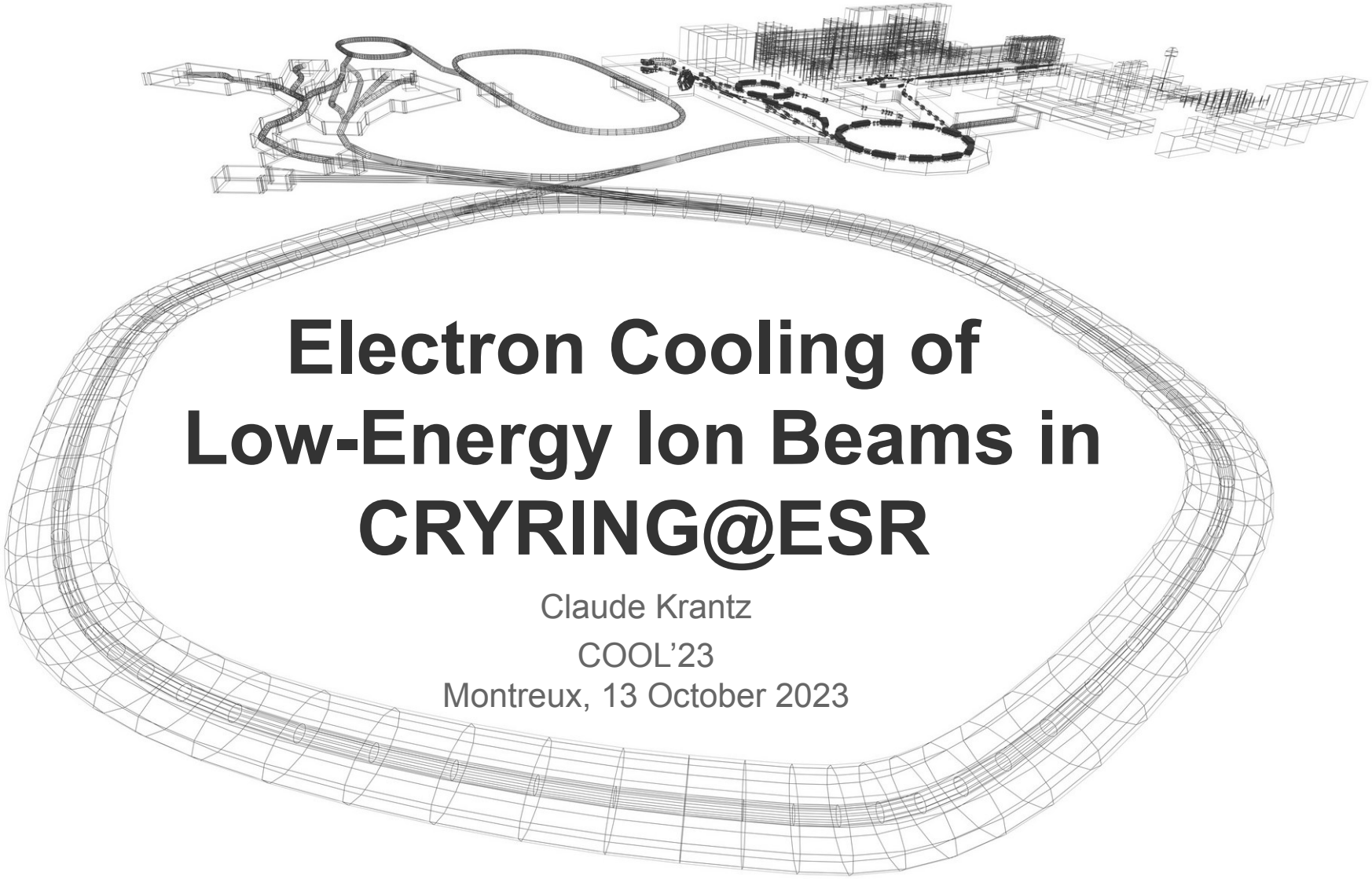


# Electron Cooling of Low-Energy Ion Beams in CRYRING@ESR

Claude Krantz

COOL'23

Montreux, 13 October 2023

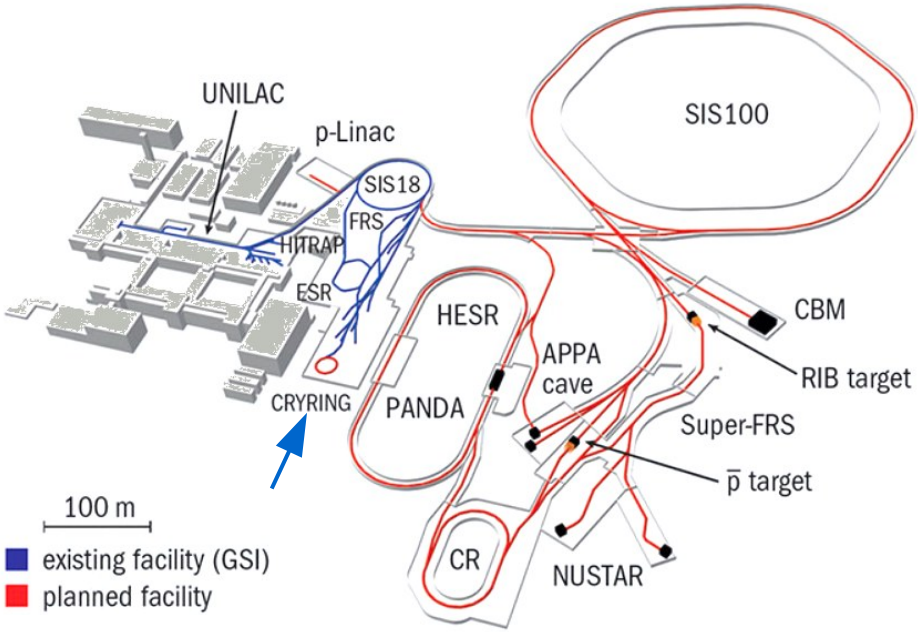
# CRYRING@ESR

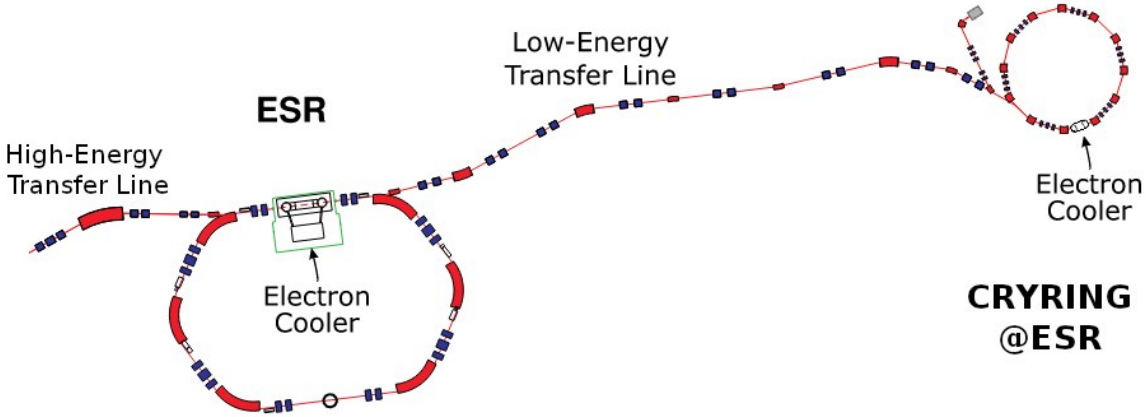
## CRYRING@ESR

CRYRING has been transferred from Stockholm to Darmstadt (Swedish in-kind contribution to FAIR).

Complements GSI facilities by a dedicated low-energy ion storage ring.

