First Operation of the Heidelberg CSR for Low-Energy Collision Experiments With Molecular Ion Beams

For the CSR team: Andreas Wolf
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COOL 2015 – Jefferson Lab, Newport News VA, 28 Sep – 02 Oct 2015

Motivation: Ion chemistry and molecular collision processes

The CSR laboratory and cryogenic setup

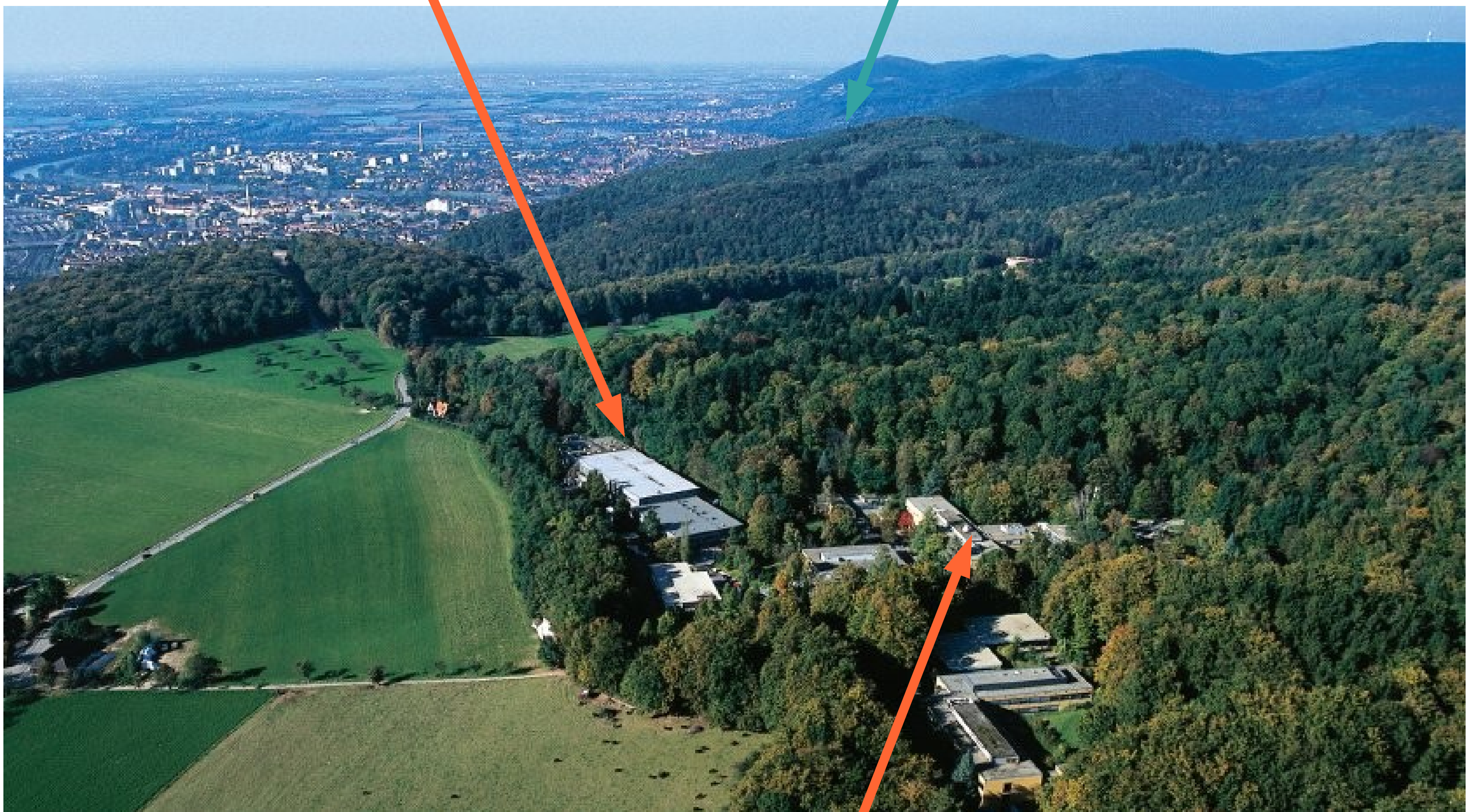
First cryogenic operation:
60 keV ion beam lifetimes
Rotational thermometry on stored molecules

The cryogenic electron cooler

Max-Planck-Institut für Kernphysik

Bothe Laboratory Experimental Hall
Atomic and Molecular Physics

Neckar Valley, Heidelberg



MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

Bothe and Gentner Laboratories

- Neutrino Physics, High Energy and Nuclear Astrophysics
- Fundamental Tests with Trapped Ions, Nuclear Physics
- Many-Body Dynamics of Atoms and Molecules

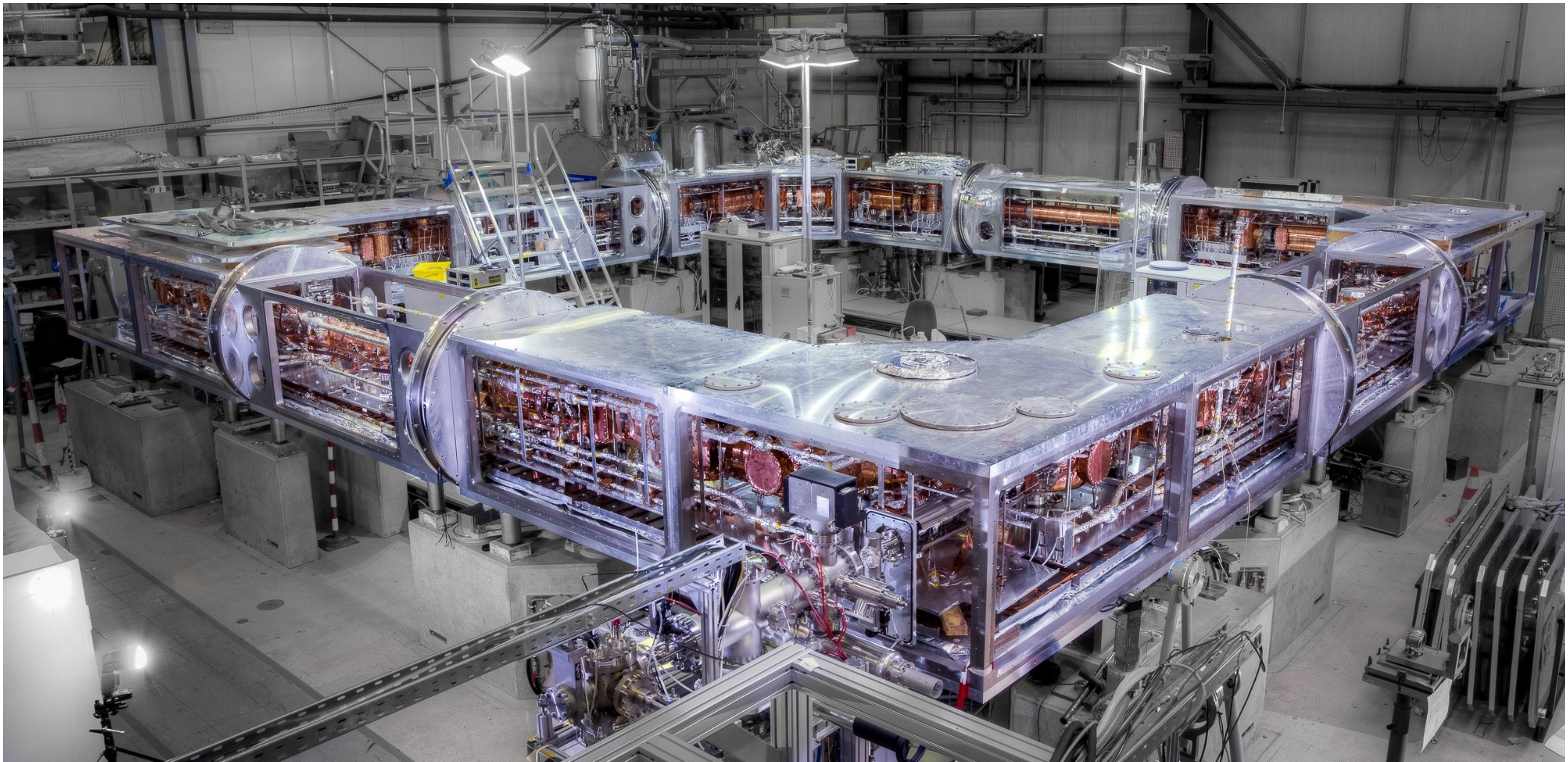
CSR Heidelberg

Electrostatic storage ring
Circumference 35 m
Energy ~20 keV·q up to 300 keV·q

Vacuum chamber temperature ~10 K
$<10^{-13}$ mbar room temp. equivalent vacuum
Ion beam lifetime: hundreds of seconds

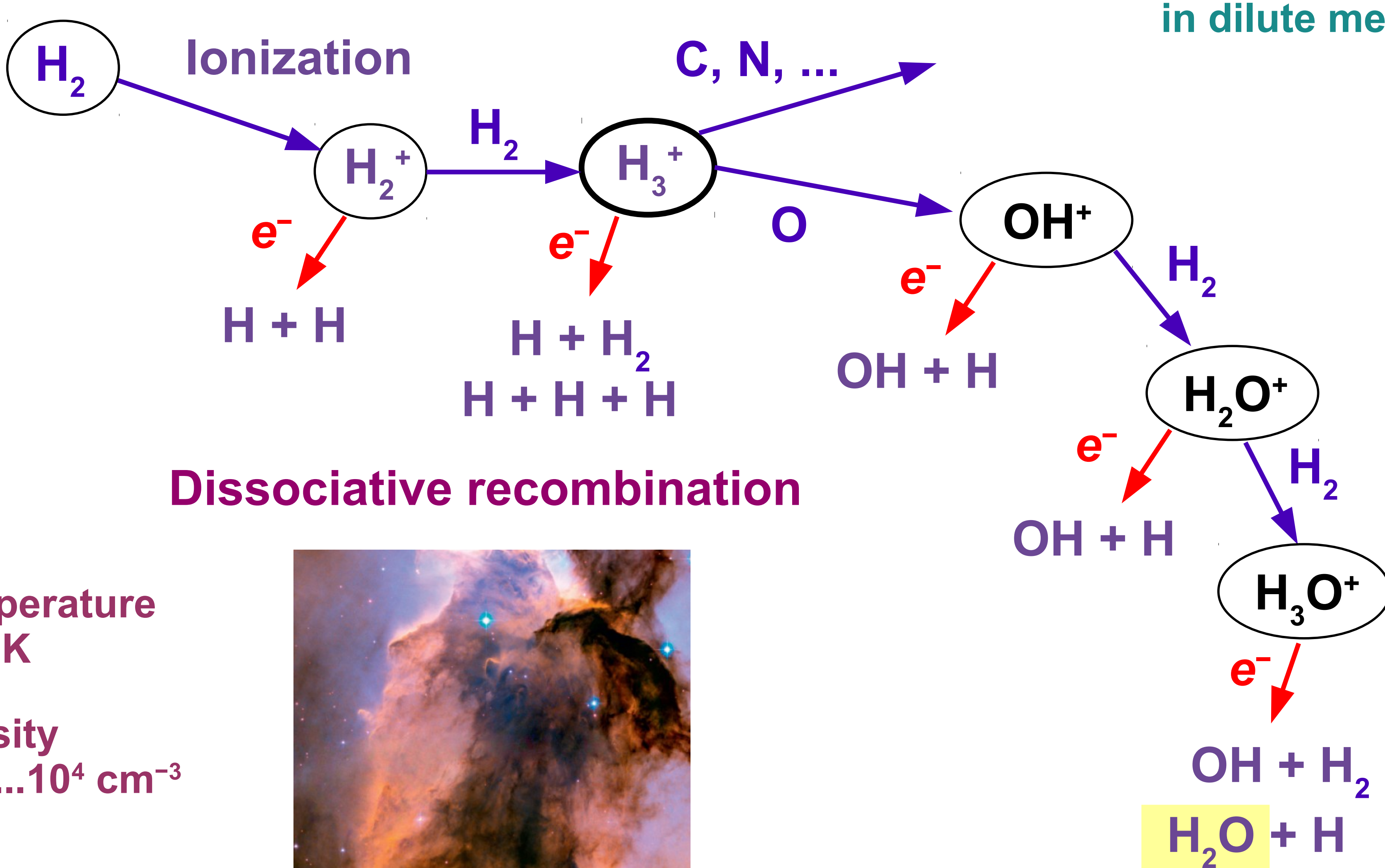
Electron cooling and collision experiments with merged beams

First cryogenic beam time April–July 2015



Motivation: Ion chemistry

Low-temperature reactions
in dilute media



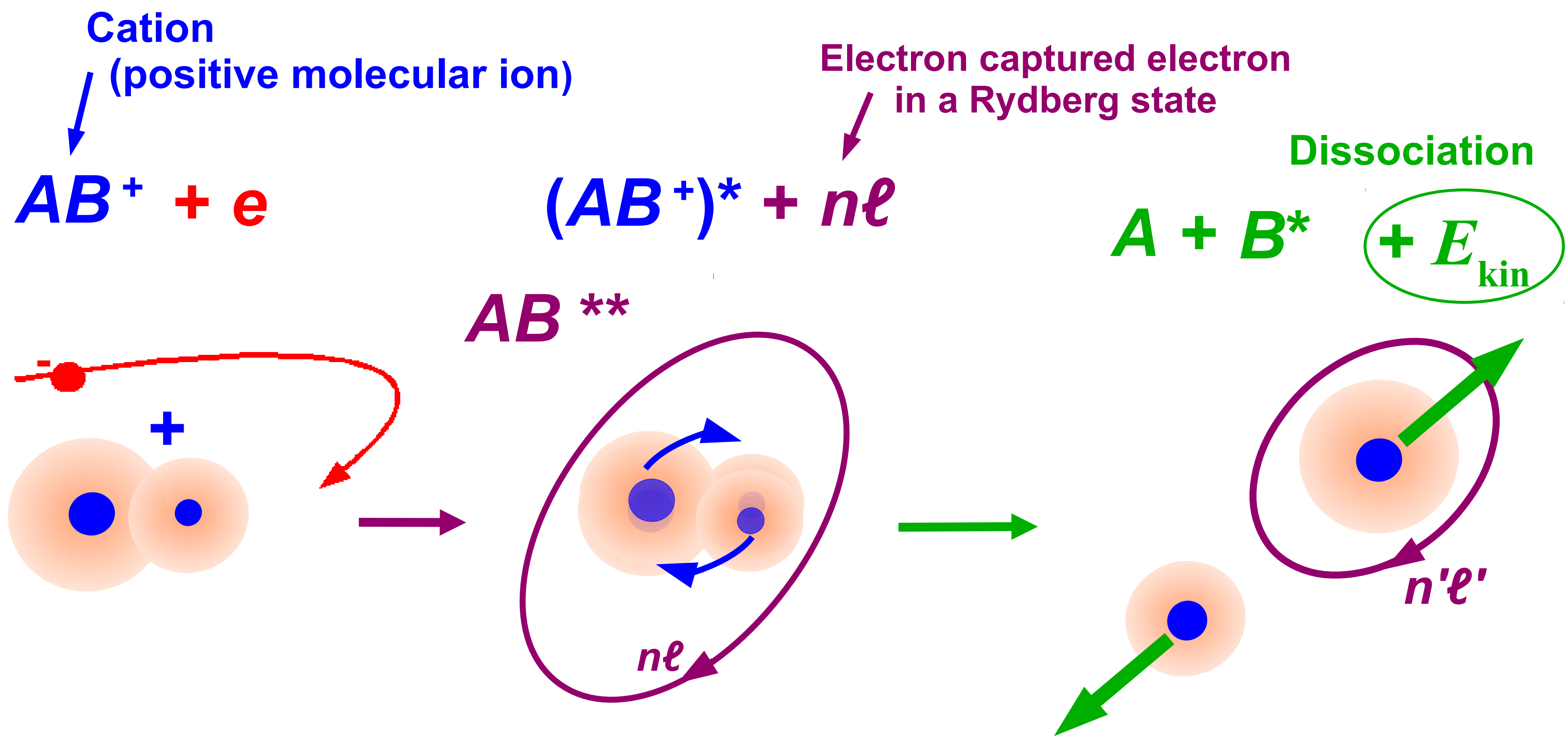
Dissociative recombination

Temperature
~ 10 K

Density
~ 10...10⁴ cm⁻³

Molecular cloud
astrochemistry

Dissociative recombination



Electron capture resonance

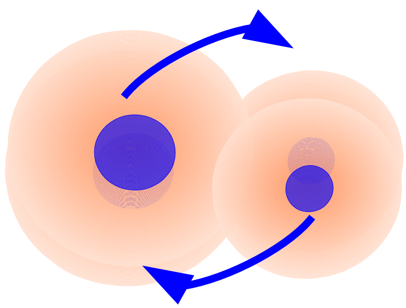
Many resonances by electronic, vibrational or rotational excitation

Molecules efficiently react and break up in encounters with low-energy electrons

Internal states of molecular ions

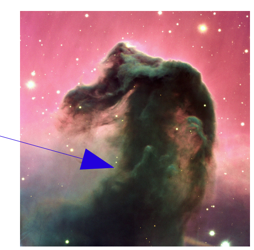
Rotation and vibration - lead to infrared emission (cooling)
- are excited by ambient infrared radiation

→ Internal states go to thermal equilibrium with ambient blackbody radiation



Thermal equilibrium populations of rotational levels

J \ T_{rot}	300 K	10 K
0	0.104	0.995
1	0.251	0.005
2	0.271	0.0
3	0.199	0.0
4	0.108	0.0

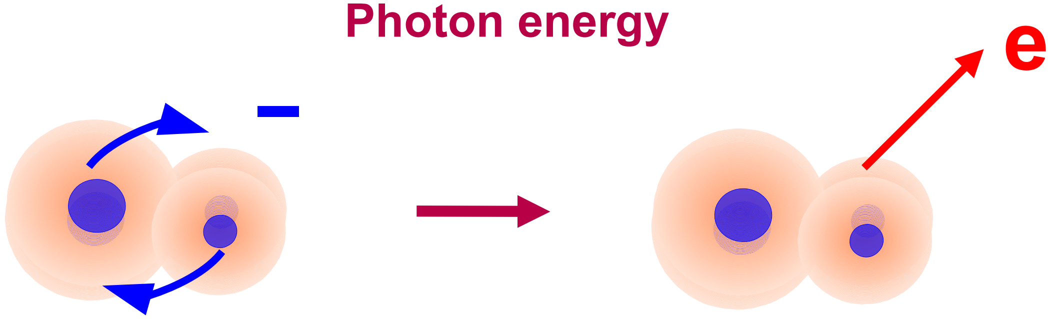


Photodetachment probing of internal states

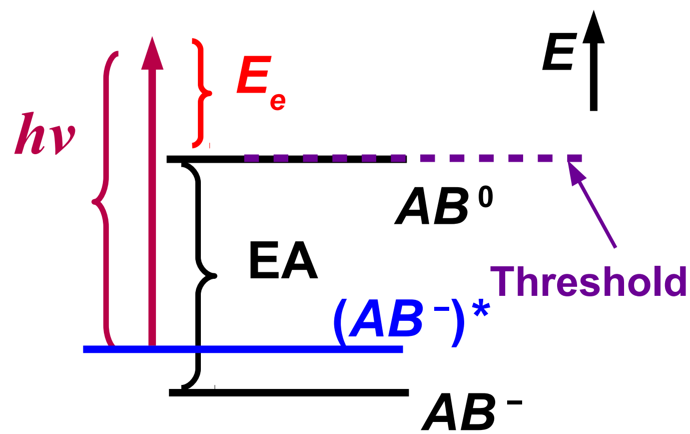
Negative molecular ion (anion)

$(AB^{-})^{*} + h\nu$ $\qquad$ $AB^{0} + e$

Photon energy



Energy level diagram



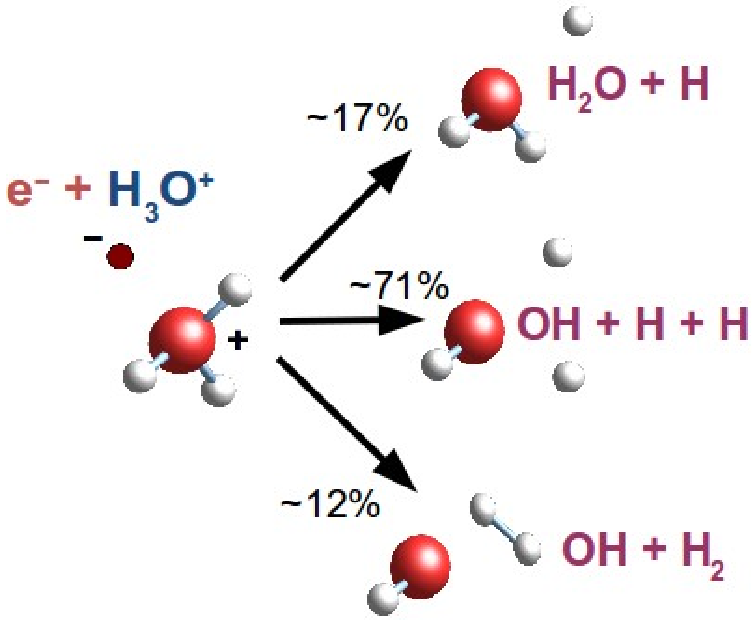
Electron detachment by photons

Threshold photon energy reveals – the electron affinity EA of AB^0

– excited energy levels of AB^-

Anions are easily converted to neutrals by visible light

Electron capture dissociation: large molecules

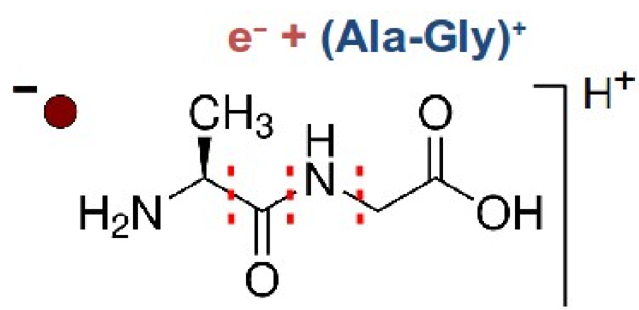


Protonated water

M = 19 u

Di-peptide ion

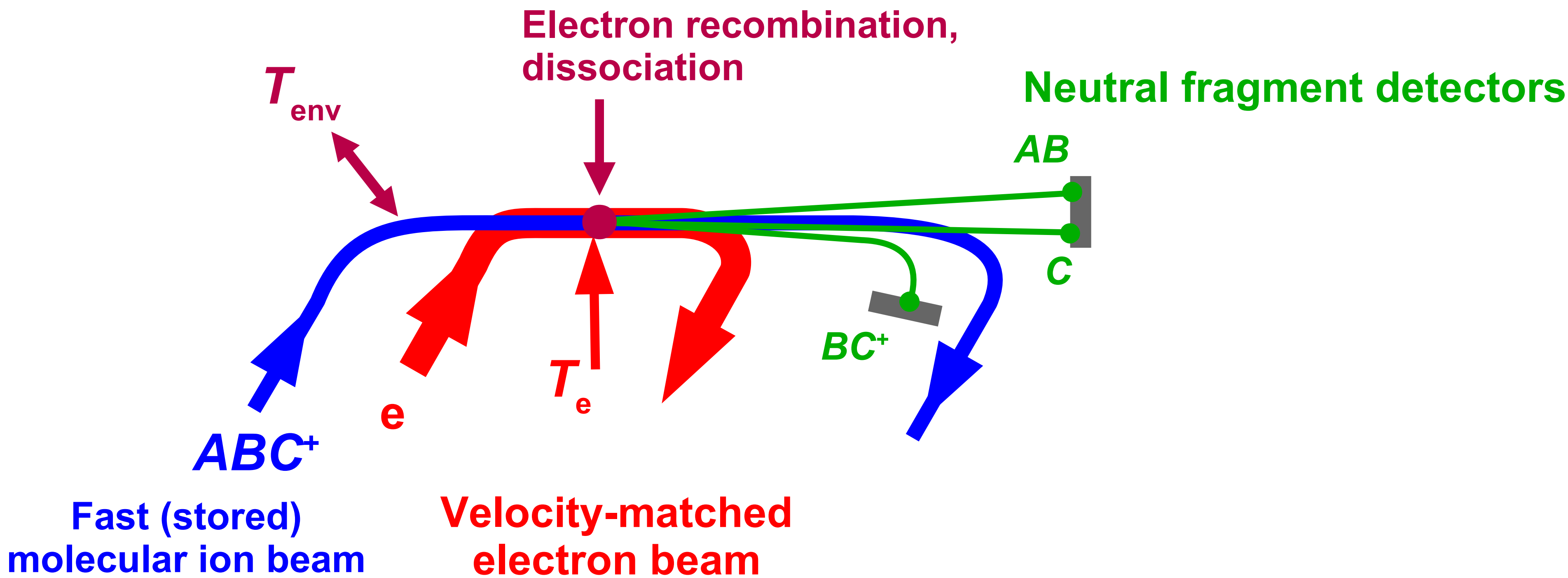
M = 147 u



Electron-induced neutral fragments from polyatomic molecules sensitively probe ion chemistry and molecular composition

