Low-energy ion beam storage and eV electron cooling

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Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany

COOL11, Alushta (Ukraine), 12-16 September 2011

Stored and Cooled Ions Division at MPIK (Klaus Blaum)

Laboratory Astrophysics Collaboration (Weizmann Institute, Rehovot; Columbia University, NYC; Universität Giessen; Stockholm University)

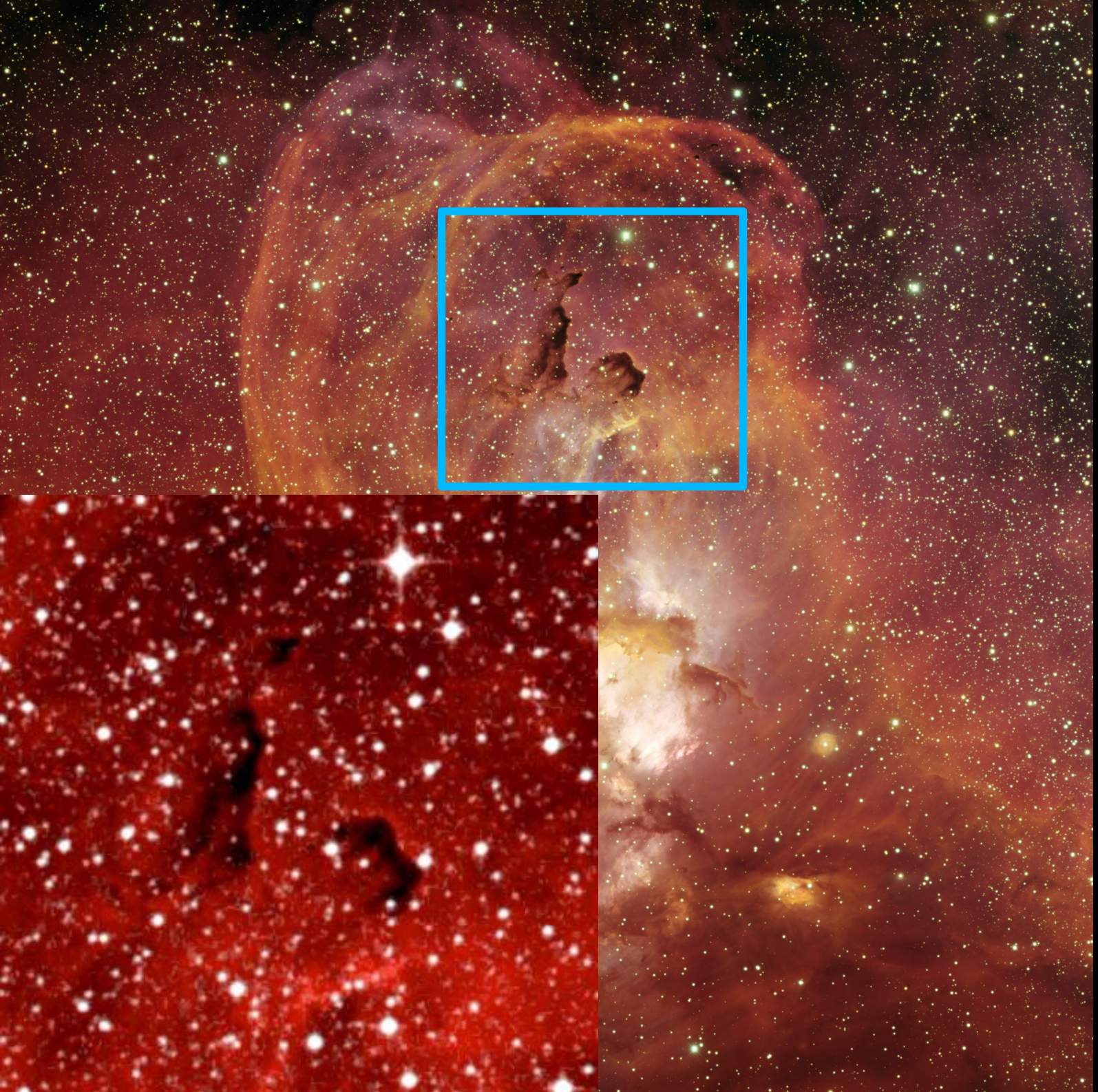
Cryogenic Storage Ring project at MPIK

Chemical physics with fast ion beams

Electron cooled molecular ion beams at TSR

The CSR project: layout and electron cooling

Outlook: experiments at CSR



Interstellar molecular clouds

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

Star forming regions

NGC 3576-86

T.A. Rector
U. of Alaska Anchorage
T. Abbott and
NOAO/AURA/NSF

Interstellar molecular clouds

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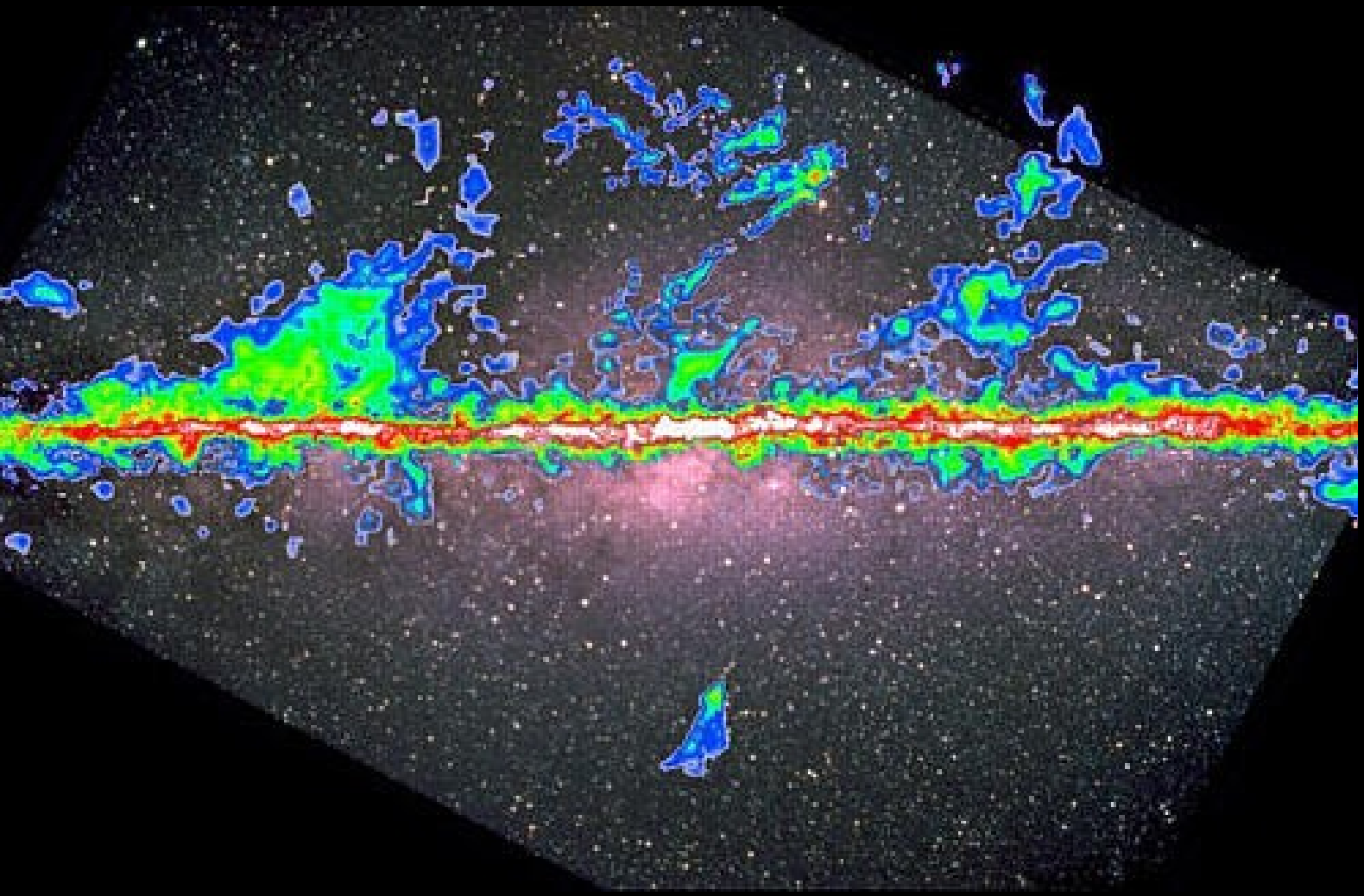
density ~10^4 cm^{-3}
temperature ~10 K

Star forming regions

Milky Way visible

Cerro Tololo
S. Kohle

Interstellar molecular clouds



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

Star forming regions

Milky Way
visible

Cerro Tololo
S. Kohle

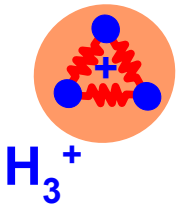
CO radio line

T. Dame
Harvard
Smithsonian

Interstellar ion chemistry

Reaction chains in interstellar clouds

- 140 observed interstellar molecules (2000)
- Heavy species: CH_3CH_2OH, glycoaldehyde, maybe benzene, ...
- Ions: CH^+
  CO^+
  SO^+
  CF^+ (2005)
  HCO^+, COH^+
  HCS^+
  $HCNH^+$
  H_2COH^+
  HC_3CNH^+
  SH^+ ... (2010)



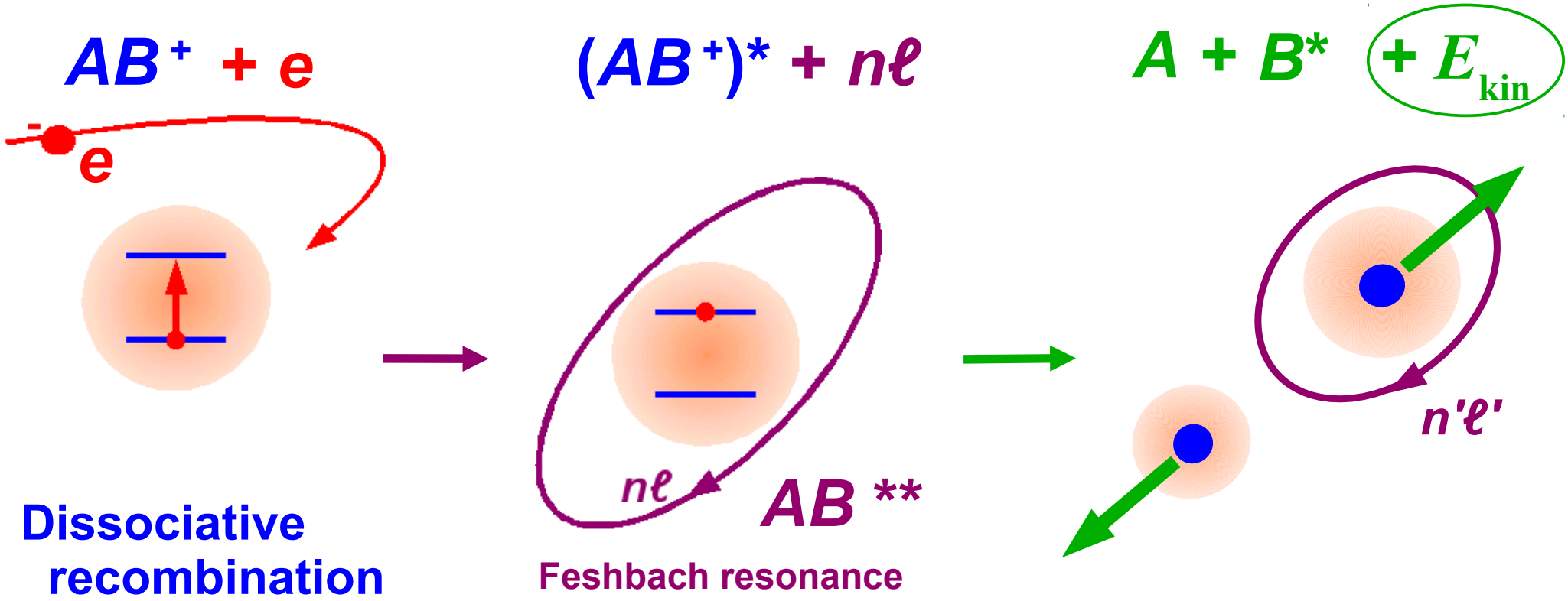
ON2
Star forming region
("Chicken" Nebula)
Infrared

UKIRT
Mauna Kea
Chris Davis (JAC)

Molecules cool the star-forming regions

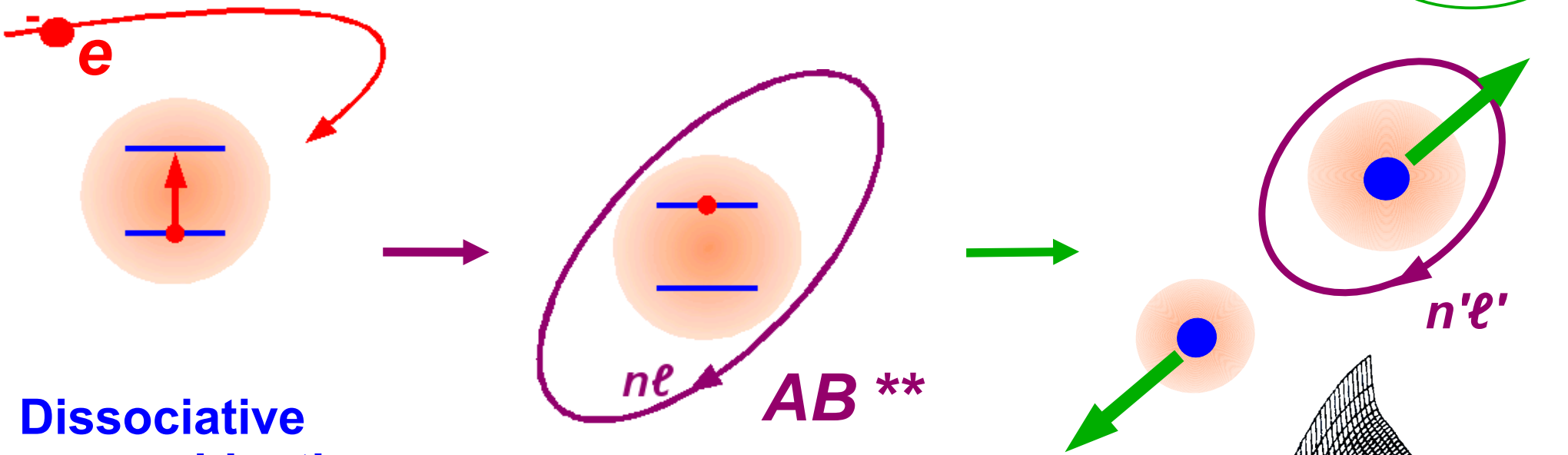
Observed by infrared and radio spectroscopy

Molecular breakup by cold electrons



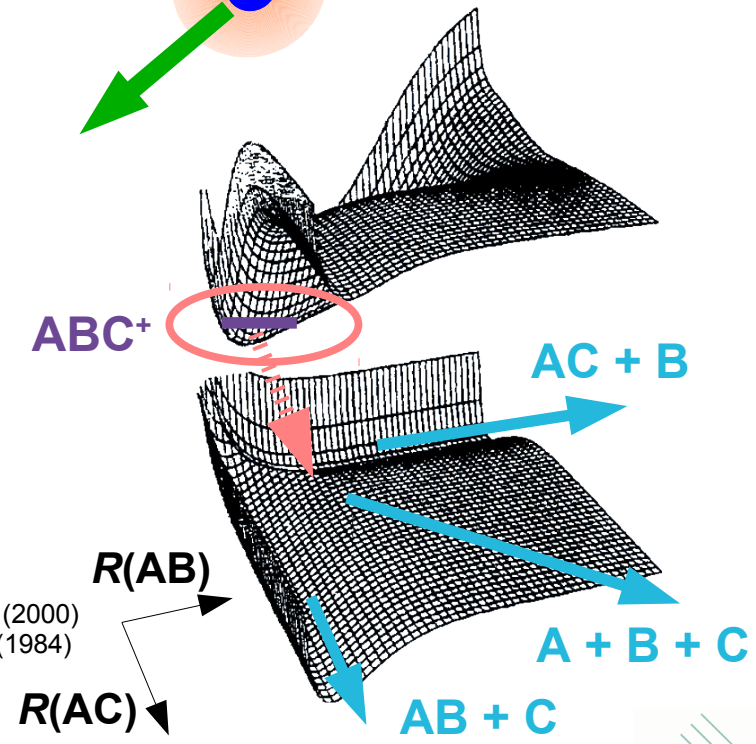
Molecular breakup by cold electrons

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



Dissociative recombination

Feshbach resonance



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

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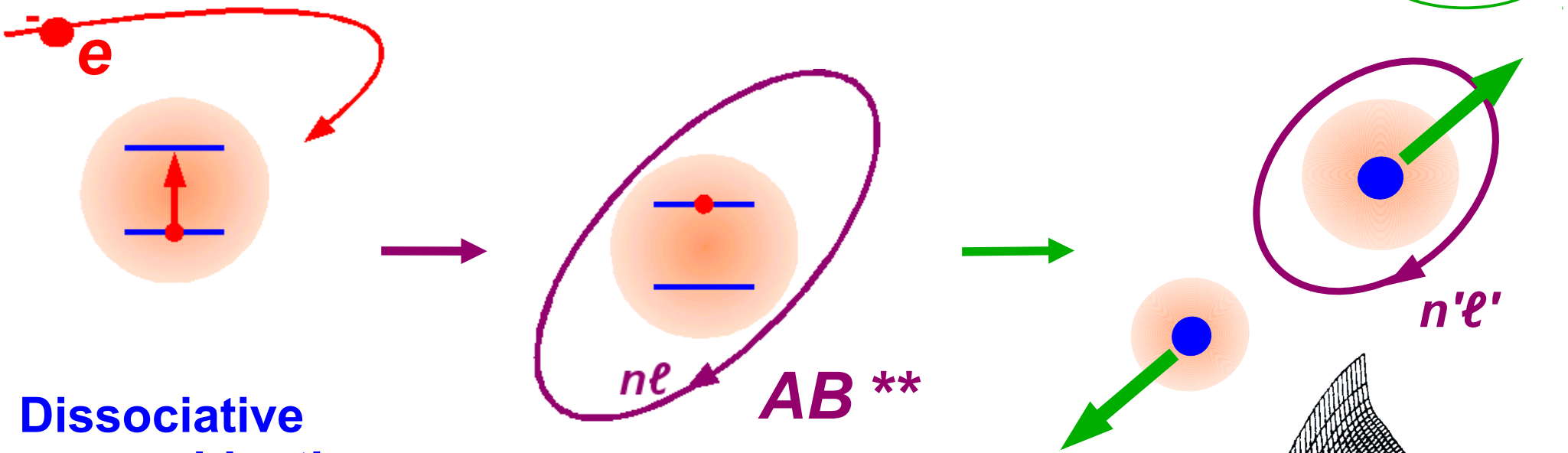
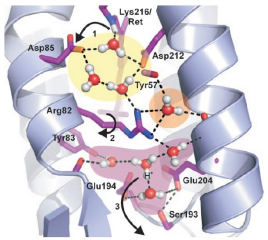
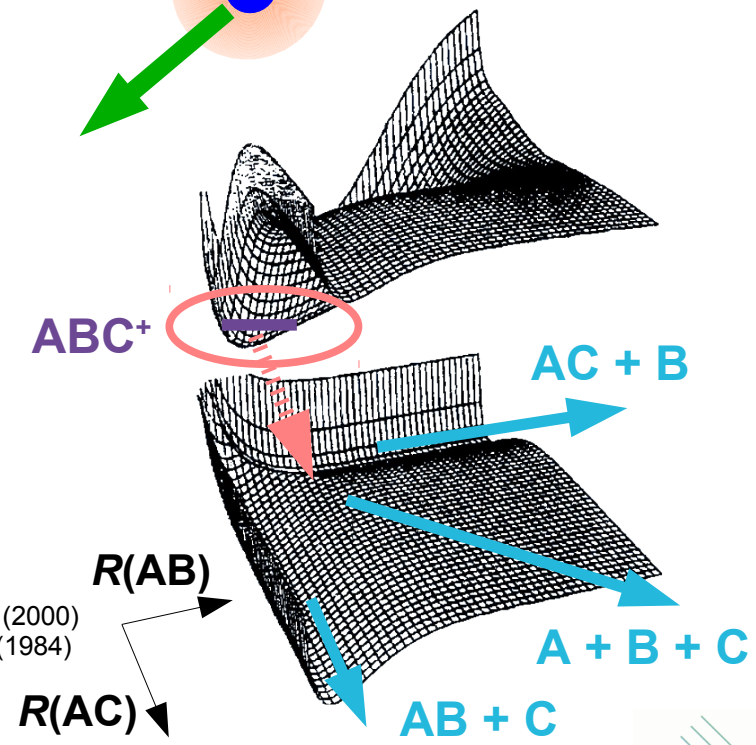


Dissociative recombination

Feshbach resonance

Dissociative electron attachment on neutral molecules

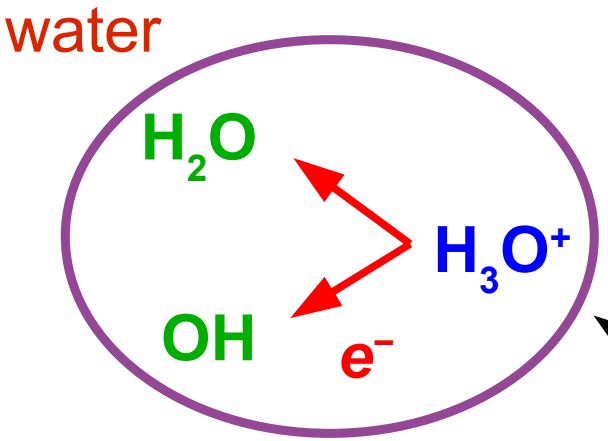




Suzor-Weiner, Nature (2000)
Murrell, … Varandas (1984)