M. Lestinsky et al., Eur. Phys. J. ST 225 (2016) 797



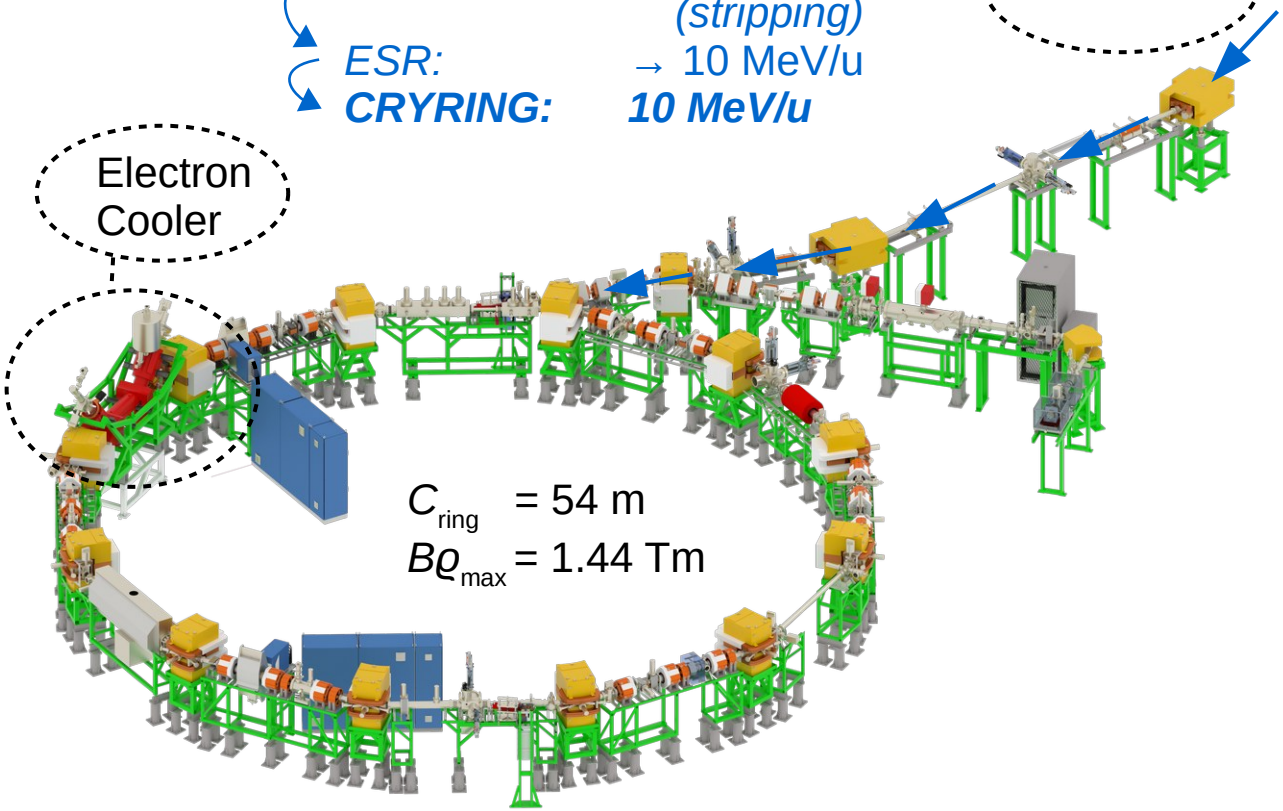



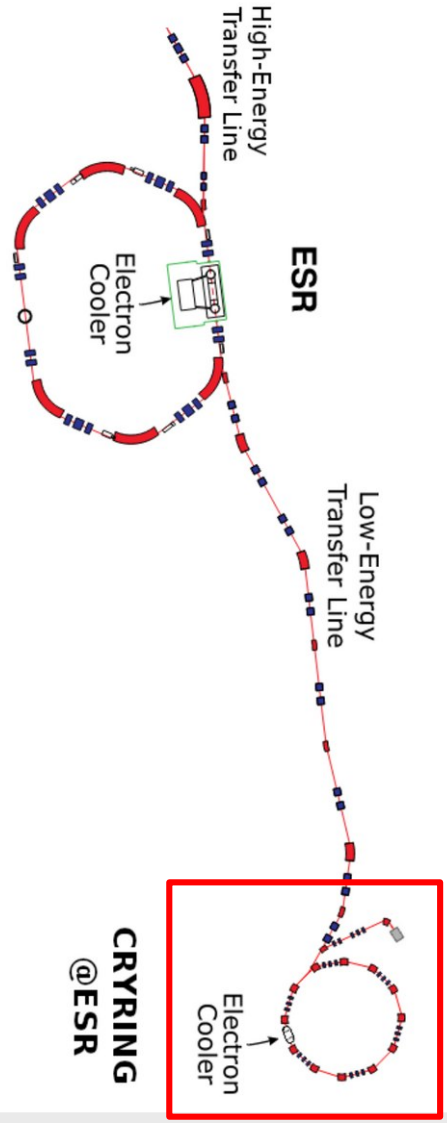

**See talk by Frank Herfurth on Wednesday.**

# 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*** |



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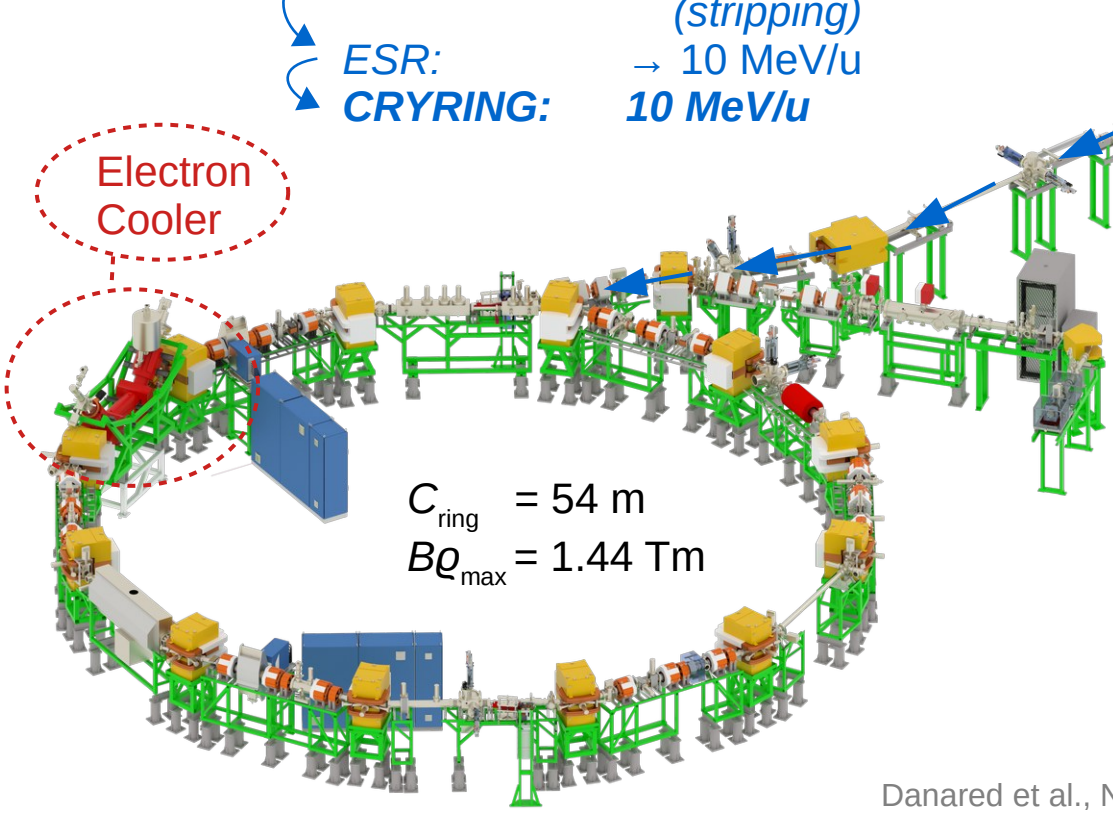
| ***CRYRING:*** | ***10 MeV/u*** |

$$E_{kin,e} = \frac{m_e}{m_i} \cdot E_{kin,i}$$

$E_{kin,i} \approx 10$ MeV/u

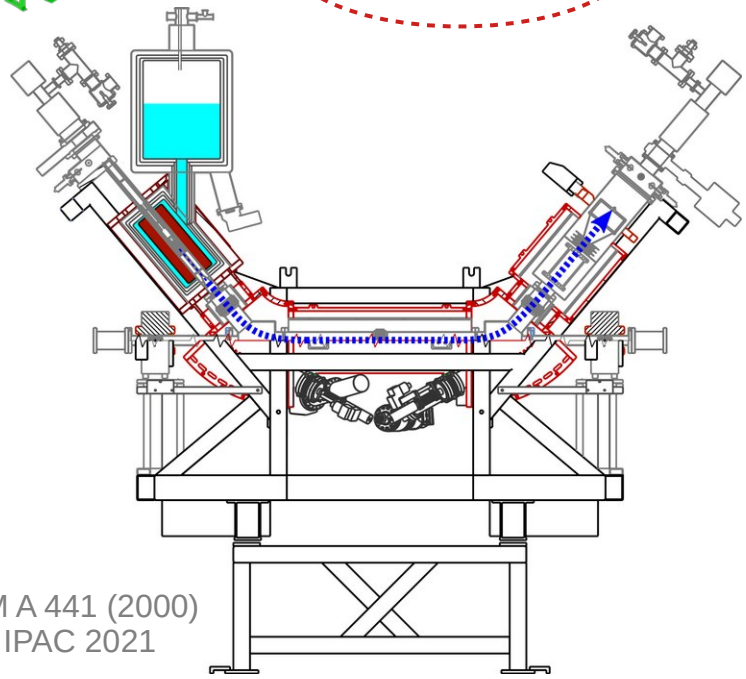
→ $E_{kin,e} \approx 5500$ eV

Electron Cooler



$C_{ring} = 54$ m

$B\varrho_{max} = 1.44$ Tm



Danared et al., NIM A 441 (2000)
Krantz et al., Proc. IPAC 2021

# CRYRING@ESR

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

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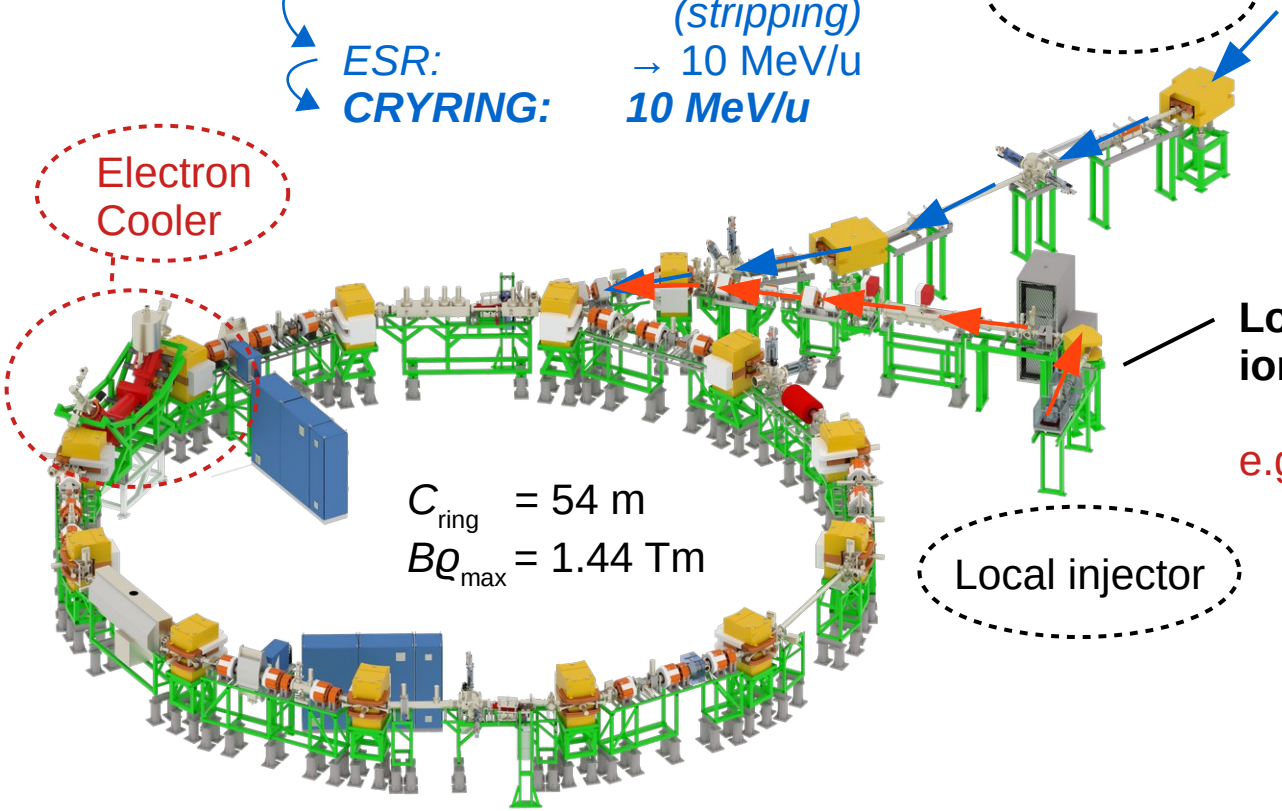
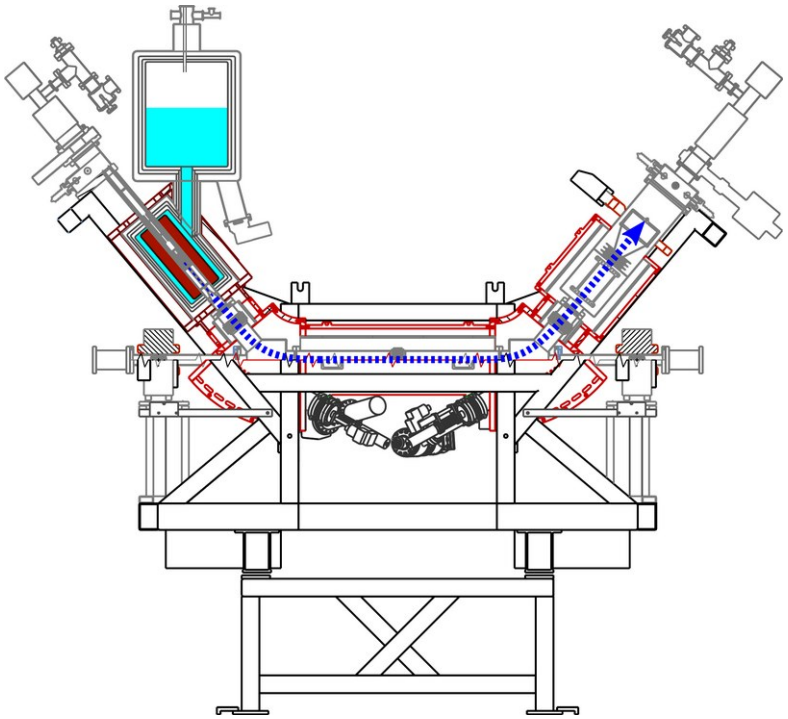



**Low- or singly charged ions:**

| | | |
|---|---|---|
| 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 cooling: Low energies



**Singly-charged ions**: *very low* cooler voltages!

$$E_{kin,e} = \frac{m_e}{m_i} \cdot E_{kin,i}$$

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

Ultra-low-energy electron cooling is a relatively recent development:

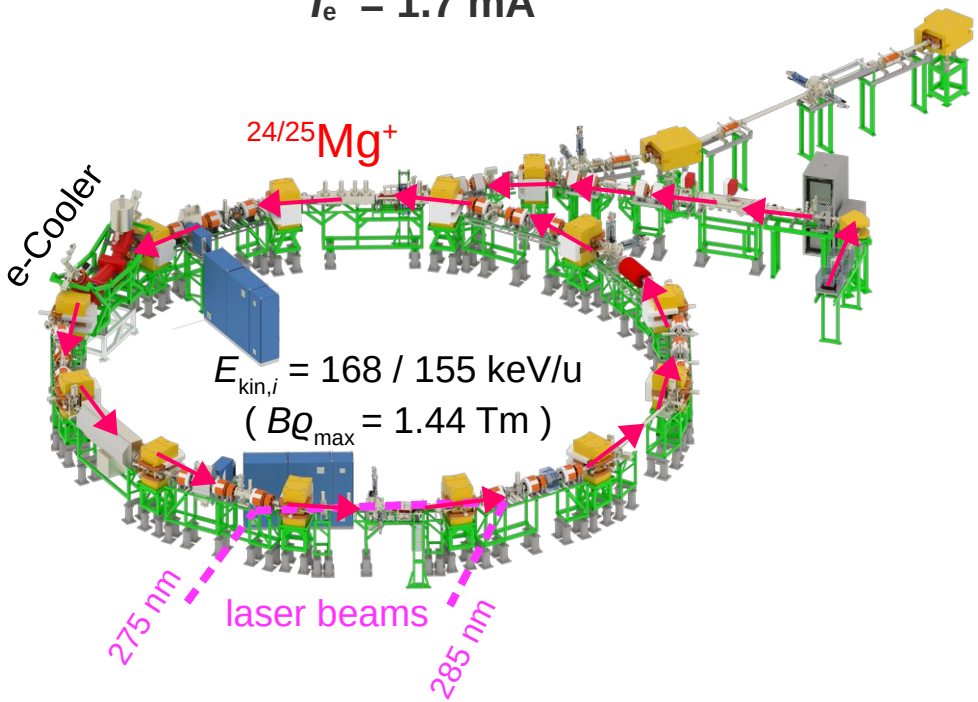
TSR (MPIK, 2007 … 2012): ~ 130 … 31 eV
ELENA (CERN, 2018 … ): 355 … 54 eV
CSR (MPIK, 2017 … ): ~ 50 … 4 eV

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

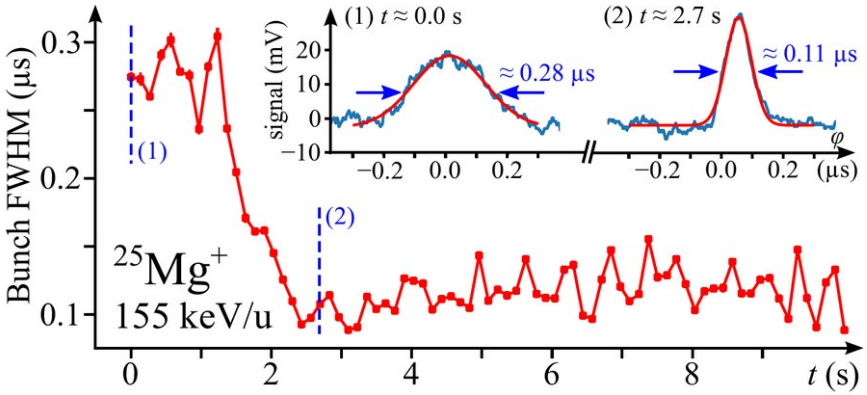
**$^{24}Mg^{+}$ and $^{25}Mg^{+}$** for in-ring laser spectroscopy.

