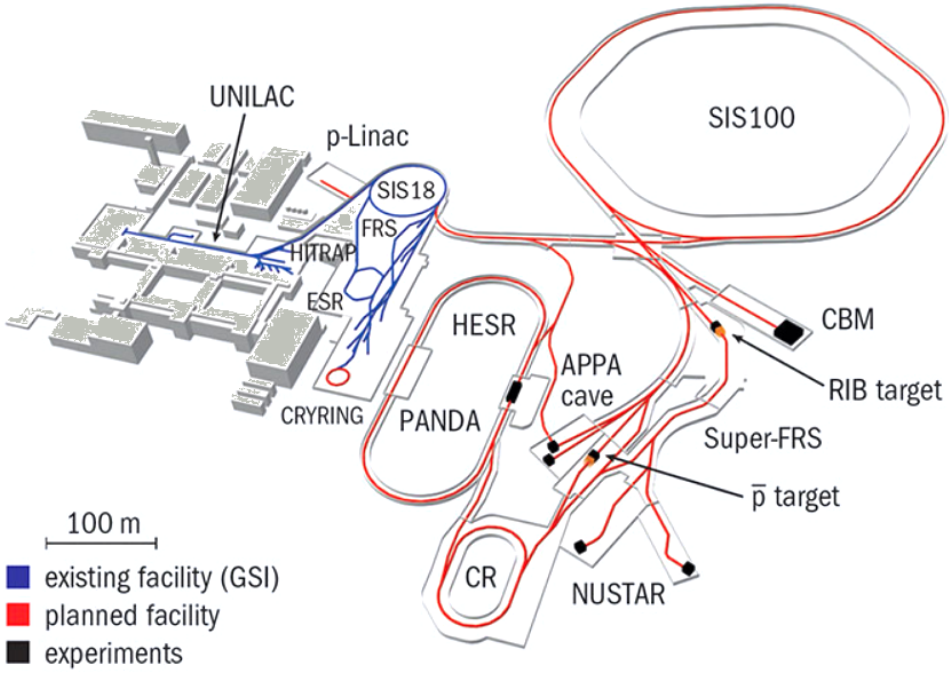
29 March 2022

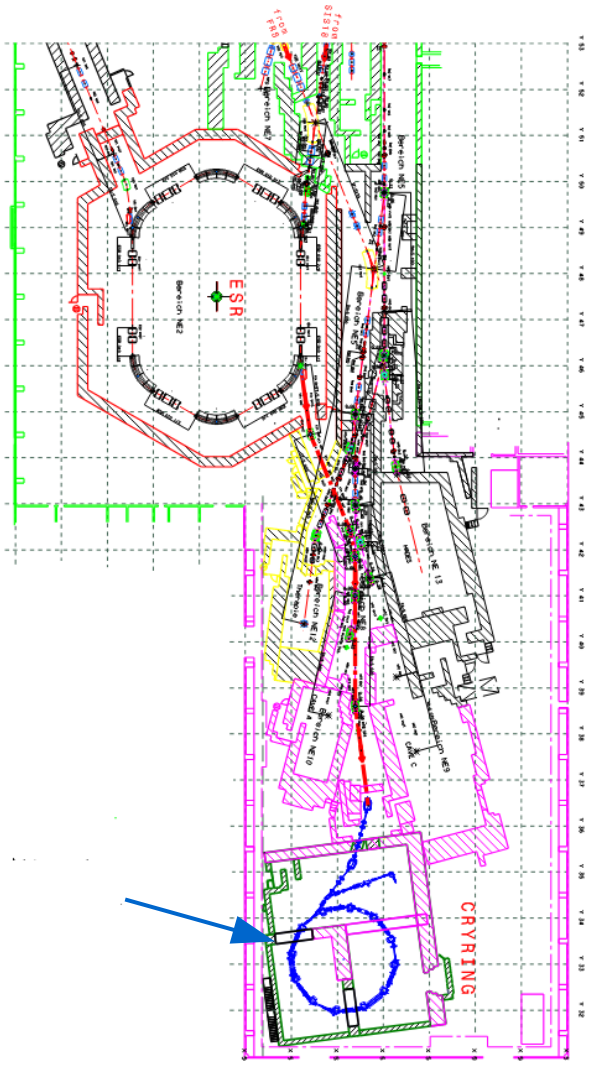
CRYRING@ESR

Complements ESR by a dedicated cooler storage ring for low energy ($\lesssim$ 10 MeV/u) highly-charged ions.

Commissioning (from 2017) almost complete.

Serving FAIR experiments since 2020.





CRYRING@ESR

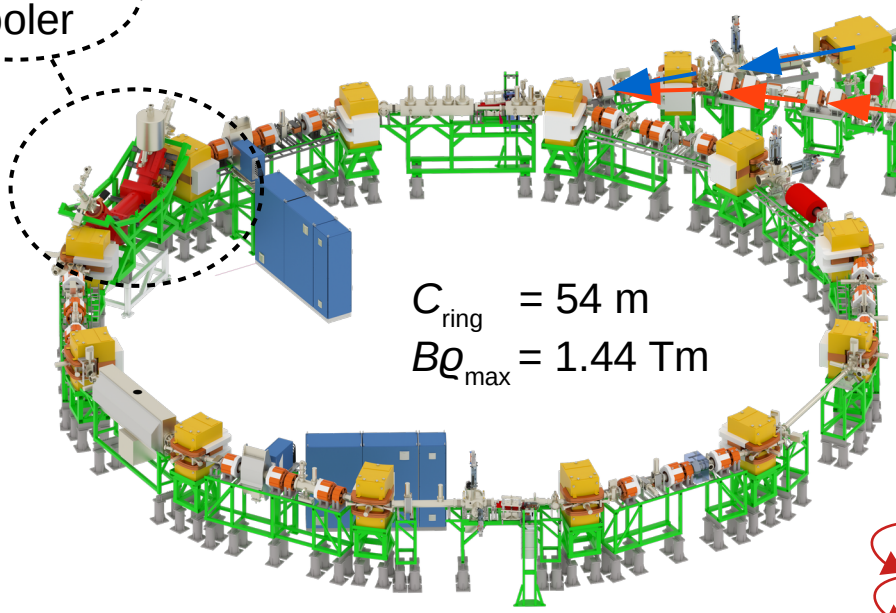
Highly-charged ions: e.g. $^{298}U^{91+}$