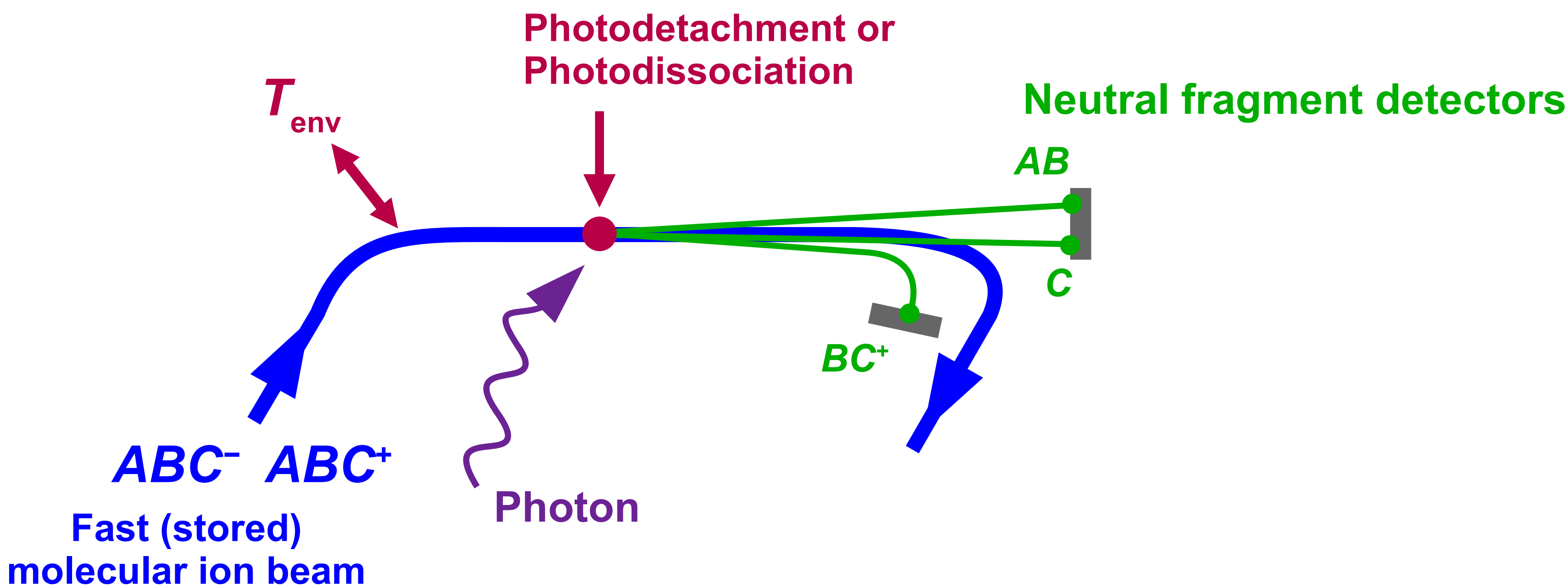
Fast beam fragmentation measurements

Experimental schematic



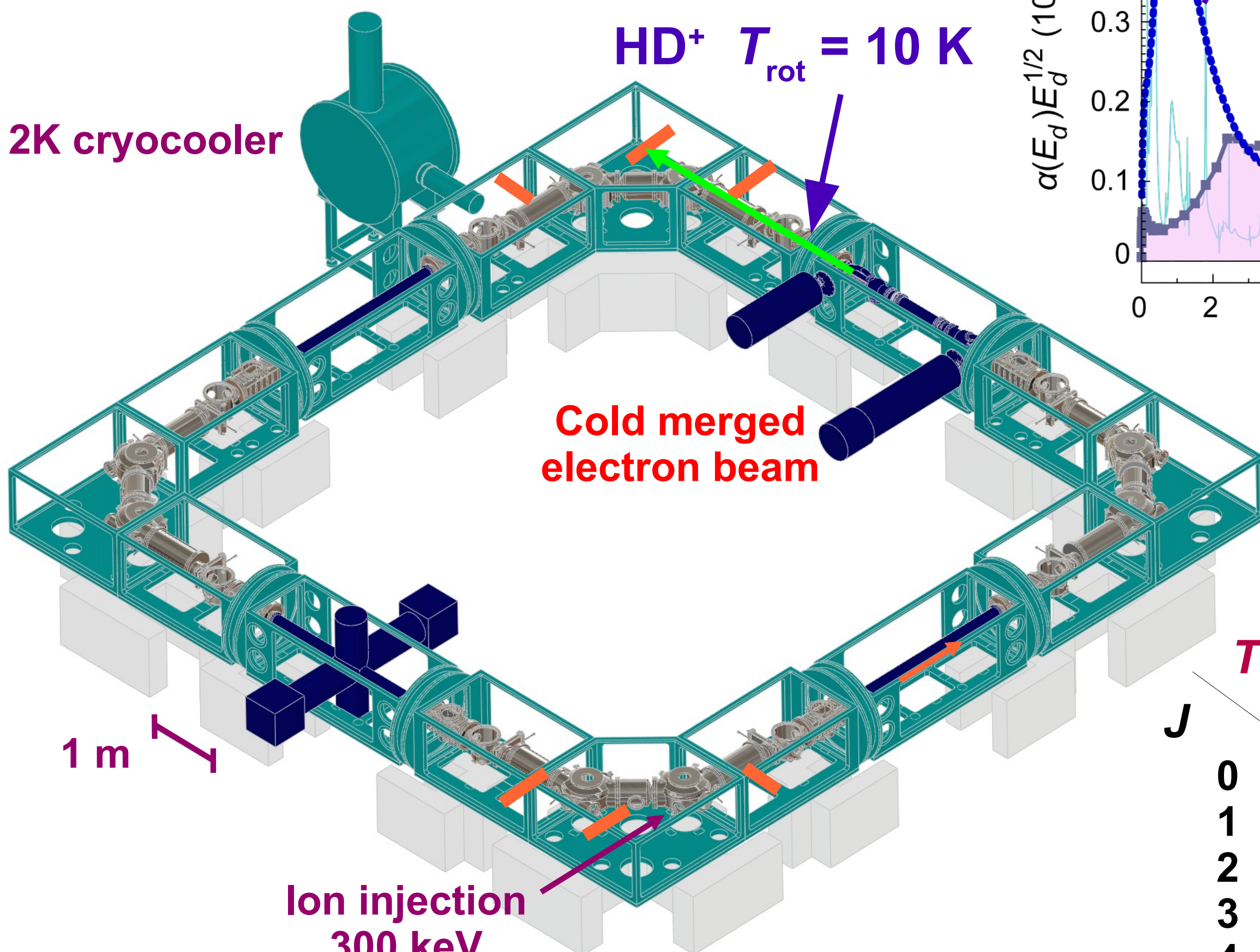
Fast beam fragmentation measurements

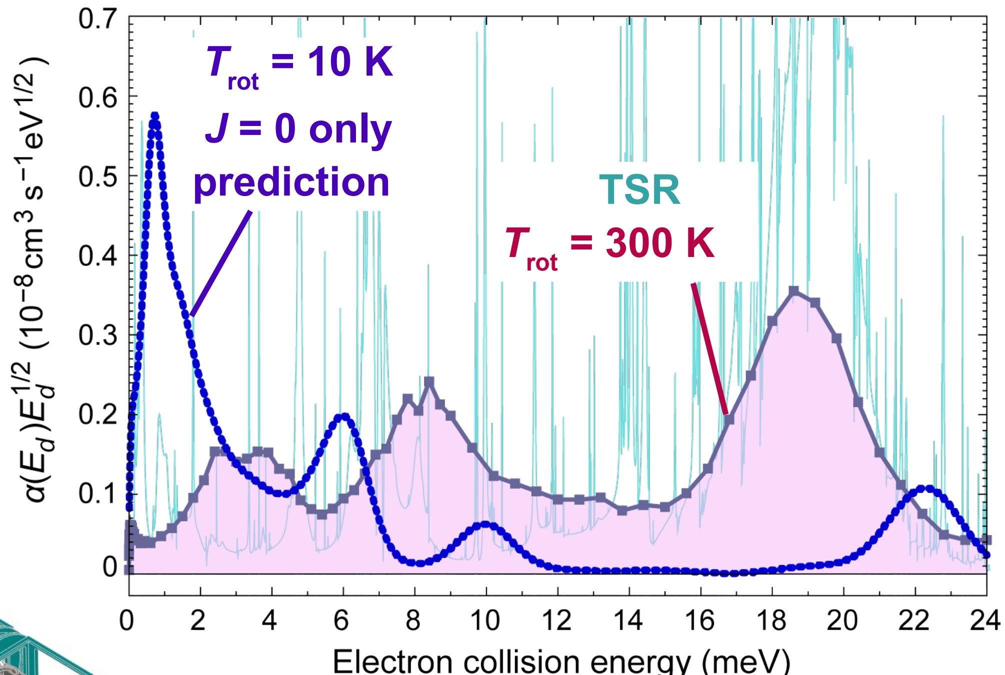
Experimental schematic



A cryogenic storage ring for molecular ion beams

Electrostatic cryogenic storage ring CSR





Stored molecular ions at low rotation

Thermal equilibrium populations of rotational levels

J \ T_{rot}	300 K	10 K
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1	0.251	0.005
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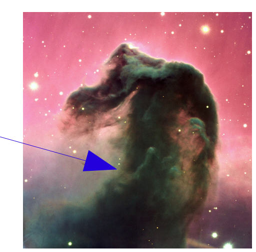
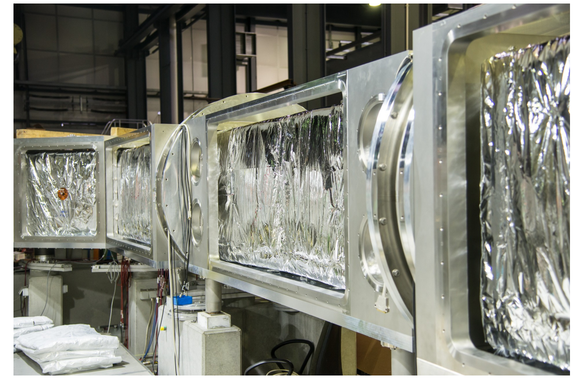
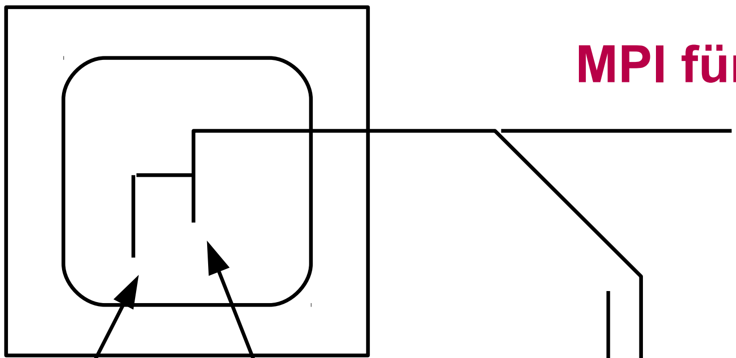


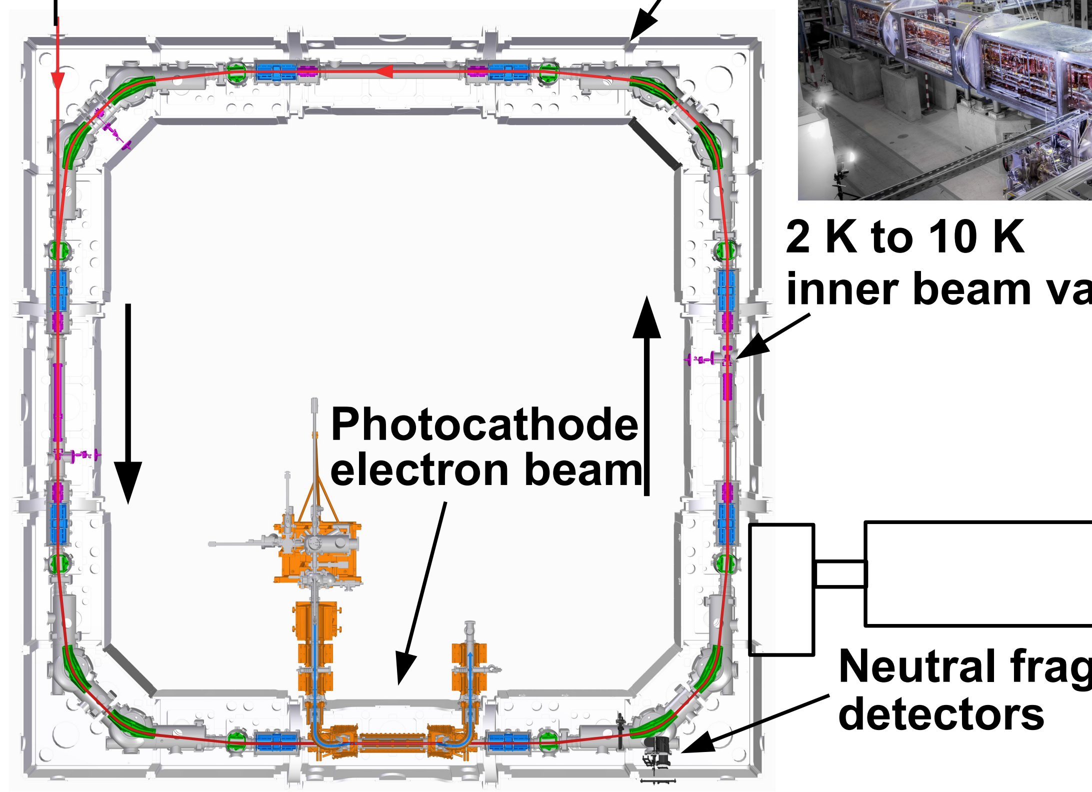
Cryogenic storage ring

CSR

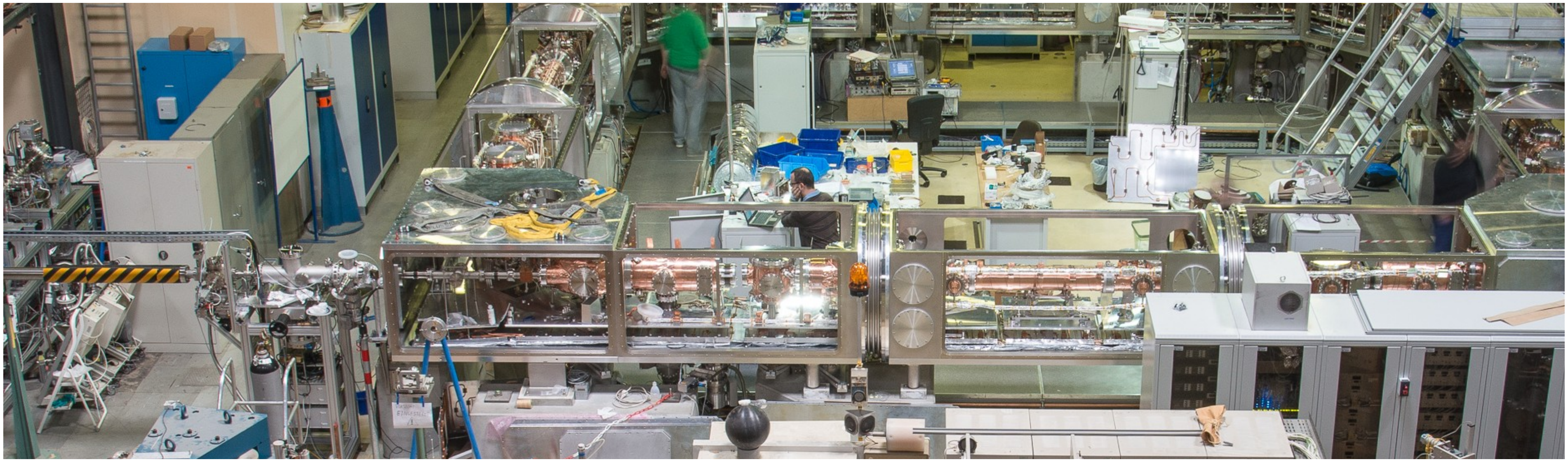
MPI für Kernphysik, Heidelberg

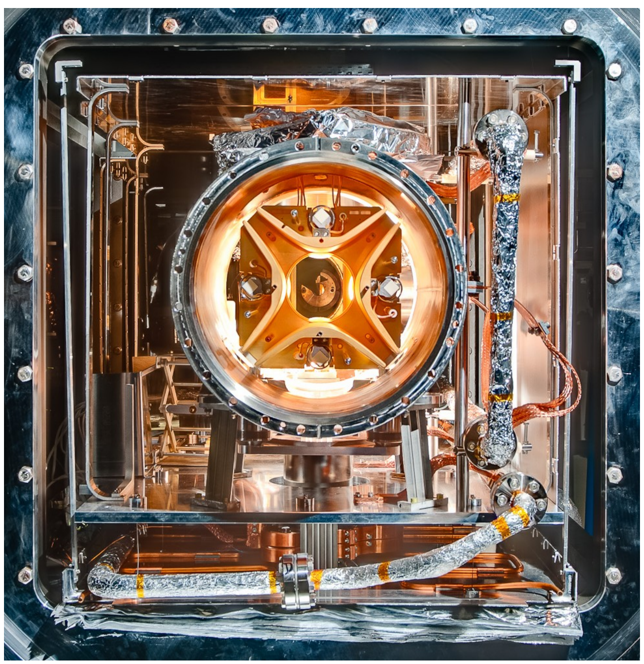


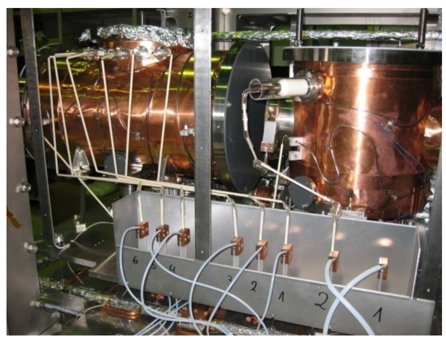


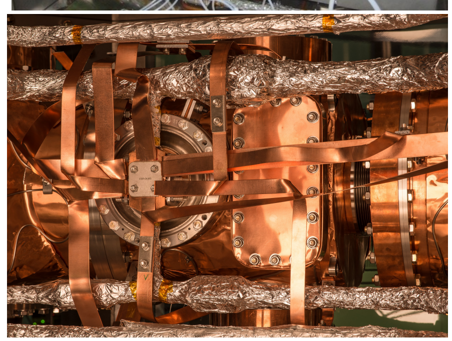


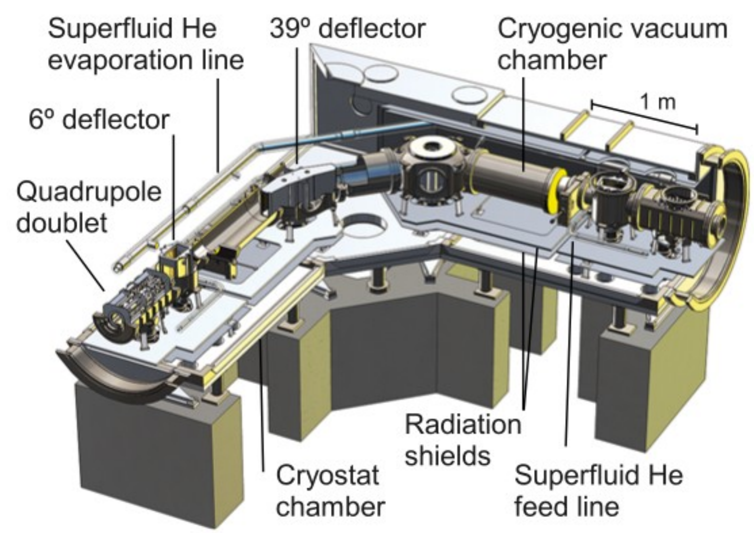
CSR assembly











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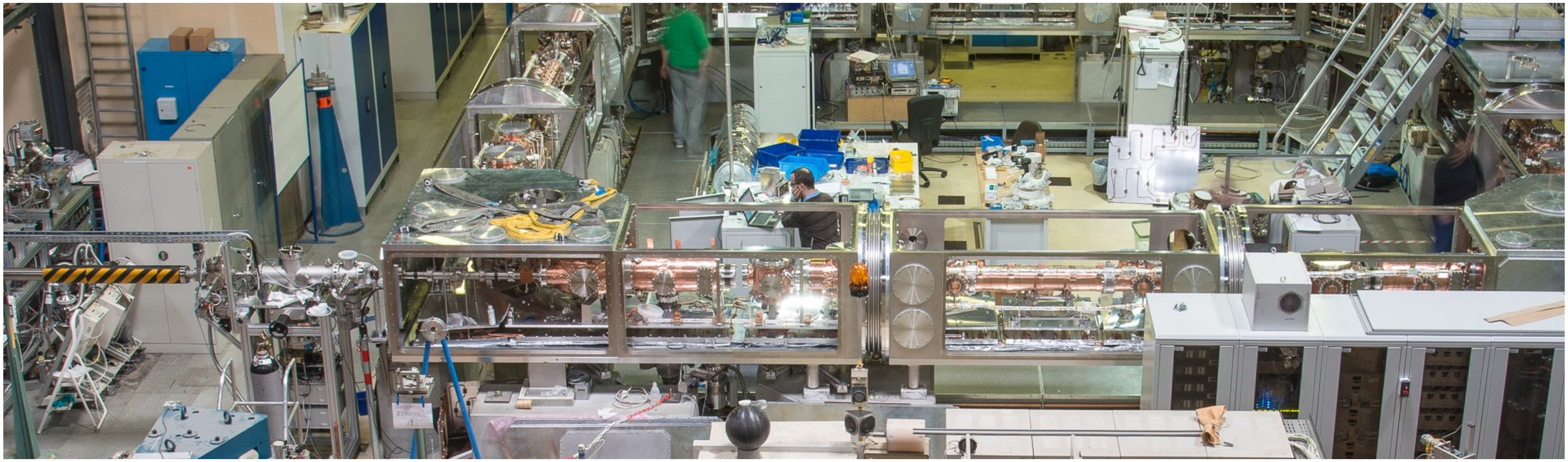
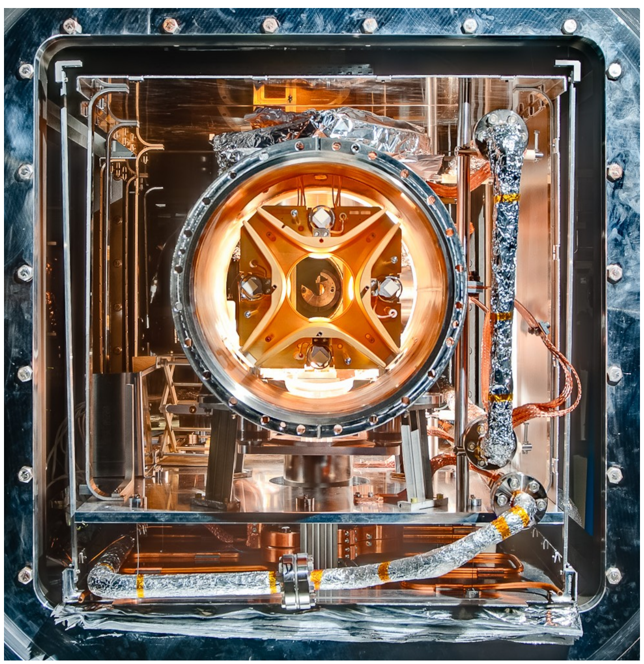
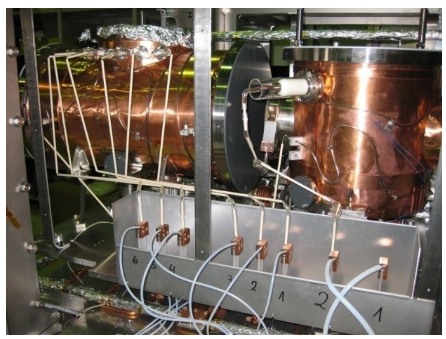
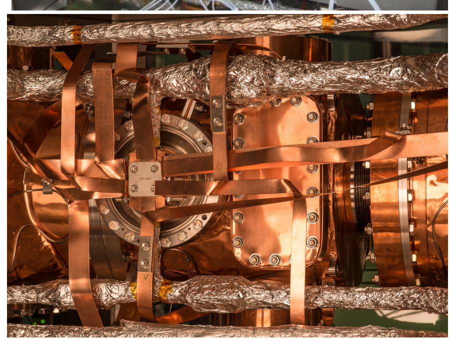