$^{24}Mg^{+}$ (0.168 MeV/u) and $^{25}Mg^{+}$ (0.155 MeV/u)

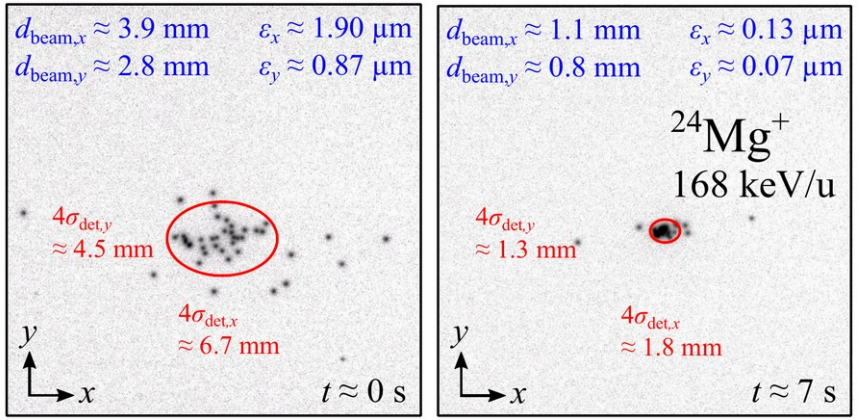
$$E_e = 92 \text{ eV} / 85 \text{ eV}$$
$$B_{gun} / B_{cooler} = 33.3$$
$$I_e = 1.7 \text{ mA}$$




## Longitudinal bunch cooling (pickup):

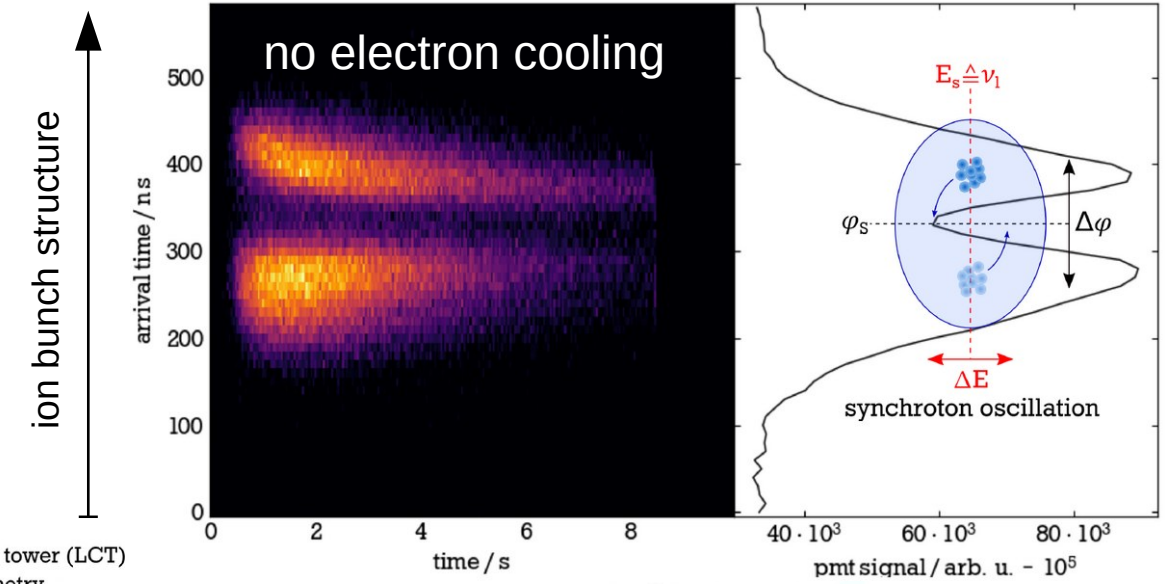


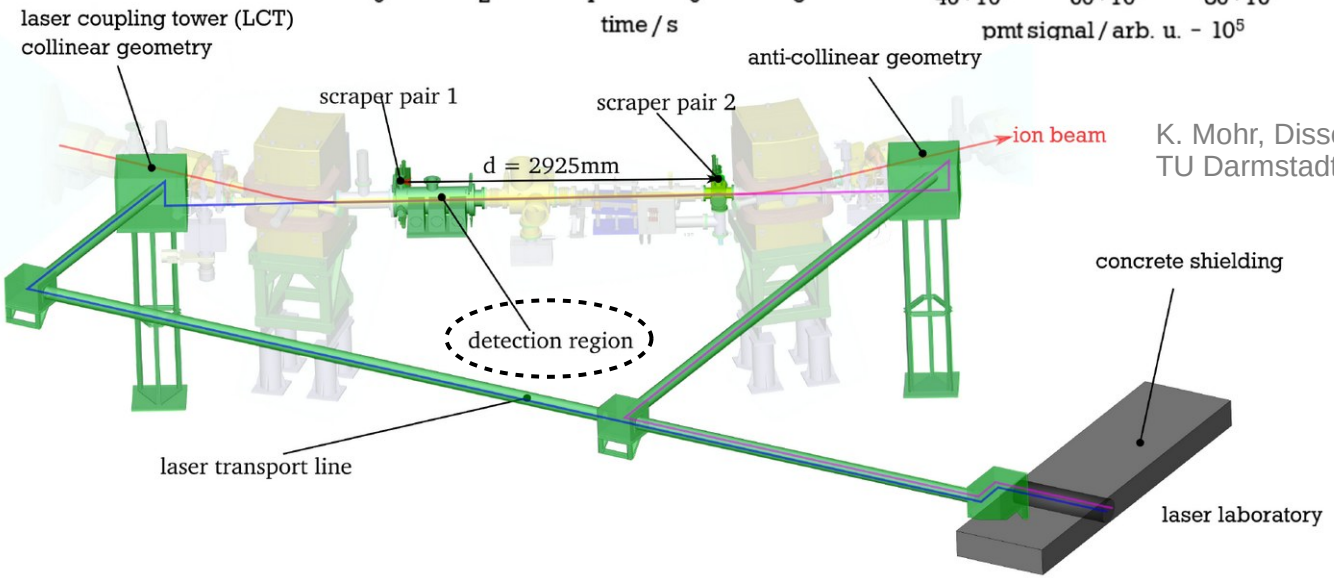

## Transverse cooling (neutral imaging):




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

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



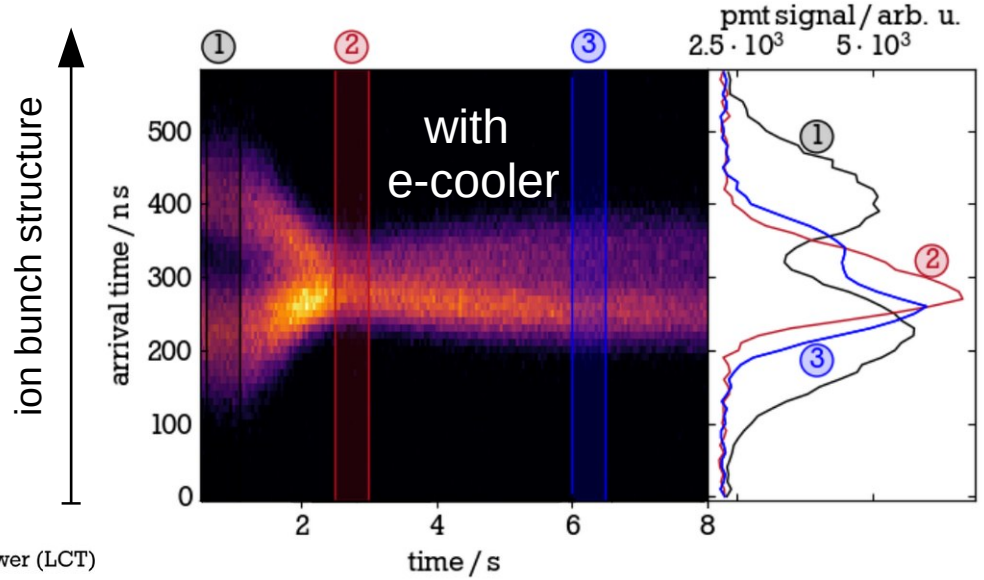

Fluorescence signal from laser-irradiated ions.

Laser frequency tuned to synchronous particle velocity.

