Low-energy Electron Cooling and Detection Methods at the Cryogenic Storage Ring

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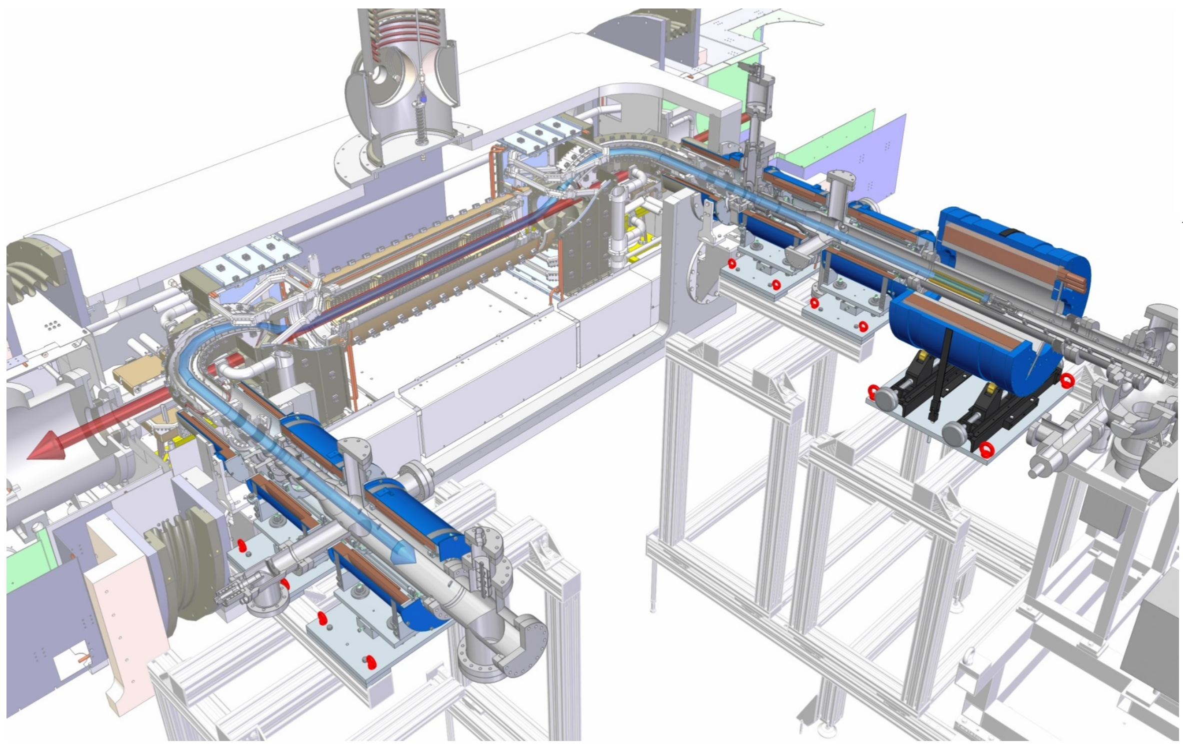
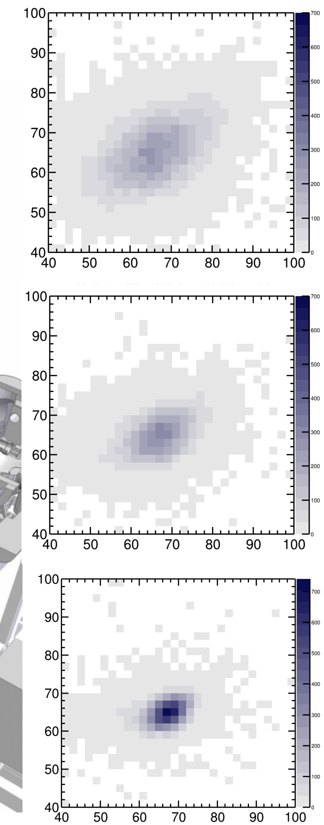
Heidelberg, Germany

Daniel Paul

for the CSR team





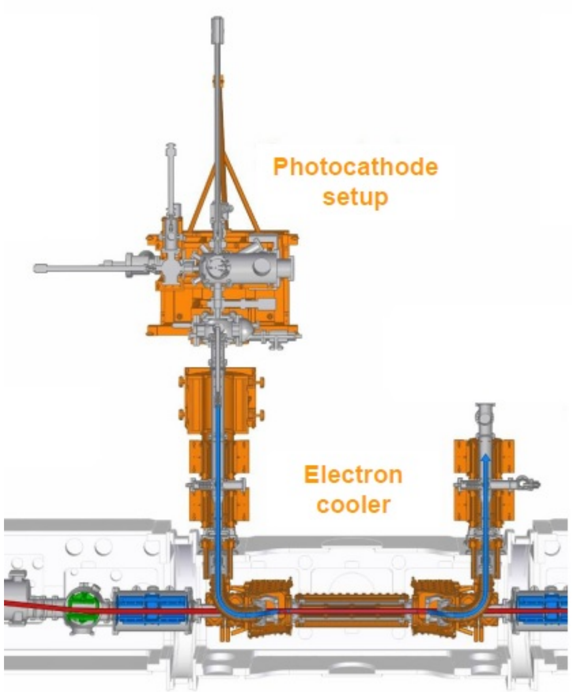
AVA Topical Workshop:

Low energy facility design and optimization through diagnostics

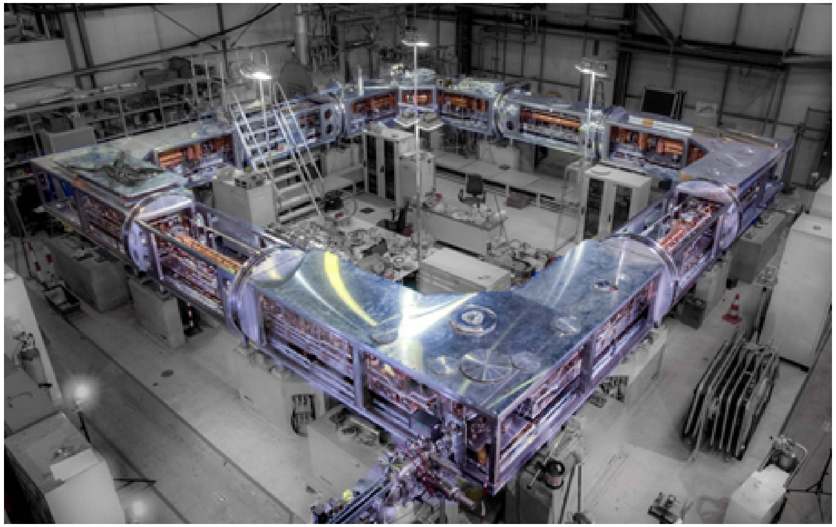
GSI, Darmstadt, Germany 06.02.2019

Outline

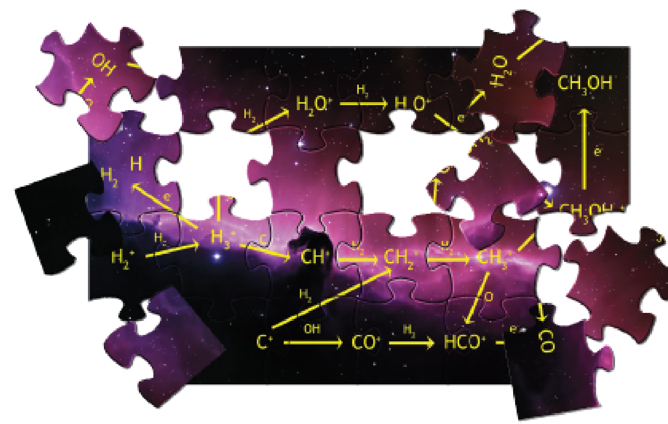
- Reminder: The electrostatic Cryogenic Storage Ring (CSR)
- CSR Detectors
- The CSR low-energy electron cooler
- Cooling Observation and Optimization
  - Longitudinal
  - Transverse
- Lifetimes of electron cooled ion beams



The CSR – Motivation



Cold molecular clouds in the ISM: Astrochemistry



	CSR	interstellar clouds
Temperature	< 10 K	~ 10 – 150 K

→ storage times ~ **1000 s**

→ **electrostatic**: mass-independent storage of ion beams

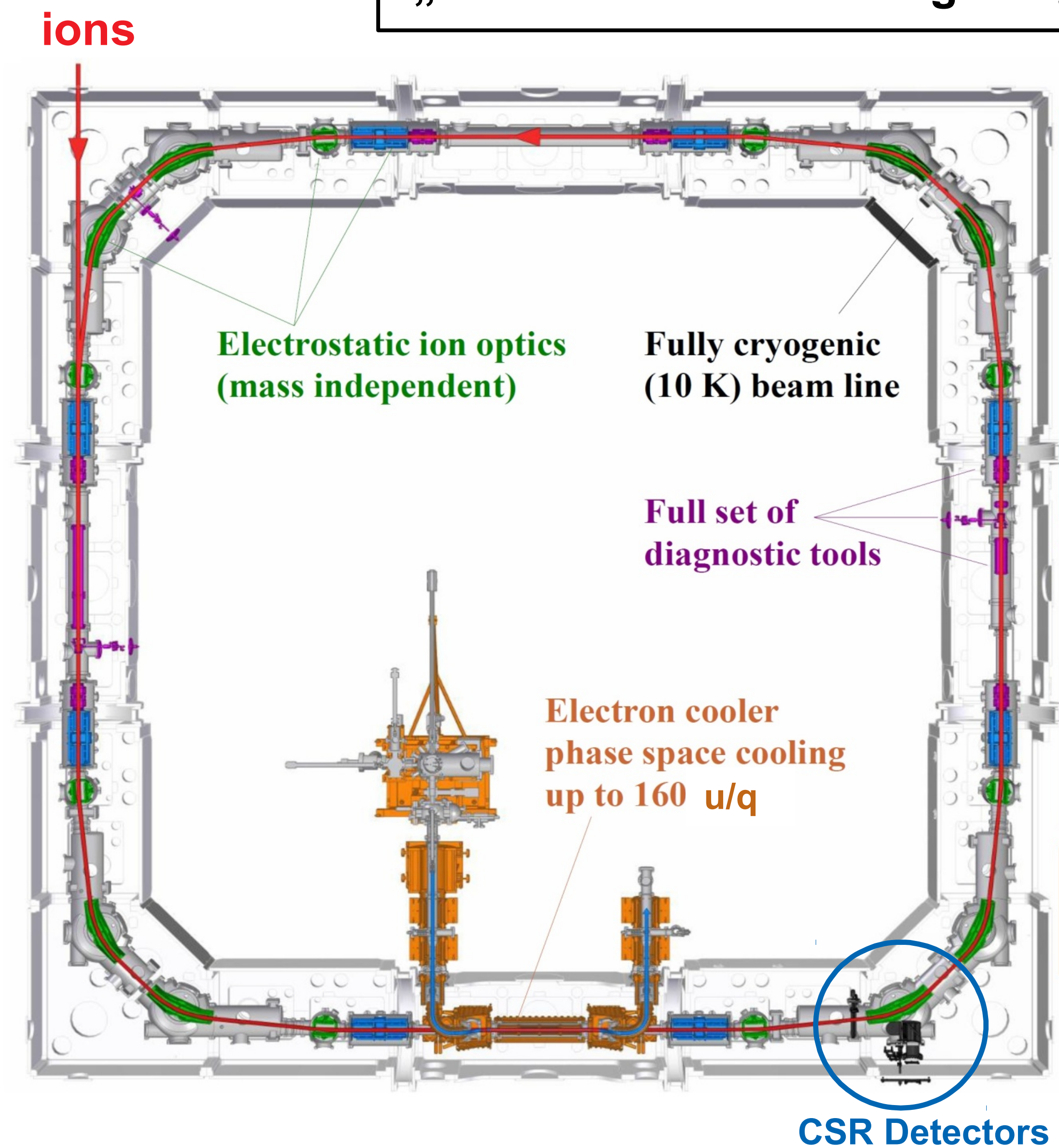
→ molecular ions in well-defined quantum states

→ velocity-matched merged-beam experiments: low collision energies

Rotationally resolved collision studies are possible

The CSR - Overview

Manfred Grieser:
„The electrostatic storage ring CSR“



circumference:	**35 m**
beam energy:	**20 keV × q ... 300 keV × q**
temperature:	**10 … 300 K**
res. gas press. (@ < 10 K):	**10^{-14} mbar (~ 100 cm^{-3})**

- Beam profile monitors (3x)
- Current pickup
- Schottky pickup
- Position pickups (6x)

... with electron cooling

m/q range:	**1 ... 160 u/e (@ 300 kV)**

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

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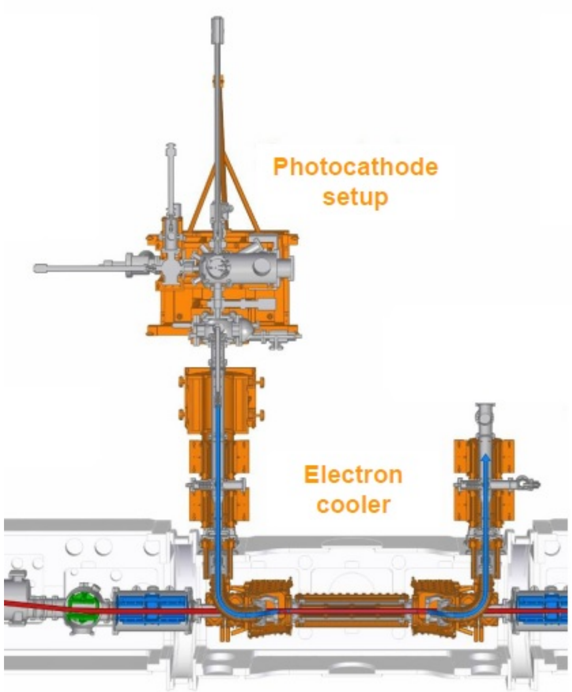
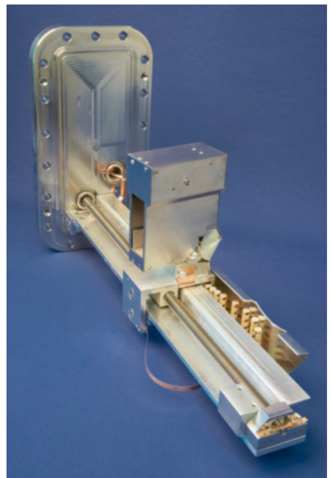


CSR Detectors

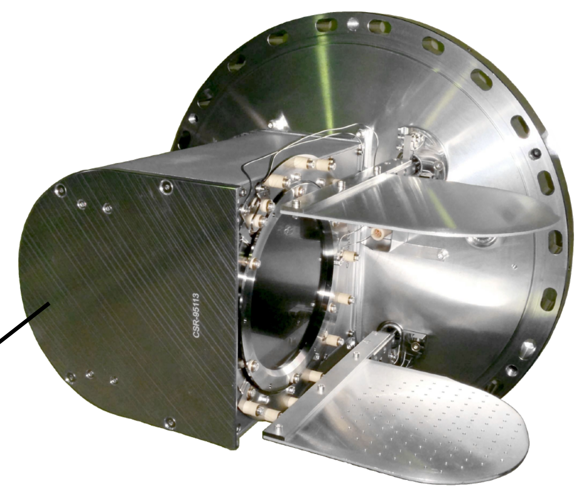
Cold Movable Particle Counter (COMPACT)

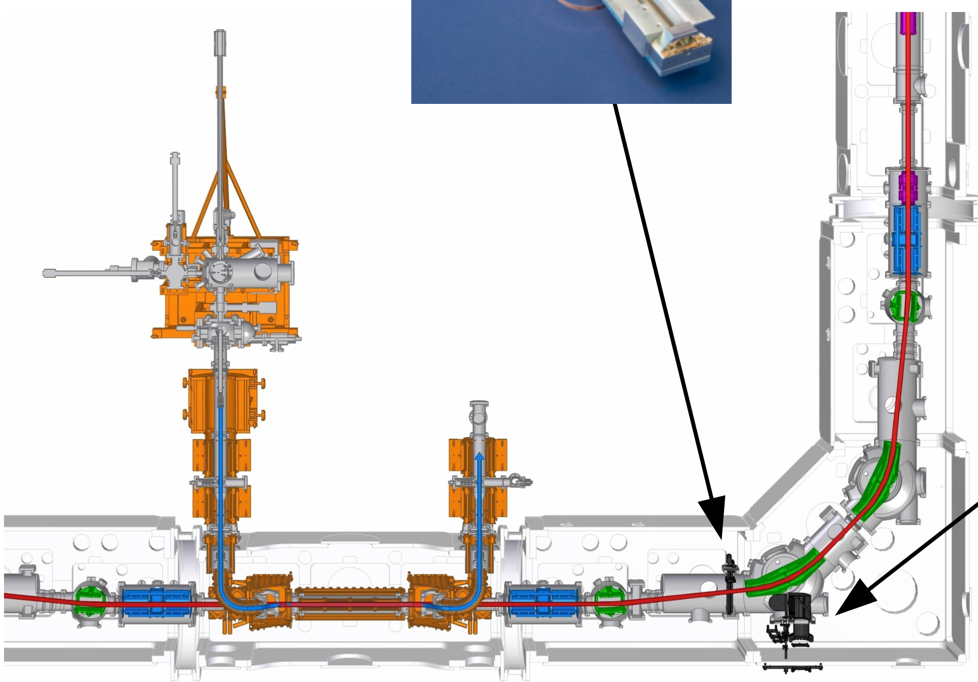
K. Spruck et al.
Rev. Sci. Instrum.
86, 023303 (2015)

C. Krantz et al.
Nucl. Instr Meth. A
851, 92 (2017)



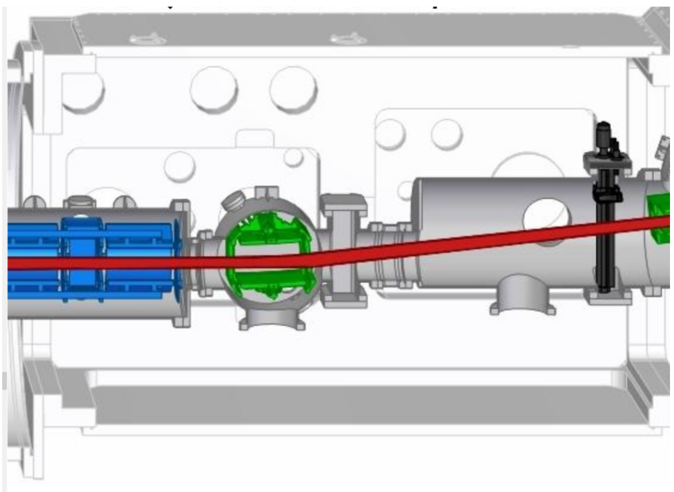
Neutral Imaging in Cryogenic Environment (NICE)

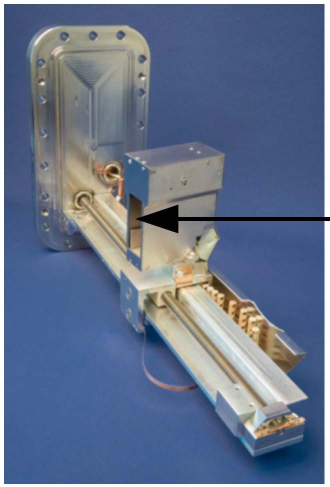


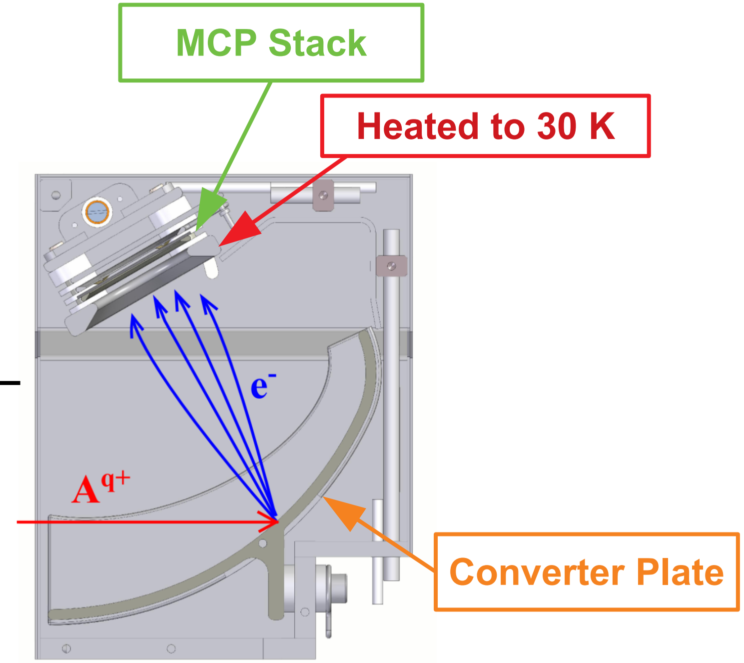


CSR Detectors - COMPACT

Cold Movable Particle Counter (COMPACT)







Fragmentation Parameter

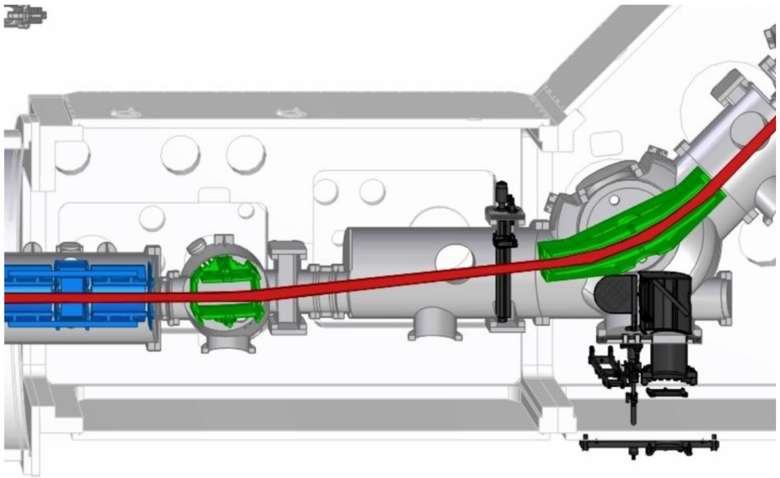
$$\eta = \frac{q_d/m_d}{q_p/m_p} - 1$$

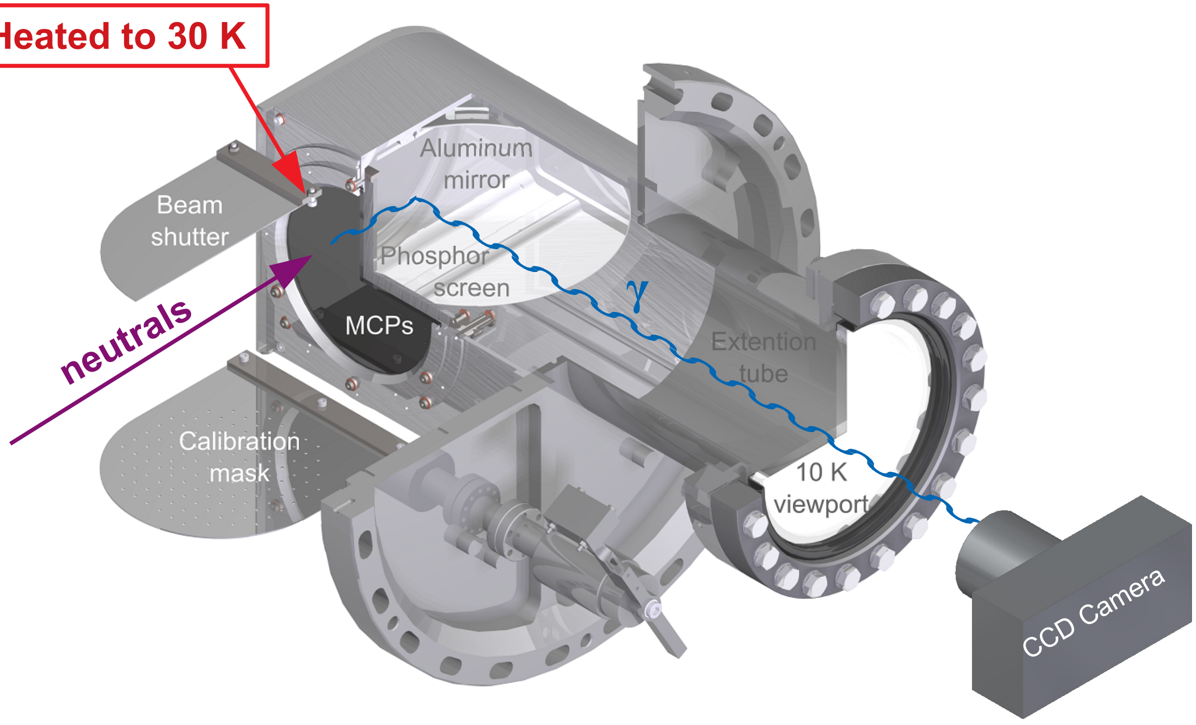
Detection Range

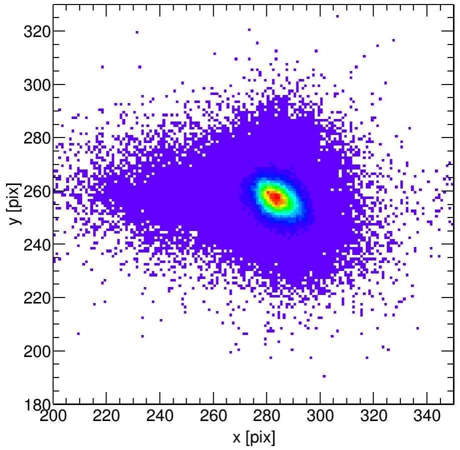
$$-1.4 \leq \eta \leq +1.1$$

- Manually movable to desired fragment position
- Movement in cryogenic and UHV environment

CSR Detectors - NICE







- Multi-coincidence imaging detector
- 3D fragment imaging under development

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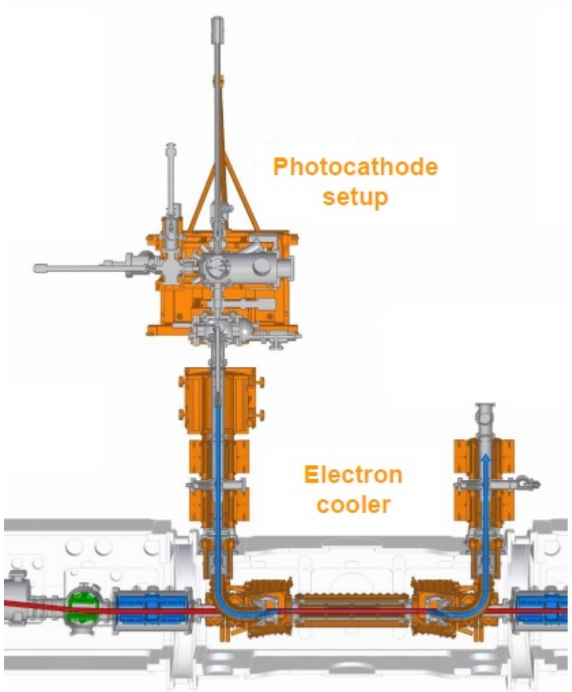
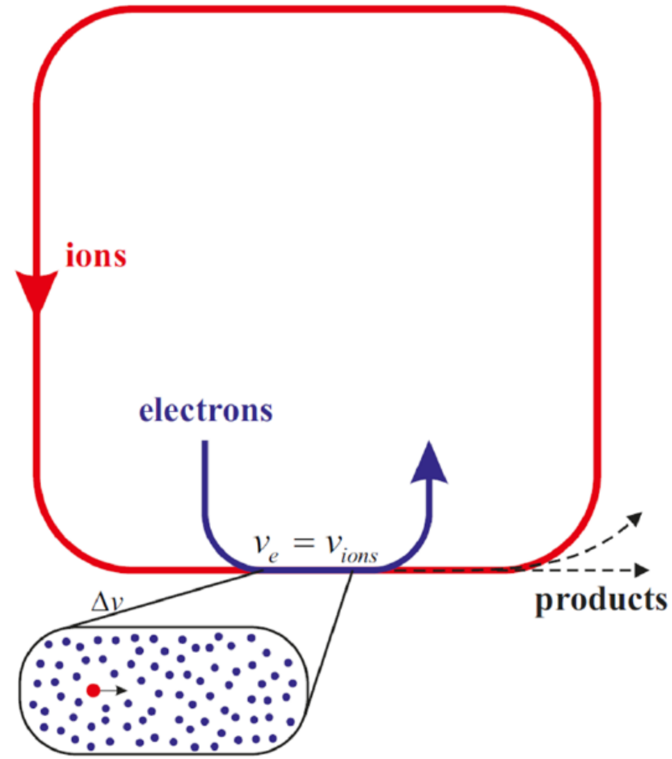


The CSR – Electron Cooling

Liouville's theorem:
Ion beam emittance is constant in absence of external forces

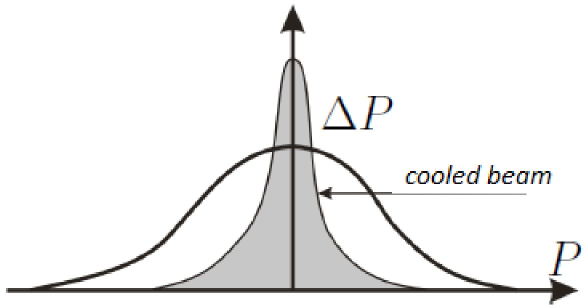


BUT :

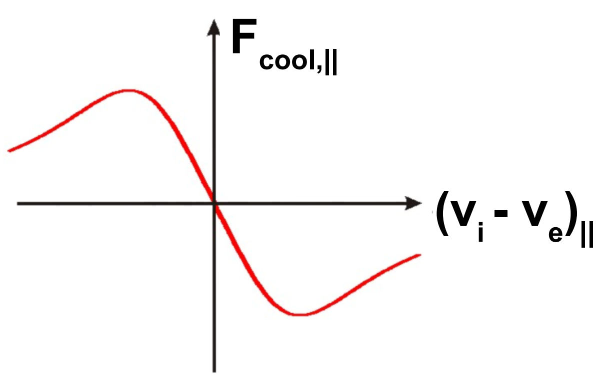
- Low beam emittance desired
- Diffusion processes increase emittance

Benefits of electron cooling at CSR :

- Narrow beam profile → defined collision geometry
- Low energy spread → defined collision energies
- Increased beam lifetimes