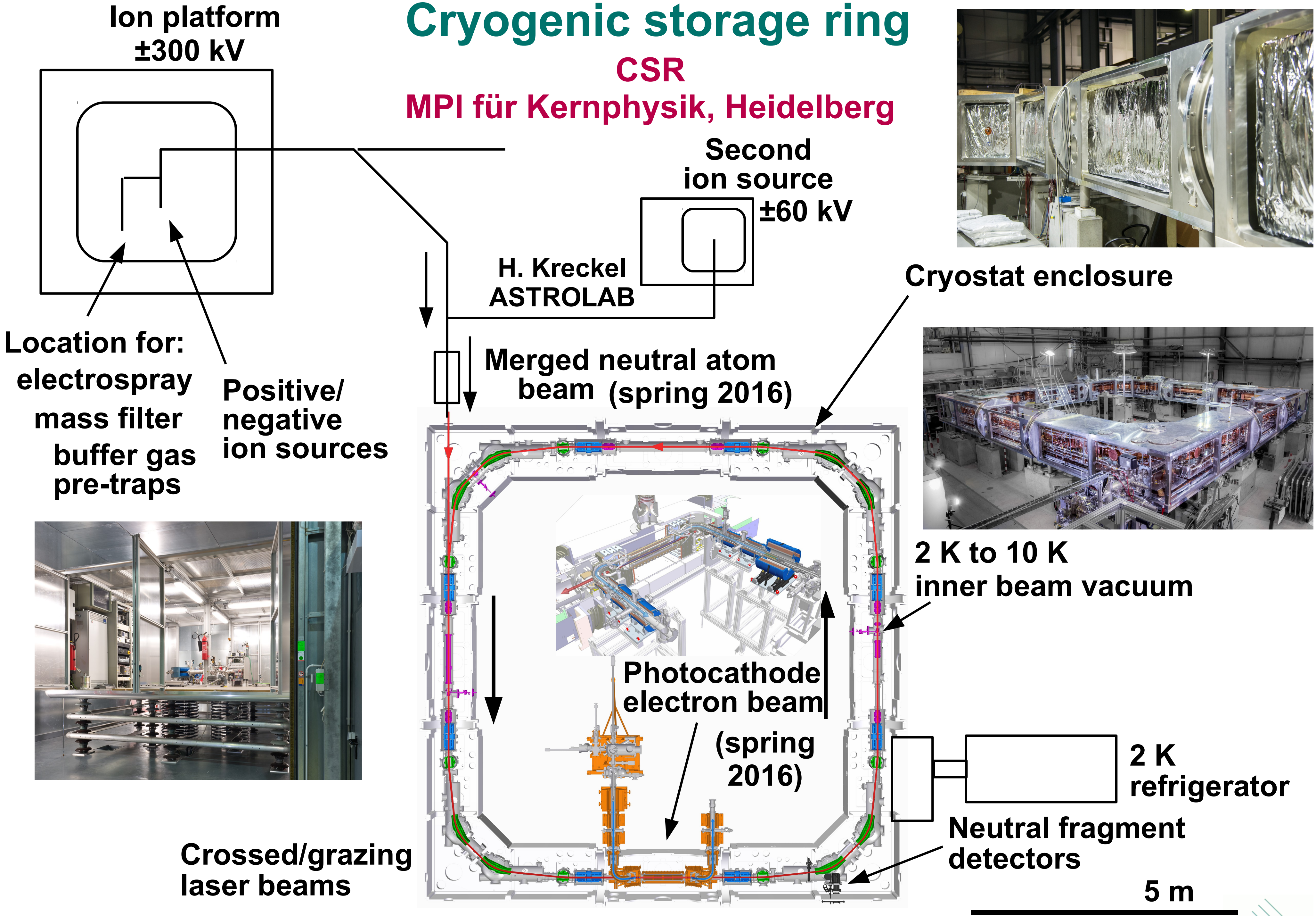




Cryogenic storage ring

CSR

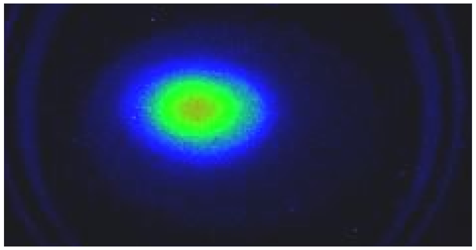
MPI für Kernphysik, Heidelberg



http://www.mpi-hd.mpg.de/ion-storage

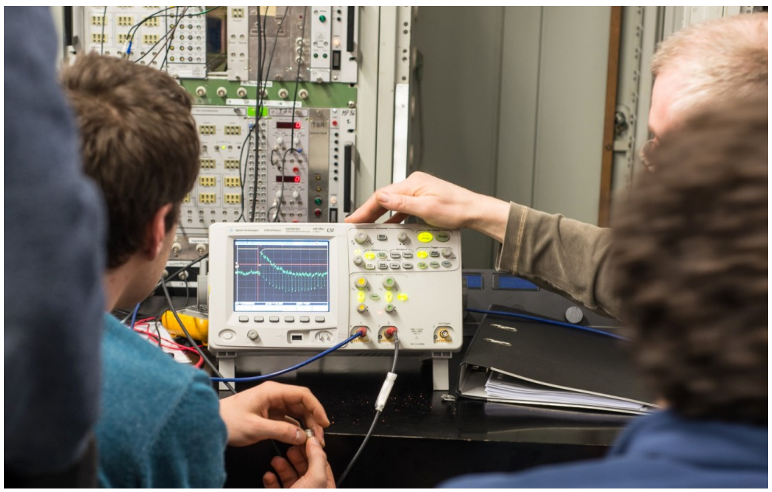
CSR starting operation

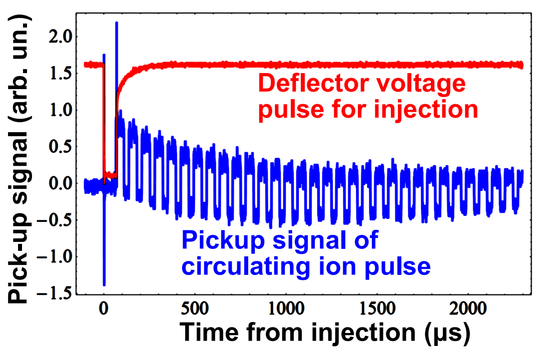
Beam after first complete turn

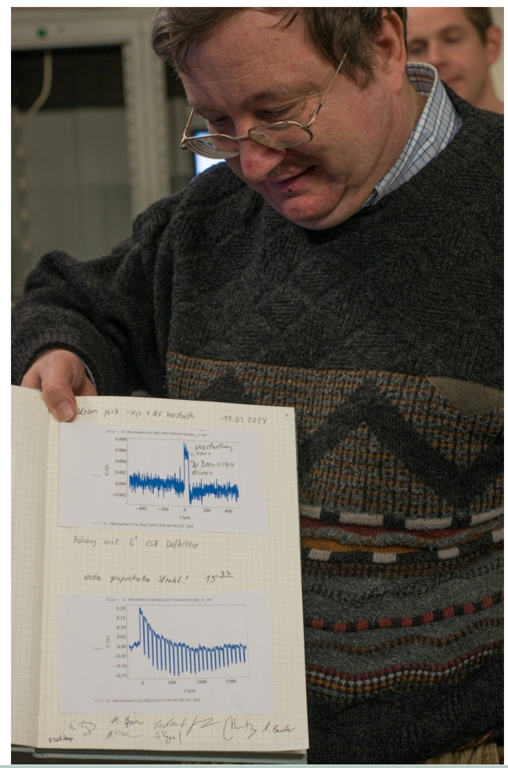


March 2014

50 keV Ar^+ beam

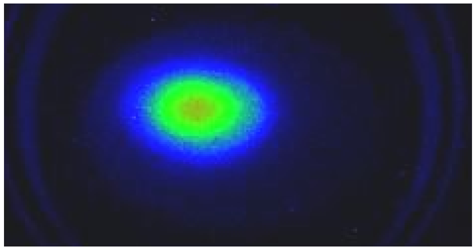




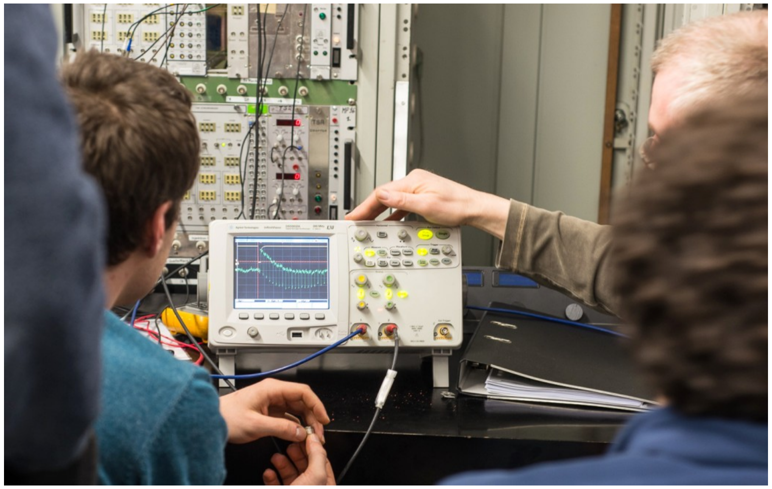


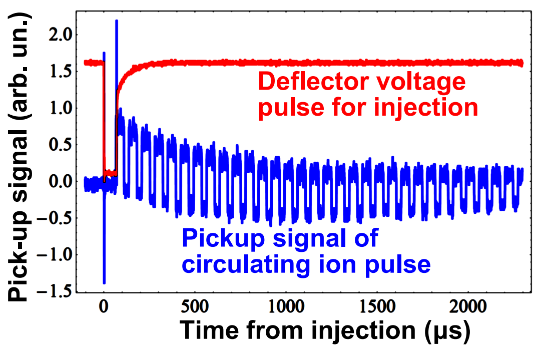
CSR starting operation

Beam after first complete turn



50 keV Ar^+ beam



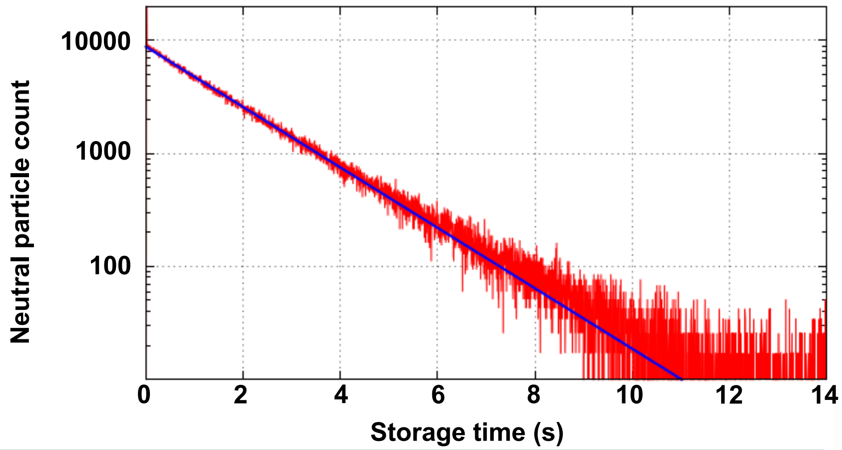


230°C bakeout of the cryogenic vacuum chamber
$\sim 2 \times 10^{-10}$ mbar at 300 K

March 2015

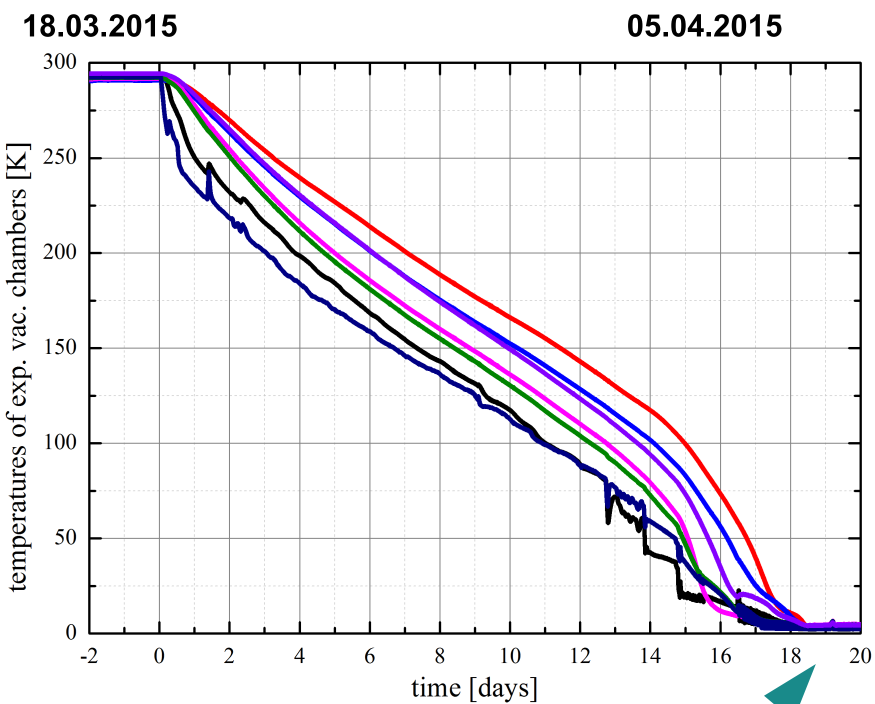
60 keV C^- beam

Room temperature CSR



CSR starting operation

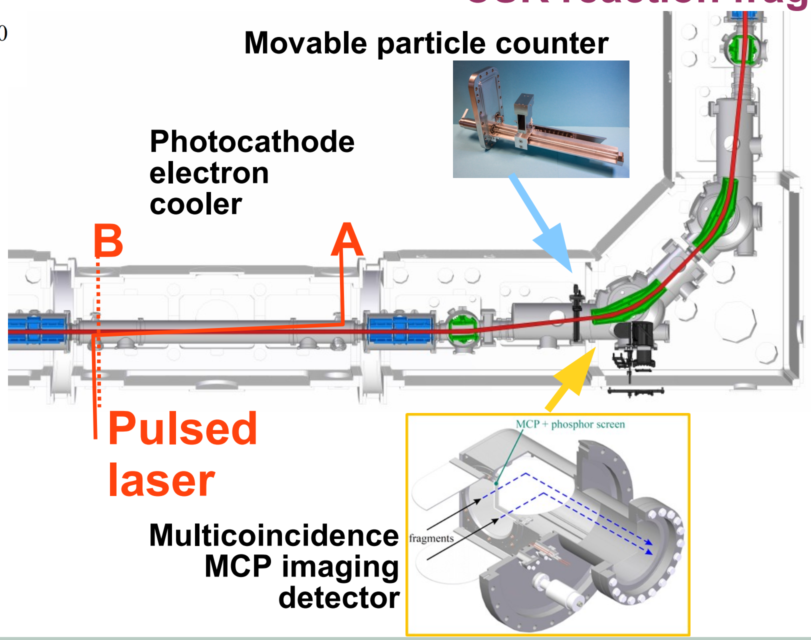
CSR cooling down



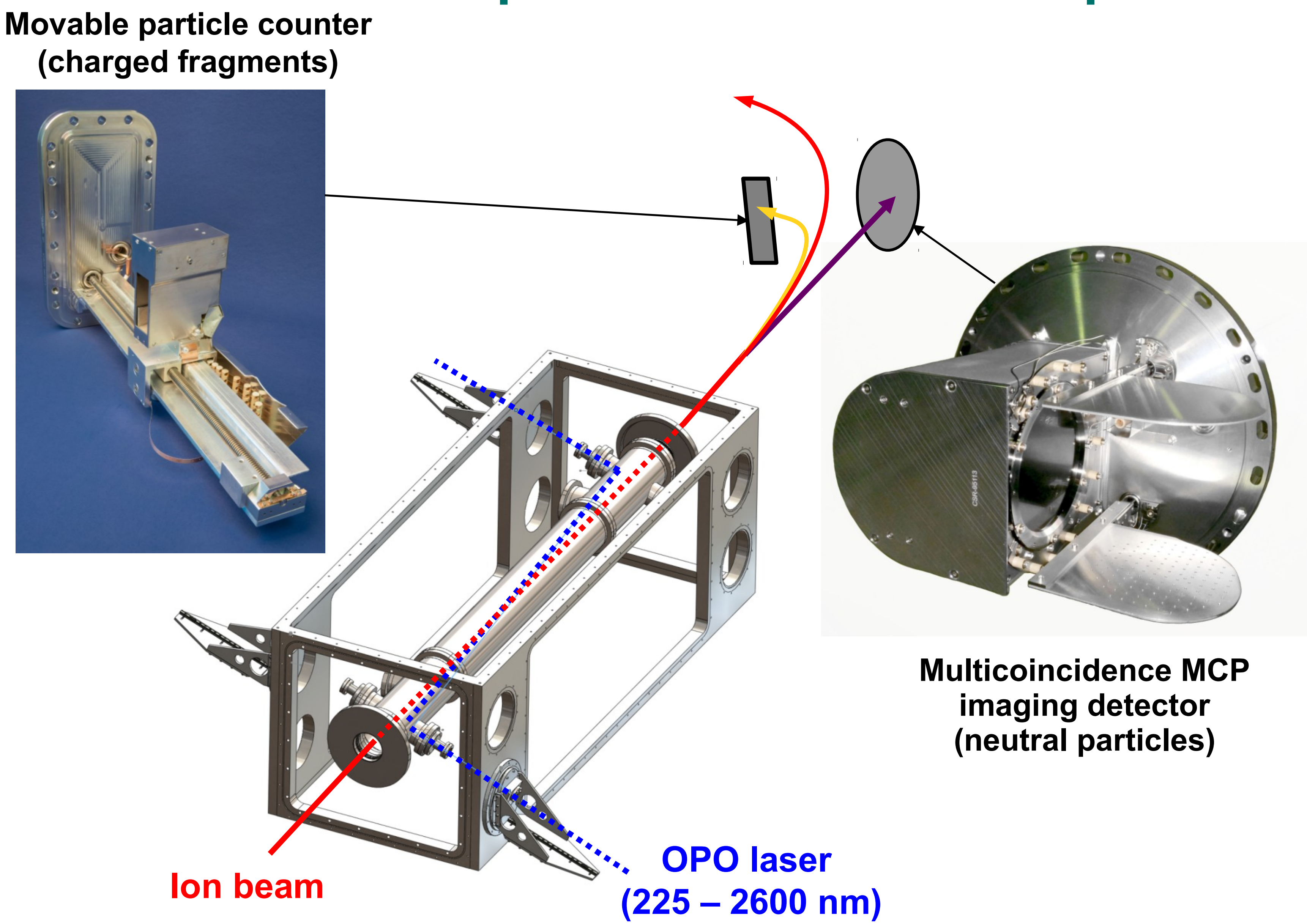
~6 K final temperature
of the beam vacuum chamber

First results from April to July 2015

CSR reaction fragment detectors



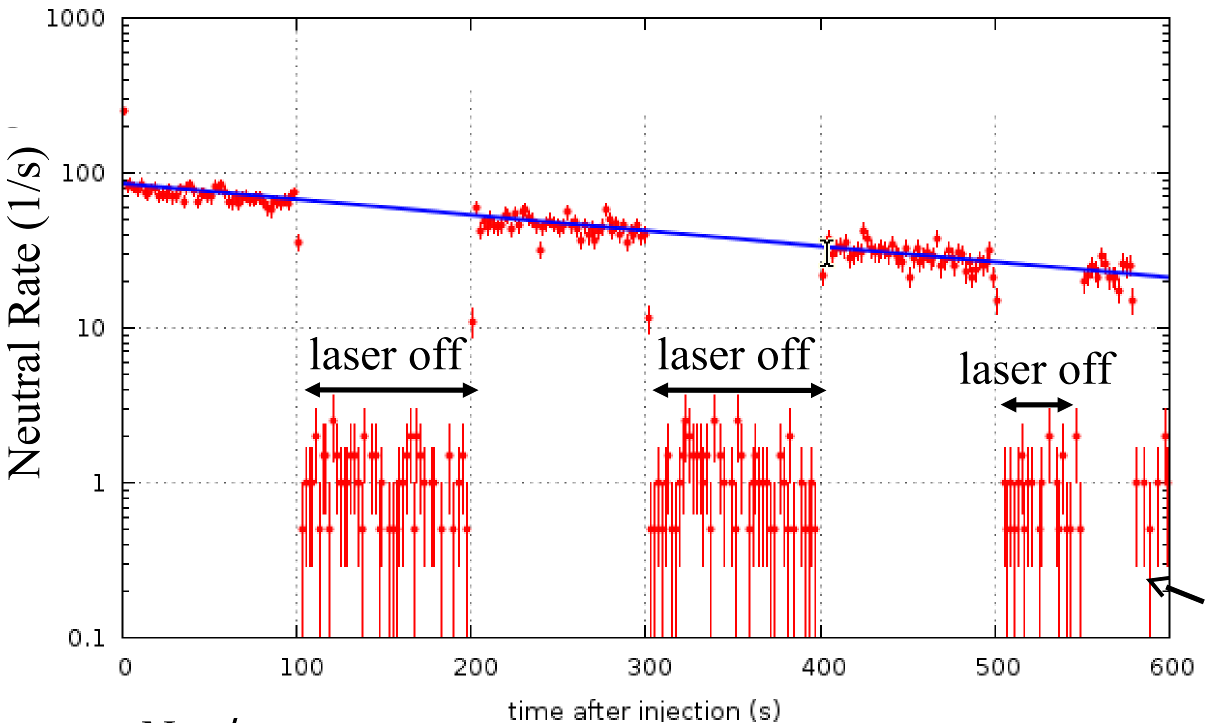
Anion photodetachment setup

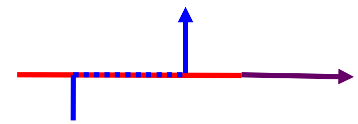


Photodetachment measurements of storage lifetime

Ion beam in ~6 K storage ring

60 keV OH^- + $h\nu$ (1.9 eV) → OH + e^- (A = 17)