Molecular cloud chemistry

"Heavy" elements: O, C, N, Si, S, Fe, ... $T \sim 10$ K



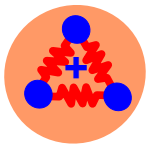
H_2O^+

hydrocarbons

$O + H_3^+ \rightarrow OH^+ + H_2$

$C + H_3^+ \rightarrow CH^+ + H_2$

Protonated hydrogen molecule H_3^+



$H_2^+ + H_2 \rightarrow H_3^+ + H$

Ionization by cosmic radiation or x-rays

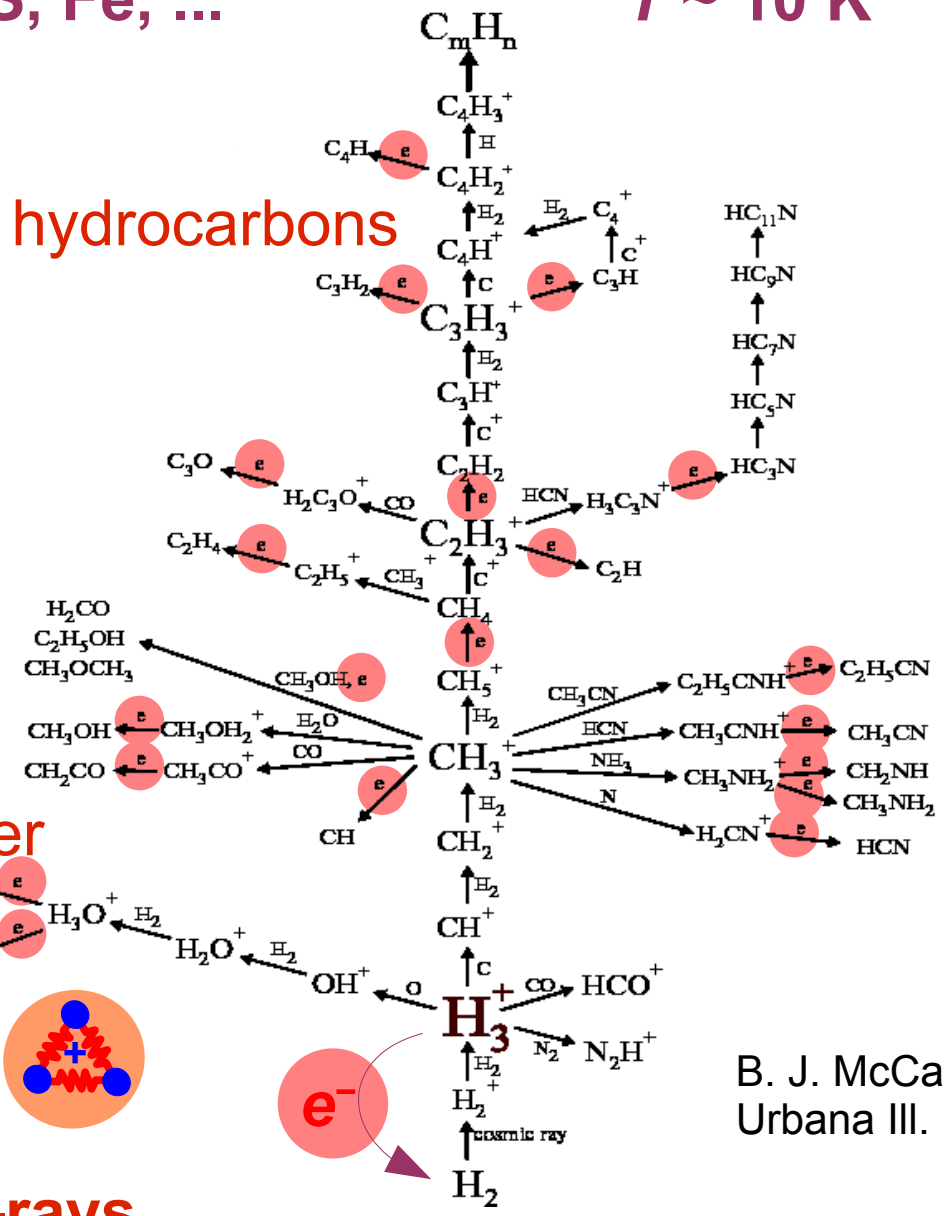
$H_2 + X \rightarrow H_2^+ + e^- + X'$

Molecular cloud chemistry

"Heavy" elements: O, C, N, Si, S, Fe, ... ***T*** **~ 10 K**

Dissociative recombination

Recombination rates,
product branching ratios

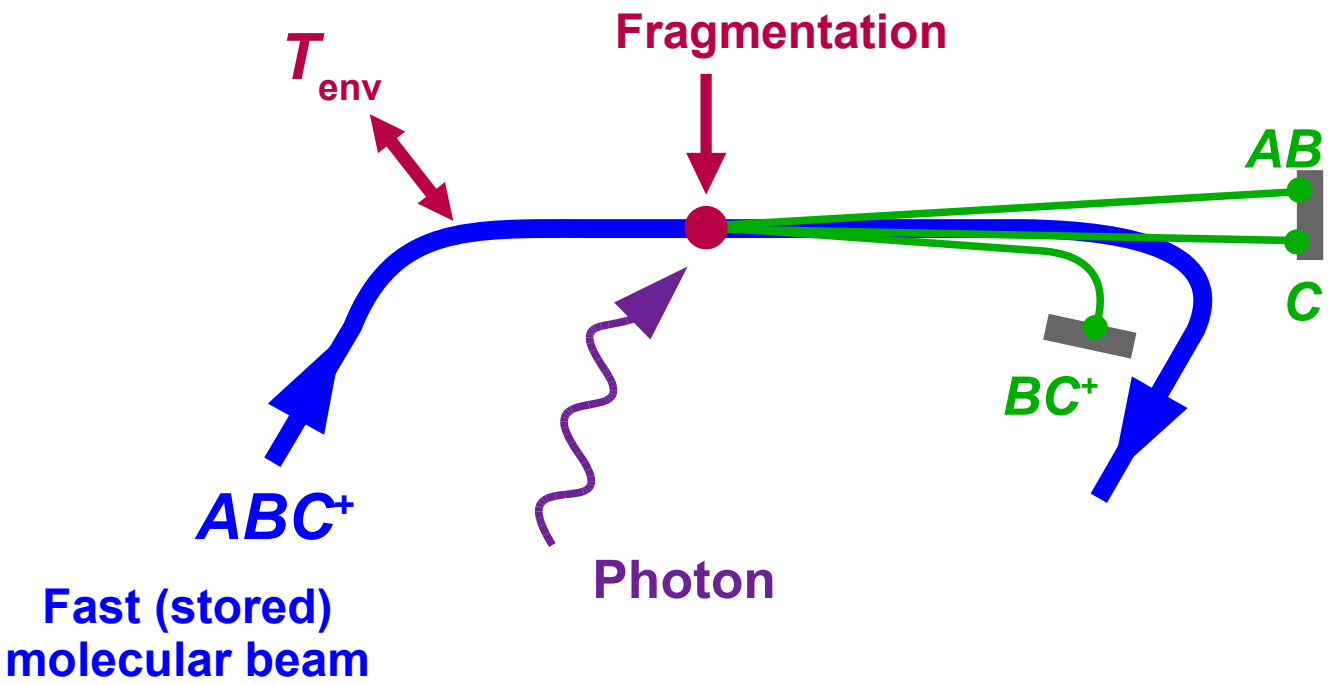


Protonated hydrogen molecule H_3^+

B. J. McCall
Urbana Ill.

Ionization by cosmic radiation or x-rays

Chemical physics using fast beam fragment imaging

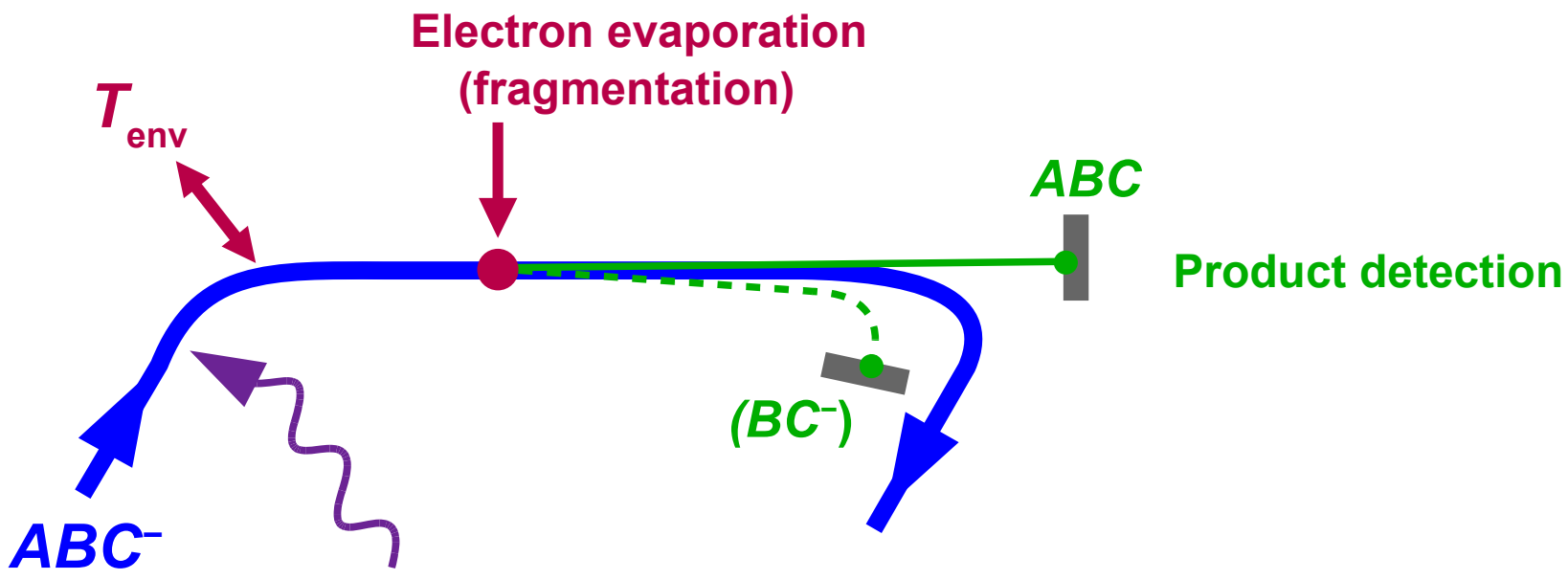


Product detection, idenfication, momentum imaging

Ion experiments at the XUV-FEL FLASH

TIFF ion-beam fragment imaging by MPIK, Aarhus Univ.

Chemical physics using fast beam fragment imaging



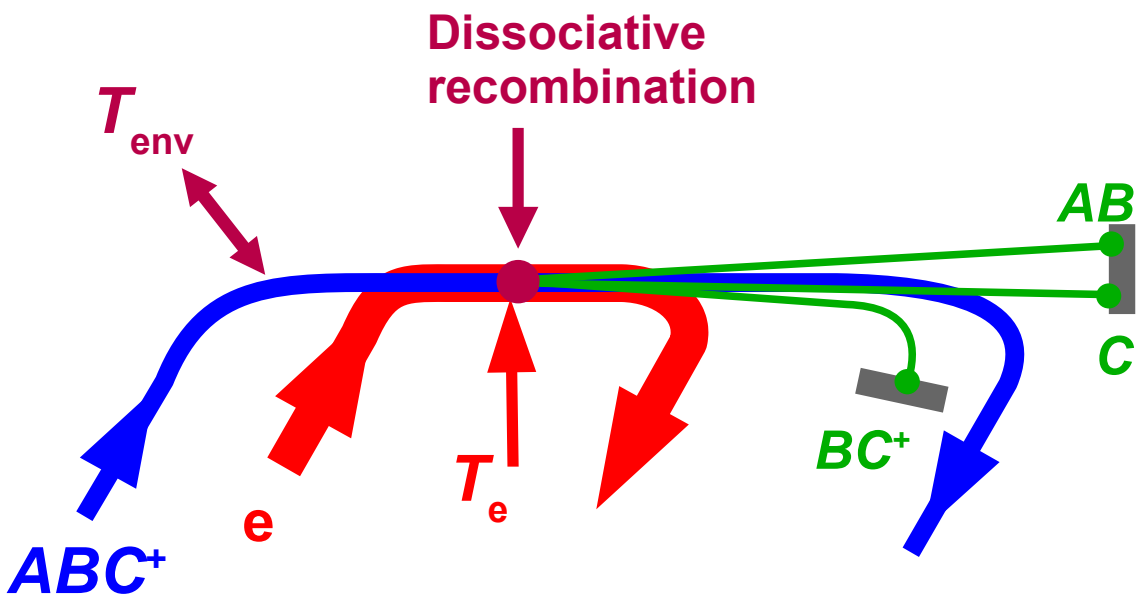
Fast (stored)
molecular beam
(negative ions)

(4...10 keV)

Electron evaporation
from vibrating molecules

Electrostatic storage rings
at Aarhus Univ., Tokyo, ...

Chemical physics using fast beam fragment imaging



Product detection, idenfication, momentum imaging

Fast (stored) molecular beam

(few MeV)

Velocity-matched electron beam

$E_d = ½\ m_e\ (v_e - v_i)^2$

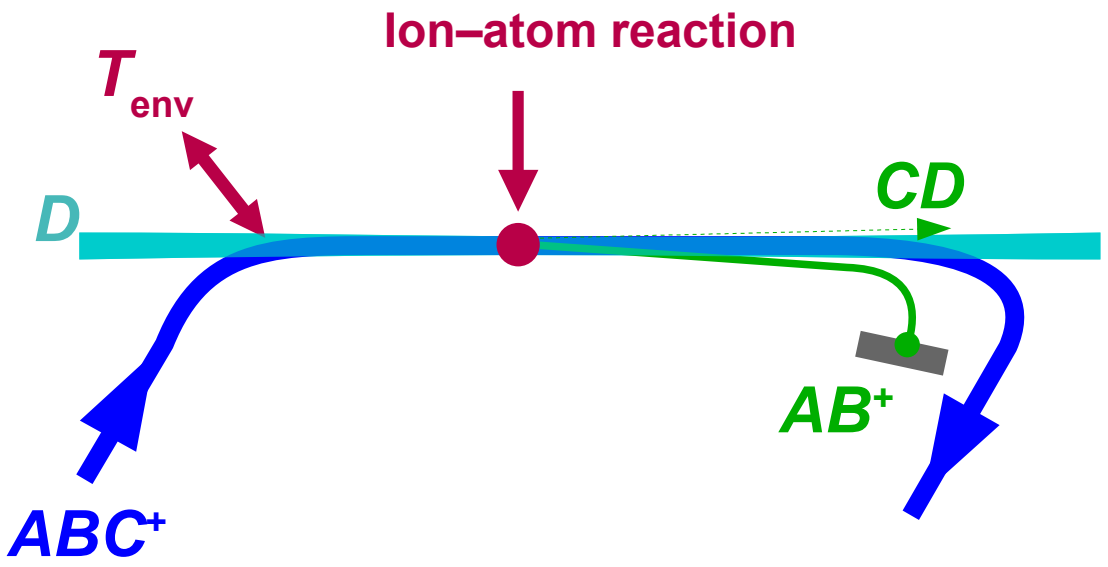
~ 1 meV … 50 eV

Electron cooler = electron "target"

Magnetic storage rings

Planned at electrostatic storage rings (~100 keV beam energy)

Chemical physics using fast beam fragment imaging



Product detection, idenfication, momentum imaging

Fast (stored) molecular beam

(~300 keV)

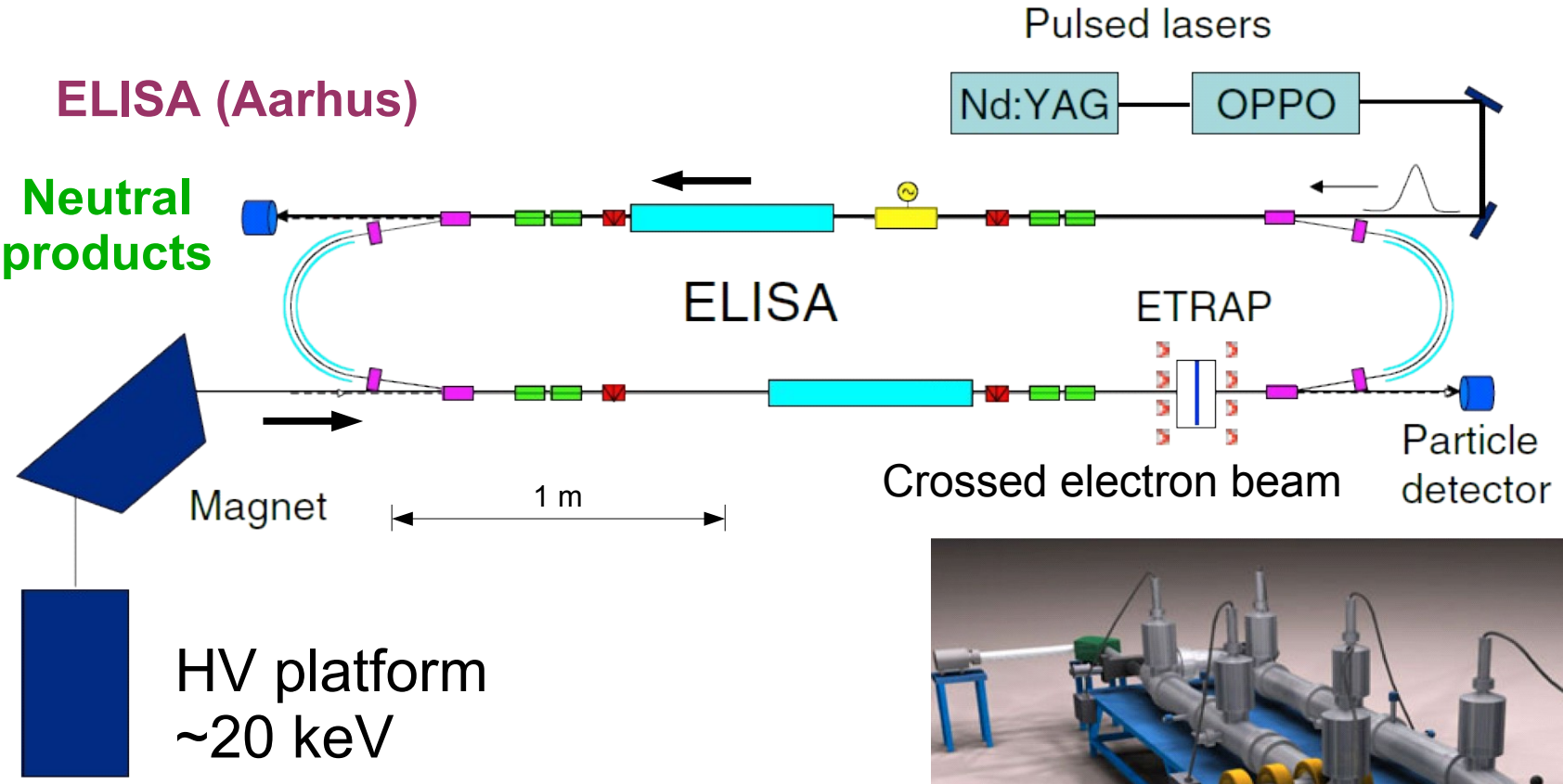
Velocity-matched atomic beam

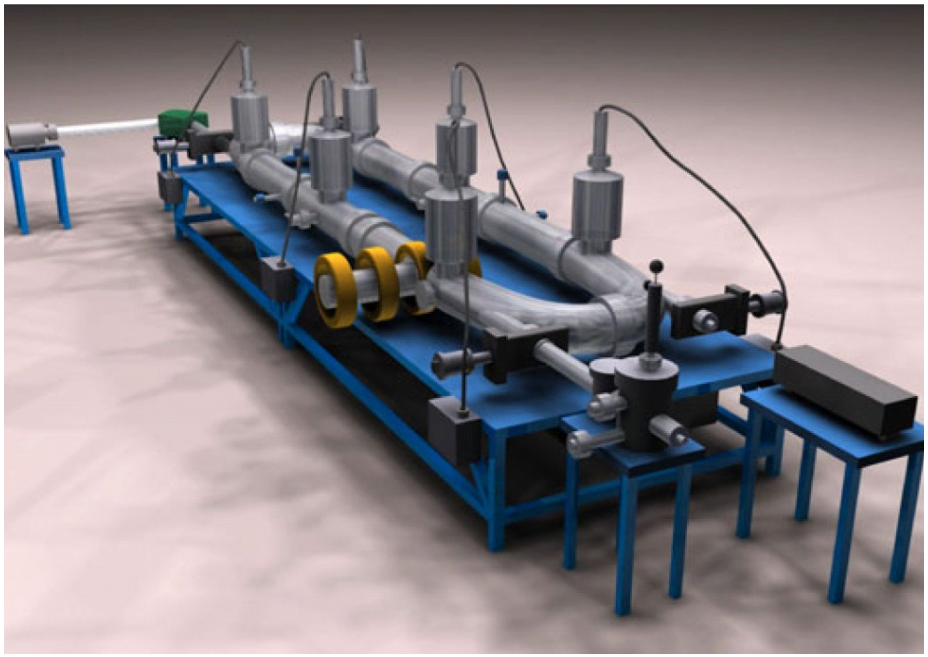
$E_d = ½\, m_e\, (v_n - v_i)^2$

$\gtrsim$ 10 meV

Planned with
cooled ion beams
at electrostatic storage rings

Electrostatic storage rings





Mass independent beam storage:
large molecules and clusters

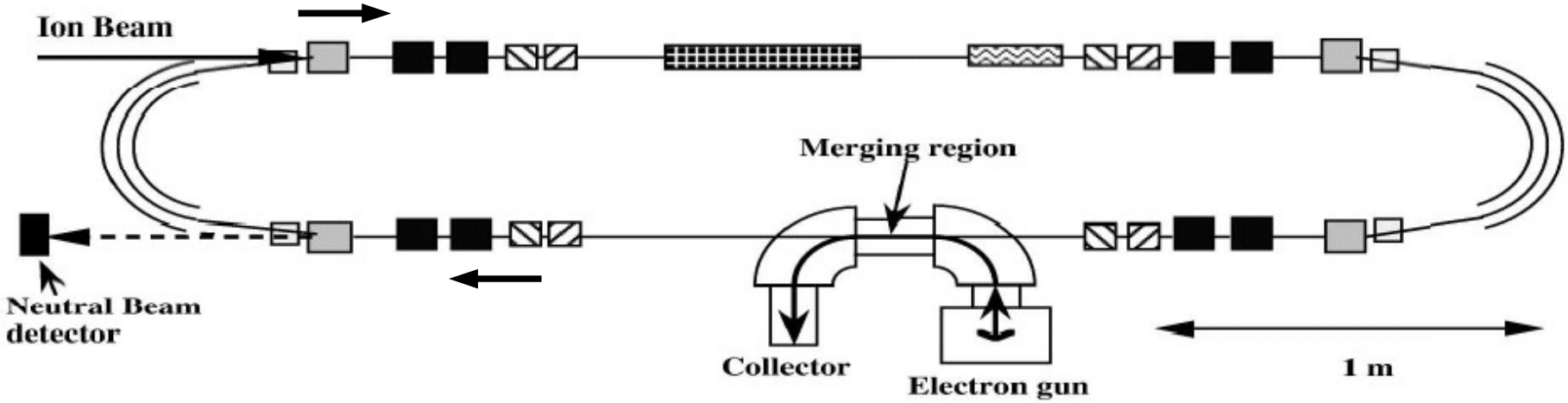
Molecular decay: evaporation of electrons and heavy fragments –
cooling of multidimensional vibrations