Friction force



The CSR – Electron Cooling

$$E_e = \frac{m_e}{m_i} \cdot E_i$$

E_e [eV]	ion
163	for 300 keV $p^+/\bar{p}$
1	for M_{ion} = 160 u

$$\vec{u} := \vec{v}_i - \vec{v}_e$$

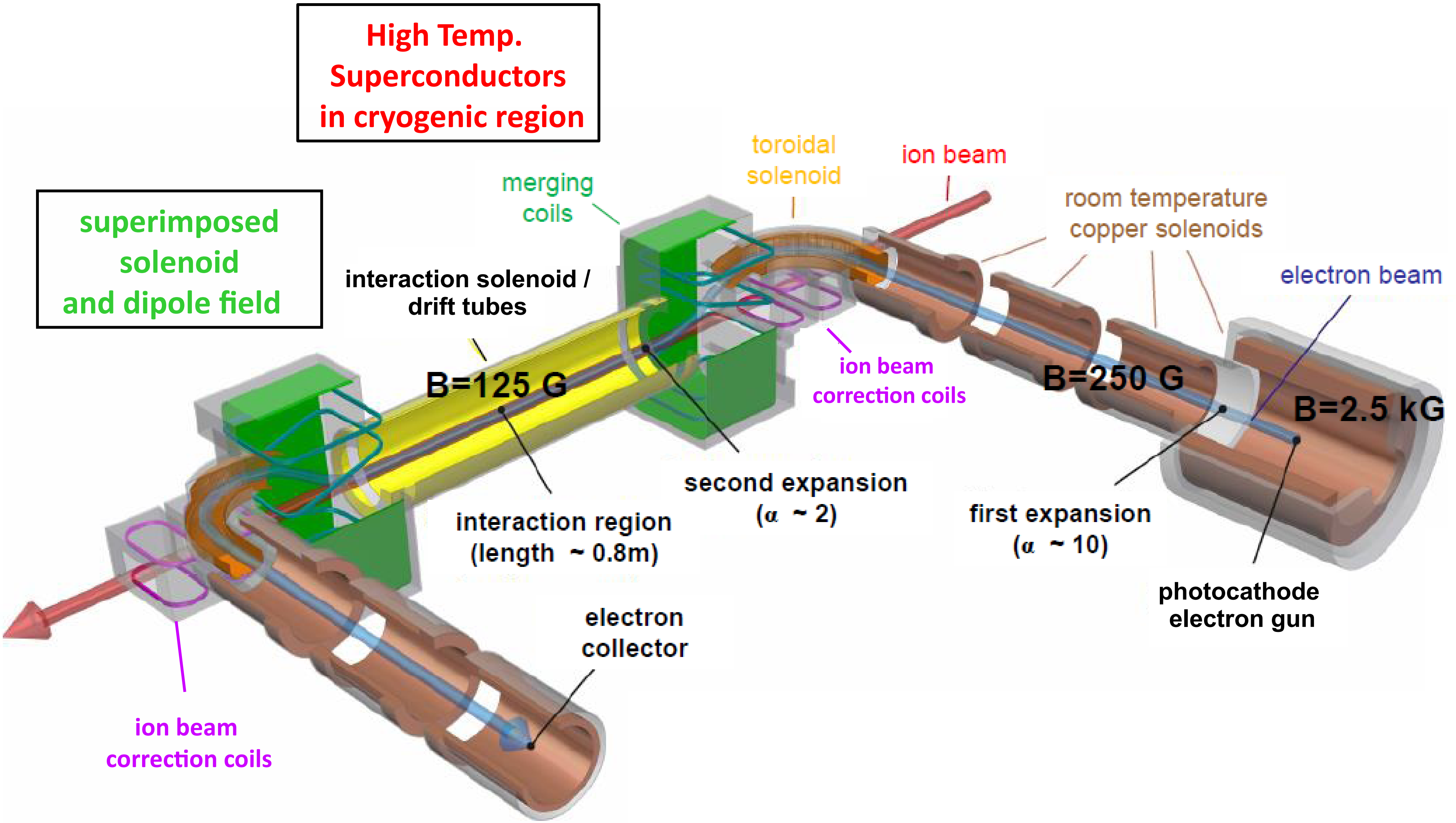
$$\frac{du}{dt} = \frac{F}{M_i} \xrightarrow{\frac{1}{e}} \tau_{cool} \sim \frac{M \cdot T_e^{3/2}}{Z^2 \cdot n_e}$$

Challenge:

- assure $\tau_{cool} \ll \tau_{store}$

  → electron beam with
  high density & low temperature
  (@ low kinetic energy)

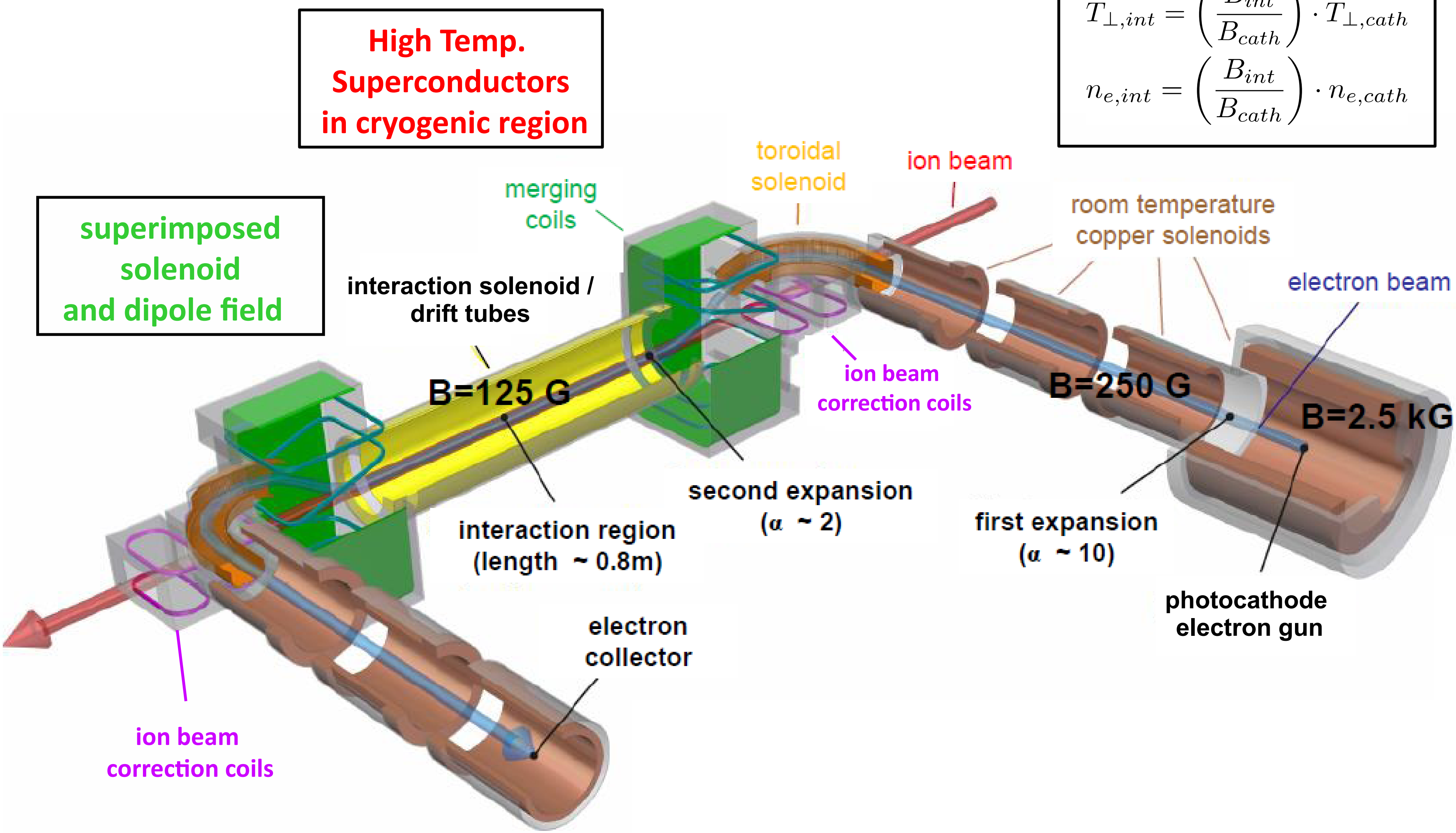
The CSR electron cooler



The CSR electron cooler

$$T_{\perp,int} = \overbrace{\left(\frac{B_{int}}{B_{cath}}\right)}^{1/\alpha} \cdot T_{\perp,cath}$$

$$n_{e,int} = \left(\frac{B_{int}}{B_{cath}}\right) \cdot n_{e,cath}$$



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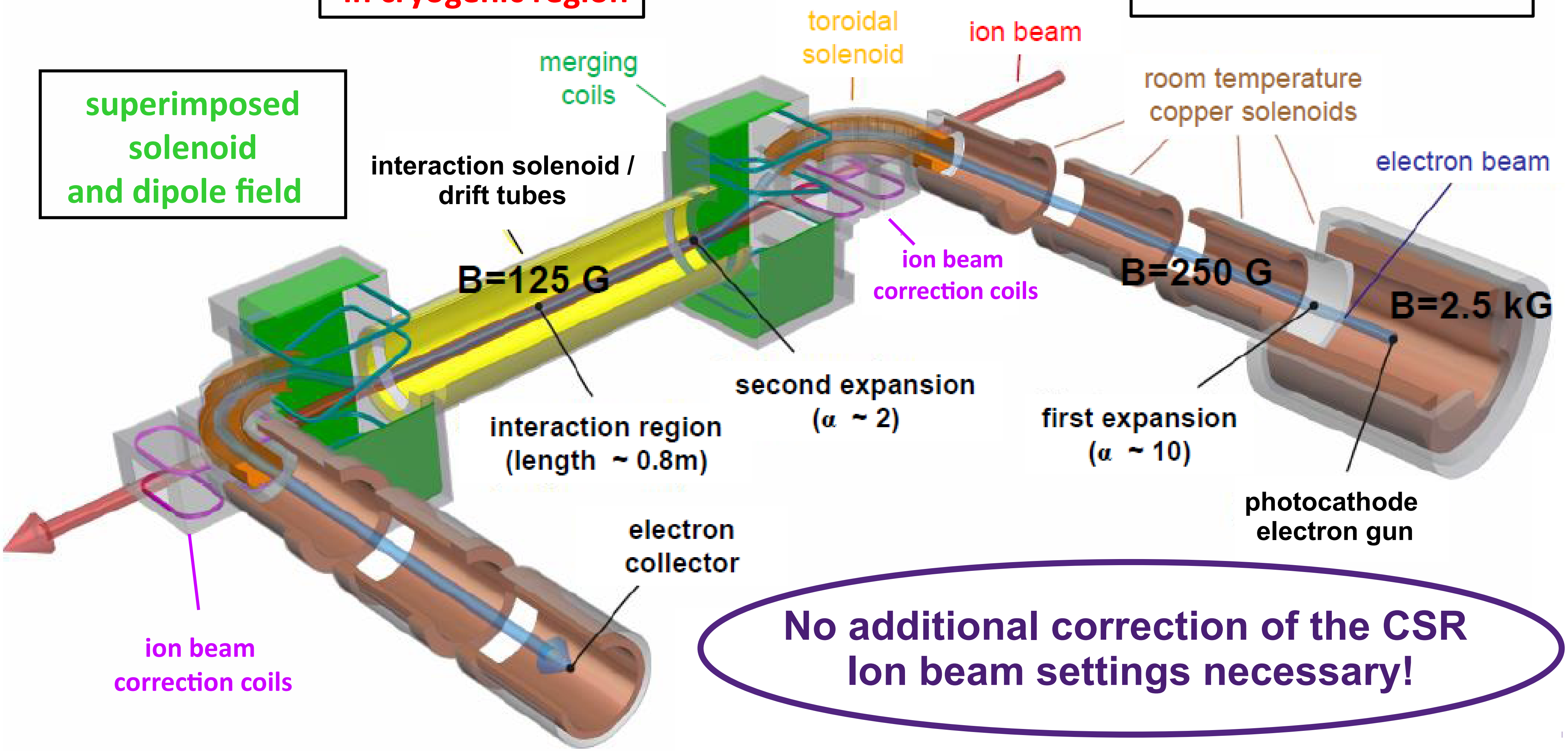
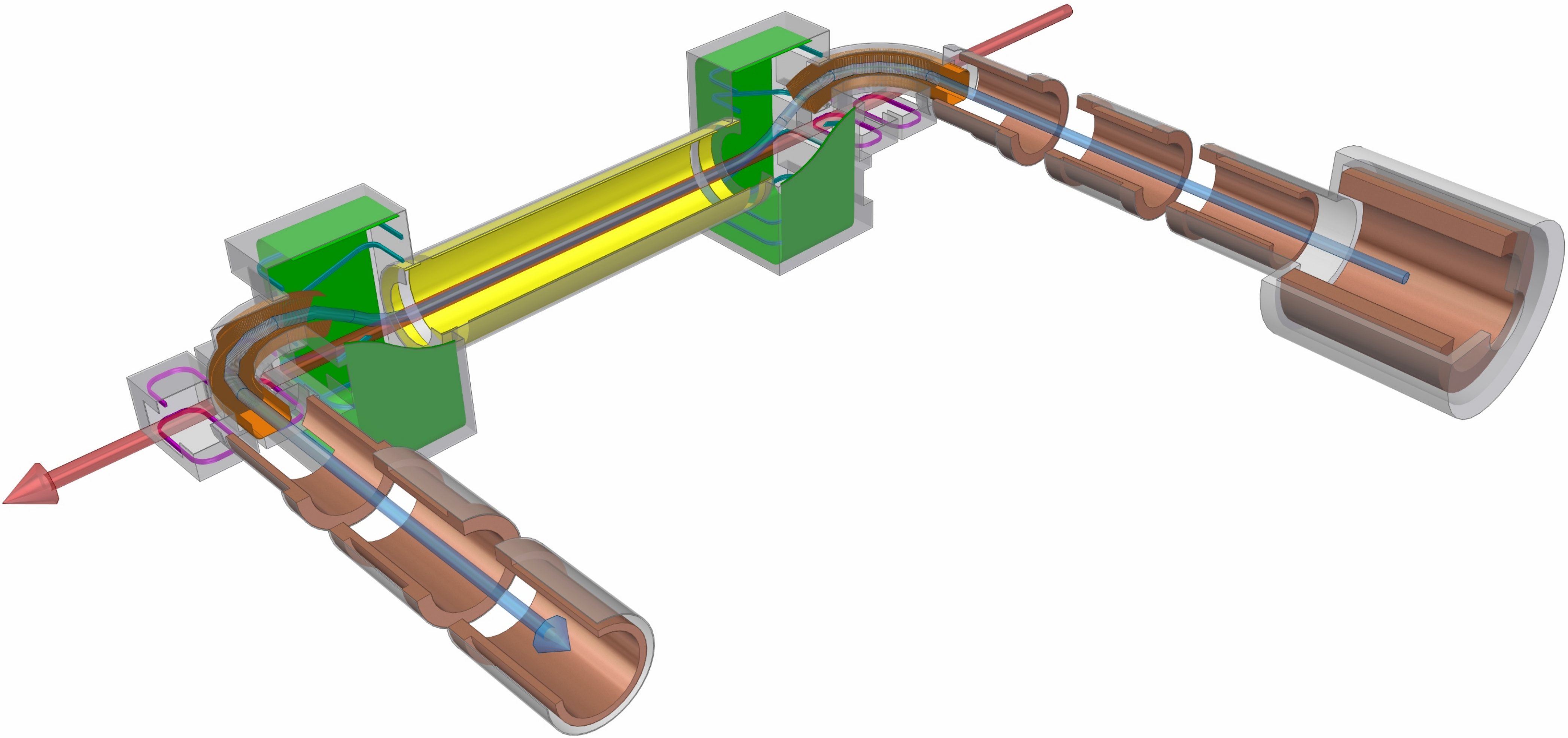
High Temp. Superconductors in cryogenic region

superimposed solenoid and dipole field



No additional correction of the CSR Ion beam settings necessary!

The CSR electron cooler



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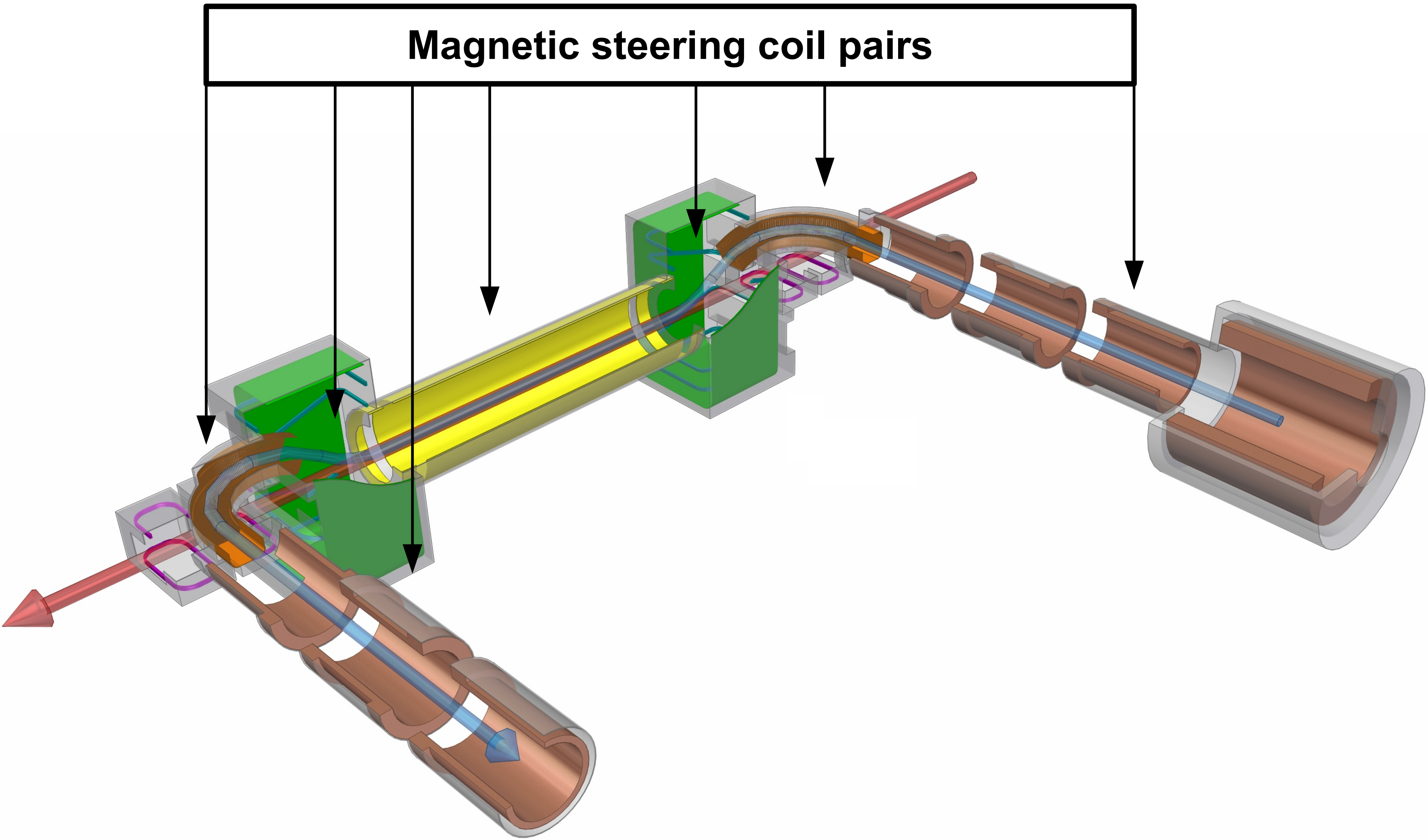

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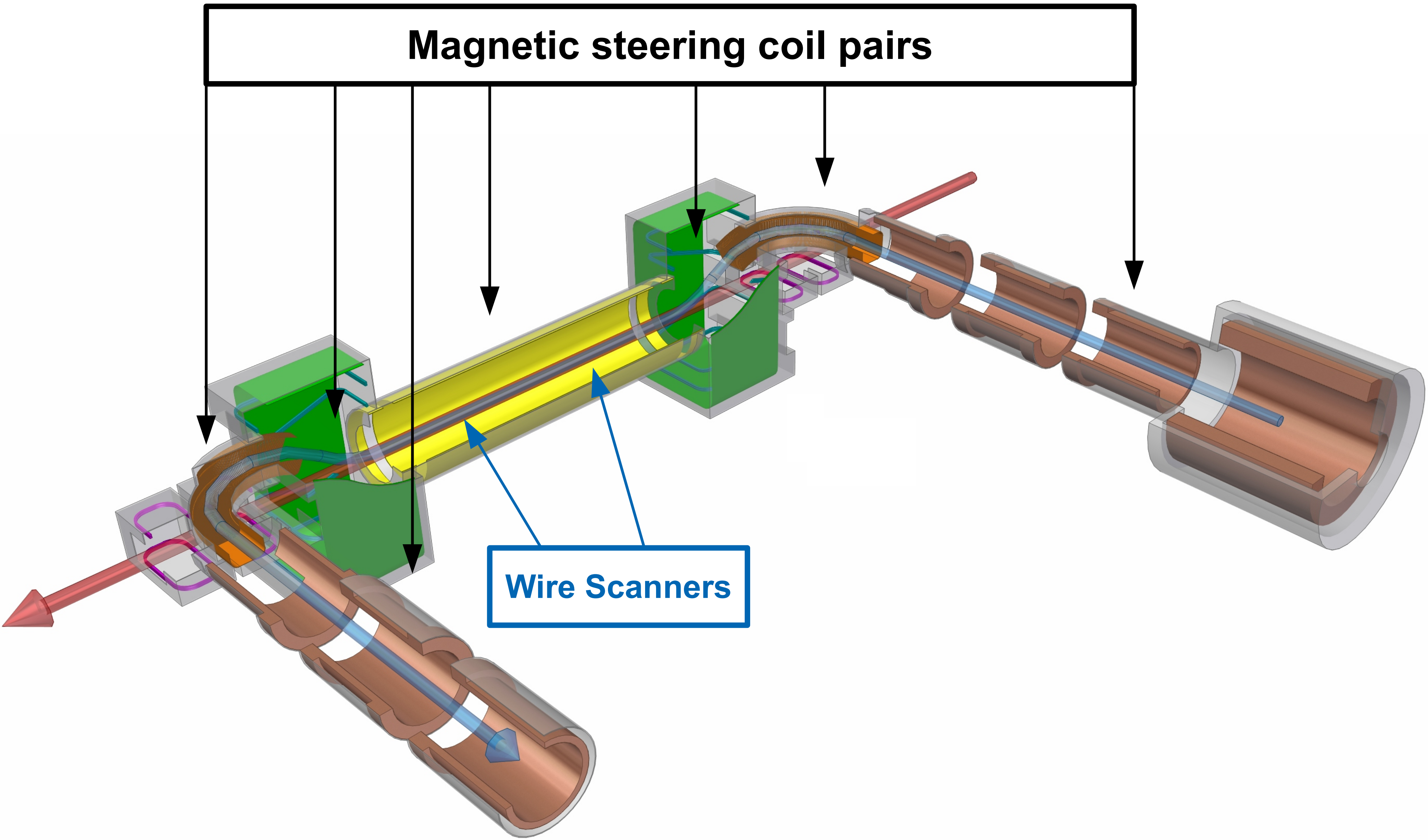

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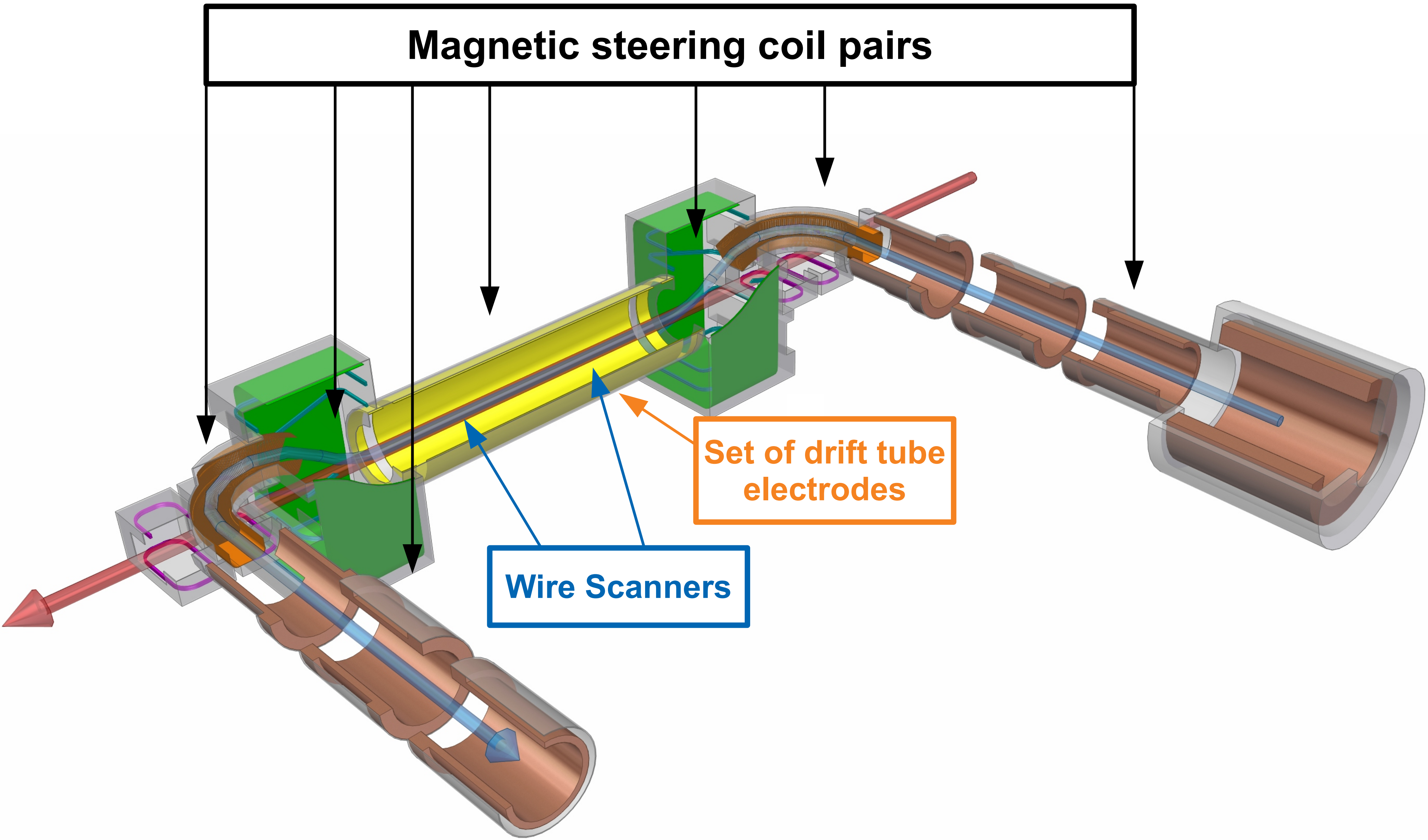

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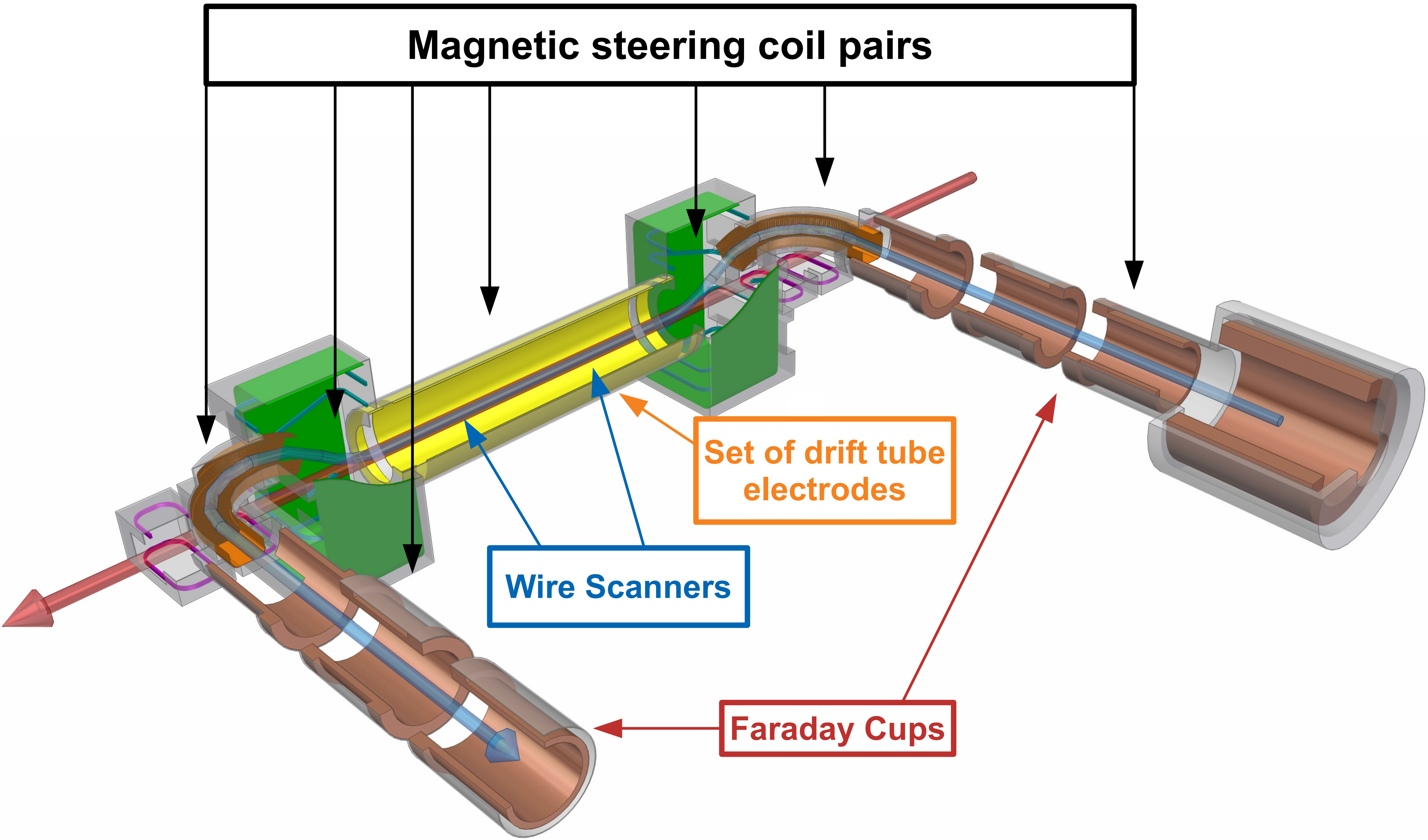

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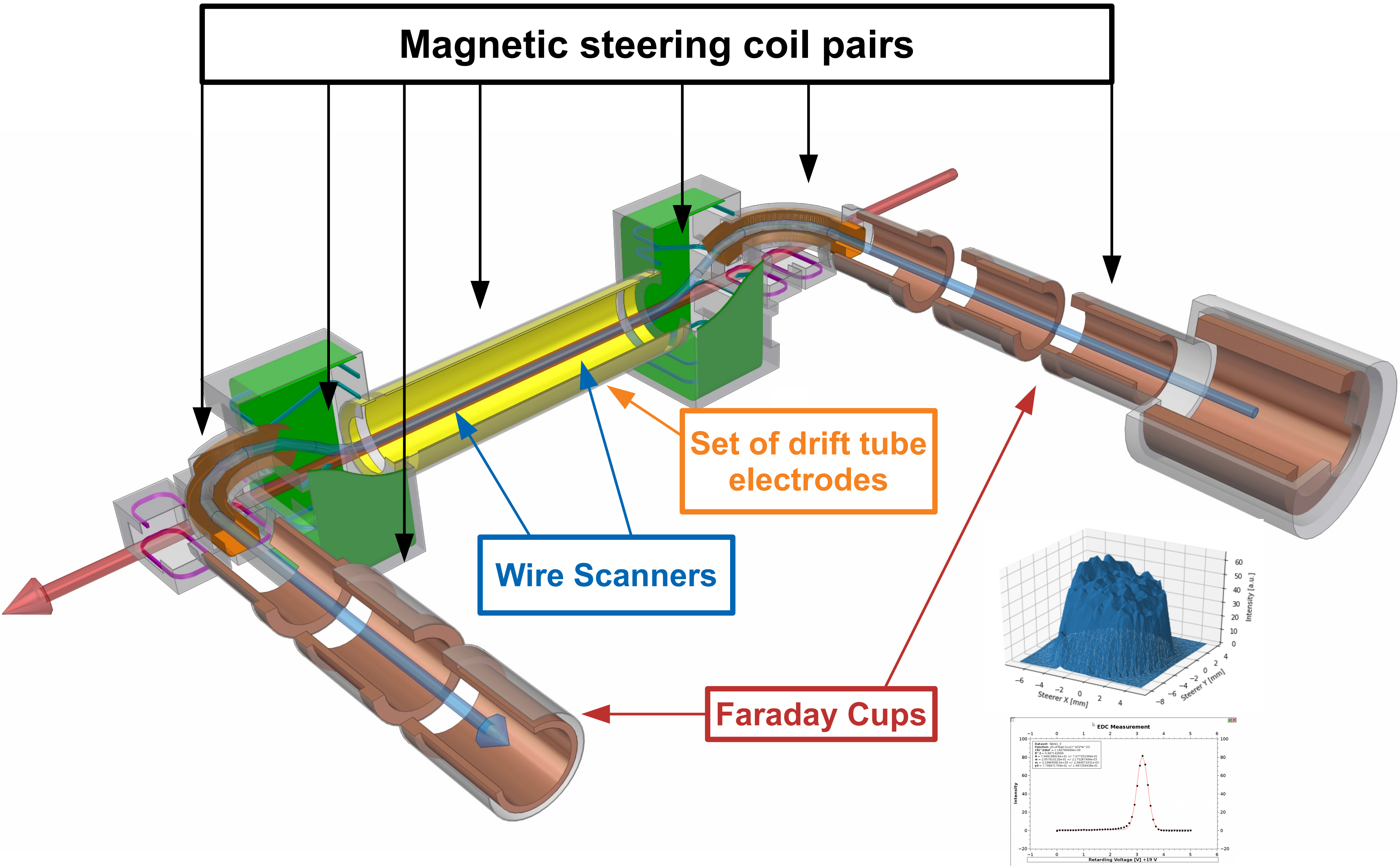

