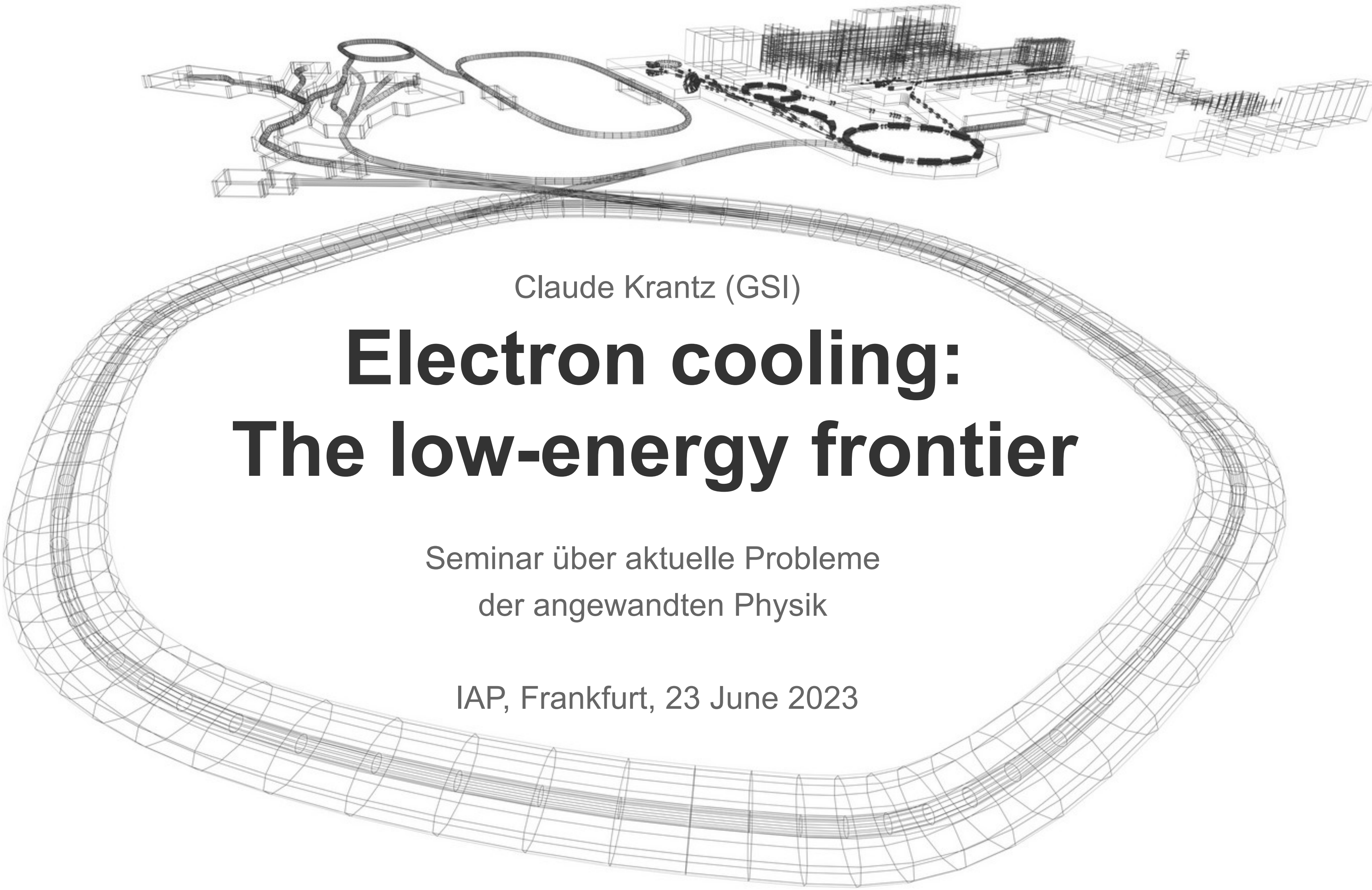


Claude Krantz (GSI)

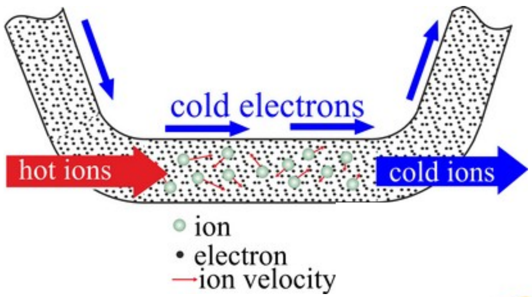
Electron cooling: The low-energy frontier

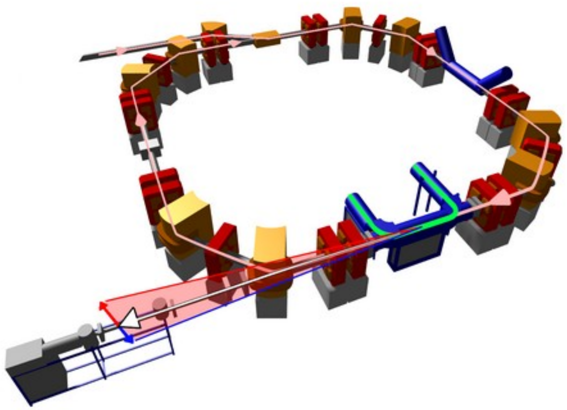
Seminar über aktuelle Probleme
der angewandten Physik

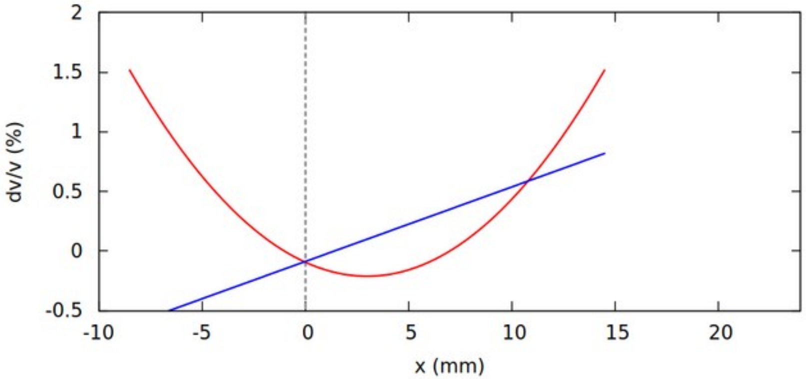
IAP, Frankfurt, 23 June 2023

Overview

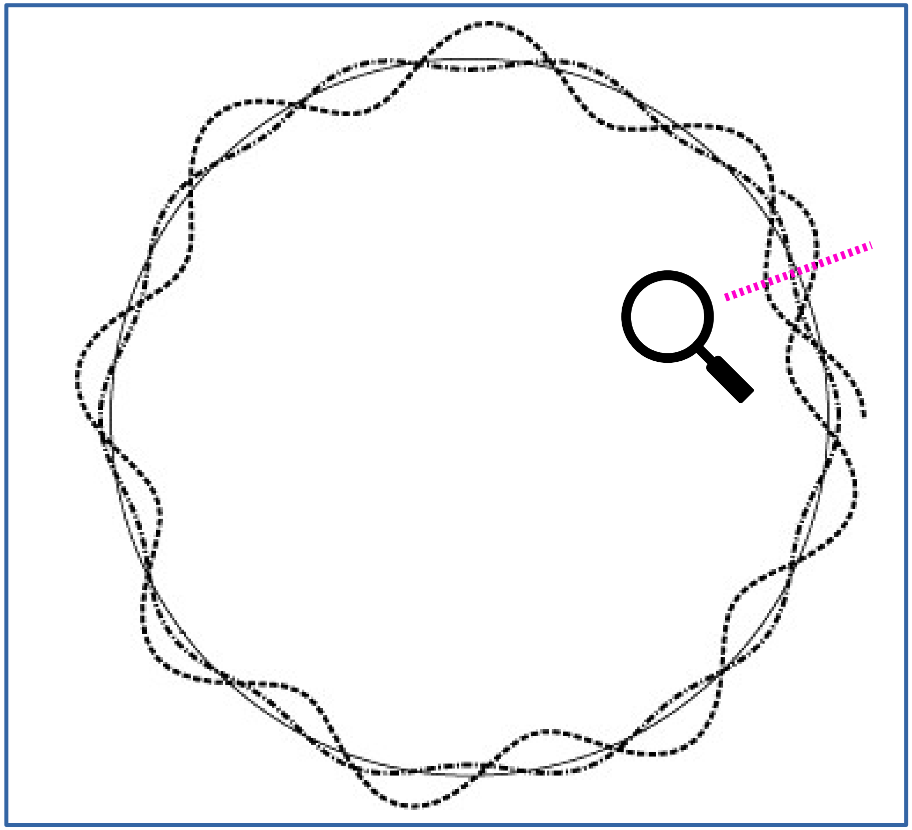
- Electron cooling
- Low-energy stored ions …
- ...and how to cool them
- Stability of low-energy cooled beams

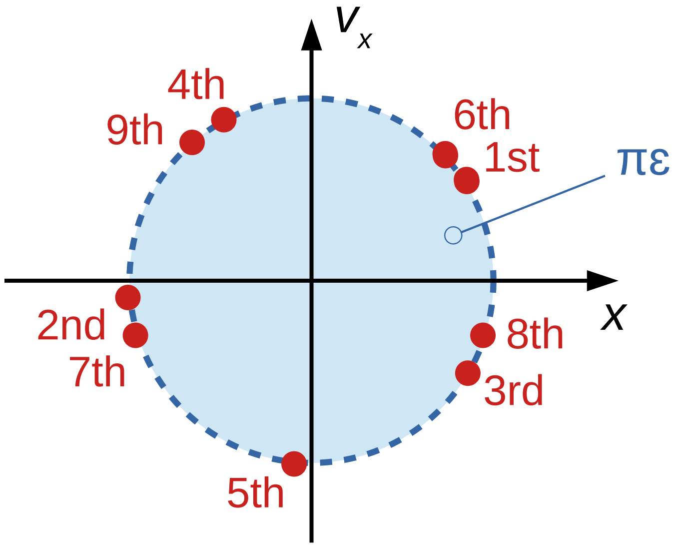






Electron cooling:
Why do we need beam cooling?



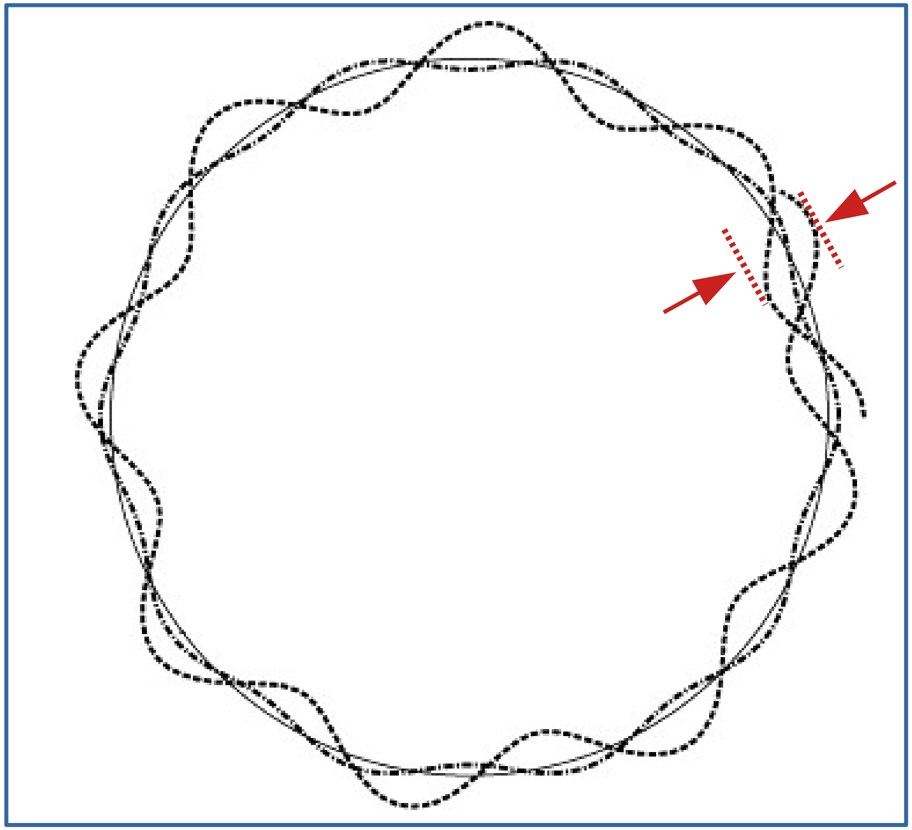


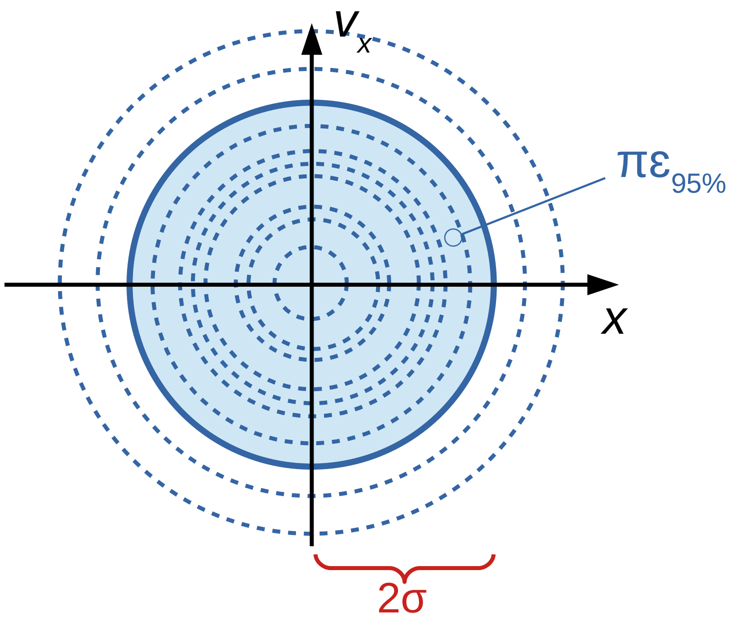
For an ion storage ring, there is no *natural* damping of transverse motion (betatron oscillation).

→ *Enclosed area in phase-space is conserved!*

→ Enclosed area / π = ε ("single-particle emittance")

Electron cooling:
Why do we need beam cooling?





As this is true for every single ion, also the transverse phase-space volume occupied by the entire beam is conserved.

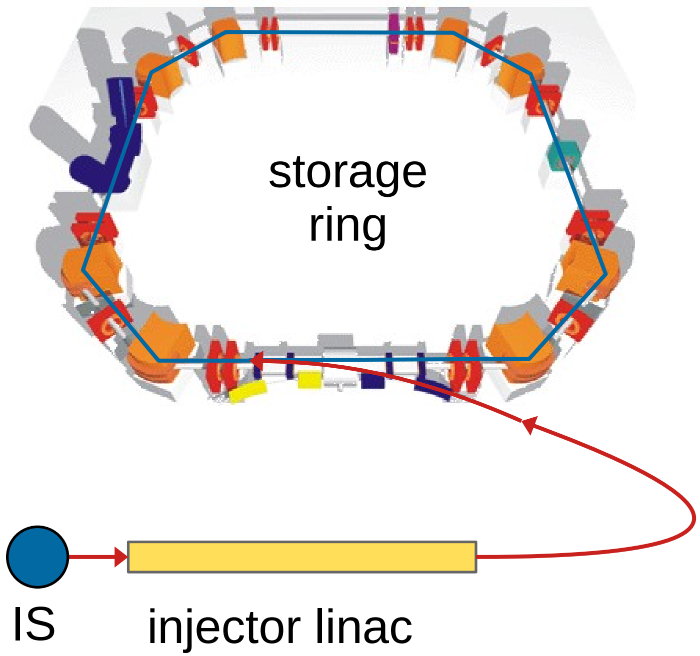
Enclosed area / π = $\varepsilon_{95\%}$ ("*beam emittance*")

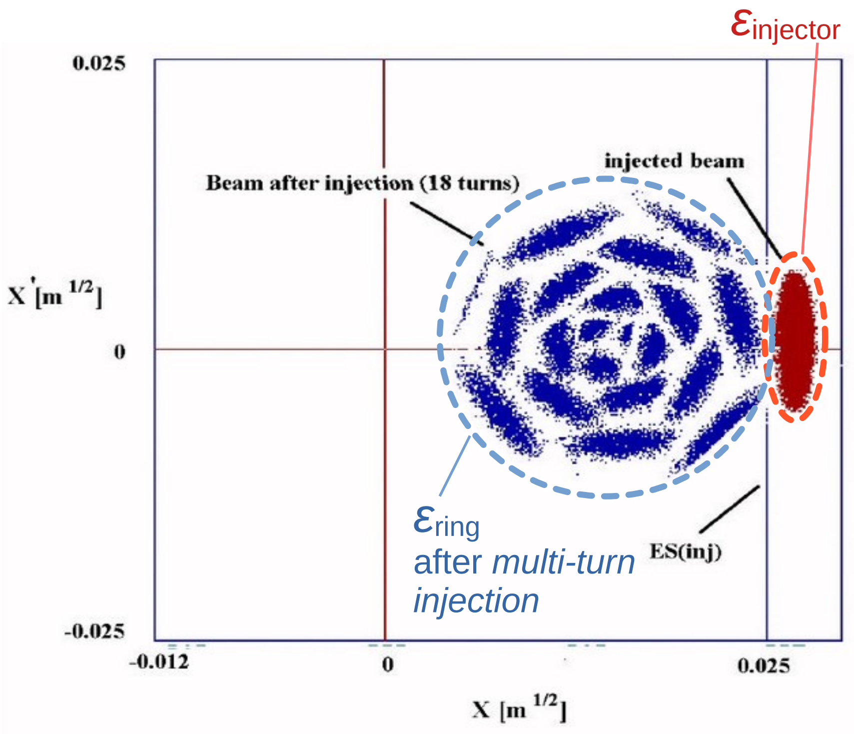
Projection onto coordinate axis:
→ "2-σ beam size"

Electron cooling:
Why do we need beam cooling?

Ring emittance ≫ injector emittance!

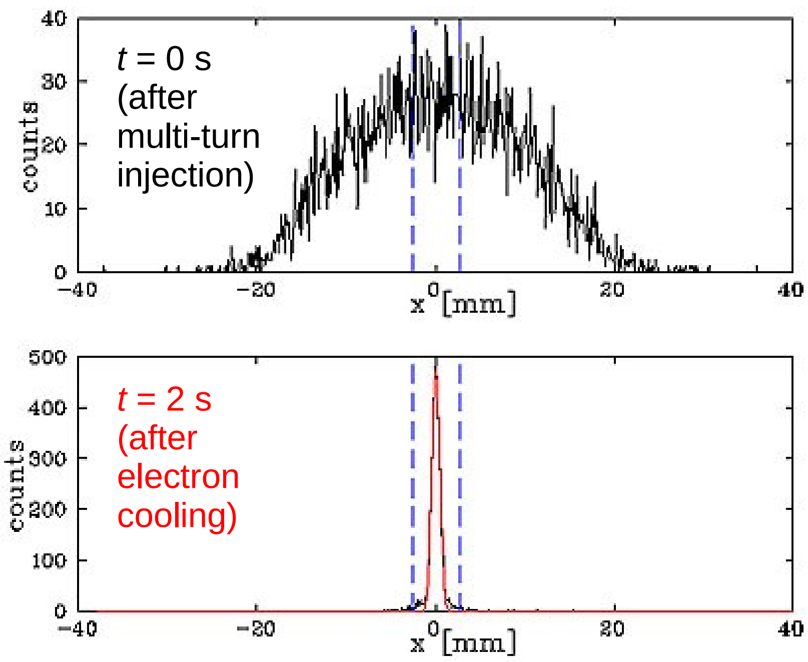
To store many ions, we have to distribute them over the available *transverse acceptance*.

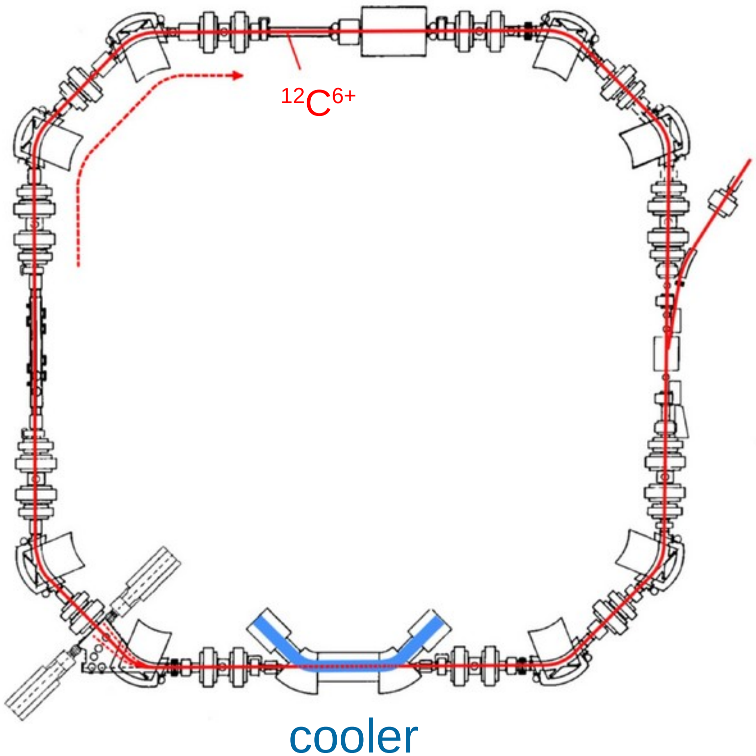




Electron cooling:
Why do we need beam cooling?

Horizontal stored beam profile of $^{12}C^{6+}$ ions at the TSR:





www.mpi-hd.mpg.de/blaum/storage-rings/

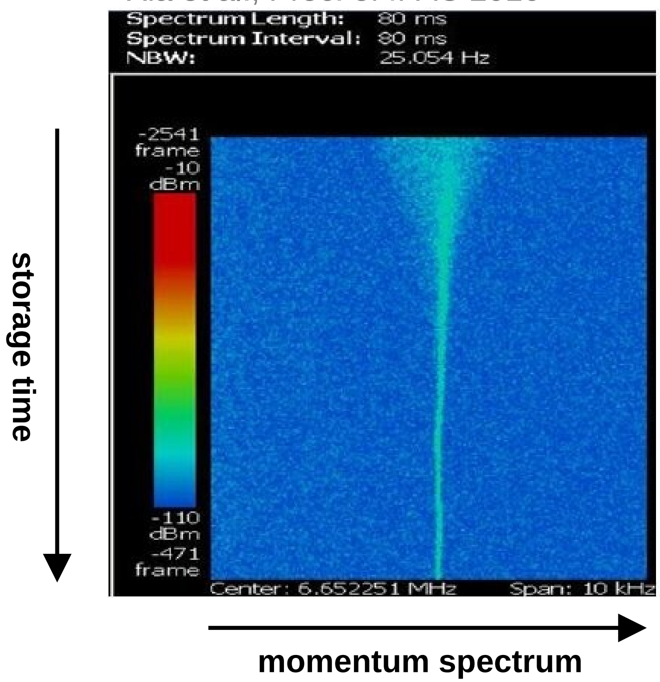
Electron cooling:
Why do we need beam cooling?

Longitudinal cooling

Coasting beam

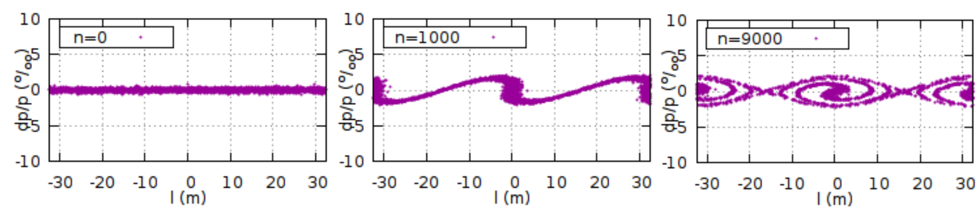
Reduce ion momentum spread inherited from injector.

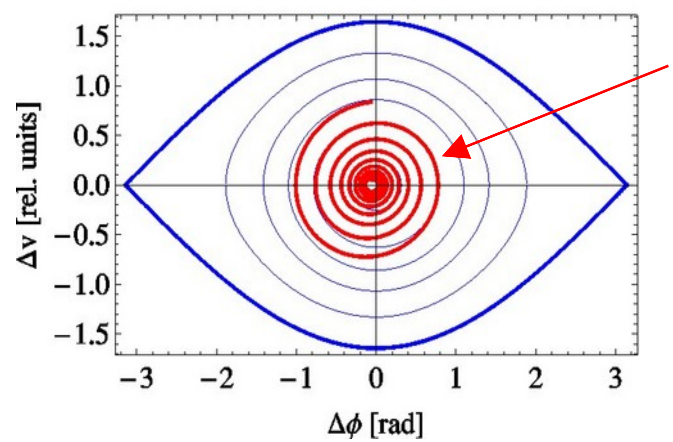
Xia et al., Proc. of IPAC 2010



Bunched beam

After bunching, ions typically fill almost the entire “bucket” due to filamentation.

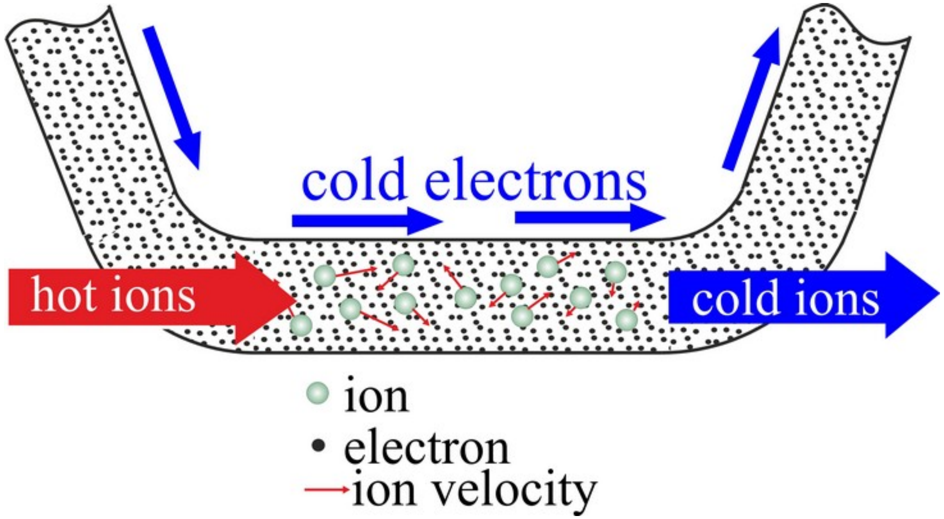




Cooling de-excites synchrotron motion: Shorter and colder bunch.