Laser excitation and delayed decay

Electrostatic storage rings

ELISA (Aarhus)

KEK Tokyo (biomolecules + 10 eV electron cooler)



Merged electron beam

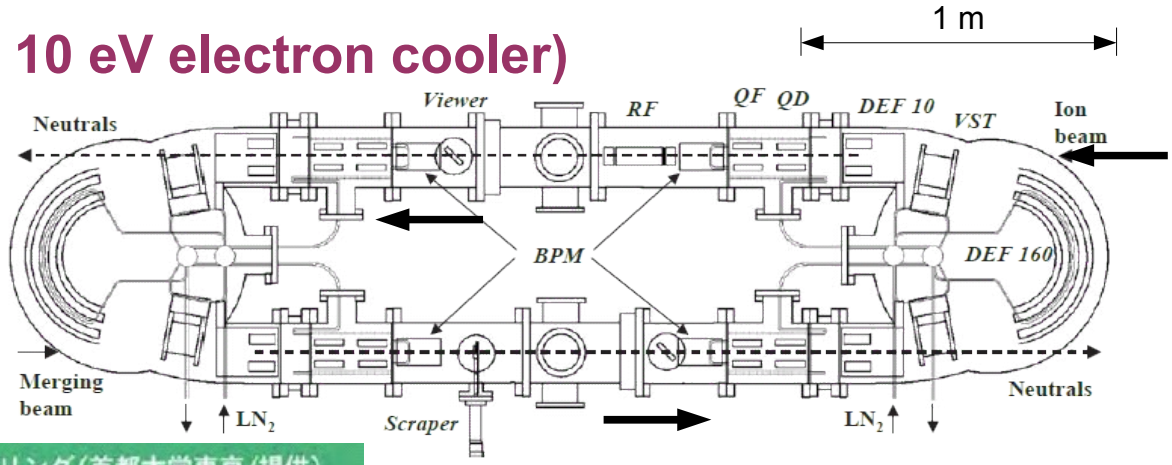
Fragmentation of amino acids, DNA base pairs, by ~10 eV electrons

T. Tanabe, PRL 93, 043201 (2004)

Electrostatic storage rings

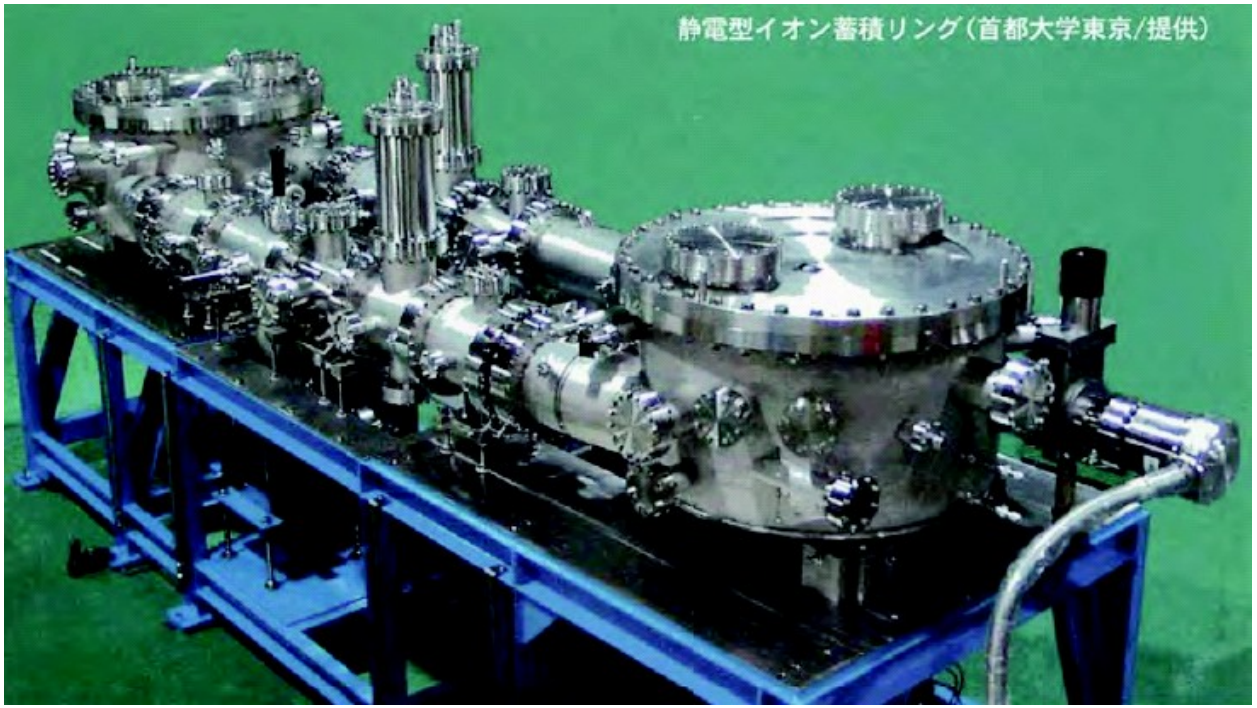
ELISA (Aarhus)

KEK Tokyo (biomolecules + 10 eV electron cooler)



TMU E-ring Tokyo (LN_2 cooling, ~70 K)

+ small 10 K ring: T. Azuma, Y. Nakano



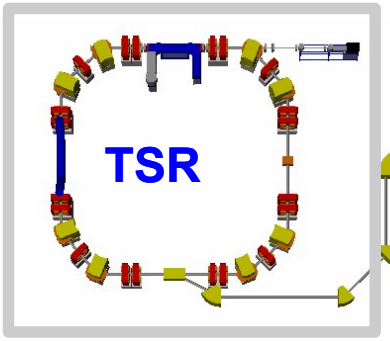
C_n^- clusters, short-lived excited states

Stability of *weakly bound anions at low* (~100 K) *temperature*

+ table-top rings,~0.4 m, 300 K, τ ~ 30 ms (Lyon)

Bernard et al., Rev. Sci. Instrum. 79, 075109 (2008)

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

~10^6–10^8 stored ions

Translational and internal cooling

0.5 MV RFQ linac

12 MV tandem accelerator

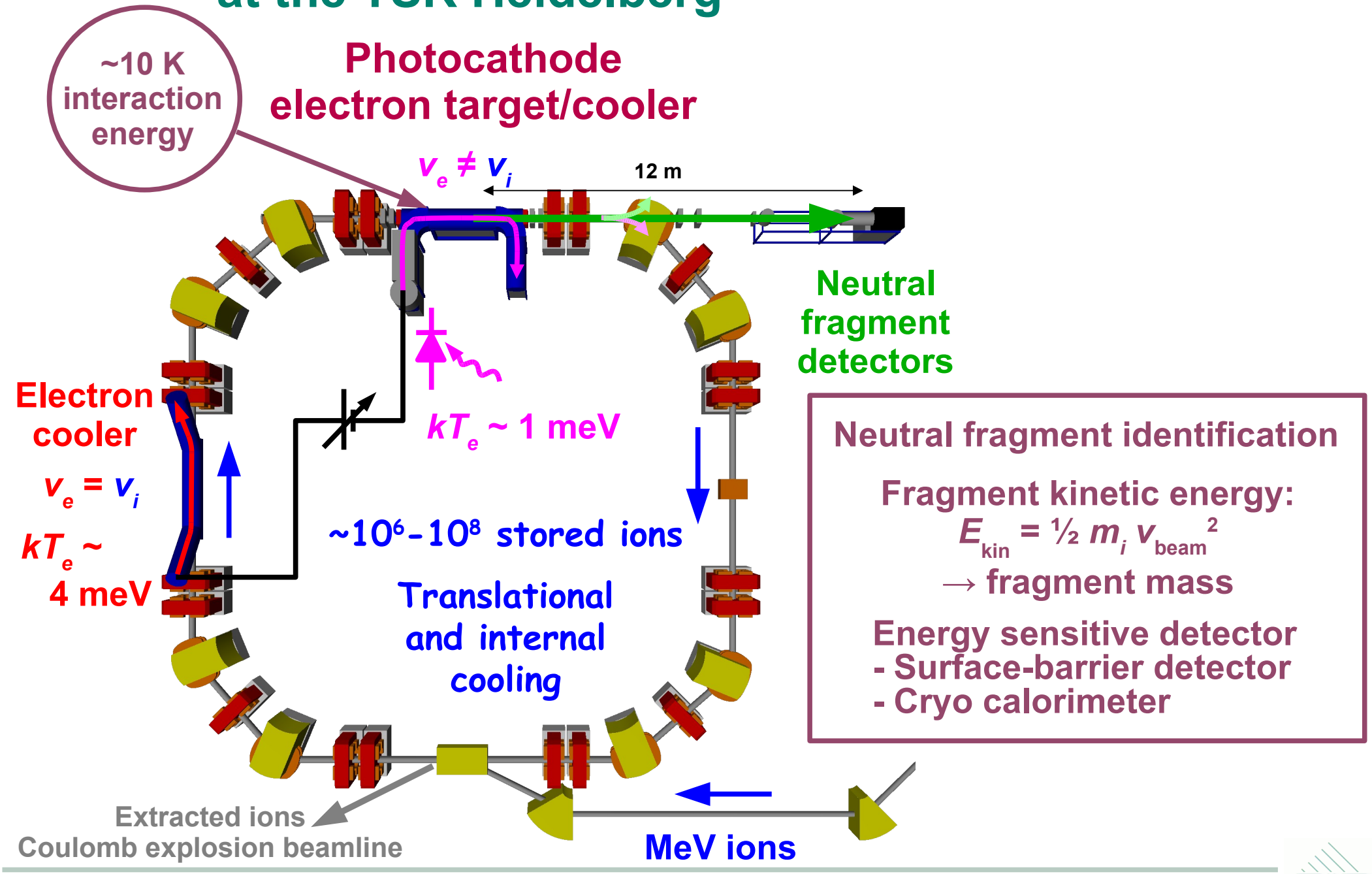
Ion sources

2.5 MeV pelletron

Extracted ions
Coulomb explosion beamline

MeV ions

Electron–ion merged beams at the TSR Heidelberg



Neutral fragment identification

Fragment kinetic energy:

$E_{kin} = ½ m_i v_{beam}^2$

→ fragment mass

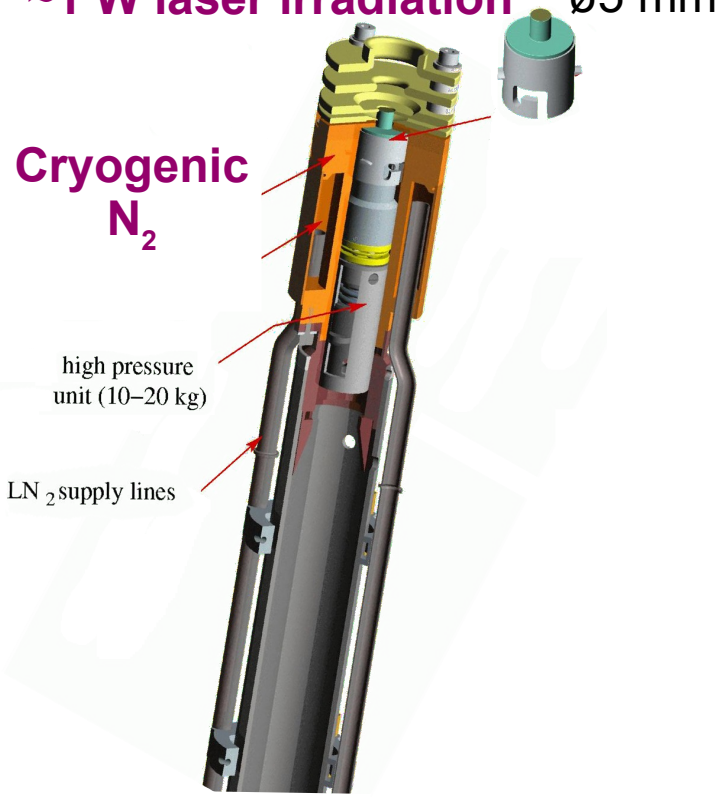
Energy sensitive detector
- Surface-barrier detector
- Cryo calorimeter

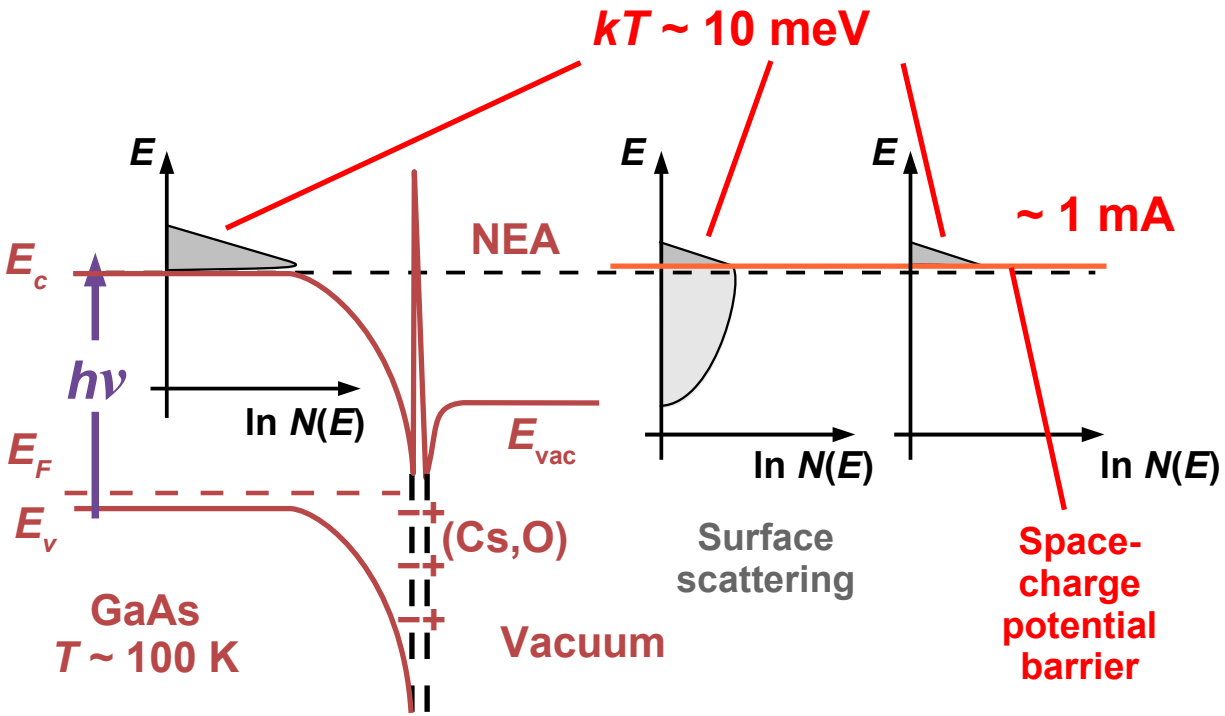
High-resolution electron target

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
- 2008: Beam transport down to < 1 eV with 10 µA current (0.01 T guiding field)

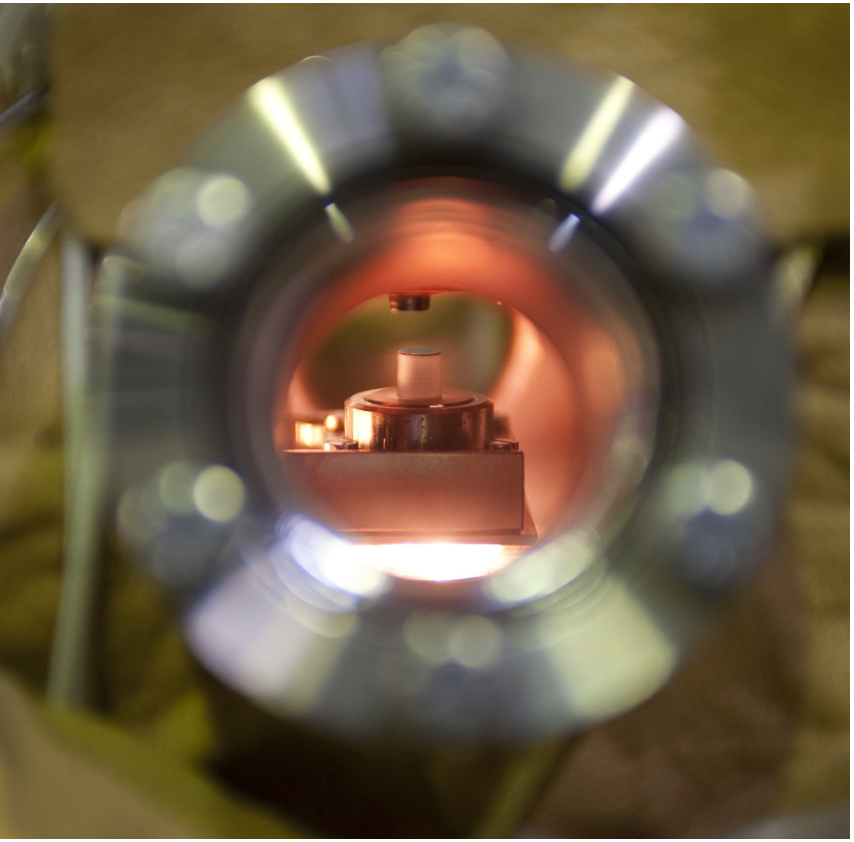
D. A. Orlov et al., J. Appl. Phys. 106, 054907 (2009)

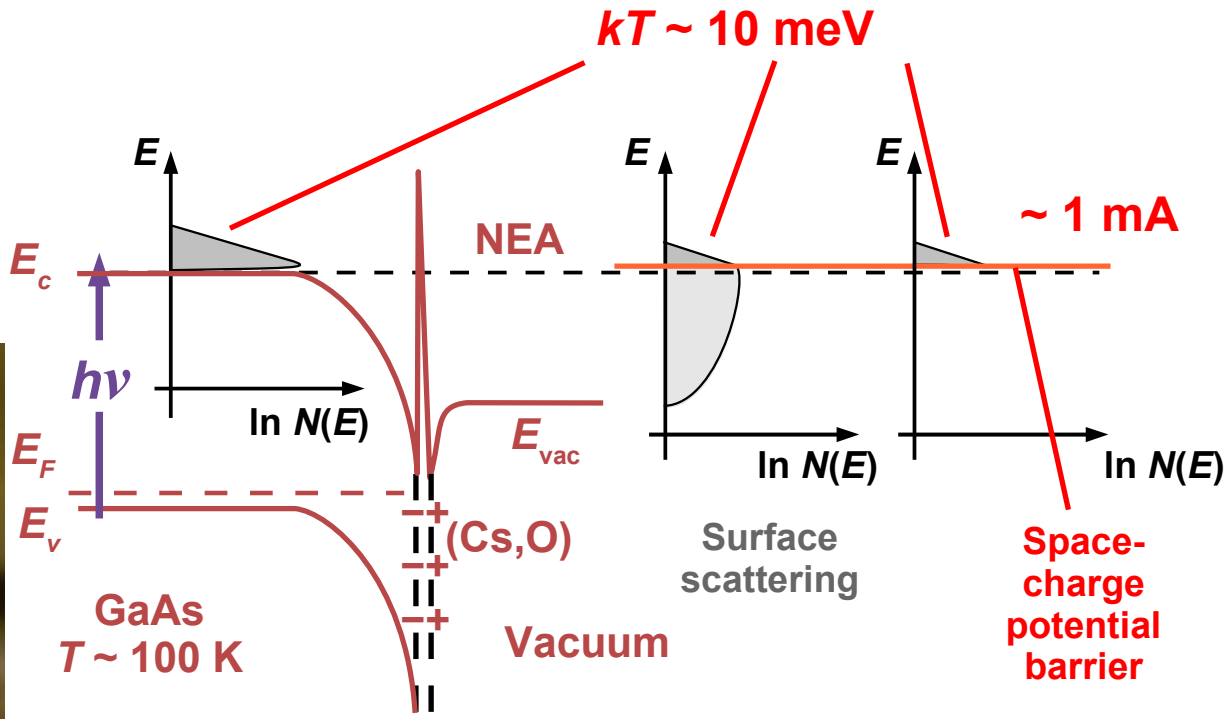
D. A. Orlov, C. Krantz, A. Shornikov
Collab. with Inst. f. Semiconductor Phys., Novosibirsk, A. N. Terekhov

High-resolution electron target

Photocathode electron target

GaAs photocathode ~100 K





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Electron cooling with a photocathode beam