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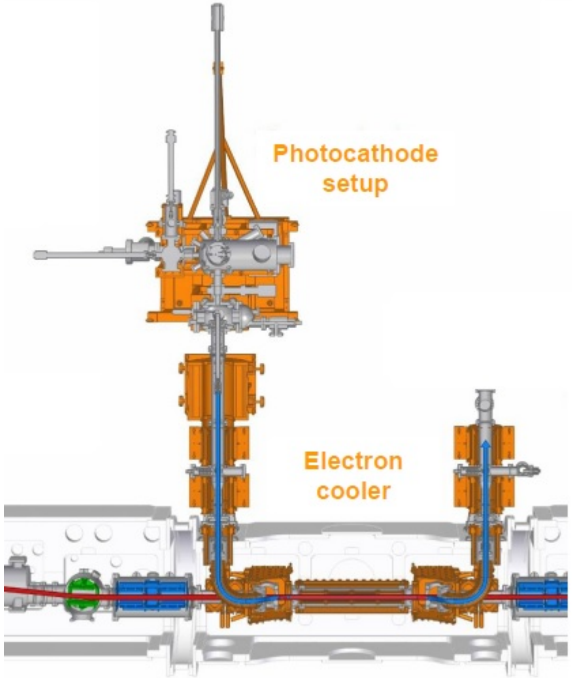
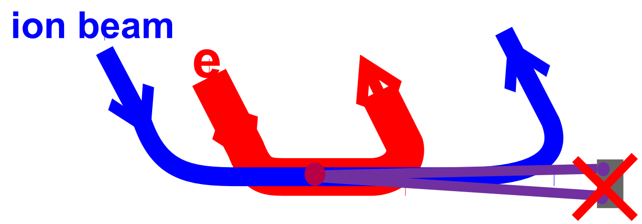
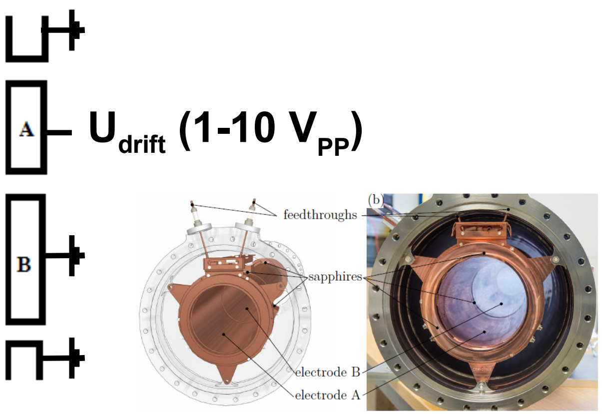
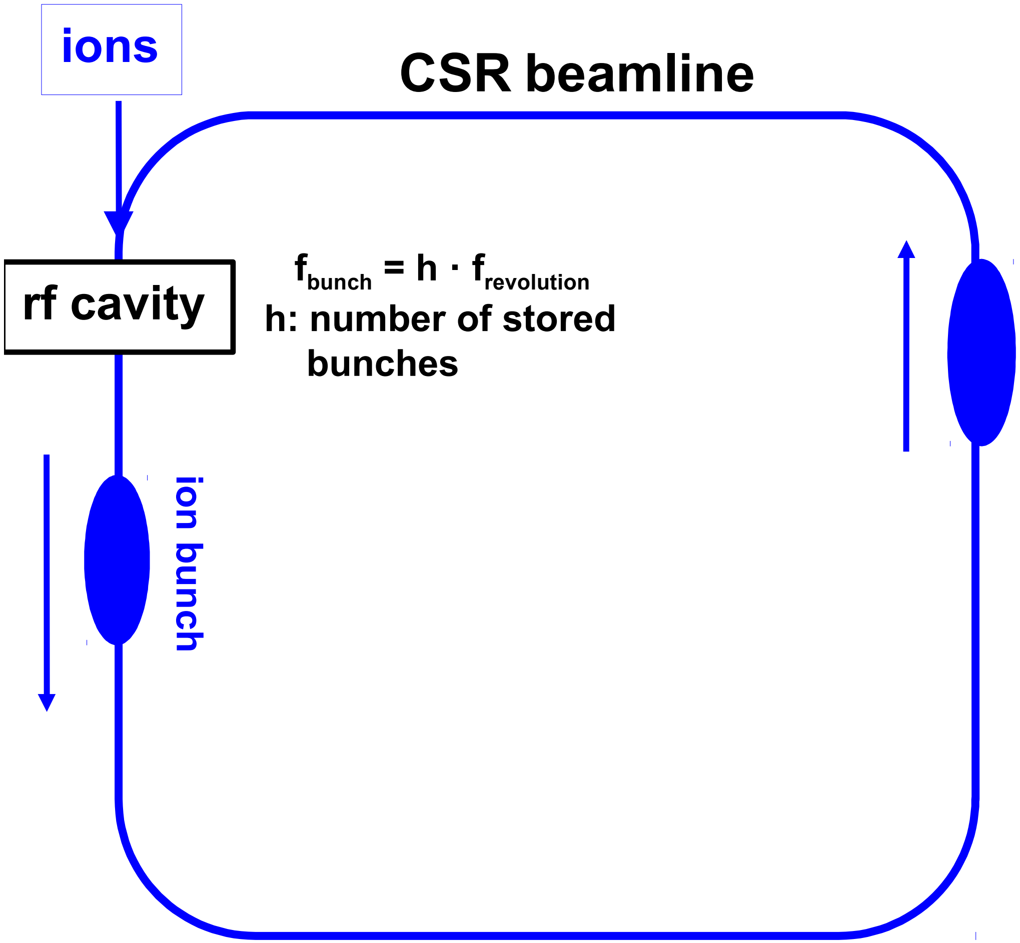


Longitudinal Cooling Demonstration – Bunched Beam



How to demonstrate and optimize electron cooling **without an imaging detector?**

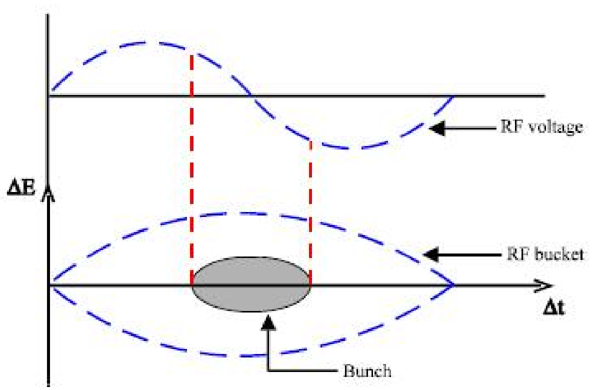




$f_{bunch} = h \cdot f_{revolution}$

h: number of stored bunches

RF system actively manipulates longitudinal ion beam structure



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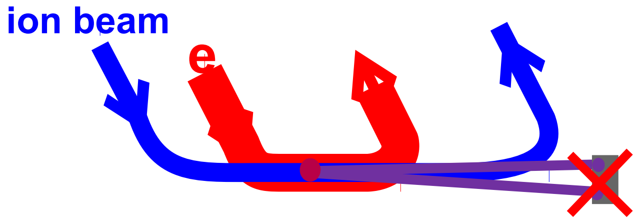

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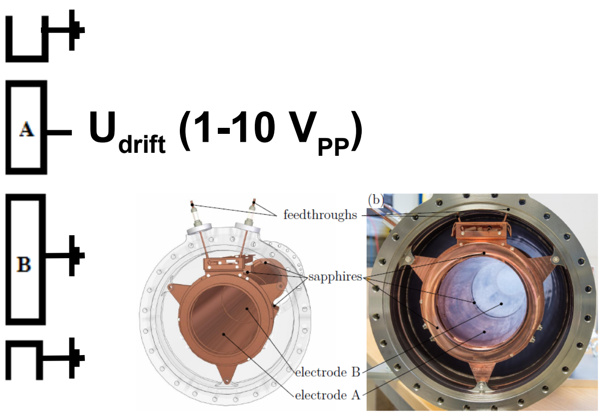

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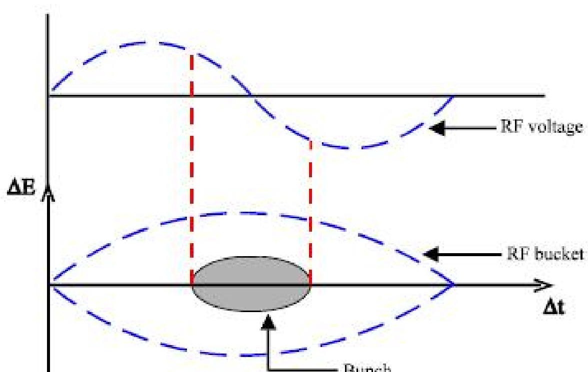
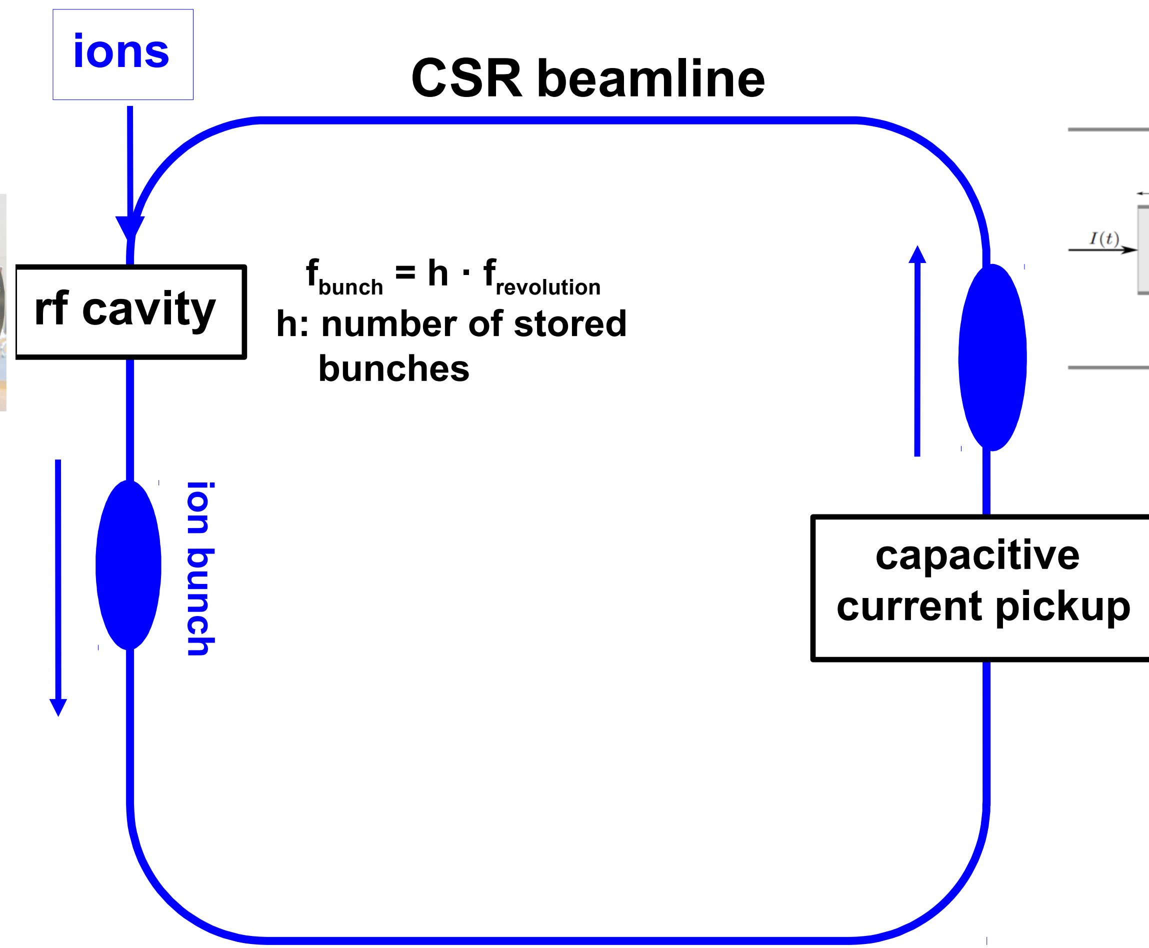
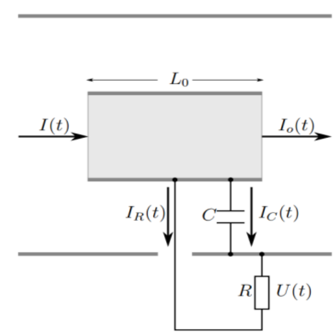
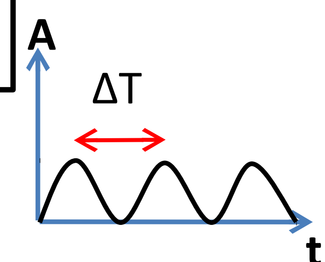






$$U(t) = \frac{L_0}{C\,v} I(t)$$



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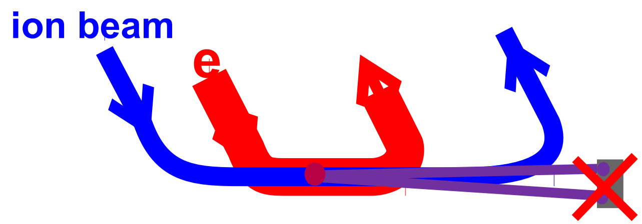

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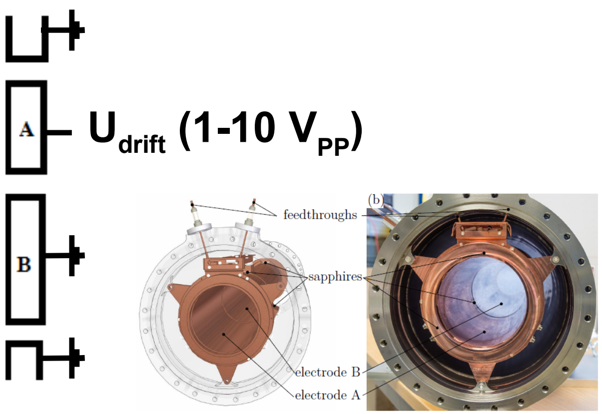

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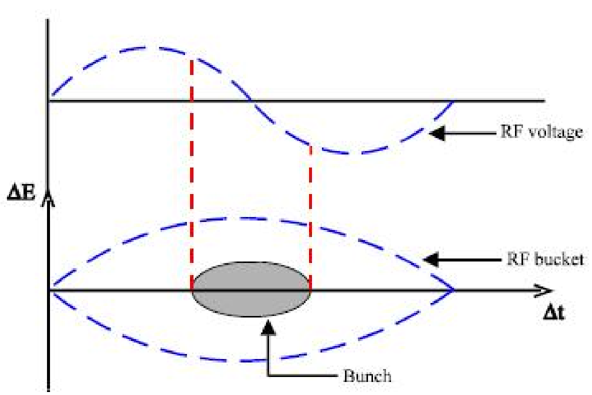

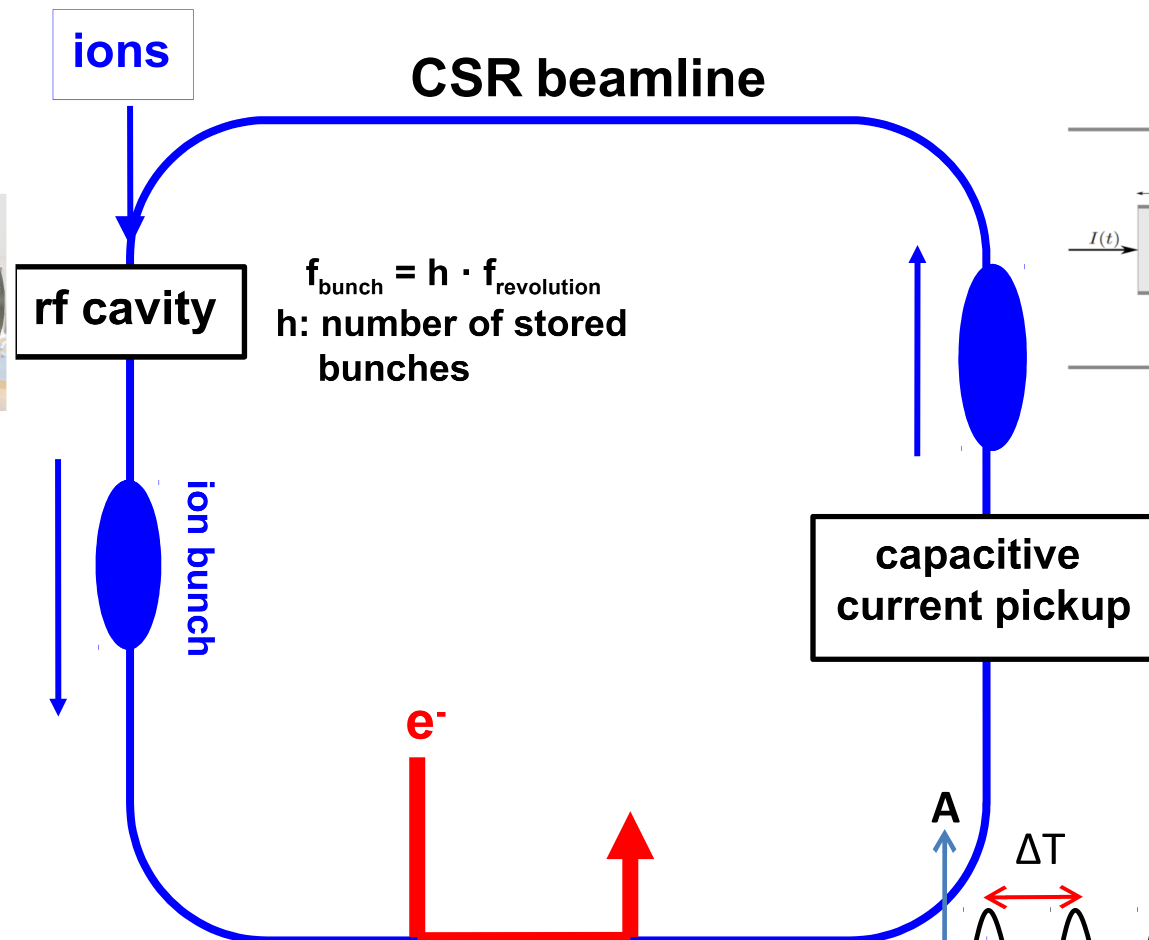

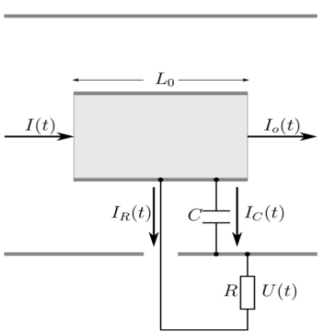

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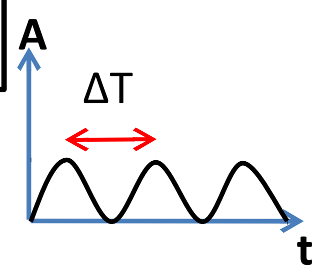
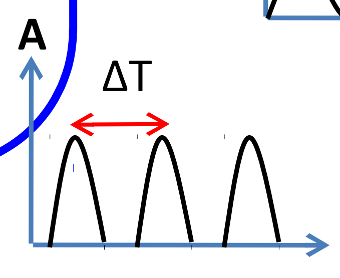
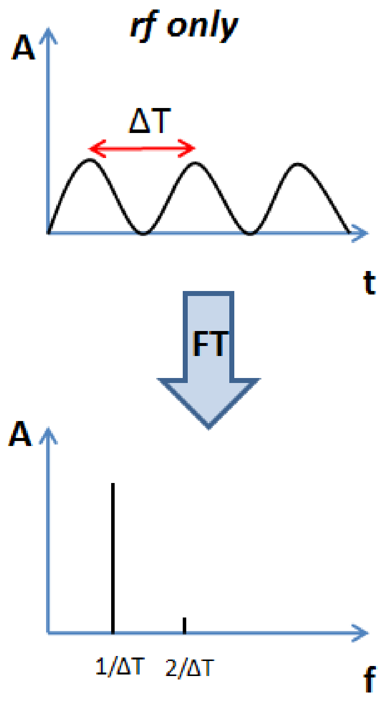




Electron Cooling → compressed longitudinal density profile of ions

Longitudinal Cooling Demonstration – Bunched Beam



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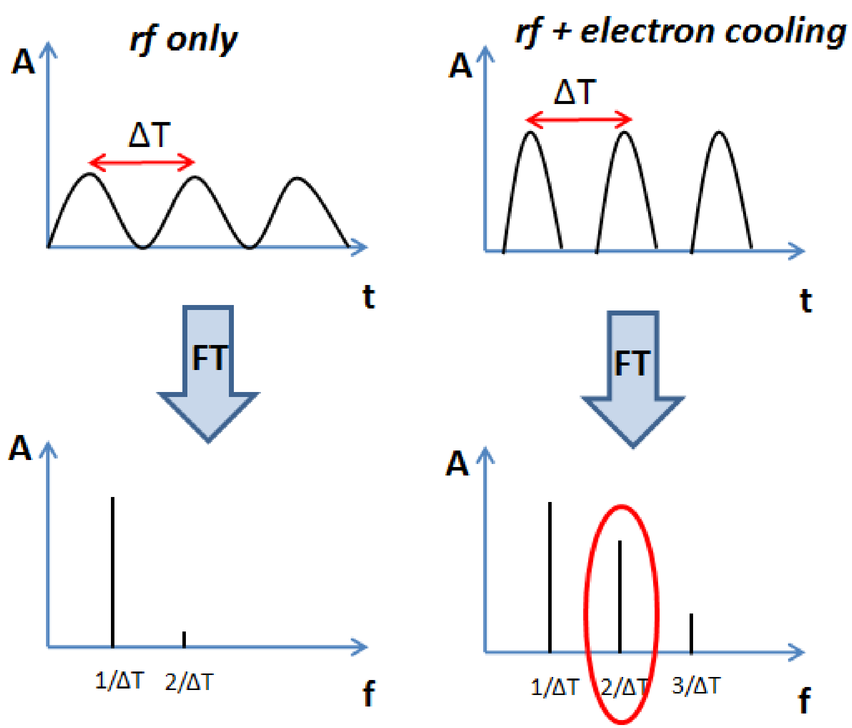

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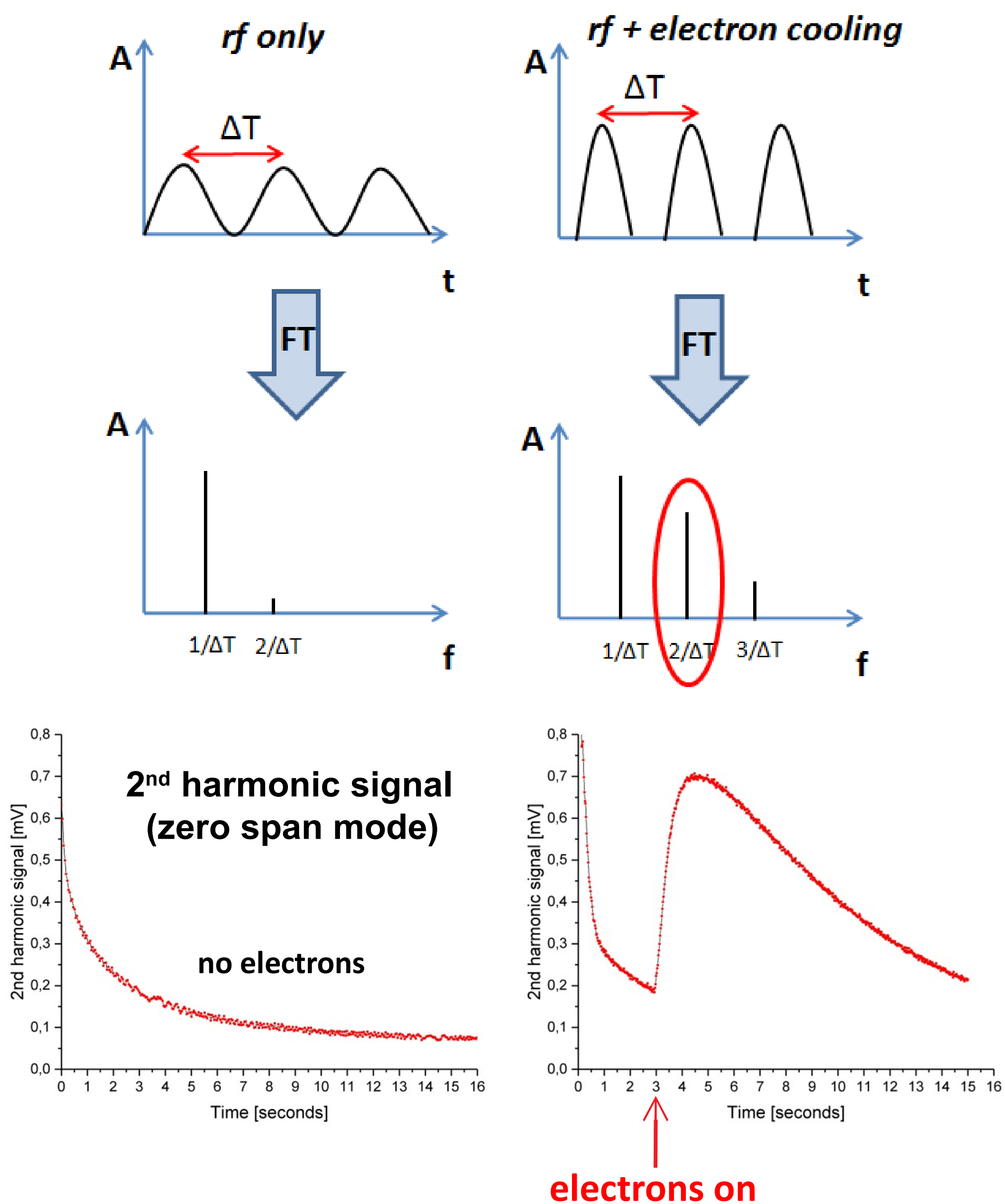
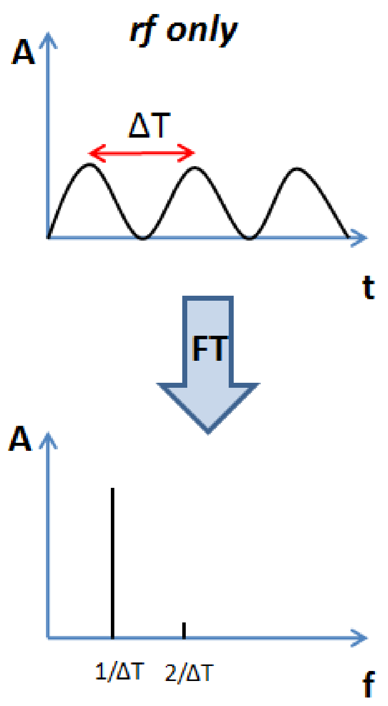


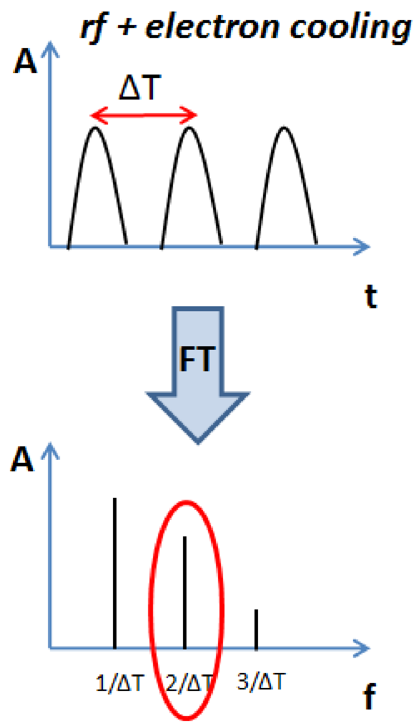
June 2017

F^{6+}

- Ion energy: **1.34 MeV**
- Ion current: **300 nA**
- Cooling energy: **38.7 eV**
- Electron current: **14.5 μA**
- Electron density: **$1.7 \cdot 10^5 cm^{-3}$**

Longitudinal Cooling Demonstration – Bunched Beam





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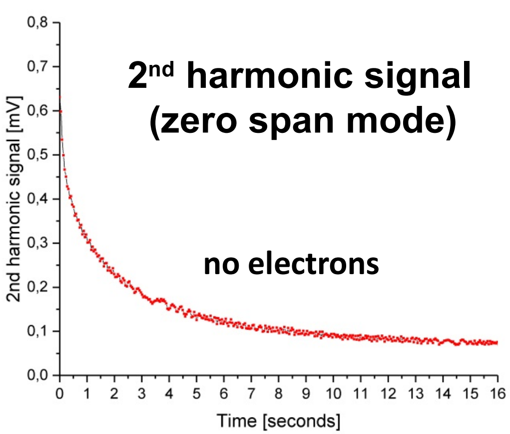
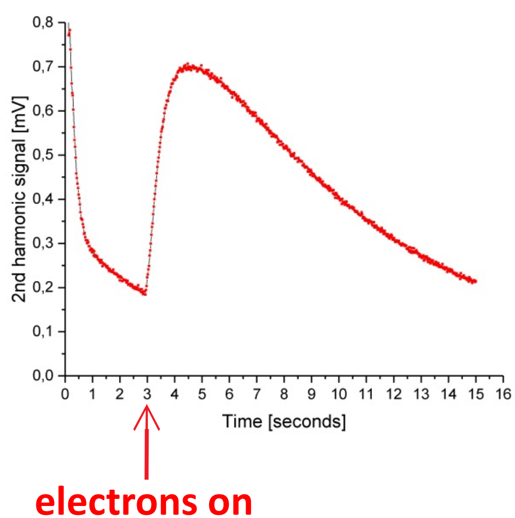
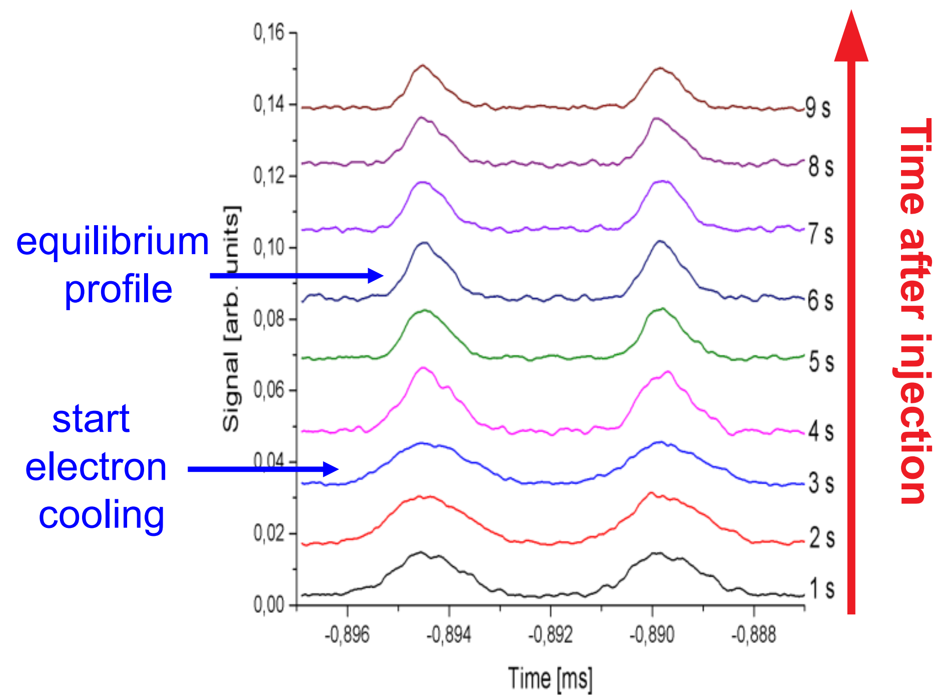