OH^-
EA: 1.83 eV

S. Vogel
O. Novotný
C. Krantz

$$R = \eta_g N_{\mathrm{ion}} / \tau$$
$$1/\tau = n\, v_{\mathrm{ion}}\, \sigma$$

$$\boxed{\begin{array}{c} n < 85\ \mathrm{cm}^{-3} \\ p_{RTE} \sim 3.5 \times 10^{-15}\ \mathrm{mbar} \end{array}}$$

$$R = 1\,\mathrm{s}^{-1}$$
$$N_{\mathrm{ion}} \geqslant 1\times 10^{7}$$
$$v_{\mathrm{ion}} = 0.00276\,c$$
$$\eta_g = 0.12 \times 0.3$$
$$\sigma = 8\times 10^{-16}\ \mathrm{cm}^2$$

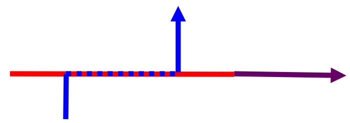
Local residual gas density in the laser region

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

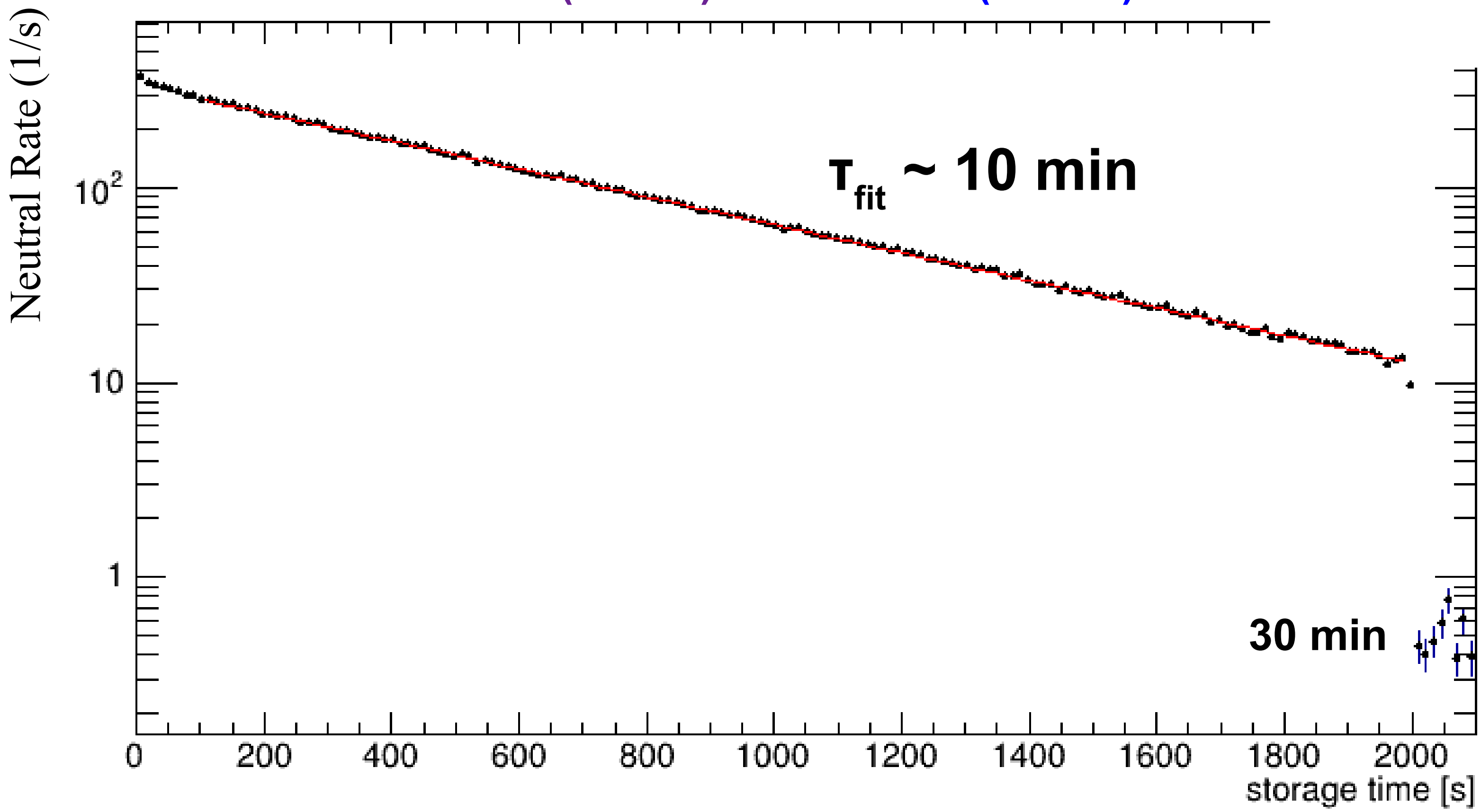
Beam storage lifetime estimated from local pressure in the laser region cold be up to 50 h !

Photodetachment measurements of storage lifetime

Ion beam in ~6 K storage ring



60 keV OH^- + $h\nu$ (1.9 eV) → OH + e^- (A = 17)

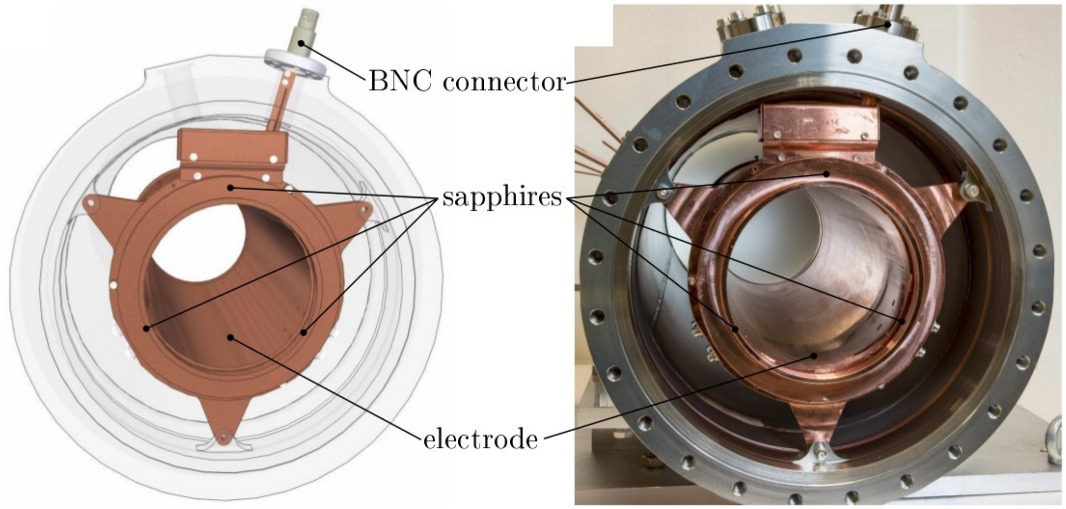


OH^-
EA: 1.83 eV

→ Beam storage lifetimes not limited by residual gas

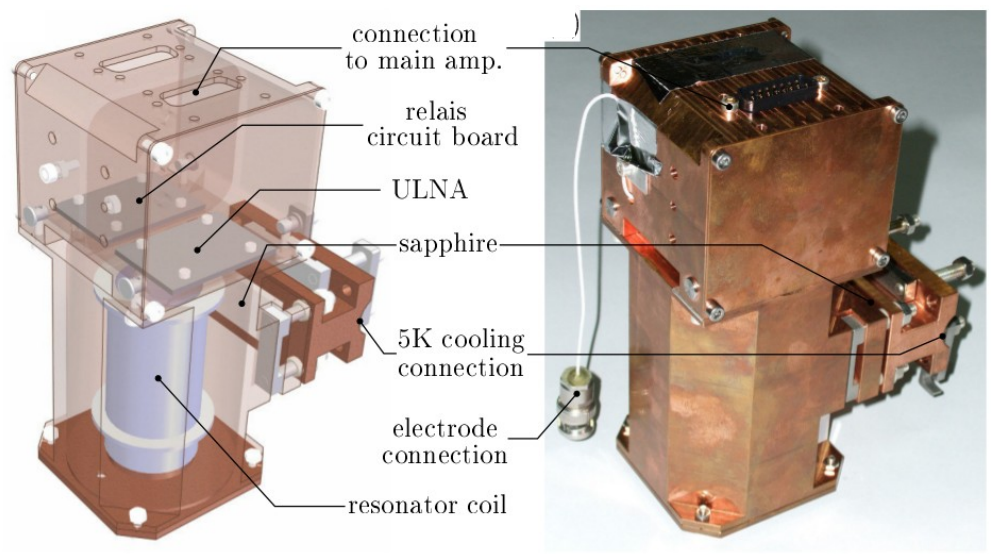
Schottky pickup of CSR

Capacitive Schottky pickup (350 mm long, 100 mm diam.) in the CSR cryogenic vacuum



S. Vogel

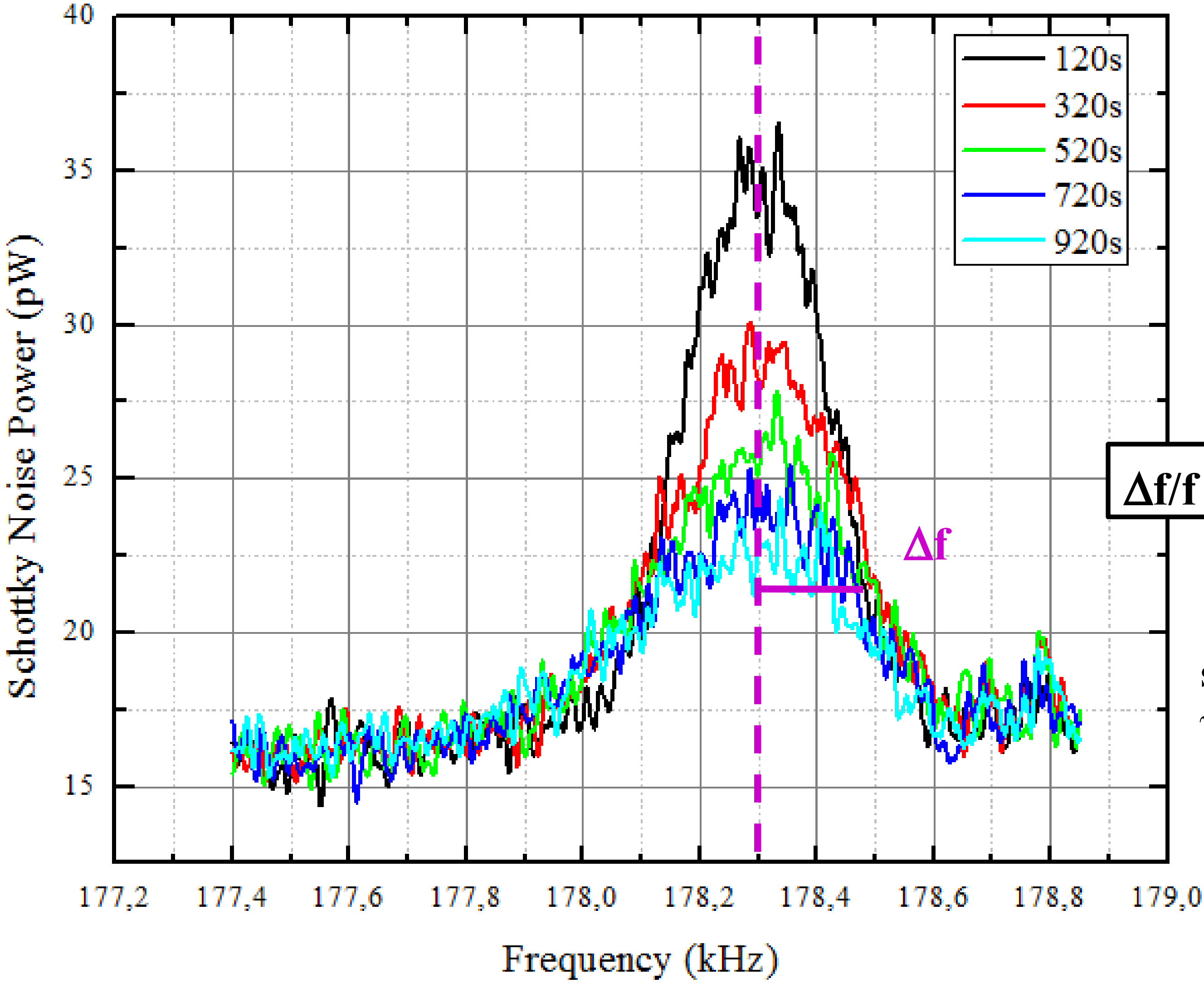
Screened low-noise preamplifier in the cryostat vacuum



Spectrum of ion circulation frequencies (Schottky noise)

60 keV Co_2^- (A = 118)

$f = h f_0$ $h = 20$



Shot noise of a DC circulating beam

S. Vogel
M. Grieser

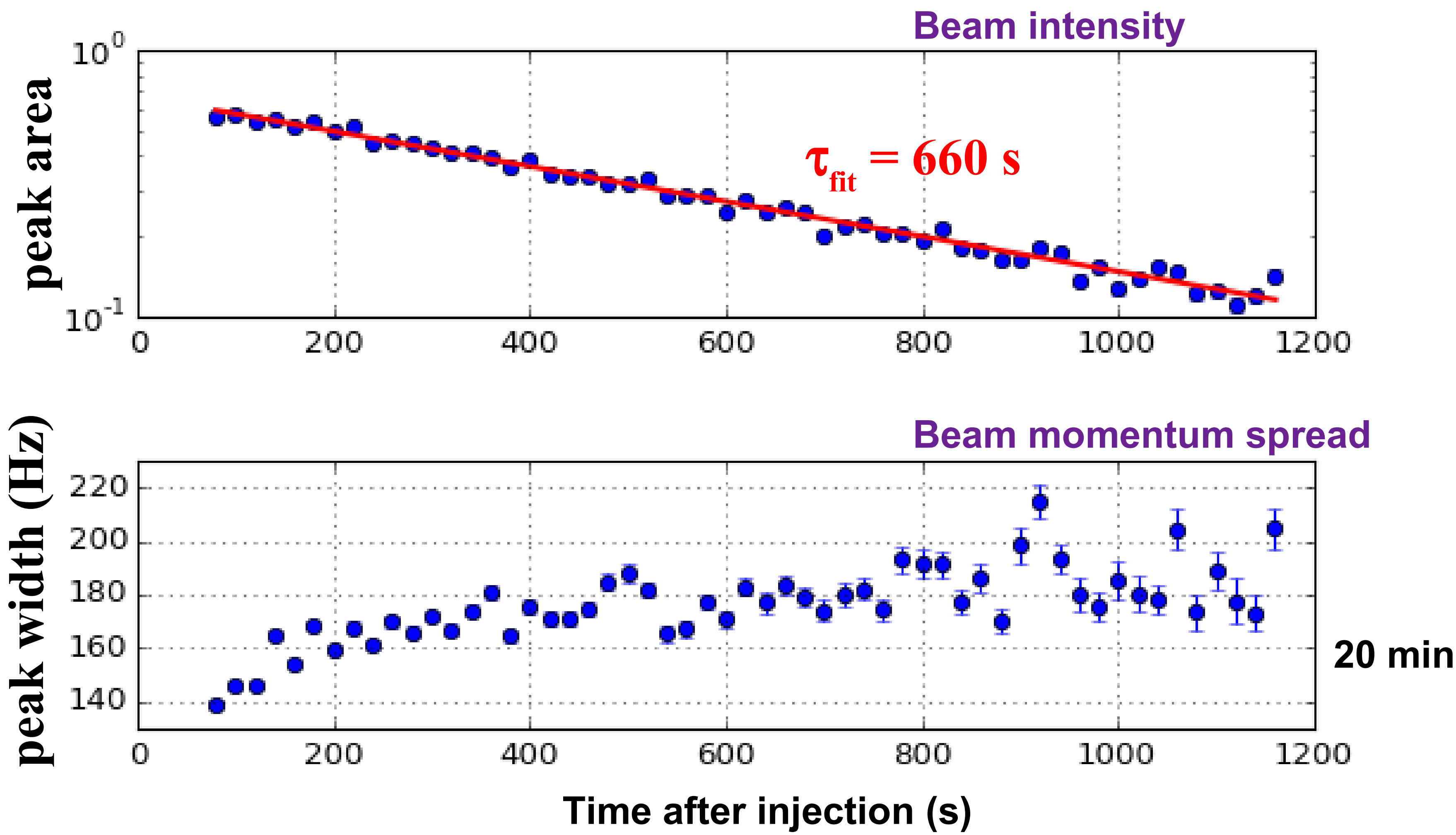
$$\Delta f/f = \eta \Delta p/p$$

slip factor
$\eta = 0.7$

Δf → ion beam longitudinal velocity (momentum) spread

Storage time dependence of Schottky noise spectrum

60 keV Co_2^- (A = 118)

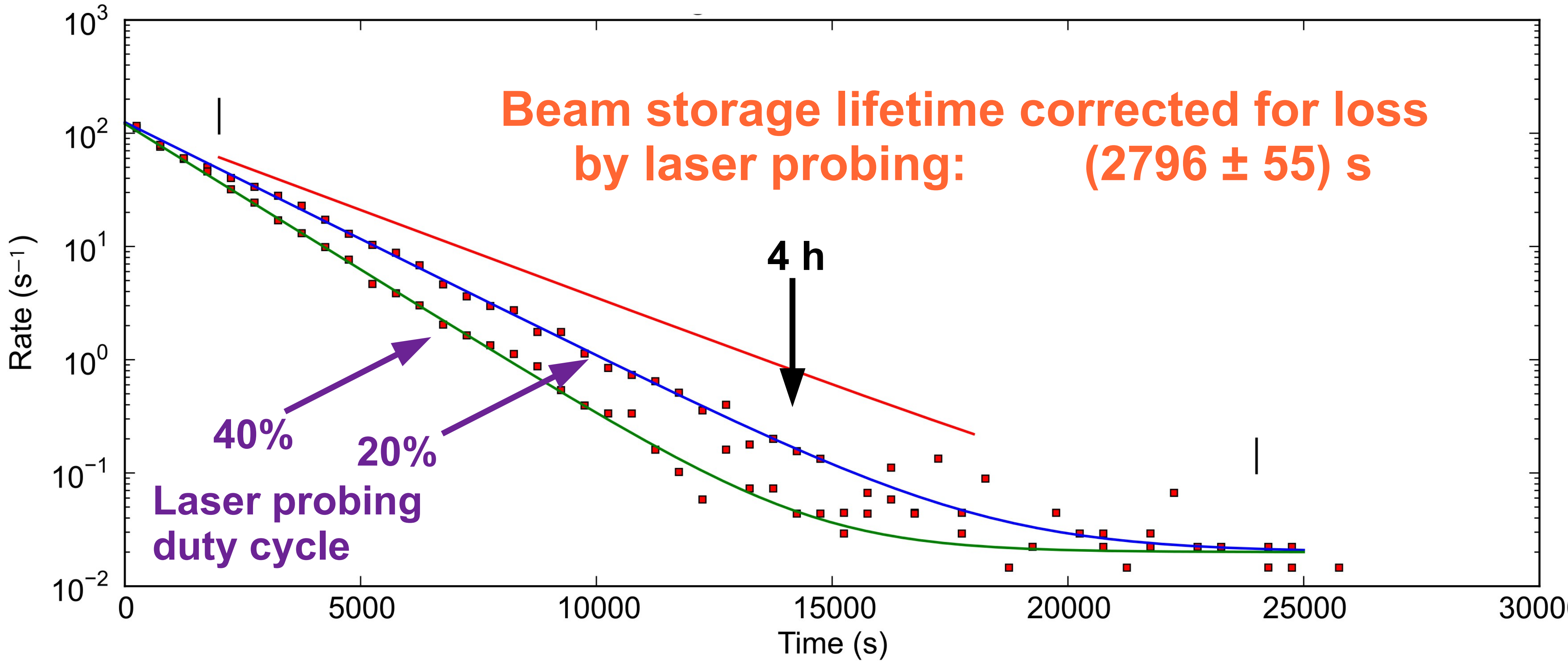


→ "Diffusion" in longitudinal ion velocity excited by electrode noise ?