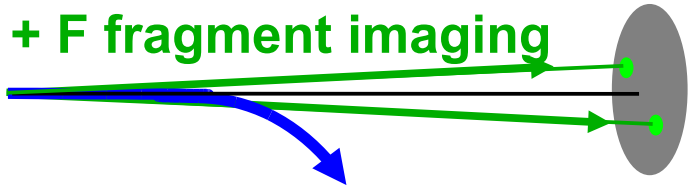
CF^+ (31 amu) at 90 keV/amu

50 eV electrons

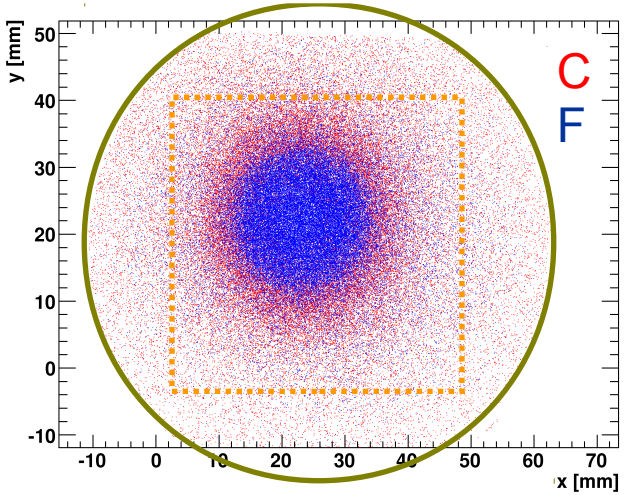
~1 mA electron current

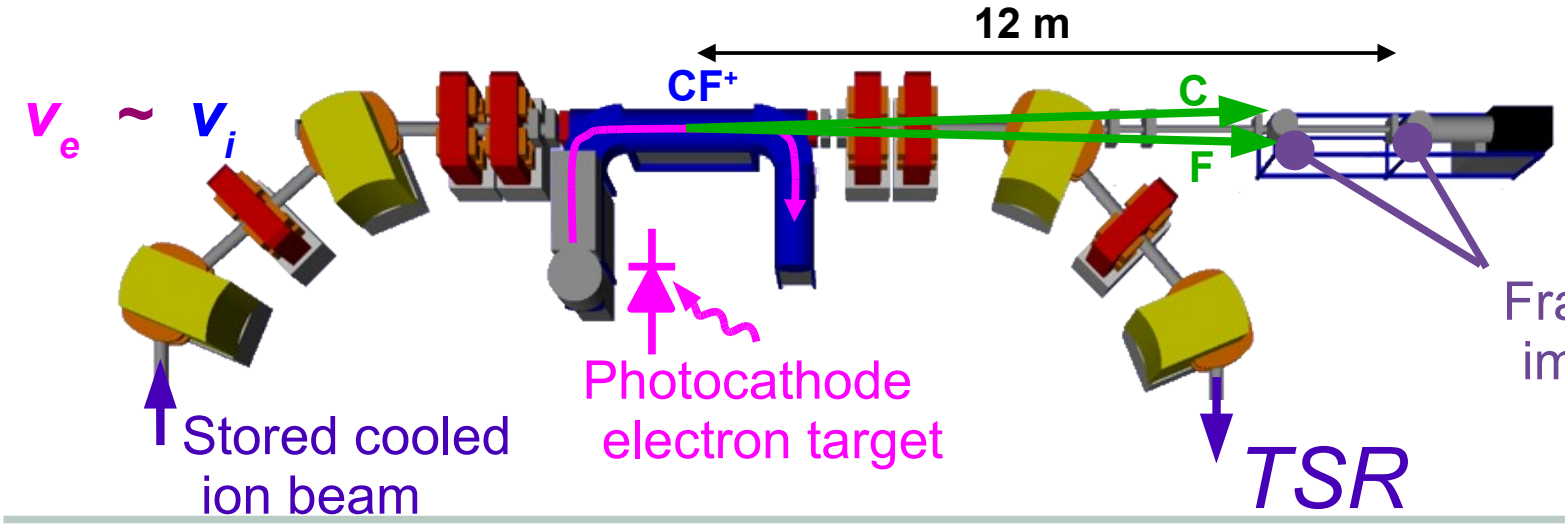
$CF^+ + e \rightarrow C + F$

C + F fragment imaging



Standard electron cooling (12-30 s after injection)





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

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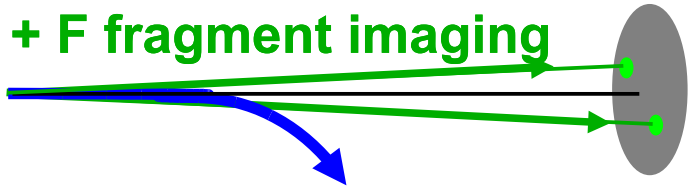
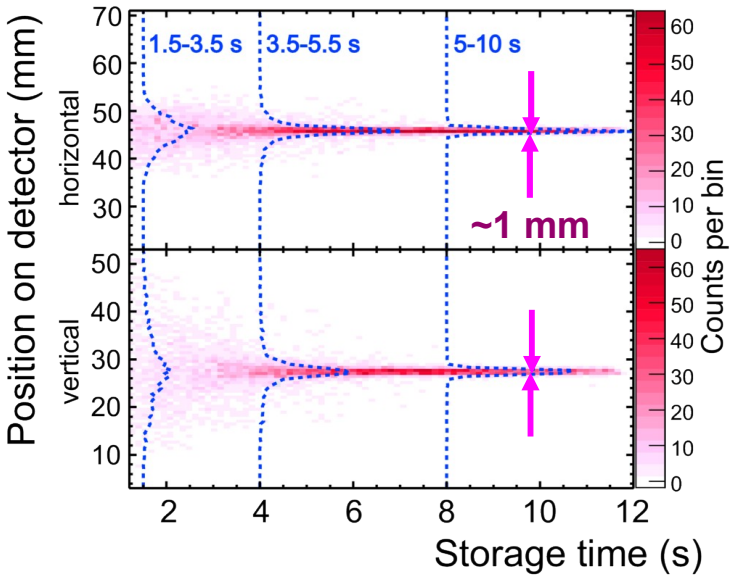
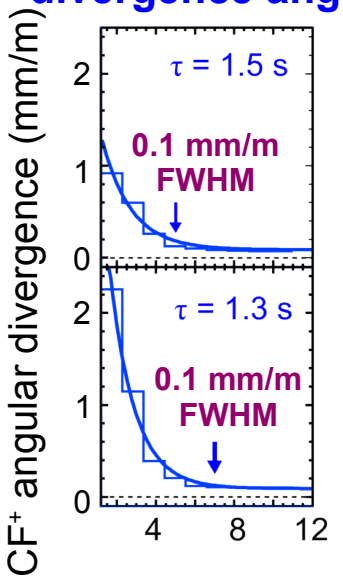


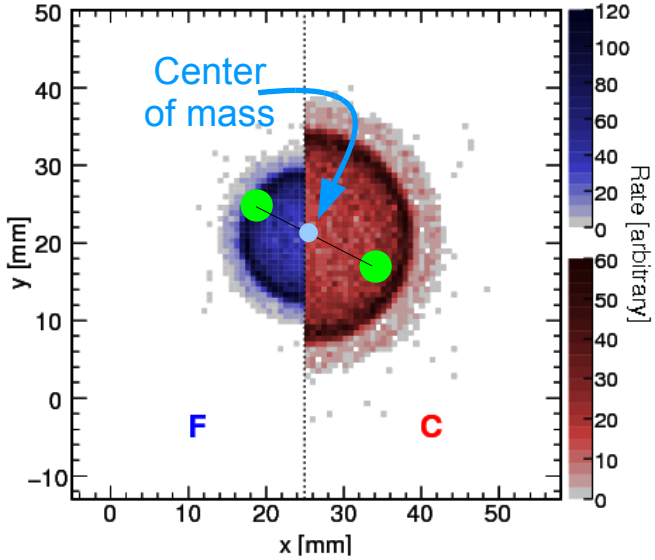
Molecular center of mass on fragment imaging detector

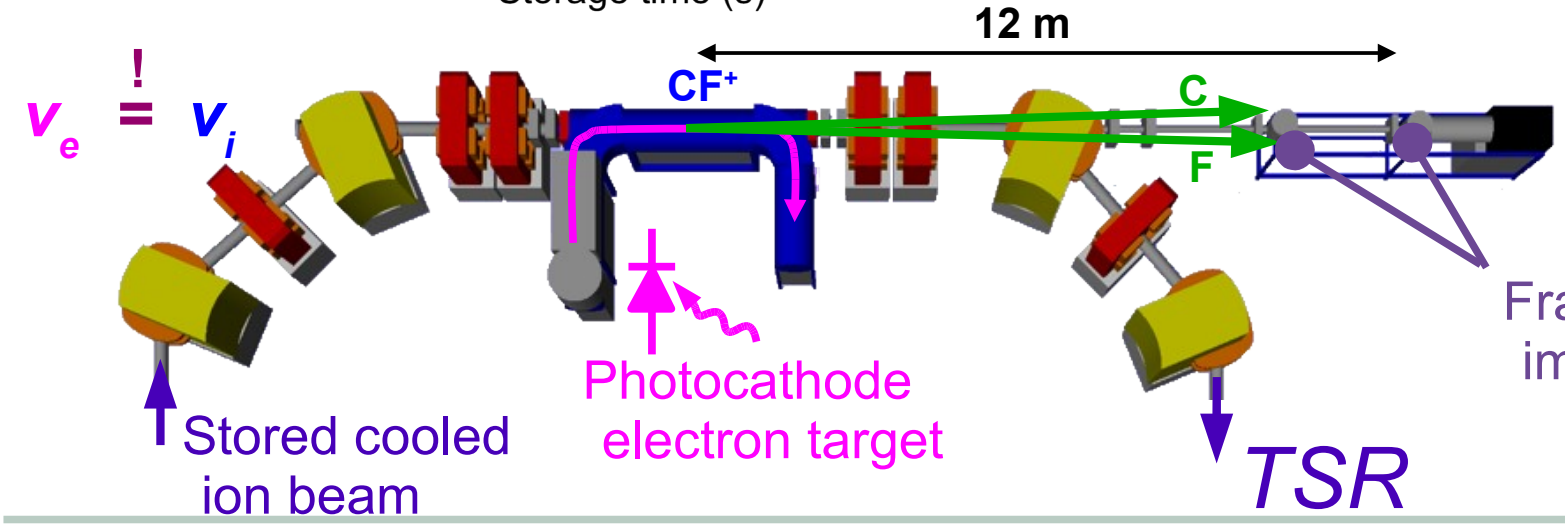


Ion beam divergence angle



Photocathode electron cooling

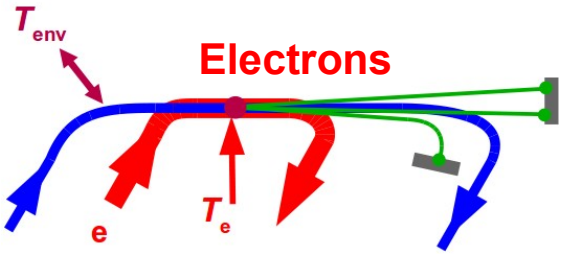




O. Novotný et al., J. Phys. Chem. A 114, 4870 (2010)

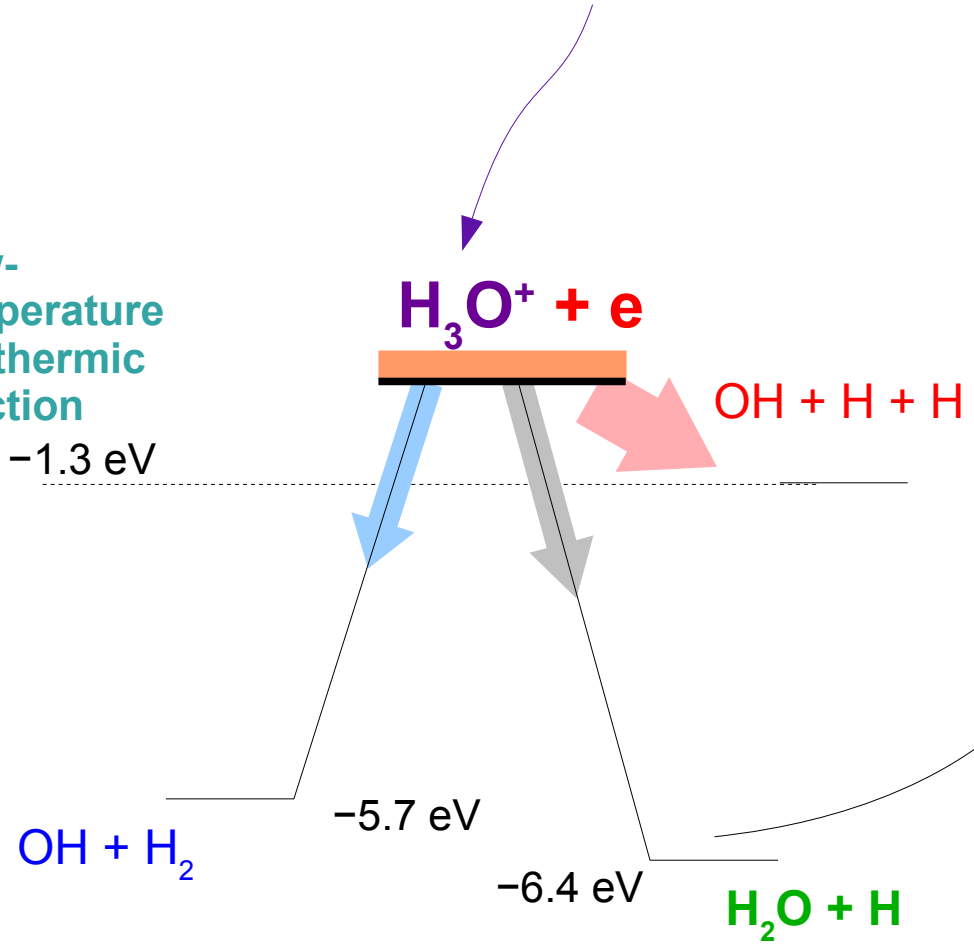
Polyatomic ions at TSR

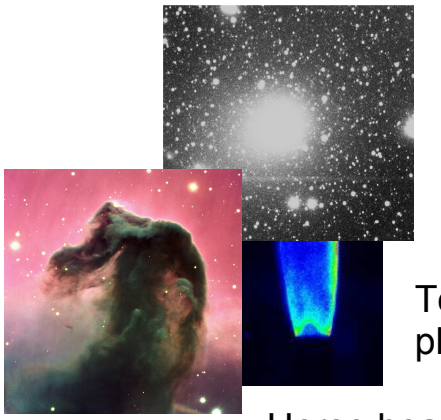
Fragmentation pathways of dissociative recombination



Molecules built up by ion chemistry

Low-temperature exothermic reaction





Coma of comet Hale-Bopp

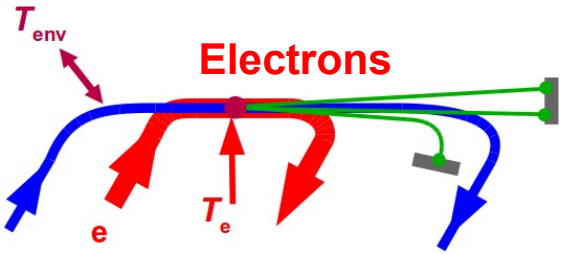
Terrestrial plasma

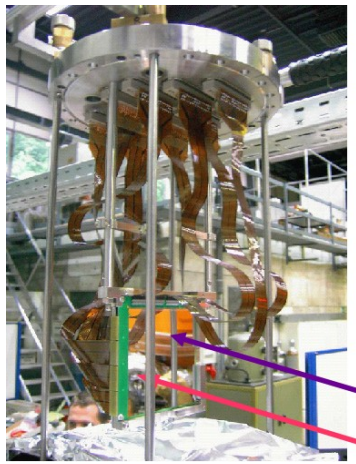
Horse head nebula

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

Polyatomic ions at TSR

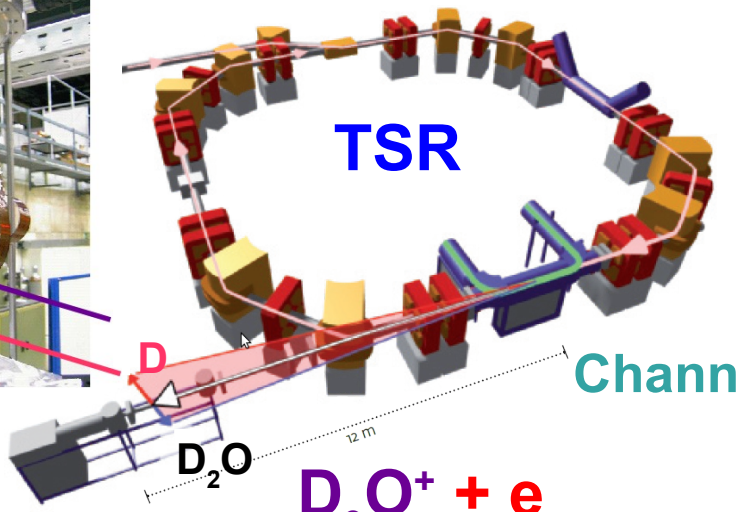
Fragmentation pathways of dissociative recombination





EMU detector

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



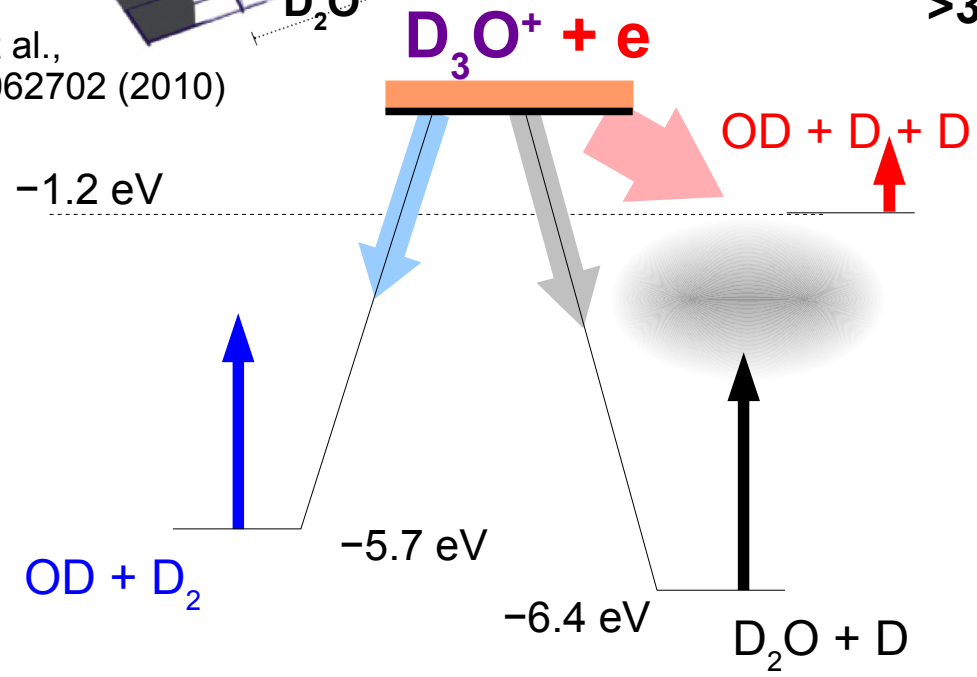
Method:

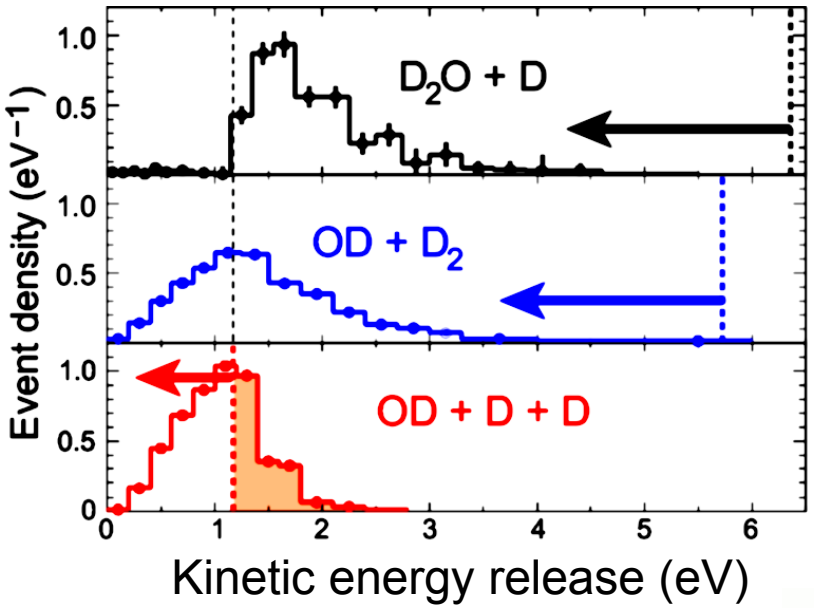
- 1 meV electron collision energy
- Imaging detector with fragment mass recognition (EMU)
- Deuterated molecules