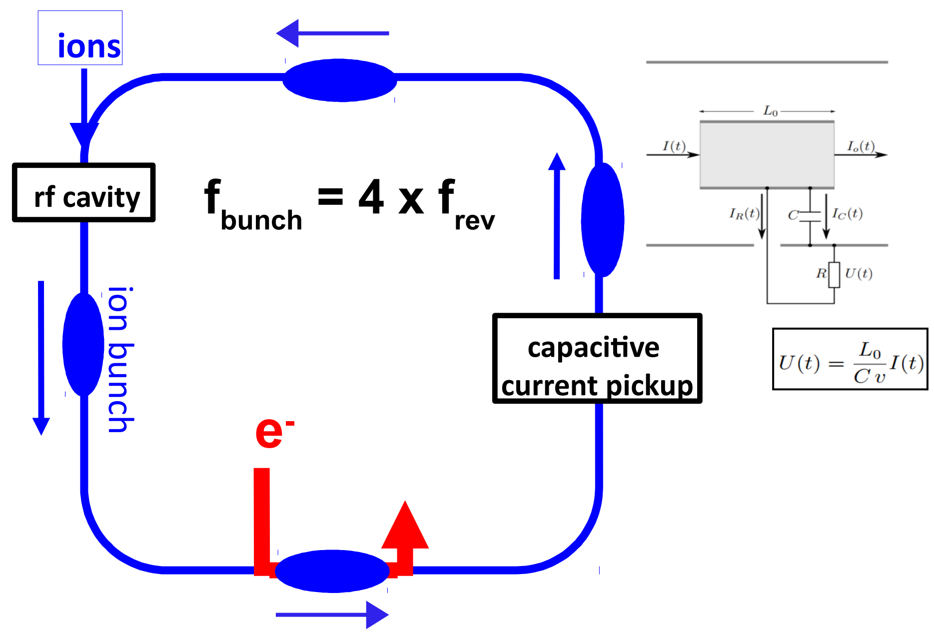


Longitudinal Cooling Demonstration – Bunched Beam

May 2018

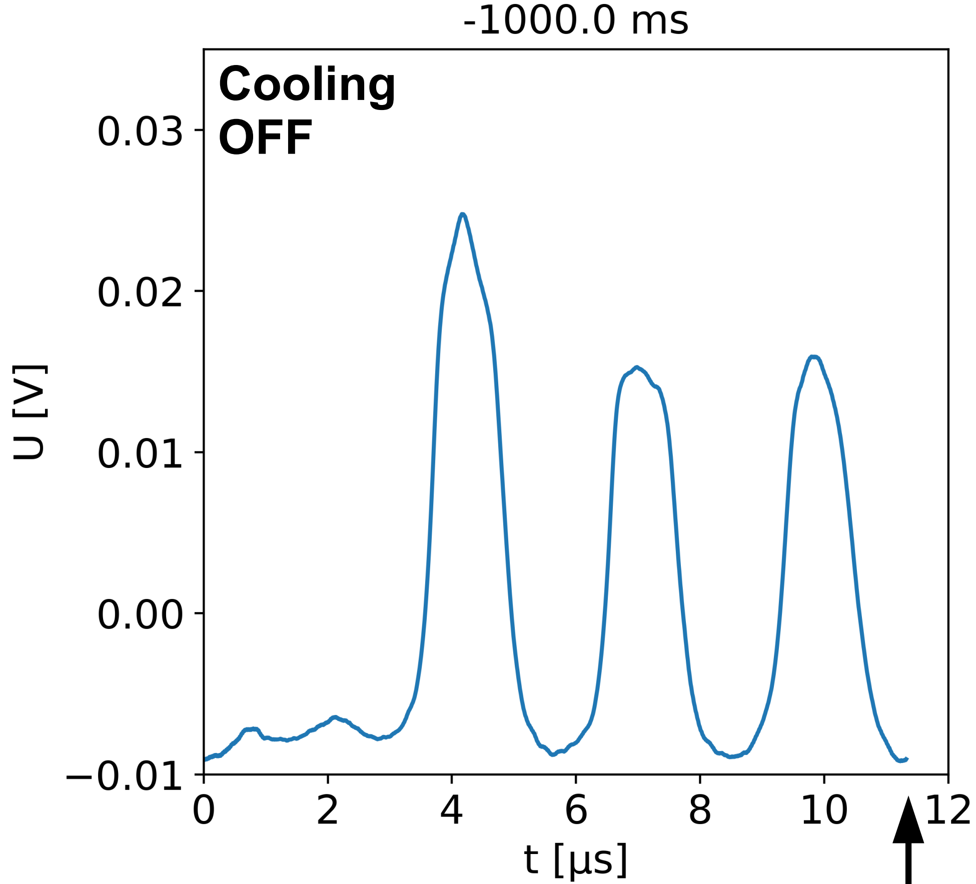
HeH^+

- Ion energy: **250 keV**
- Ion current: **300 nA**
- Cooling energy: **27.4 eV**
- Electron current: **27.0 µA**
- Electron density: **$3.7 \cdot 10^5 \, cm^{-3}$**
- Revolution Frequency: **88.28 kHz**



Longitudinal Cooling Demonstration – Bunched Beam

Averaged (40 ms) Current Pickup Signal
(Cooling @ 0 ms)



t_{rev} = 11.32 µs

May 2018

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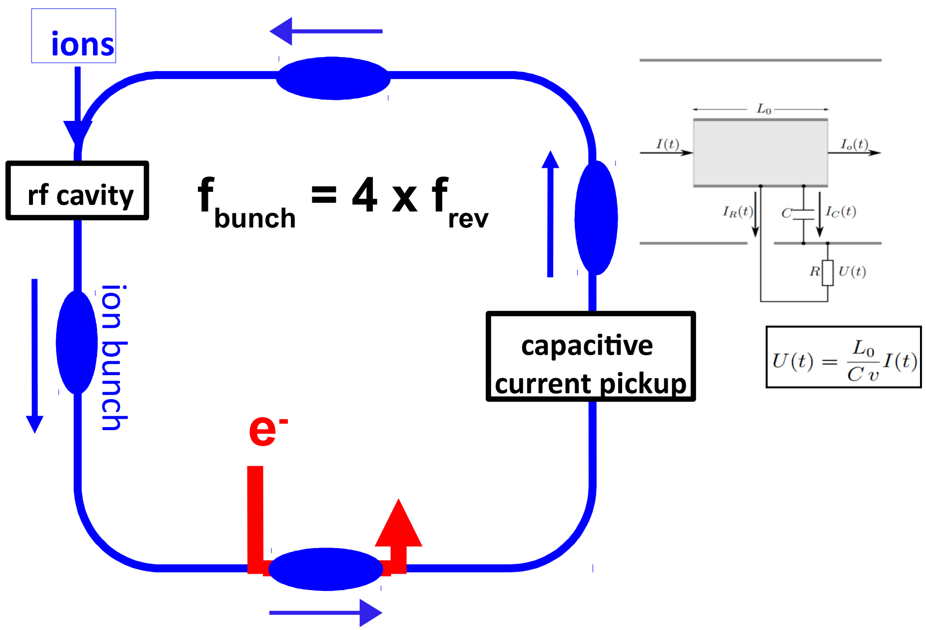

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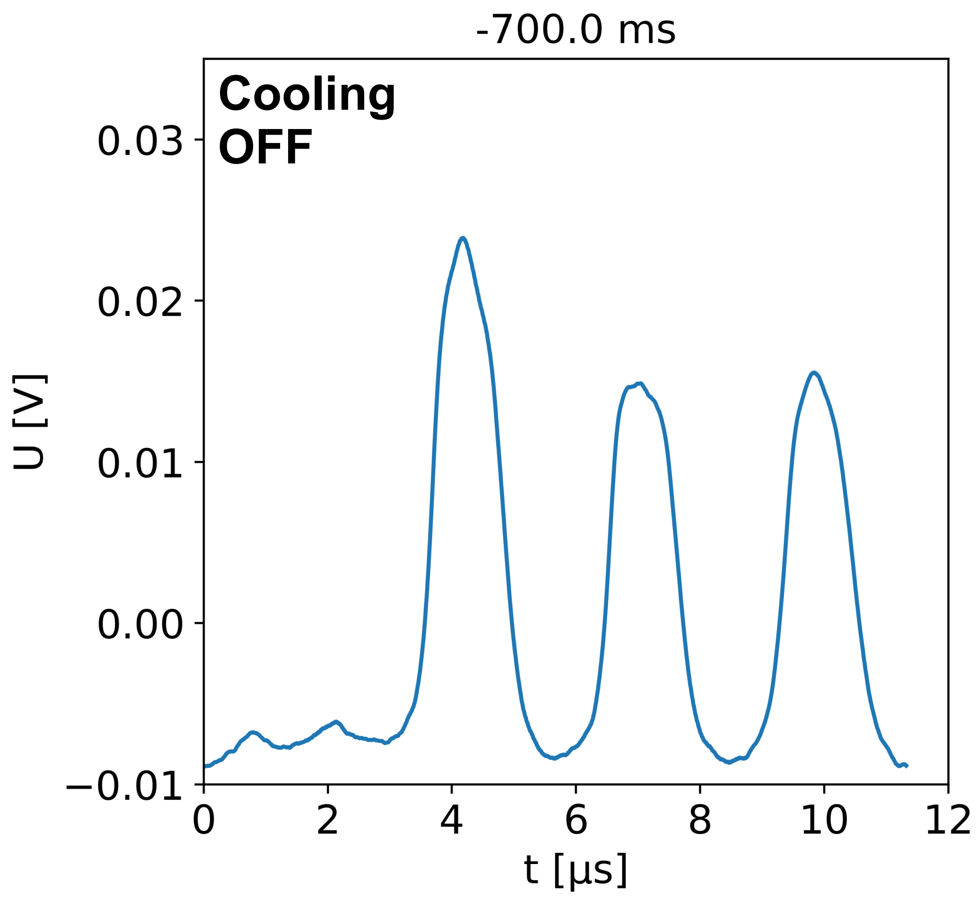

May 2018

HeH^+

- Ion energy: **250 keV**
- Ion current: **300 nA**
- Cooling energy: **27.4 eV**
- Electron current: **27.0 µA**
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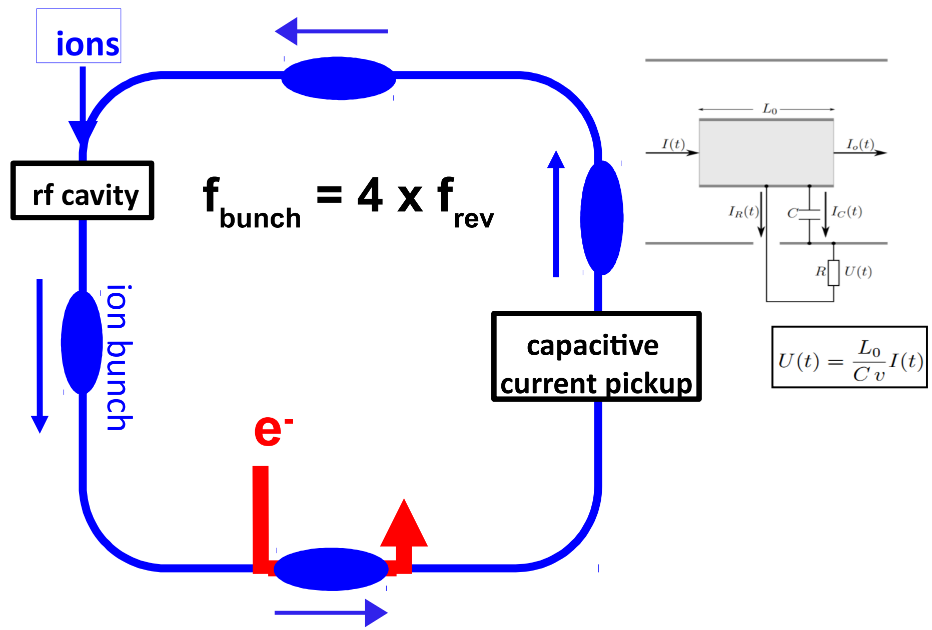

Longitudinal Cooling Demonstration – Bunched Beam

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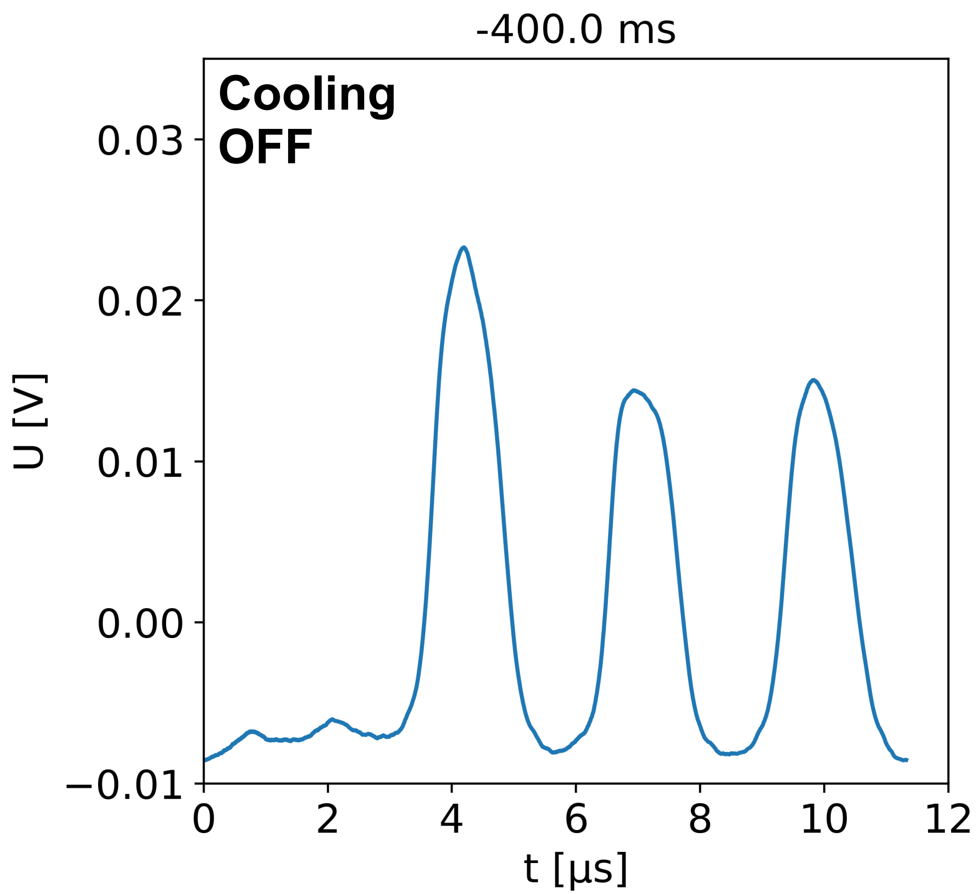

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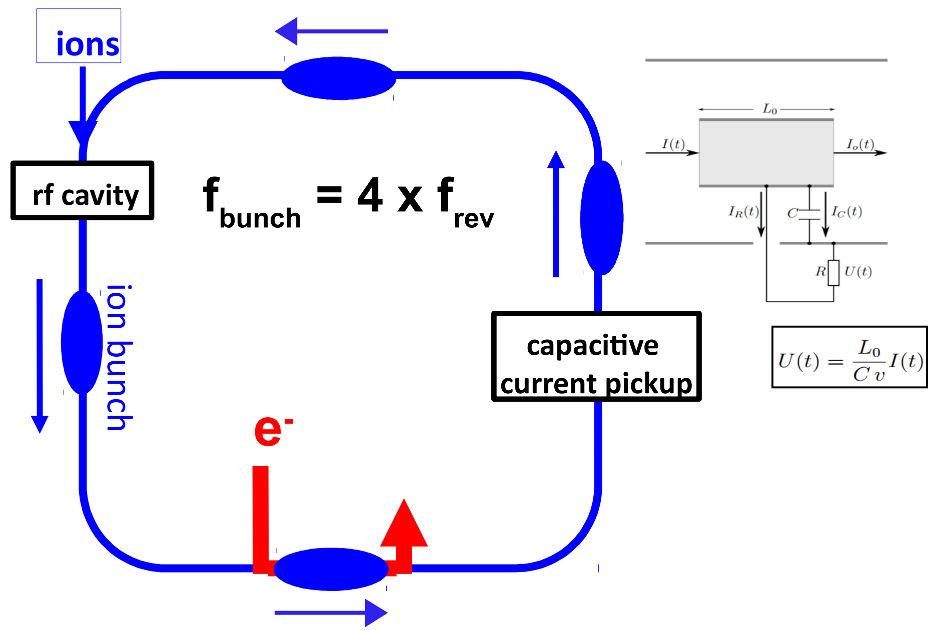

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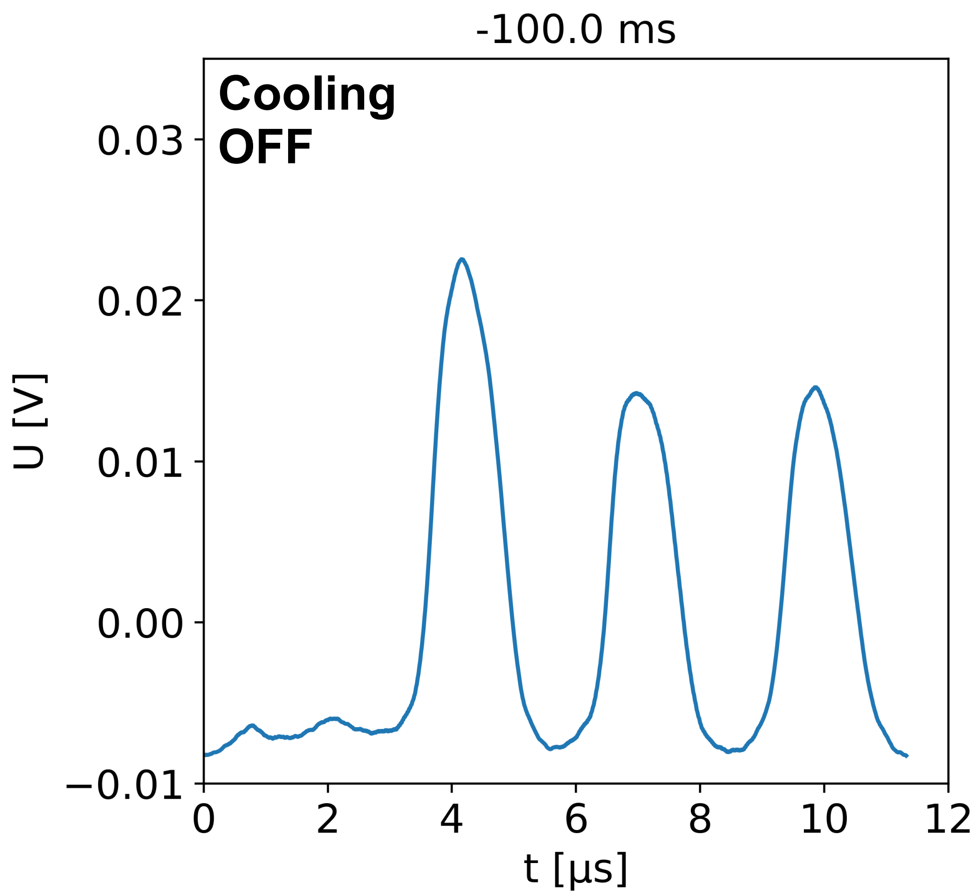

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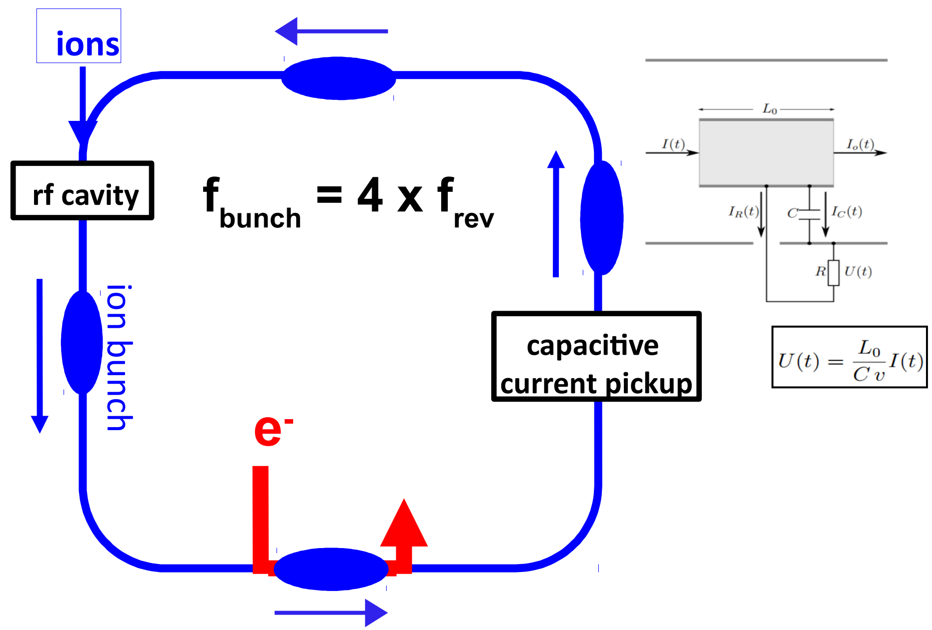

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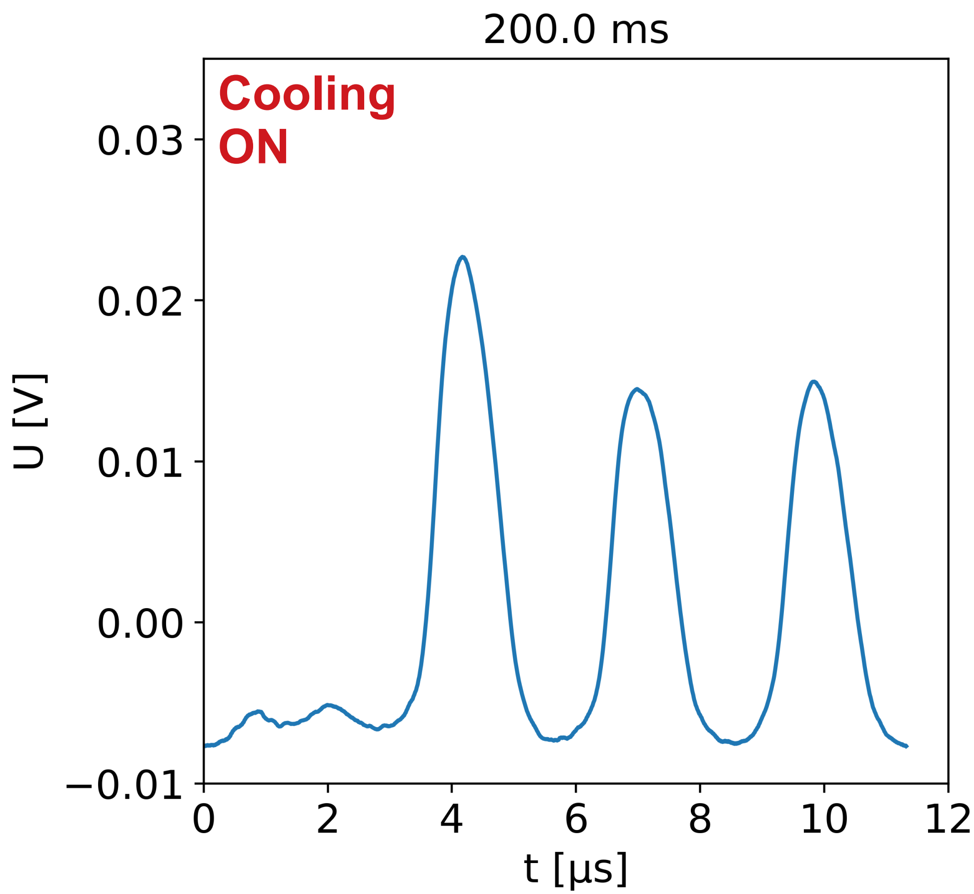

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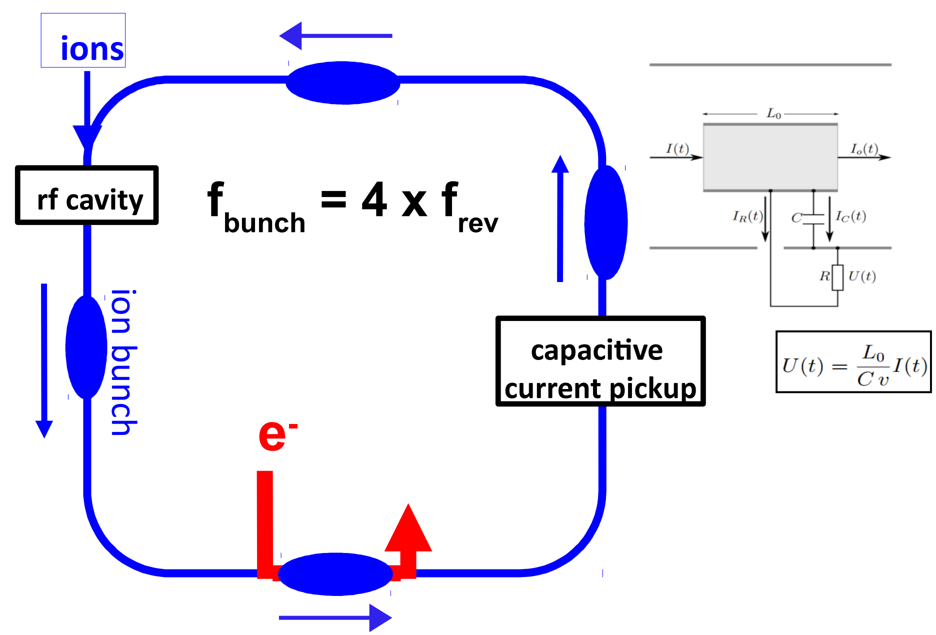

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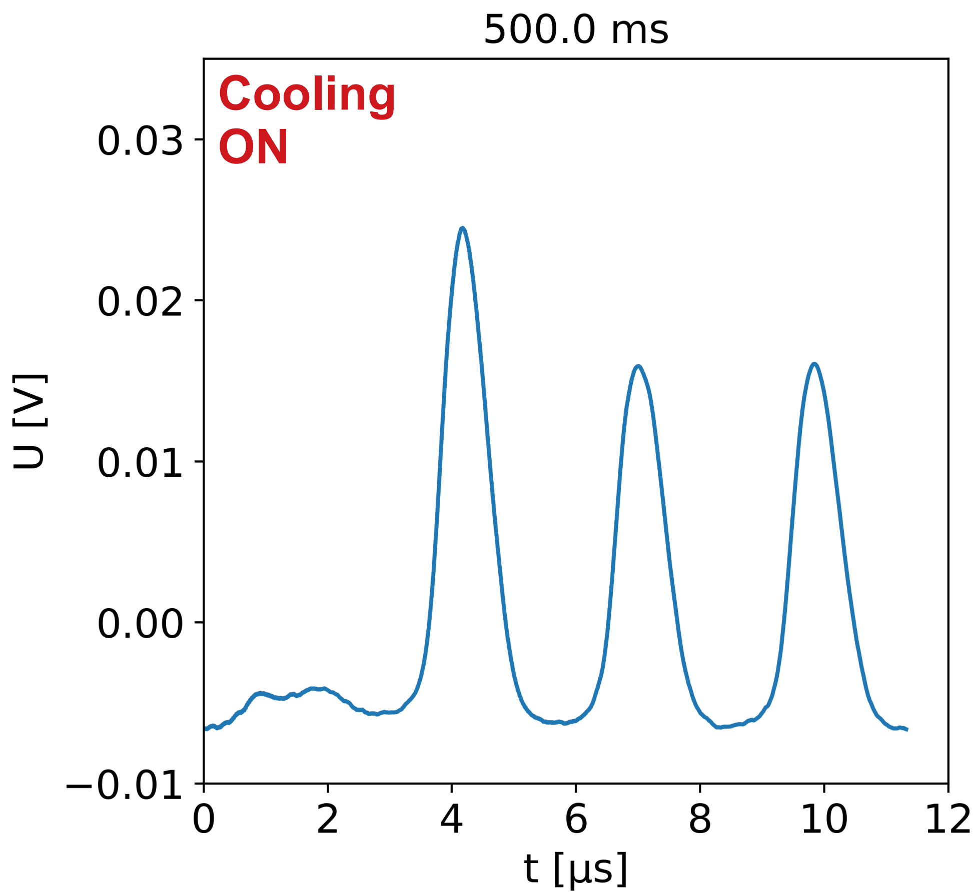

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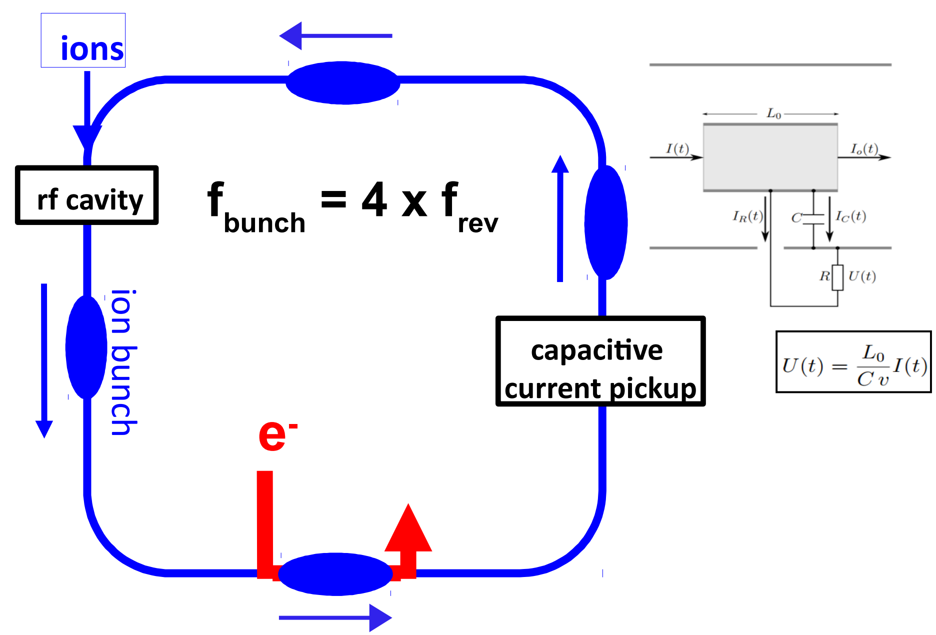

