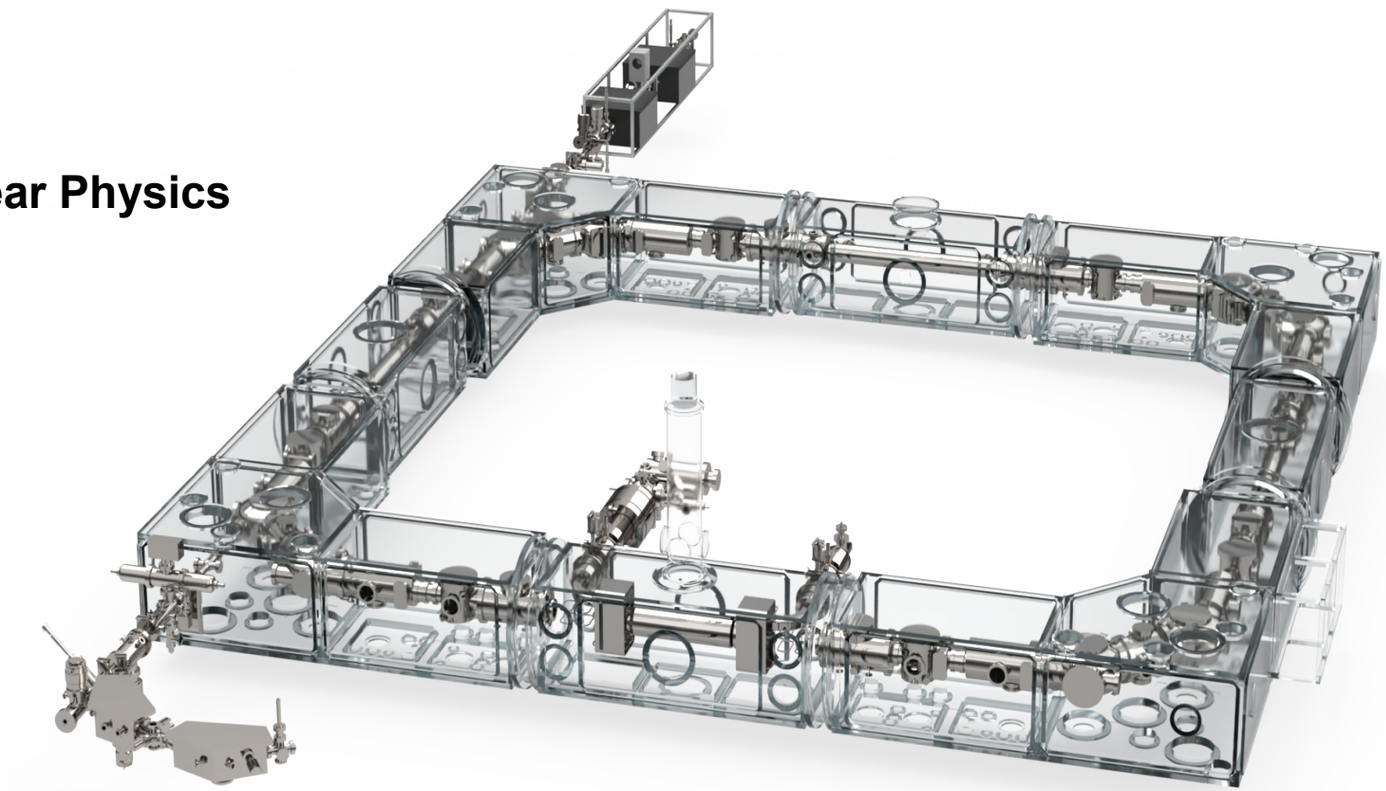
Ultra-low-energy electron-cooling
at the Cryogenic Storage Ring (CSR)

Oldřich Novotný
for the CSR team

Max Planck Institute for Nuclear Physics
Heidelberg, Germany



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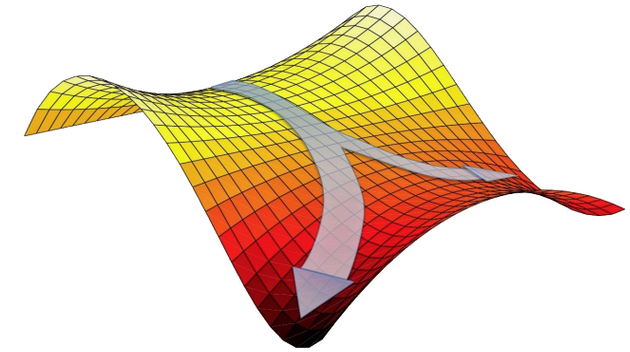
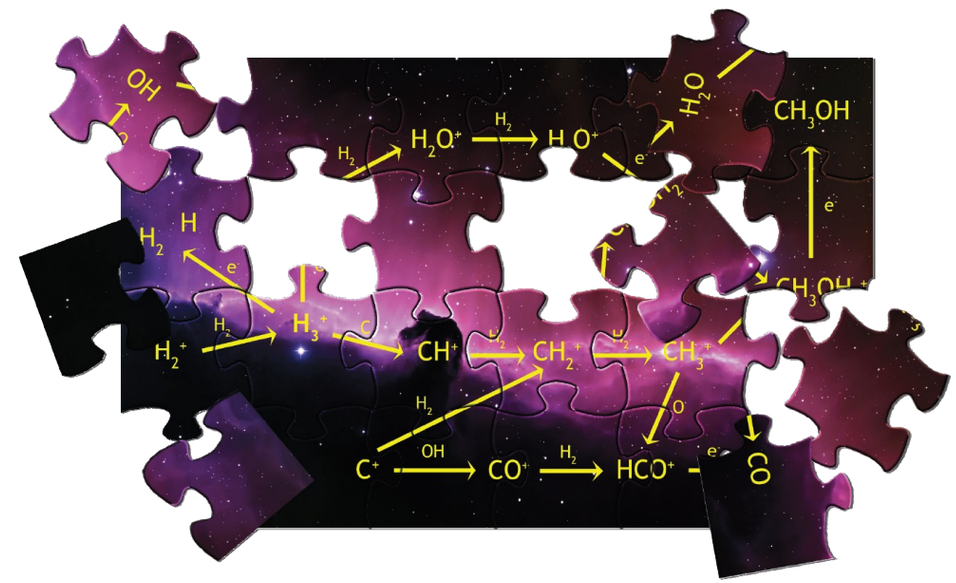
Cold molecular ions



Cold chemistry:

Fundamental reaction quantum dynamics

Astrochemistry



Ultimate goal:

Rotationally resolved

state-to-state studies

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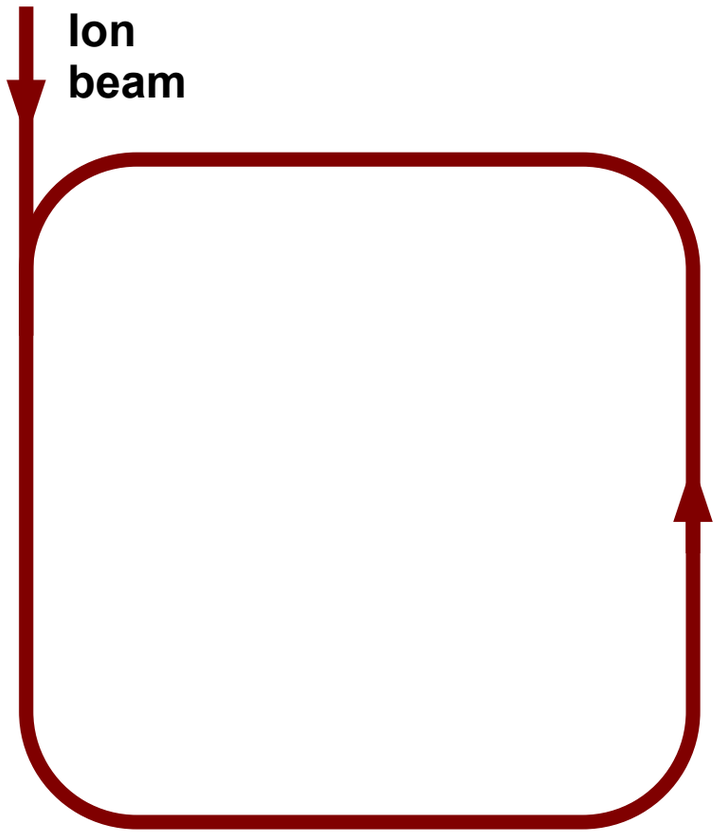
Molecular ions in a storage ring



Ion "recycling"
+
Long storage times
⇓
Ion deexcitation
to ambient temperature

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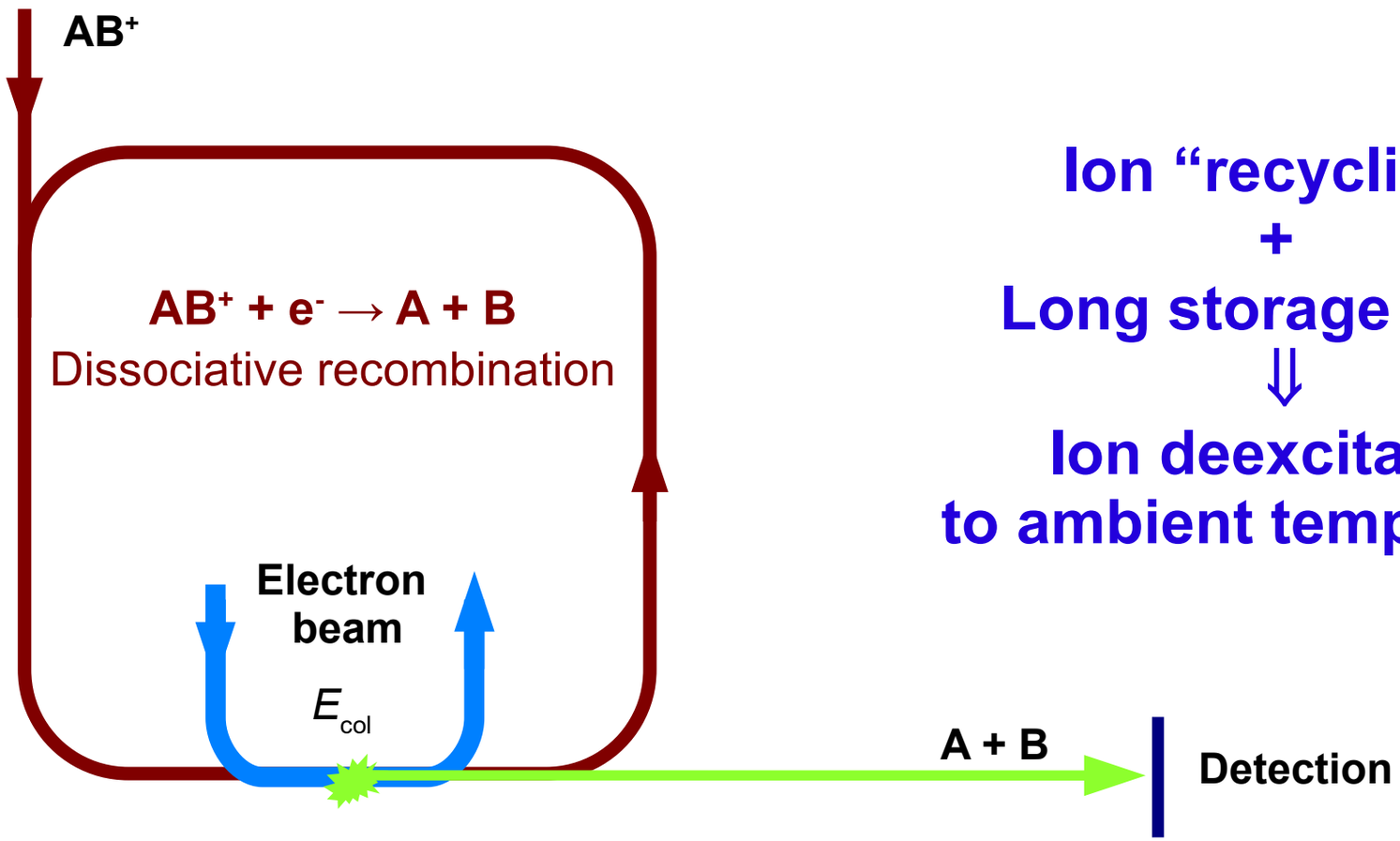
Molecular ions in a storage ring



Ion "recycling"
+
Long storage times
⇓
Ion deexcitation to ambient temperature

Merged beams technique → low collision energies accessible

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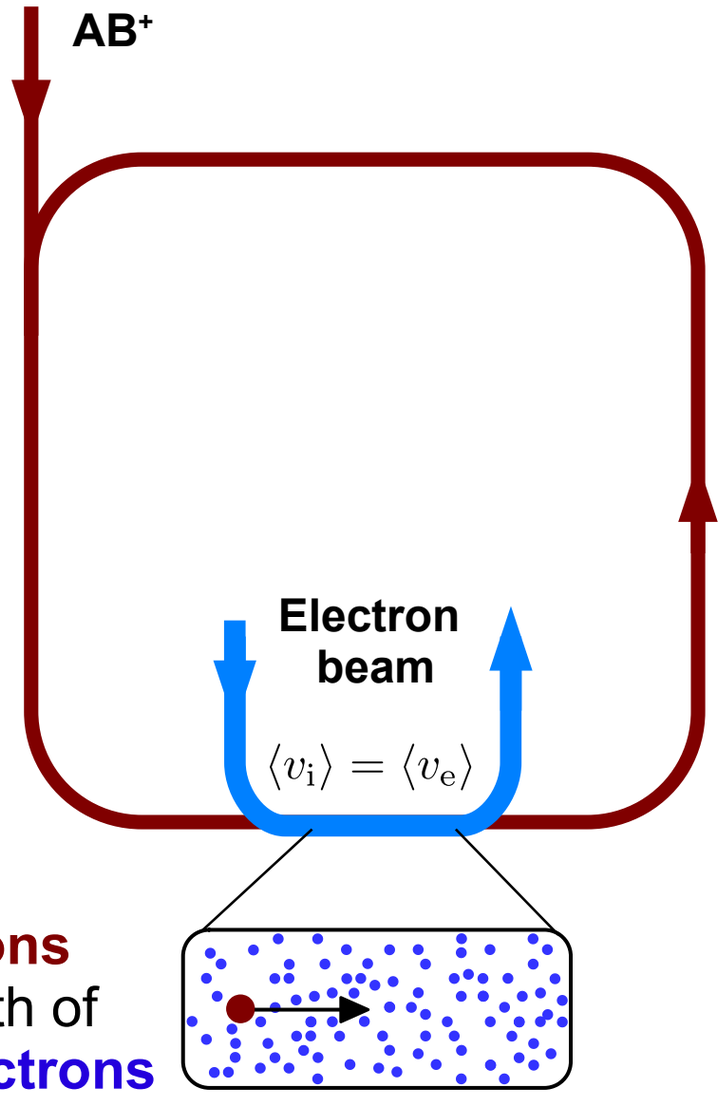
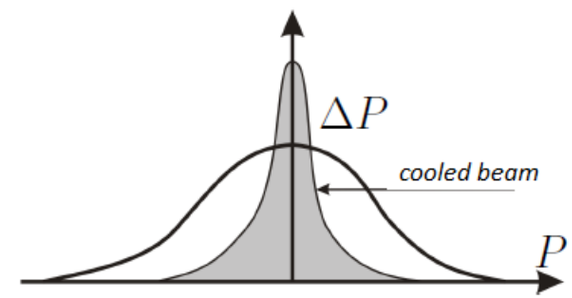
Electron cooling



Hot ions
in a bath of
cold electrons



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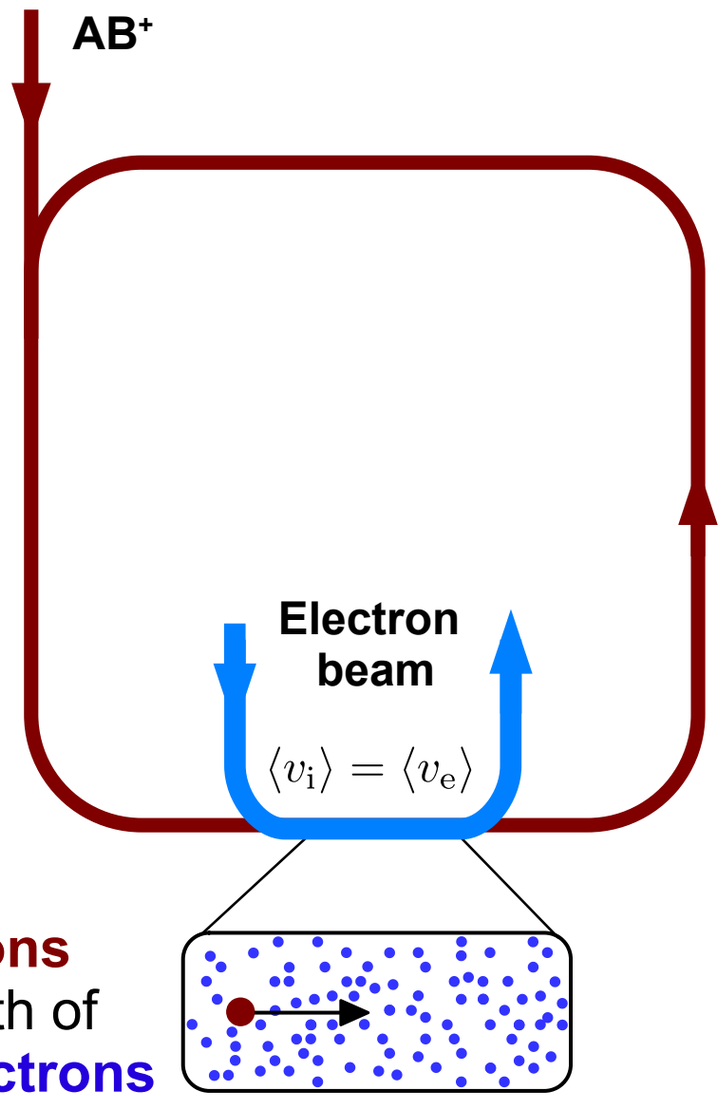
Electron cooling



Hot ions
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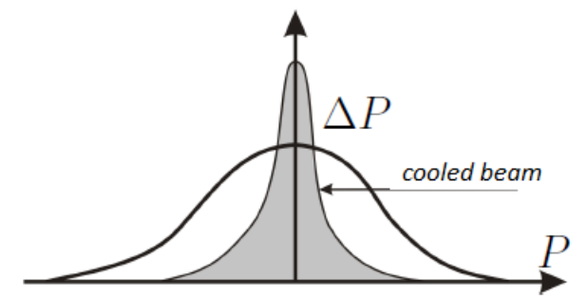

→ **Improved energy resolution**

→ **Defined overlap geometry**

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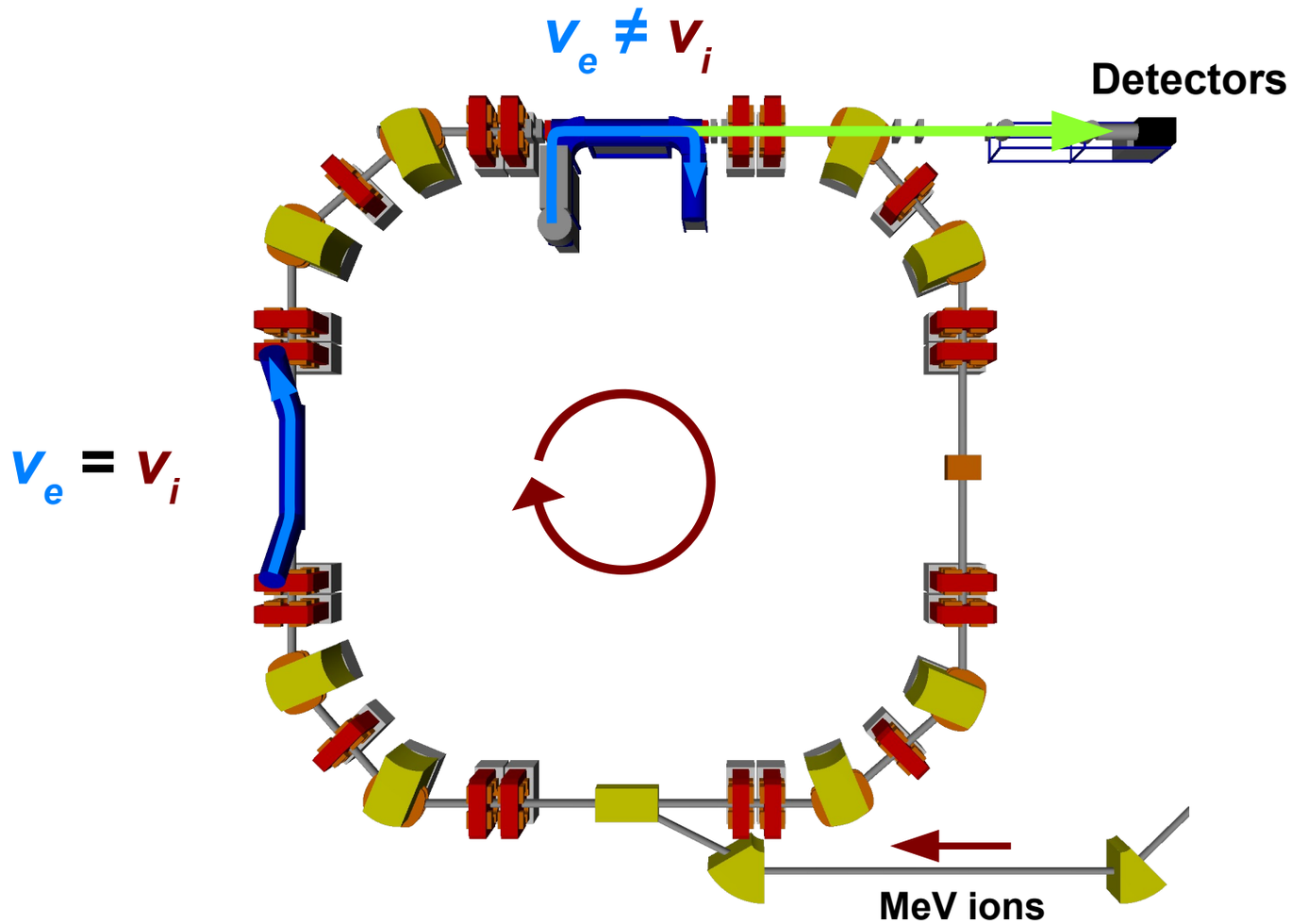
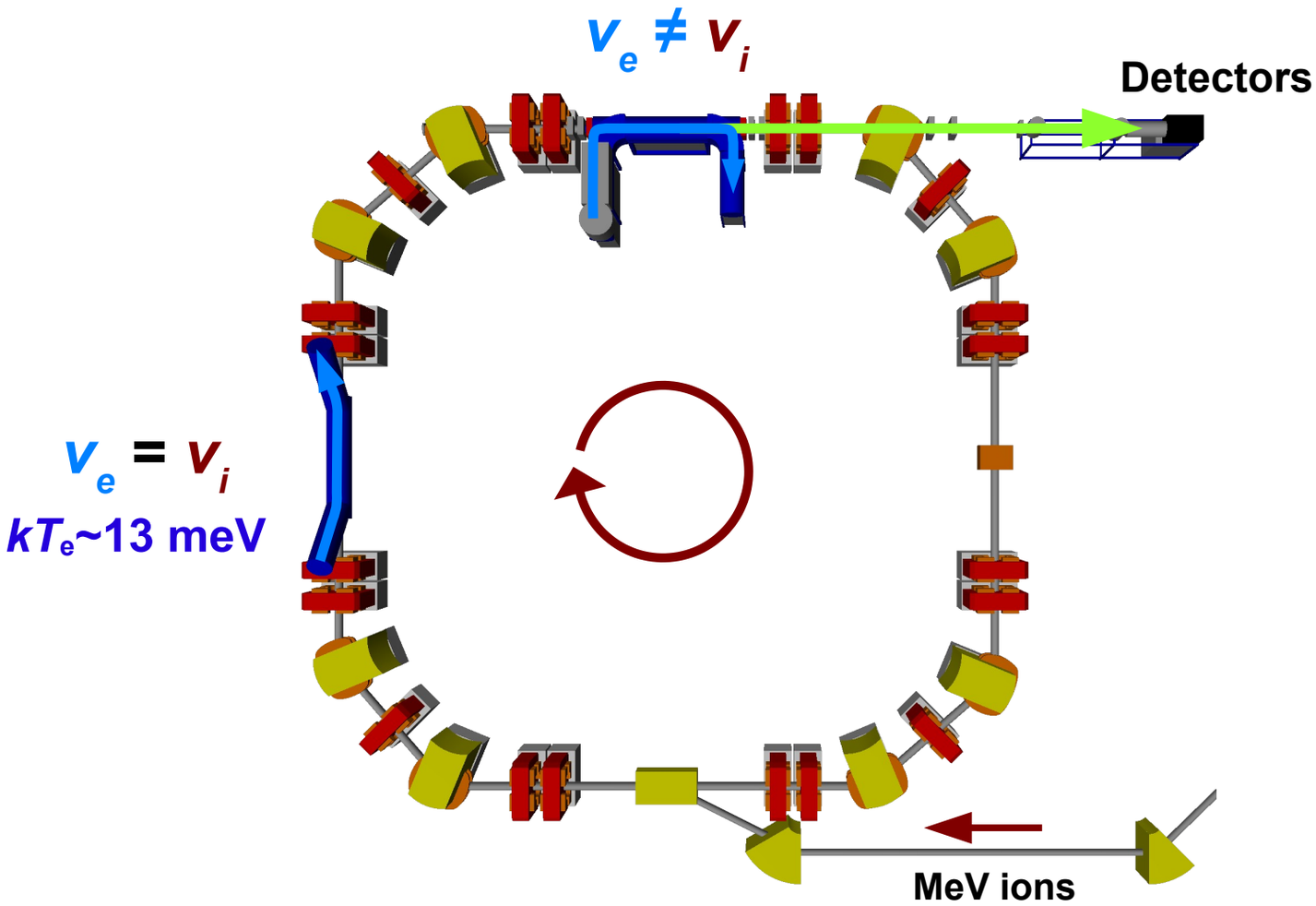
Molecular-ion physics in TSR



TSR @ MPIK Heidelberg, decommissioned 2012

Molecular-ion physics in TSR



TSR @ MPIK Heidelberg, decommissioned 2012

Singly-charged molecular ions

+

Limited dipole strength

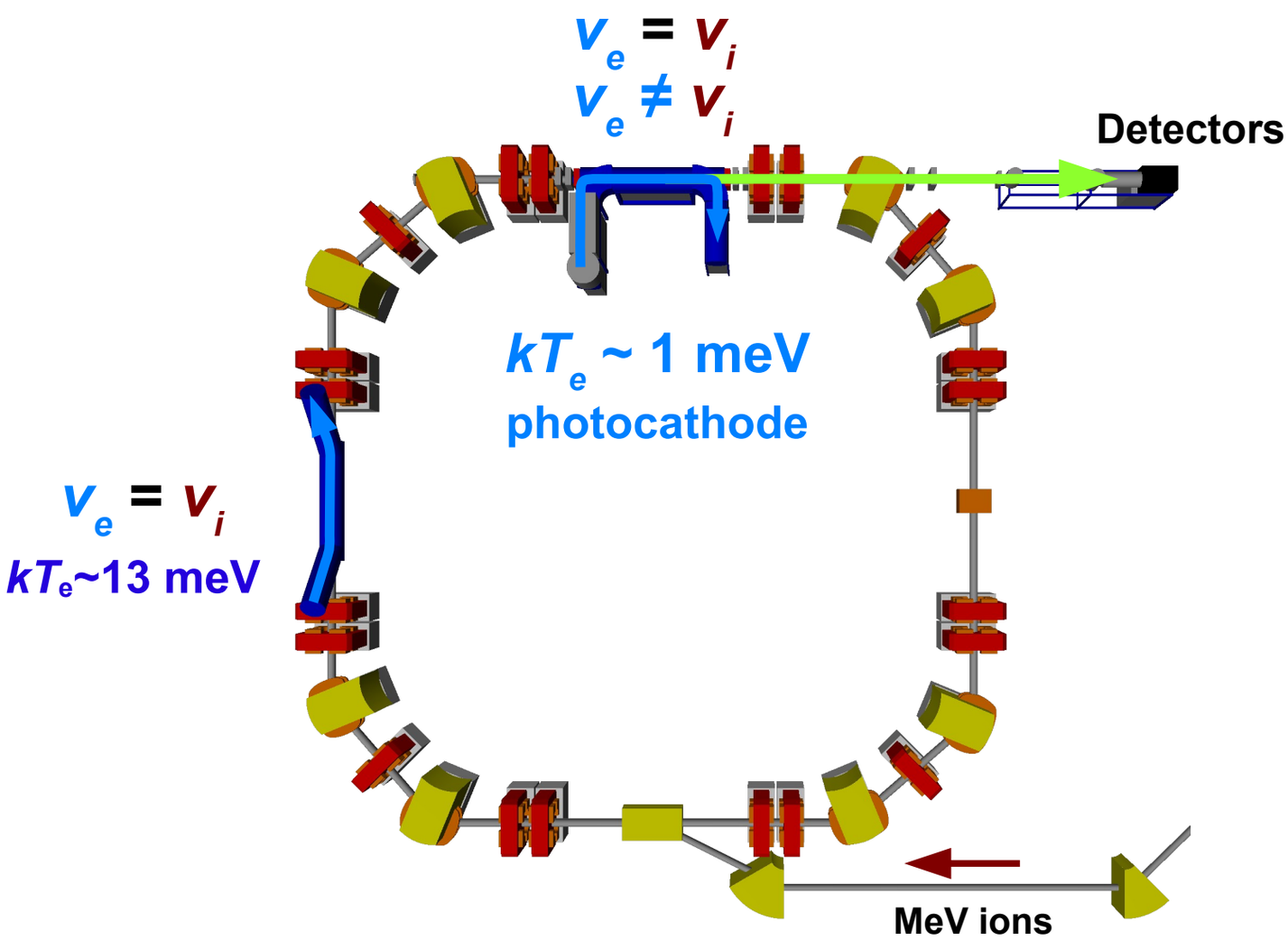
→

Slow beams

→

Weak electron cooling

Molecular-ion physics in TSR



TSR @ MPIK Heidelberg, decommissioned 2012

Photocathode electron beam

→

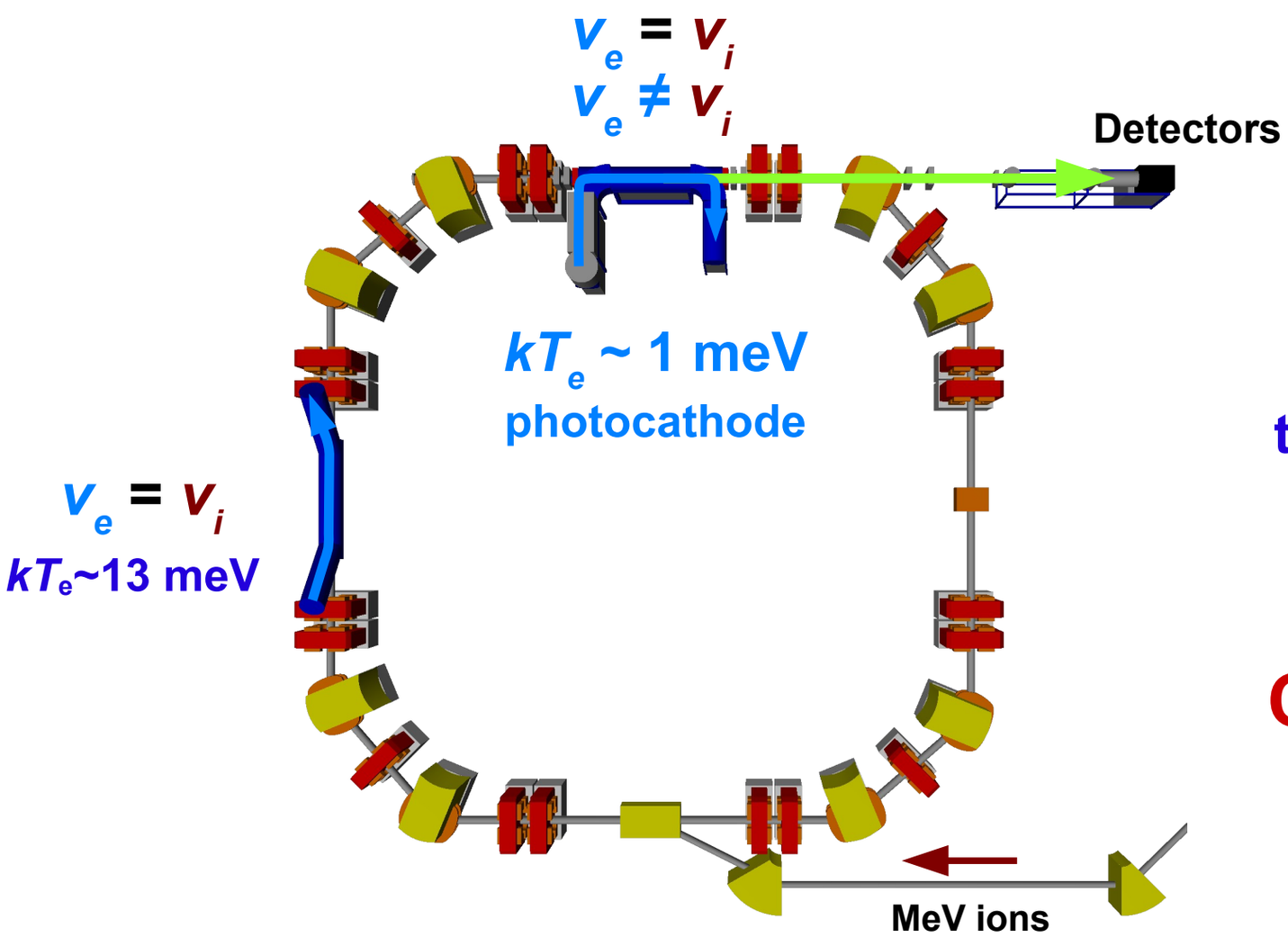
Improved electron cooling

Largest M/Q electron cooling:

E_{cool} ~ 30 eV

D_2Cl^+ (41 u/e) @ ~2.3 MeV

Molecular-ion physics in TSR



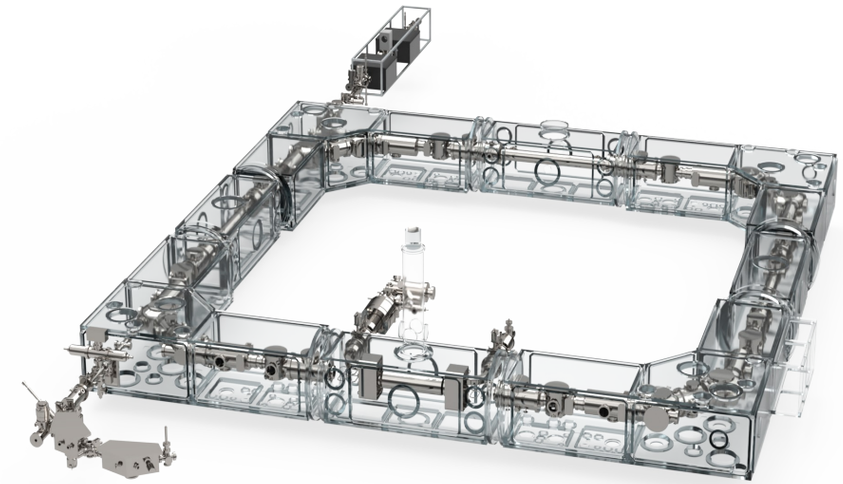
TSR @ MPIK Heidelberg, decommissioned 2012

300 K radiation field

→ Ions NOT relaxed to ro-vibrational ground state

Cryogenic storage ring needed...