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

K. Mohr, Dissertation, TU Darmstadt, 2022

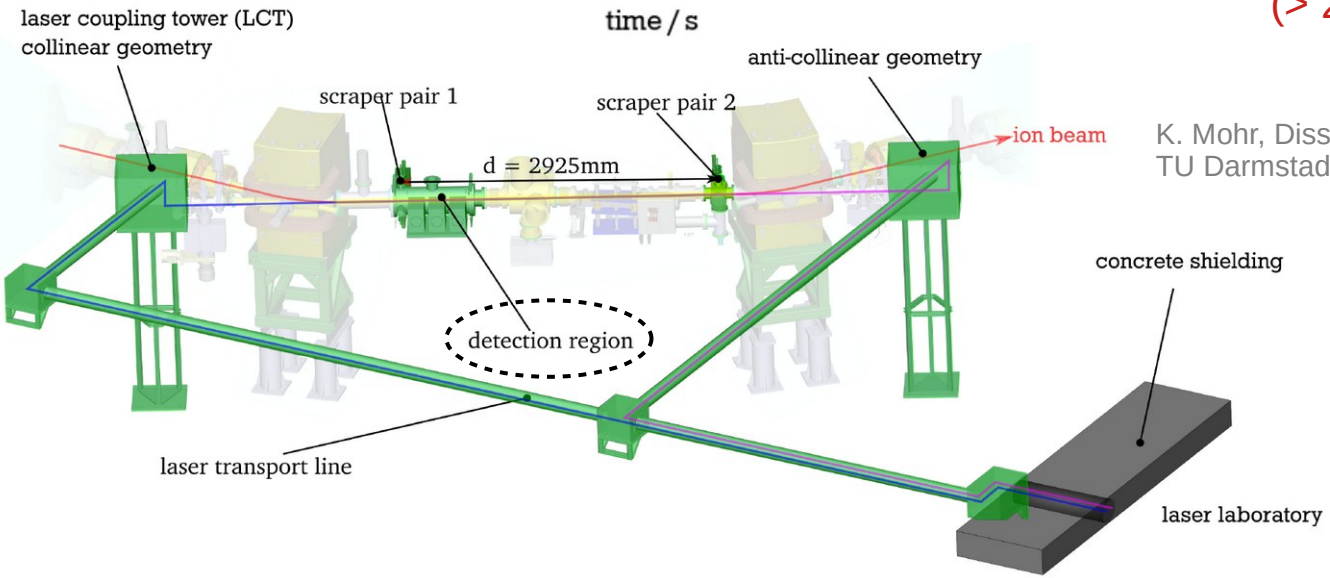
# Experiment: $^{24/25}Mg^{+}$




With electron cooler active …

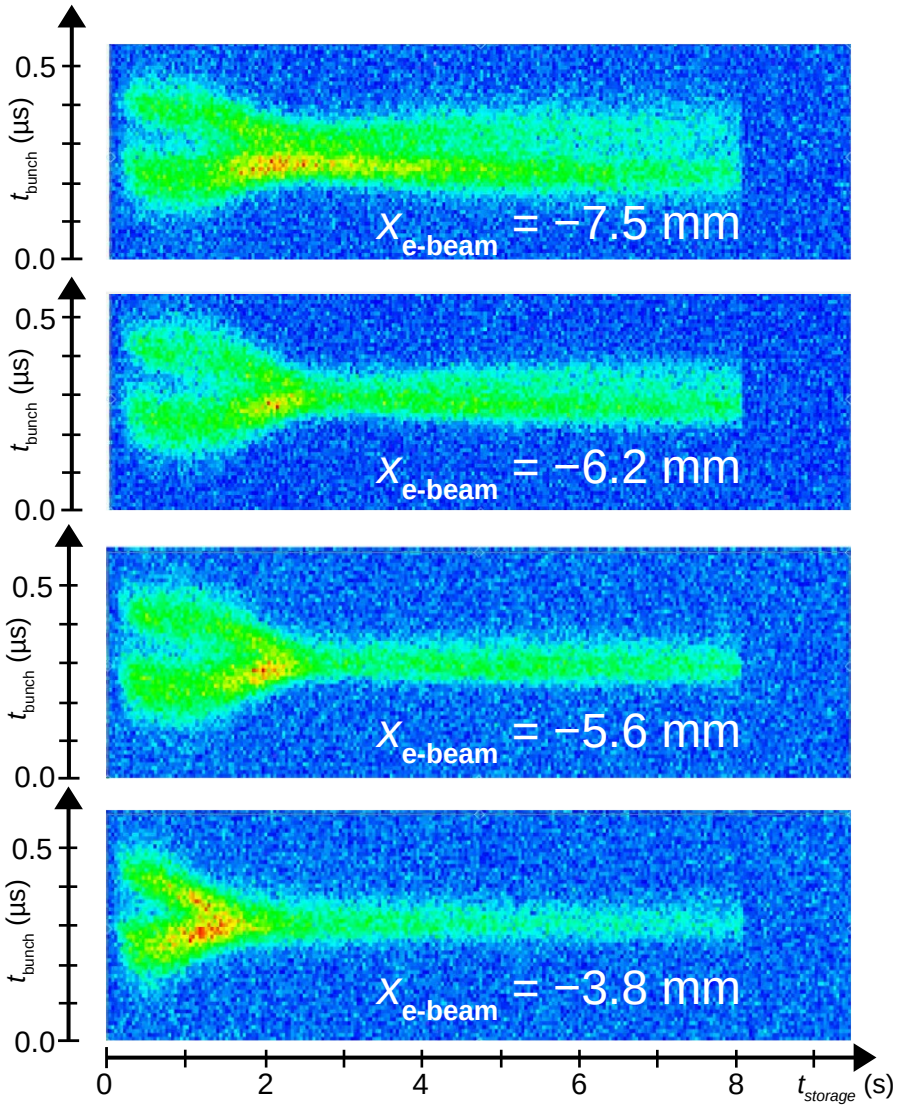
… bunches cool down at first (< 2 s) …

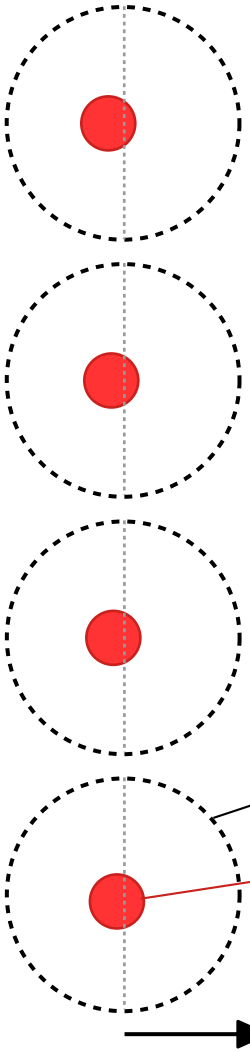
… but then synchrotron oscillation slowly restarts (> 2s) ?!?




K. Mohr, Dissertation, TU Darmstadt, 2022

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



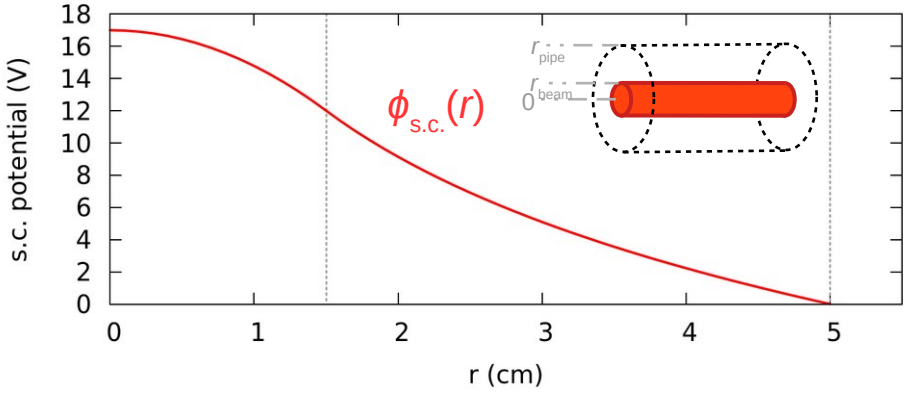



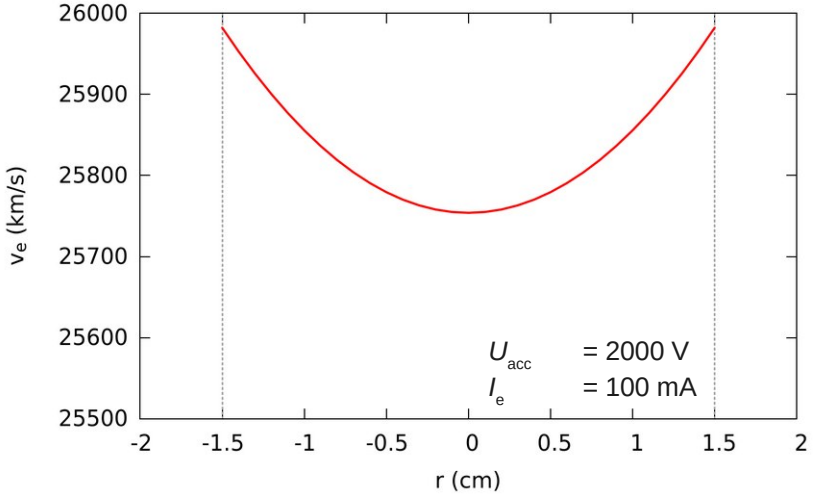

Fix:

Small horizontal, parallel shift of electron beam

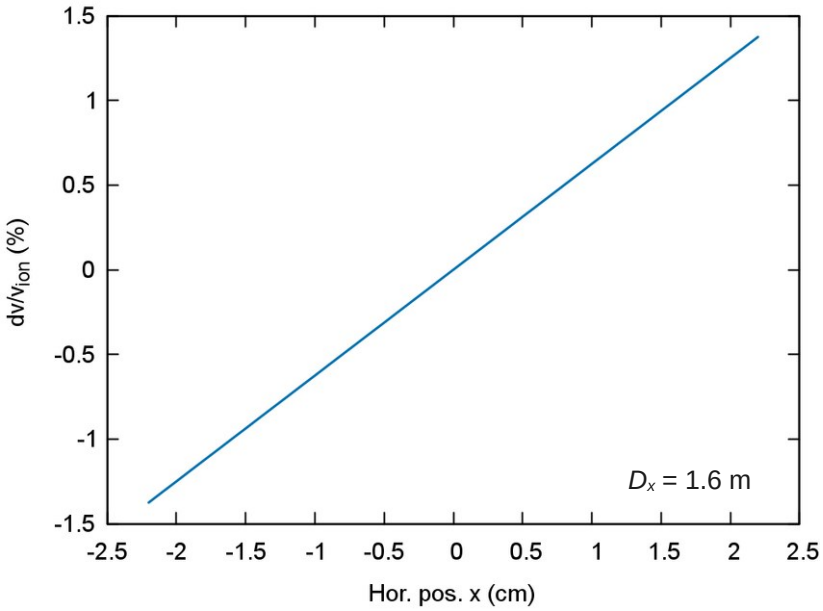
# Electron space-charge and ion dispersion

**Space-charge of e-beam** creates electron velocity profile across beam diameter.



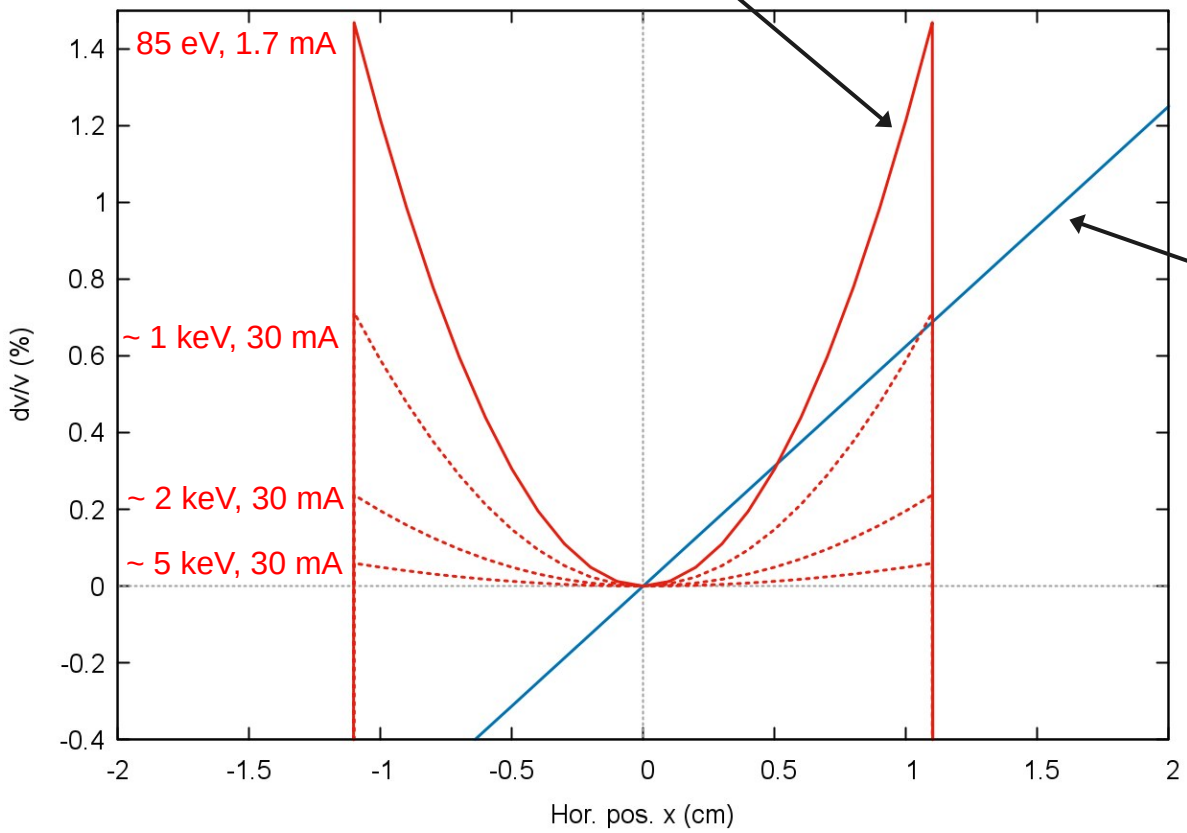




**Dispersion of ring** introduces dependence of horizontal ion position on ion velocity.



# Electron space-charge and ion dispersion

$$\frac{d}{dx}\left(\frac{dv}{v}\right)_{\text{electrons}} = \frac{n_e e^2}{4\,\epsilon_0 E_e} x$$



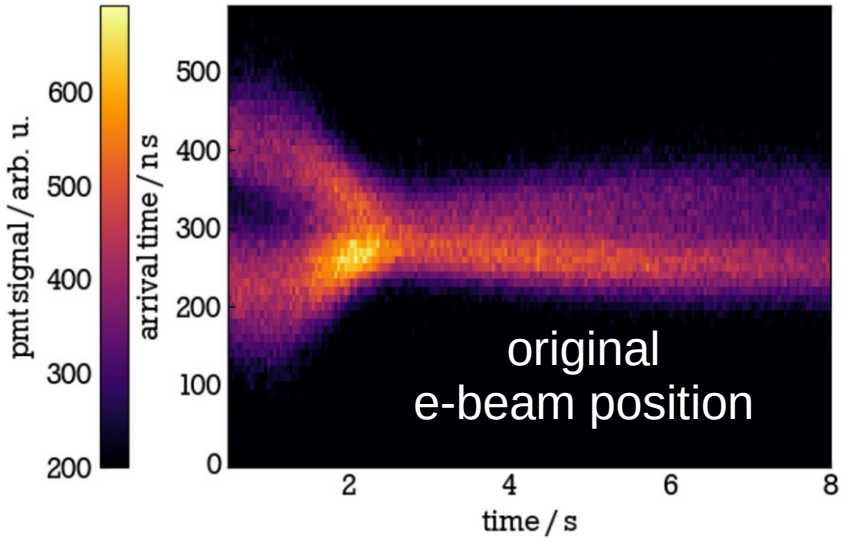

$$\frac{d}{dx}\left(\frac{dv}{v}\right)_{\text{ions}} = \frac{1}{D_x}$$

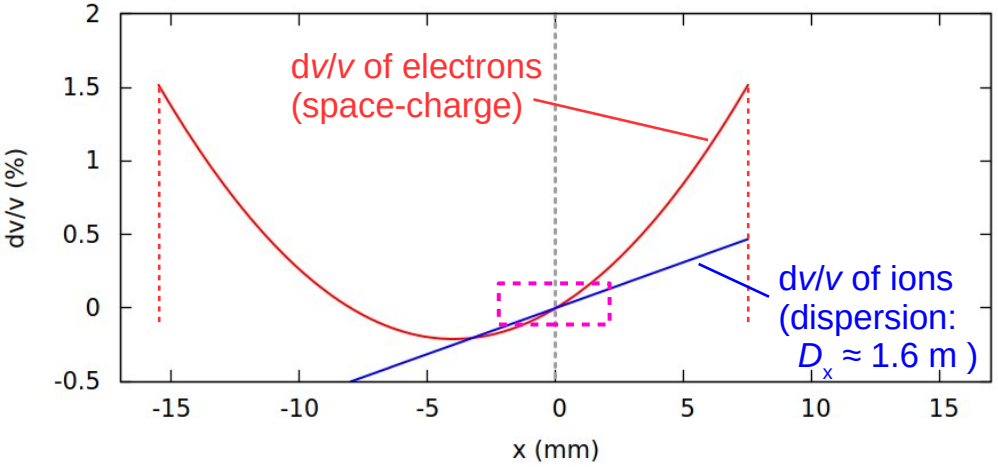
At low energies, electron velocity profile becomes very steep.