Channel-specific energy release measurement

>3 eV vibrational excitation of water

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



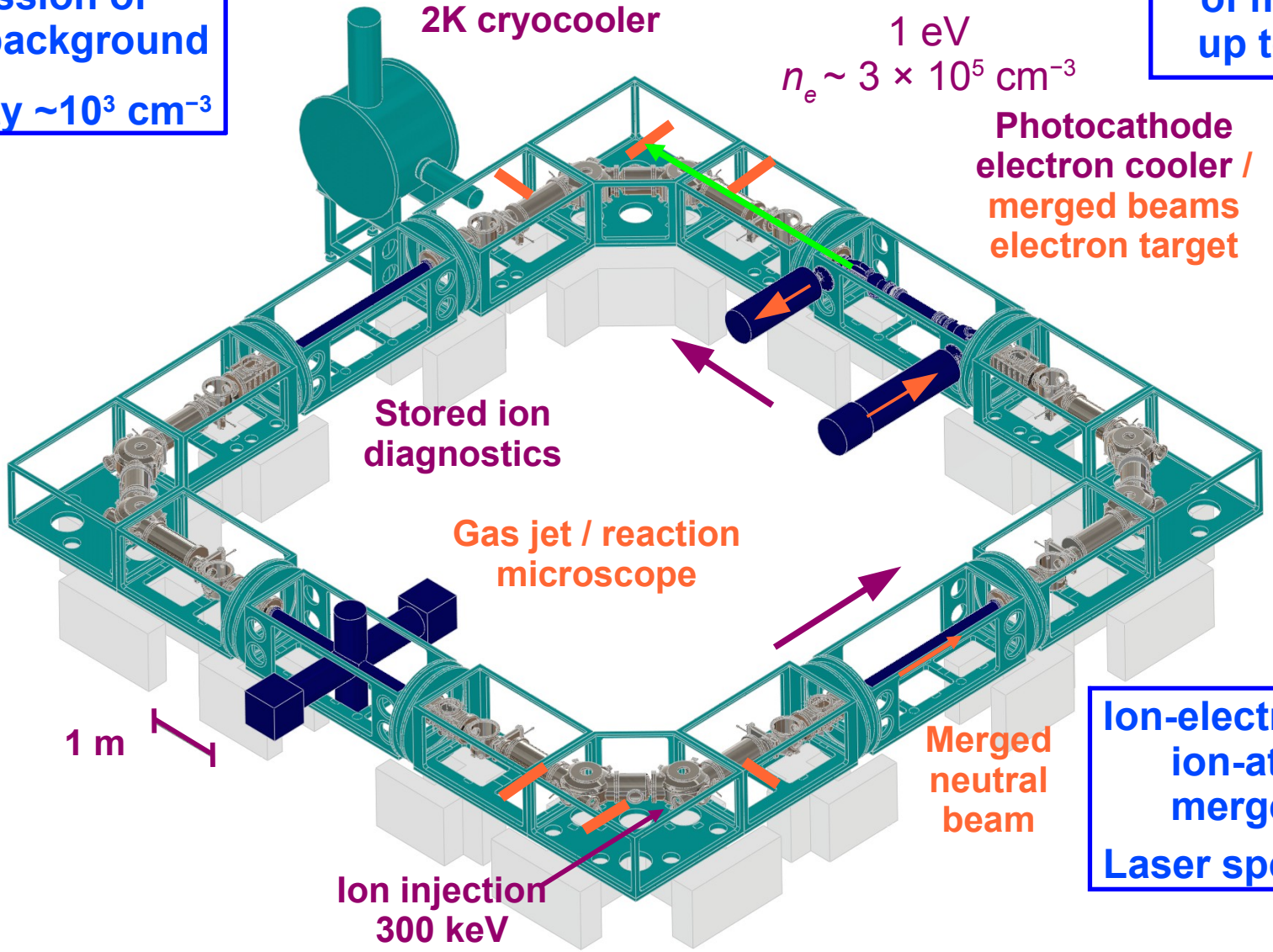


Cryogenic electrostatic storage ring CSR

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}



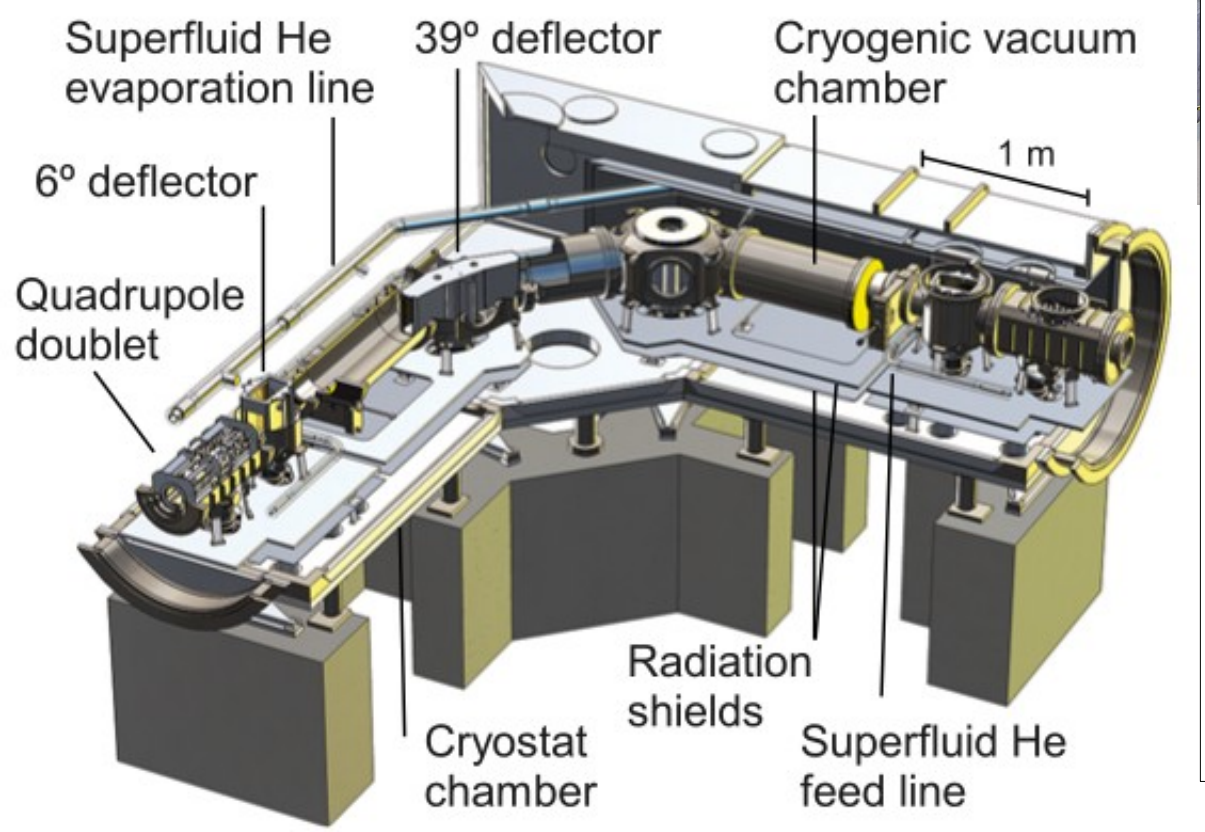
Electron cooling of molecules up to A ~ 160

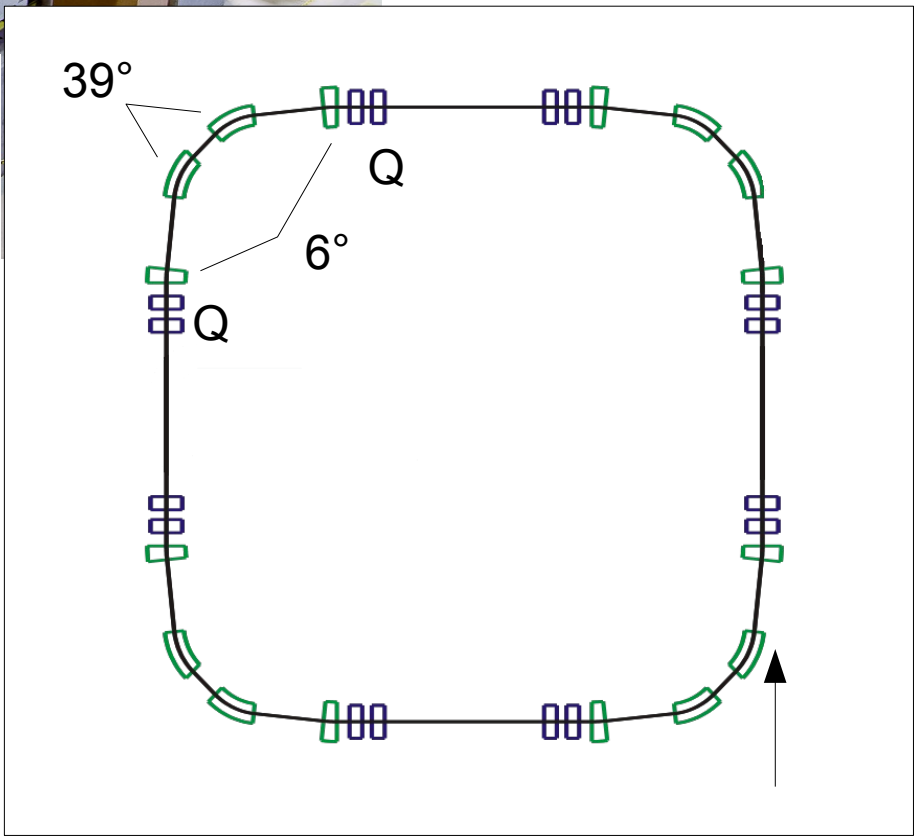
D. A. Orlov, C. Krantz, A. Shornikov et al.