Ultra-low-energy electron-cooling at CSR



- The CSR facility
- Low energy electron-cooling challenges
- CSR electron cooler
- Electron cooling performance
- Inelastic “electron cooling”

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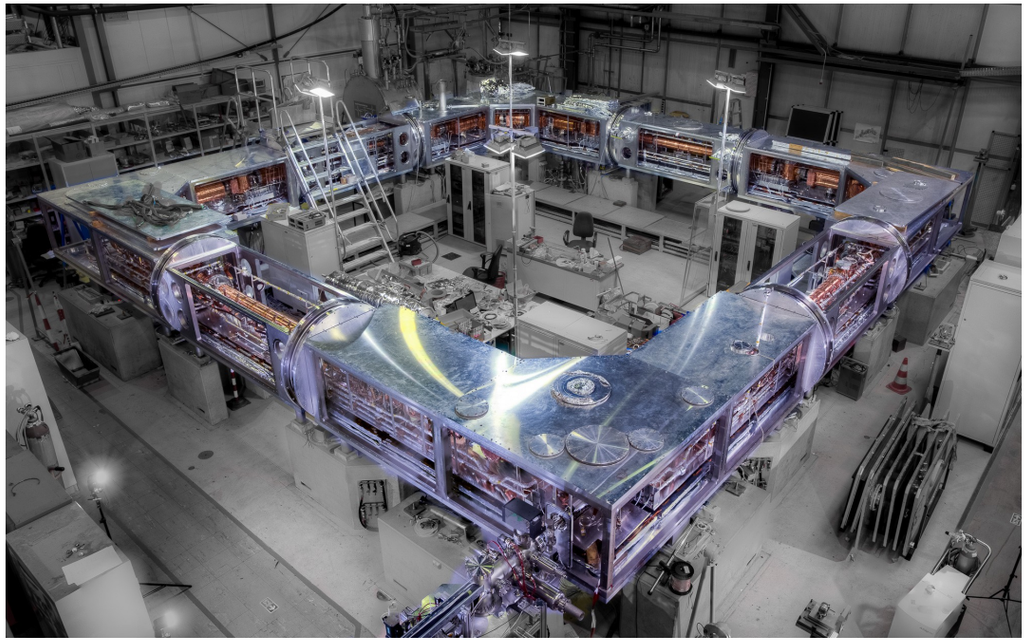
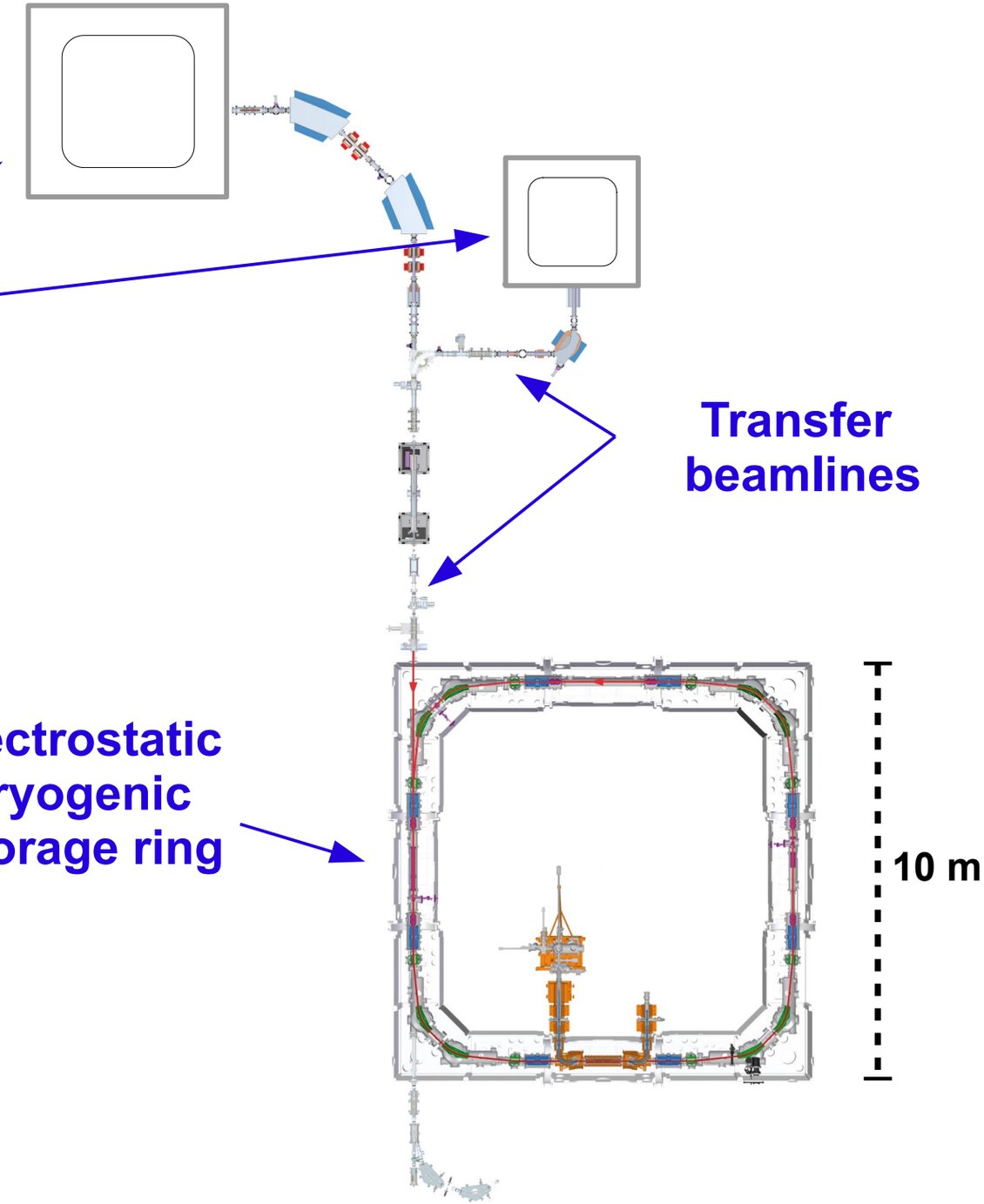
The CSR facility





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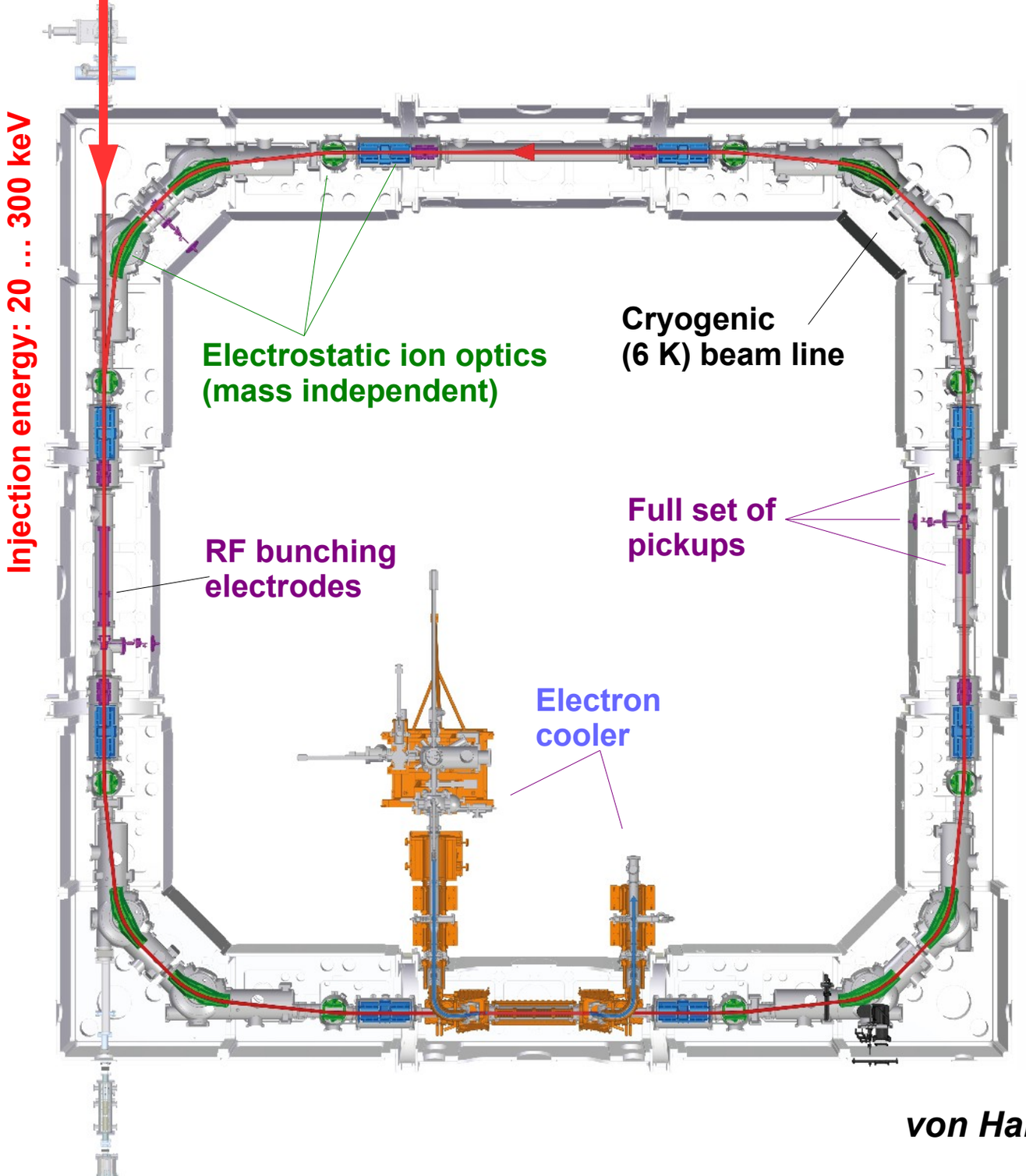
HEIDELBERG



The CSR

Electrostatic lattice

→

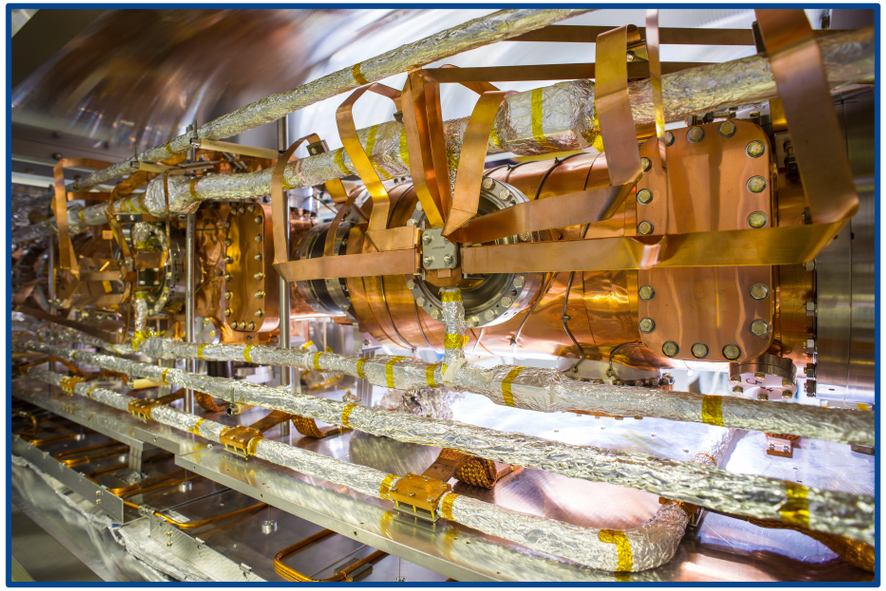
Energy filtering

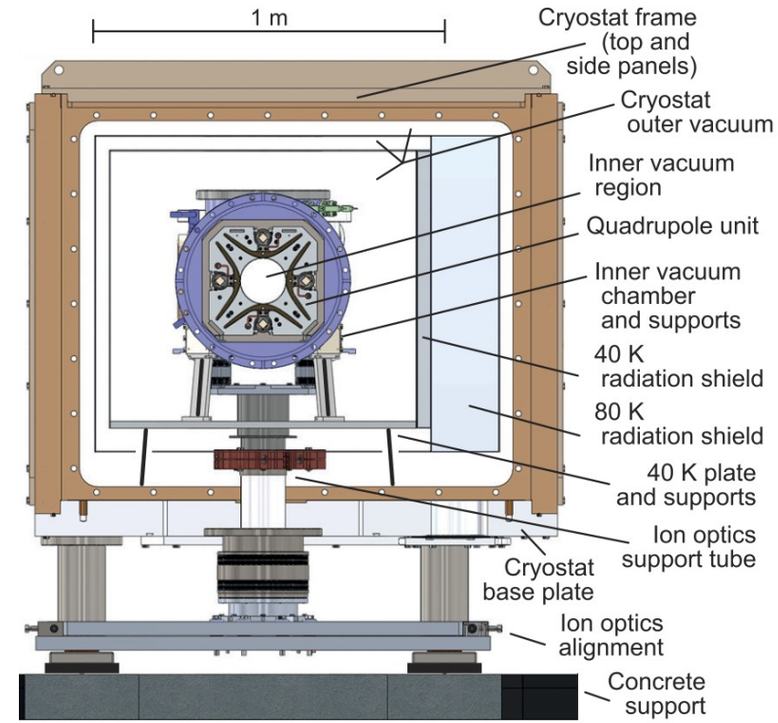
Tools
as in magnetic
storage rings

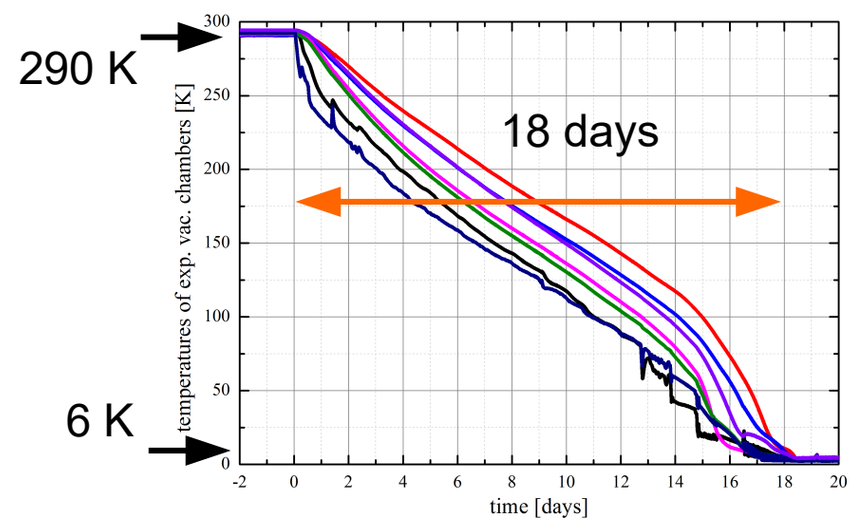
von Hahn et al., Rev. Sci. Instr. 87 (2016) 063115

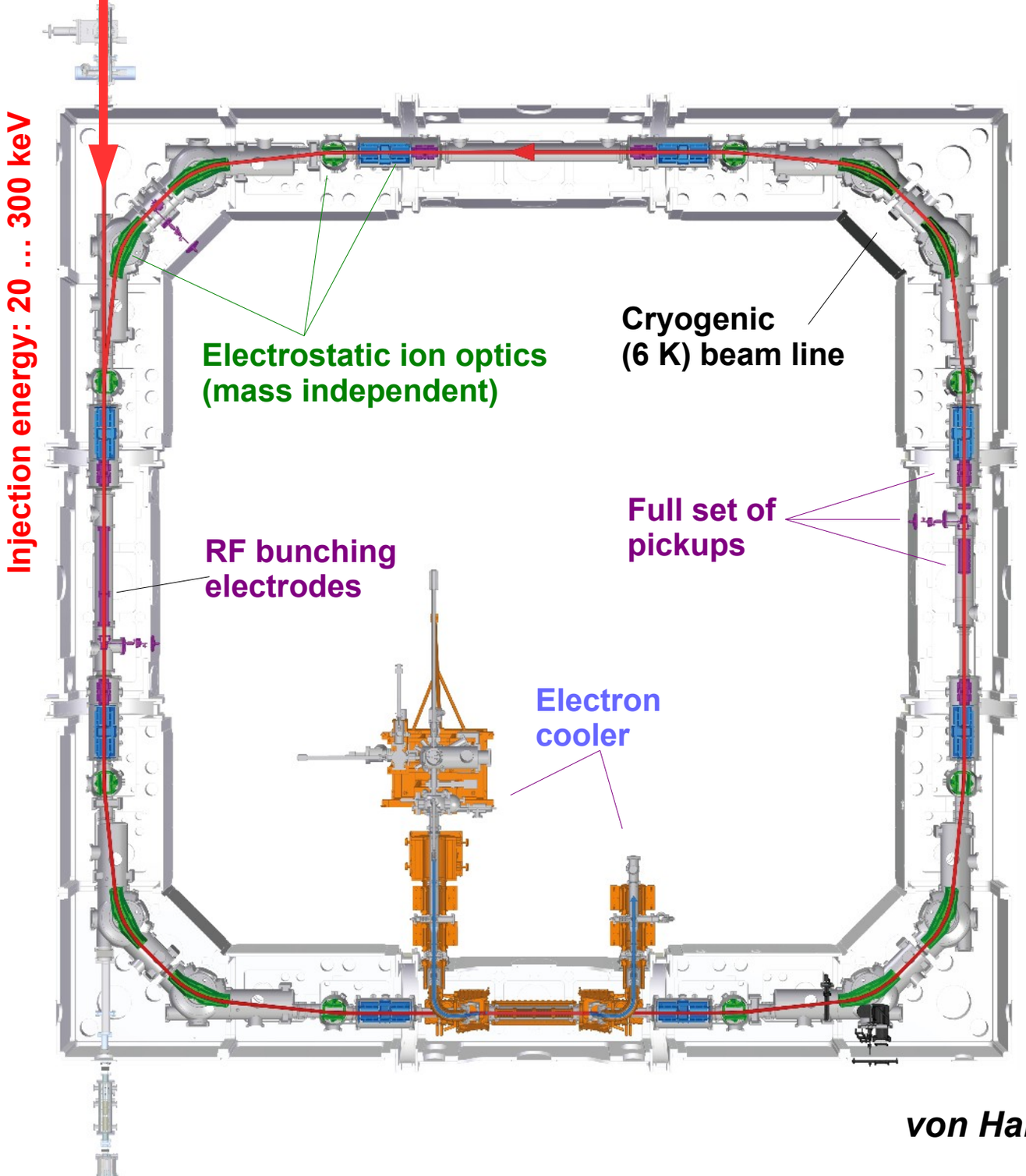
CSR cryogenics

- Inner vacuum chamber (≤ 10 K)
  2000 kg, cooled by superfluid He (20 W).
- 2 radiation shields (40 and 80 K)
  cooled by 5-K He (600 W)
- Multi-layer insulation
- Isolation vacuum chamber
- Bakeout to 200 °C





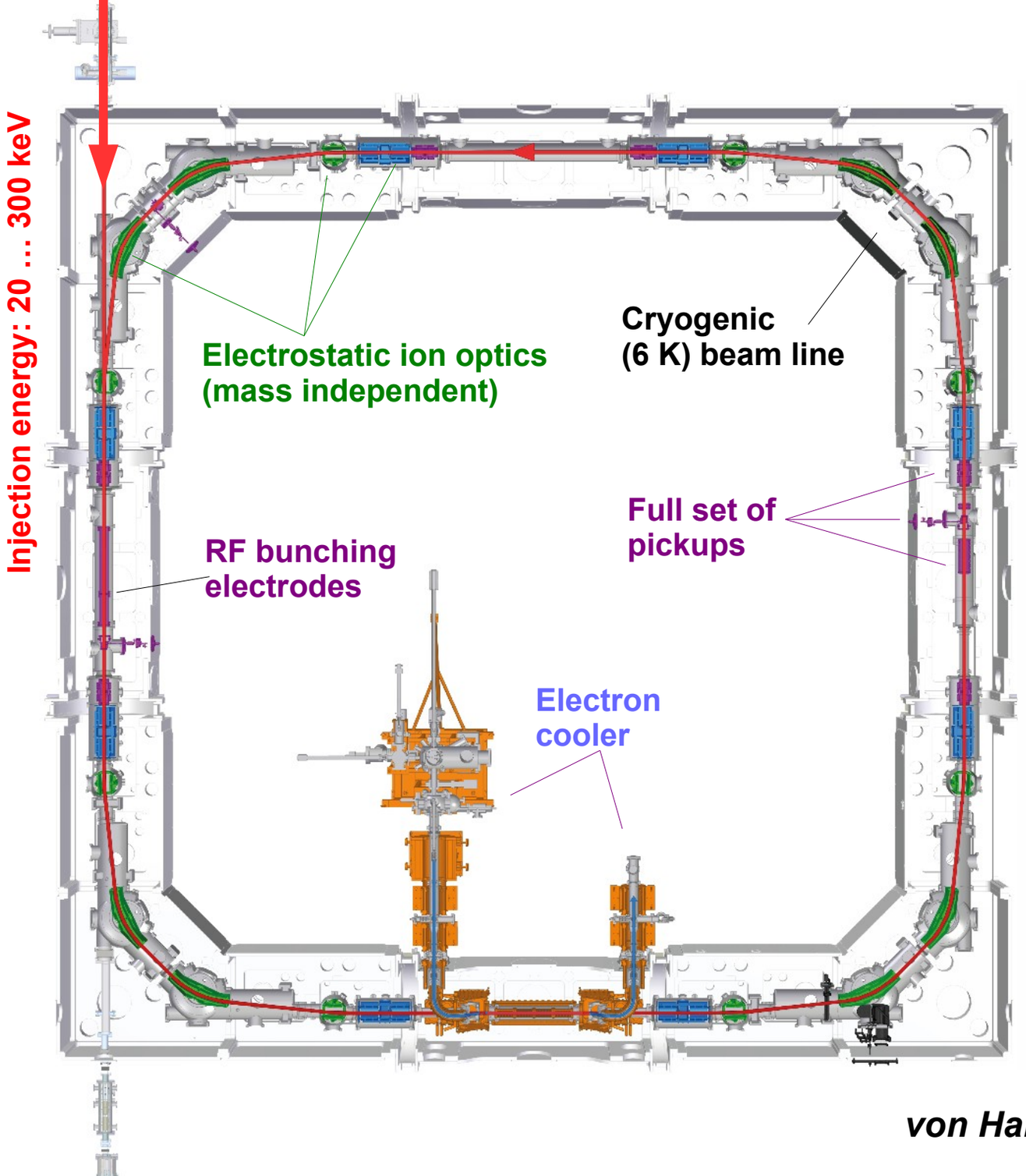




The CSR

Circumference:	**35 m**
Beam energy:	**20 keV × q ... 300 keV × q**
Temperature:	**3 … 300 K**
Res. gas dens. (RTE pressure):	**~> 1000 cm^{-3} (~>10^{-14} mbar)**
Storage times:	**τ > 1000 s**
m/q range:	**unlimited**
Cryogenic operation:	**since 2015**

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



The CSR

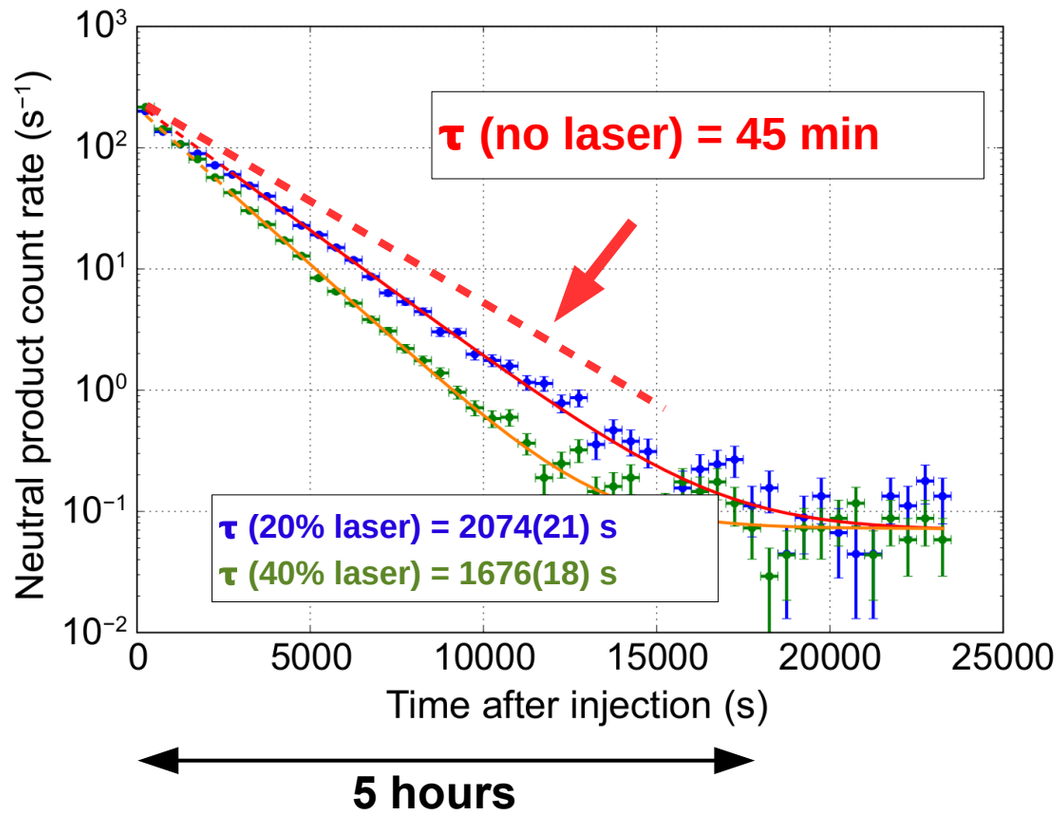
Experimental toolbox

- Laser beam
- Electron beam
- Neutral atomic beam
- Reaction microscope
- Cryogenic detectors

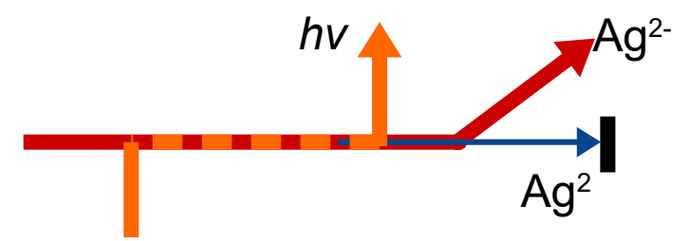
von Hahn et al., Rev. Sci. Instr. 87 (2016) 063115

Ion beam lifetime

Ag_2^- (60 keV, 216 u) + photon (1.9 eV) → Ag_2 + e^-



EA (Ag_2^-) = 1.02 eV

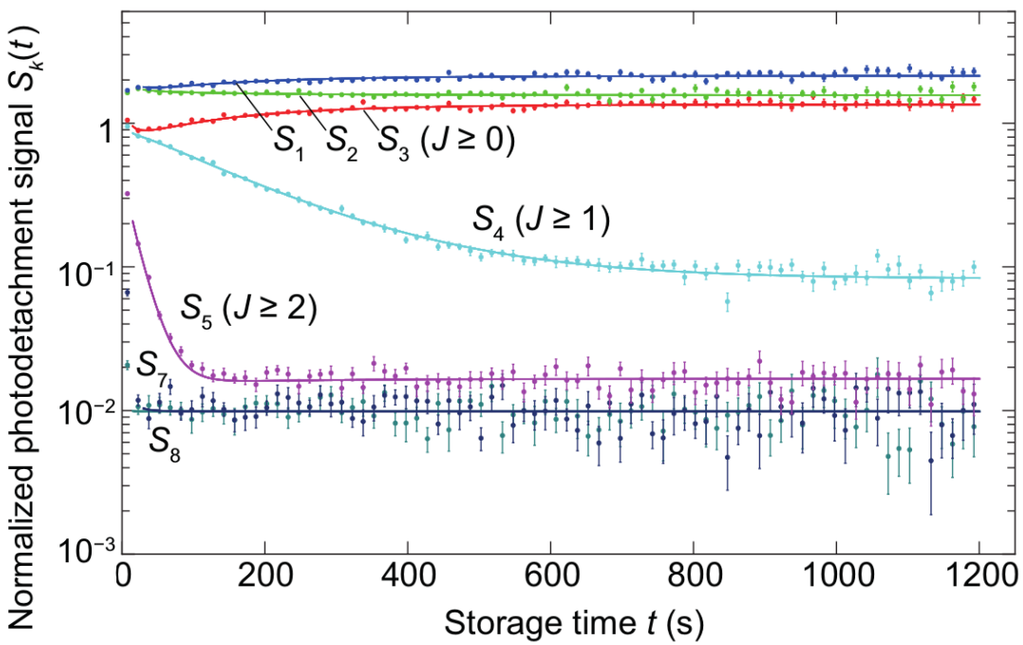


$n \leq 140$ cm^{-3}
P_{RTE} ~ 5.8 x 10^{-15} mbar
~ ISM conditions

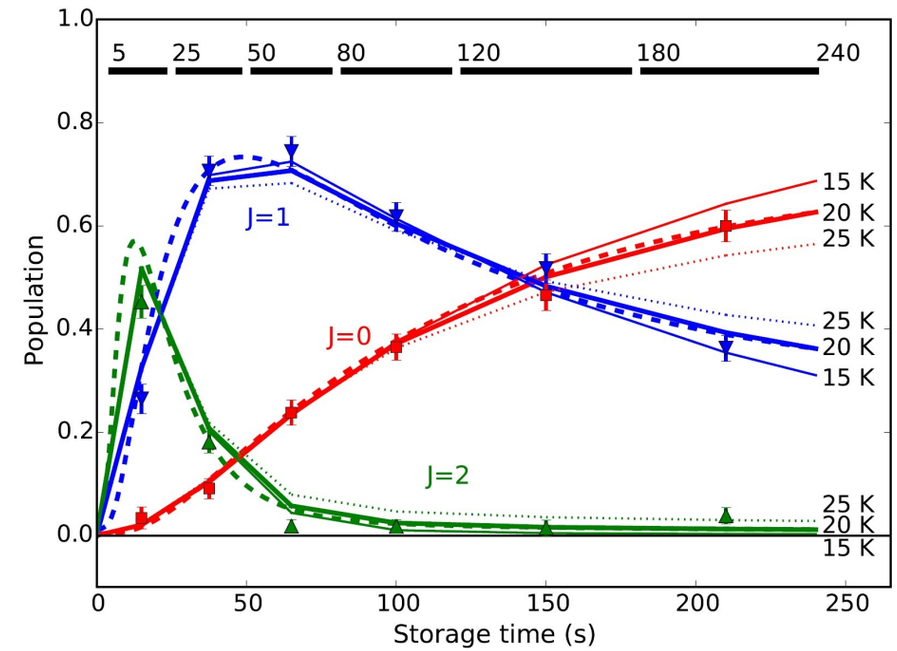
von Hahn et al., Rev. Sci. Instr. 87 (2016) 063115

Radiative ion cooling in CSR radiation field

$OH^- + h\nu \rightarrow OH + e^-$



$CH^+ + h\nu \rightarrow C^+ + H$



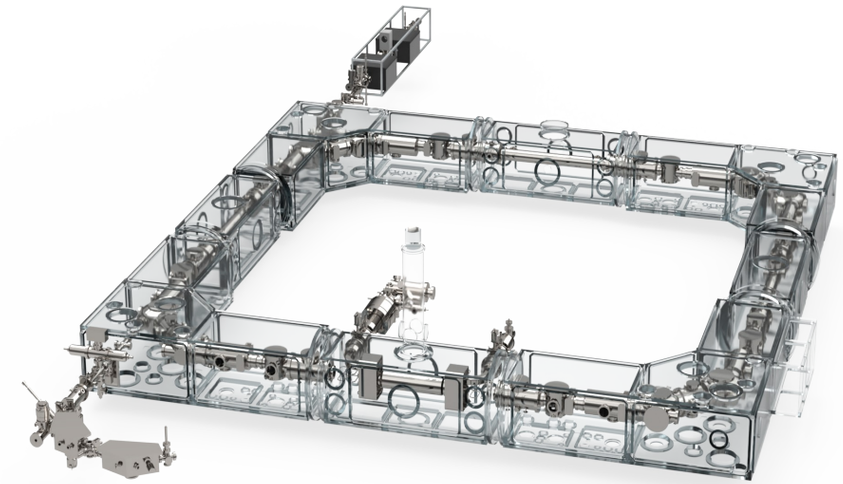
Effective black body field: **15.1(1) K**

2-component model: 0.6% @ 300 K, rest 6 K

Meyer et al., Phys. Rev. Lett. 119 (2017) 023202

O'Connor et al., Phys. Rev. Lett. 116 (2016) 113002

Ultra-low-energy electron-cooling at CSR



- The CSR facility
- **Low energy electron-cooling challenges**
- CSR electron cooler
- Electron cooling performance
- Inelastic “electron cooling”

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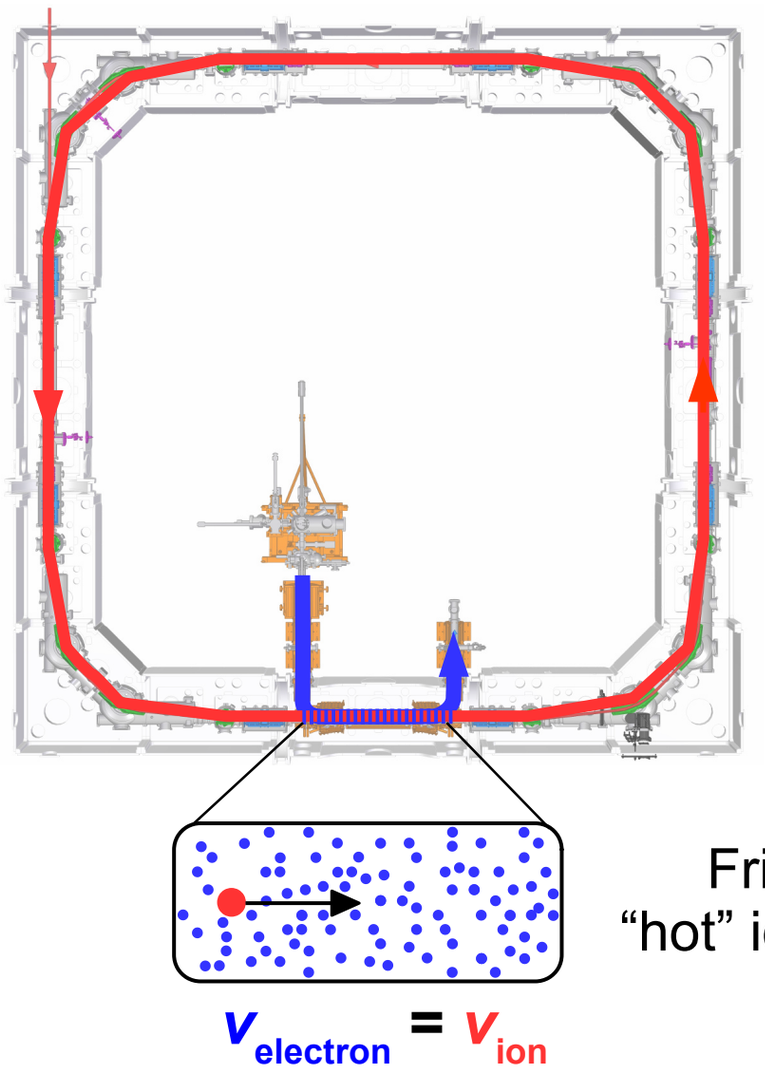
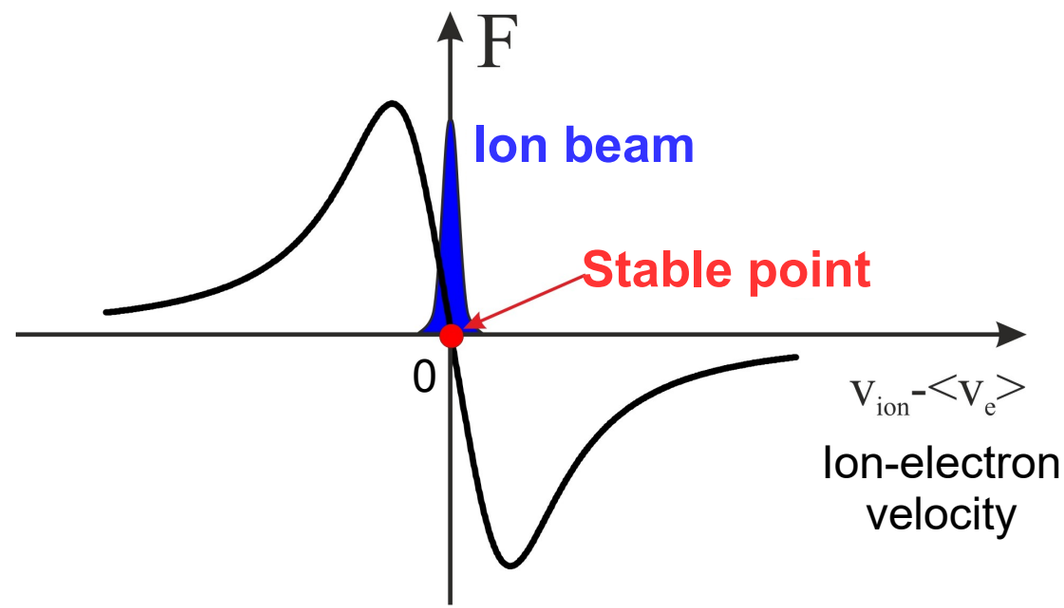
Electron cooling



Electron-cooling force



Friction force between
“hot” ions and “cold” electrons

Electron cooling

Phase-space compression
(energy and angular spread reduction)

