Electron cooling of bunched ion beams and recent results at the Heidelberg cryogenic storage ring (CSR)

Patrick Wilhelm

for the **CSR Team**

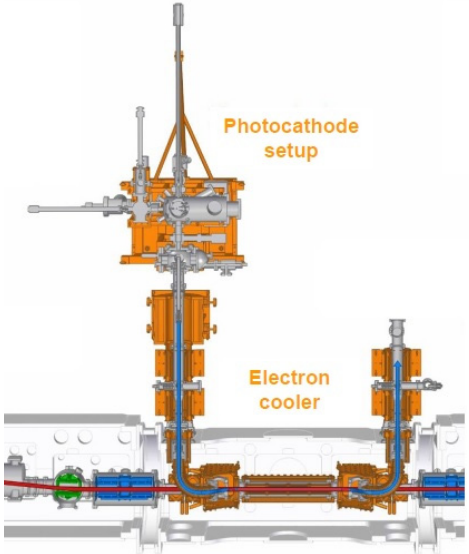
Max Planck Institute for Nuclear Physics

COOL 2017

Bonn

Outline

- The Cryogenic Storage Ring
- Rotational cooling of stored molecules
- The CSR electron cooler
- Beam Time 2017: Recent results
- Outlook: Electron-beam collision studies



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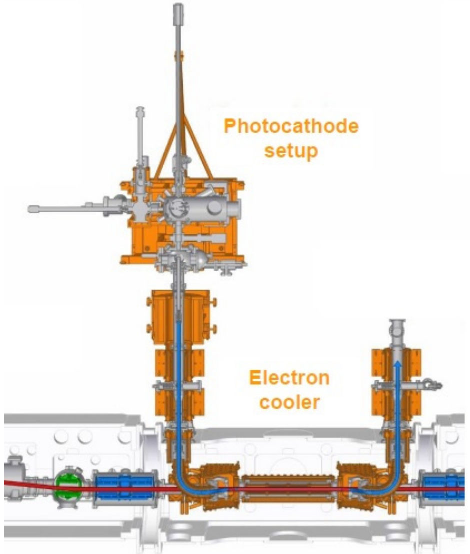
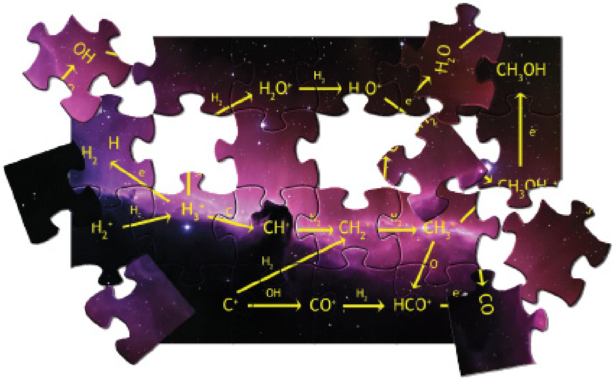


The CSR – motivation

Eagle nebula

Cold molecular clouds in the ISM: Astrochemistry



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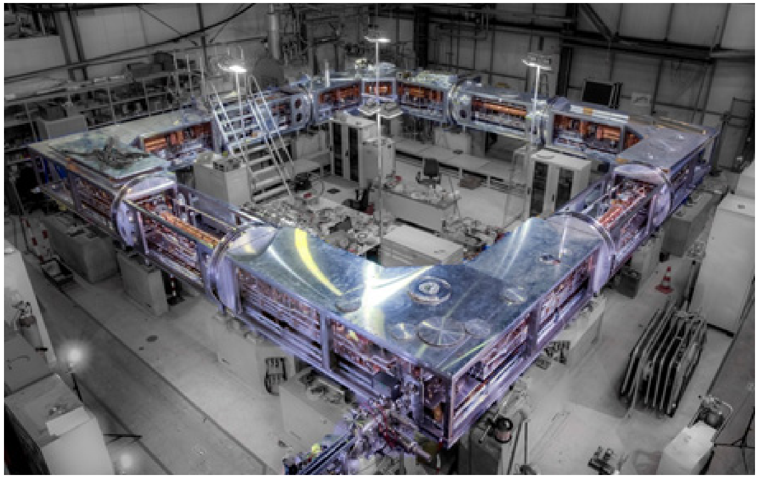

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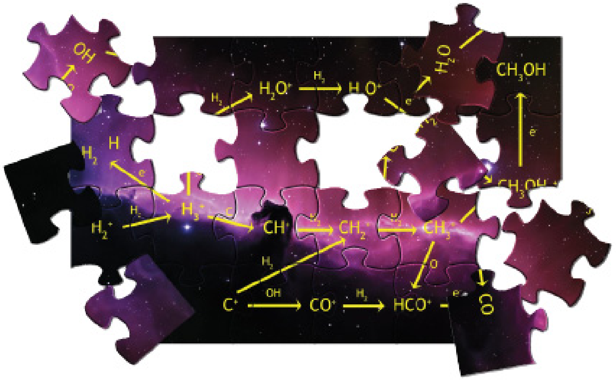

	CSR	interstellar clouds
Temperature	< 10 K	~ 10 – 150 K
Density	~ 100 cm^{-3}	~ 10 – 1000 cm^{-3}

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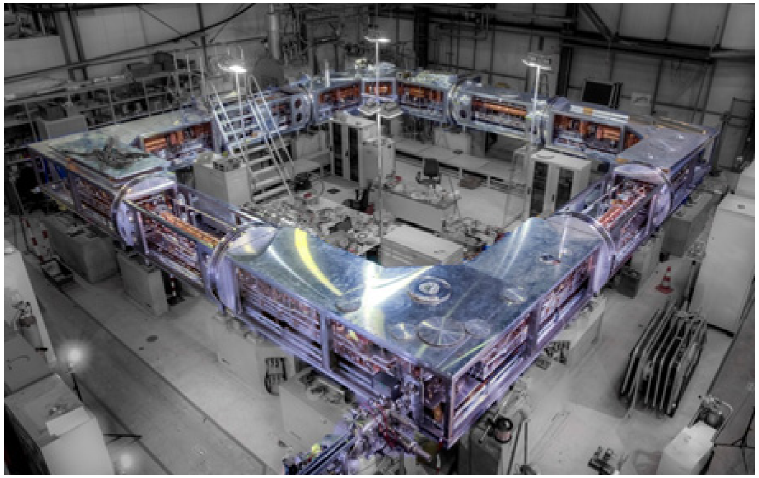

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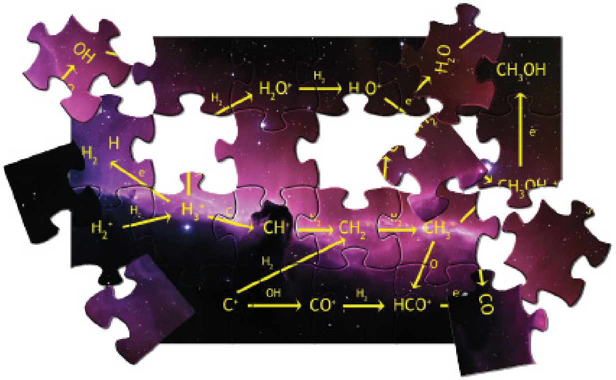

→ storage times **> 1000s**

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

→ molecular ions in well-defined quantum states

→ merged beam experiments at low collision energies

Goal:
Rotationally resolved state-to-state studies

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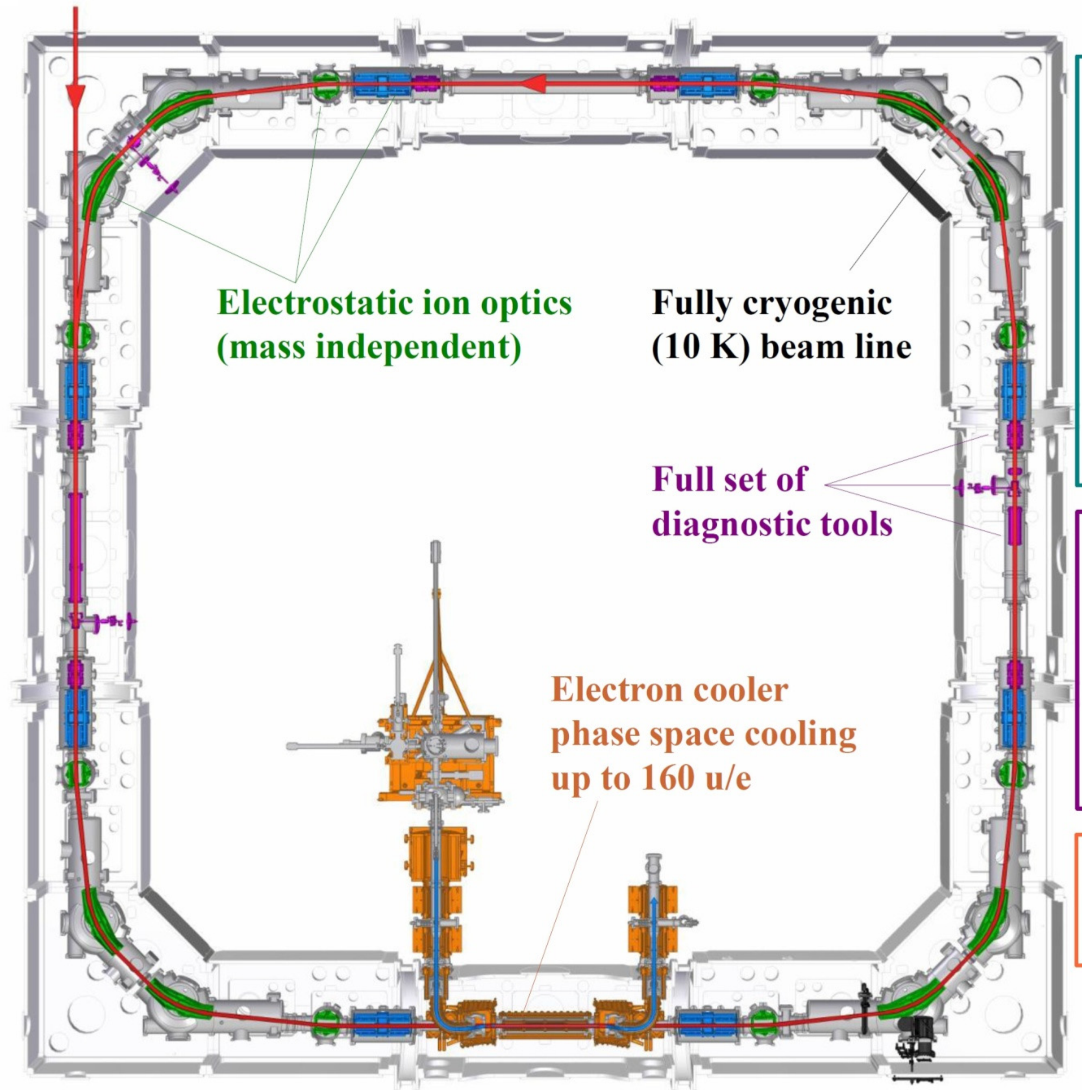
The CSR – overview



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)**

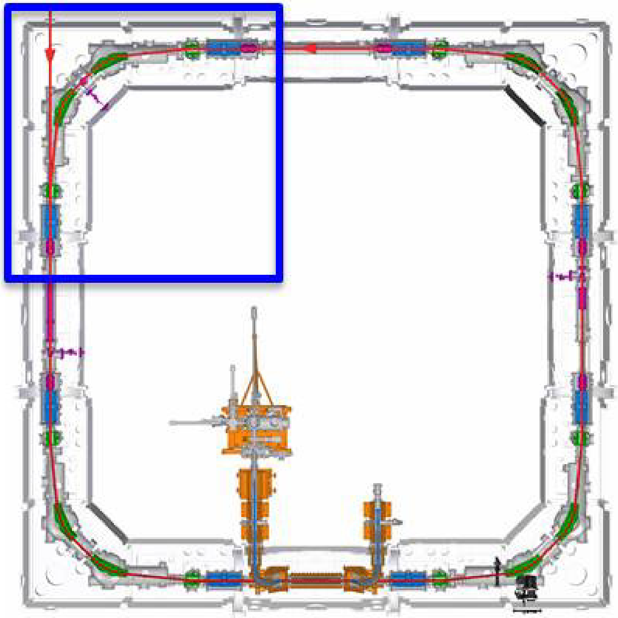
R. v. Hahn
M. Grieser

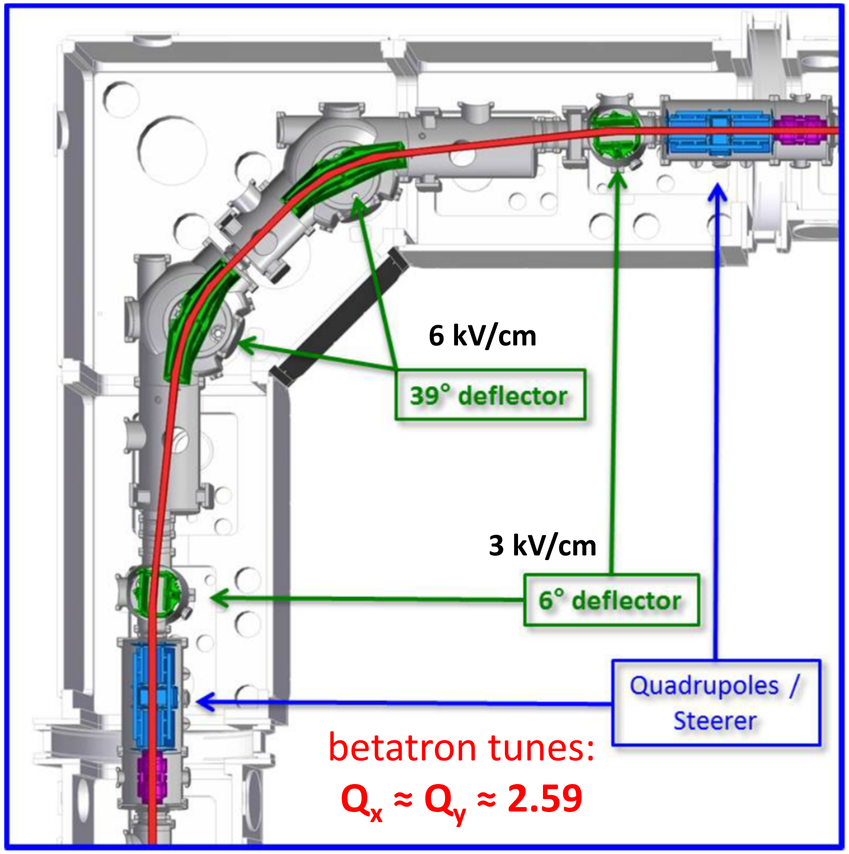
The CSR – electrostatic beam optics

- fully **electrostatic** storage → mass independent

- 24 optical elements
  - 4 x 2 pairs of **quadrupoles (10 kV)**
  - 4 x 2 **6°-deflector** electrodes **(30 kV)**
  - 4 x 2 **39°-deflector** electrodes **(30 kV)**

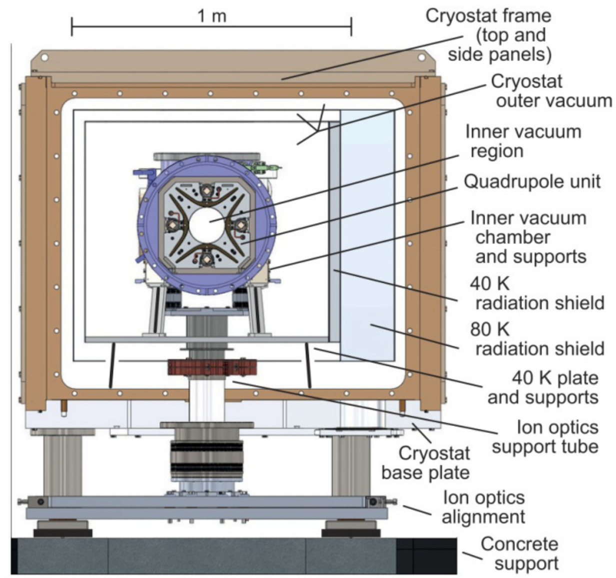
- 4 field-free straight sections (2.4 m each)



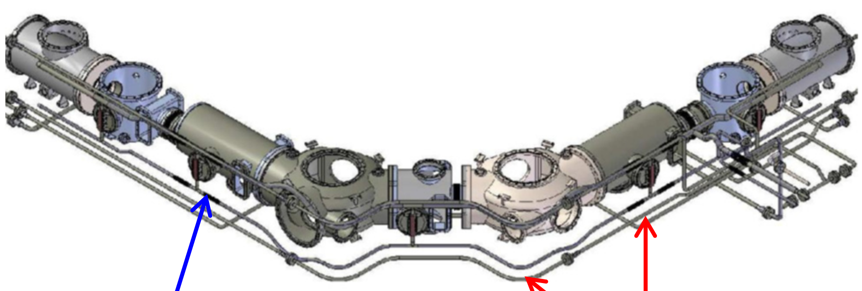


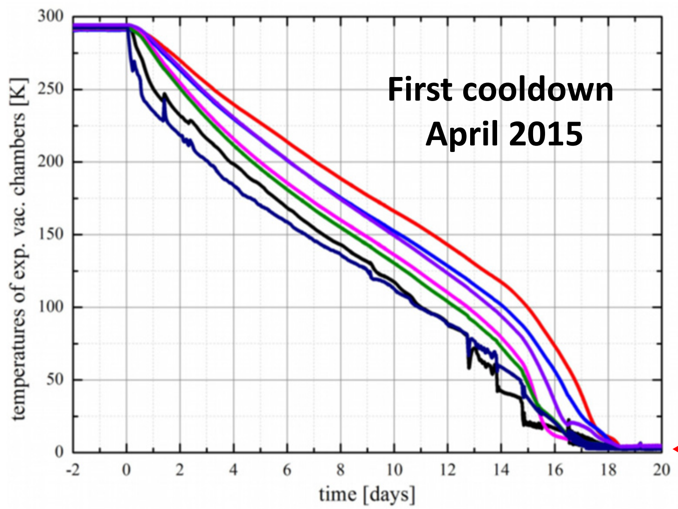
The CSR – cryogenics

- **Multi-layer cryostat**
  - Inner vacuum chamber ≤ 10 K
  - 2 radiation shields (40 K & 80 K)
  - Multi-layer insulation
  - Isolation vacuum chamber