Ion-electron and ion-atom merged beams

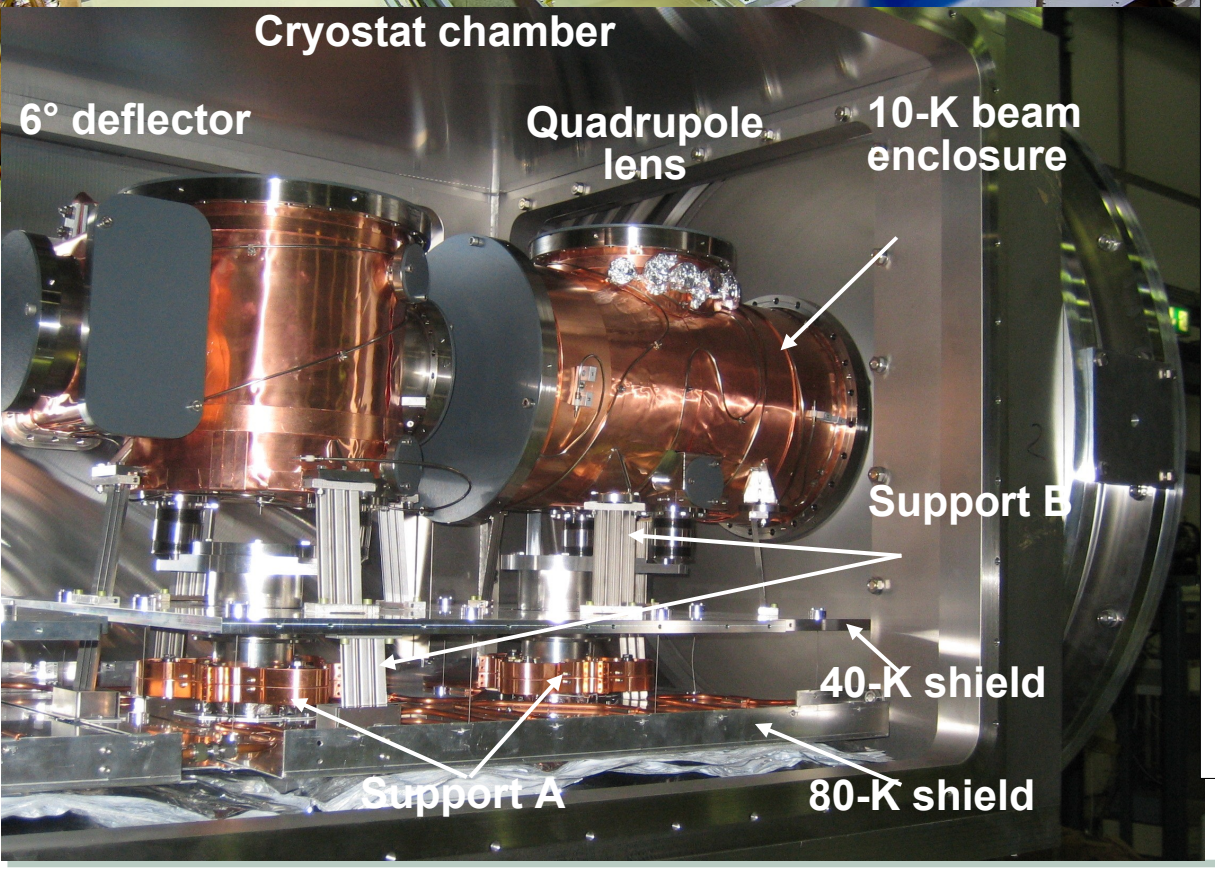
Laser spectroscopy

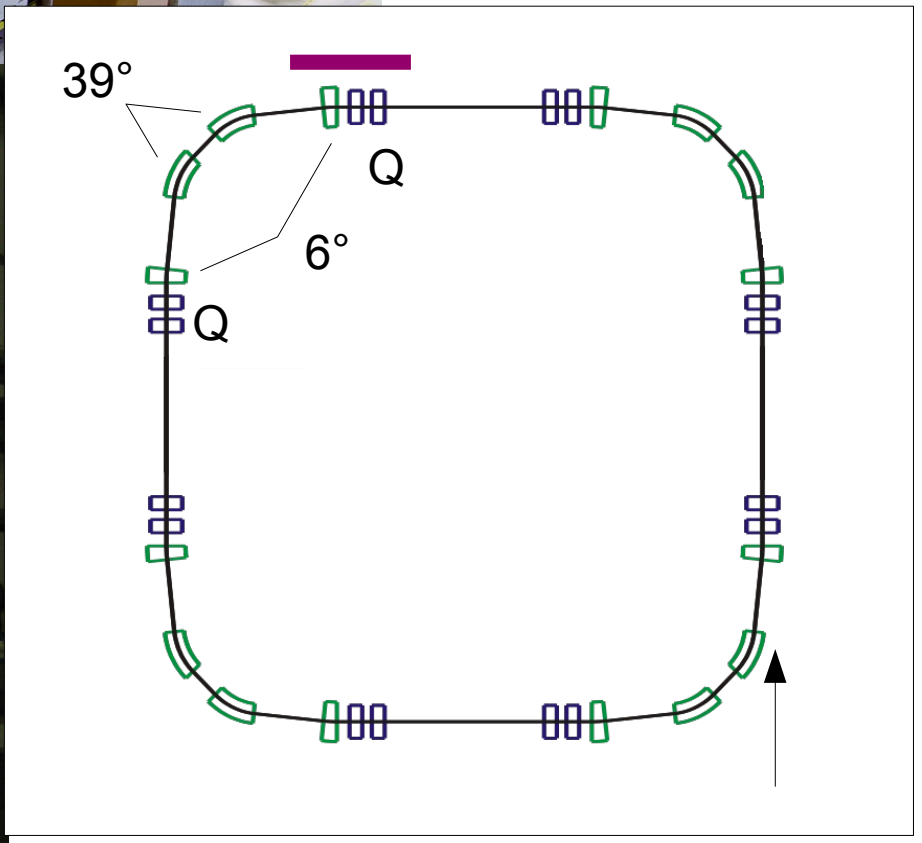
Cryogenic storage ring CSR



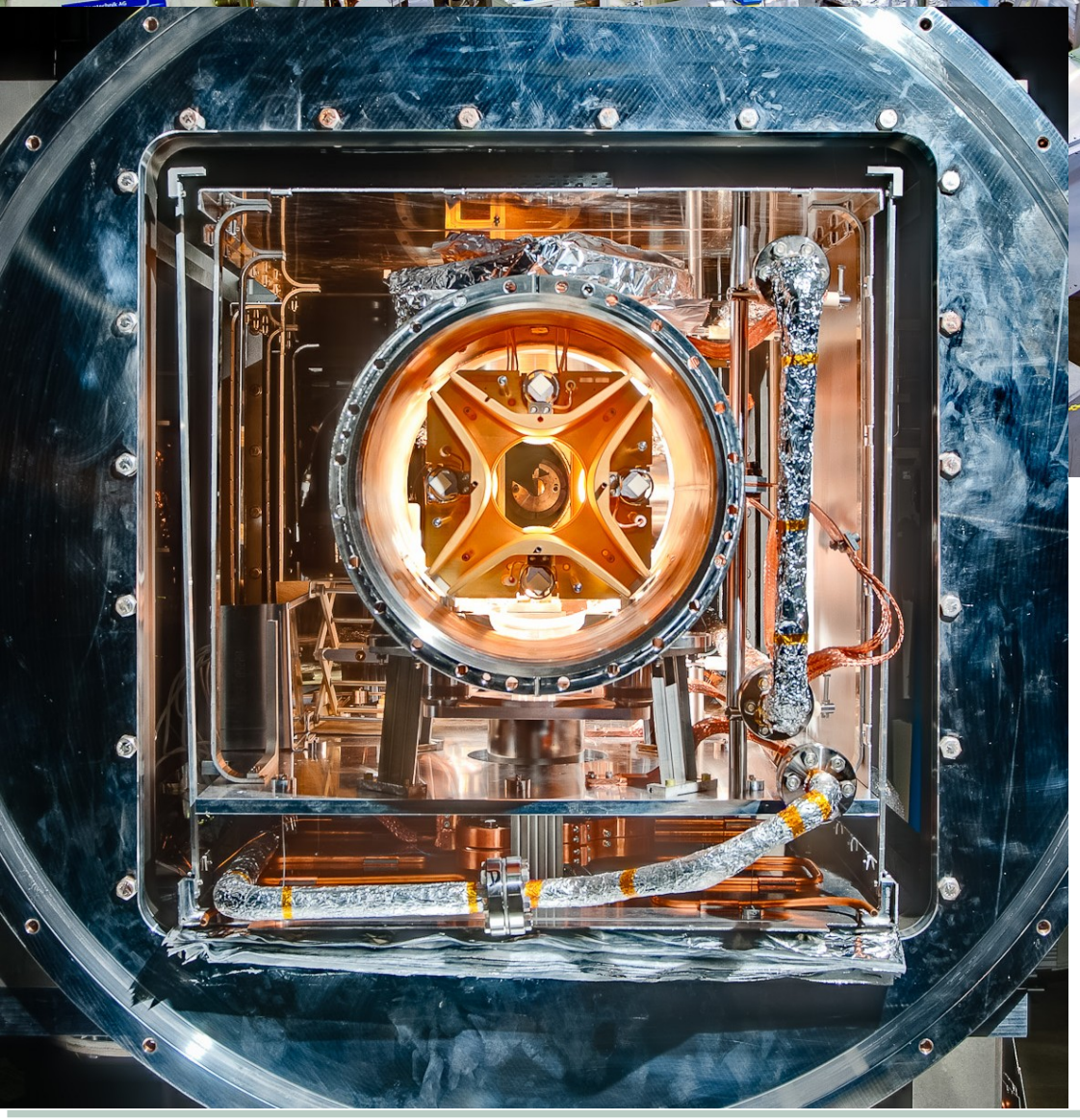


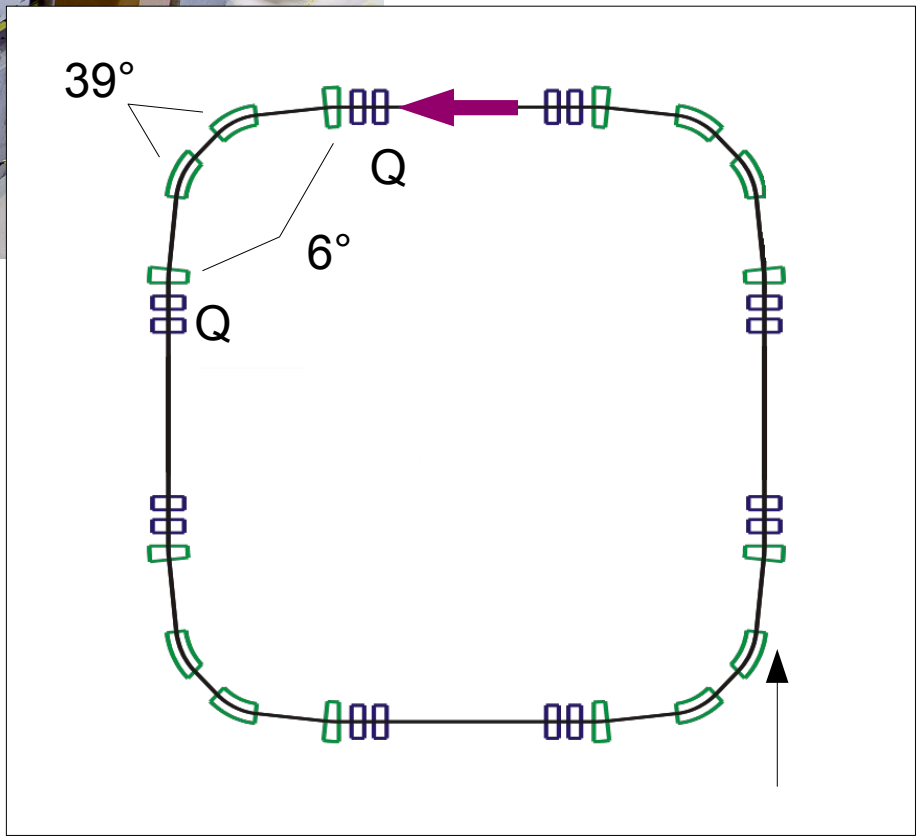
Cryogenic storage ring CSR



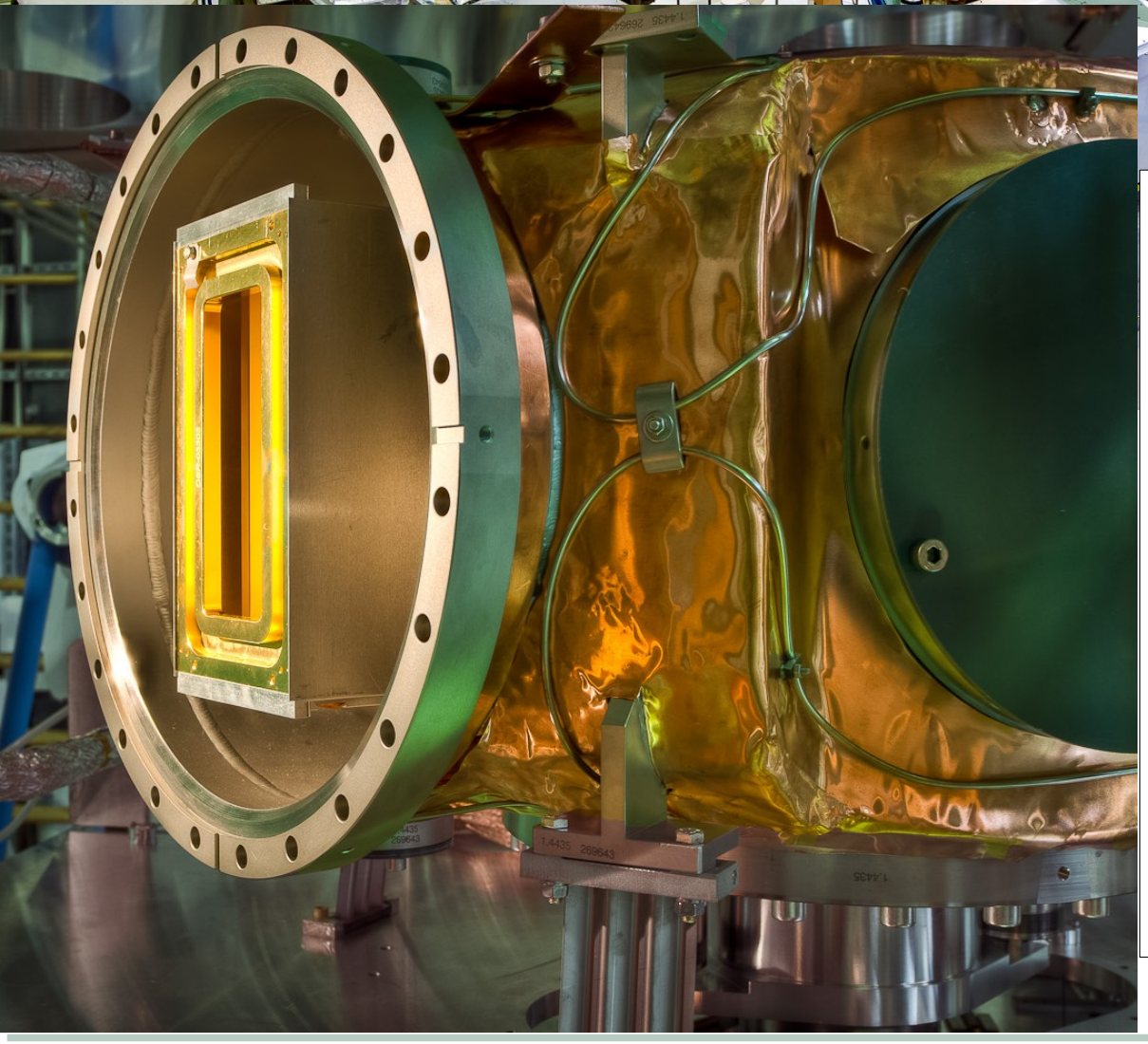


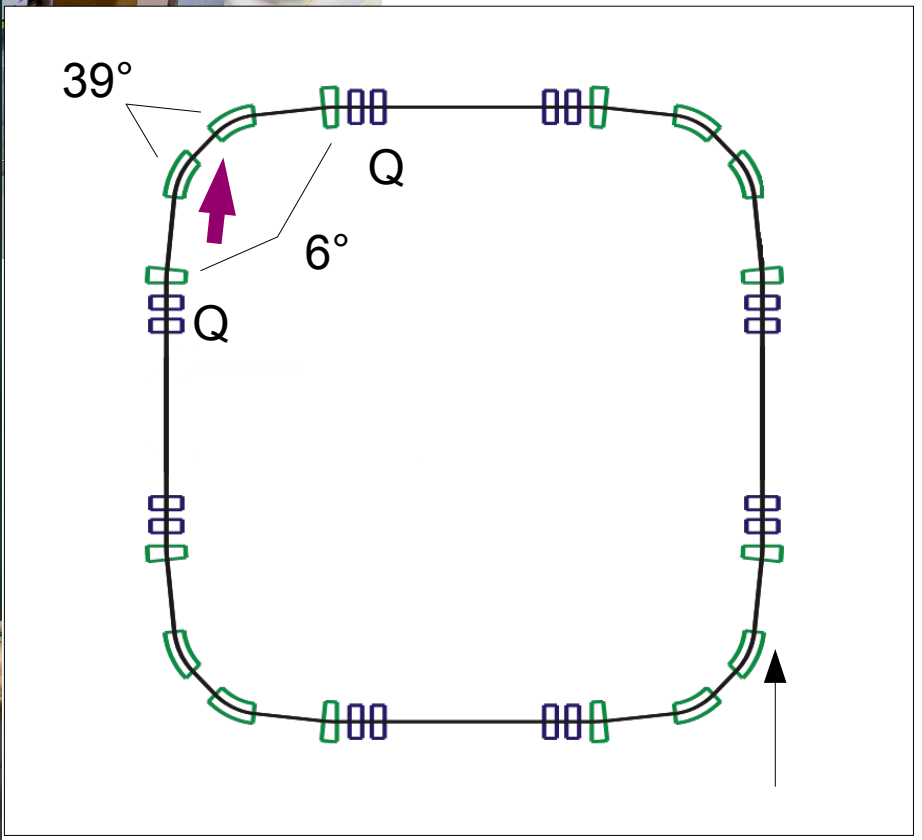
Cryogenic storage ring CSR





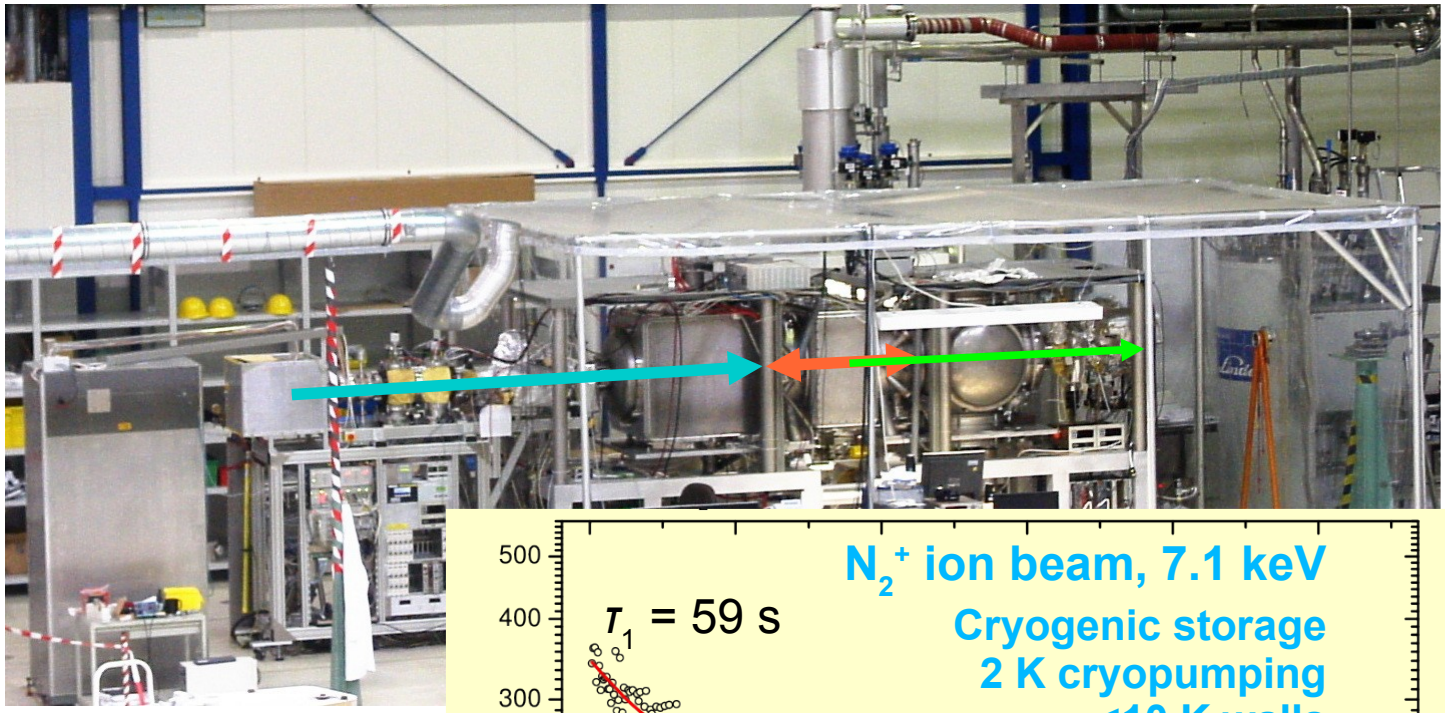
Cryogenic storage ring CSR

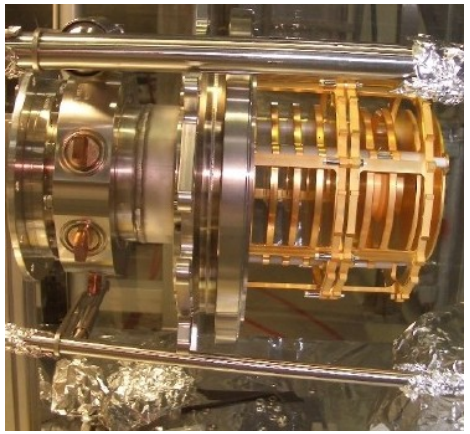


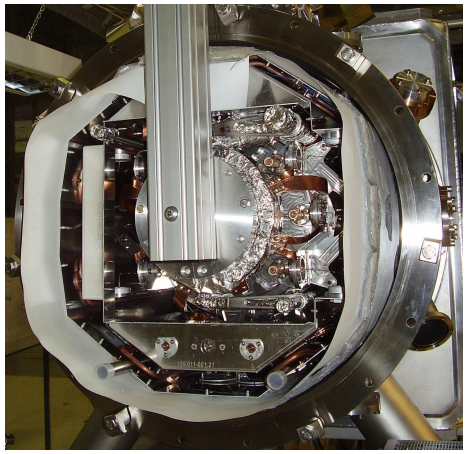


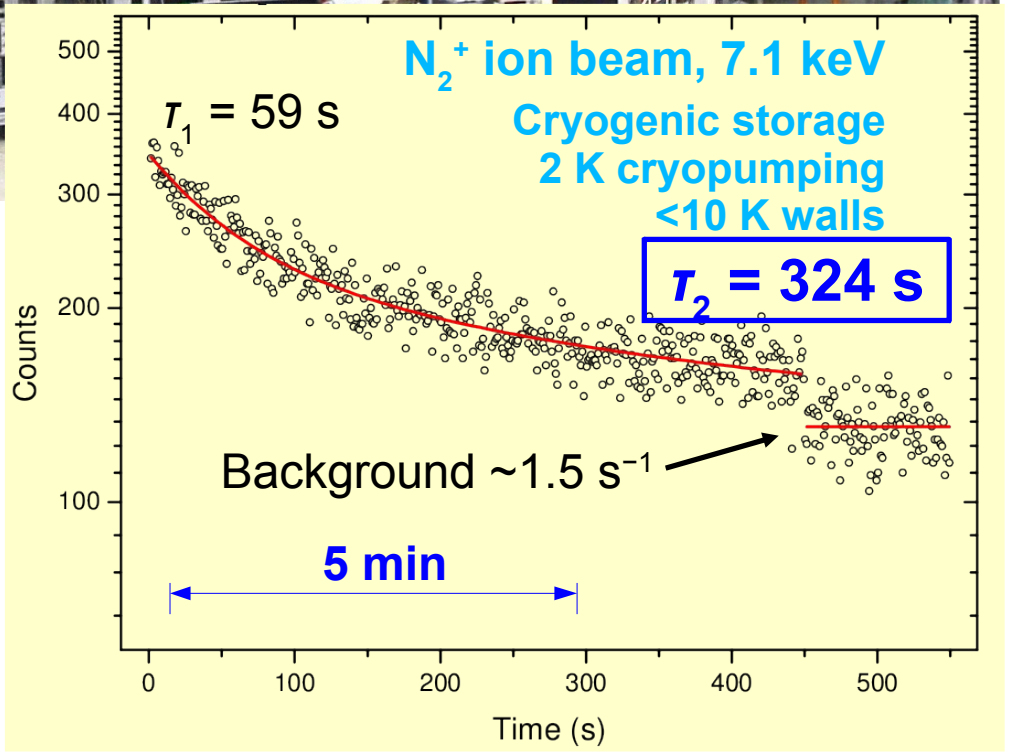
CSR cryo and vacuum tests – the CTF

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









Count rate from ion neutralization

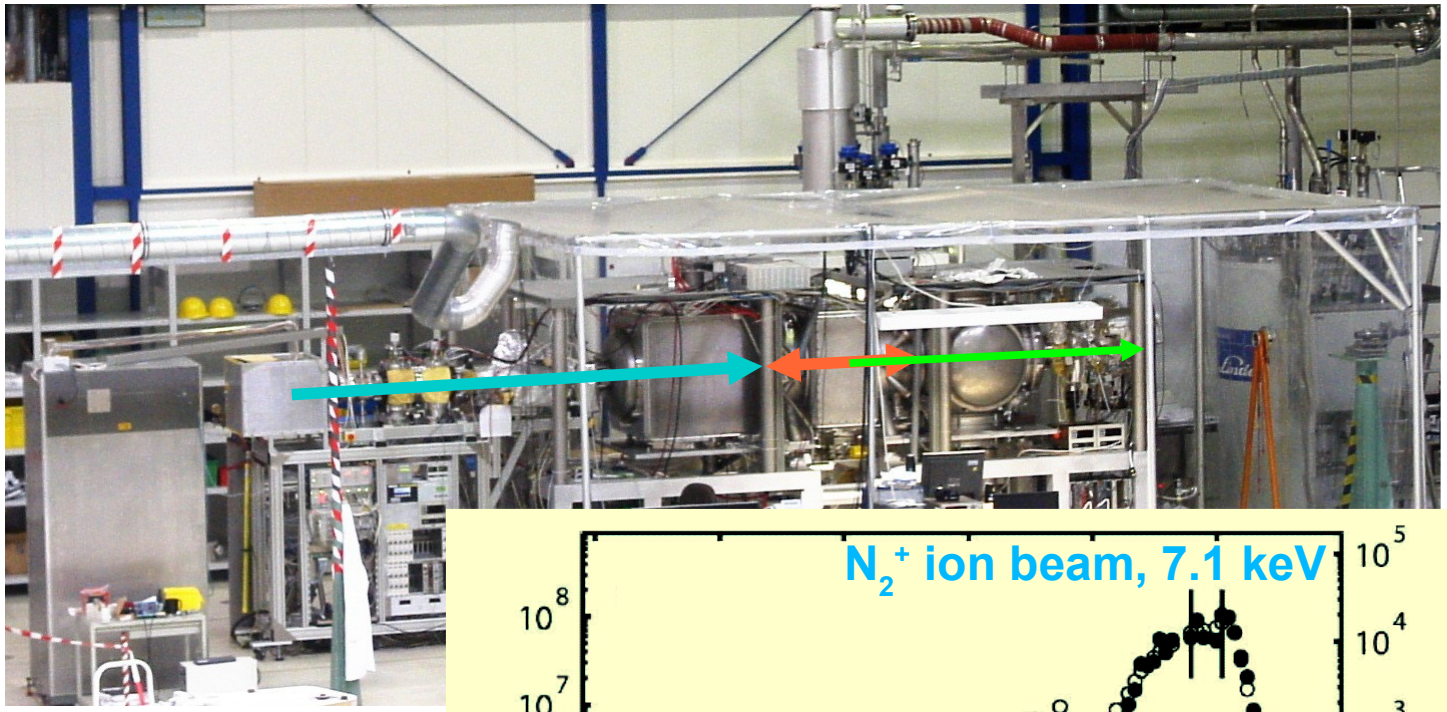
>10^8 reflections

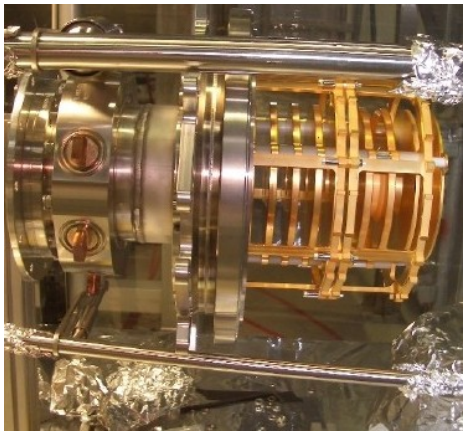
M. Lange et al., Rev. Sci. Instrum. 281, 055105 (2010)

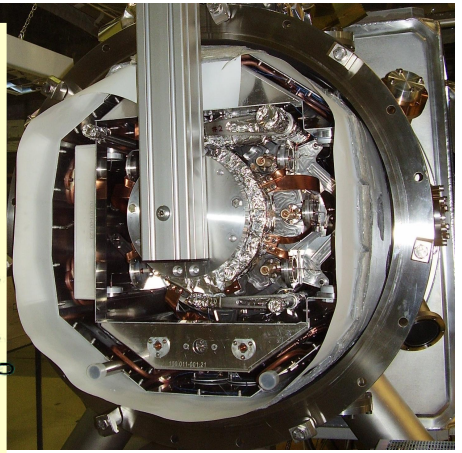
M. Froese, M. Lange, S. Menk et al.

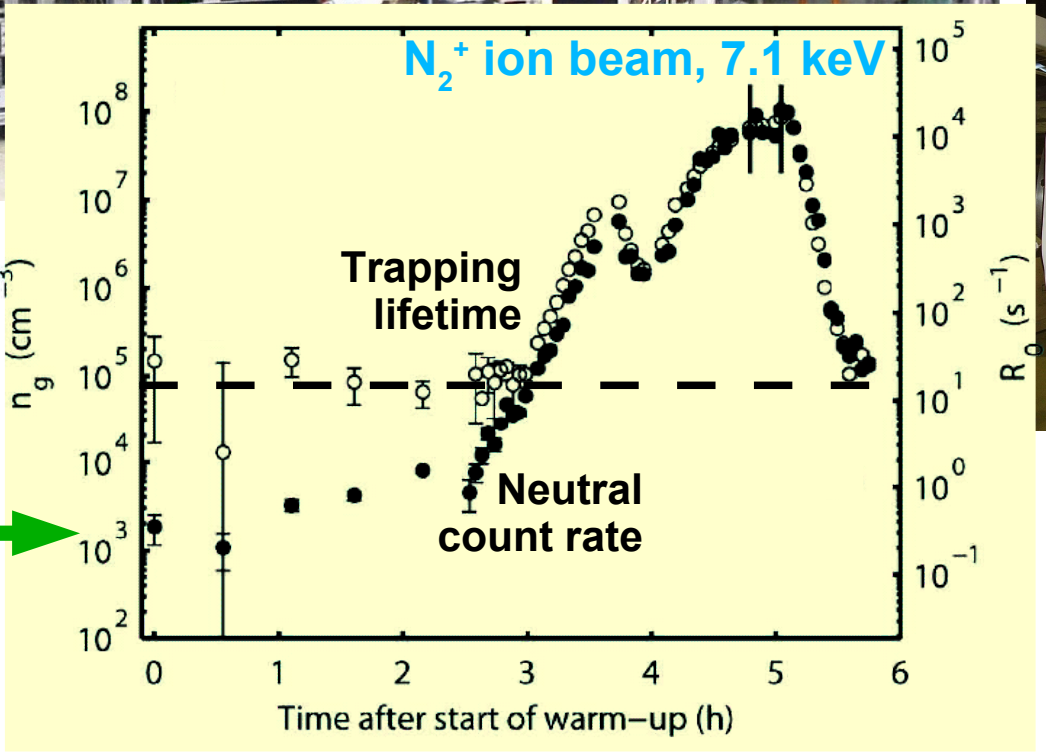
CSR cryo and vacuum tests – the CTF

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









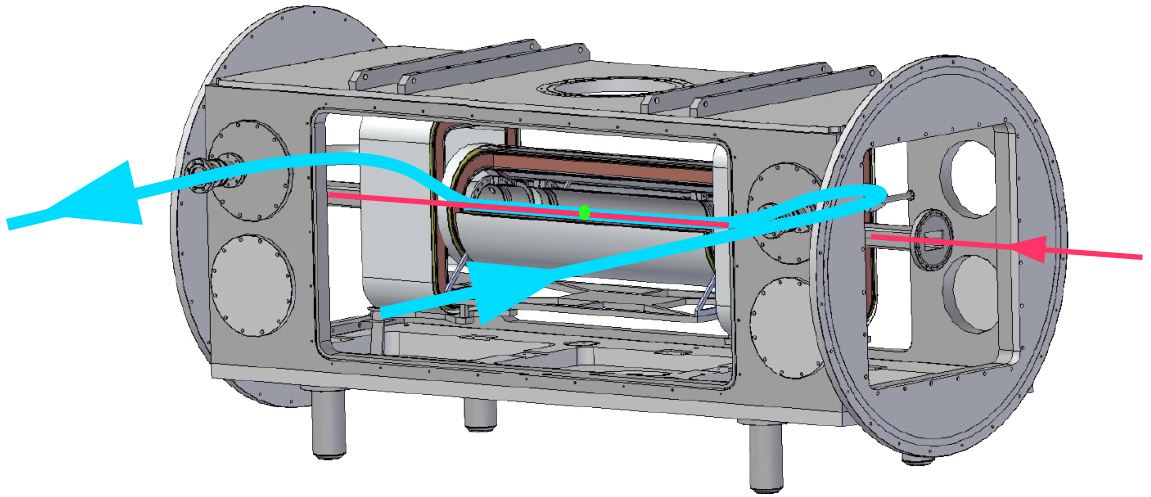
Count rate from ion neutralization

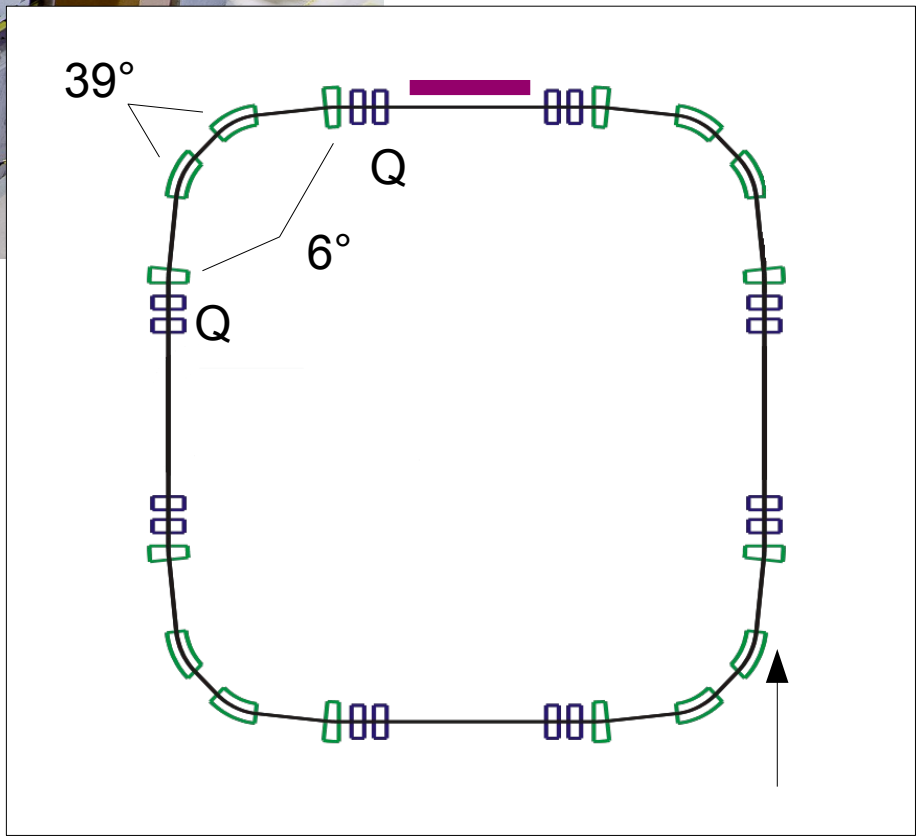
Residual gas density
2×10^3 cm^{-3}
~1×10^{-13} mbar