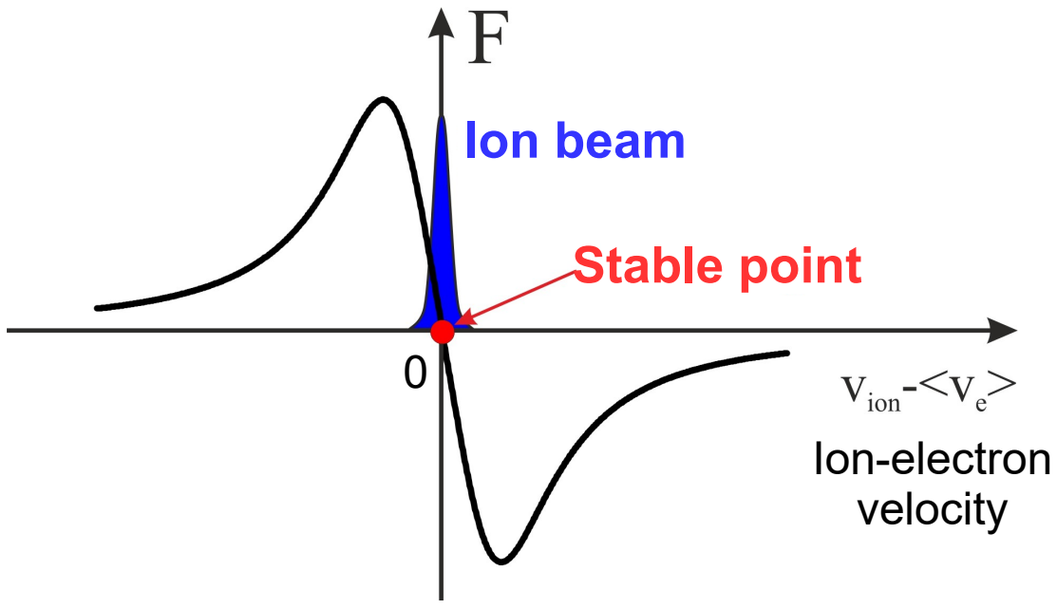
→ **High energy-resolution studies**

→ **Defined target geometry**

Ion beam dragging

→ **Ion beam manipulation**

Electron-cooling force



Low-energy electron cooling

Electron-cooling time

Electron temperature

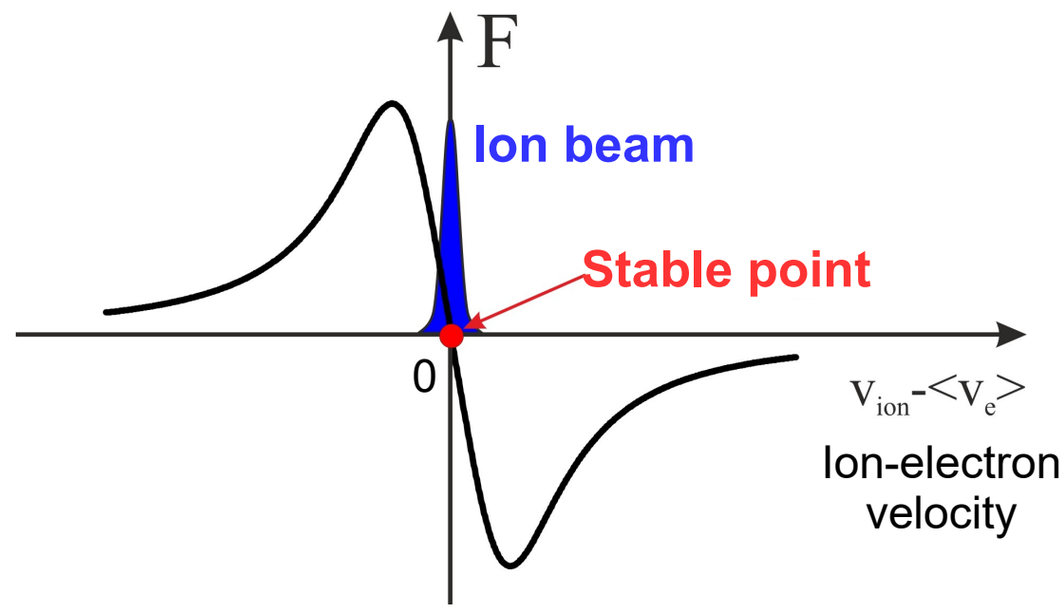
Ion mass

$$\tau_{\mathrm{ecool}} \propto T_{\mathrm{e}}^{3/2} \frac{m_{\mathrm{ion}}}{Z^2 n_{\mathrm{e}}}$$

Ion charge

Electron density

Electron-cooling force



Challenge:

Low-energy electron cooling of heavy molecular ions

Low-energy electron cooling

Electron temperature

Ion mass

$$\tau_{\mathrm{ecool}} \propto T_{\mathrm{e}}^{3/2} \frac{m_{\mathrm{ion}}}{Z^2 n_{\mathrm{e}}}$$

Ion charge

Electron density

- **Electron source @ T_{cath}**
- **Kinematic compression** (acceleration)

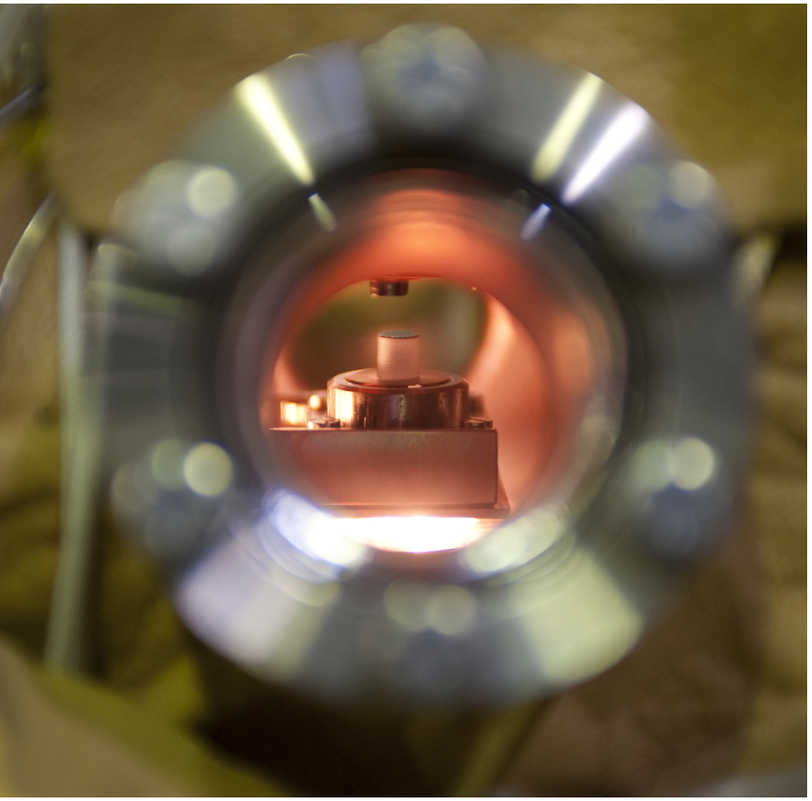
  $\rightarrow k_{\mathrm{B}} T_{\parallel} \approx T_{\mathrm{cath}}^2 / 2E_{\mathrm{acc}}$

- **Expansion in guiding *B*-field**

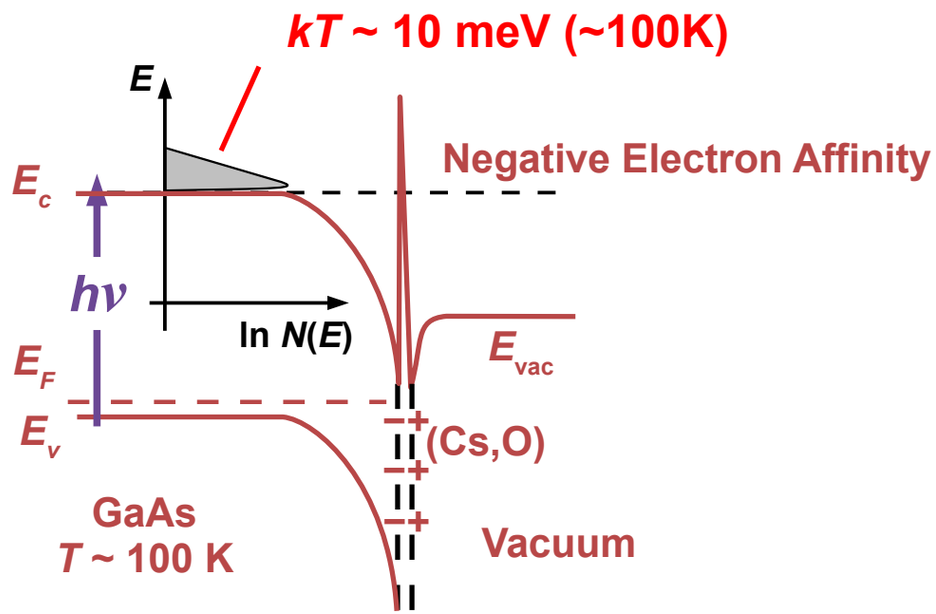
  $\rightarrow k_{\mathrm{B}} T_{\perp} \approx T_{\mathrm{cath}} / \alpha$

Cold electron source - photocathode

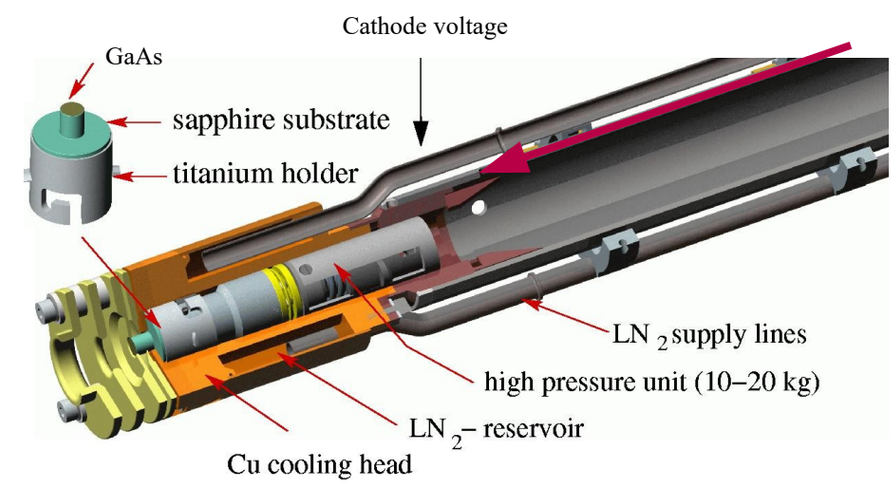
p-GaAs on sapphire
Cs-O surface layer
down to ~100 K



D. A. Orlov et al., J. Appl. Phys. 106, 054907 (2009)



Transmission-mode
GaAs photocathode



D. A. Orlov, C. Krantz, A. Shornikov @ TSR
A. S. Terekhov, Rzhanov Institute of Semiconductor Physics

Maximizing electron density

$$\tau_{\mathrm{ecool}} \propto T_{\mathrm{e}}^{3/2} \frac{m_{\mathrm{ion}}}{Z^2 n_{\mathrm{e}}}$$

Perveance law

Perveance

$$I = p\, U_{\mathrm{ext}}^{3/2}$$

Extracted current

Extraction voltage

Maximizing electron density

Perveance law

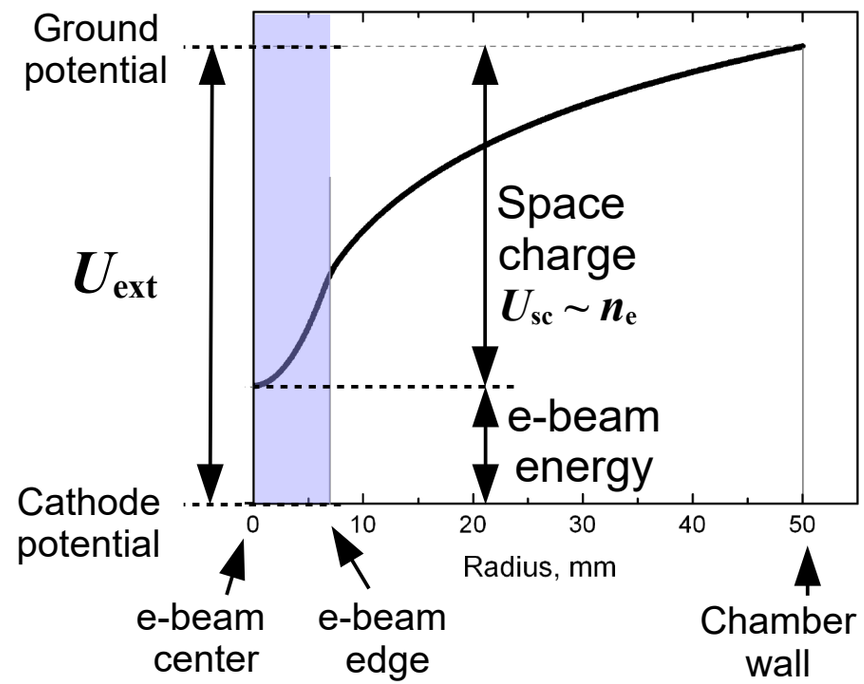
Perveance

$$I = p\,U_{\mathrm{ext}}^{3/2}$$

Extracted current

Extraction voltage

Space charge limit



High density → e-beam reflection!

Trick: high U_{ext} → Expansion → Deceleration

Maximizing electron density

A. Shornikov
PhD thesis
Univ. Heidelberg
2012

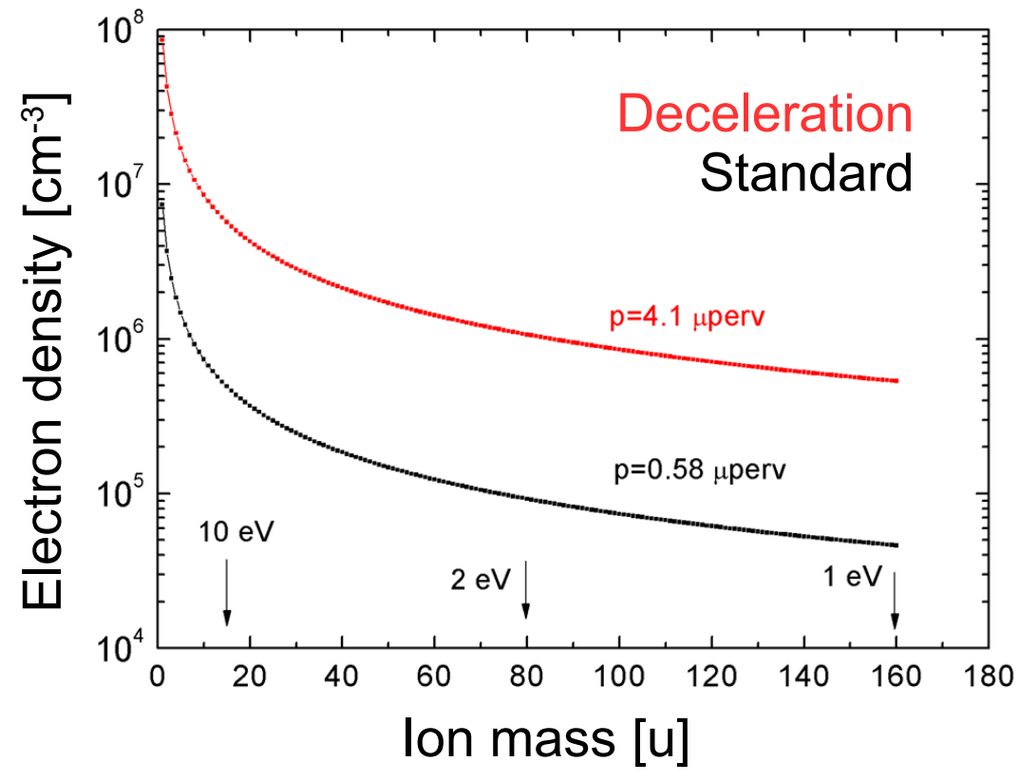
Perveance law

Perveance

$$I = p\,U_{\mathrm{ext}}^{3/2}$$

Extracted current

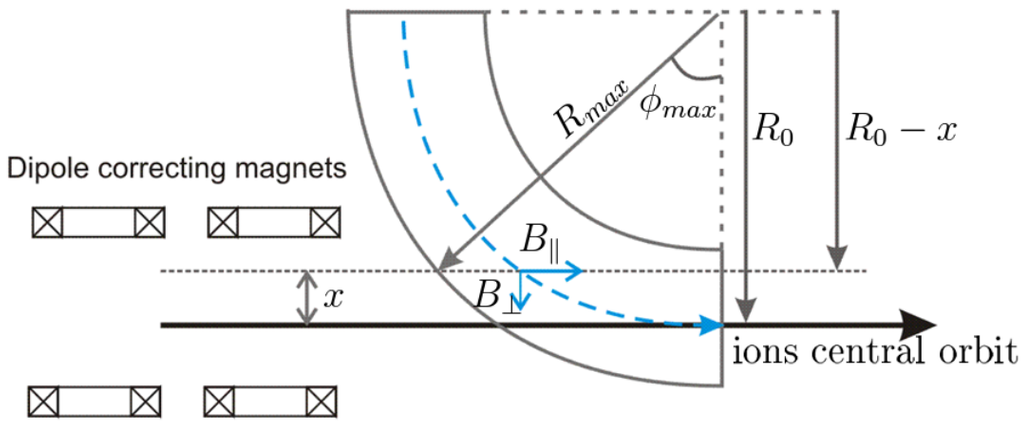
Extraction voltage



Trick: high U_{ext} → Expansion → Deceleration

Electron-ion beams merging geometry

Usual electron cooler:
ion beam passing a **toroid field**



Low energies (magnetic rigidity) →
higher order distortions
cannot be corrected!

Electron-ion beams merging geometry

Usual electron cooler:
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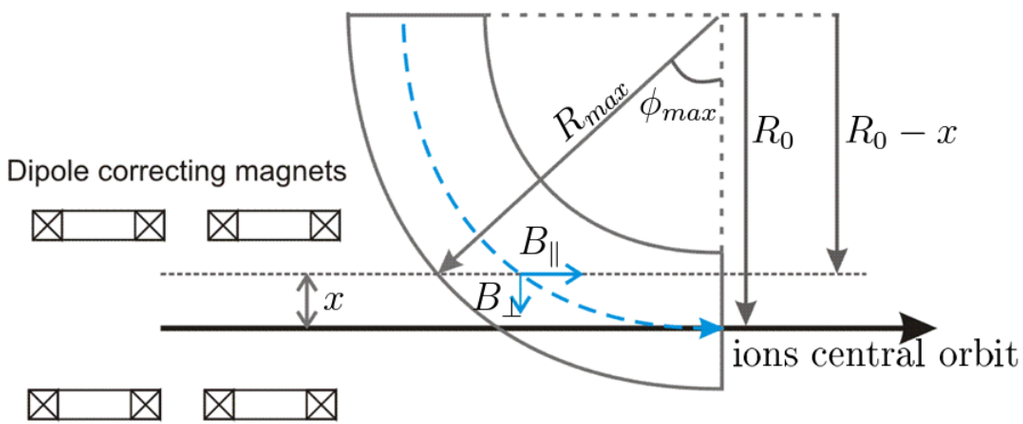
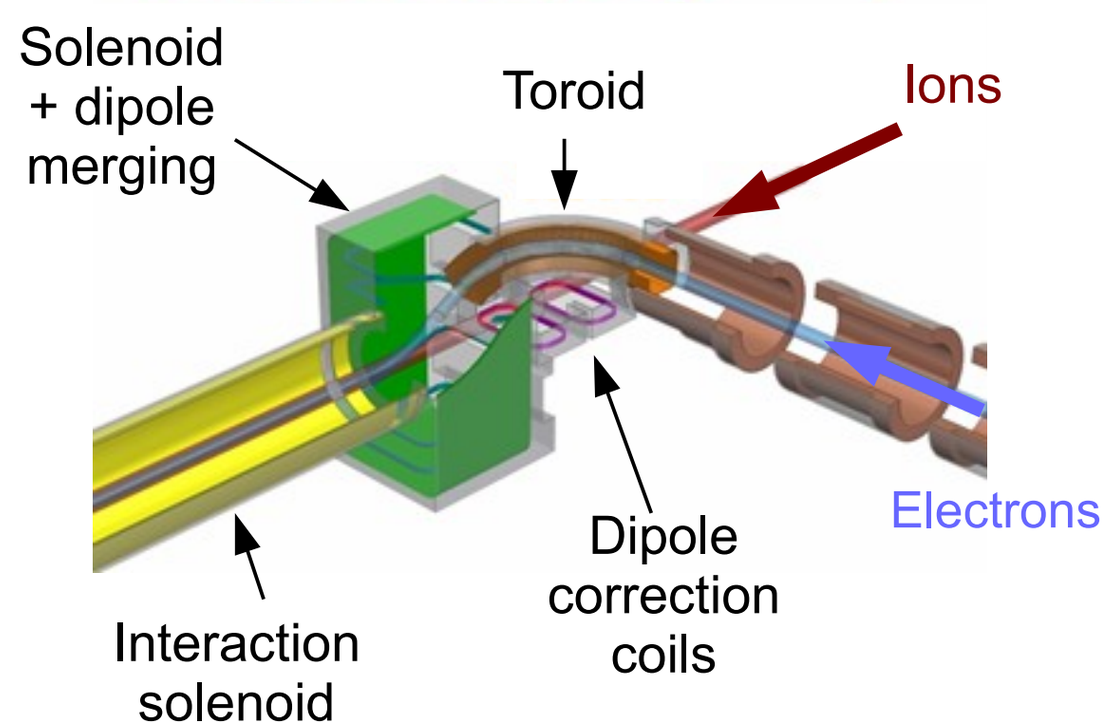
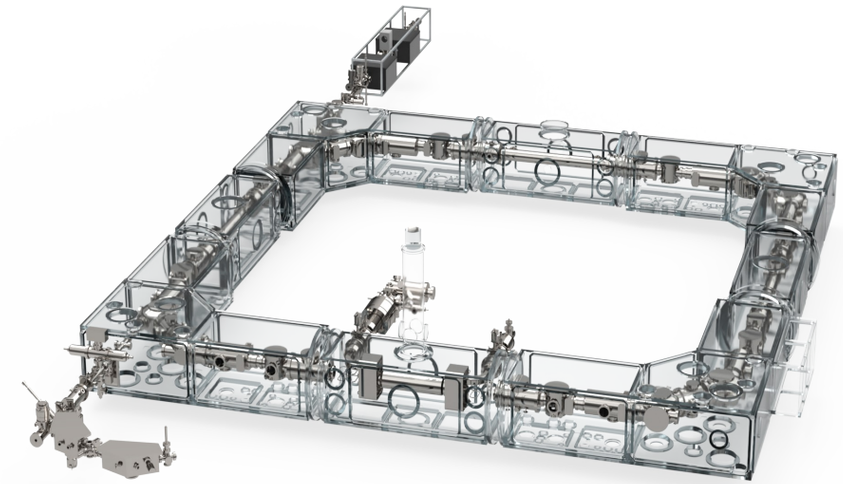


Low energies (magnetic rigidity) →
higher order distortions
cannot be corrected!

CSR electron cooler:
combined **solenoid and dipole field**



Ultra-low-energy electron-cooling at CSR



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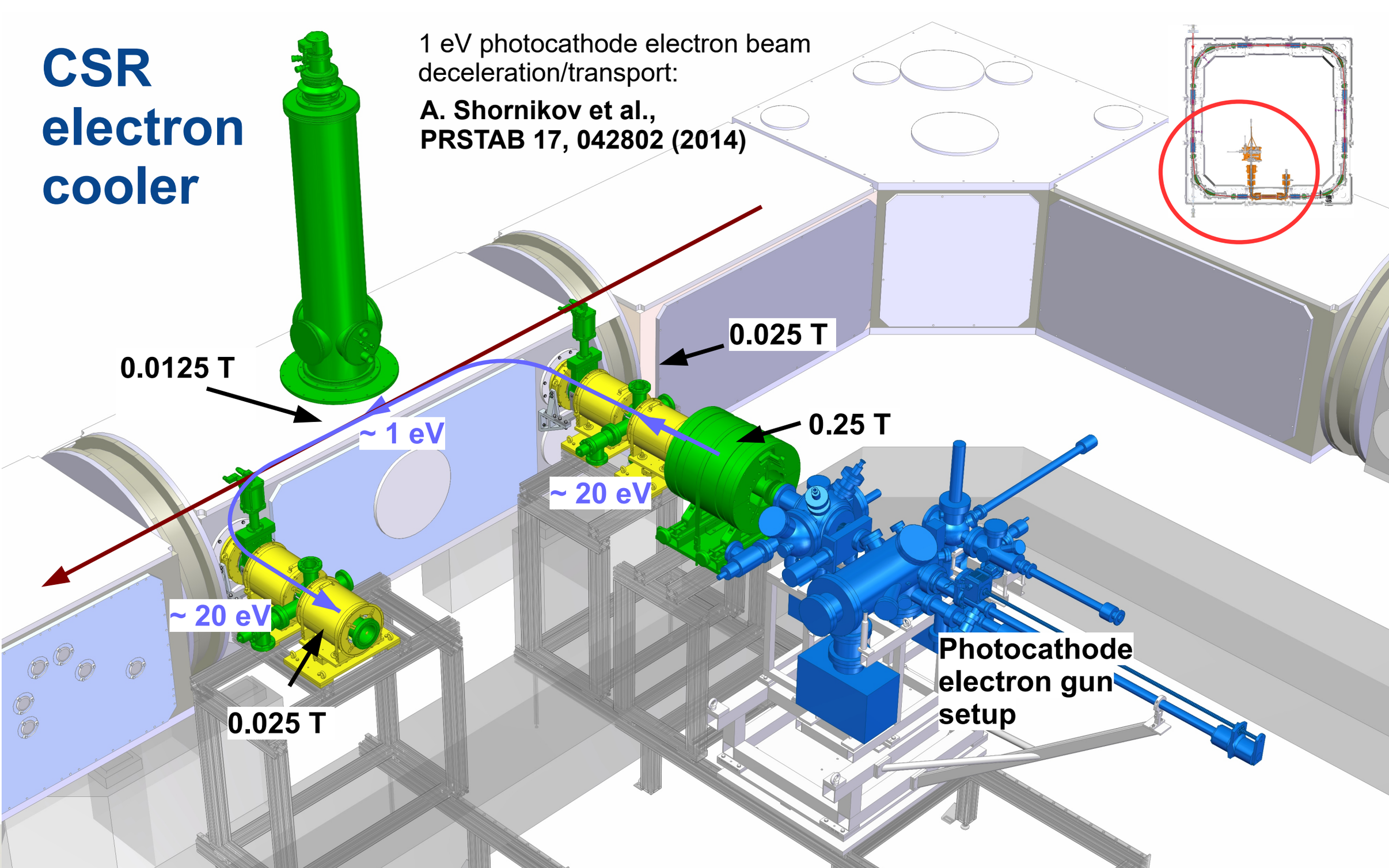
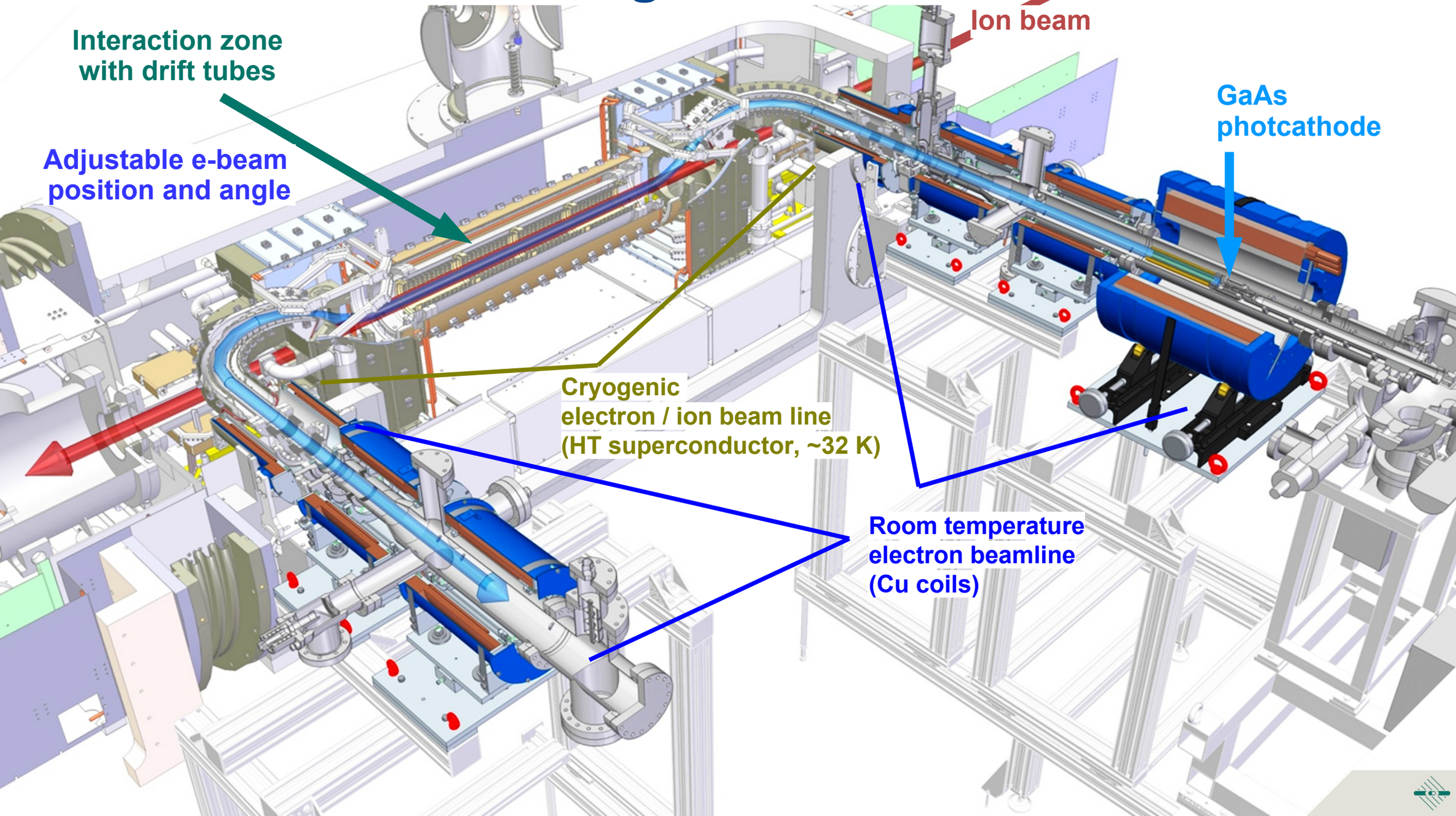
CSR electron cooler

1 eV photocathode electron beam deceleration/transport:

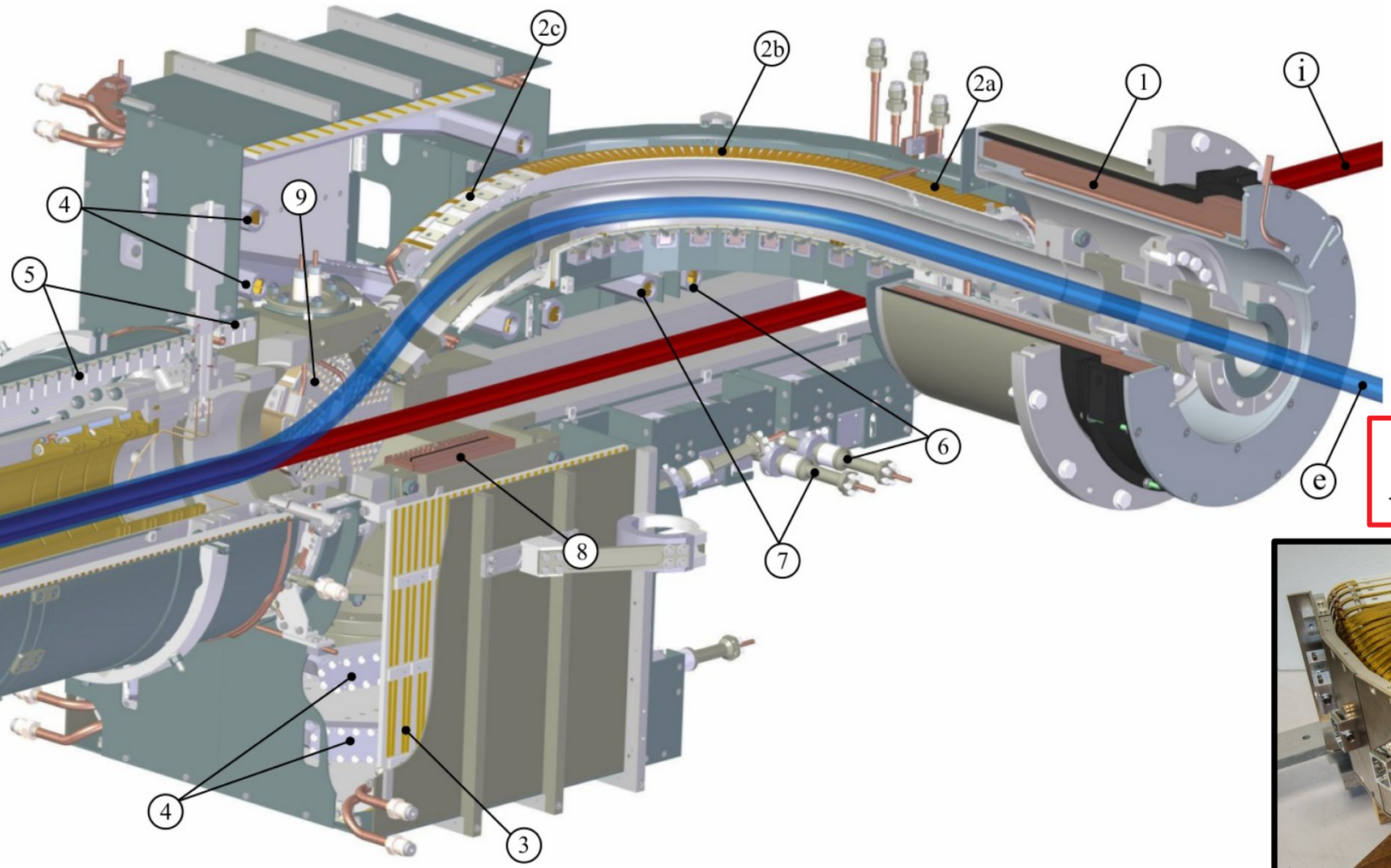
A. Shornikov et al., PRSTAB 17, 042802 (2014)



Photocathode merged electron beam at CSR

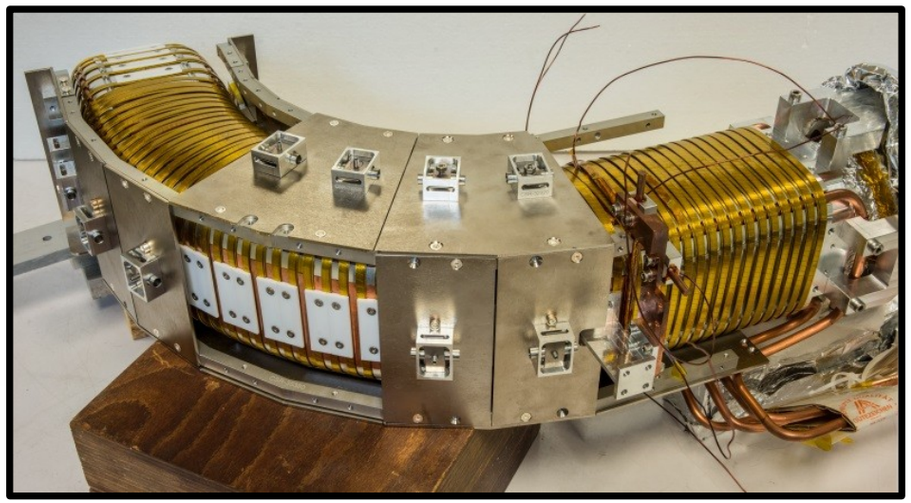


CSR electron cooler – merging region



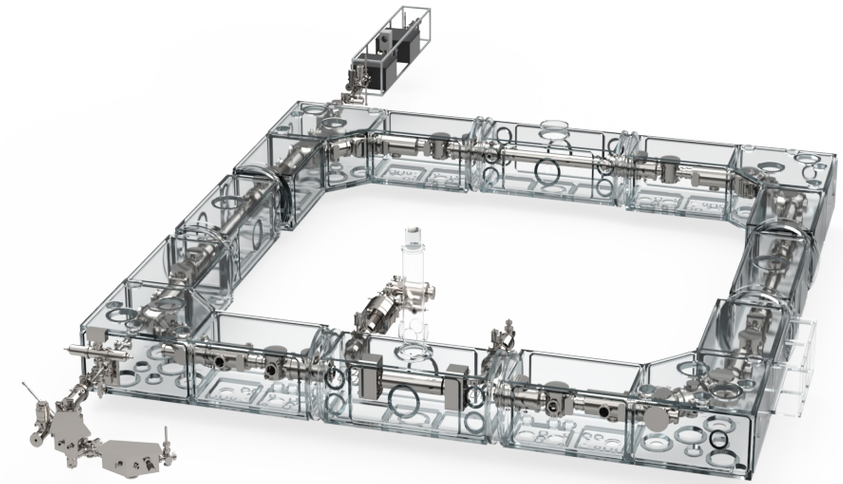
S. Vogel
PhD thesis
Univ. Heidelberg
2016