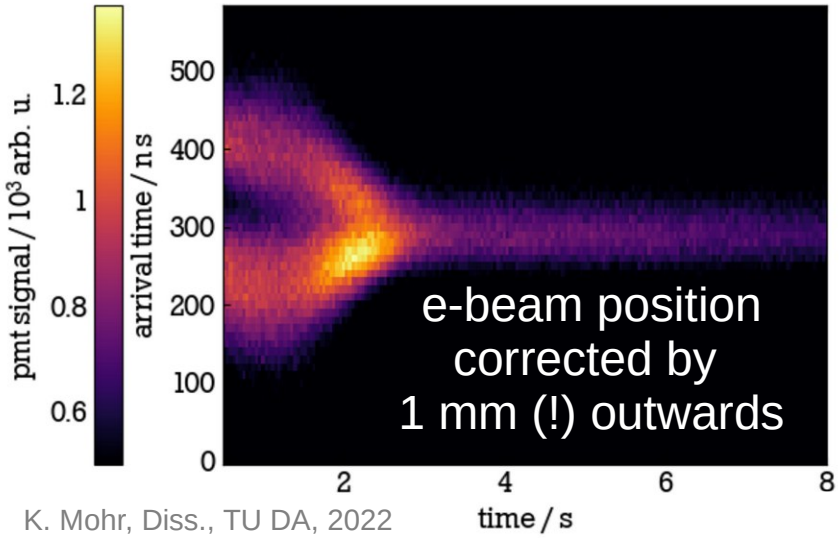
→ Strong dispersive coupling effects!

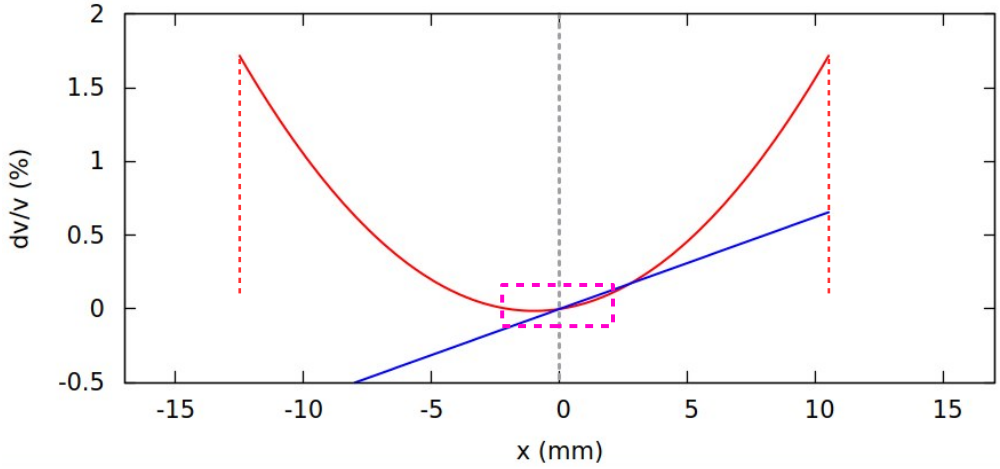
Beutelspacher, NIM A 512 (2003) 459
Bosser, NIM A 441 (2000) 60

# Dispersive longitudinal heating



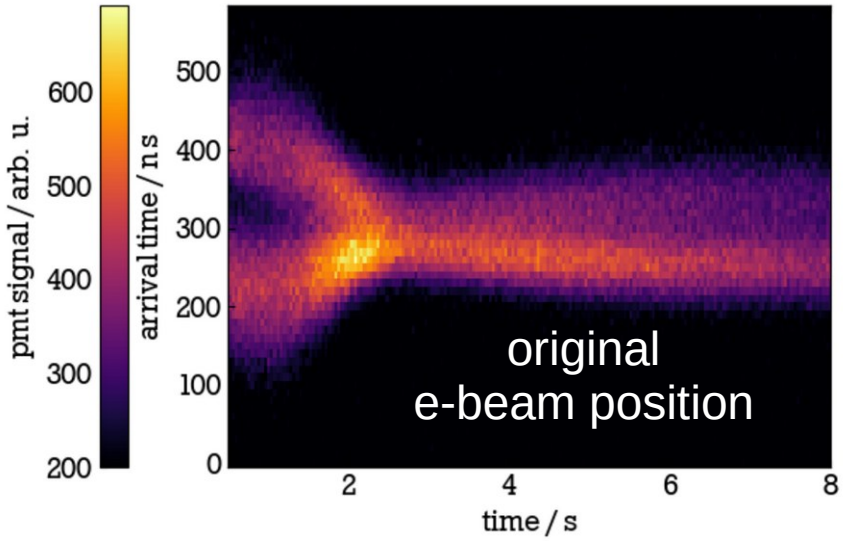



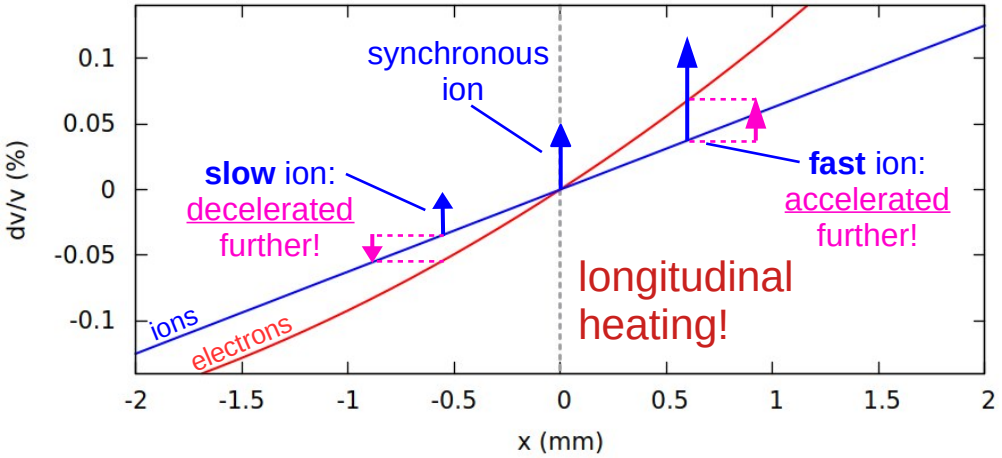



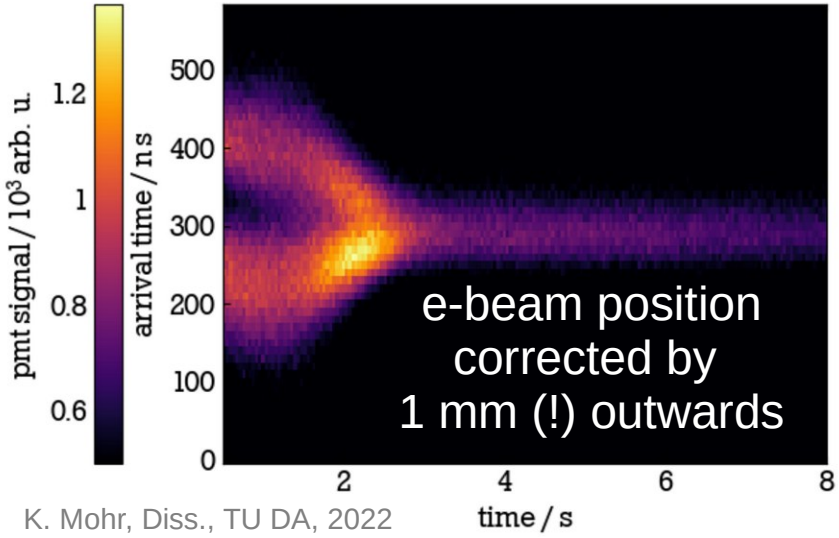



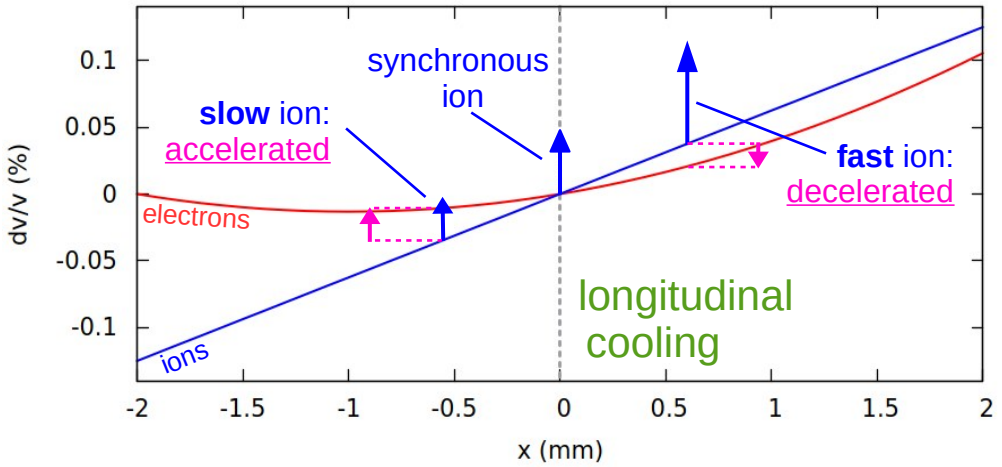

K. Mohr, Diss., TU DA, 2022

# Dispersive longitudinal heating



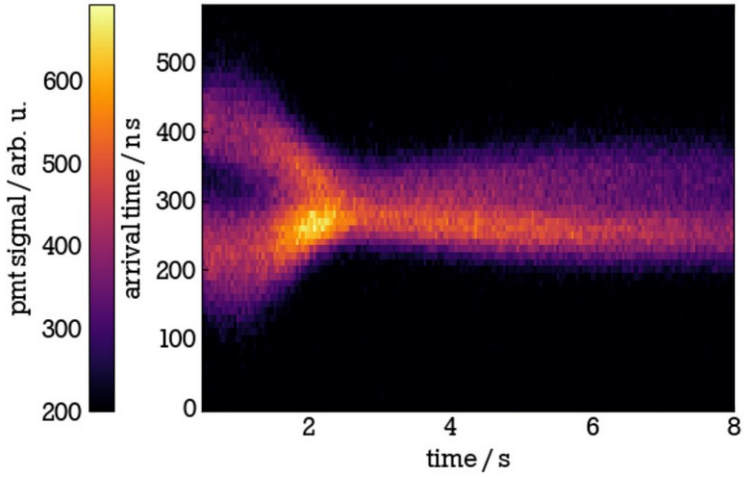




K. Mohr, Diss., TU DA, 2022

# Horizontal acceptance for e-cooling

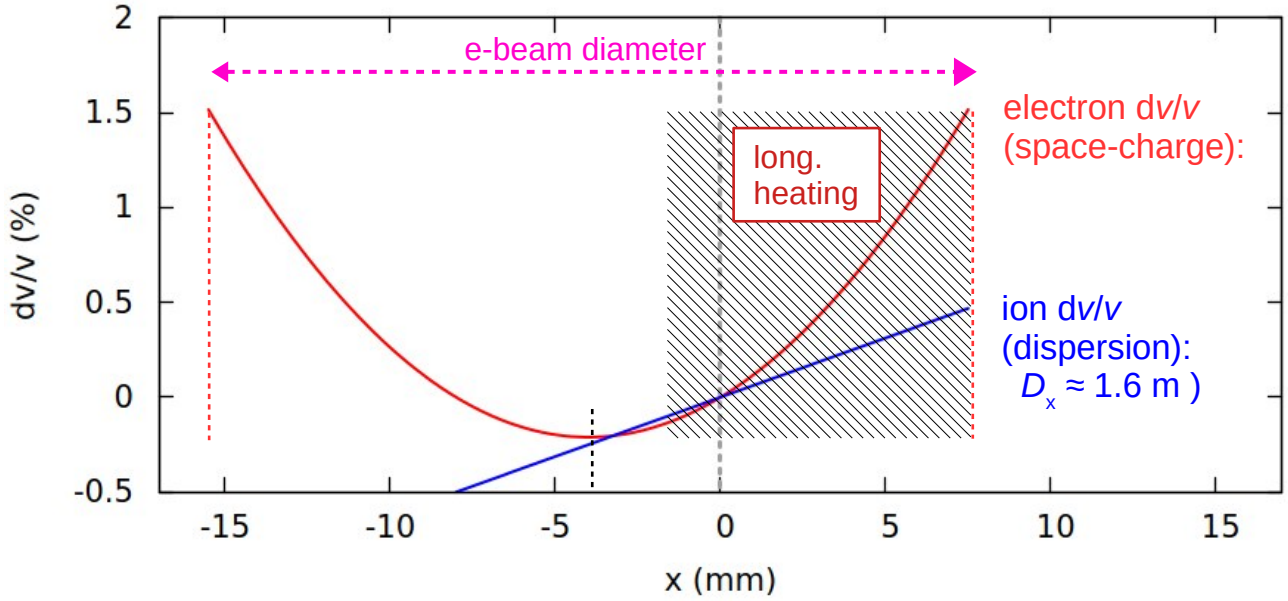



For $(dv/v)_e' > (dv/v)_i'$

→ Longitudinal heating by electron beam.