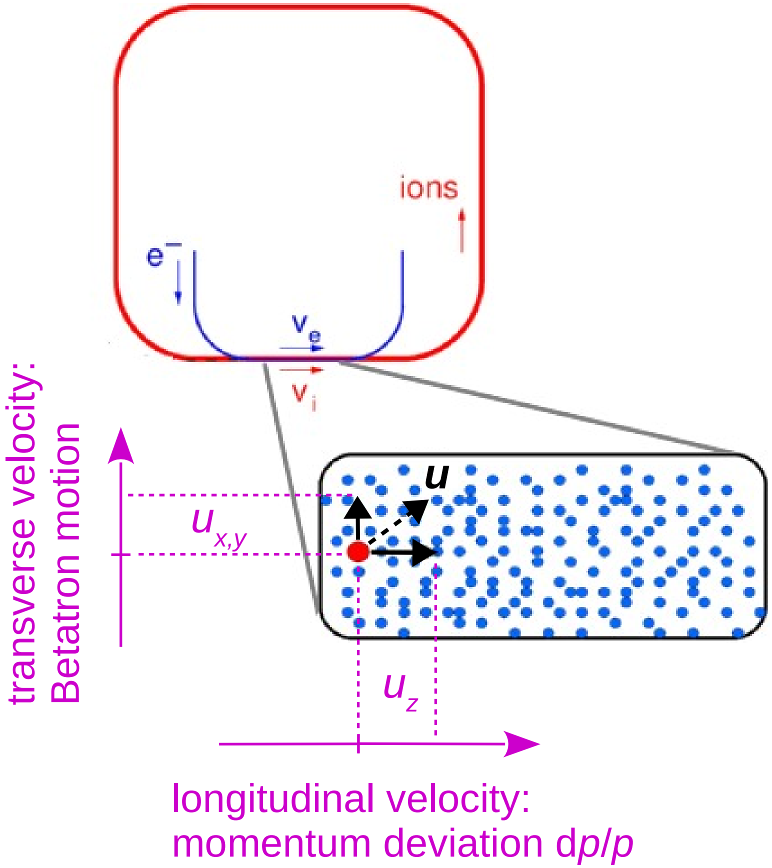
Electron cooling:
Why do we need beam cooling?

Electron cooling is one method of beam cooling,
proposed by G. Budker in 1966. G. I. Budker et al. Part. Accel 7 (1976)



- Obtain brilliant beams.
- Achieve higher precision in collision experiments.
- Compensate emittance blow-up on internal targets.
- Accumulate higher intensities (inject → compress → inject → …).
- …

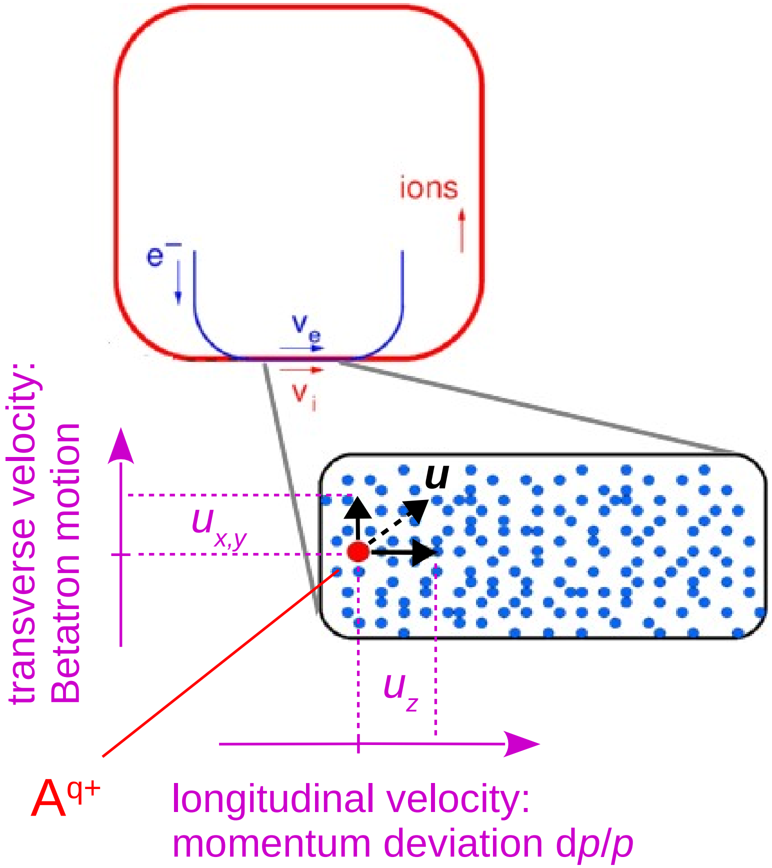
Electron cooling



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

Any relative ion velocity $\boldsymbol{u} = (u_x, u_y, u_z)$ leads to a “friction” force $\boldsymbol{F}$.

Electron cooling



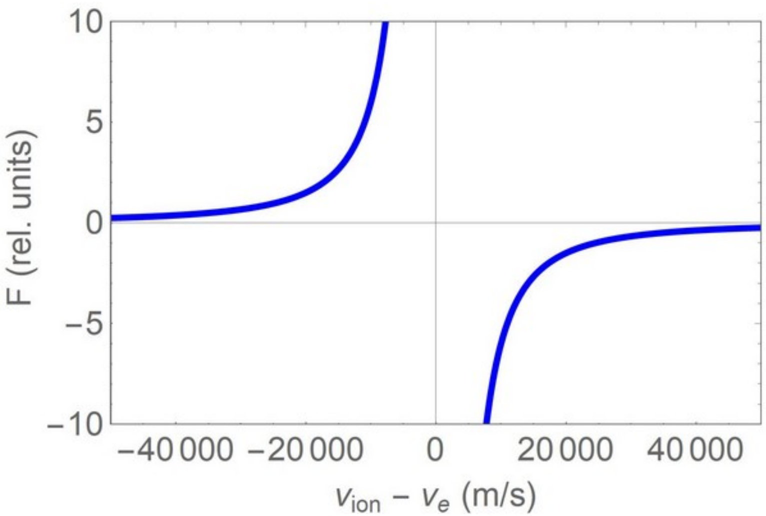
If one *assumes* the electron beam to be mono-energetic …

… the electrons are at rest in the co-moving frame of the two beams.

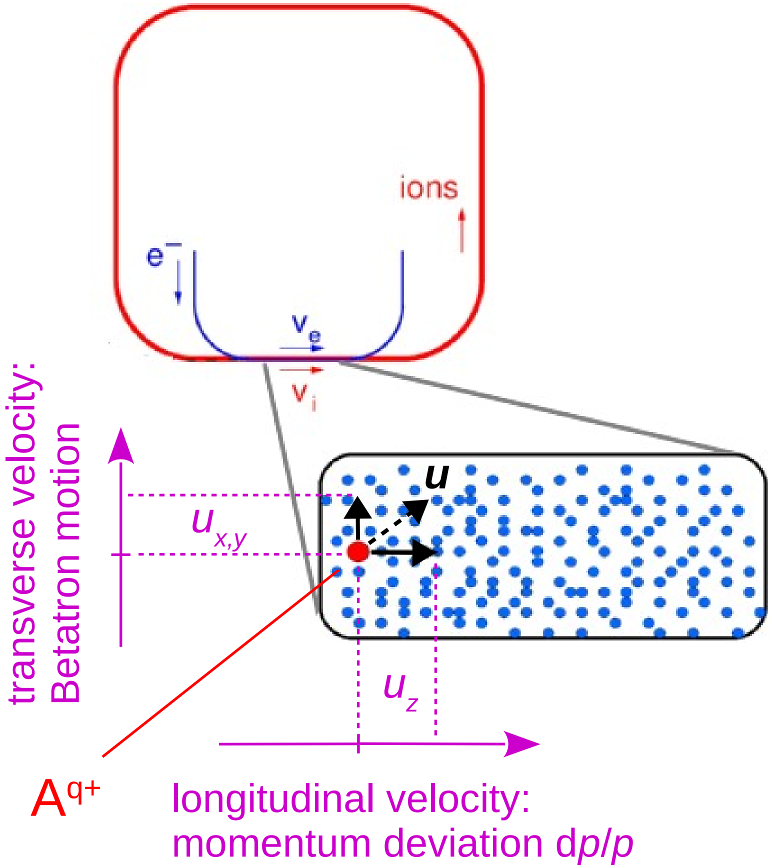
Stopping force derives analogously to the *Bethe formula*:

$$\vec{F}(\vec{u}) \sim -n_e q_{\mathrm{ion}}^2 \times \frac{\vec{u}}{|u|^3}$$

n_e: e density



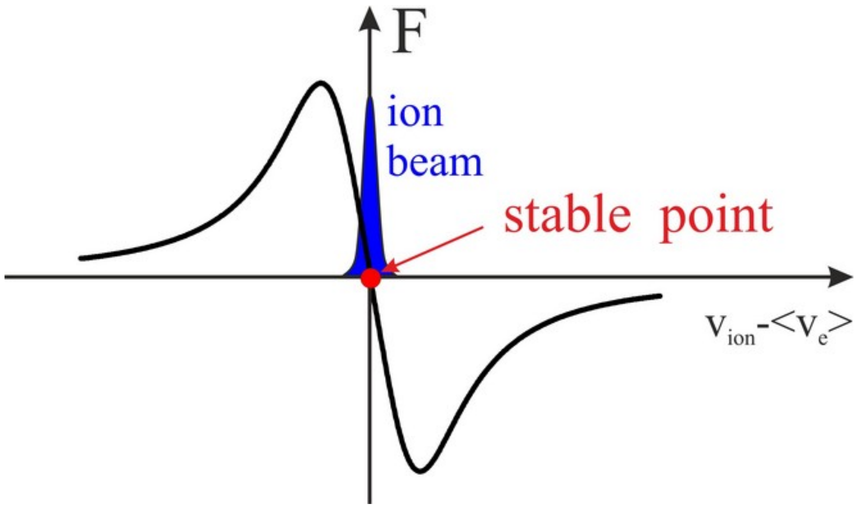
Electron cooling



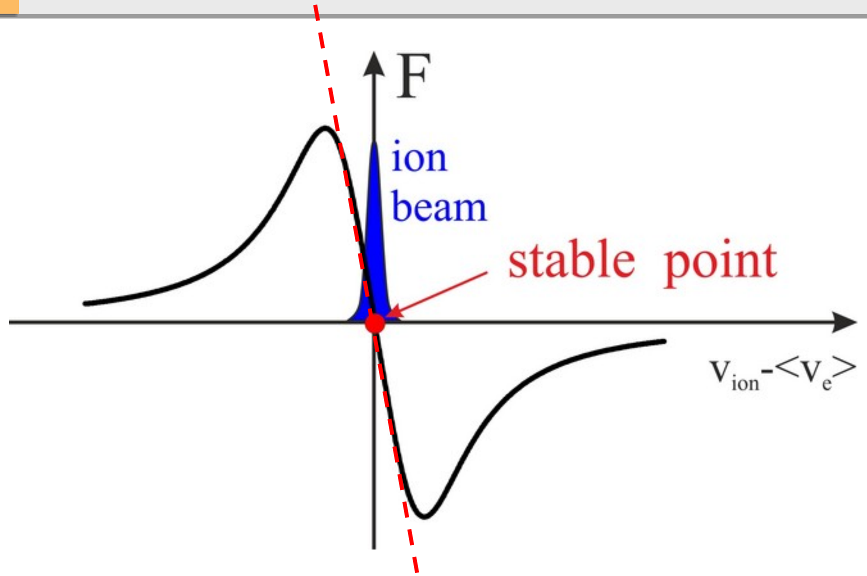
In reality, electrons have a rather large velocity spread.

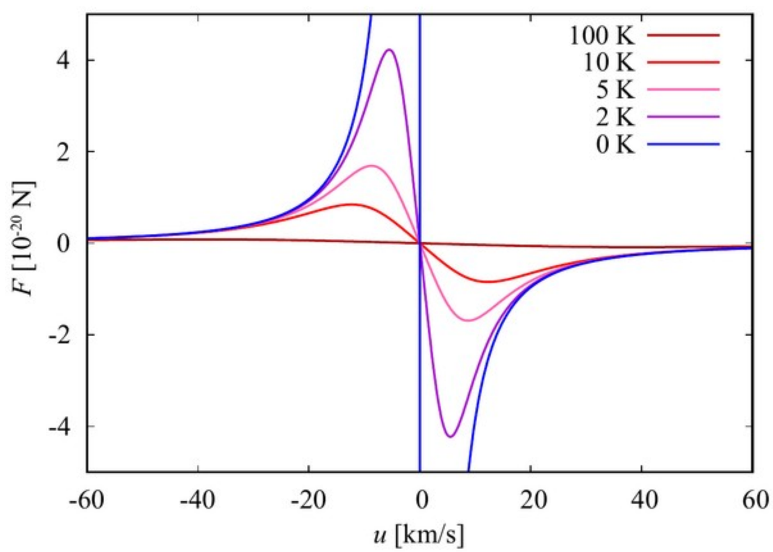
→ Convolution with electron velocity distribution $f(\boldsymbol{v}_e)$:

$$\mathbf{F}(\mathbf{v}_i) = -4\pi \left(\frac{q_{\text{ion}} e^2}{4\pi\epsilon_0}\right)^2 \frac{n_e L_C}{m_e} \int f(\mathbf{v}_e) \frac{\mathbf{v}_i - \mathbf{v}_e}{|\mathbf{v}_i - \mathbf{v}_e|^3} d^3 v_e$$



Electron cooling





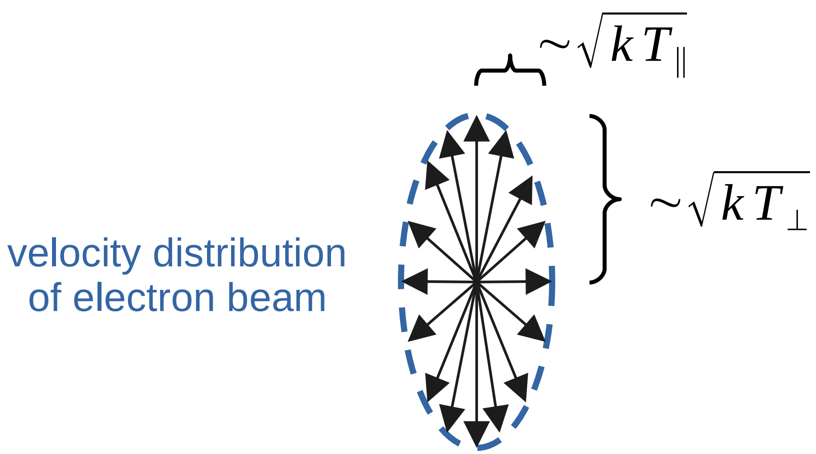
For small velocity deviations $\boldsymbol{u} = \boldsymbol{v}_i - \langle \boldsymbol{v}_e \rangle$

$$F_{x,y} \approx -d_{x,y} \cdot u_{x,y} \qquad \text{(trans.)}$$
$$F_z \approx -d_z \cdot u_z \qquad \text{(long.)}$$

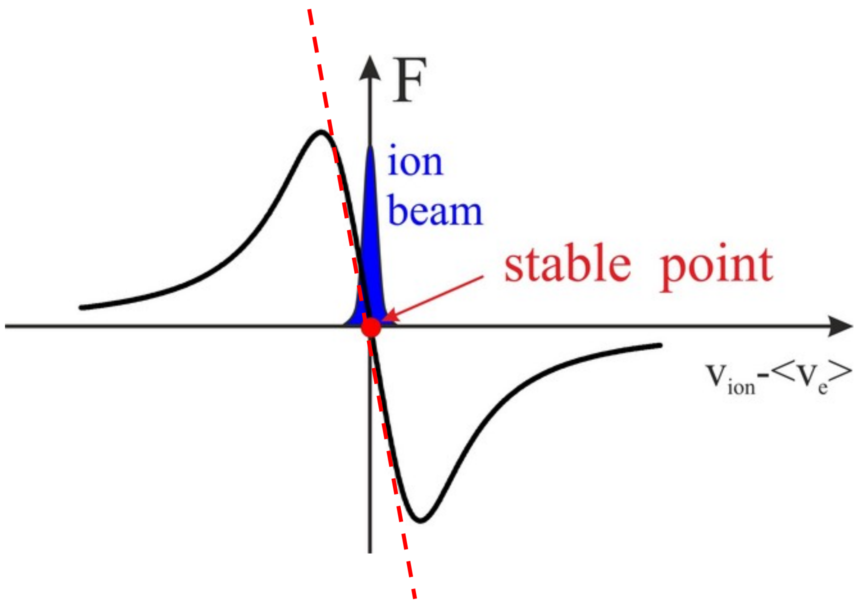
With

$$d_{x,y} < d_z \qquad d \propto \frac{n_e q_{\text{ion}}^2}{T_e^{3/2}}$$

Reason: Velocity distribution of electrons is anisotropic: $T_\perp > T_\parallel$ (later …)



Electron cooling



For any dimension:

$F(u) \approx -d \cdot u = m_{\text{ion}} \cdot \dot{u}$

→ Exponential damping of ion motion:

$u(t) \sim \exp(-t/\tau_{\text{cool}})$

Characteristic cooling time scale

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

T_e = "Effective electron temperature".

Electron cooling

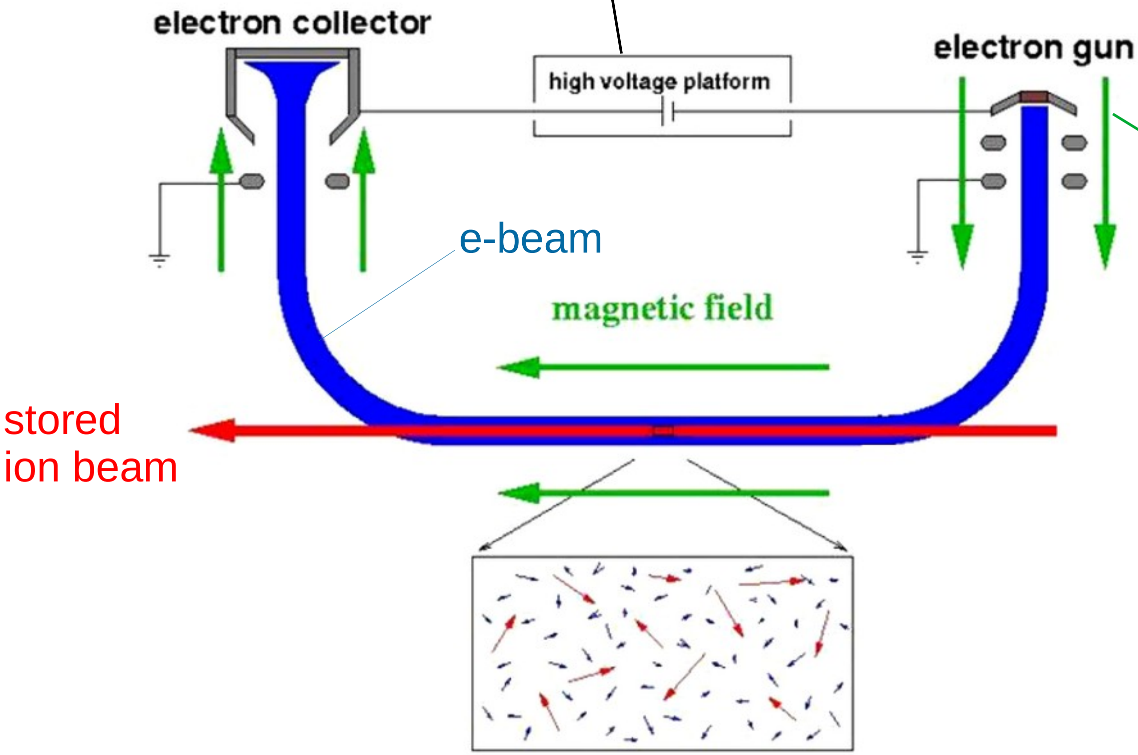
Need: $v_e = v_{ion}$

$$\rightarrow E_e = \frac{m_e}{m_{ion}} E_{ion}$$

e.g. E_{ion} = 10 MeV/u

→ $E_e \approx$ 5500 eV

$U_{platform}$
defines e-energy in the interaction region $E_e \sim eU_{cath}$

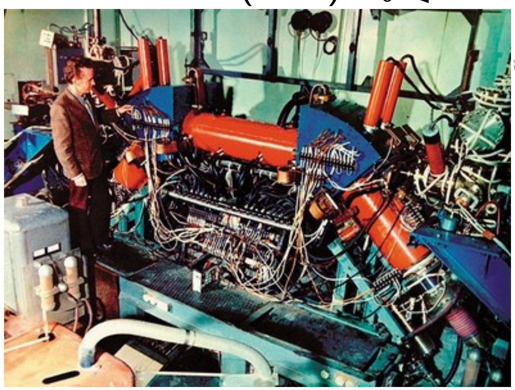


Magnetic field:
Strong enough to guide electrons, but only small disturbance for ion beam

Electron cooling

Medium energies: ~10 … 100 MeV/u

NAP-M cooler (1974): $E_e \leqslant 55$ keV



scfh.ru

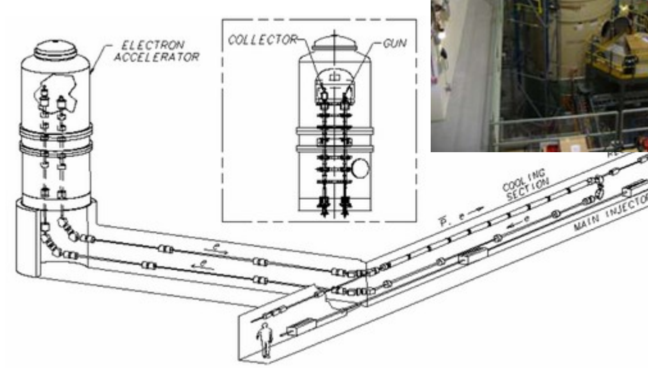
SIS-18 cooler: $E_e \leqslant 35$ keV

Medium-high energies:
~100 … 500 MeV/u

ESR cooler: $E_e \leqslant 300$ keV

High energies: > GeV/u

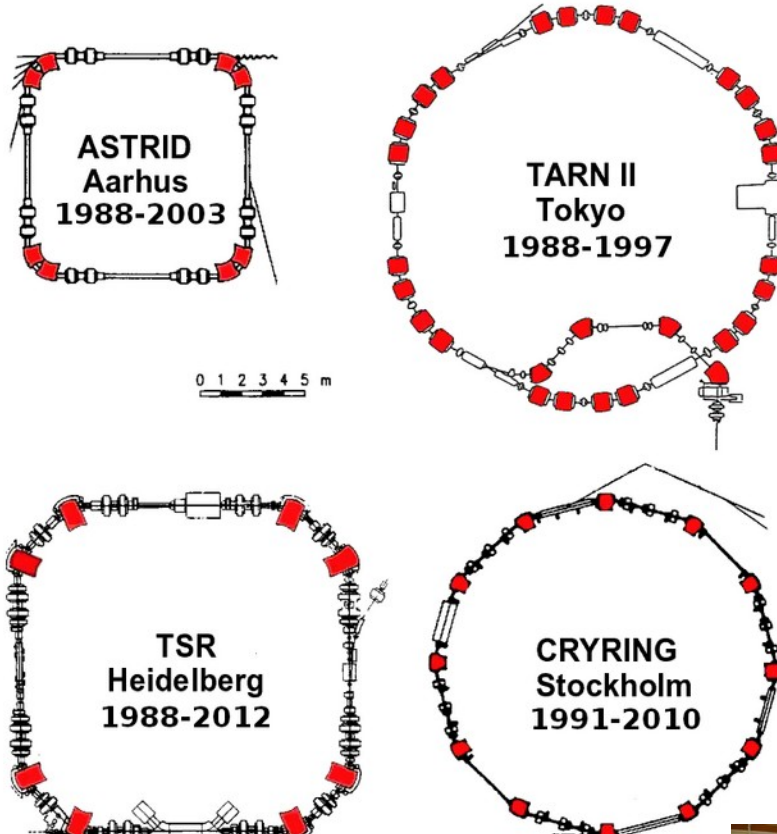
$$\tau_{\text{cool}} \overset{!}{\propto} \gamma^2$$

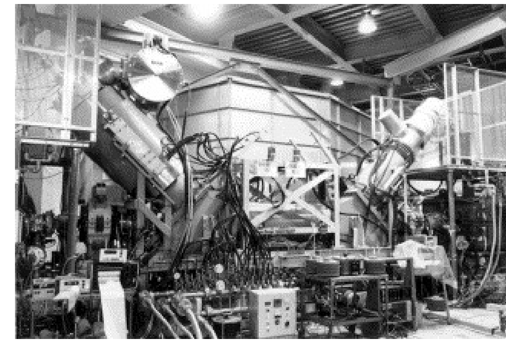


FNAL Recycler cooler:
$E_e \leqslant 4.3$ MeV (Pelletron)

Low-energy stored ions ...