Beam storage lifetimes (book of records)

(EA: 1.02 eV)

60 keV Ag_2^- + $h\nu$(1.9 eV) → Ag_2 + e^- (A = 216)



Ion beam lifetime (storage time constant)
approaching 1 h for ion mass A ~ 200

Trend of increasing lifetime for higher ion masses seen, under study

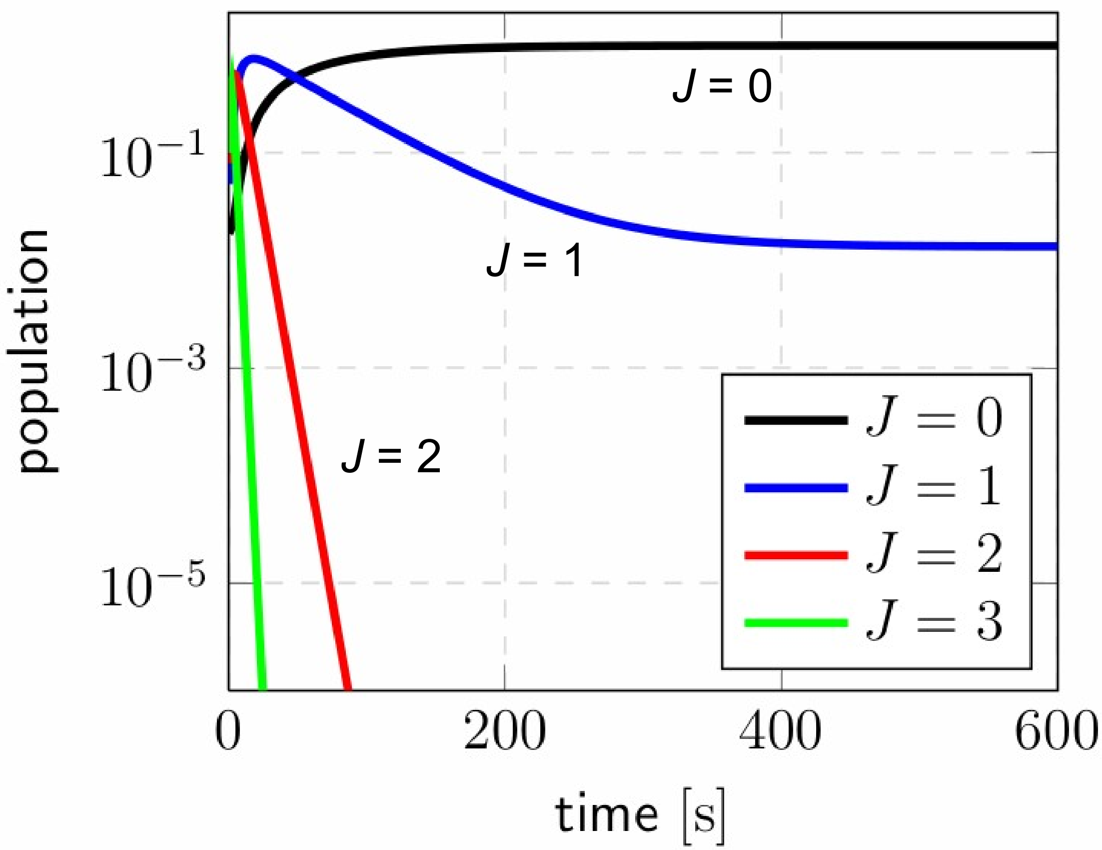
Stored-ion rotational excitation (“thermometry”)

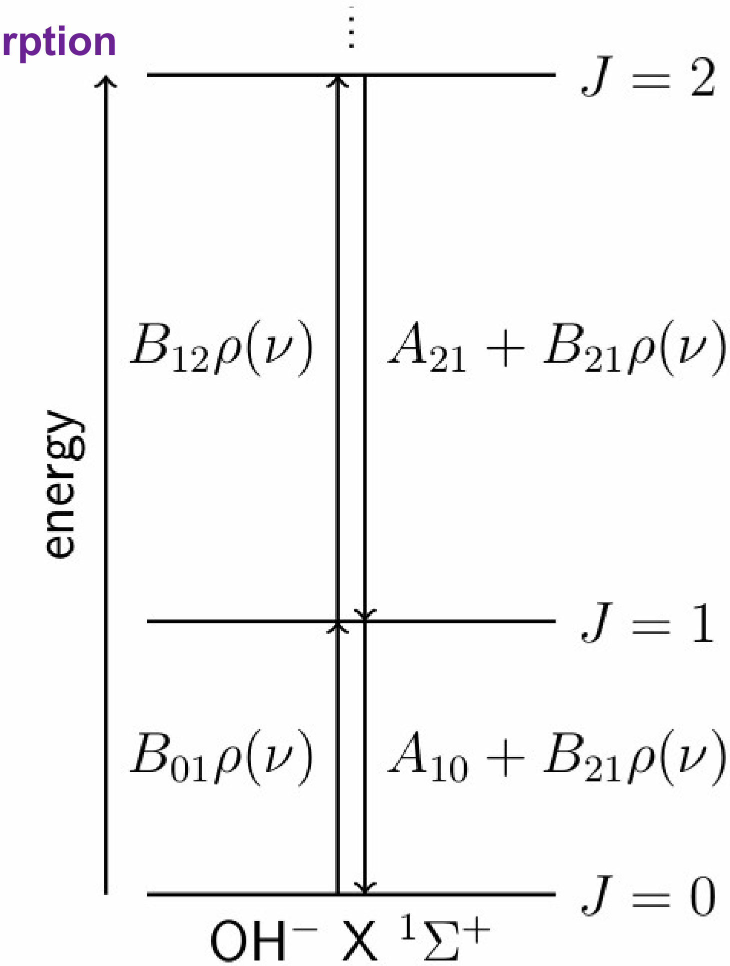
$$\mathrm{OH}^-:\ 1\sigma^2\ 2\sigma^2\ 3\sigma^2\ 1\pi^4 \quad {}^1\Sigma^+\ J=0,\ 1,\ 2,\ 3,\ \cdots$$

Modeled radiative relaxation of stored OH⁻ ions

- from 1000 K to 10 K final temperature
- spontaneous (stimulated) emission and (blackbody) absorption

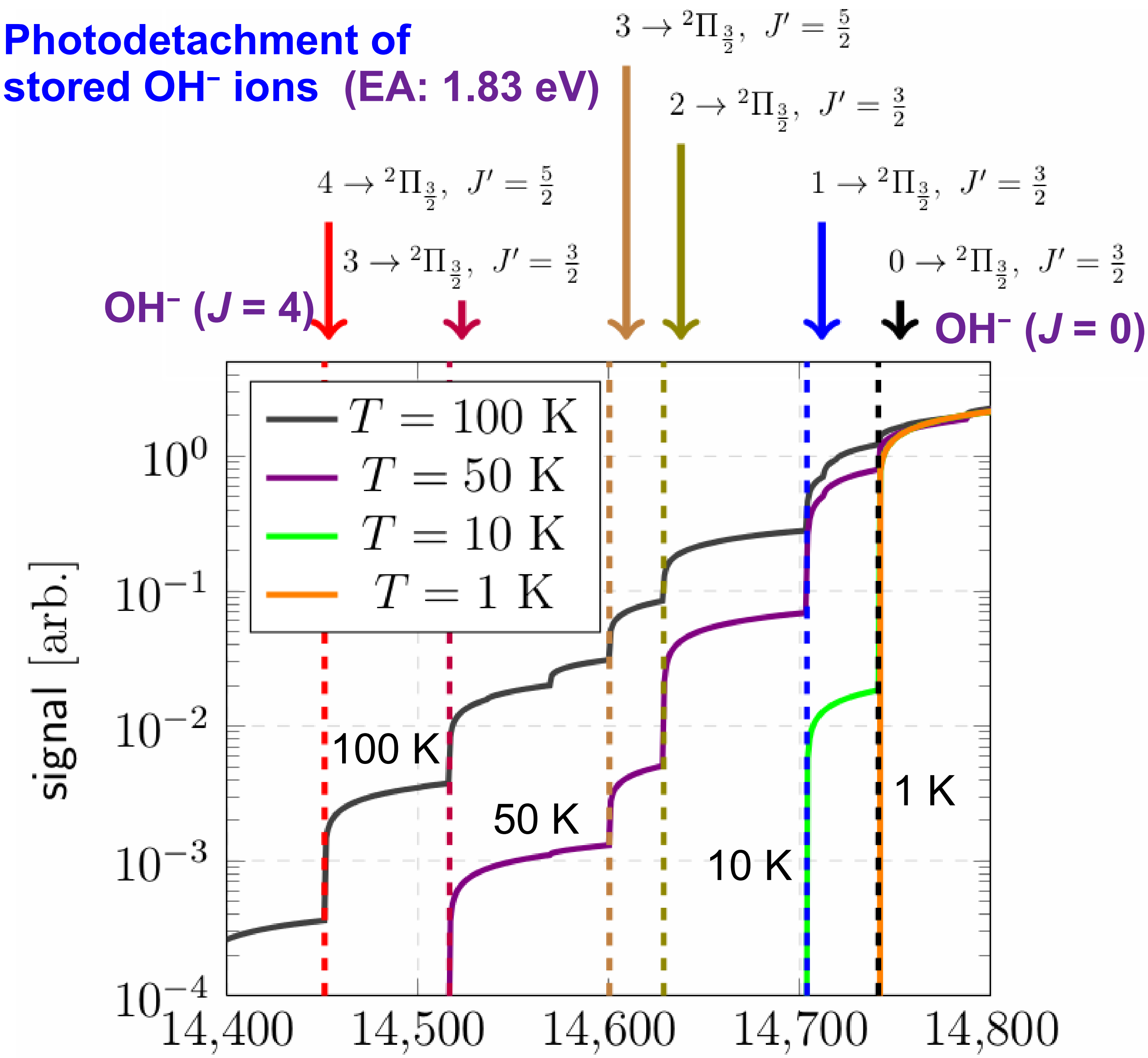
C. Meyer

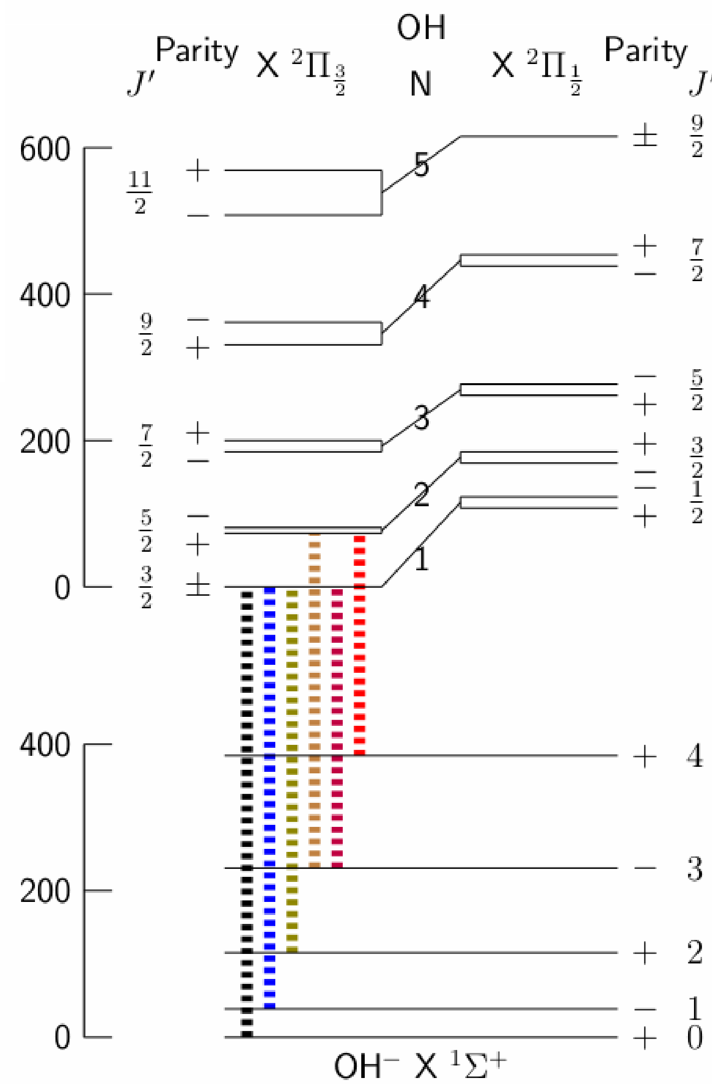




Stored-ion rotational excitation (“thermometry”)

Photodetachment of stored OH⁻ ions (EA: 1.83 eV)

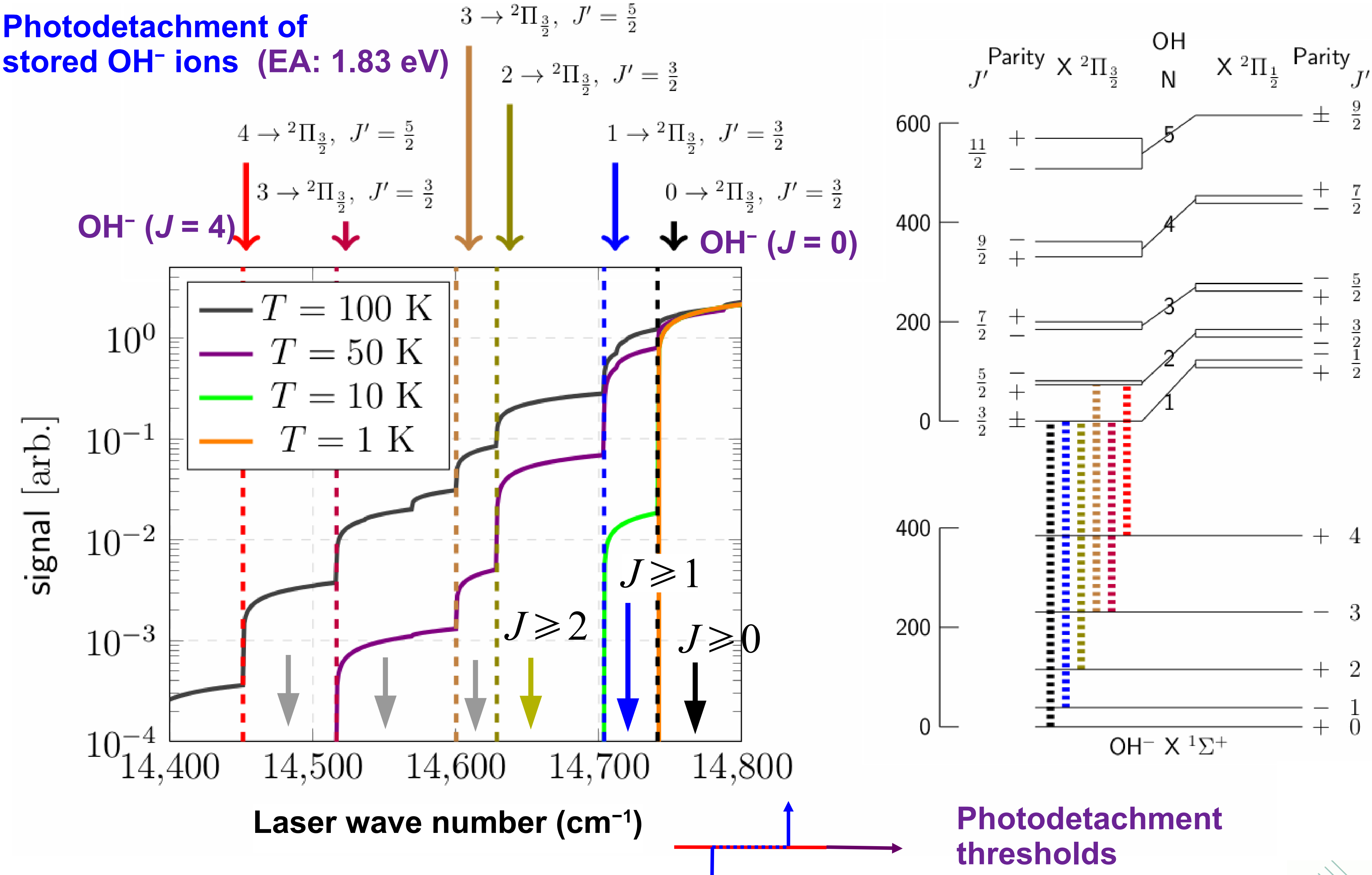




Photodetachment thresholds

Stored-ion rotational excitation ("thermometry")

Photodetachment of stored OH^- ions (EA: 1.83 eV)



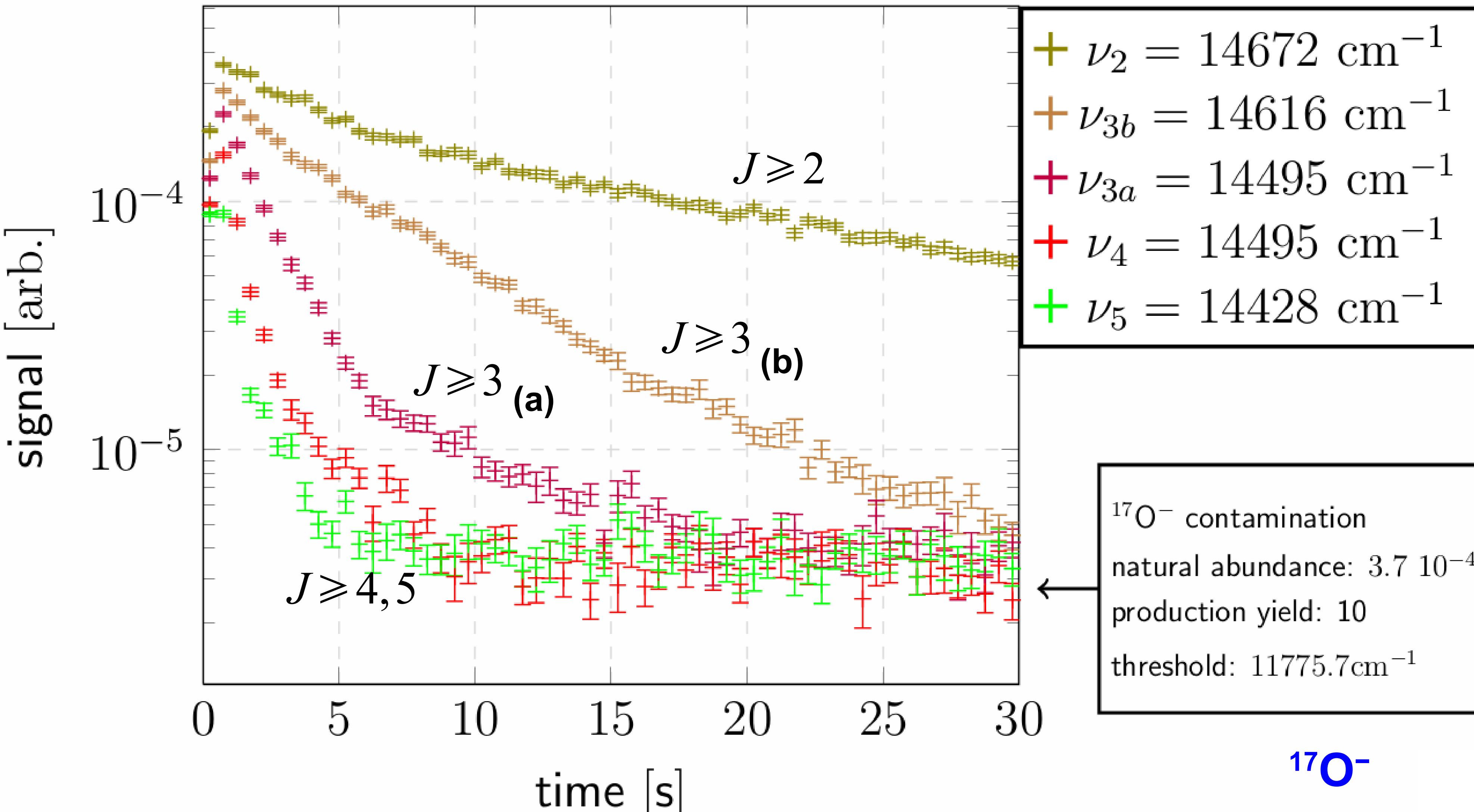
Photodetachment thresholds

Stored ion thermometry results

(EA: 1.83 eV)

60 keV OH^- + $h\nu$ → OH + e^- (A = 17)

Early times



$^{17}O^-$ contamination

natural abundance: $3.7\ 10^{-4}$

production yield: 10

threshold: $11775.7\mathrm{cm}^{-1}$

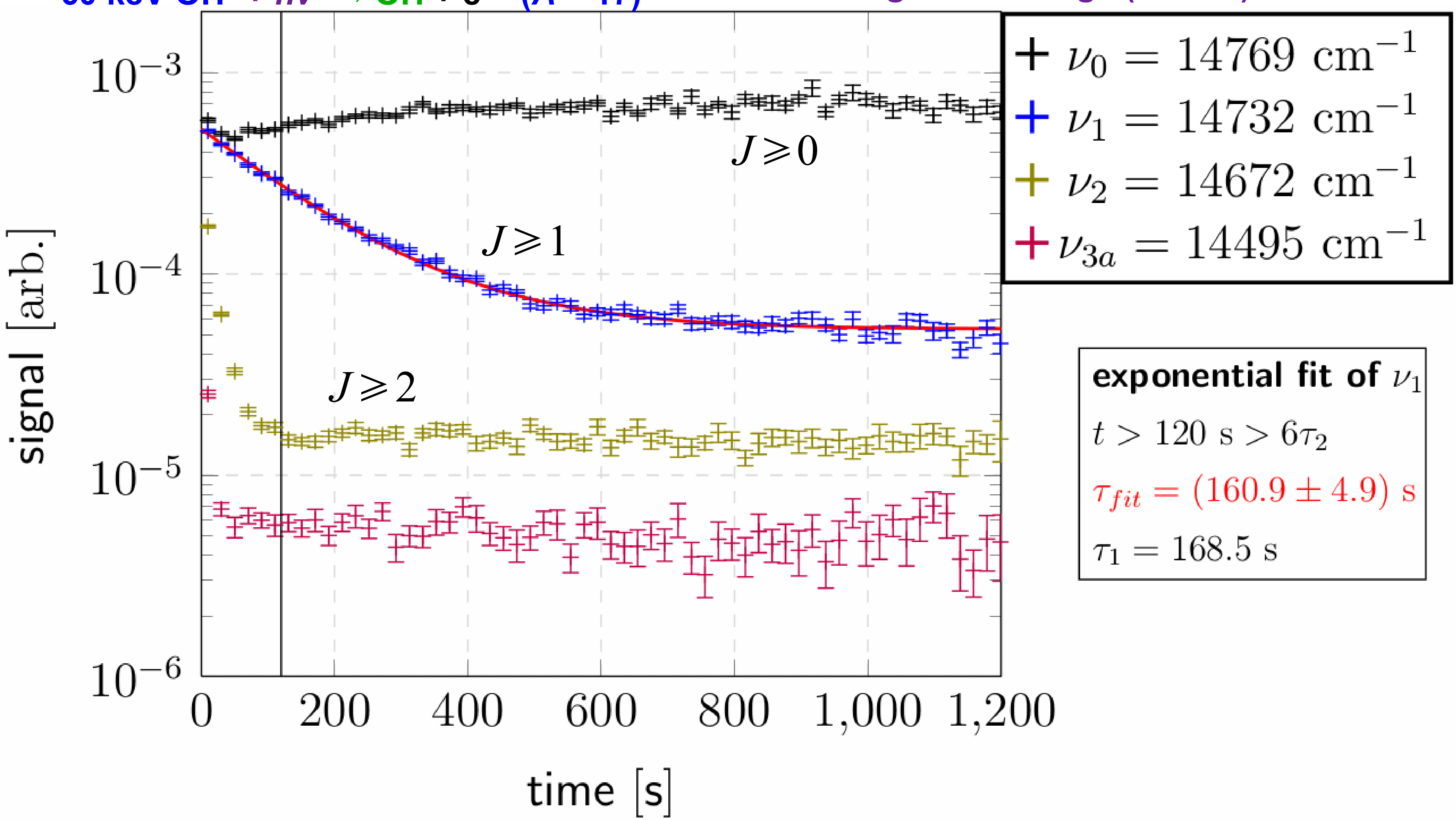
$^{17}O^-$

(EA: 1.46 eV)

Stored ion thermometry results

60 keV OH^- + $h\nu$ → OH + e^- (A = 17)

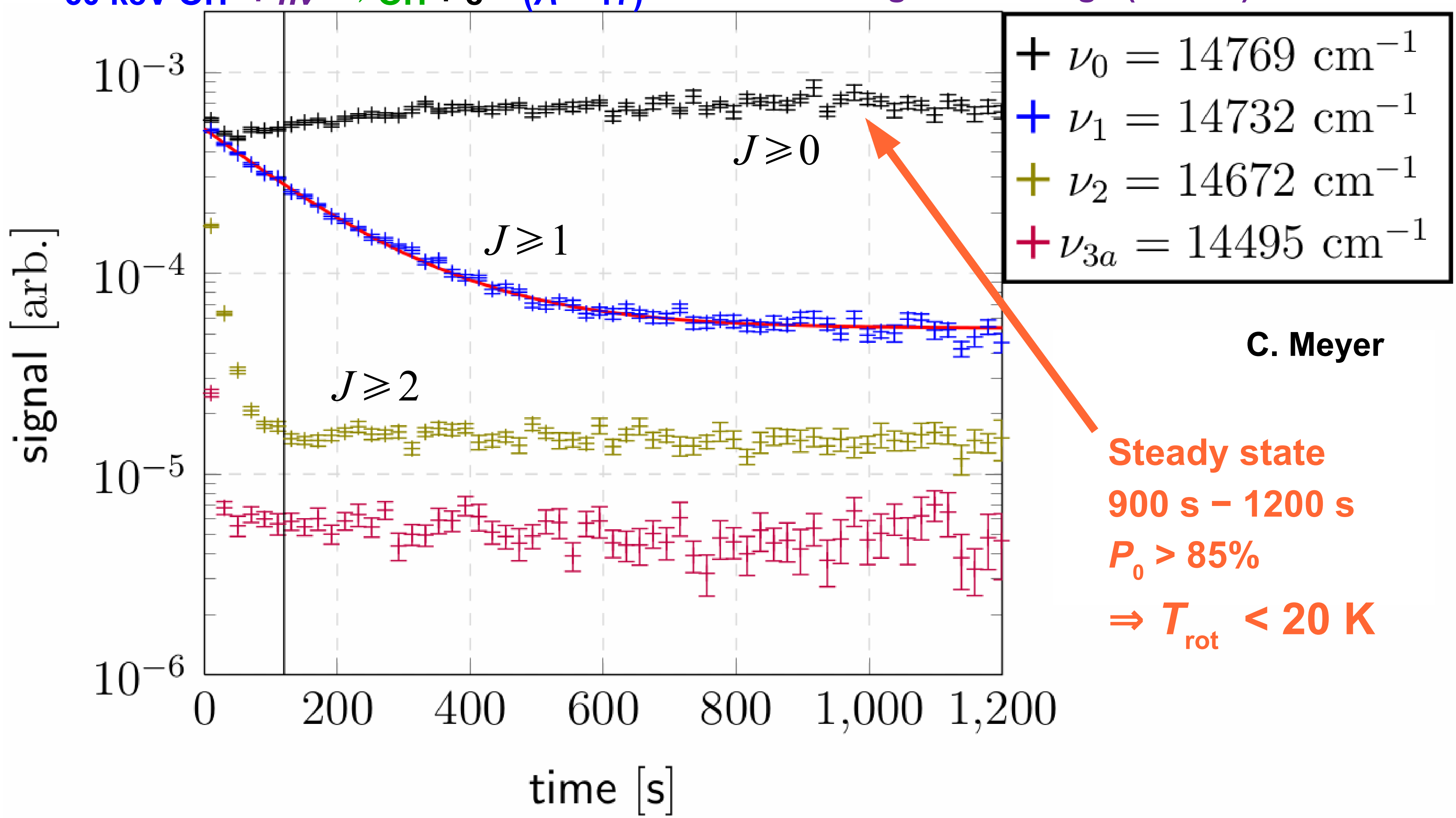
Long-time storage (20 min)