UNILAC: 11.4 MeV/u
SIS18: → 300 MeV/u *(stripping)*
ESR: → 10 MeV/u
CRYRING: ***10 MeV/u***

from ESR

Electron Cooler

Local injector



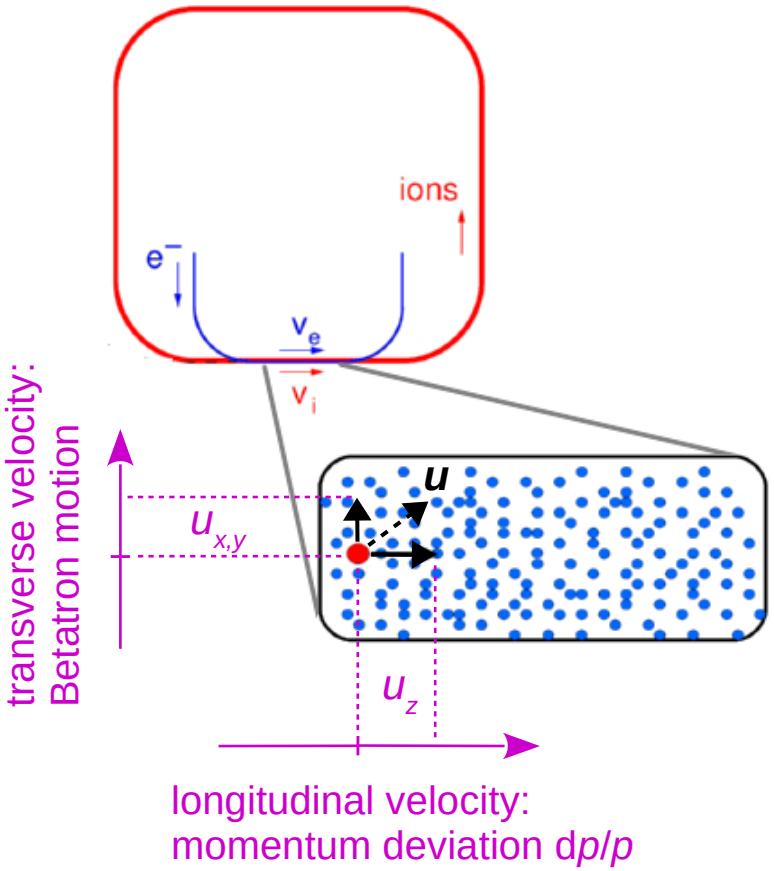
C_{ring} = 54 m
$B\varrho_{max}$ = 1.44 Tm

Low- or singly charged ions: e.g. $^{24,25}Mg^{+}$

Local injector + synchrotron accel.

Ion source: 35 kV
[*RFQ (m/q < 3.2)*]
CRYRING: → ***< 1 MeV/u***

Electron cooling



Merged, single-pass electron beam with $\langle \boldsymbol{v}_e \rangle = \langle \boldsymbol{v}_i \rangle$.

Any relative ion velocity $\boldsymbol{u} = (u_x, u_y, u_z)$ is damped by a "stopping" force ***F:***

$$F_{x,y} \approx -a_{x,y} \cdot u_{x,y} \quad \text{(trans.)}$$
$$F_z \approx -a_z \cdot u_z \quad \text{(long.)}$$

With

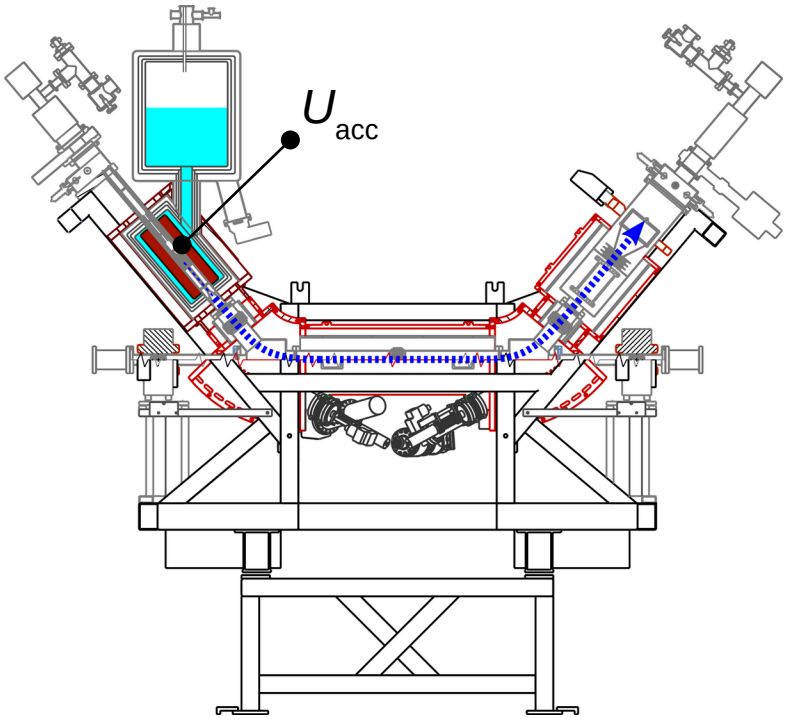
$$a_{x,y} < a_z$$

and

$$a_{x,y,z} \sim q_i^2 \cdot n_e \ .$$

(q = ion charge, n_e = electron density)

Electron cooling: Low energies



From $\langle \boldsymbol{v}_e \rangle = \langle \boldsymbol{v}_i \rangle$ follows that $E_{kin,e} \approx \frac{m_e}{m_i} \cdot E_{kin,i}$

Highly charged ions: cooler voltages $U_{acc} \gtrsim$ few kV

e.g. U^{91+}: $E_{kin,i} \approx 10$ MeV/u → $E_{kin,e} \approx 5500$ eV

→ pretty standard, much experience (also from other cooler rings).

Singly-charged ions: *very low* cooler voltage

e.g. $^{25}Mg^{+}$: $E_{kin,i} \approx 155$ keV/u → $E_{kin,e} \approx 85$ eV

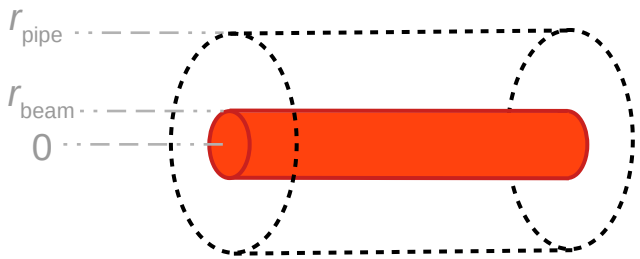
→ Ultra-low-energy electron cooling is a young field!

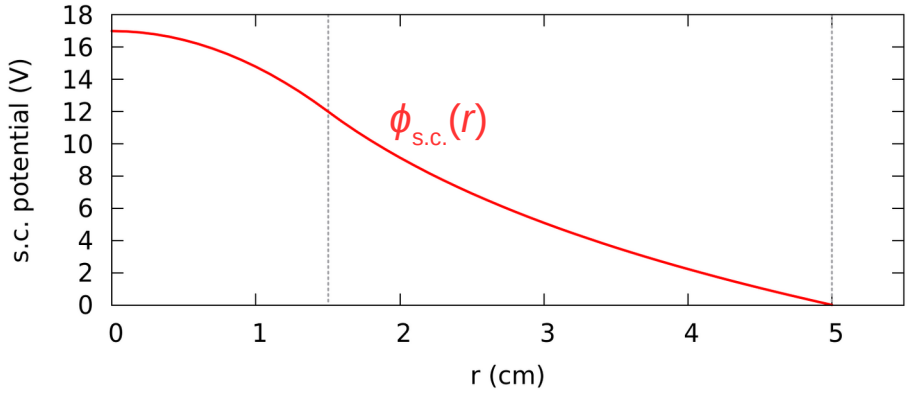
TSR (MPIK, 2007 … 2012): 130 … 31 eV
ELENA (CERN, 2018 …): 355 … 54 eV
CSR (MPIK, 2017 …): 50 … 5 eV

Electron cooling: Low energies

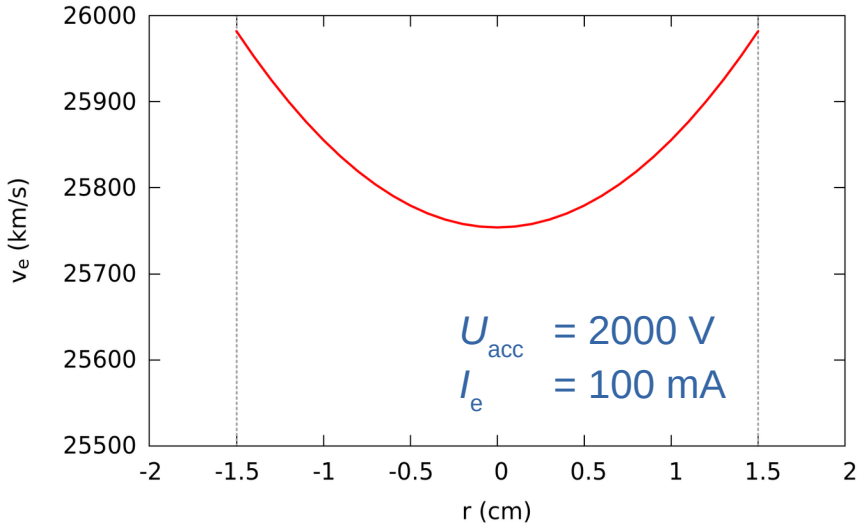
Space-charge of beam partly screens electrons from acceleration voltage:

$$E_e(r) = e \cdot U_{acc} - e \cdot \phi_{s.c.}(r)$$





→ Electrons are faster near edge of beam.



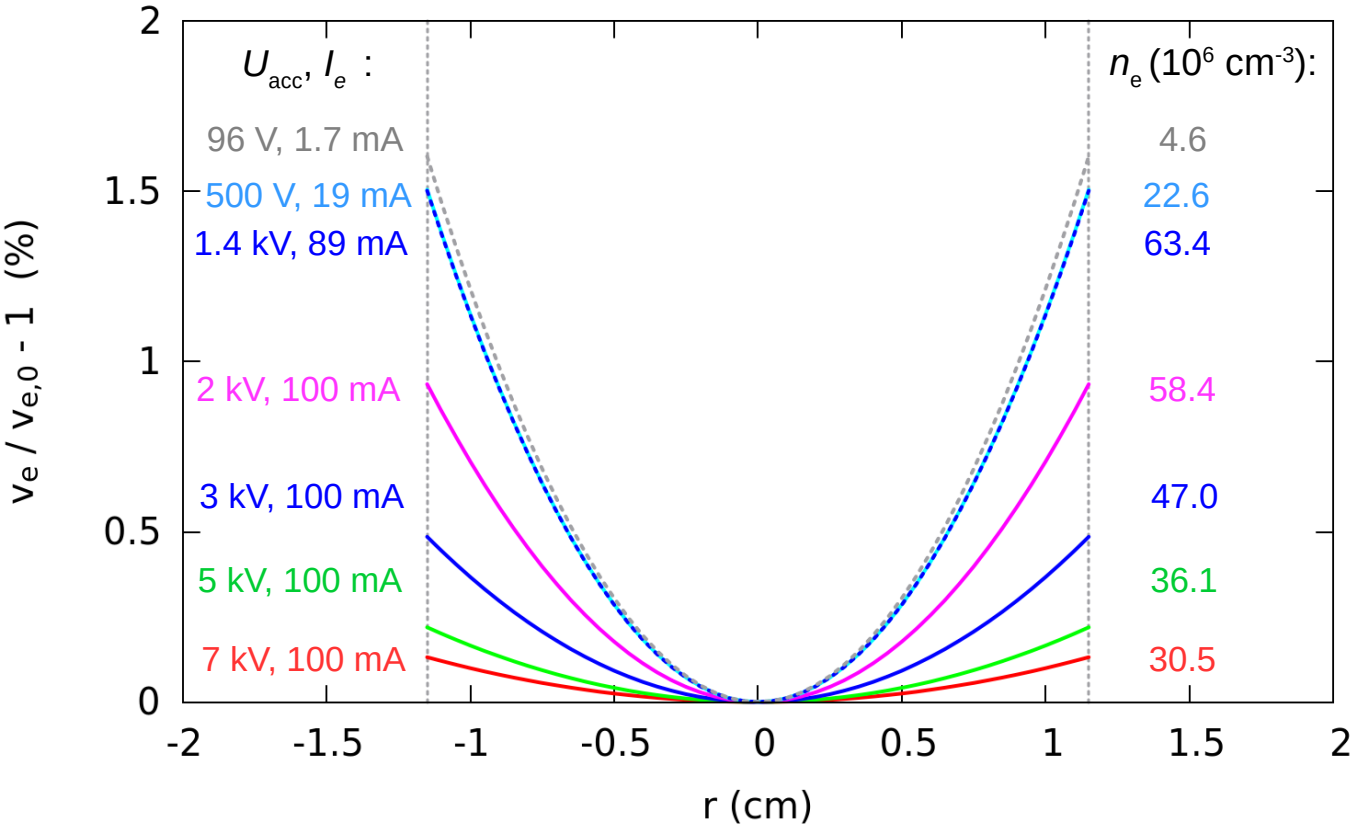
→ Not all ions "see" the same $\langle \boldsymbol{v}_e \rangle$!

Possible effects on cooling are known *in principle* …

Bosser, NIM A 441 (2000), 60
Beutelspacher, NIM A 512 (2003), 459

Electron cooling: Low energies

… *relatively*, space-charge effects tend to become **more important for low-energy beams**.



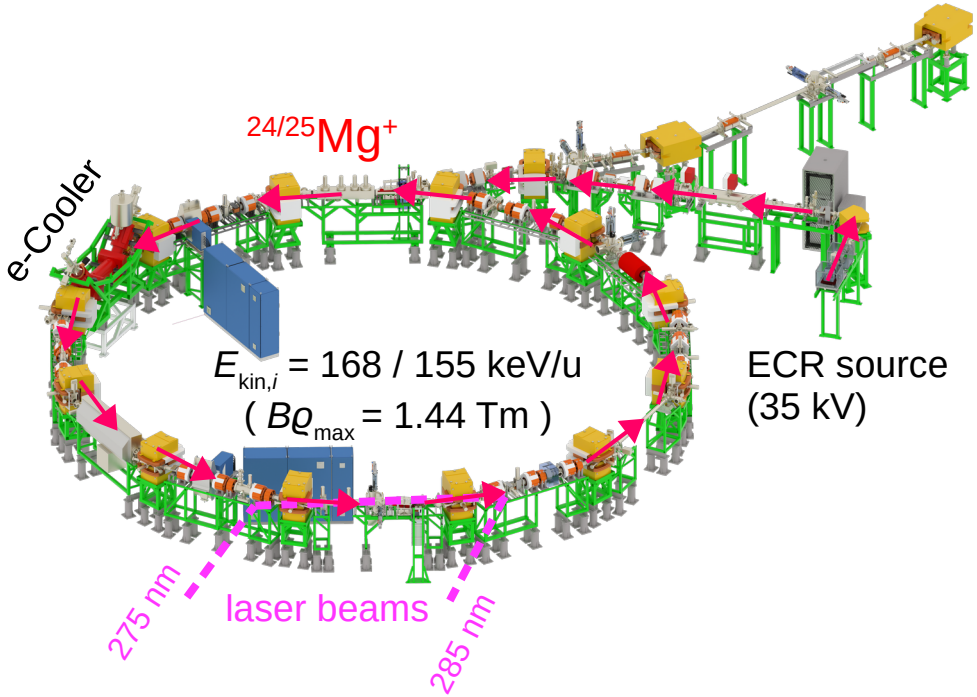
Reason: Need to approach “space-charge limit” to keep acceptable n_e (*Child-Langmuir*-Law).