- cooled by **closed-cycle helium system**





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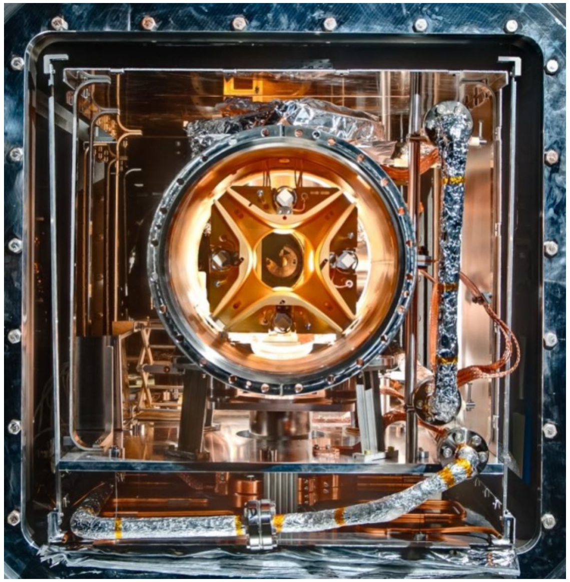

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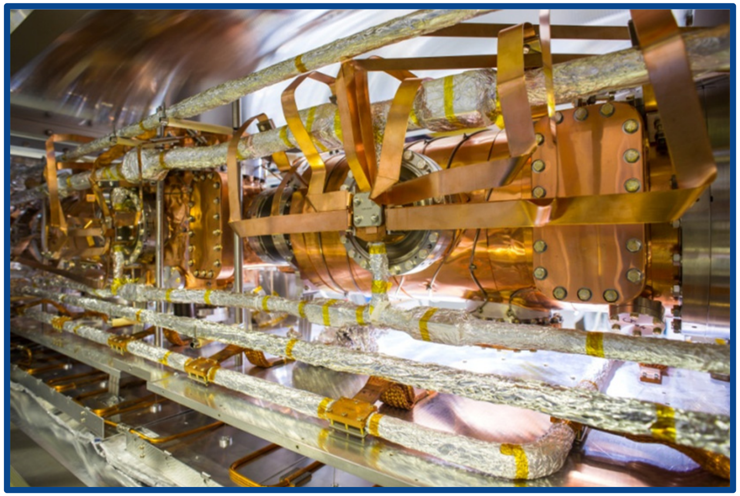
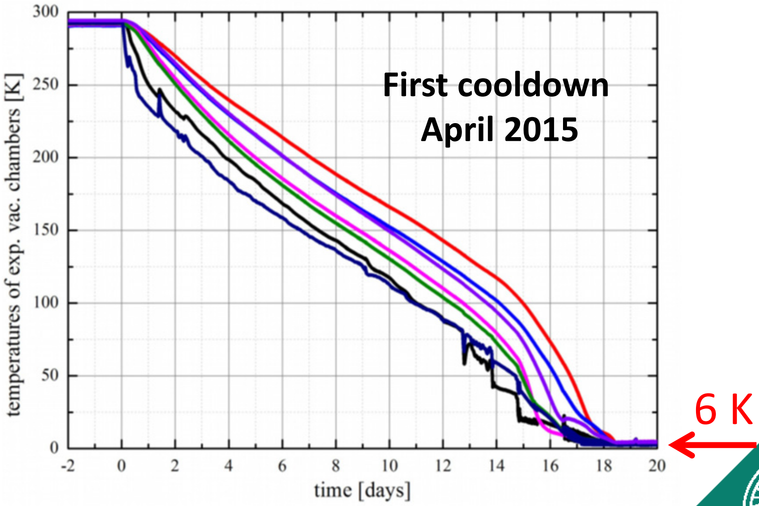
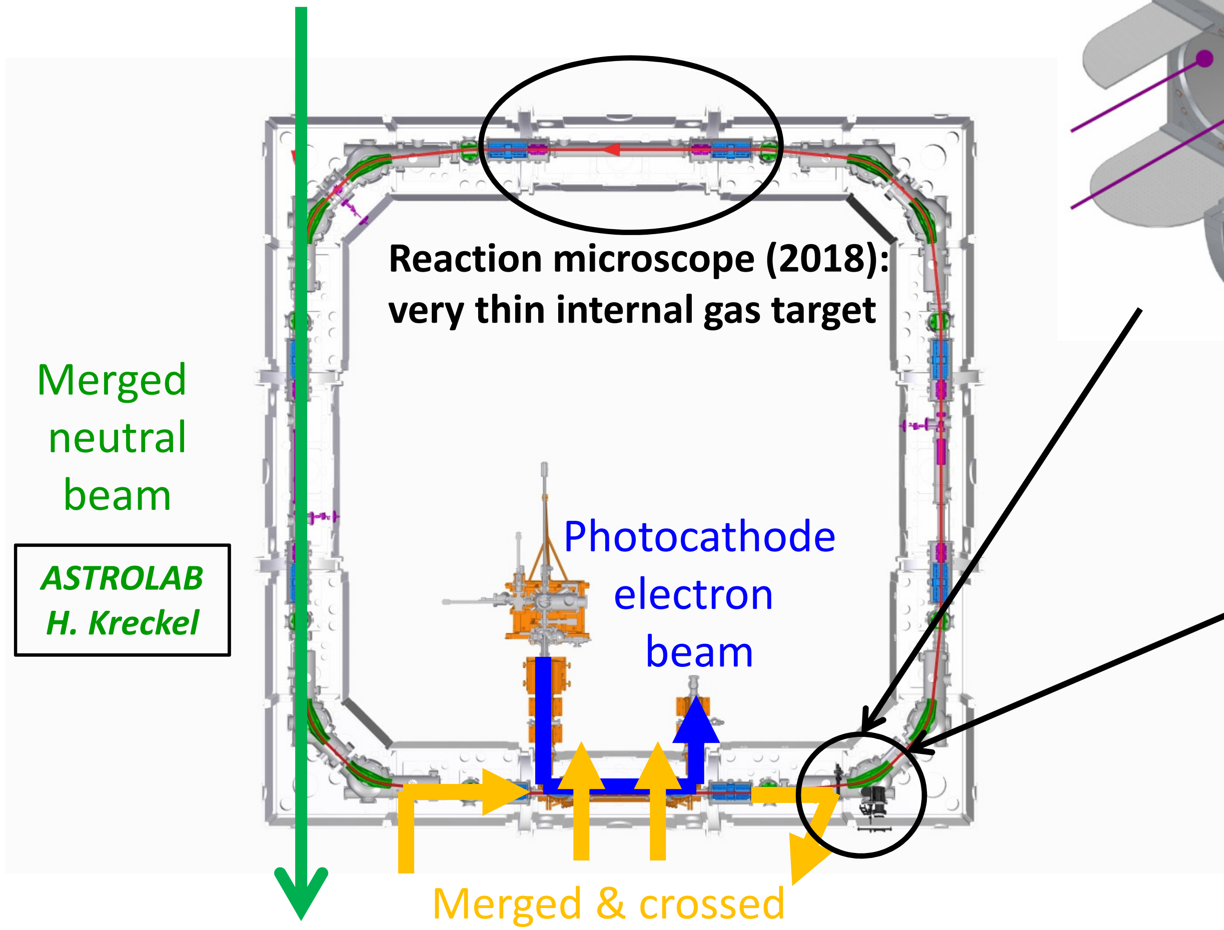
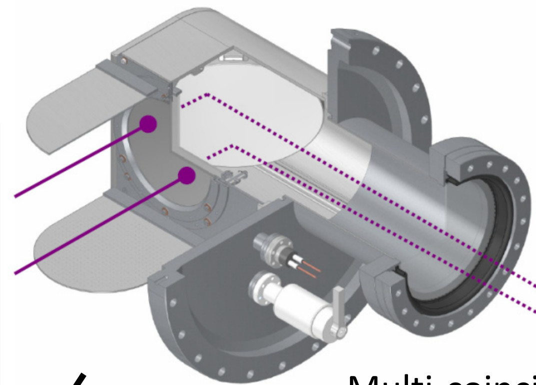


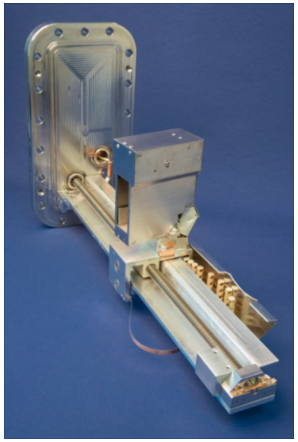


The CSR – Experimental Setup





Multi-coincidence MCP Imaging detector for neutral particles



Movable particle counter for charged fragments

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

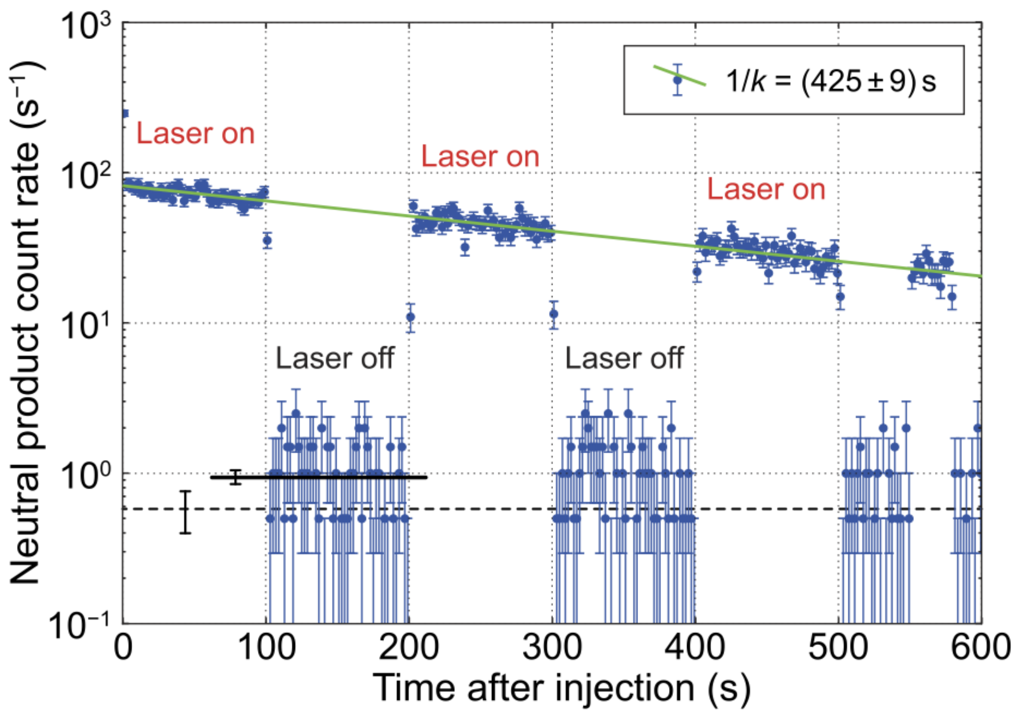
C. Krantz et al. Nucl. Instr Meth. A 851, 92 (2017)

The CSR – residual gas density

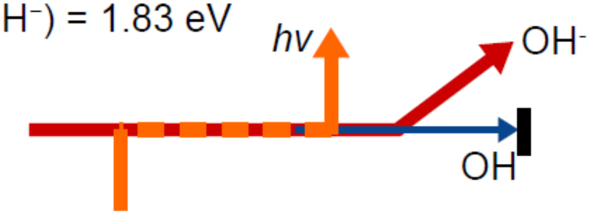
Photodetachment diagnostics

$OH^- + X \rightarrow OH + X'$ **rest gas**

$OH^- + \gamma \rightarrow OH + e$ **Laser**



EA (OH^-) = 1.83 eV



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

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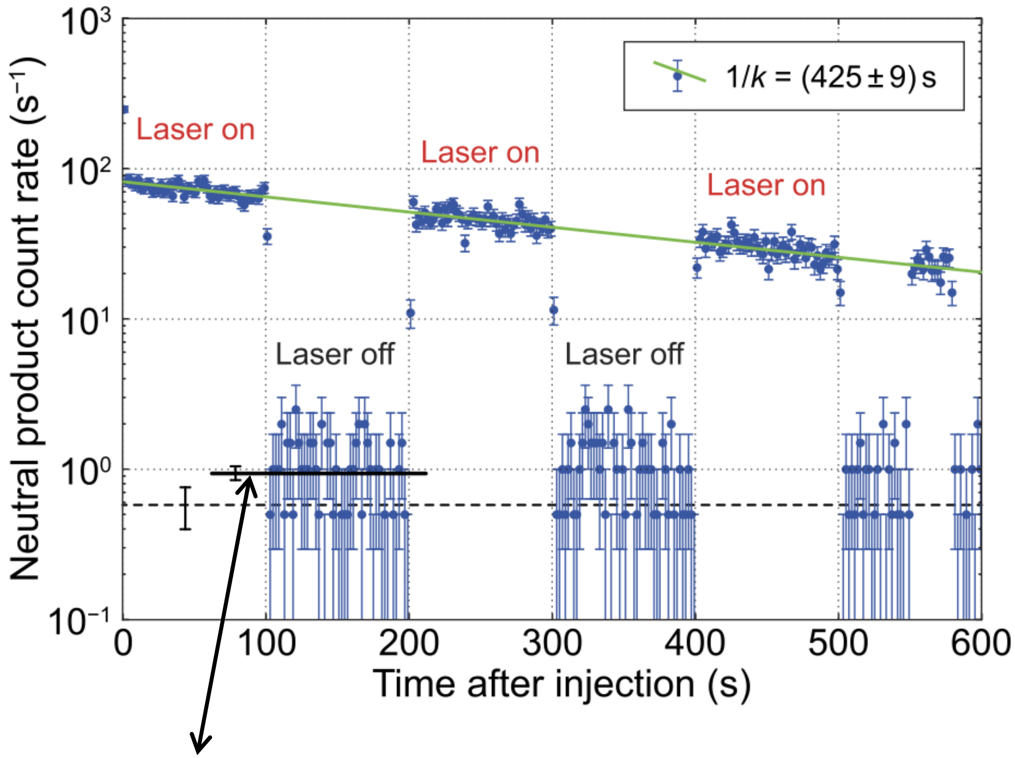

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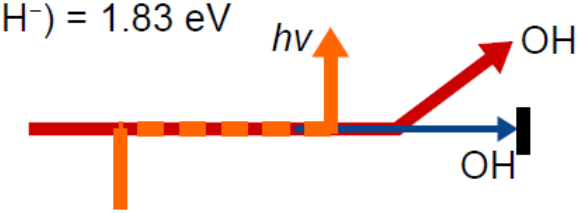


von Hahn et al., Rev. Sci. Instr. 87 (2016) 063115

$R < 0.6 s^{-1}$

$\sigma > 6 \times 10^{-16} cm^2$

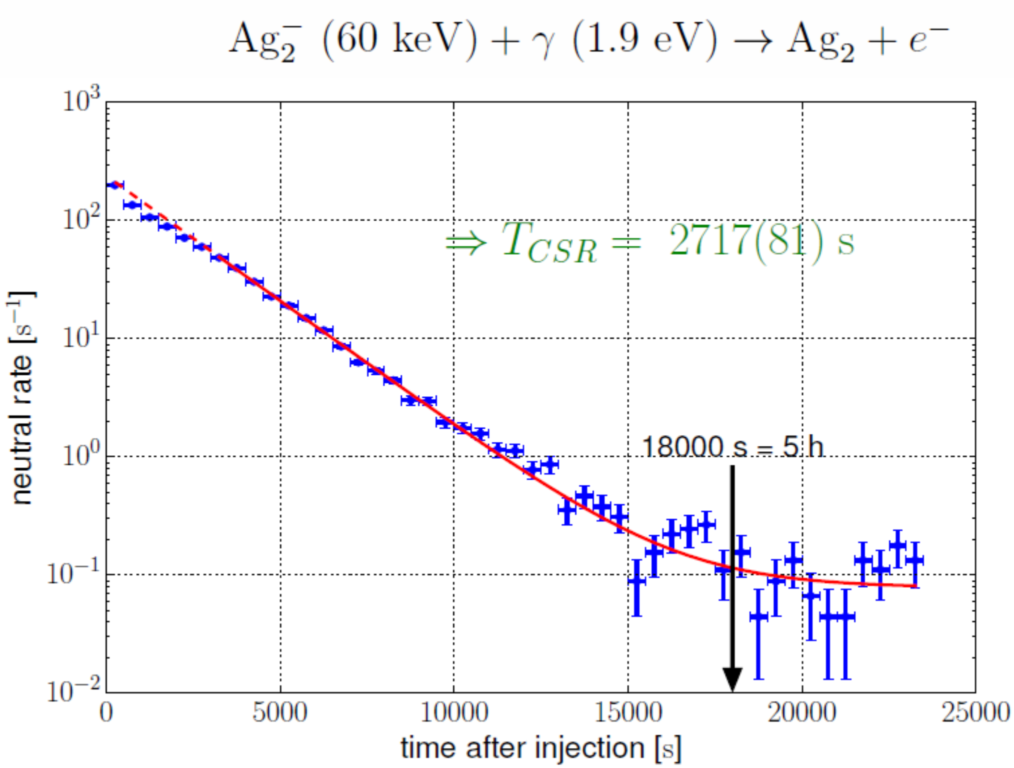
$N_{ion} > 1.5 \times 10^7$

$$n = \frac{R}{N_{ion} v_{ion} \eta_g \sigma}$$

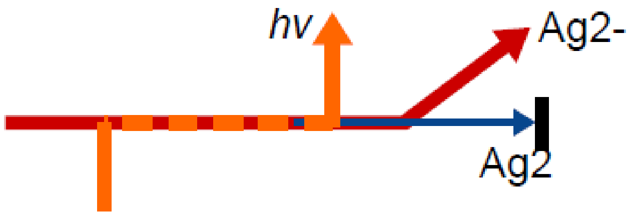
***n* ≤ 140 cm$^{-3$}**

***P*$_{RTE}$ ~ 5.8 x 10^{-15} mbar**

The CSR – storage lifetime



EA (Ag_2^-) = 1.02 eV



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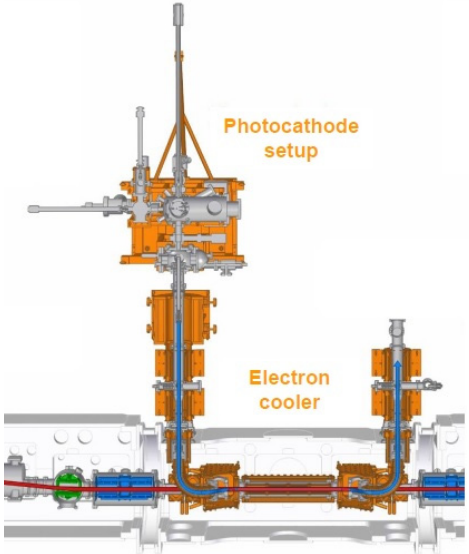
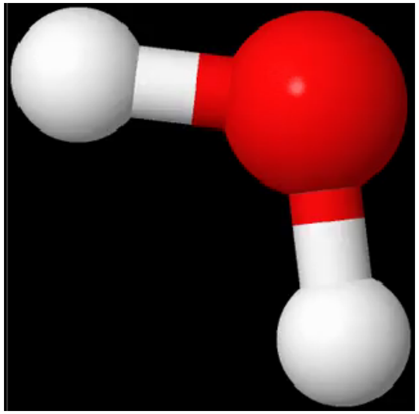


