Low-energy ion beam storage and eV electron cooling

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Low-energy ion beam storage

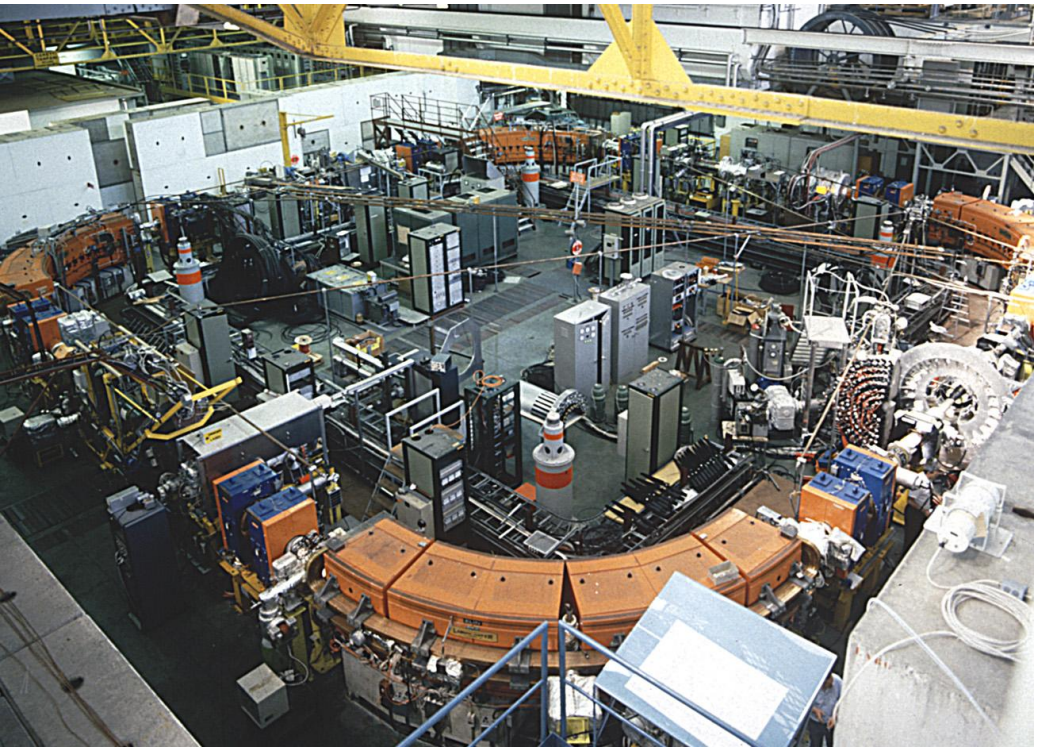
Electron cooling and collision physics with molecular ion beams

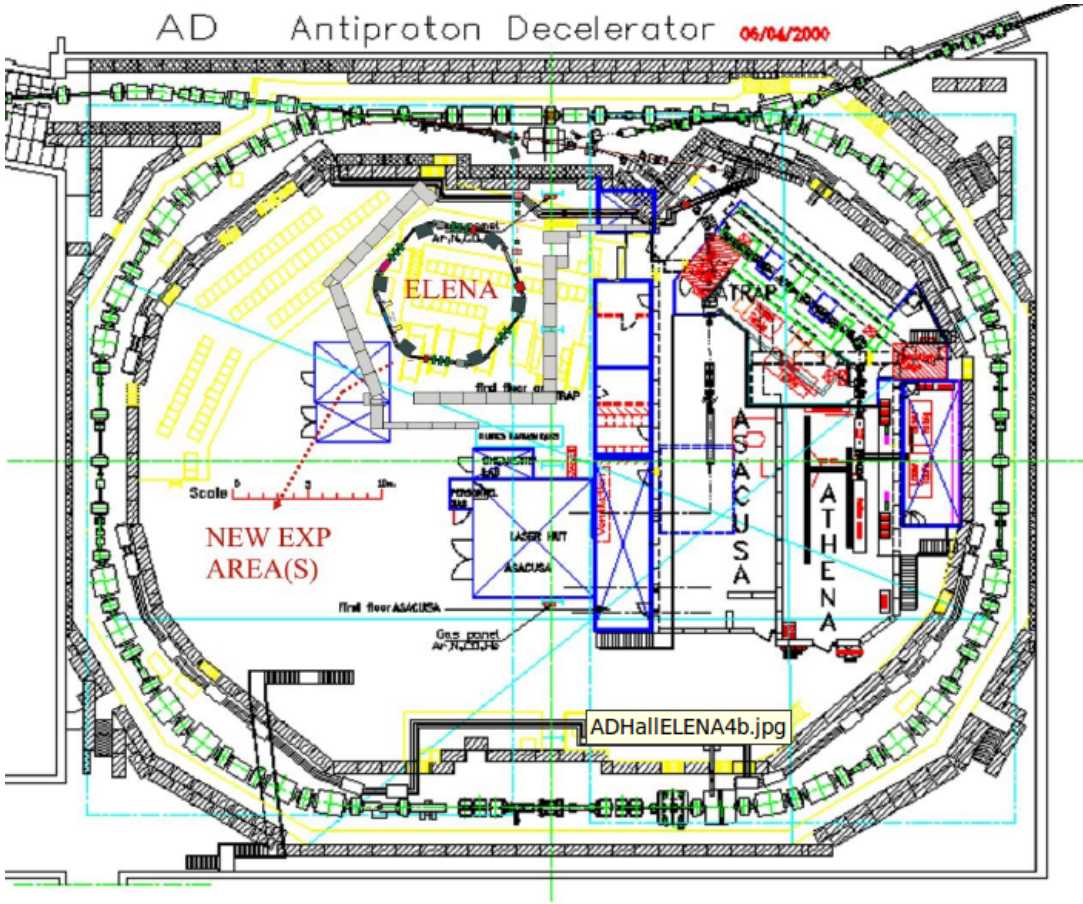
The Cryogenic Storage Ring project: layout, electron cooling, planned experiments

Dedicated to Dieter Moehl
for his early support, his example, and his open mind

Low-energy stored ion beams for atomic, molecular and fundamental particle research

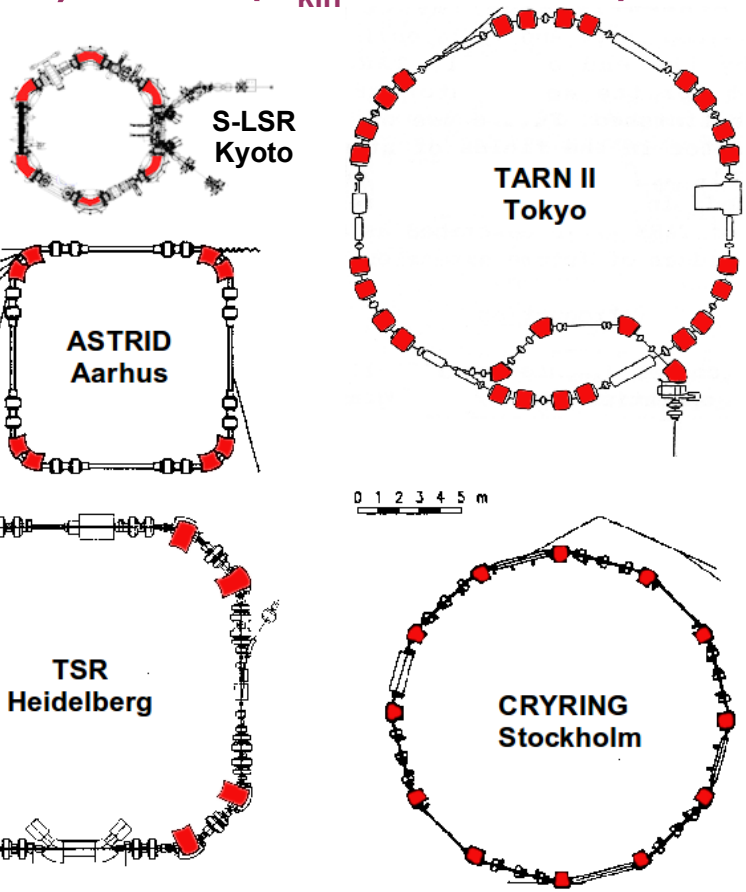
Low-energy *antiprotons* **LEAR, AAC, ELENA (CERN)** **down to 5 MeV (and below)**





Low-energy stored ion beams for atomic, molecular and fundamental particle research

Low-energy *antiprotons*	LEAR, AAC, ELENA (CERN)	down to 5 MeV (and below)
Cooler storage rings	CRYRING (Stockholm→ FAIR)	~5 MeV/u
	TSR (Heidelberg→ISOLDE/ CERN)	→ ~100 keV/u
		(E_{kin} ~ few MeV)
	S-LSR (ICR Kyoto)	
Large ion rings (ESR, COSY, CSR Lanzhou, ...)		



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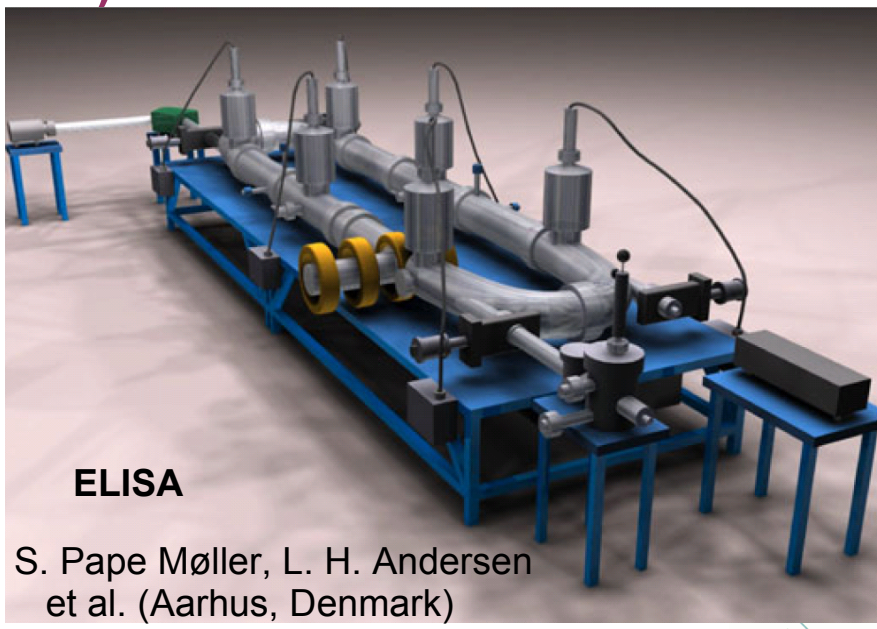
Electrostatic storage rings	ELISA (Aarhus) KEK & TMU (Tokyo) DESIREE (Stockholm) CSR Heidelberg	E_{kin} ~ 20-100 keV (300 keV, CSR)



ELISA

S. Pape Møller, L. H. Andersen et al. (Aarhus, Denmark)

Low-energy stored ion beams for atomic, molecular and fundamental particle research

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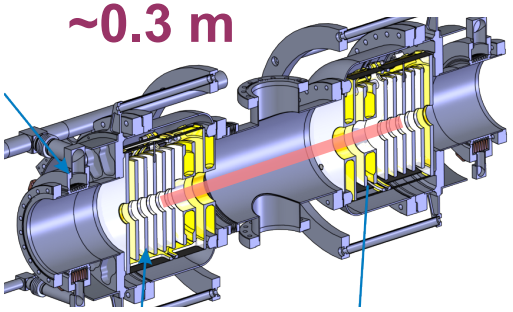
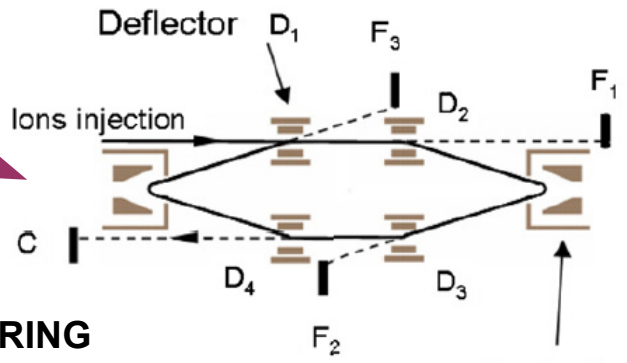
Electrostatic ion beam traps and table-top storage rings	Weizmann Inst., Israel Stockholm (Cone trap) Lyon, France (0.4 × 0.1 m ring) + ...	E_{kin} ~ 4 keV (typ.)

~0.3 m



Ion beam trap (switched reflectron)

D. Zaijfman et al. (WIS)
and meanwhile many other labs

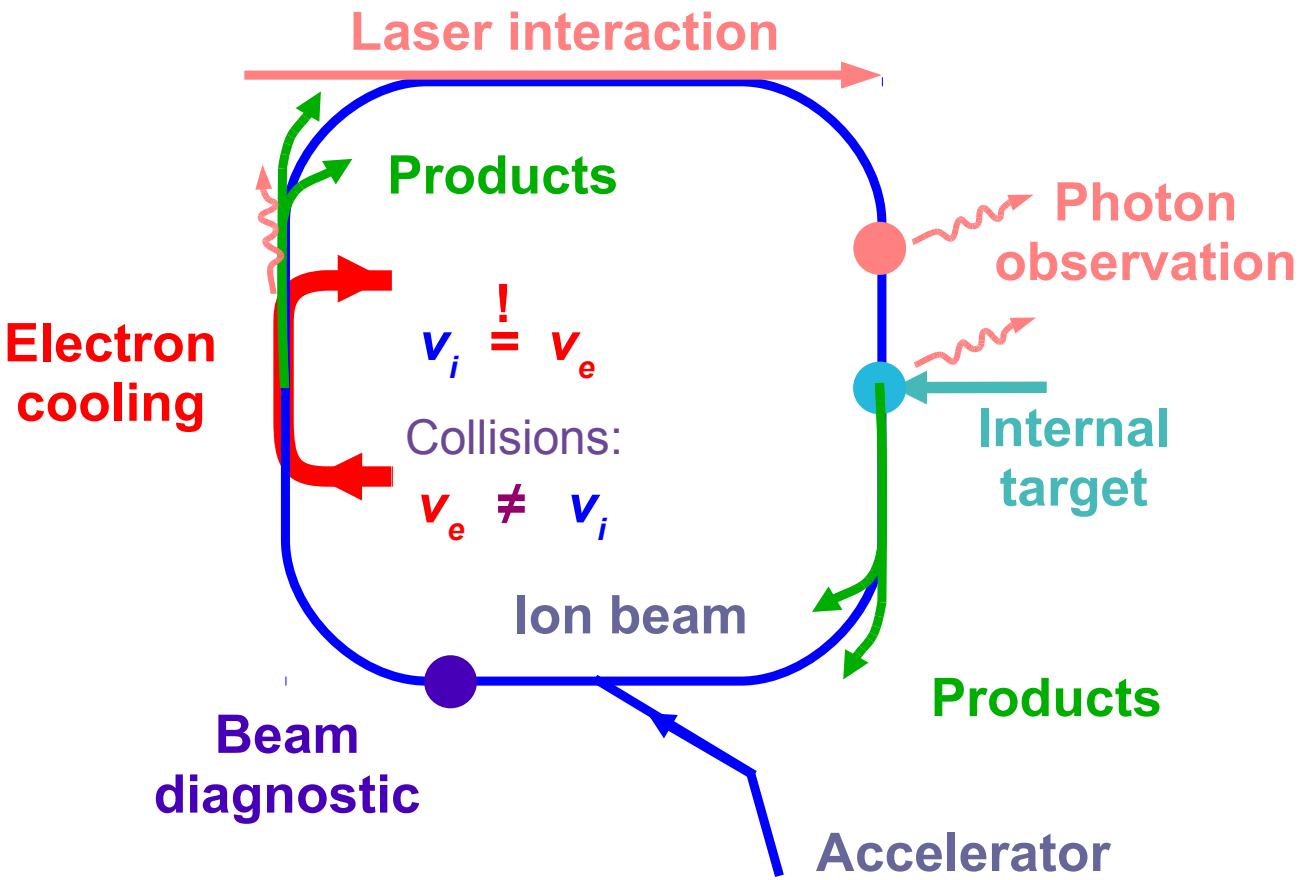


MINRING

Bernard, Bredy,
Martin et al. (LASIM, Lyon)

Conical mirror

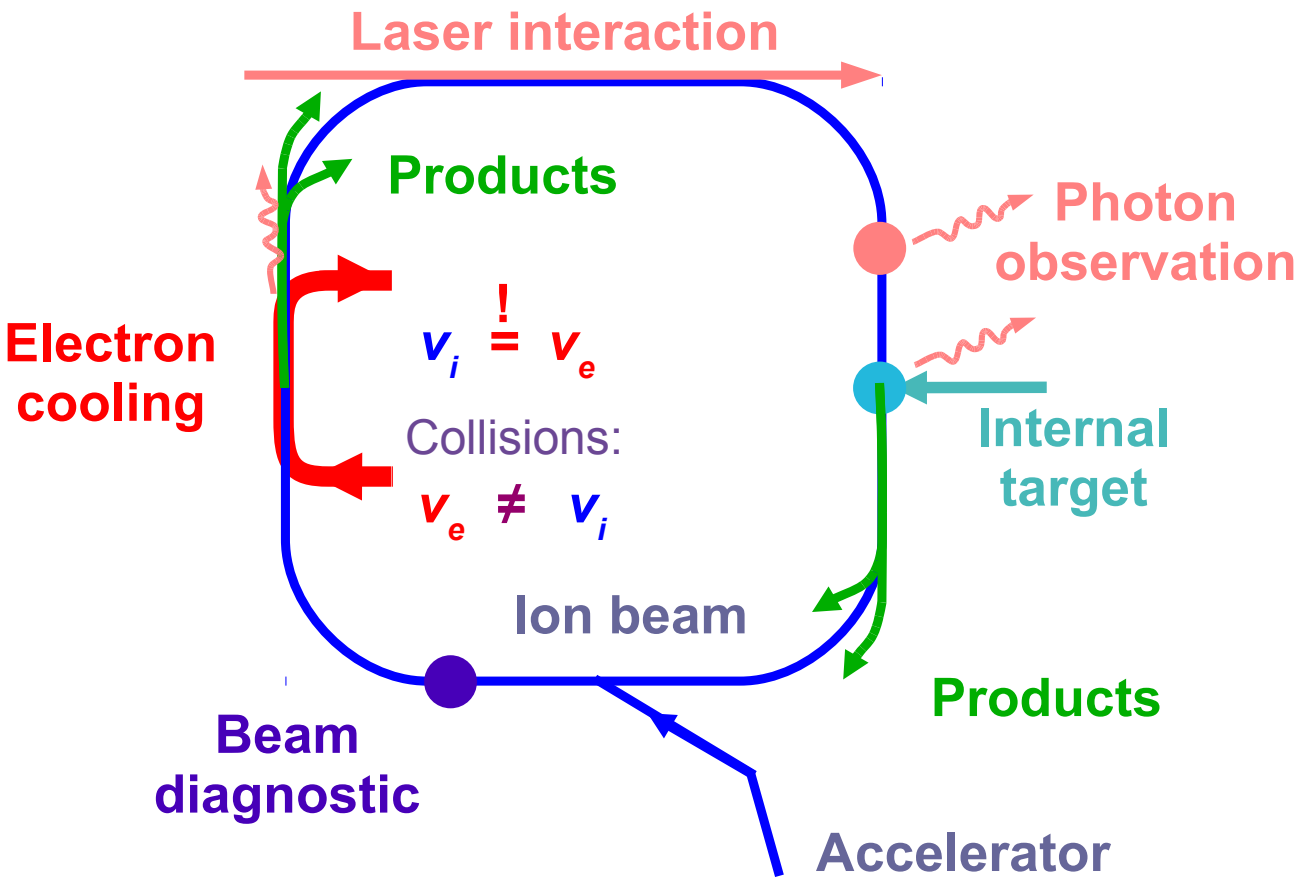
Low-energy cooler storage rings



Ultrahigh vacuum

Beam lifetime seconds to minutes (typical)

Low-energy cooler storage rings



Ultrahigh vacuum

Beam lifetime seconds to minutes (typical)

Atomic (highly charged) ions

Fe^{q+}

Si^{q+}

W^{q+}

Molecular ions

H_3^+ H_3O^+ $HCNH^+$

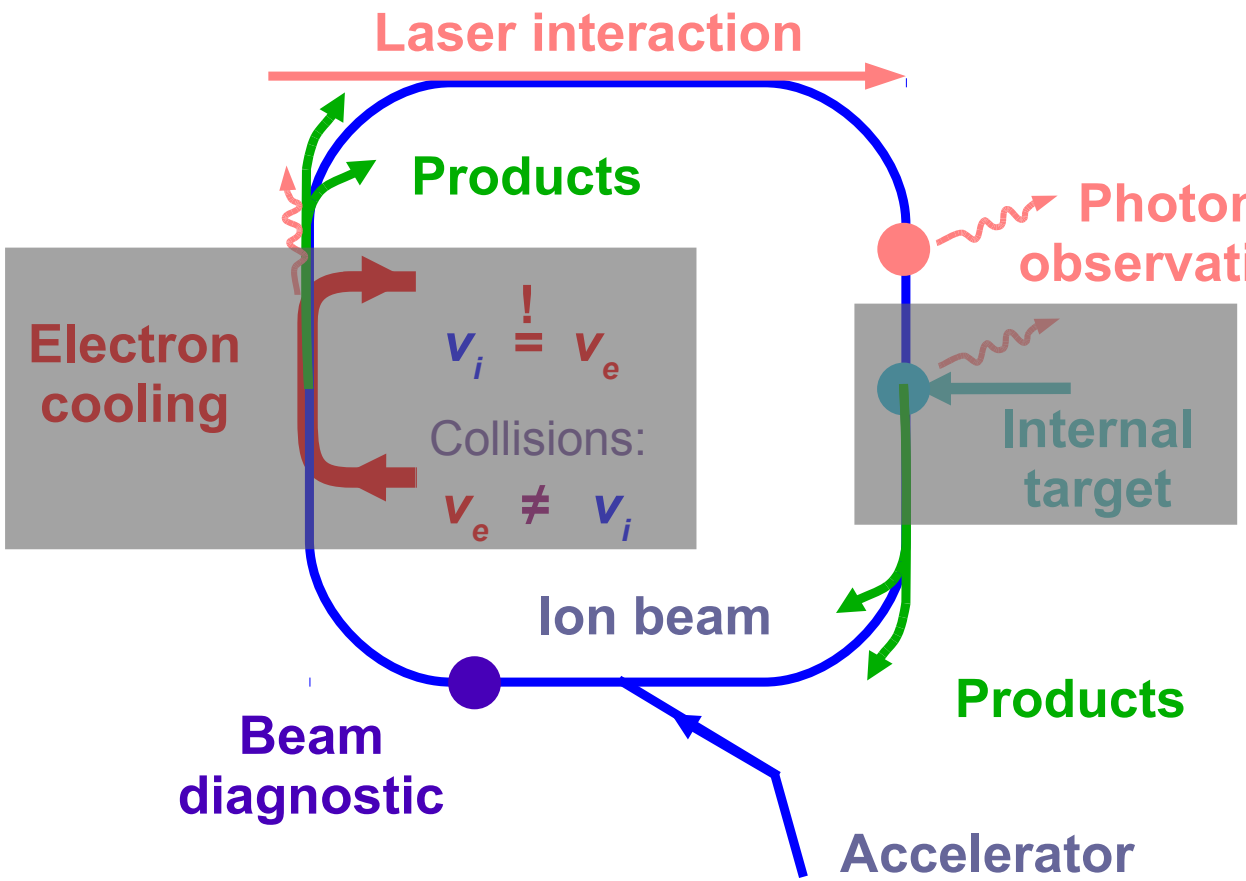
Negative ions (anions)

H^- C^- C_2H^- SF_6^-

Organic cations and anions

Atomic and molecular clusters

Low-energy cooler storage rings



So far not available at electrostatic storage rings

Ultrahigh vacuum

Beam lifetime seconds to minutes (typical)

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Fe^{q+}

Si^{q+}

W^{q+}

Molecular ions

H_3^+

H_3O^+

$HCNH^+$

Negative ions (anions)

H^-

C^-

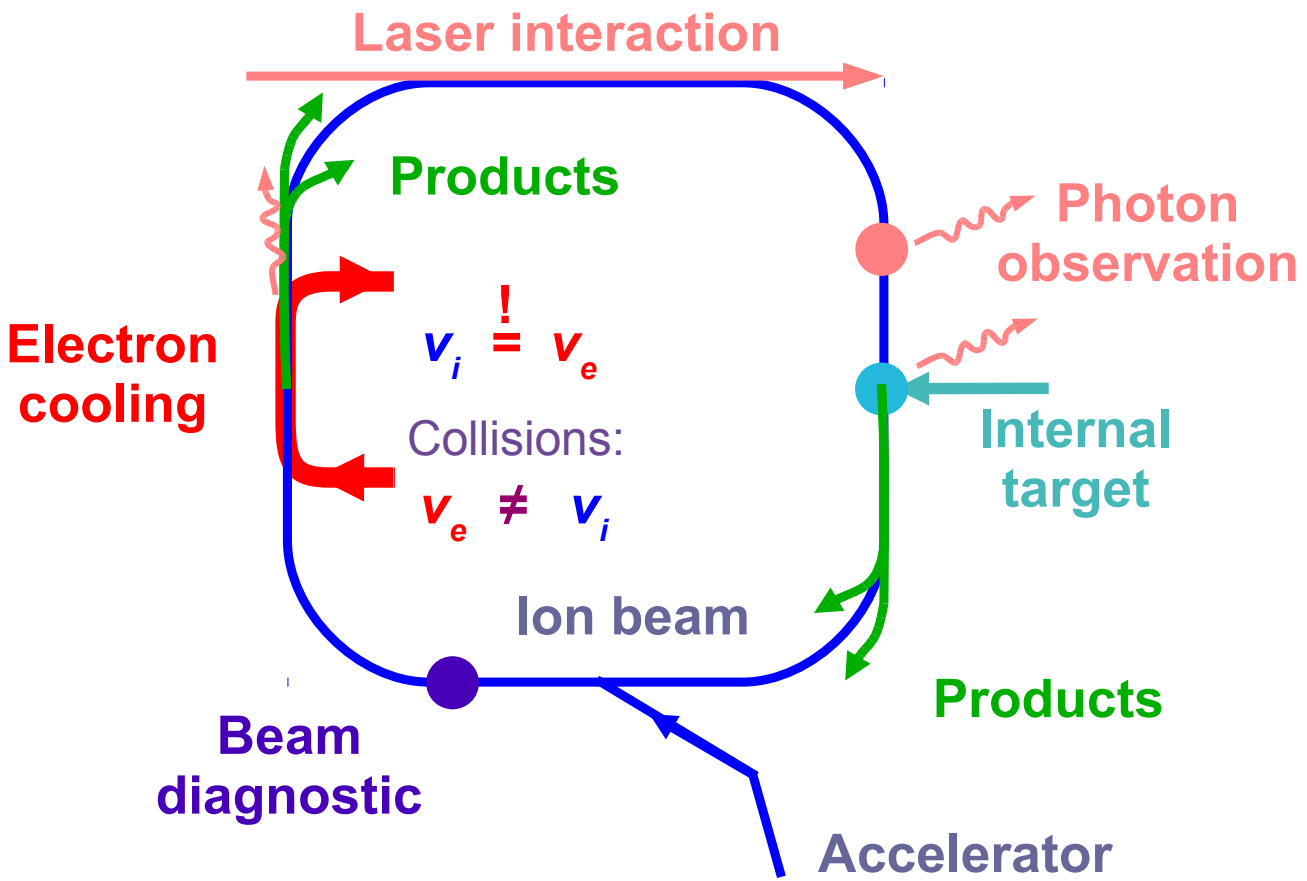
C_2H^-

SF_6^-

Organic cations and anions

Atomic and molecular clusters

Low-energy cooler storage rings



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H_3^+ H_3O^+ $HCNH^+$

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Hot interstellar gas

Gas heated by active galactic nucleus (supermassive black hole)

X-ray view (blue) of galaxy M106

Palomar observatory
A. S. Wilson et al.