Stored ion thermometry results

60 keV OH^- + *hν* → OH + e^- (*A* = 17)

Long-time storage (20 min)



C. Meyer

Steady state
900 s – 1200 s
P_0 > 85%
⇒ T_{rot} < 20 K

Further results of first cryogenic beam time

Many ion beams including

O^-, OH^-, CH^+, Ar^+, Co_2^-, Ag_2^-, Co_3^-

Beam energy mostly 60 keV

Storage ring parameters

Measurement of betatron tune

Optimization of tune for electron cooling

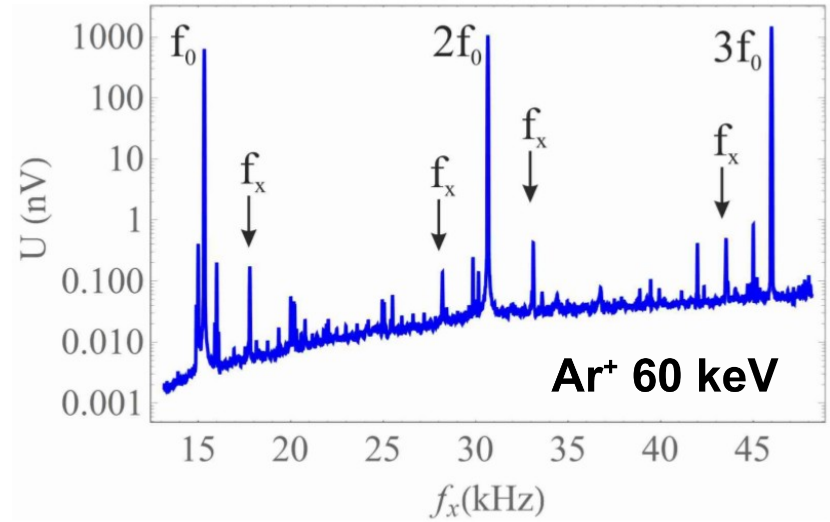
Betatron function values

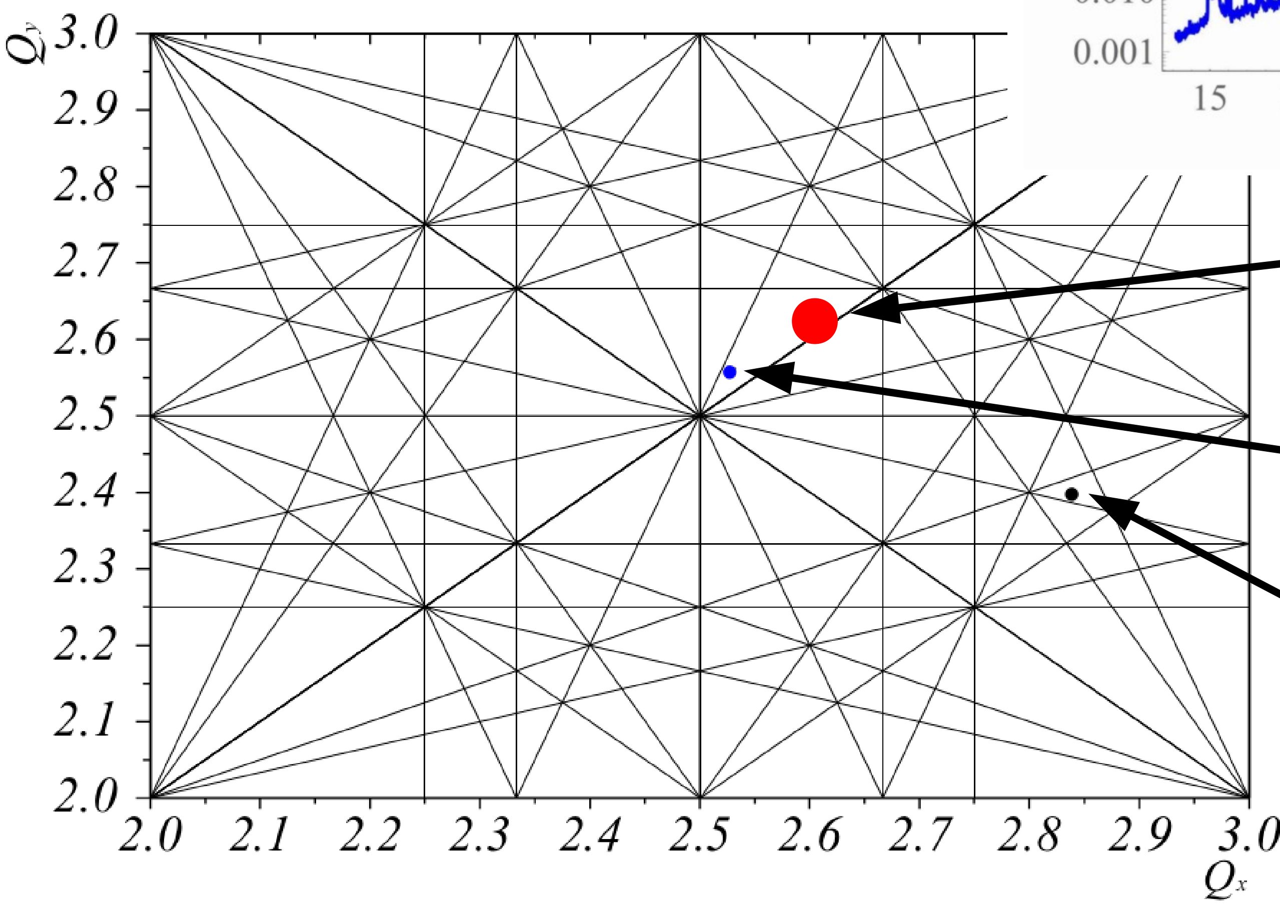
Beam position pickup measurements with bunched ion beams

Absolute beam current measurements (bunched beams)

Working point optimization towards electron cooling

Betatron side bands observed on a horizontal position pickup plate





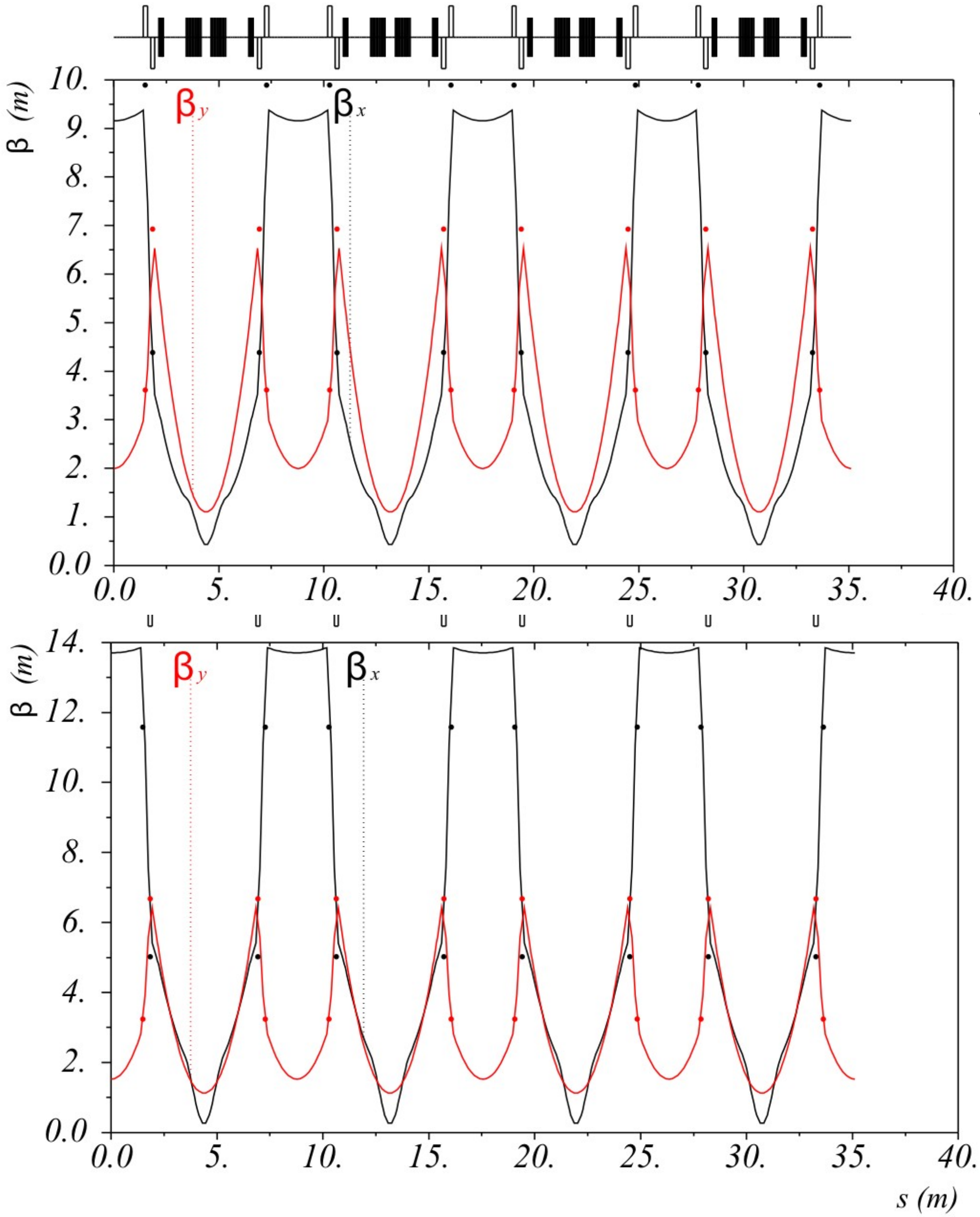
Goal for electron cooling

Working point 2 $Q_x \sim 2.52$, $Q_y \sim 2.57$

Working point 1 $Q_x = 2.840(1)$, $Q_y = 2.397(1)$

S. Vogel
M. Grieser

Measurement of beta functions at the quadrupoles



Working point 1

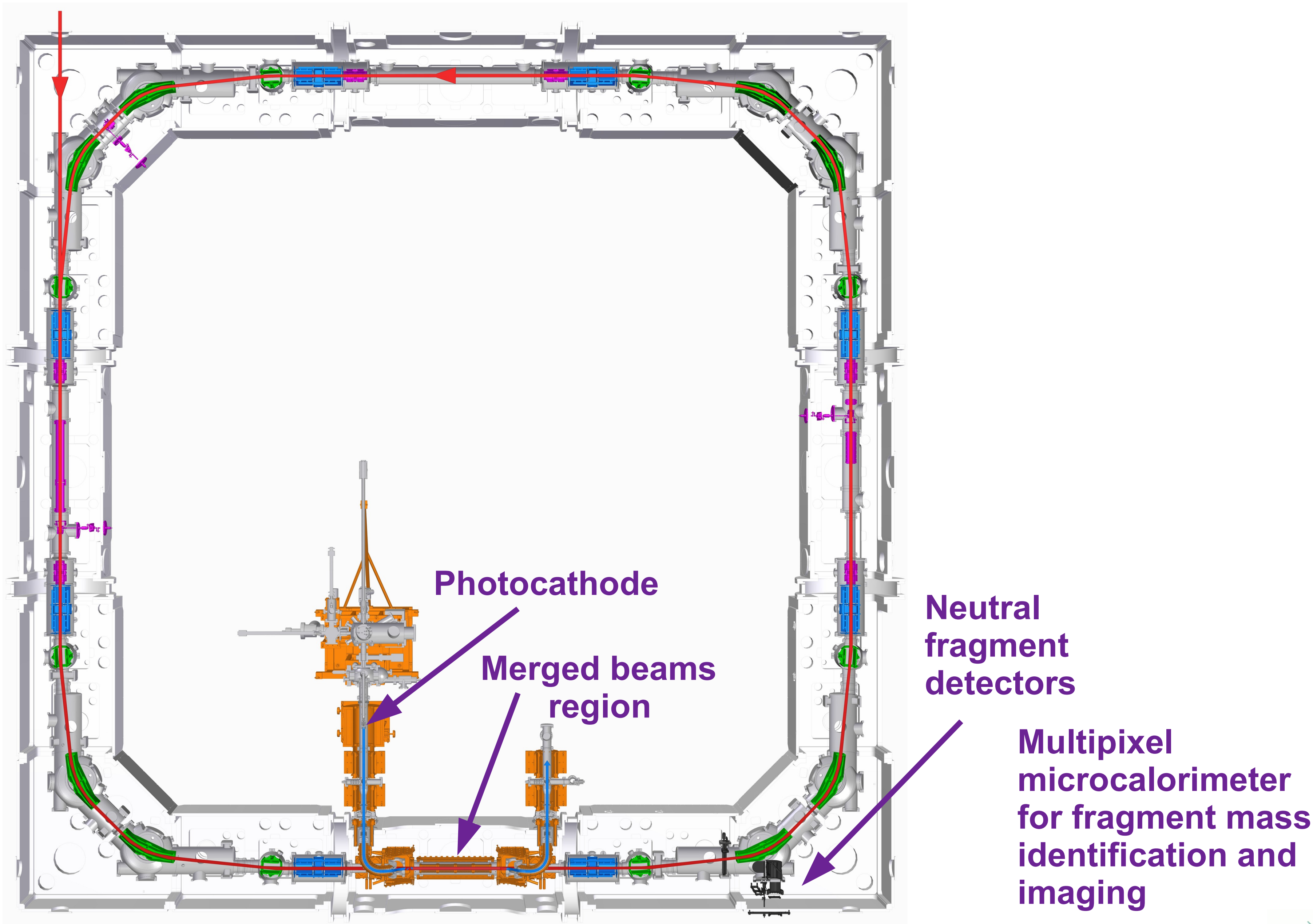
$Q_x = 2.840(1)$
$Q_y = 2.397(1)$

Working point 2

$Q_x \sim 2.52$
$Q_y \sim 2.57$

Ar^+ 60 keV

Merged electron beam and neutral fragment detection



Electron cooling of molecular ions at the TSR Heidelberg

CF^+ (31 amu) at 90 keV/amu

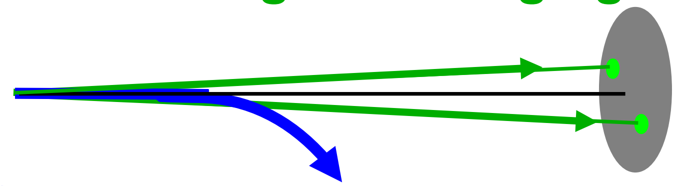
C + F fragment imaging

Down to 30 eV electrons at TSR

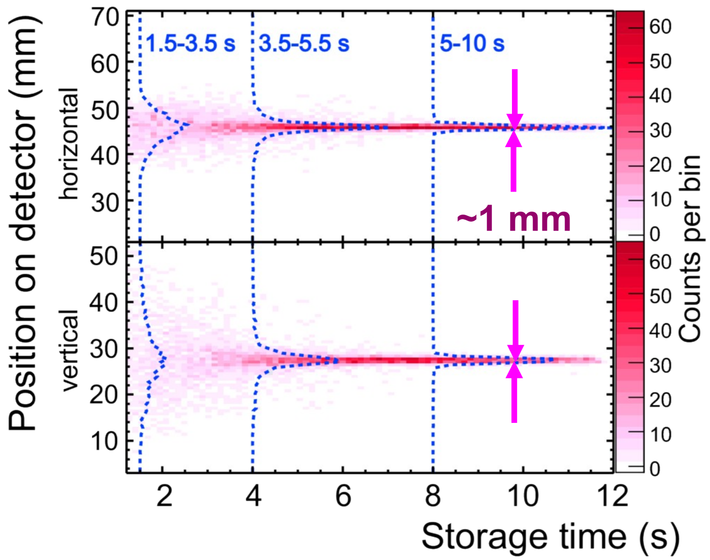
50 eV electrons

~1 mA electron current

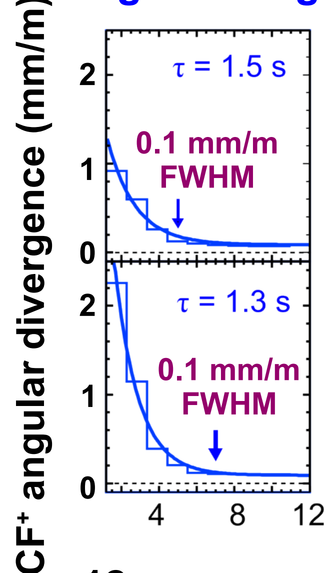
$CF^+ + e \rightarrow C + F$



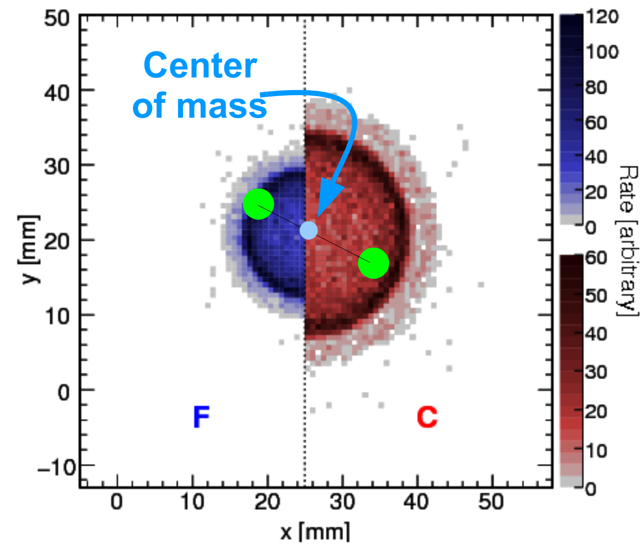
Molecular center of mass on fragment imaging detector