Structure contained in **CSR cryostat:**
→ 10 K, <10^{-13} mbar & bakeable to 200°C



(1) Last low-field guiding magnet, toroid, consisting of (2a) a solenoidal extension, (2b) horizontal 90◦ bend, and (2c) vertical 30◦ bending, (3) longitudinal merging solenoid, (4) four vertical merging coils, (5) interaction solenoid, (6-7) two pairs of ion beam compensation coils, (8) charcoal cryopump, (9) NEG-pump

Ultra-low-energy electron-cooling at CSR



- The CSR facility
- Low energy electron-cooling challenges
- CSR electron cooler
- **Electron cooling performace**
- Inelastic “electron cooling”

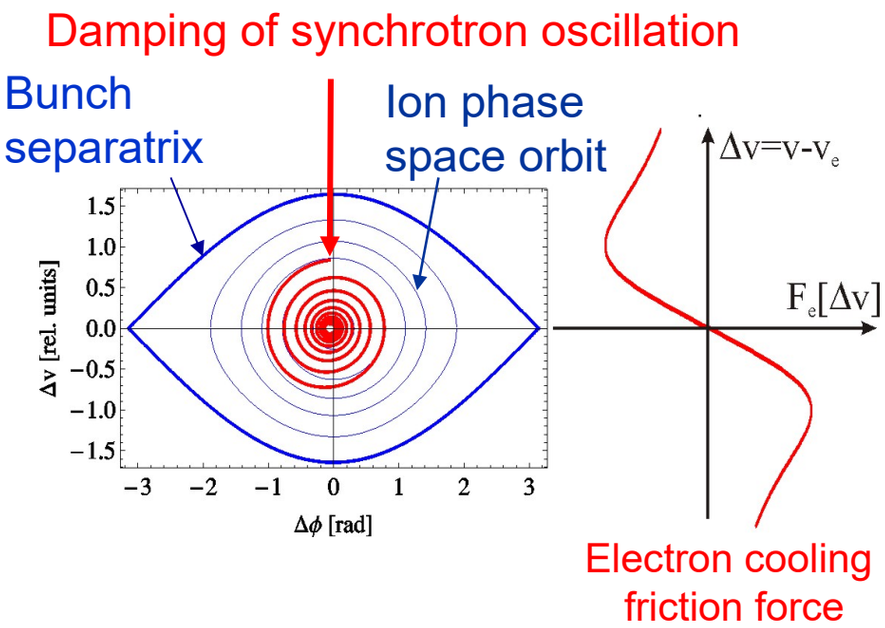
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Electron cooling demonstration - longitudinal

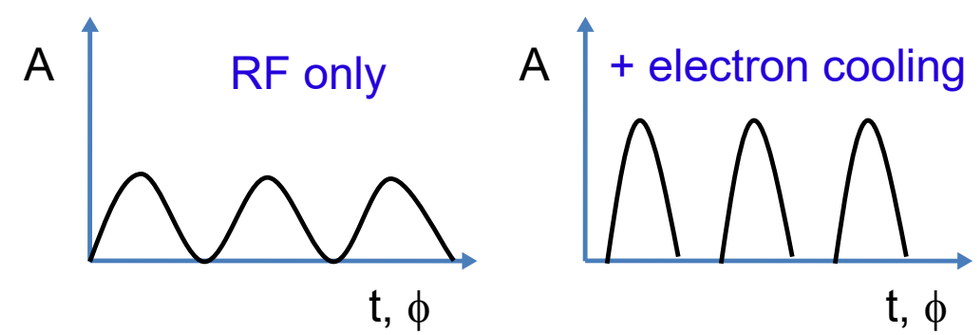
HeH$^+$ ions at 250 keV, **RF bunched**

E_{cool} = 27.3 eV, n_e = 3.7 × 10^5 cm^{-3}, N_i=2x10^7

Longitudinal phase space



Beam charge pickup



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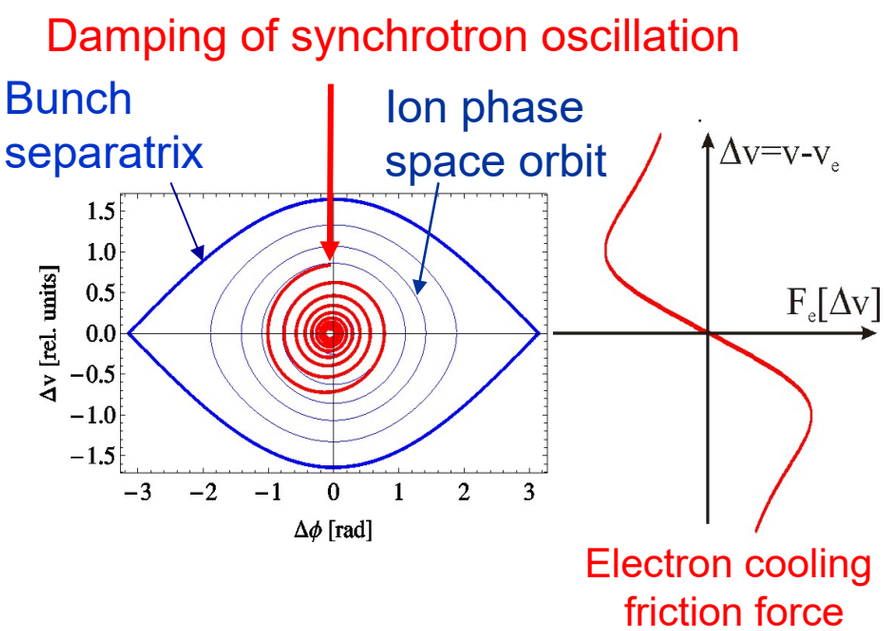

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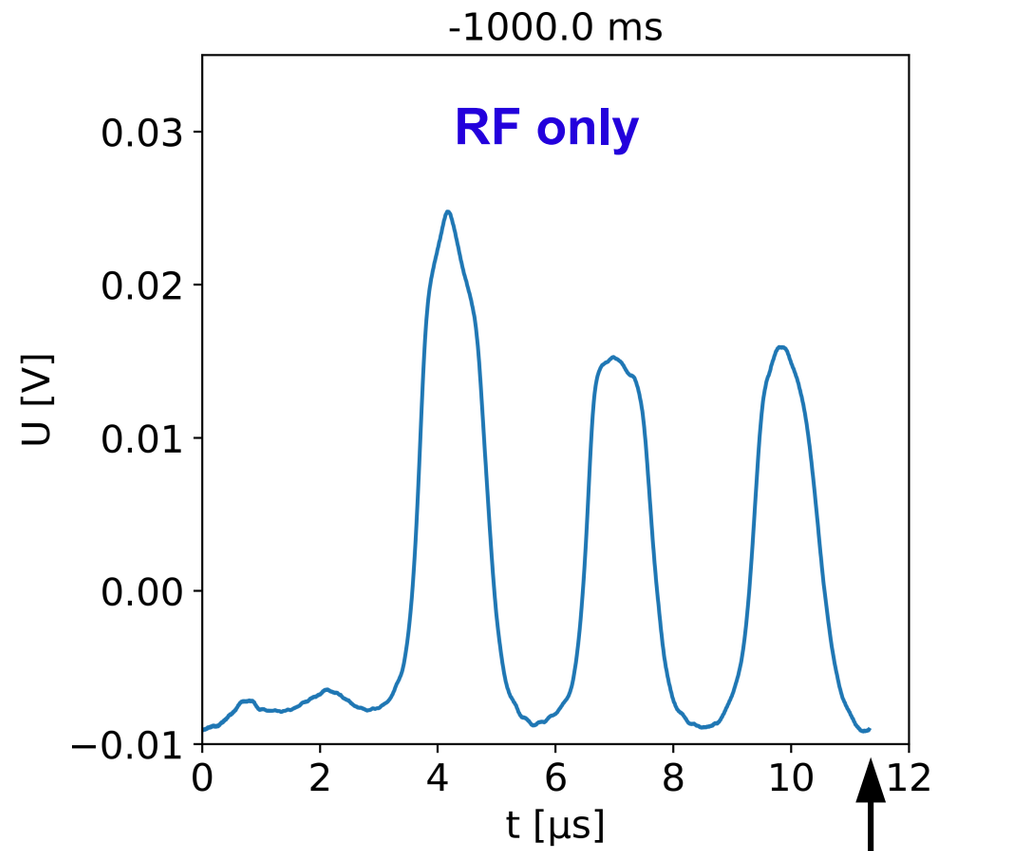

f_{rev} ~ 88.28 kHz

t_{rev} = 11.32 μs

Electron cooling demonstration - longitudinal

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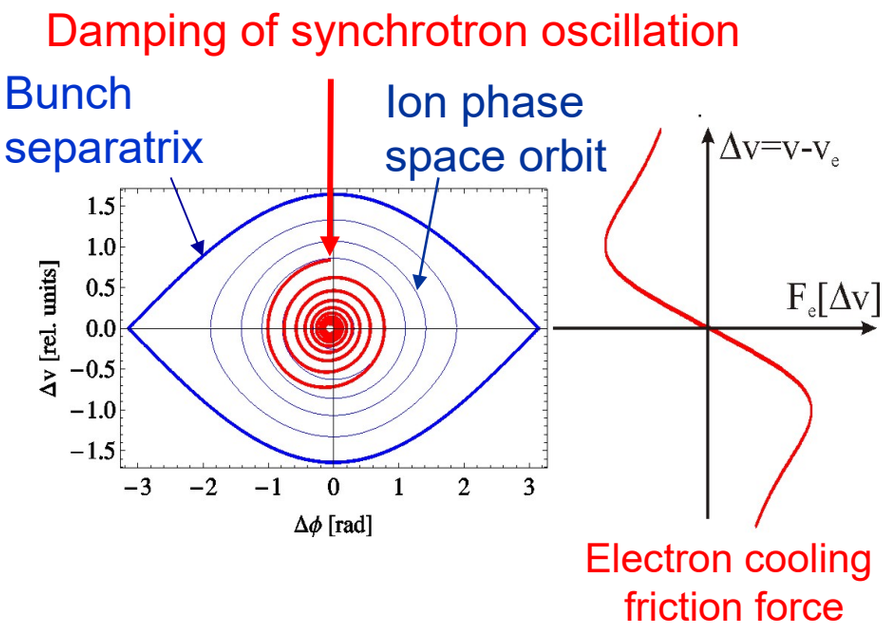
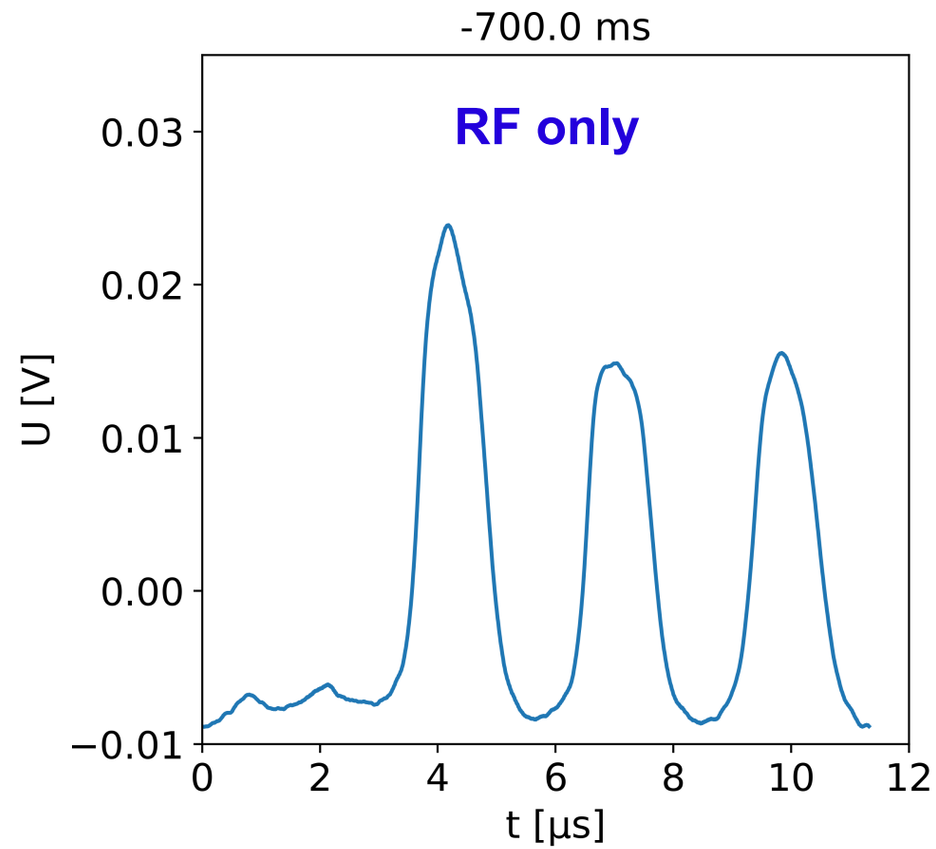


Beam charge pickup



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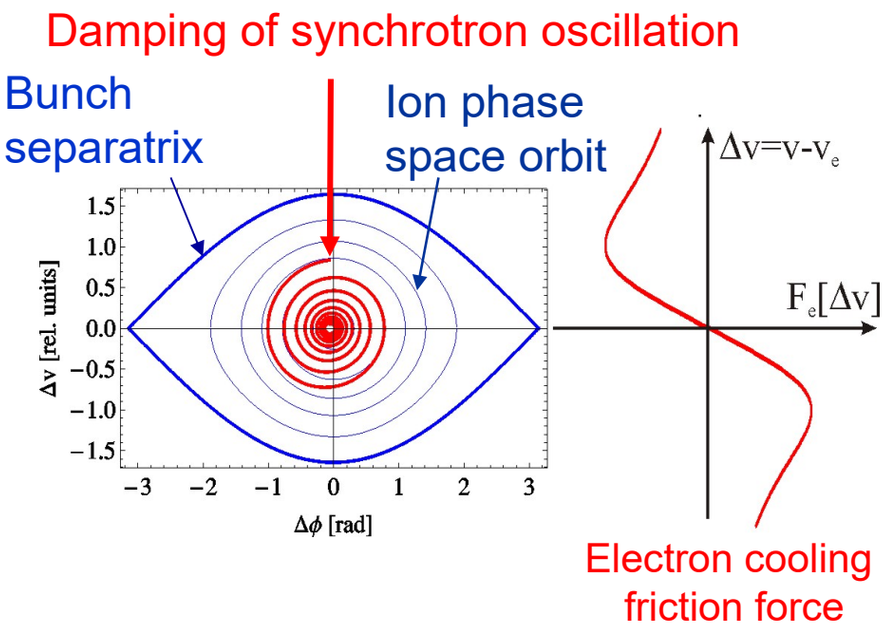

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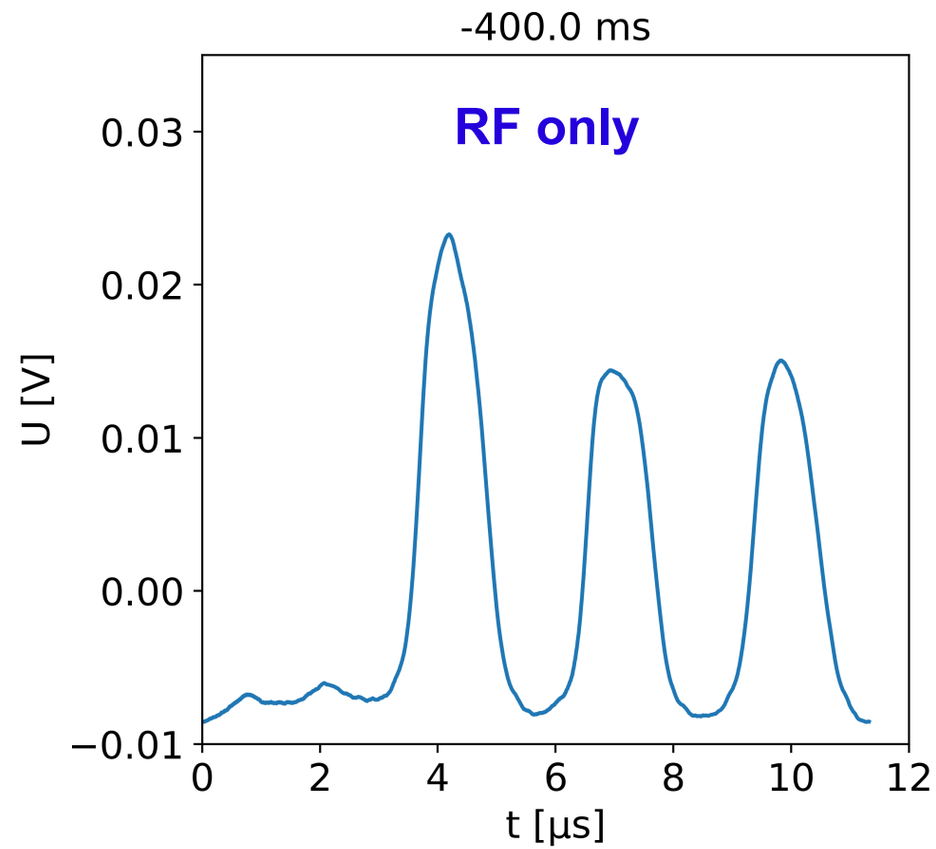

Electron cooling demonstration - longitudinal

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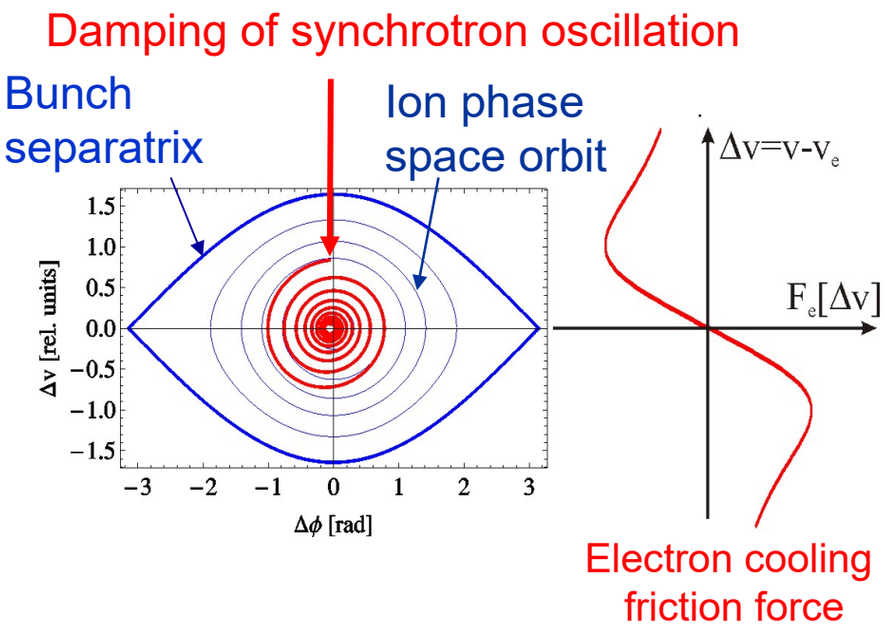

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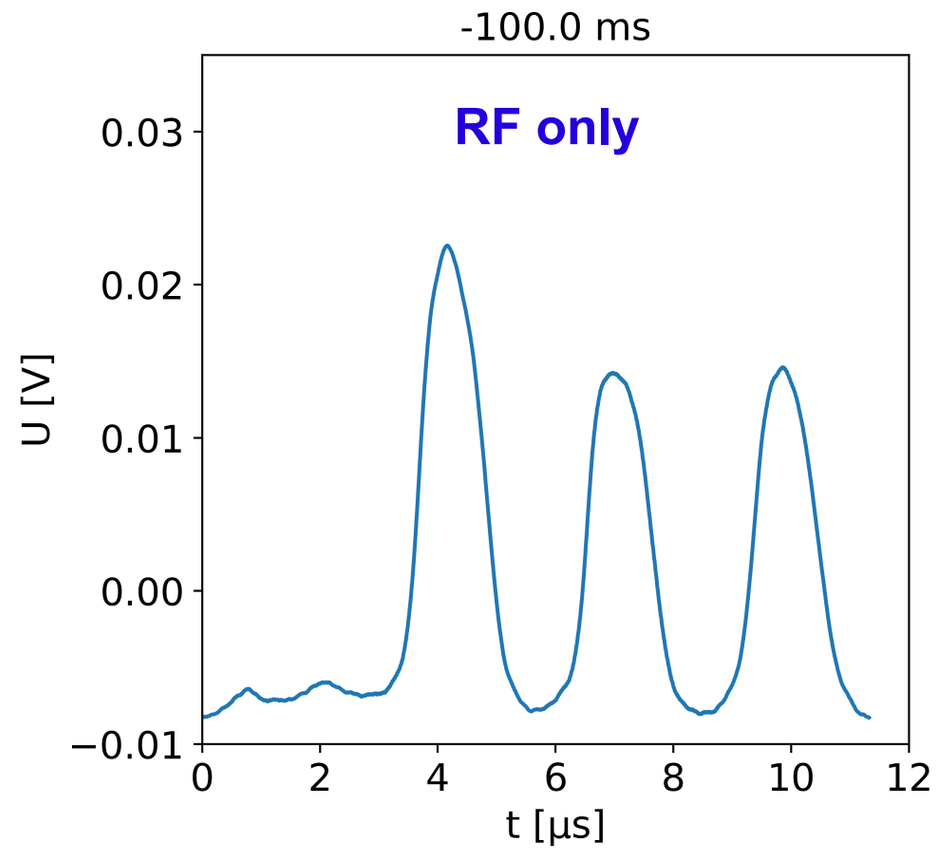

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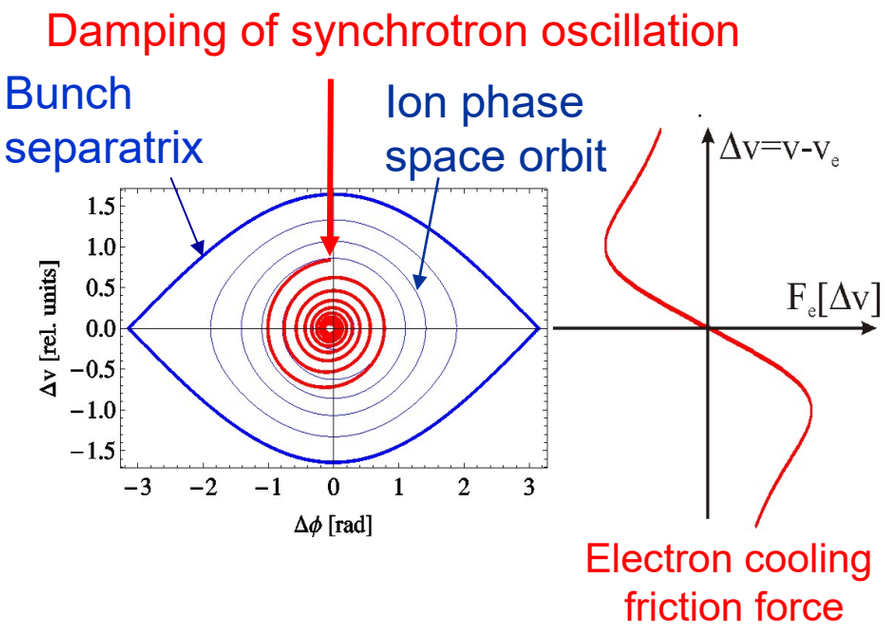

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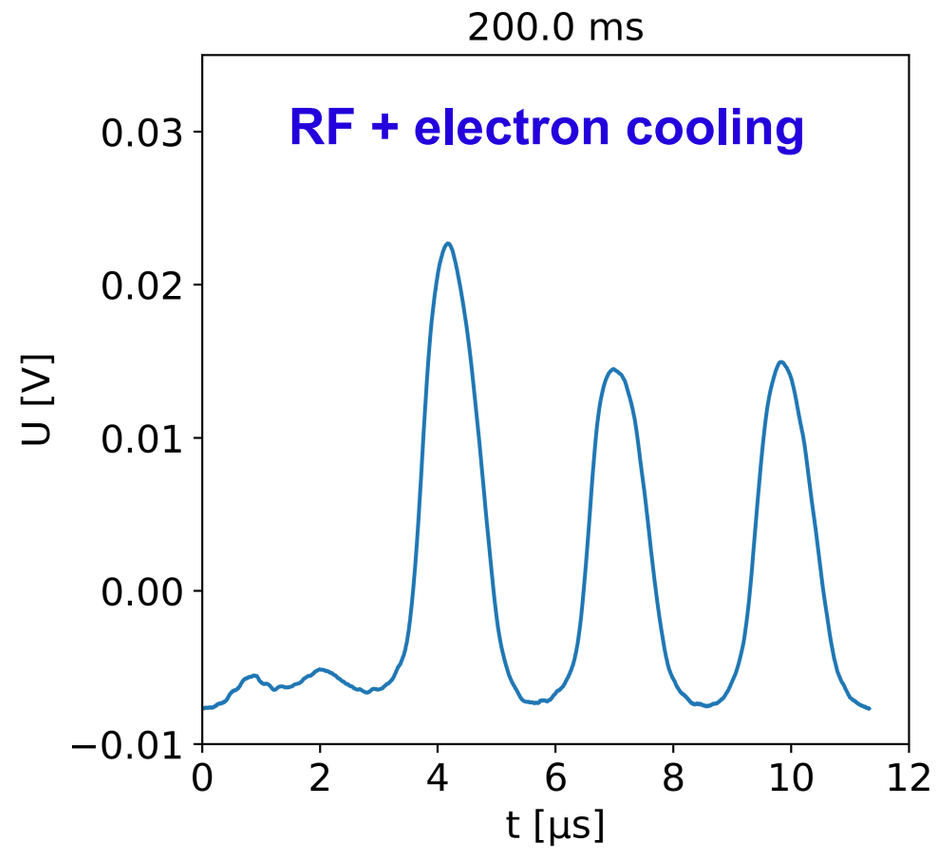

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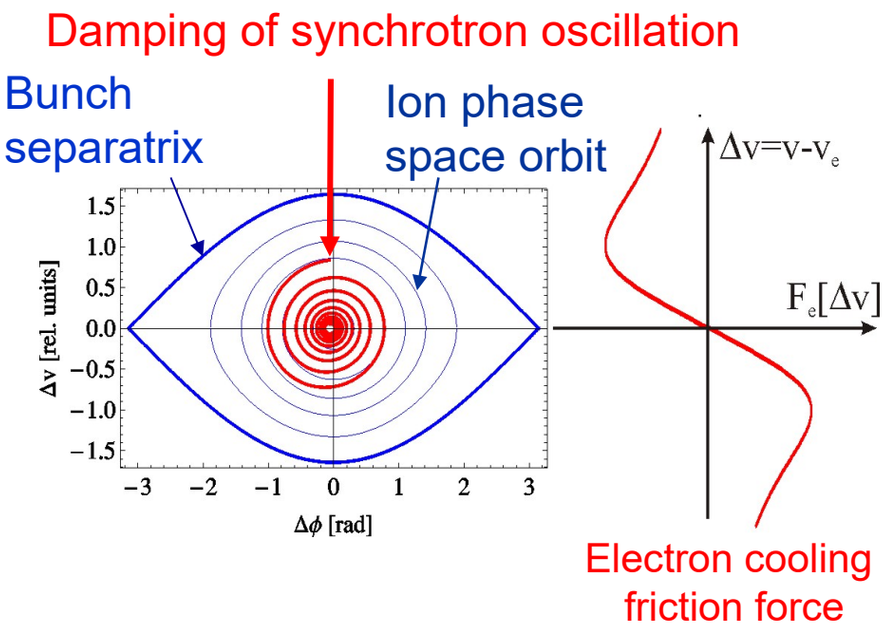

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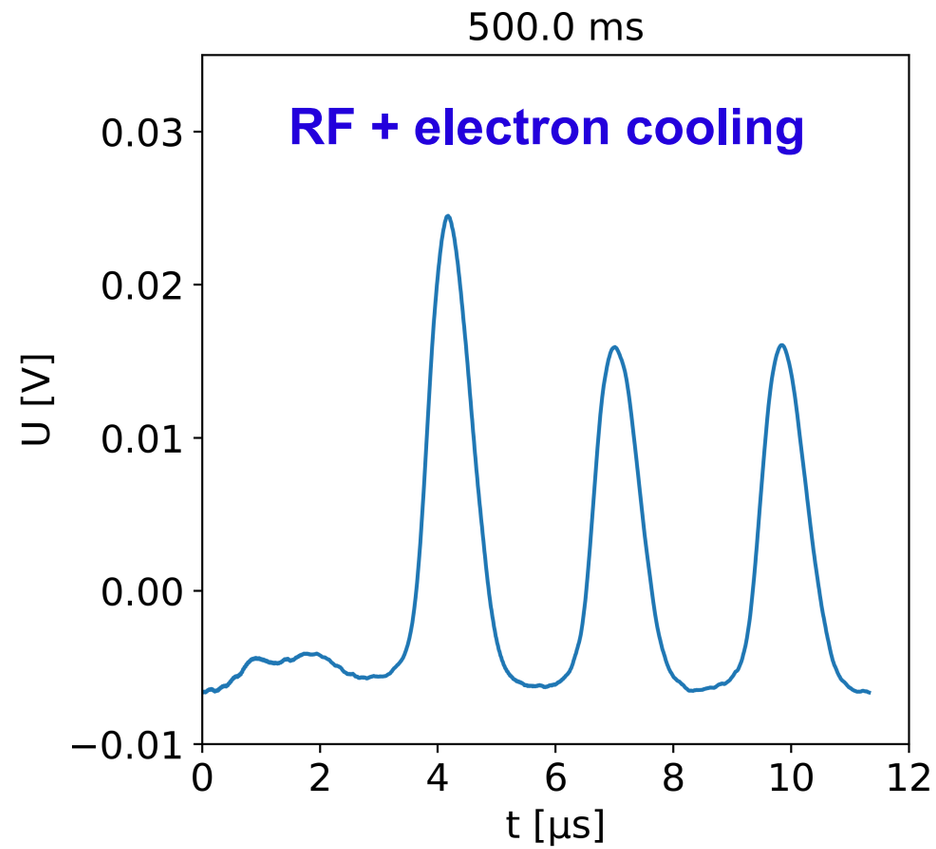

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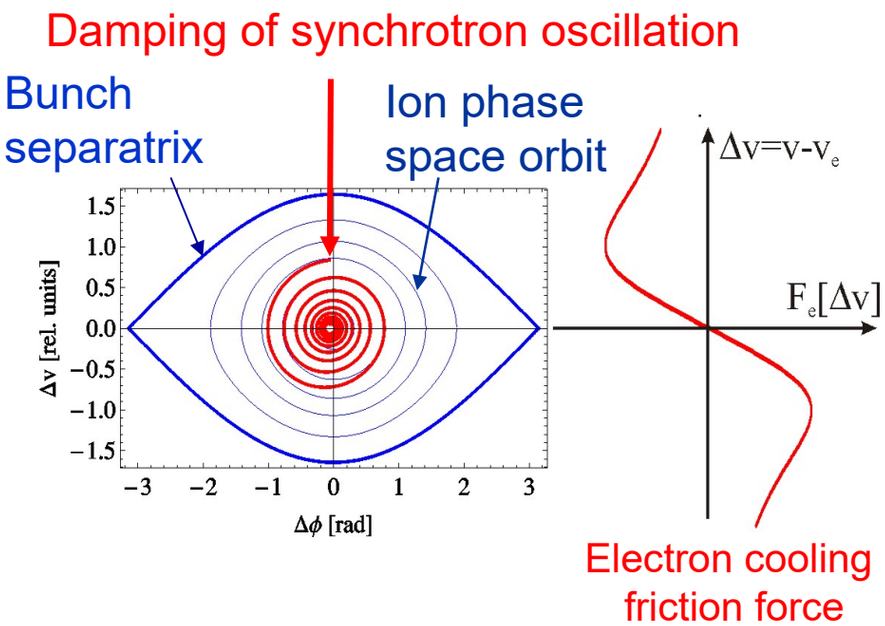
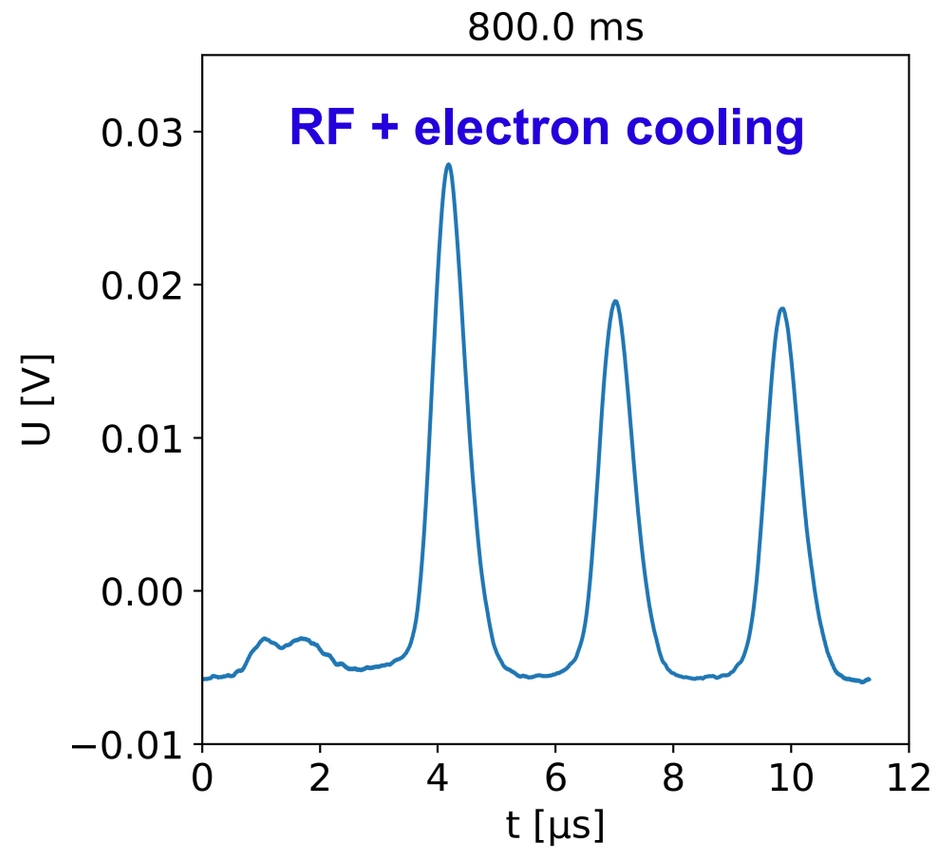


Beam charge pickup



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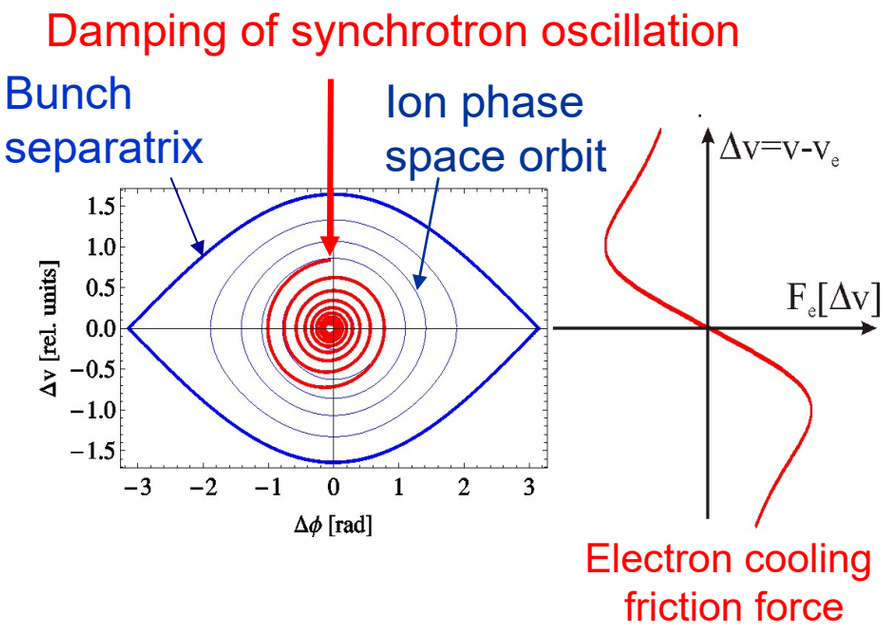