Interstellar molecular clouds

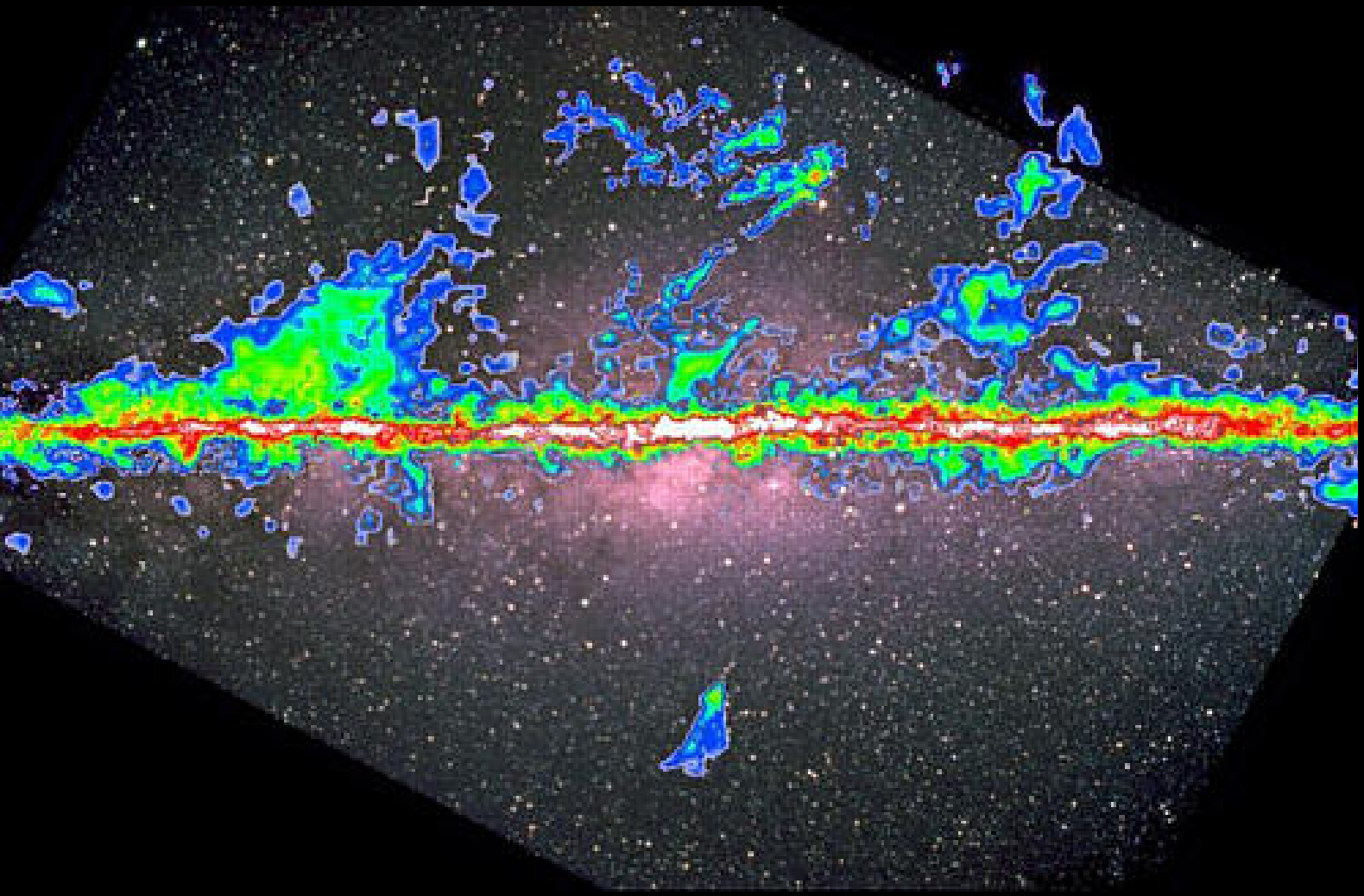
Ion chemistry
density ~10^4 cm^{-3}
temperature ~10 K

Star forming regions

Milky Way visible

Cerro Tololo
S. Kohle

Interstellar molecular clouds



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density ~10^4 cm^{-3}
temperature ~10 K

Star forming regions

Milky Way
visible

Cerro Tololo
S. Kohle

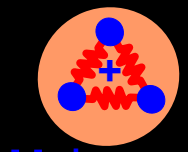
CO radio line

T. Dame
Harvard
Smithsonian

Interstellar ion chemistry

Reaction chains in interstellar clouds

- About 175 observed interstellar molecules (May 2012)
- Heavy species: CH_3CH_2OH, sugar (glycoaldehyde), ...
- Ions: CH^+
  CO^+
  SO^+
  CF^+
  HCO^+, COH^+
  HCS^+
  $HCNH^+$
  H_2COH^+
  SH^+
  HCl^+... (2012)



H_3^+

CN^- (2010)

G. Rothfuss, S. Byers, F. Haase and NOAO/AURA/NSF

IC 5067 Star forming region "Pelican nebula"

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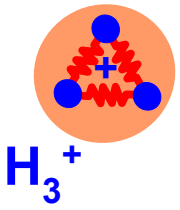

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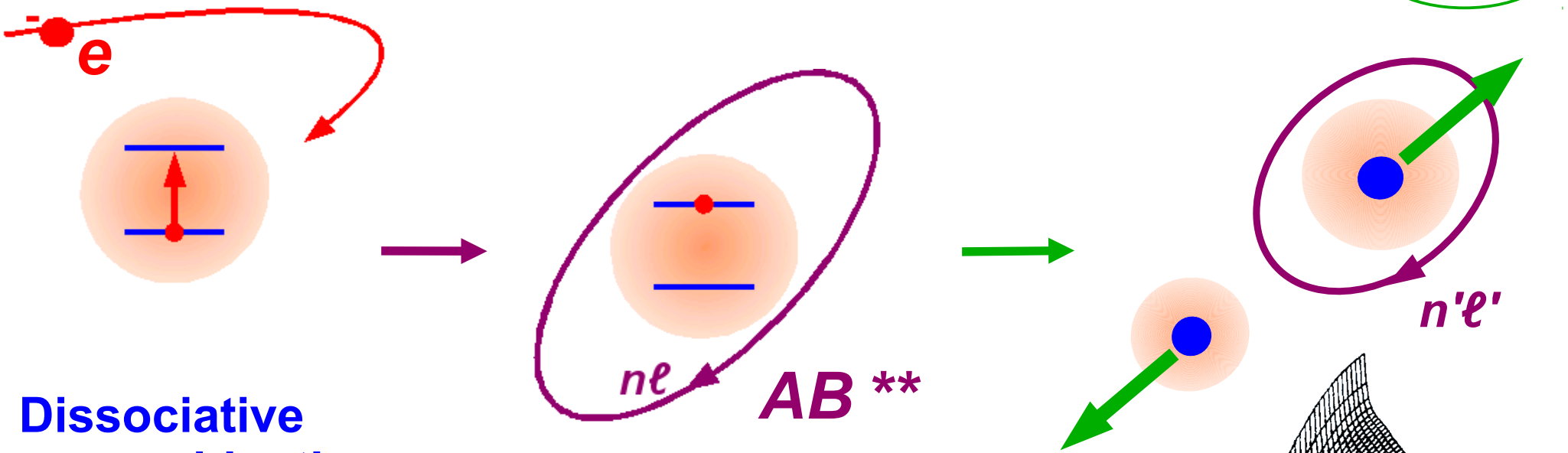
IC 5067 Star forming region "Pelican nebula"

Interstellar clouds, star-forming regions, protoplanetary disks

Observed by infrared and radio spectroscopy

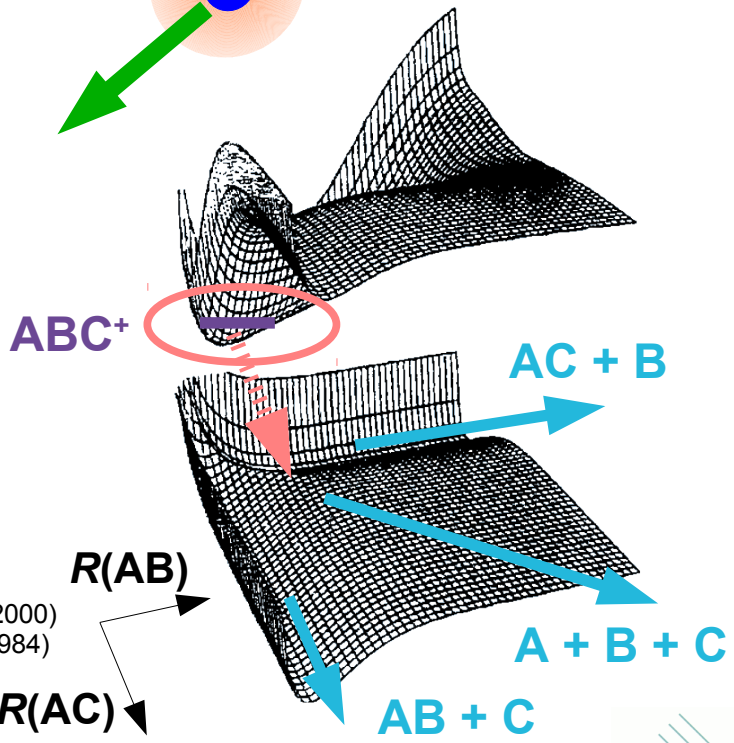
Molecular breakup by cold electrons

$AB^+ + e$ → $(AB^+)^* + n\ell$ → $A + B^* + E_{kin}$



Dissociative recombination

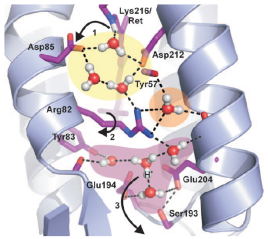
"Compound" resonance



Suzor-Weiner, Nature (2000)
Murrell, … Varandas (1984)

Dissociative electron attachment on neutral molecules

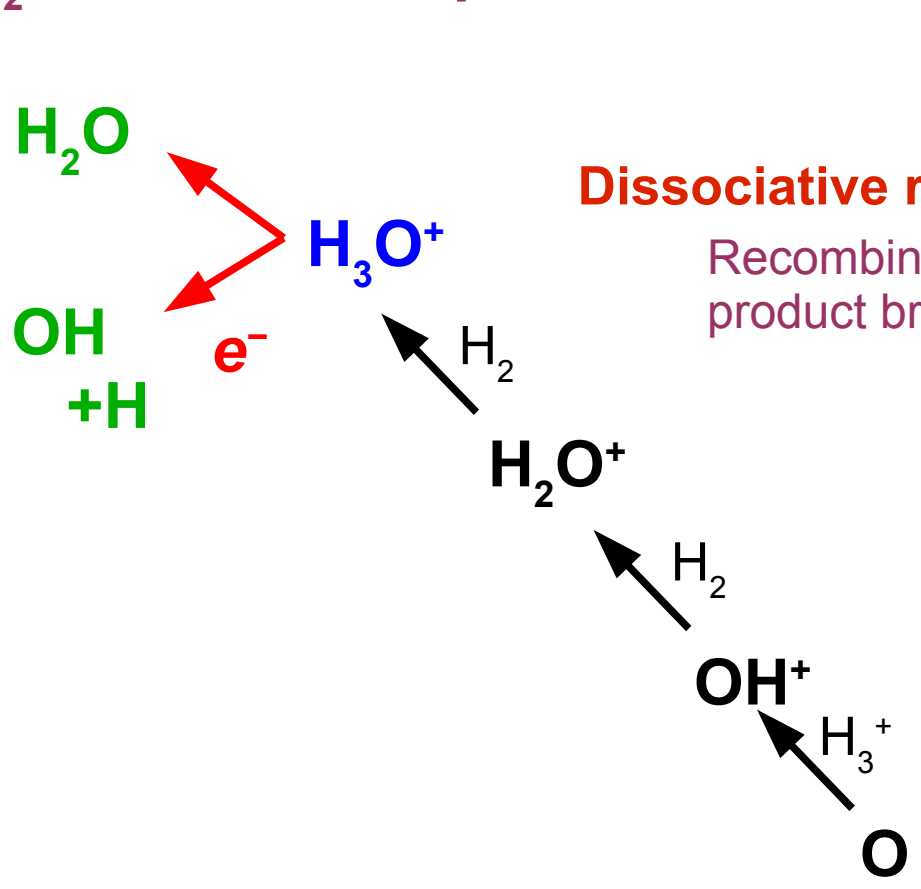
Slow electron → negative ion + dissociation



Ion chemistry building up interstellar molecules

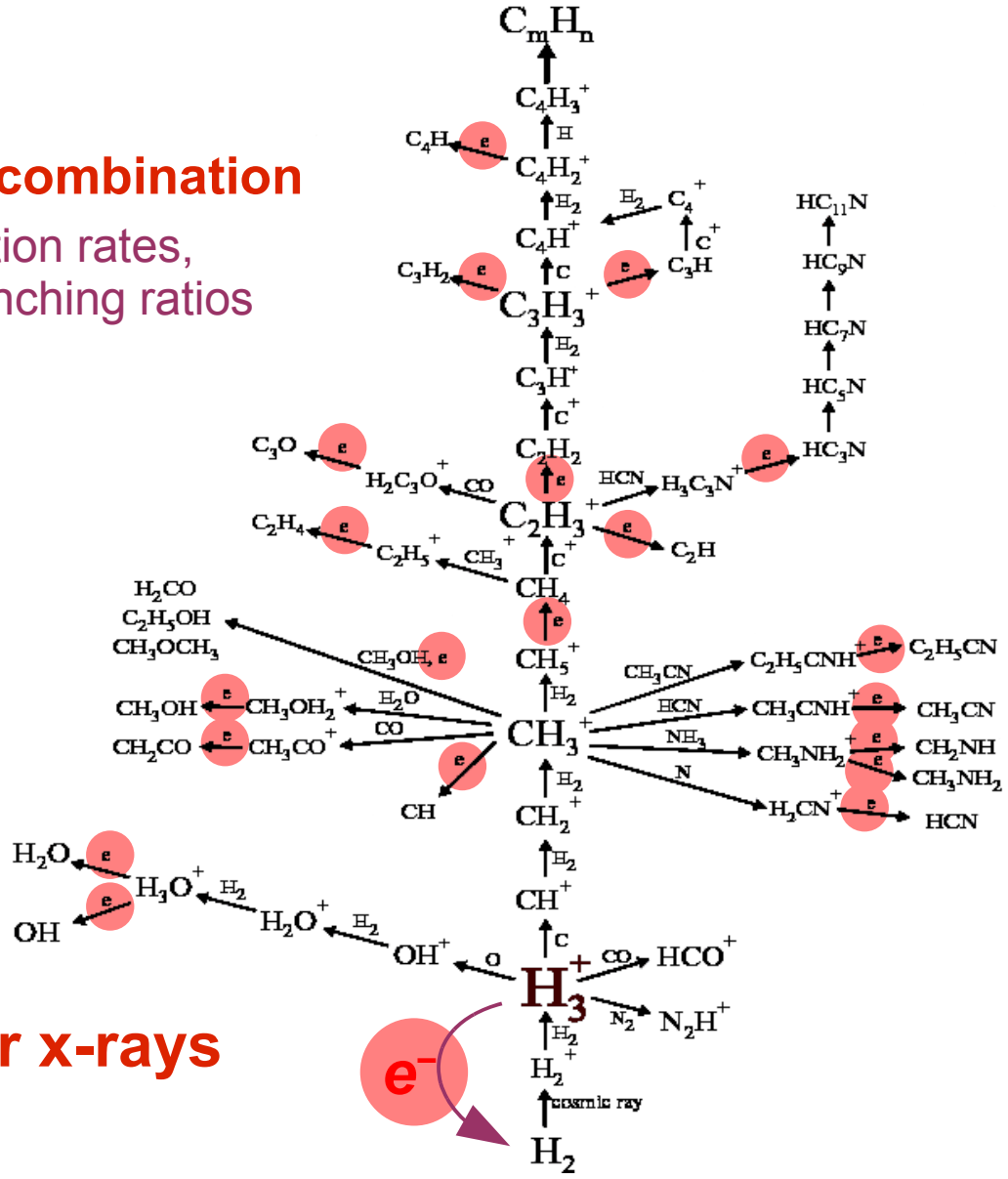
H_2 + atomic components: O, C, N, Si, S, Fe, ...

$T \sim 10$ K



Dissociative recombination

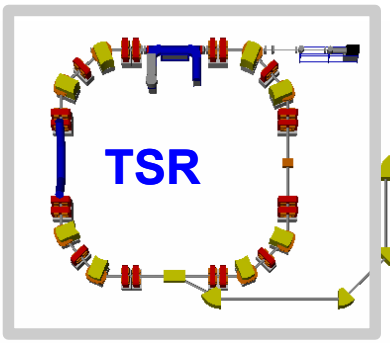
Recombination rates,
product branching ratios



Ionization by cosmic radiation or x-rays

Start of ion chemistry by H_3^+

Electron–ion merged beams at the TSR Heidelberg



~10 K interaction energy

Photocathode electron target/cooler

$v_e \neq v_i$

12 m

10 m

25 MV cavity linac

Neutral fragment detectors

Electron cooler

$v_e = v_i$

$kT_e \sim 4$ meV

$kT_e \sim 1$ meV

Synchrotron acceleration/ deceleration

0.5 MV RFQ linac

12 MV tandem accelerator

~10^6–10^8 stored ions

Translational and internal cooling

Ion sources

2.5 MeV pelletron

Extracted ions
Coulomb explosion beamline

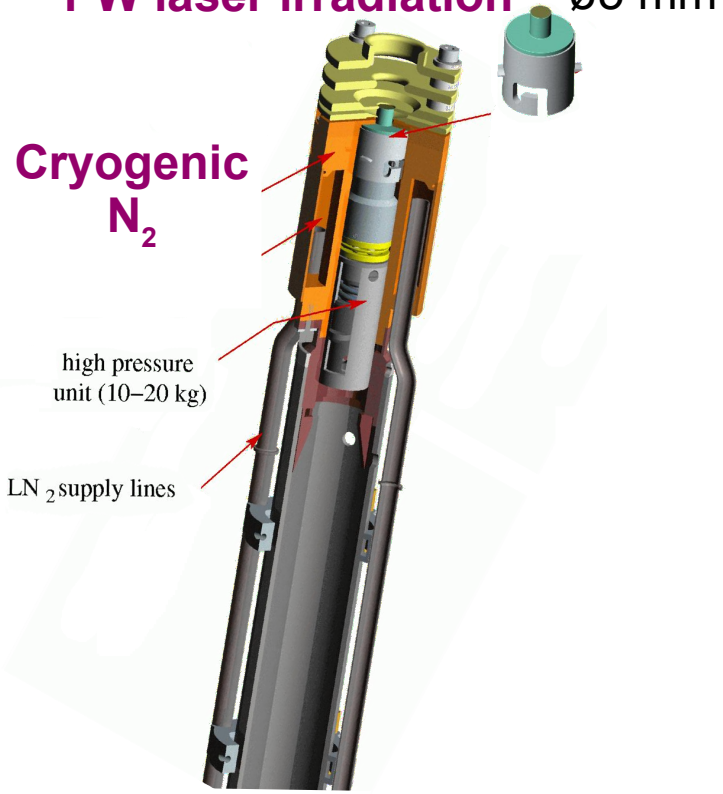
MeV ions

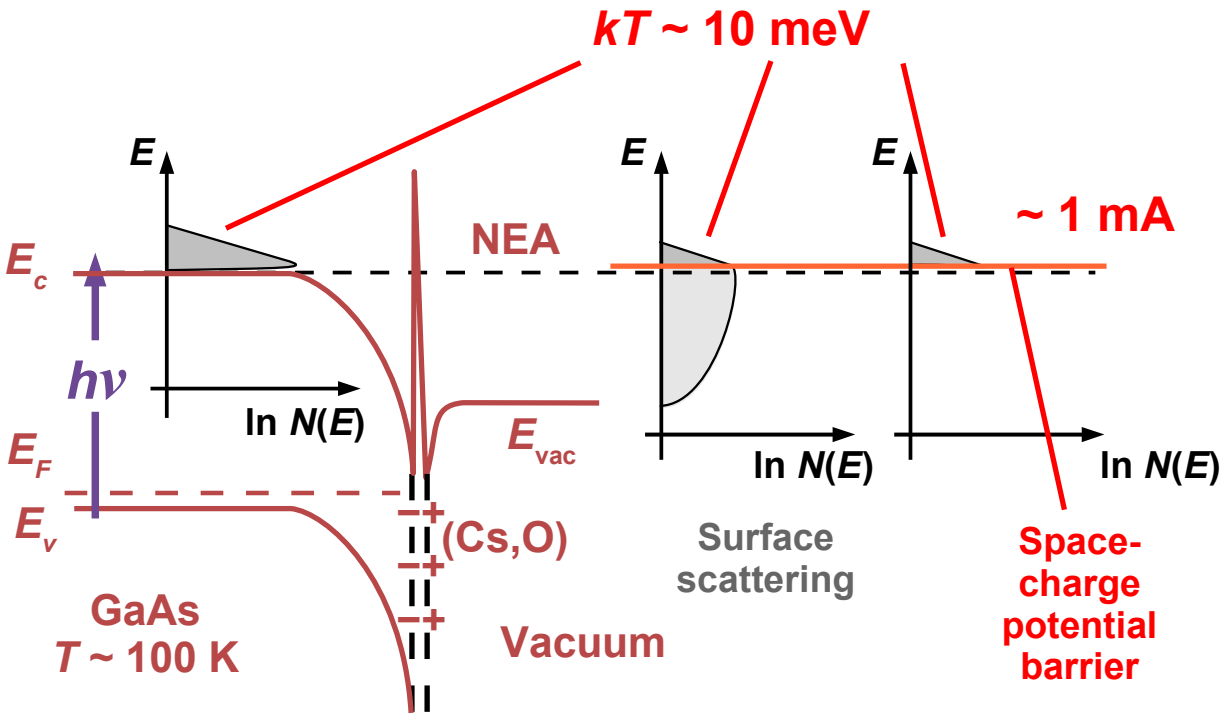
High-resolution electron target

Photocathode electron target

GaAs photocathode ~100 K

~1 W laser irradiation ø5 mm





- 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 since >2 years
- Beam transport down to < 1 eV with 10 μA current (0.01 T guiding field)

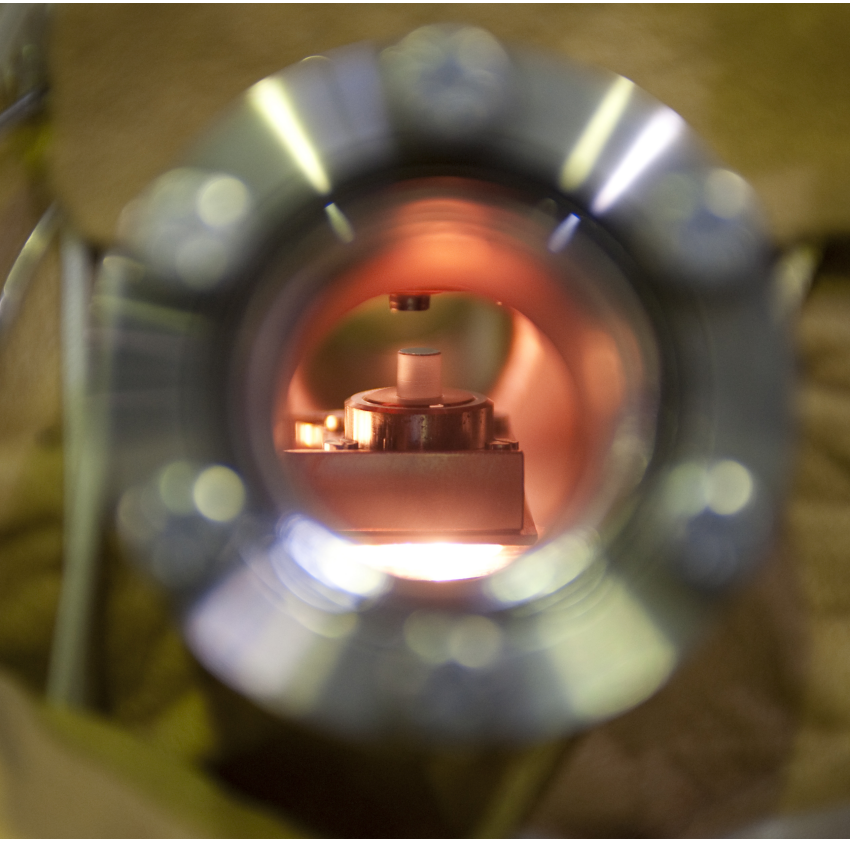
D. A. Orlov et al., J. Appl. Phys. 106, 054907 (2009)

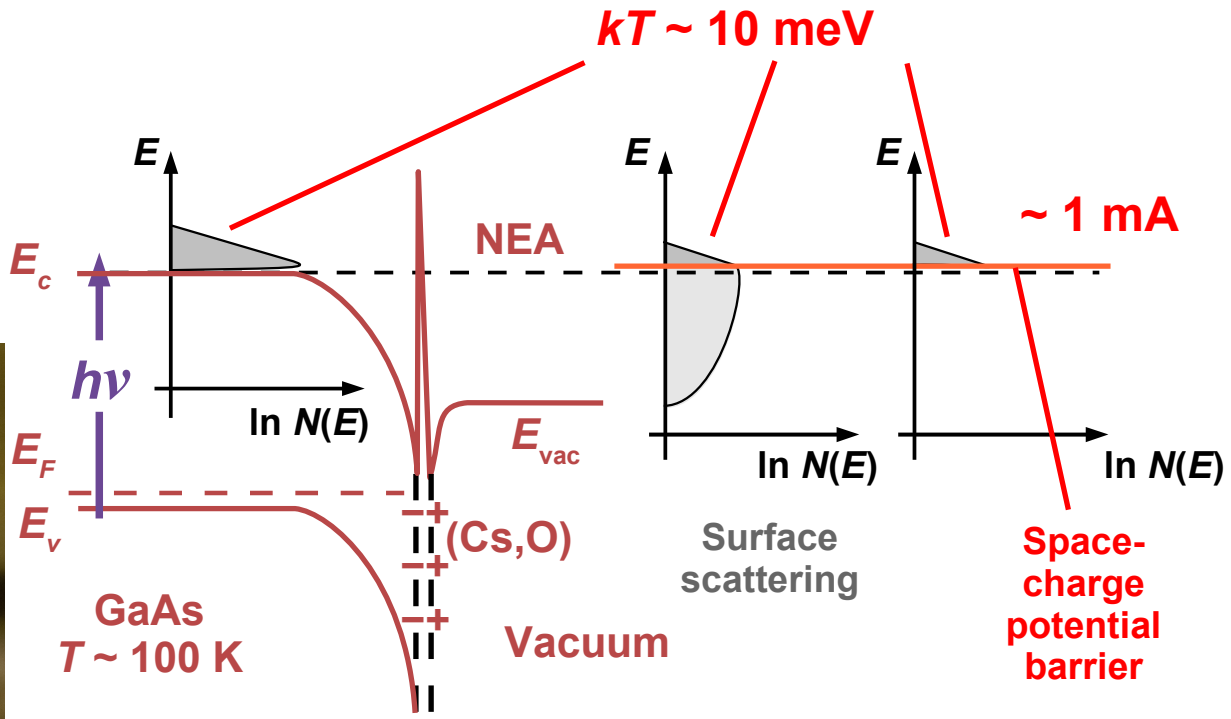
D. A. Orlov, C. Krantz, A. Shornikov
Collab. with Inst. f. Semiconductor Phys., Novosibirsk, A. N. Terekhov

High-resolution electron target

Photocathode electron target

GaAs photocathode ~100 K





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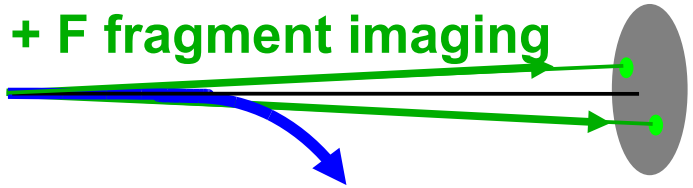
Electron cooling with a photocathode beam