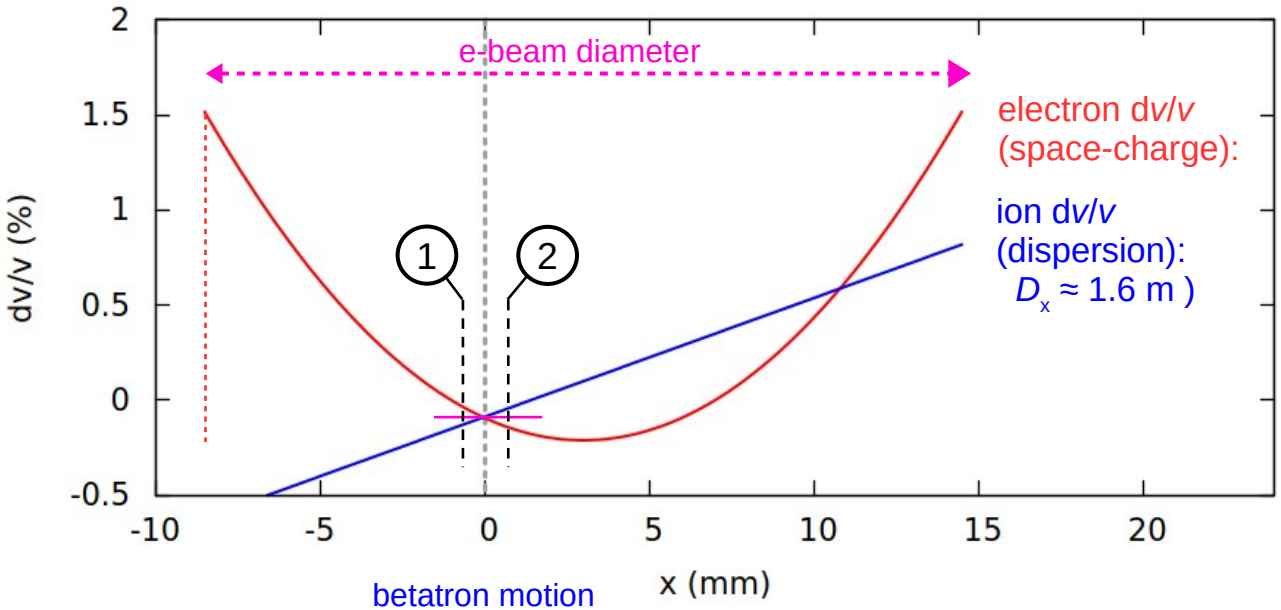
**Critical inward** e-beam **displacement**:

$$x_{\text{e-beam}} \overset{!}{<} \frac{4\,E_{kin,e}\,\epsilon_0}{D_x e^2 n_e}$$




For $^{25}Mg^+$: 1.7 mm (!)

# Horizontal acceptance for e-cooling

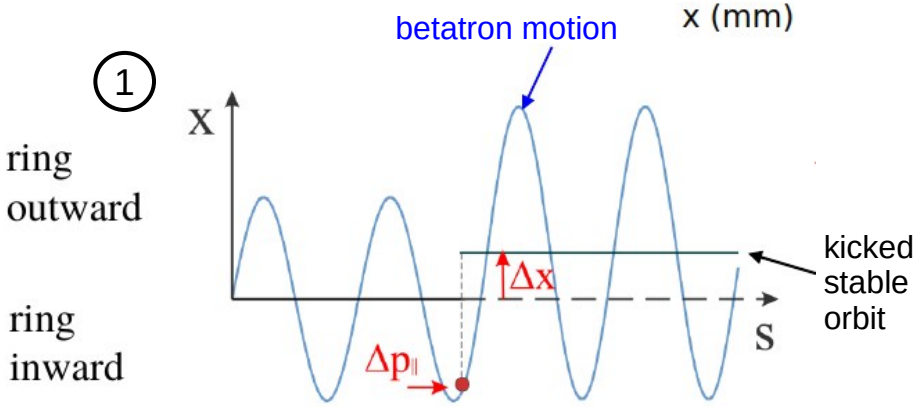


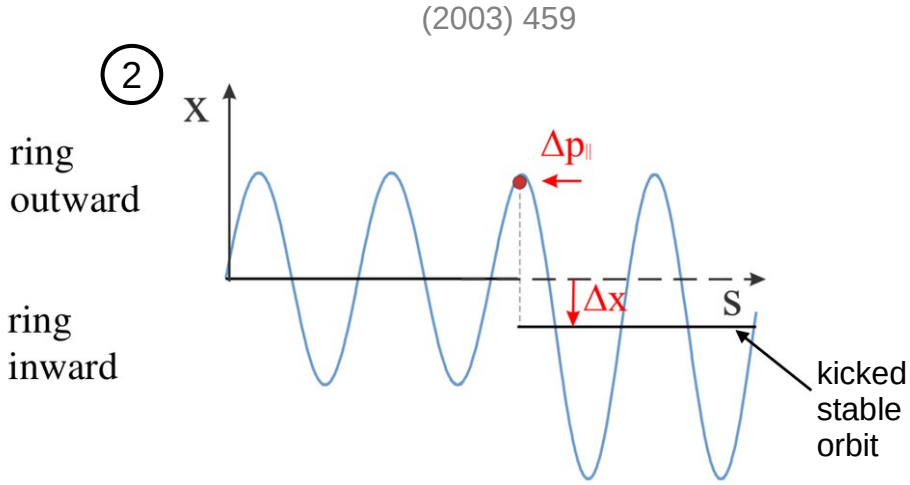

For $(dv/v)_e' < 0$

Longitudinal cooling kicks orbit *away* from ion position for every betatron phase.

→ horizontal heating source.

Beutelspacher, NIM A 512 (2003) 459



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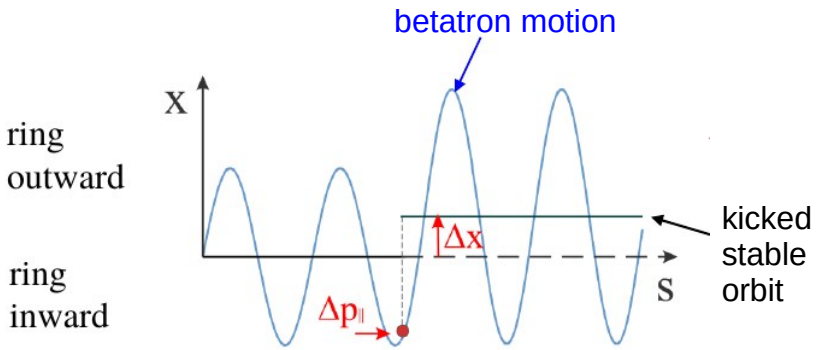


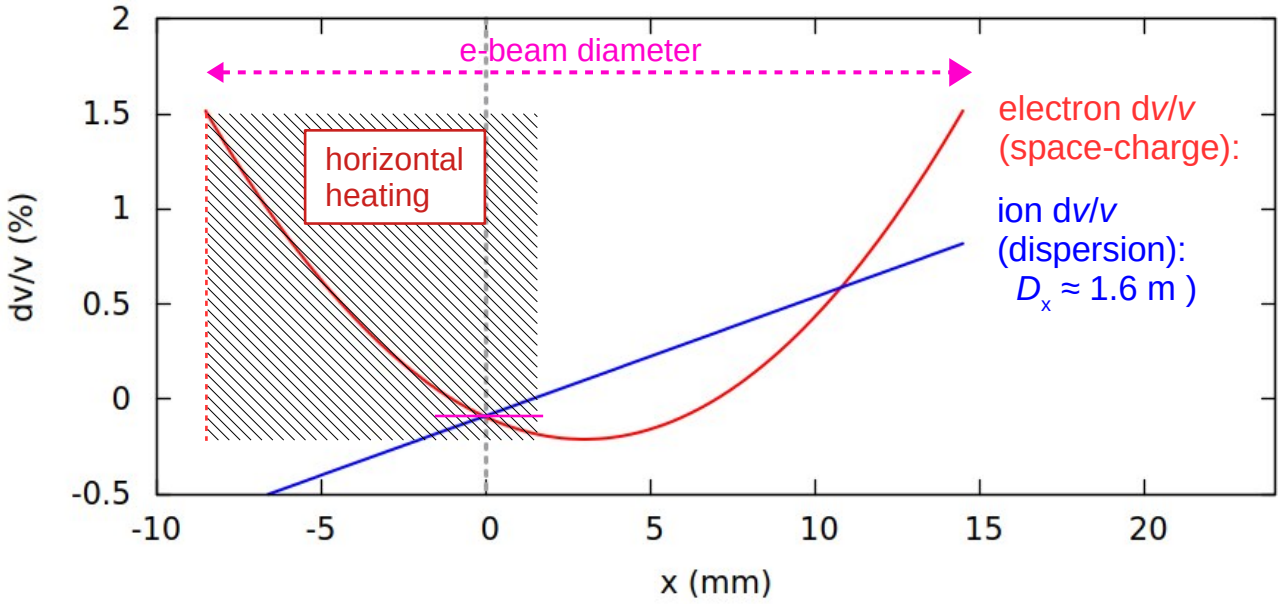

Beutelspacher, NIM A 512 (2003) 459
M. Grieser, O. Novotný, in prep.

At some **critical outwards e-beam** displacement, dispersive horizontal heating becomes *faster* than horizontal cooling.

Breaks **horizontal** cooling for

$$x_{\text{e-beam}} > \frac{8\,E_e\,\epsilon_0}{D_x\,e^2\,n_e}\,f_b\,\frac{\tau_{\text{cool},s}}{\tau_{\text{cool},x}}$$

$$f_b = \begin{cases} 1 & \text{(coasting)} \\ 1/2 & \text{(bunched)} \end{cases}$$




For $^{25}Mg^+$:
~ 1.0 … 2.5 mm (!)

# Horizontal acceptance for e-cooling

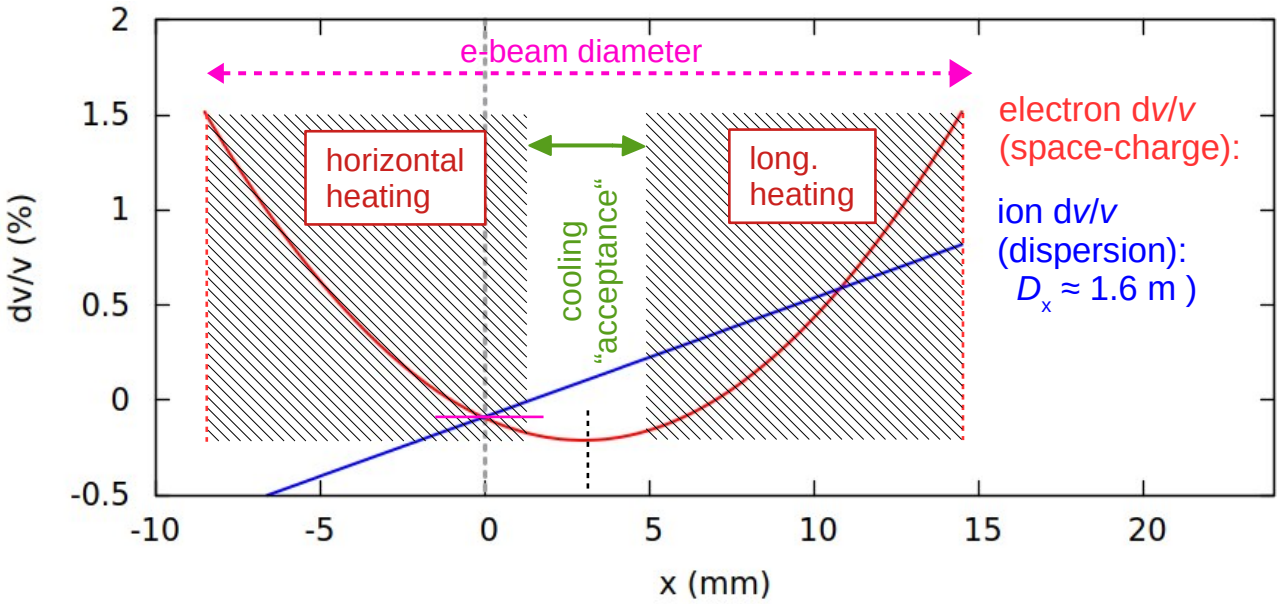
**Horizontal "acceptance"** for low-energy e-cooling:

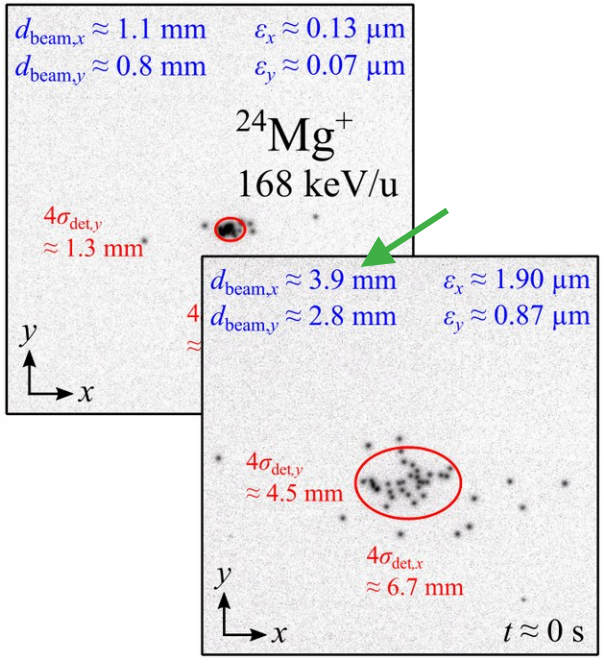
$$\Delta x_{\text{accept}} \sim \frac{E_{kin,e}}{D_x n_e}$$

$^{25}Mg^+$ @CRYRING: $E_e$ = 85.0 eV, $n_e = 4.7 \cdot 10^6$ cm$^{-3}$

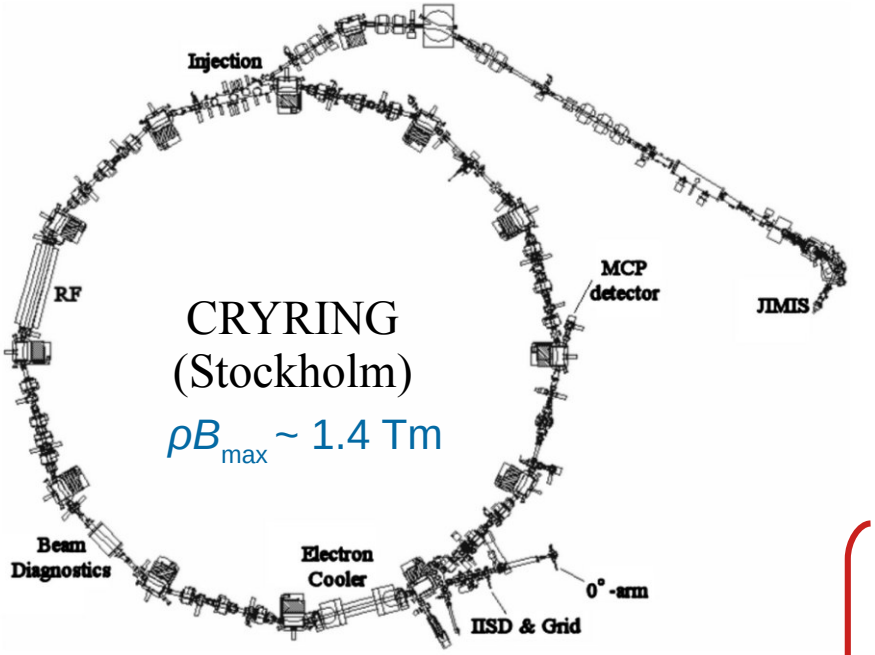
→ $-2.0\ \text{mm} < x_{\text{e-beam}} < 1.7\ \text{mm}$

→ "Cooling window" *just* wide enough for the initial horizontal $Mg^+$ beam diameter!



# Previous CRYRING experience?




R. D. Tomas et al., ApJ 758 (2012)

No electron cooling attempted!
Cooler used as internal target only.

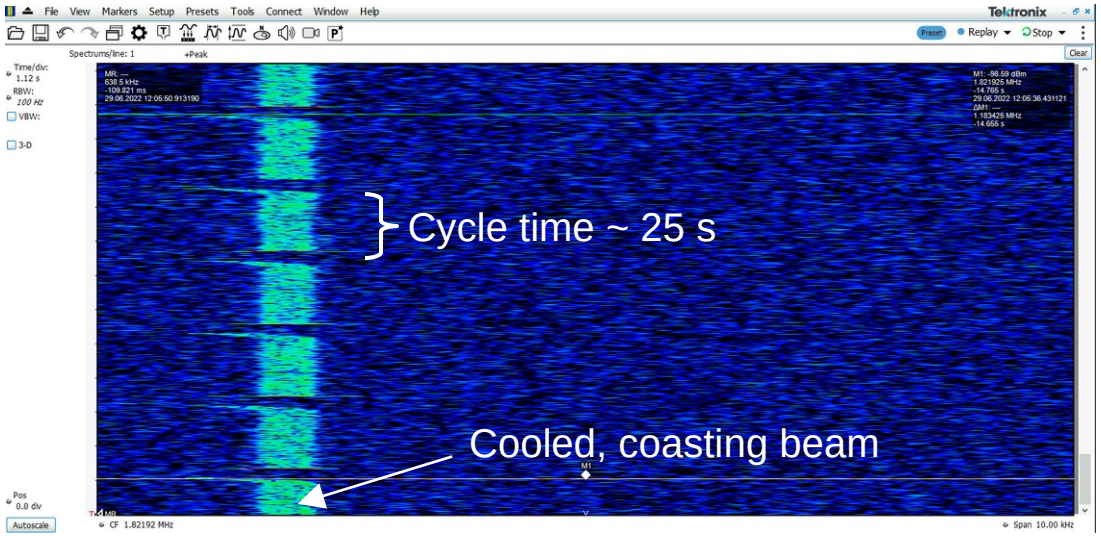
Mid-2000's:
Recombination experiments with large organic molecules at **CRYRING in Stockholm**

Hamberg et al. Mol. Phys. 105 (2007)
Hamberg et al. Astron. Astrophys. 514 (2010)
Hamberg et al. Astron. Astrophys. 522 (2010)

| ion | $q/m_{ion}$ [e/u] | 0.5 ( $v_{ion}$ )$^2$ | $E_e$ |
|---|---|---|---|
| ... | | | |
| $CH_2OH^+$ | 1 / 31 | 0.099 MeV/u | **54 eV** |
| $CD_2OD^+$ | 1 / 34 | 0.083 MeV/u | **46 eV** |
| $CD_2OD_2^+$ | 1 / 36 | 0.074 MeV/u | **41 eV** |
| $CH_3CH_2OH_2^+$ | 1 / 47 | 0.043 MeV/u | **24 eV** |
| $CD_3CDOD^+$ | 1 / 50 | 0.038 MeV/u | **21 eV** |
| $CD_3OCD_2^+$ | 1 / 50 | 0.038 MeV/u | **21 eV** |
| $(CD_3)_2OD^+$ | 1 / 54 | 0.033 MeV/u | **18 eV** |

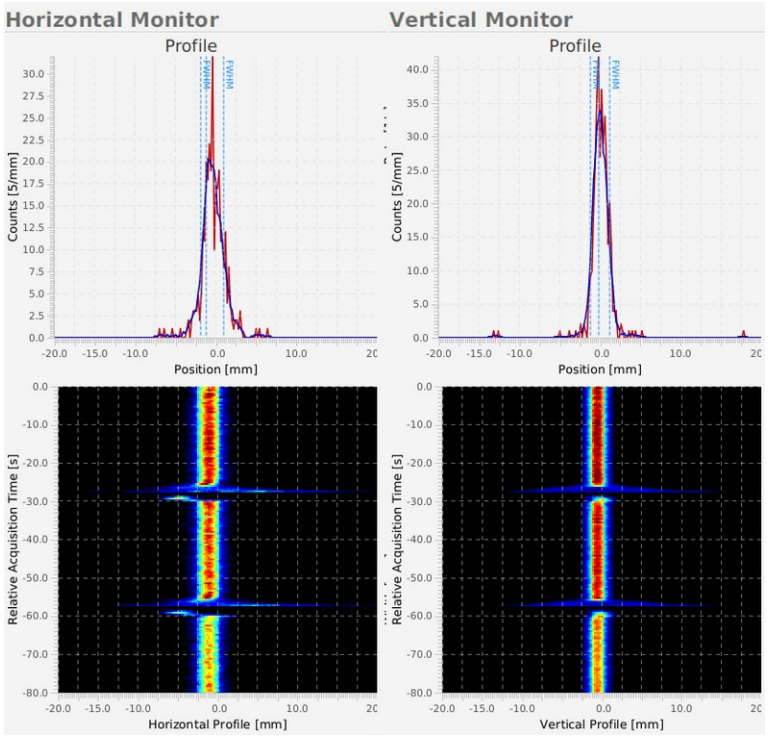
# Horizontal acceptance for e-cooling

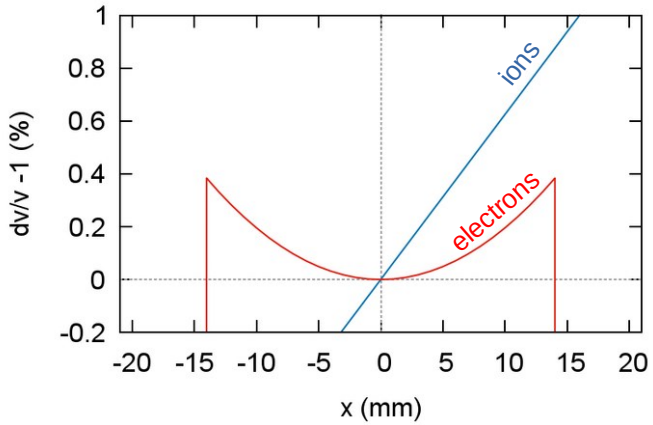
Schottky spectrum ($h$ = 5)

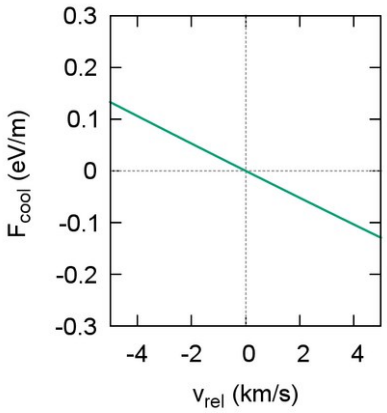



$D^+$ (2 MeV/u)
Optimal cooling conditions.

Transverse beam profiles

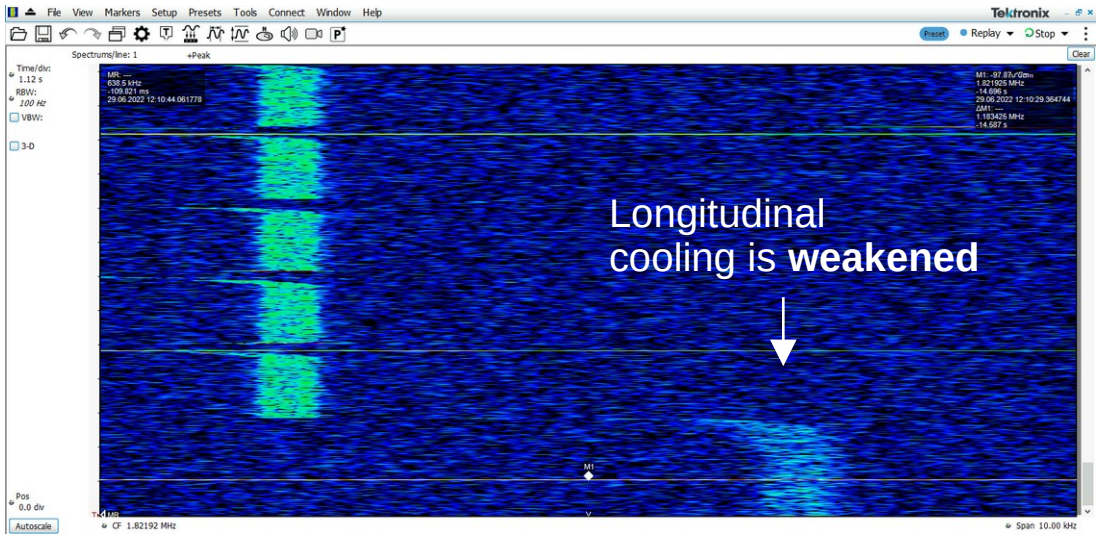


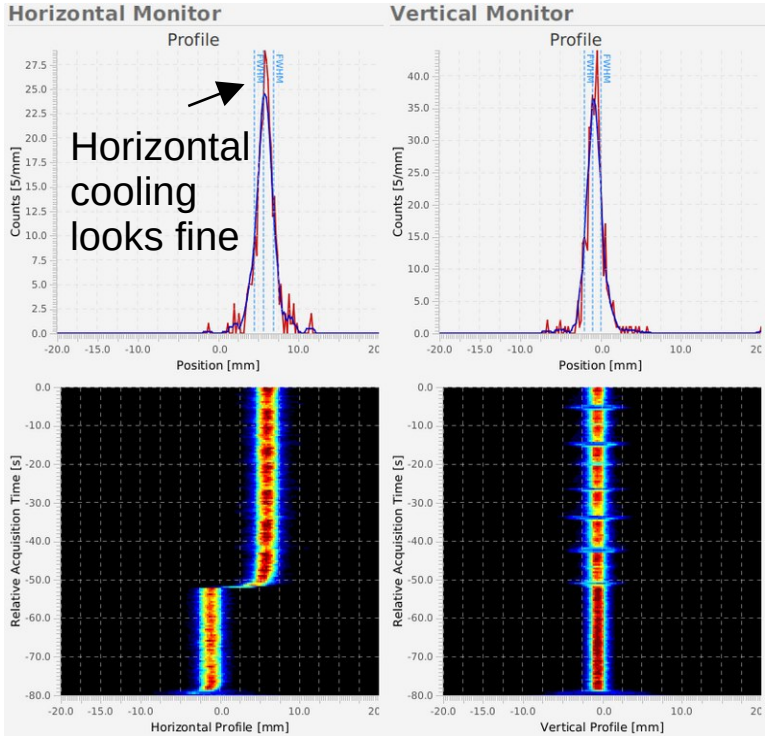
# Horizontal acceptance for e-cooling

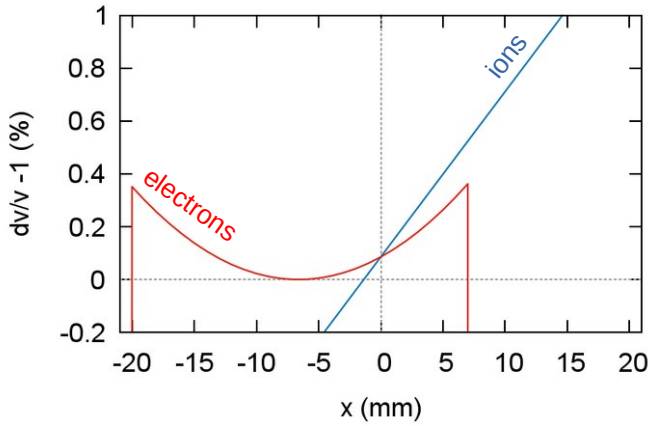
Schottky spectrum ($h$ = 5)