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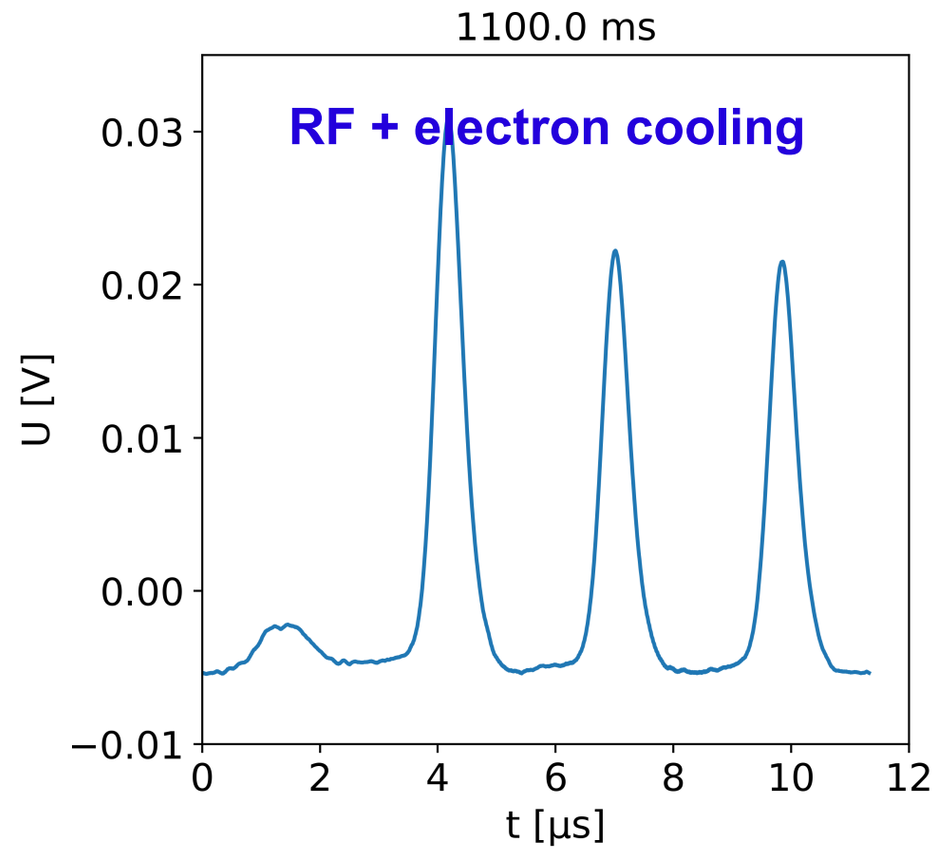

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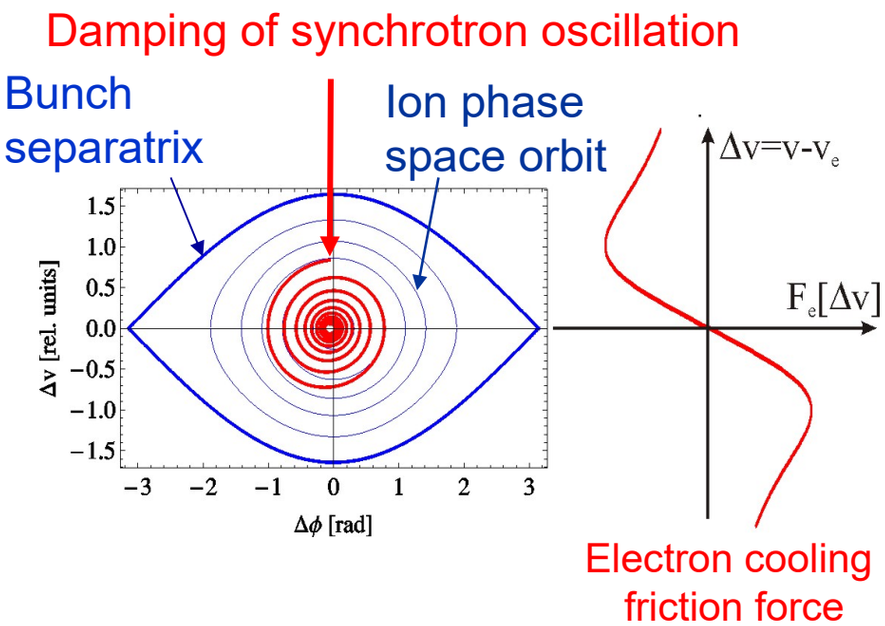

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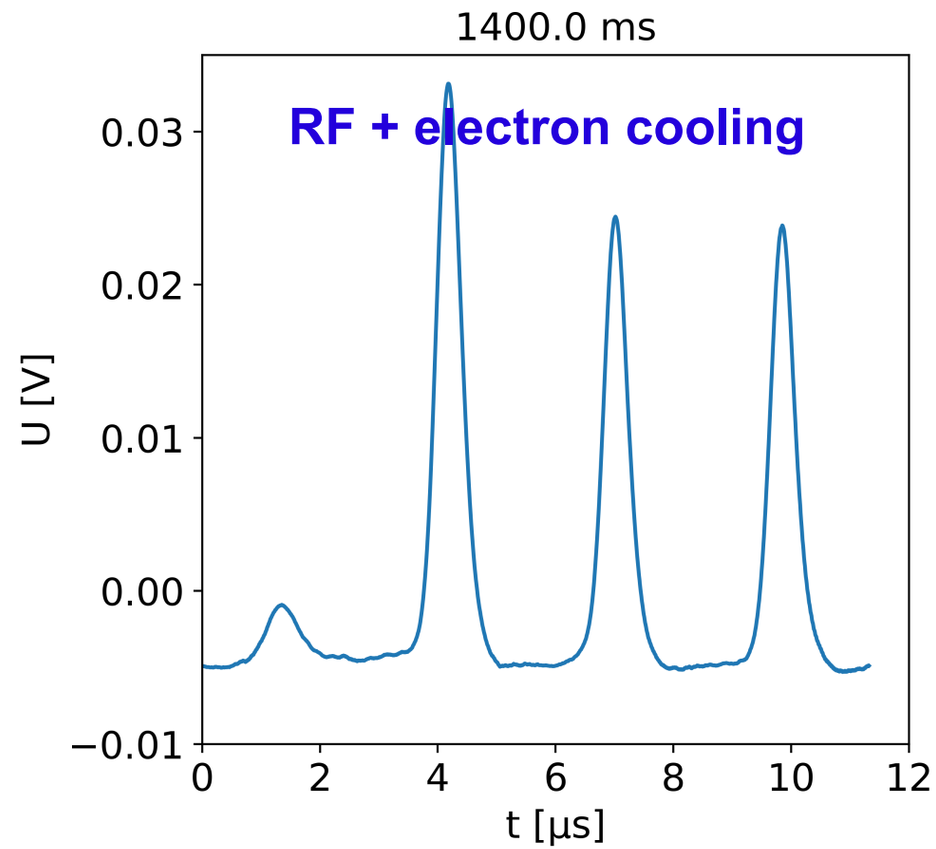

Electron cooling demonstration - longitudinal

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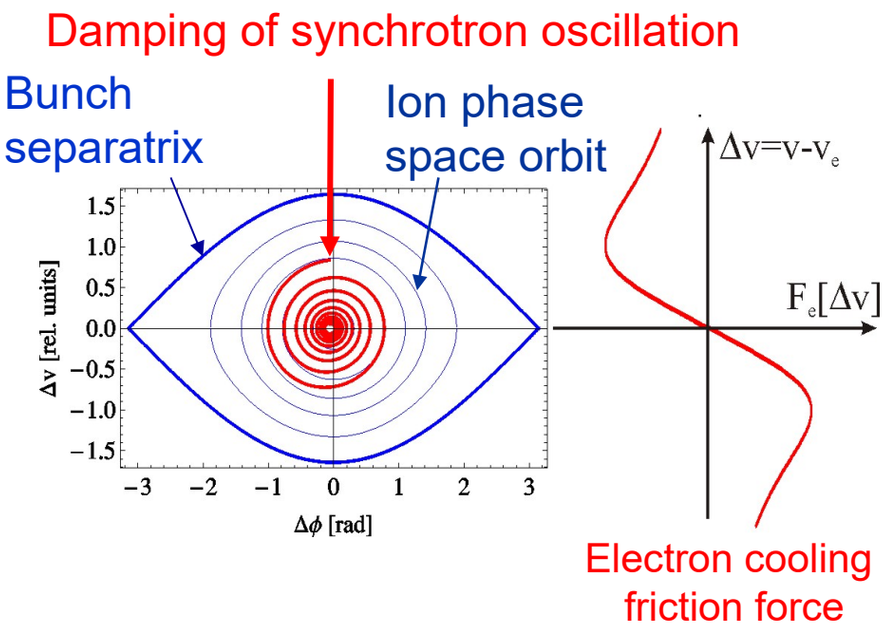

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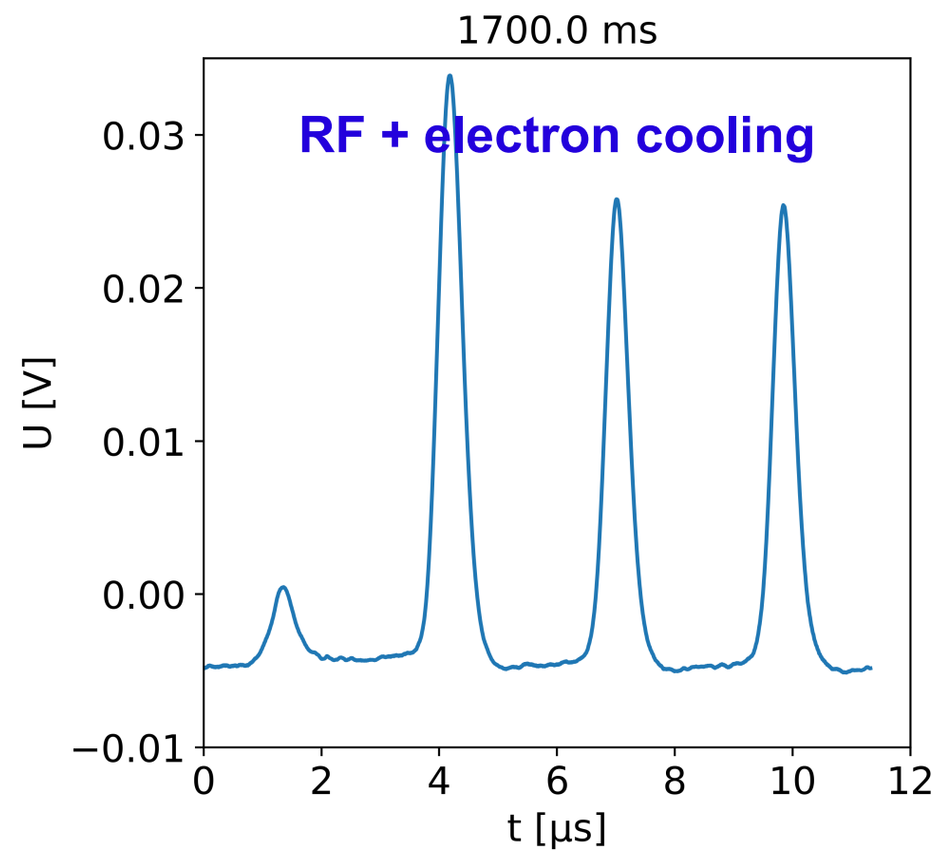
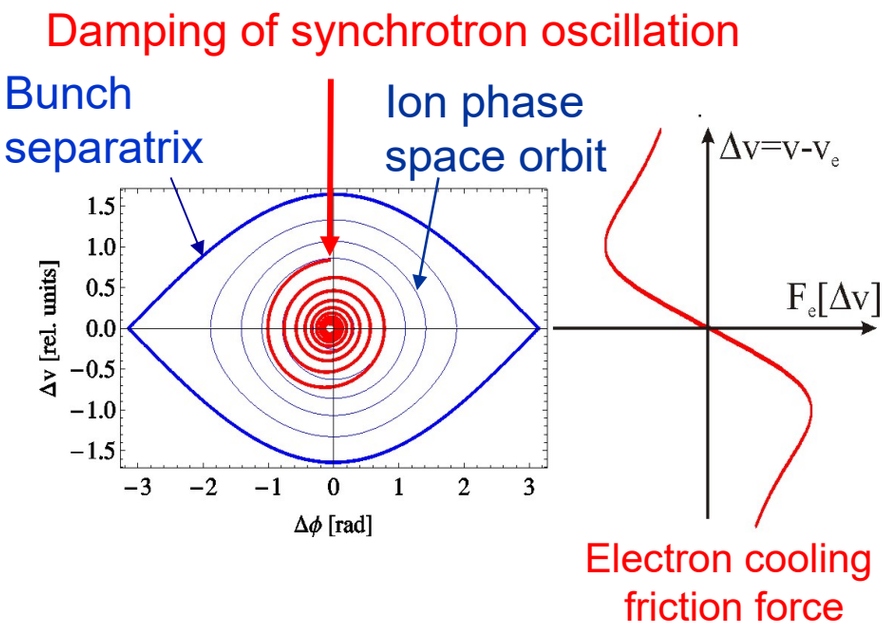


Electron cooling demonstration - longitudinal

HeH⁺ ions at 250 keV, **RF bunched**

E_{cool} = 27.3 eV, n_e = 3.7 × 10^5 cm^{-3}, N_i=2x10^7

Longitudinal phase space



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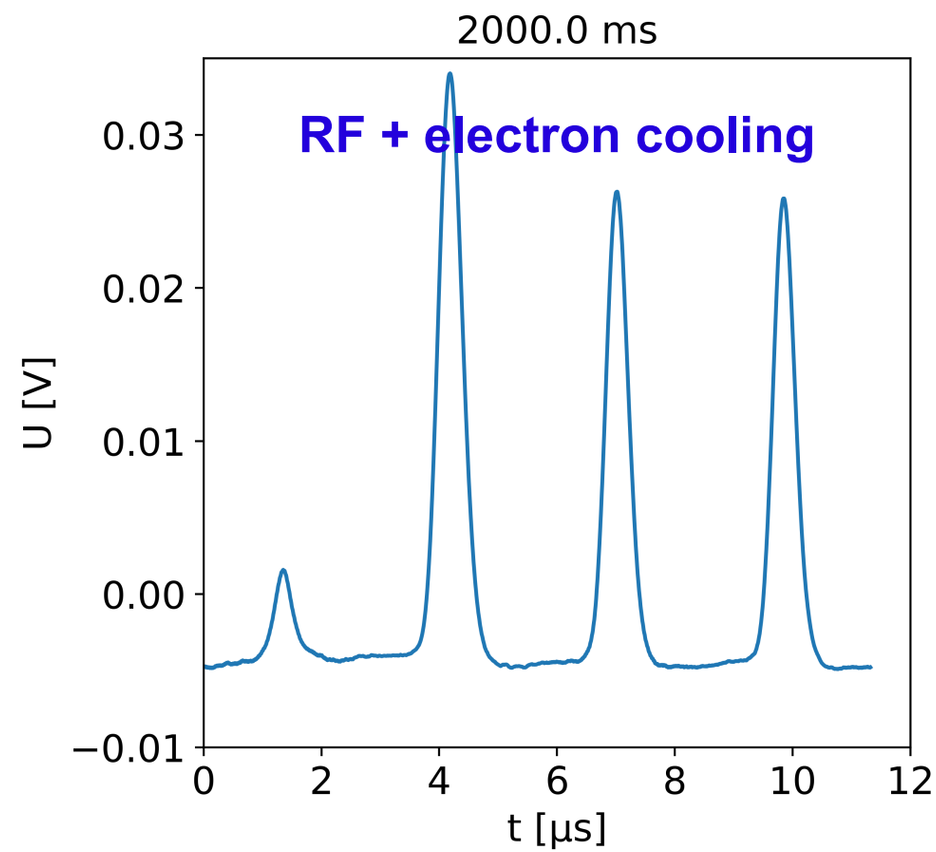

Electron cooling demonstration - longitudinal

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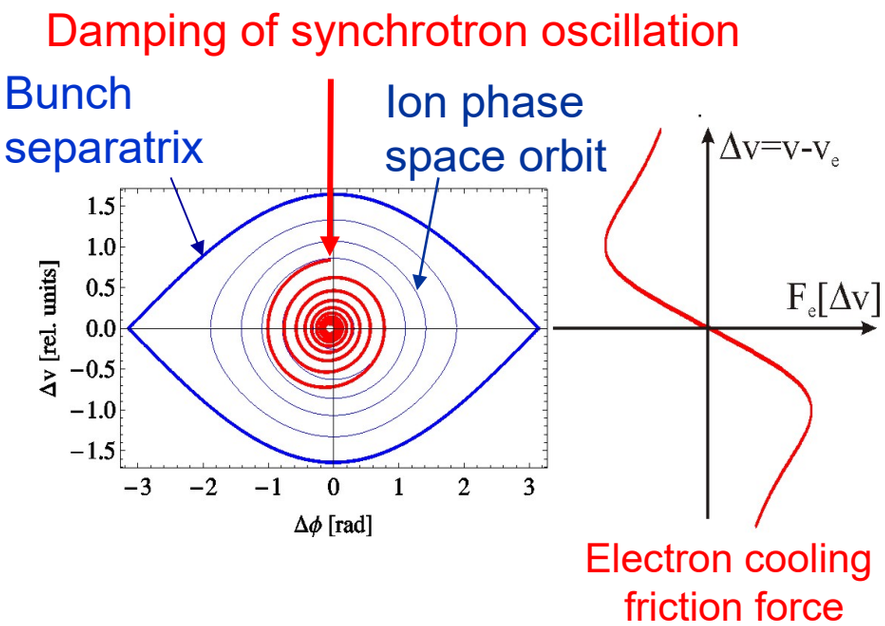

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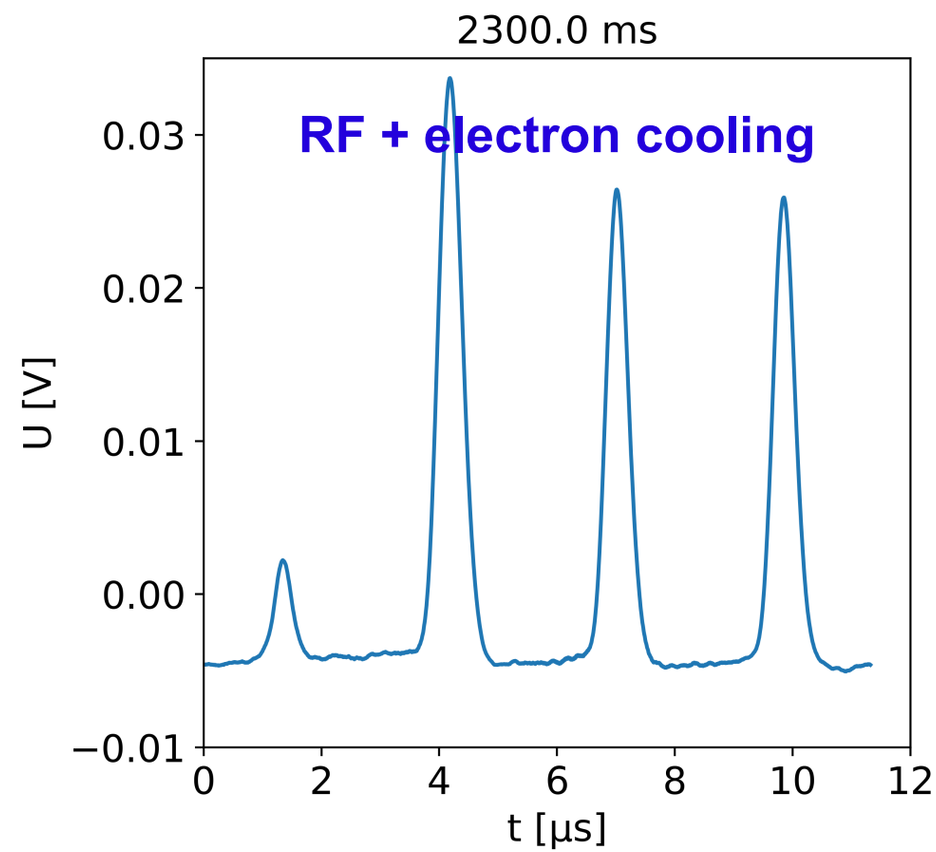

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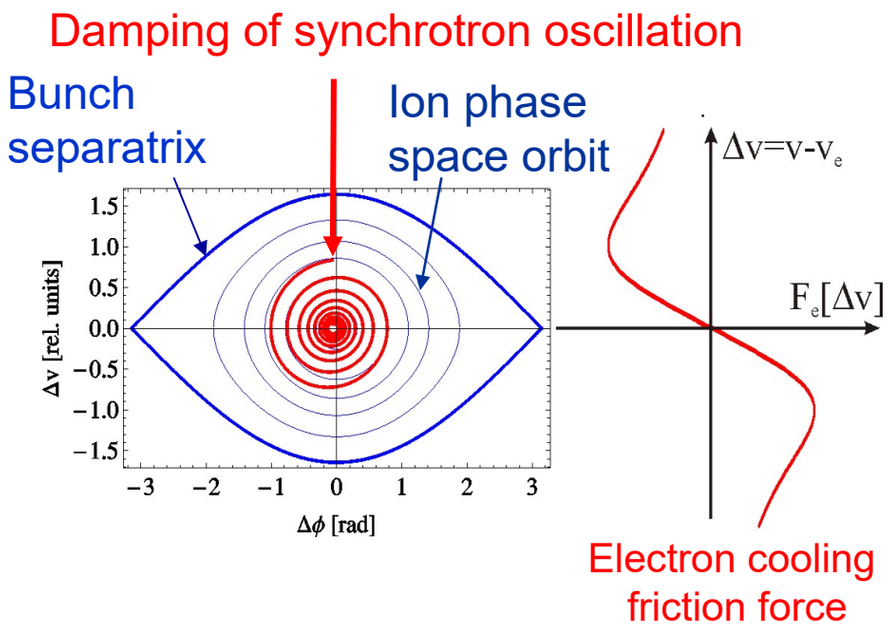

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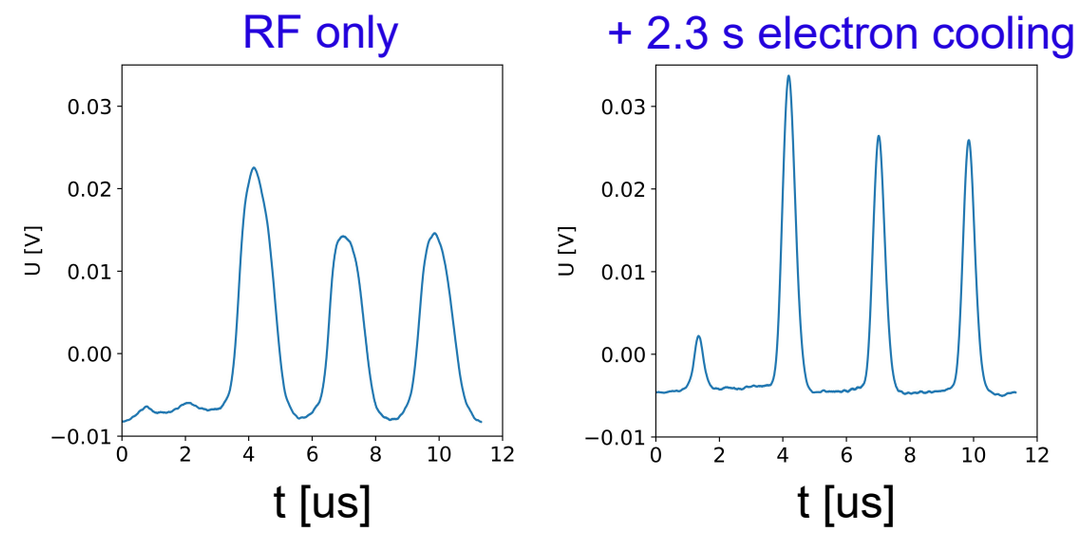
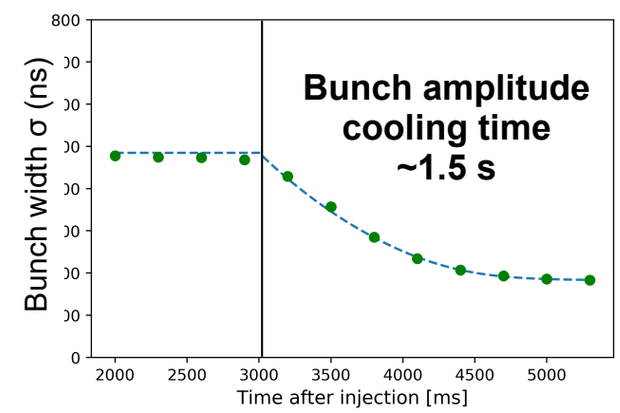


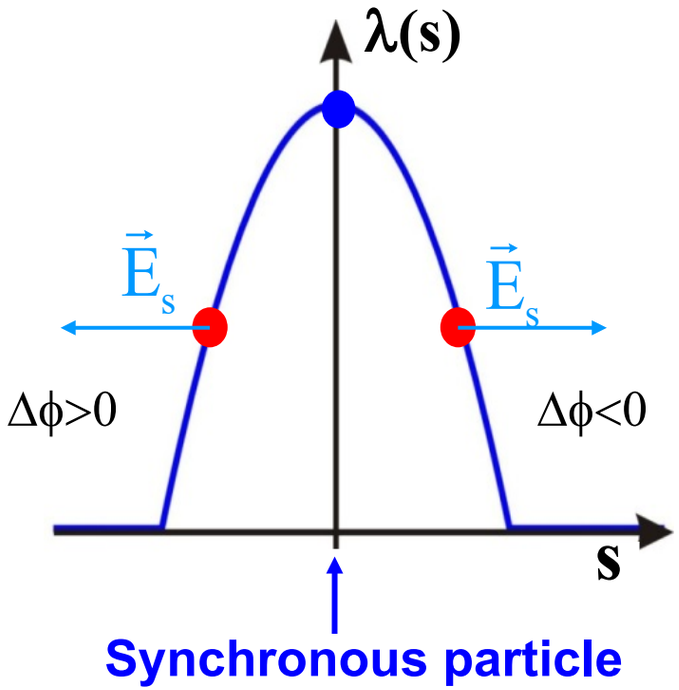


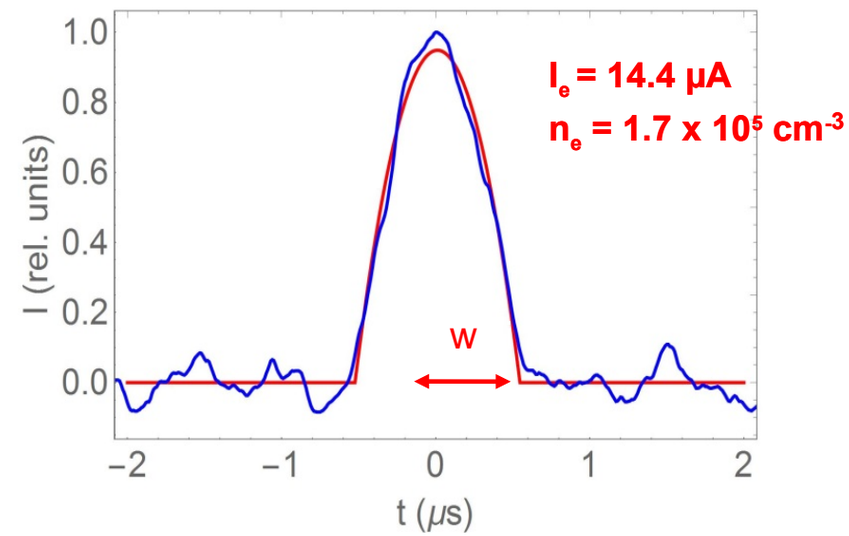
Space-charge and IBS limit

M. Grieser
MPIK

F^{6+} ions at 1.34 MeV, **RF bunched**
E_{cool} = 38.7 eV, n_e = 1.7 × 10^5 cm^{-3}, N_i=1x10^6

Longitudinal density profile of space charge ion bunch

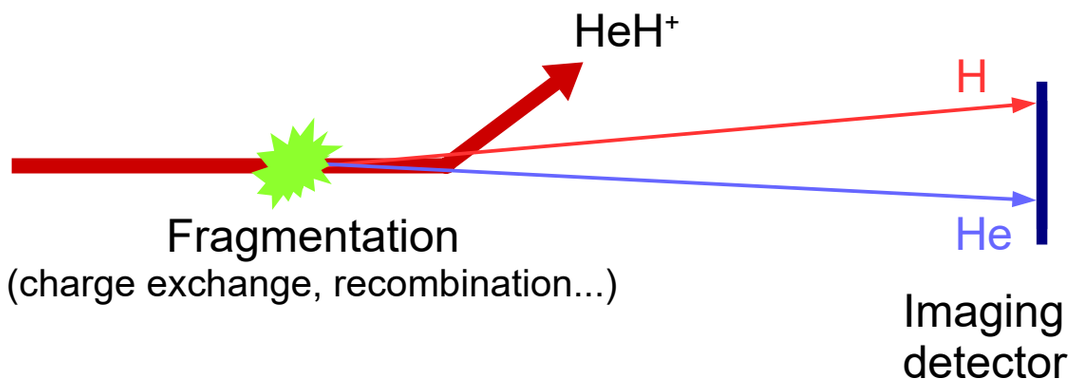




Reached bunch width: w_{exp} **= 535 ns**
Space charge limit: $w_{space\ charge}$ **= 597.5 ns**

Electron cooling demonstration - transverse

Fragment imaging
for transverse beam-profile measurements



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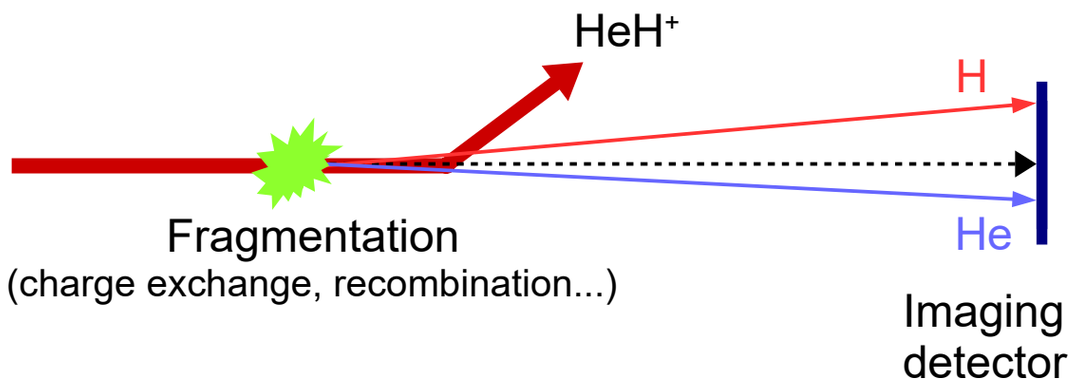
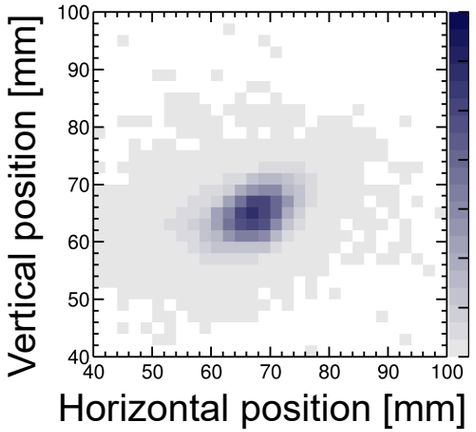


Momentum
conservation
+
known
fragment masses

Projected
center-of-mass distribution



Electron cooling demonstration - transverse

HeH⁺ ions at 250 keV, **coasting (DC) beam**

E_{cool} = 27.3 eV, n_e = 3.7 × 10^5 cm^{-3}, N_i=2x10^7

Fragment imaging
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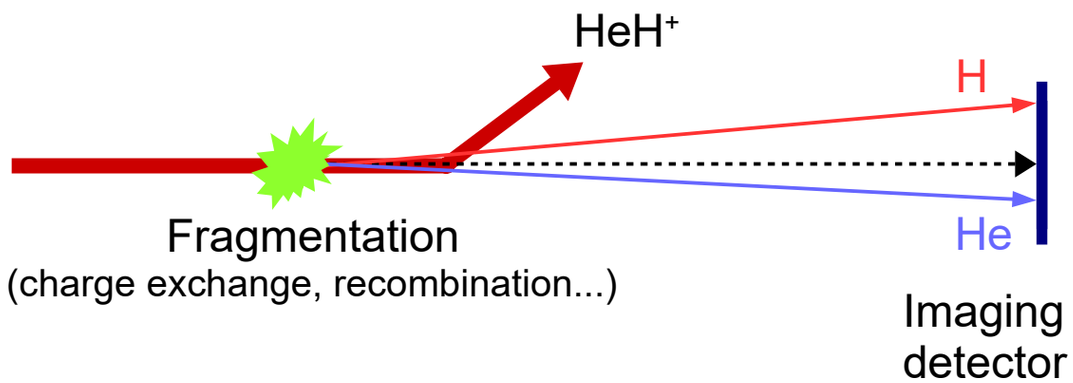
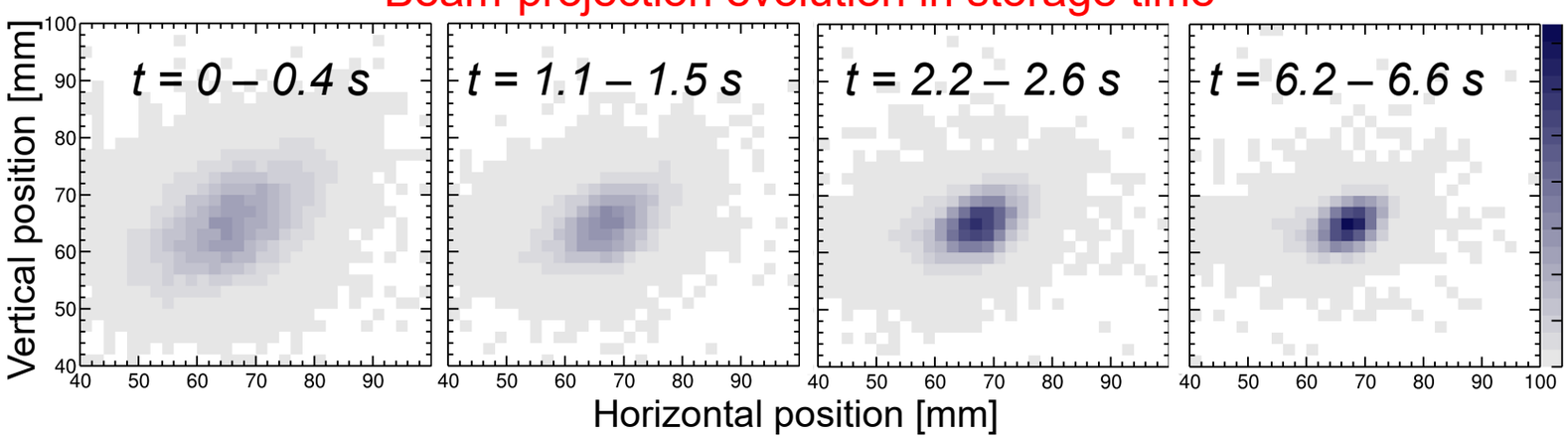


Beam-projection evolution in storage time



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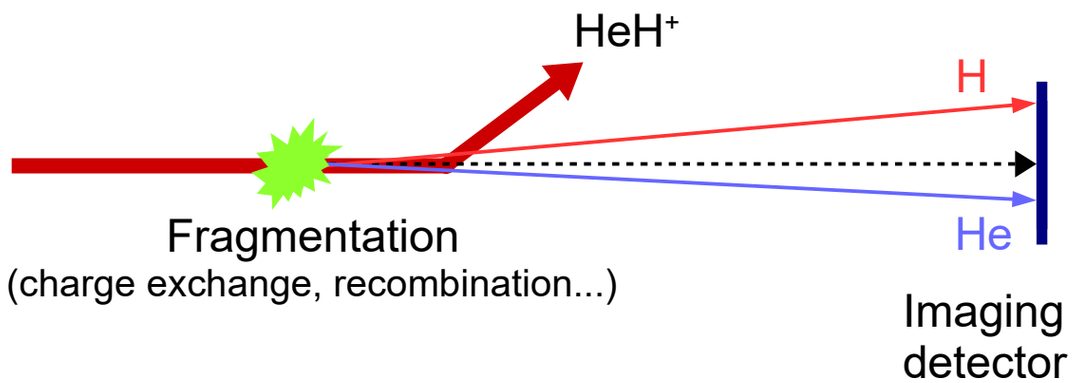
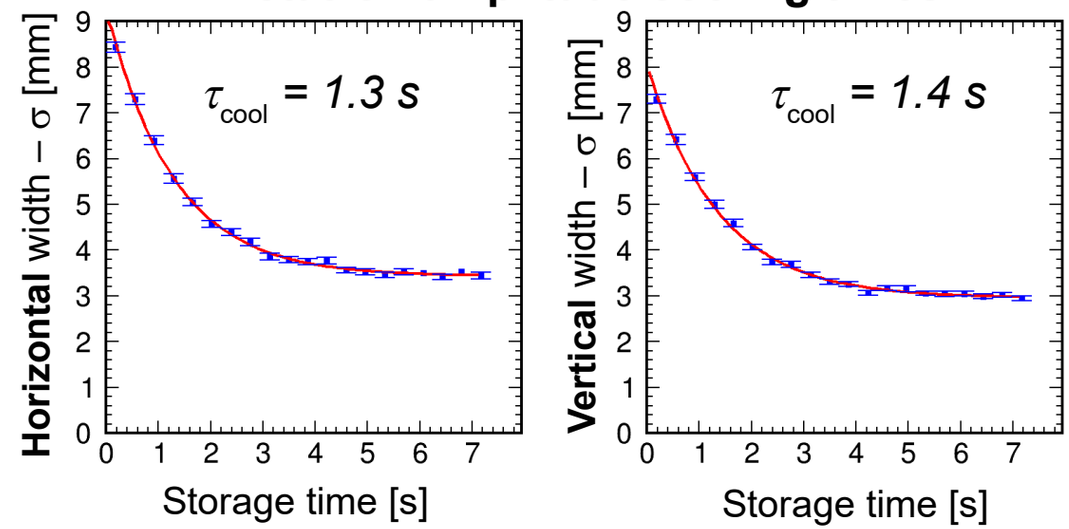
Equilibrium 2σ emittance:
~ 3 mm mrad

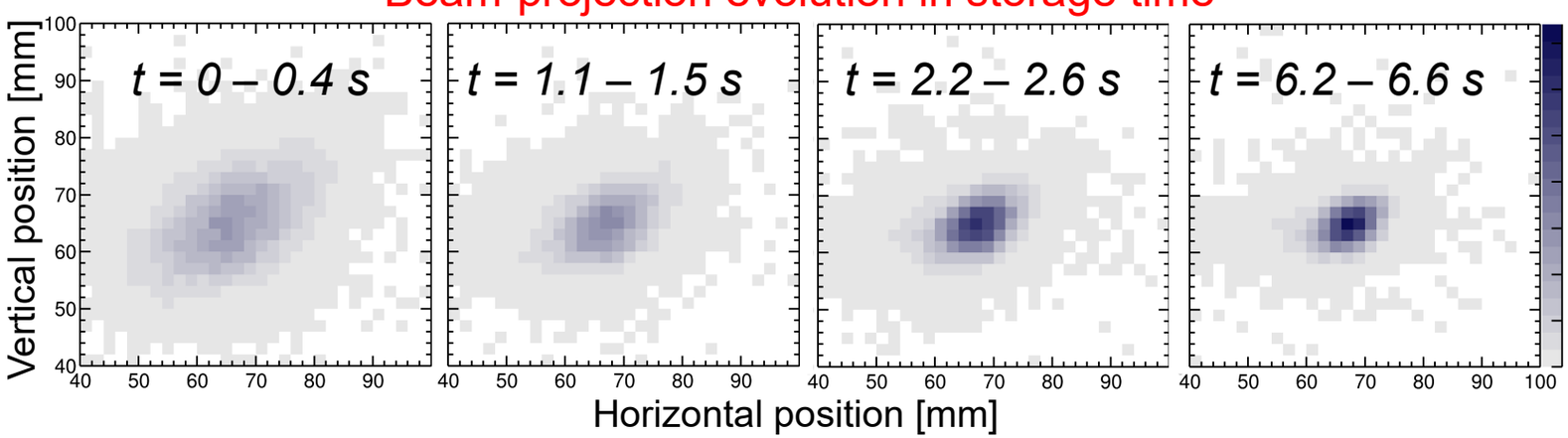
Fragment imaging
for transverse beam-profile measurements



Betatron amplitude cooling times



Beam-projection evolution in storage time



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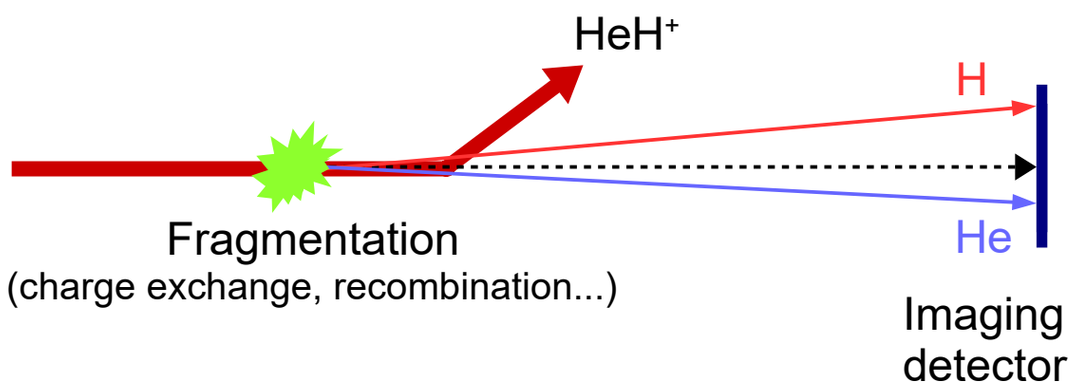
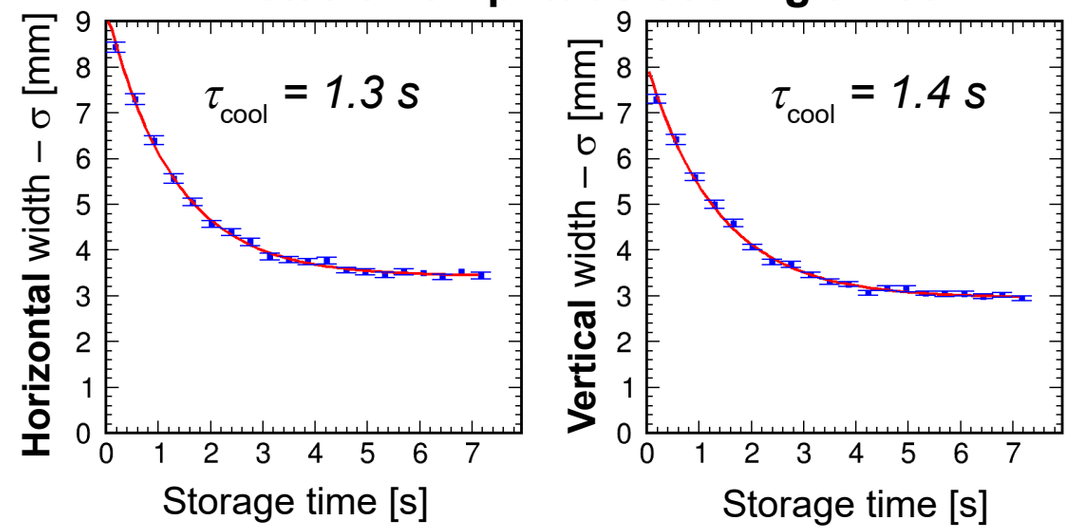
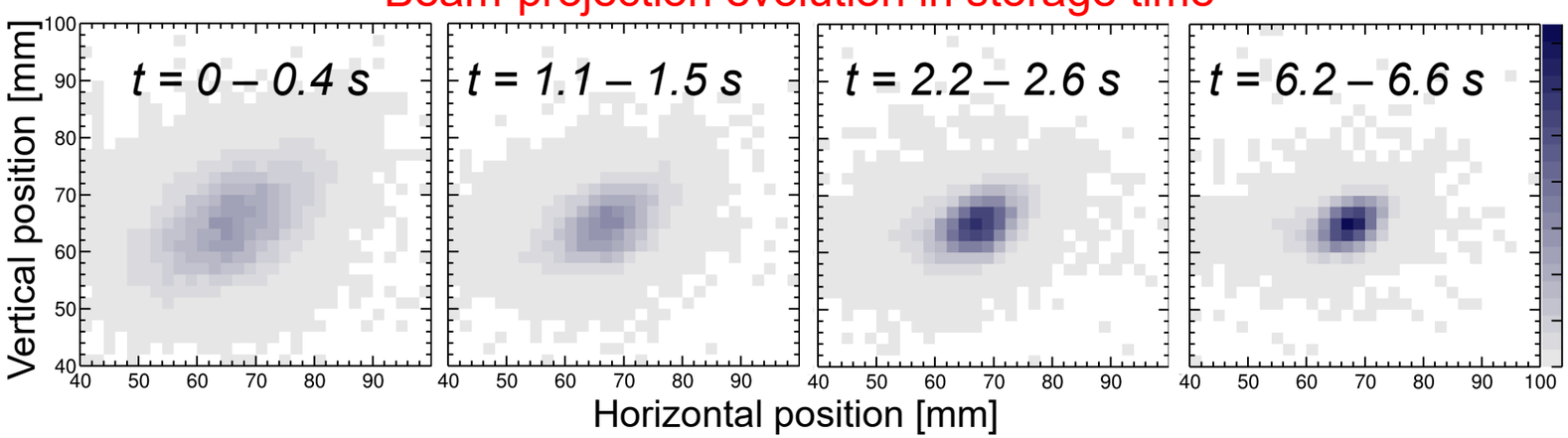


Betatron amplitude cooling times



Beam-projection evolution in storage time



First electron cooling in electrostatic storage ring!

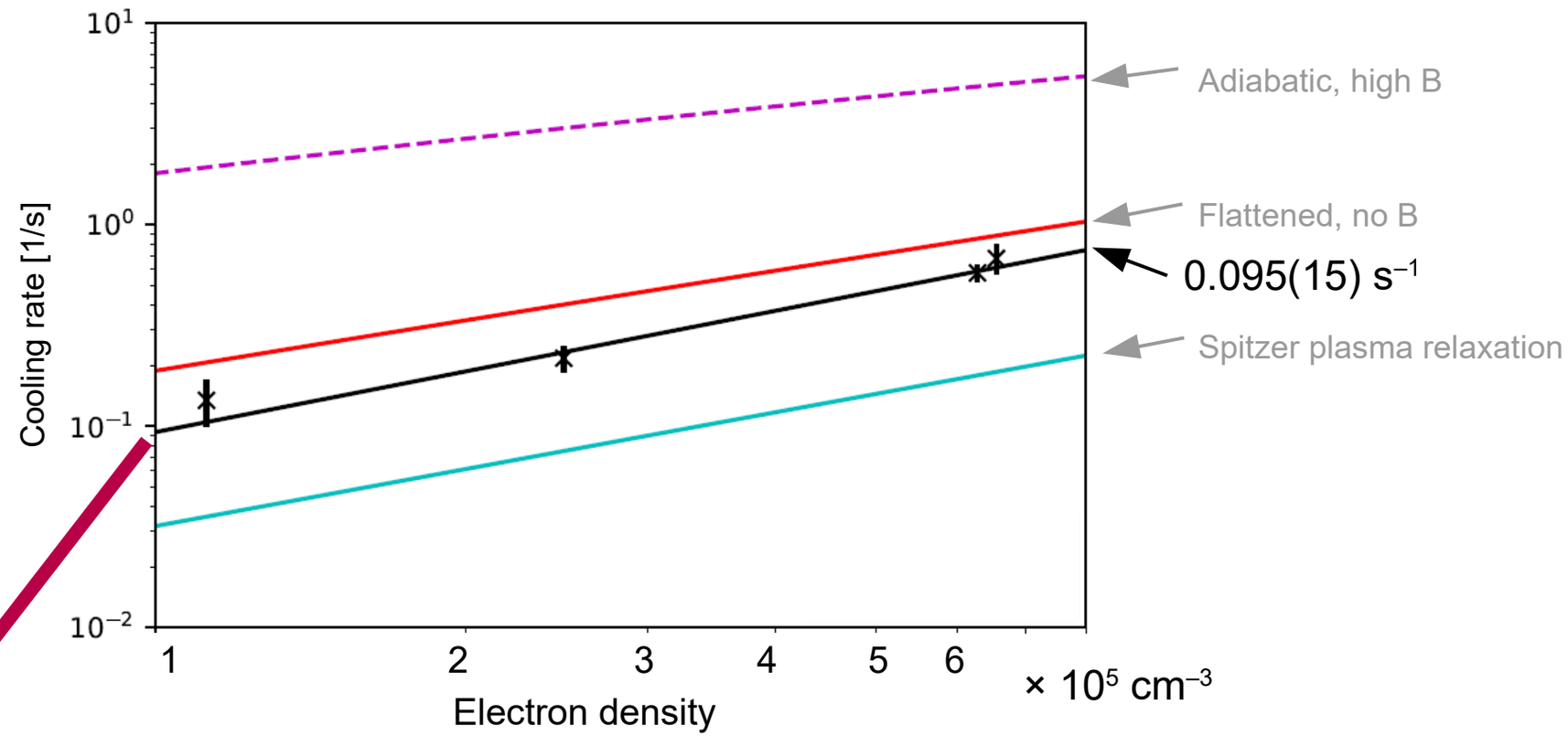
Previous lowest cooling energy:
E_{cool} = 30 eV
D_2Cl^+ (41 u/e) @ TSR

Electron cooling rates

P. Wilhelm
PhD thesis
Univ. Heidelberg
(2019)

HeH⁺ ions at 250 keV, **coasting (DC) beam**
E_{cool} = 27.3 eV, n_e = 3.7 × 10^5 cm^{-3}, N_i=2x10^7

B = 0.009 T (typ.)
$kT_\perp$ ~ 2 meV
$kT_\parallel$ ~ 0.1 meV
L_c/C_0 = 0.9/35 = 0.025



$$r_\parallel = 0.48(8)\,\mathrm{s}^{-1} \cdot \frac{q^2}{A} \cdot \frac{n_e}{10^5\,\mathrm{cm}^{-3}}$$

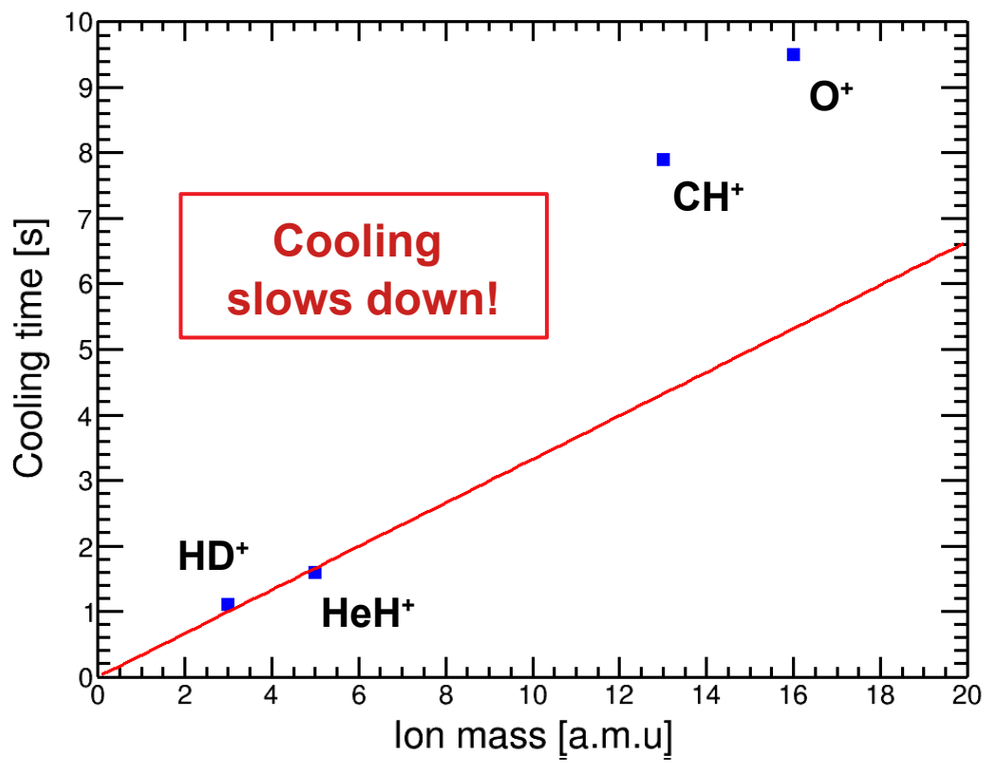
TSR: $r \approx 0.3 \ldots 0.9\,\mathrm{s}^{-1} \cdot \frac{q^2}{A} \cdot \frac{n_e}{10^5\,\mathrm{cm}^{-3}}$

Toward phase-space cooling of heavier ions

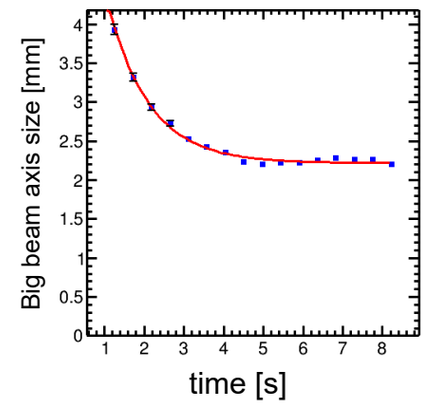
Plasma Model

$$\tau_{cool} \sim \frac{M \cdot T_e^{3/2}}{Z^2 \cdot n_e}$$

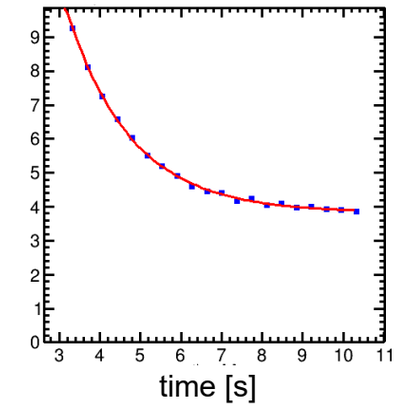
Cooling time vs. ion mass



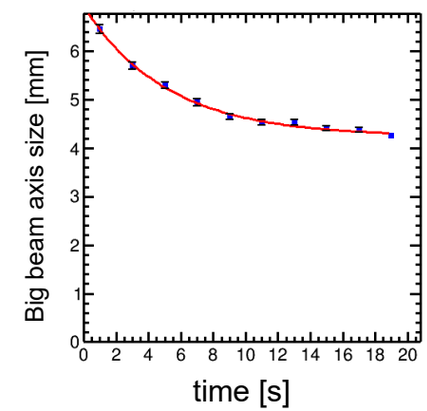
HD+



HeH+



CH+



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

No cooling reached!!!

Dispersive electron cooling / heating

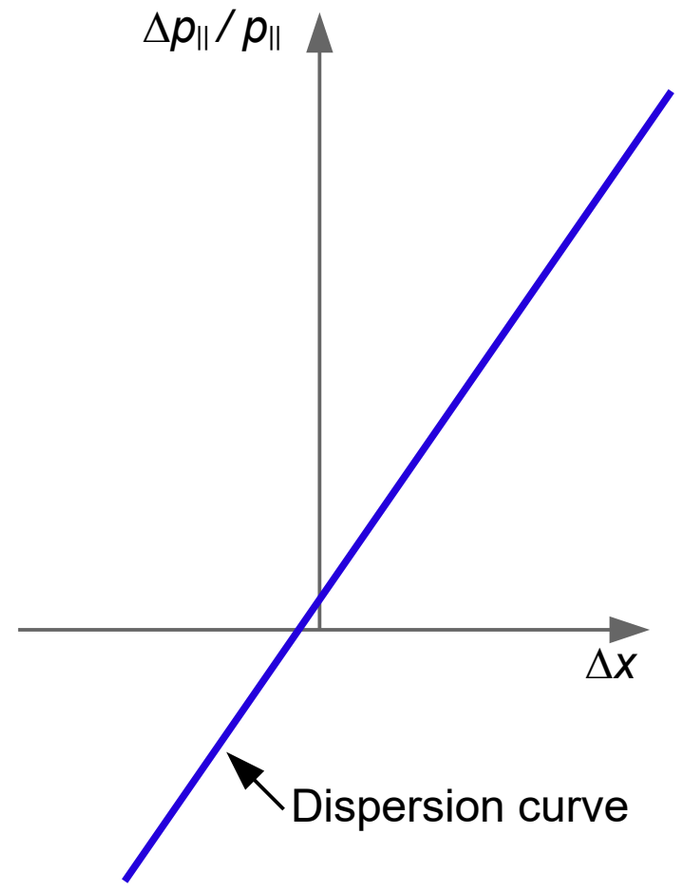
M. Grieser
MPIK

$$\Delta x = D_x \cdot \Delta p_{\|} / p_{\|}$$

Horizontal beam shift

Dispersion function

Longitudinal momentum change



Dispersive electron cooling / heating

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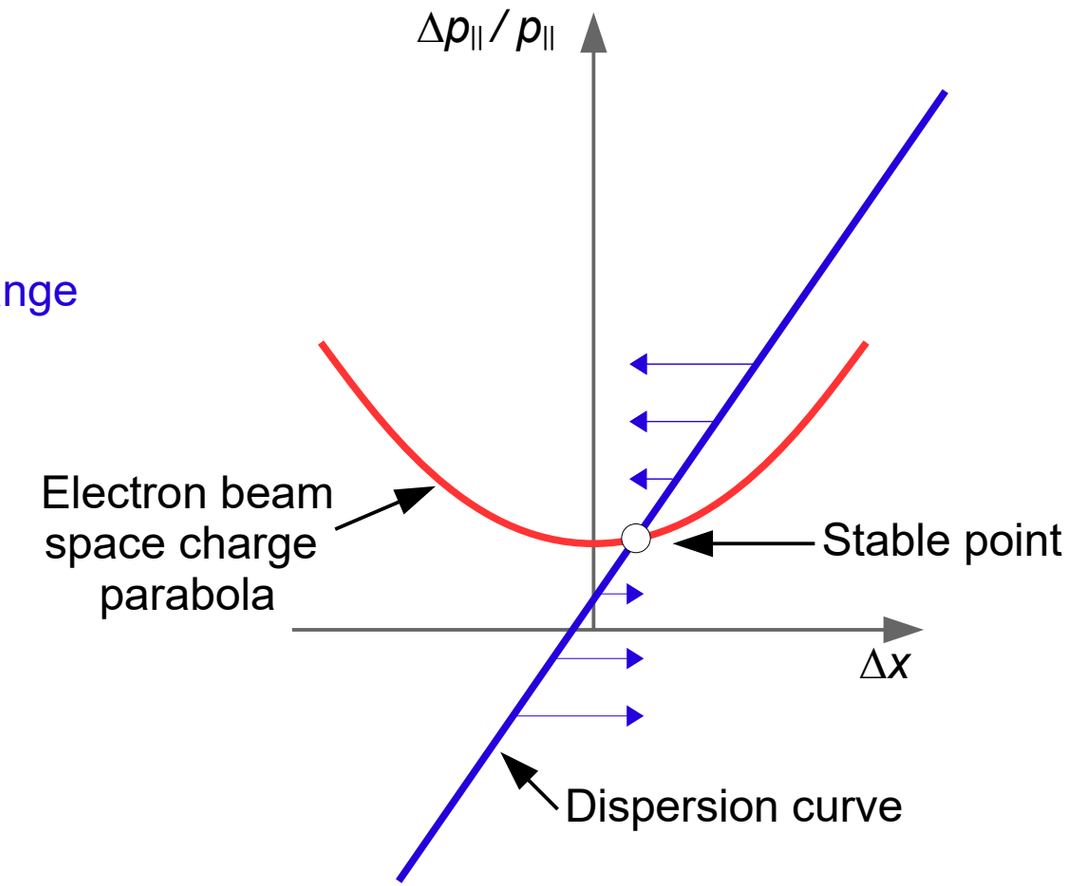


Electron beam self-shielding

→ Space charge profile

→ Ion beam dragging

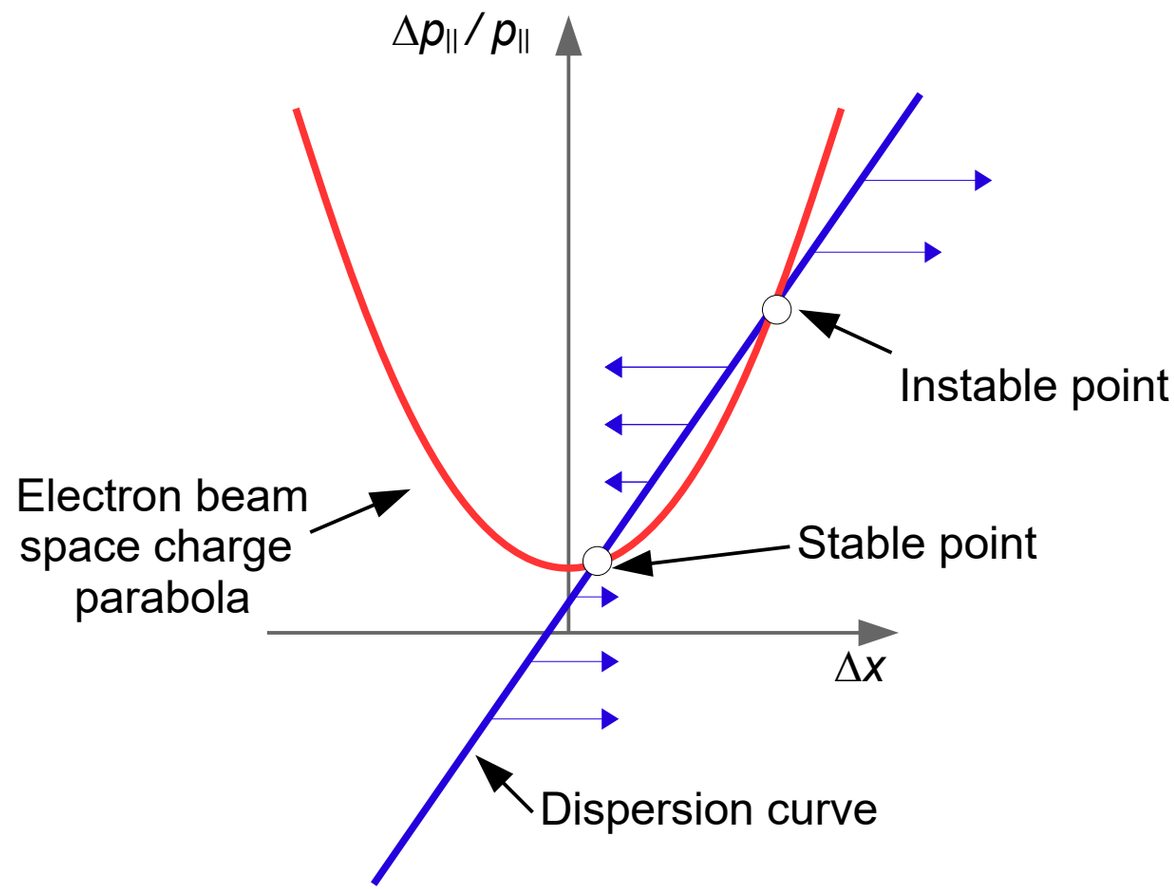
Dispersive electron cooling / heating

M. Grieser
MPIK

Low electron energies:

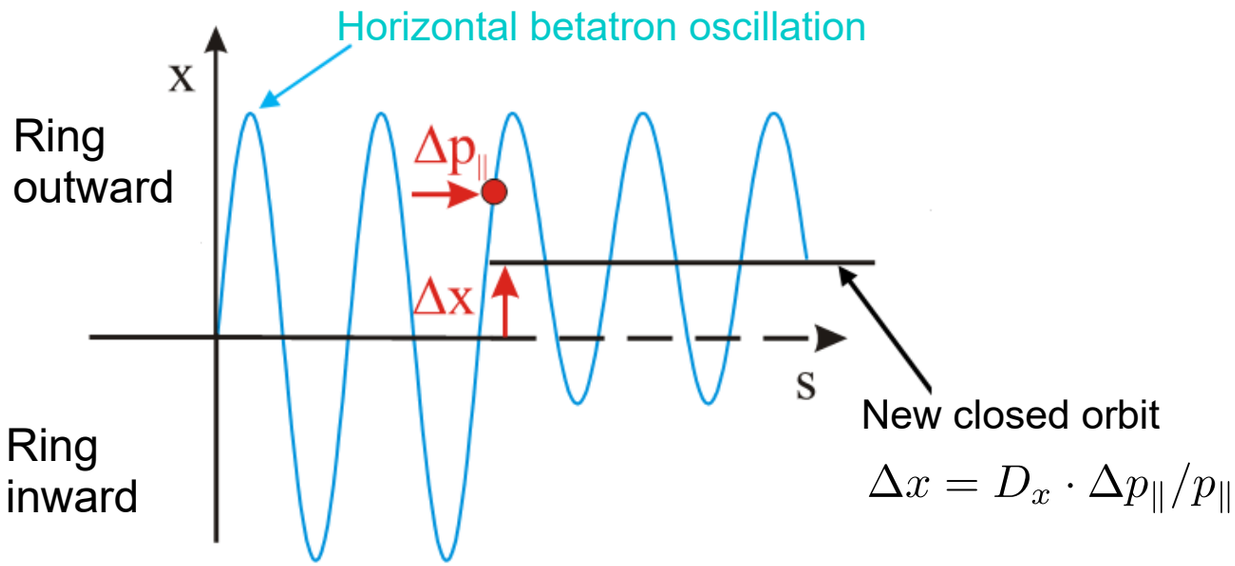
→ Deeper space charge parabola

→ Dispersive heating possible

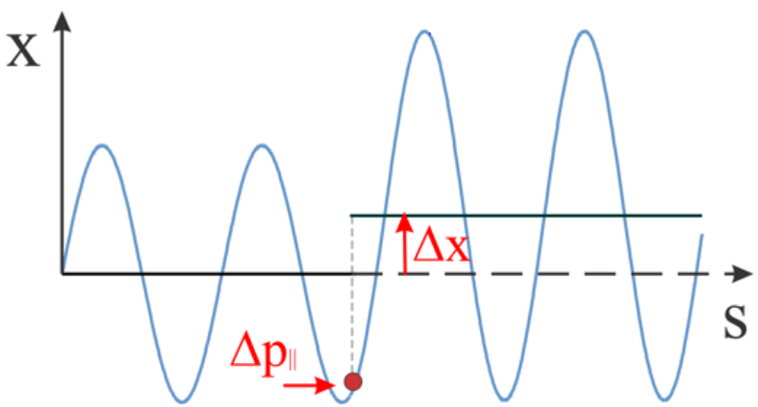


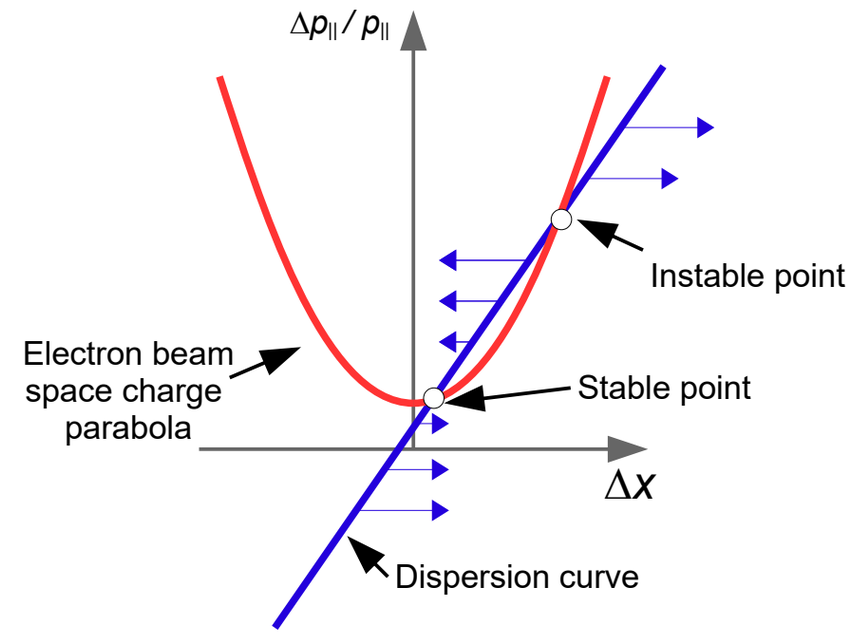
Dispersive electron cooling / heating

M. Grieser
MPIK



$$\Delta x = D_x \cdot \Delta p_{\parallel}/p_{\parallel}$$





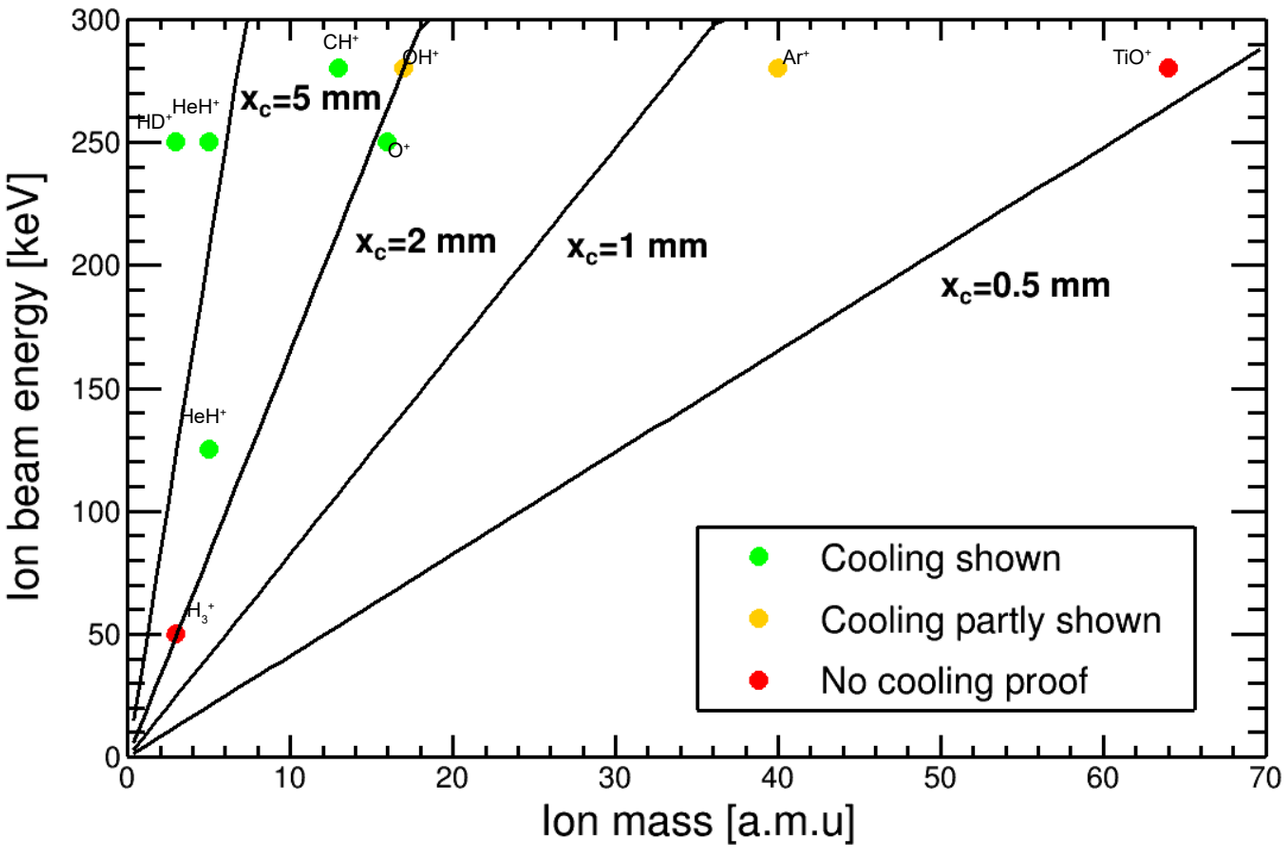
Gradient in cooling force

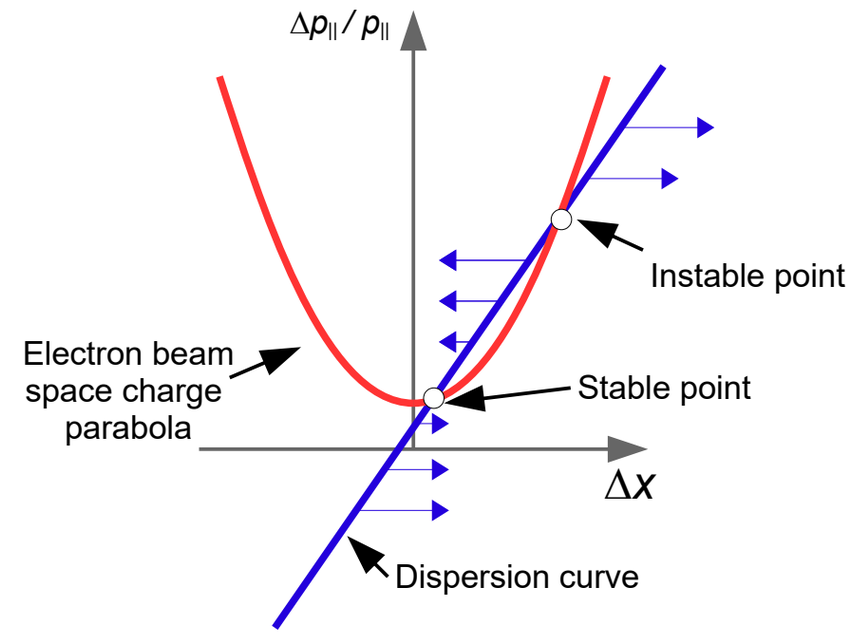
→

Exchange between longitudinal and horizontal degrees of freedom

Dispersive electron cooling / heating

M. Grieser
MPIK



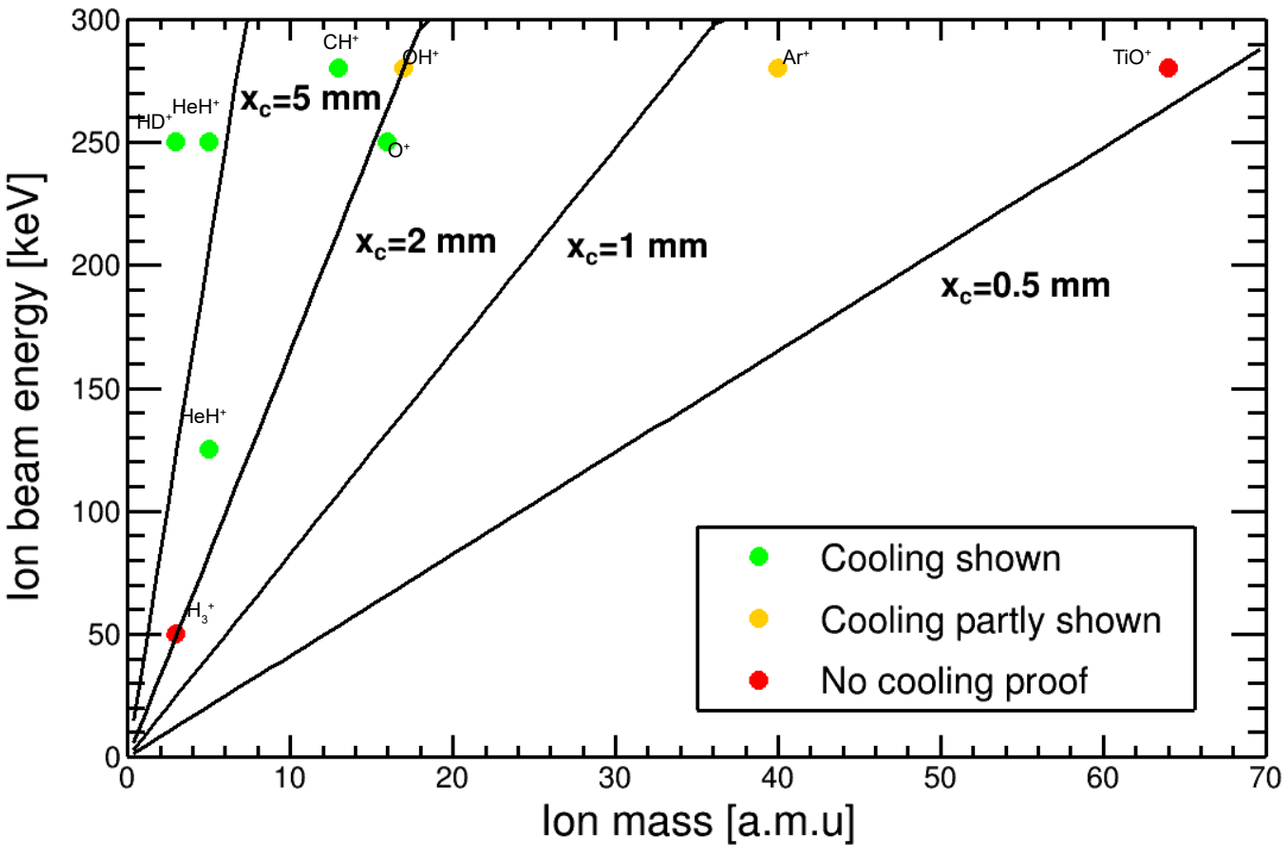


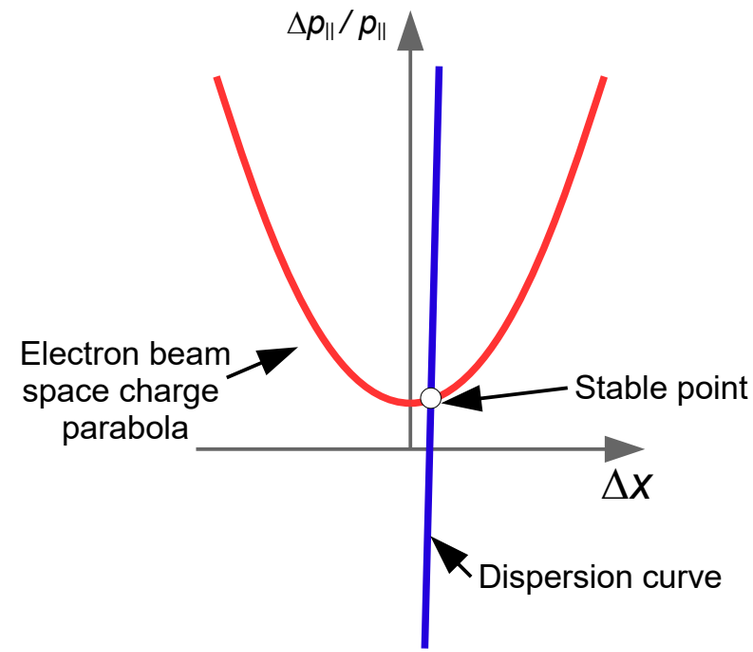
$$|x_c| \lesssim \frac{4E_e\varepsilon_0}{D_x e^2 n_e}$$

Dispersive heating above ion beam size limit

Dispersive electron cooling / heating

M. Grieser
MPIK





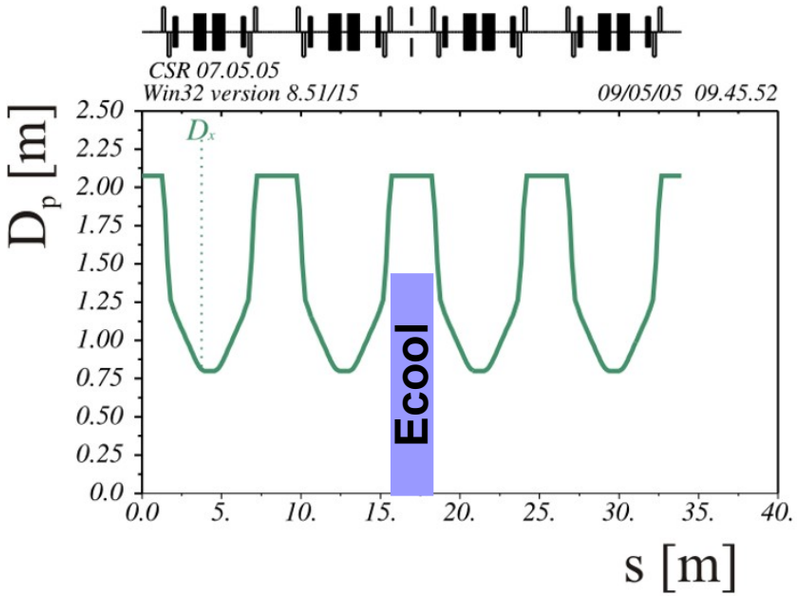
$$|x_c| \lesssim \frac{4E_e\varepsilon_0}{D_x e^2 n_e}$$

Solution: Achromat mode

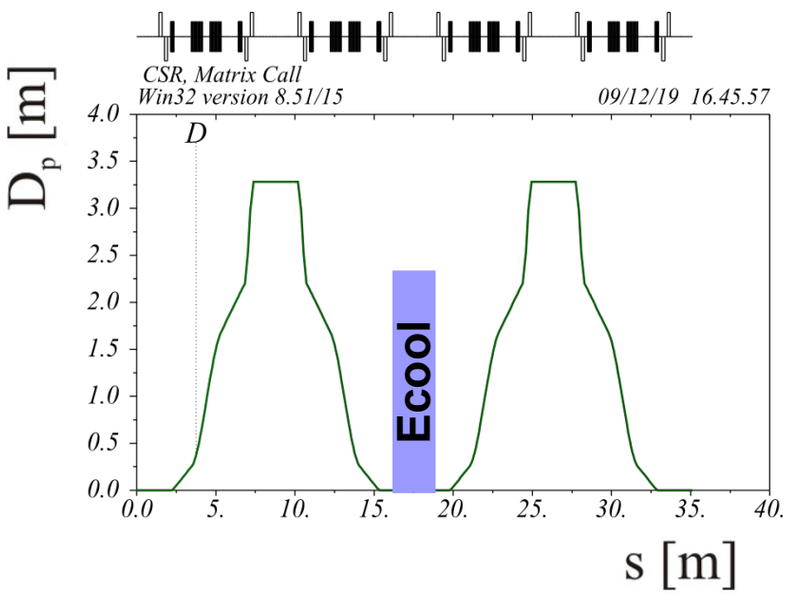
$\rightarrow D_x = 0$

Dispersive electron cooling / heating

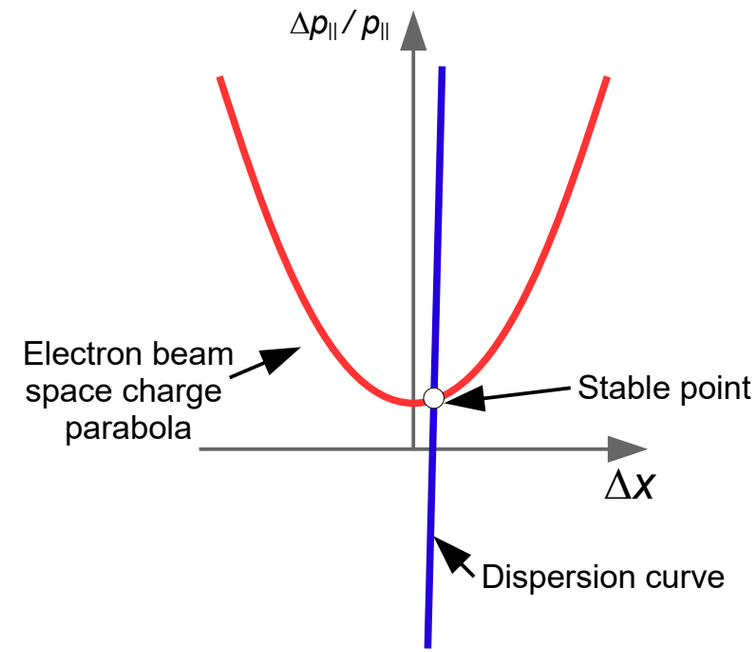
M. Grieser
MPIK



Standard mode

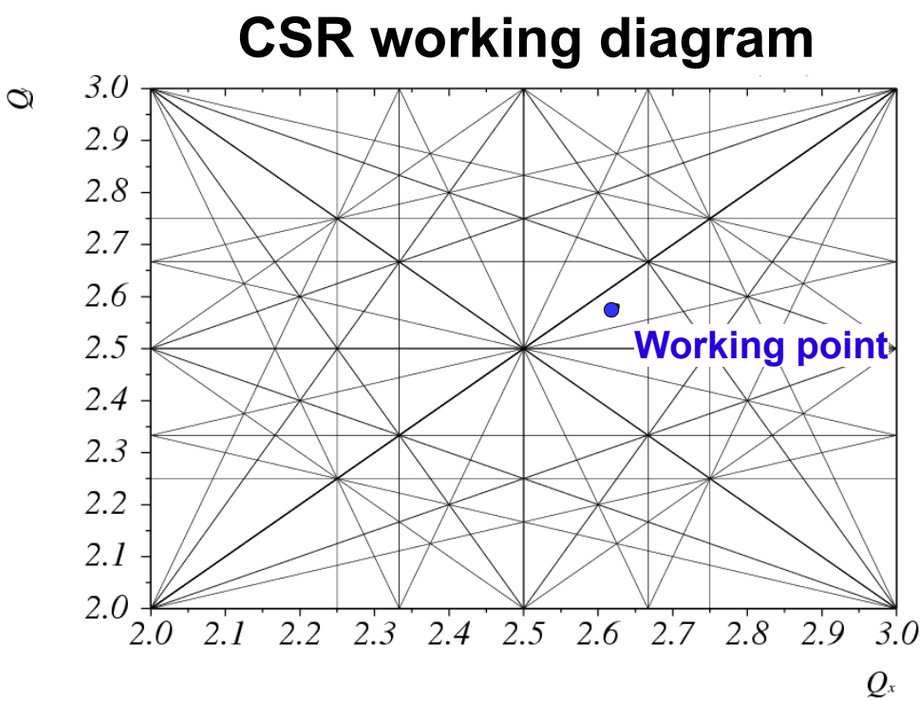


Achromat mode



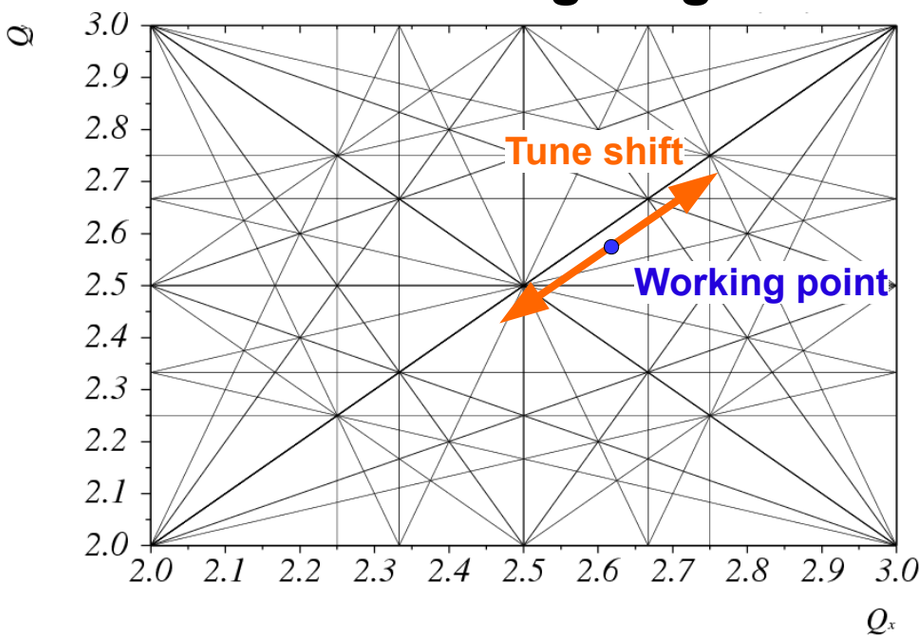
- 2 → 4 quadrupole families
- Zero dispersion in e-cooler
- Fixed cooling geometry!

Working point studies - tune shifts



Working point studies - tune shifts

CSR working diagram



Electron-beam induced tune shifts:

→ **Electron beam lensing**

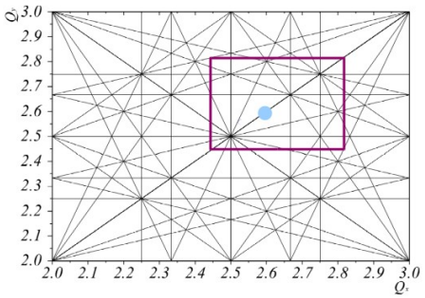
(E-beam presence)

→ **Ion beam coulomb repulsion**

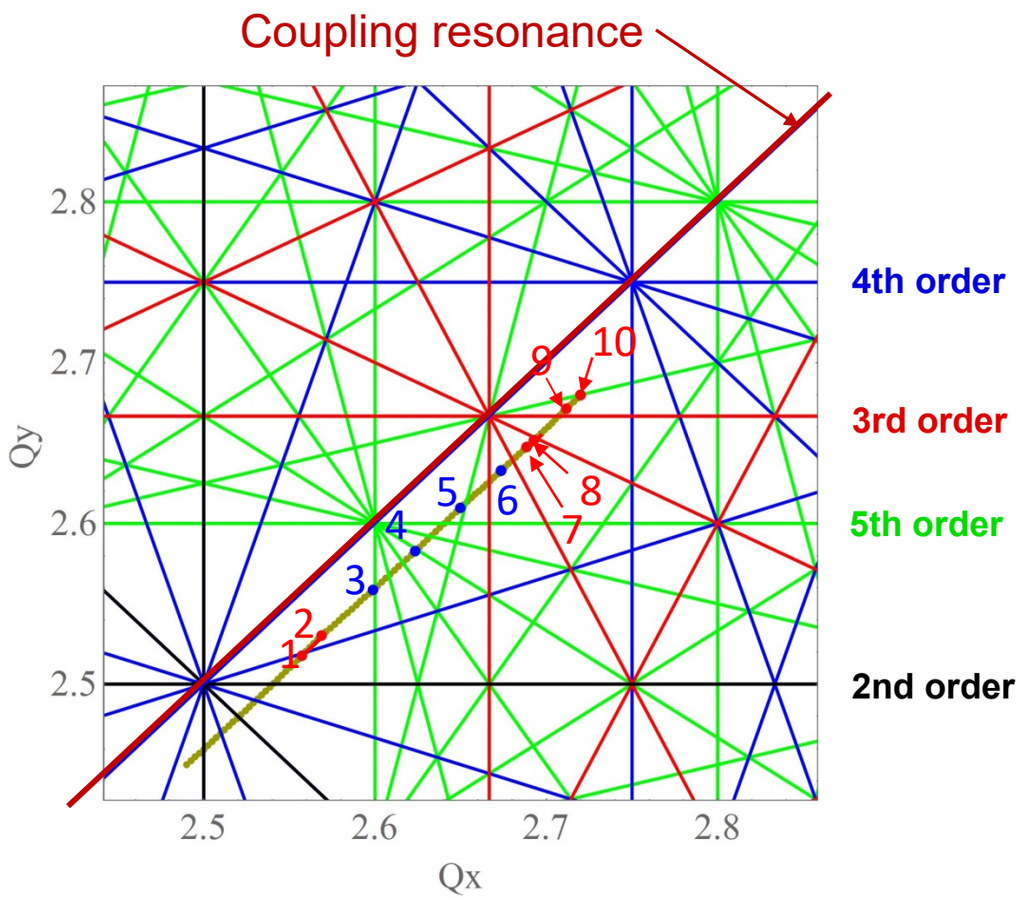
(Electron cooling condition)

→ **Both scale with $1/E_{ion}$!**

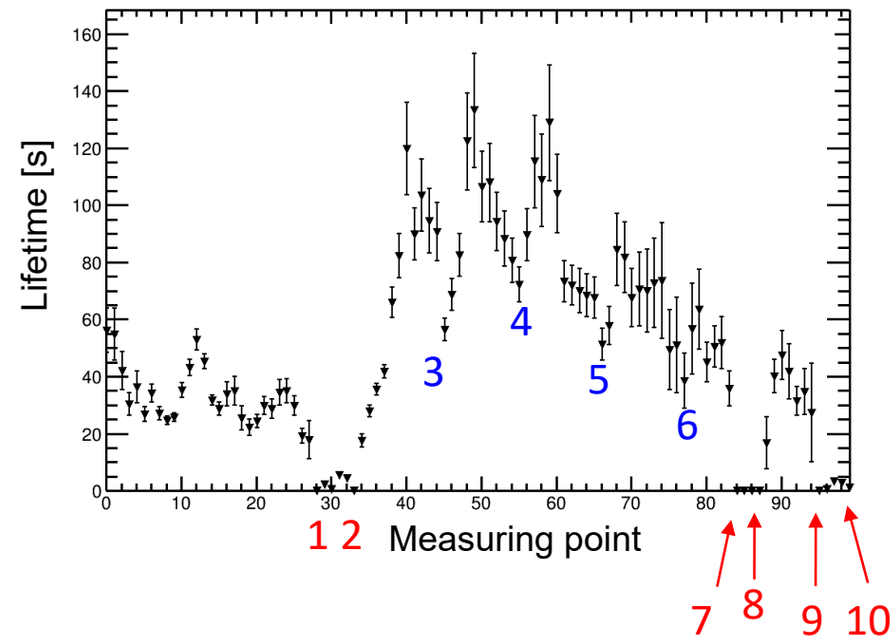
Working point studies - tune shifts



CH^+ @ 280 keV,
coasting (DC) beam
N_i=2x10^5

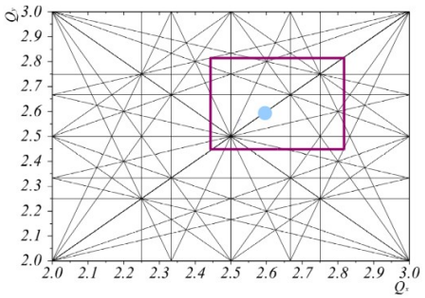


No electron beam, no fields



Sensitive to
5th order resonances!

Working point studies - tune shifts



CH^+ @ 280 keV,
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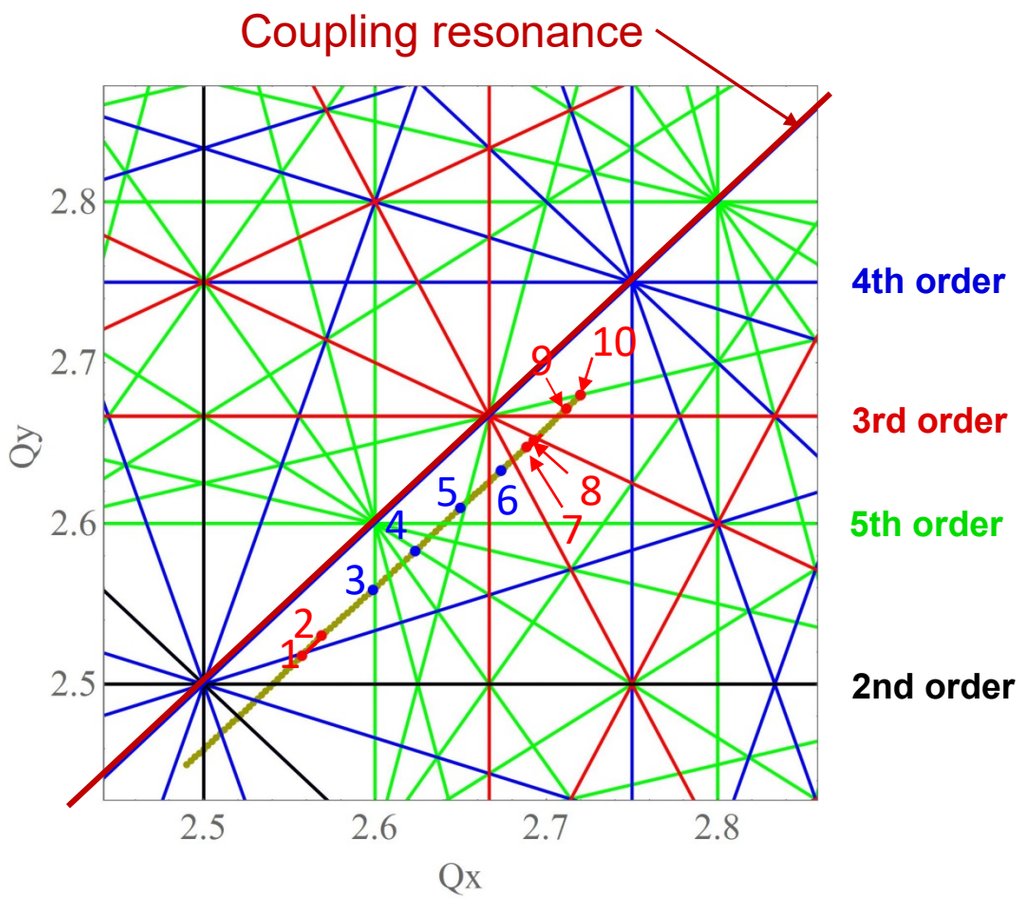
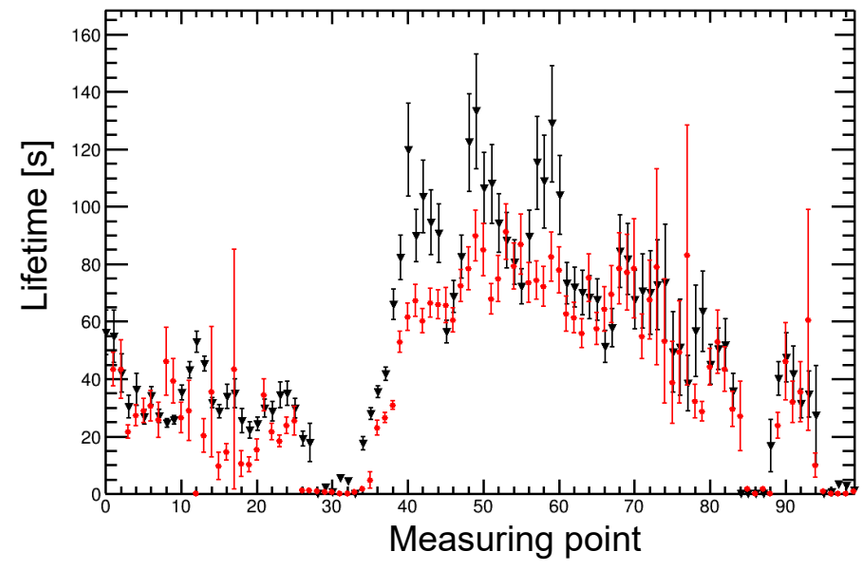
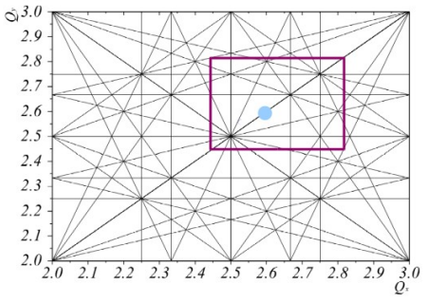


No electron beam, fields on

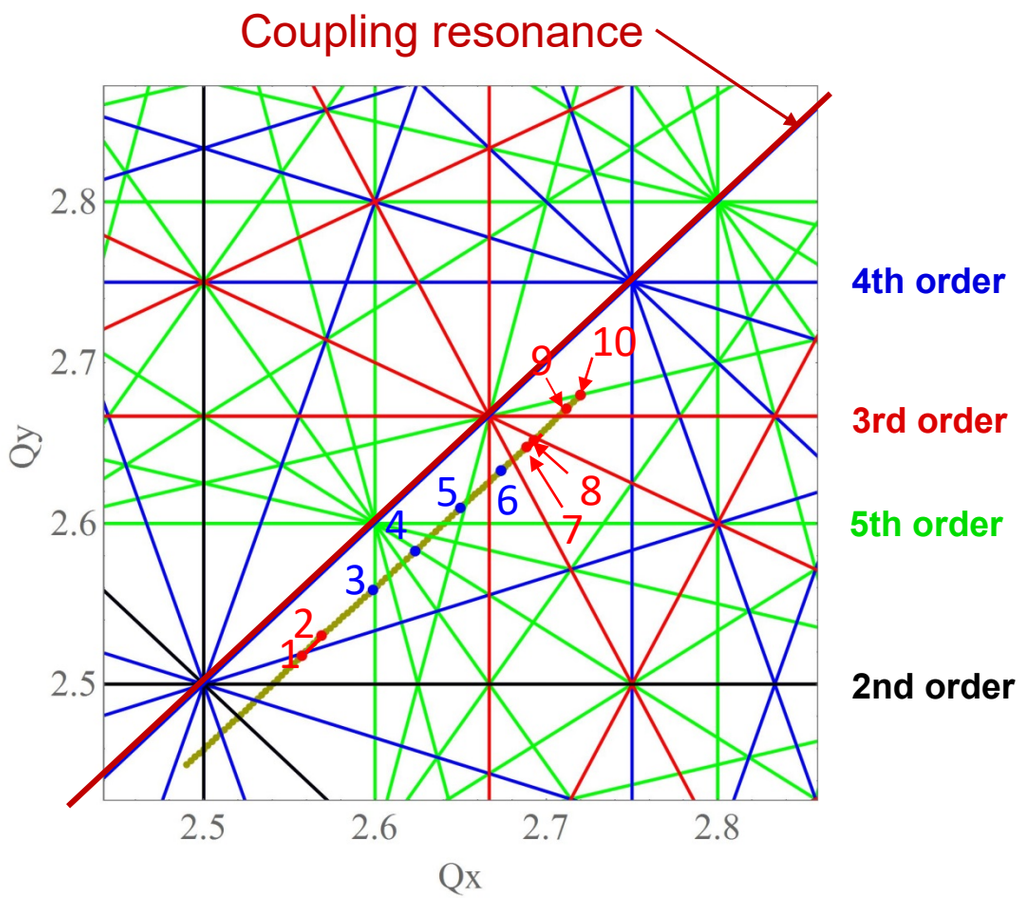
No electron beam, no fields



Working point studies - tune shifts



CH^+ @ 280 keV,
coasting (DC) beam
N_i=2x10^5

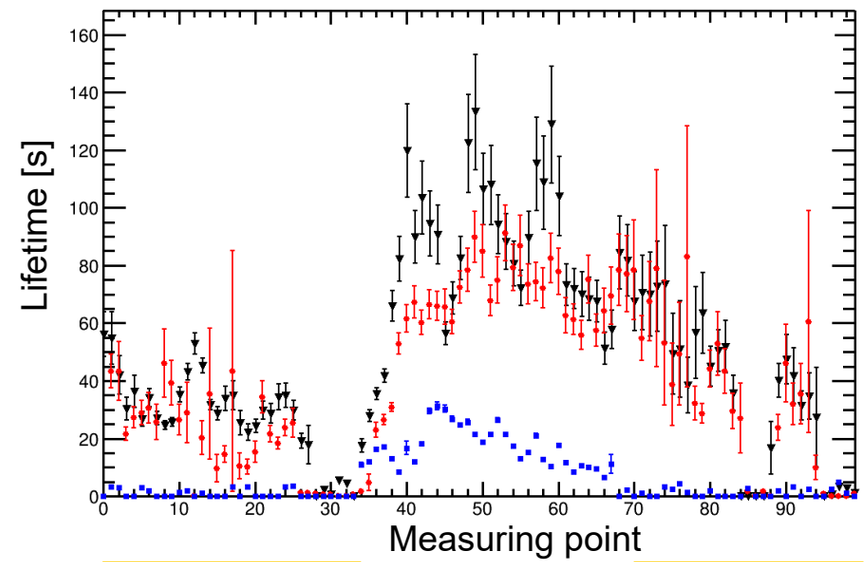


Electron beam on, fields on

No electron beam, fields on

No electron beam, no fields

E_e = 11.8 eV
n_e ~ 6 × 10^5 cm^{-3}



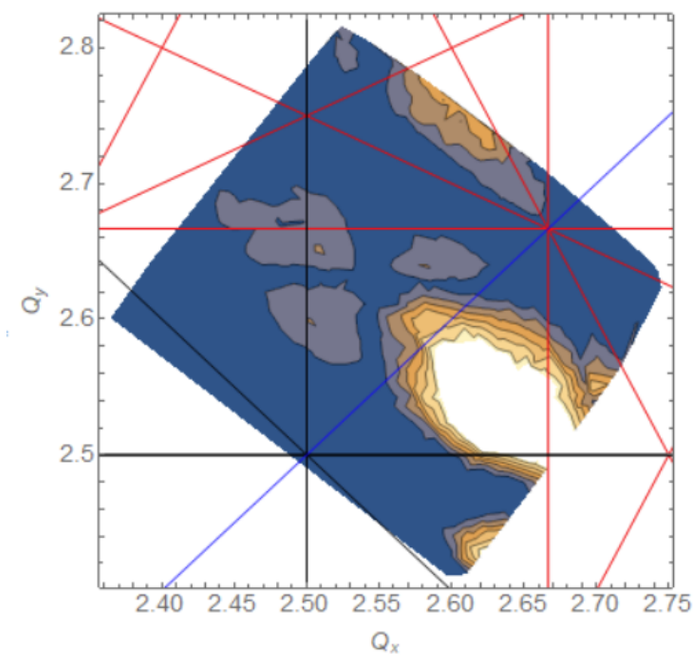
No storage possible

Slow intense ion beams

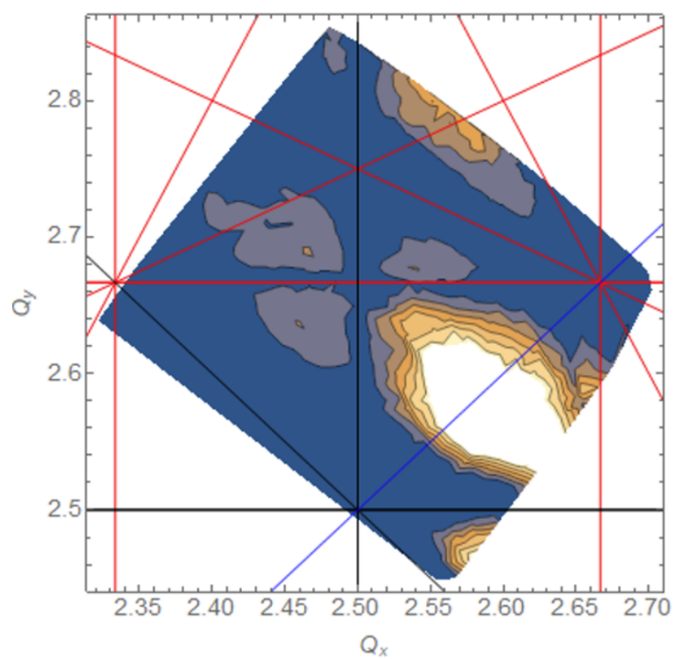
HeH^+ @ 85 keV, N_i~1x10^8

Earth magnetic field!

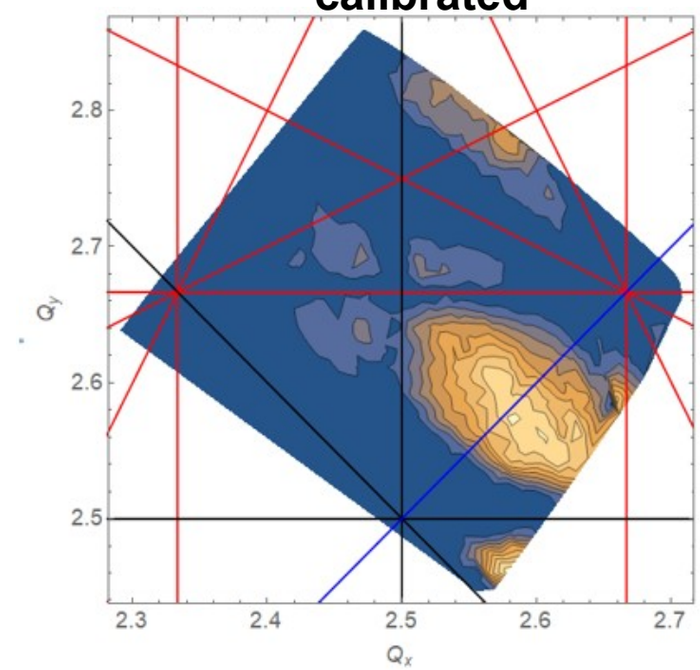
No electron beam, fields on



No electron beam, fields on calibrated



Electron beam on, fields on calibrated



Higher order corrections needed

Low-energy electron cooling – pushing the limits

Pre-CSR lowest cooling energy:

E_{cool} = 30 eV

D_2Cl^+ (41 u/e) @ TSR

Low-energy electron cooling – pushing the limits

Pre-CSR lowest cooling energy:

E_{cool} = 30 eV

D_2Cl^+ (41 u/e) @ TSR

Also electron-cooled:

HeH^+	85 keV
HD^+	250 keV
O^+	250 keV
CH^+	280 keV
OH^+	280 keV
F^{6+}	1.68 MeV
ArH^+	300 keV
CF^+	300 keV
Ne^{++}	600 keV
Xe^{+++}	900 keV
H_2D^+	300 keV
D_2H^+	300 keV

...

Xe^{+++} @ 900 keV

Mass	= 129 u → 43 u/e
E_{cool}	**= 3.8 eV**
n_e	= 4×10^5 cm^{-3}
N_{ion}	= 3×10^7

Slowest electron-cooled ion beam!