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

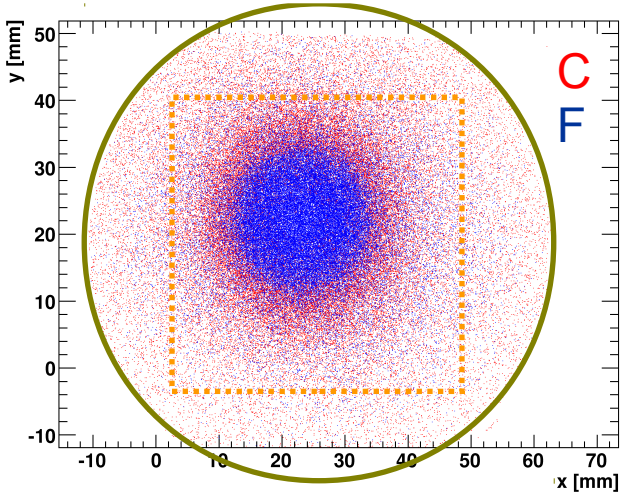
50 eV electrons

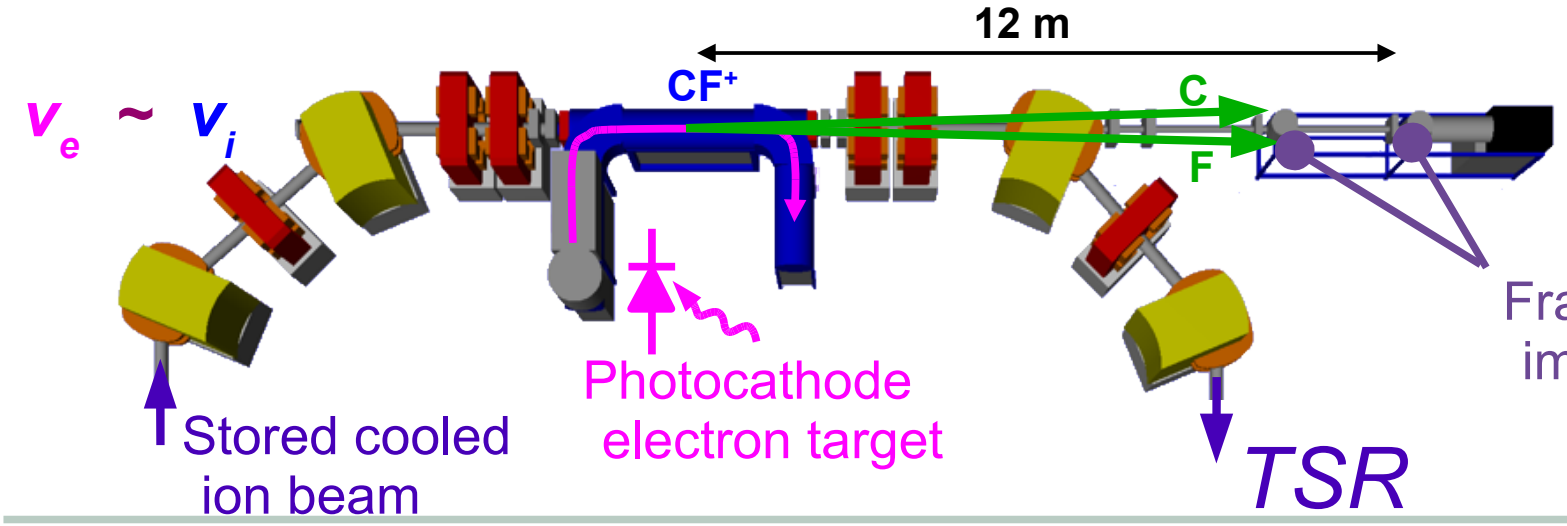
~1 mA electron current

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



Standard electron cooling (12-30 s after injection)





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

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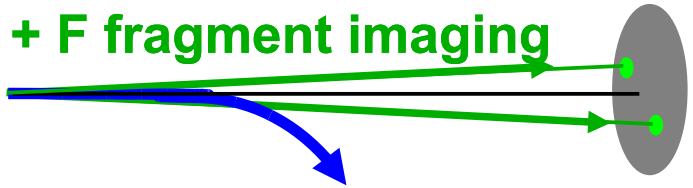
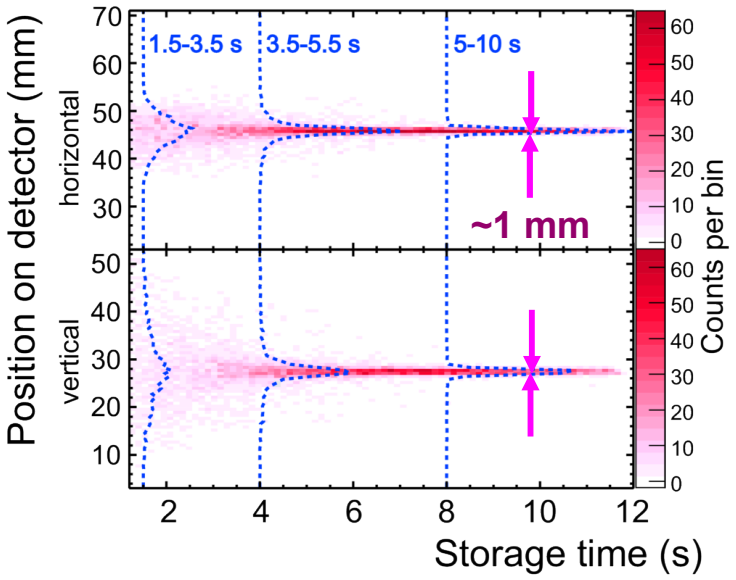
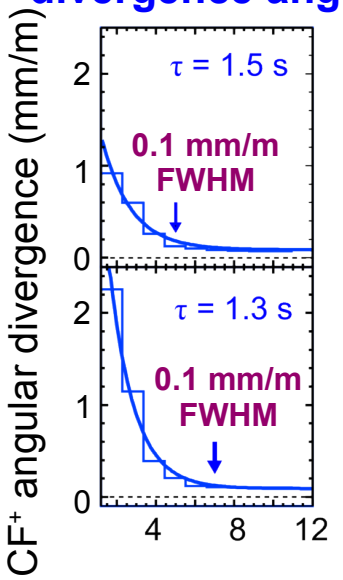
C + F fragment imaging



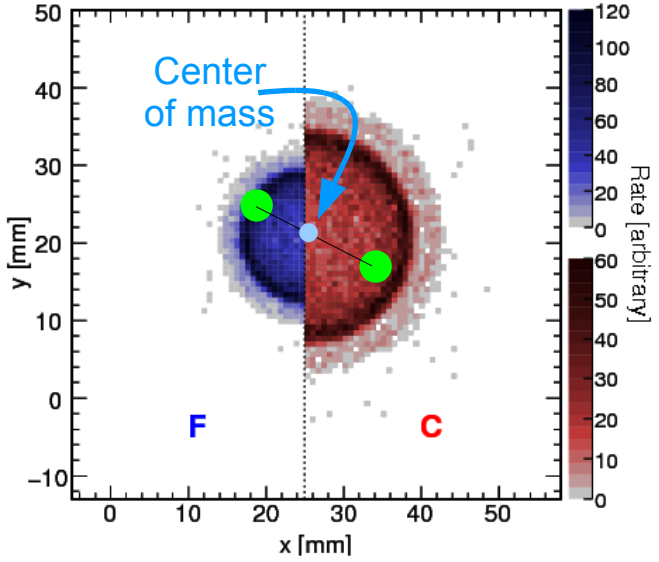
Molecular center of mass on fragment imaging detector

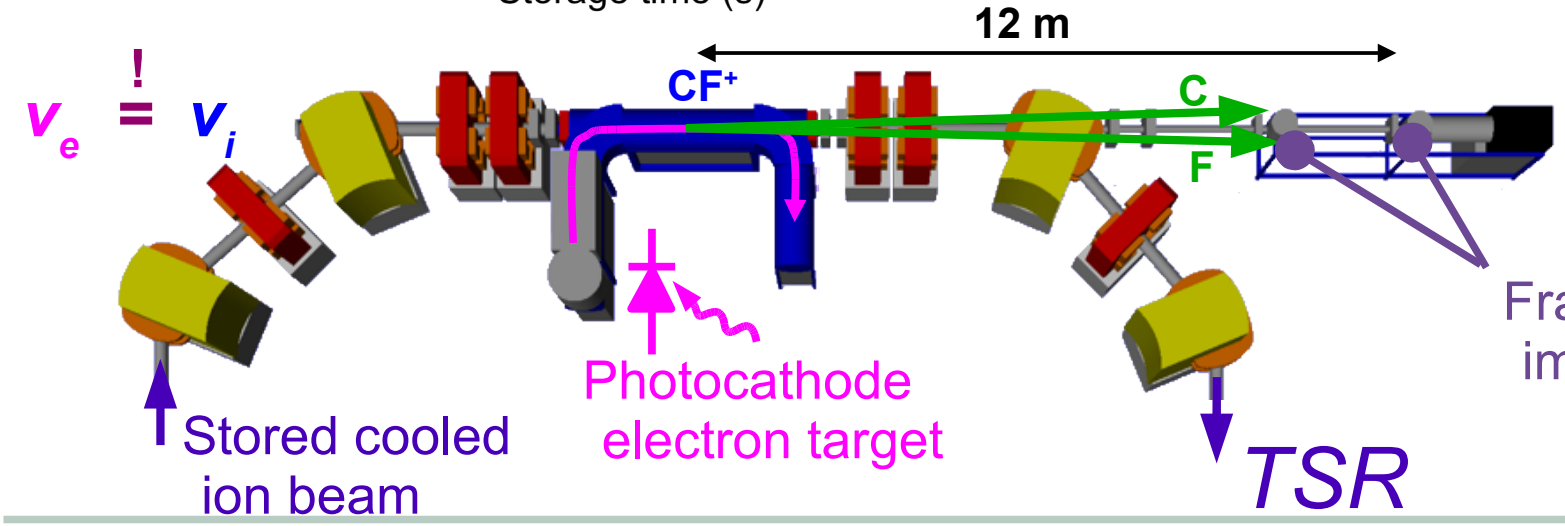


Ion beam divergence angle



Photocathode electron cooling





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

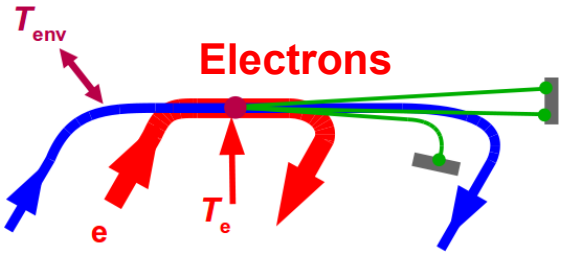
Molecular ion recombination

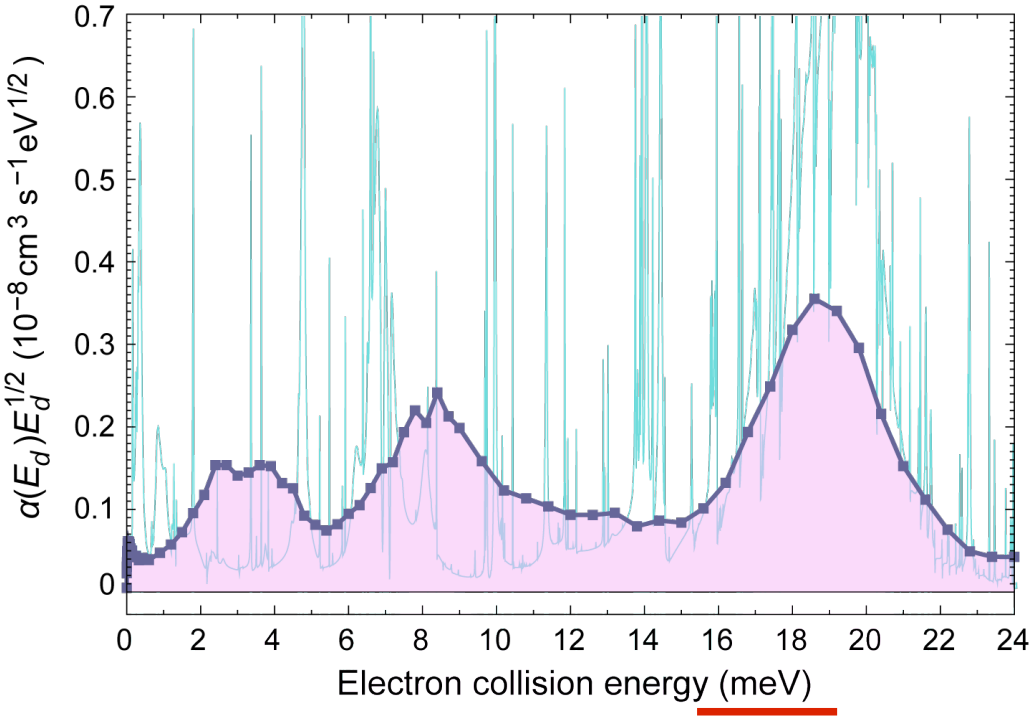
High-resolution cross section at low energies

$HD^+ + e^- \rightarrow H + D$

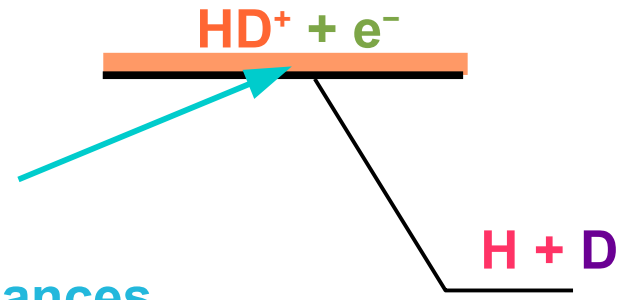
TSR measurement:
1) Photocathode electron cooling
2) Scan electron energy near "cooling"

Waffeu-Tamo et al., PRA 84, 022710 (2011)





1 meV = 10 K



Theory:
Rovibrational capture resonances

Molecular ion recombination

High-resolution cross section at low energies

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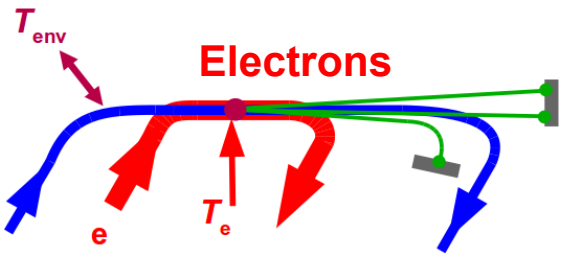
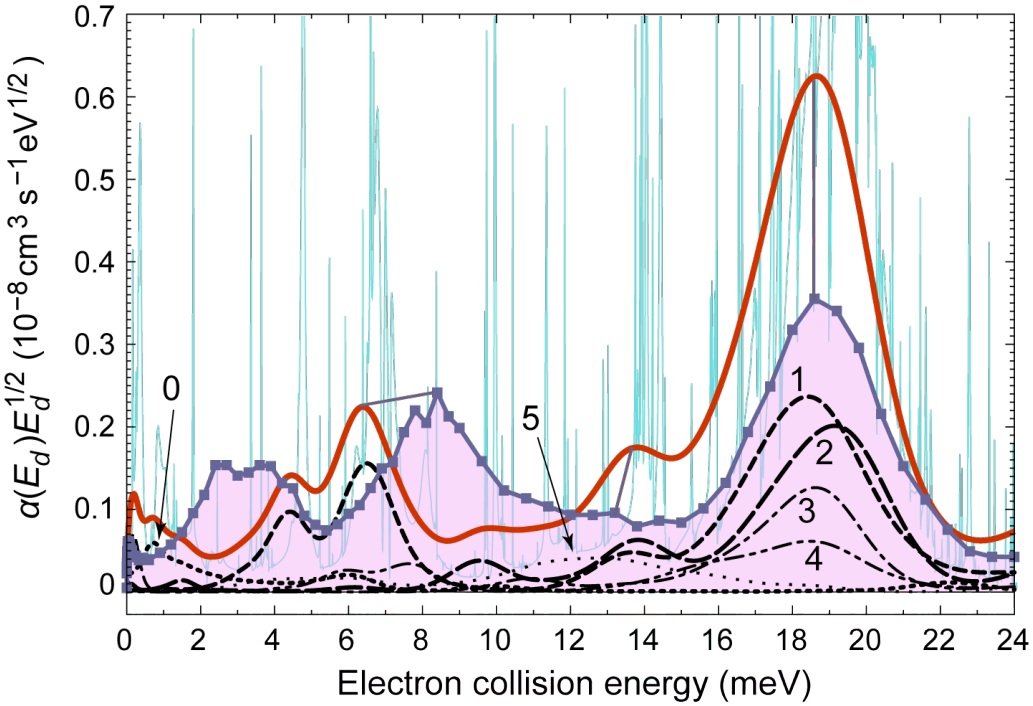
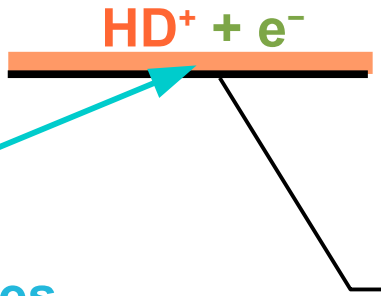






Theory:
Rovibrational capture resonances

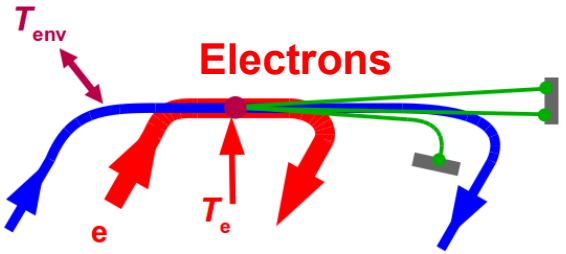
Measured recombination dominated by rotating molecules at 300 K: $J \geq 1$

J	T_{rot} 300 K
0	0.104
1	0.251
2	0.271
3	0.199
4	0.108

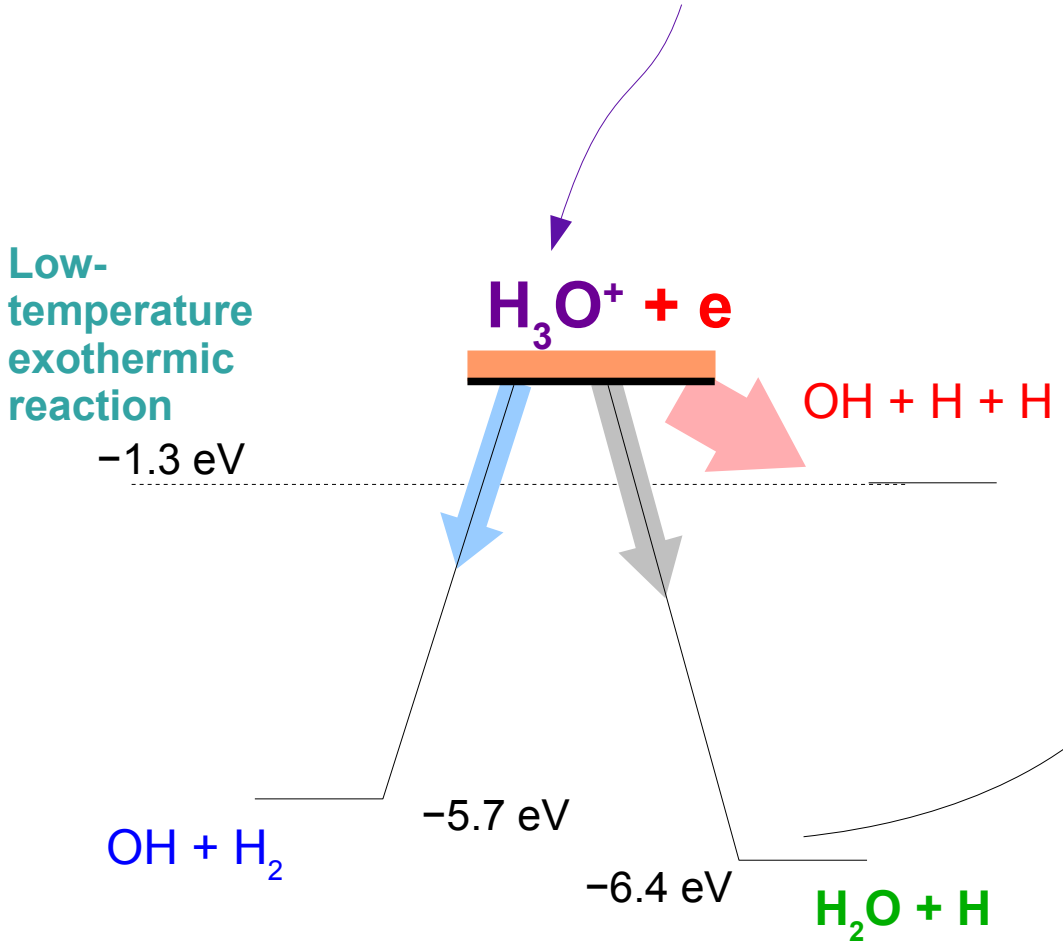
Relative population of rotational levels

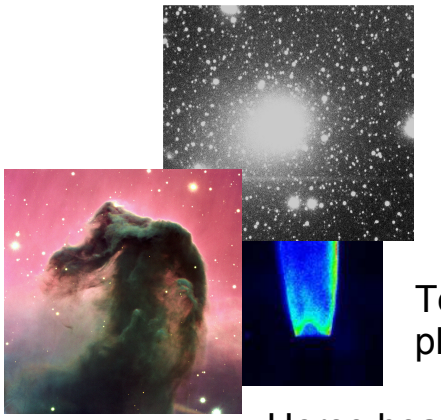
Polyatomic ions at TSR

Fragmentation pathways of dissociative recombination



Molecules built up by ion chemistry





Coma of comet Hale-Bopp

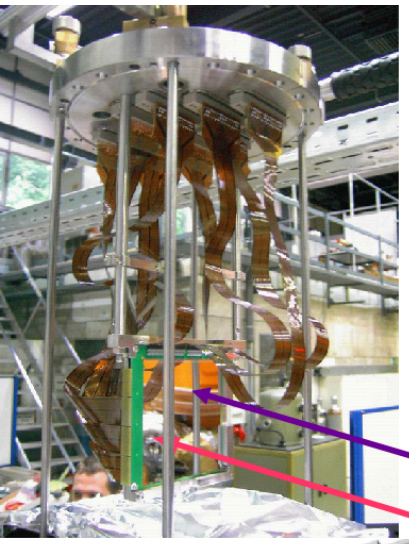
Terrestrial plasma

Horse head nebula

Source of water in cold molecular clouds, comets, ...

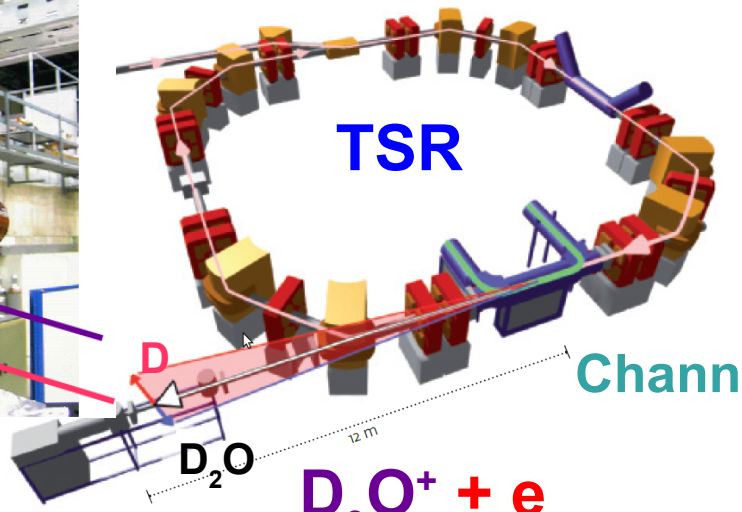
Polyatomic ions at TSR

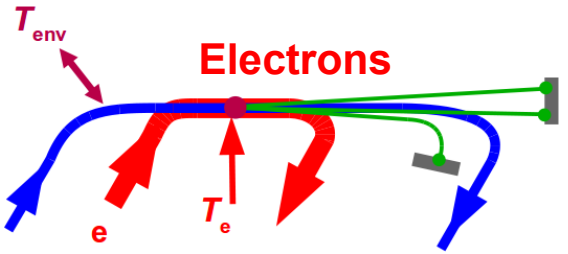
Fragmentation pathways of dissociative recombination



EMU detector

H. Buhr et al.,
PRA 81, 062702 (2010)





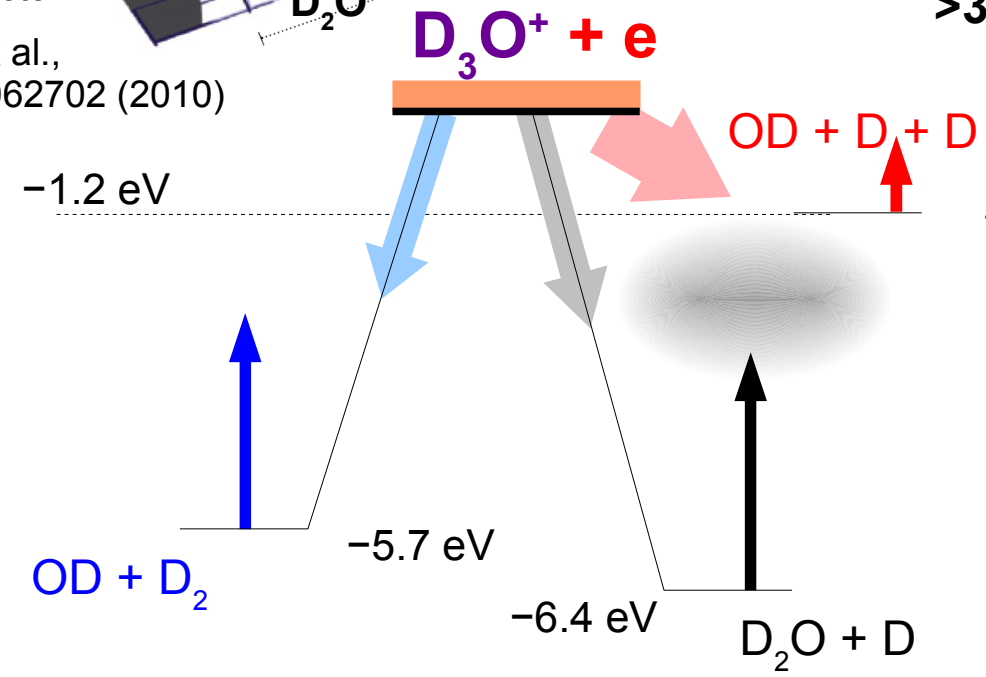
Method:

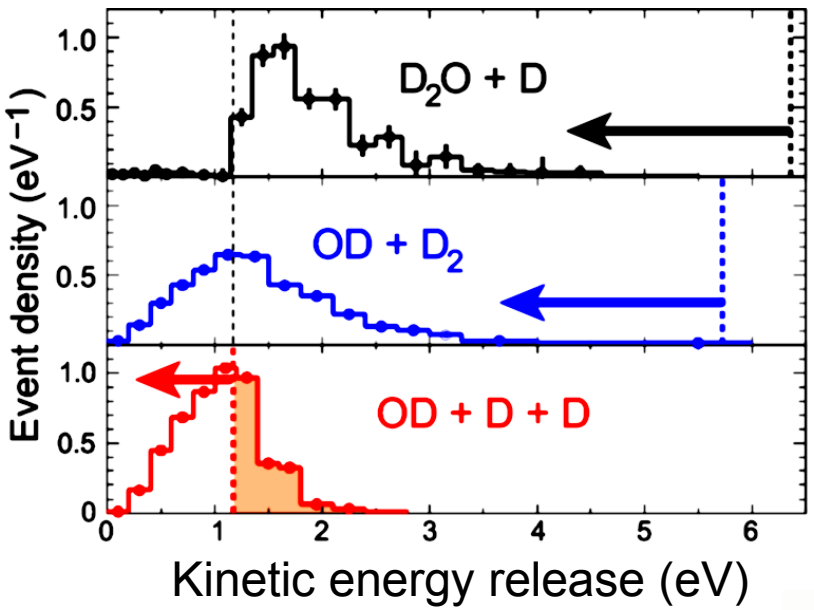
- 1 meV electron collision energy
- Imaging detector with fragment mass recognition (EMU)
- Deuterated molecules

Channel-specific energy release measurement

>3 eV vibrational excitation of water

H. Buhr et al., PRL 105, 103202 (2010)



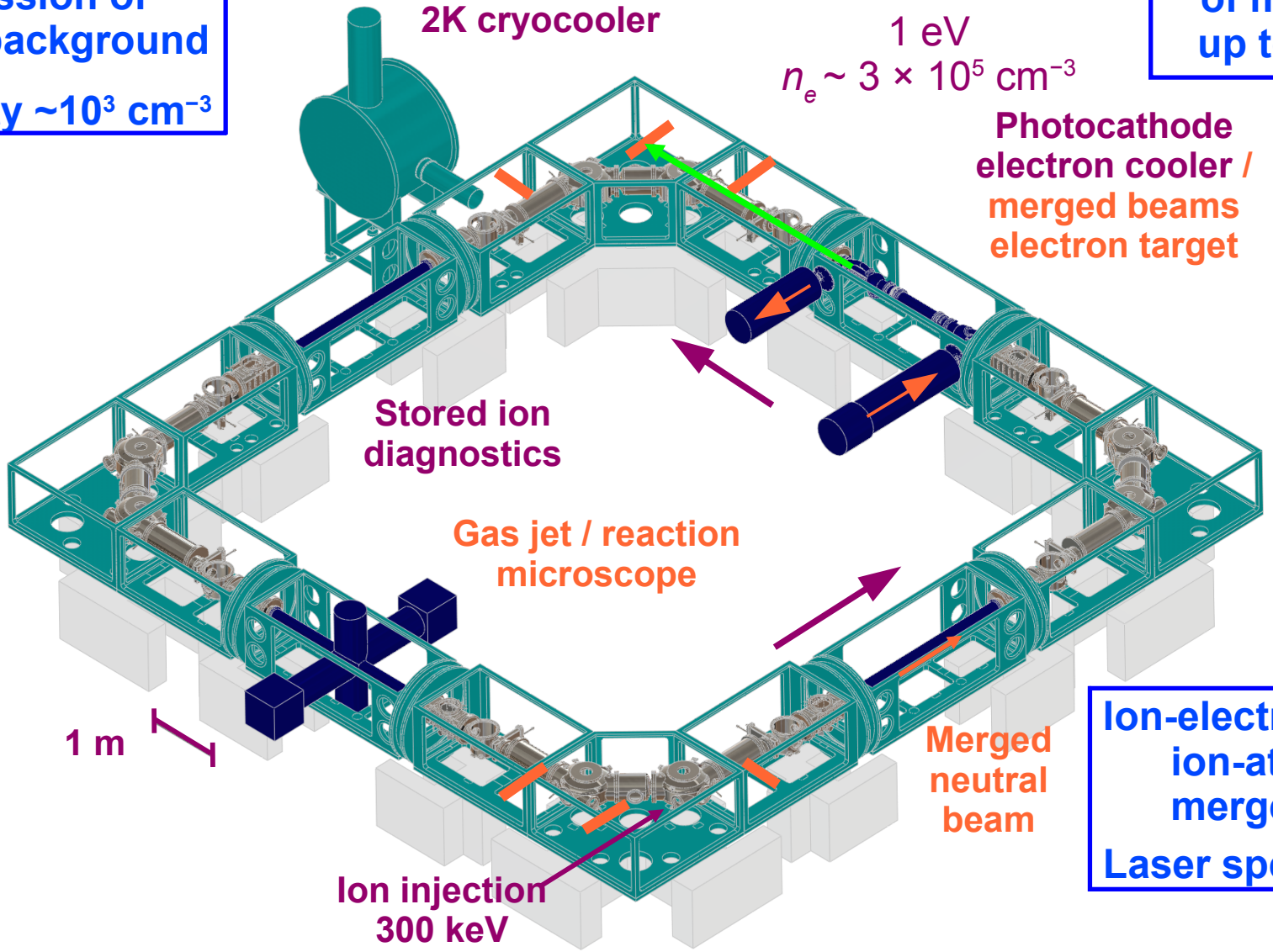


Cryogenic electrostatic storage ring CSR

Stored ion beams with keV energies of large compounds, clusters (cations, anions), heavy atomic beams, highly charged ions

2 K cryopumping and suppression of radiation background

Gas density ~10^3 cm^{-3}



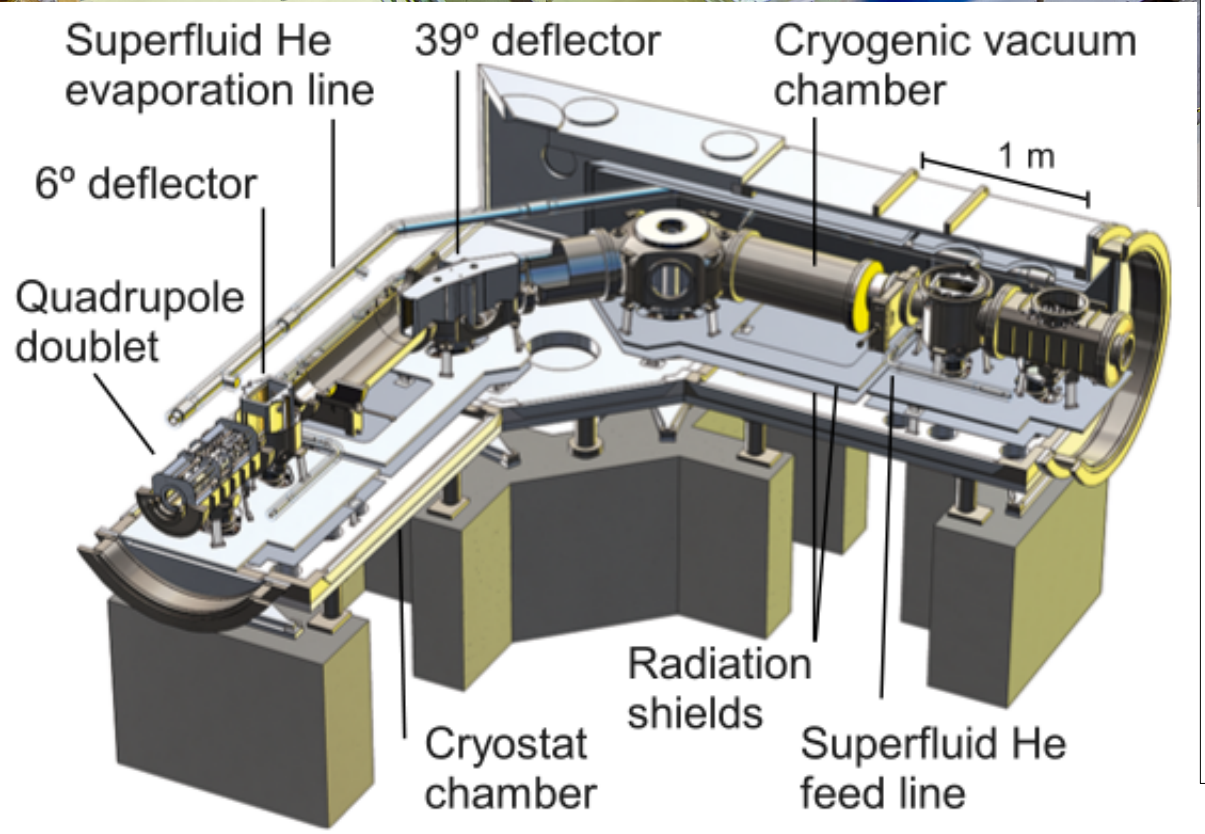
Electron cooling of molecules up to A ~ 160

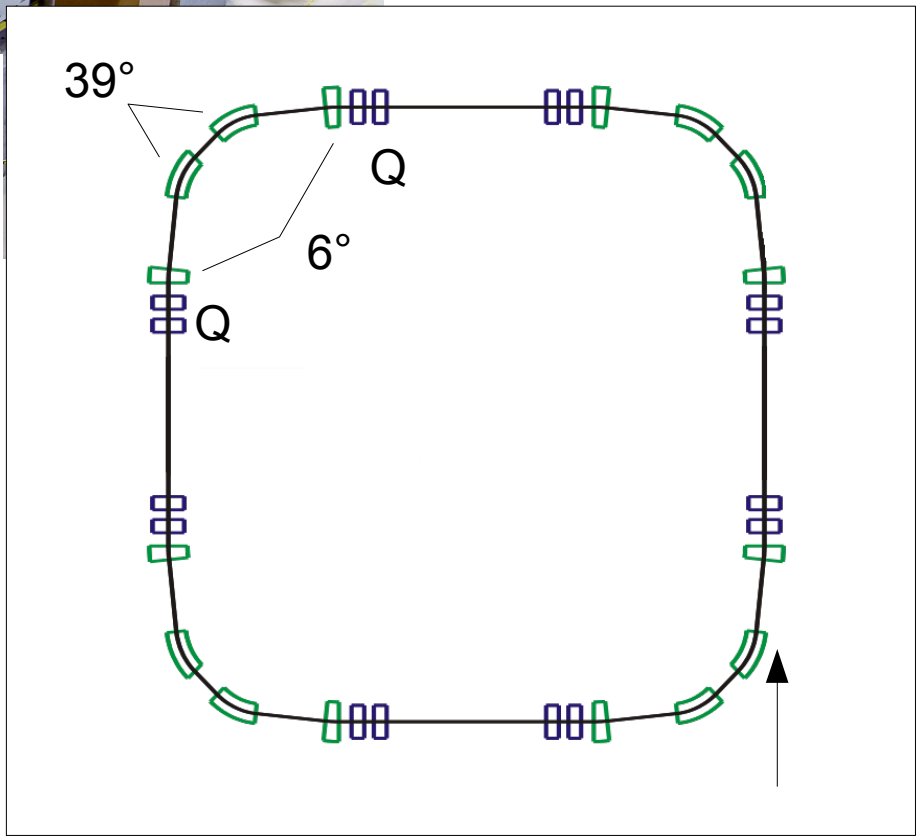
D. A. Orlov, C. Krantz, A. Shornikov et al.

Ion-electron and ion-atom merged beams

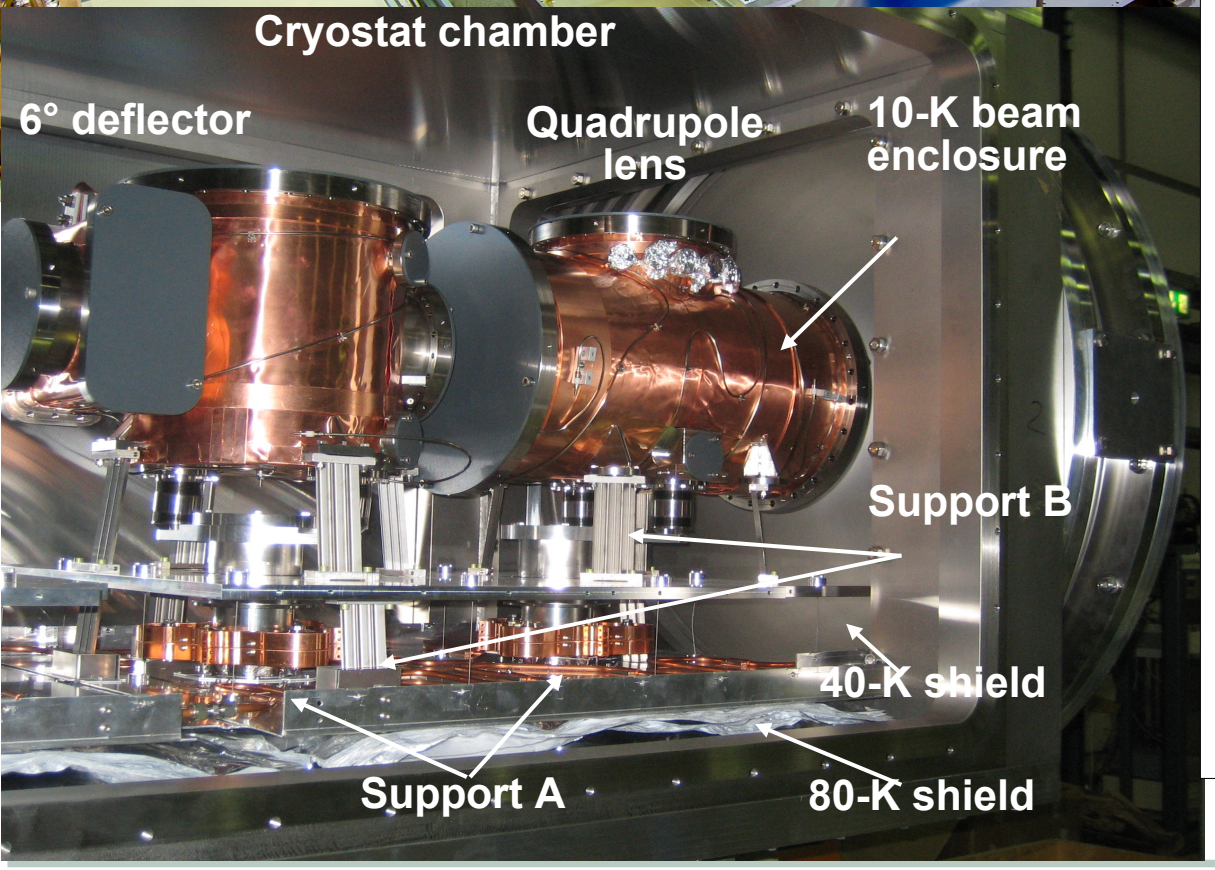
Laser spectroscopy

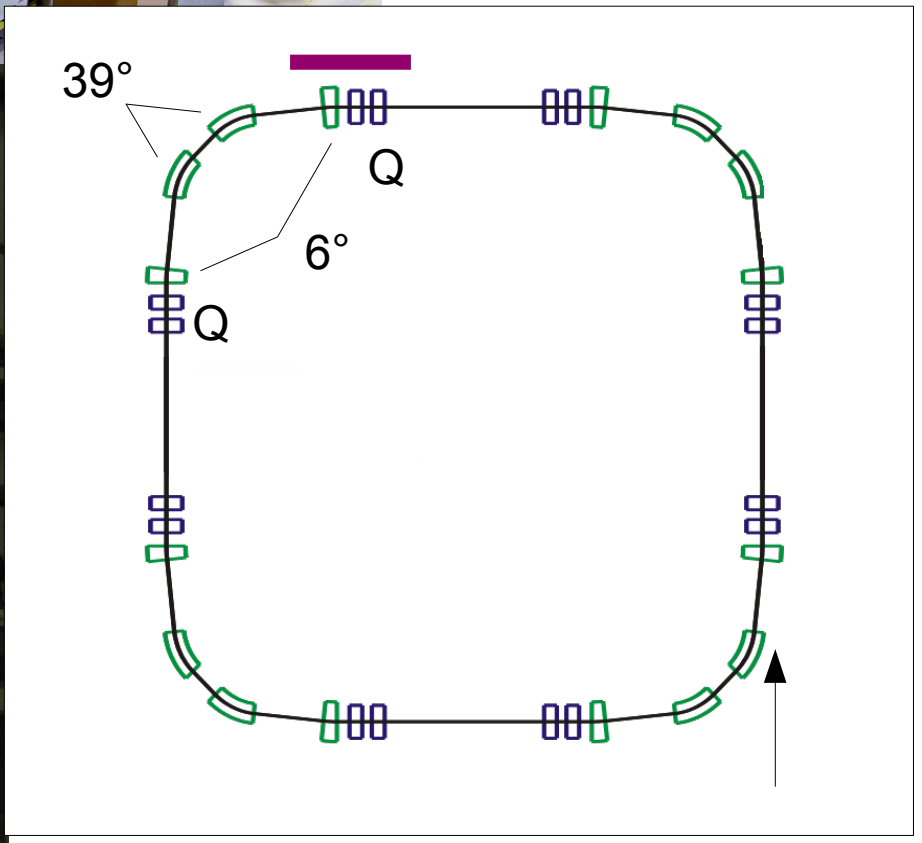
Cryogenic storage ring CSR



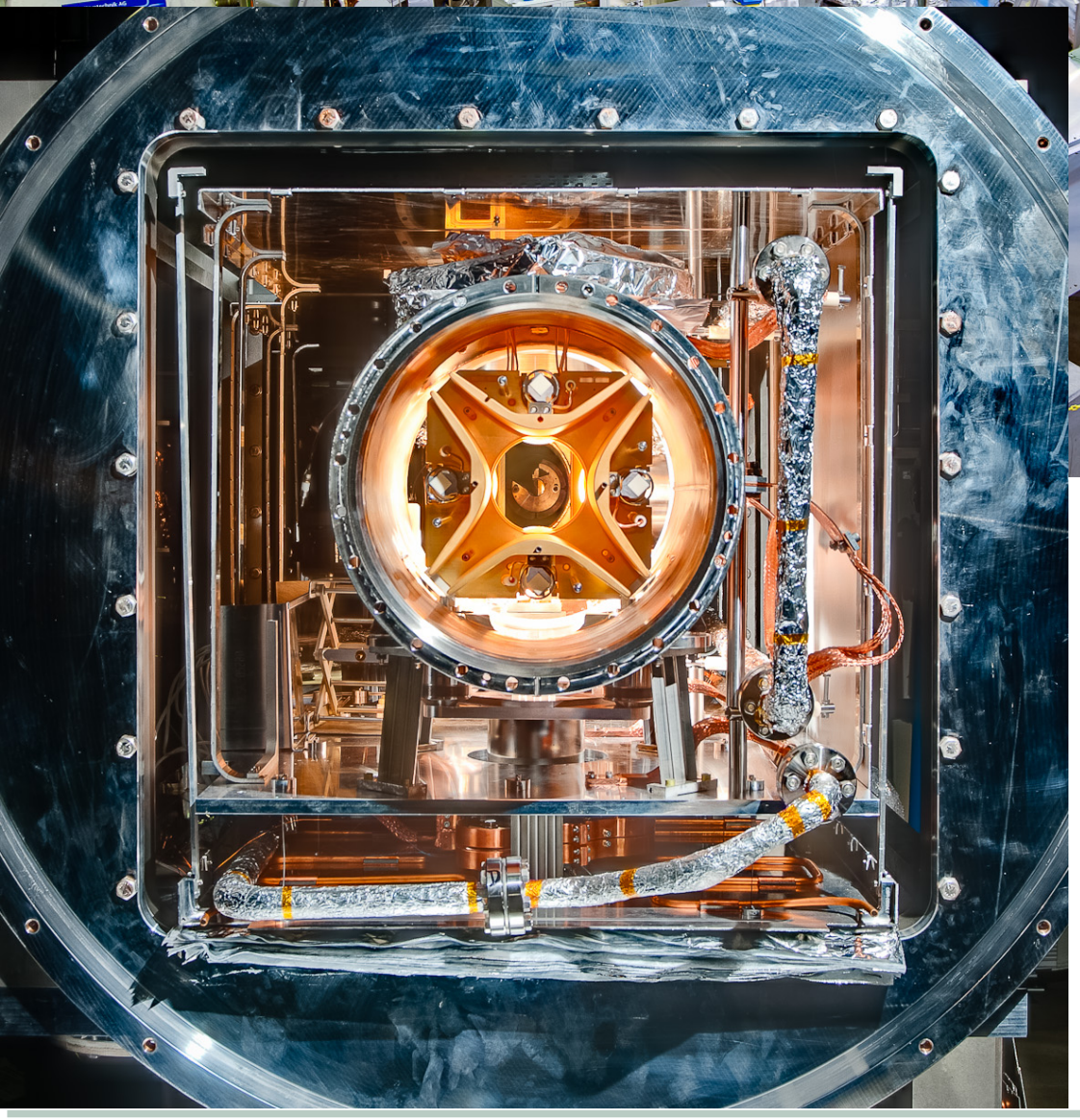


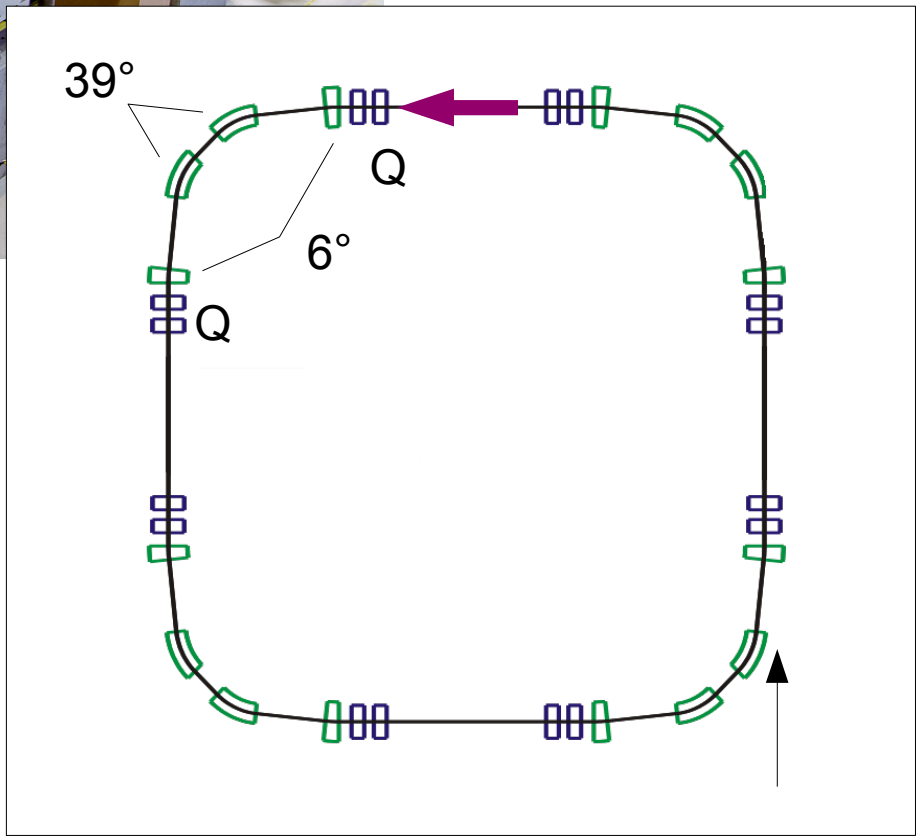
Cryogenic storage ring CSR



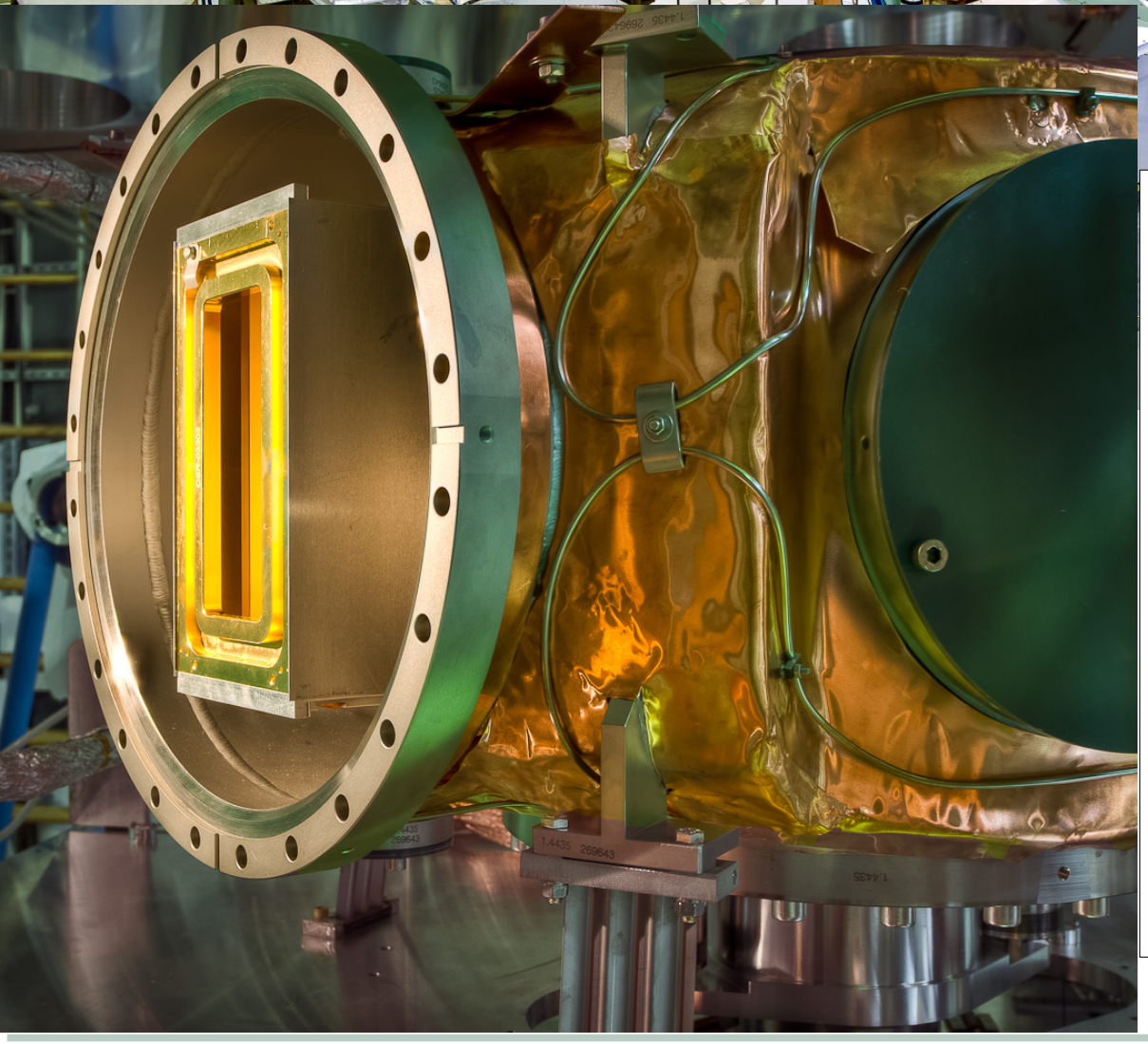


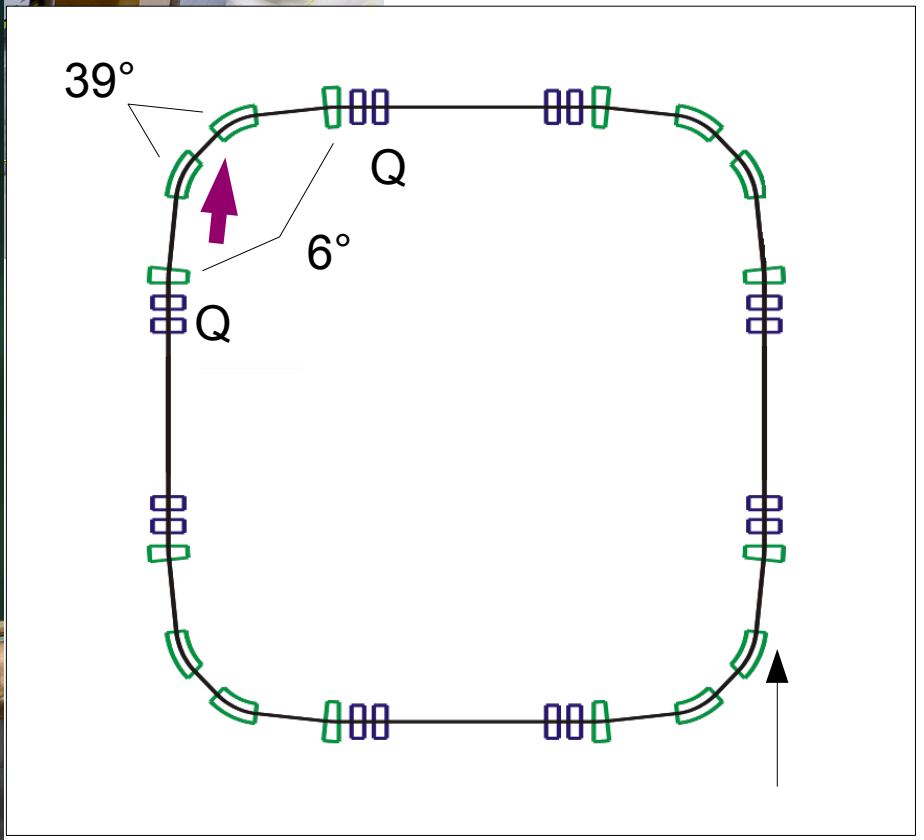
Cryogenic storage ring CSR





Cryogenic storage ring CSR



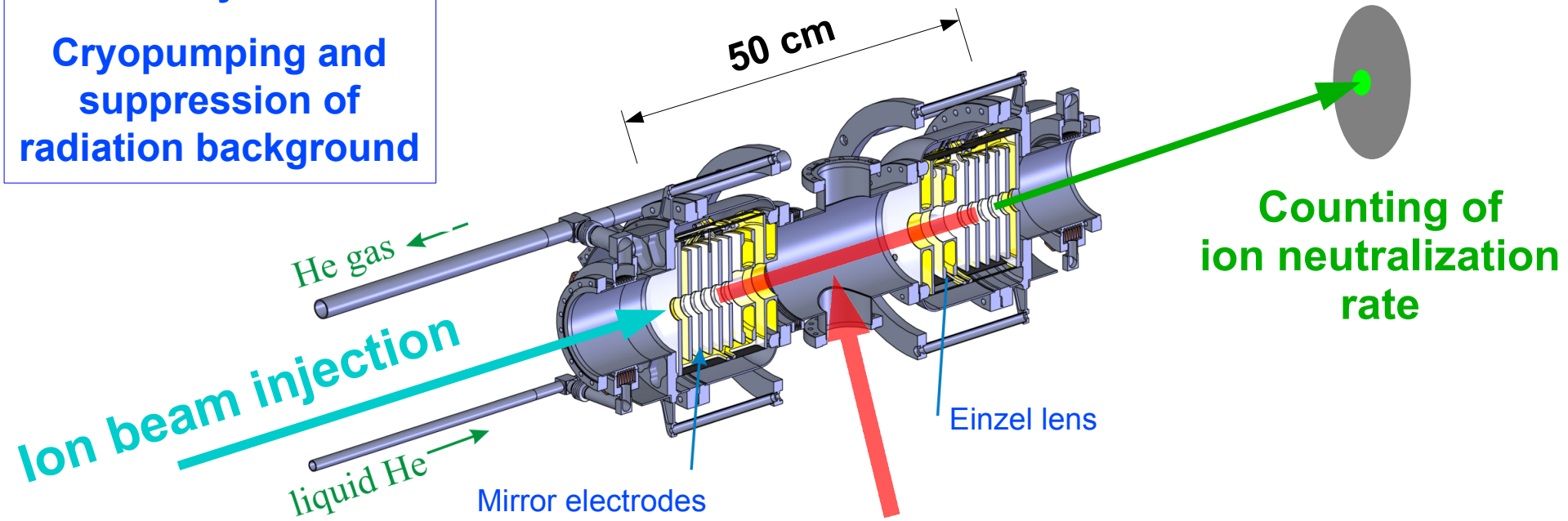


CSR cryo and vacuum tests – the CTF

CTF : Ion beam trap with CSR cryogenic (2 K) and vacuum concept

Gas density ~10^3 cm^{-3}

Cryopumping and suppression of radiation background

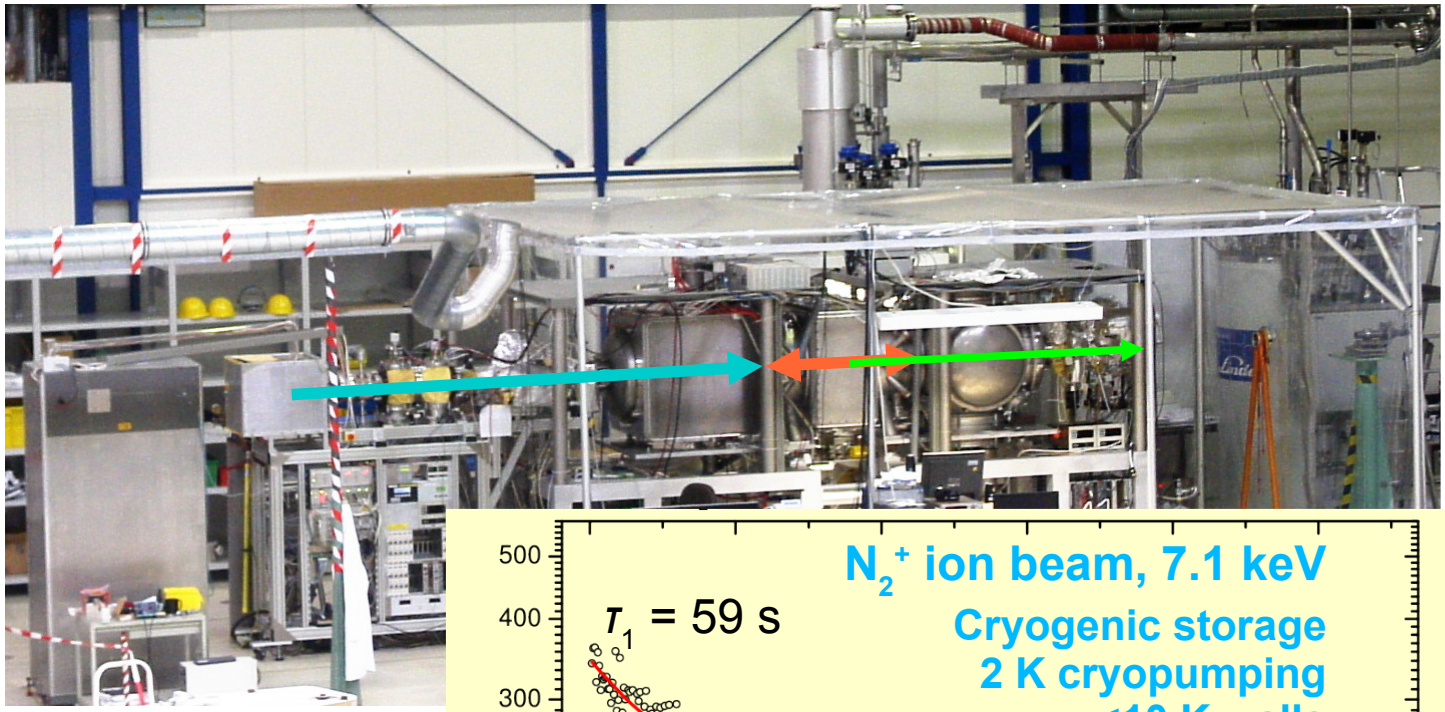


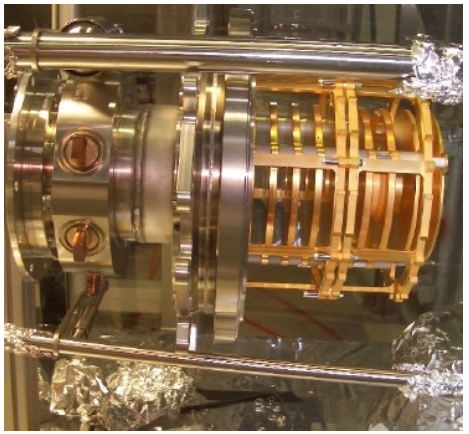
Storage of ~ 5 keV ion beam

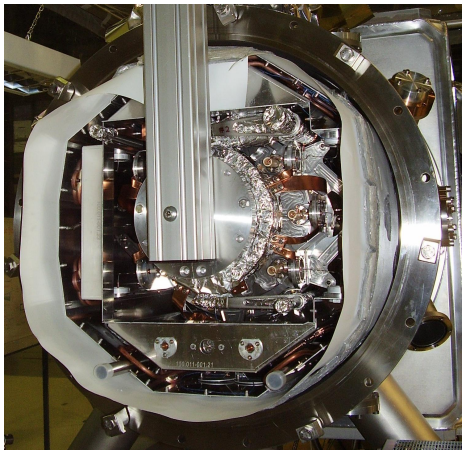
Typical storage lifetime in room-temperature devices: τ ~ 5 s (gas density few 10^5 cm^{-3})

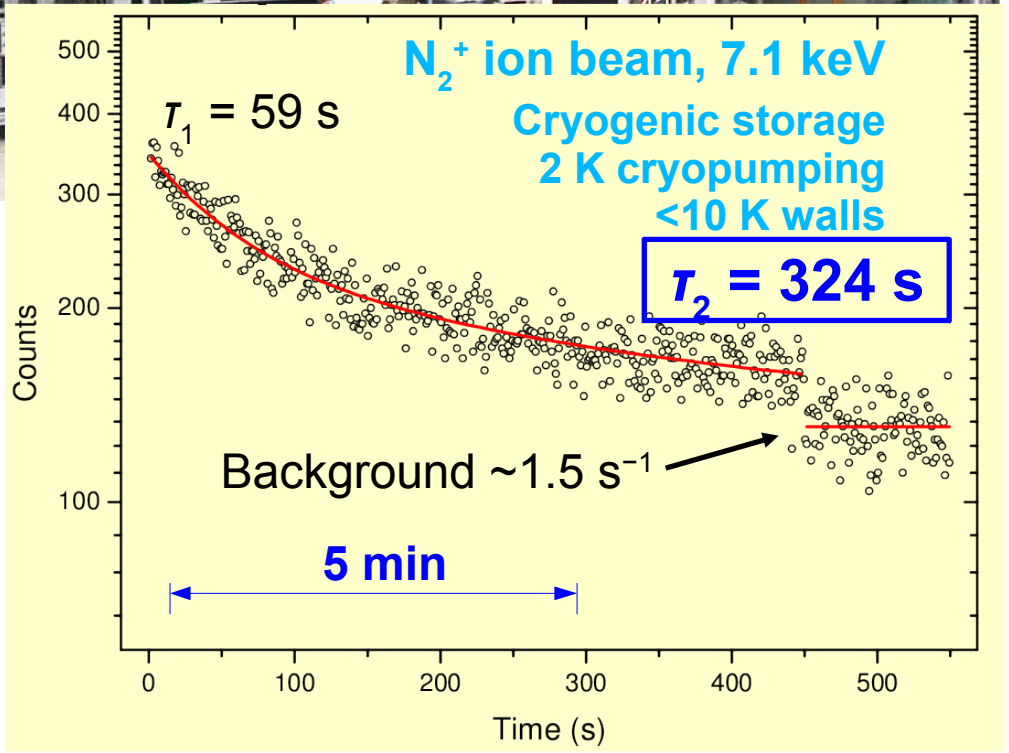
CSR cryo and vacuum tests – the CTF

CTF : Ion beam trap with CSR cryogenic (2 K) and vacuum concept









Count rate from ion neutralization

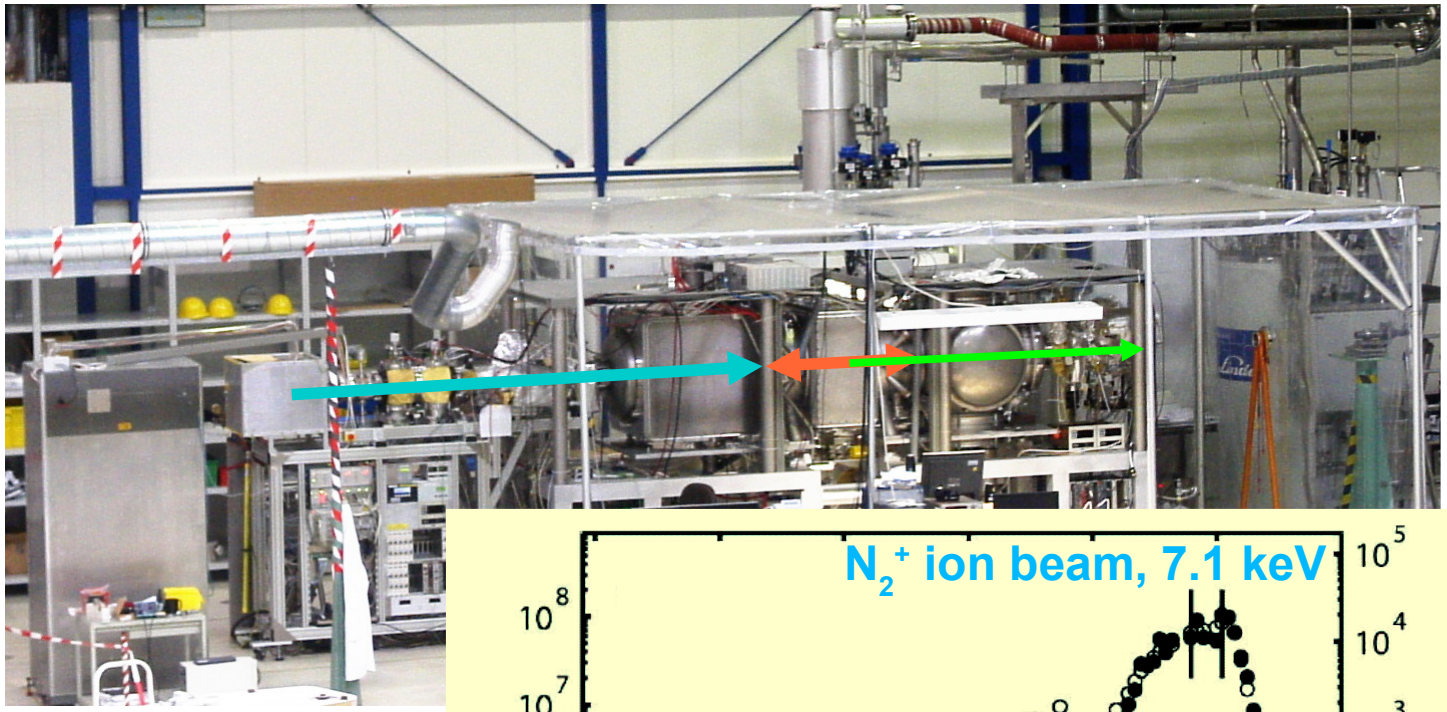
>10^8 reflections

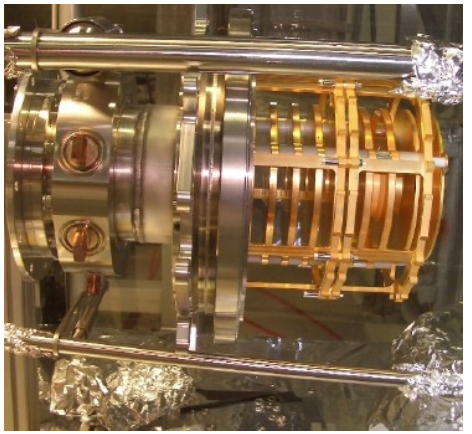
M. Lange et al., Rev. Sci. Instrum. 281, 055105 (2010)

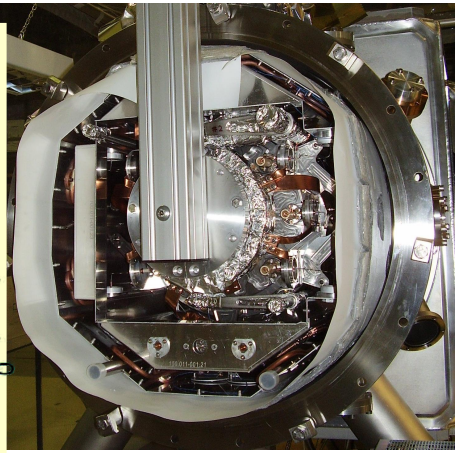
M. Froese, M. Lange, S. Menk et al.

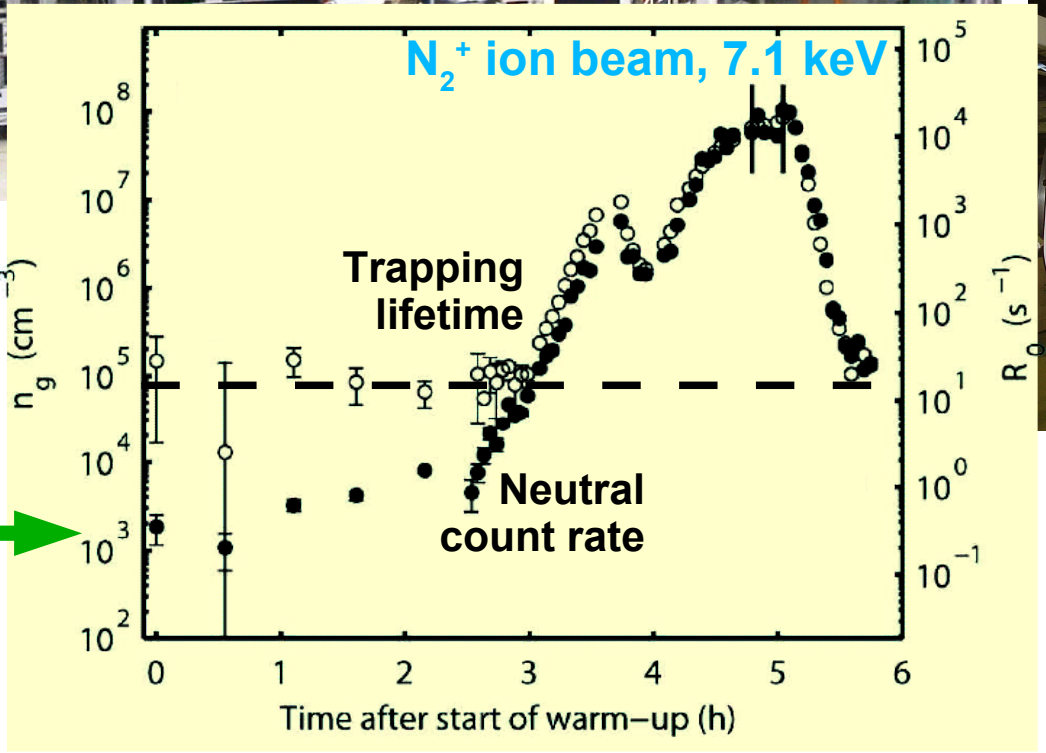
CSR cryo and vacuum tests – the CTF

CTF : Ion beam trap with CSR cryogenic (2 K) and vacuum concept









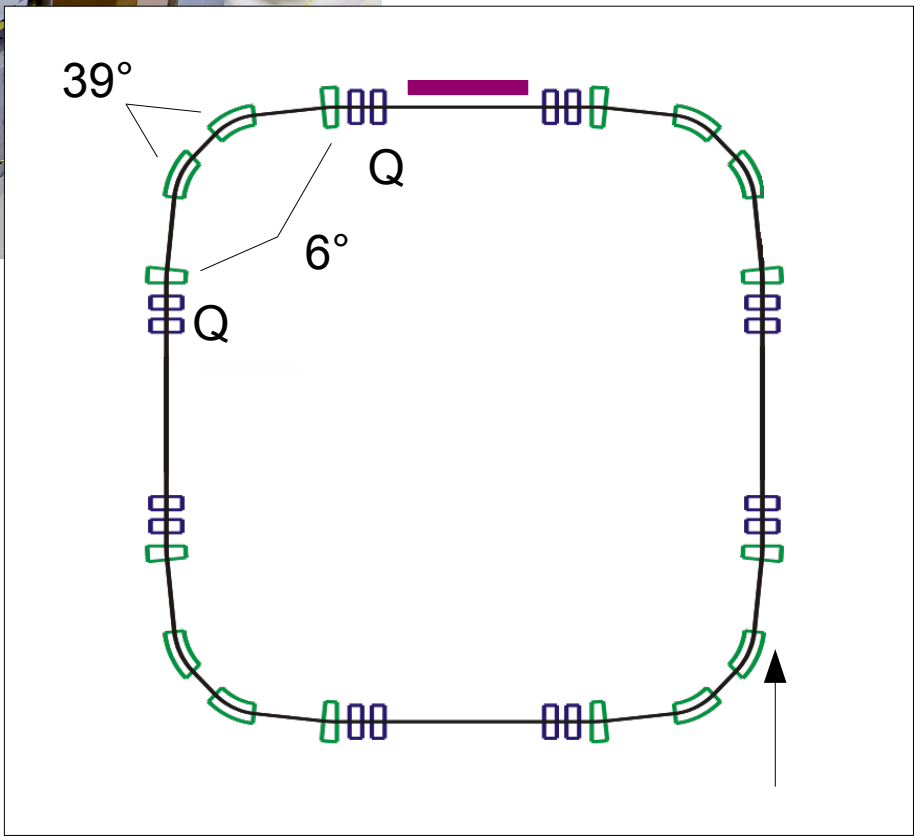
Count rate from ion neutralization

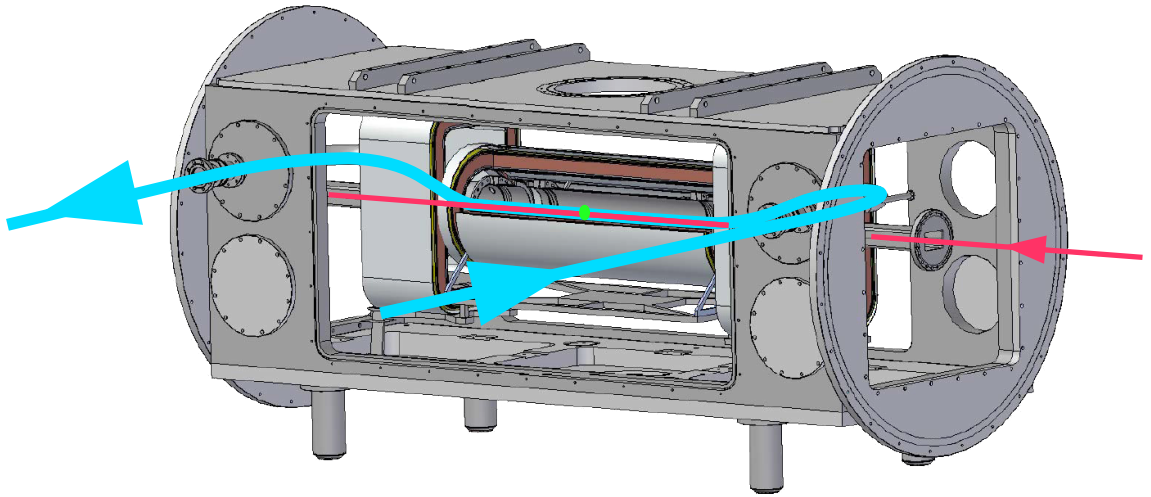
Residual gas density
2×10^3 cm^{-3}
~1×10^{-13} mbar

M. Lange et al.,
Rev. Sci. Instrum.
281, 055105 (2010)

M. Froese, M. Lange,
S. Menk et al.

Cryogenic storage ring CSR

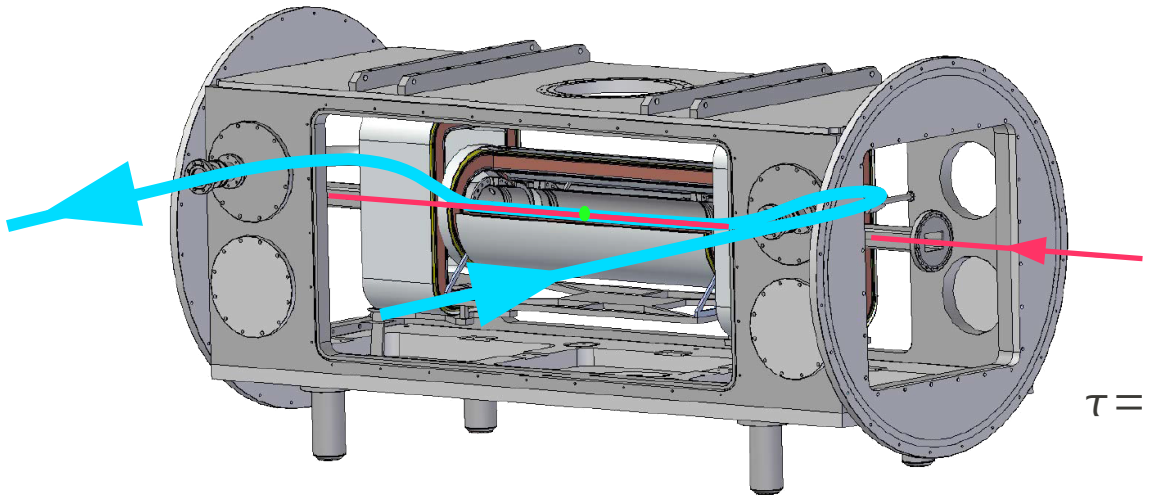




Photocathode electron beam

A. Shornikov, C. Krantz

Low-energy photocathode electron beam



$$\tau = C\,\frac{A^2}{Z^2 E_i}\,\frac{(1-x)^{3/2}\,T_e^{3/2}\,\alpha}{p(x)}\,\lambda$$

A. Shornikov, C. Krantz

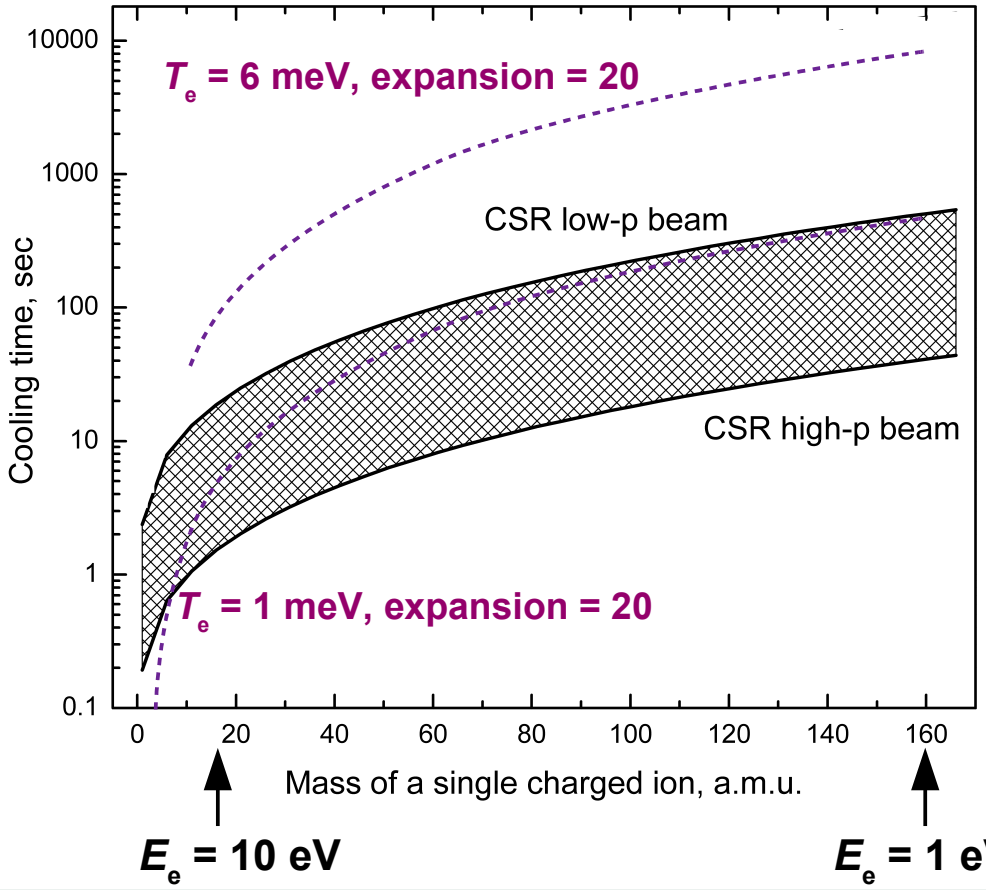
α: magnetic expansion

$$\lambda = \frac{L_{RING}}{L_{COOLER}} = 50$$

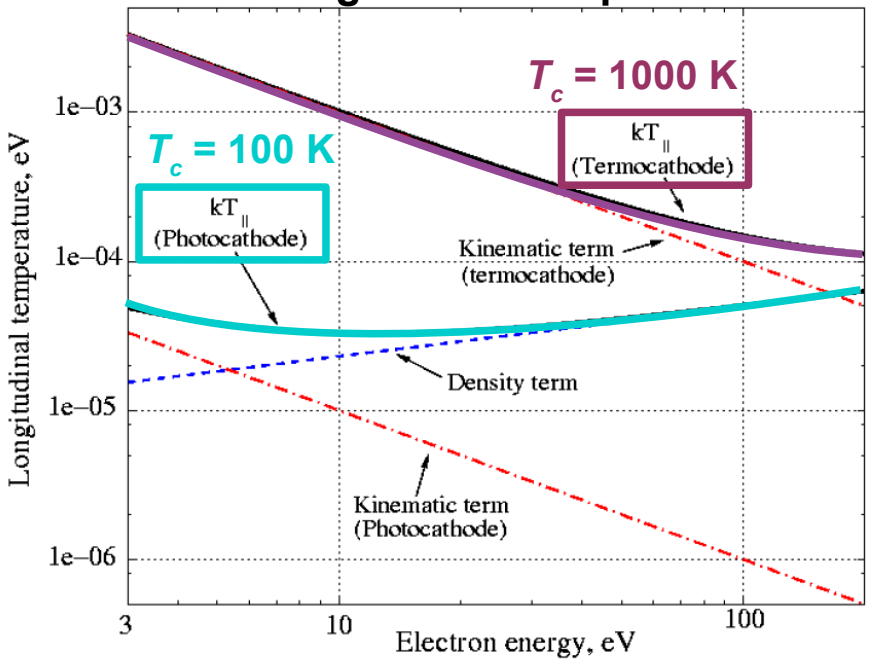
$$p_{high} = 4.1 (x = 0.33)$$

$$p_{low} = 0.6 (x = 0.03)$$

Cooling time of high-mass singly charged ions



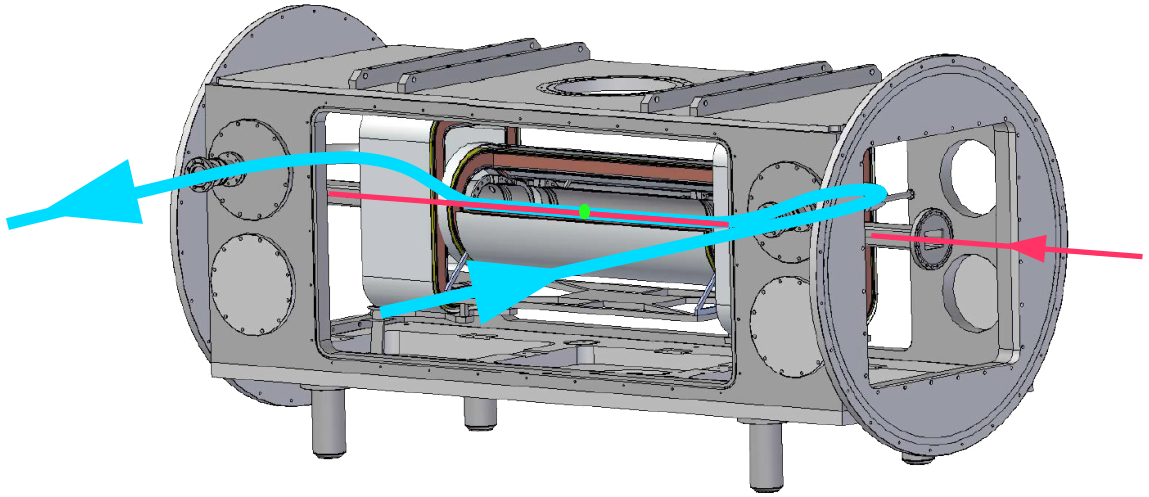
Photocathode longitudinal temperature



D. A. Orlov et al., COOL07, FRM1C03

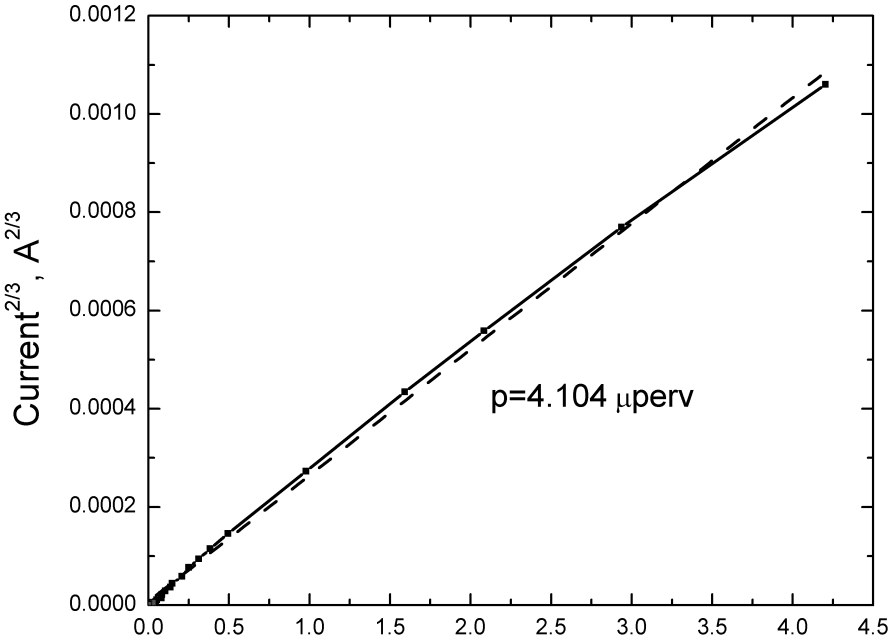
Low-energy photocathode electron beam

A. Shornikov, C. Krantz

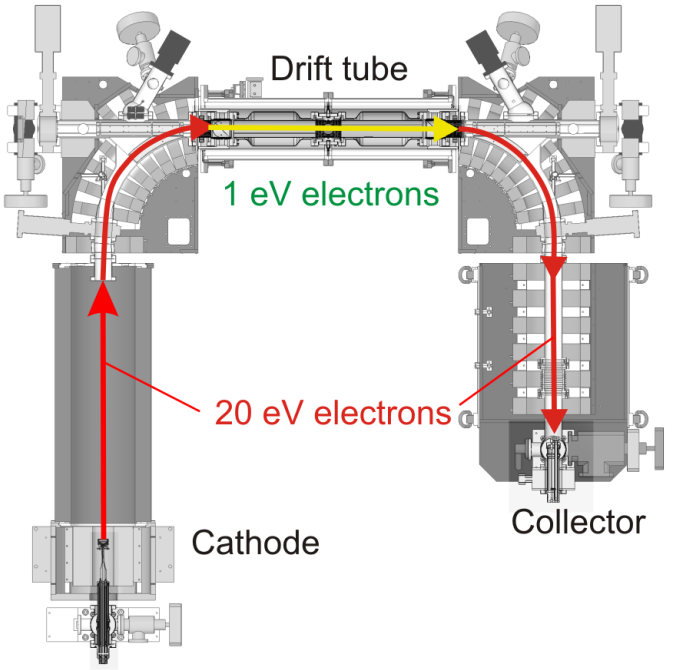


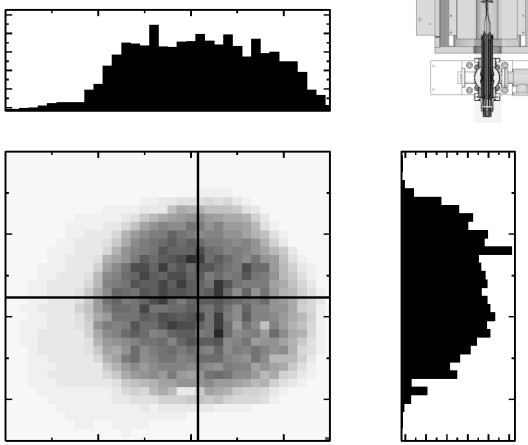
Tests at TSR electron target

Deceleration of low-current photocathode beams



$$I = pU_0^{3/2}$$



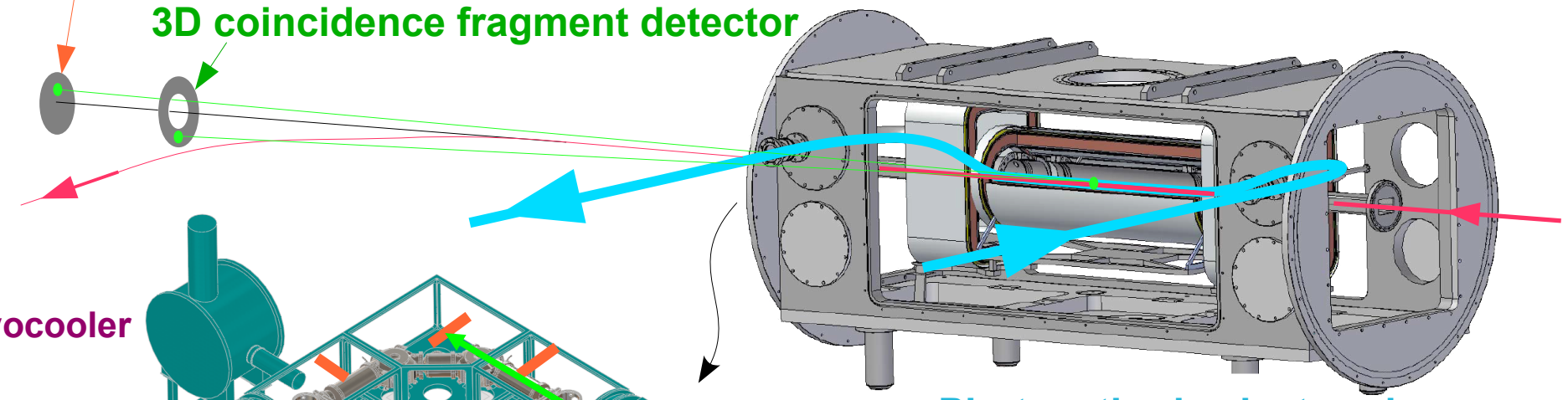


Beam profiles

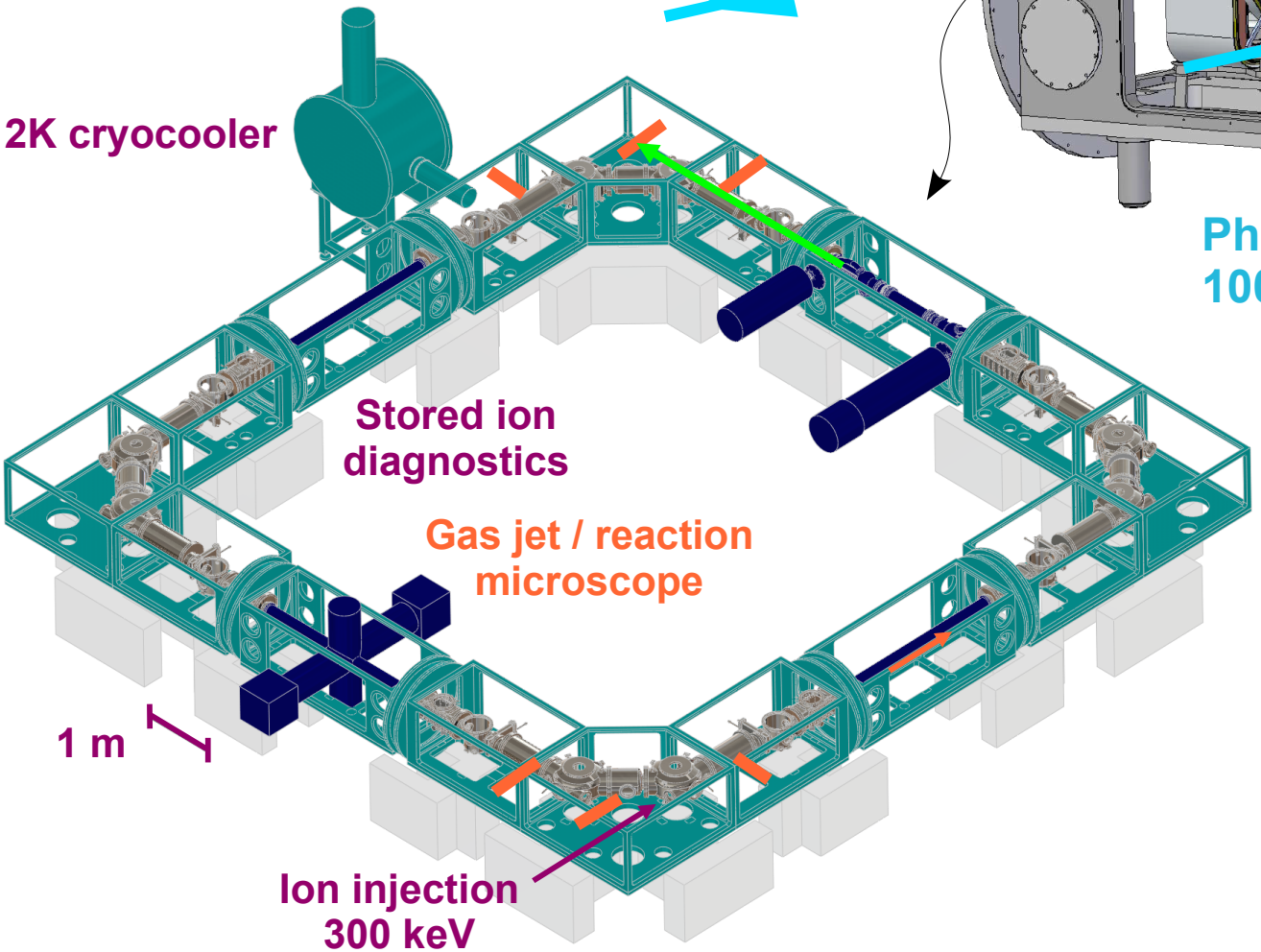
Outlook to experiments at CSR

In development: segmented microcalorimeter detector

3D coincidence fragment detector



2K cryocooler

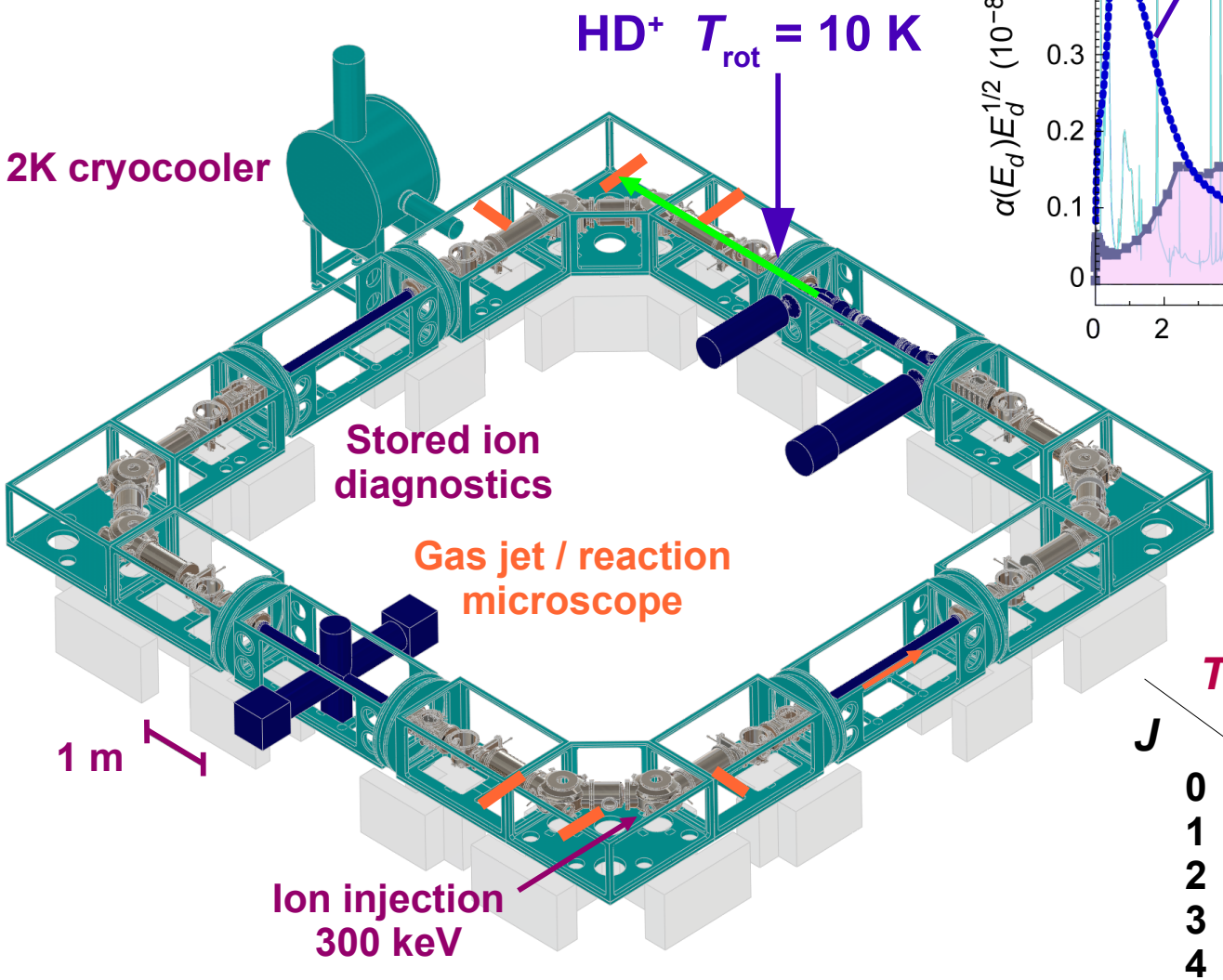


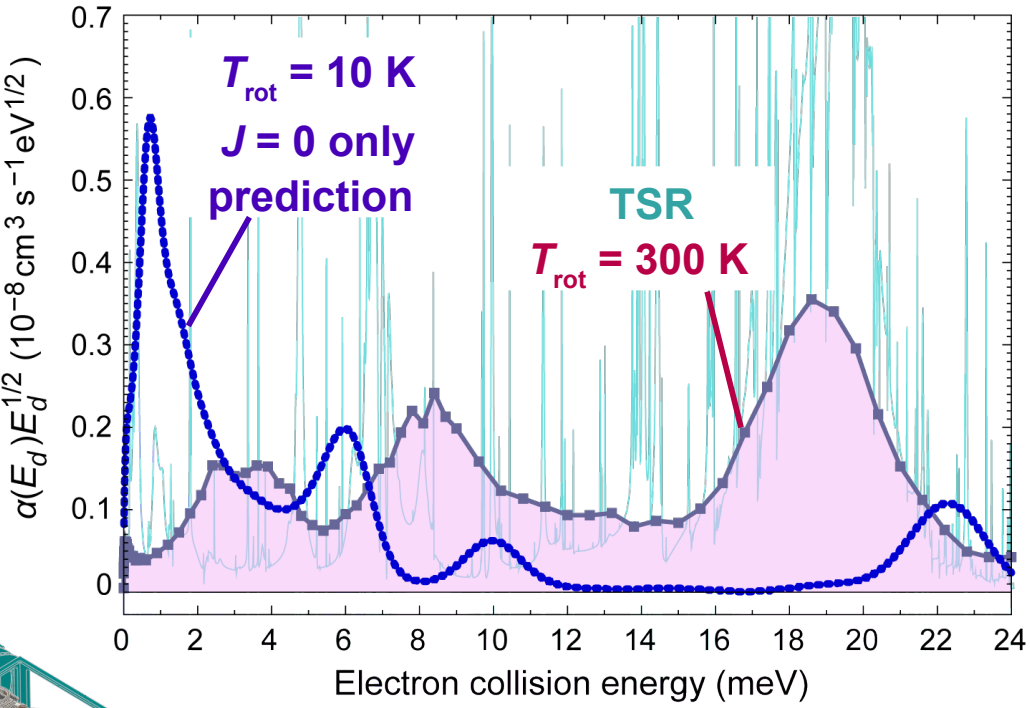
Photocathode electron beam
100 eV → ~1 eV

A. Shornikov, C. Krantz

Outlook to experiments at CSR

Rotational dependence of cross section

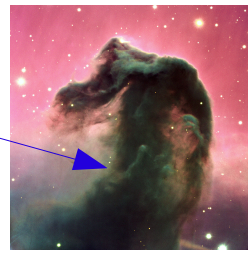




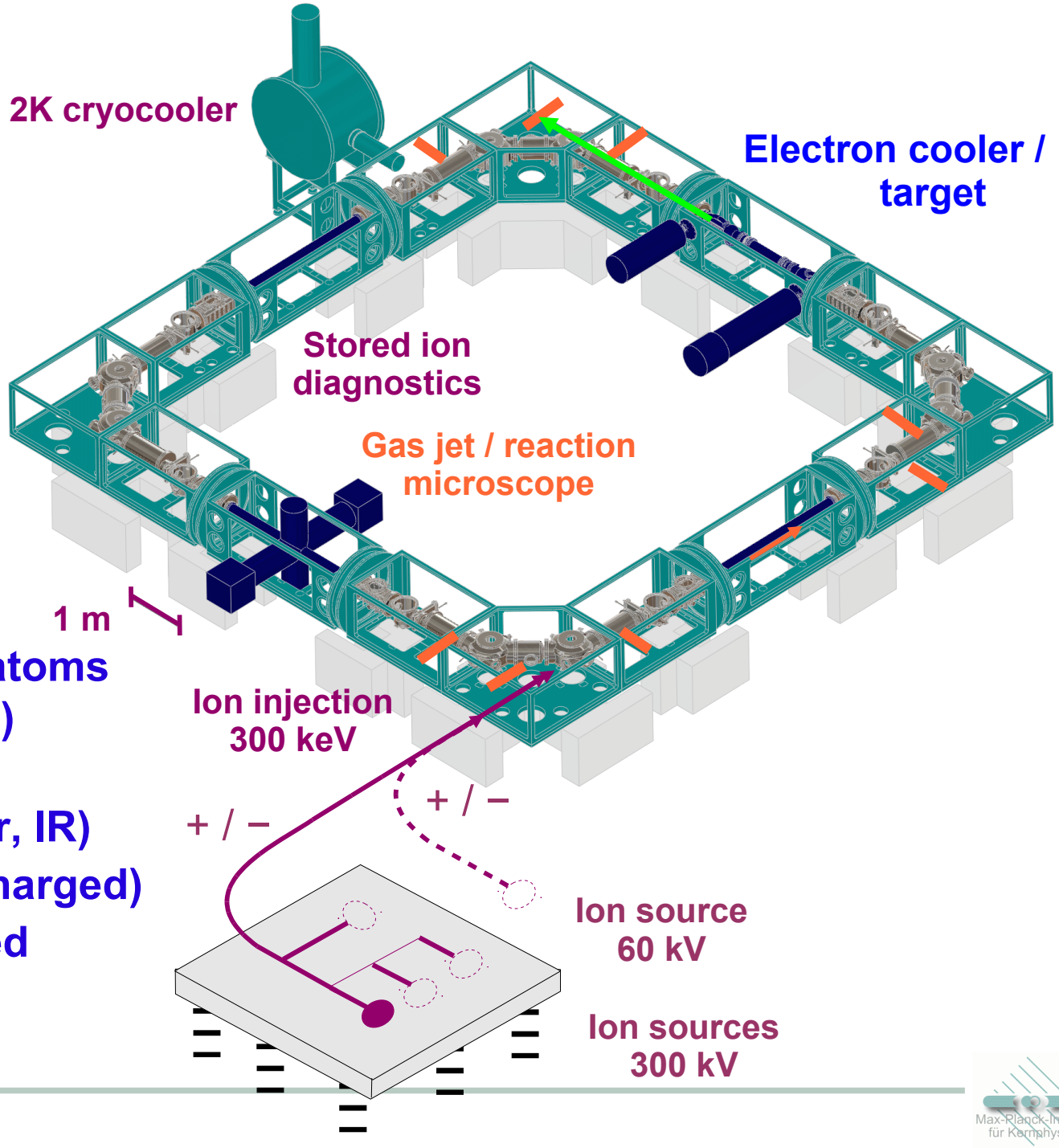
Rydberg capture resonances at low rotation

Waffeu-Tamo et al.,
Phys. Rev. A 84, 022710 (2011)

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



Outlook to experiments at CSR



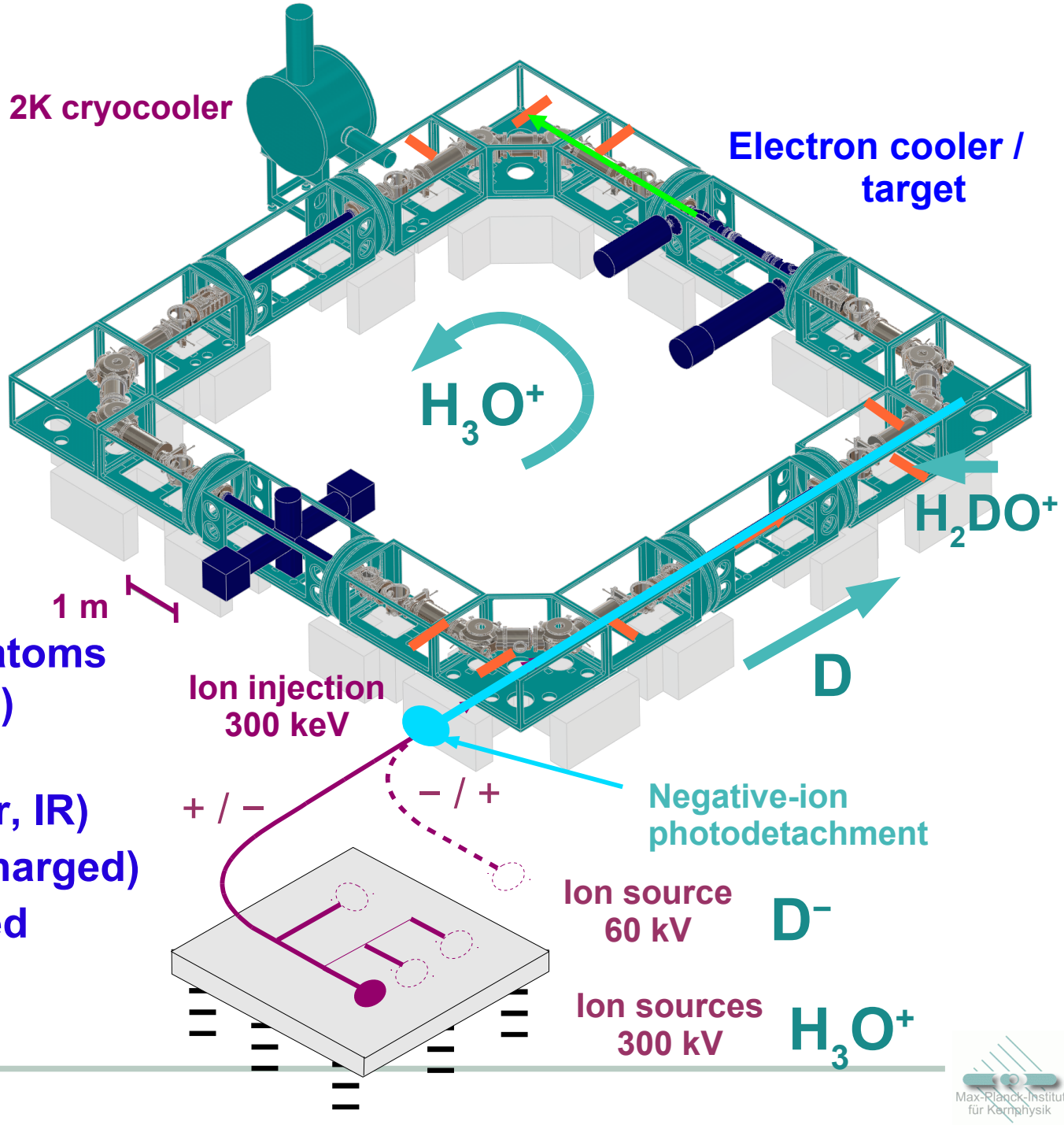
- Stored ion beams at 10 K internal temperature
- Organic molecules, heavy atoms (300 keV for all masses)
- Rotationally resolved ion spectroscopy (laser, IR)
- Negative ions (also multi-charged)
- Cluster systems, H_2O-loaded

Outlook to experiments at CSR

Ion–atom merged beams

$D + H_3O^+ \rightarrow H + H_2DO^+$

Deuterium enrichment by ion chemistry



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Max-Planck Institute for Nuclear Physics,
Heidelberg, Germany

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

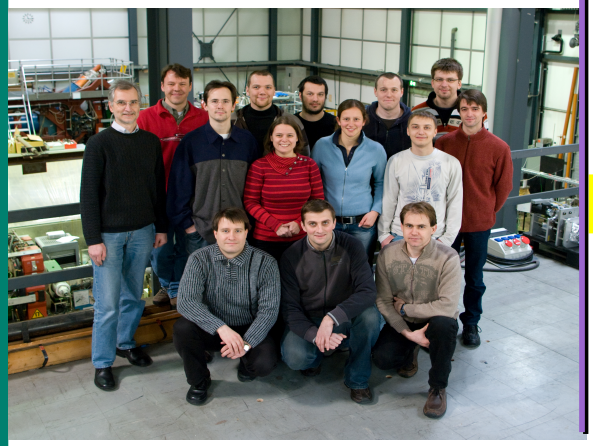
Stored and Cooled Ions (K. Blaum)

Atomic and molecular quantum dynamics

Atomic and molecular physics

Electron target

Photocathode



A. W.
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X. Urbain

Stored and cooled ion instrumentation

TSR and accelerator

M. Grieser
R. Repnow
R. von Hahn

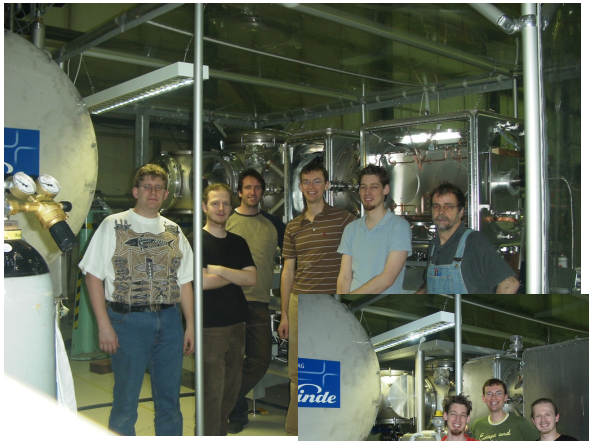
Microcalorimeter ion detector

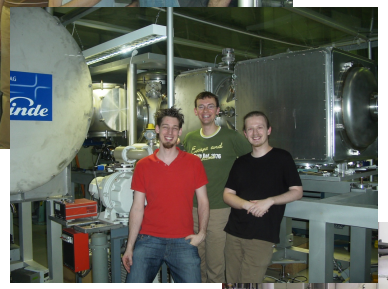
Kirchhoff Inst., Univ. Heidelberg
A. Fleischmann
C. Enss

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

Max-Planck Institute for Nuclear Physics, Heidelberg, Germany

Stored and Cooled Ions (K. Blaum)

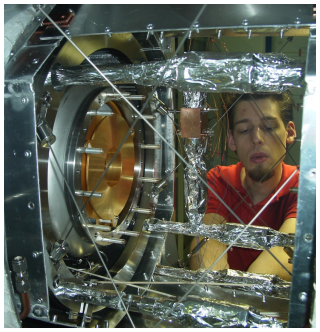


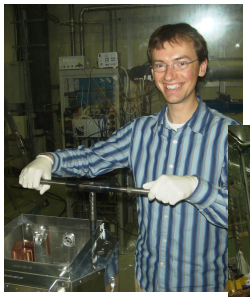


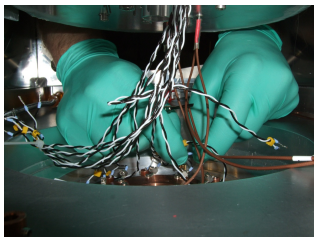
CSR and CTF

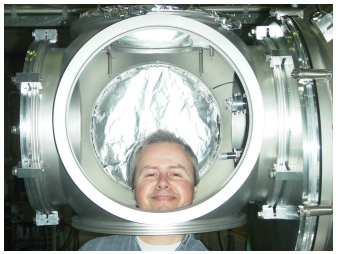
K. Blaum
R. von Hahn
M. Grieser
R. Repnow
M. Lange
S. George

F. Fellenberger
F. Berg
S. Menk
M. Froese (*)
F. Laux (*)
J. Varju (*)









Photocathode electron beams and cooled molecular beams

C. Krantz
S. Vogel
A. Shornikov (*)
D. A. Orlov (*)

J. Ullrich, K.-U. Kühnel, J. R. Crespo Lopéz-Urrutia, C. D. Schröter

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O. Heber **D. Schwalm**

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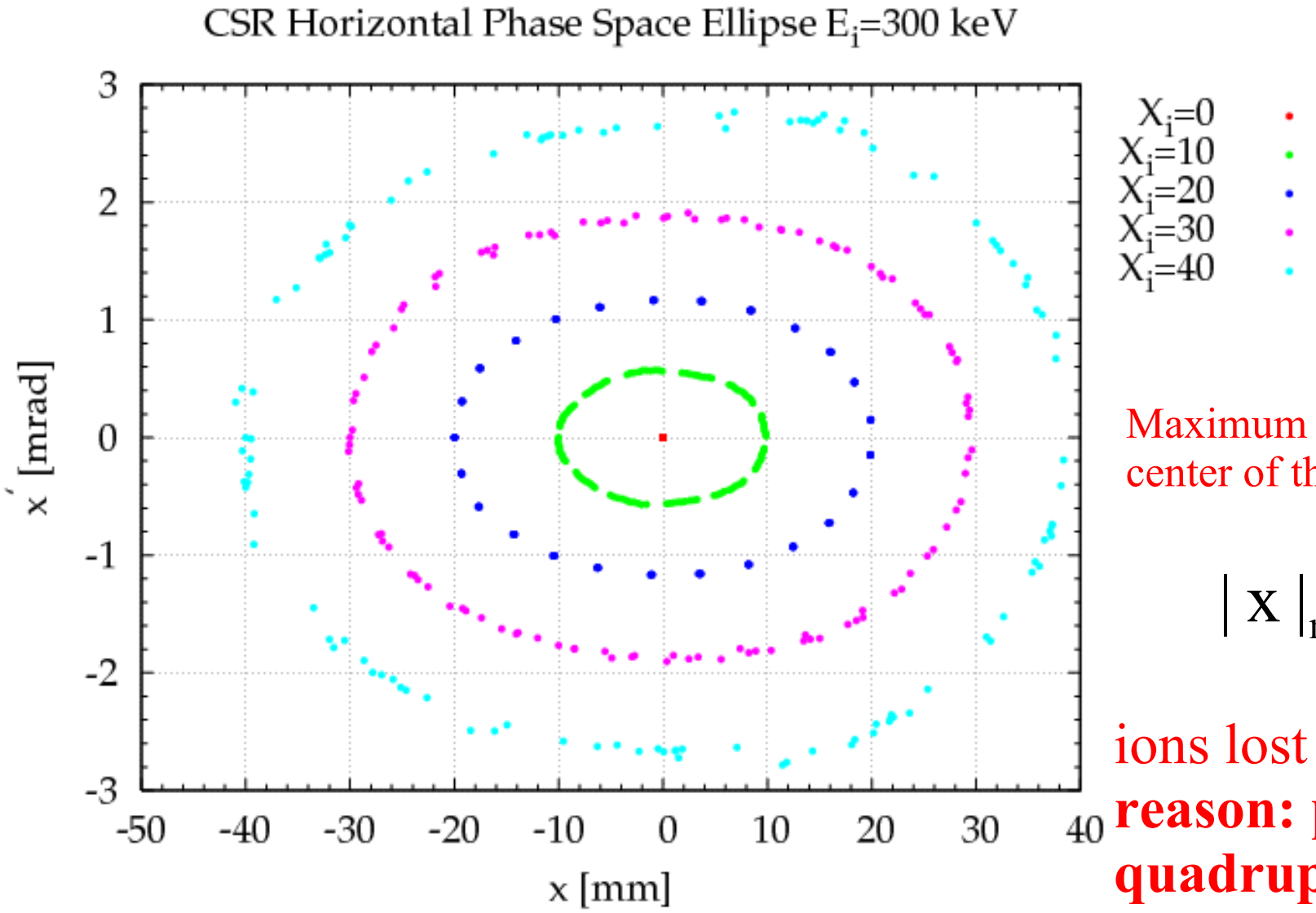
www.mpi-hd.mpg.de/blaum/molecular-qd storage-rings

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Horizontal Acceptance of the CSR (p 300 keV)

ECOOL OFF



Maximum Beam Size in the center of the straight section

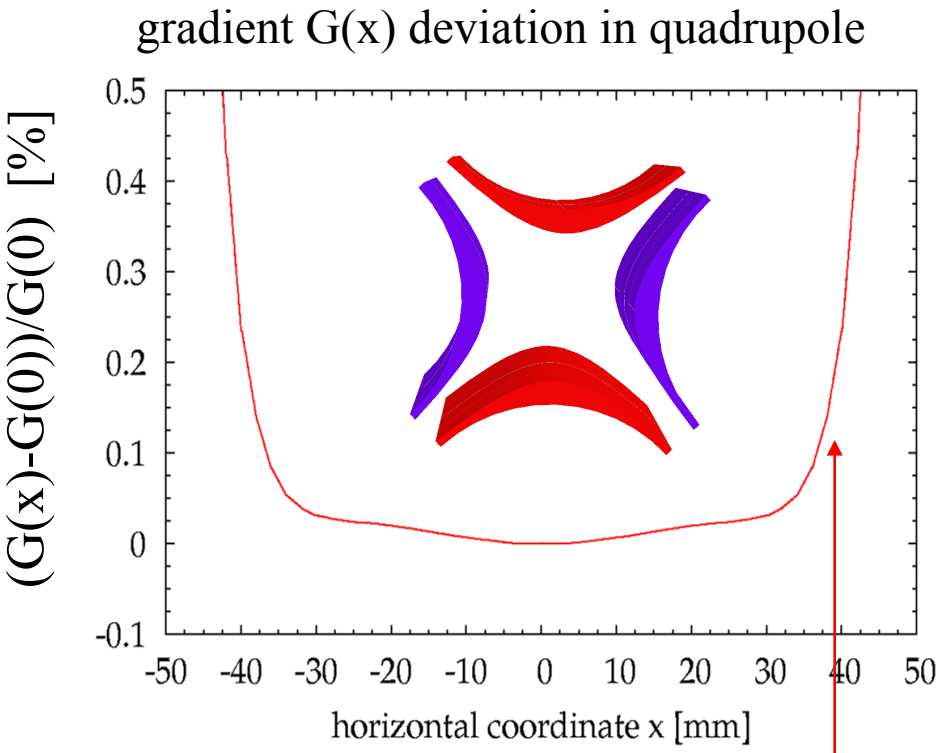
$$|x|_{max} \approx 4\text{cm}$$

ions lost for x>4 cm
reason: property of the quadrupole

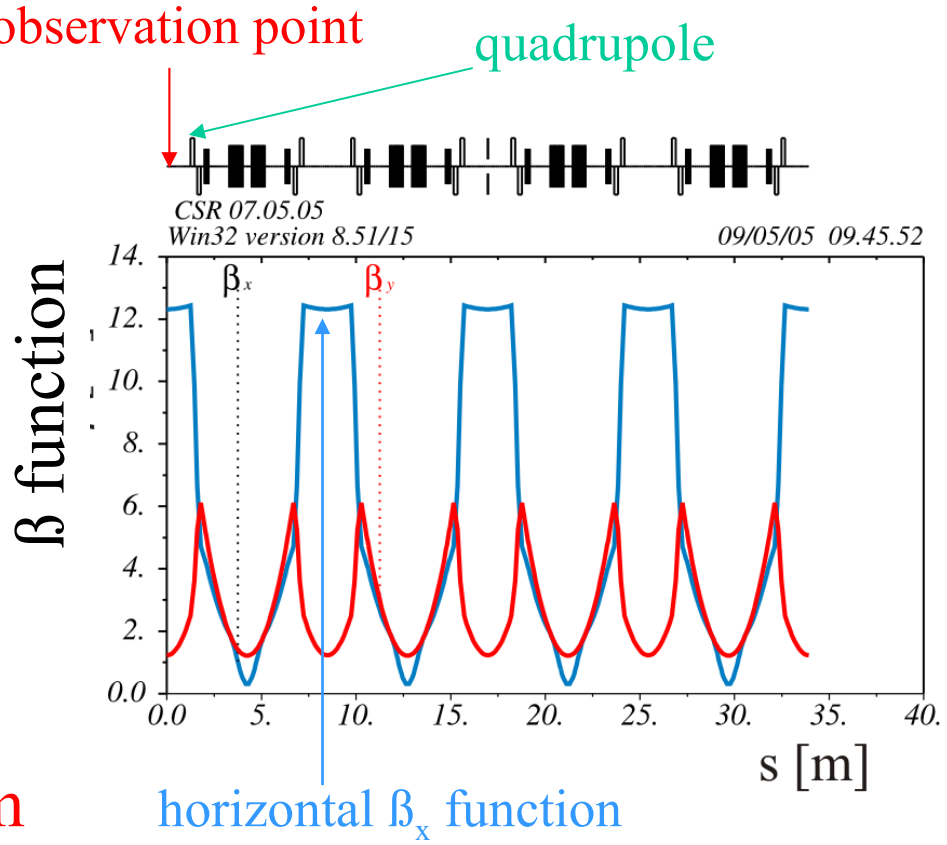
M. Grieser, H. Fadil

Horizontal acceptance and quadrupole gradient

Orbit calculations with real fields: ion lost for x>4cm



x = 4 cm



horizontal $ß_x$ function

if x reaches 4 cm ions see a dramatically change of the quadrupole gradient
⇒ tune change ⇒ ions lost due to resonances

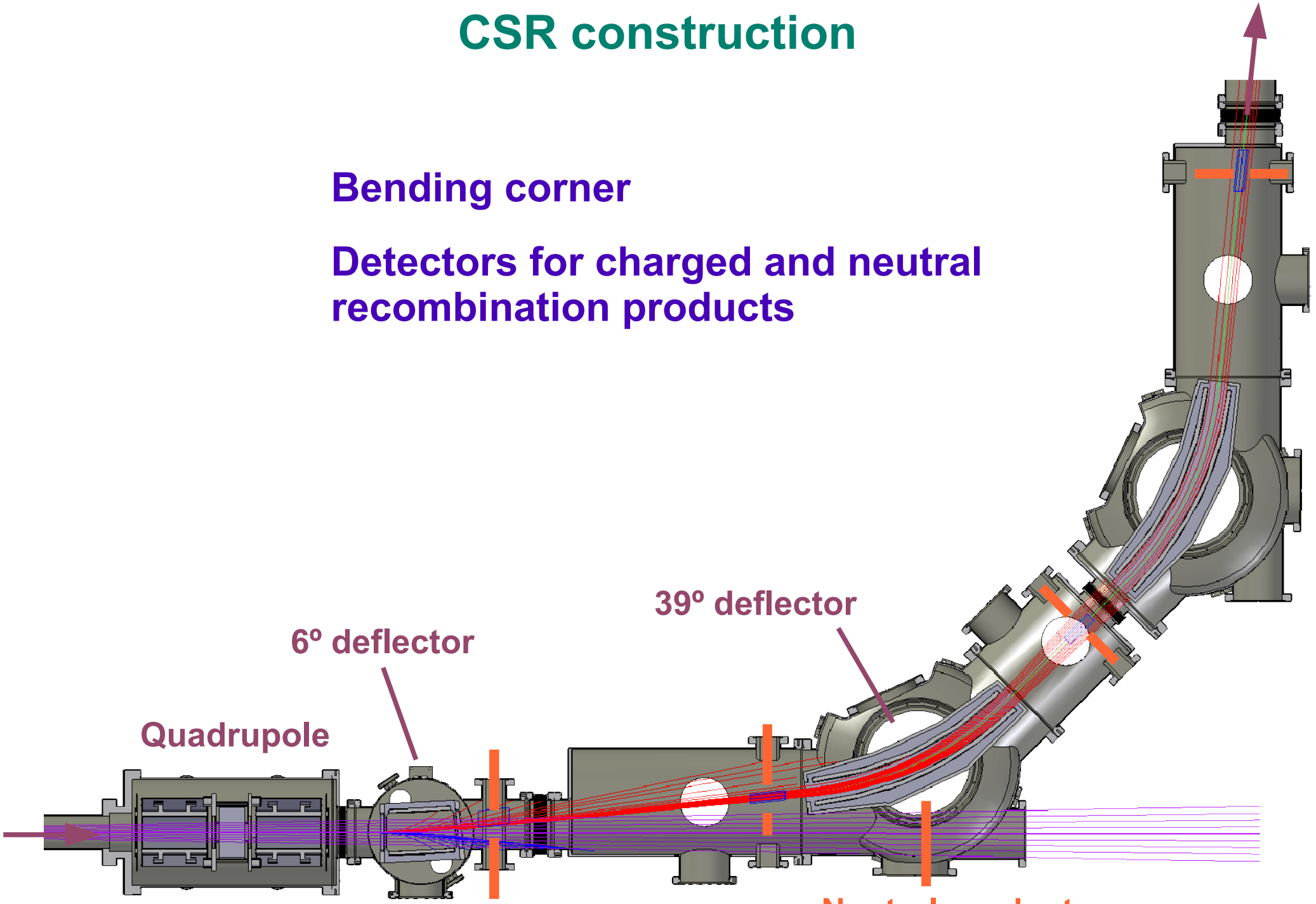
horizontal beam size
centre straight section
≈ beam size in quadrupole

M. Grieser

CSR construction

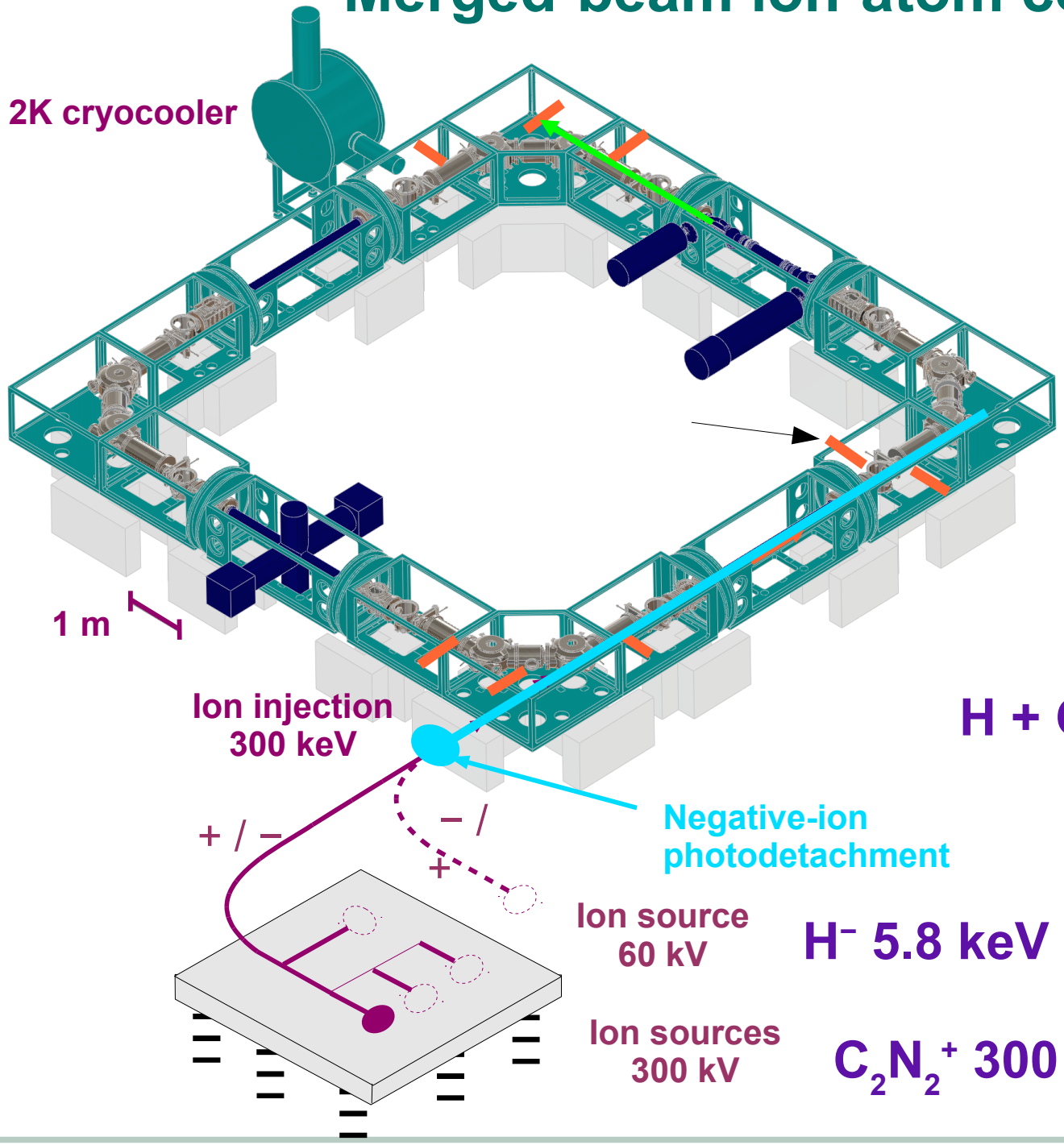
Bending corner

Detectors for charged and neutral recombination products



F. Fellenberger, M. Grieser

Merged-beam ion-atom collisions



1 μA H^-
6 mm diam.
25% yield
10 nA $C_2N_2^+$
$k = 10^{-10}$ cm³ s⁻¹ → **~1/s**

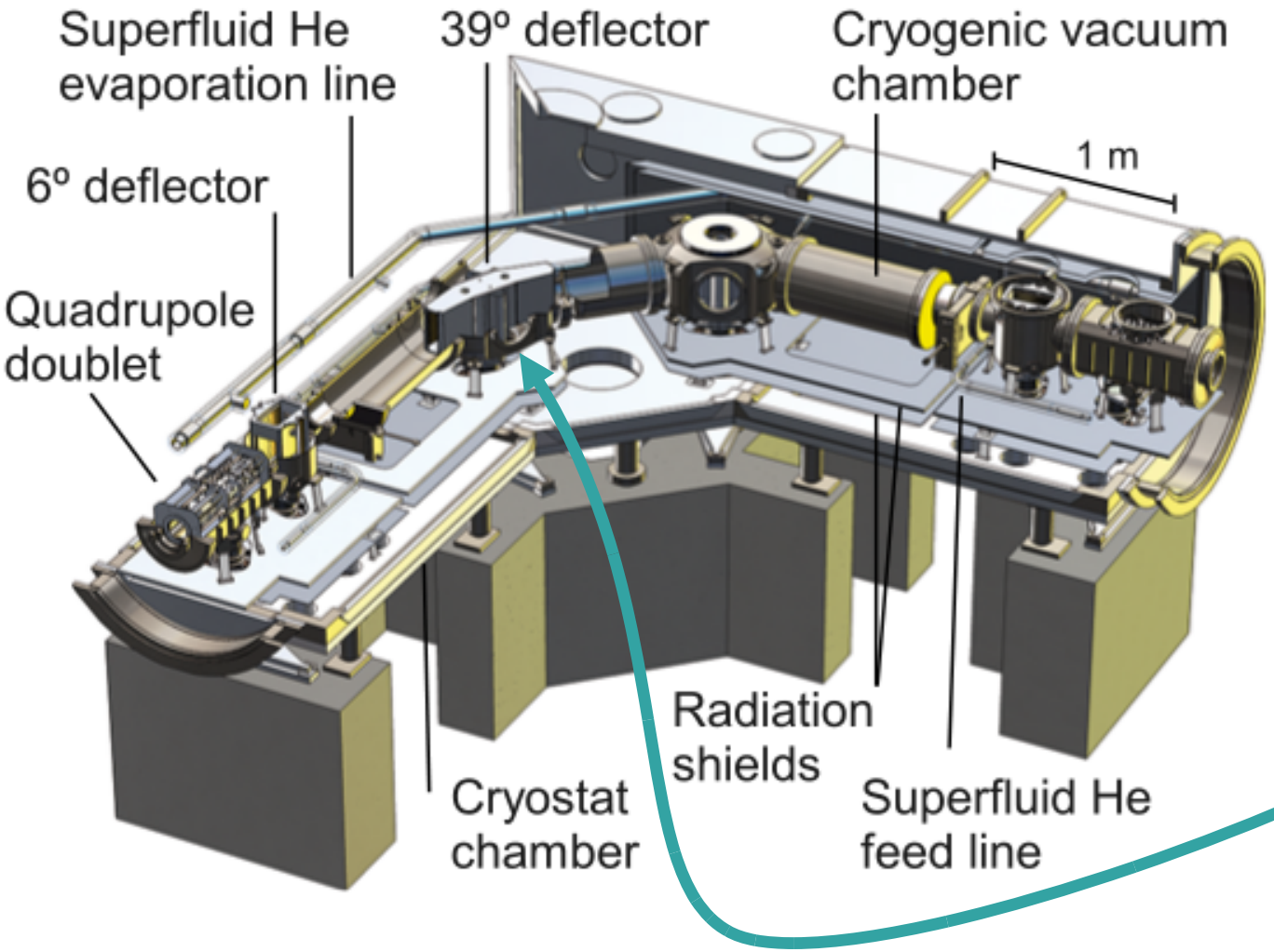
$H + C_2N_2^+ \rightarrow N_2 + C_2H^+$
$H + C_2N_2^+ \rightarrow CN + HCN^+$

Δx ~ 3 mm

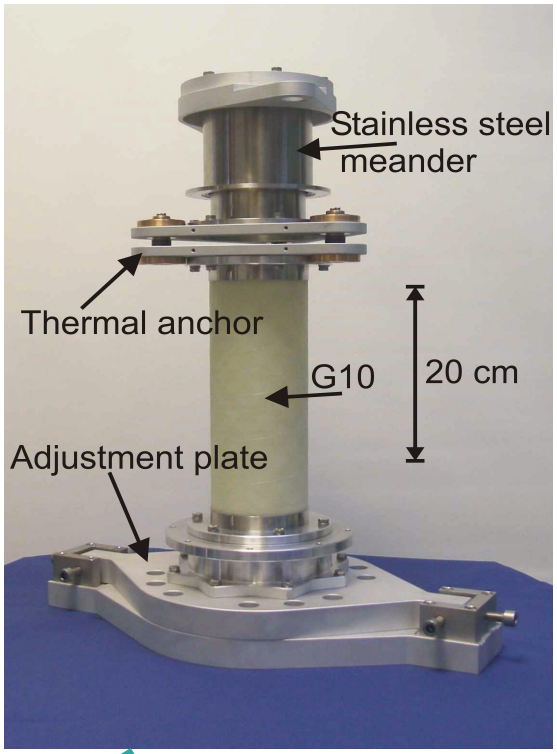
$\Delta E/E = 10^{-3}$ → ~3 meV

CSR construction

CSR ion optics and deflection cell

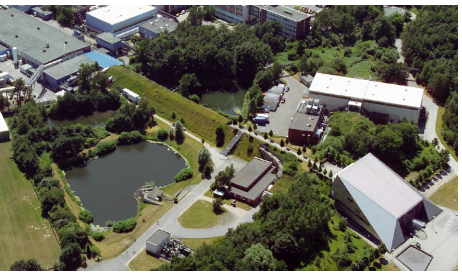


Ion optics support



Water cluster photofragmentation

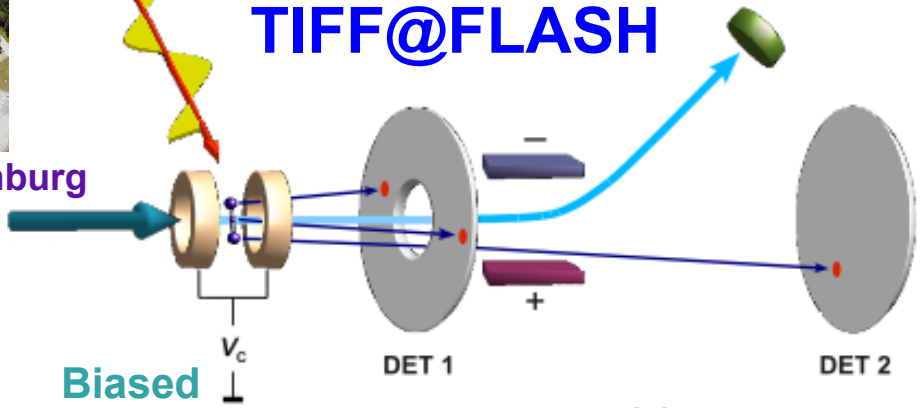
Fragmention following valence ionization