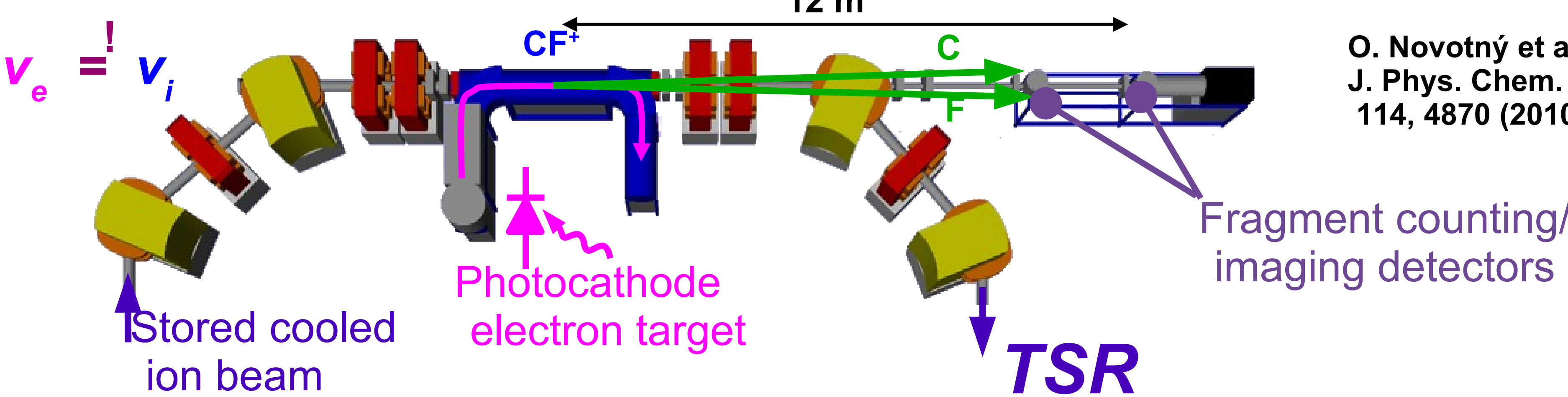


Ion beam divergence angle



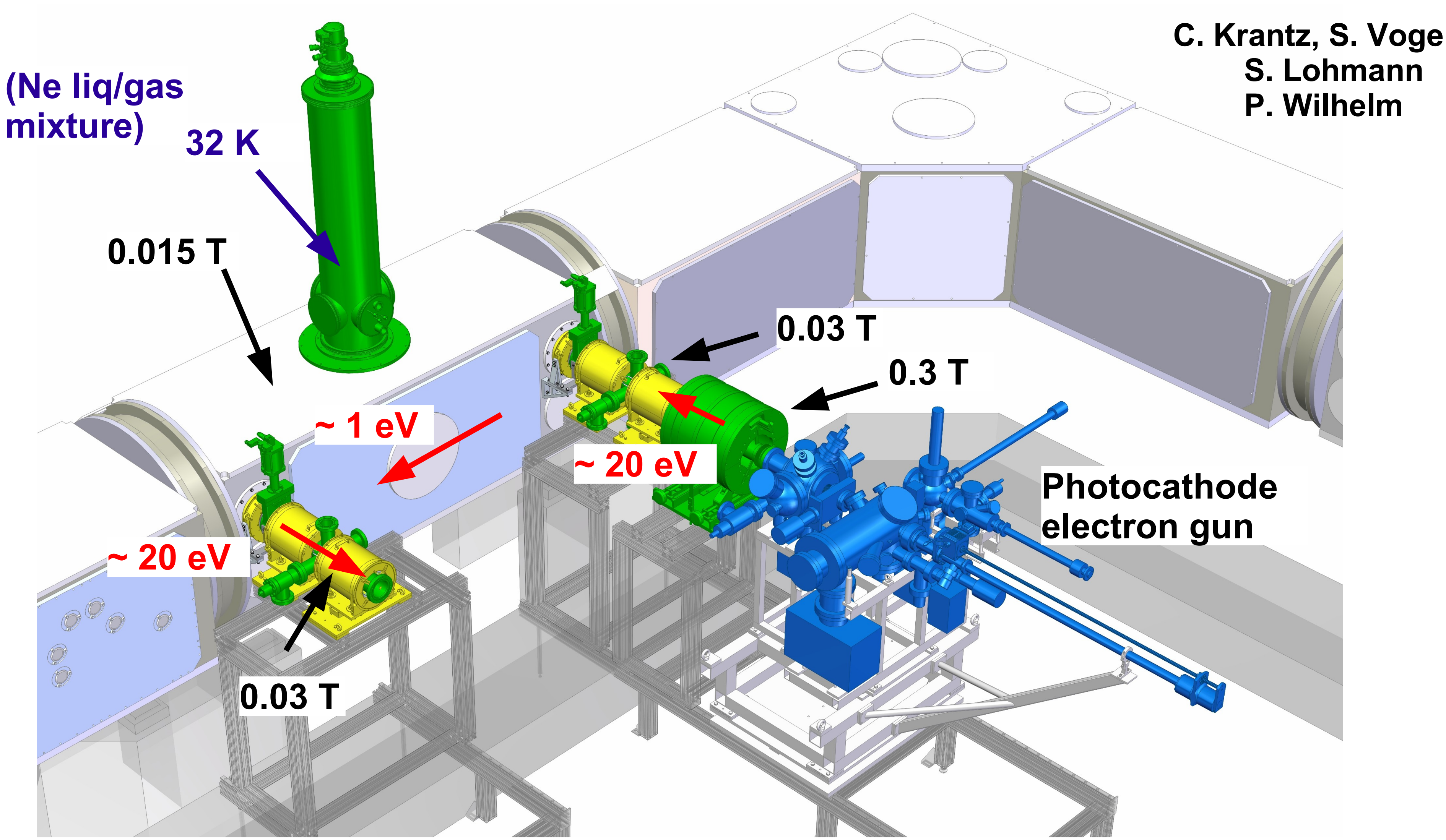
Photocathode electron cooling





O. Novotný et al., J. Phys. Chem. A 114, 4870 (2010)

CSR electron cooler and target: setup

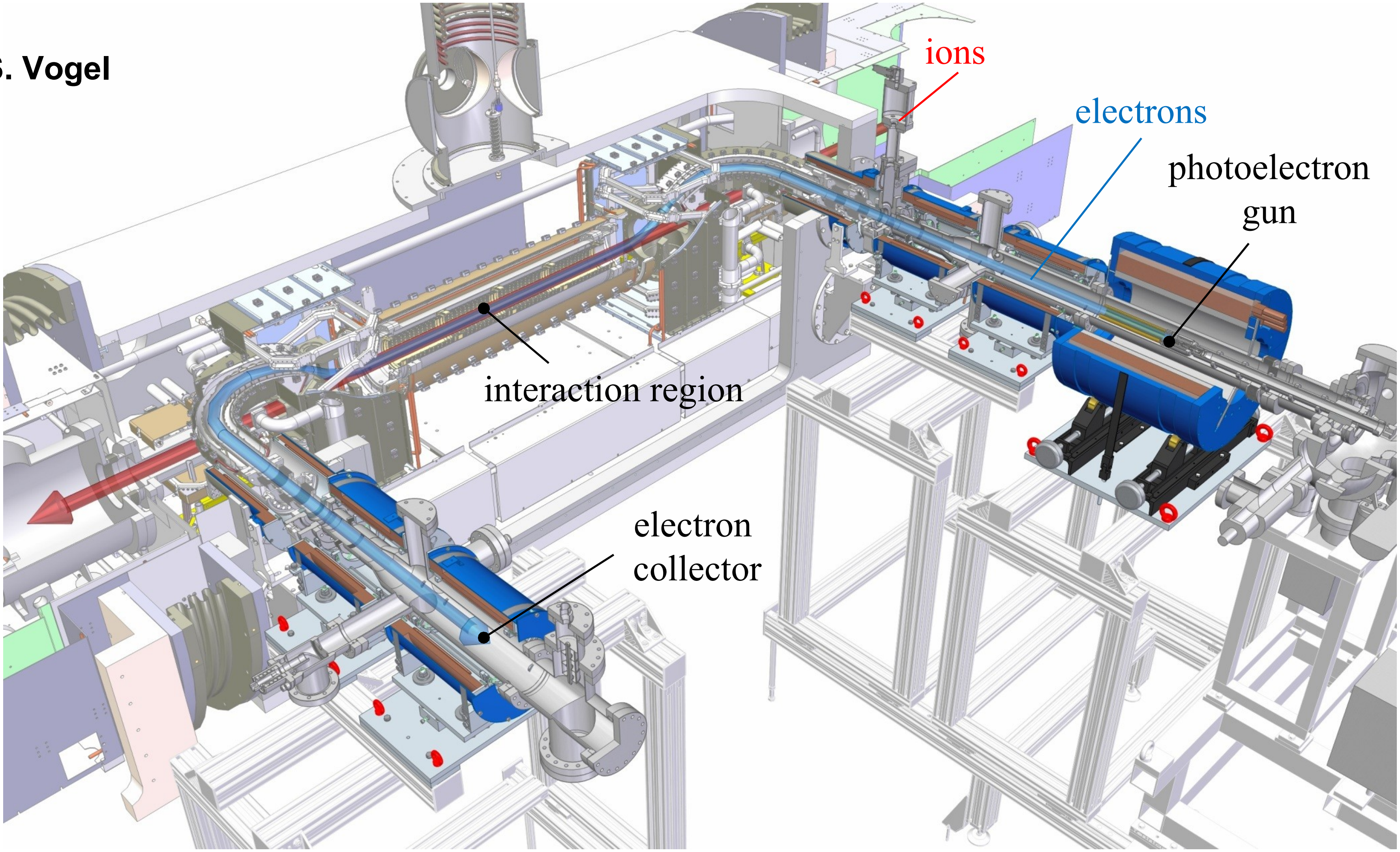


1 eV photocathode electron beam deceleration/transport:

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

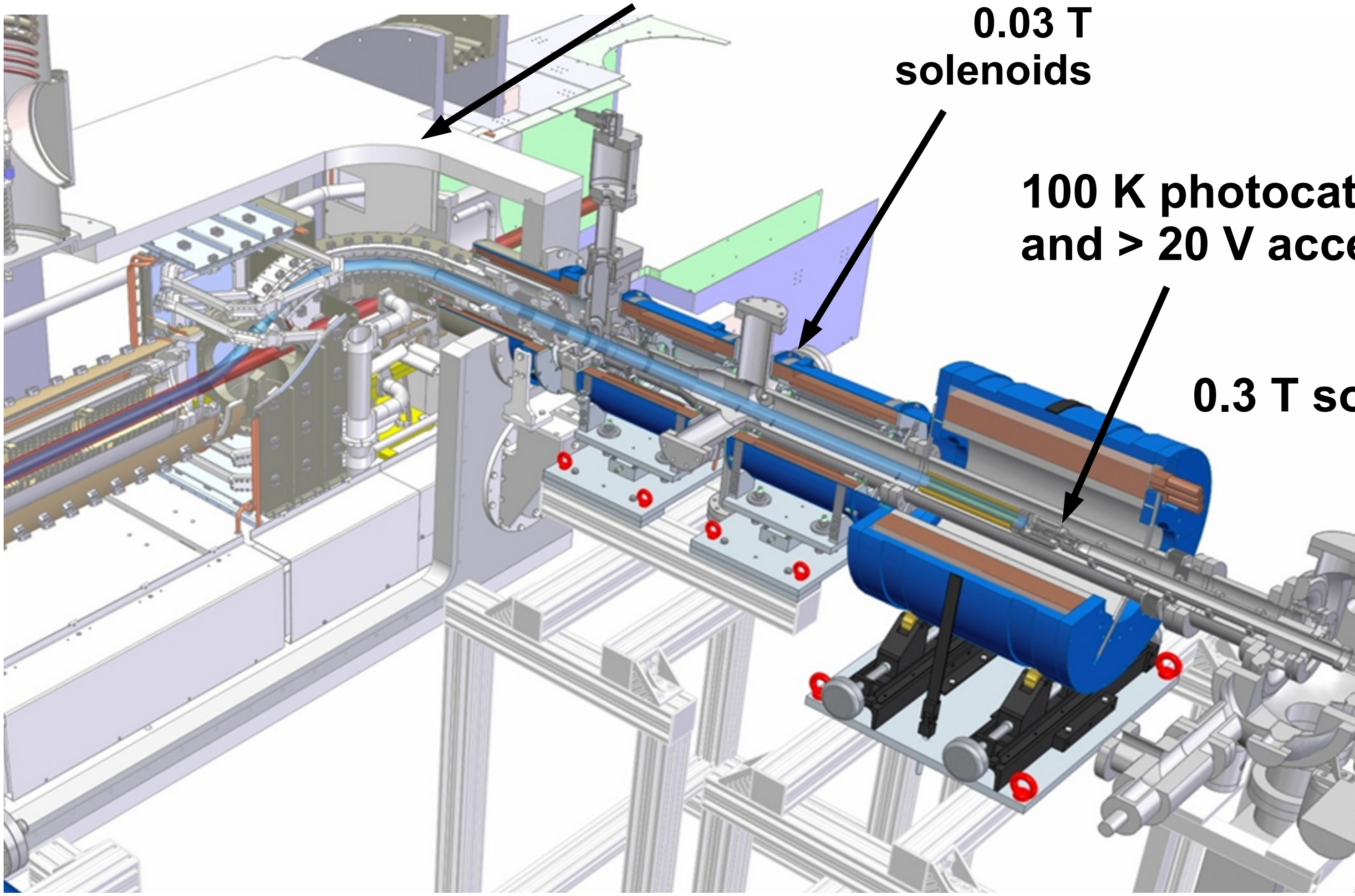
Merged electron beam in CSR

S. Vogel

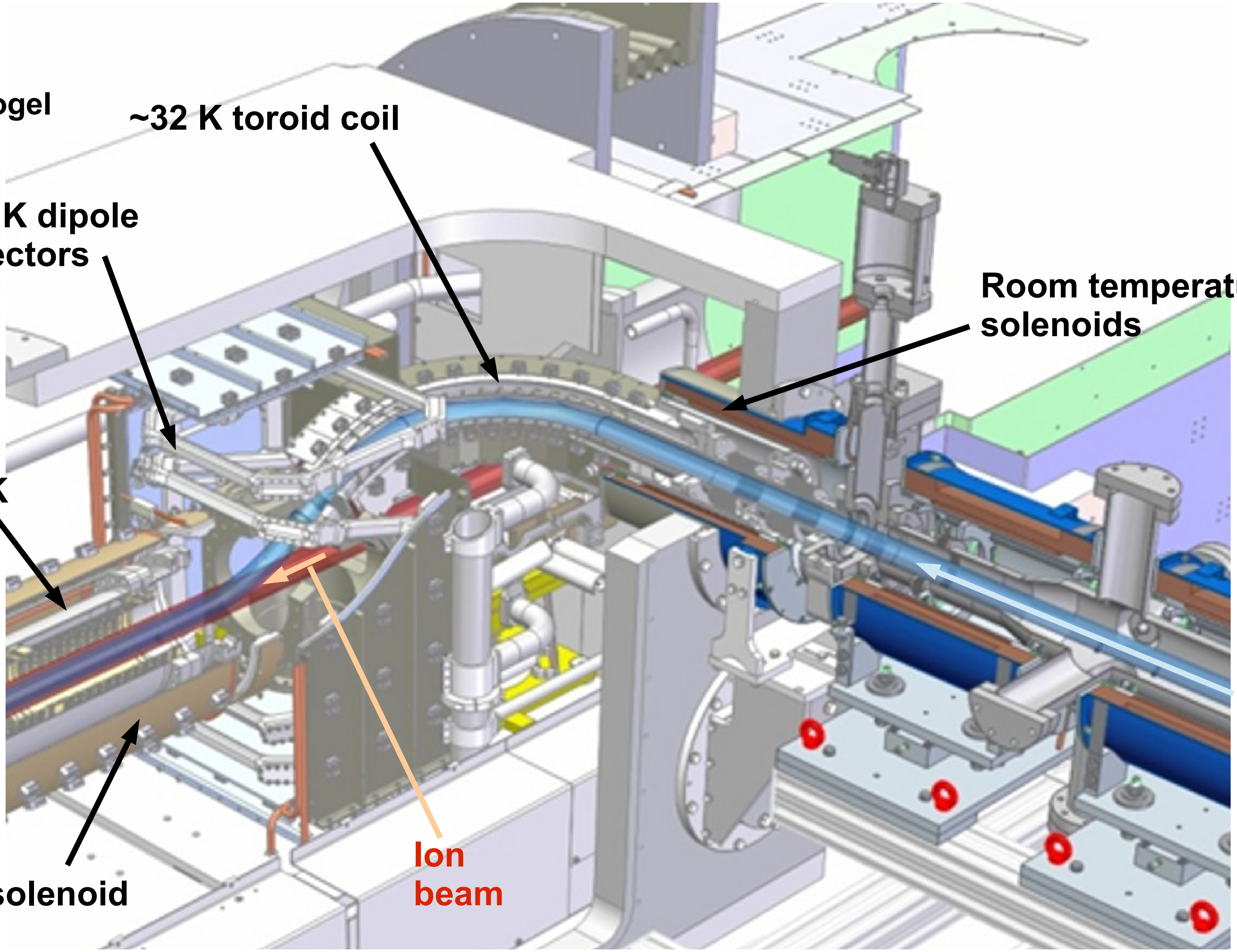


Photocathode beam preparation

S. Vogel

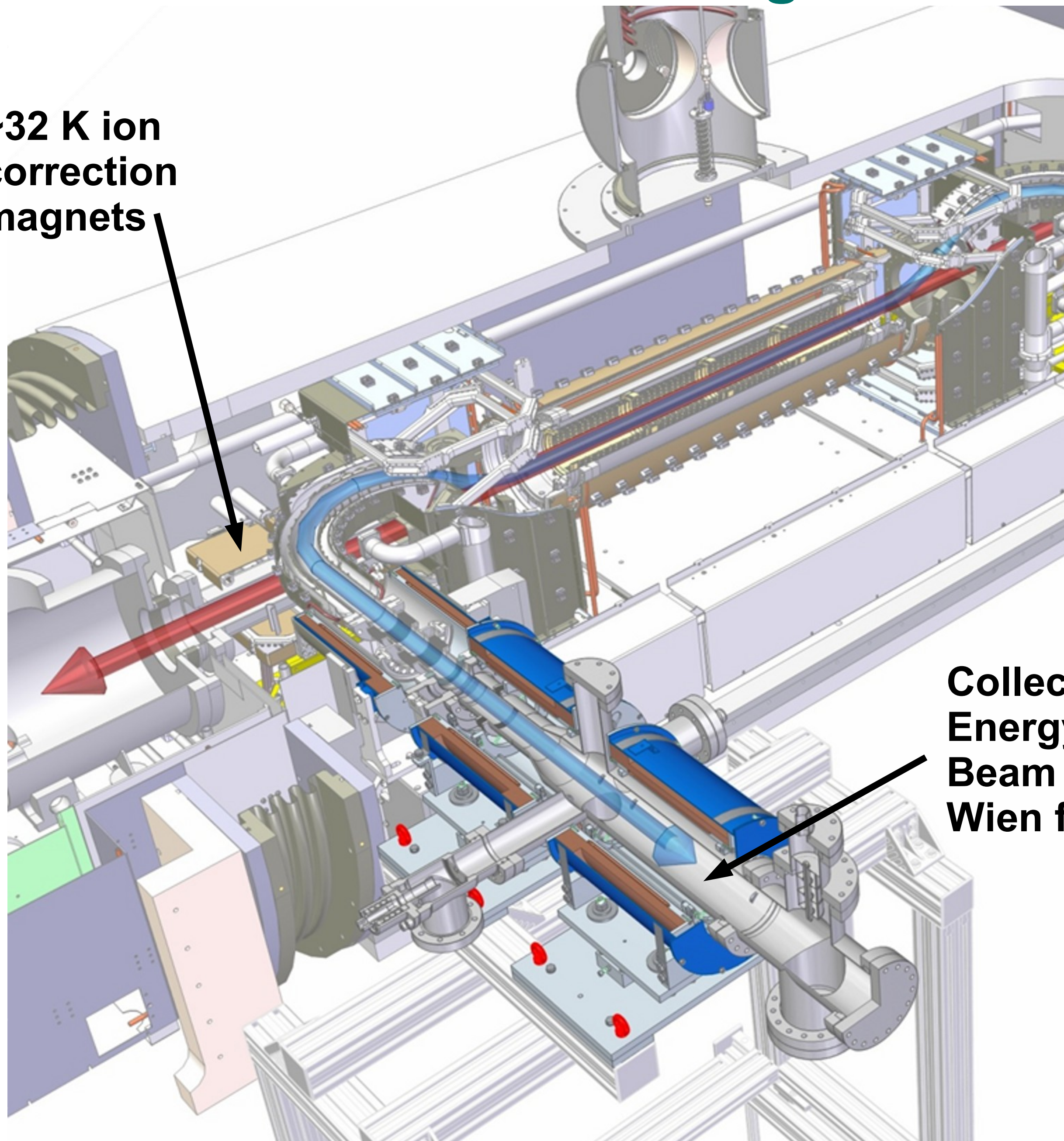


Cryogenic transition and beam merging region



Drift and collector regions

S. Vogel



Summary

CSR Heidelberg operating at ~ 6 K
  with molecular ion beams up to (so far) *A* ~ 200

Cryogenic vacuum probably <10^{-14} mbar
  Ion beam lifetimes (1/e) up to ~2500 s
    (limit from residual gas scattering not yet reached)

For merged-beams electron collision experiments:
  rotational relaxation of infrared active hydrides down to *J* = 0

Ion beam optics characterized, optimized towards electron cooling

Photocathode electron cooler and merged beams experiments upcoming in 2016

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CSR detectors, electron cooler, laser experiments

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A. O'Connor
F. Grussie
S. Kumar

CSR team

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F. Fellenberger
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M. Lange
R. Repnow
P. Herwig

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S. Vogel
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H. Kreckel (Astrolab)
F. Grussie (Astrolab)
A. O'Connor (Astrolab)

K. Blaum

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Collaborations CSR and experiments

Astrolab ERC/MPIK (H. Kreckel)
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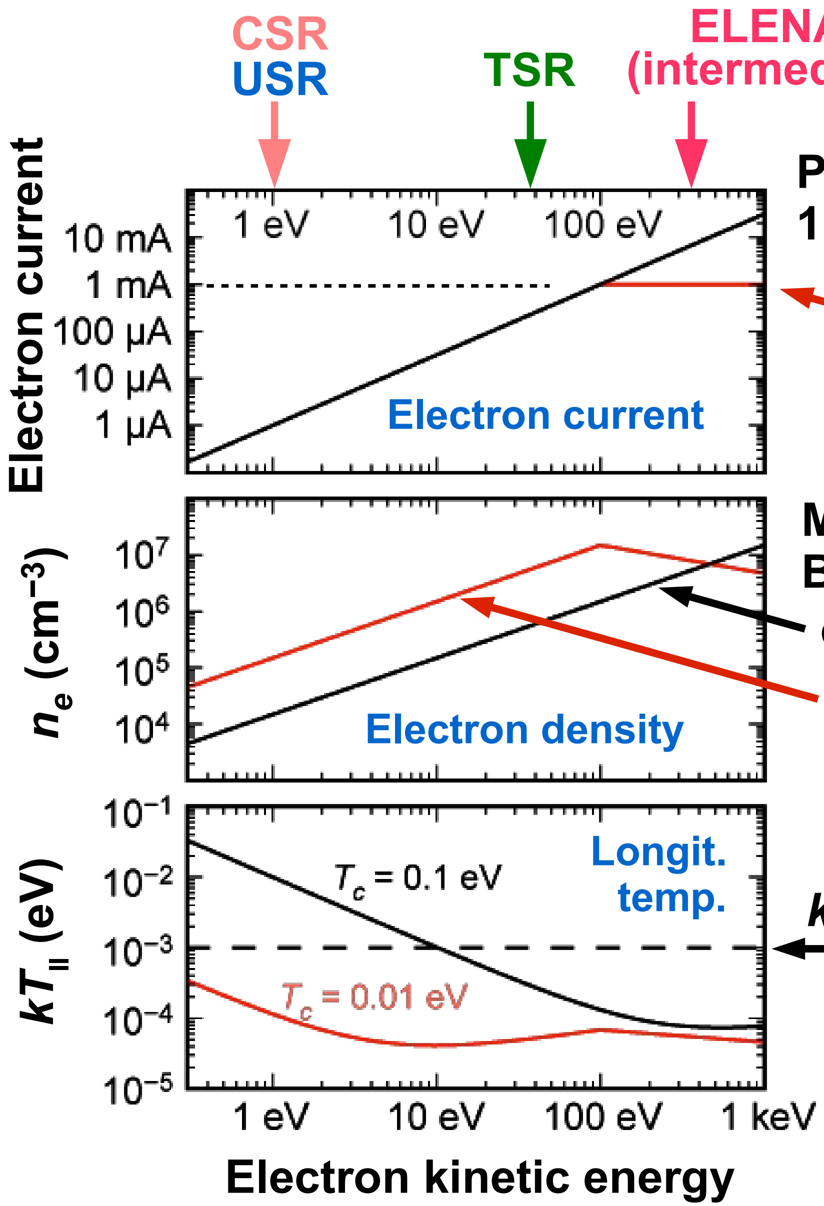
MPG
WIS
ERC

DFG Priority Program “Physics of the Interstellar Medium”
NASA and NSF (Columbia Univ.)

(COOL13, Mürren, A.W.)

Low energy electron beams for cooling



Perveance
1 μA/V$^{3/2}$

1 mA
max. current

Magnetic expansion
Beam cross section ratio

α = 100 (Cathode diam.: 3 mm)

α = 10

$kT_{\perp} = T_c/\alpha$
= 1 meV

Thermal emission cathode (near 1000 K):

kT_c = 0.1 eV

LN_2 cooled (near 100 K) GaAs photocathode:

kT_c = 0.01 eV

Kinematic velocity compression

$$kT_{\parallel} = \left[1+\left(1-\frac{1}{\alpha}\right)^2\right]\frac{(kT_c)^2}{2E_{kin}} + C\,\frac{e^2}{4\pi\varepsilon_0}\,n_e^{1/3}$$

[D. Orlov et al., AIP Conf. Proc. 862, 274 (2006); $C \sim 2$]

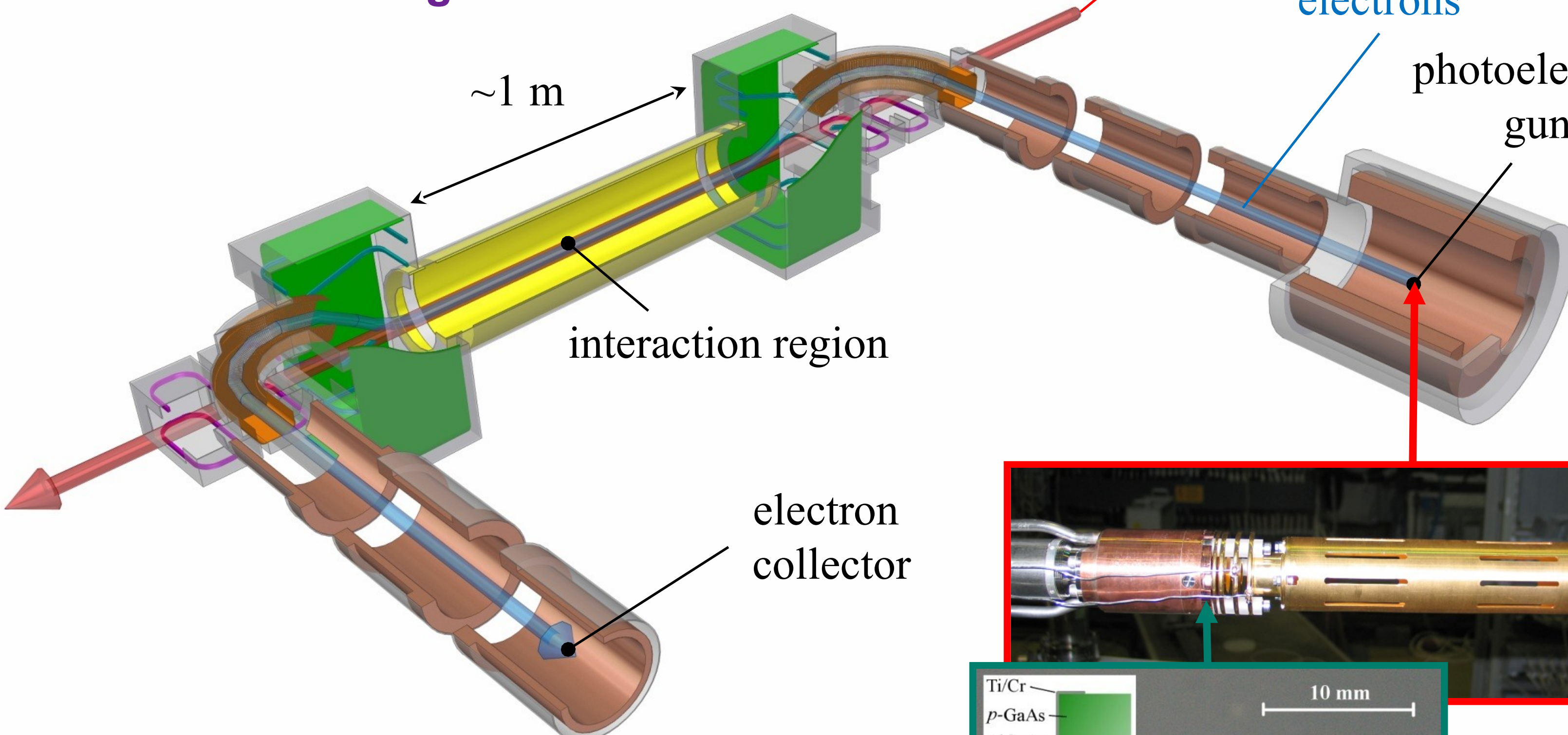
Photocathode electron beam

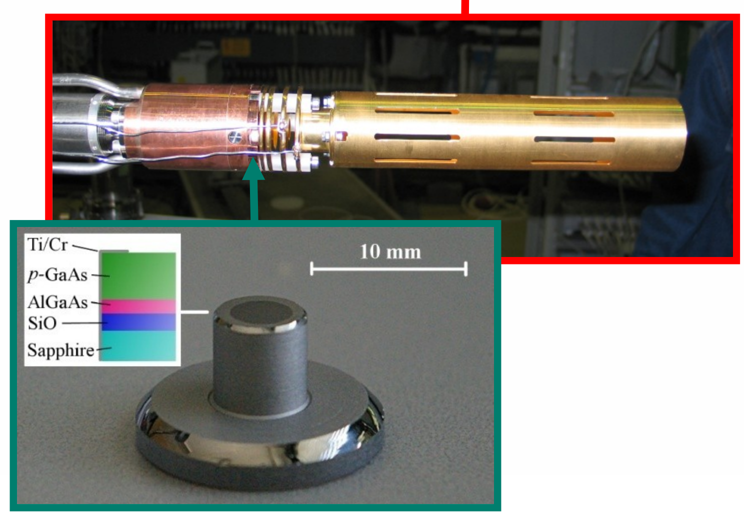
Low-energy dense electron beam

- **magnetically guided**
- **cryogenic merging region with the circulating ion beam**

$k_B T_e \sim 1$ **meV**

$n_e \sim 10^5$ **cm^{-3} @ 1 eV laboratory beam energy**



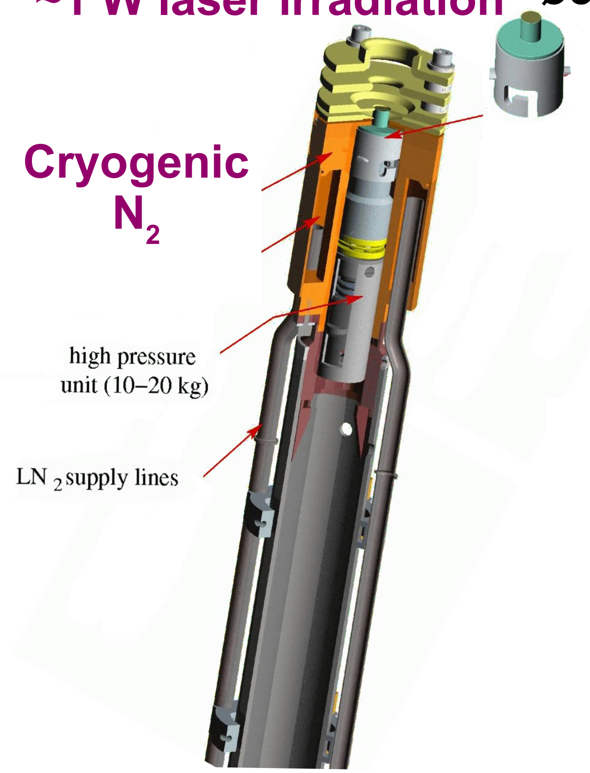


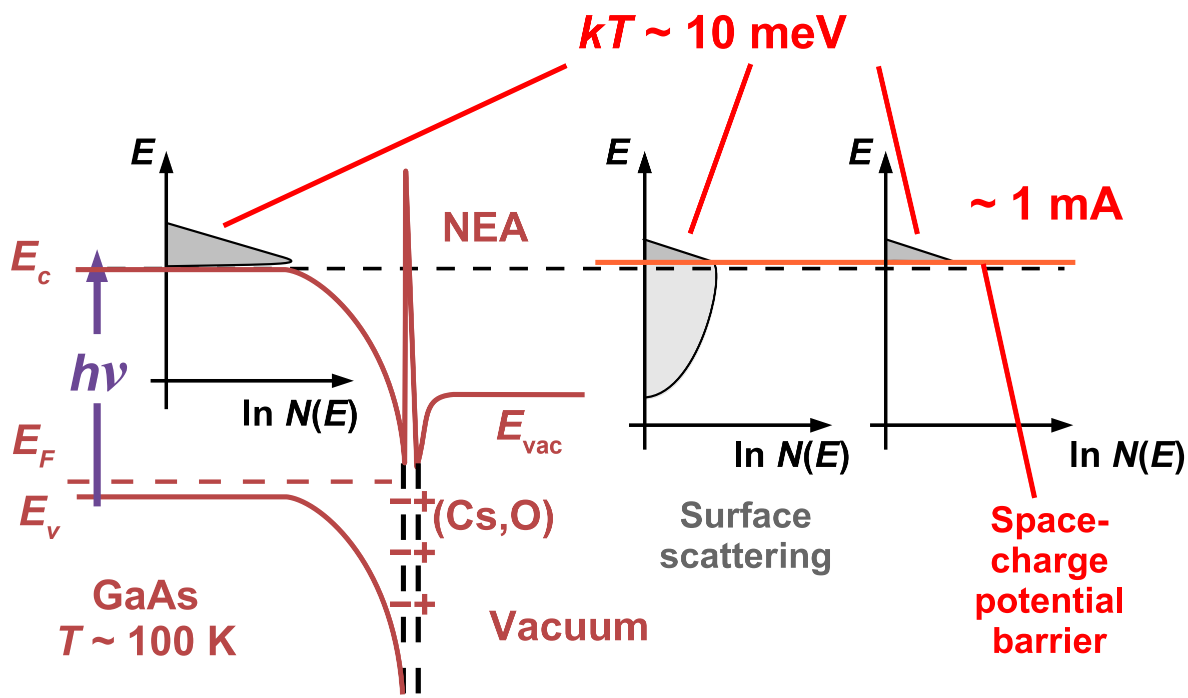
Shornikov et al., Phys. Rev. ST AB **17**, 042802 (2014)

High-resolution electron target at TSR

GaAs photocathode at ~100 K
~ 1 mA continuous current

~1 W laser irradiation





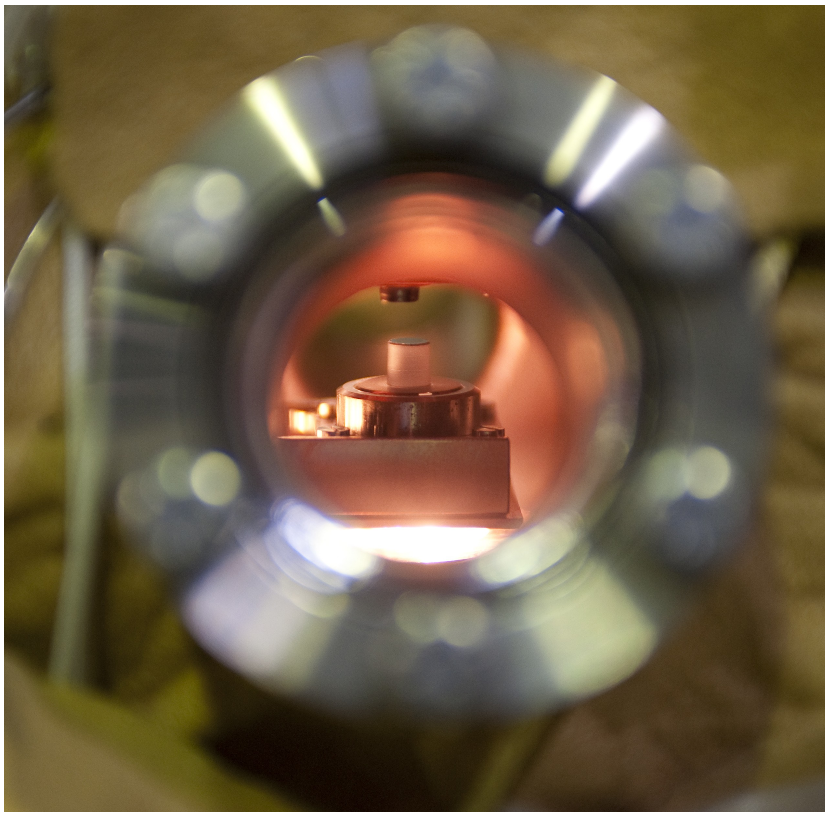
- Magnetic expansion (~0.4 T → 0.02 T) yields 0.5...1 meV electron temperature (~5...10 K)
- Cathode lifetime typ. 24 h
- ~4 cathodes under vacuum in closed-cycle operation
- Electron beam energy down to < 1 eV with 10 μA current (0.01 T guiding field)

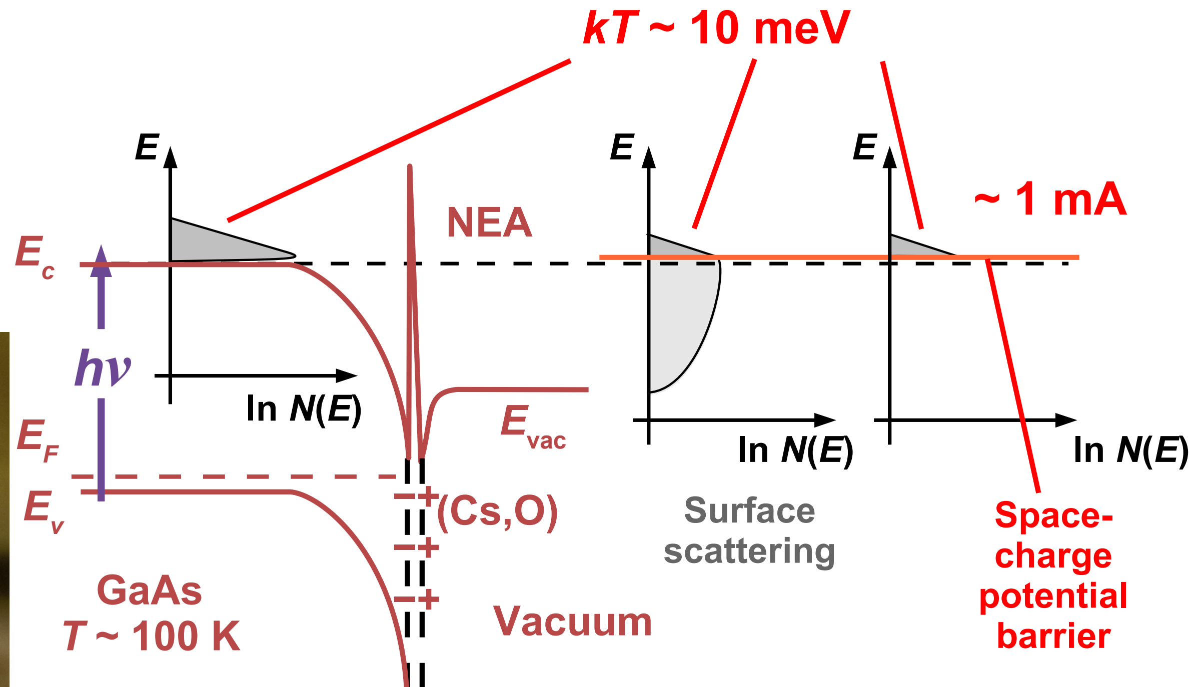
D. A. Orlov et al., J. Appl. Phys. 106, 054907 (2009)

D. A. Orlov, C. Krantz, A. Shornikov
Collab. with Inst. f. Semiconductor Phys., Novosibirsk, A. N. Terekhov

High-resolution electron target

GaAs photocathode at ~100 K
~ 1 mA continuous current





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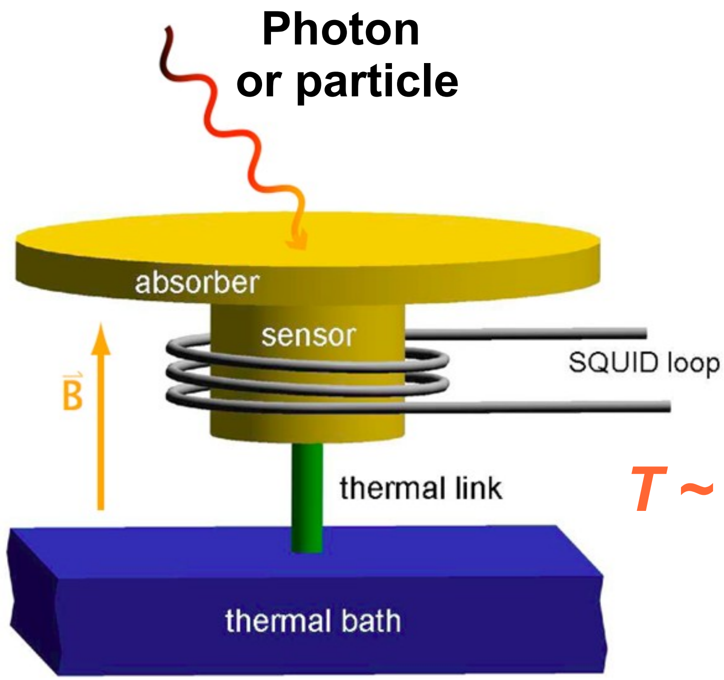
Microcalorimeter detectors

Kirchhoff Institute of Physics,
Univ. Heidelberg (A. Fleischmann, C. Enss et al.)



T ~ 20 mK

Great success in gamma and X-ray spectroscopy

Resolution: ~1 eV @ ~10 keV

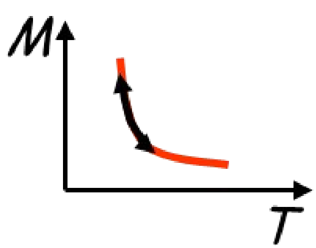
Fragment energy:

$E_f = \frac{1}{2} M_f v_i^2$

Kinetic energy → fragment mass

Metallic Magnetic Calorimeter (MMC)

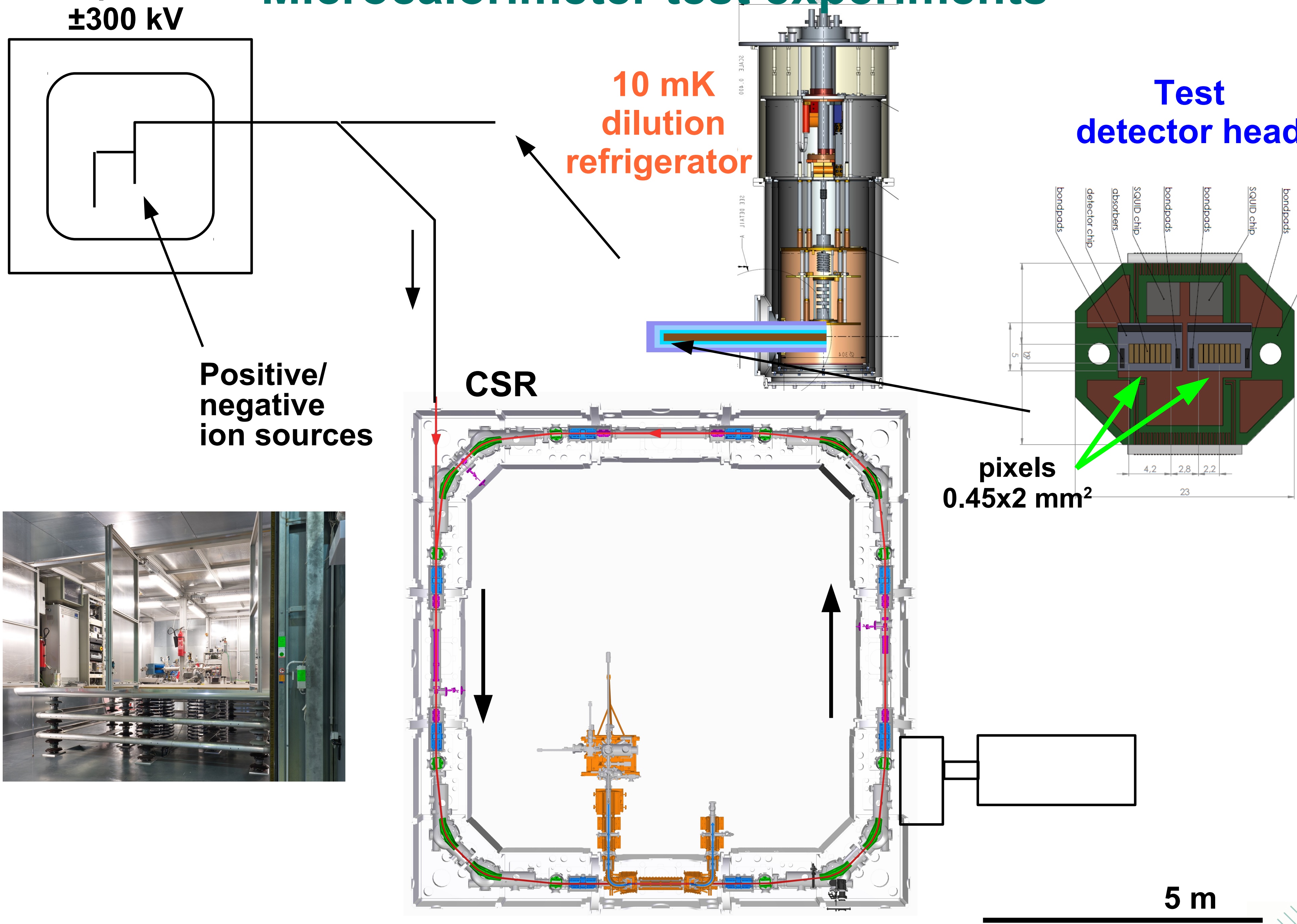
Paramagnetic sensor: $Au{:}Er_{500ppm}$



Temperature change measurement via magnetization

Can the resolution reach 1/10000 for fragment mass identification ?

Microcalorimeter test experiments



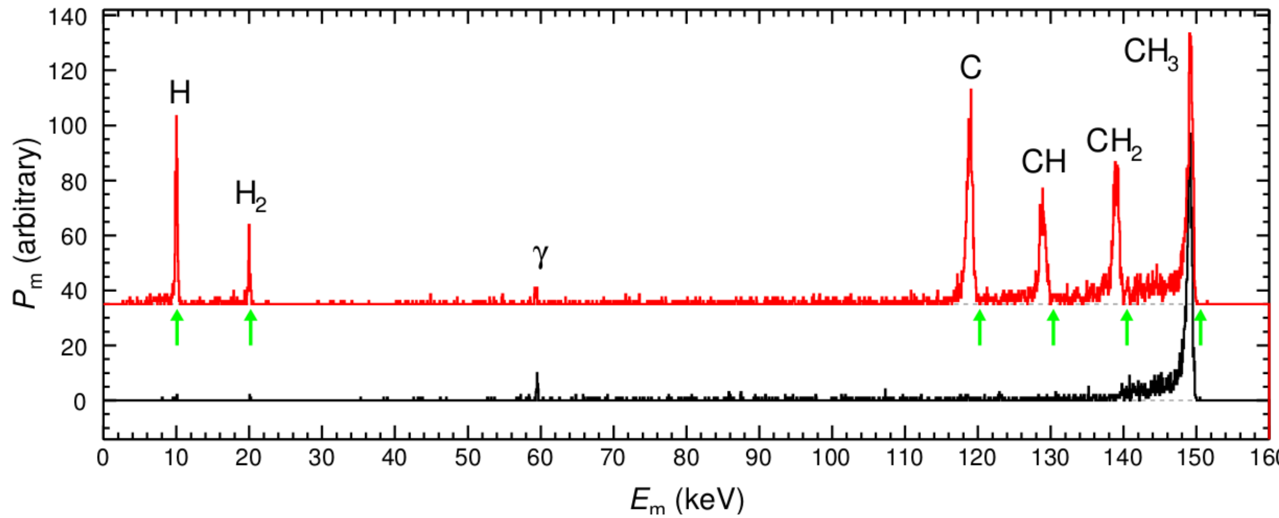
Ion beam microcalorimeter tests

O. Novotný et al.,
J. Appl. Phys. 118, 104503 (2015)

Pulse height spectra of calorimeter hits

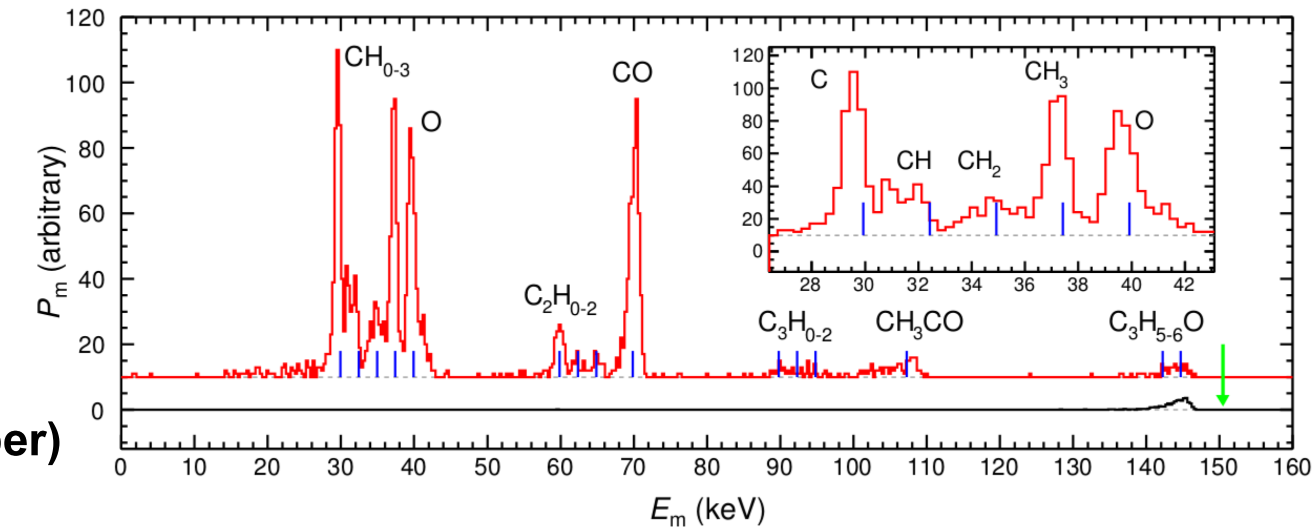
Molecular ion neutral fragments from residual gas collisions

CH_3^+ ion beam
150.6 keV



$C_3H_6O^+$ ion beam
150.5 keV

(Al coated absorber)



Max-Planck-Institut für Kernphysik