Experiment: $^{24/25}Mg^{+}$

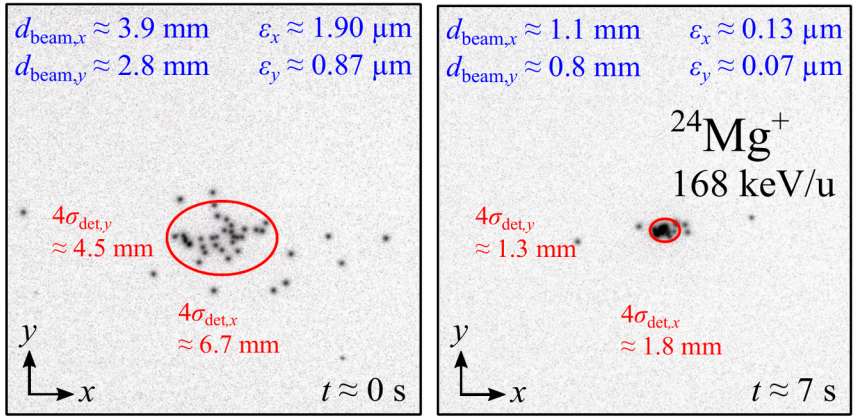
$^{24}Mg^{+}$ and $^{25}Mg^{+}$ for in-ring laser spectroscopy.

Maximum Bϱ: 168 keV/u and 155 keV/u.

Electron cooler: $U_{acc} \approx 102$ V and 96 V.

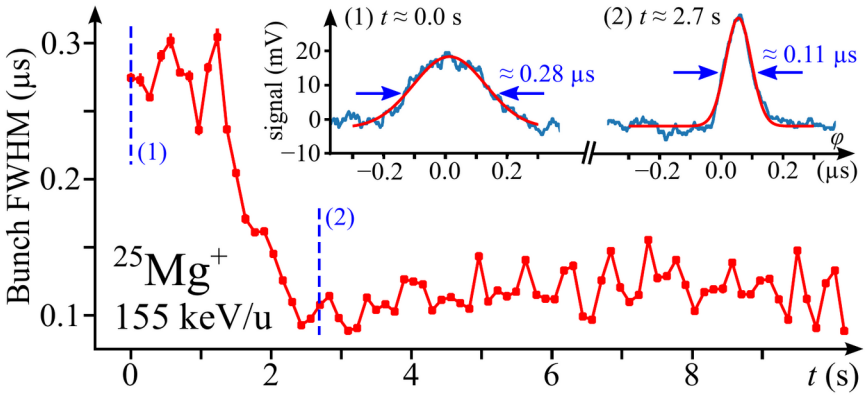


Transverse cooling (neutral imaging):

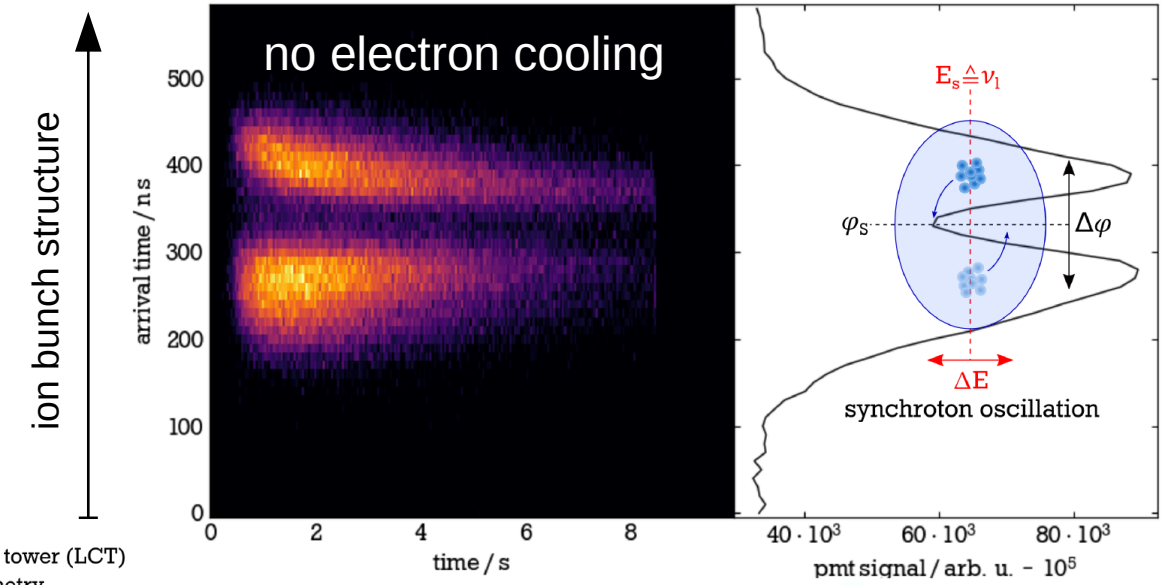


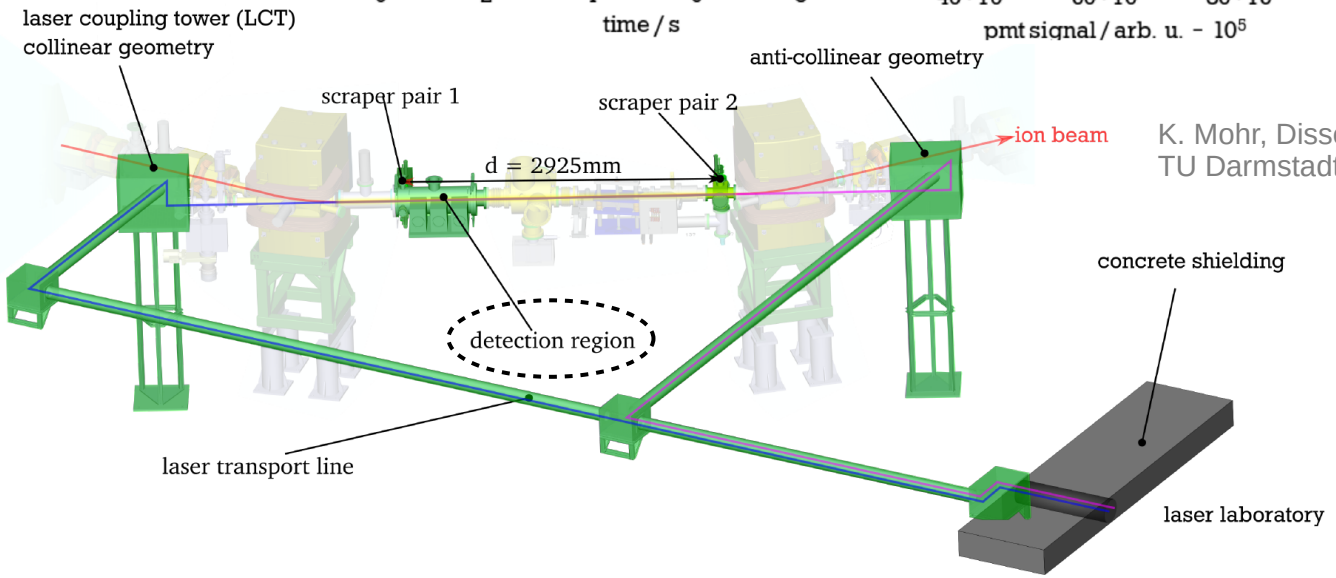
E. B. Menz *in prep.* / C. Krantz, Proc. IPAC 2021