Rotational cooling of stored molecules

CSR
- $p < 10^{-14}$ mbar
- $\tau > 2500$ s
- $T_{wall} \sim 6K$

- **"antenna":** stored molecules equilibrate with black body radiation field



***J*: rotational level**

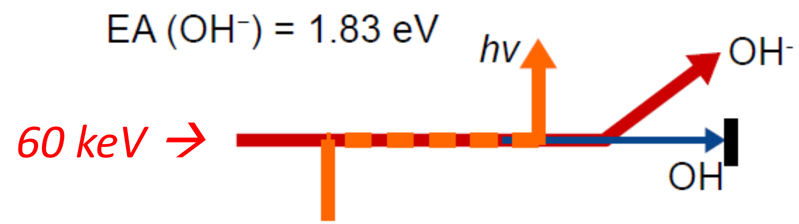
- *What is the **internal temperature** of a stored molecular ion?*
- *What is the **radiative field in the CSR**?*
- ***Space (ISM) conditions?***

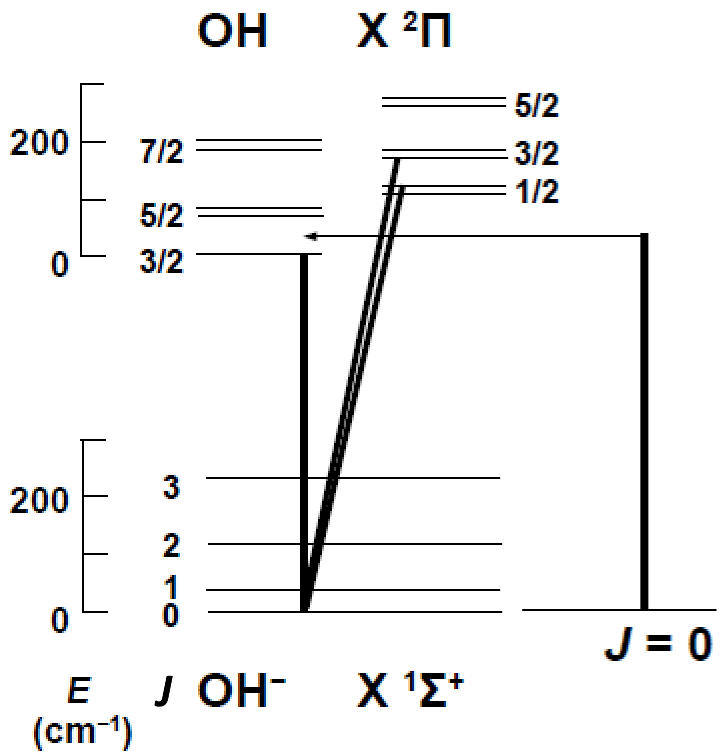
measuring the population of rotational states

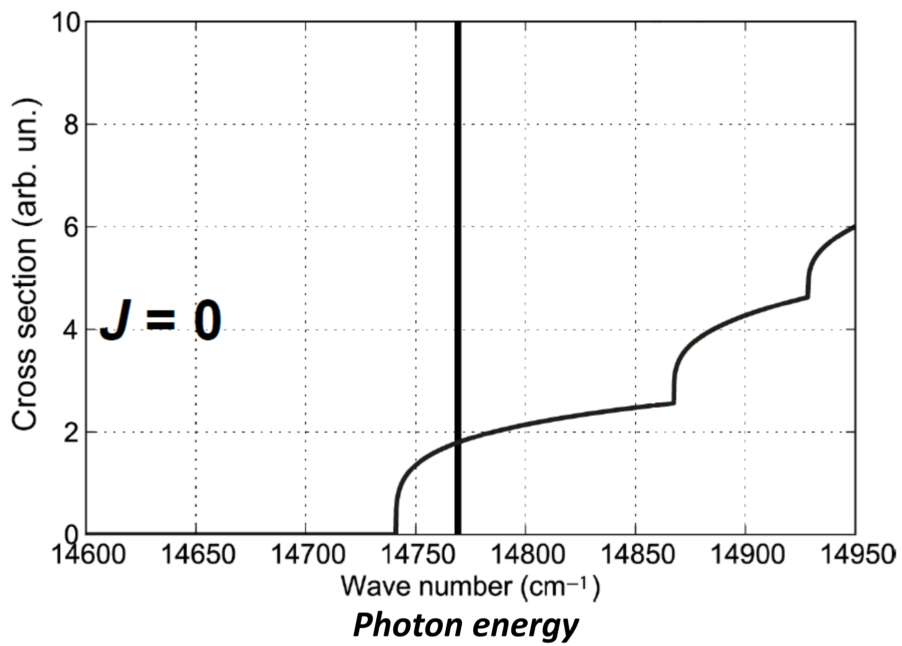
→ **internal state thermometry**

Rotational cooling of stored molecules

state-selective OH- photodetachment







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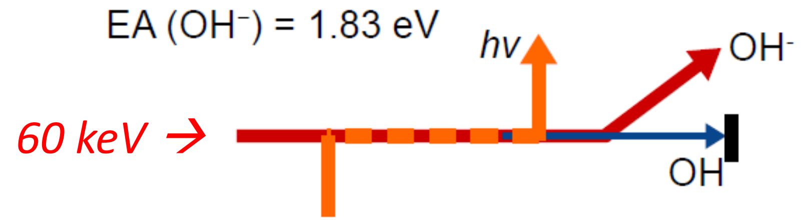

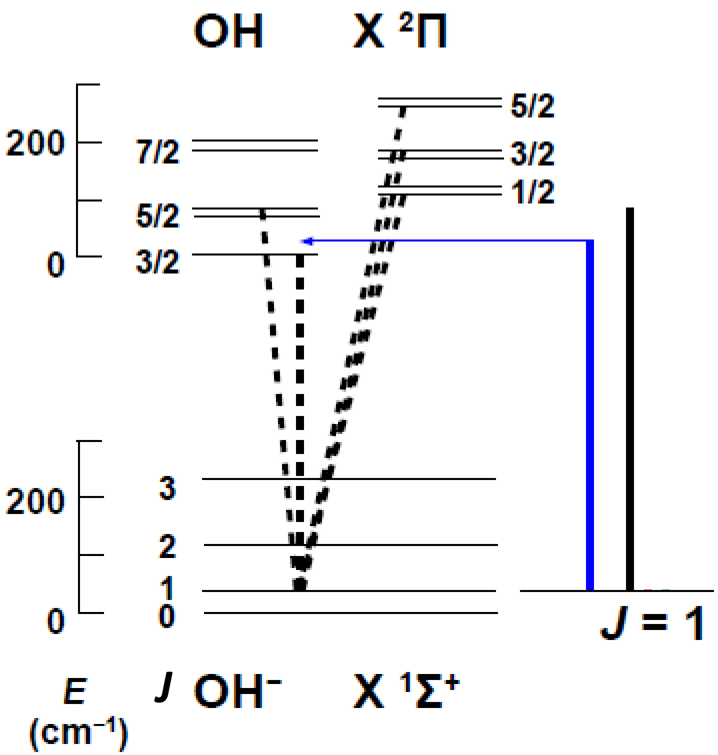

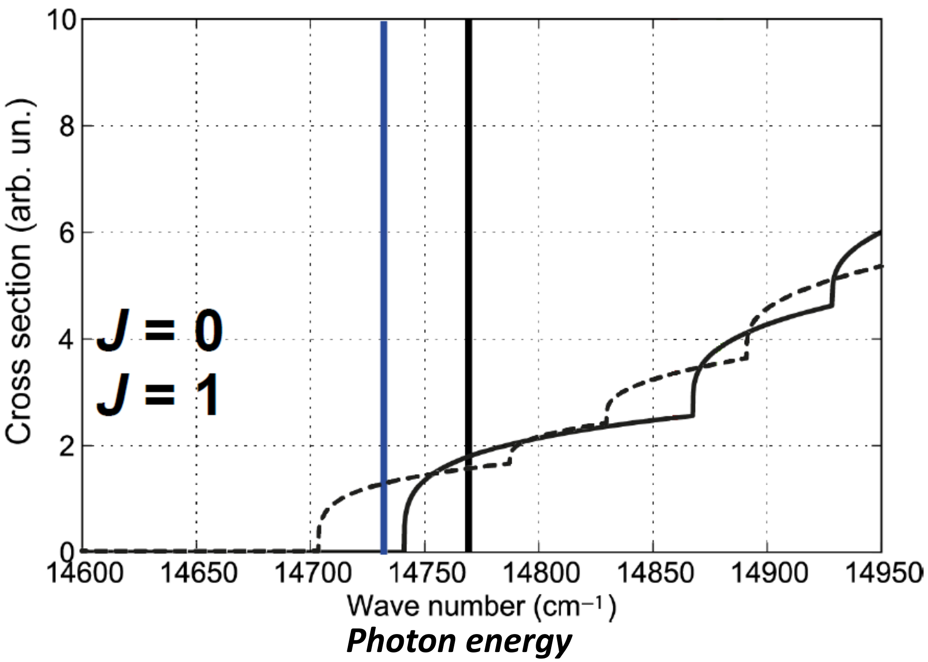

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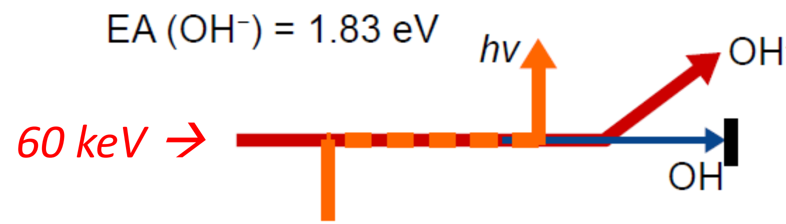

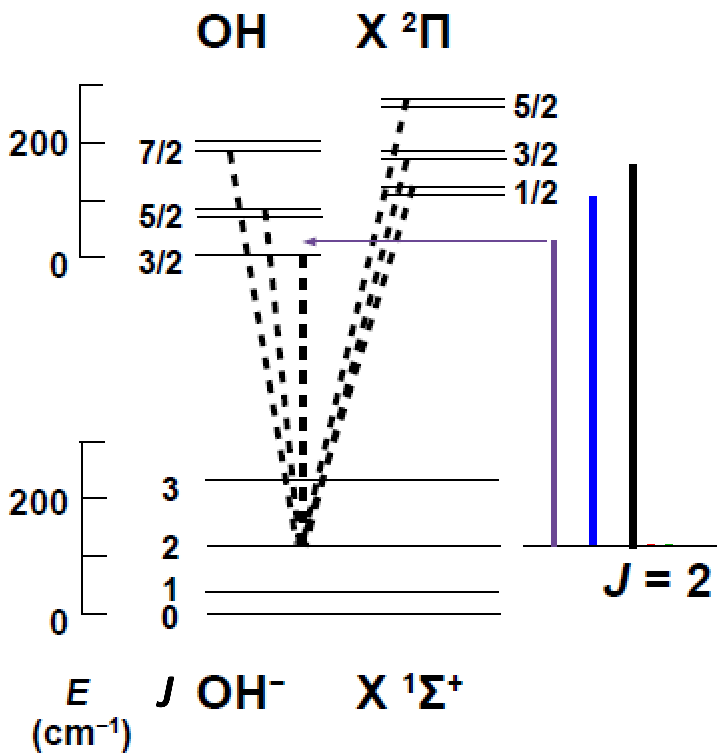

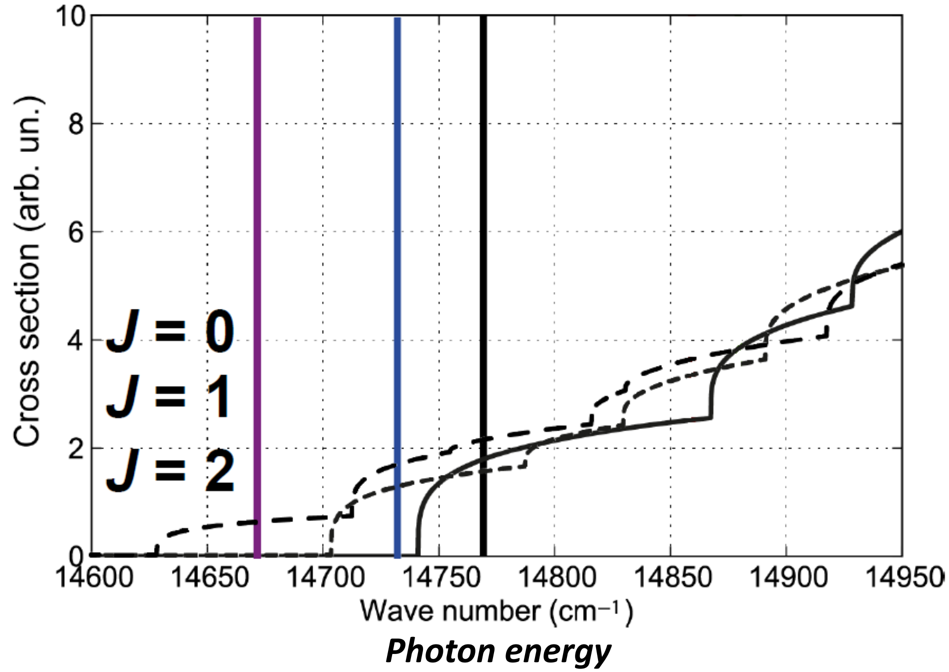

Rotational cooling of stored molecules

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S. George
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(MPIK)

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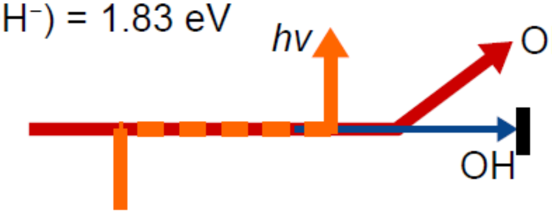
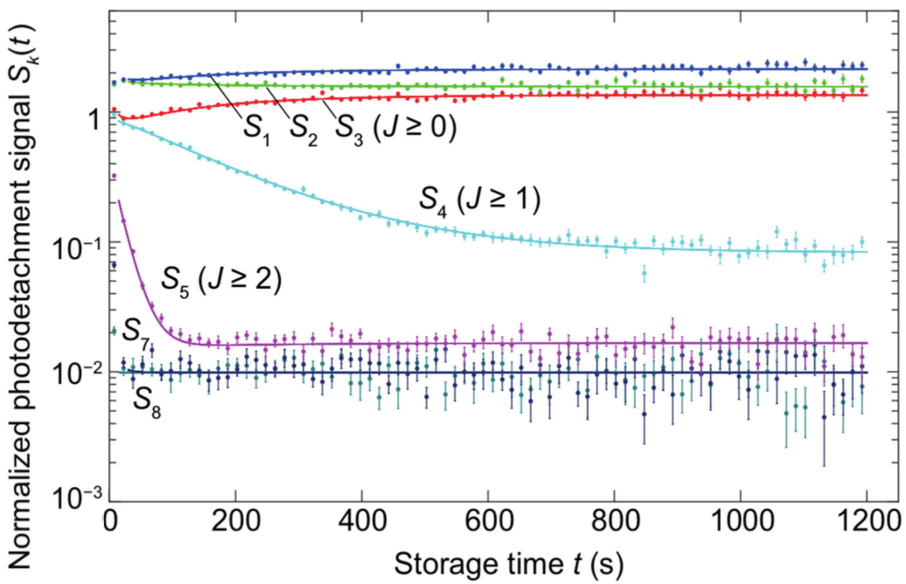


Measured photodetachment rates



C. Meyer, Phys. Rev. Lett. 119, 023202 (2017)

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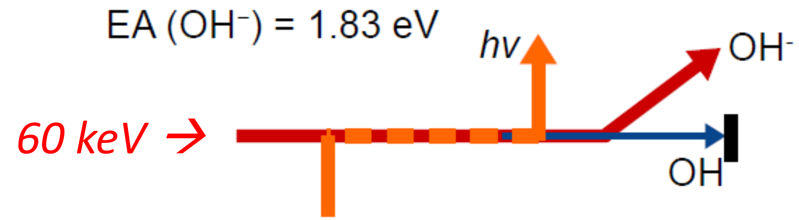

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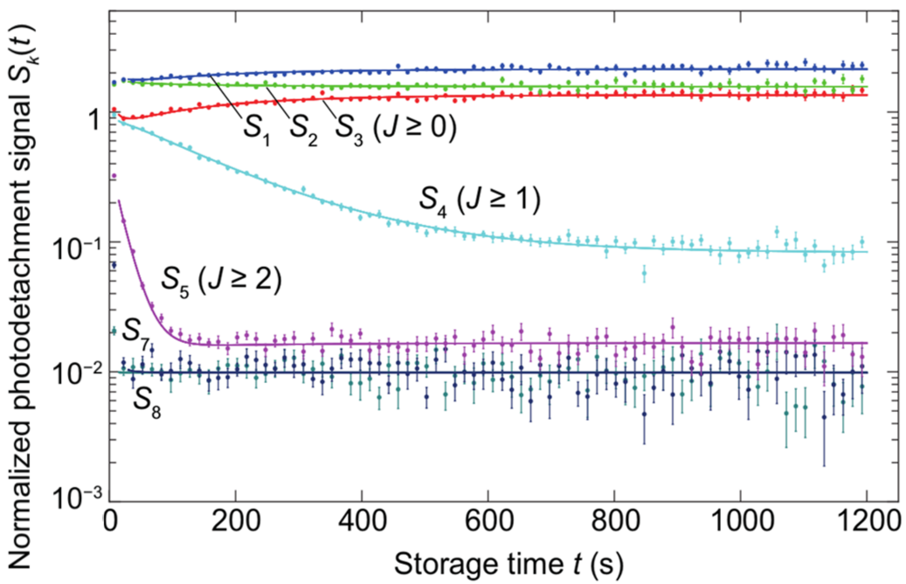