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

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

Cryogenic storage ring CSR

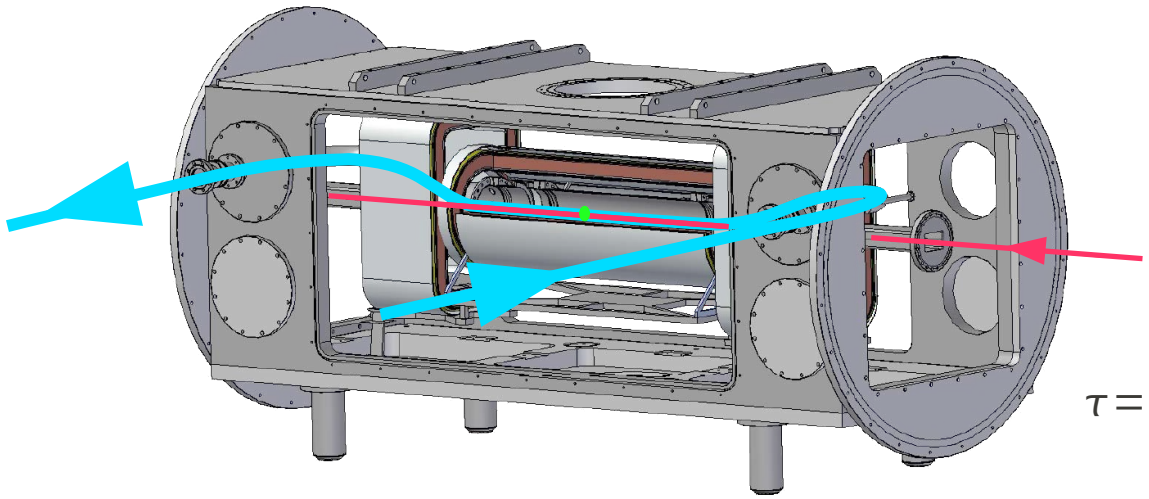




Photocathode electron beam

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

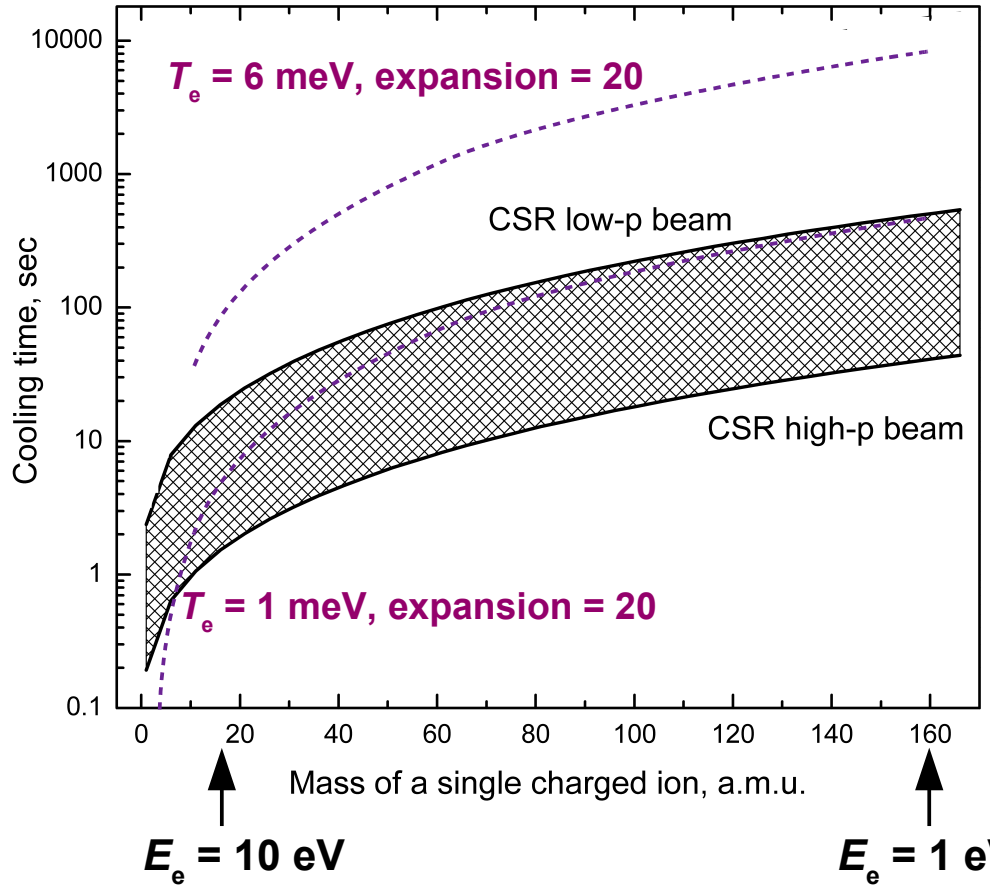
α: magnetic expansion

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

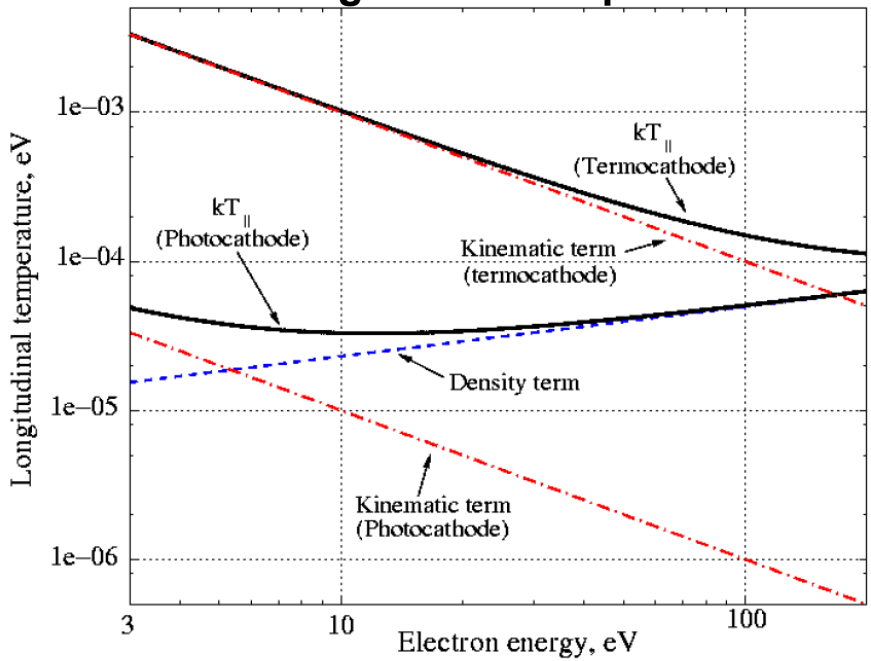
$$p_{high} = 4.1 (x = 0.33)$$

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

Cooling time of high-mass singly charged ions



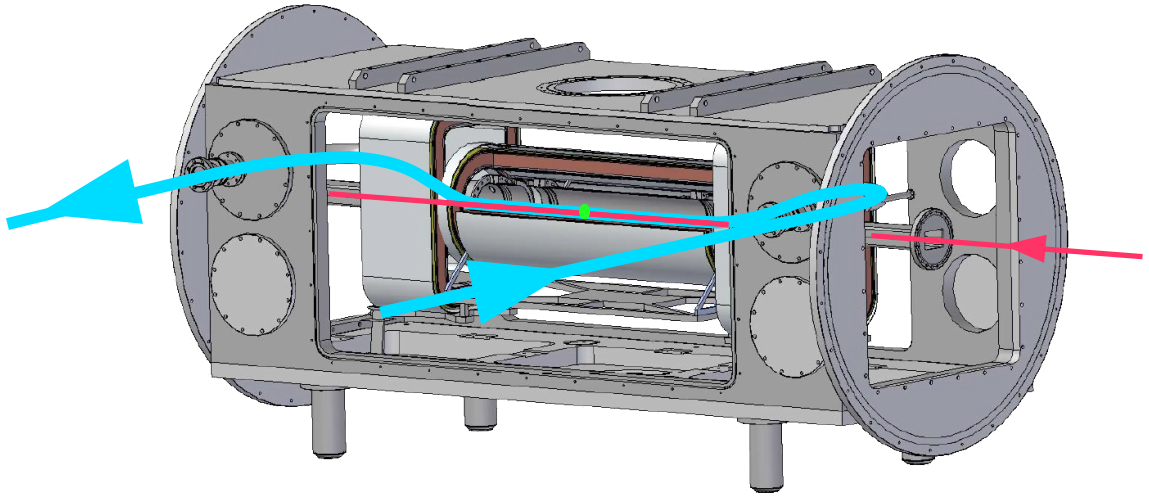
Photocathode longitudinal temperature



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

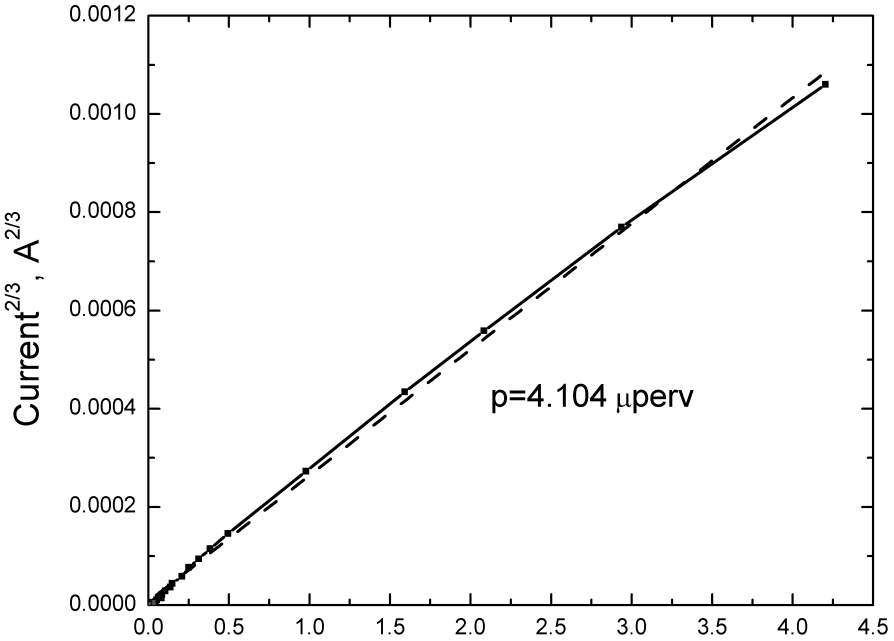
Low-energy photocathode electron beam

A. Shornikov, C. Krantz

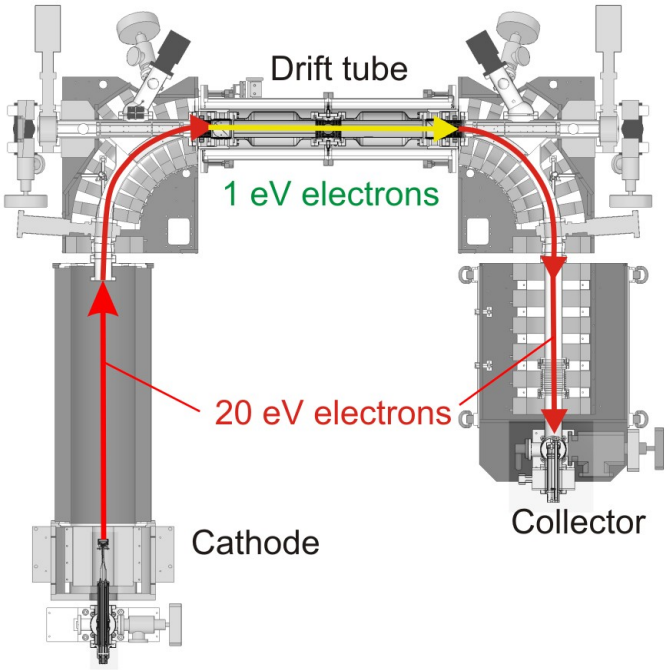


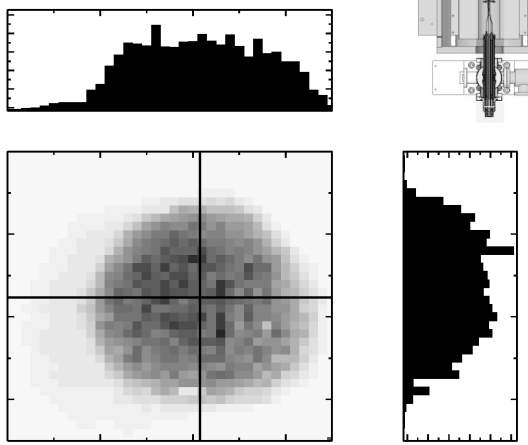
Tests at TSR electron target

Deceleration of low-current photocathode beams

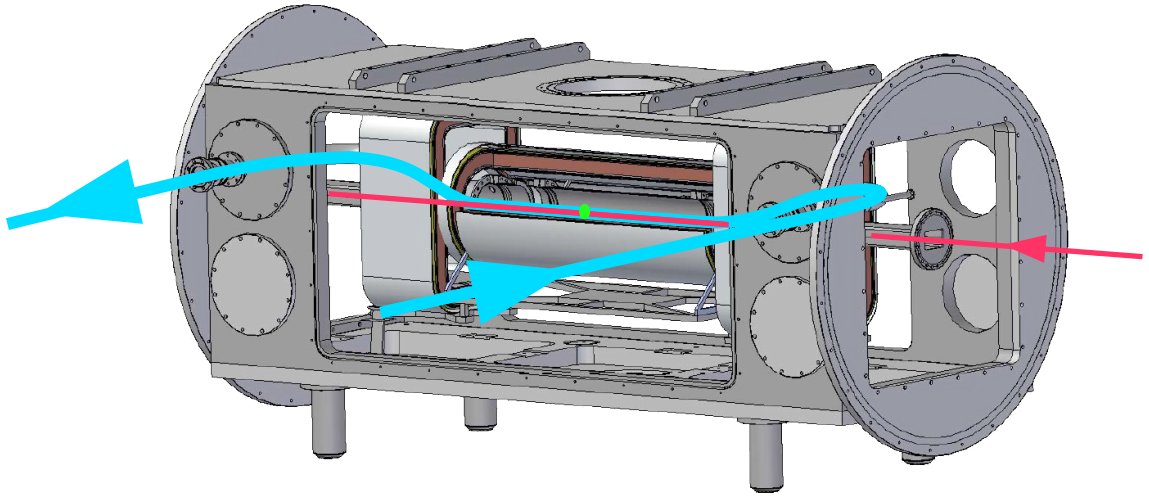


$$I = pU_0^{3/2}$$





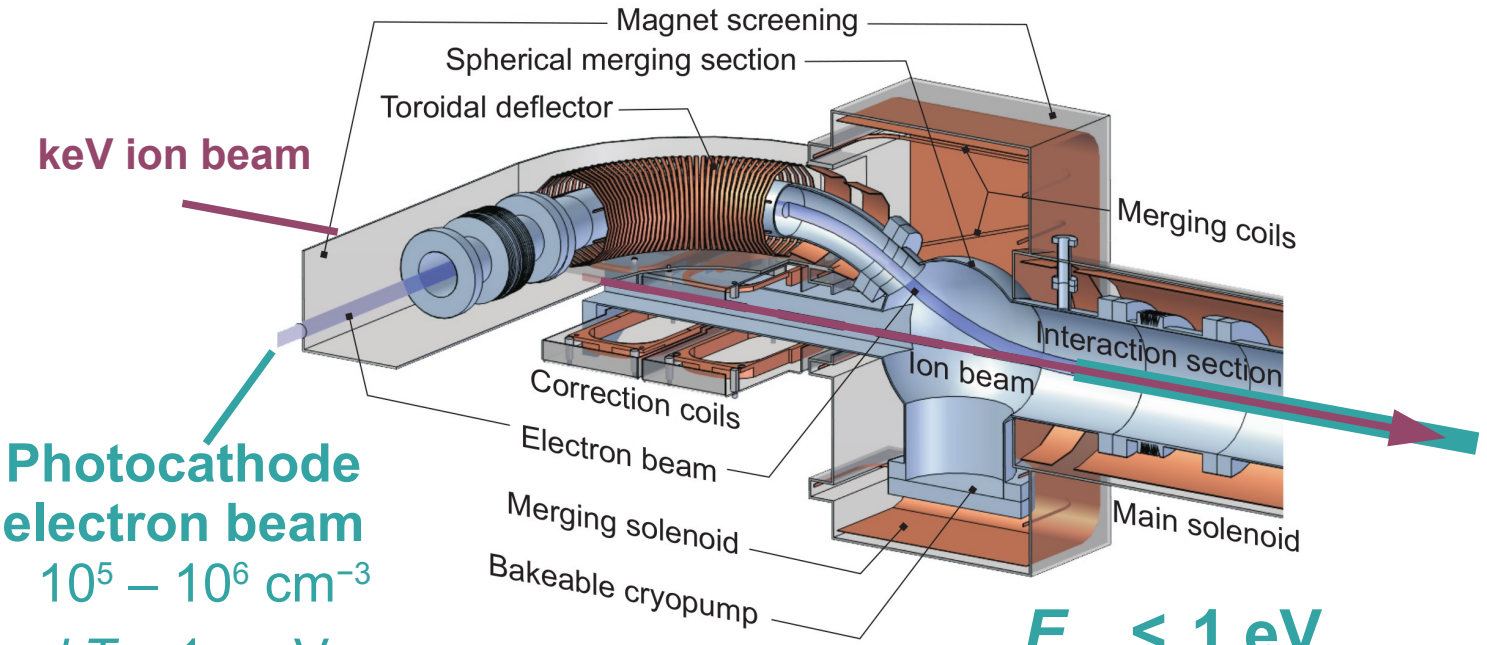
Beam profiles



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

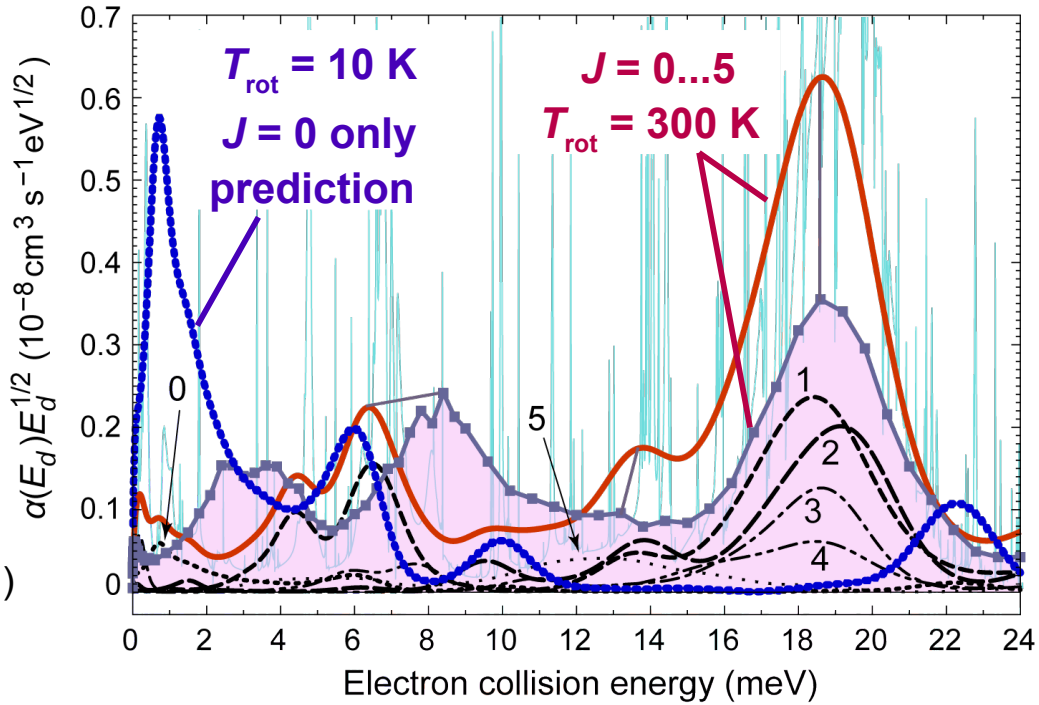
Outlook to experiments at CSR

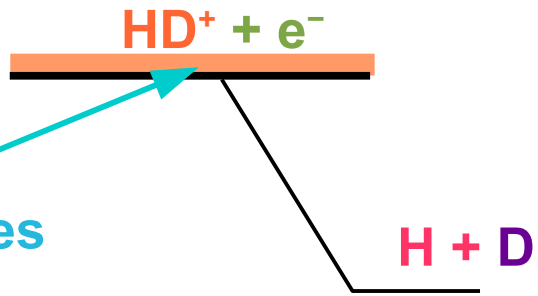
Rotational dependence of cross section

TSR result for recombination cross section

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

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

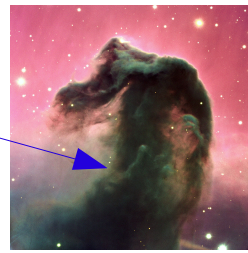




Rovibrational capture resonances

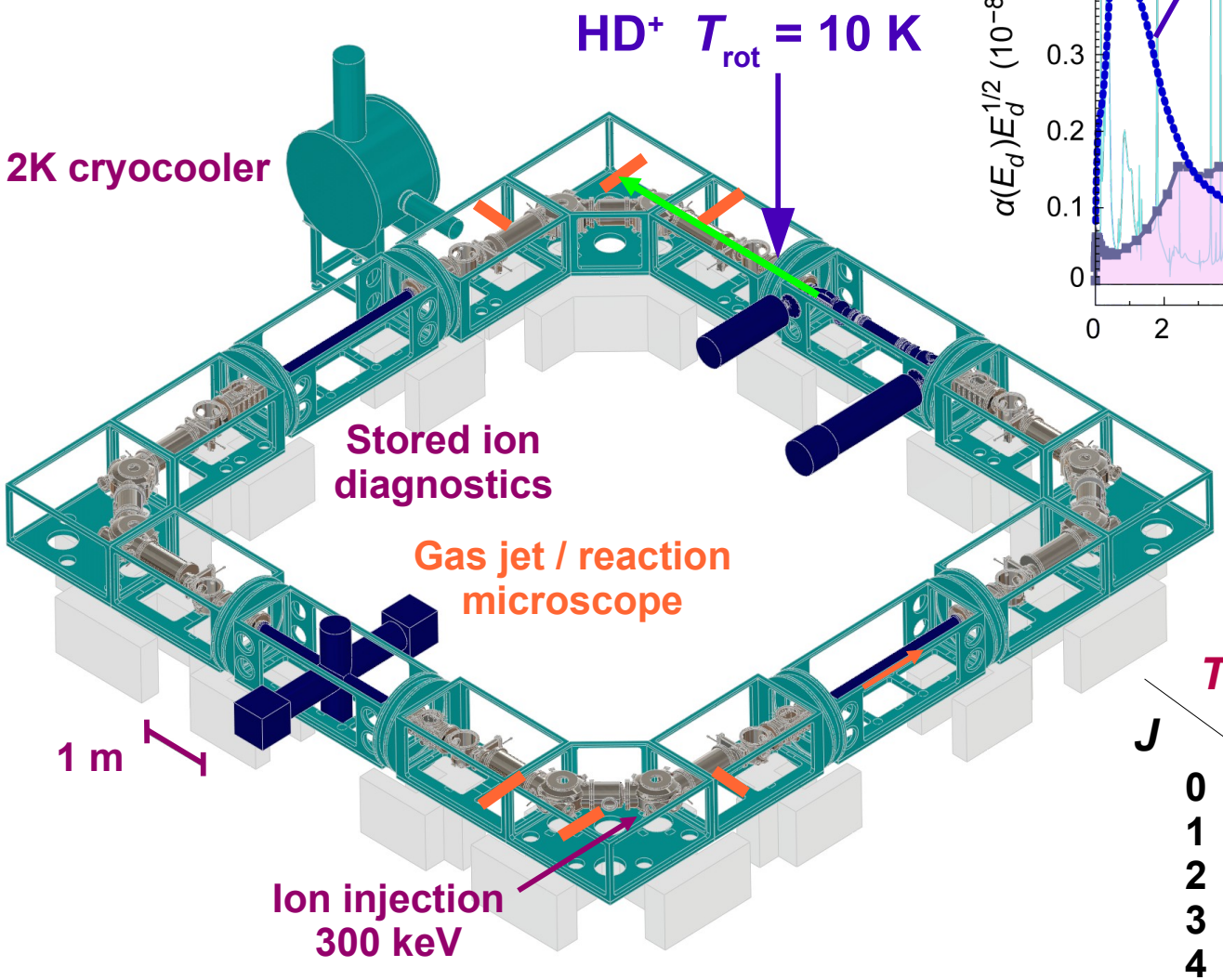
Measured recombination cross section dominated by $J \geq 1$