Low-energy electron cooling – pushing the limits

Pre-CSR lowest cooling energy:

***E_{cool}* = 30 eV**

D_2Cl^+ (41 u/e) @ TSR

Also electron-cooled:

HeH^+	85 keV
HD^+	250 keV
O^+	250 keV
CH^+	280 keV
OH^+	280 keV
F^{6+}	1.68 MeV
ArH^+	300 keV
CF^+	300 keV
Ne^{++}	600 keV
Xe^{+++}	900 keV
H_2D^+	300 keV
D_2H^+	300 keV

...

Xe^{+++} @ 900 keV

Mass	= 129 u → 43 u/e
E_{cool}	**= 3.8 eV**
n_e	= 4×10^5 cm^{-3}
N_{ion}	= 3×10^7

ArH^+ @ 300 keV

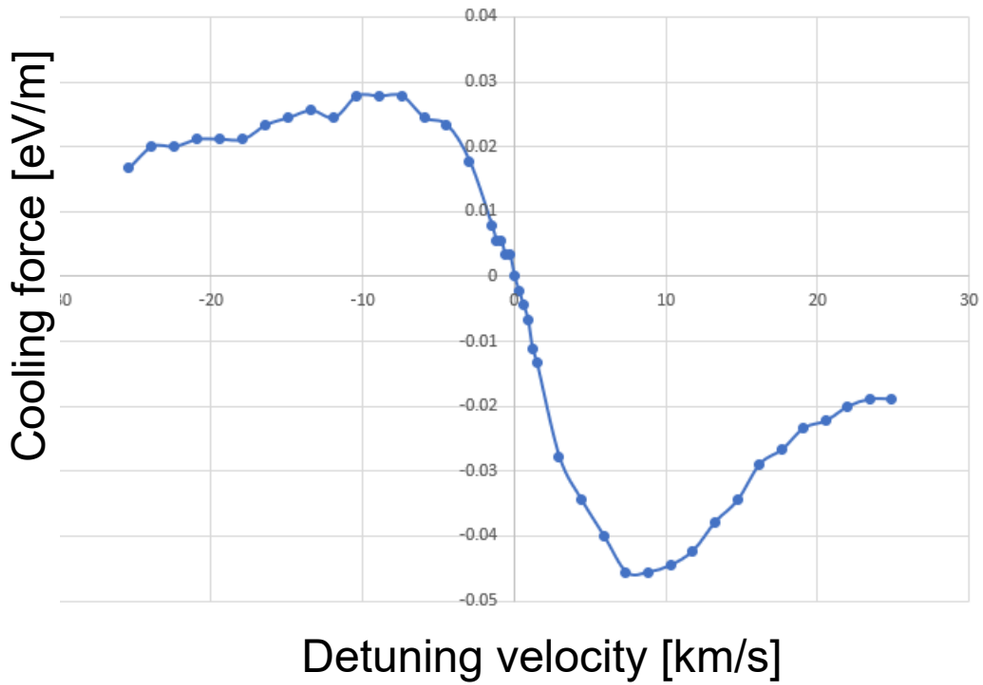
Mass	= 41 u
E_{cool}	**= 4.0 eV**
n_e	= 4.1×10^5 cm^{-3}
N_{ion}	= 7×10^6

HeH^+ @ 85 keV

Mass	= 5 u
E_{cool}	= 9.3 eV
N_e	= 2.5×10^5 cm^{-3}
N_{ion}	**= 1×10^8**

Low-energy electron cooling – supporting techniques

Cooling force measurement
(bunch-phase-shift method)

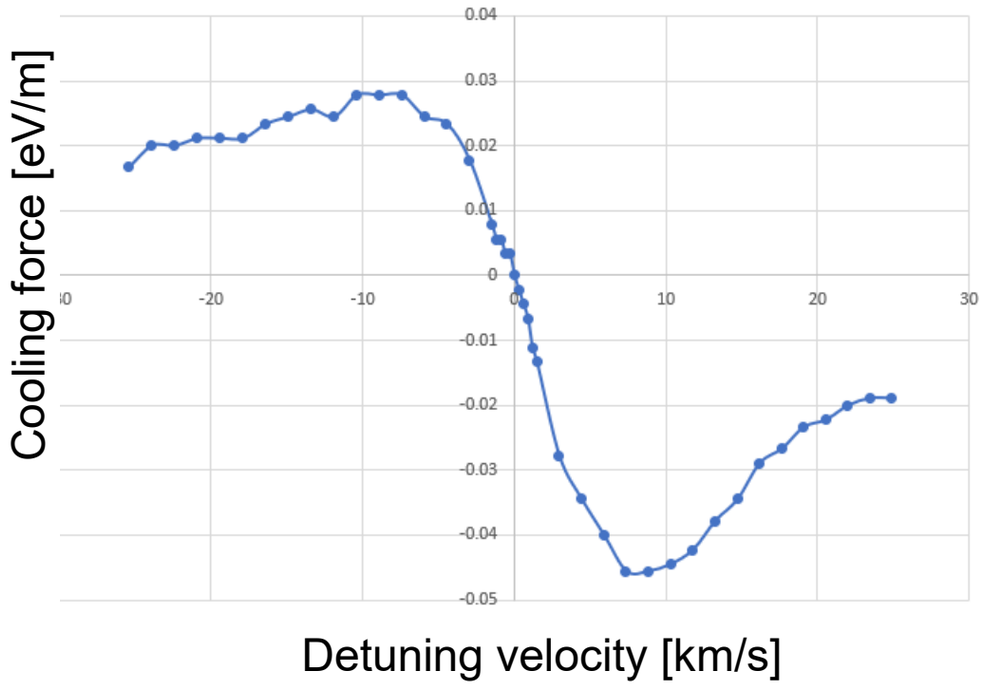


Method: Caussyn et al. Phys. Rev. Lett. 73, 2696–2699 (1994).

Jonas Bechtel
Bc thesis
Univ. Heidelberg (2022)

Low-energy electron cooling – supporting techniques

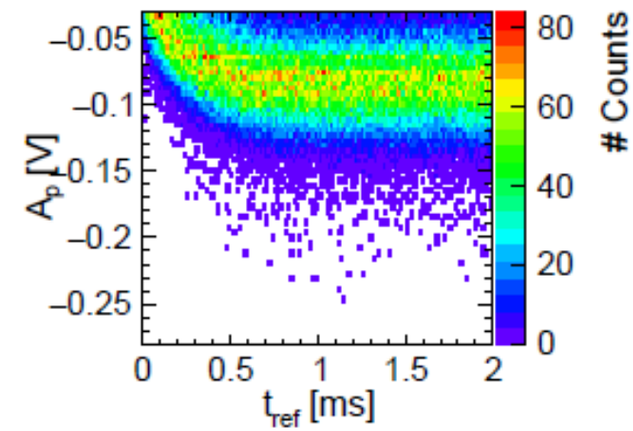
Cooling force measurement
(bunch-phase-shift method)



Method: Caussyn et al. Phys. Rev. Lett. 73, 2696–2699 (1994).

Jonas Bechtel
Bc thesis
Univ. Heidelberg (2022)

Enhanced dynamic range of cryogenic MCP detector

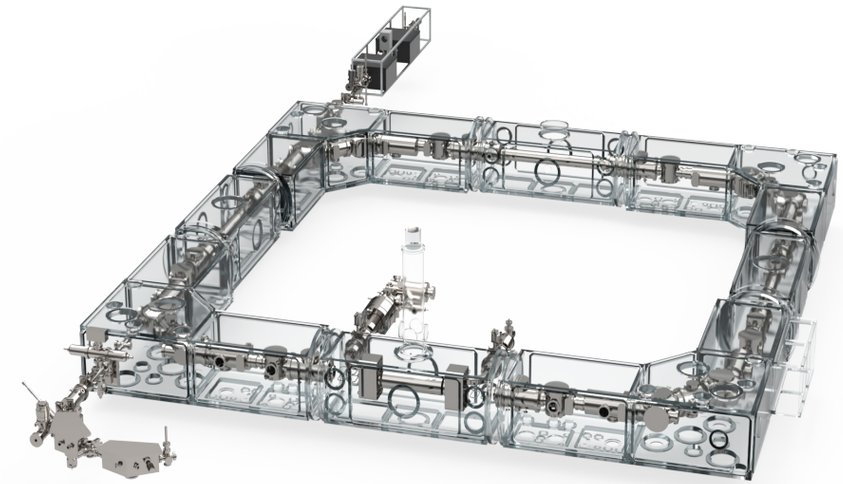


10^5 s^{-1} impact rates, also for imaging

Fast MCP bias voltage switching avoids saturation

Selina Gaisser
Bc thesis
Univ. Heidelberg (2022)

Ultra-low-energy electron-cooling at CSR



- The CSR facility
- Low energy electron-cooling challenges
- CSR electron cooler
- Electron cooling performace
- **Inelastic “electron cooling”**

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Inelastic electron collisions with molecular ions

$$AB^+ + e^- \rightarrow AB^{**}$$

Reactive collisions
(Dissociative Recombination)

$$A + B$$

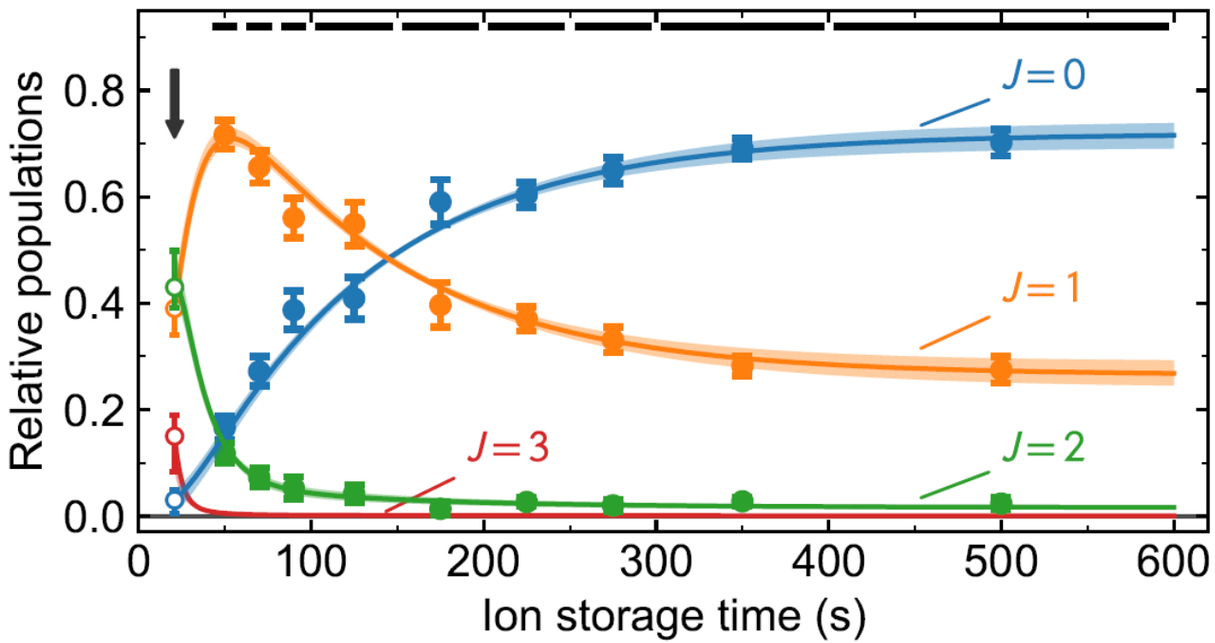
$$AB^+ + e^-$$

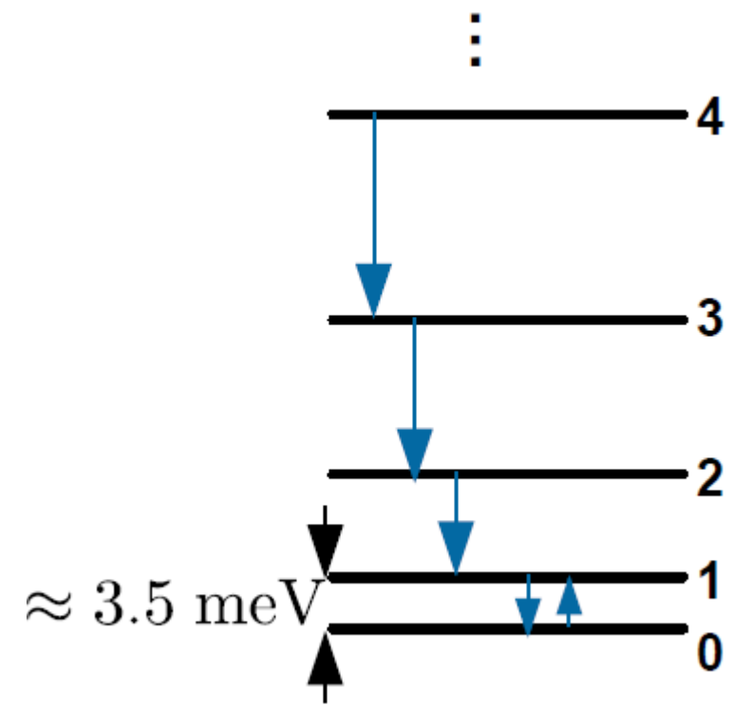
Internal-state-changing collisions

Radiative cooling of CH^+

Probing by resonant photodissociation

$$CH^+(J) + h\nu \rightarrow C^+ + H$$



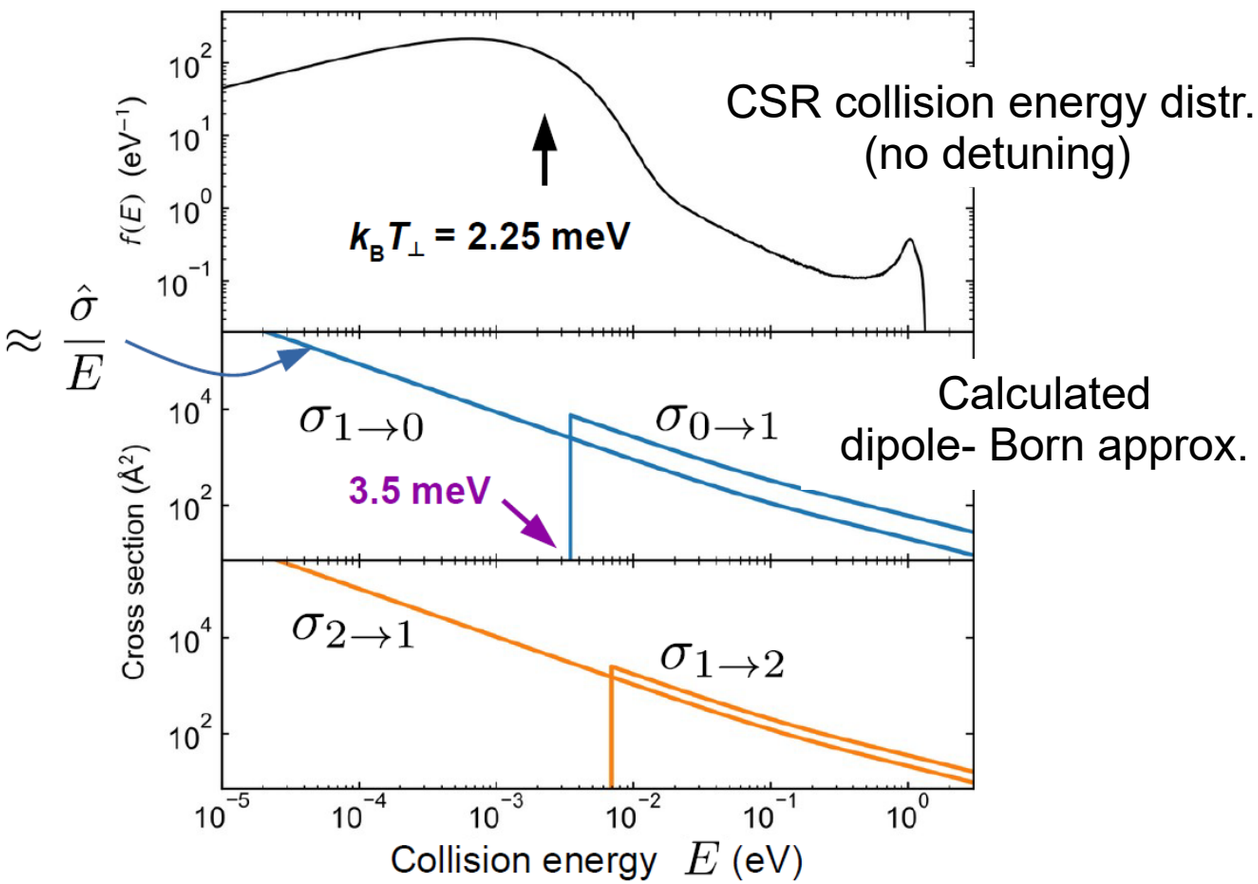


Eff. black body temperature ~17K

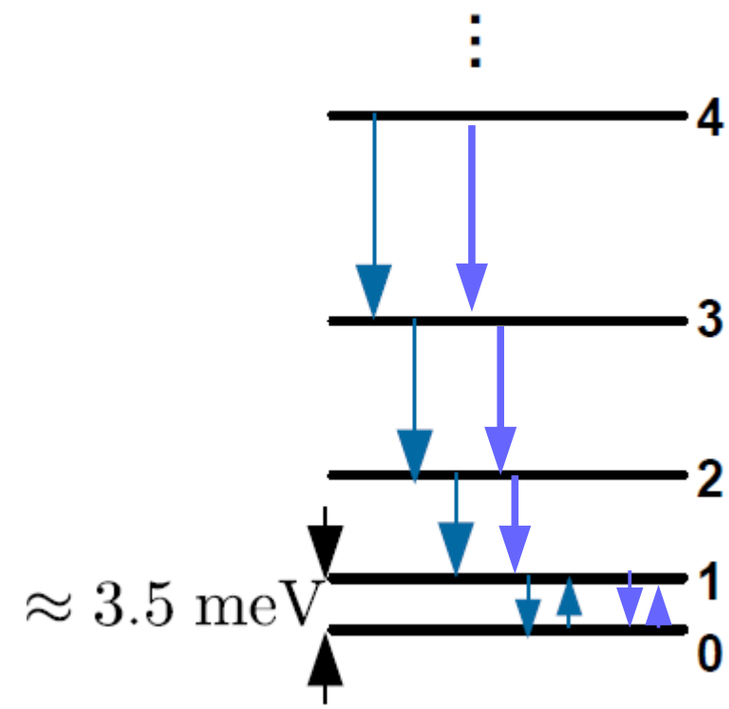
O'Connor et al., Phys. Rev. Lett. 116 (2016) 113002

Inelastic electron-CH⁺ collisions

$CH^+(J) + e^- \rightarrow CH^+(J') + e^-$

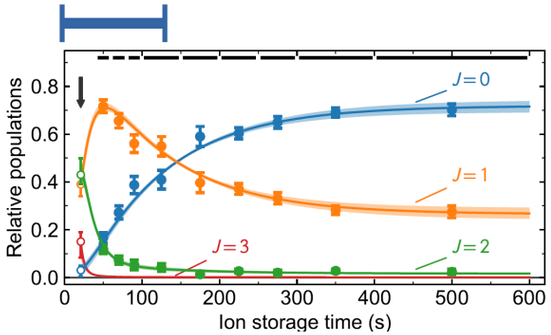


Electron induced Rotational cooling

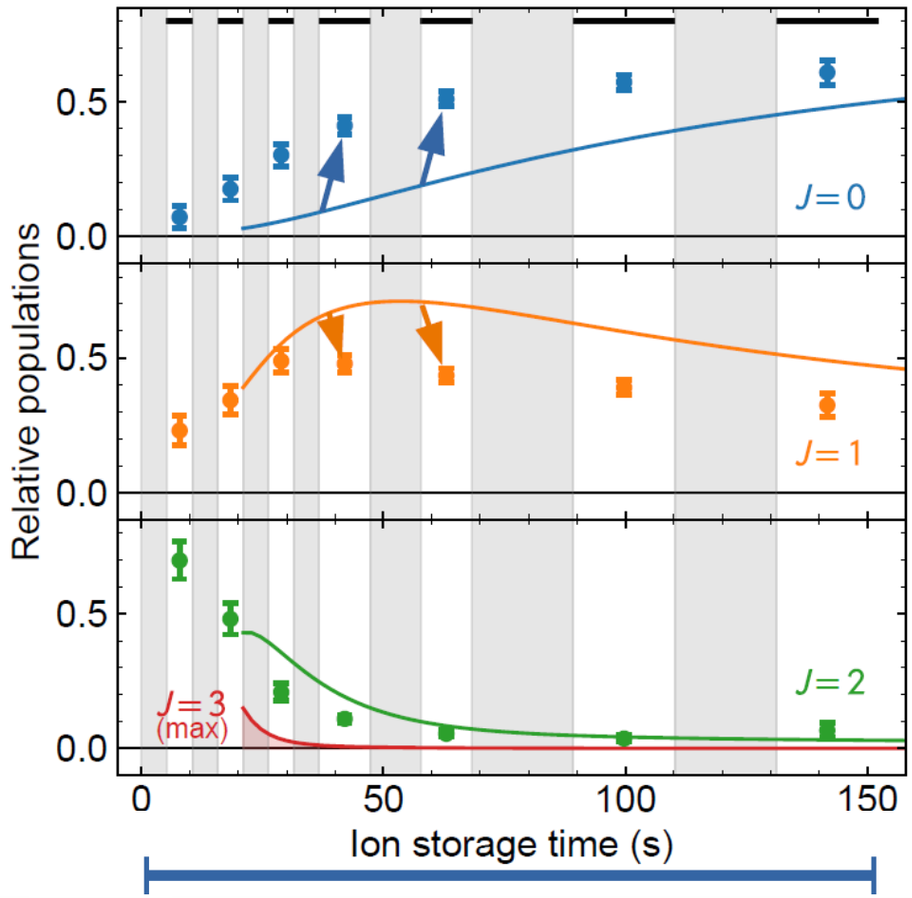


Eff. black body temperature ~17K

Rotational electron cooling measurement



> 50% in J = 0:
~150 s without electrons
~ 50 s with electrons



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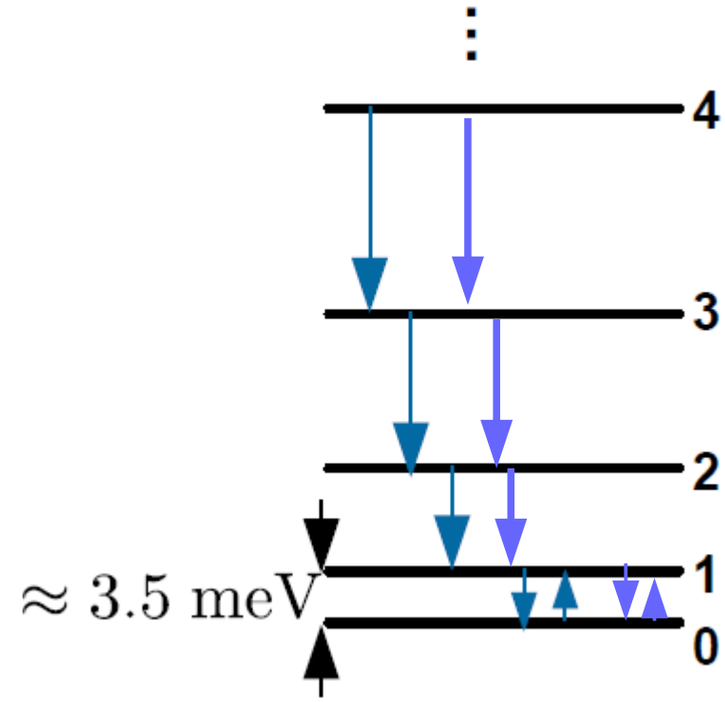
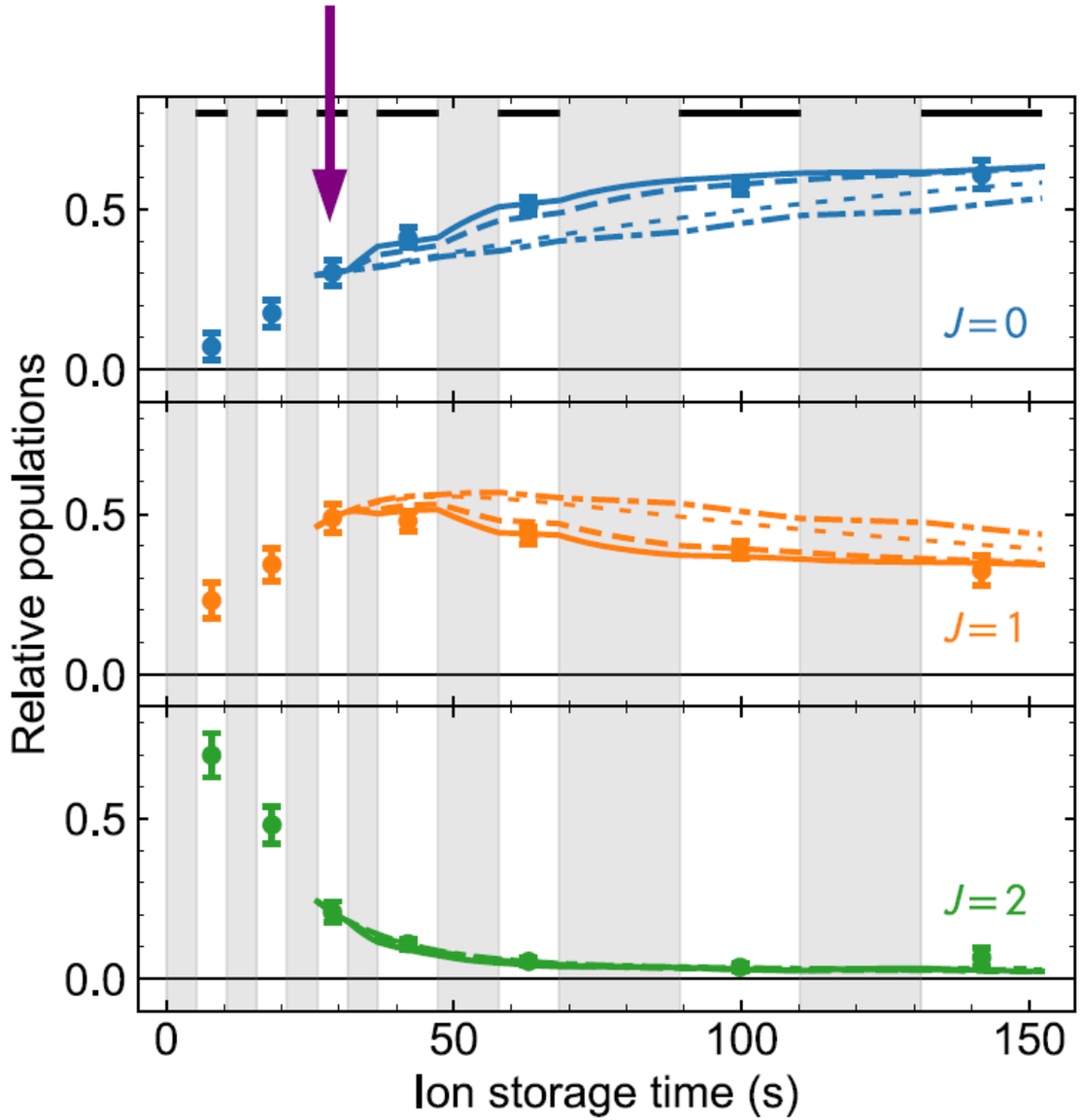


Eff. black body temperature ~17K

Modeling with theoretical collision cross sections



Dashed: Inelastic collisions in Coulomb–Born approximation

Full: Inelastic collisions from recent *R*-matrix molecular calculations

J. R. Hamilton, A. Faure, and J. Tennyson, Mon. Not. R. Astron. Soc. 455, 3281 (2016).

First quantitative measurement

In-ring cooling of ions without dipole moment possible

Á. Kálosi et al., *PRL* **128**, 183402 (2022)

CSR experiments with low-energy electron beams

CSR experiments with low-energy electron beams

… are challenging

Experimental wishes

- Long storage times
- Strong ion beam
- Phase space compression
- Inelastic electron collision cooling

Electron cooling

- Is slow
- Tune shifts
- Recombination depletion
- ...

→ **Complex measurement schemes**
(timing, E_e, n_e, ...)

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→ **Complex measurement schemes**
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… but well possible!

$HeH^+ + e^-$ (dissociative recombination)
O. Novotny et al., *Science* **365,** 676-679 (2019)

$CH^+ + e^-$ (inelastic electron collisions)
Á. Kálosi et al., *PRL* **128**, 183402 (2022)

$CH^+ + e^-$ (dissociative recombination)
D. Paul et al., *ApJ* **939**, 122 (2022)

$OH^+ + e^-$ (dissociative recombination)
Á. Kálosi et al., to be submitted in ApJ

Papers in preparation:

$ArH^+ + e^-$ **$CF^+ + e^-$**

$H_2D^+ + e^-$ **$D_2H^+ + e^-$**

Student / Post-doc positions open!

The CSR Team

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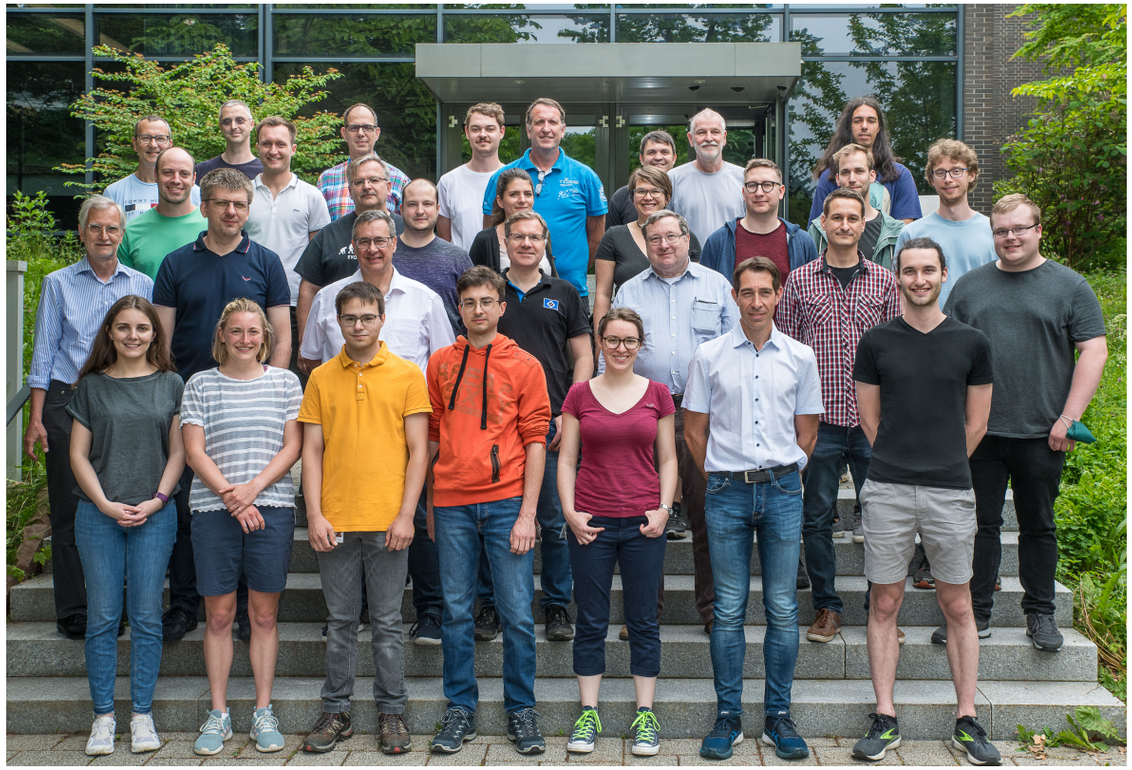

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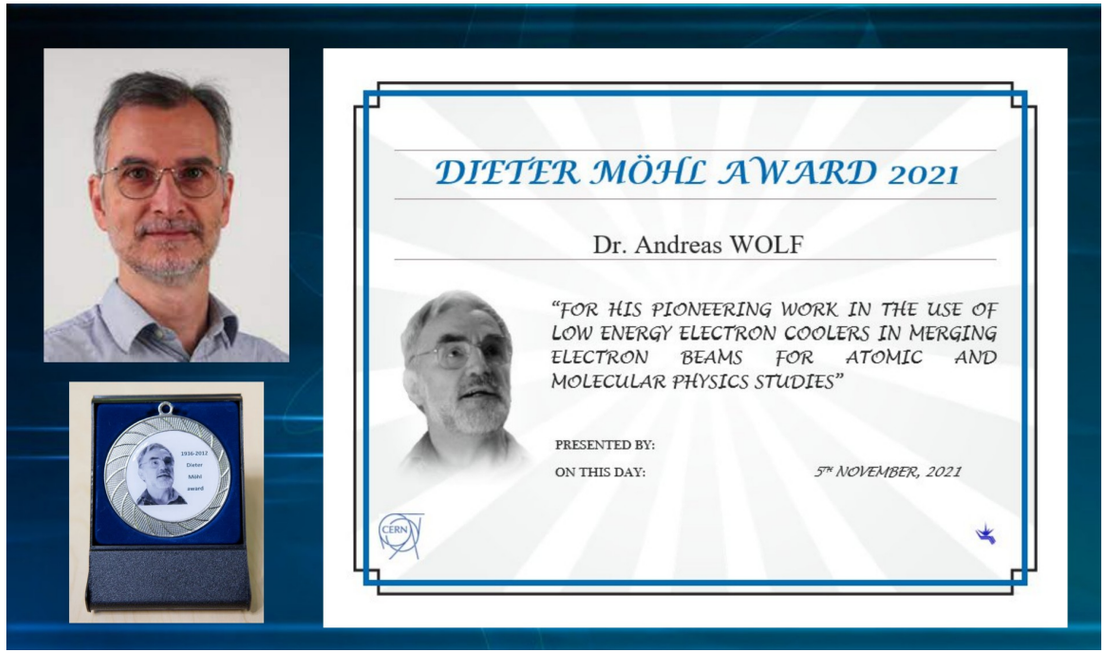

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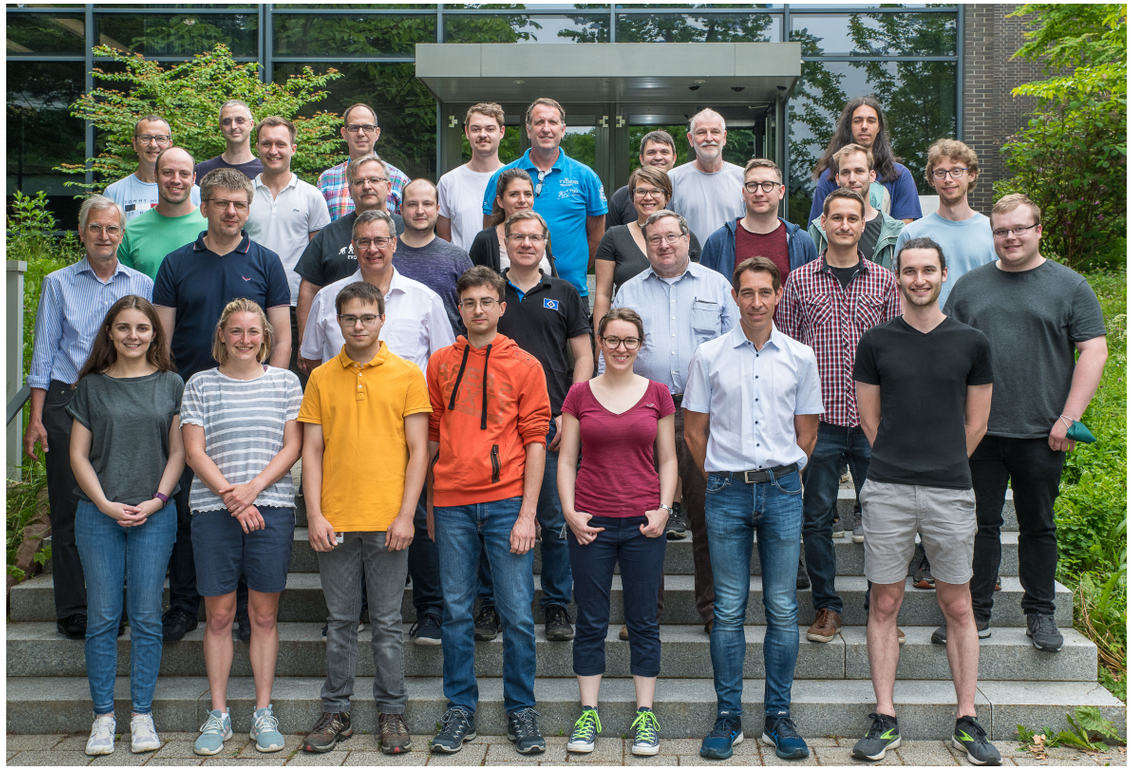

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