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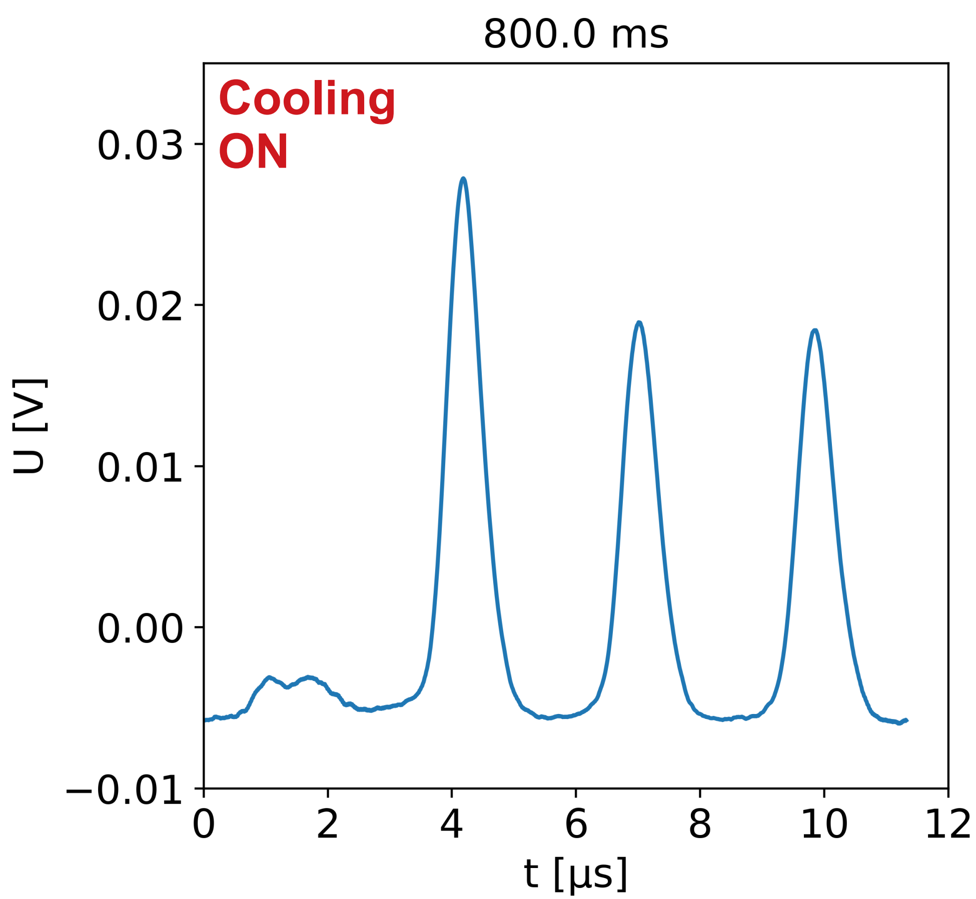

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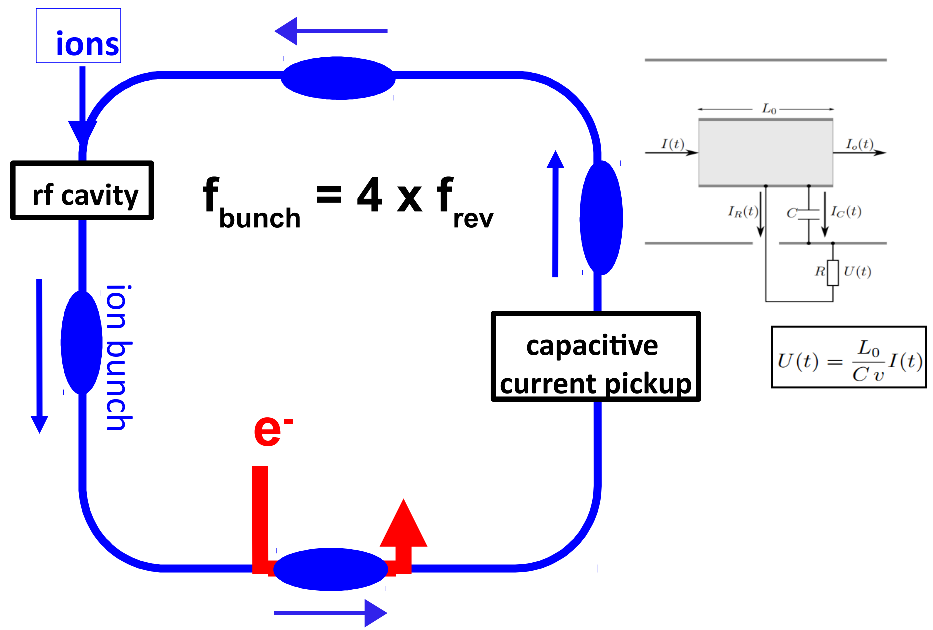

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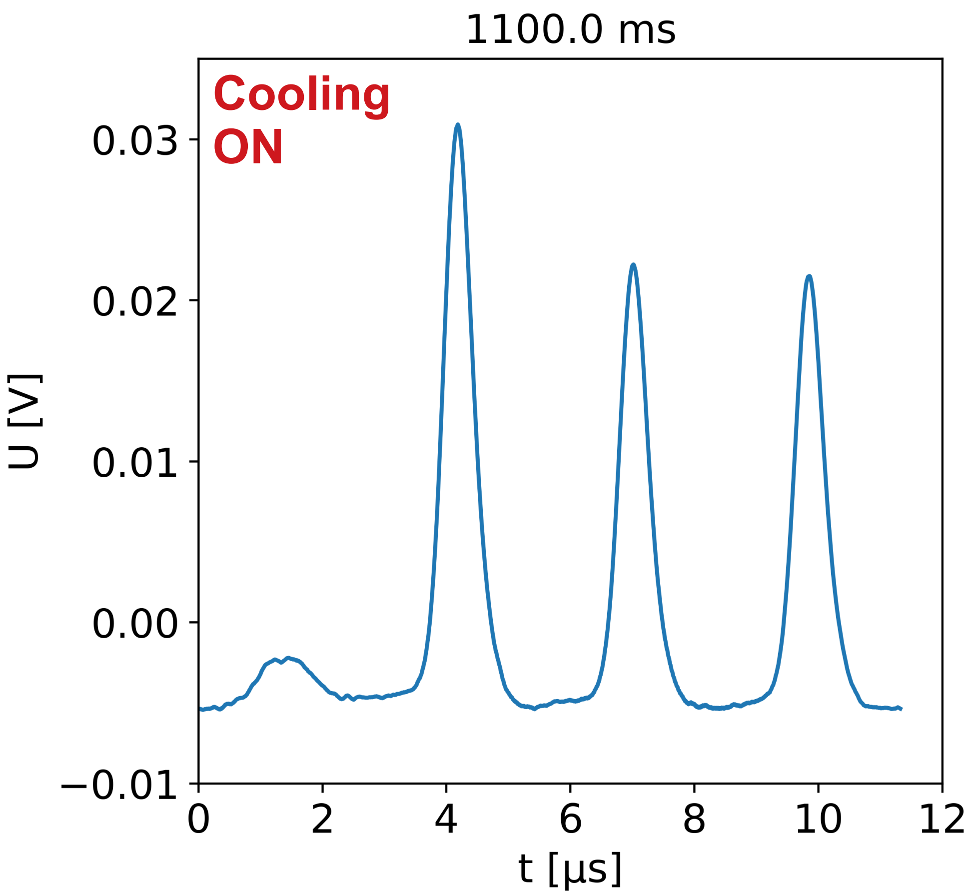

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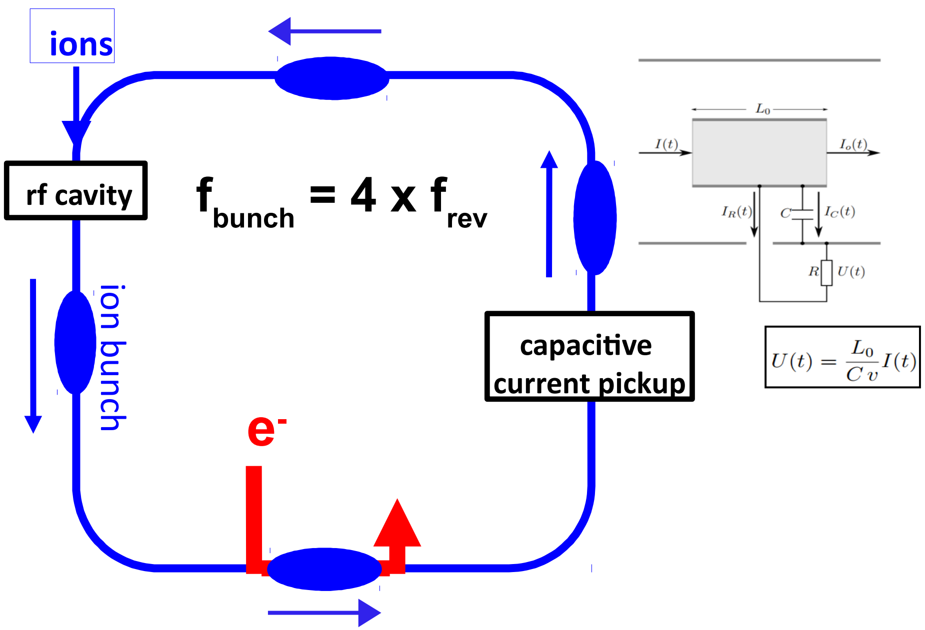

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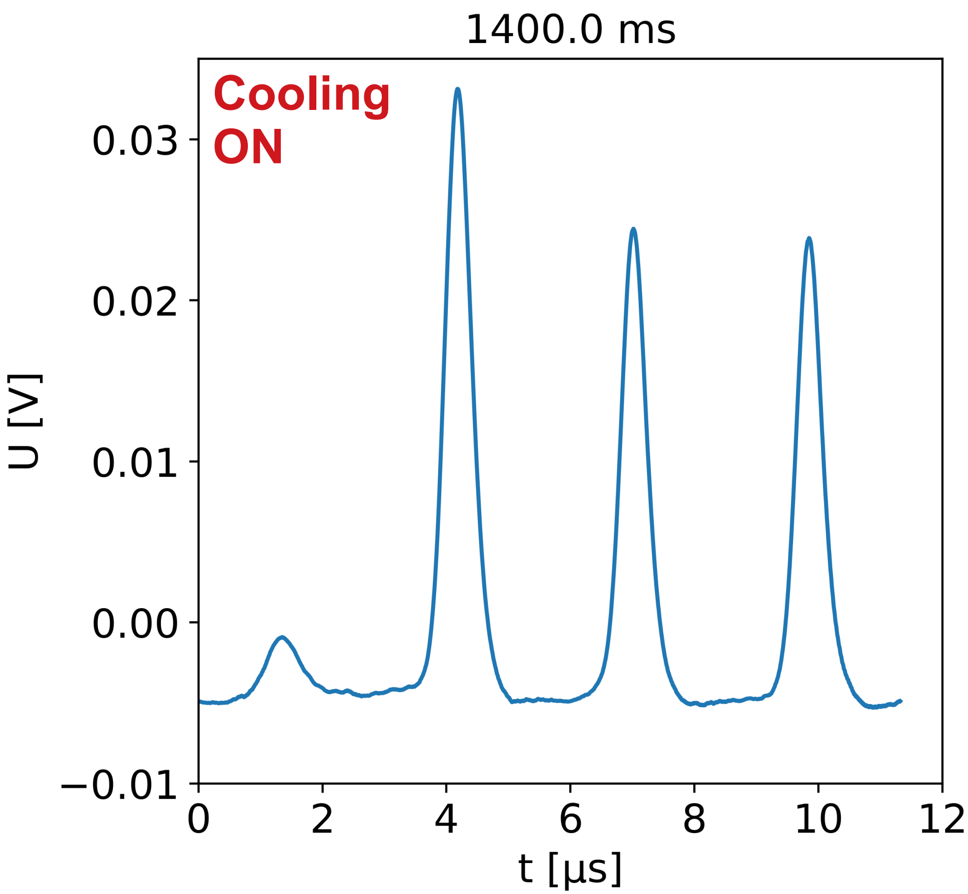

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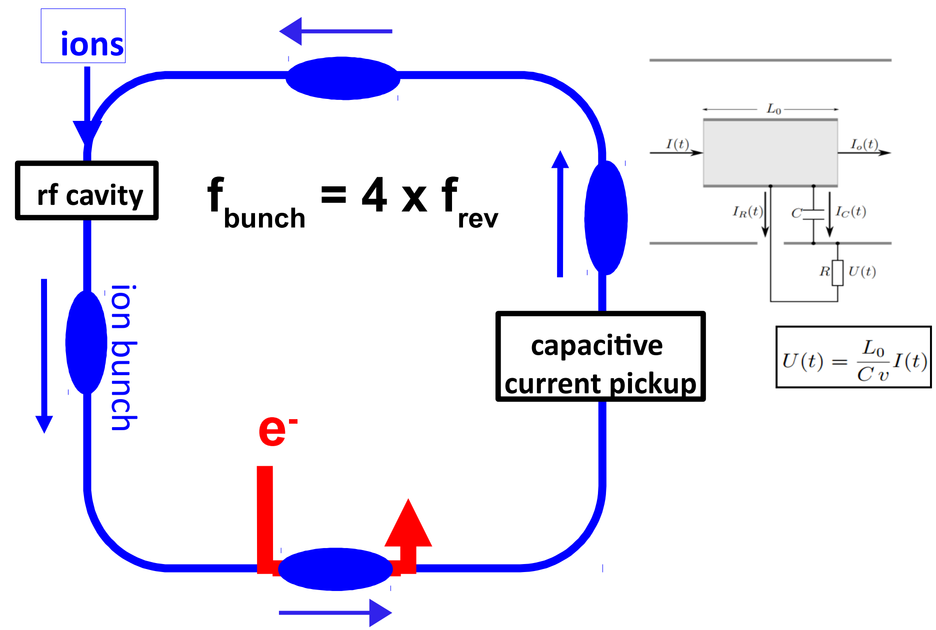

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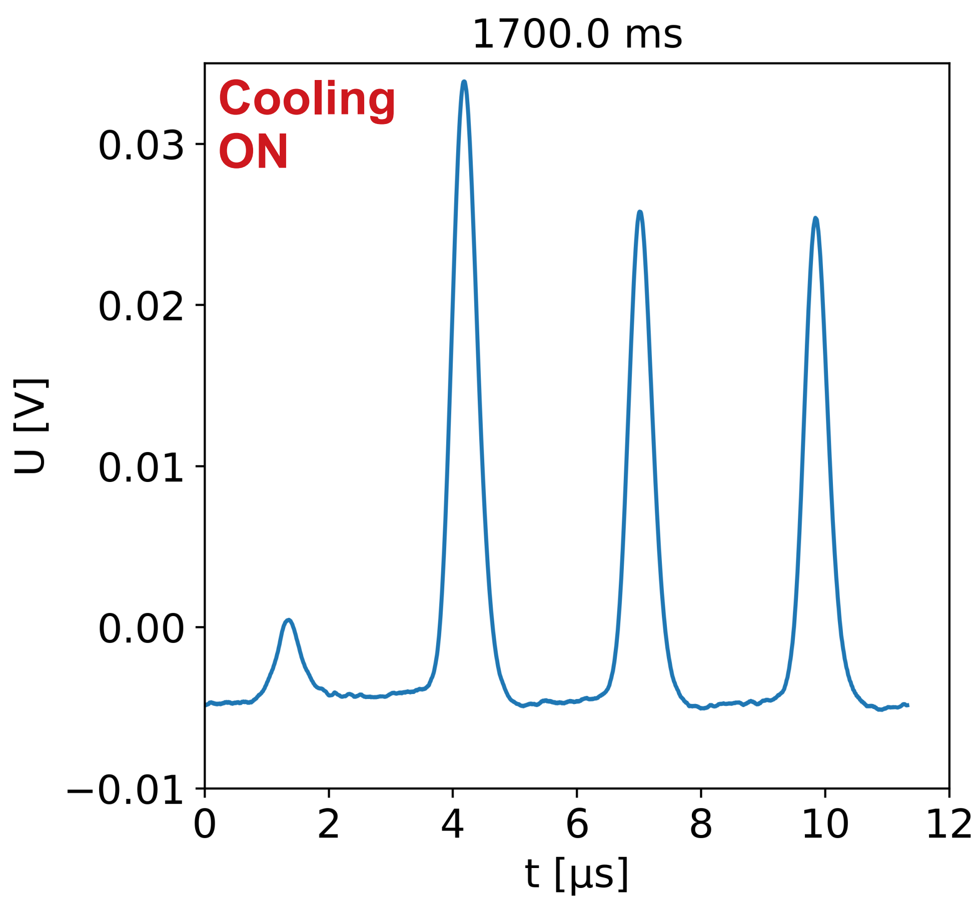

May 2018

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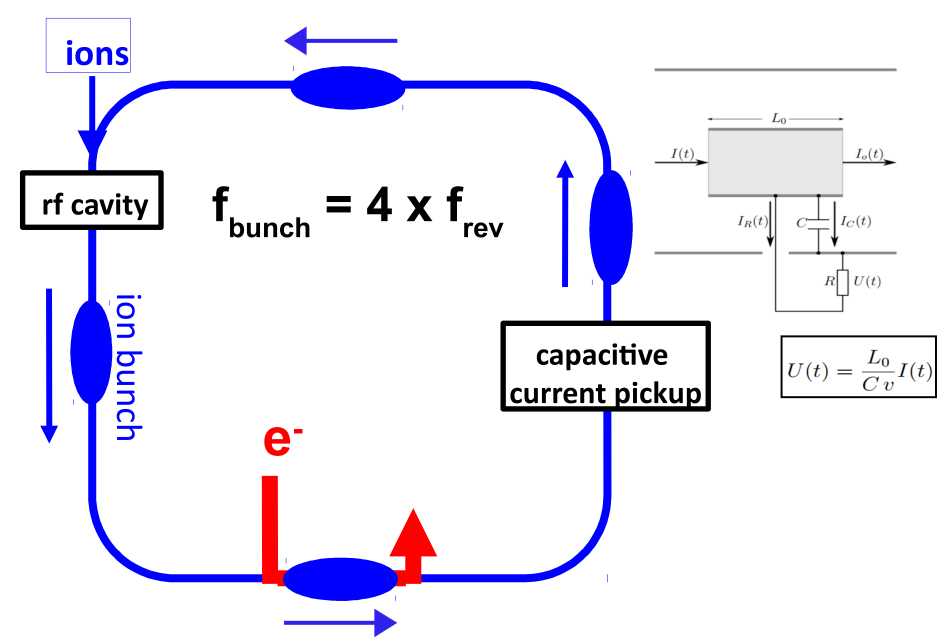

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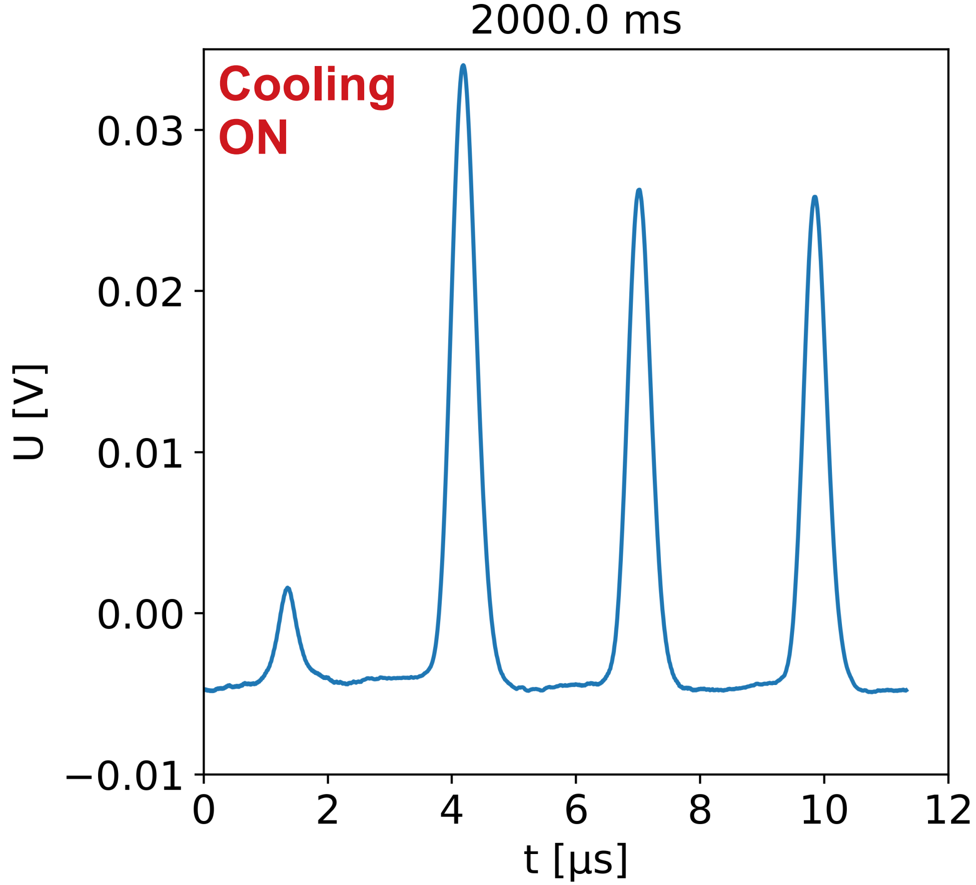

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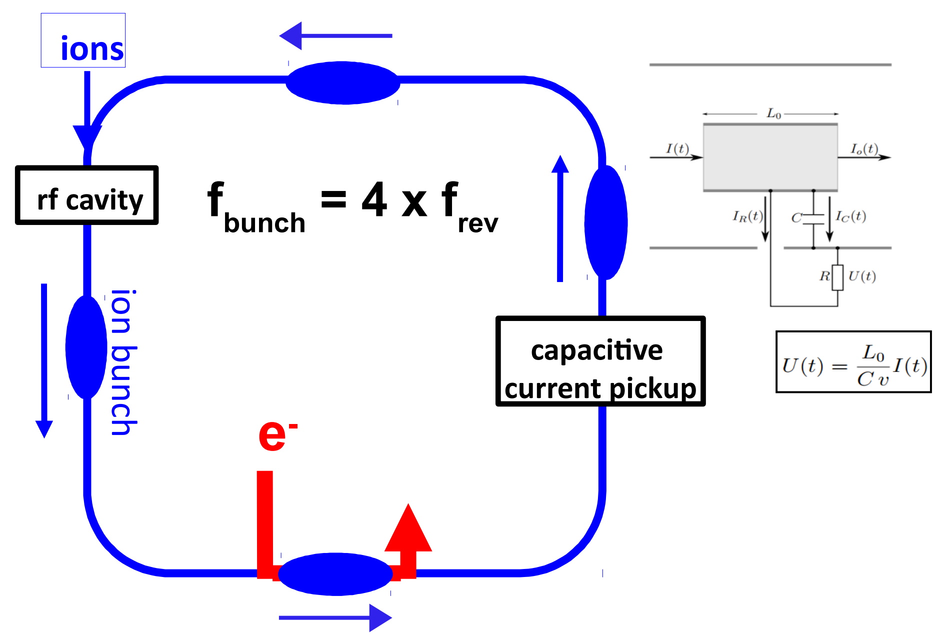

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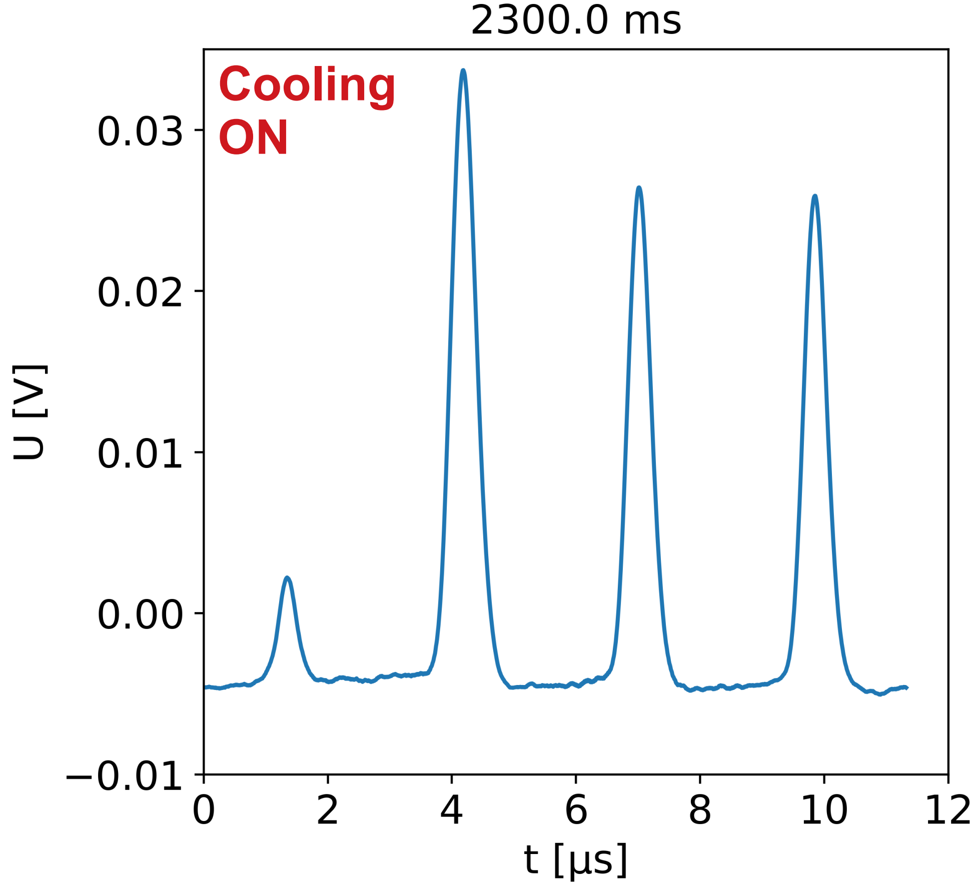

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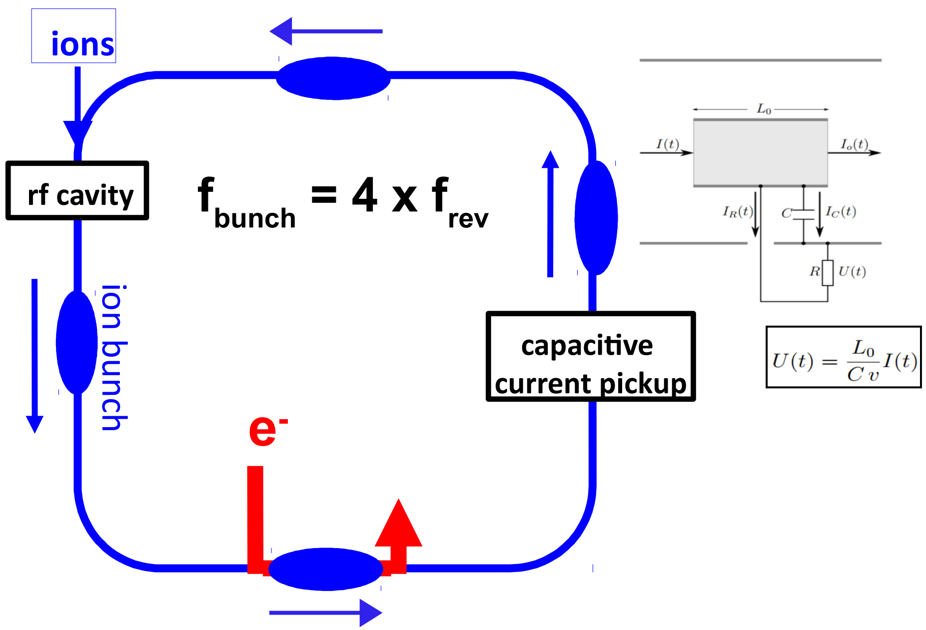

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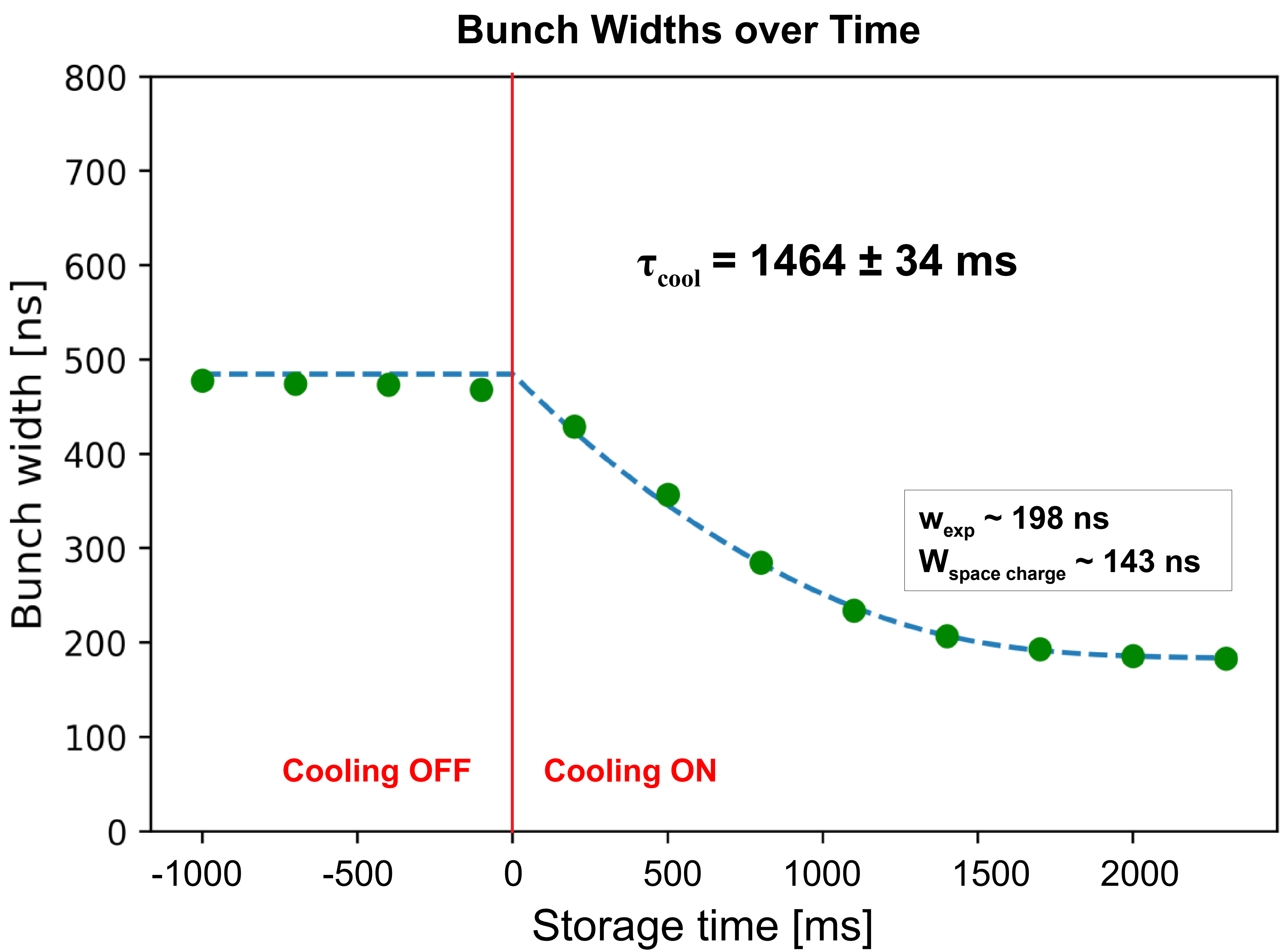