Population of ~ 90% in J = 0
~ 15 K effective blackbody field

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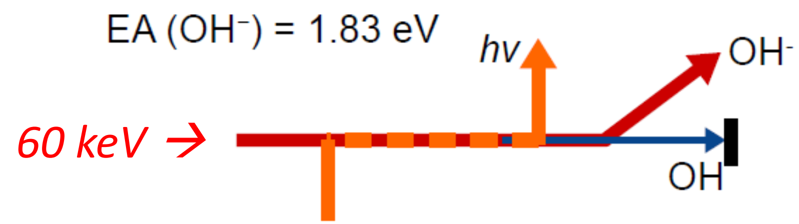

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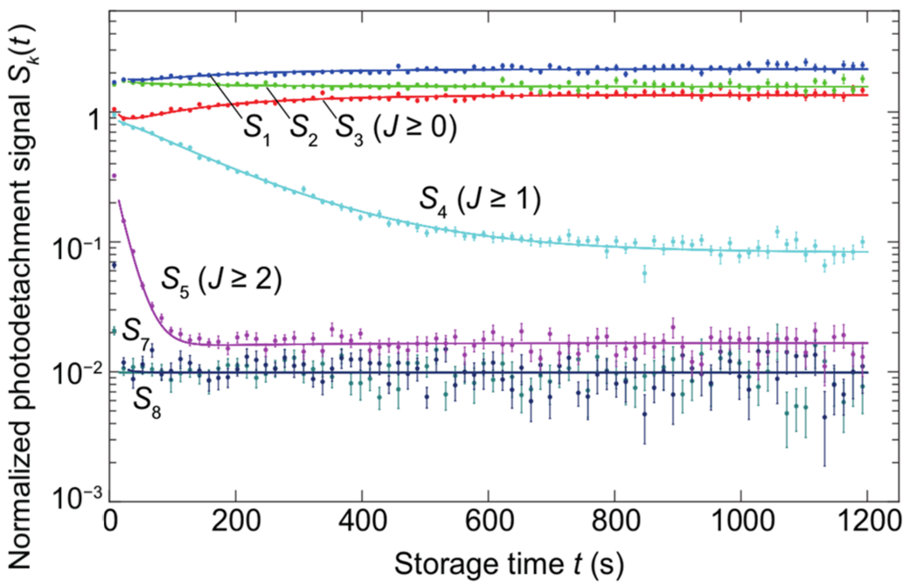

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1st direct pure-rotational lifetime in-vacuo measurement

OH^- rotational level lifetimes and dipole moment

	$\tau = A_J^{-1}$ (s)	μ_0 (D)
$J = 1$	193(7)	0.970(17)
$J = 2$	20.9(2.1)	0.952(48)
$J = 3$	5.30(37)	0.997(35)

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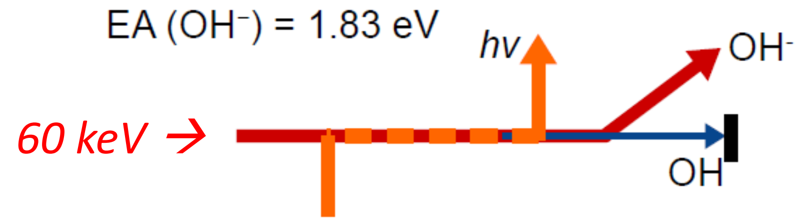

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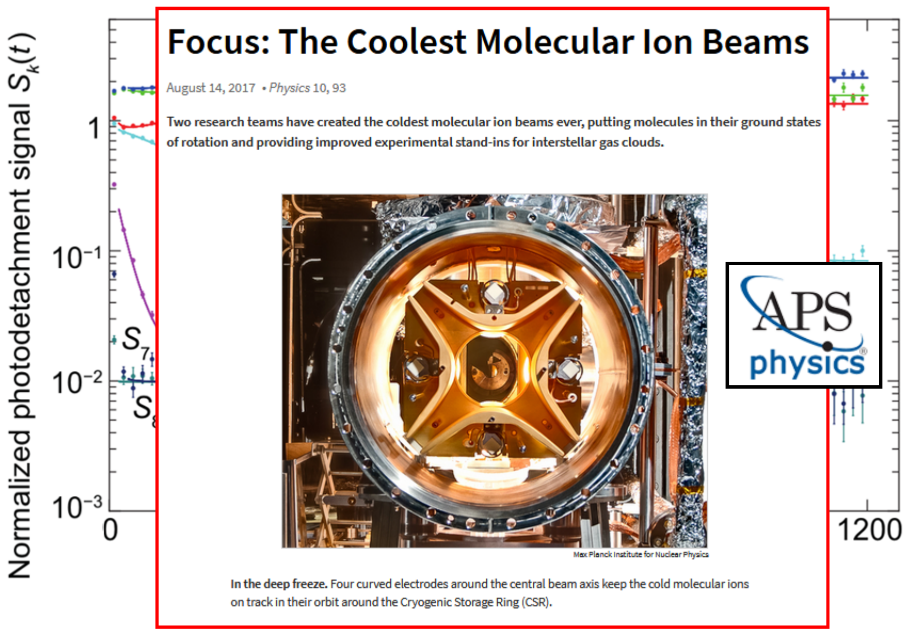

Focus: The Coolest Molecular Ion Beams

August 14, 2017 • *Physics* 10, 93

Two research teams have created the coldest molecular ion beams ever, putting molecules in their ground states of rotation and providing improved experimental stand-ins for interstellar gas clouds.

APS physics

Max Planck Institute for Nuclear Physics

In the deep freeze. Four curved electrodes around the central beam axis keep the cold molecular ions on track in their orbit around the Cryogenic Storage Ring (CSR).

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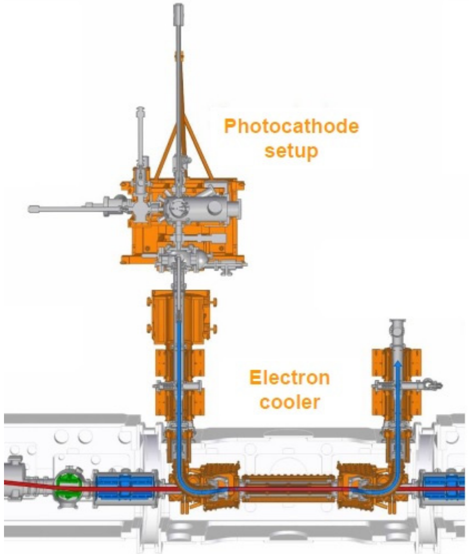


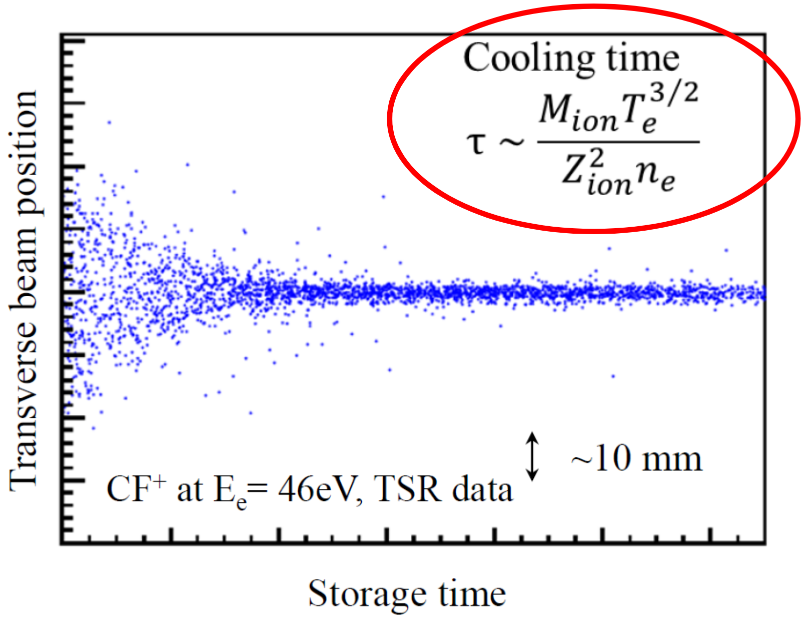
The CSR electron cooler

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

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

$$\frac{du}{dt} = \frac{F}{M_i}$$

$\frac{1}{e}$



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E_e / eV	ion
163	for 300 keV p^+
~20	for most ions
1	for M_{ion} = *160 u*

Photocathode in space-charge-limited current operation:

$$I = p \cdot U^{3/2}$$

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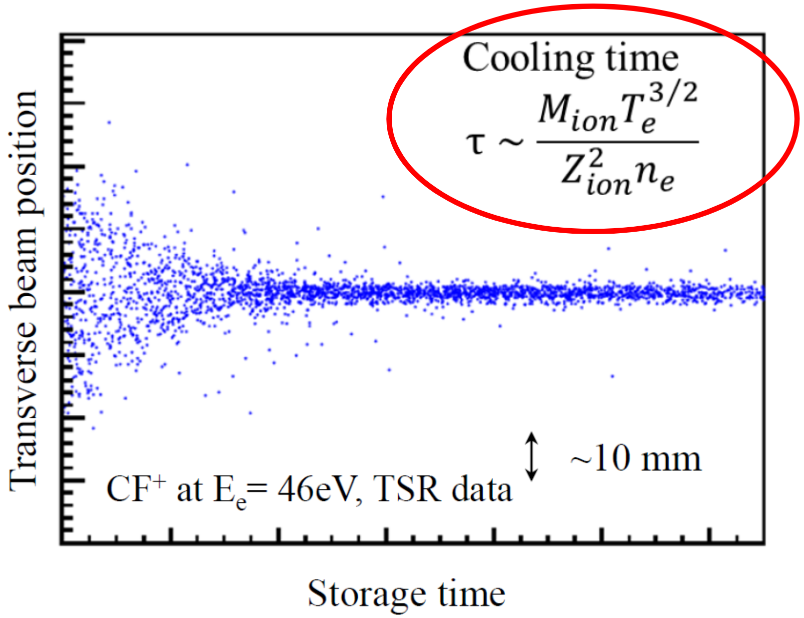

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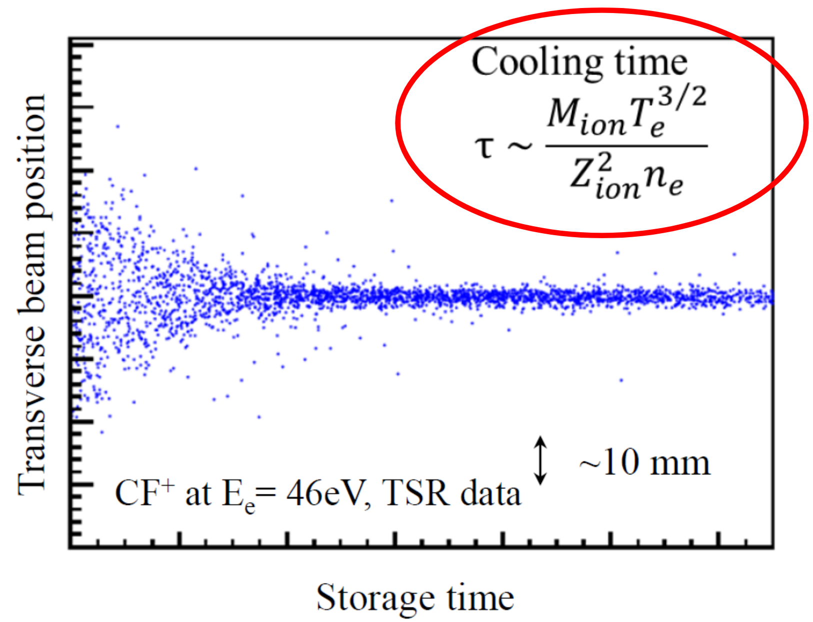
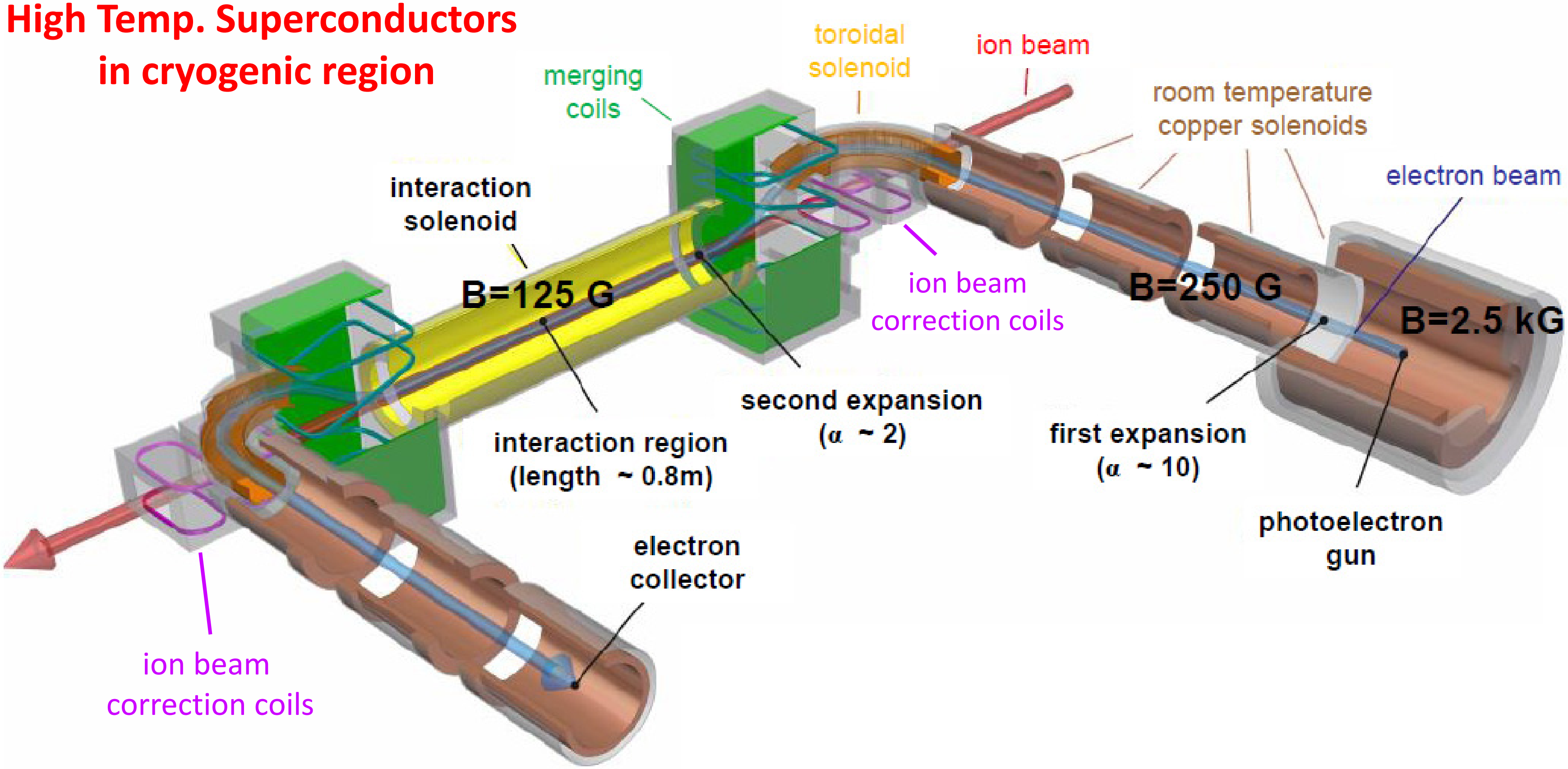


main challenges:

- assure $\boldsymbol{\tau_{cool} < \tau_{store}}$
  → ~ eV electron beam with **high densities & low temperature**
- cooler must be contained in **CSR cryostat**
  → 10 K, 10^{-13} mbar, bakeable to 250°C