Longitudinal bunch cooling (pickup):



Experiment: $^{24/25}Mg^{+}$





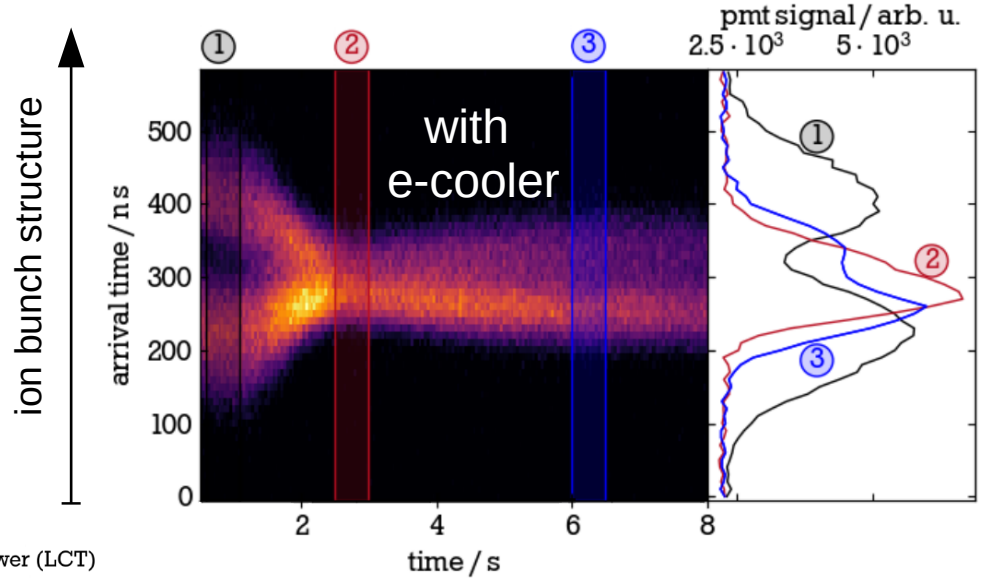
K. Mohr, Dissertation, TU Darmstadt, 2022

Fluorescence signal from laser-irradiated ions.

Laser frequency tuned to synchronous particle velocity.

→ *Very sensitive* probe of bunch structure vs. storage time!

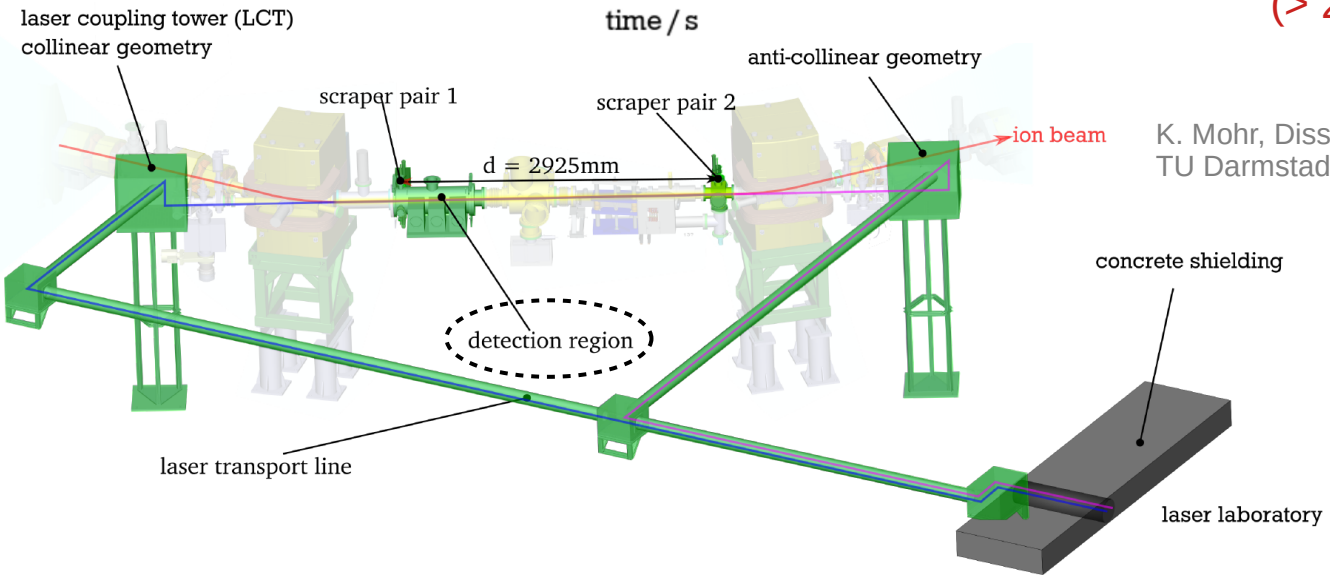
Experiment: $^{24/25}Mg^{+}$



With electron cooler active …

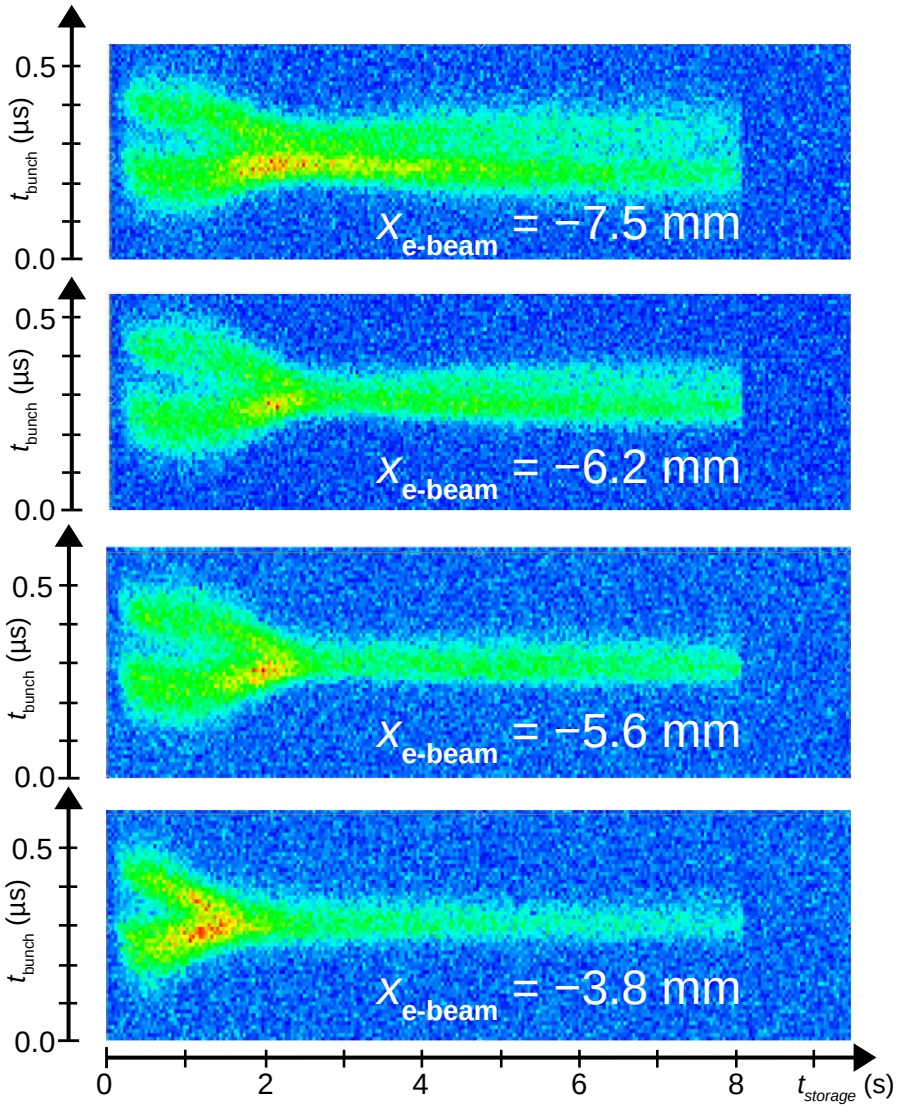
… bunches cool down at first (< 2 s) …

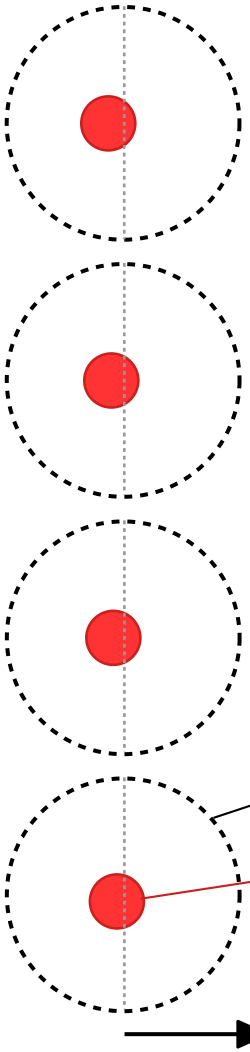
… but then synchrotron oscillation slowly restarts (> 2s) ?!?



K. Mohr, Dissertation, TU Darmstadt, 2022

Experiment: $^{24/25}Mg^{+}$

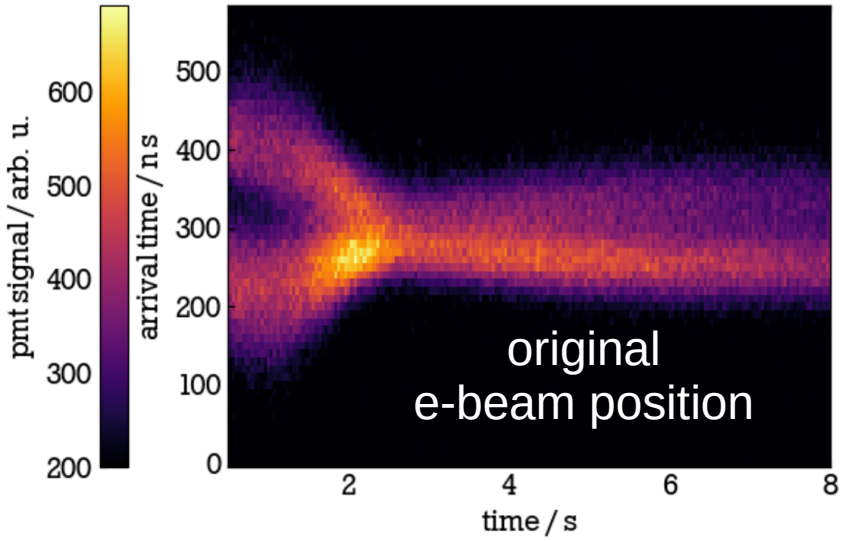


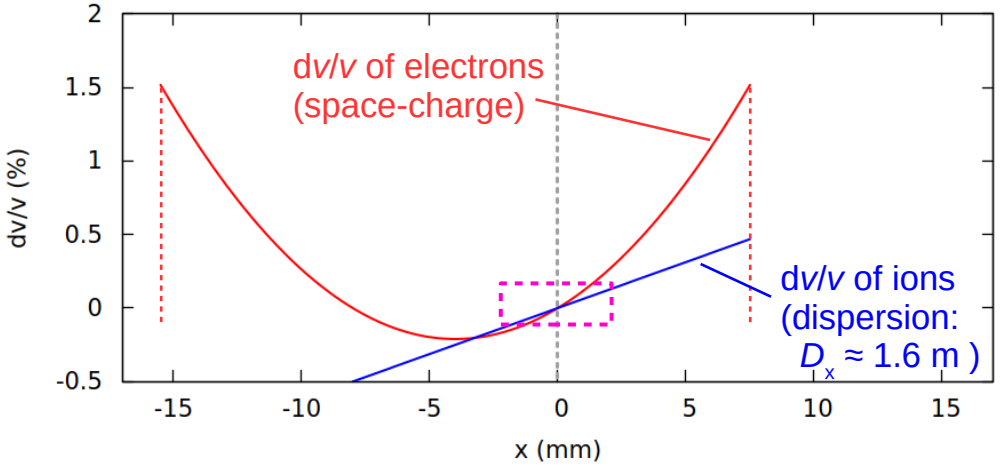


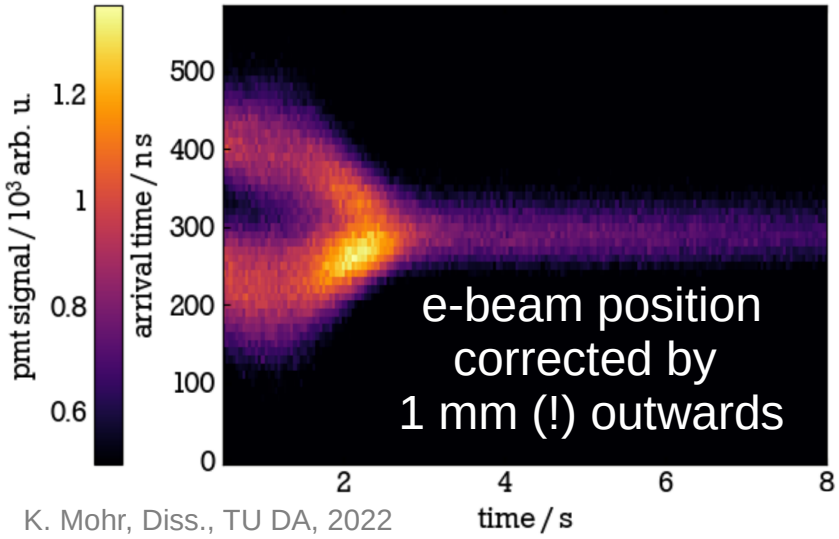
Fix:

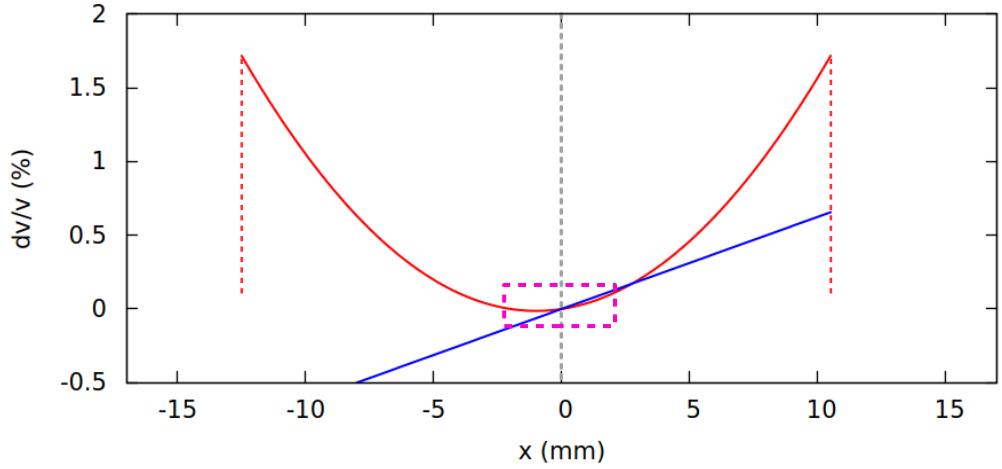
Small horizontal shift of electron beam

Dispersive heating by e-cooler



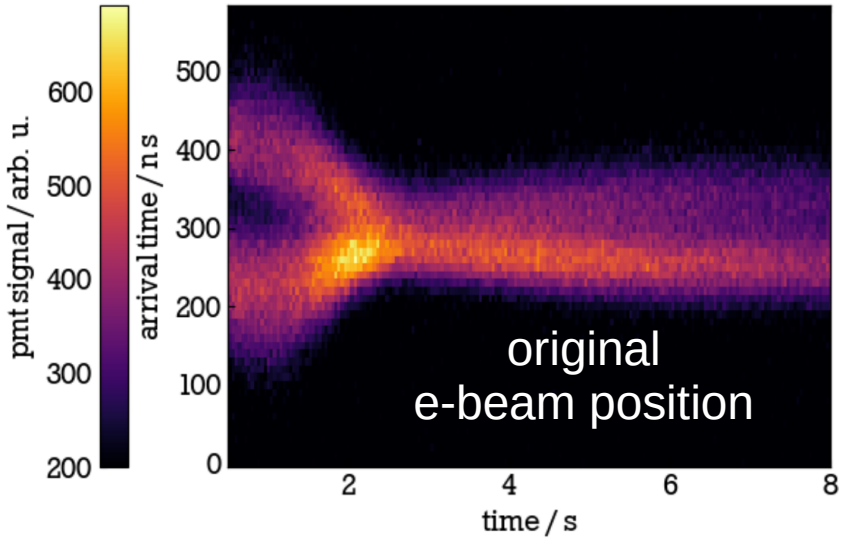


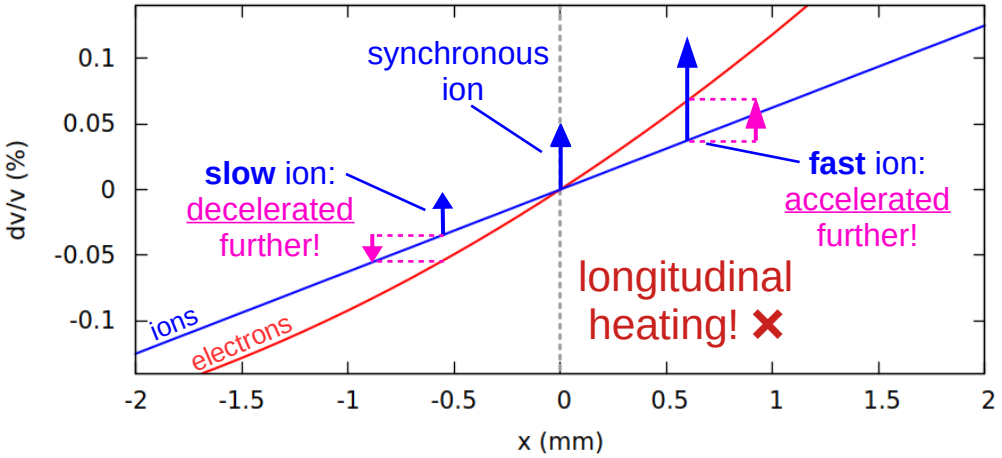


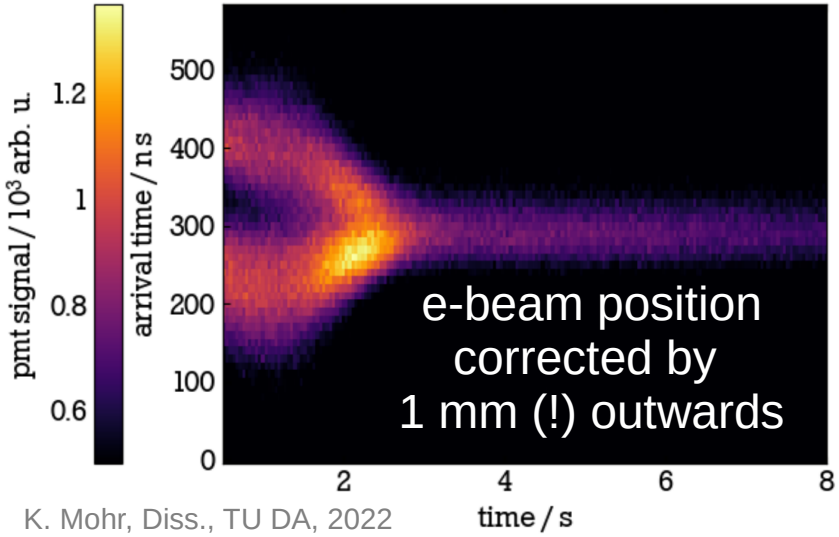


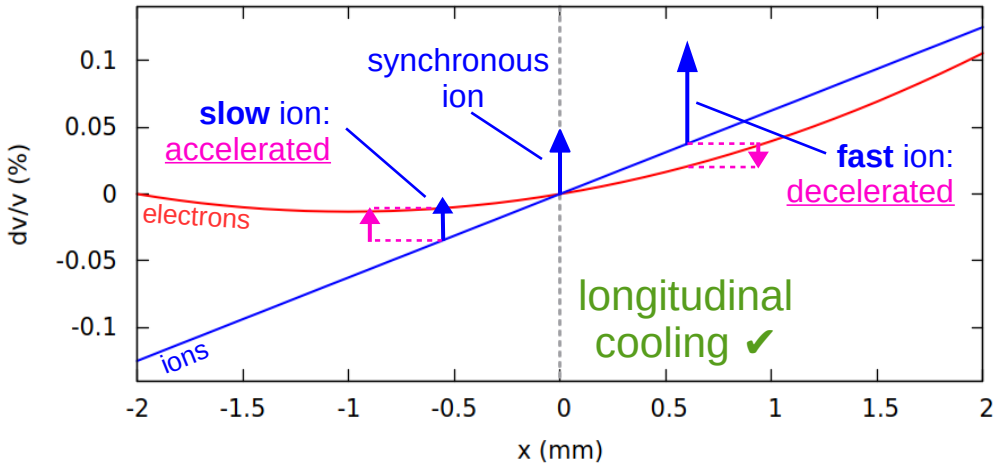
K. Mohr, Diss., TU DA, 2022

Dispersive heating by e-cooler









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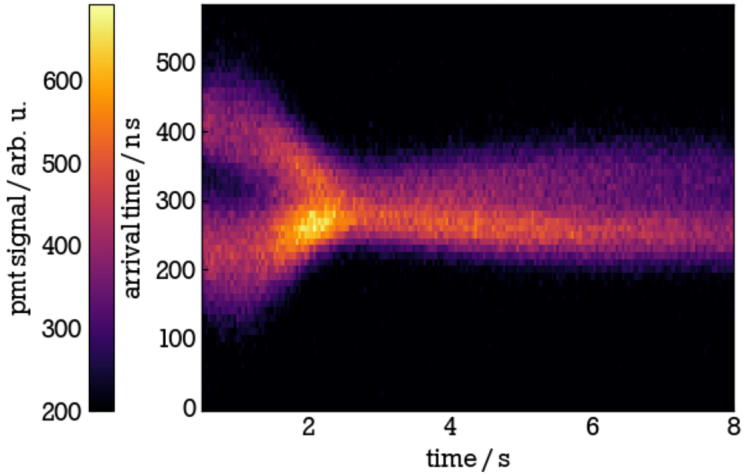
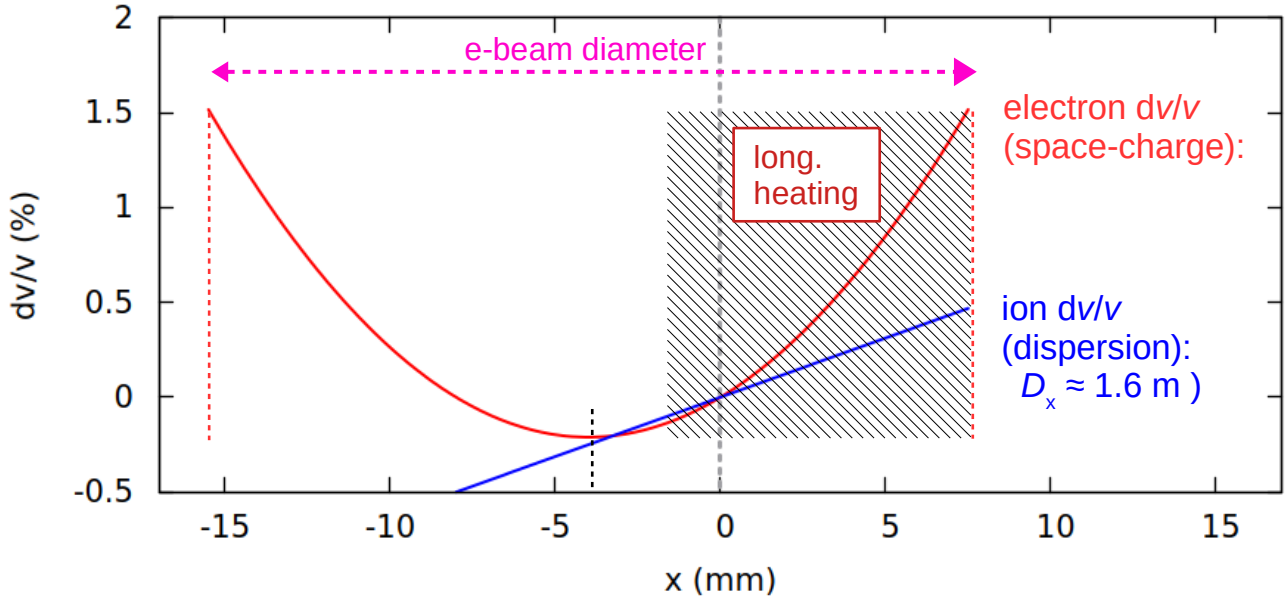
Horizontal acceptance for e-cooling



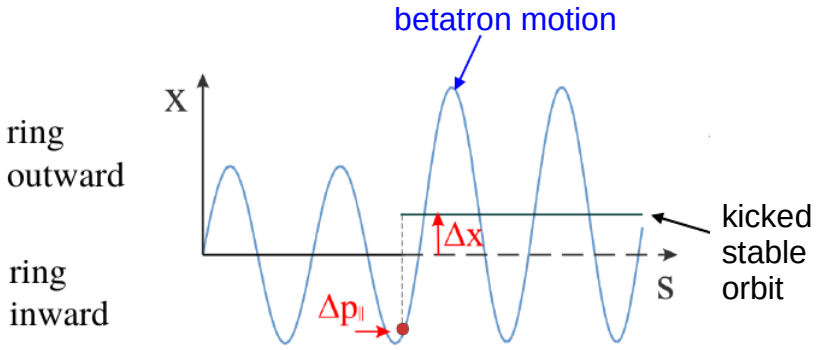
For $(dv/v)_e' > (dv/v)_i'$:

→ Longitudinal heating by electron beam.

Critical e-beam displacement: $x < \frac{4 E_{kin,e} \epsilon_0}{D_x e^2 n_e}$



Horizontal acceptance for e-cooling



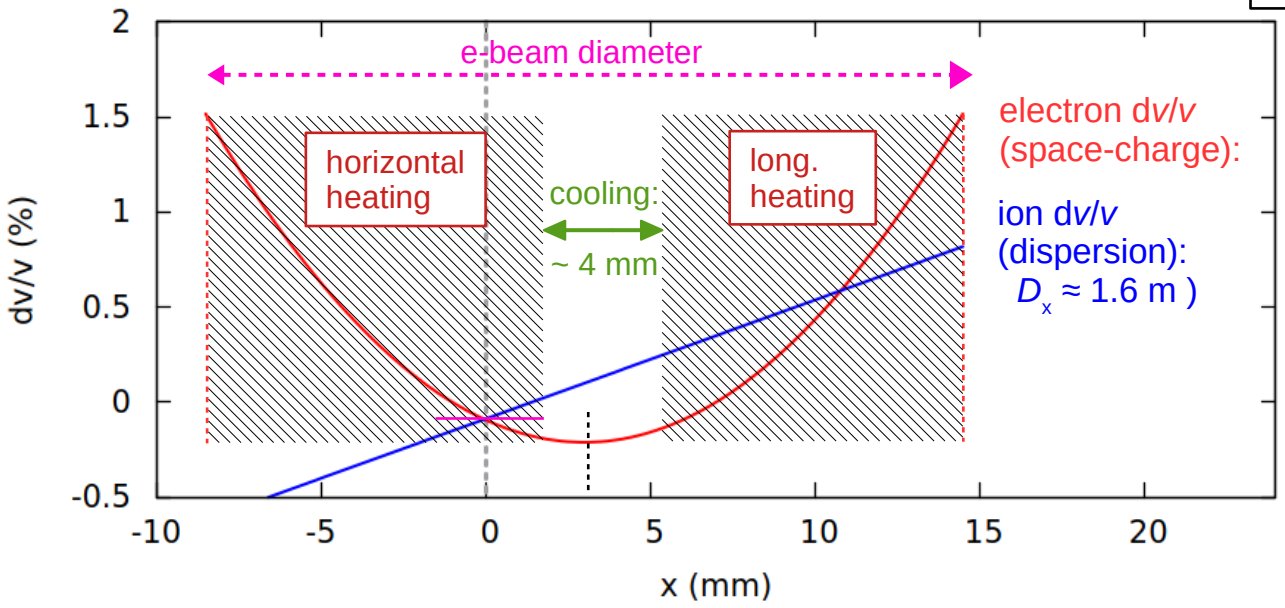
Beutelspacher, NIM A 512 (2003) 459

For $(dv/v)_e' < 0$:

Cooling kicks orbit *away* from ion position.

For $x > \frac{4 E_{kin,e} \epsilon_0}{D_x e^2 n_e} \frac{a_x}{a_z}$ → breaks horizontal cooling!

Hor. acceptance for cooling: $\Delta x_{cool} \sim \frac{E_{kin,e}}{D_x n_e}$



Summary

- Singly charged ions at CRYRING@ESR require **low-energy electron cooling**.
- High **e-beam space charge** and **dispersive ion optics** limit horizontal acceptance for electron cooling.
- Ultimately, **control of dispersion** at the cooler may become necessary.

Thank you!

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