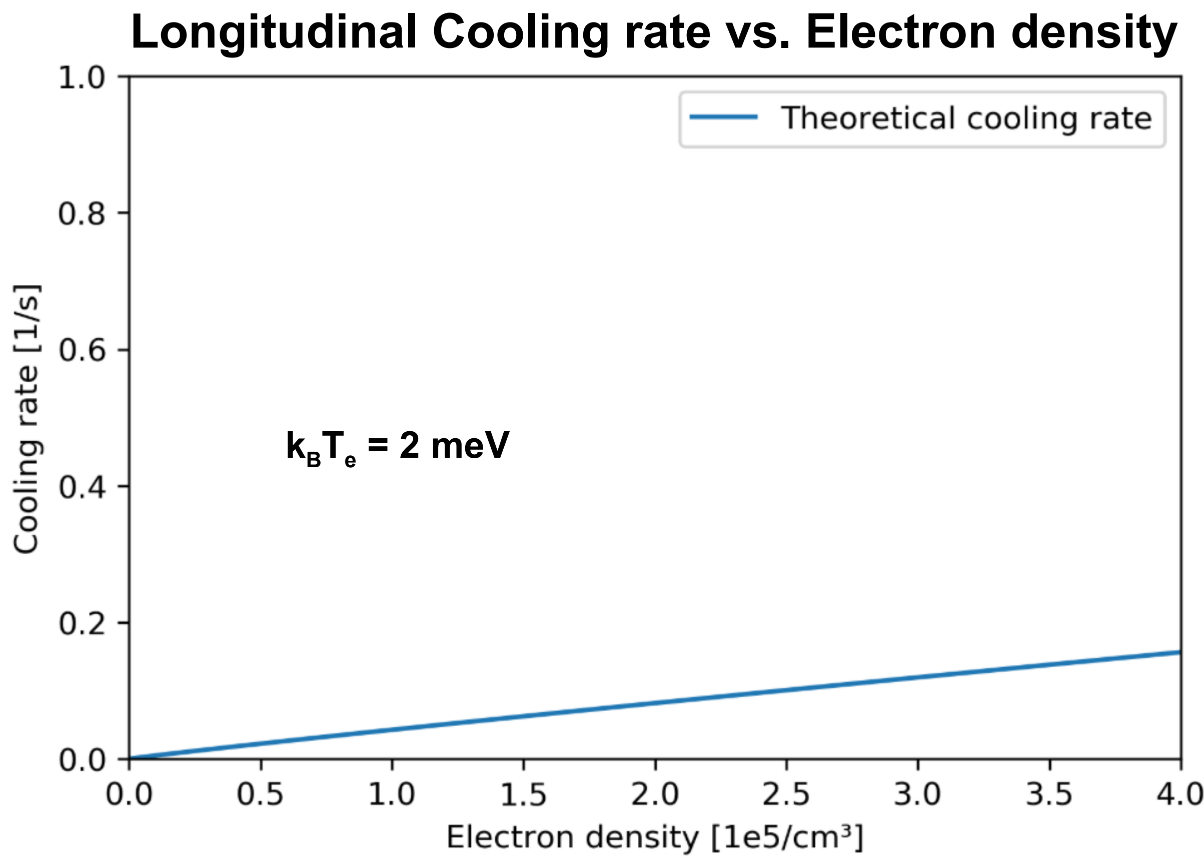
Longitudinal Cooling Demonstration – Bunched Beam

Theoretical cooling rate estimated from temperature relaxation time in an isotropic Maxwellian plasma

$$r_{cool,bunchsize} = \frac{1}{4 \cdot \tau_{cool,plasma}} \cdot \frac{L}{C_0}$$

$$\tau_{cool,plasma} = \frac{3(4\pi\epsilon_0)^2 m_e}{8\sqrt{(2\pi)}e^4} \frac{m_i}{z^2} \frac{1}{n_e L_C} \left(\frac{k_B T_e}{m_e}\right)^{3/2}$$

L. Spitzer, Physics of Fully Ionized Gases



Coulomb logarithm:

$$L_C = \int_{b_{min}}^{b_{max}} db/b = \ln(b_{max}/b_{min})$$

Impact parameters:

$$b_{max} = \lambda_D \equiv \sqrt{\frac{\varepsilon_0 k_B T_e}{n_e e^2}}$$

$$b_{min} = \frac{Ze^2}{4\pi\varepsilon_0 3 k_B T_e}$$

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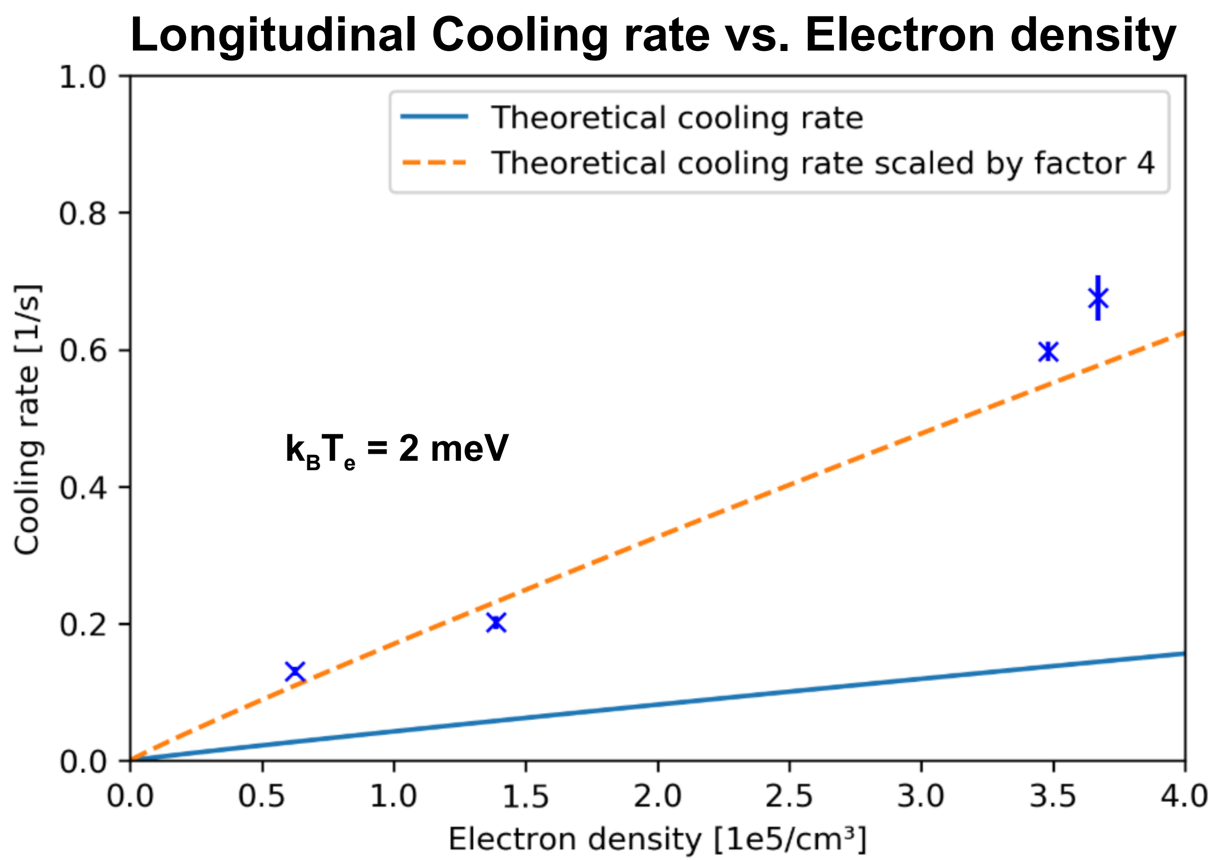

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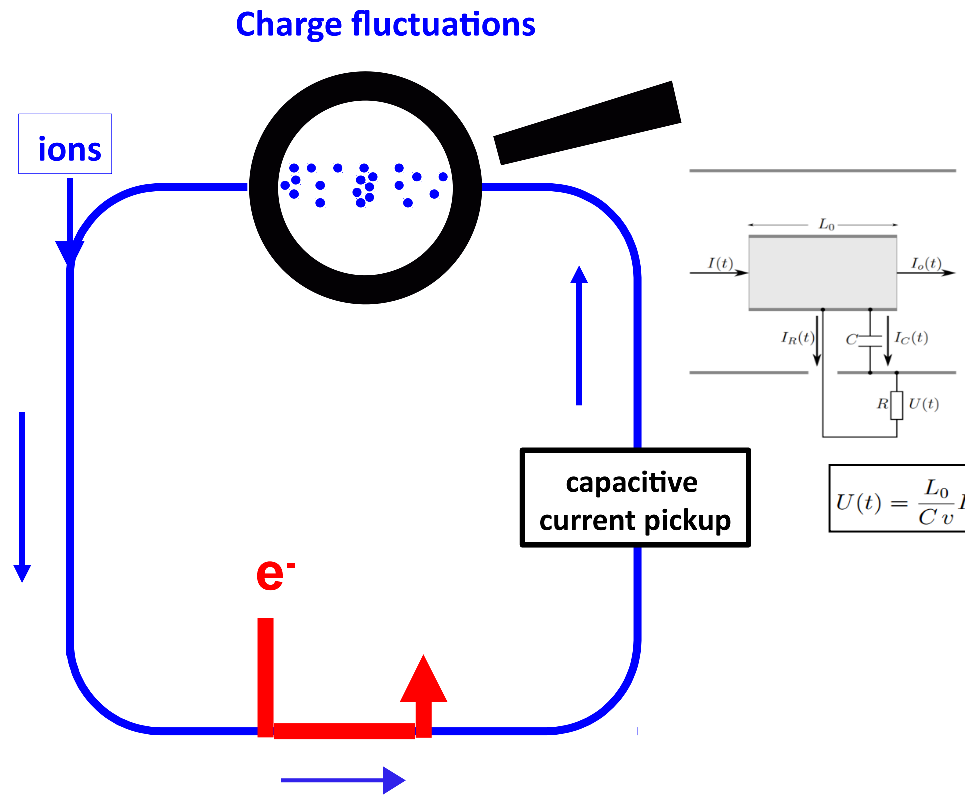
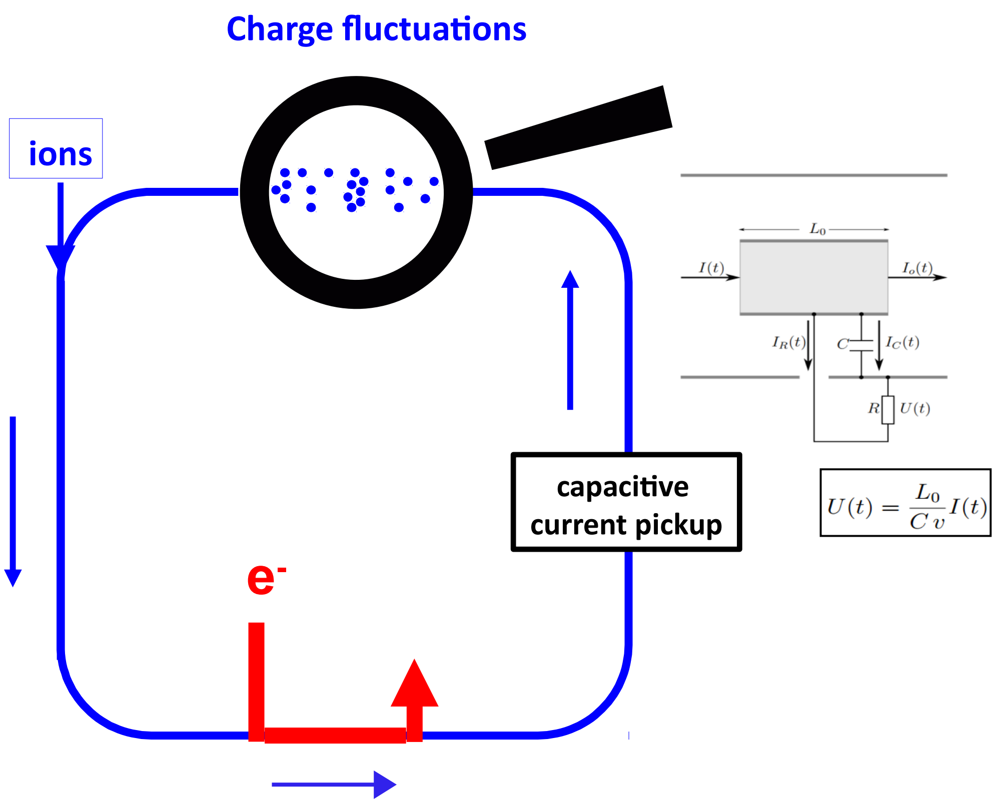
Longitudinal Cooling – Coasting Beam

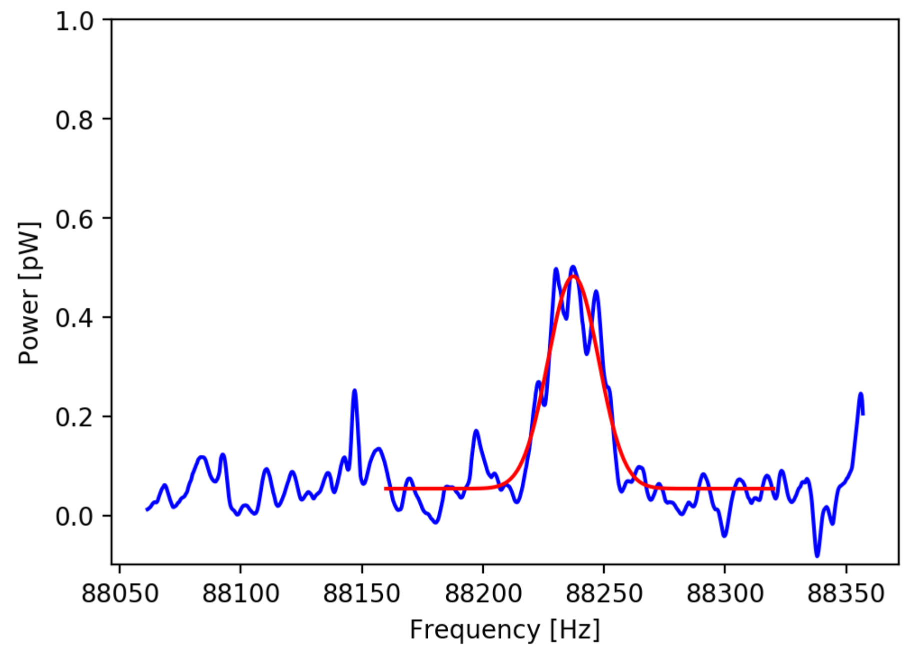


$$U(t) = \frac{L_0}{C\,v} I(t)$$

Longitudinal Cooling – Coasting Beam



Background subtracted Schottky noise spectrum

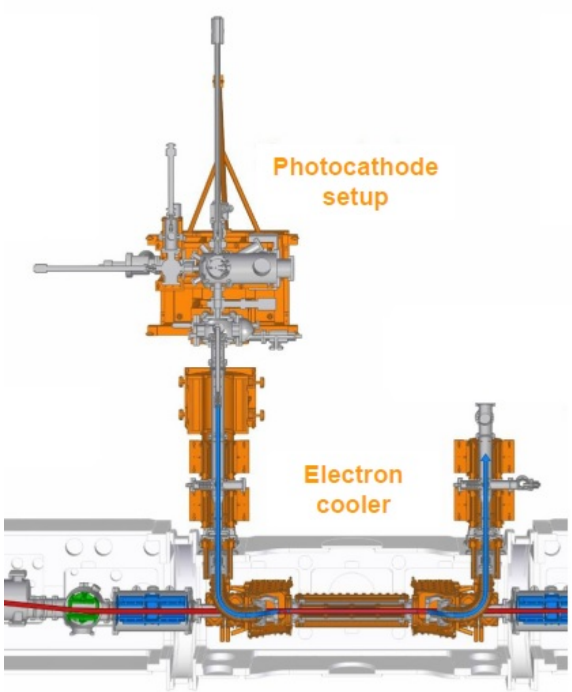


Estimate of ion beam momentum spread:

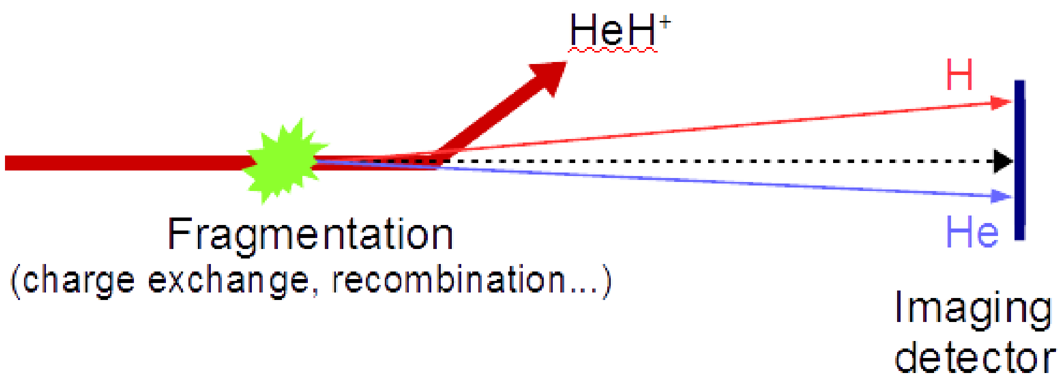
$$\frac{\Delta p}{p} = \frac{1}{\eta}\frac{\Delta f}{f} \approx 1.7 \cdot 10^{-4}$$

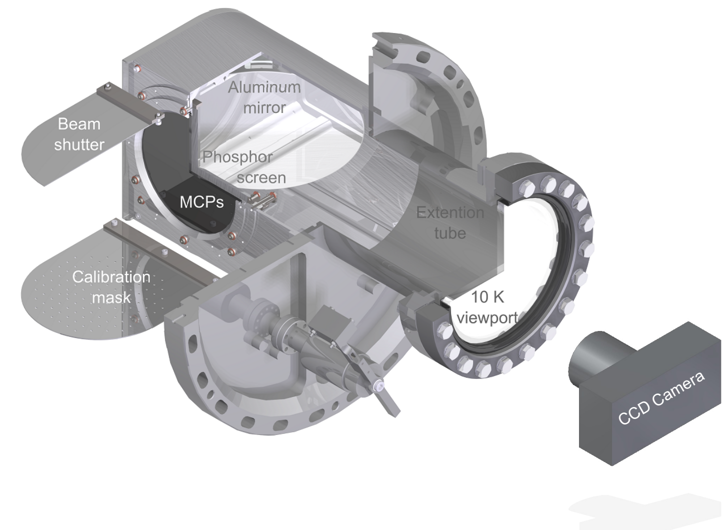
Outline

- Reminder: The electrostatic Cryogenic Storage Ring (CSR)
- CSR Detectors
- The CSR low-energy electron cooler
- **Cooling Observation and Optimization**
  - Longitudinal
  - **Transverse**
- Lifetimes of electron cooled ion beams



Transverse Cooling – Detection Principle





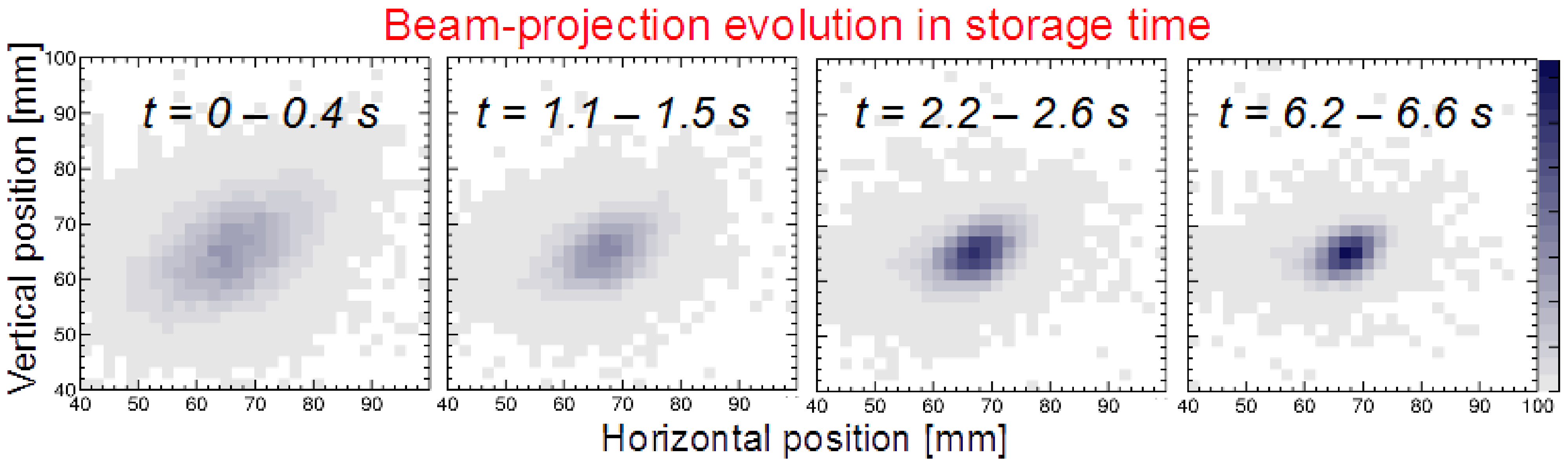
- **Center-of-mass** distribution of two-body events
  → **transverse emittance** of stored ions

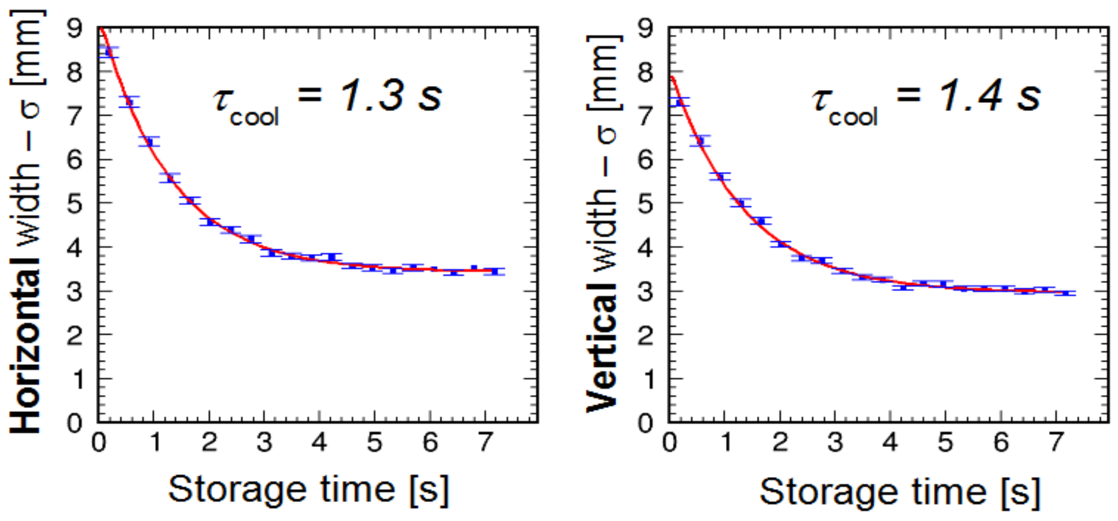
Fragmentation processes

Dissociative Recombination: $HeH^+(\nu, J) + e^- \rightarrow He + H$

Residual gas charge transfer: $HeH^+ + H_2 \rightarrow He + H + H_2^+$

Transverse Cooling – Coasting Ion Beam





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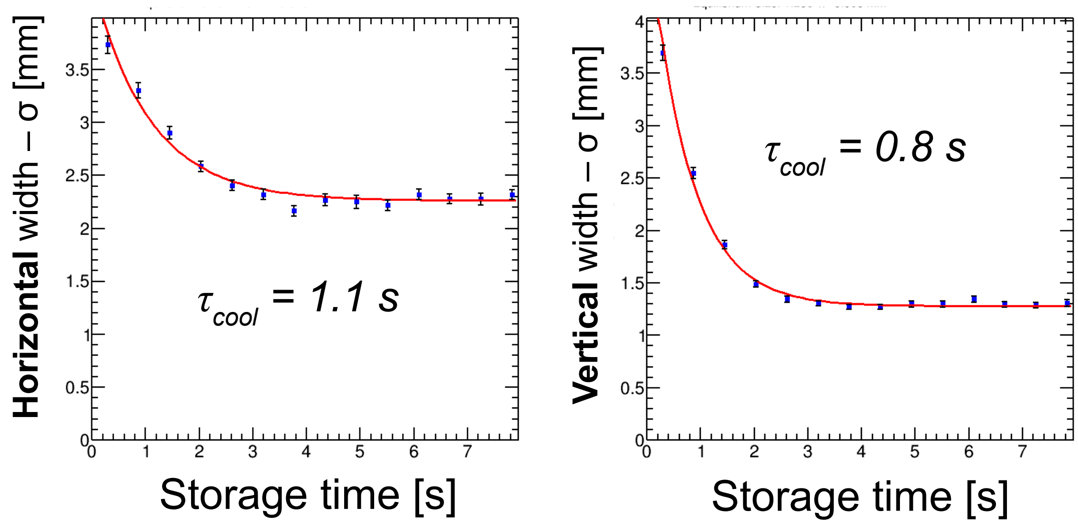
- Ion energy: 250 keV
- Ion current: 311 nA
- Cooling energy: **27.4 eV**
- Electron current: 26.0 μA
- Electron density: $\mathbf{3.7 \cdot 10^5 cm^{-3}}$

Transverse Cooling – Coasting Ion Beam

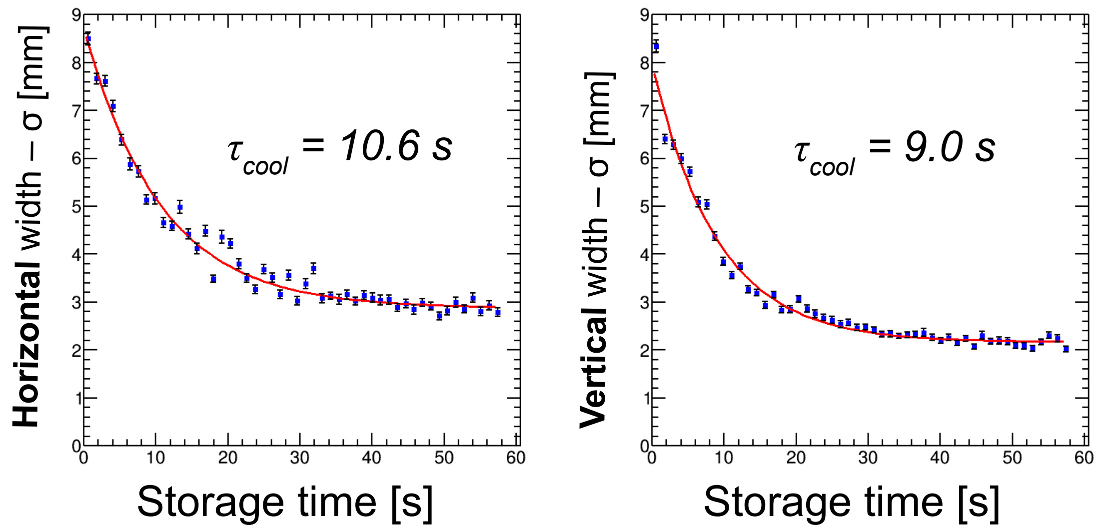
HD⁺

- Ion energy: 250 keV
- Ion current: 182 nA
- Cooling energy: **45.7 eV**
- Electron current: 34.7 μA
- Electron density: **$2.6 \cdot 10^{5}\,cm^{-3}$**



O⁺

- Ion energy: 250 keV
- Ion current: 602 nA
- Cooling energy: **8.57 eV**
- Electron current: 31.2 μA
- Electron density: **$5.3 \cdot 10^{5}\,cm^{-3}$**



Transverse Cooling – Density Comparison

Plasma Model

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

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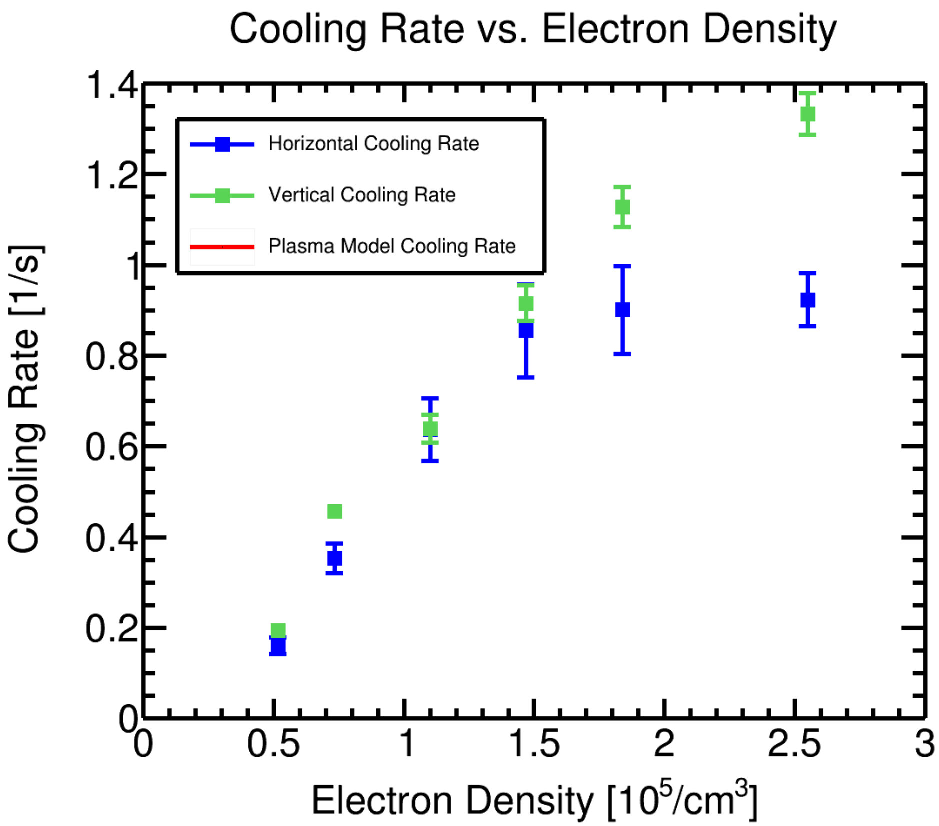