The CSR electron cooler

High Temp. Superconductors in cryogenic region



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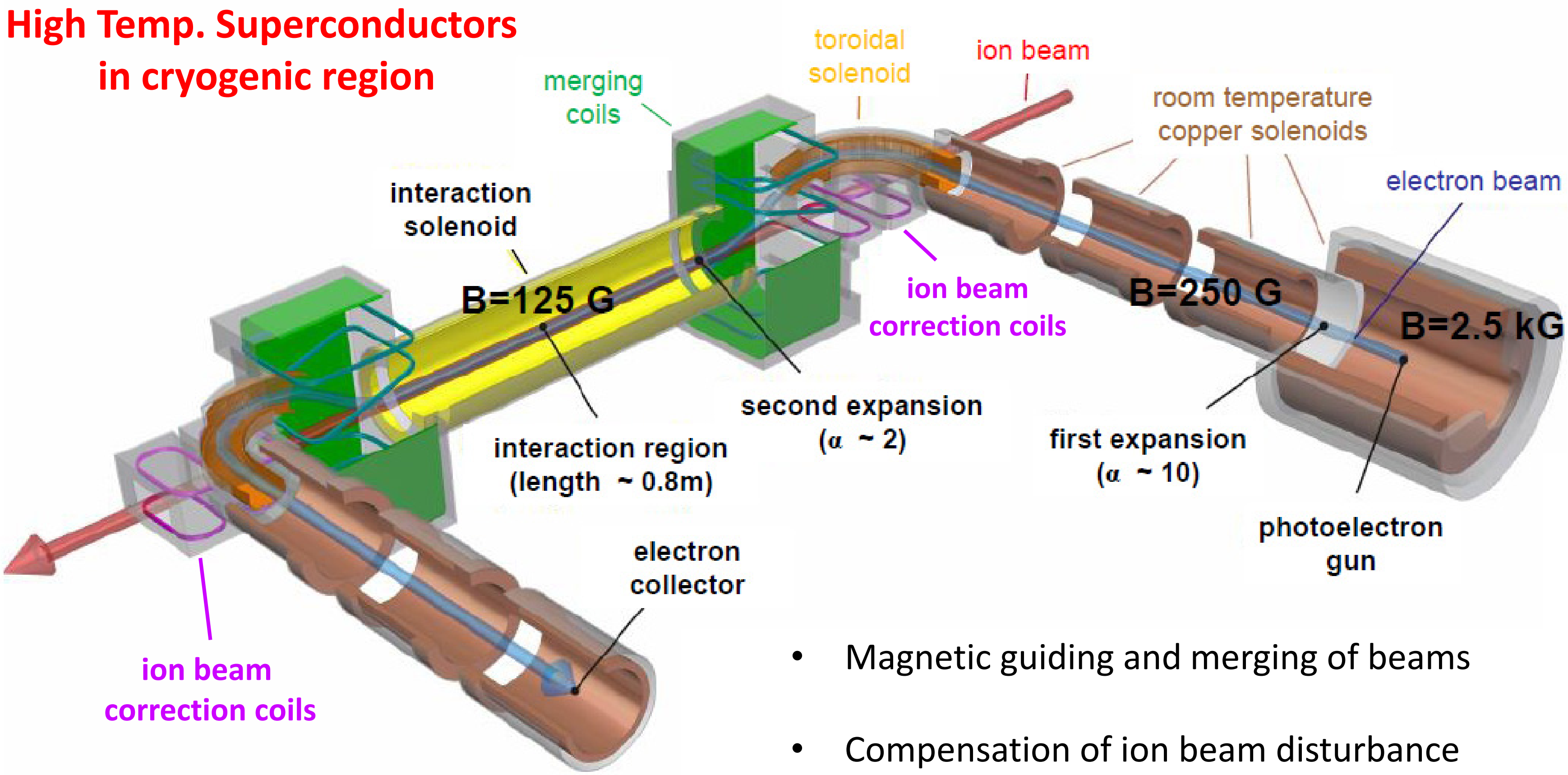
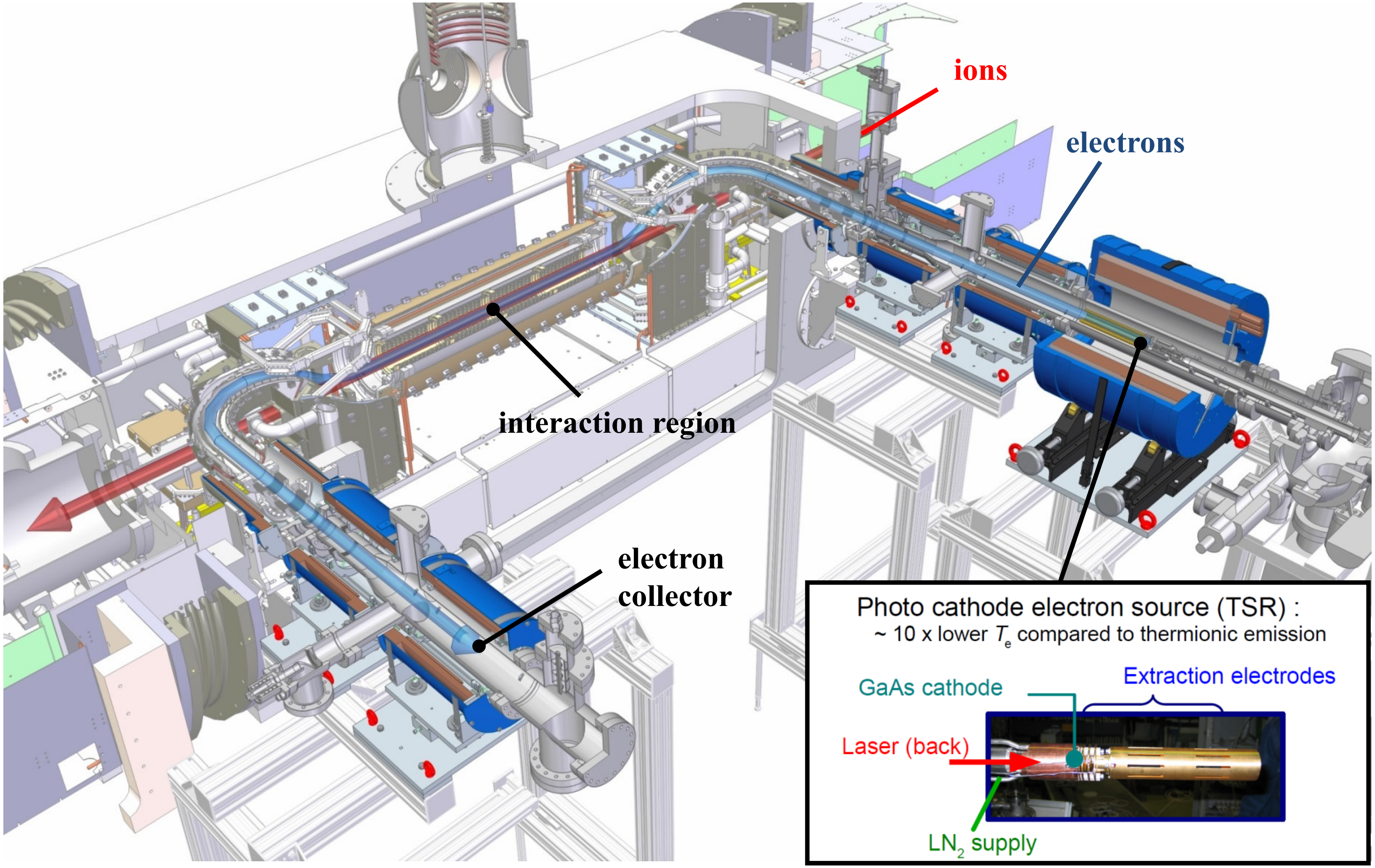
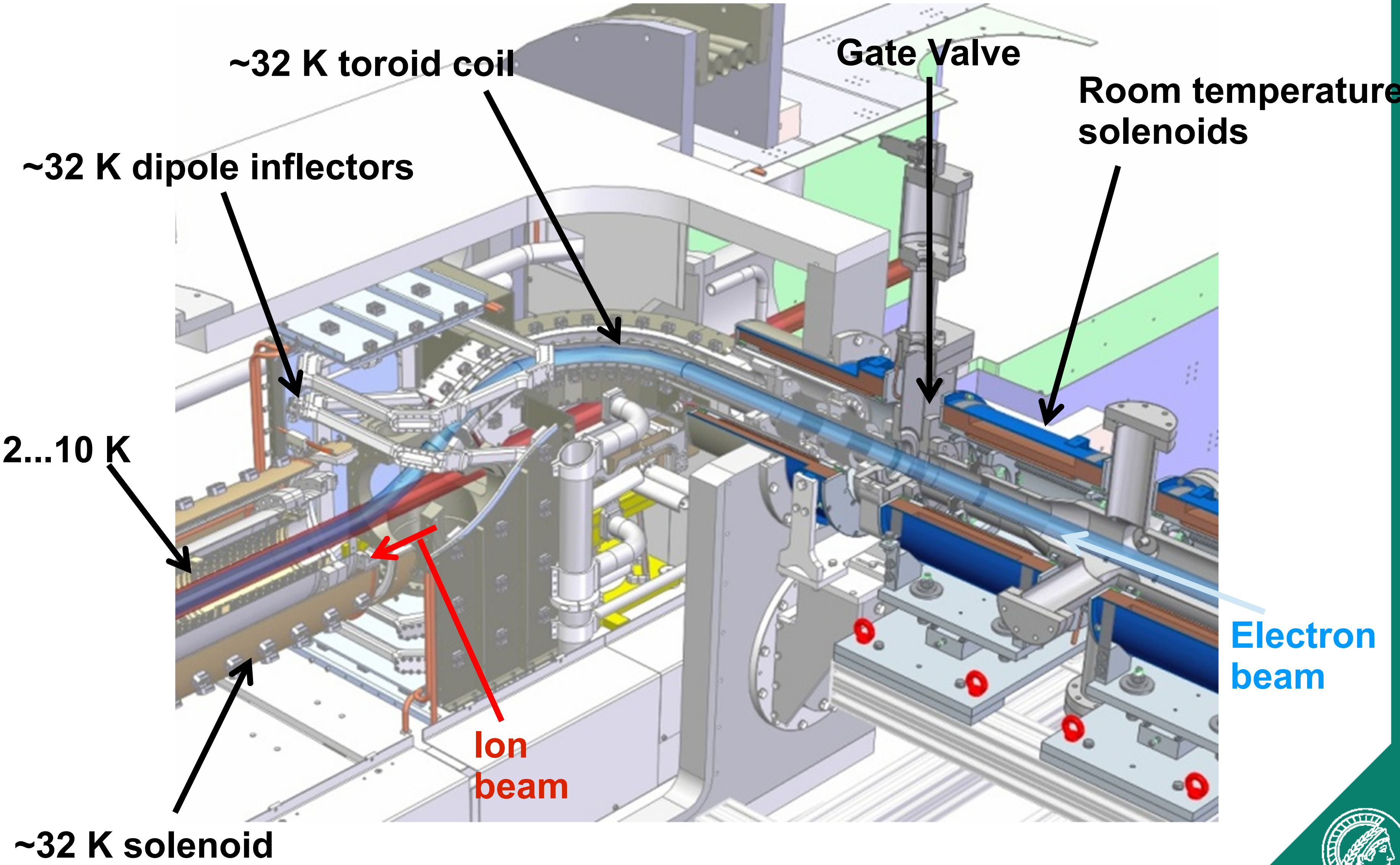


- Magnetic guiding and merging of beams
- Compensation of ion beam disturbance
- Variable electron energy (drift tube)
- Beam diagnostics (two wire scanners)

The CSR electron cooler

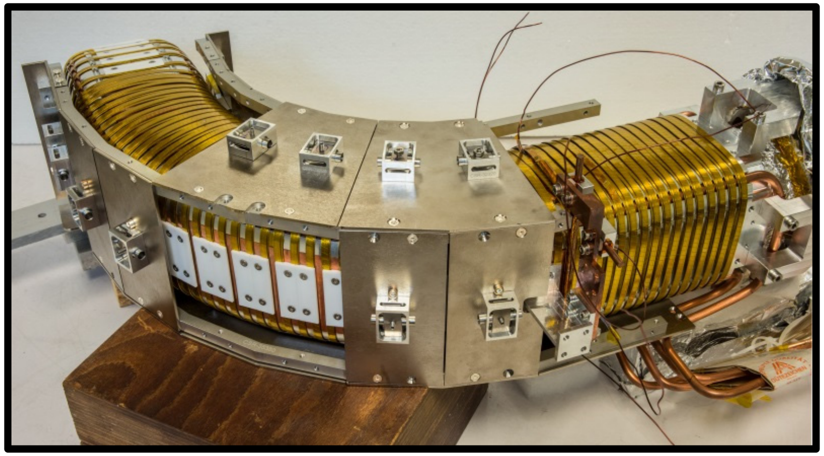


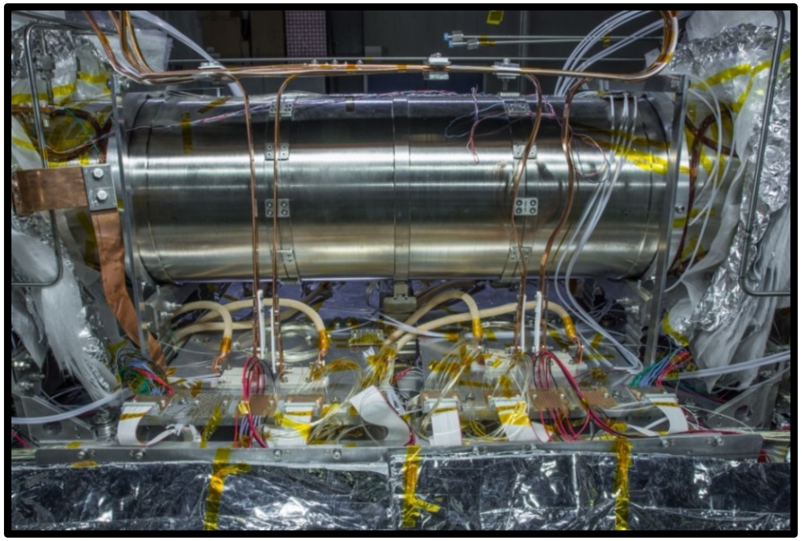
The CSR electron cooler



The CSR electron cooler

steering copper coil pairs located inside aluminum body for toroidal drift compensation



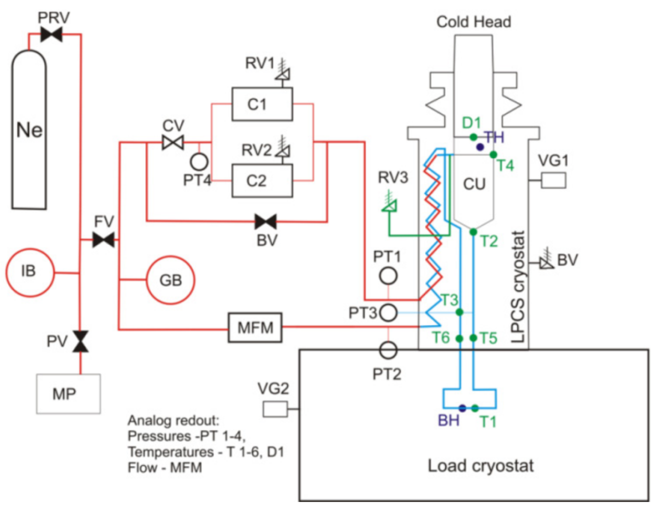


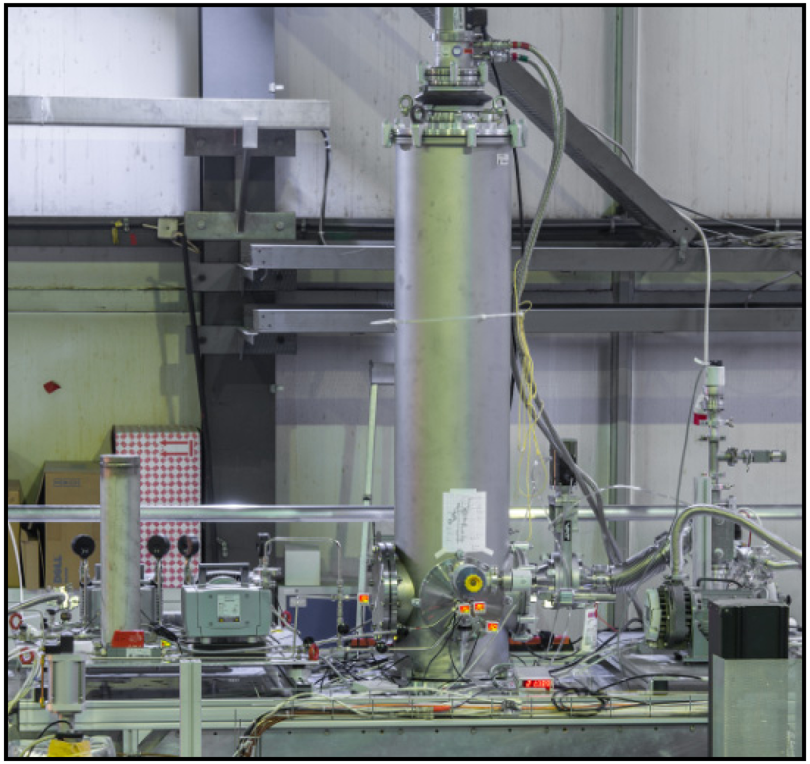
High-temperature superconductor attached onto cooled copper strips distributes ~ 60 A currents to the magnets

The CSR electron cooler

Independent HTS coil-cooling system provides sufficient cooling power for the HTS magnets

30W @ 30K





Low cryogen inventory, forced flow Ne cooling system with room temperature compression stage and heat recuperation

A. Shornikov *, C. Krantz, A. Wolf

Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

ARTICLE INFO

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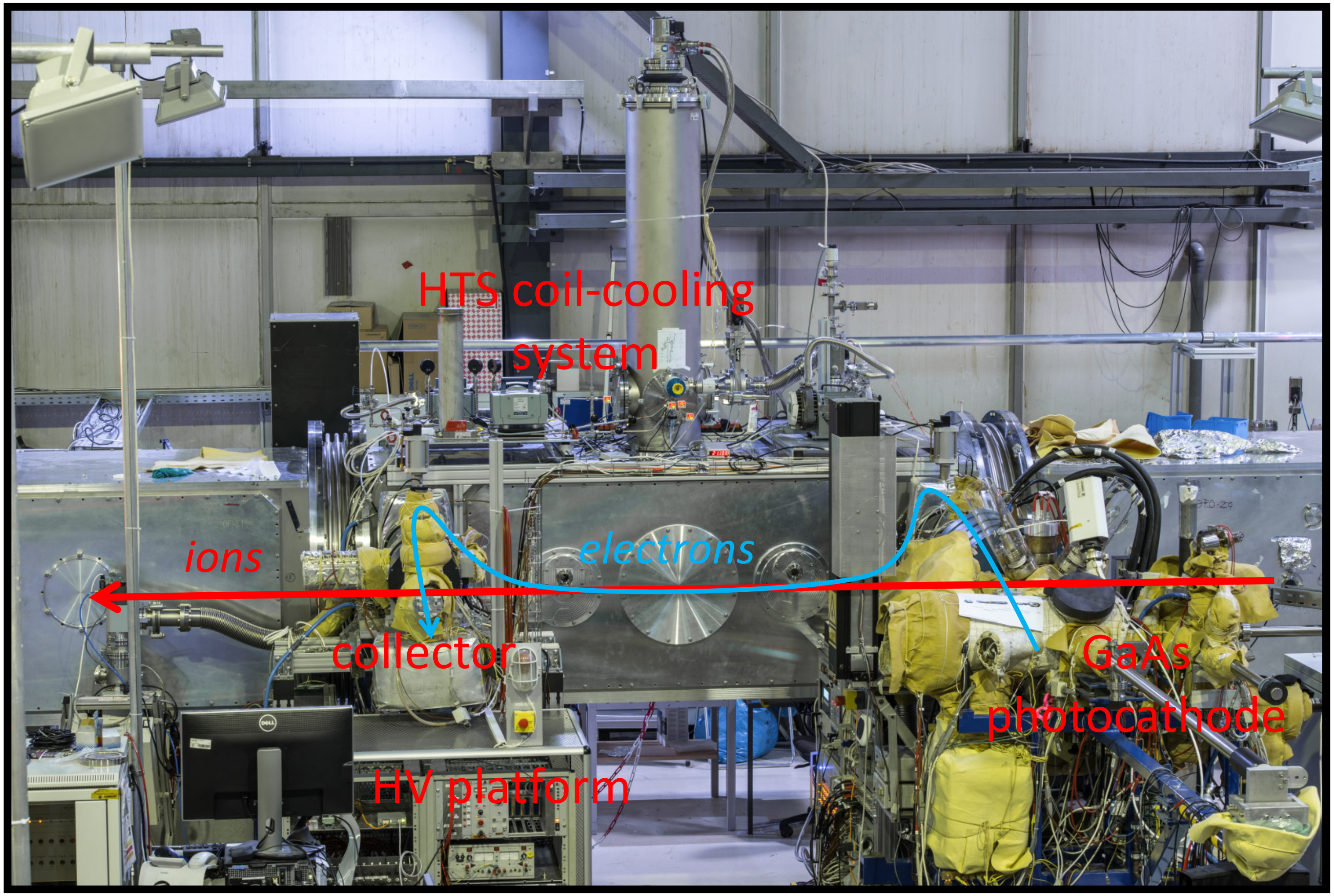
ABSTRACT