Wikimedia commons



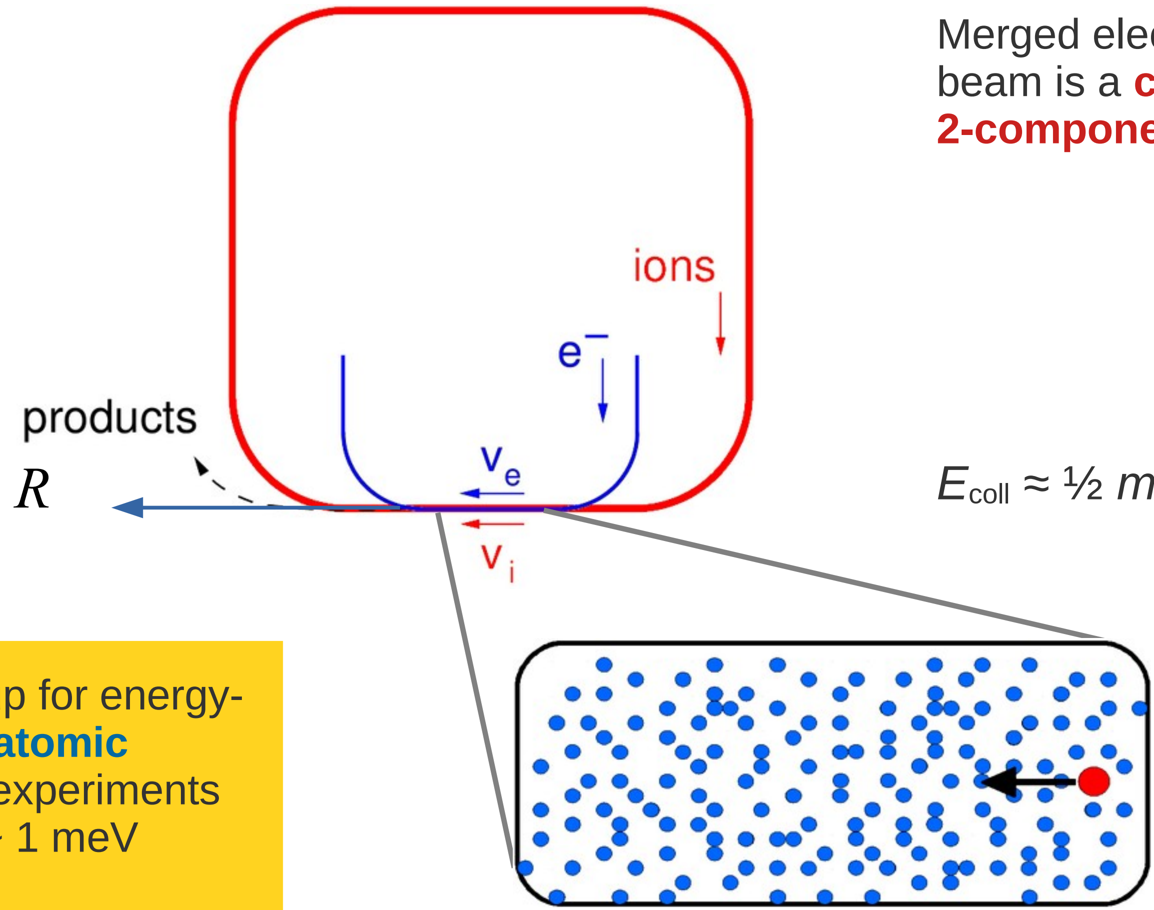

Tanabe, NIM A 441 (2000)

~ 1990:
Several **small electron cooler rings** to store *atomic and molecular* ions.

www.mpi-hd.mpg.de


www.msi.se


Low-energy stored ions ...



Merged electron-ion beam is a **cold, 2-component plasma**.

$E_{coll} \approx \frac{1}{2}\, m_e\, \Delta v^2$

$\Delta v = |v_i - v_e|$

Ideal setup for energy-resolved **atomic physics** experiments down to ~ 1 meV (~10 K).

Low-energy stored ions ...

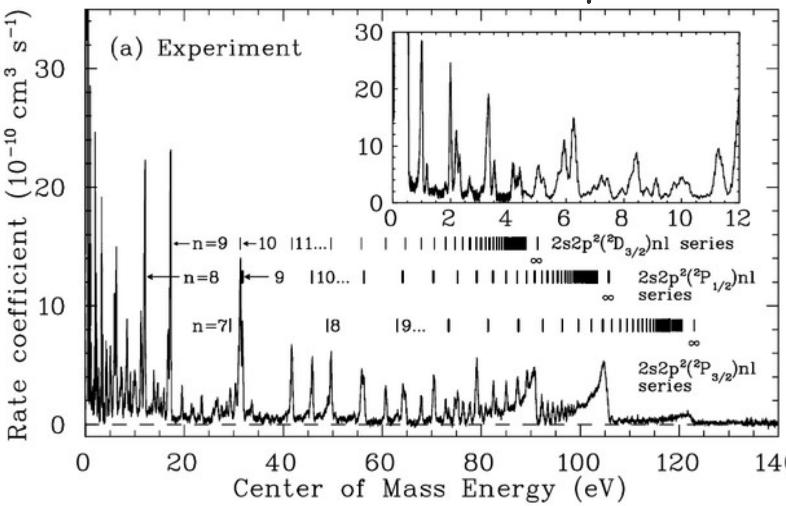
Resonant recombination of highly-charged atomic ions.

$$A^{q+} + e \longrightarrow [A^{(q-1)+}]^{**} \longrightarrow A^{(q-1)+} + \gamma$$

Ions have significant electronic shells
→ lower q/m compared to bare nuclei.

TSR (MPIK) 1988 - 2012

$Fe^{21+} + e \rightarrow Fe^{20+} + \gamma$

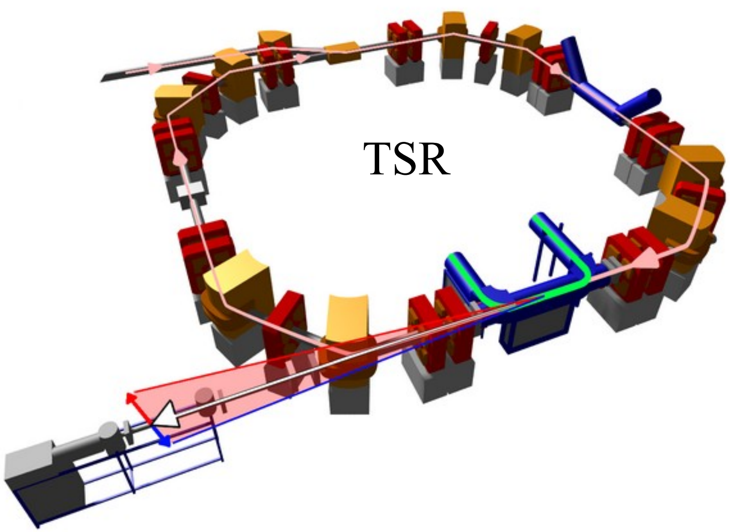


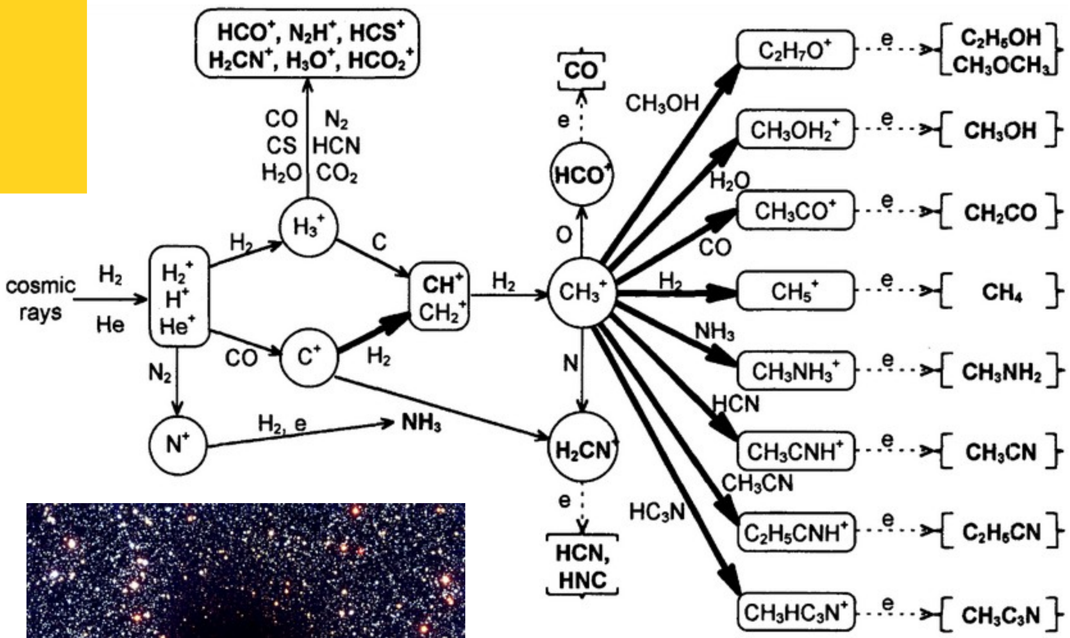
Savin, ApJ Suppl. Ser. 147 (2003)

Low-energy stored ions ...

Recombination of molecular ions:

Replicate the chemistry of
dark clouds.





Smith & Spanel, Mass. Spectrom. Rev. 14 (1995) 255

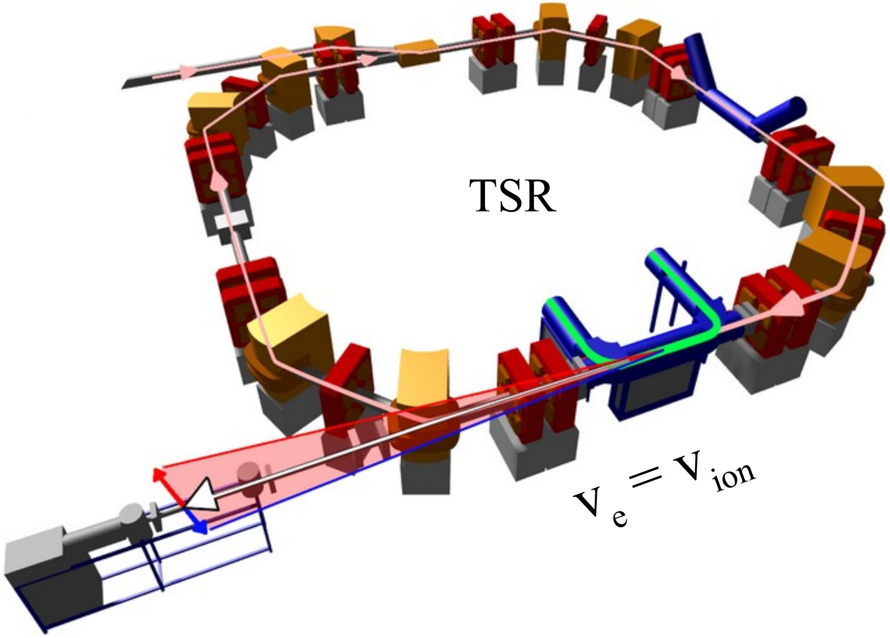
Low-energy stored ions ...

Maximum rigidity ρB_{max} of experimental storage rings tends to be low.

→ Maximum velocity $v_{ion} = \frac{q_{ion}}{m_{ion}} \rho\, B_{max}$

With low q/m

...



storage times **decrease**:

τ_{stor} ↘ ~ seconds

e-cooling times **increase!**

τ_{cool} ↗ ~ seconds

$$\tau_{cool} \sim \frac{m_{ion}}{q_{ion}^2}$$

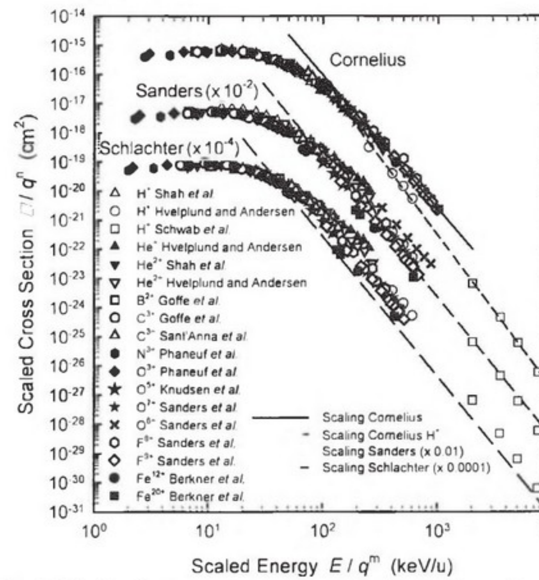


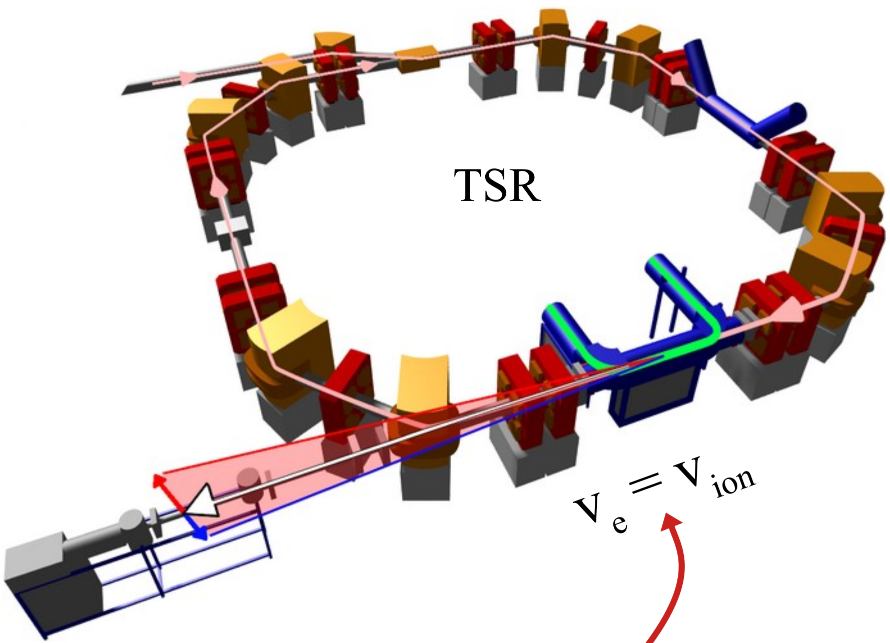
Fig. 2 Single electron capture cross section scalings for $A^{q+} + H_2$ collisions by Schlachter *et al.* [2], Sanders *et al.* [3], and Cornelius [4].

Imai, Univ. Kyoto Report

Successful beam preparation requires

$\tau_{stor} \gg \tau_{cool}$

Low-energy stored ions ...



$$E_e = E_{ion} \frac{m_e}{m_{ion}}$$

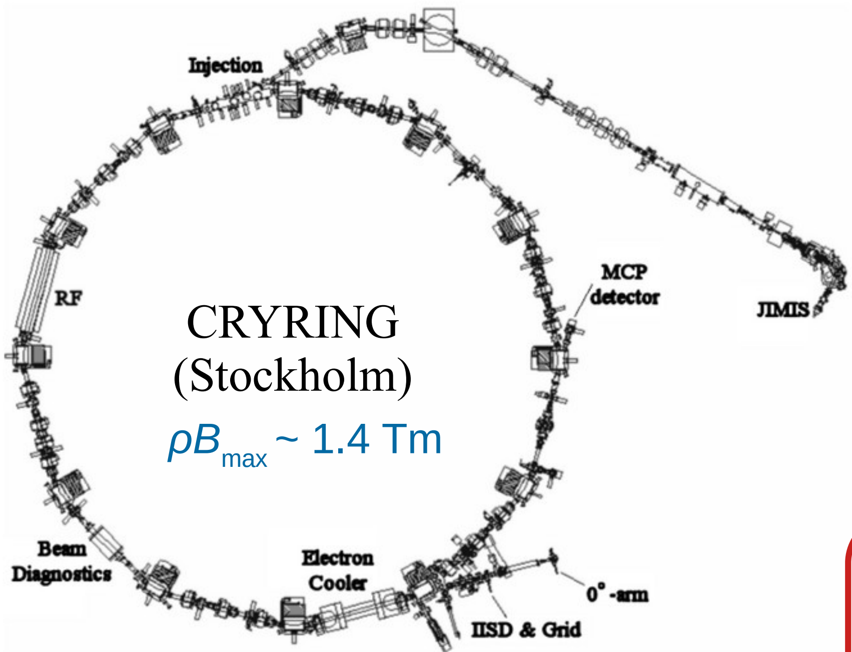
For TSR (Heidelberg): ρB_{max} ~ 1.4 Tm

$$v_{ion} = \frac{q_{ion}}{m_{ion}} \rho B_{max}$$

E-cooler must operate at very low energy

ion	q/m_{ion} [e/u]	½ (v_{ion})^2	E_e
H_3^+	1 / 3	1.367 MeV/u	**736 eV**
HF^+	1 / 20	0.235 MeV/u	**128 eV**
DF^+	1 / 21	0.214 MeV/u	**117 eV**
N_2H^+	1 / 29	0.110 MeV/u	**61 eV**
DCO^+	1 / 30	0.103 MeV/u	**51 eV**
CF^+	1 / 31	0.084 MeV/u	**44 eV**
HS^+	1 / 33	0.082 MeV/u	**44 eV**
$^{16}O^{18}O^+$	1 / 34	0.079 MeV/u	**43 eV**
$H^{35}Cl^+$	1 / 36	0.067 MeV/u	**37 eV**
$D_2{}^{37}Cl^+$	1 / 41	0.056 MeV/u	**31 eV**

Low-energy stored ions ...



$\rho B_{max} \sim 1.4$ Tm

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

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

→ Need to improve the ion beam lifetime in the ring!

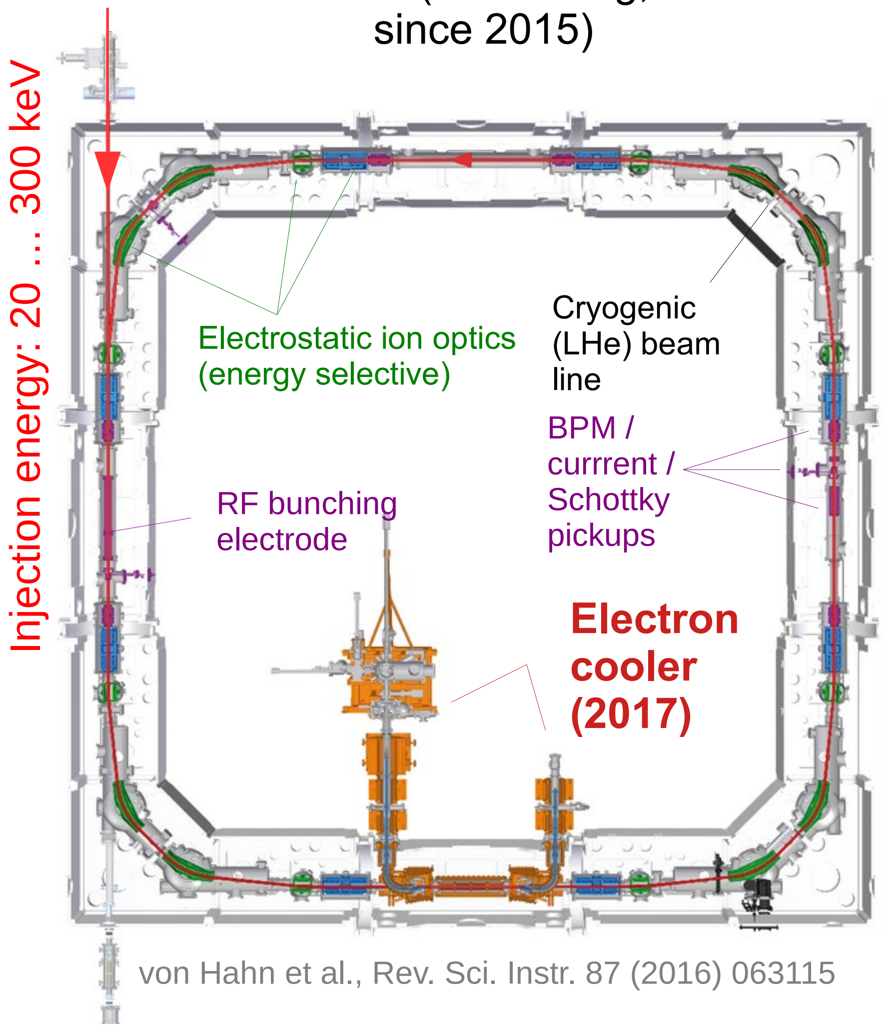
Recombination of large organic molecules at CRYRING (Stockholm)

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

Low-energy stored ions ...

CSR (Heidelberg, since 2015)



von Hahn et al., Rev. Sci. Instr. 87 (2016) 063115

Fully-electrostatic **C**ryogenic **S**torage **R**ing

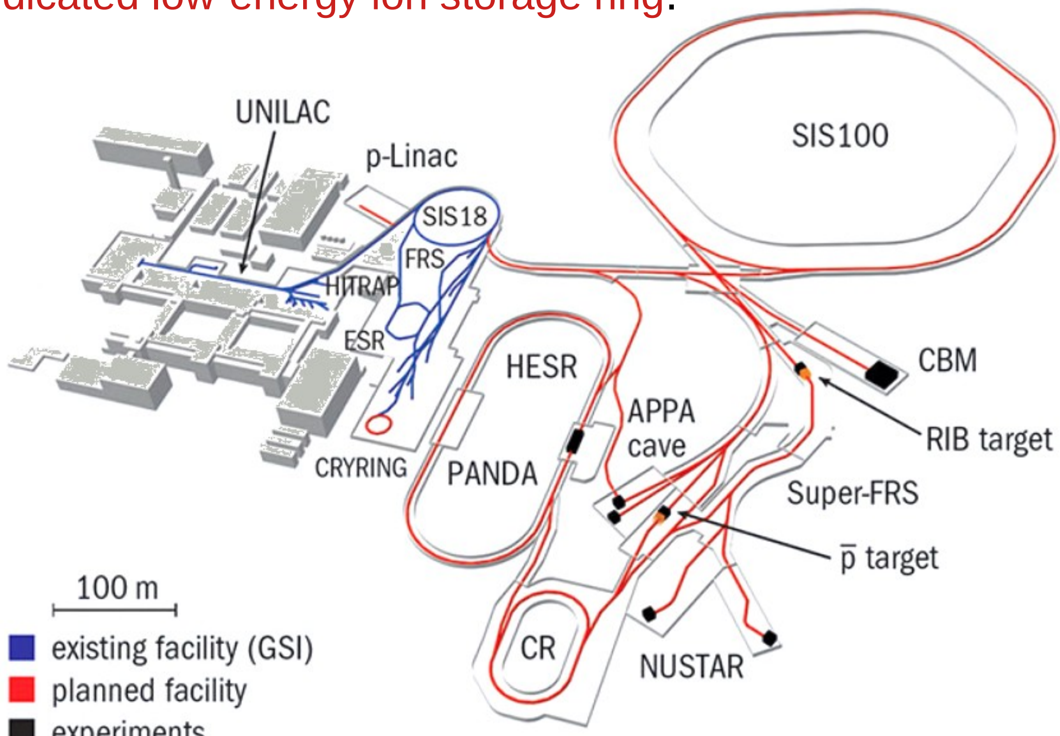
Optimized from ground-up for storage of molecular ions.

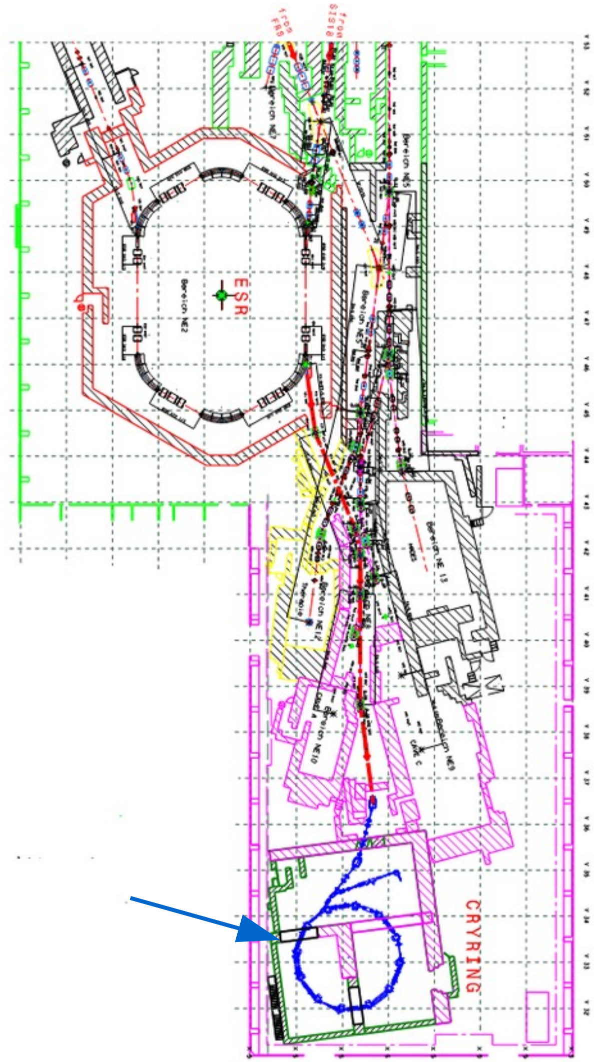
Circumference:	**35 m**
Beam energy:	**≤ 300 keV × q**
Temperature:	**≥ 3 K**
Res. gas dens. (RTE pressure):	**≳ 1000 cm^{-3} (≳ 10^{-14} mbar)**
Storage times:	**τ > 1000 s**
E-cool energies:	**Ee ≥ 1 eV**

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.