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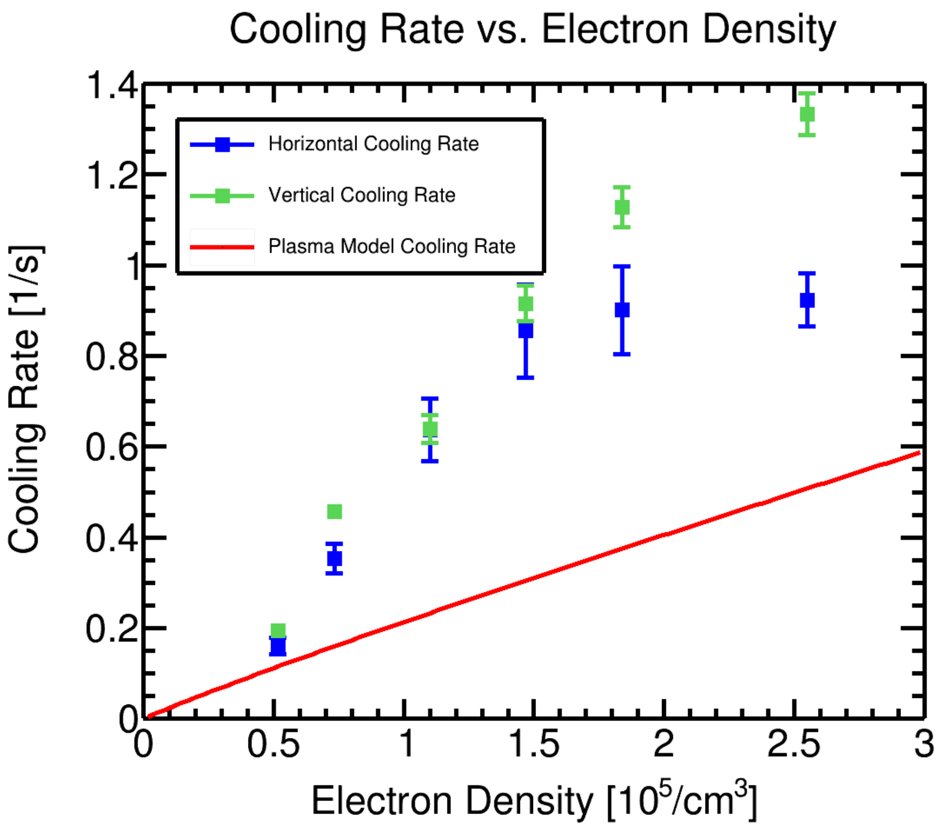

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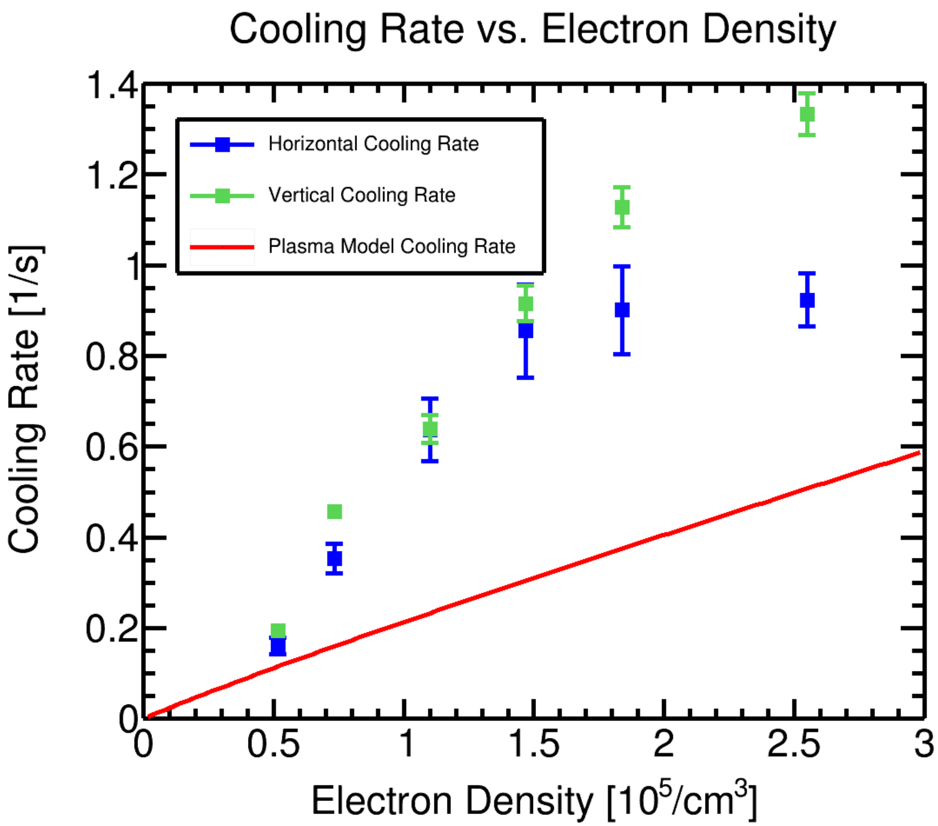

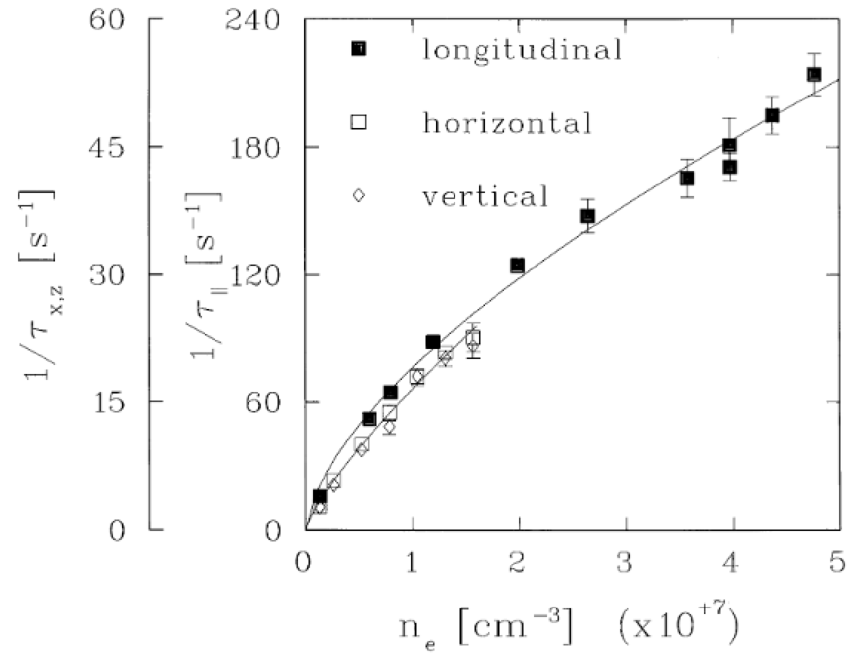

Beutelspacher et al., Nucl. Instr. Meth. A 441 (2000) 110-115

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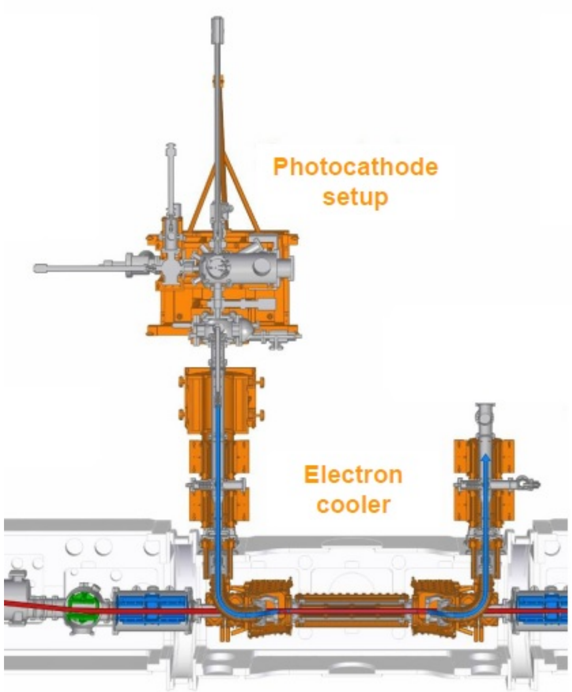

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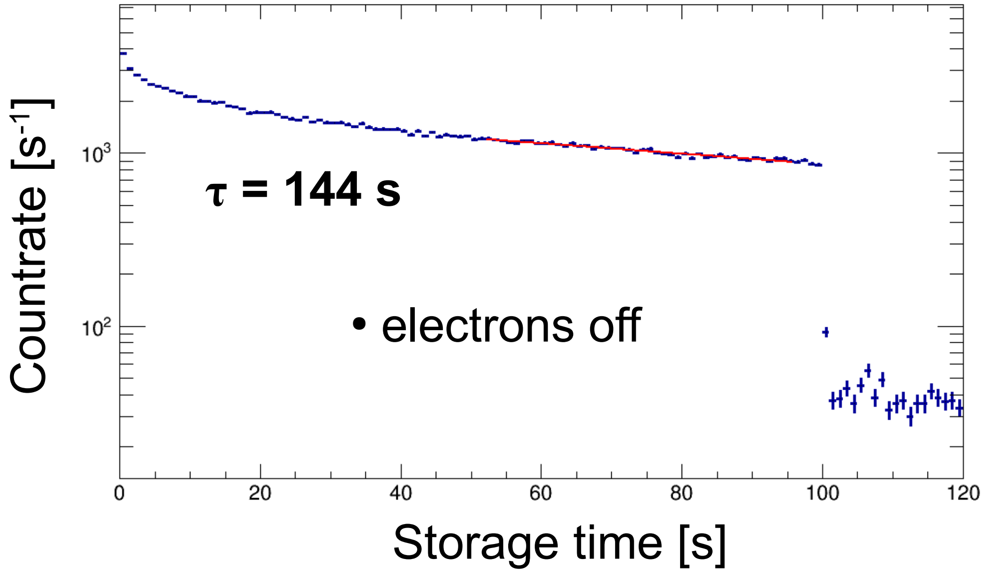

May 2018

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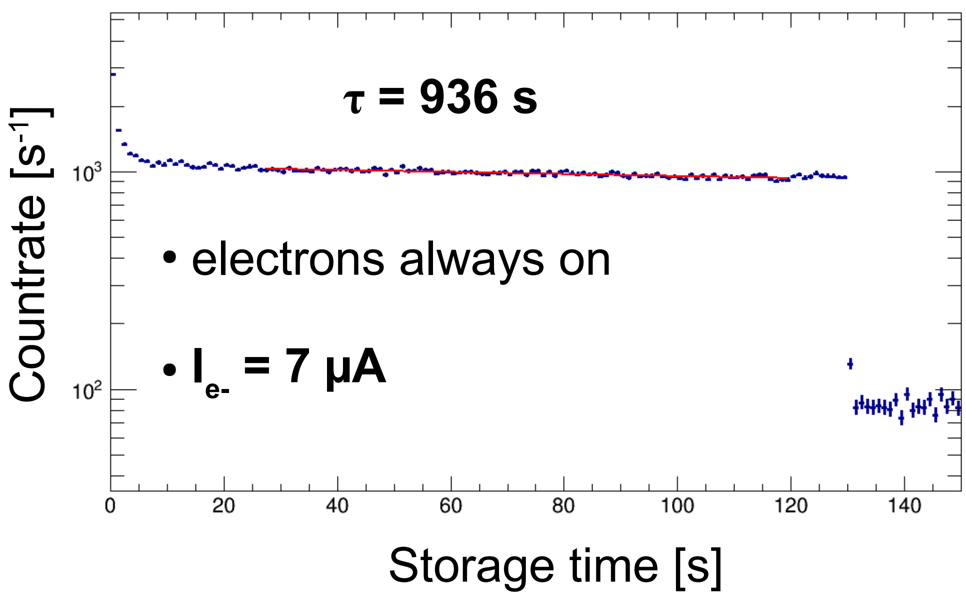
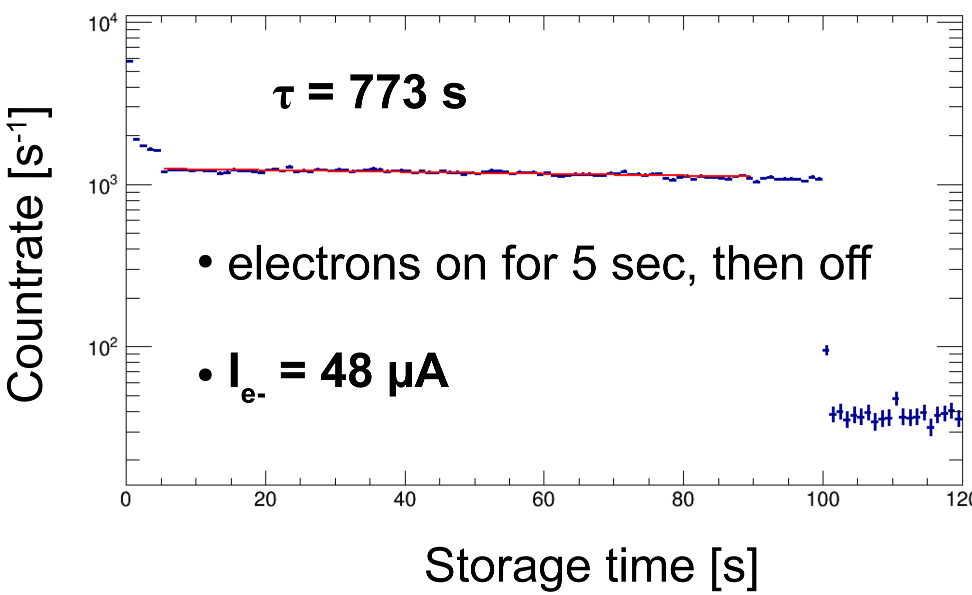




Outlook - Different Ion Species

20 keV, n_e similar to O^+

Ion	m [u]	E_{cool} [eV]	τ_{cool} [s]
$p^+ / \bar{p}$	1	10.9	0.6 ?

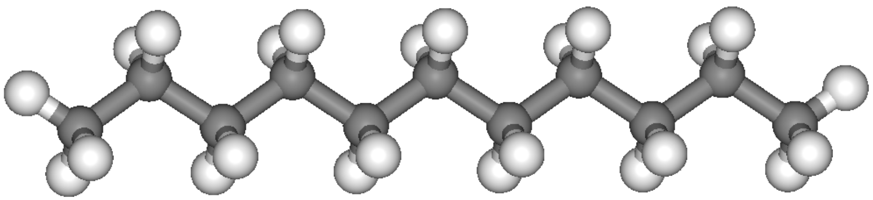
250 keV

Ion	m [u]	E_{cool} [eV]	τ_{cool} [s]
HD^+	3	45.7	1.0
HeH^+	5	27.4	1.4
O^+	16	8.6	9.8

Cooling times to be proven...

250 keV, n_e halved compared to O^+

Ion	m [u]	E_{cool} [eV]	τ_{cool} [s]
TiO^+	64	2.1	78.4 ?
Xe^+	132	1.0	161.8 ?
$C_{10}H_{22}^+$	142	1.0	174.0 ?



https://upload.wikimedia.org/wikipedia/commons/e/e2/Undecane-stick.png

Summary

- CSR electron cooler as prototype low-energy cooler for electrostatic storage rings.
- Ions undergo only small, easily correctable distortions.
- Longitudinal & transverse cooling proven for low ion masses.
- Search for cooling energy and overlap done fast (within < 1 h for O^+ beamtime)
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Next beamtime:

March 2019

Thanks for your attention!

Max Planck Institute for Nuclear Physics, Heidelberg, Germany

Stored Ions / Atomic and Molecular Physics

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J. Karthein

Cryogenic Storage Ring

M. Grieser, R. Repnow, **R. von Hahn**
Alumni: F. Fellenberger, F. Berg

Molecular Ions and Astrophysics (ASTROLAB)

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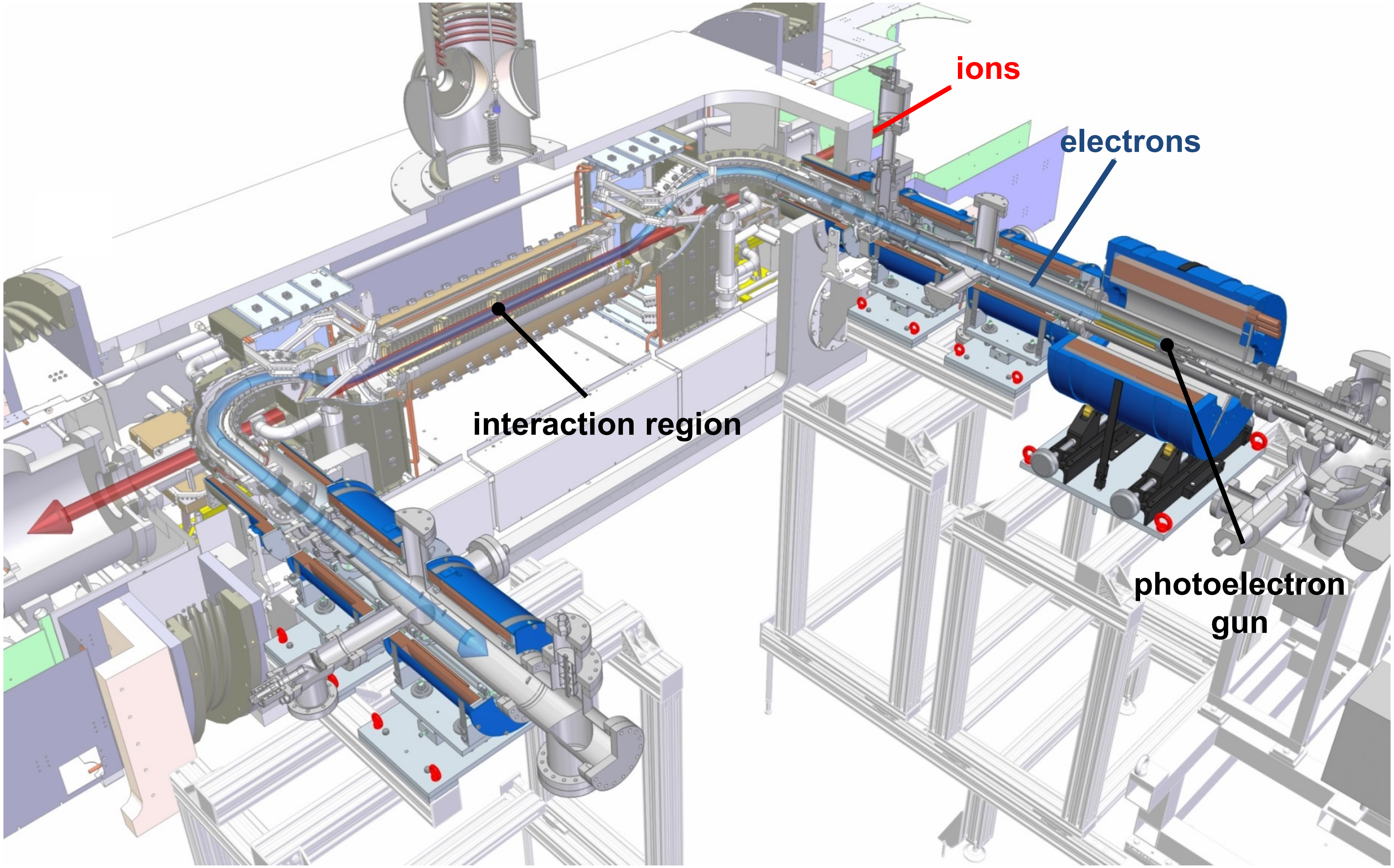
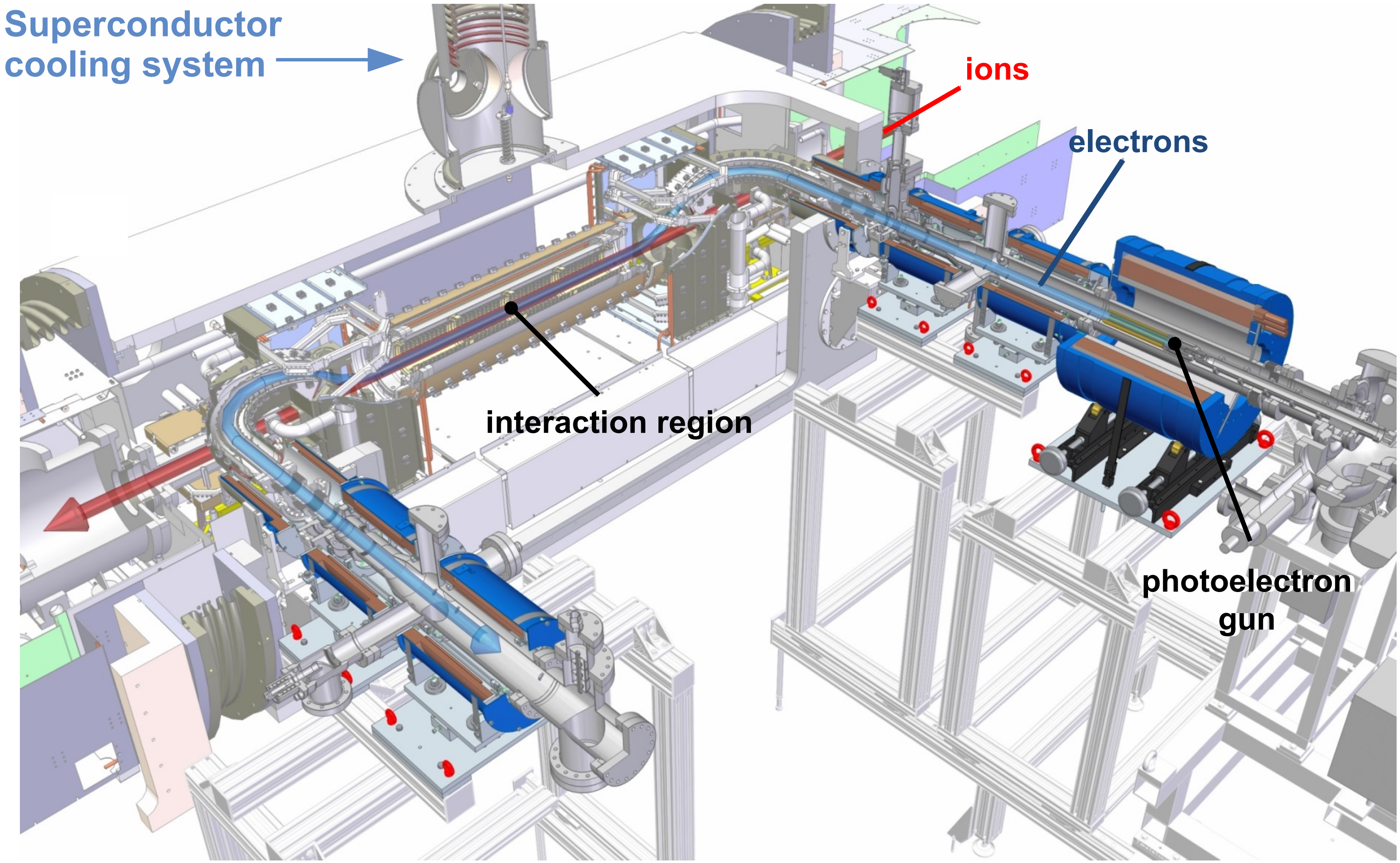
Backup Slides

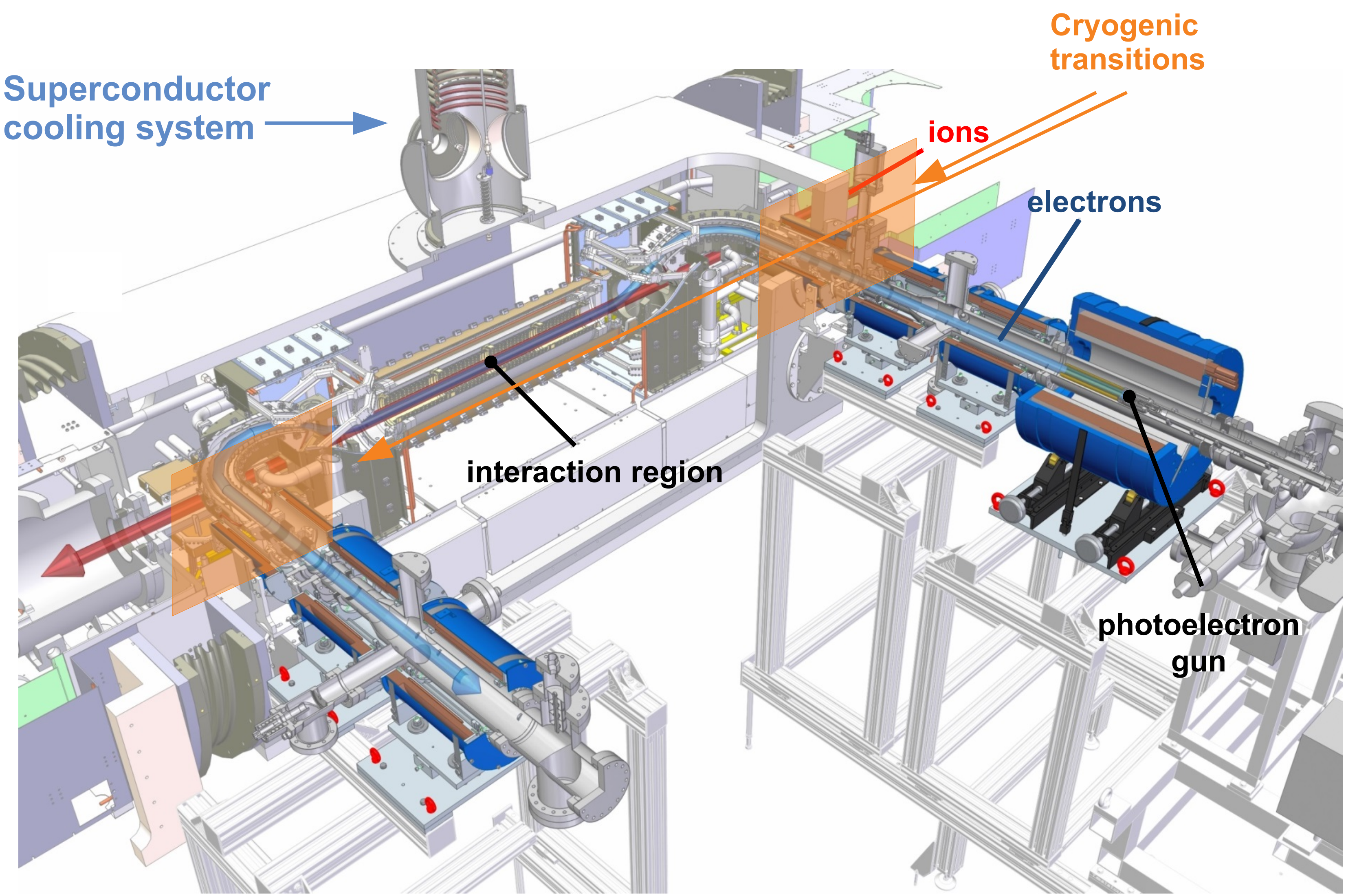
The CSR electron cooler



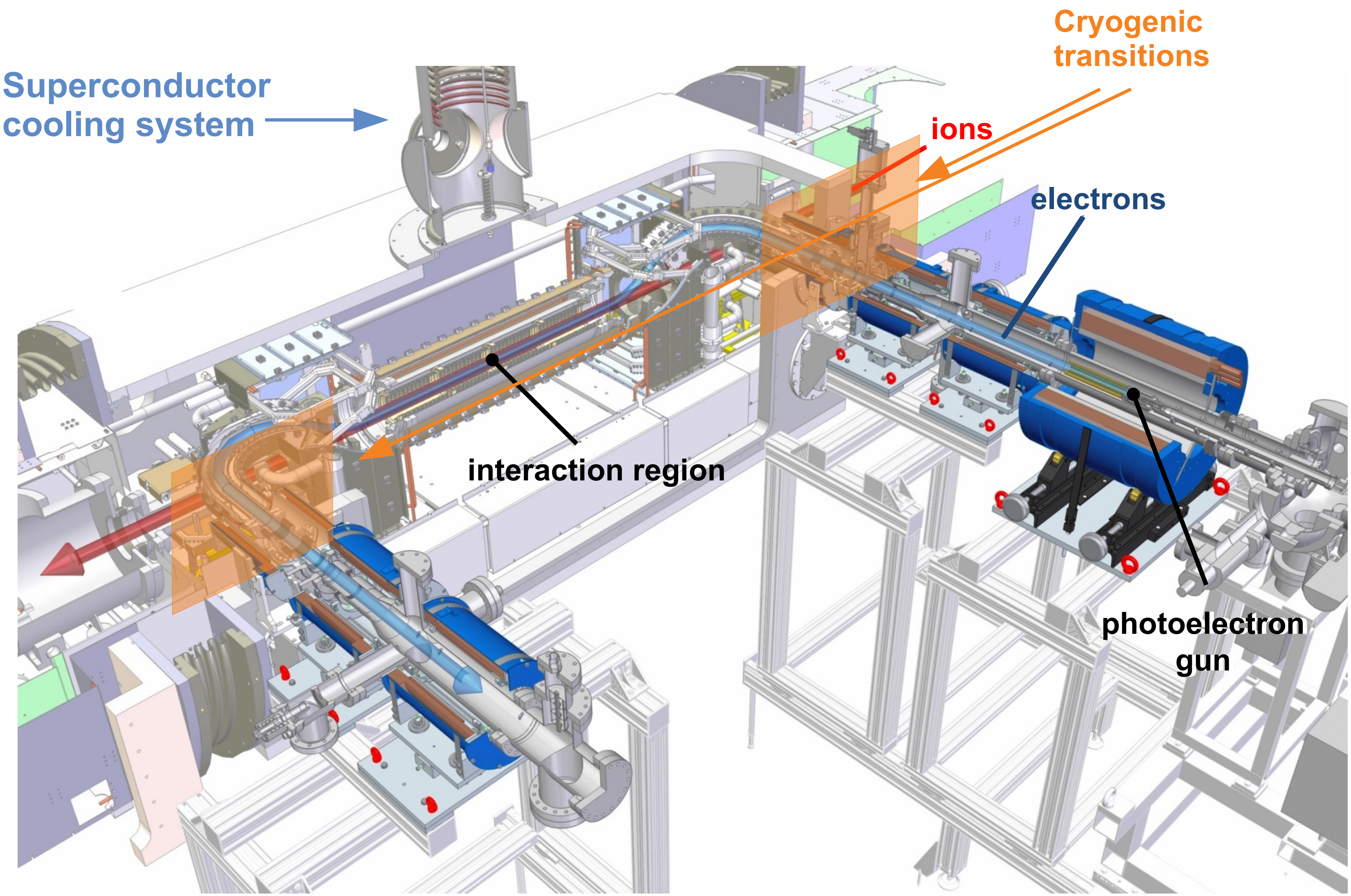
The CSR electron cooler



The CSR electron cooler

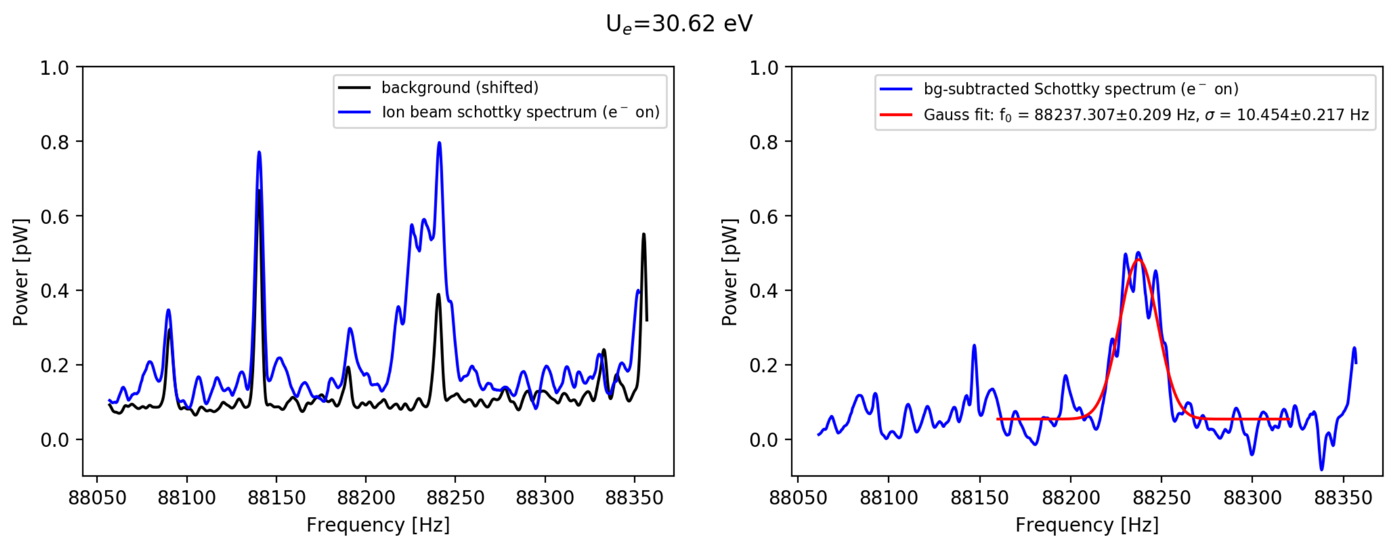


The CSR electron cooler



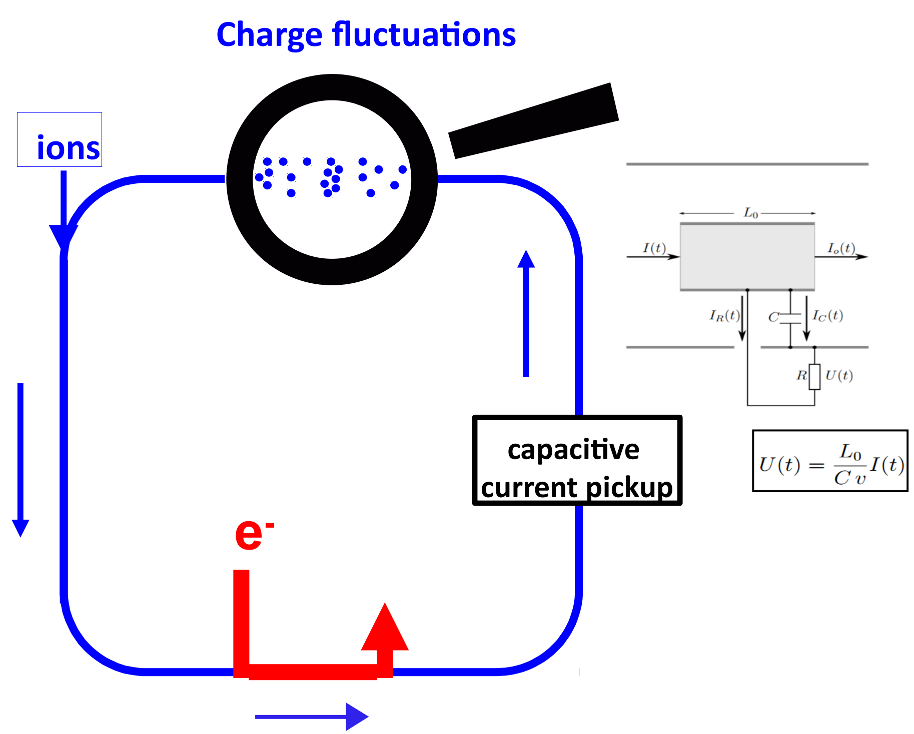
- structure must be contained in **CSR cryostat:**
  → 10 K, 10^{-13} mbar & bakeable to 100-200°C