We present design and commissioning results of a forced flow cooling system uti
cryogen is pumped through the system by a room-temperature compression stag

The CSR electron cooler



The CSR electron cooler – temperature spreads

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

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

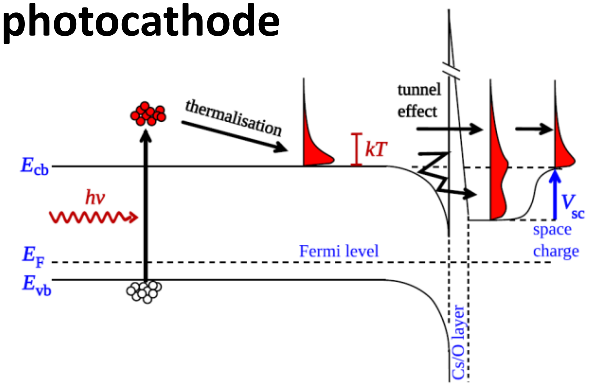
- **Photocathode:** $I = p \cdot U^{3/2}$

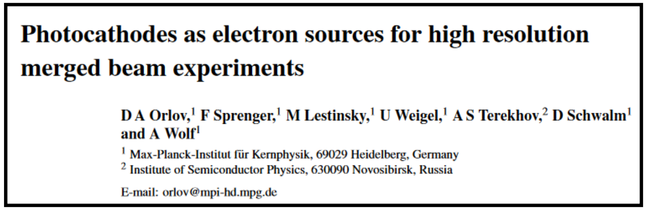
space-charge-limited current operation

  – 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

D A Orlov,[1] F Sprenger,[1] M Lestinsky,[1] U Weigel,[1] A S Terekhov,[2] D Schwalm[1] and A Wolf[1]

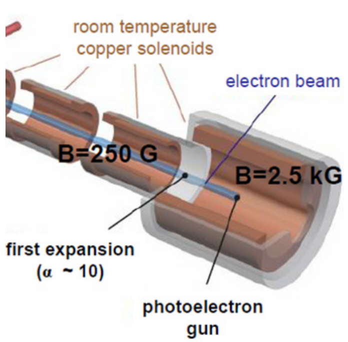
[1] Max-Planck-Institut für Kernphysik, 69029 Heidelberg, Germany
[2] Institute of Semiconductor Physics, 630090 Novosibirsk, Russia

E-mail: orlov@mpi-hd.mpg.de

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

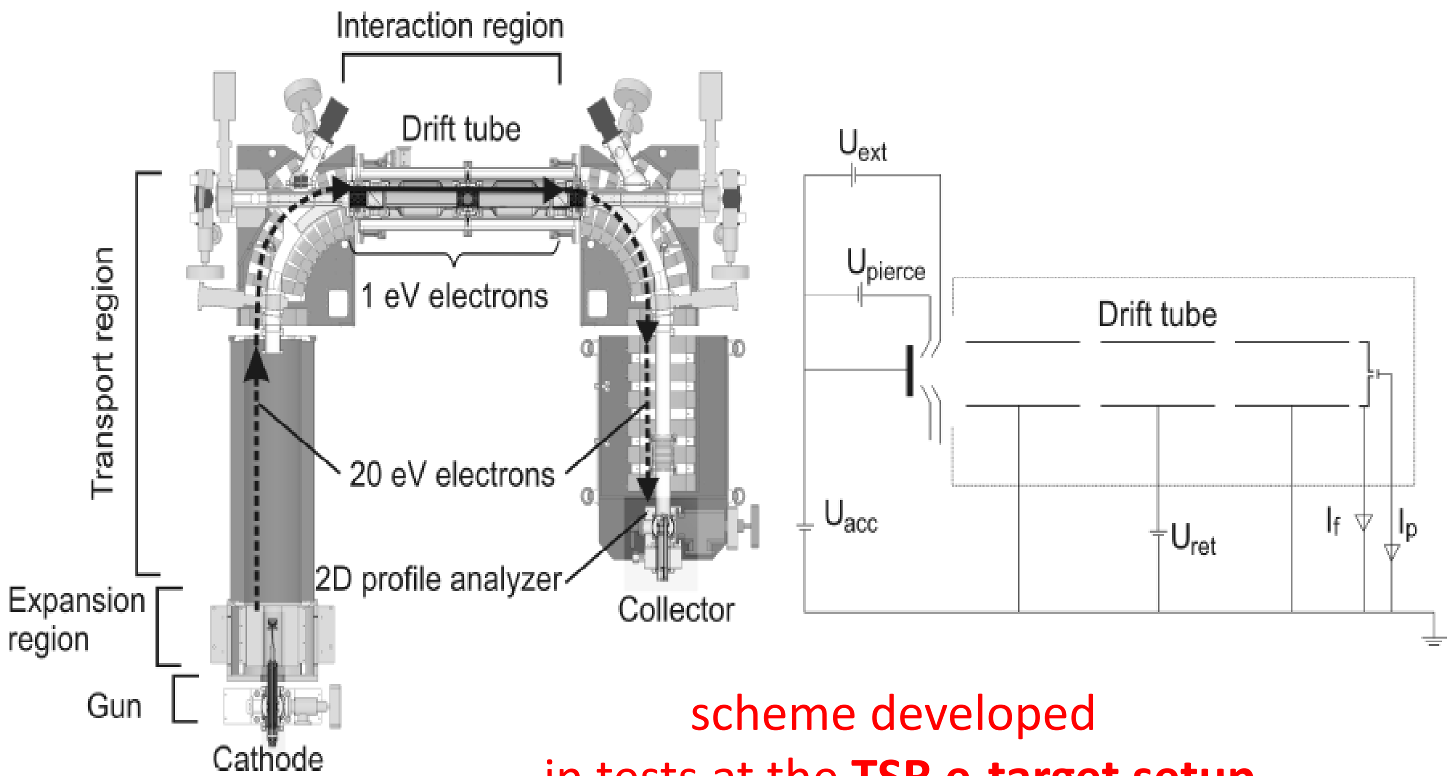
$$k_B T_\| = \frac{(k_B T_c)^2}{2eU}$$

$T_\|$ ~ (10-100) μeV

Max-Planck-Institut für Kernphysik

Ultra low energy electron deceleration scheme

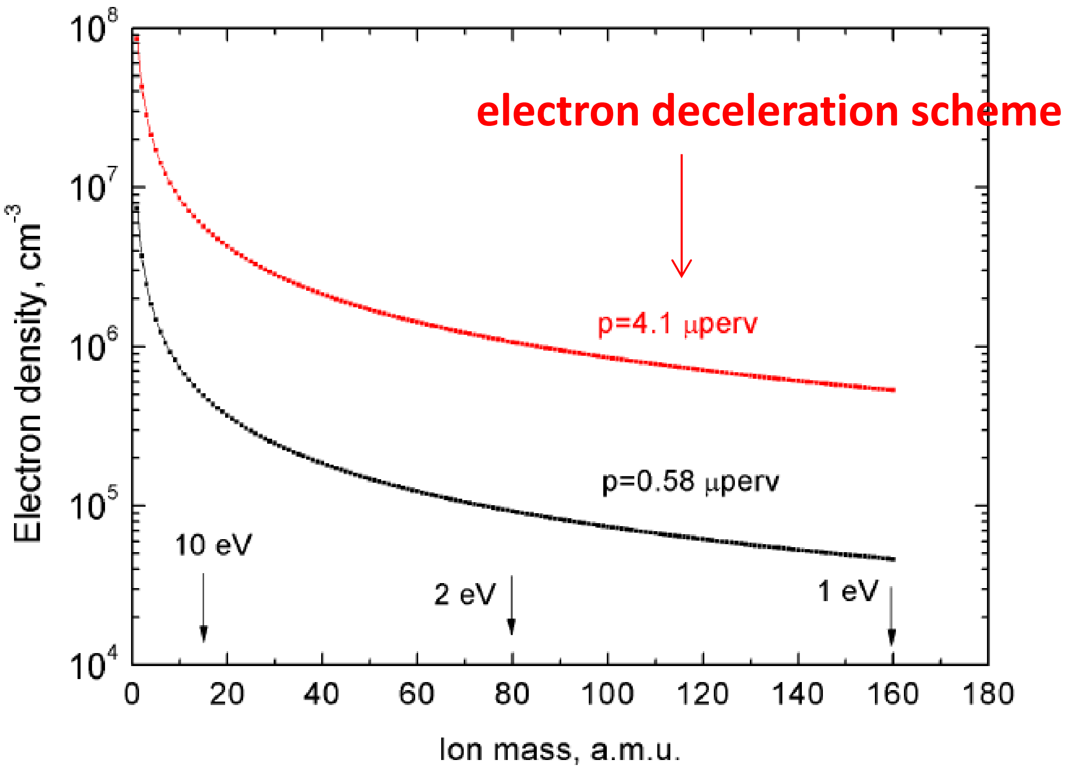
- difference of contact potentials ~ $E_{kin,e-}$ ~ $U_{space\ charge}$ ~ **eV !**



scheme developed
in tests at the **TSR e-target setup**

A. Shornikov et al., Phys. Rev. ST Accel. Beams 17, 042802 (2014)

Electron density in interaction region

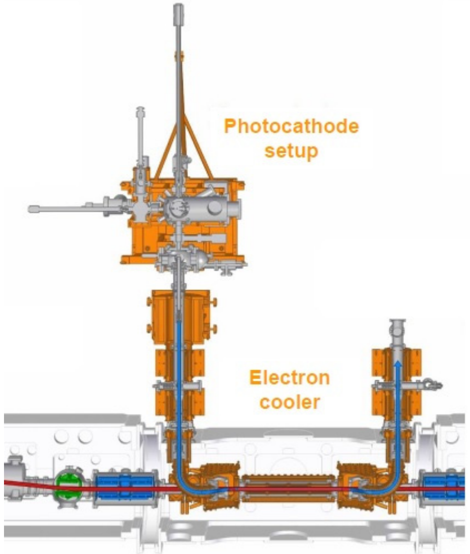


$\alpha_{expansion}$	=	20
$d_{cathode}$	=	3mm
E_{ion}	=	300 keV

A. Shornikov, phd thesis

Outline

- The Cryogenic Storage Ring
- Rotational cooling of stored molecules
- The CSR electron cooler
- **Beam Time 2017: Recent results**
- Outlook: Electron-beam collision studies



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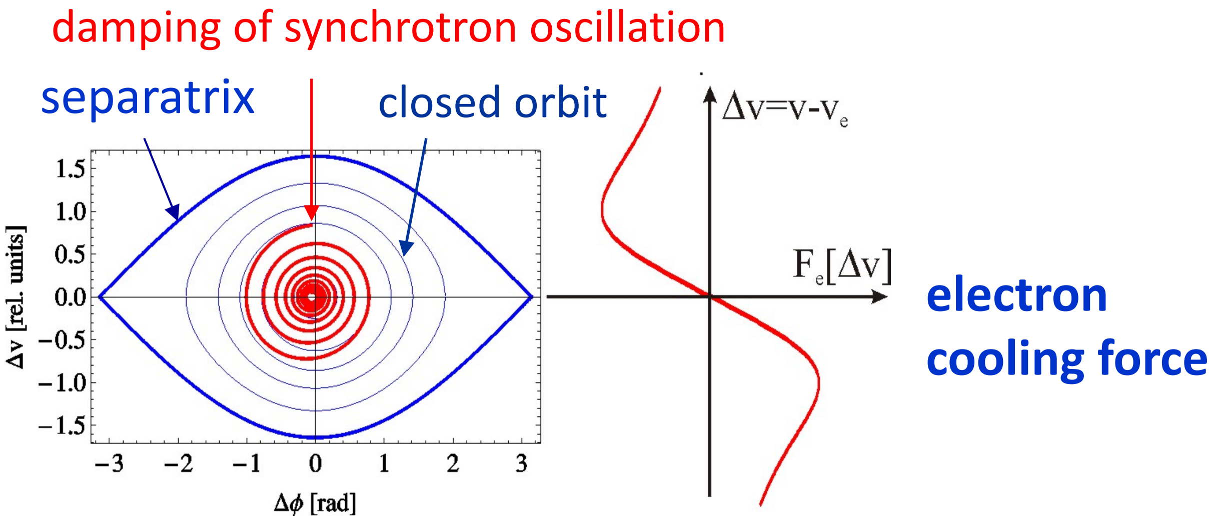
Bunched-beam electron cooling

longitudinal phase space

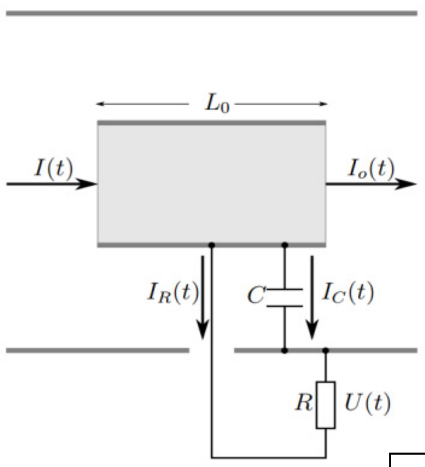


Electron cooling of F^{6+}

- F6+ acceleration voltage = 223 kV
  → E(F6+) = 1.34 MeV
  → Ee = 38.7 eV
- F6+ current ~ 300 nA
- N ~ 1e6 particles

- rf bunching frequency = 2nd harmonic of revolution frequency ~ 214 kHz

capacitive current pickup



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

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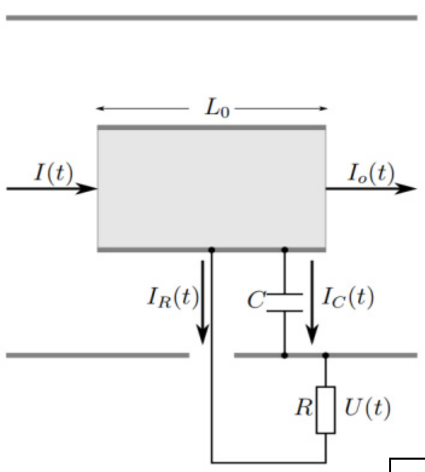

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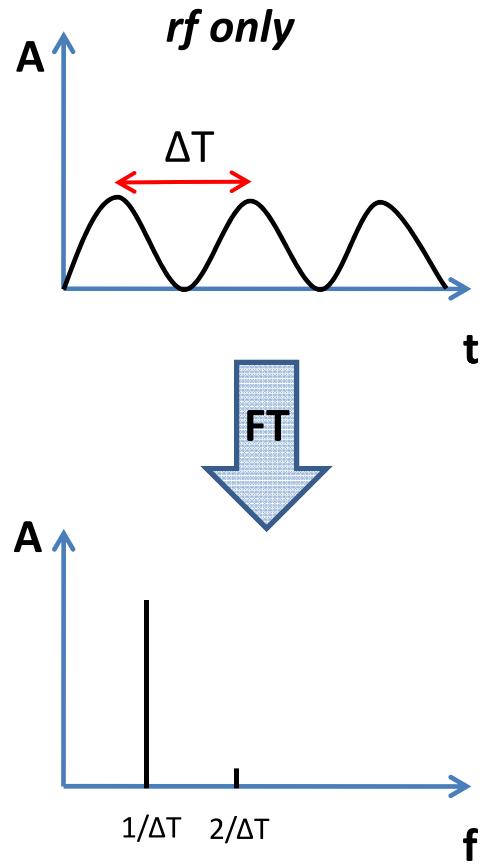