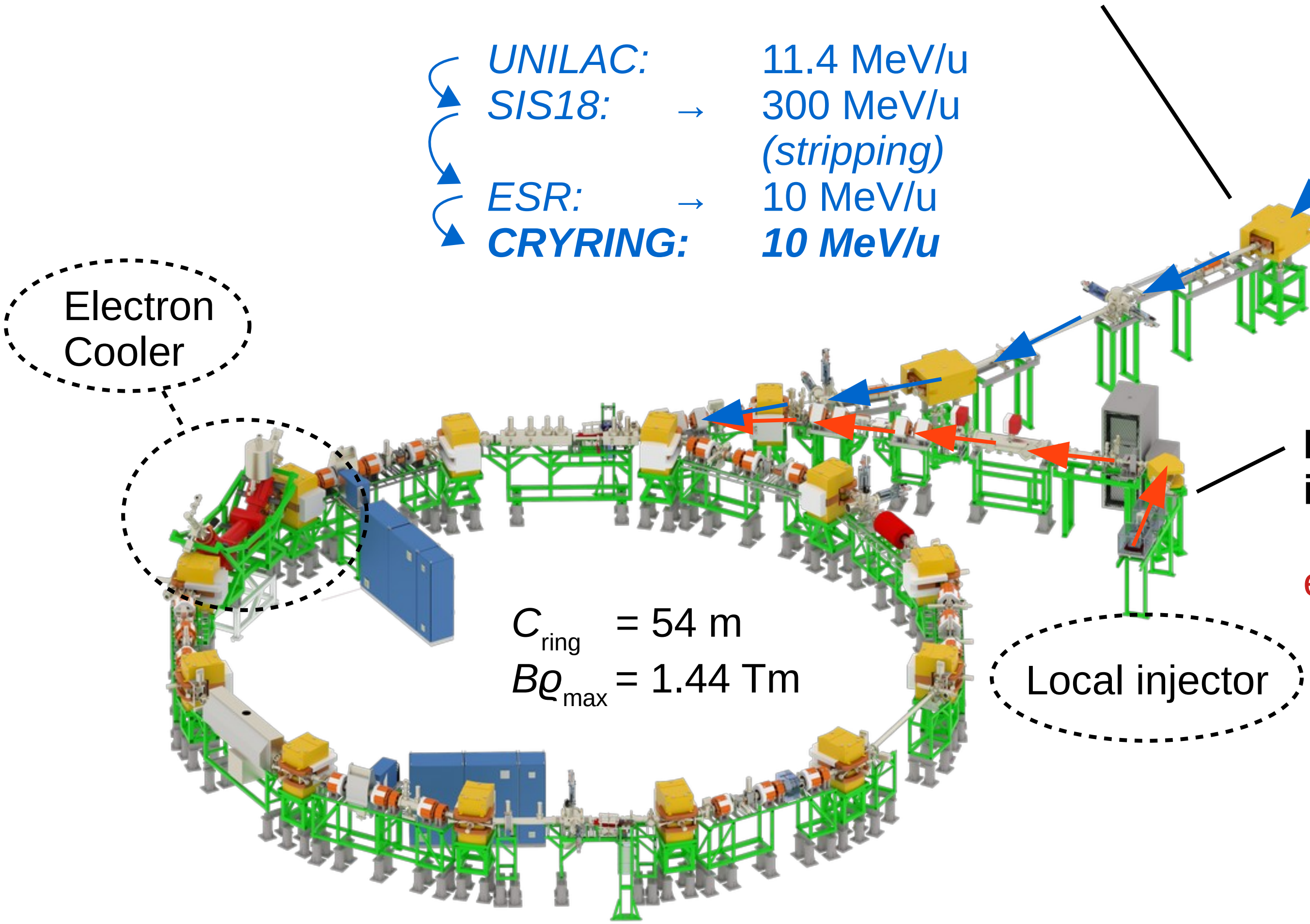
M. Lestinsky et al., Eur. Phys. J. ST 225 (2016) 797

Low-energy stored ions ...

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***



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)
	…	

… and how to cool them

Basic scaling law of electron cooling time:

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

Highly charged ions: ~ 0.03 … 0.33 u/e^2
($^{238}U^{92+}$ … $^{12}C^{6+}$)

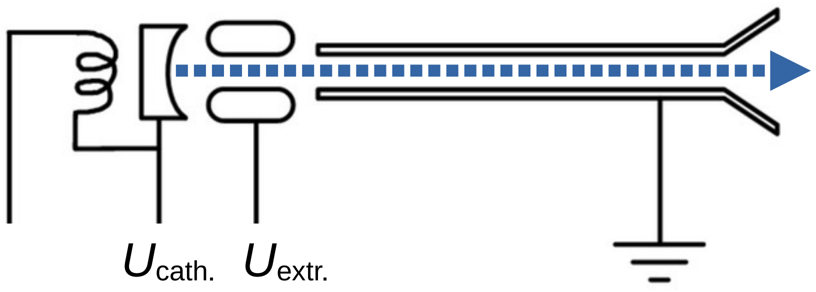
Protons: = 1 u/e^2

Weakly-charged ions,
singly charged molecules: **~ 5 … 41 u/e^2 …**
($^{20}Ne^{2+}$ … $D_2{}^{37}Cl^+$ …)

◄ These are our cases ...

… and how to cool them

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

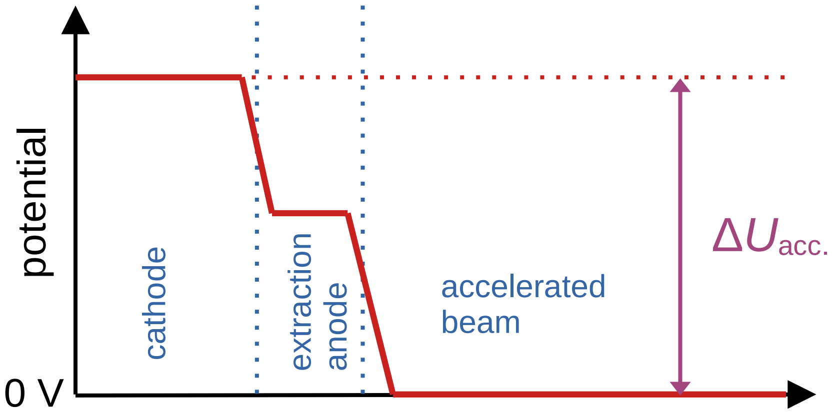


e-density limited by law of Child-Langmuir:

$$I_e = p \times |U_{cath.} - U_{extr.}|^{3/2}$$

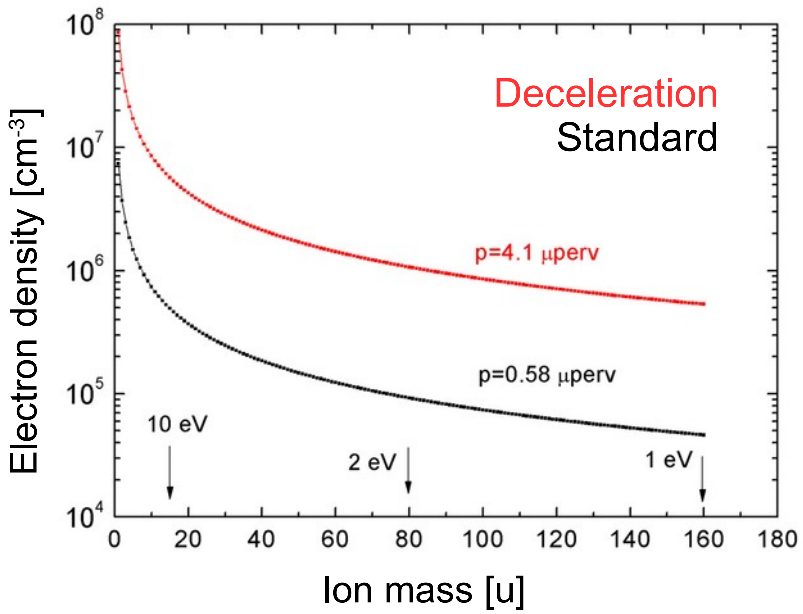
p: „perveance" of electron gun.

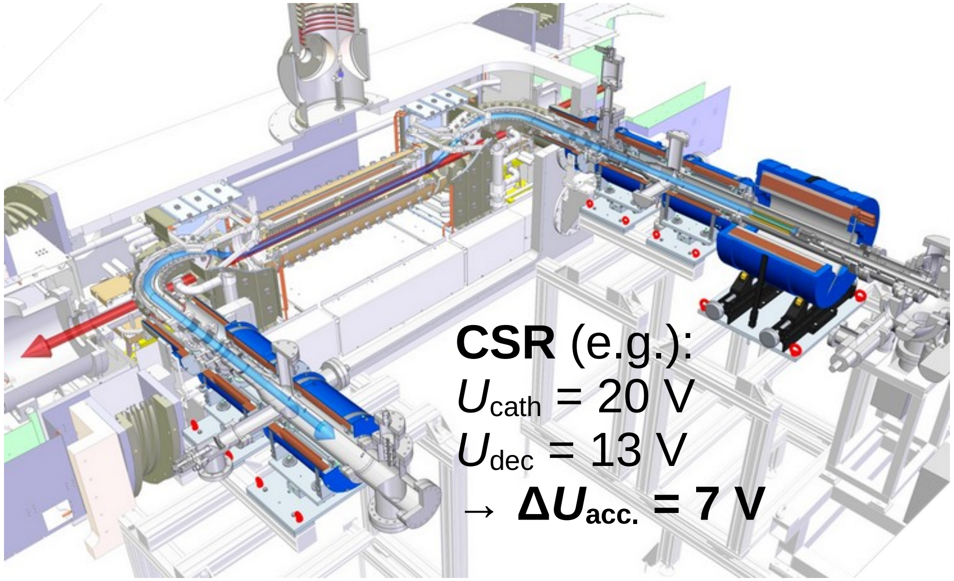
Typical value: $p \sim 10^{-6}$ A/V$^{3/2}$



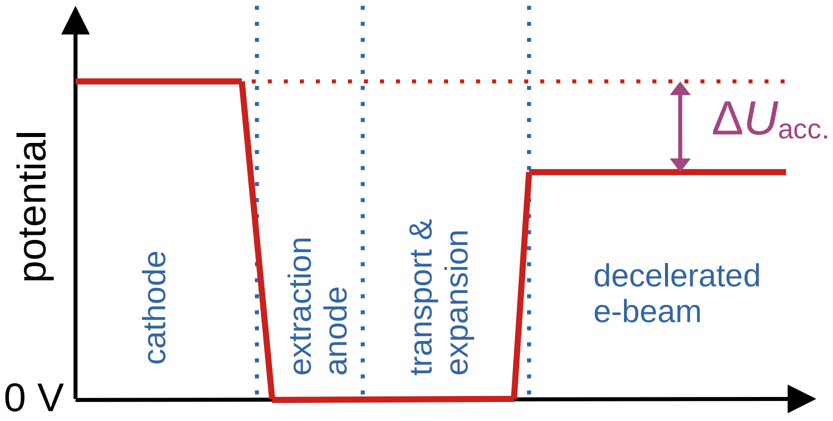
… and how to cool them

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

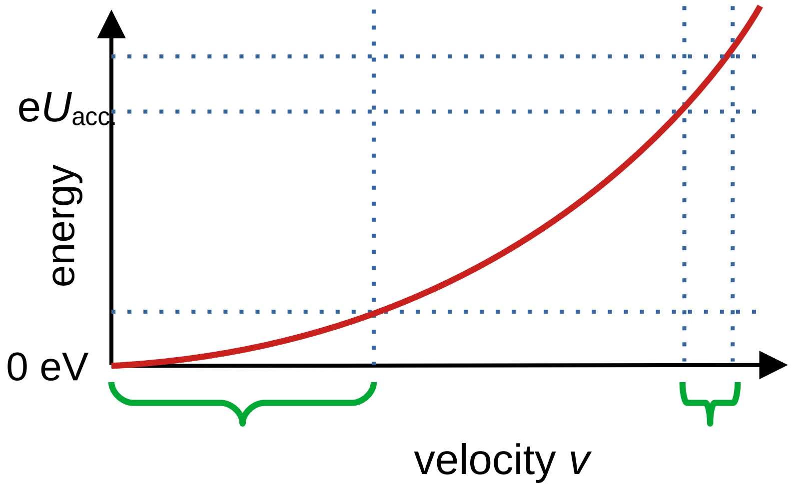


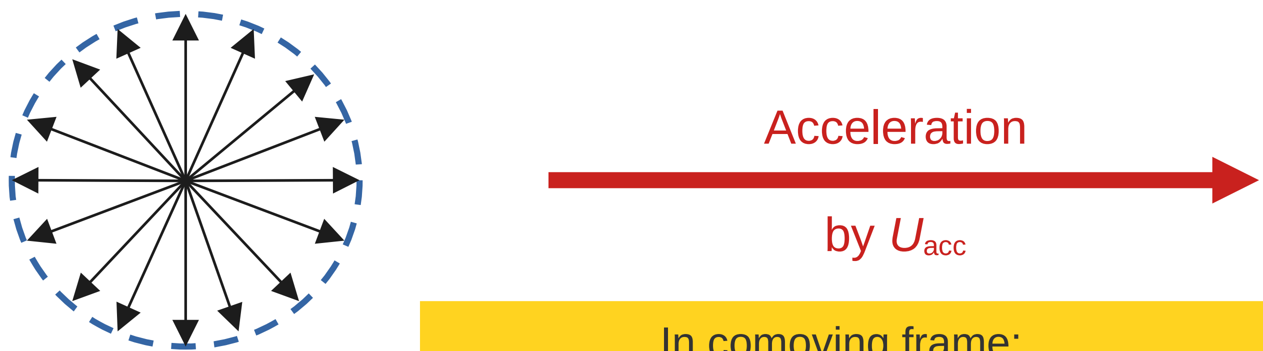


A. Shornikov, Phys. Rev. ST AB 17 (2014)

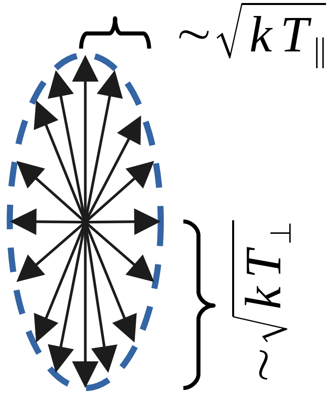


$$\tau_{\text{cool}} \propto \frac{m_{\text{ion}}}{q_{\text{ion}}^2} \times \frac{T_e^{3/2}}{n_e}$$





velocity distribution at rest



velocity distribution of accelerated beam

In comoving frame:

$$T_{e,\parallel} = \frac{kT_{\text{cath}}^2}{2eU_{\text{acc}}} + C_{\text{relax}}\left(n_e^{1/3}\right) \qquad T_{e,\perp} = T_{\text{cath}}$$

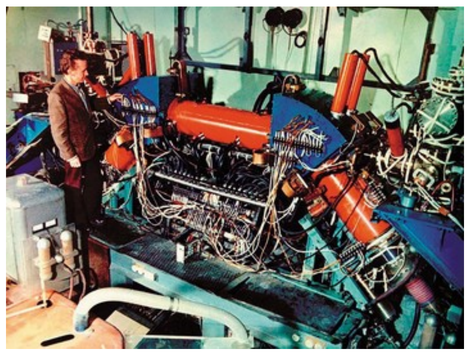
(conserved)

… and how to cool them

How to decrease $T_{e,\perp}$?

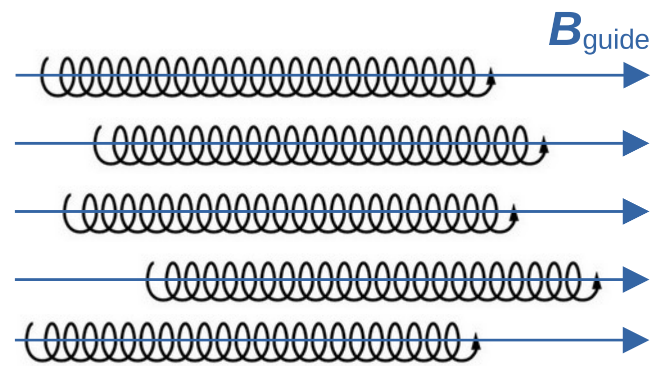
Option 1: Strong magnetization

Proposed to explain the cooling rates at NAP-M that were "too fast".
Derbenev & Skrinsky, Part. Accel. 8 (1978) 255



scfh.ru

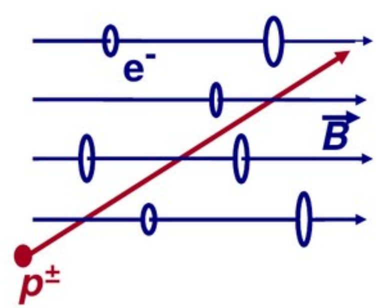
Transversely, electrons perform **cyclotron motion** around the mag. field lines.



Issues:

1) Effect not (clearly) observed at several other labs … (field precision issues?)

2) For low-$(B\rho)_0$ rings, strong disturbance of ion optics.



For strong fields:

$r_{cyc} \ll$ distance e - ion

$1/\omega_{cyc} \ll$ interaction time

→ Interaction averaged over "Larmor circle".

→ Only $T_\parallel$ "matters".

How to decrease $T_{e,\perp}$?

Option 2: Beam expansion

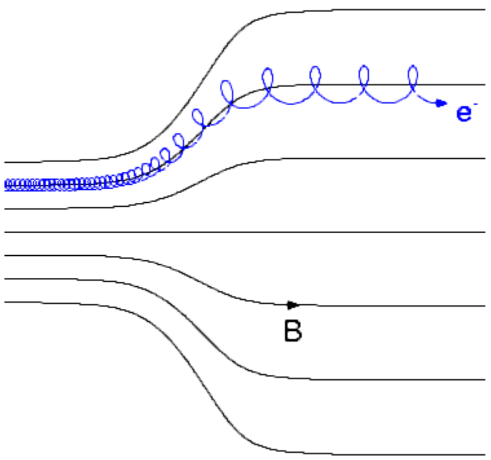
When drifting from high-*B* to low-*B* region, transverse energy spread is reduced by the inverse magnetic bottle effect:

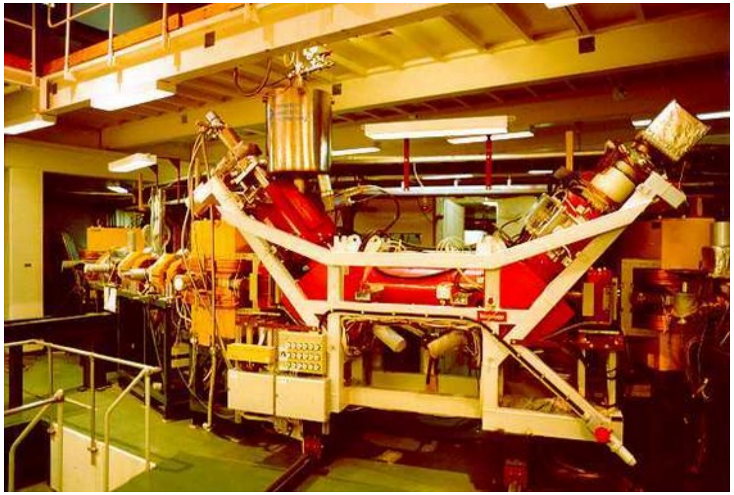
$$T_{\perp} = T_{cath} \frac{B_{cooler}}{B_{gun}}$$

Strong expansion ratio pioneered by CRYRING e-cooler:
H. Danared, NIM A 441 (2000) 123

B_{gun}	= 3 T	(s.c. solenoid)
B_{cooler}	= 0.03 T	

	T_{cath}	~ 1200 K
→	$T_{\perp}$	~ 12 K





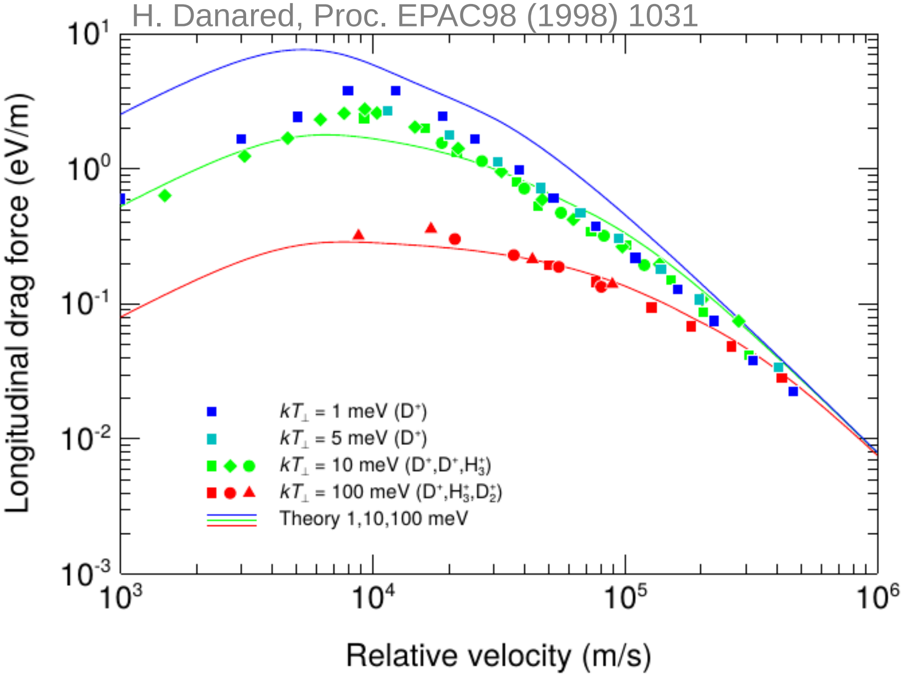
msi.se

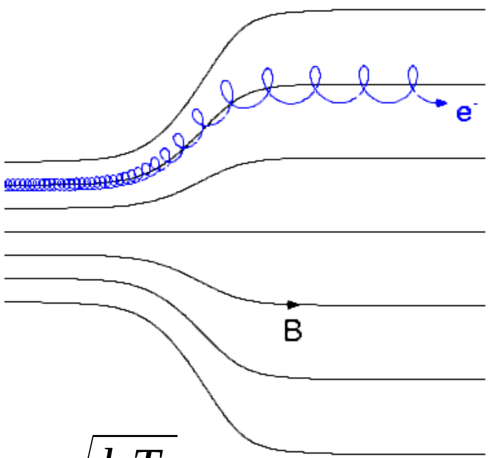
How to decrease $T_{e,\perp}$?

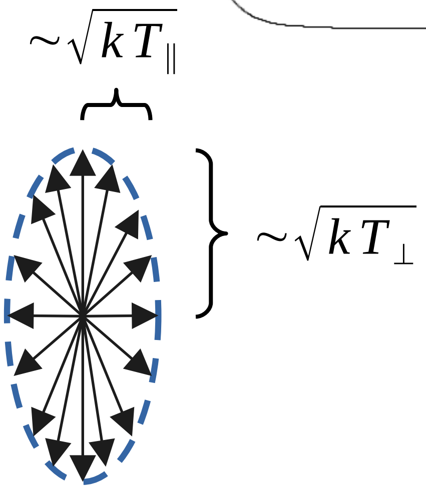
Option 2: Beam expansion

$$\mathbf{F}(\mathbf{v}_i) = -4\pi \left(\frac{Ze^2}{4\pi\epsilon_0}\right)^2 \frac{n_e L_C}{m_e} \int \underbrace{f(\mathbf{v}_e)} \frac{\mathbf{v}_i - \mathbf{v}_e}{|\mathbf{v}_i - \mathbf{v}_e|^3} d^3 v_e$$

H. Danared, Proc. EPAC98 (1998) 1031







velocity distribution of accelerated beam

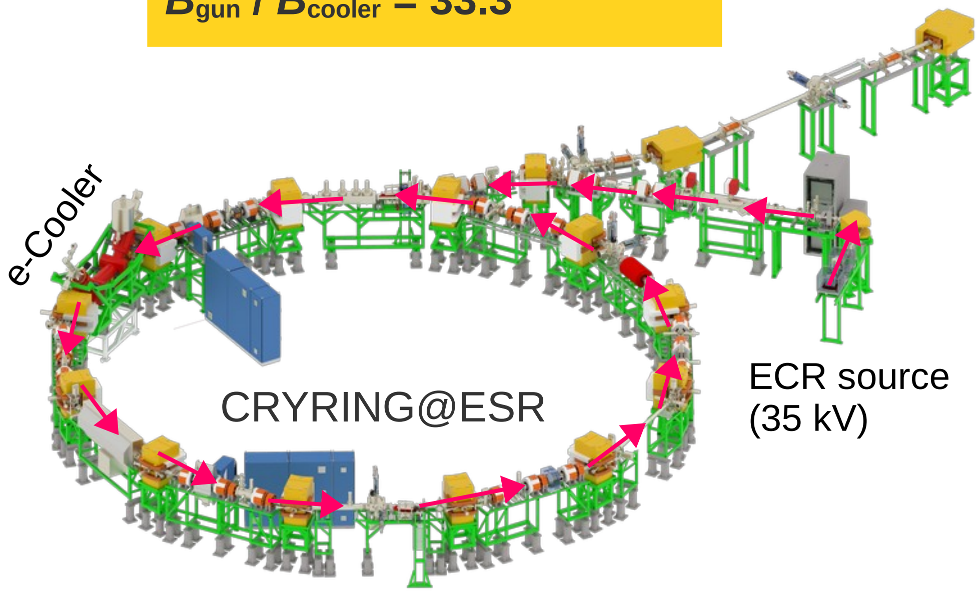
How to decrease $T_{e,\perp}$?