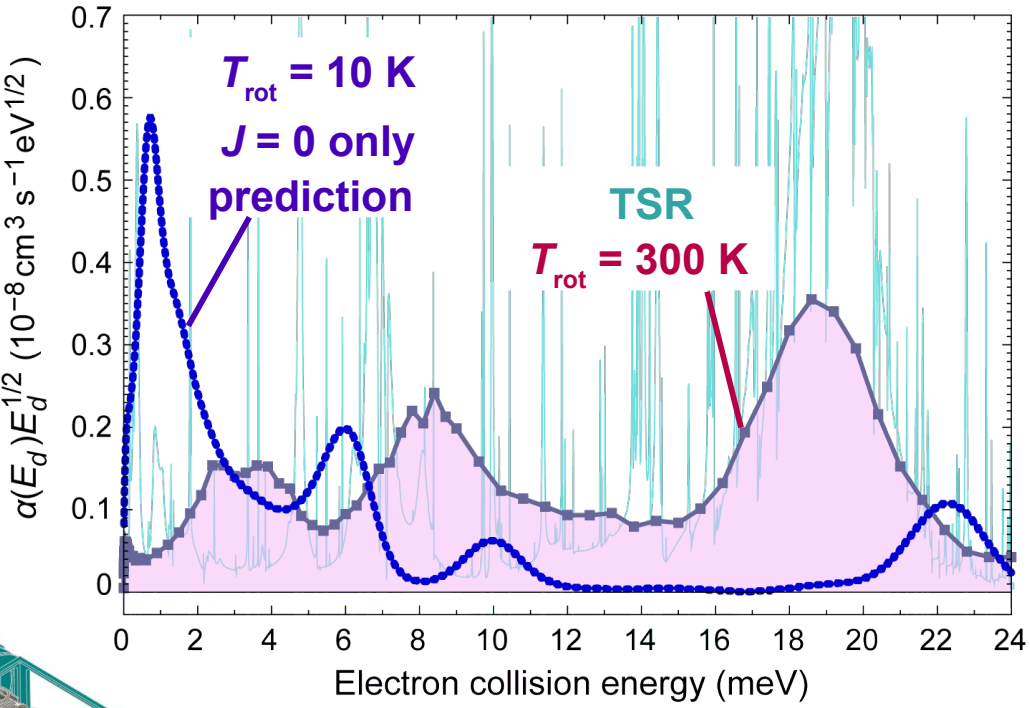
J	T_{rot} 300 K	10 K
0	0.104	0.995
1	0.251	0.005
2	0.271	0.0
3	0.199	0.0
4	0.108	0.0



Outlook to experiments at CSR

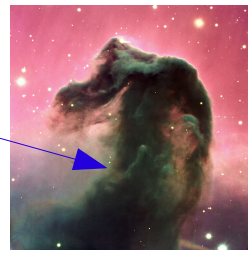
Rotational dependence of cross section



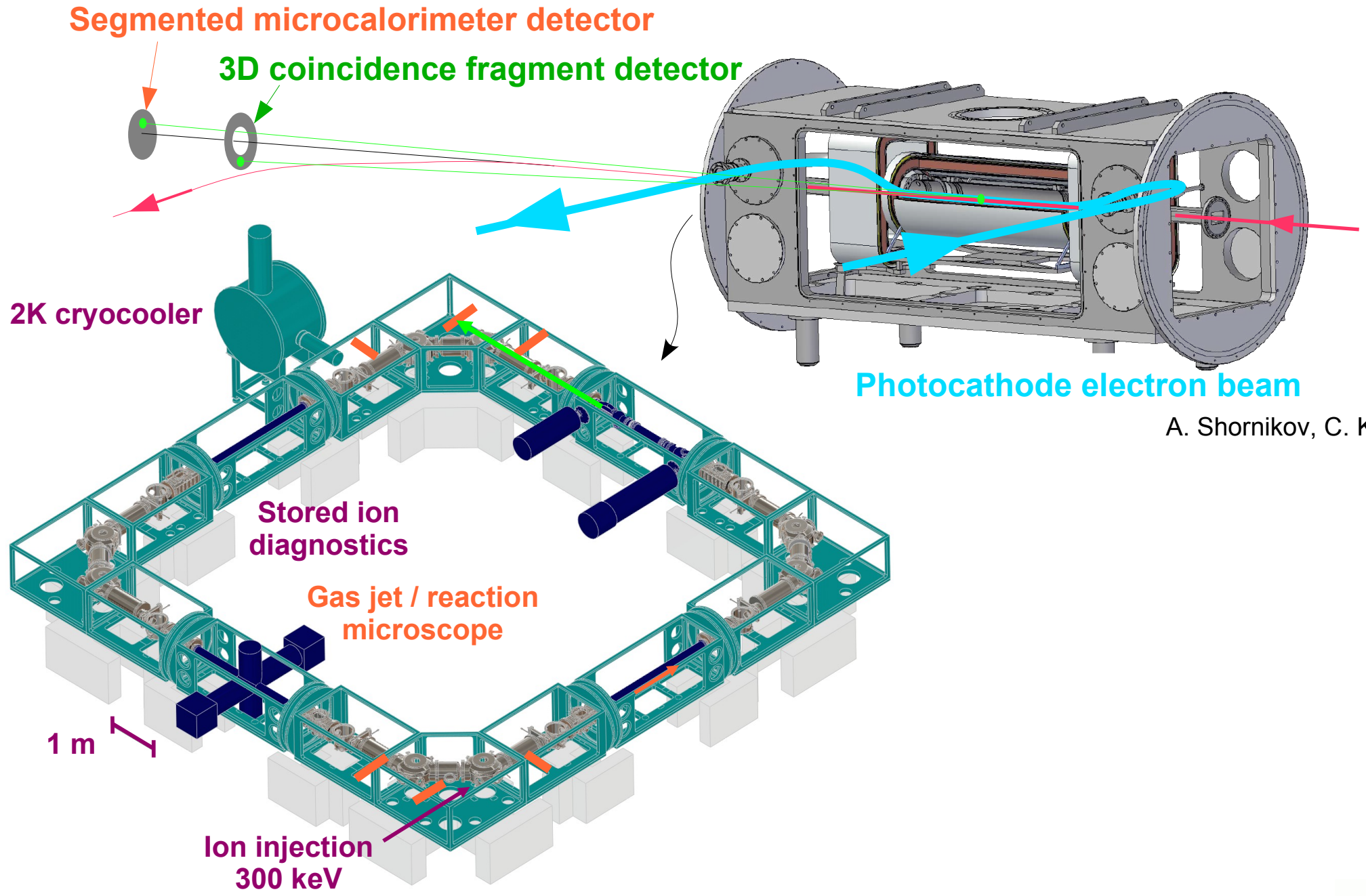


Rydberg capture resonances at low rotation

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



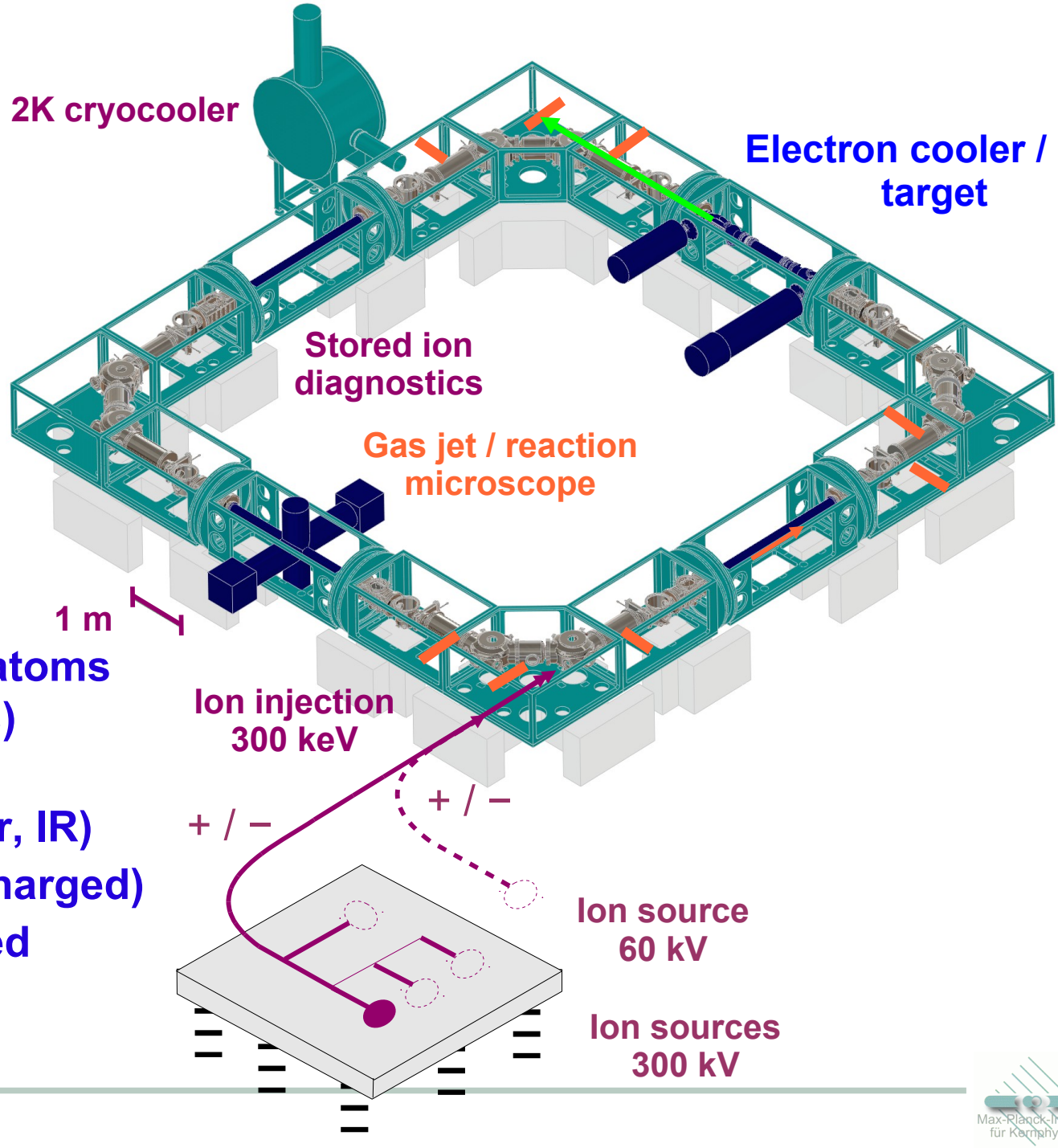
Outlook to experiments at CSR



A. Shornikov, C. Krantz

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

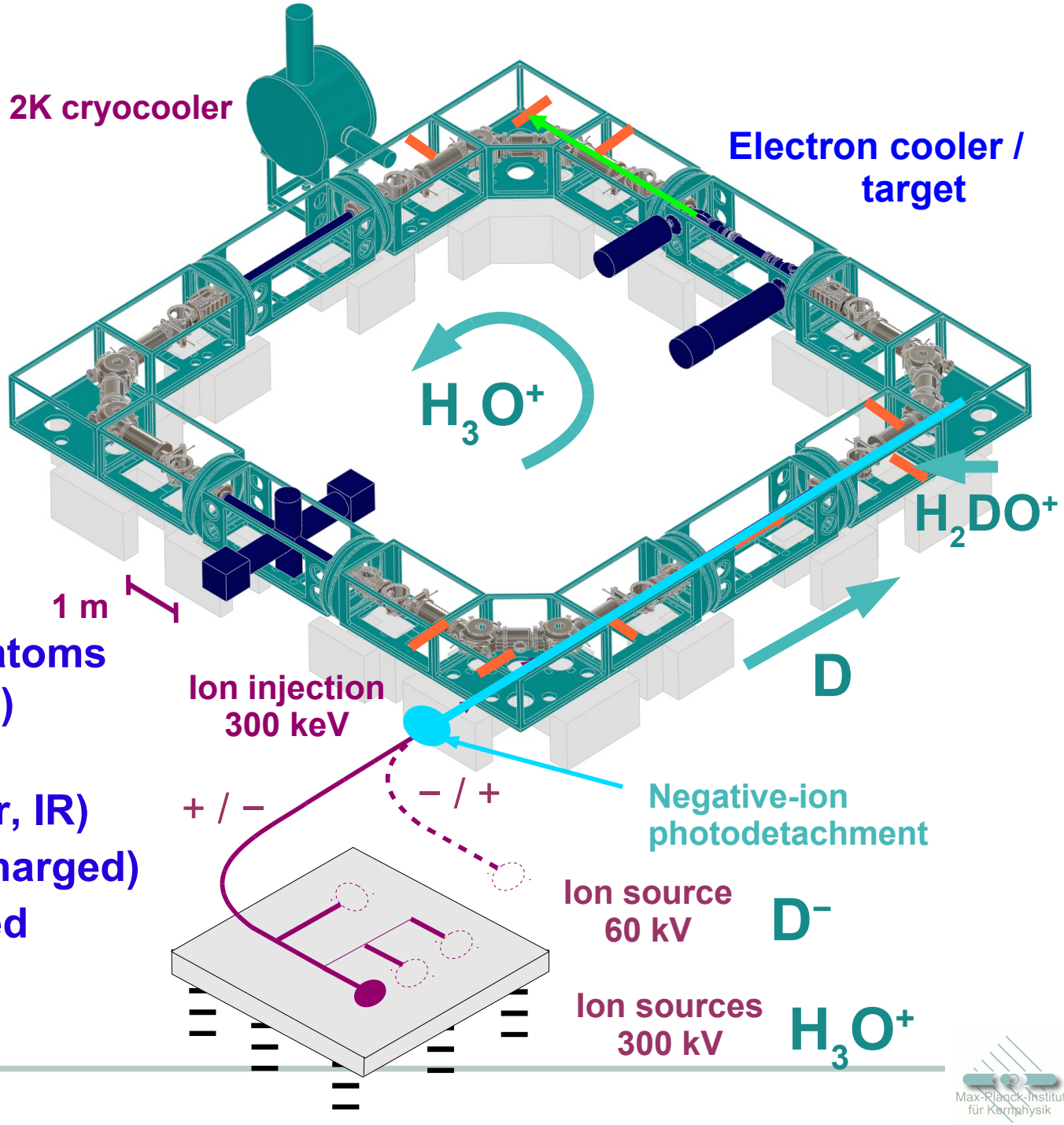


Outlook to experiments at CSR

Ion–atom merged beams

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

Deuterium enrichment by ion chemistry



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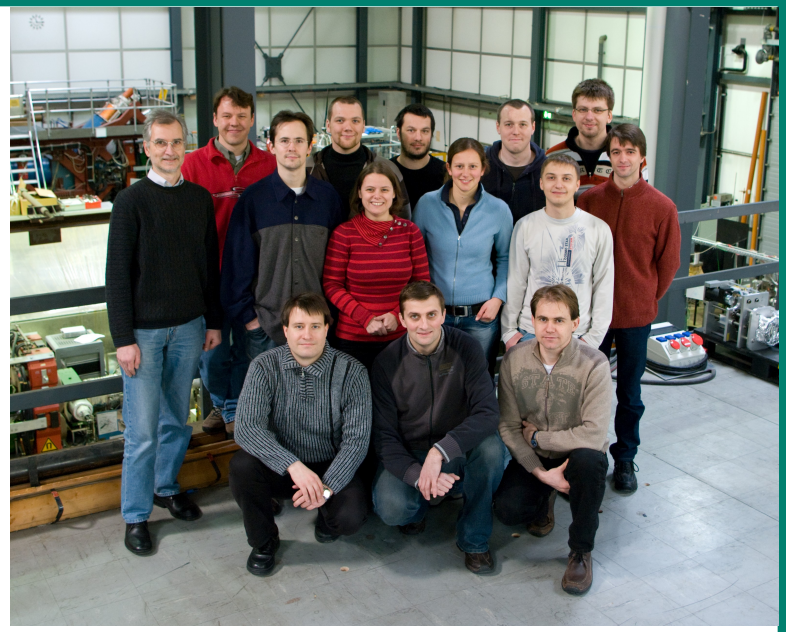
- Cluster systems, H_2O-loaded

Max-Planck Institute for Nuclear Physics,
Heidelberg, Germany

Stored and Cooled Ions (K. Blaum)



Atomic and molecular quantum dynamics

Atomic and molecular physics	**A. W.** **O. Novotný (**)** **H. Buhr (*)** **C. Krantz**
Electron target	**A. Petrignani (*)** **B. Jordon-Thaden (*)**
Photocathode	**D. A. Orlov (*)**
	A. Shornikov **C. Domesle** **D. Bing (*)** **M. Mendes (*)** **M. Berg** **J. Stützel** **F. Grussie** **Bian Yang** **C. Nordhorn (*)**

Stored and cooled ion instrumentation

TSR and accelerator	**M. Grieser** **R. Repnow** **R. von Hahn**

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

Collaborations

Weizmann Institute of Science
Rehovot, Israel

H. Buhr (*) **D. Schwalm** **D. Zajfman**
O. Heber **M. Rappaport** **D. Shafir (*)**

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W. D. Geppert **M. Hamberg**

Univ. Louvain-La-Neuve, Belgium

X. Urbain

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

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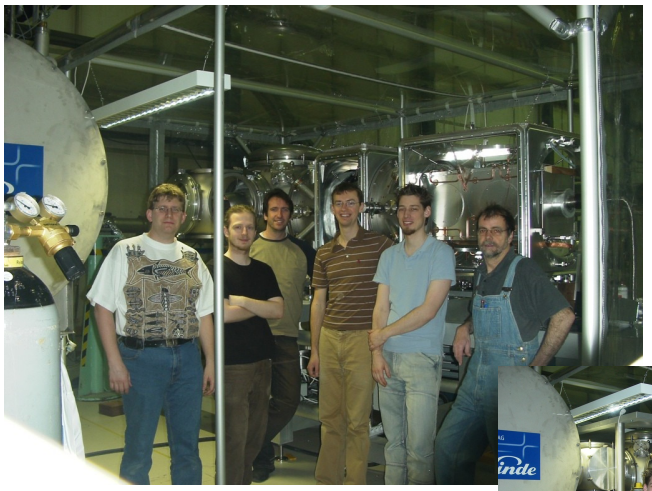
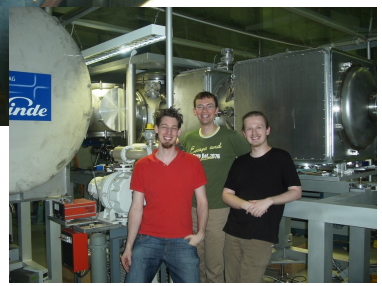
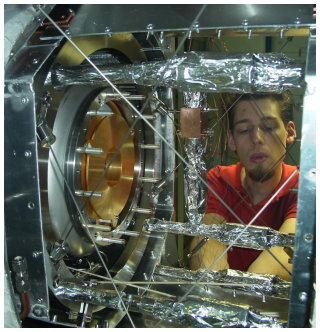
Heidelberg, Germany

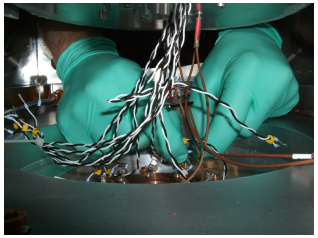
Stored and Cooled Ions (K. Blaum)

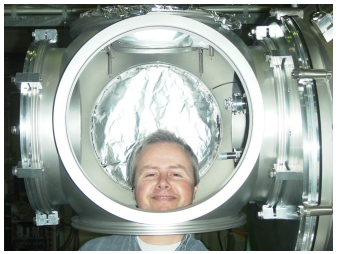




CSR and CTF







K. Blaum
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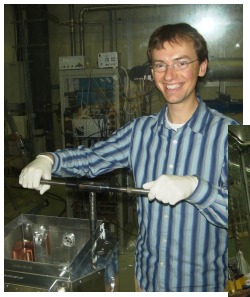
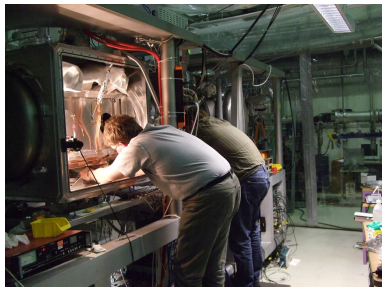
M. Grieser
R. Repnow
M. Froese
M. Lange
D. A. Orlov (*)

F. Fellenberger
S. Menk
F. Laux
T. Sieber (*)
J. Varju
F. Berg
R. Bastert (*)

Photocathode electron beams and cooled molecular beams





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

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

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A. Terekhov ISP Novosibirsk, Russia

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