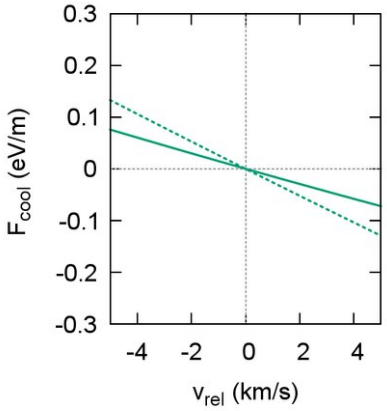



$D^+$ (2 MeV/u)
e-beam shifted **ring-inwards**

Transverse beam profiles

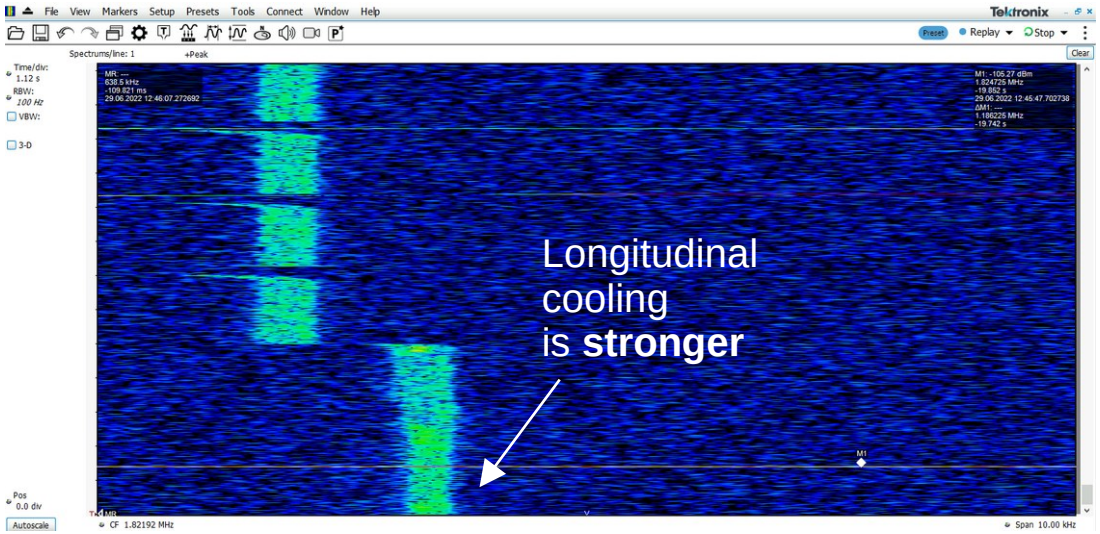


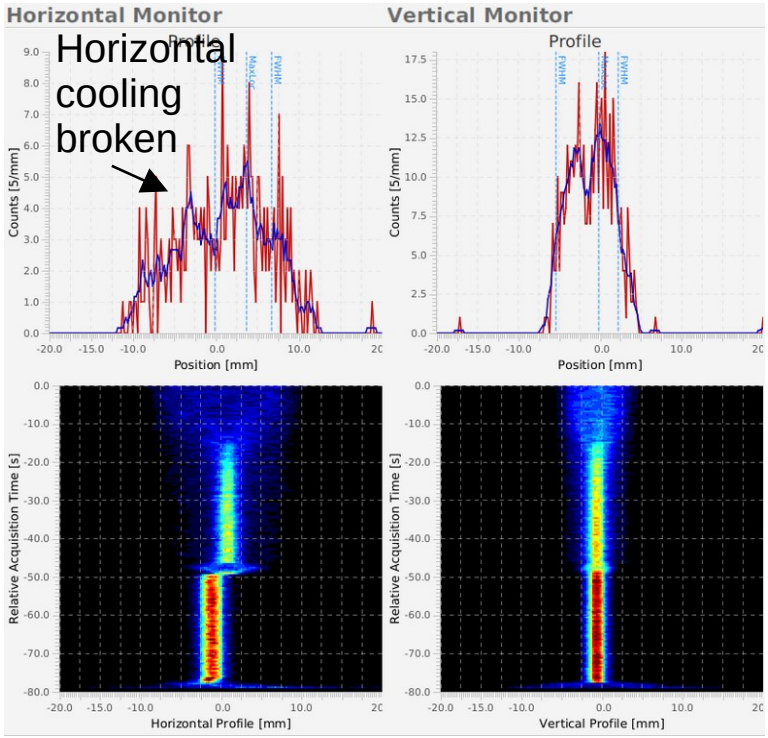
# Horizontal acceptance for e-cooling

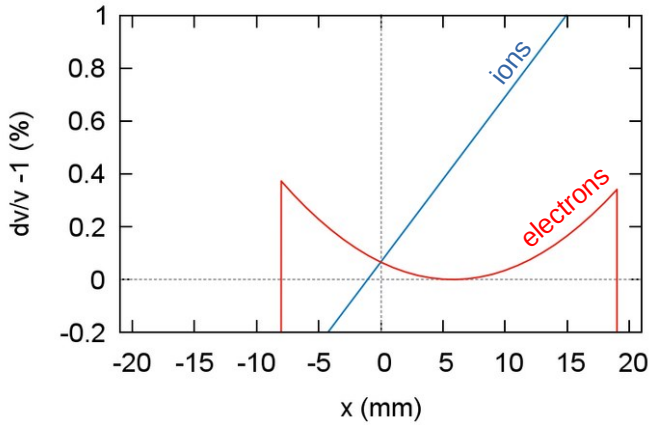
Schottky spectrum ($h$ = 5)

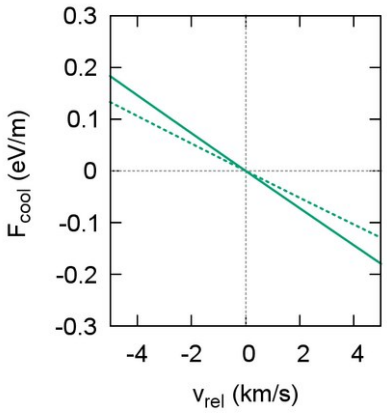



D$^+$ (2 MeV/u)
e-beam shifted **ring-outwards**

Transverse beam profiles



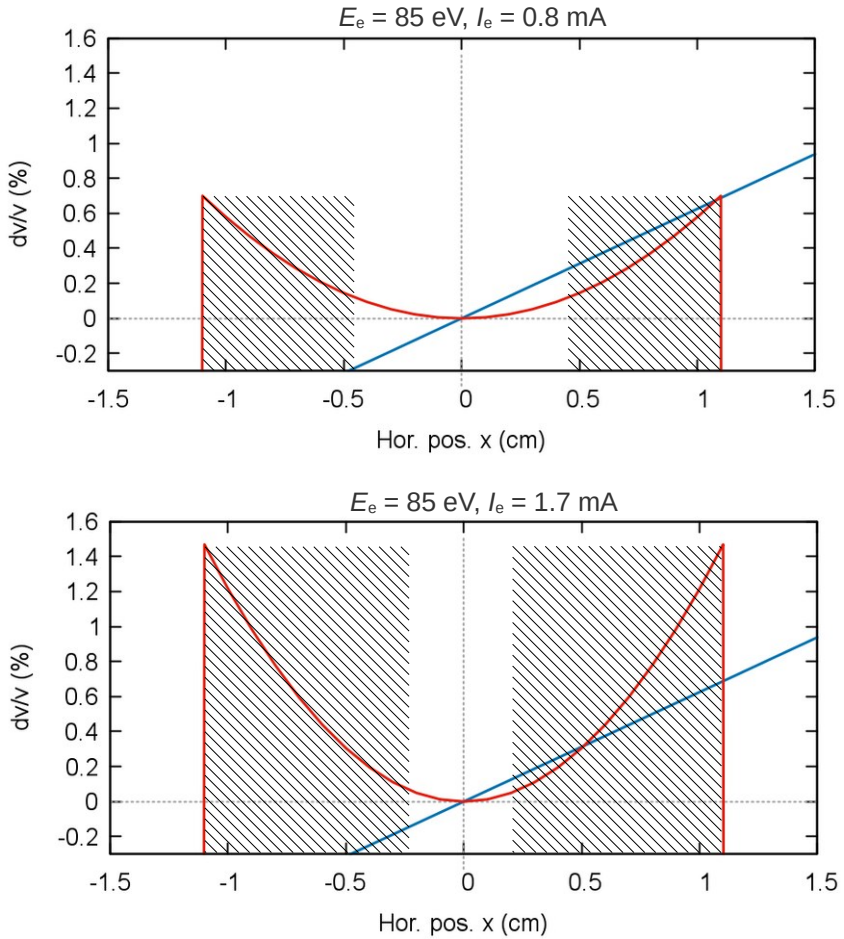
# How to improve?

More runs with singly and weakly charged ions ahead!

Possible idea: Two-stage cooling

1) Start at reduced electron current:
Wider hor. acceptance for uncooled beam.

2) Increase e-density once horizontal beam diameter is decreased.



# How to improve?

Ultimate solution:

Decrease dispersion: $D_x$ = 1.6 m ↘ $D_x$ ~ 0.0 m

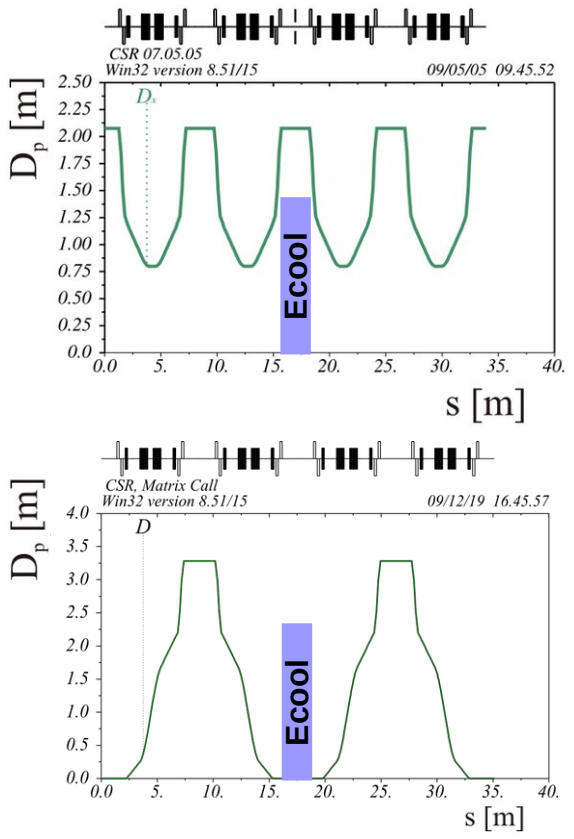
Give up high optics symmetry to gain control of $D_x$ in straight sections.

→ *c.f. talk by O. Novotný (Monday).*

*Would* also possible at CRYRING@ESR.

(At the expense of rewiring the quads and buying more power converters …)

CSR, Heidelberg




M. Grieser, O. Novotný, in prep.

# Thank you!

**Summary:**

Electron cooling at very low energy is challenged by **dispersive heating**.

Singly-charged ions have been cooled at **CRYRING@ESR down to $E_e$ = 85 eV**.

Can be overcome by advanced cooling schemes and/or dispersion-free optics.

**CRYRING@ESR Team**

Z. Andelkovic, C. Brandau, H. Danared
C. Dimopoulou, S. Fedotova,
W. Geithner, V. Hannen, M. Herber,
F. Herfurth, R. Heß, C. K., M. Lestinsky,
E. B. Menz, K. Mohr, W. Nörtershäuser,
A. Reiter, J. Roßbach, R. Sánchez,
S. Schippers, C. Schroeder,
A. Täschner, G. Vorobyev, D. Winzen
…

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M. Grieser (MPIK)