Option 2: Beam expansion

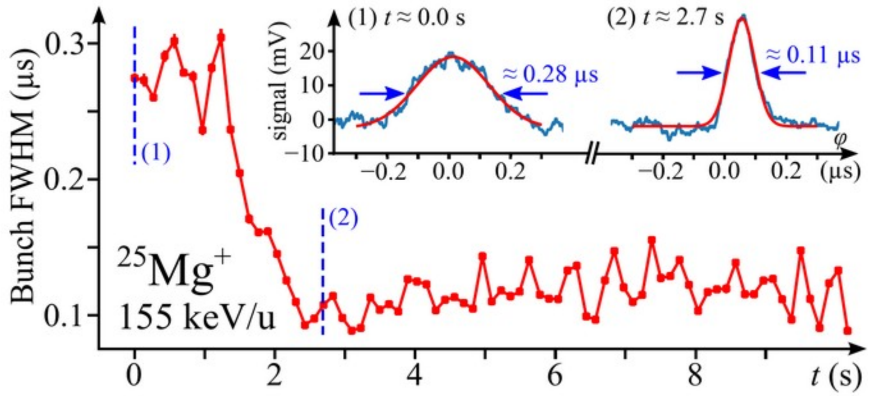
Example: Electron cooling of

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

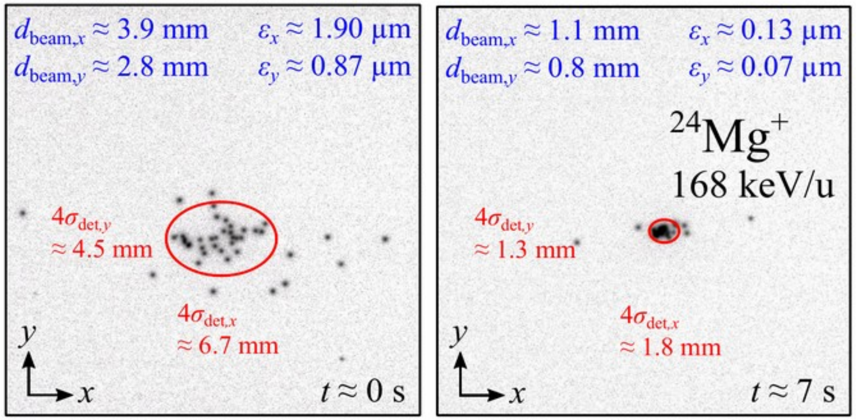
E_e = 92 eV / 85 eV
B_{gun} / B_{cooler} = 33.3



Longitudinal bunch cooling (pickup):



Transverse cooling (neutral imaging):



C. Krantz, Proc. IPAC 2021

… and how to cool them

How to decrease $T_{e,\perp}$?

Option 2: Beam expansion

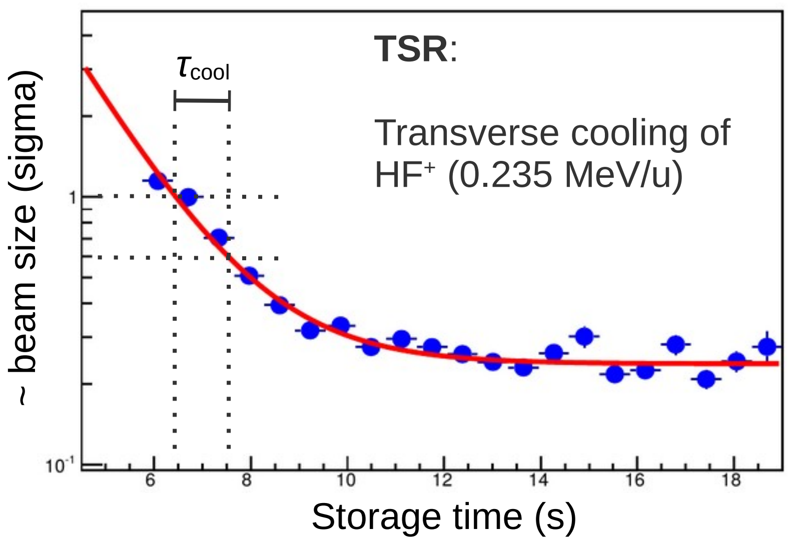
$$\tau_{\text{cool}} \propto \frac{m_{\text{ion}}}{q_{\text{ion}}^2} \times \frac{T_e^{3/2}}{n_e}$$

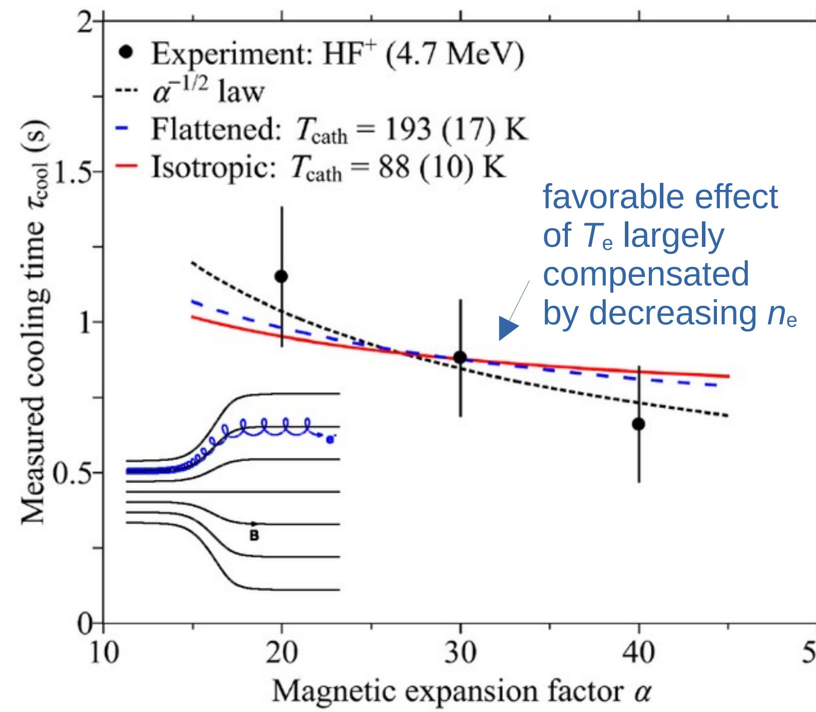
Caveat with low energy beams:

$$T_\perp = T_{\text{cath}} \frac{B_{\text{cooler}}}{B_{\text{gun}}}$$

Expansion decreases n_e!

$$n_{e,\text{cooler}} = n_{e,\text{cath}} \frac{B_{\text{cooler}}}{B_{\text{gun}}}$$





Krantz et al., PRAB 24 (2021) 050101

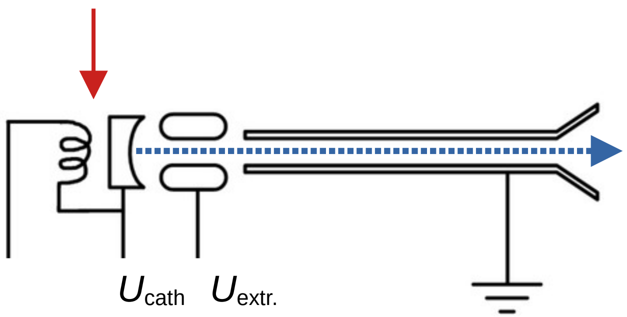
… and how to cool them

How to decrease $T_{e,\perp}$?

Option 3: Cold cathode

Standard electron cooler:

BaO-based thermal emitter

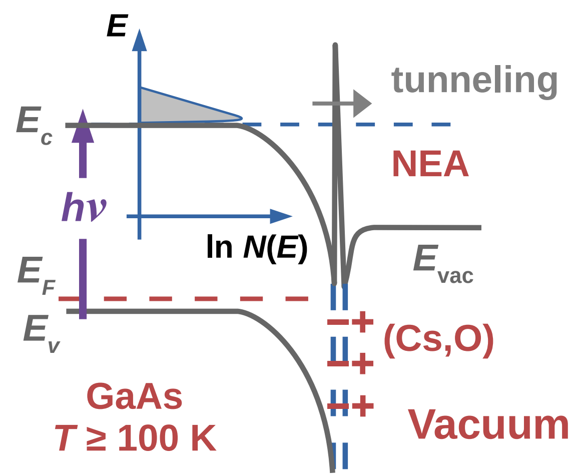


Workfunction: $e\phi_{WF}$ ~ 1.9 … 2.1 eV
(bare-metal: 4 … 5 eV)

→ **T_{cath} = 1100 … 1300 K**

Photo-electron cooler:

GaAs:(Cs,O) photocathode



Orlov et al., APL 78 (2001) 2721

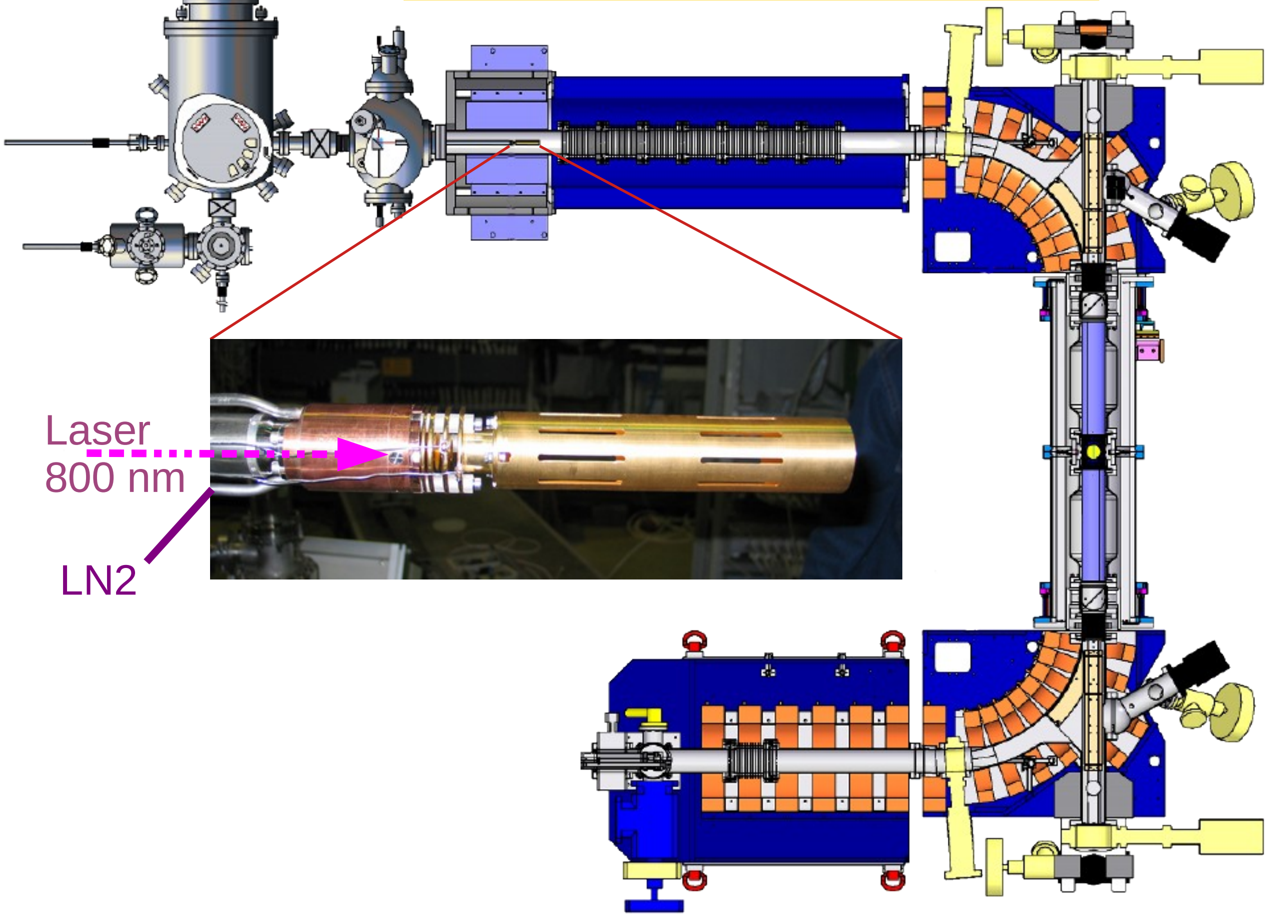
Band-gap: E_{gap} ~ 1.4 eV (λ ~ 800 nm)
Cs-coating: Negative Electron Affinity.

→ **T_{cath} = 100 … 300 K**

How to decrease $T_{e,\perp}$?

Option 3: Cold cathode

TSR "Photo-Electron" Cooler (2006 … 2012)



… and how to cool them

How to decrease $T_{e,\perp}$?

Option 3: Cold cathode

Photocathode preparation & handling

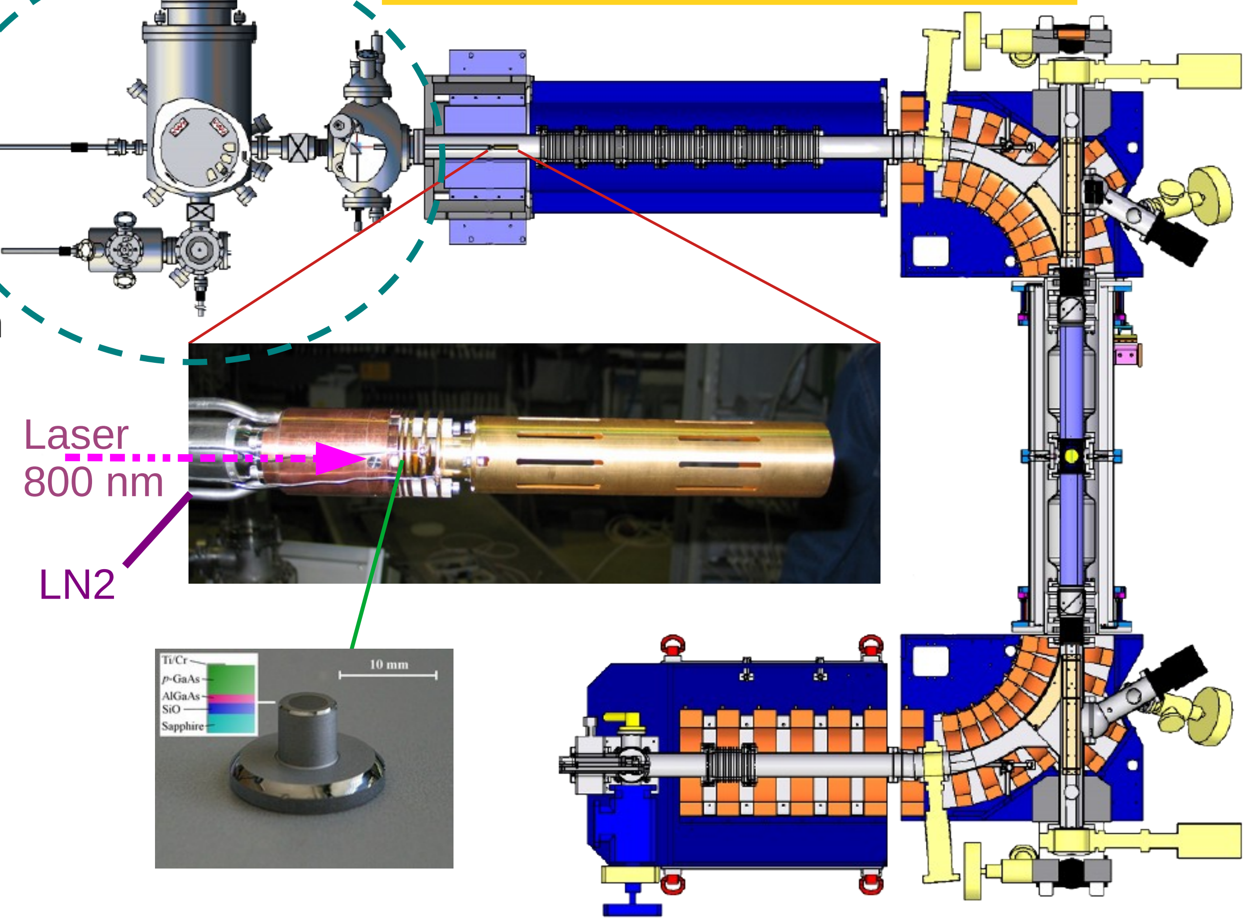
- (Cs,O) activation
- loading,
- cleaning,
- …

Max. emission current
~ 1 mA for 24 h

But: $I_e = p\, U^{3/2}$!!

→ For low-E ions:
0.2 … 0.3 mA
(several days of op.)

TSR "Photo-Electron" Cooler
(2006 … 2012)



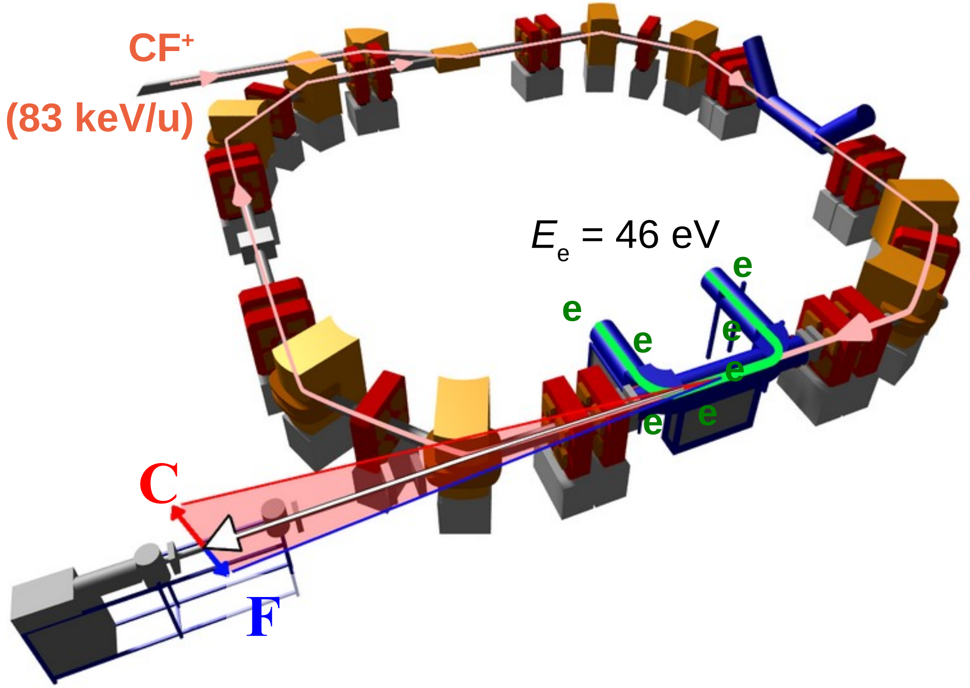
Orlov et al., J. Apl. Phys 106 (2009) 054907
Krantz et al., J. Phys. Conf. Ser. 192 (2009) 012025

… and how to cool them

TSR "Photo-Electron" Cooler
(2006 … 2012)

Used exclusively for electron cooling molecular ions in TSR in 2006 … 2012.

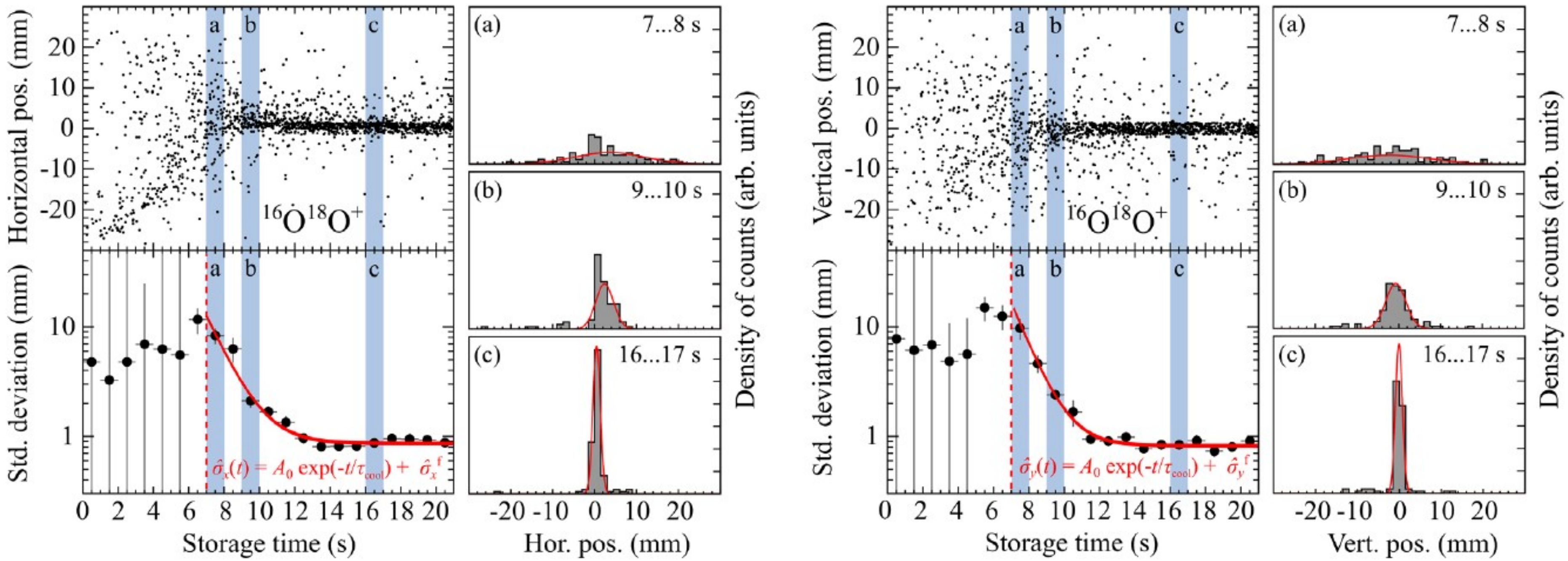
Beam diagnostics:
Neutral imaging.



Neutral fragment imaging (TSR data)

→ Final (cooled) ion beam diameters
→ Transverse cooling rates

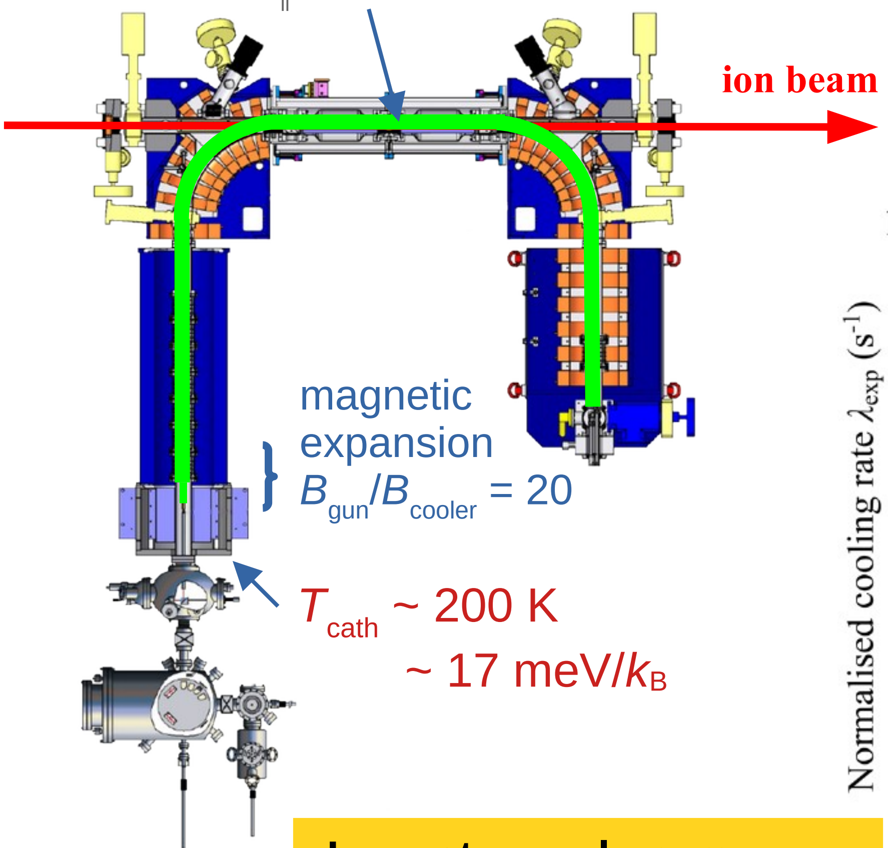
Krantz et al., PRAB 24 (2021) 050101

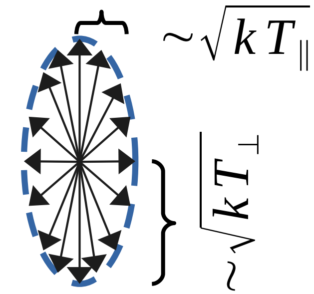


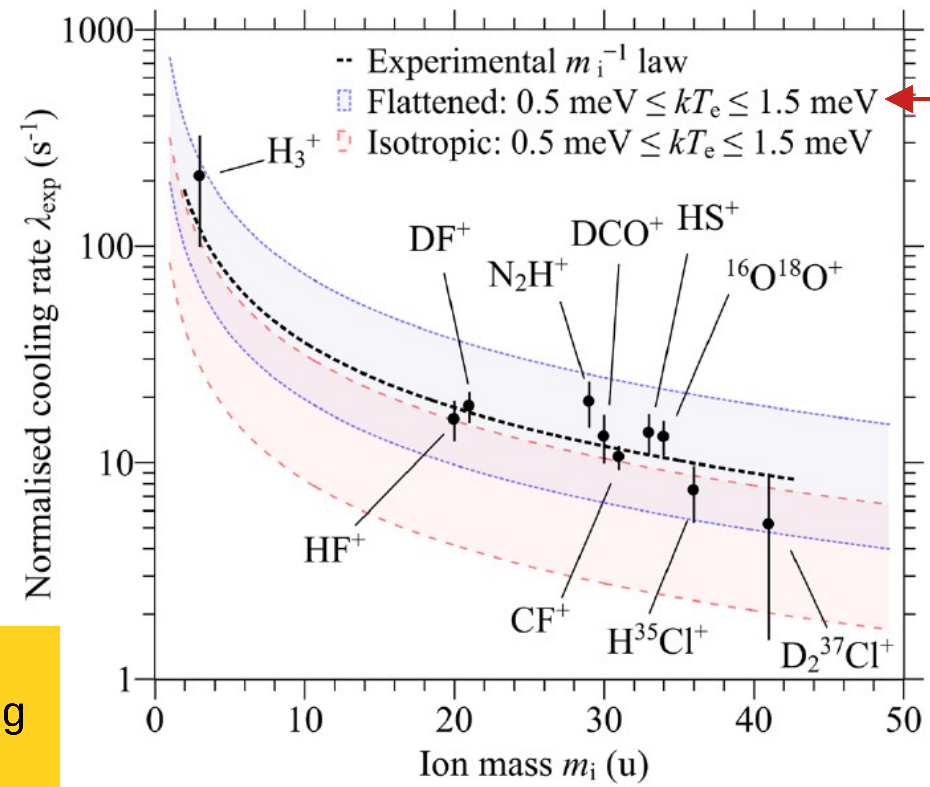
… and how to cool them

expected: $T_\perp \sim 10$ K ~ 0.9 meV/k_B

($T_\parallel < 1$ K ~ 0.1 meV/k_B)



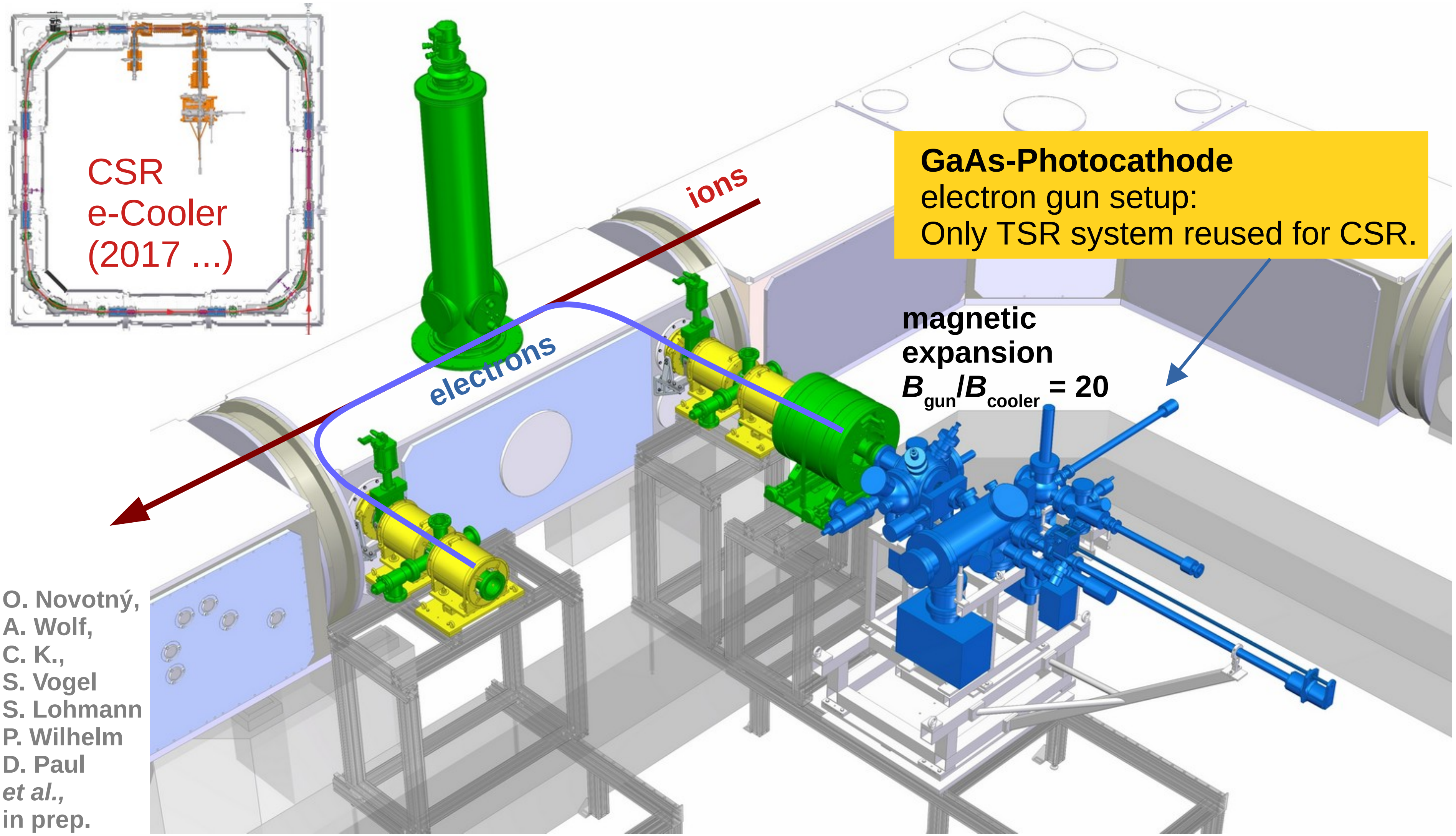




Krantz et al., PRAB 24 (2021) 050101

Lowest e-cool energy
in *conventional* storage ring
so far: E_e = 31 eV.

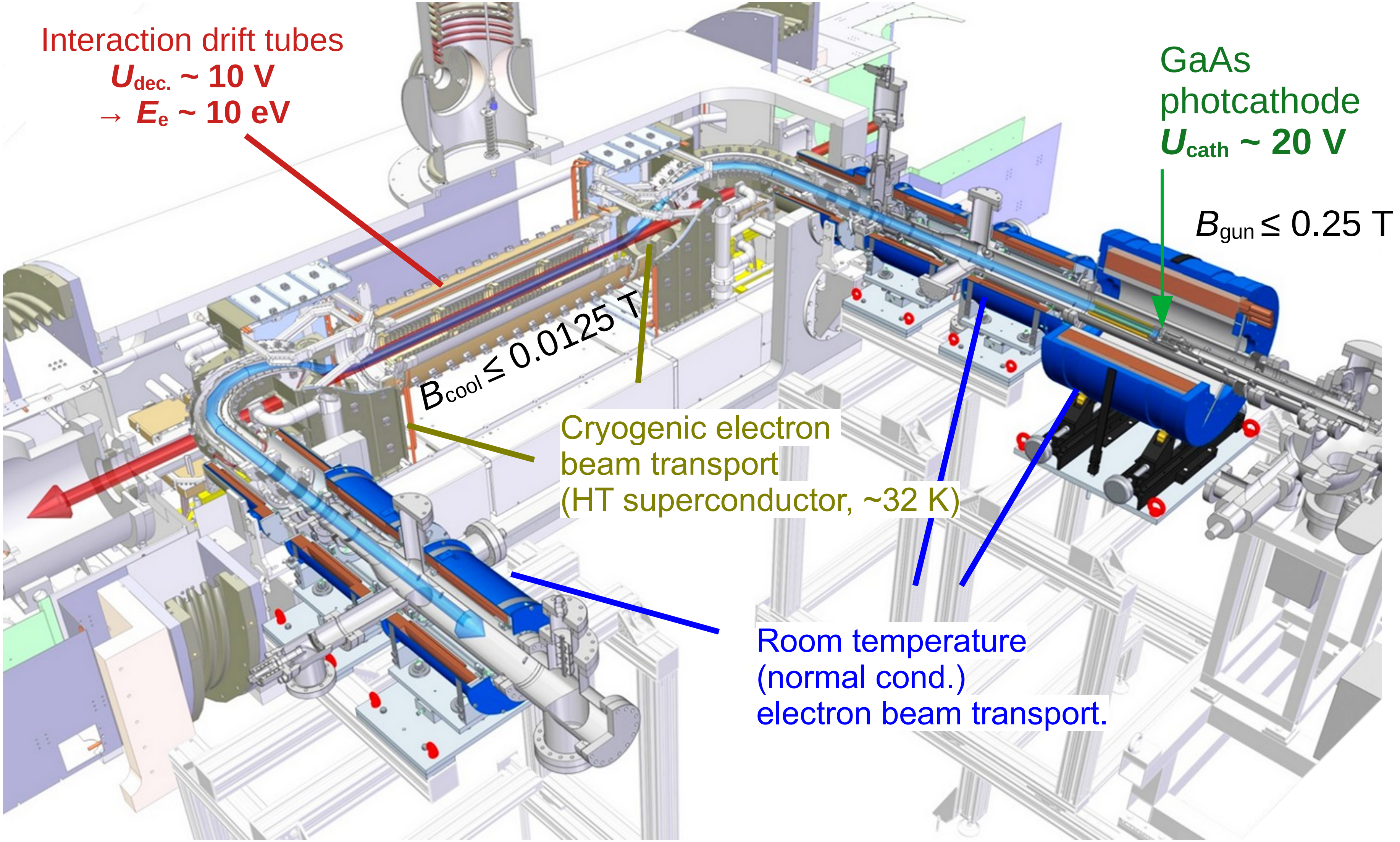
… and how to cool them



GaAs-Photocathode
electron gun setup:
Only TSR system reused for CSR.

O. Novotný,
A. Wolf,
C. K.,
S. Vogel
S. Lohmann
P. Wilhelm
D. Paul
et al.,
in prep.

… and how to cool them



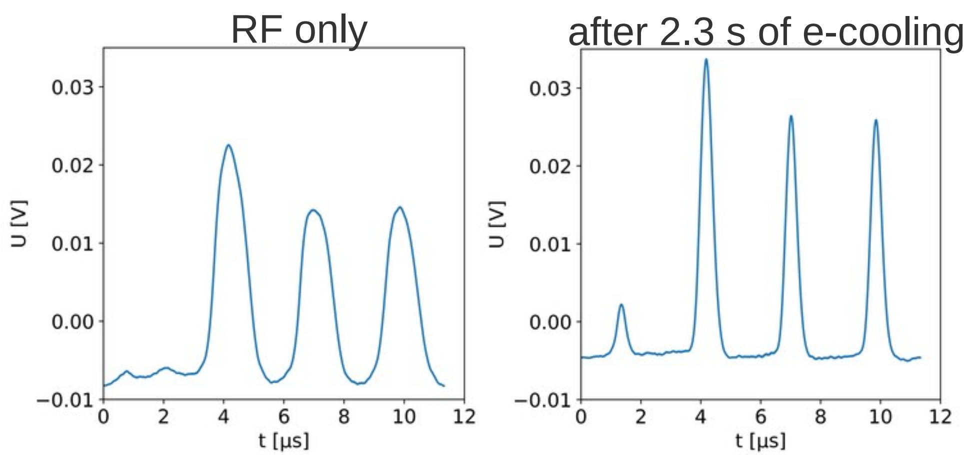
… and how to cool them

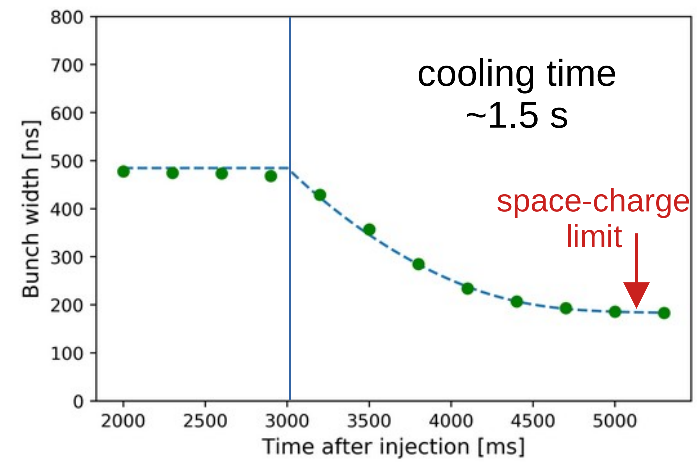
First demonstration of longitudinal electron cooling in CSR:

HeH$^+$ @ 0.050 MeV/u

E_e = 27.3 eV
$n_e = 3.7 \cdot 10^5$ cm^{-3}

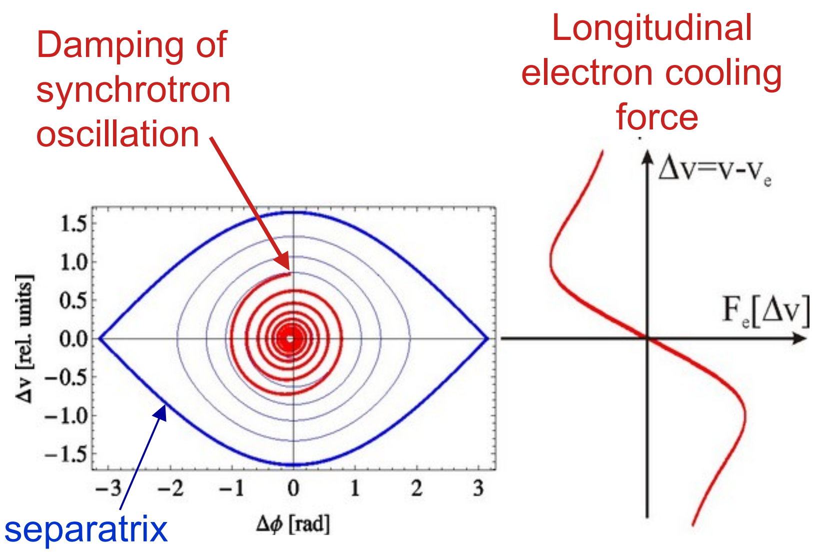
Bunch monitor signal





O. Novotný, M. Grieser et al., in prep.

Longitudinal ion phase space



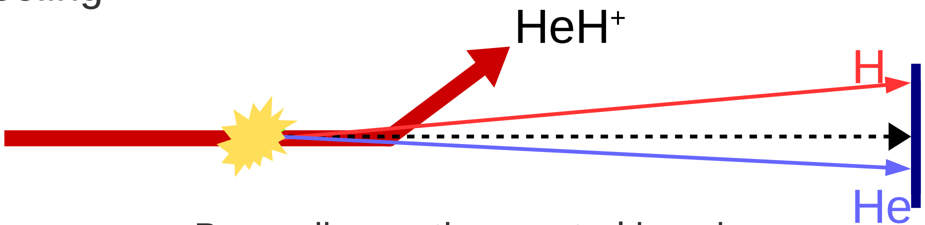
… and how to cool them

Demonstration of **transverse** electron cooling in CSR (with coasting beam):

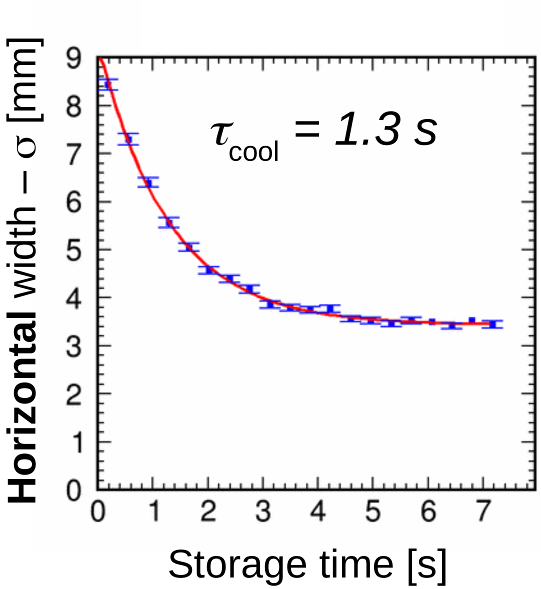
HeH^+ @ 0.050 MeV/u

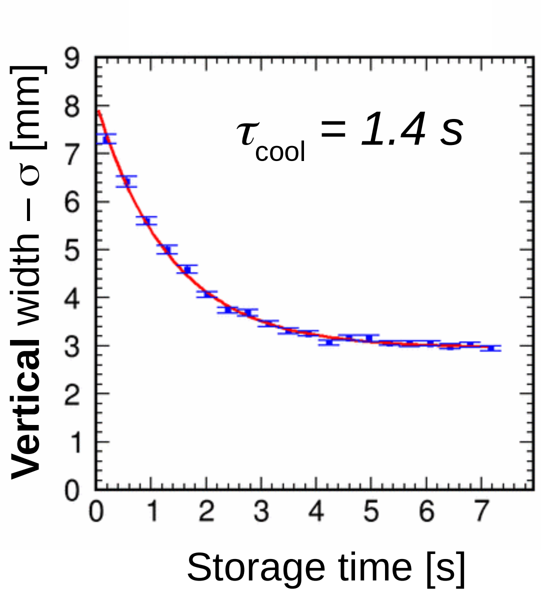
$\boldsymbol{E_e}$ **= 27.3 eV**
$n_e = 3.7 \cdot 10^5\ cm^{-3}$

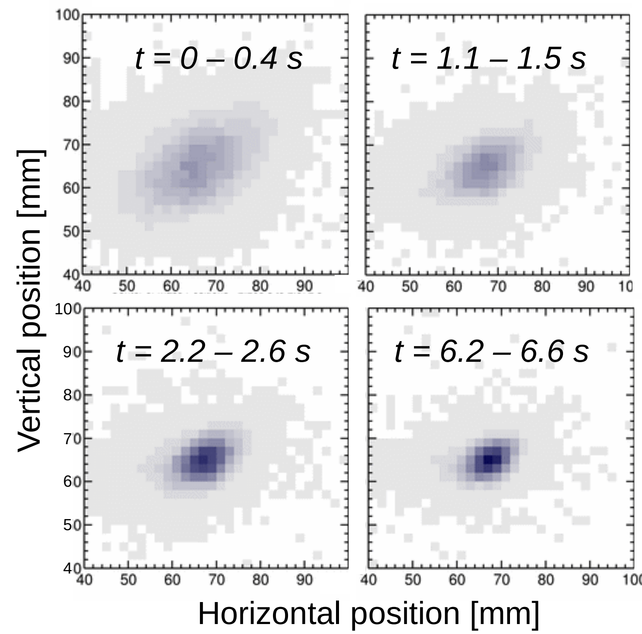
m_{ion} = 5 u, but already slower than TSR or CRYRING ...



Beam diagnostics: neutral imaging







Novotný et al., in prep.

Stability of low-energy cooled beams

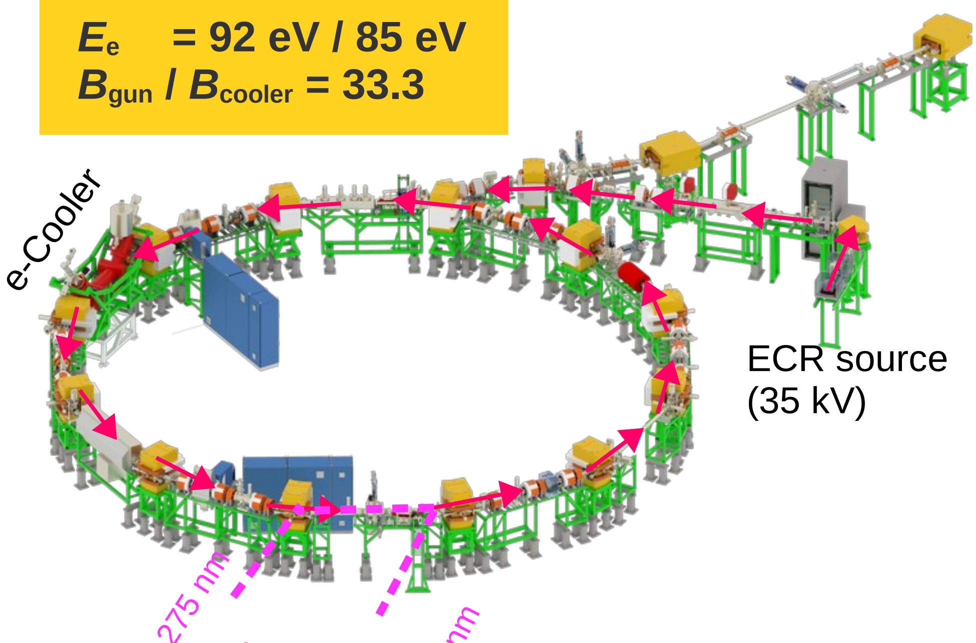
CRYRING@ESR

Electron cooling of

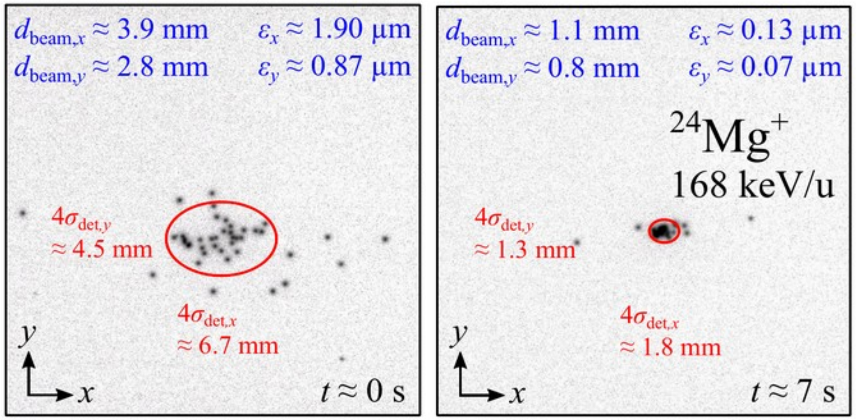
$^{24}Mg^{+}$ (0.168 MeV/u) and

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

E_e = 92 eV / 85 eV
B_{gun} / B_{cooler} = 33.3

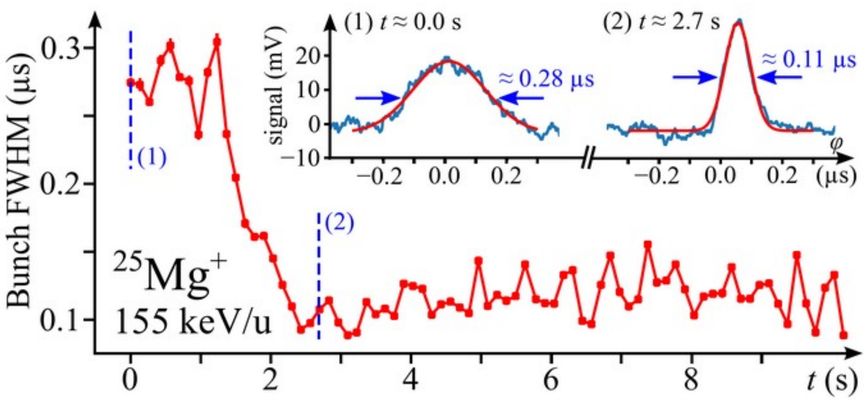


Transverse cooling (neutral imaging):

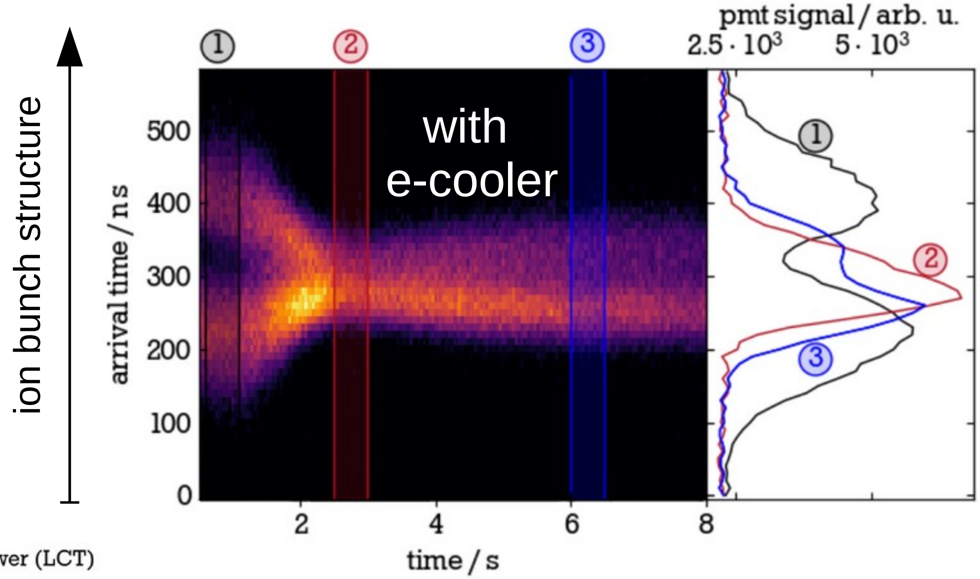


C. Krantz, Proc. IPAC 2021

Longitudinal bunch cooling (pickup):



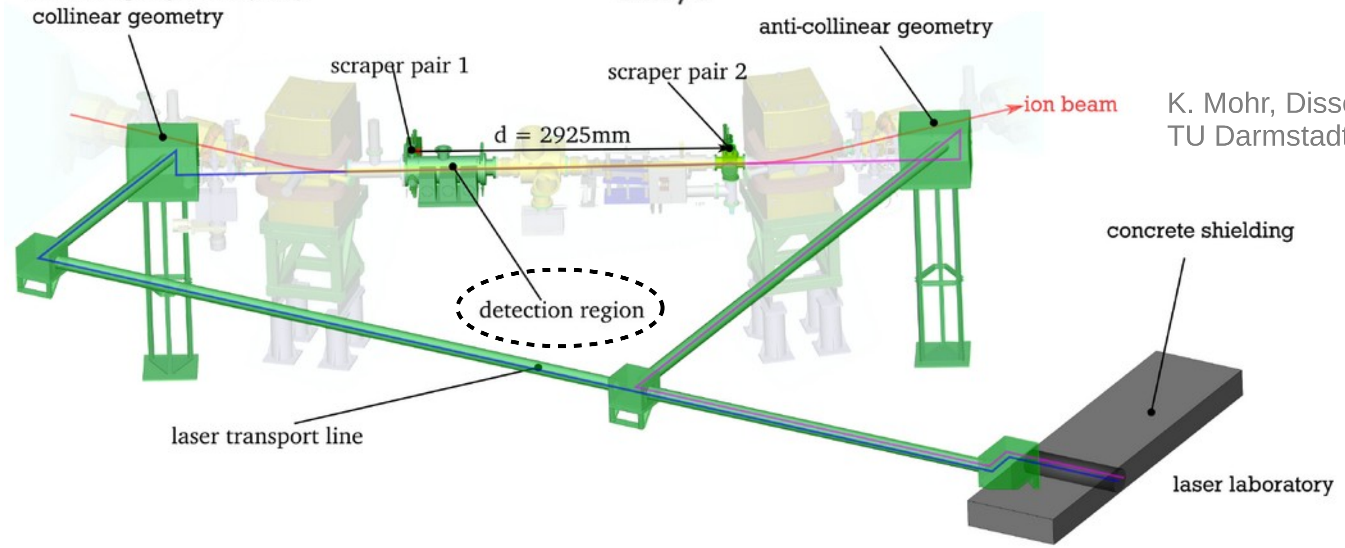
Stability of low-energy cooled beams



With electron cooler active …

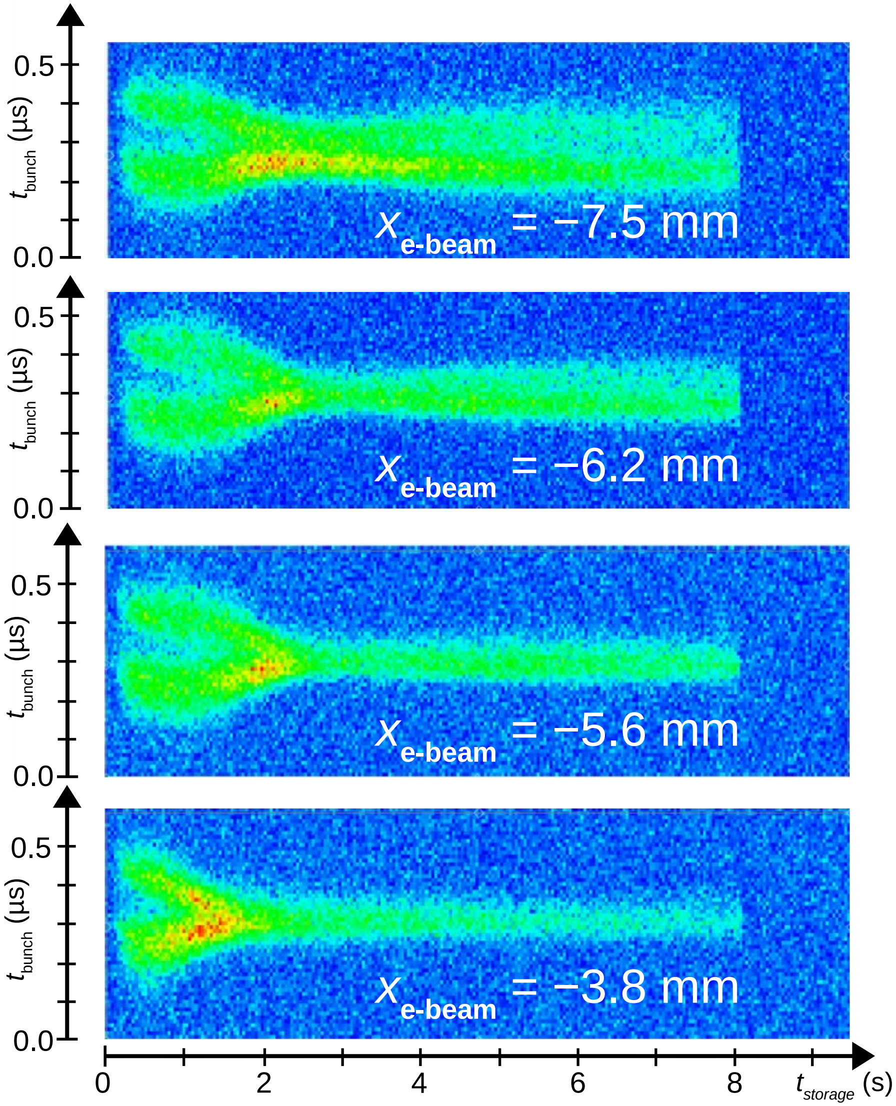
… bunches cool down at first (< 2 s) …

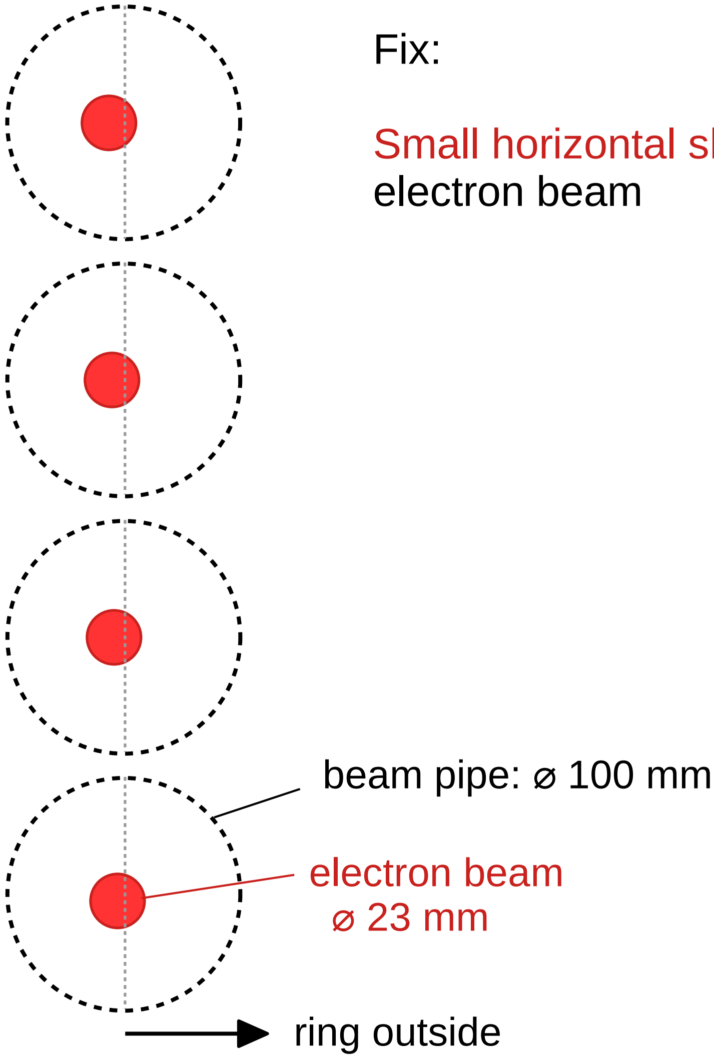
… but then synchrotron oscillation slowly restarts (> 2s) ?!?



K. Mohr, Dissertation, TU Darmstadt, 2022

Stability of low-energy cooled beams





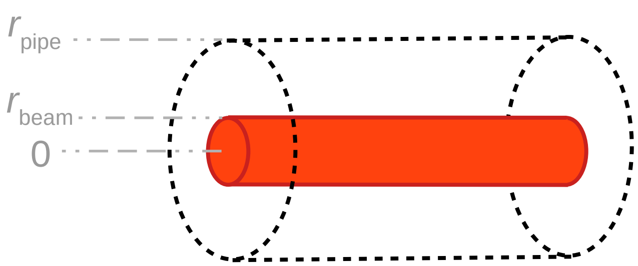
Fix:

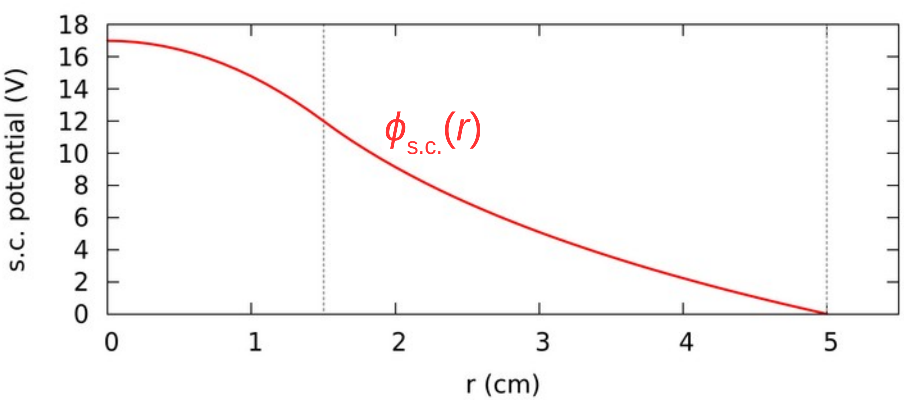
Small horizontal shift of electron beam

Stability of low-energy cooled beams

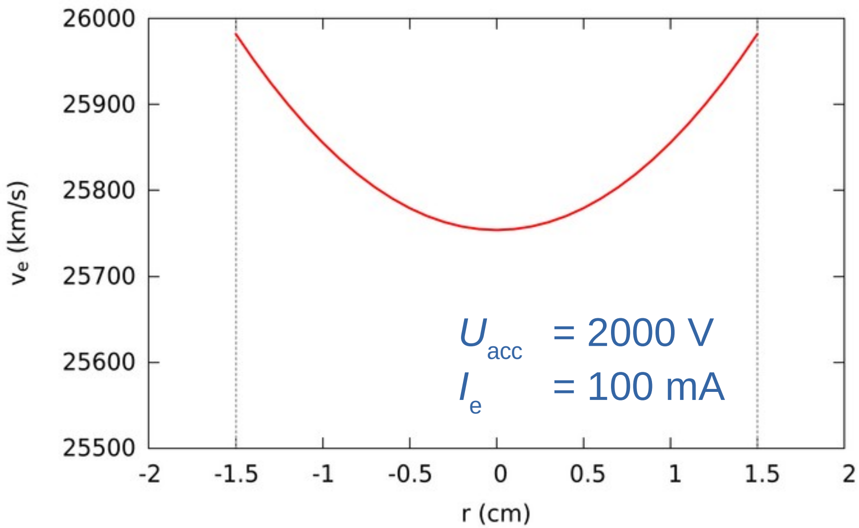
Space-charge of beam partly screens electrons from acceleration voltage:

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





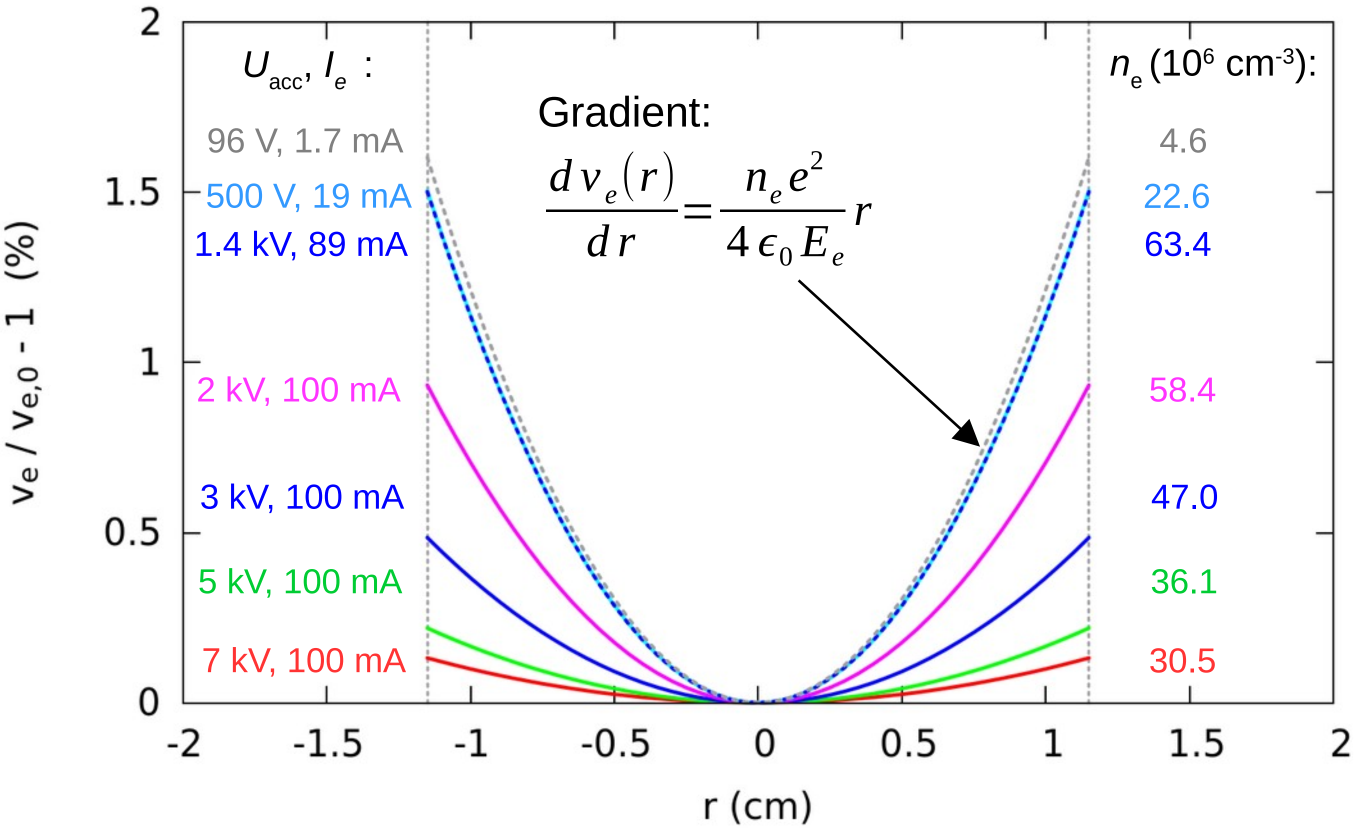
→ Electrons are faster near edge of beam.



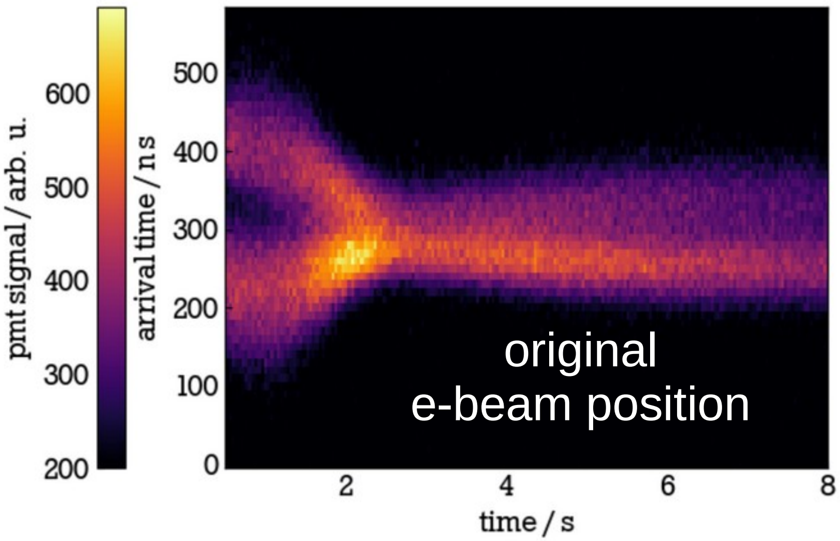
→ Not all ions "see" the same $\langle \boldsymbol{v}_e \rangle$!

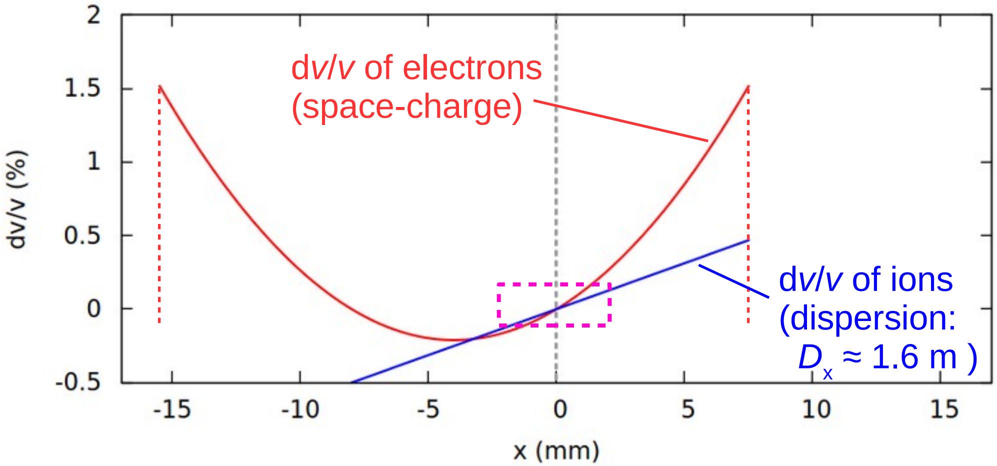
Stability of low-energy cooled beams

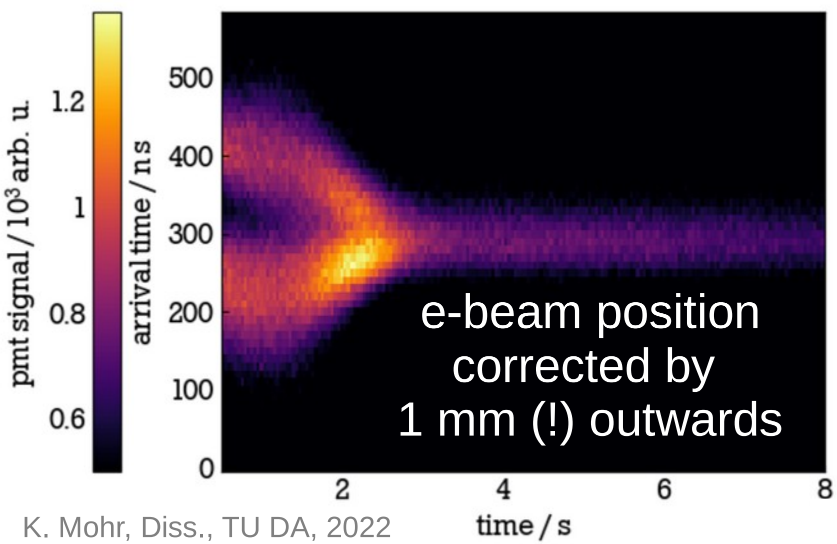
Relatively, space-charge effects become much **more important for low-energy beams**.

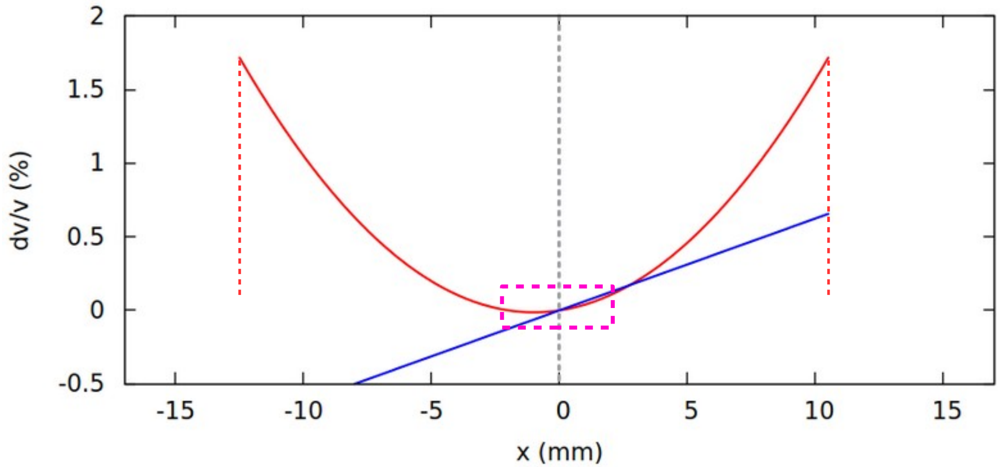


Stability of low-energy cooled beams



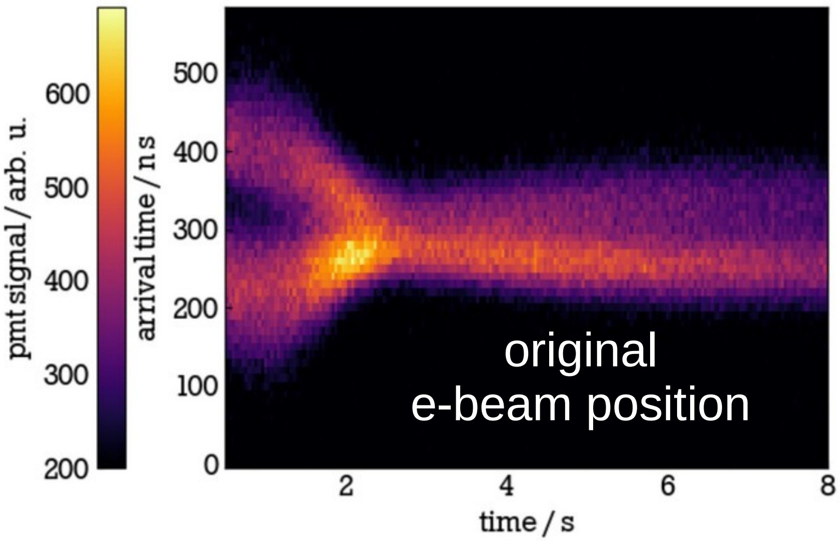


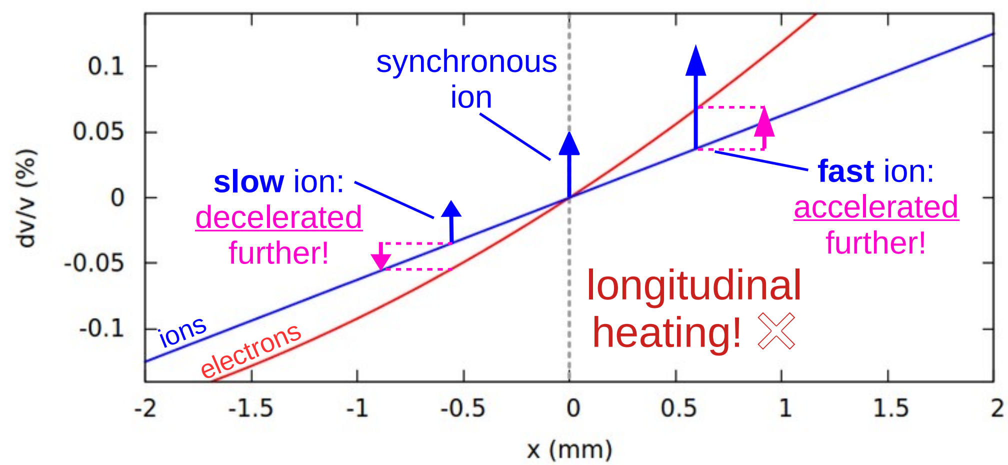


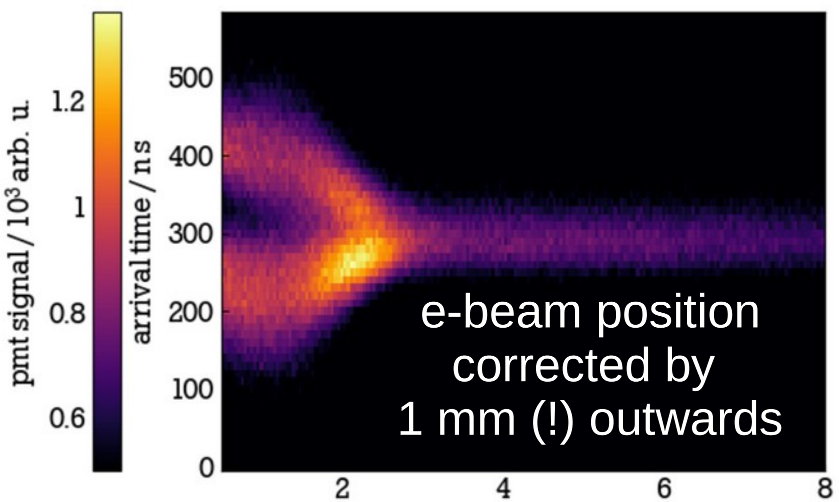


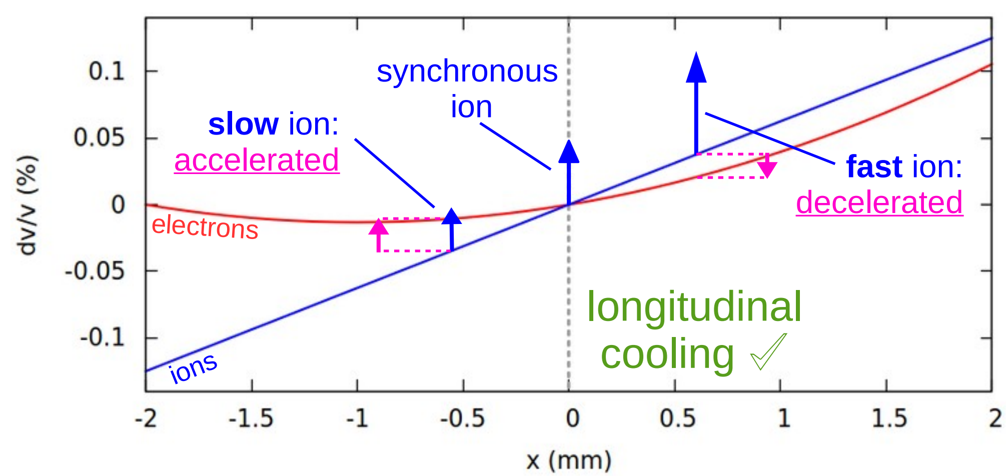
K. Mohr, Diss., TU DA, 2022

Stability of low-energy cooled beams



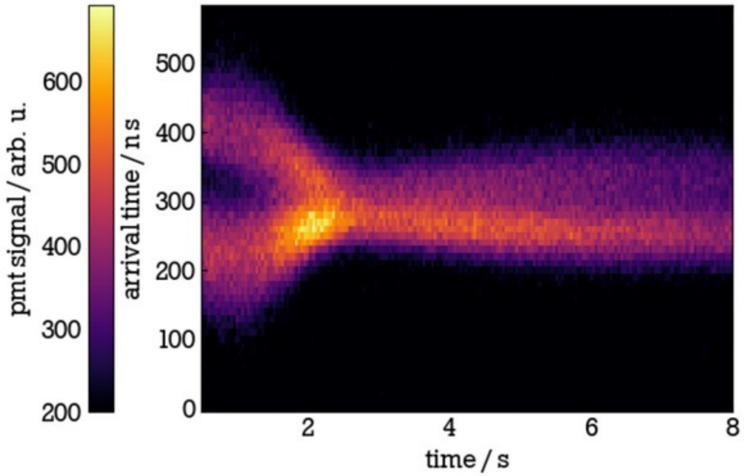






K. Mohr, Diss., TU DA, 2022

Stability of low-energy cooled beams

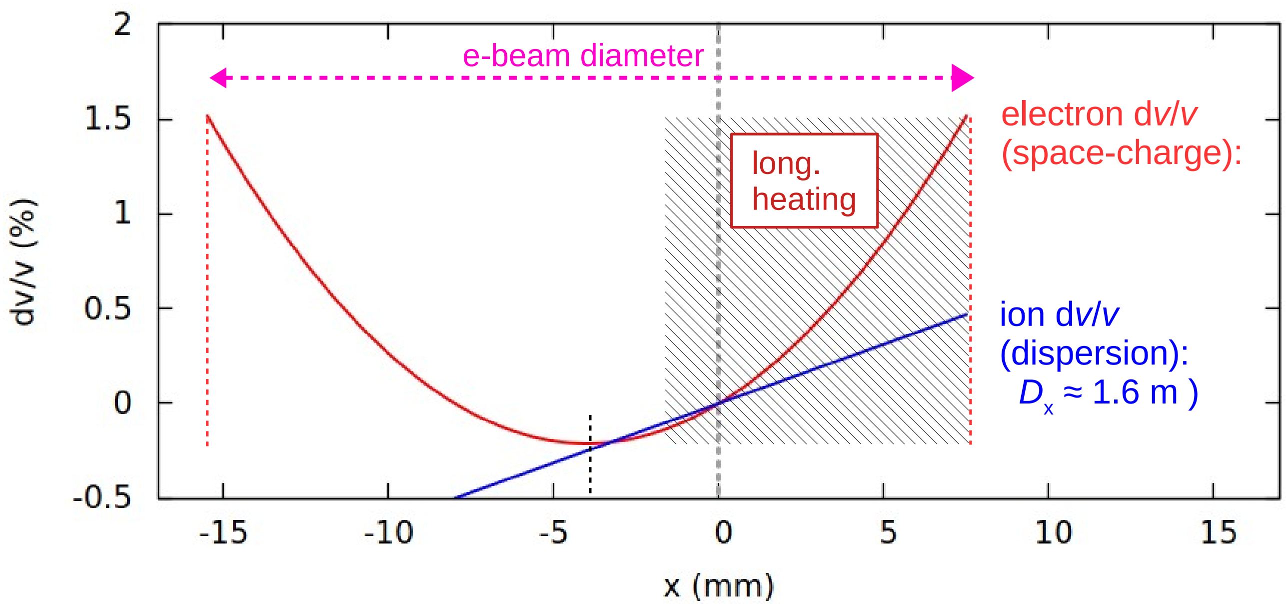


For $(dv/v)_e' > (dv/v)_i'$:

→ Longitudinal heating by electron beam.