Longitudinal Cooling – Coasting Beam



Estimate of ion beam momentum spread:

$$\frac{\Delta p}{p} = \frac{1}{\eta}\frac{\Delta f}{f} \approx 1.7 \cdot 10^{-4}$$



The CSR Electron Cooler – Temperature Spreads

- **Thermocathode:** $J \propto T^2 \exp \frac{-W}{kT}$

→ higher I_e needs higher $T_{cathode}$ (~ 1300-1800 K)

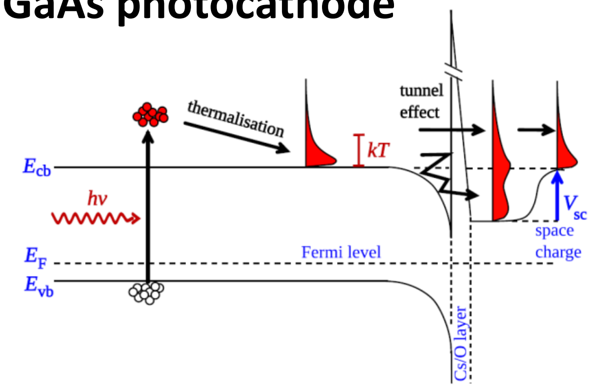
- **Photocathode:** $I = p \cdot U^{3/2}$

space-charge-limited current operation

  – GaAs(Cs,O): effective **negative electron affinity** (NEA= E_c-E_{vac})

$T_\perp$ **~ 10 meV**

GaAs photocathode



Photocathodes as electron sources for high resolution merged beam experiments

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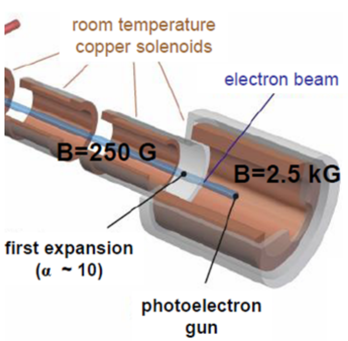
adiabatic magnetic expansion

$T_{f,\perp} = T_{i,\perp} / \alpha$

$T_\perp$ **~ 0.5 meV**



kinematic compression

- acceleration of electron cloud by potential difference U

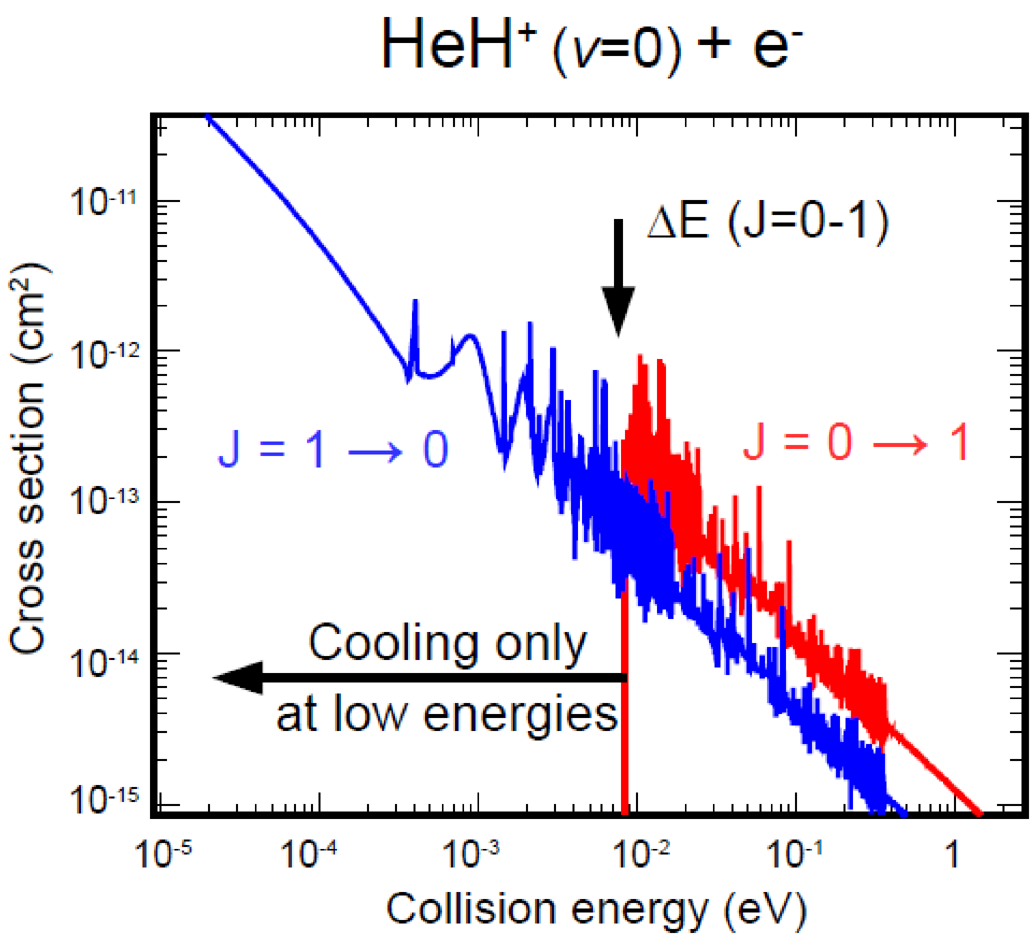
$$k_B T_\parallel = \frac{(k_B T_c)^2}{2eU}$$

$T_\parallel$ ~ (10-100) μeV

Outlook – Electron induced (de-)excitation

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

internal cooling/heating by inelastic electron collisions



Collaboration:
C. Greene, S. Kokoouline, R. Curik, arXiv:1705.10153

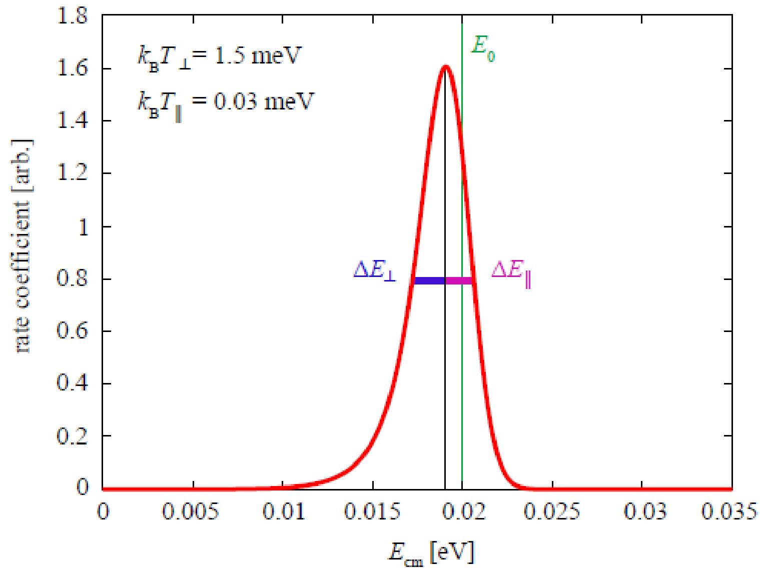
Absolute measurement of the electron energy distribution

$$E_{e,0} = \frac{m_e}{m_{ion}} E_{ion}$$ *velocity matched beams*

$$E_{coll} = \left[\sqrt{E_e} - \sqrt{E_{e,0}} \right]^2$$ *detuning of electron energy*

E_{coll} = ½ m_e (v_e – v_i)²
can be scanned
from **~ 1 meV … 50 eV**

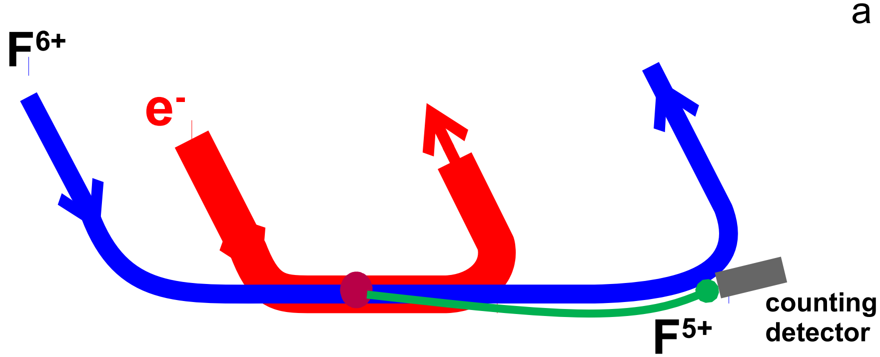
very low detuning velocities:
electron-ion collision energy resolution limited by **thermal energy spread** of the electrons



$$f(\vec{v}_e, u) = \sqrt{\frac{m^3}{(2\pi k_B)^3 T_\parallel T_\perp^2}} \exp\left(-\frac{m(v_\parallel - u)^2}{2k_B T_\parallel} - \frac{m v_\perp^2}{2k_B T_\perp} \right)$$

anisotropic/flattened Maxwellian velocity distribution due to $T_\parallel \ll T_\perp$

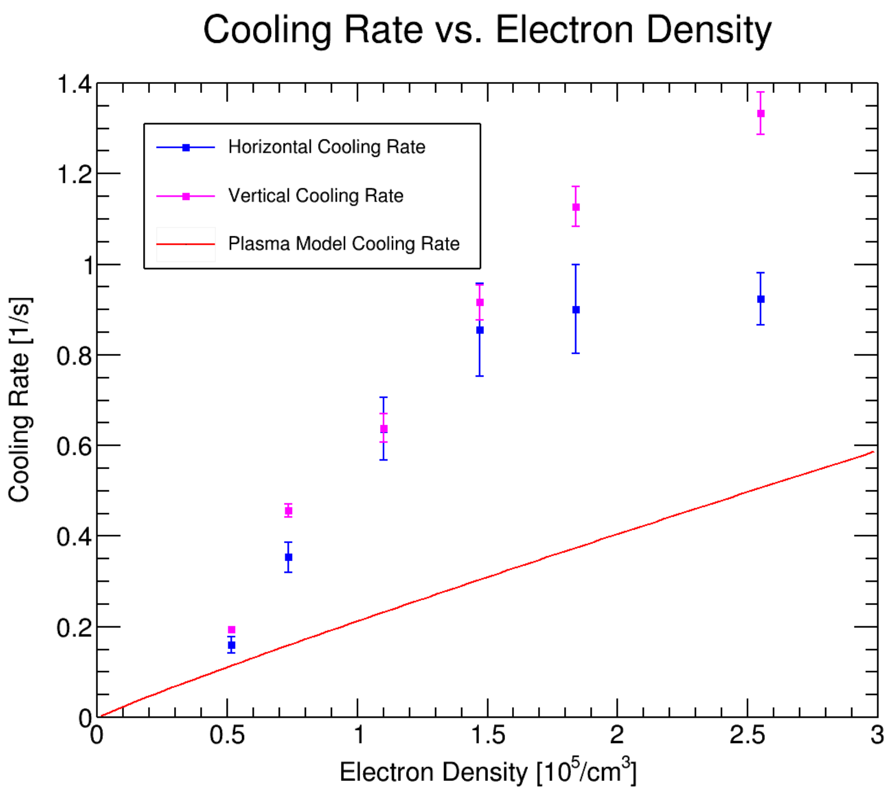
recombination process with a very sharp resonance: $\mathrm{F}^{6+} + \mathrm{e} \rightarrow (\mathrm{F}^{5+})^{**} \rightarrow (\mathrm{F}^{5+})^{*} + h\nu$



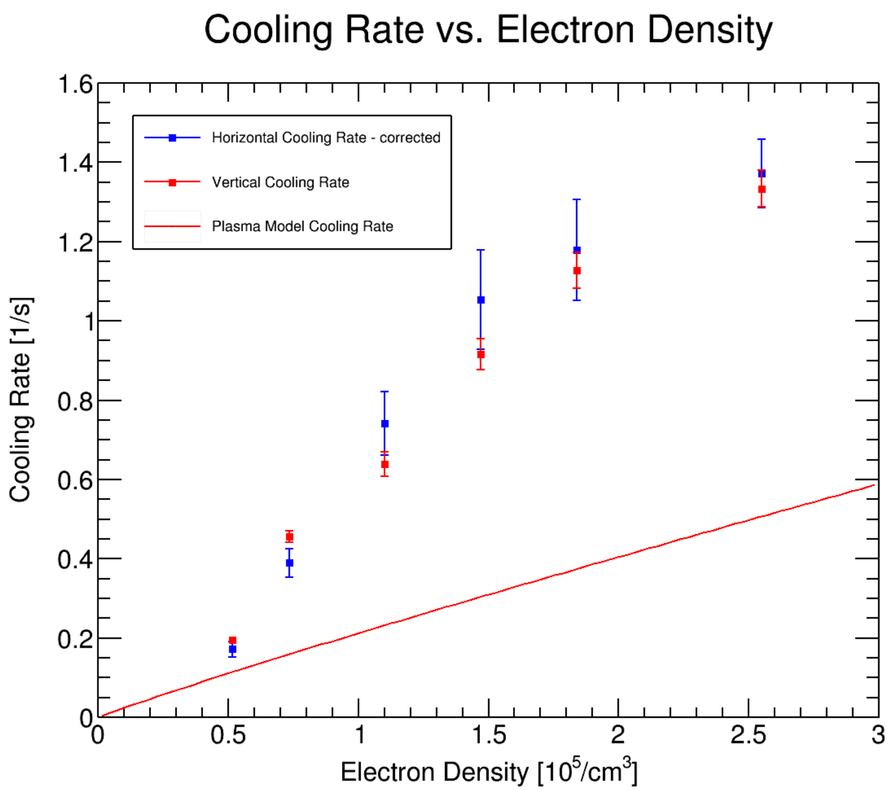
excited F^{5+} state	energy [meV]	width [meV]	strength [10^{-20} cm^{2}eV]
$(2p_{3/2}\,6p_{1/2})_1$	6.9	25.8	415.09
$(2p_{3/2}\,6p_{1/2})_2$	10.31	0.1	388.9
$(2p_{1/2}\,6d_{3/2})_2$	52.4	8.7	67.6

Transverse Cooling – Dispersive cooling effects

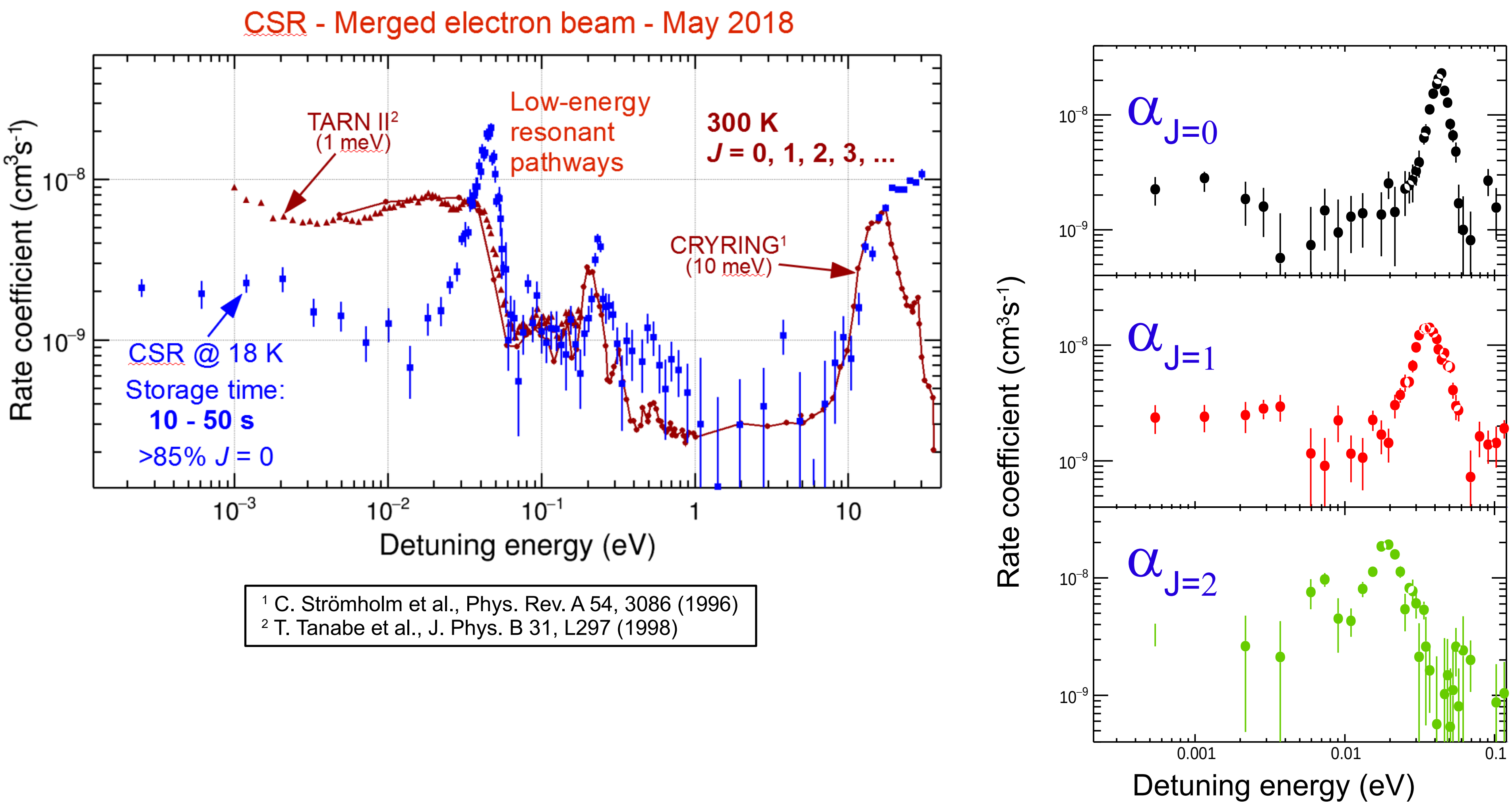
Measured Cooling Rates



Corrected Cooling Rates

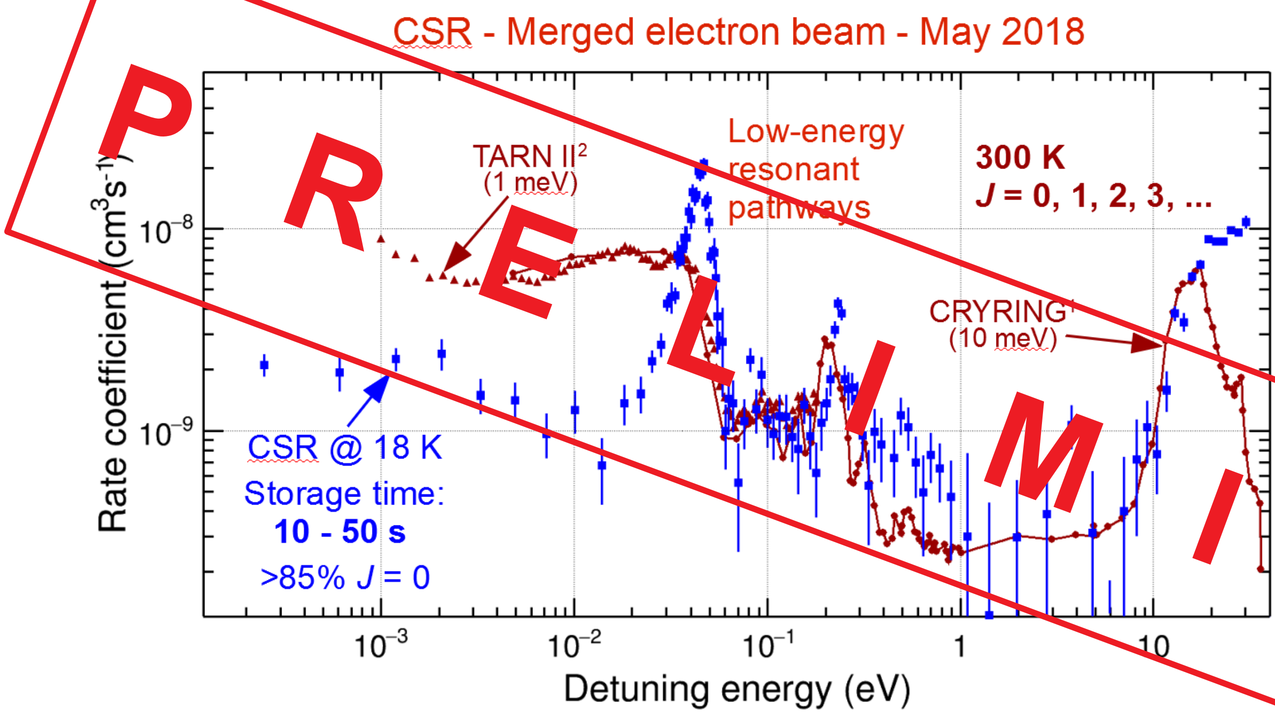


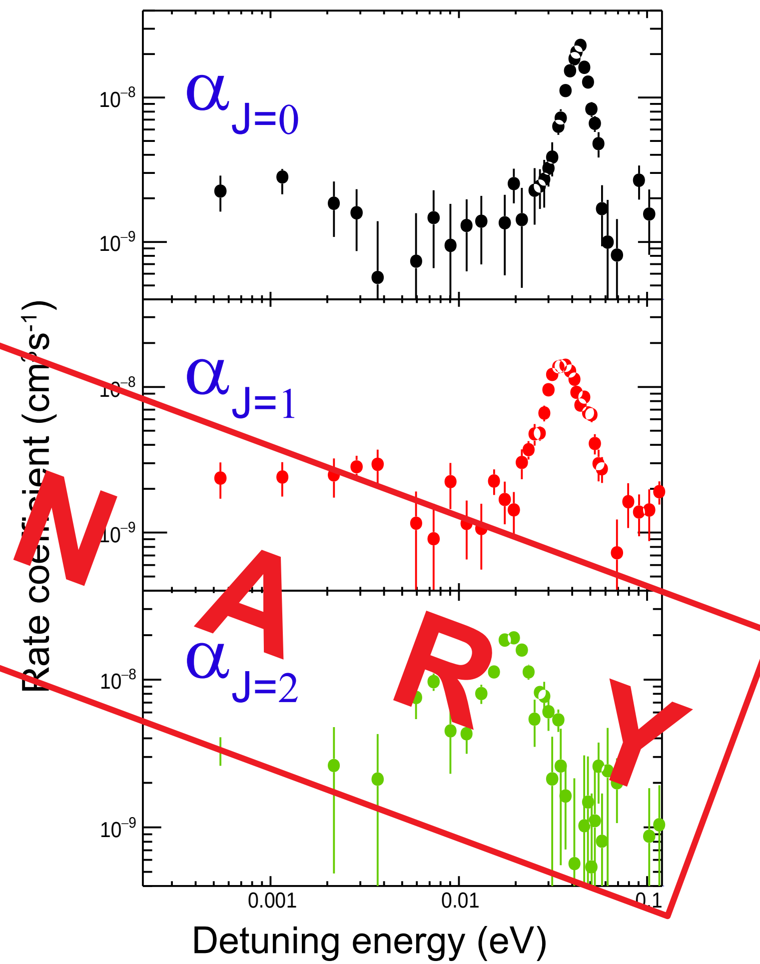
Outlook – Dissociative Recombination Experiments



[1] C. Strömholm et al., Phys. Rev. A 54, 3086 (1996)
[2] T. Tanabe et al., J. Phys. B 31, L297 (1998)

Outlook – Dissociative Recombination Experiments





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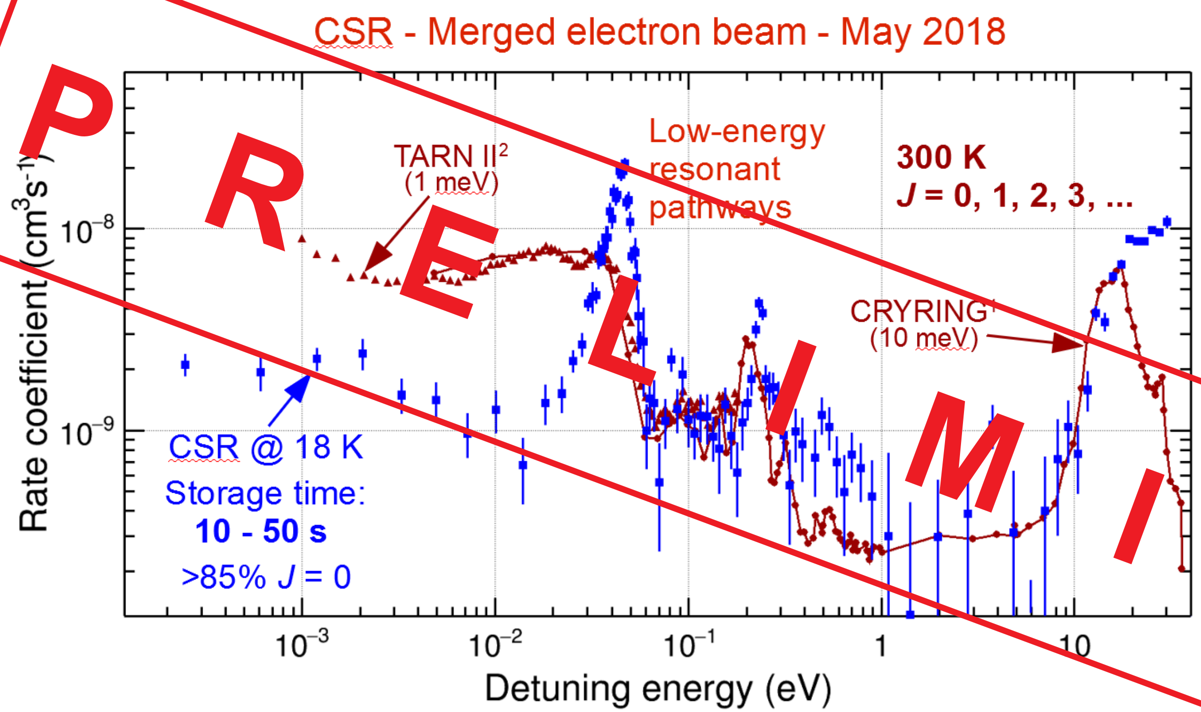

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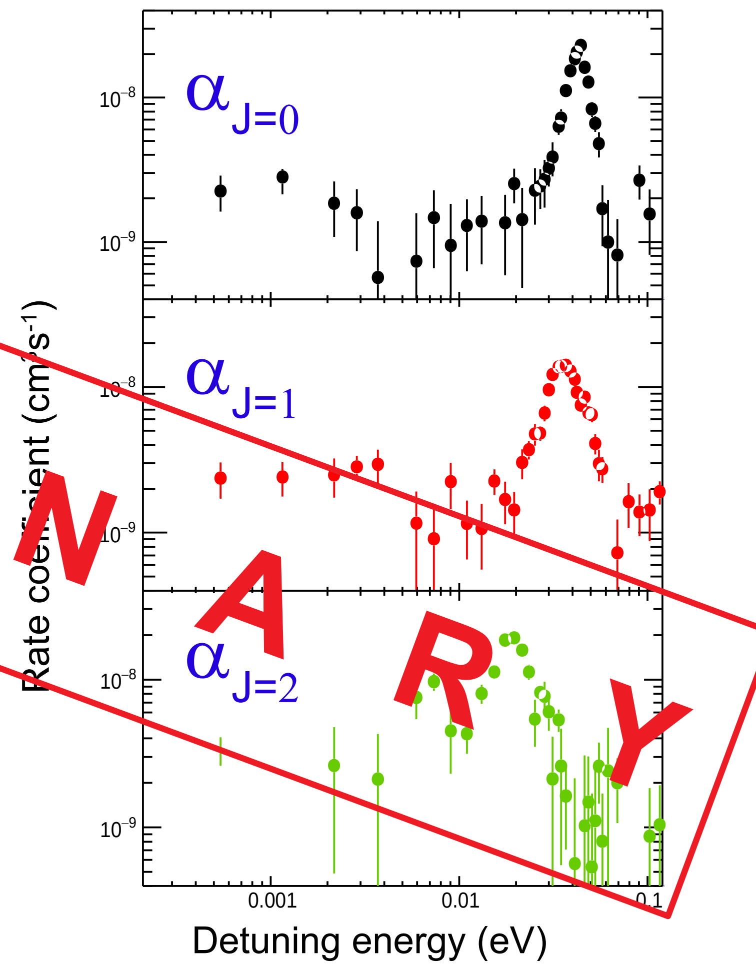

Next beamtime:

March 2019