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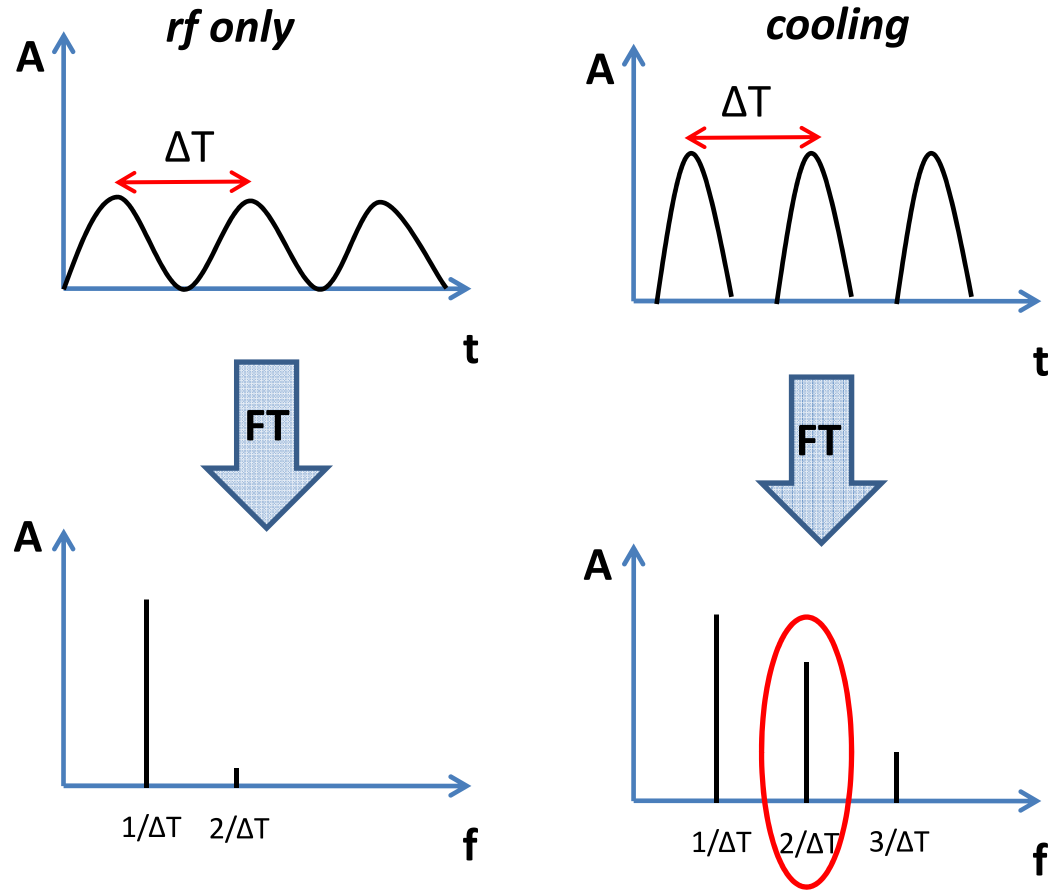
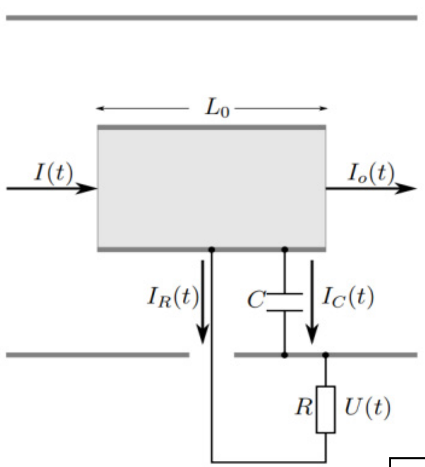


capacitive current pickup



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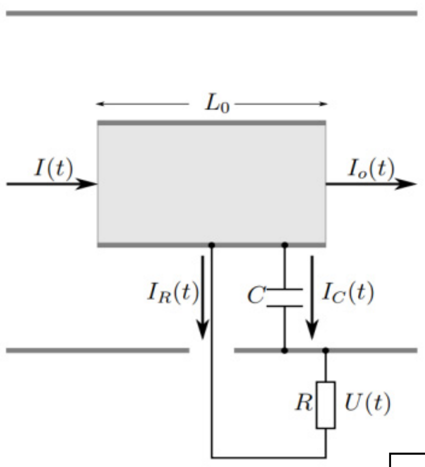
1 second: Ion beam injection
+3 seconds: Electron beam **on**
+5 seconds: Electron beam **off**

capacitive current pickup



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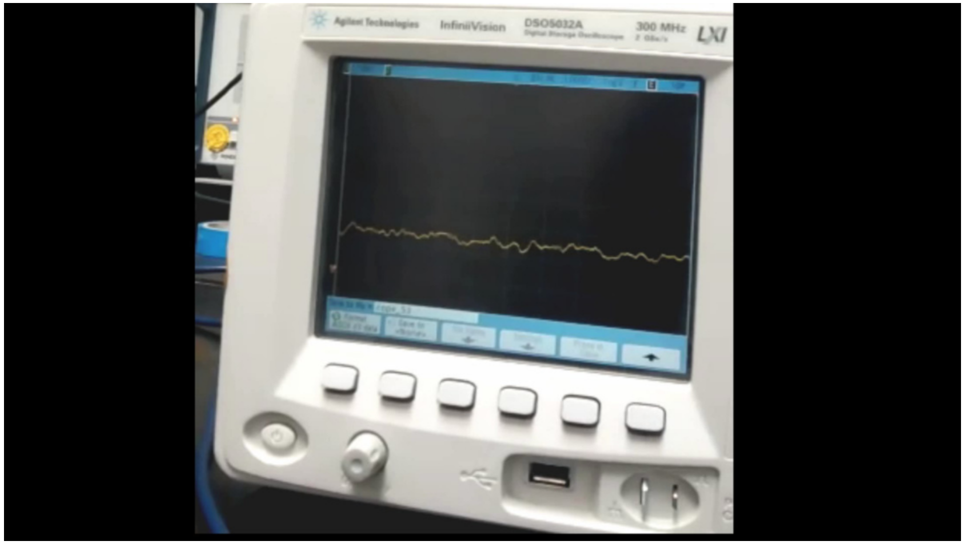

Electron cooling of F^{6+}

12th June 2017

Bunched beam electron cooling realized in an electrostatic storage ring!

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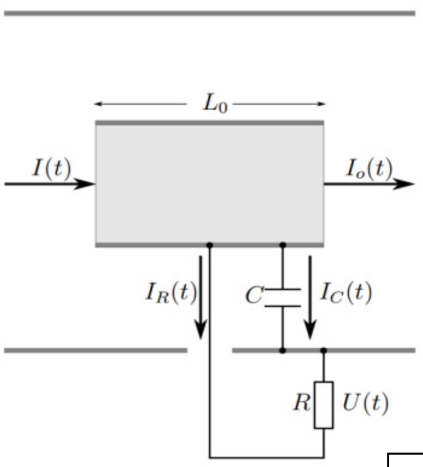
capacitive current pickup



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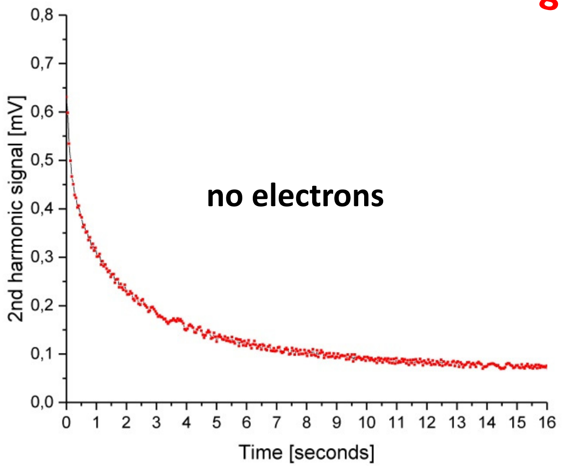

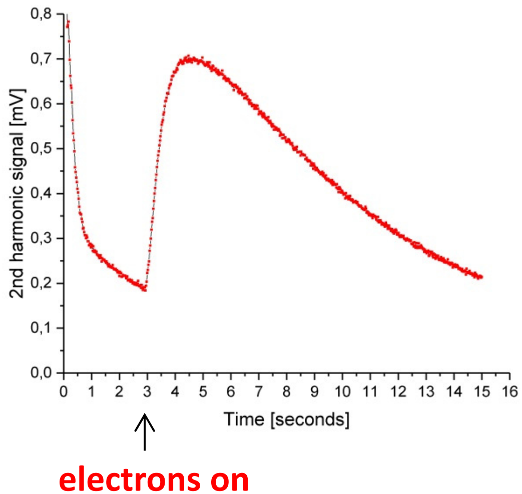

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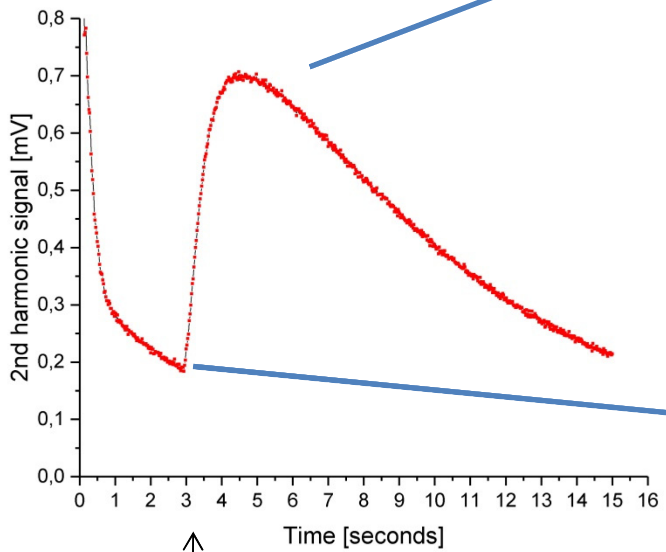
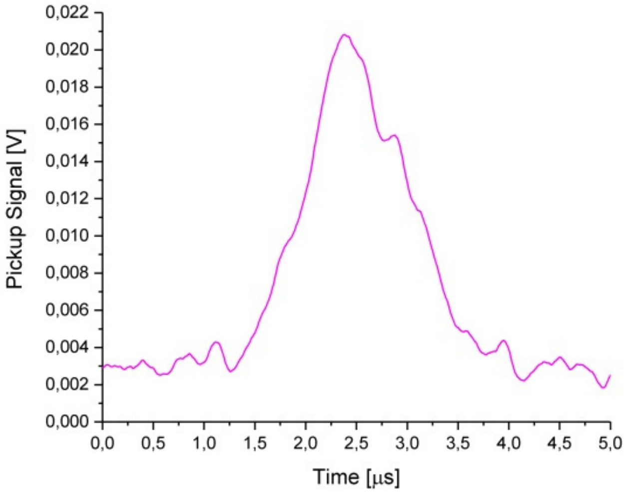
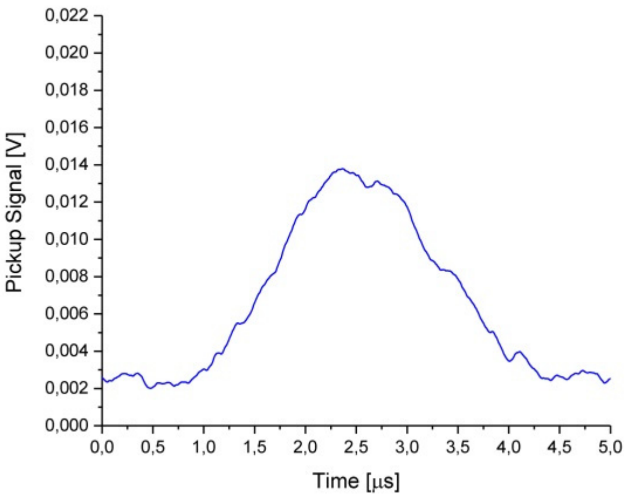


electrons on

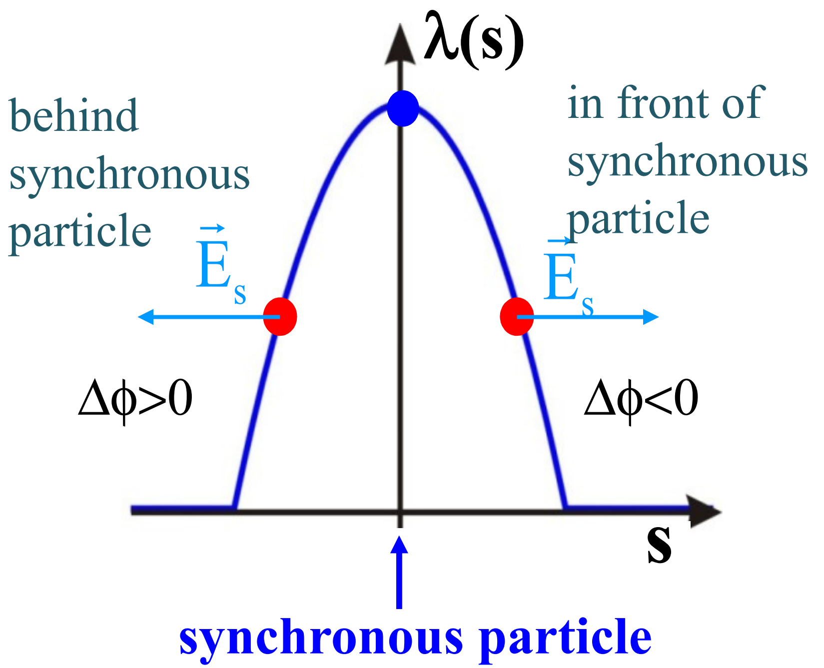


n_e = 1.7 x 10^5 cm^{-3}



Space charge limitation of bunch length

space charge ion bunch longitudinal profile



$$U_{eff}(\Delta\phi) = U\cdot \sin(\Delta\phi+\phi_s)+U_s(\Delta\phi)$$

$$U_s(\Delta\phi) = E_s(\Delta\phi)\cdot C_0$$

$$E_{\parallel}(s) = -\frac{1+2\ln(\frac{R}{r})}{4\pi\epsilon_0\gamma^2}\frac{\partial\lambda(s)}{\partial s}$$

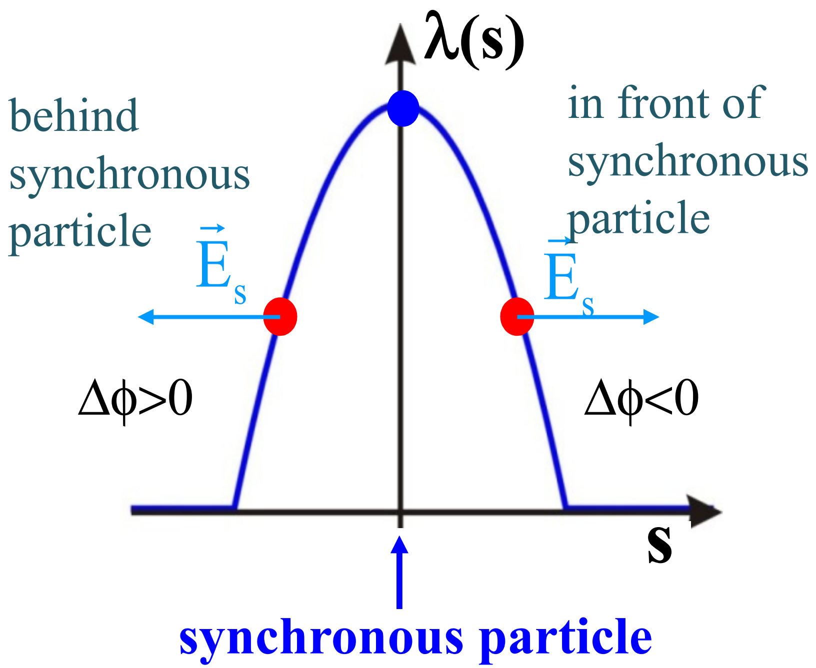
Proceedings of COOL2013, Murren, Switzerland WEAM1HA03

COOLING ACTIVITIES AT THE TSR STORAGE RING

M. Grieser, S. Artikova, R. Bastert, K. Blaum, A. Wolf
Max-Planck-Institut für Kernphysik, D-69029 Heidelberg, Germany

Space charge limitation of bunch length

space charge ion bunch longitudinal profile



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$$E_{\parallel}(s) = -\frac{1 + 2\ln(\frac{R}{r})}{4\pi\epsilon_0\gamma^2}\frac{\partial\lambda(s)}{\partial s}$$

$$\lambda(s) = \frac{3N_B Q}{4w_s}(1 - \frac{s^2}{w_s^2})$$

parabola profile: only distribution to compensate the synchrotron motion of each ion (for $\Delta\phi$ << 2π)

$$U_{eff}(\Delta\phi) = 0$$

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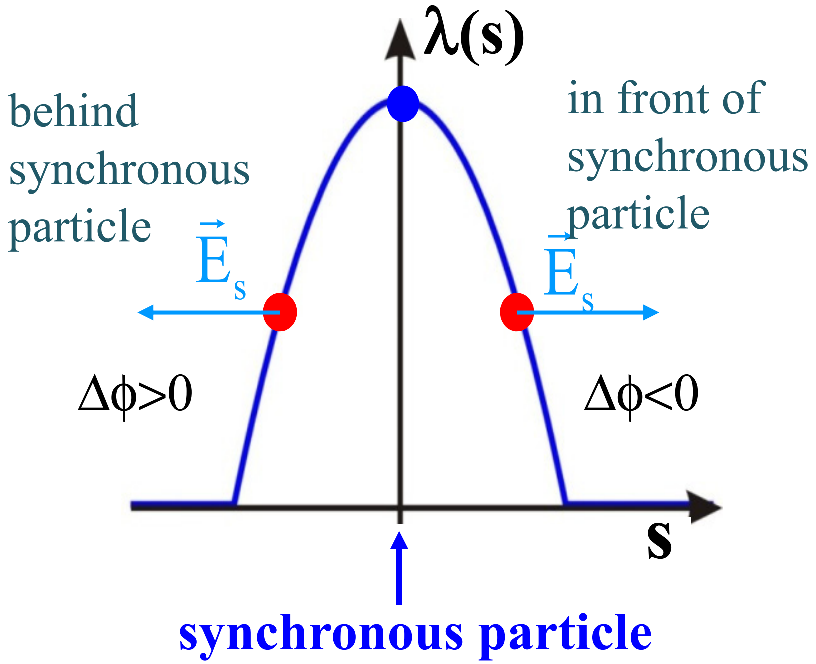

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$$\lambda(s) = \frac{3N_B Q}{4w_s}\left(1 - \frac{s^2}{w_s^2}\right)$$

→ RF resonator voltage is compensated by space charge voltage of the ion beam

→ frozen synchrotron oscillation

→ **Electron cooling creates a stable, space charge limited bunch length**

parabola profile: only distribution to compensate the synchrotron motion of each ion (for $\Delta\phi \ll 2\pi$)

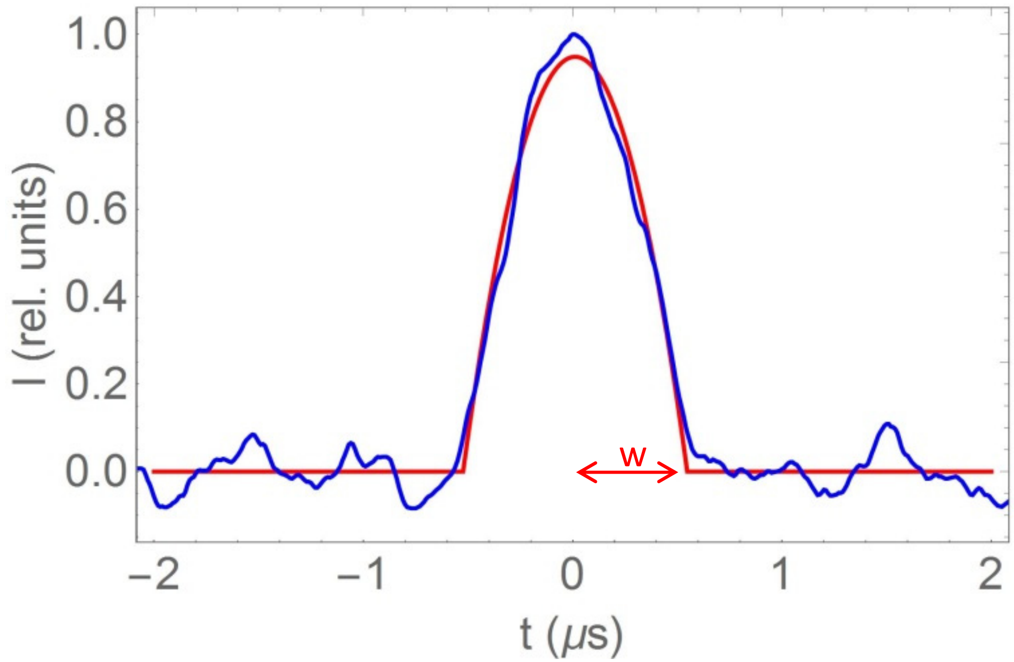
$$U_{eff}(\Delta\phi)=0$$

Space charge limitation of bunch length

beam width at space charge limit:

$$w = C_0 \sqrt[3]{\frac{3(1+2\ln(\frac{R}{r}))I}{2^4\pi^2 c^4 \epsilon_0 \gamma^2 h^2 \beta^4 U}}$$