Critical e-beam displacement relative to ion axis:

$$x_{\text{e-beam}} < -\frac{4\,E_e\,\epsilon_0}{D_x\,e^2\,n_e}$$

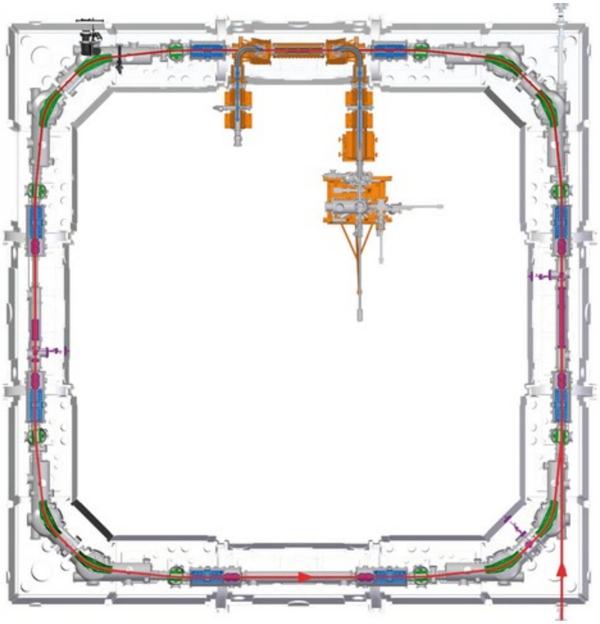


For Mg^+ at CRYRING@ESR:

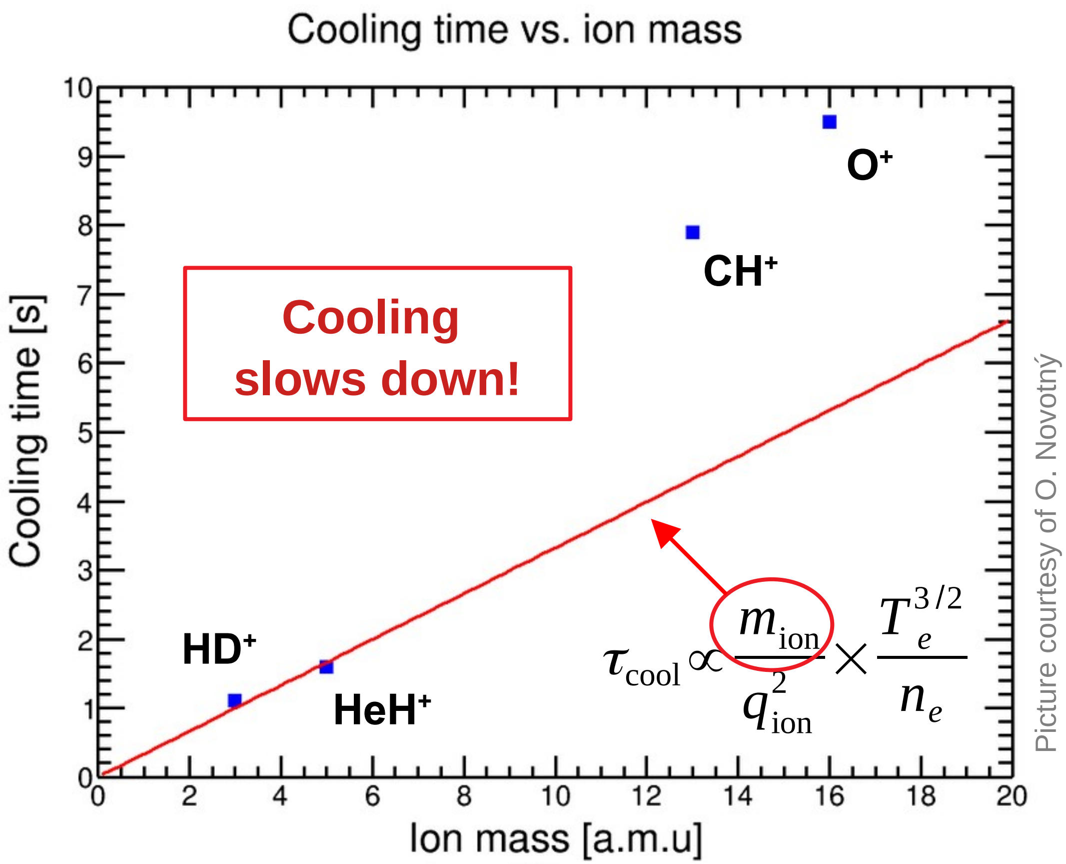
E_e = 85 eV
$n_e = 4.7 \cdot 10^6$ cm^{-3}
D_x = 1.6 m

→ **$x_{\text{e-beam}} < -2.5$ mm**

Stability of low-energy cooled beams



CSR: Cooling of higher-mass ions slower than expected from scaling law ...

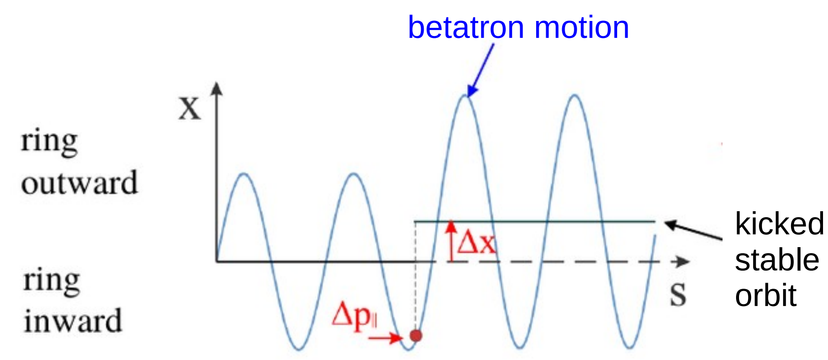


… then (2019):

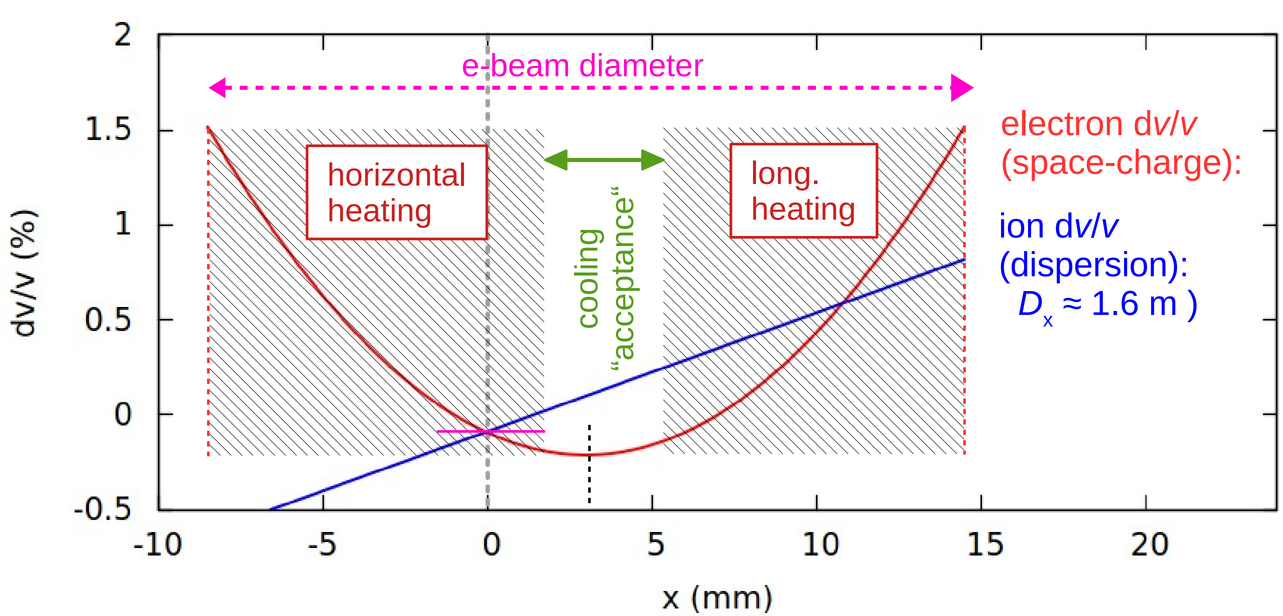
TiO⁺: m_{ion} = 64 u,
E_e = 2.4 eV
$n_e = 1 \times 10^5$ cm^{-3}

→ **No cooling possible ?!?**

Stability of low-energy cooled beams



Beutelspacher, NIM A 512 (2003) 459



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

Cooling kicks orbit *away* from ion position.

Breaks **horizontal** cooling for

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

(coasting beam)

$$x_{\text{e-beam}} > \frac{4\,E_e\,\epsilon_0}{D_x\,e^2\,n_e}\,\frac{\tau_{\text{cool},z}}{\tau_{\text{cool},x}}$$

(bunched beam)

M. Grieser, O. Novotný, in prep..

Stability of low-energy cooled beams

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

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

HeH+ @CSR: $\boldsymbol{E_e}$ **= 27.3 eV,** $\boldsymbol{n_e}$ **= 3.7·10⁵ cm⁻³**

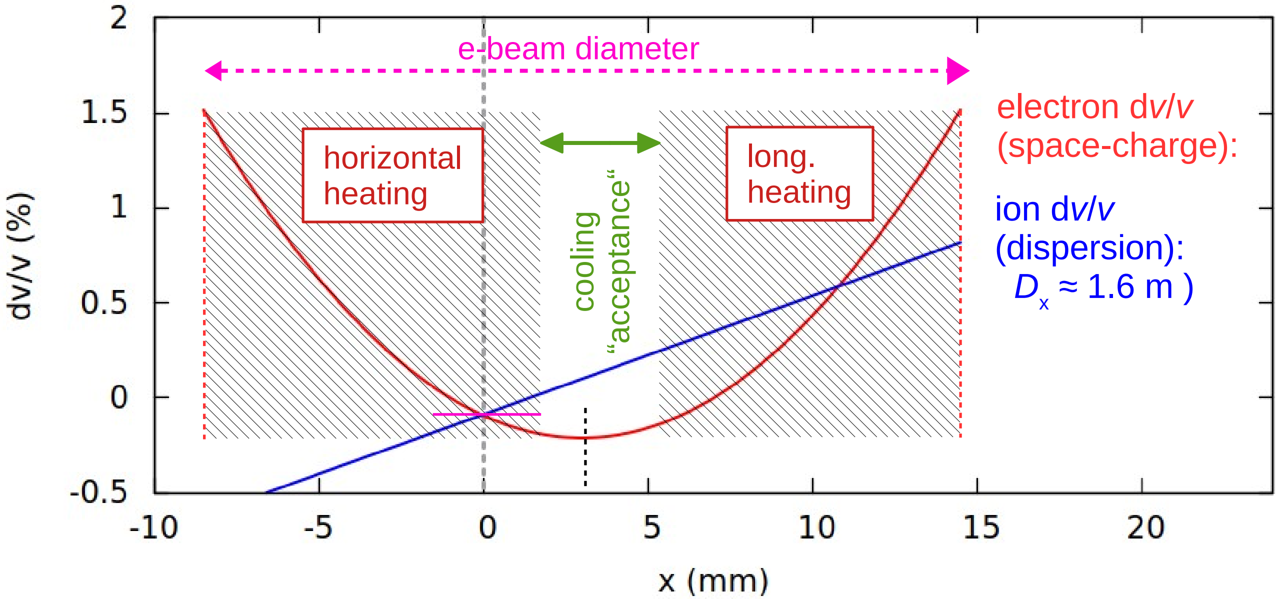
→ - 4.7 mm < $x_{\text{e-beam}}$ < 4.4 mm ✓

$^{25}Mg^{+}$ @CRYRING: $\boldsymbol{E_e}$ **= 85.0 eV,** $\boldsymbol{n_e}$ **= 4.7·10⁶ cm⁻³**

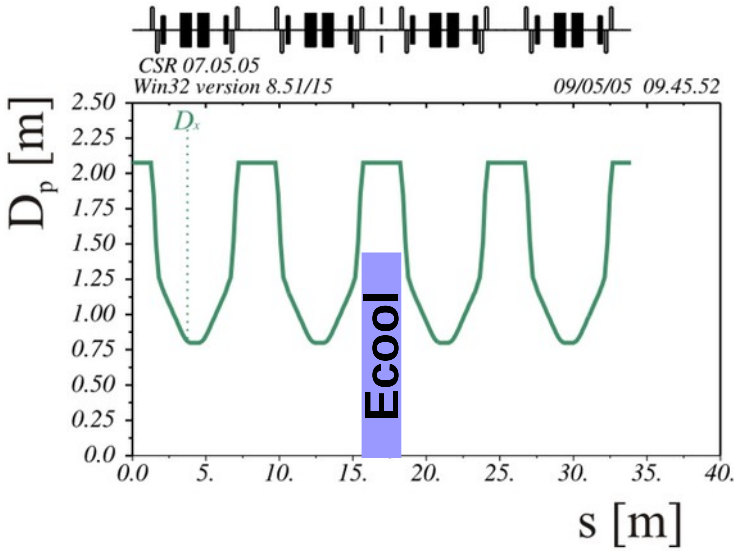
→ - 2.5 mm < $x_{\text{e-beam}}$ < 1.7 mm ✓

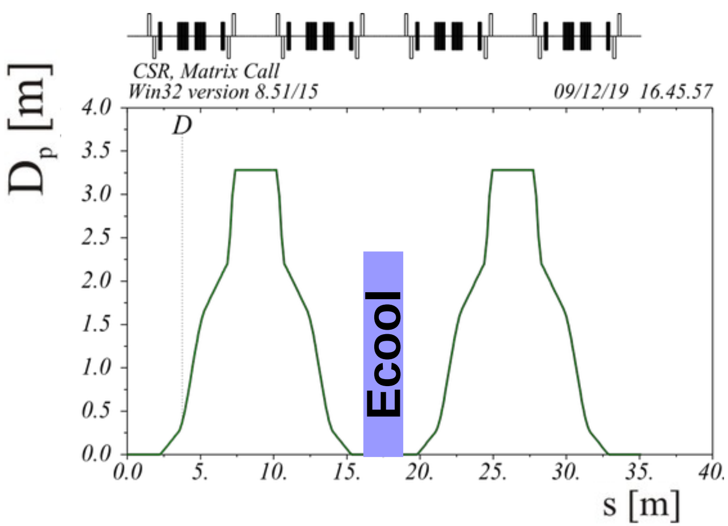
TiO+ @CSR: $\boldsymbol{E_e}$ **= 2.4 eV,** $\boldsymbol{n_e}$ **= 1.0·10⁵ cm⁻³**

→ - 0.5 mm < $x_{\text{e-beam}}$ < 0.5 mm ✗



Stability of low-energy cooled beams





Solution at CSR

Reduce symmetry: **2** → **4 Quad families**.

→ $D_x \simeq 0$ at **e-cooler**

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

Meanwhile, slowest electron-cooled beam at CSR:

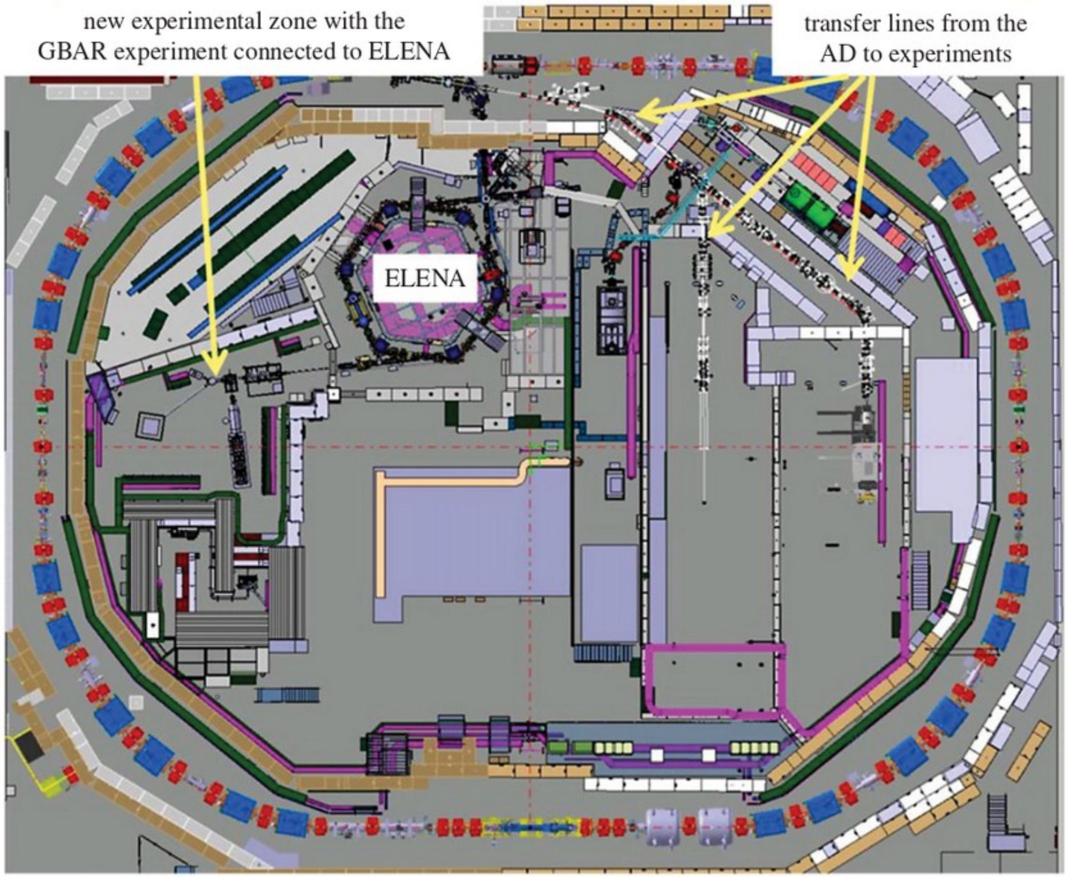
Xe^{3+} (0.007 MeV/u)

m_{ion}	= 129 u
$\boldsymbol{E_e}$	**= 3.8 eV**
n_e	= 4×10^5 cm^{-3}

O. Novotný, in prep.

(Friendly) competitors ...

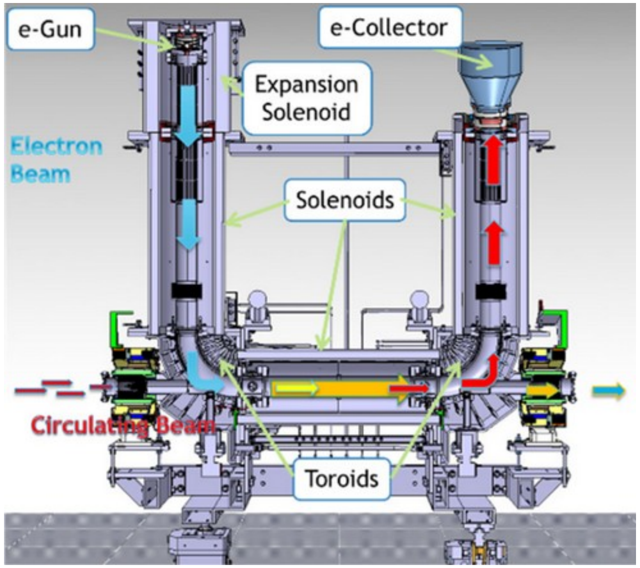
Another low-energy cooler ring: ELENA (CERN)



Bartmann et al., Phil. Trans. R. Soc. A 376 (2018)

Decelerates and cools p-bar from AD from 5.3 MeV → 100 keV.

e-cooler comm. 2020.



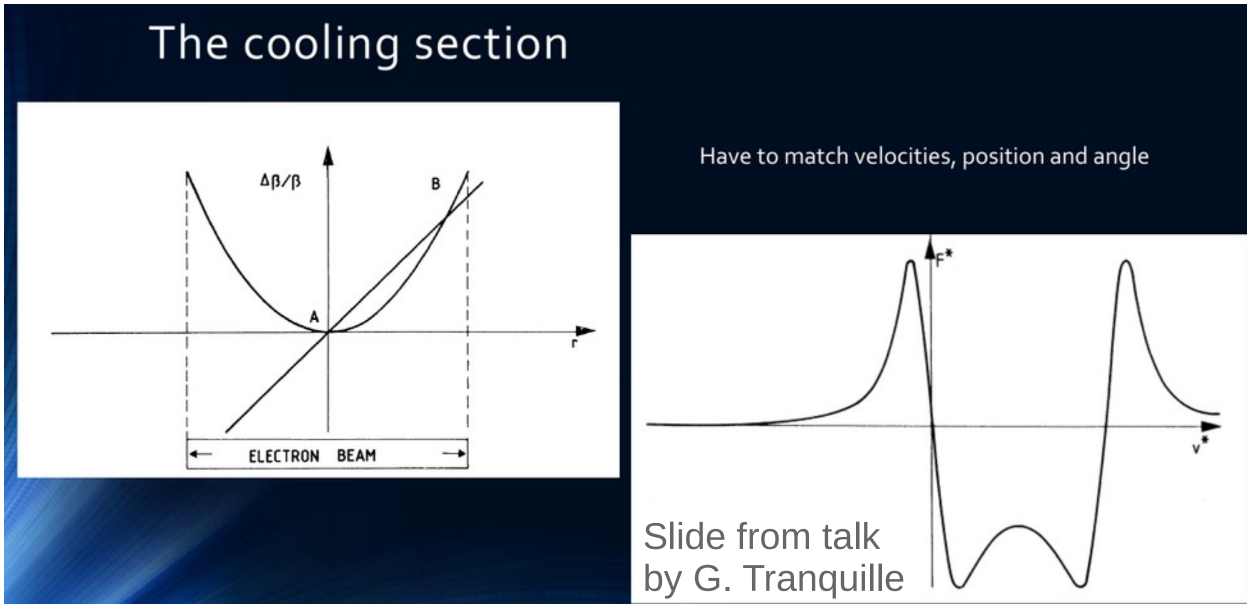
G. Tranquille et al., Proc. of IPAC 2018

Cooler energy on extraction plateau:

E_e = 55 eV

(Friendly) competitors ...

Another low-energy cooler ring: ELENA (CERN)



Slide from talk by G. Tranquille

Bartmann et al., Phil. Trans. R. Soc. A 376 (2018)

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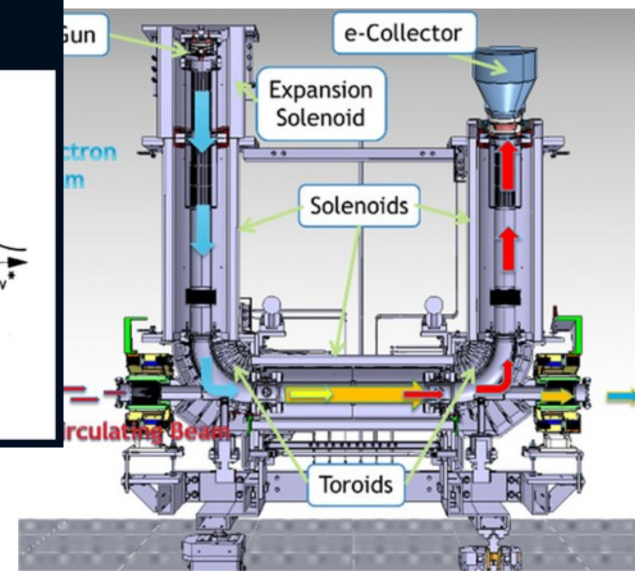

G. Tranquille et al., Proc. of IPAC 2018

Cooler energy on extraction plateau:

E_e = 55 eV

Summary

Electron cooling is a universal beam cooling technique at ion storage rings.

Application at low ion energy is technically challenging.
(Longer cooling times / shorter storage times)

Interaction between electron cooler space charge and dispersive ring optics can lead to beam instability at low energy.

Several low-energy cooler storage rings operate successfully.

Thank you!

TSR / CSR Group

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