FLASH FEL, DESY, Hamburg

35 eV

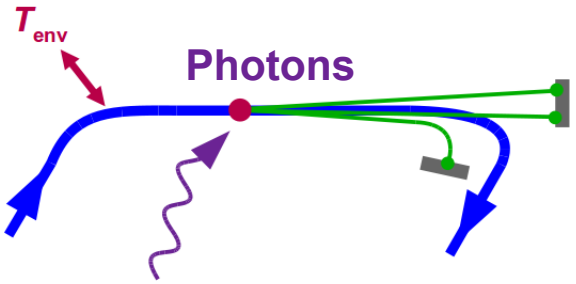
TIFF@FLASH



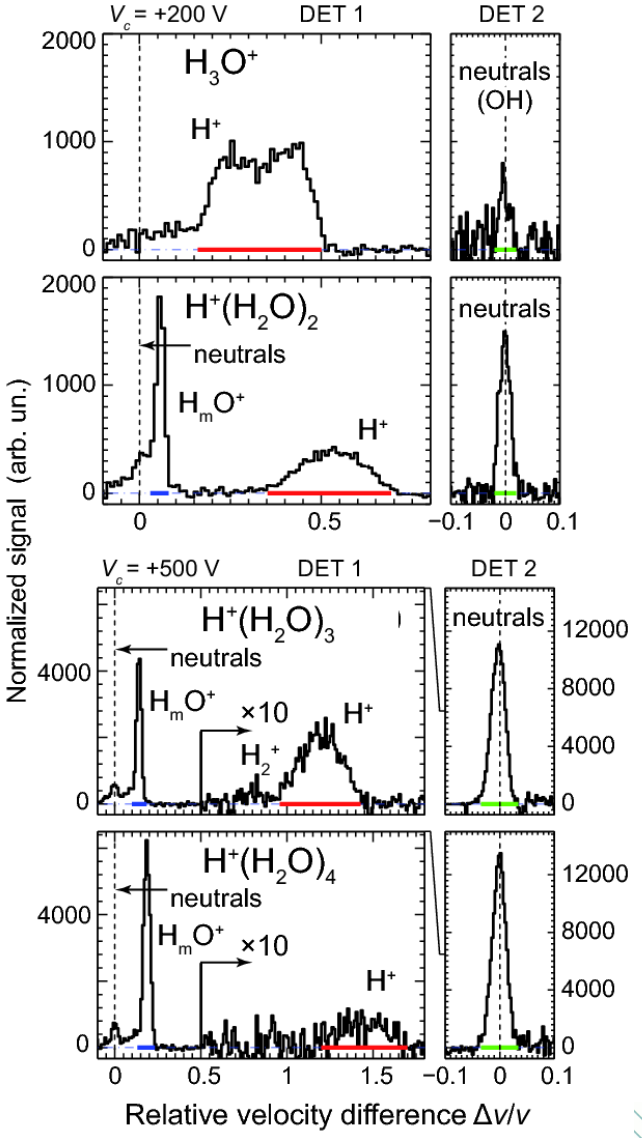
TIFF ion beam
(~4 keV)
pulsing, trapping

Biased interaction zone

Fragment time-of-flight, imaging



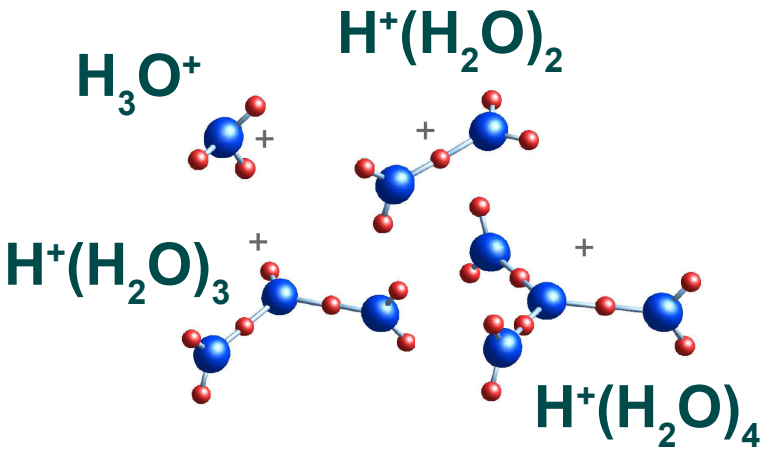
Fragment time-of-flight spectra

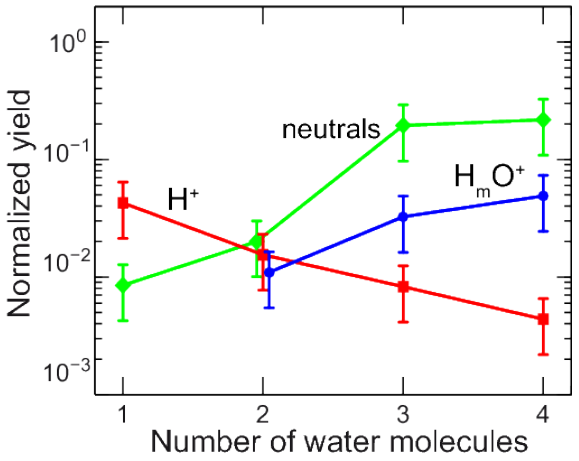


2009: Strong channel of $H_2O^+ + H_3O^+$ from $H^+(H_2O)_2$

L. Lammich et al., PRL 105, 253003 (2010)

2010: Strong suppression of proton fragments for n > 2

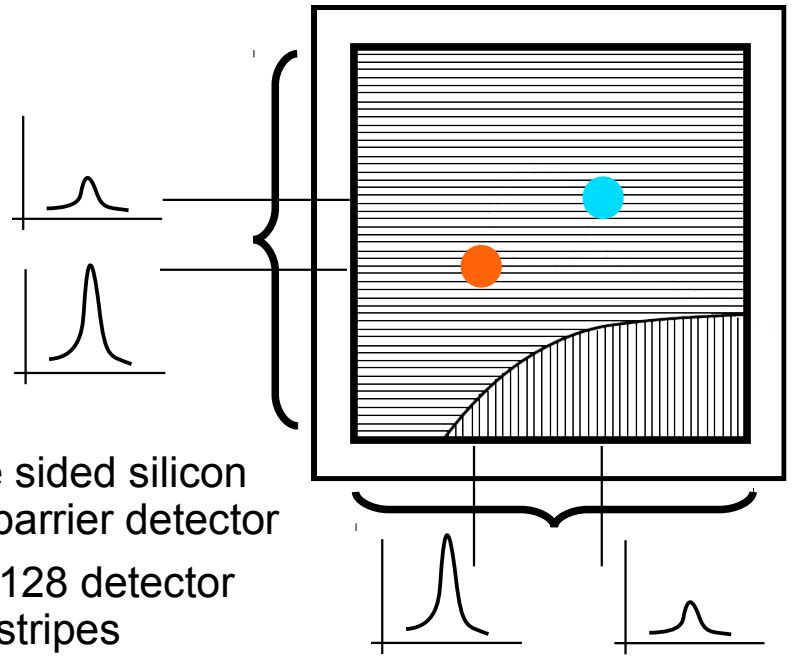




Multistrip silicon detector for fast-beam imaging

2008

Energy-sensitive MUlti-strip detector



Double sided silicon surface-barrier detector

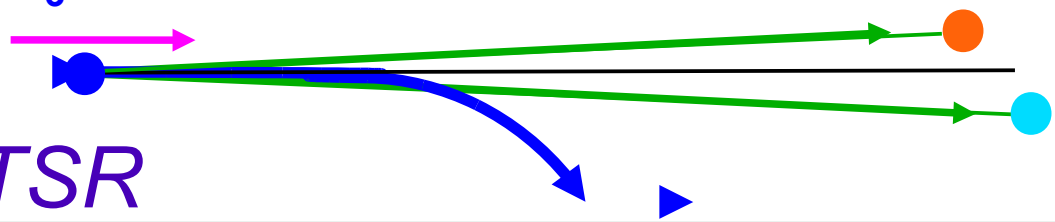
128 x 128 detector stripes on 100 x 100 mm area

Energy readout →
fragment channel identification

e.g.: $D_3O^+ + e$ → $D_2O + D$
→ $OD + D_2$
→ $OD + D + D$
→ ...

Polyatomic fragmentation by cold electrons

$D_3O^+ + e$



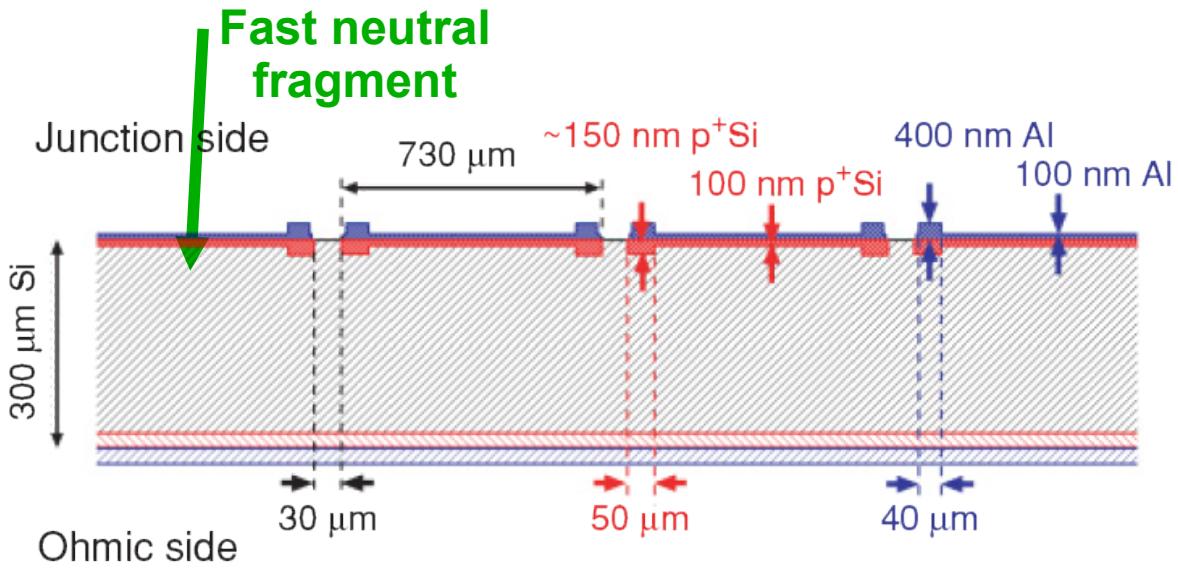
EMU imaging system @ TSR

H. Buhr et al., Phys. Rev. A 81, 062702 (2010)
MPIK, Heidelberg + Weizmann Institute, Rehovot

Multistrip silicon detector for fast-beam imaging

2008

Energy-sensitive MUlti-strip detector



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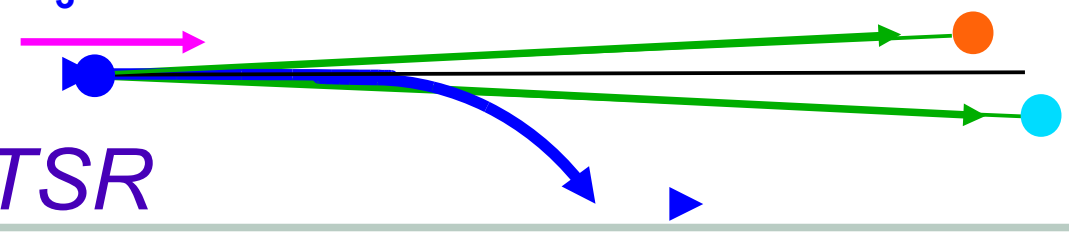

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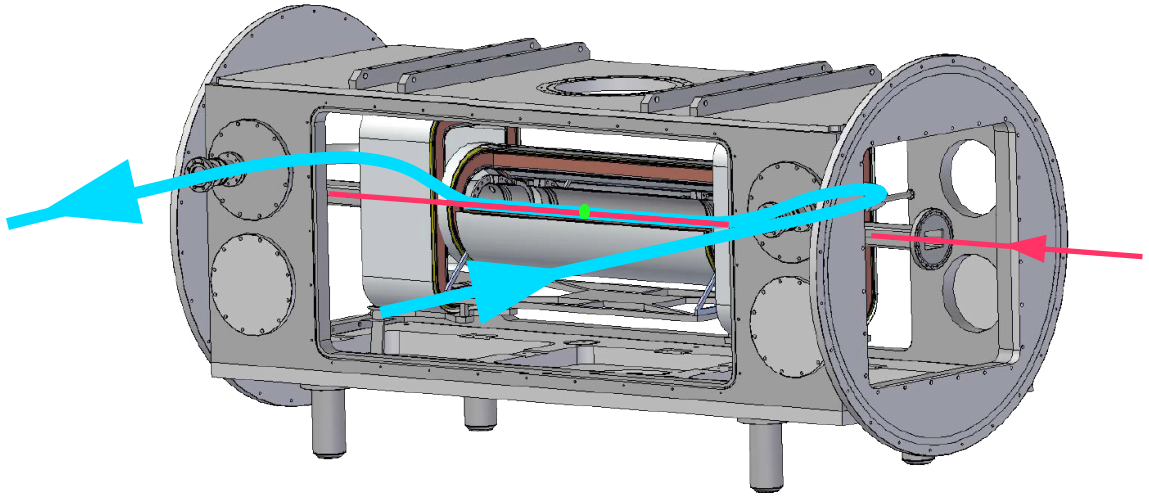
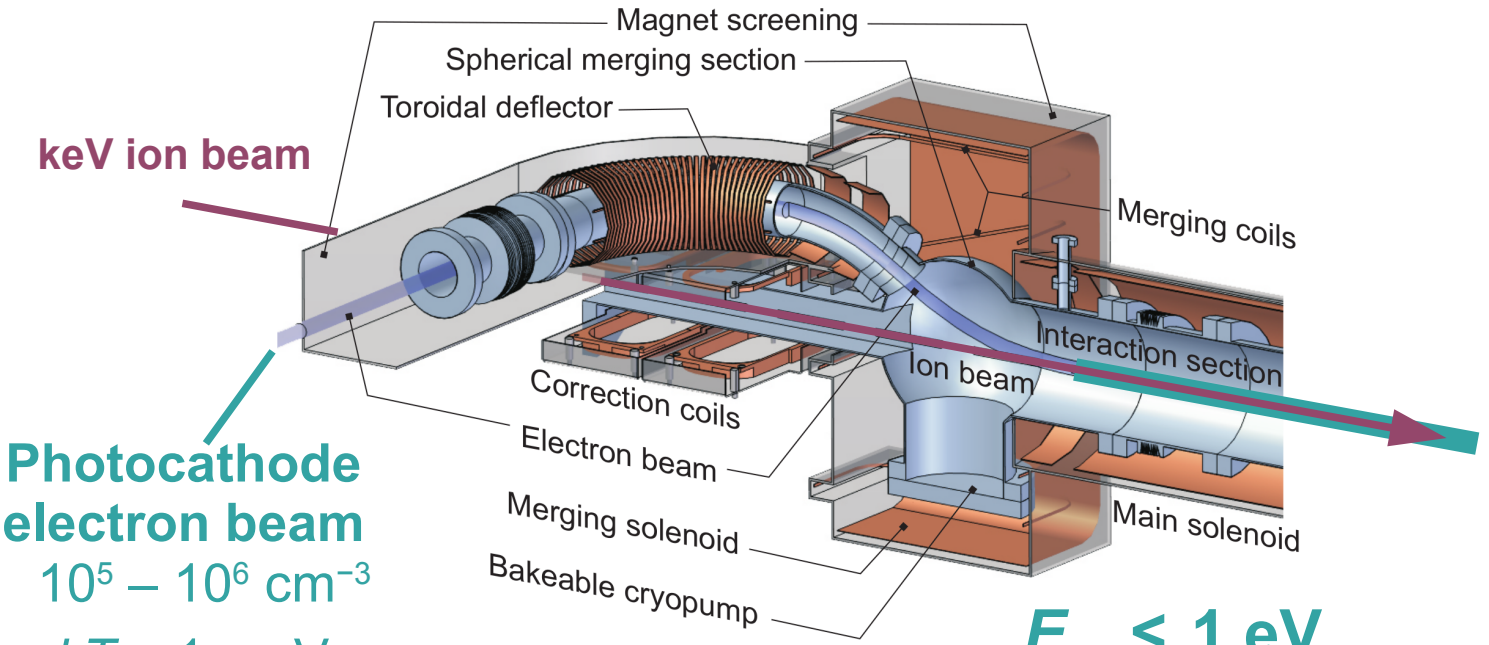


Low-energy photocathode electron beam

A. Shornikov, C. Krantz

Merging section for electrostatic rings



Photocathode electron beam

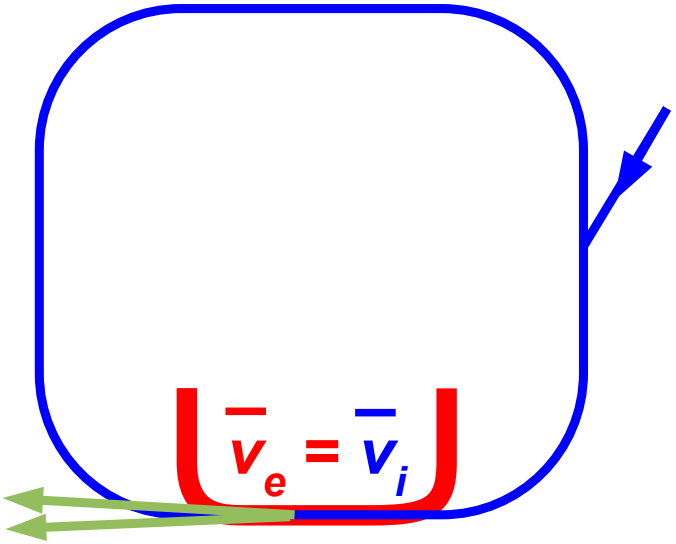
$10^5 – 10^6$ cm^{-3}

$kT \sim 1$ meV

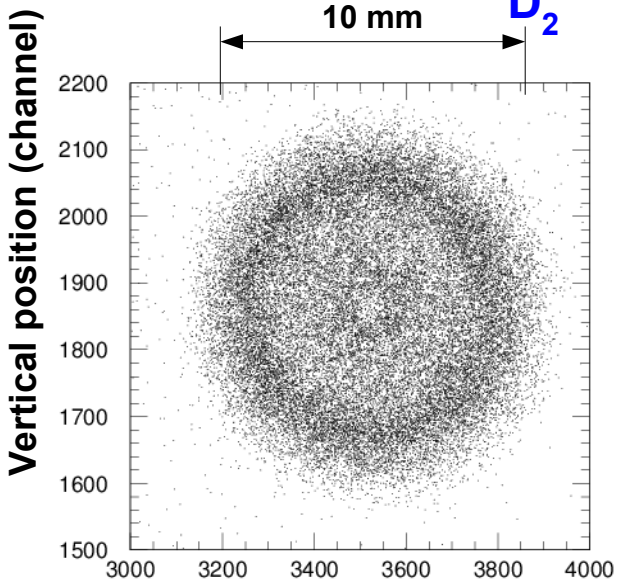
$E_{kin} \lesssim 1$ eV

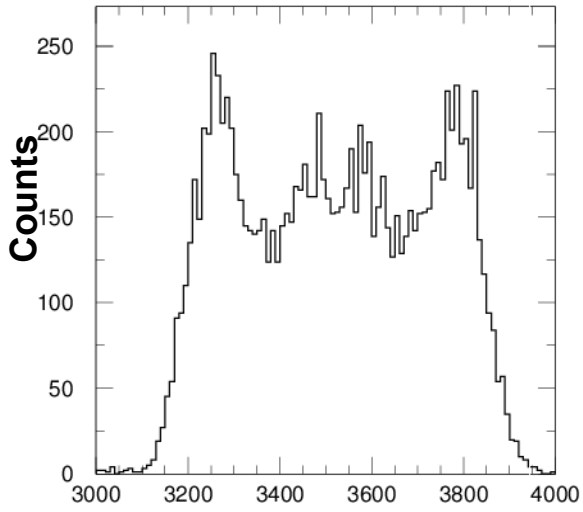
A. Shornikov et al., COOL09,THM2MCCO03

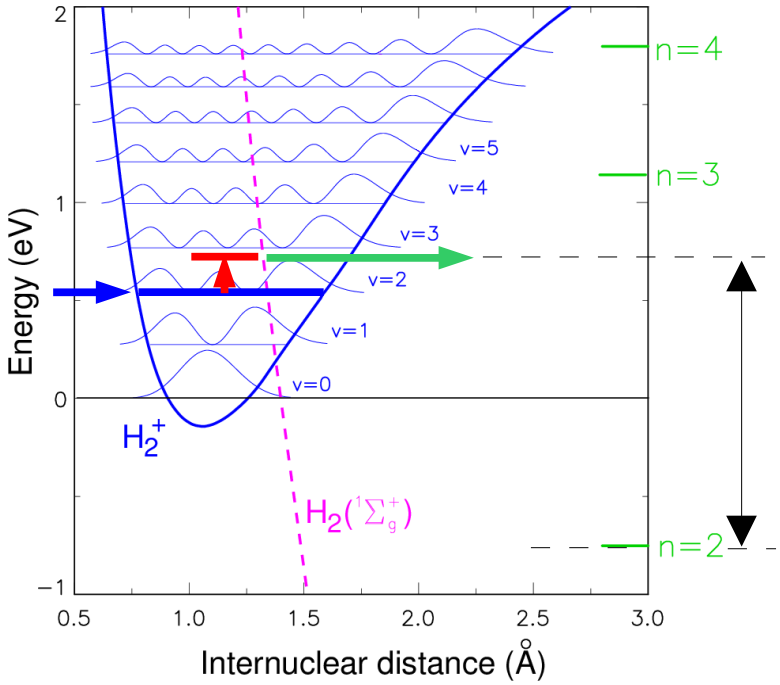
Electron cooling of molecular ions



Correlated 2-hit events on imaging detector





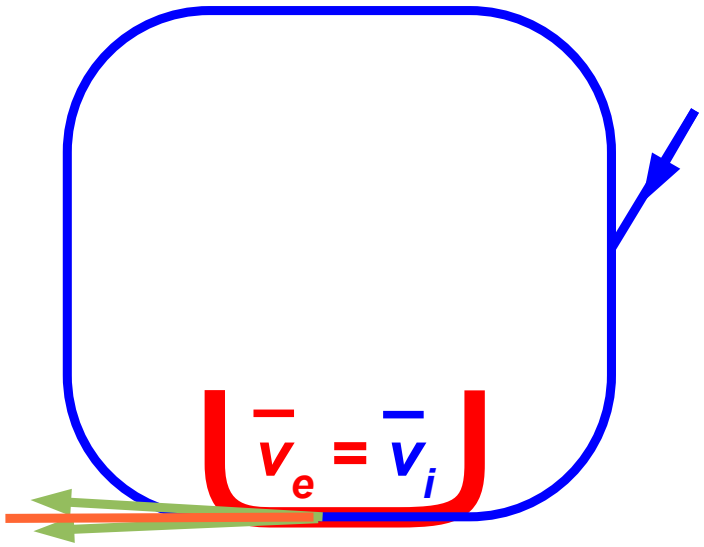


$E_k\,[\,v,n\,]$

⇓

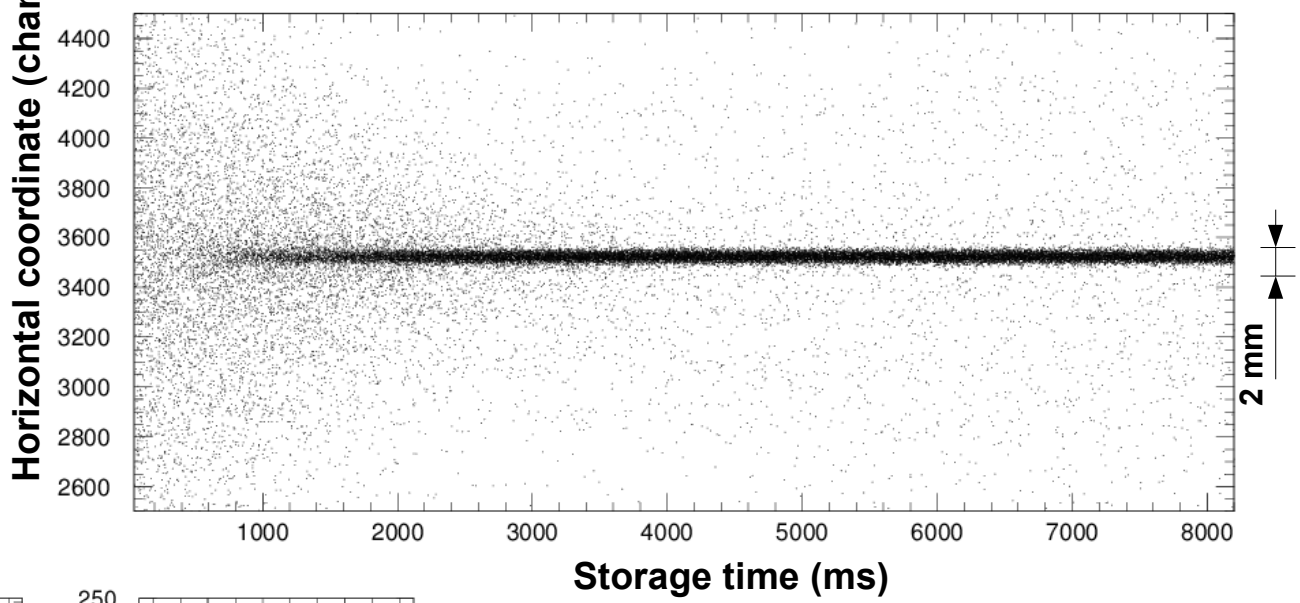
D_{max}

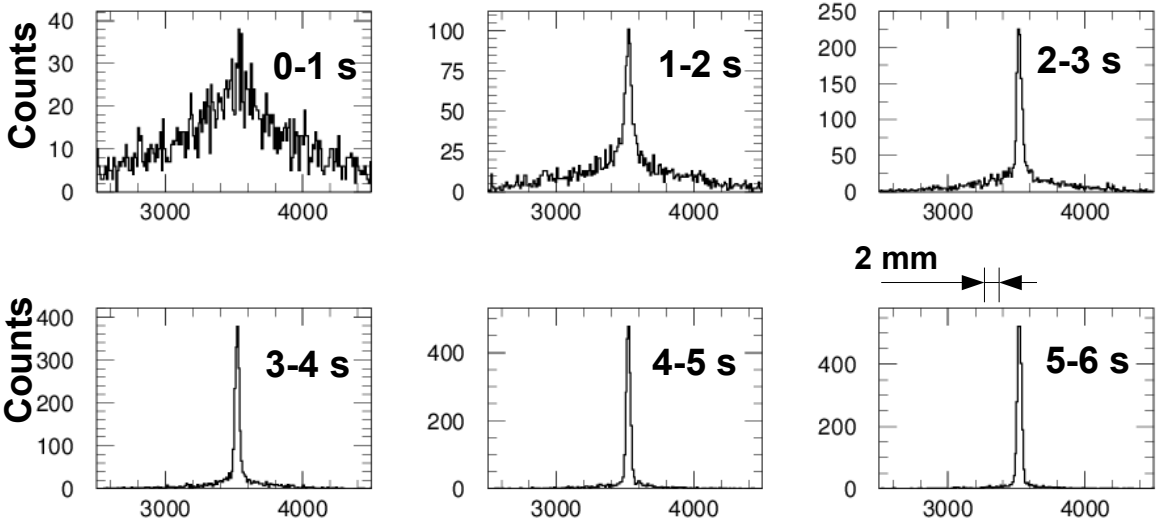
Electron cooling of molecular ions



Fragment center-of-mass impact position

D_2^+ 1.9 MeV (TSR)





TSR: NIM A 532, 69 (2004)

$n_e = 5.5 \times 10^6$ cm^{-3}