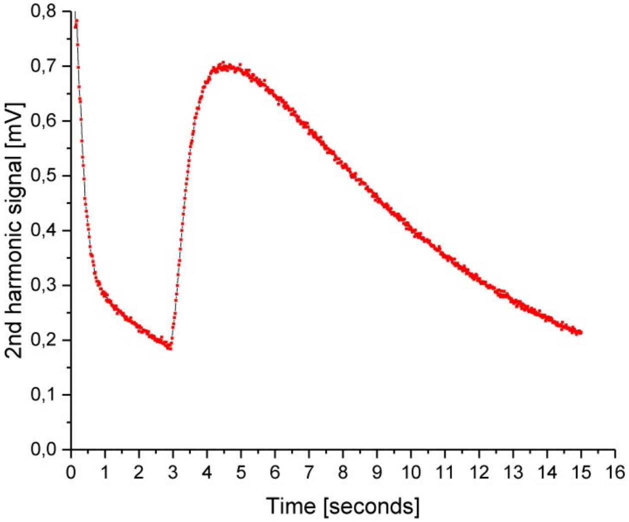
10 sec after injection,
7 sec after cooling



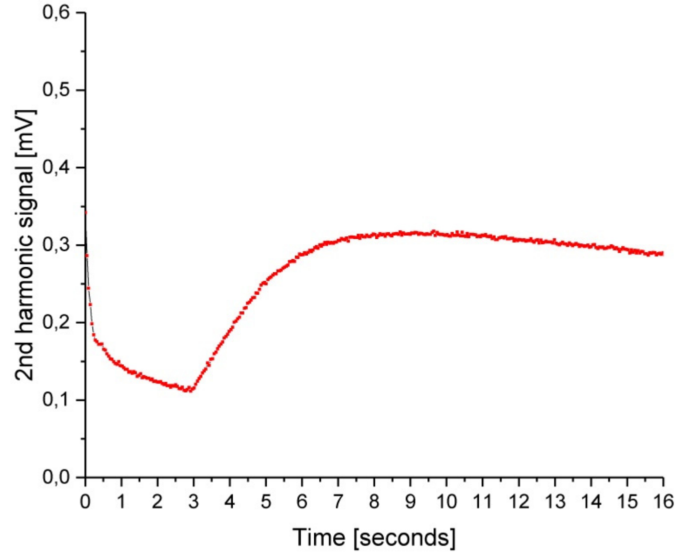
w_{exp} = 535 ns

w_{theo} = 597.5 ns

I_e = 14.4 µA
$n_e = 1.7 \times 10^5\ cm^{-3}$

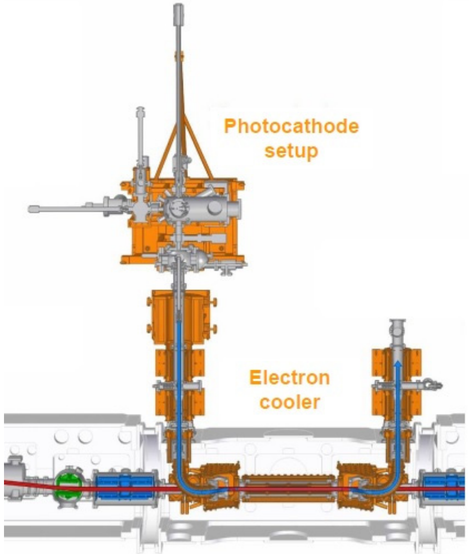


I_e = 1.6 µA
$n_e = 1.6 \times 10^4\ cm^{-3}$

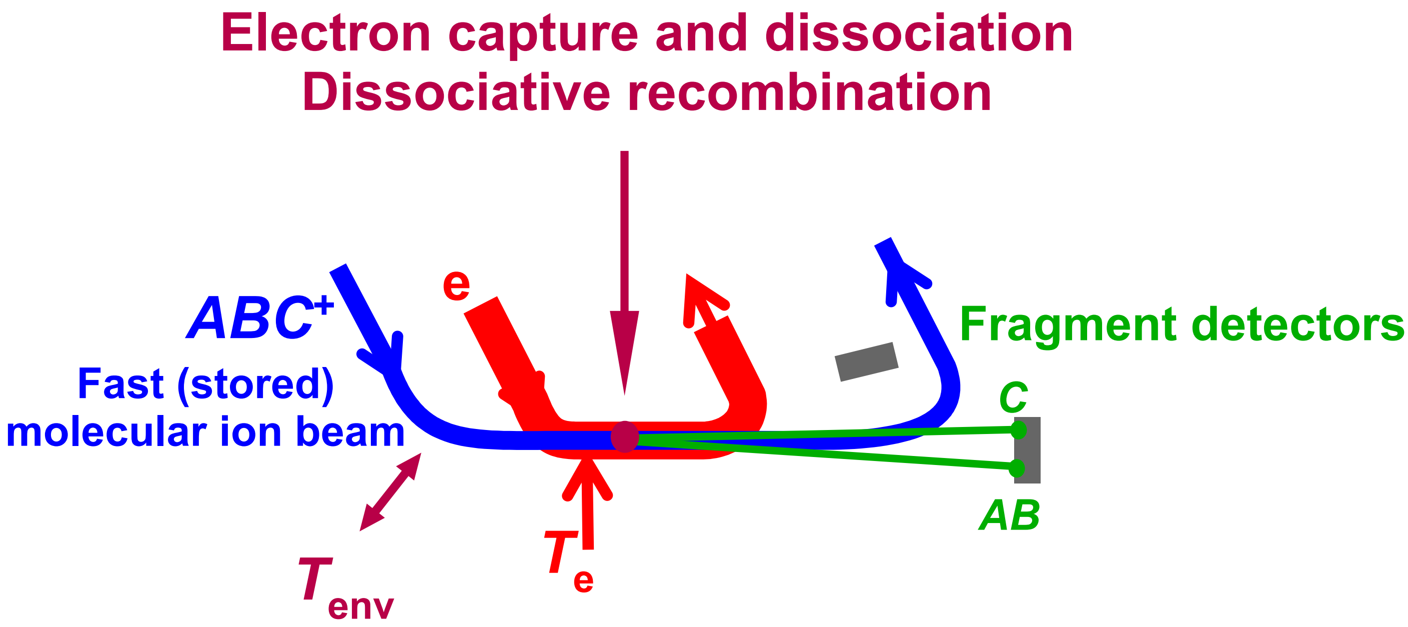


Outline

- The Cryogenic Storage Ring
- Rotational cooling of stored molecules
- The CSR electron cooler
- Beam Time 2017: Recent results
- **Outlook: Electron-beam collision studies**



Outlook: Electron-beam collision studies



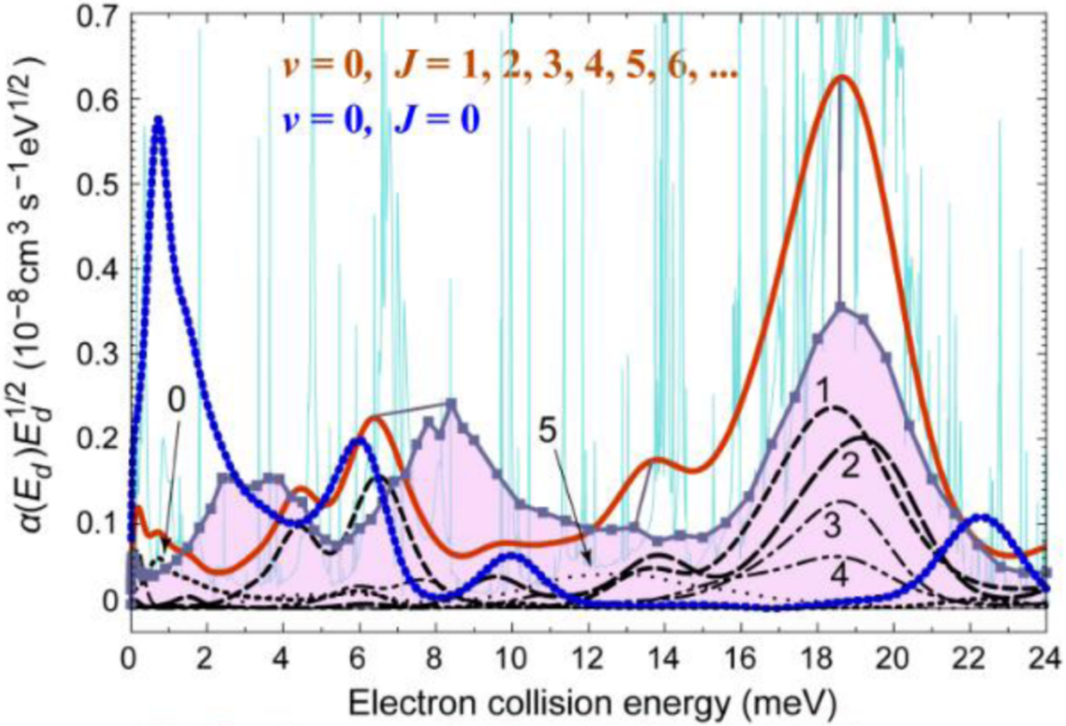
$$E_{coll} = ½\, m_e\, (v_e – v_i)^2$$

can be scanned from ~ 1 meV … 50 eV

Outlook: Electron-beam collision studies

Benchmark experiment: **DR of HD⁺**

$HD^+(\nu, J) + e^- \rightarrow H + D$



Waffeu-Tamo *et al.*, PRA 84 (2011) (0 K)

TSR data ($kT_e \sim 1$ meV, $T_{ion} \sim 300$ K)

CSR prediction ($T_{ion} = 10$ K)

Outlook: Electron-beam collision studies

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

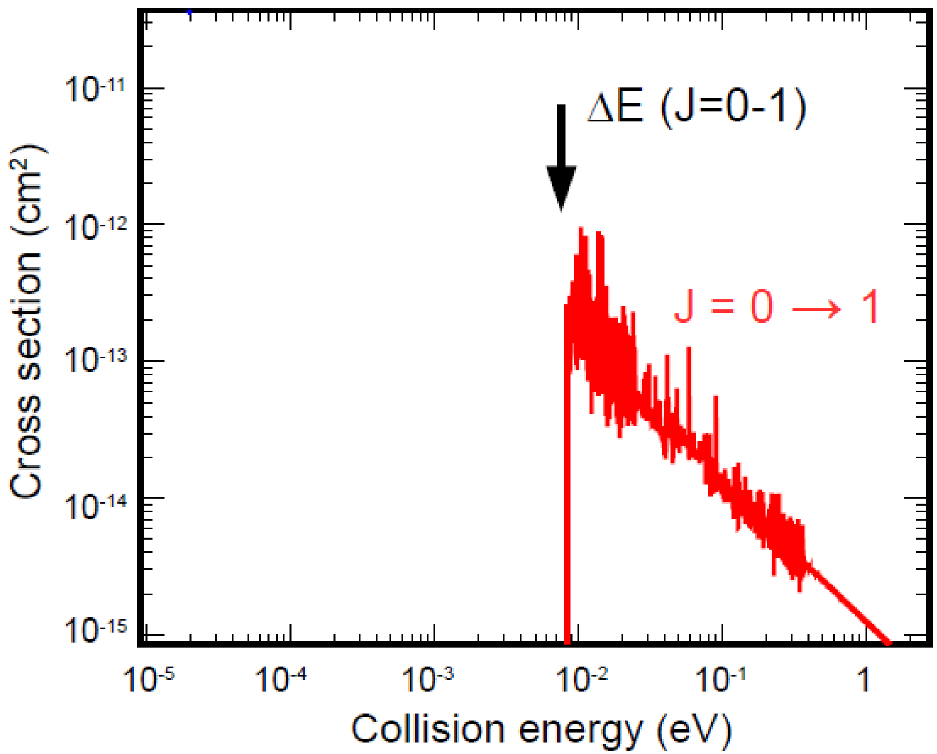
internal cooling/heating by inelastic electron collisions

Outlook: Electron-beam collision studies

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

internal cooling/heating by inelastic electron collisions

$HeH^+ (v=0) + e^-$



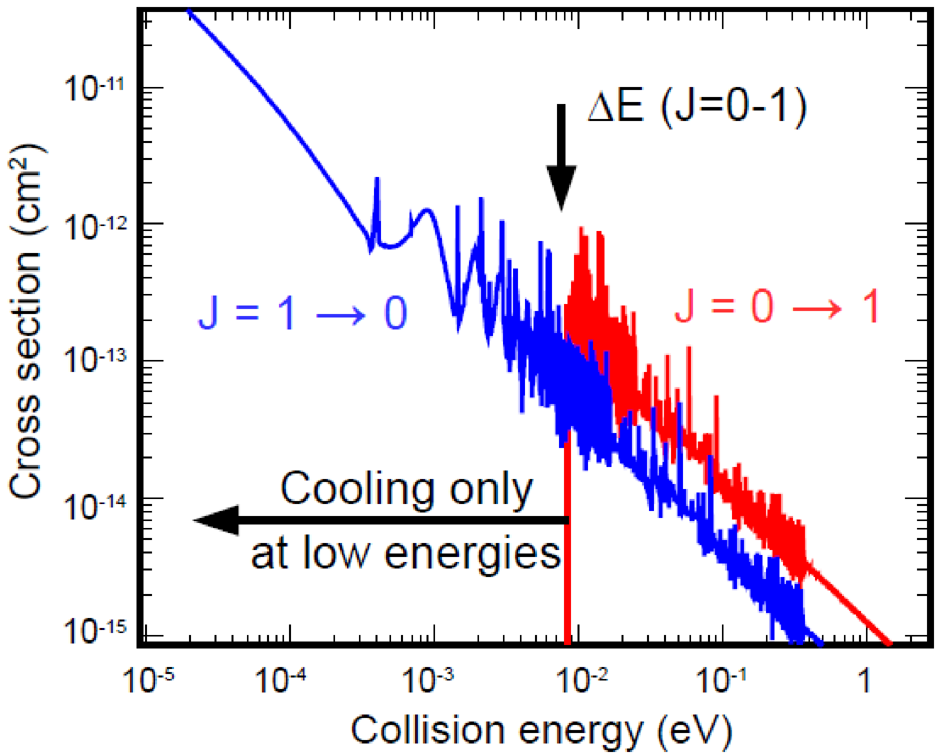
Collaboration:
C. Greene, S. Kokoouline, R. Curik,
arXiv:1705.10153

Outlook: Electron-beam collision studies

ABC$^+$(J) + e$^-$ → ABC$^+$(J') + e$^-$

internal cooling/heating by inelastic electron collisions

HeH$^+$ (v=0) + e$^-$



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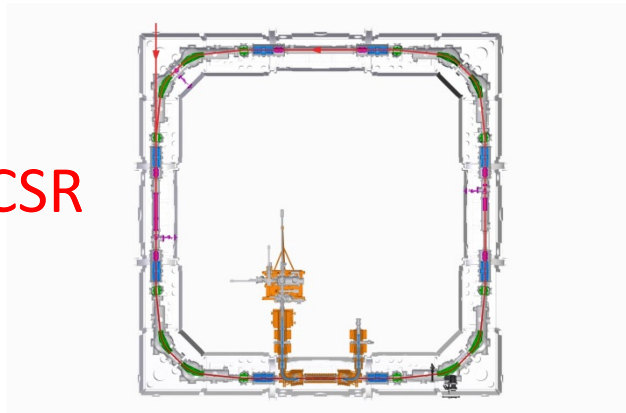
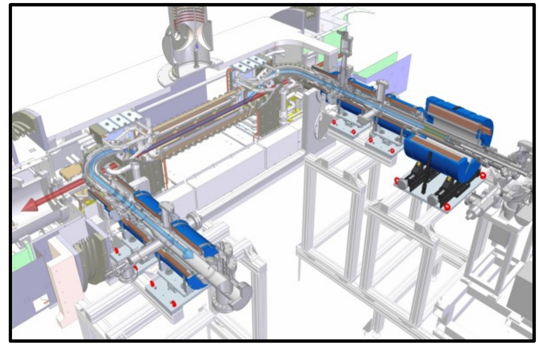
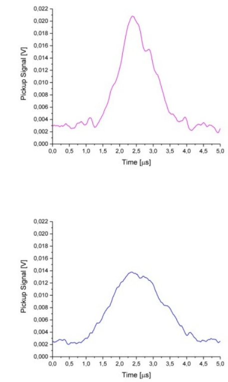
Summary

Special thanks to
Stephen Vogel   Oldrich Novotný
Marius Rimmler   ANDREAS WOLF

CSR





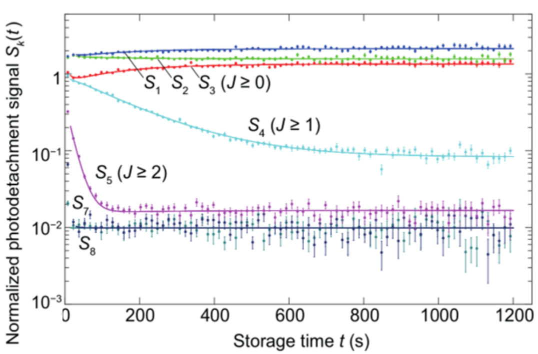


- ion-beam storage lifetime up to ~1h
- molecular ions cool down to 15 K
- facilities for cold molecular collisions with
  - photons
  - electrons
  - neutral atoms

June 2017:
First (bunched-beam) electron cooling in an electrostatic storage ring

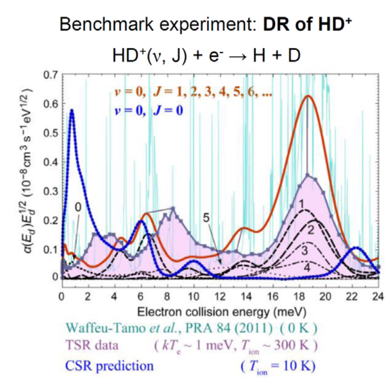
in preperation:
Low-temperature inelastic electron-ion collision studies

Photodetachment:
OH^- beam stored over 20 min



Radiative rotational level lifetimes & dipole moments

	$\tau = A_J^{-1}$ (s)	μ_0 (D)
$J = 1$	193(7)	0.970(17)
$J = 2$	20.9(2.1)	0.952(48)
$J = 3$	5.30(37)	0.997(35)



Thank you for your attention!

The

CSR Team

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

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JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE