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

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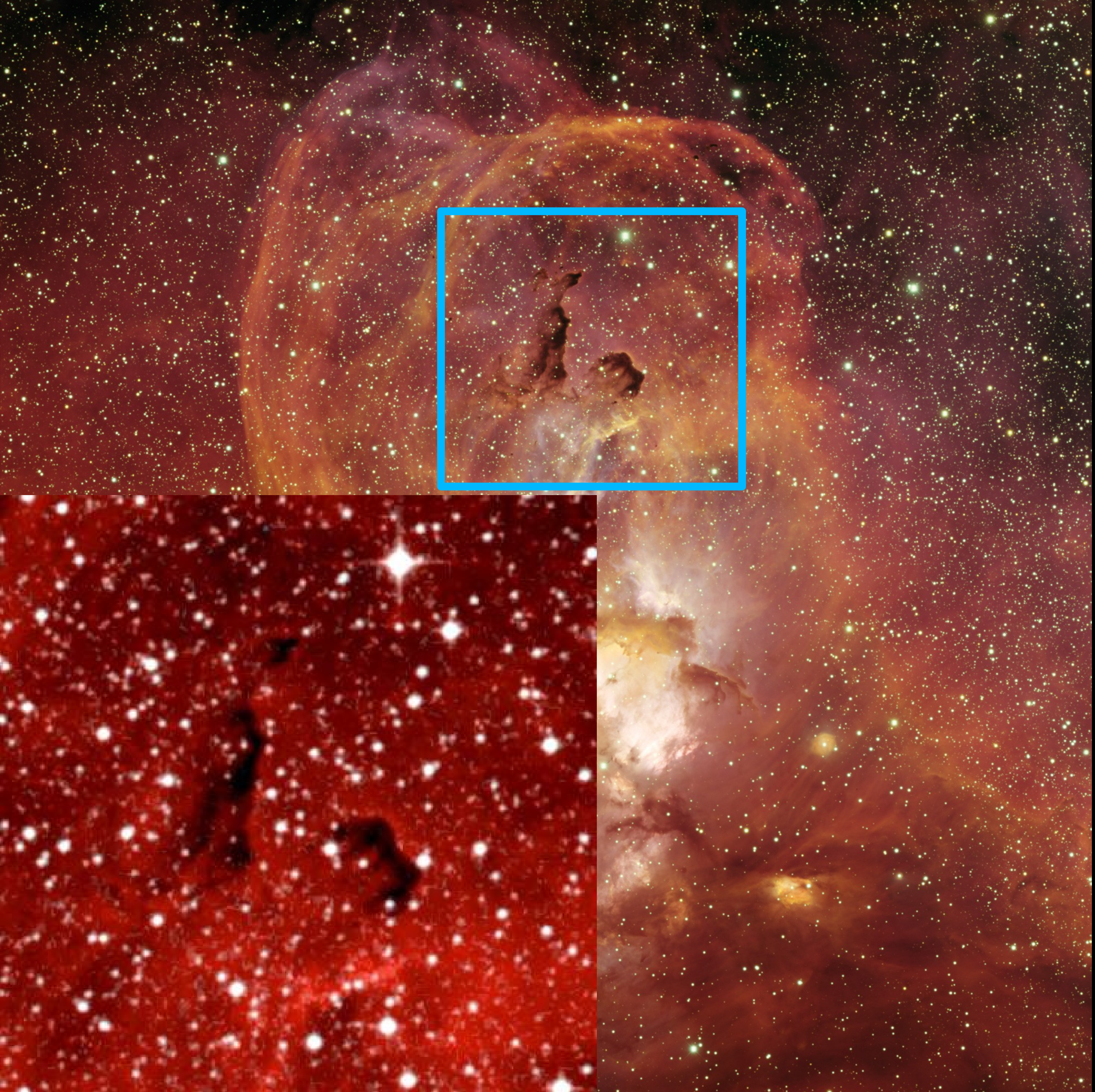
MAX-PLANCK-GESELLSCHAFT



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

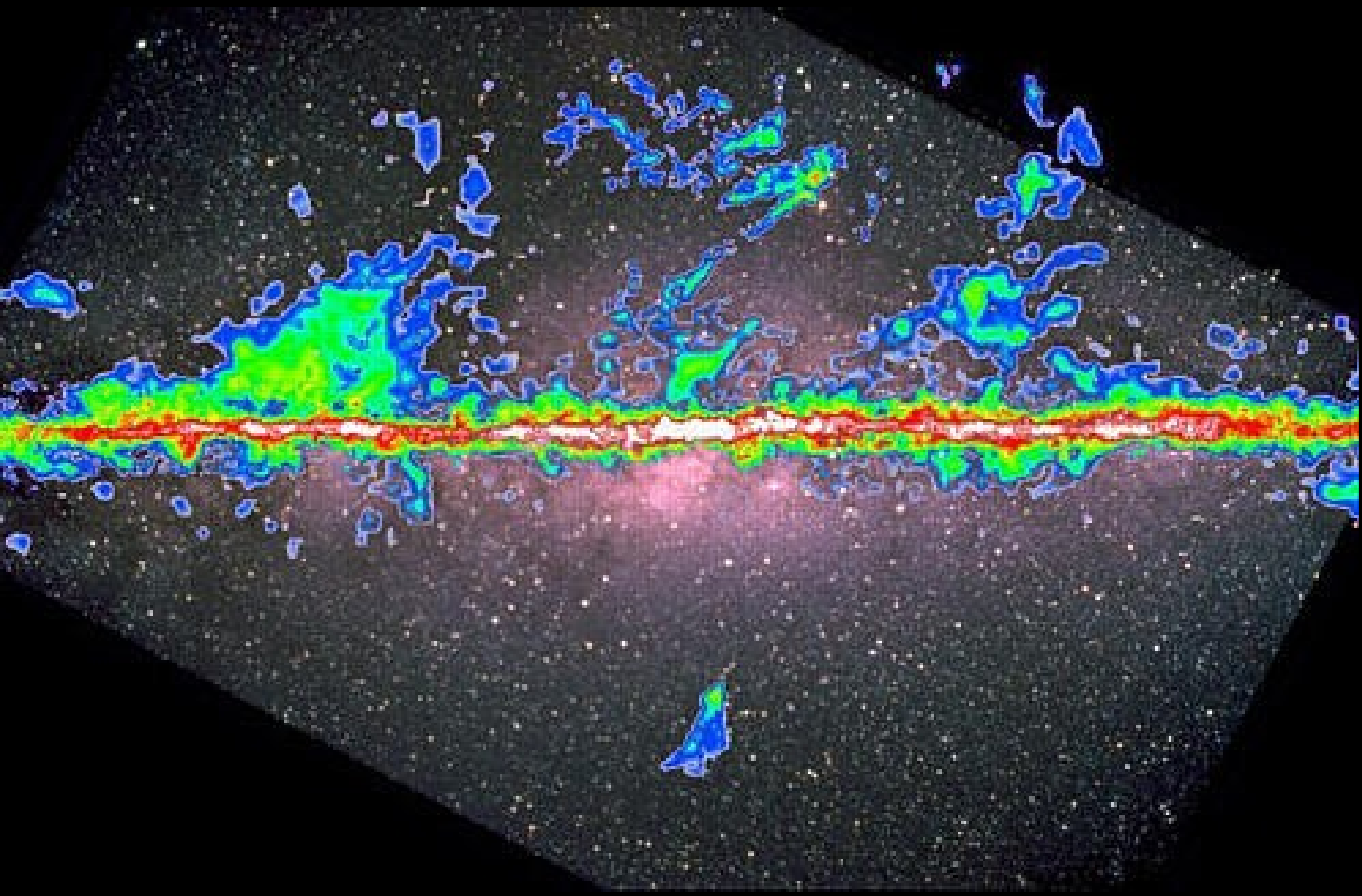
Ion chemistry
density ~10^4 cm^{-3}
temperature ~10 K

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

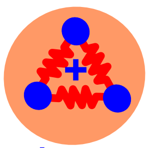
Cerro Tololo
S. Kohle

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) ...



H_3^+

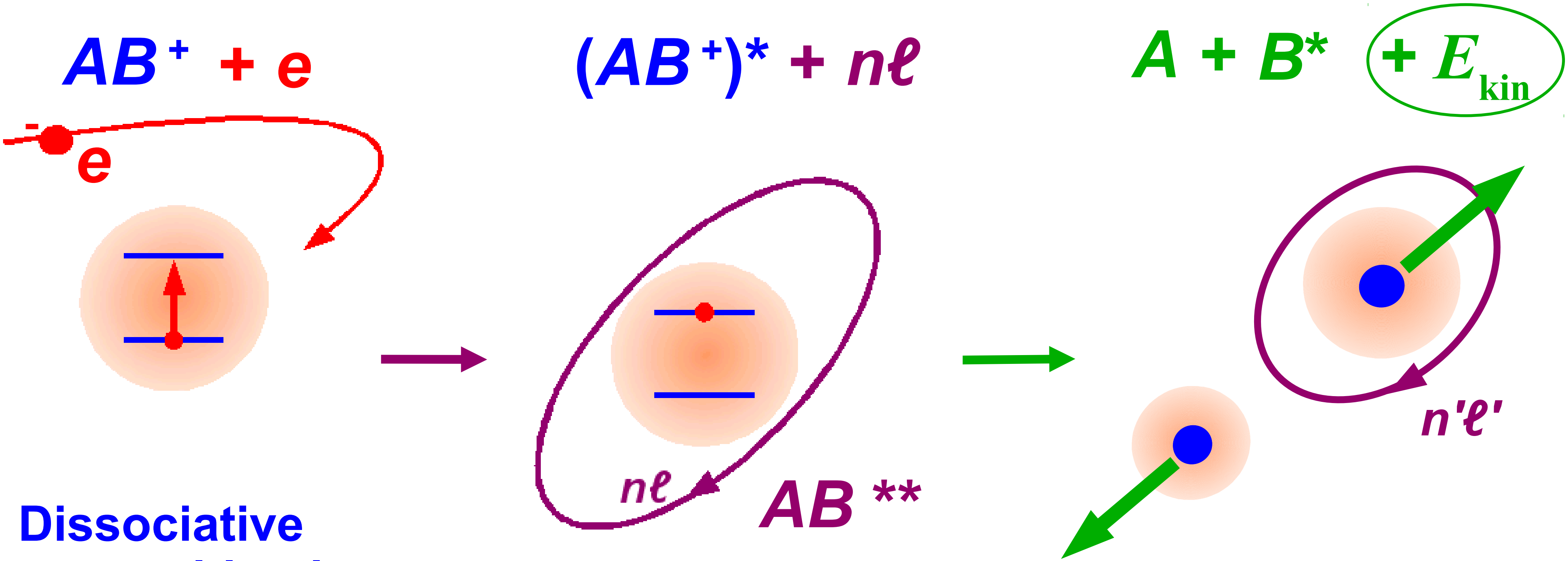
ON2
Star forming region
("Chicken" Nebula)
Infrared

UKIRT
Mauna Kea
Chris Davis (JAC)

Molecules cool the star-forming regions

Observed by infrared and radio spectroscopy

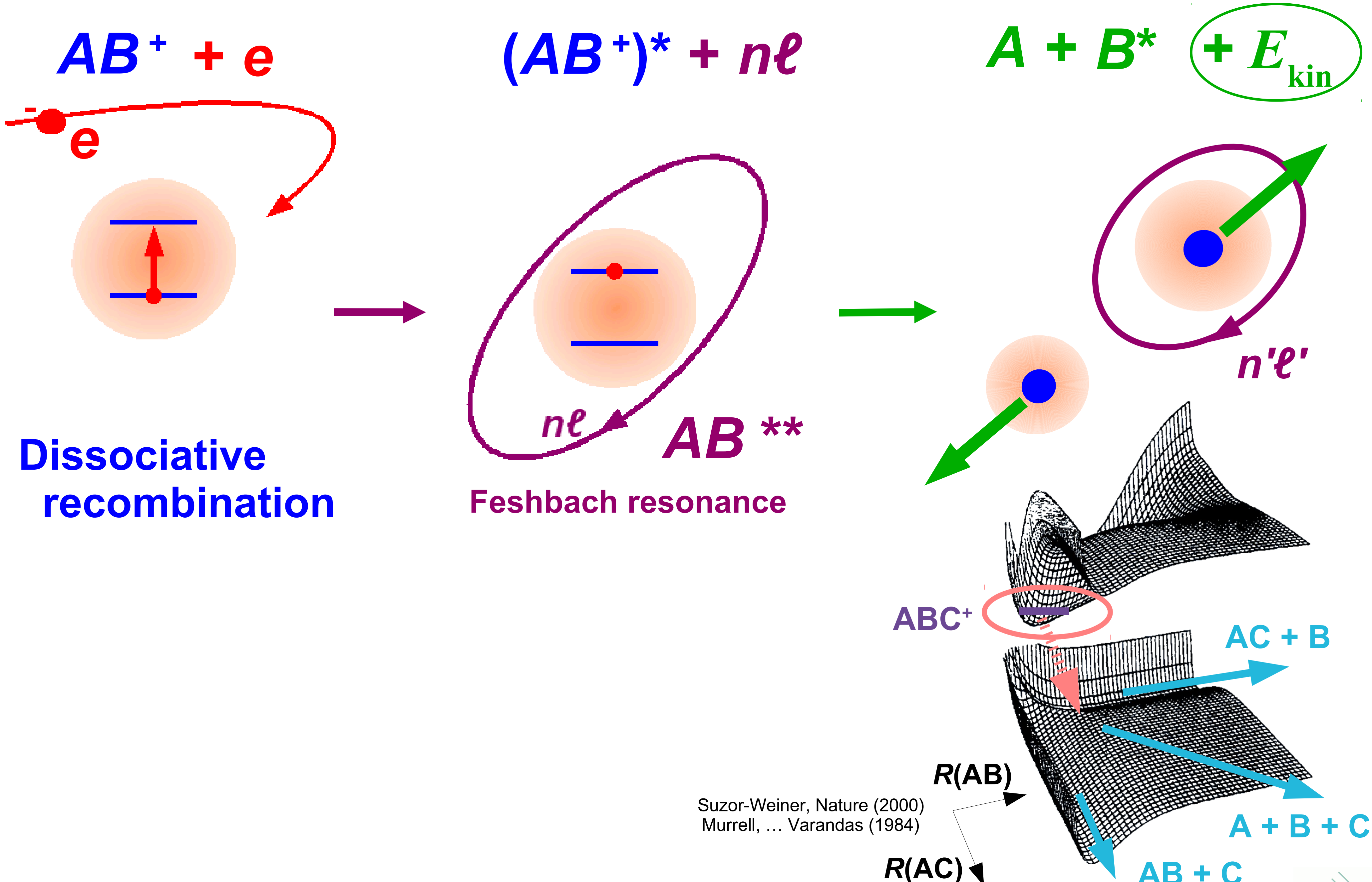
Molecular breakup by cold electrons



Dissociative recombination

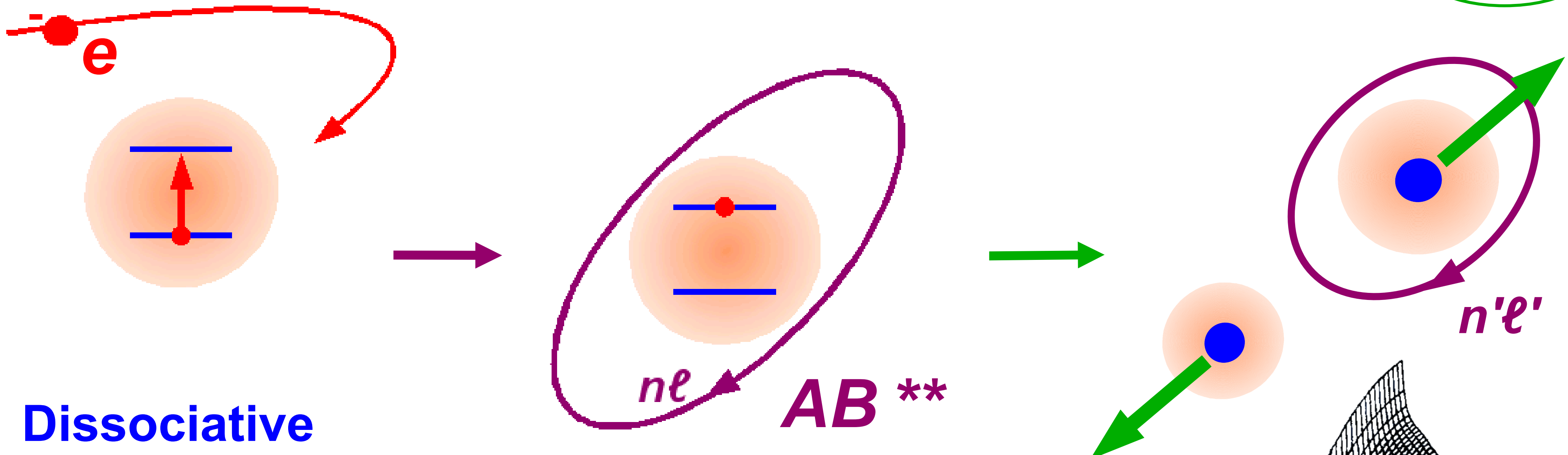
Feshbach resonance

Molecular breakup by cold electrons



Molecular breakup by cold electrons

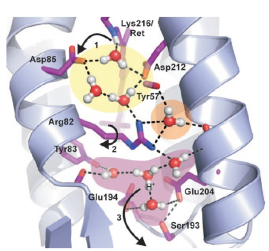
$AB^{+} + e$ $\quad$ $(AB^{+})^{*} + n\ell$ $\quad$ $A + B^{*}$ $(+E_{\mathrm{kin}})$

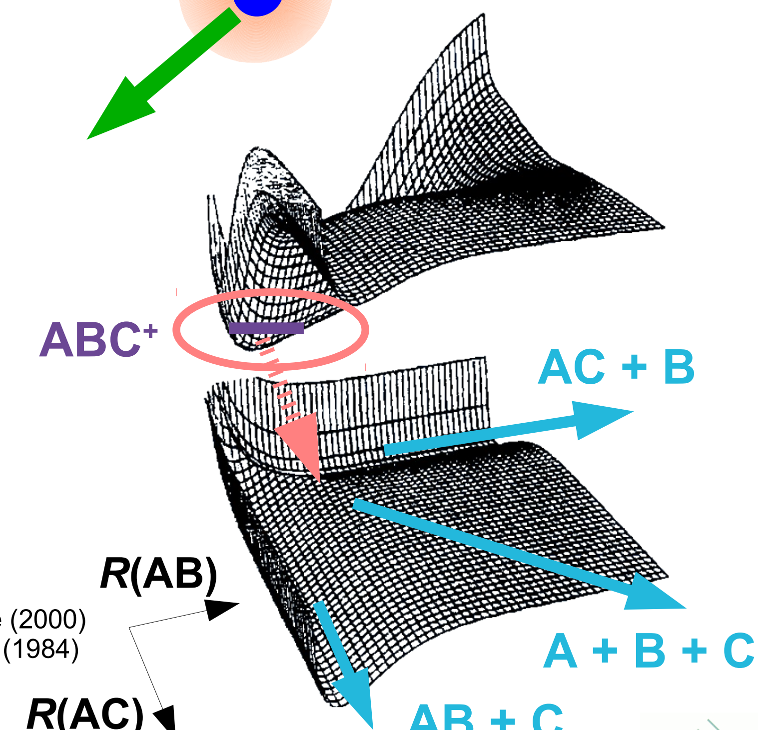


Dissociative recombination

Feshbach resonance

Dissociative electron attachment on neutral molecules

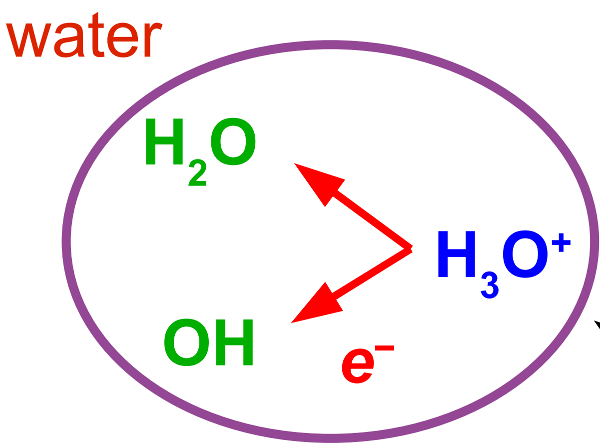




Suzor-Weiner, Nature (2000)
Murrell, … Varandas (1984)

Molecular cloud chemistry

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



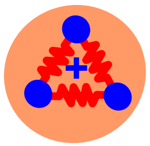
H_2O^+

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

hydrocarbons

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

Protonated hydrogen molecule H_3^+



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

Ionization by cosmic radiation or x-rays

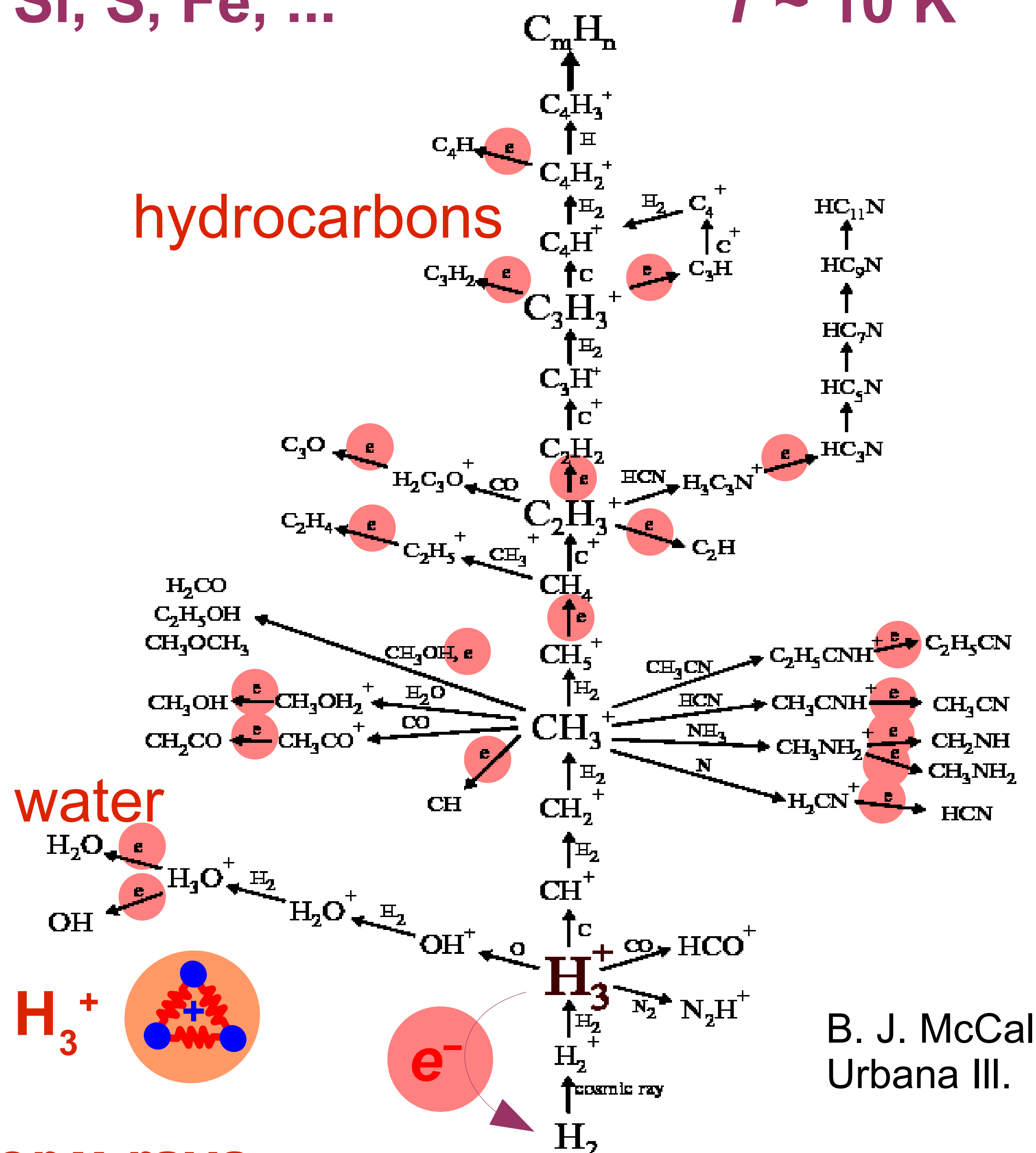
$H_2 + X \rightarrow H_2^+ + e^- + X'$

Molecular cloud chemistry

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

Dissociative recombination

Recombination rates,
product branching ratios

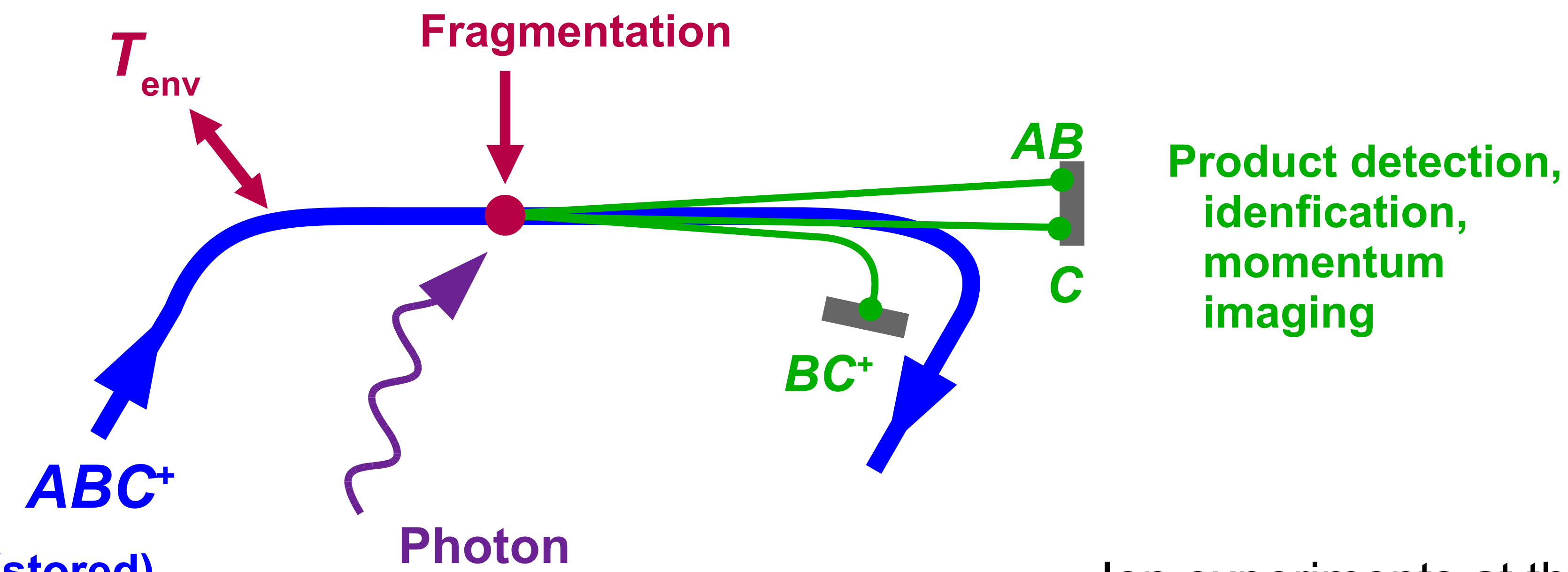


B. J. McCall
Urbana Ill.

Protonated hydrogen molecule H_3^+

Ionization by cosmic radiation or x-rays

Chemical physics using fast beam fragment imaging



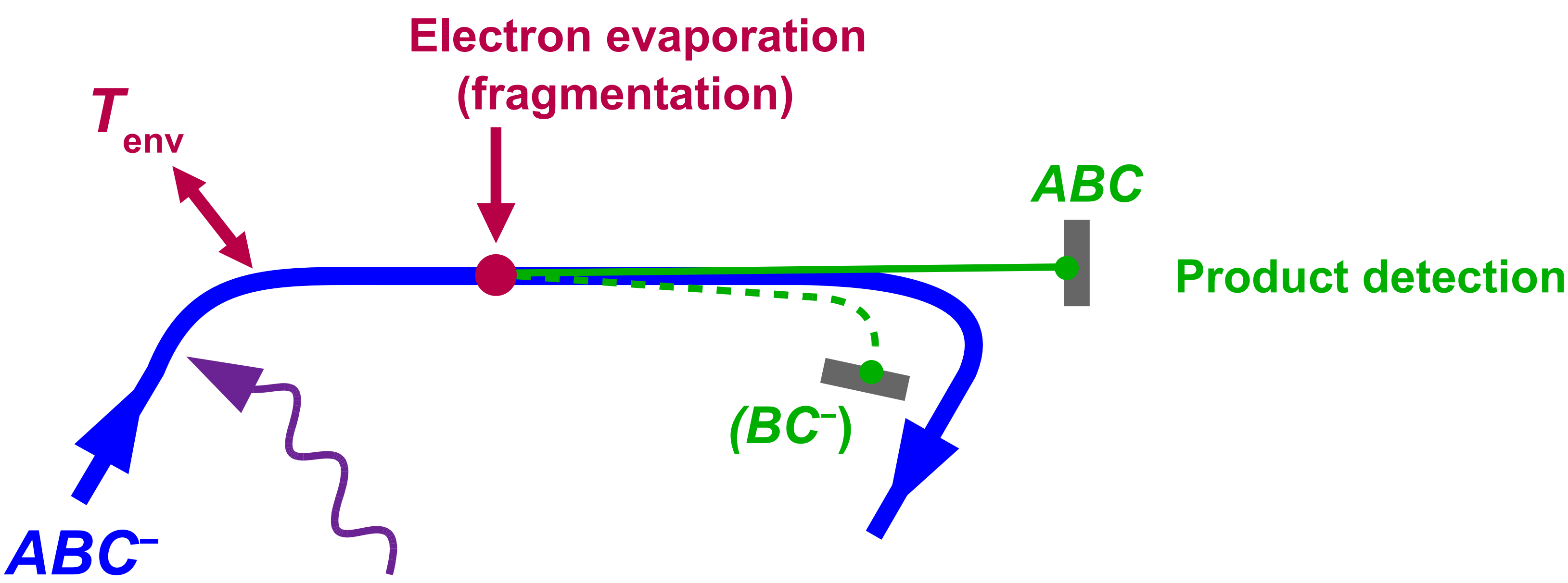
Fast (stored) molecular beam

(4...10 keV)

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)

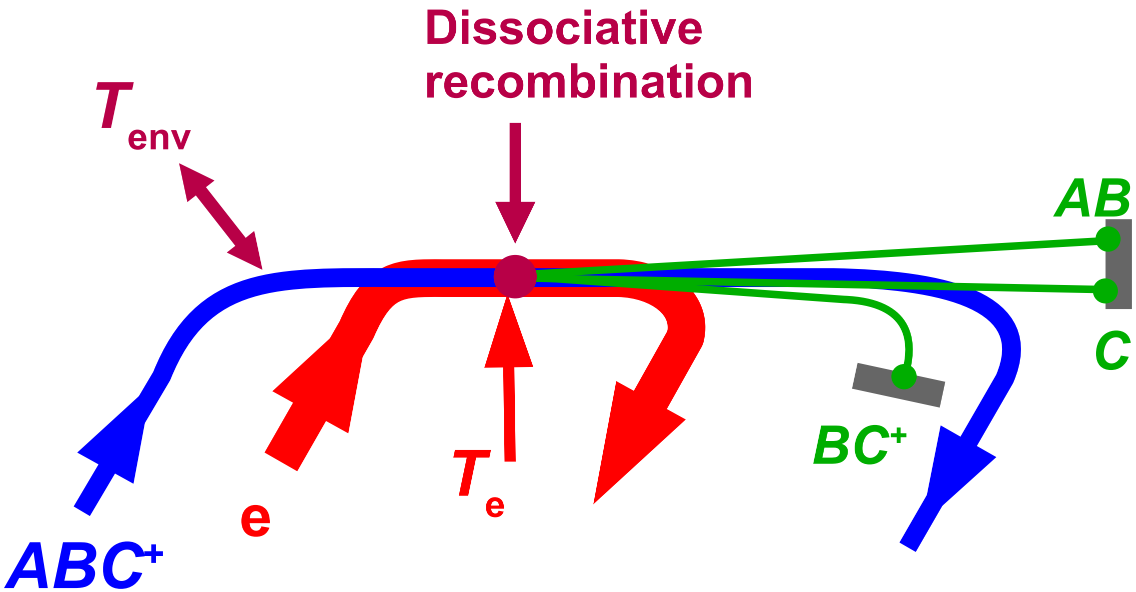
(4...10 keV)

Ion excitation
(photons, collisions, ion production)

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

$E_d = ½\, m_e\, (v_e - v_i)^2$

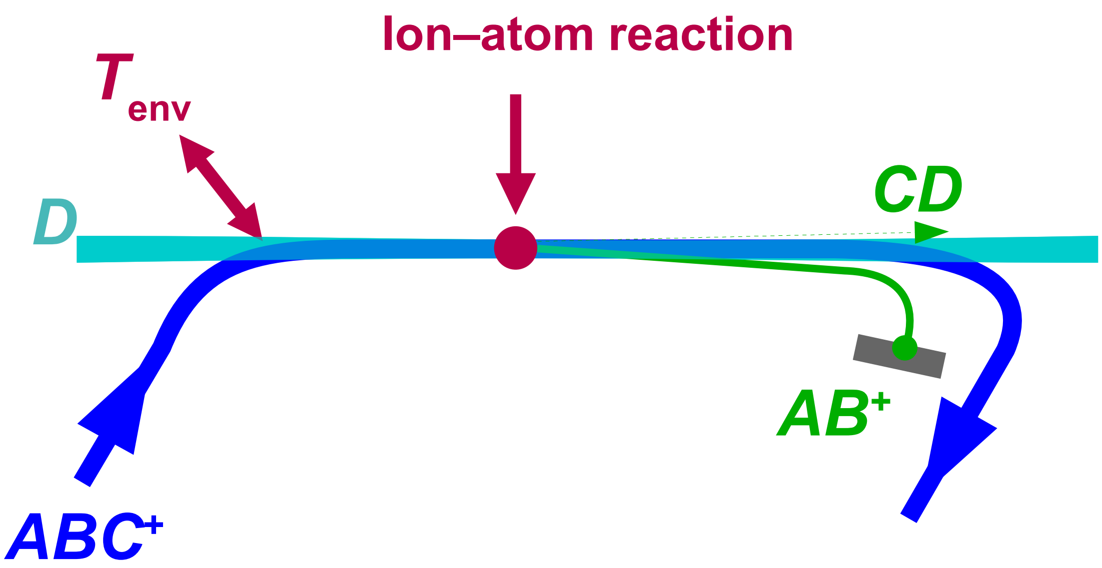
~ 1 meV … 50 eV

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

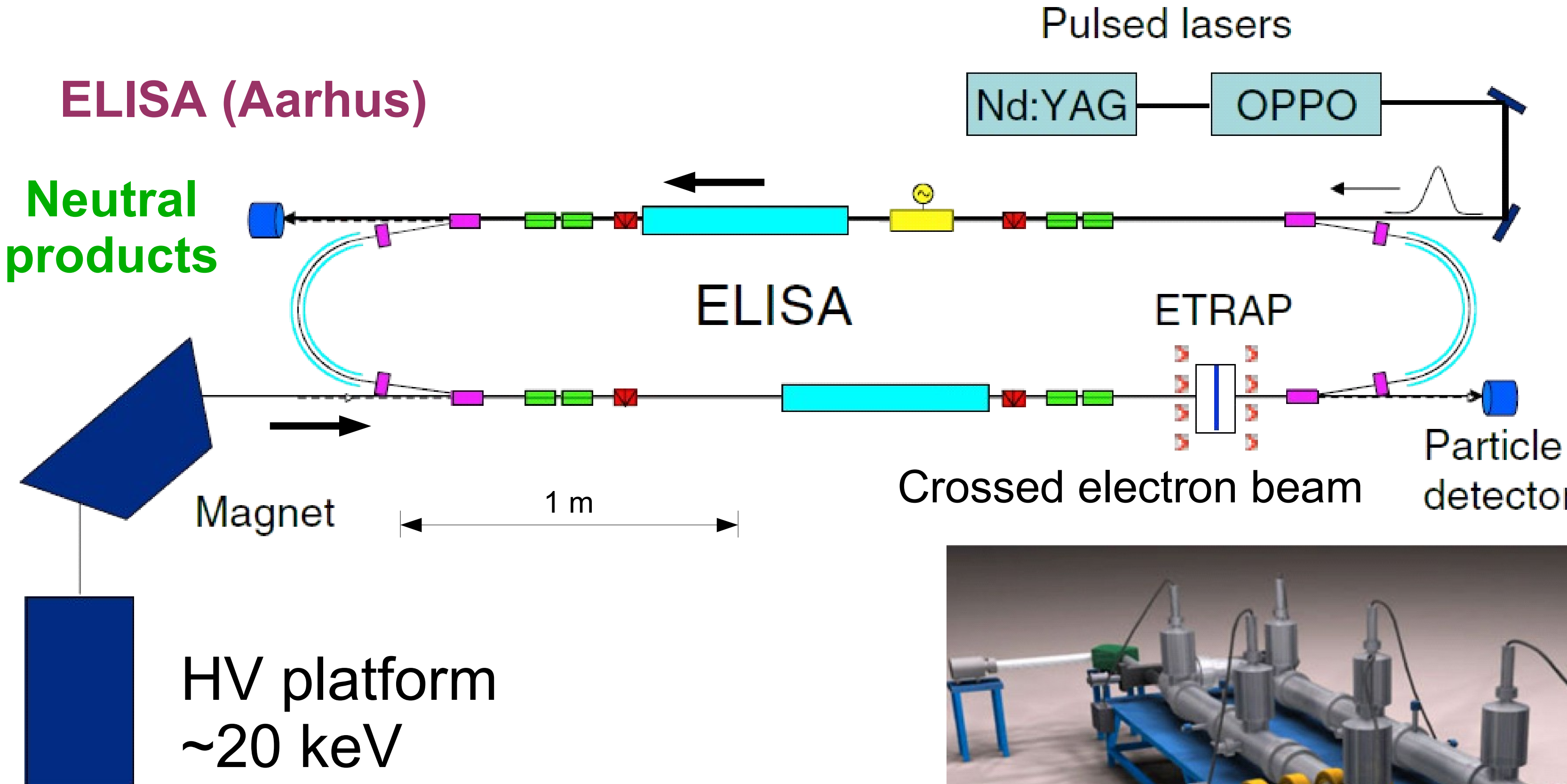
$$E_d = \frac{1}{2} m_e (v_n - v_i)^2$$

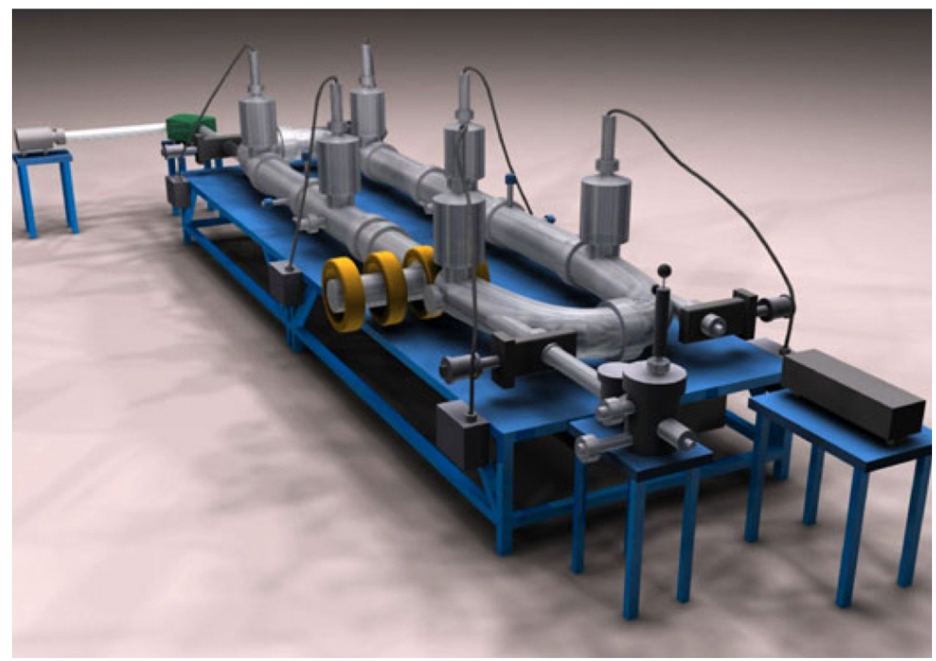
$\gtrsim$ 10 meV

Planned with
cooled ion beams
at electrostatic storage rings

Electrostatic storage rings

ELISA (Aarhus)





Mass independent beam storage:
large molecules and clusters

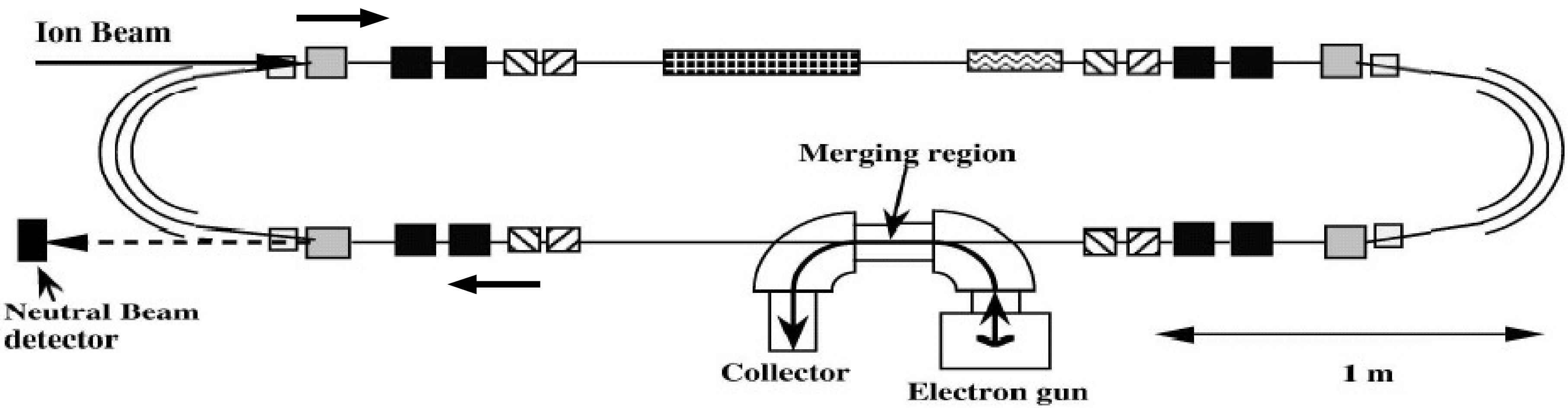
Molecular decay: evaporation of electrons and heavy fragments –
cooling of multidimensional vibrations

Laser excitation and delayed decay

Electrostatic storage rings

ELISA (Aarhus)

KEK Tokyo (biomolecules + 10 eV electron cooler)



Merged electron beam

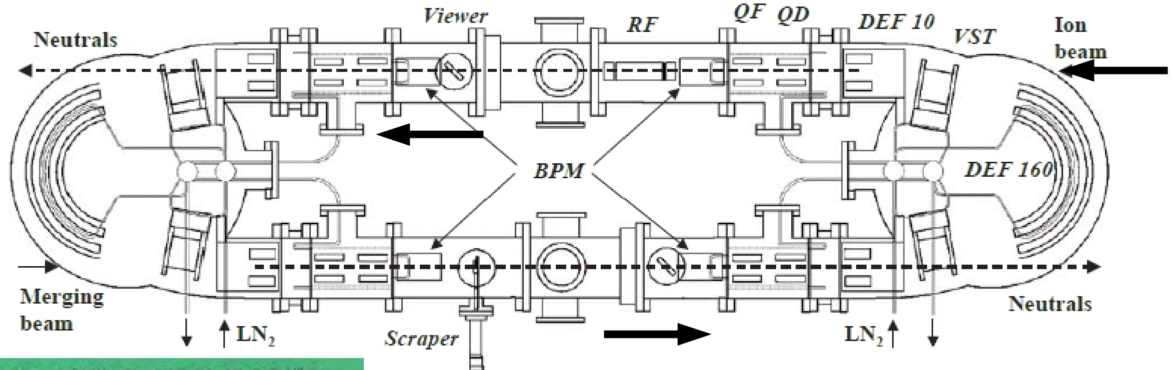
Fragmentation of amino acids, DNA base pairs, by ~10 eV electrons

T. Tanabe, PRL 93, 043201 (2011)

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

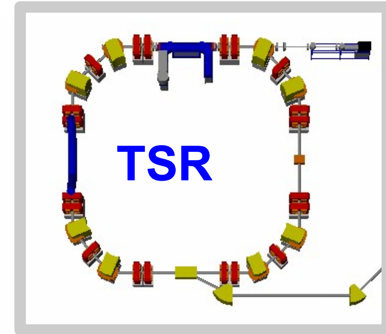
C_n^- clusters, short-lived excited states

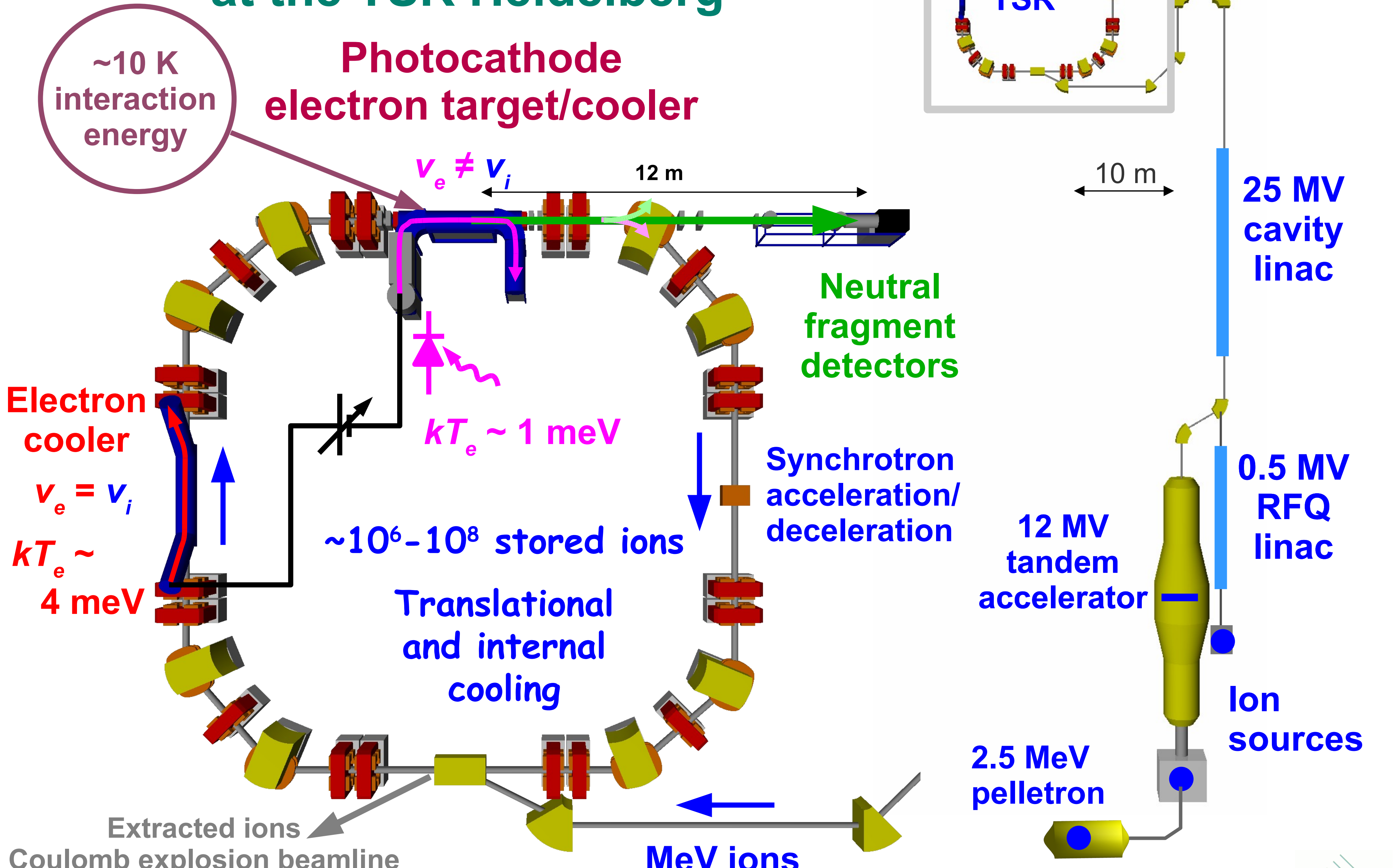
Stability of *weakly bound anions at low* (~100 K) *temperature*

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

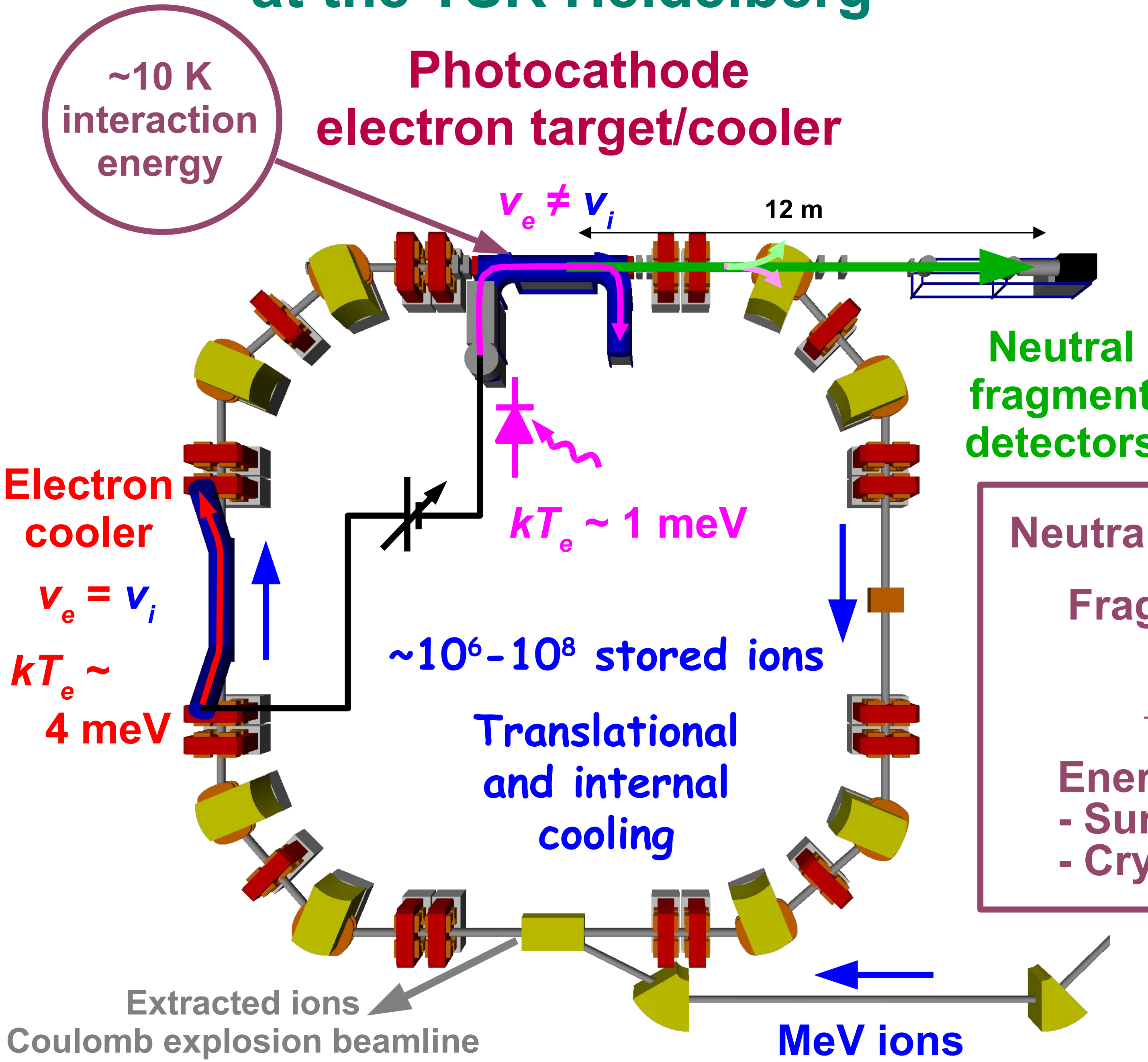
Bernard et al., Rev. Sci. Instrum. 79, 075109 (2008)

Electron–ion merged beams at the TSR Heidelberg





Electron–ion merged beams at the TSR Heidelberg



Neutral fragment identification

Fragment kinetic energy:

$$E_{kin} = m_i \, v_{beam}^2$$

$\rightarrow$ **fragment mass**

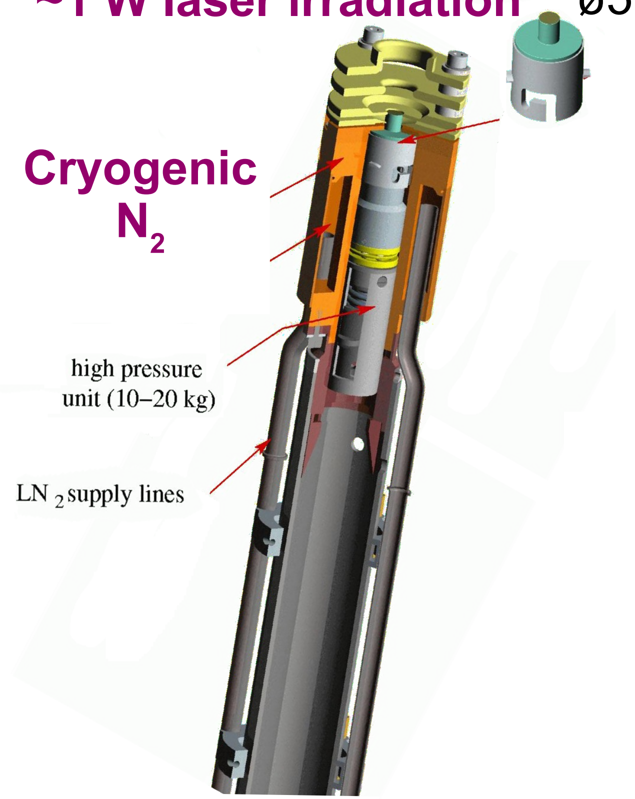
Energy sensitive detector
- **Surface-barrier detector**
- **Cryo calorimeter**

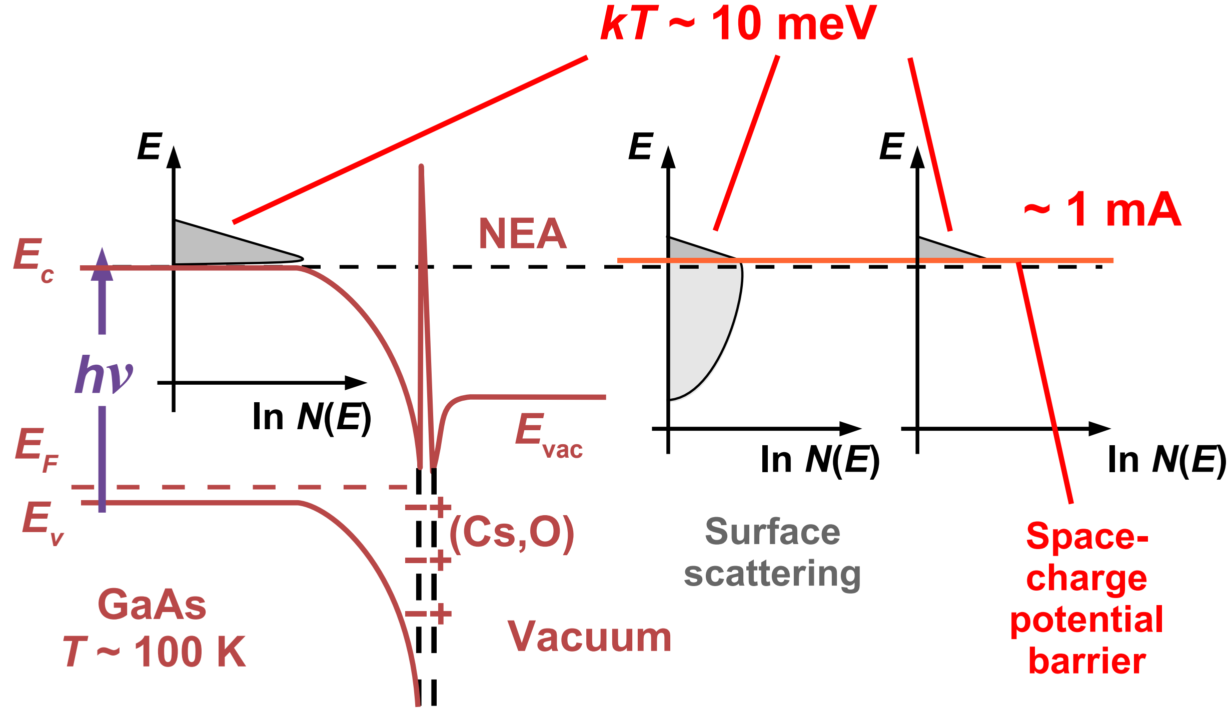
High-resolution electron target

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)

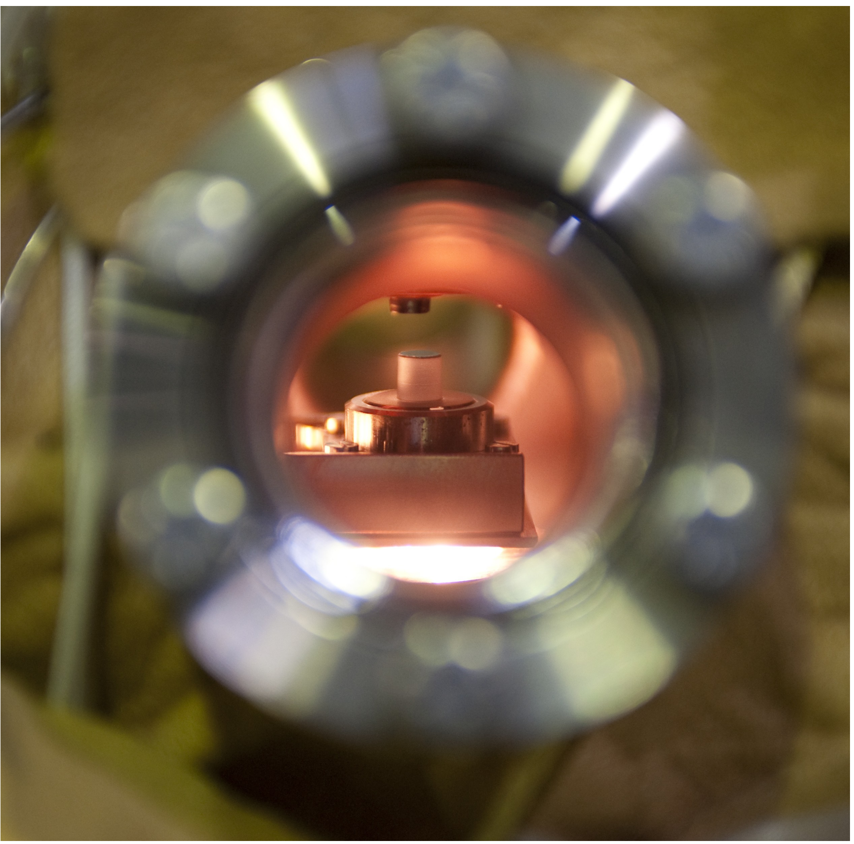
D. A. Orlov et al., J. Appl. Phys. 106, 054907 (2009)

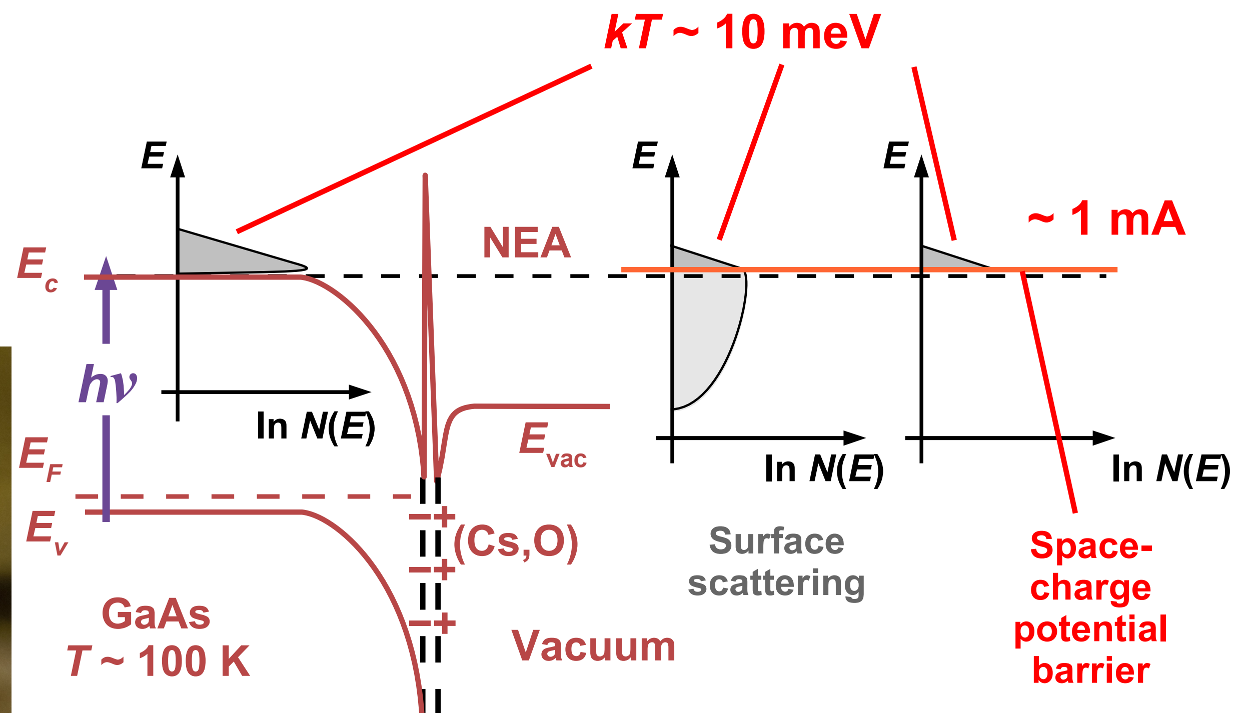
D. A. Orlov, C. Krantz, A. Shornikov
Collab. with Inst. f. Semiconductor Phys., Novosibirsk, A. N. Terekhov

High-resolution electron target

Photocathode electron target

GaAs photocathode
~100 K





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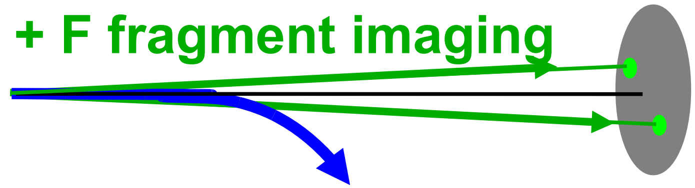
Electron cooling with a photocathode beam

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

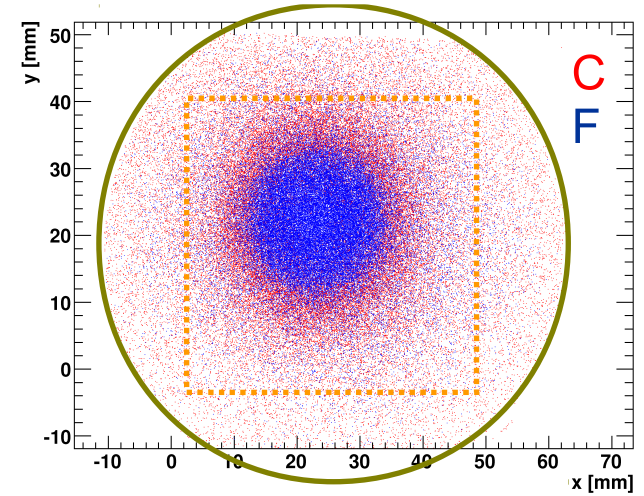
50 eV electrons

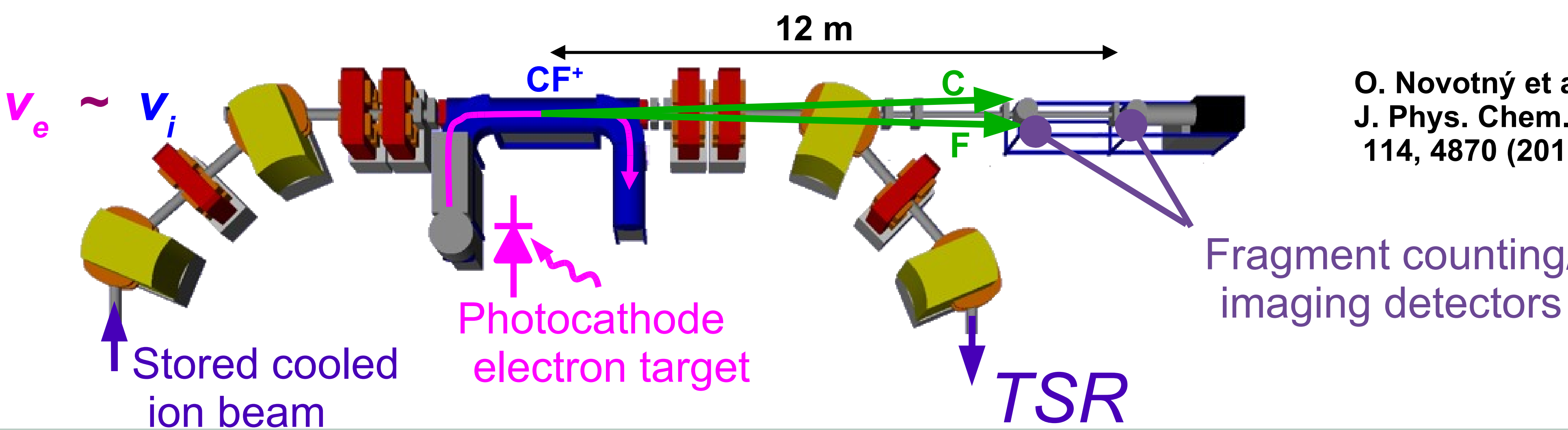
~1 mA electron current

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



Standard electron cooling (12-30 s after injection)





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

Electron cooling with a photocathode beam

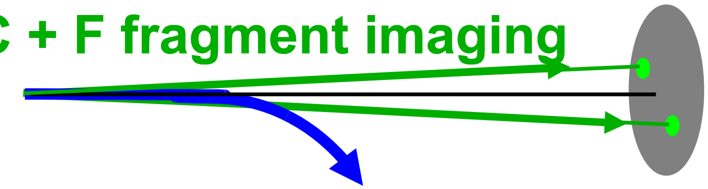
CF^+ (31 amu) at 90 keV/amu

50 eV electrons

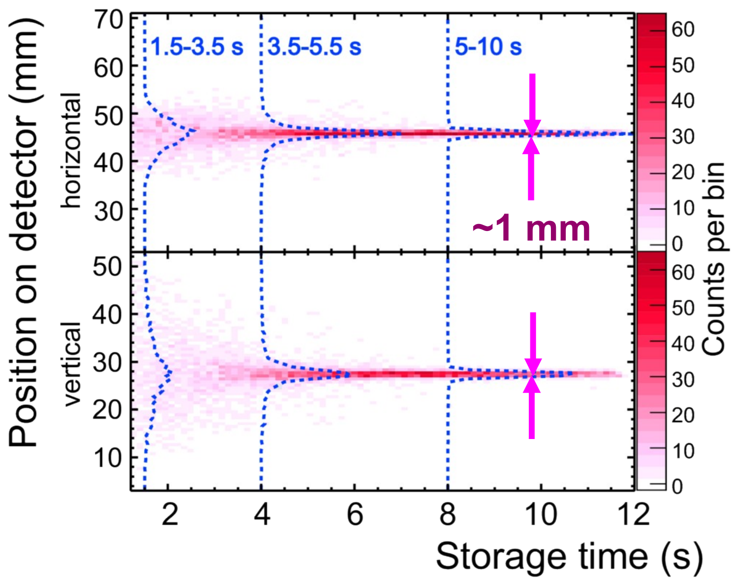
~1 mA electron current

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

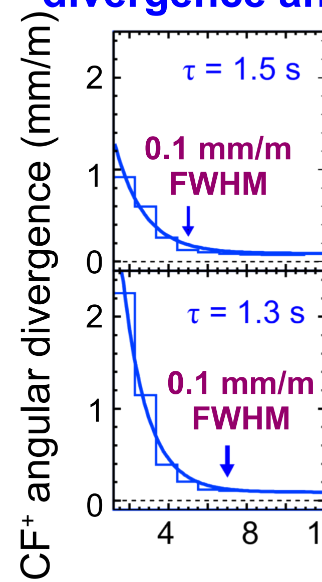
C + F fragment imaging



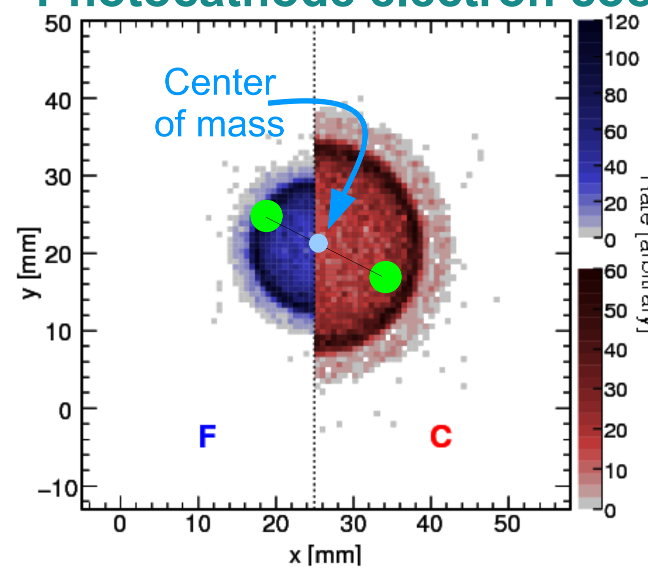
Molecular center of mass on fragment imaging detector

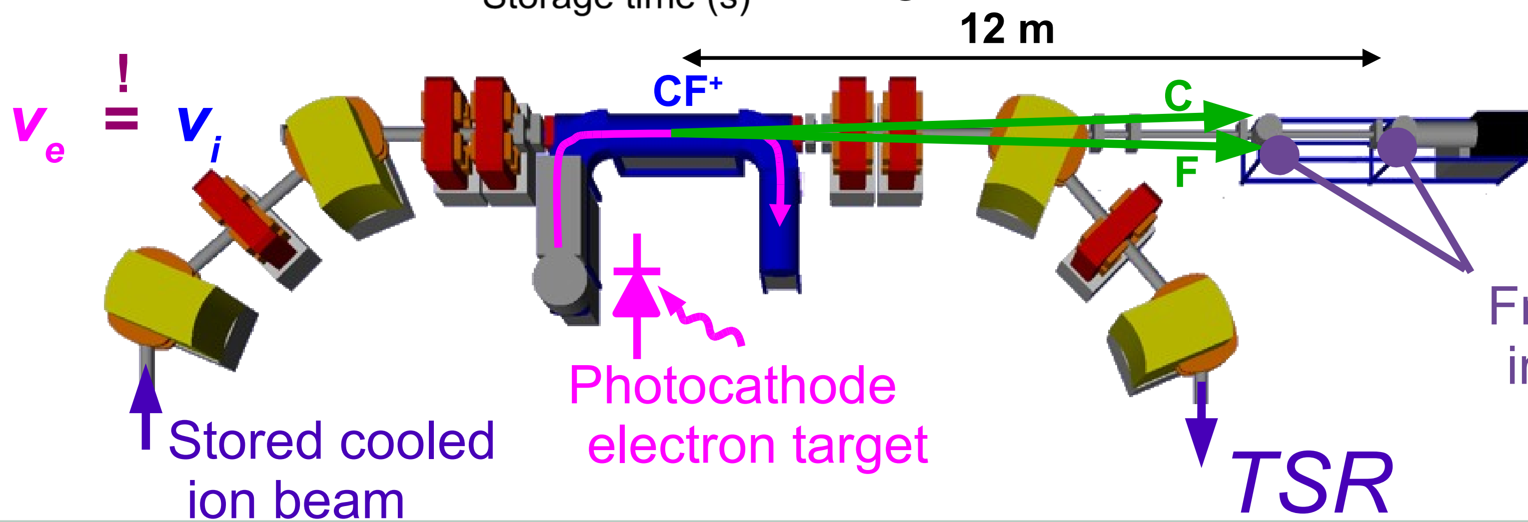


Ion beam divergence angle



Photocathode electron cooling



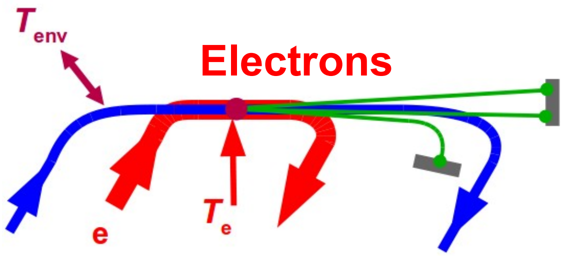


$$v_e \overset{!}{=} v_i$$

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

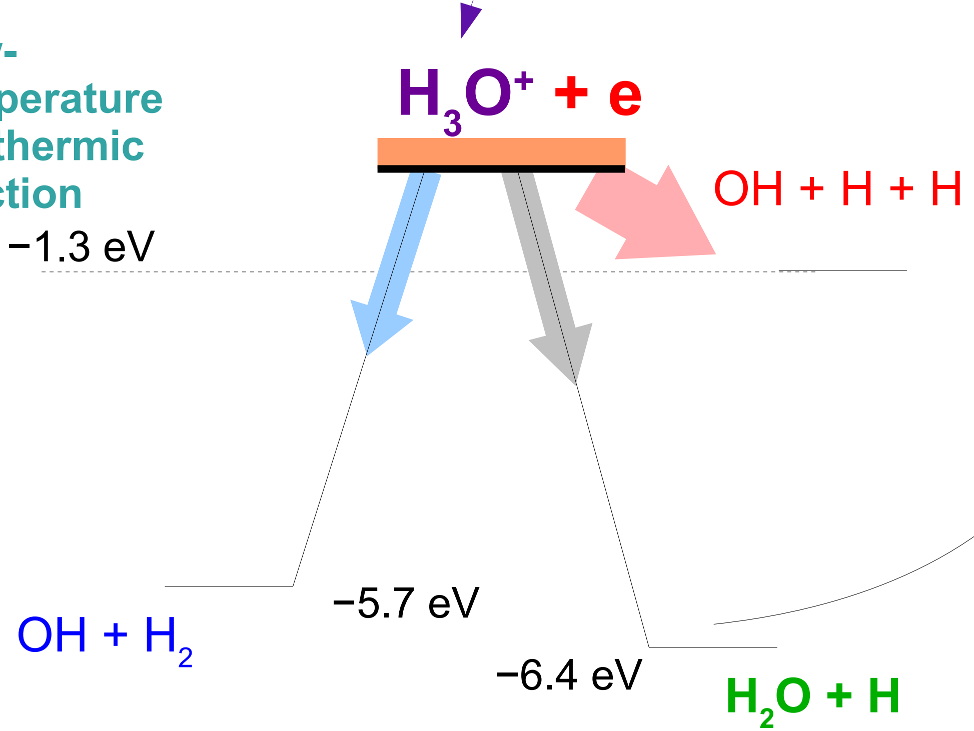
Polyatomic ions at TSR

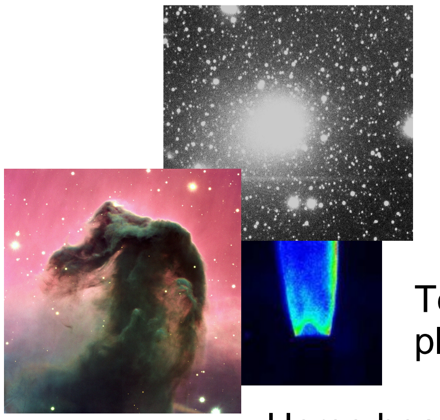
Fragmentation pathways of dissociative recombination



Molecules built up by ion chemistry

Low-temperature exothermic reaction





Coma of comet Hale-Bopp

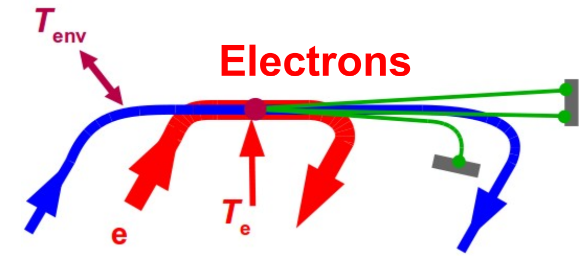
Terrestrial plasma

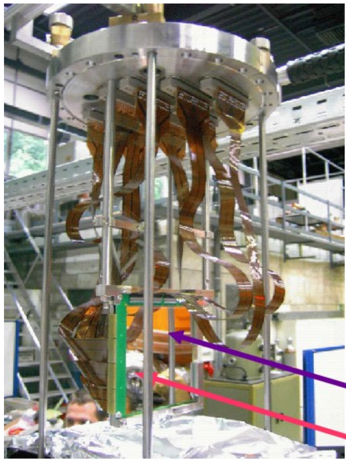
Horse head nebula

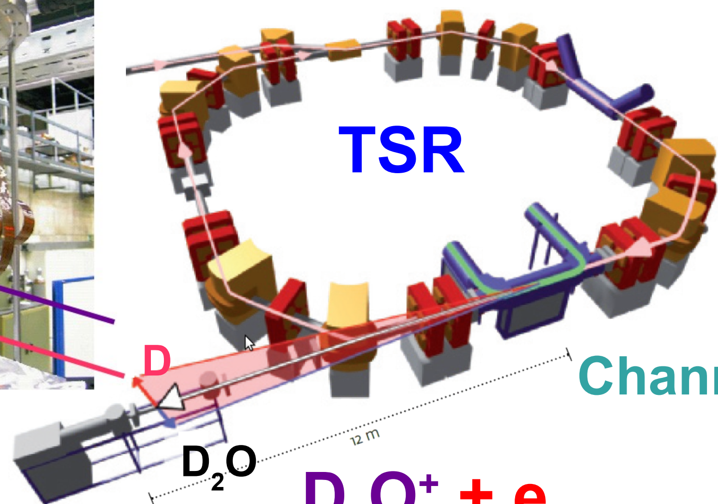
Source of water in cold molecular clouds, comets, ...

Polyatomic ions at TSR

Fragmentation pathways of dissociative recombination







EMU detector

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

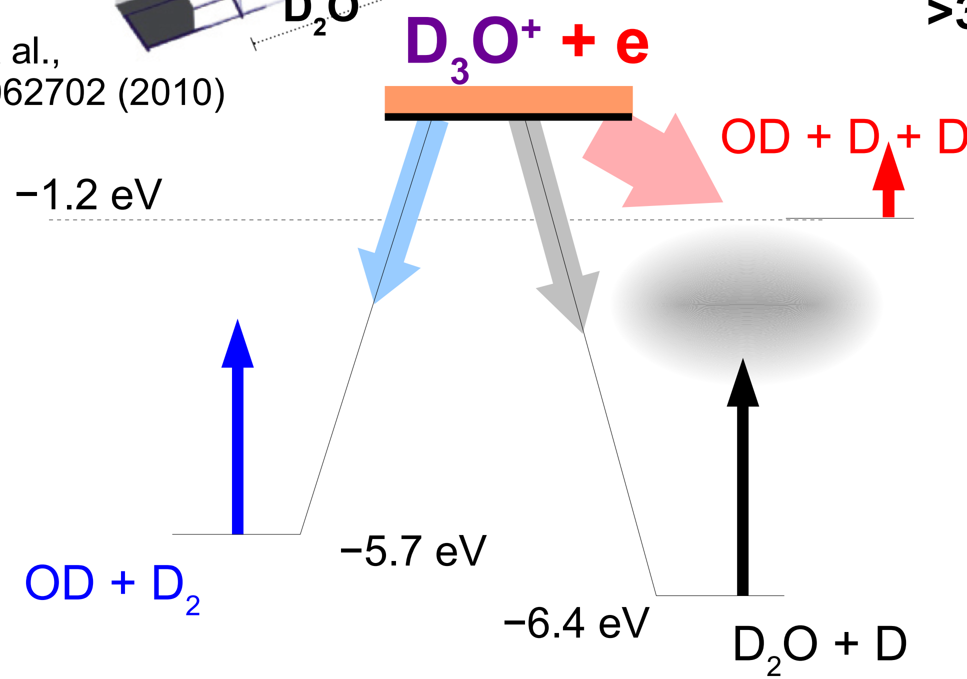
Method:

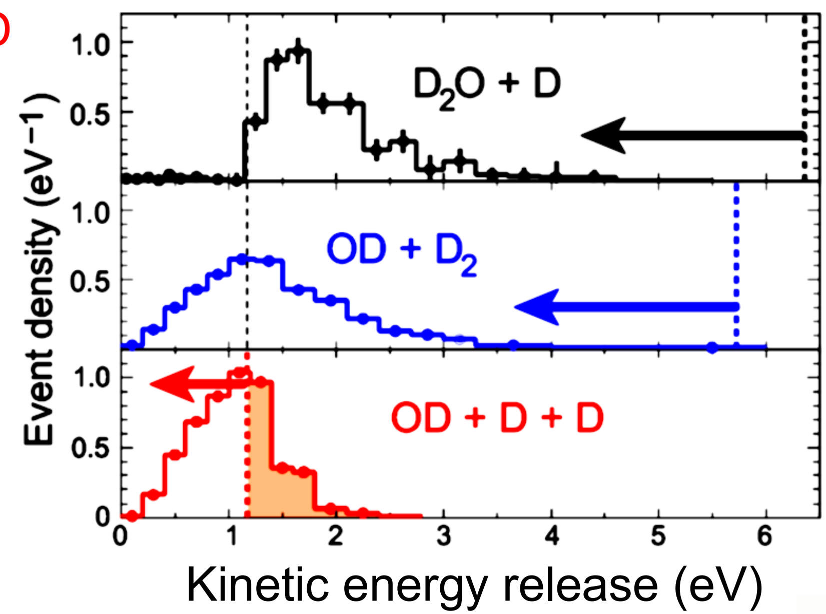
- **1 meV electron collision energy**
- **Imaging detector with fragment mass recognition (EMU)**
- **Deuterated molecules**

Channel-specific energy release measurement

>3 eV vibrational excitation of water

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





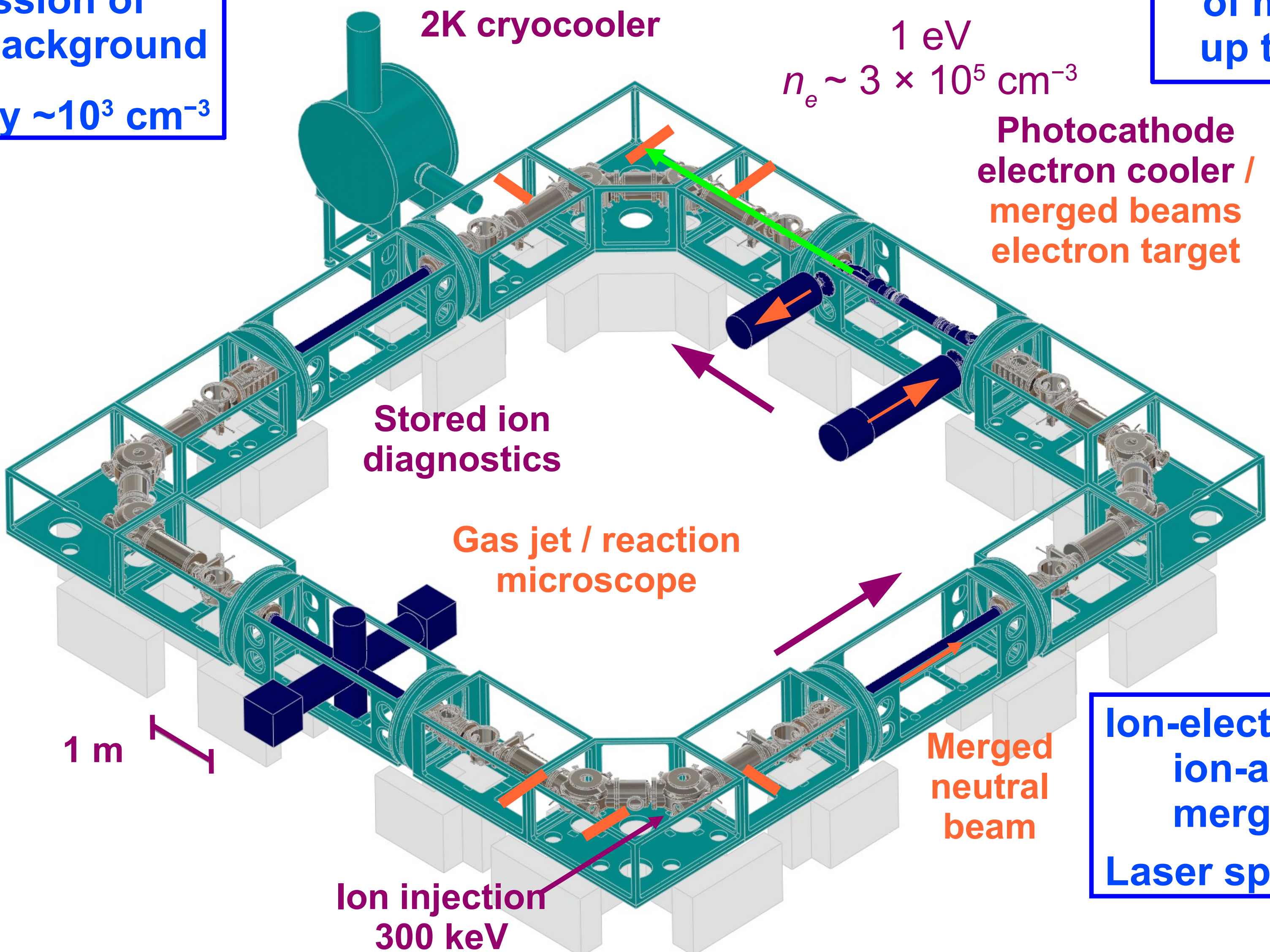
Cryogenic electrostatic storage ring CSR

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

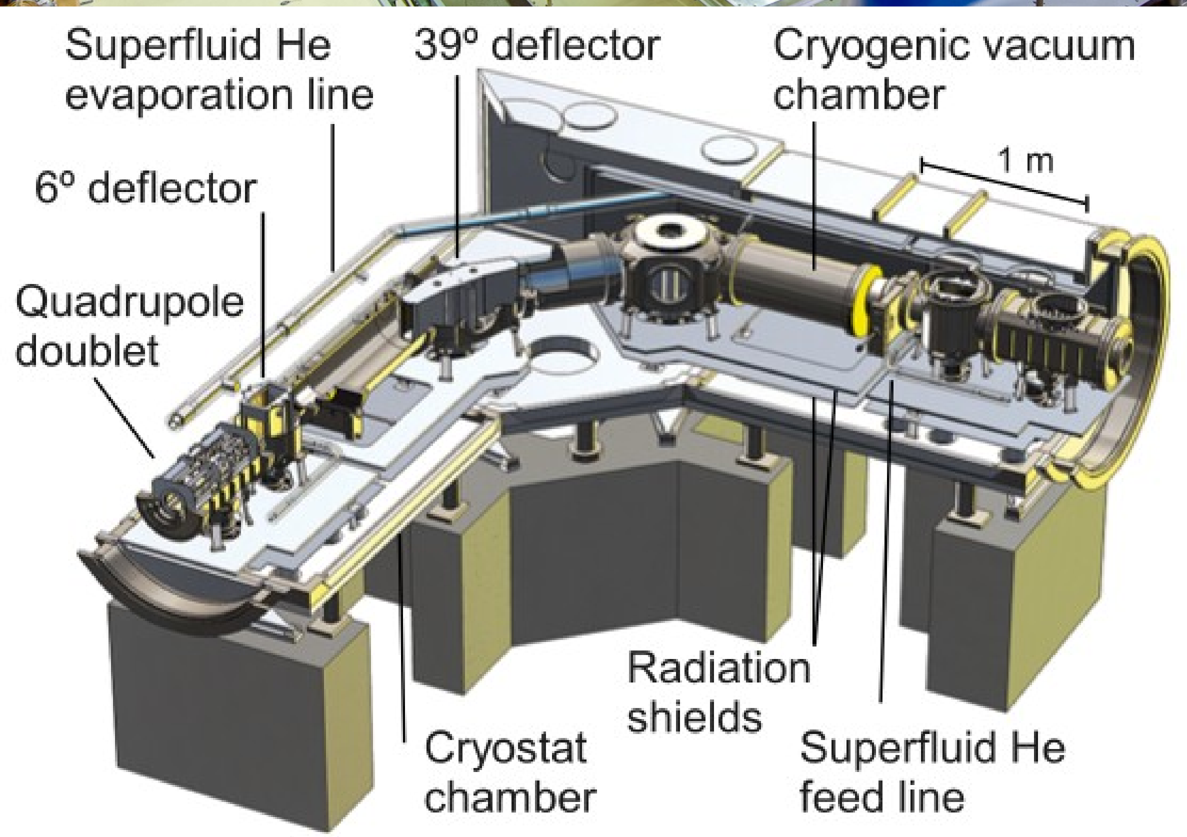


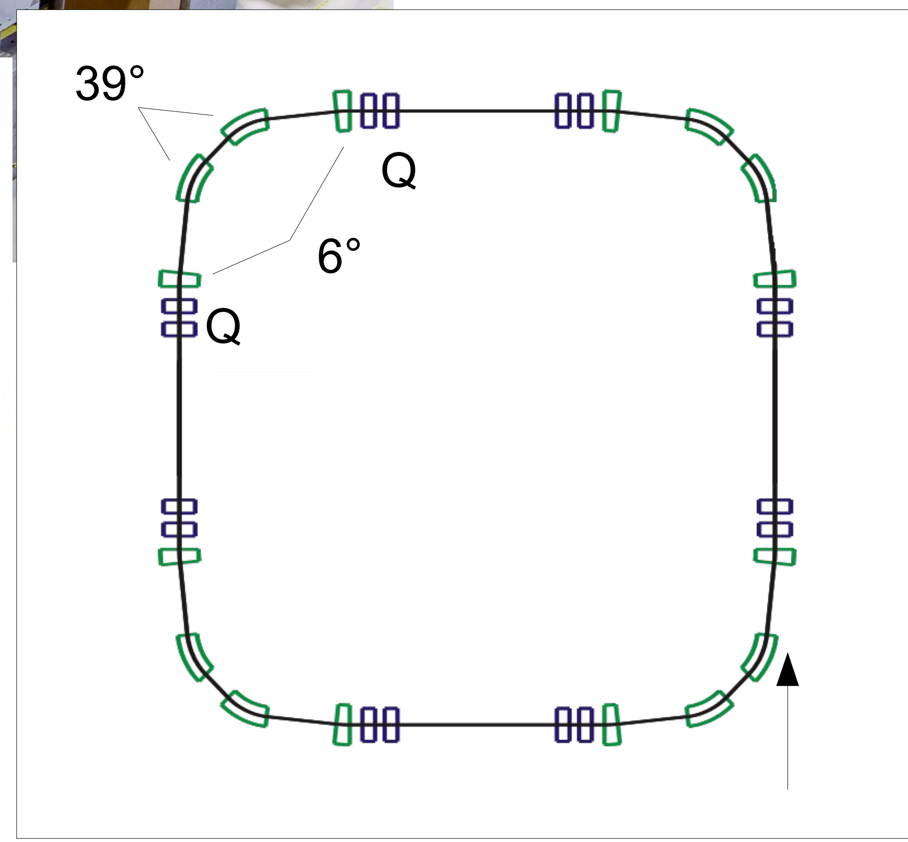
D. A. Orlov, C. Krantz, A. Shornikov et al.

Ion-electron and ion-atom merged beams

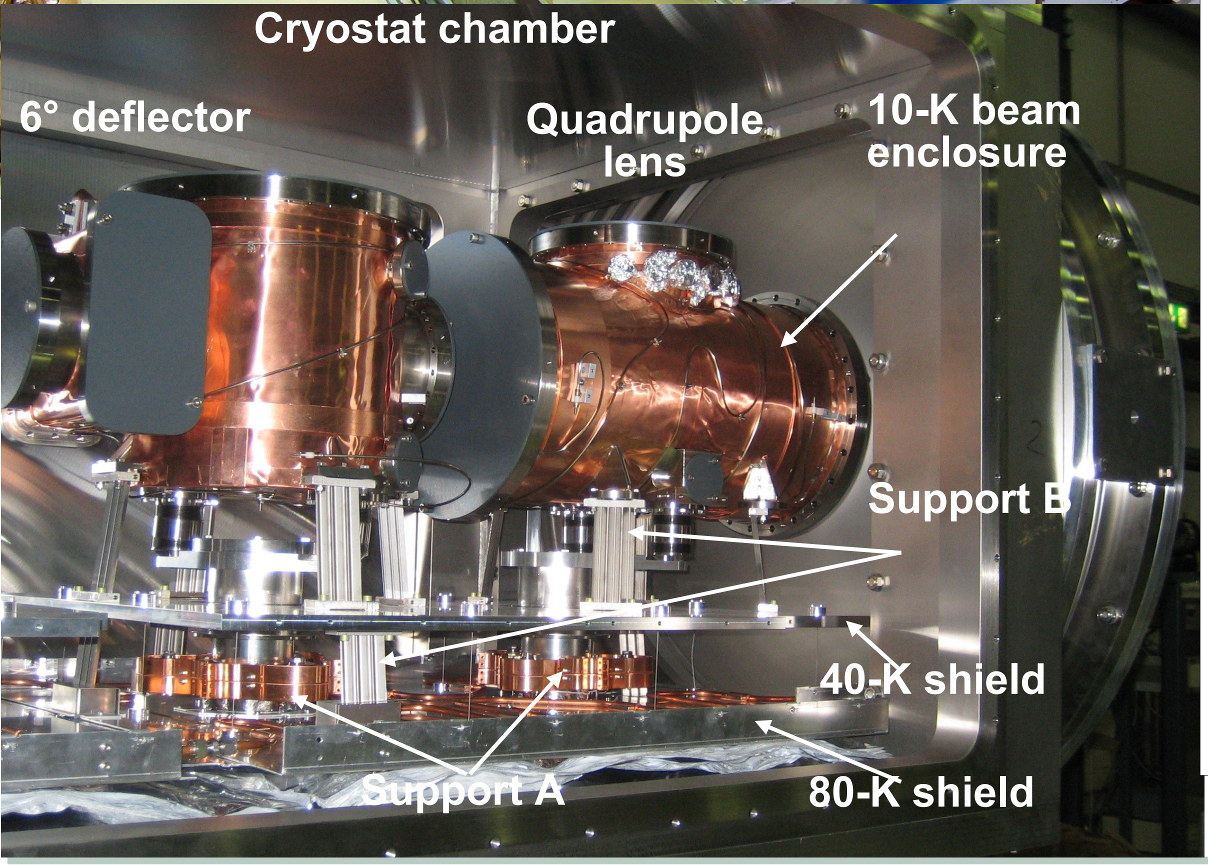
Laser spectroscopy

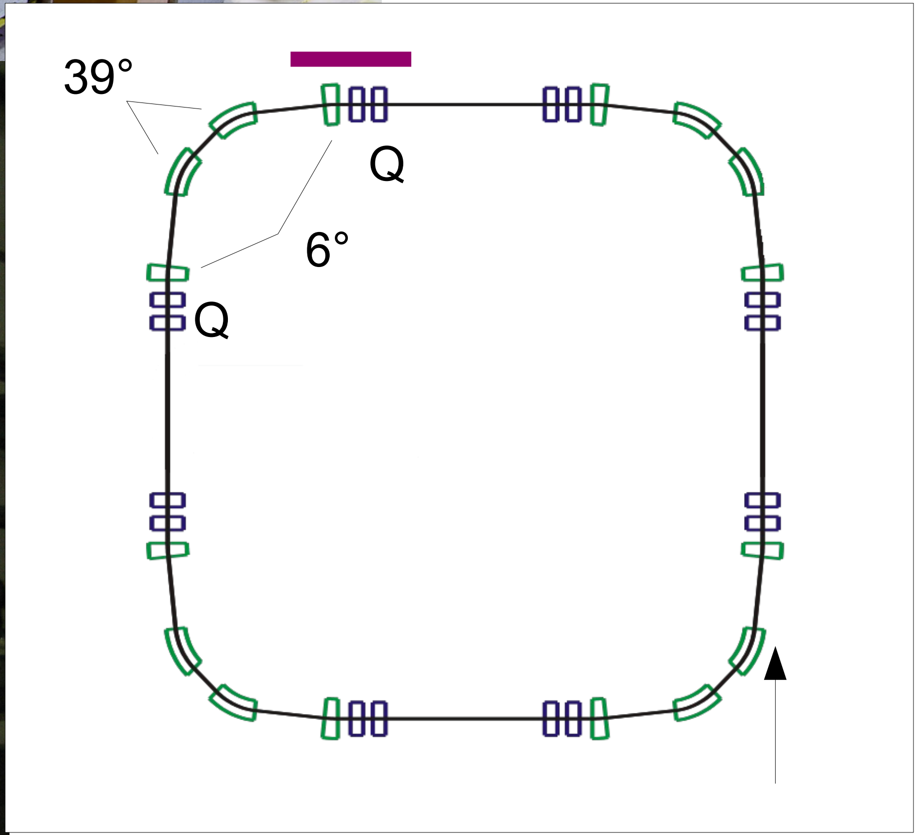
Cryogenic storage ring CSR



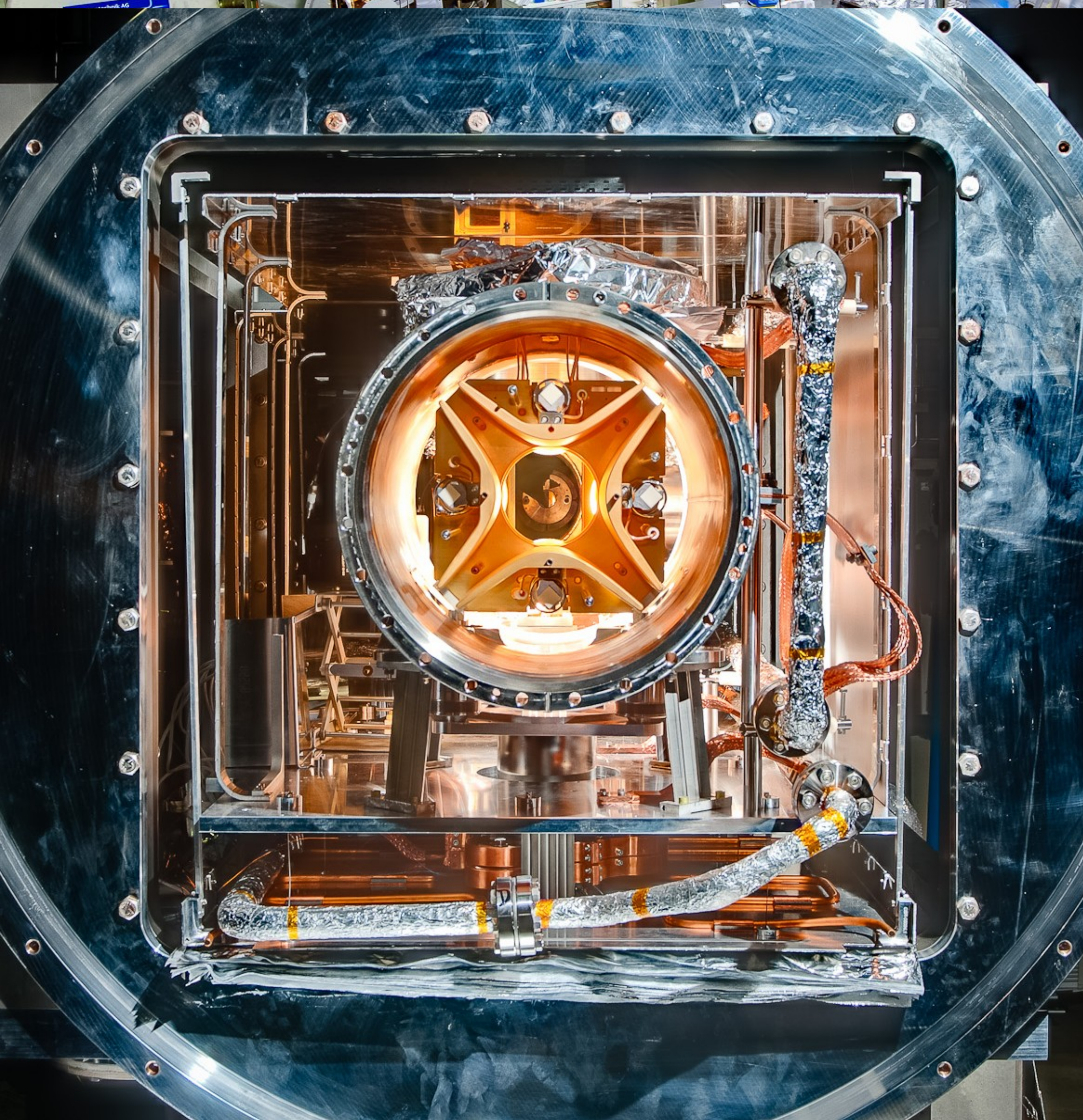


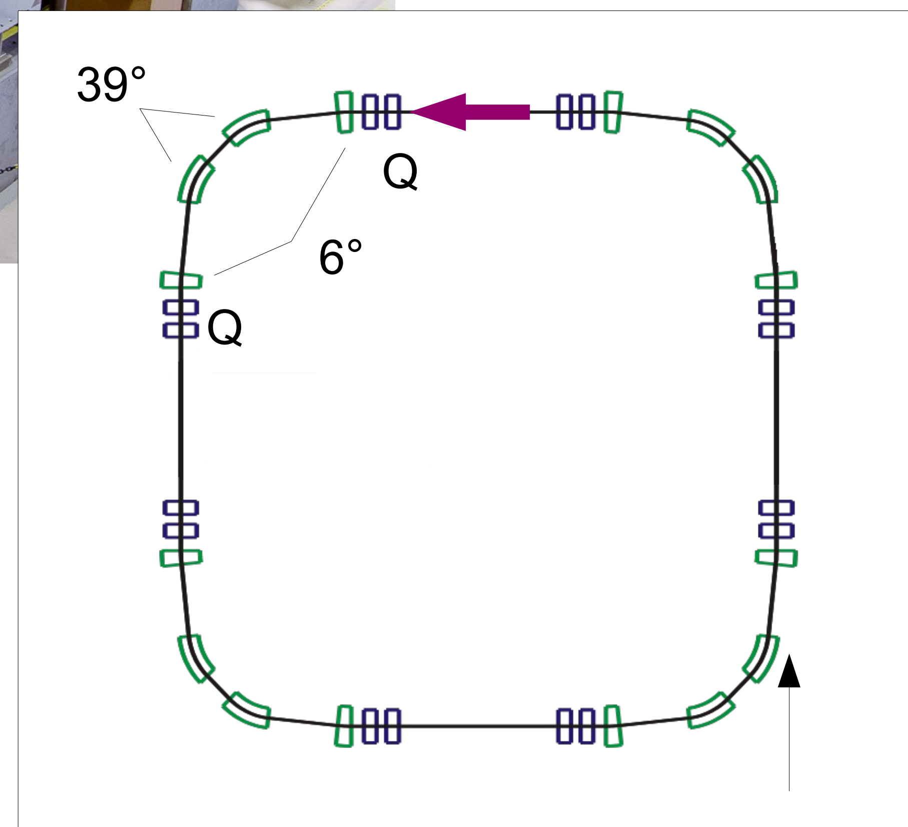
Cryogenic storage ring CSR



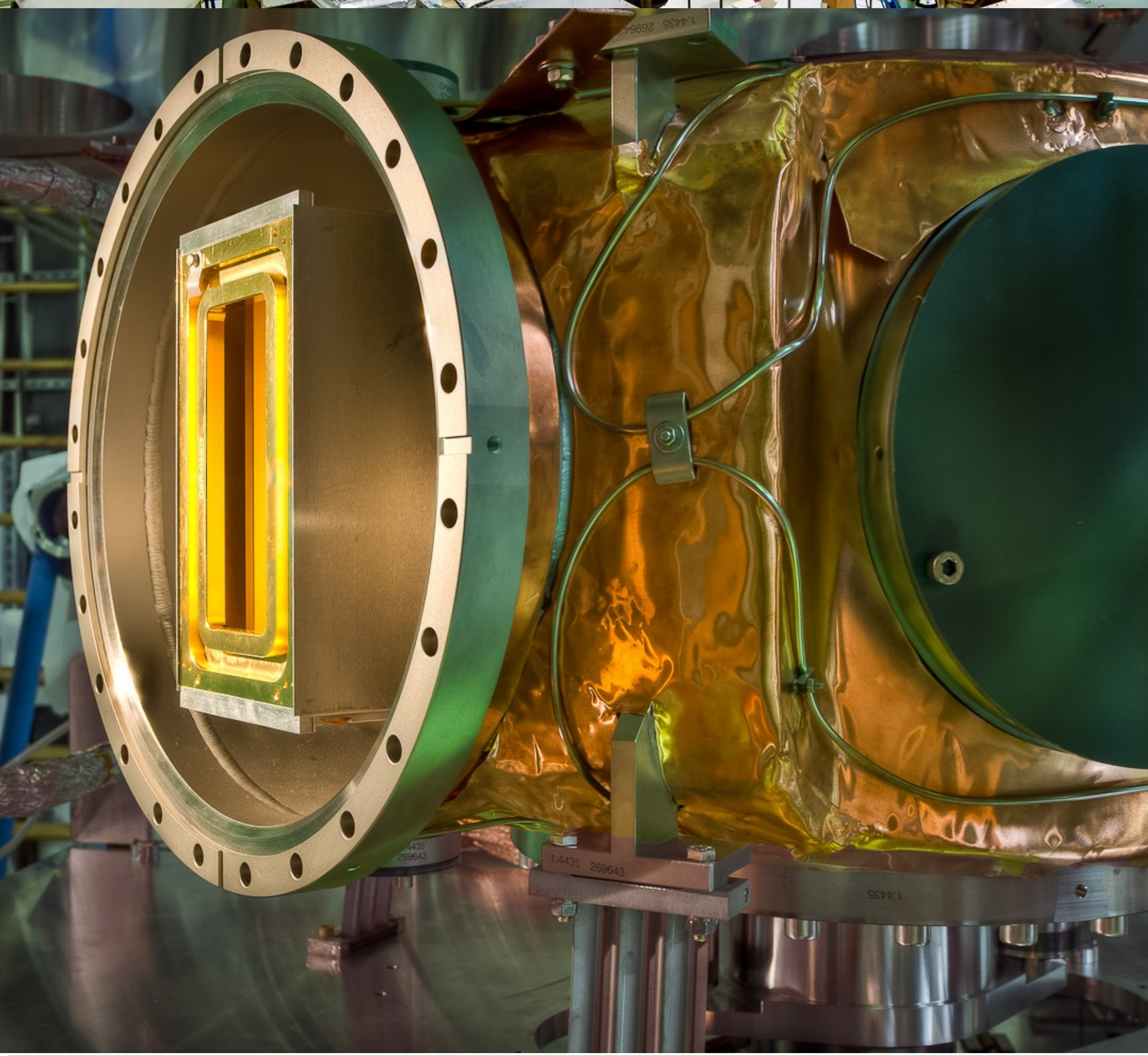


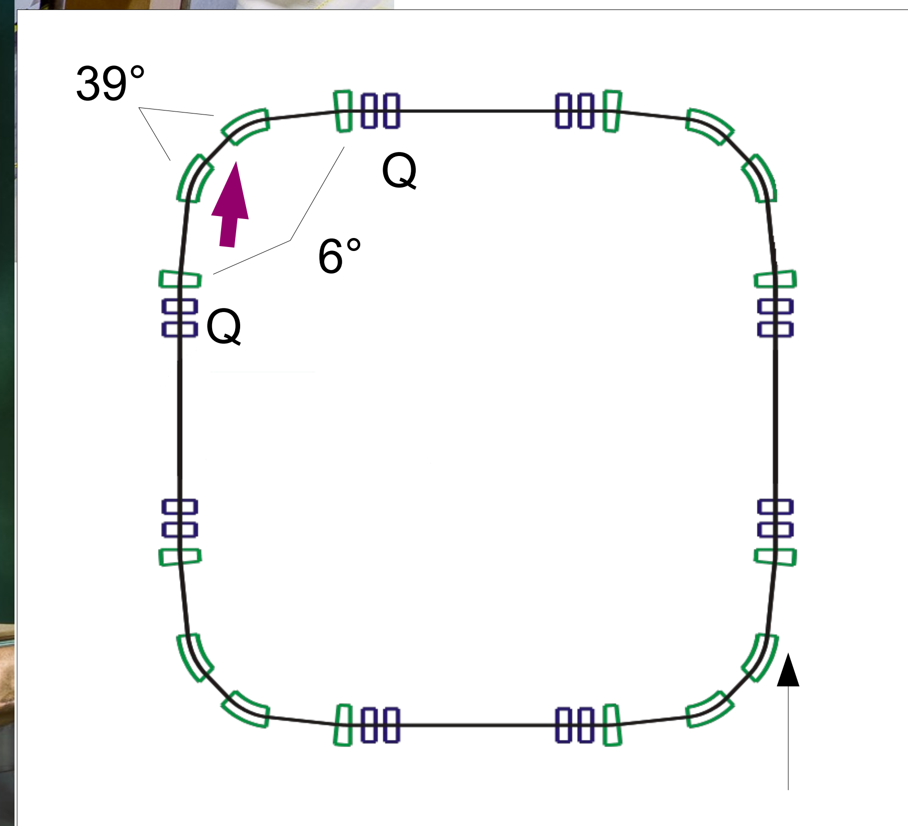
Cryogenic storage ring CSR





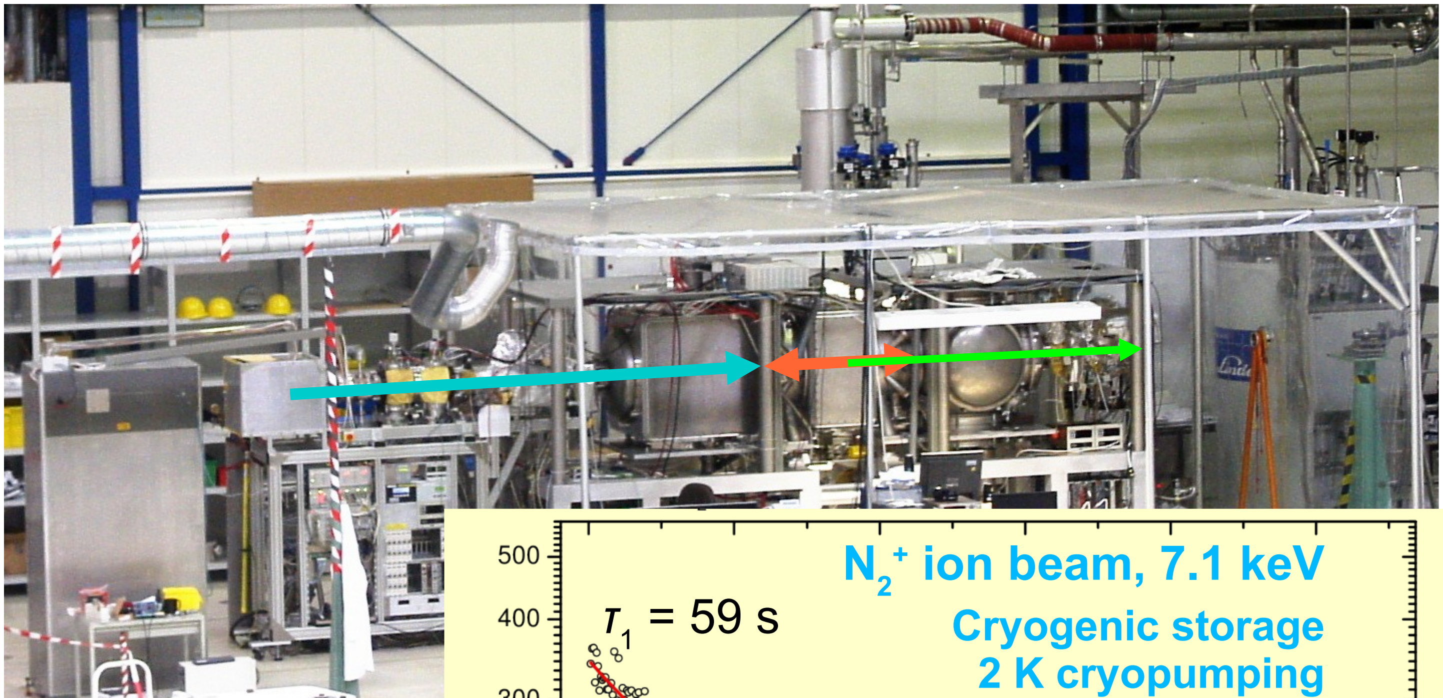
Cryogenic storage ring CSR

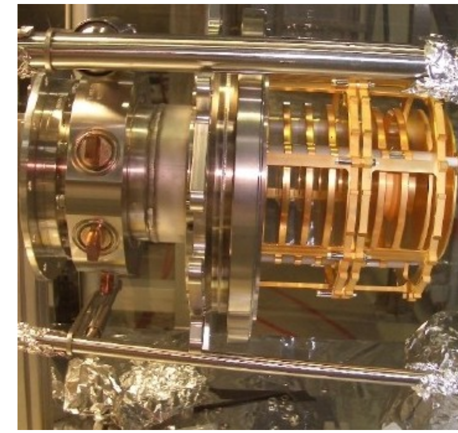


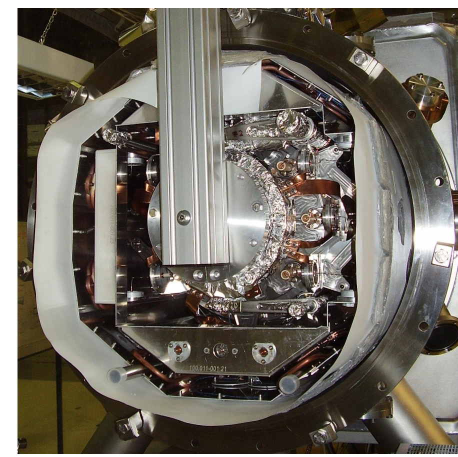


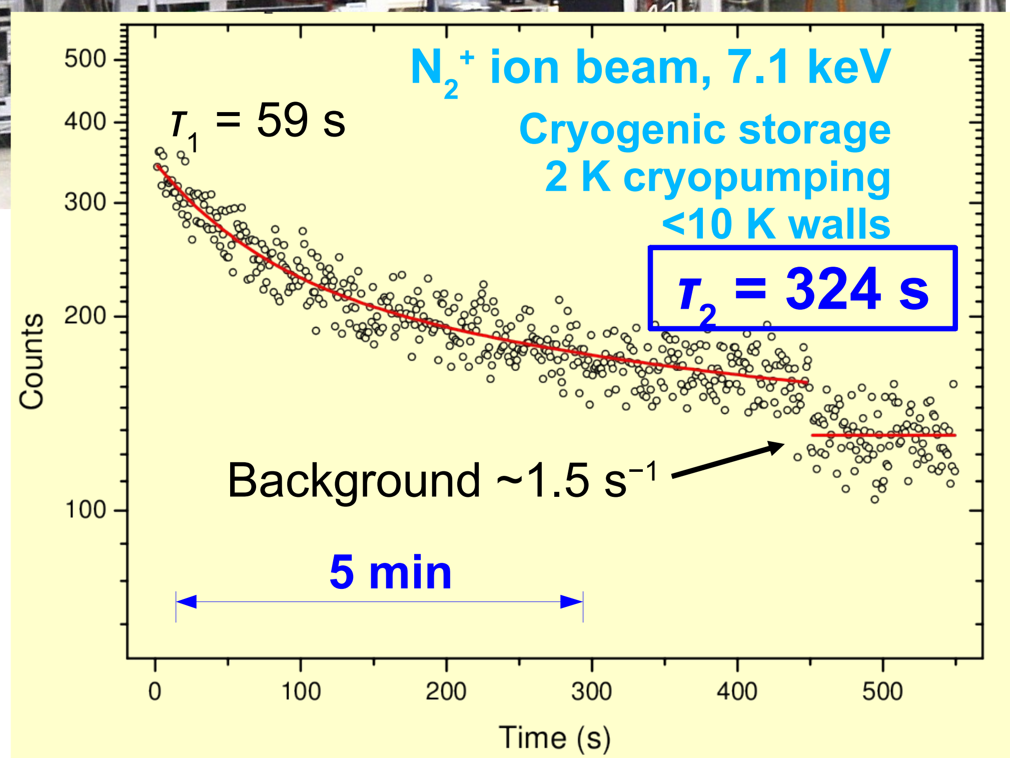
CSR cryo and vacuum tests – the CTF

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









Count rate from ion neutralization

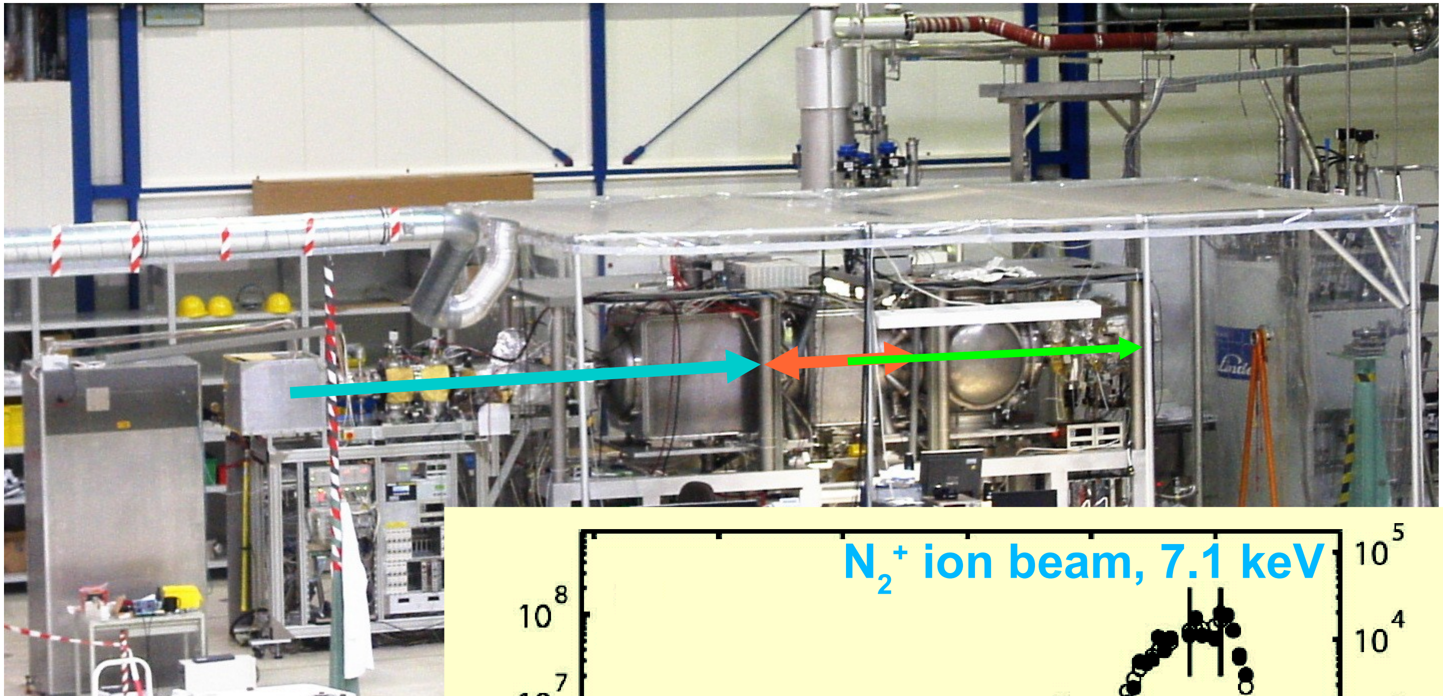
>10^8 reflections

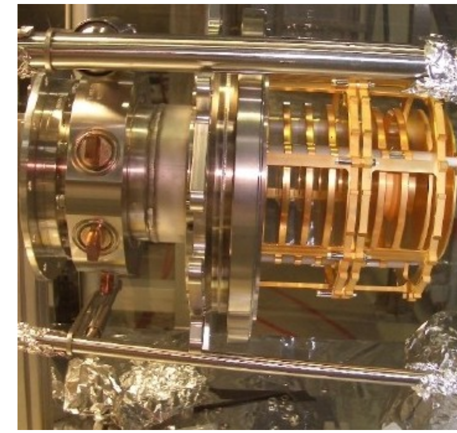
M. Lange et al., Rev. Sci. Instrum. 281, 055105 (2010)

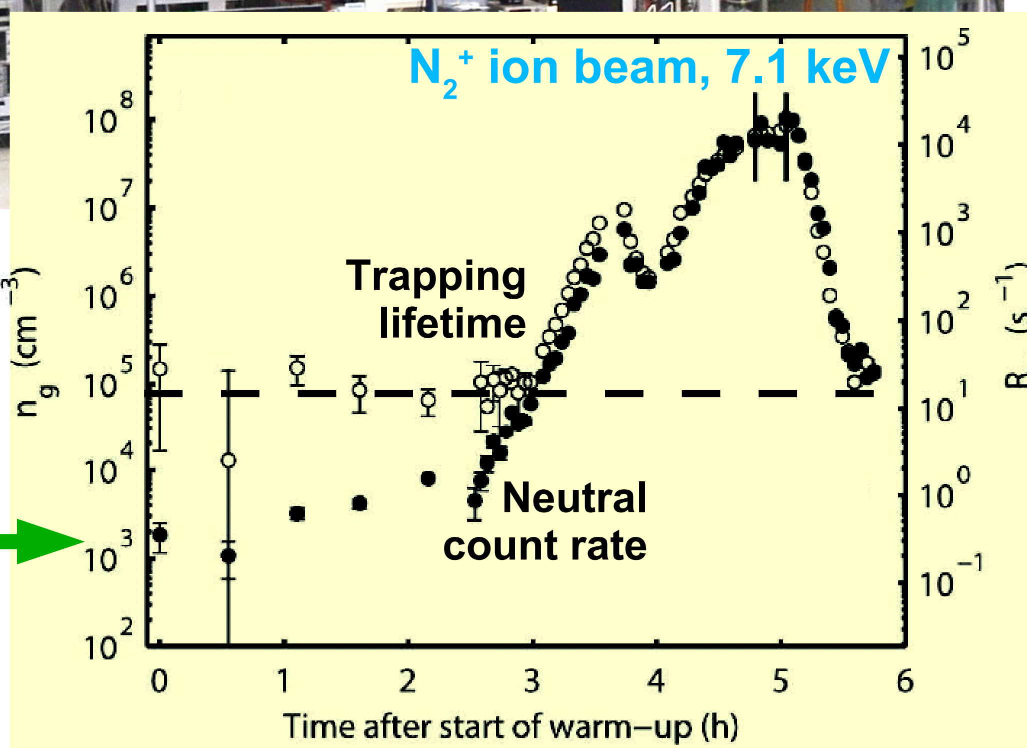
M. Froese, M. Lange, S. Menk et al.

CSR cryo and vacuum tests – the CTF

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

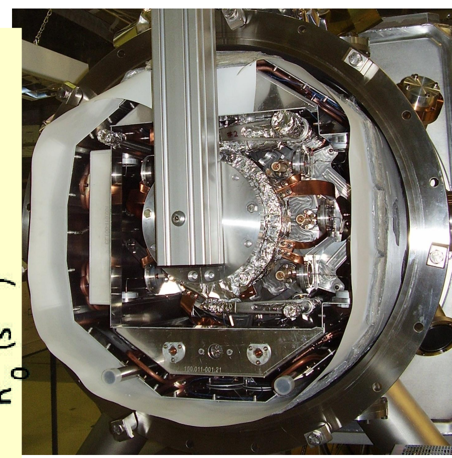






Count rate from ion neutralization

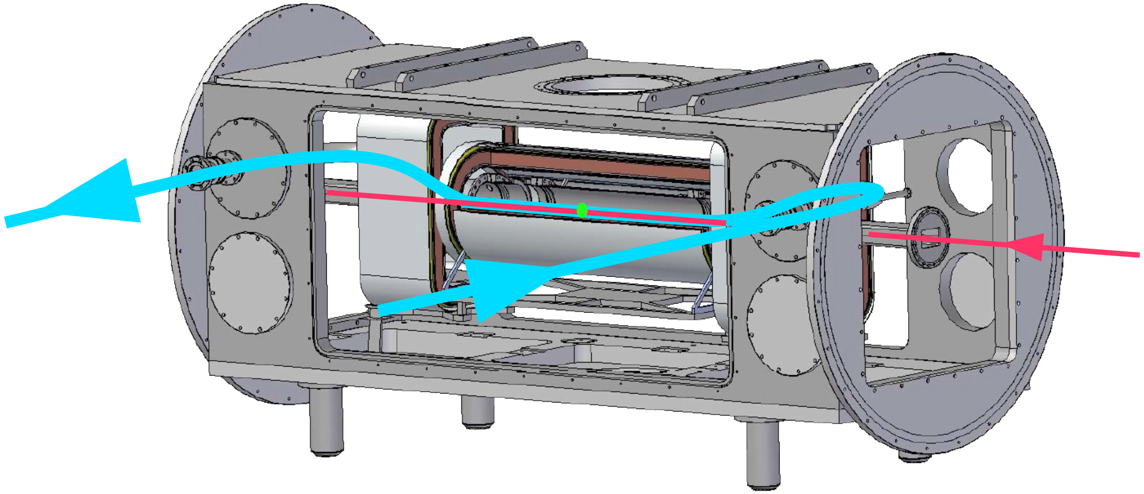
Residual gas density
2×10^3 cm^{-3}
~1×10^{-13} mbar

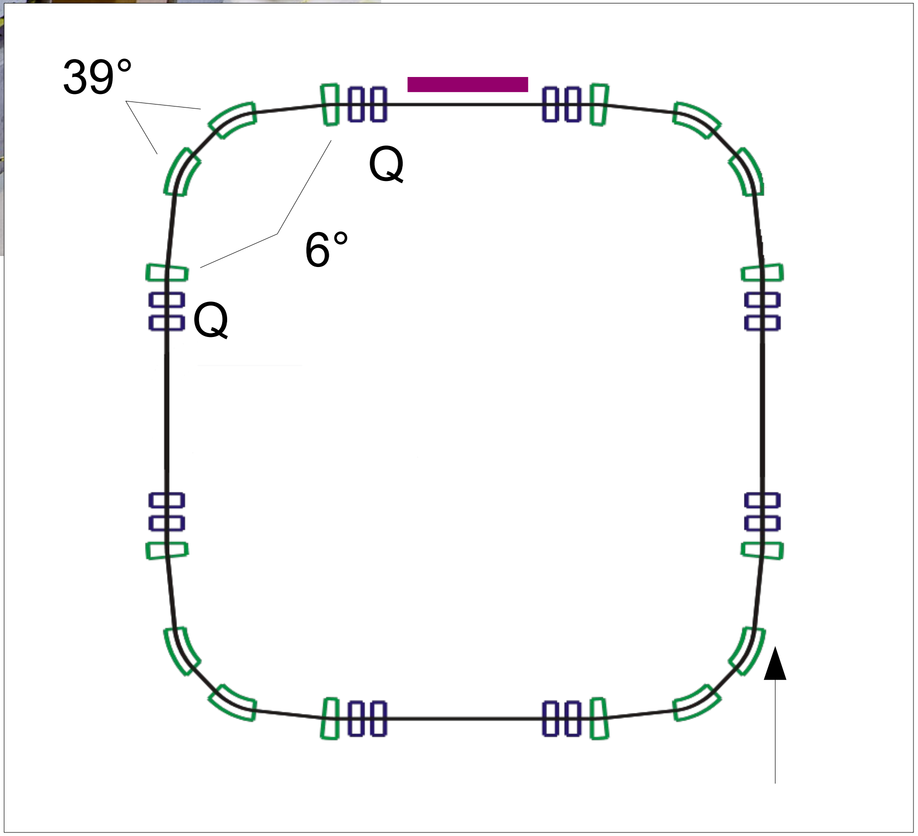


M. Lange et al., Rev. Sci. Instrum. 281, 055105 (2010)

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

Cryogenic storage ring CSR



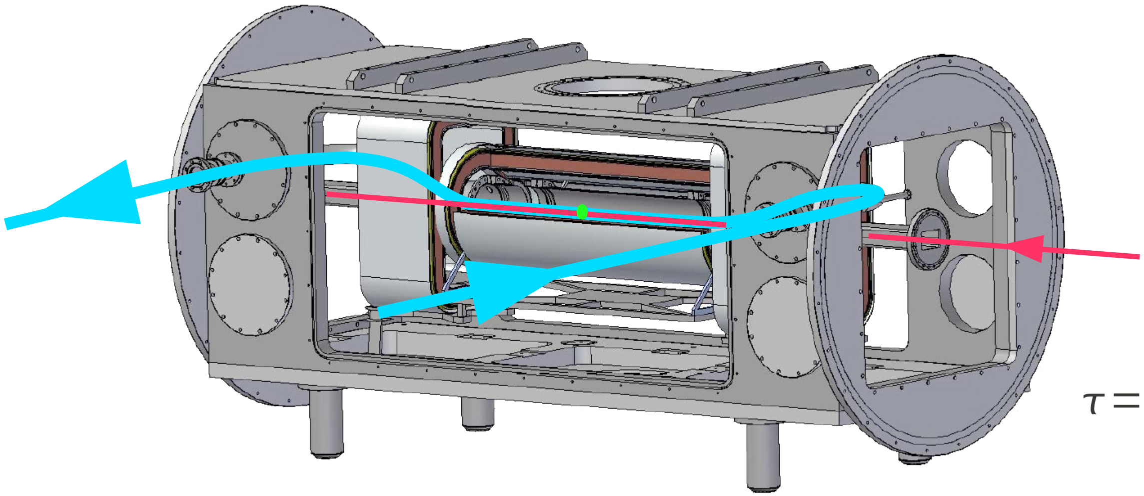


Photocathode electron beam

A. Shornikov, C. Krantz

Low-energy photocathode electron beam

A. Shornikov, C. Krantz



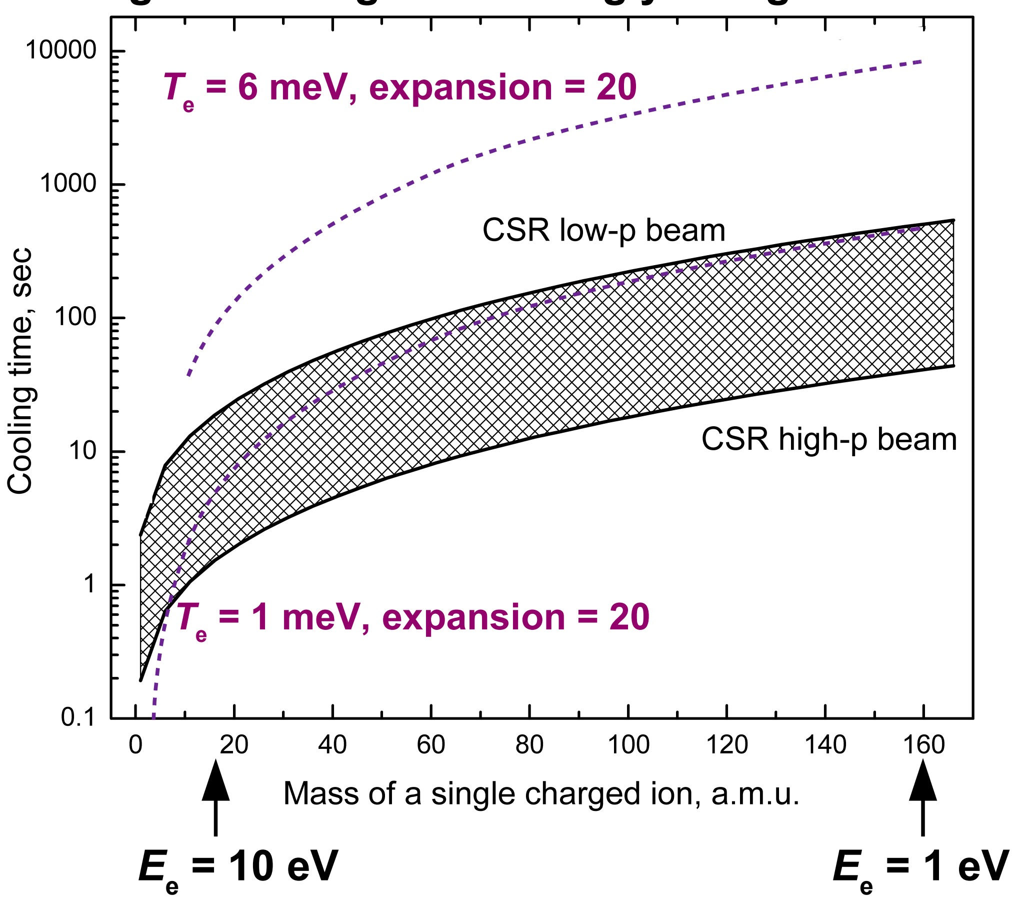
$$\tau = C \frac{A^2}{Z^2 E_i} \frac{(1-x)^{3/2} T_e^{3/2} \alpha}{p(x)} \lambda$$

α : magnetic expansion

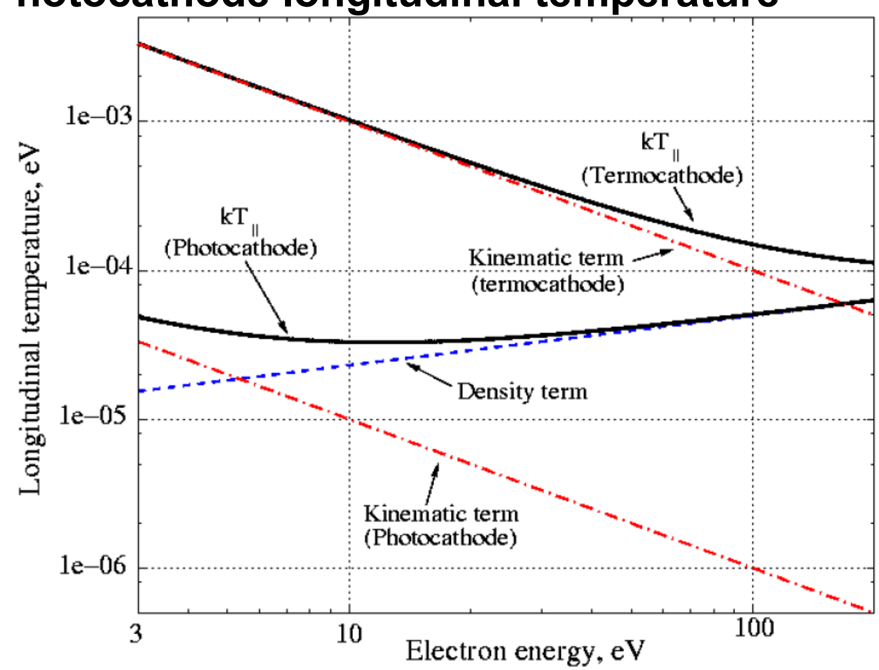
$$\lambda = \frac{L_{RING}}{L_{COOLER}} = 50$$

$$p_{high} = 4.1 (x = 0.33)$$
$$p_{low} = 0.6 (x = 0.03)$$

Cooling time of high-mass singly charged ions

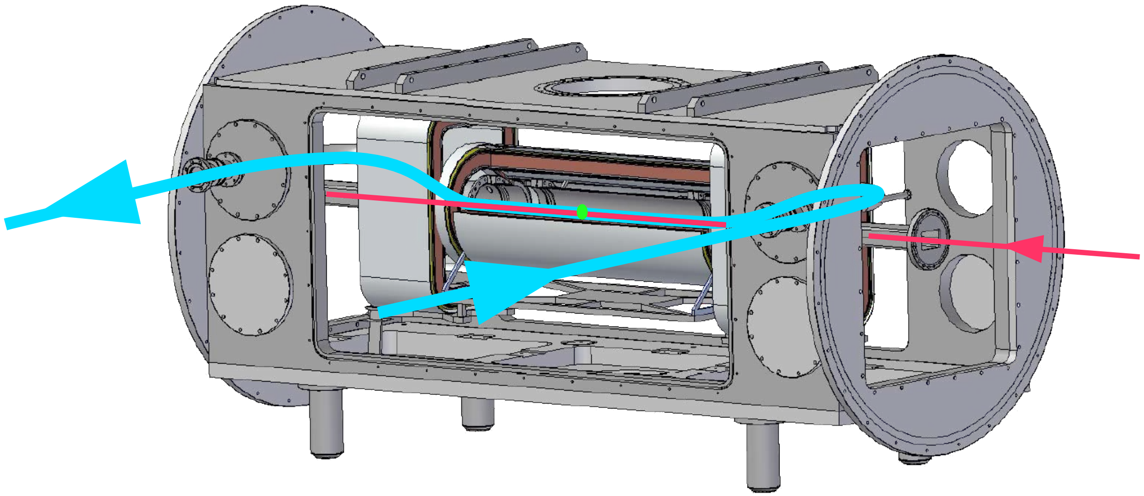


Photocathode longitudinal temperature



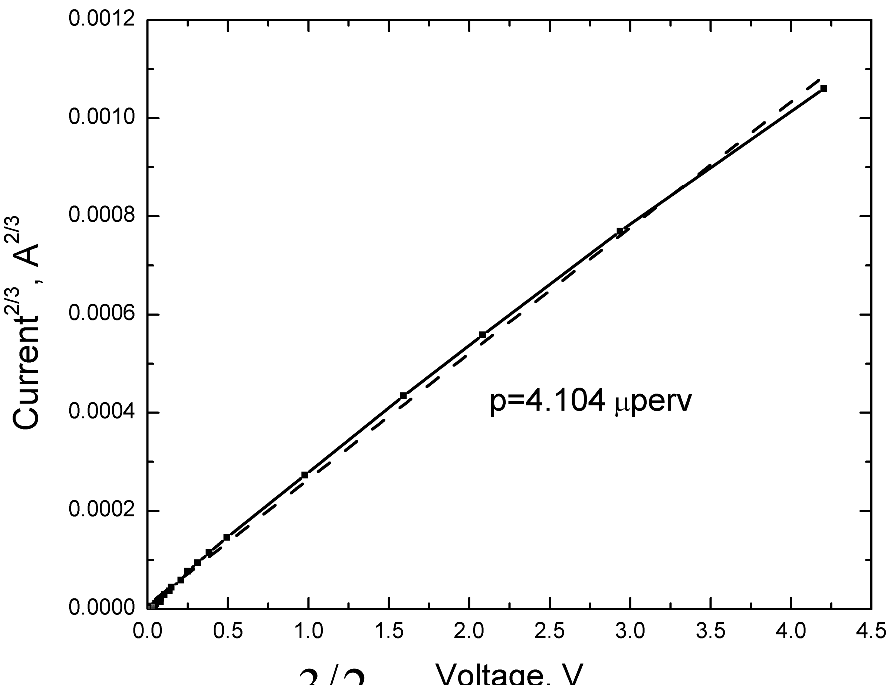
Low-energy photocathode electron beam

A. Shornikov, C. Krantz

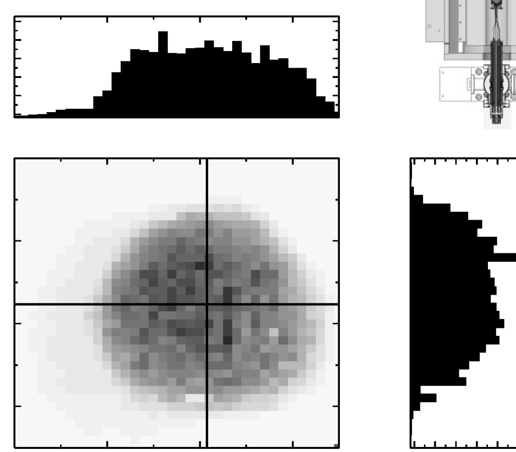


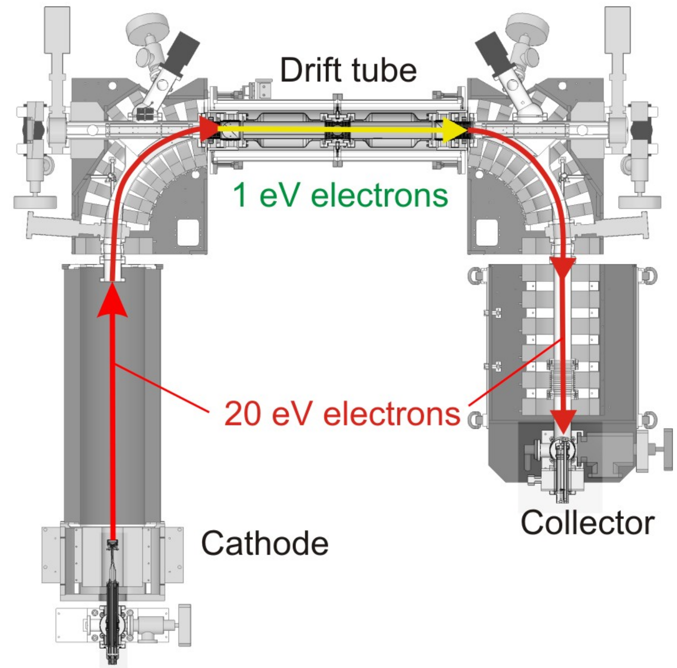
Tests at TSR electron target

Deceleration of low-current photocathode beams



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

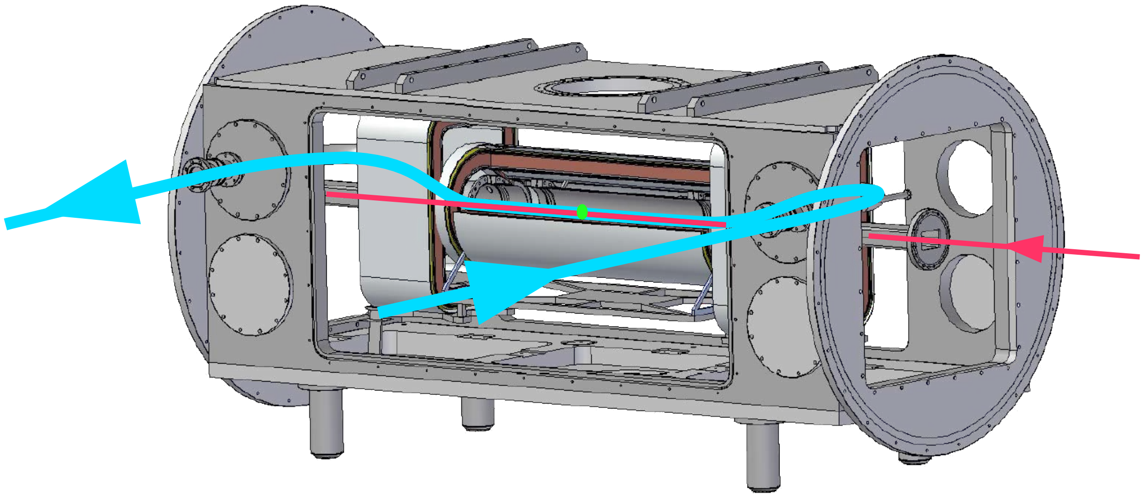




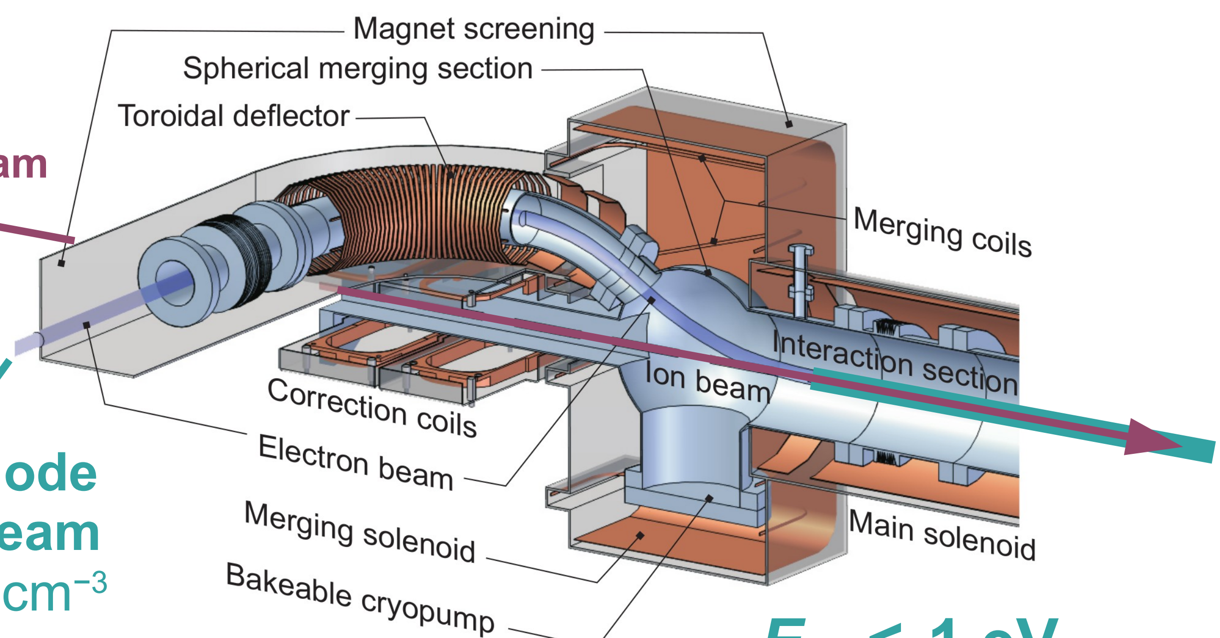
Beam profiles

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

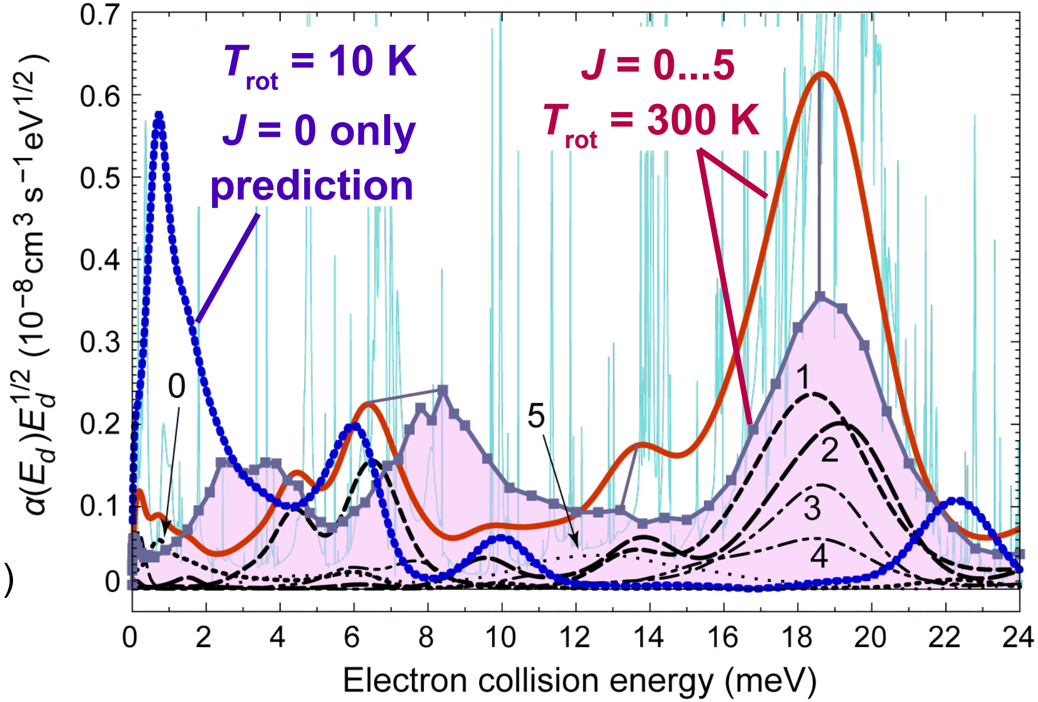
$E_{kin} \lesssim 1$ eV

Outlook to experiments at CSR

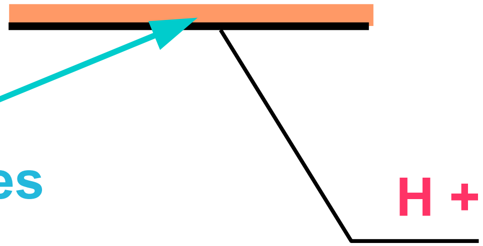
Rotational dependence of cross section

TSR result for recombination cross section

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



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



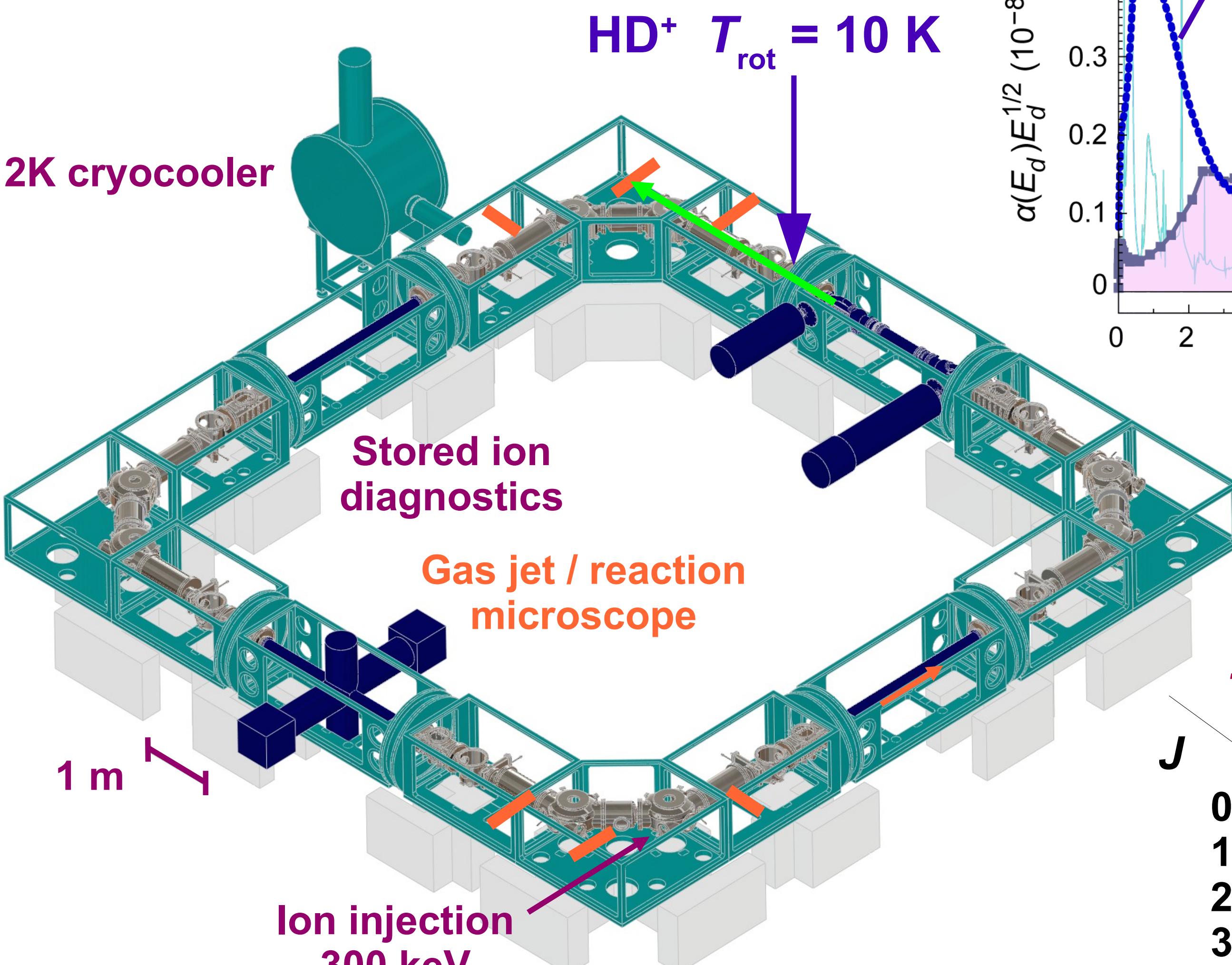
Rovibrational capture resonances

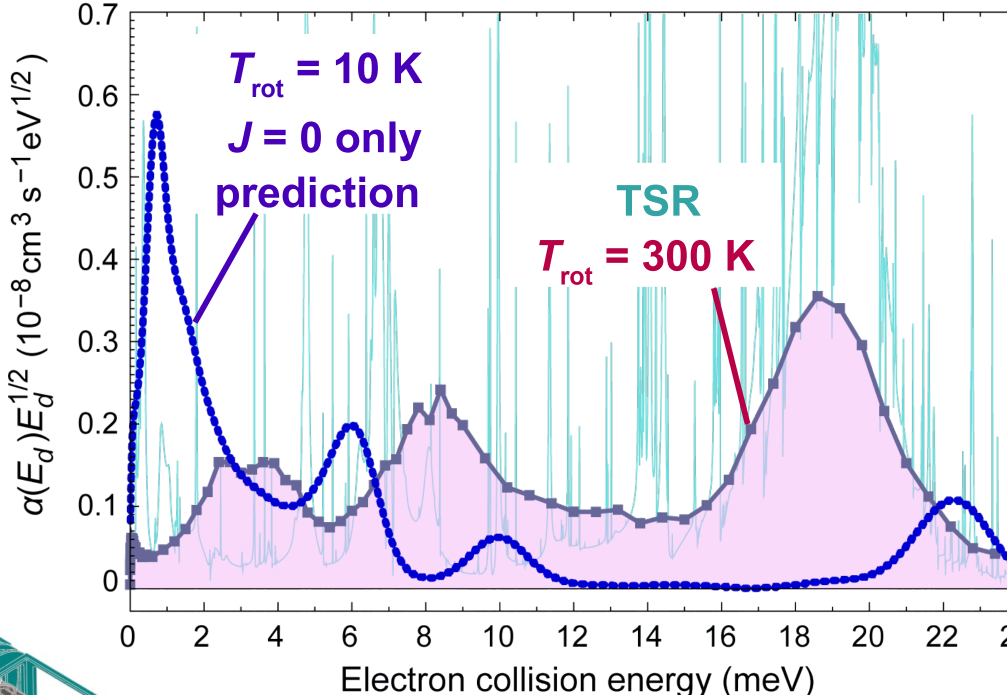
Measured recombination cross section dominated by $J \geq 1$

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

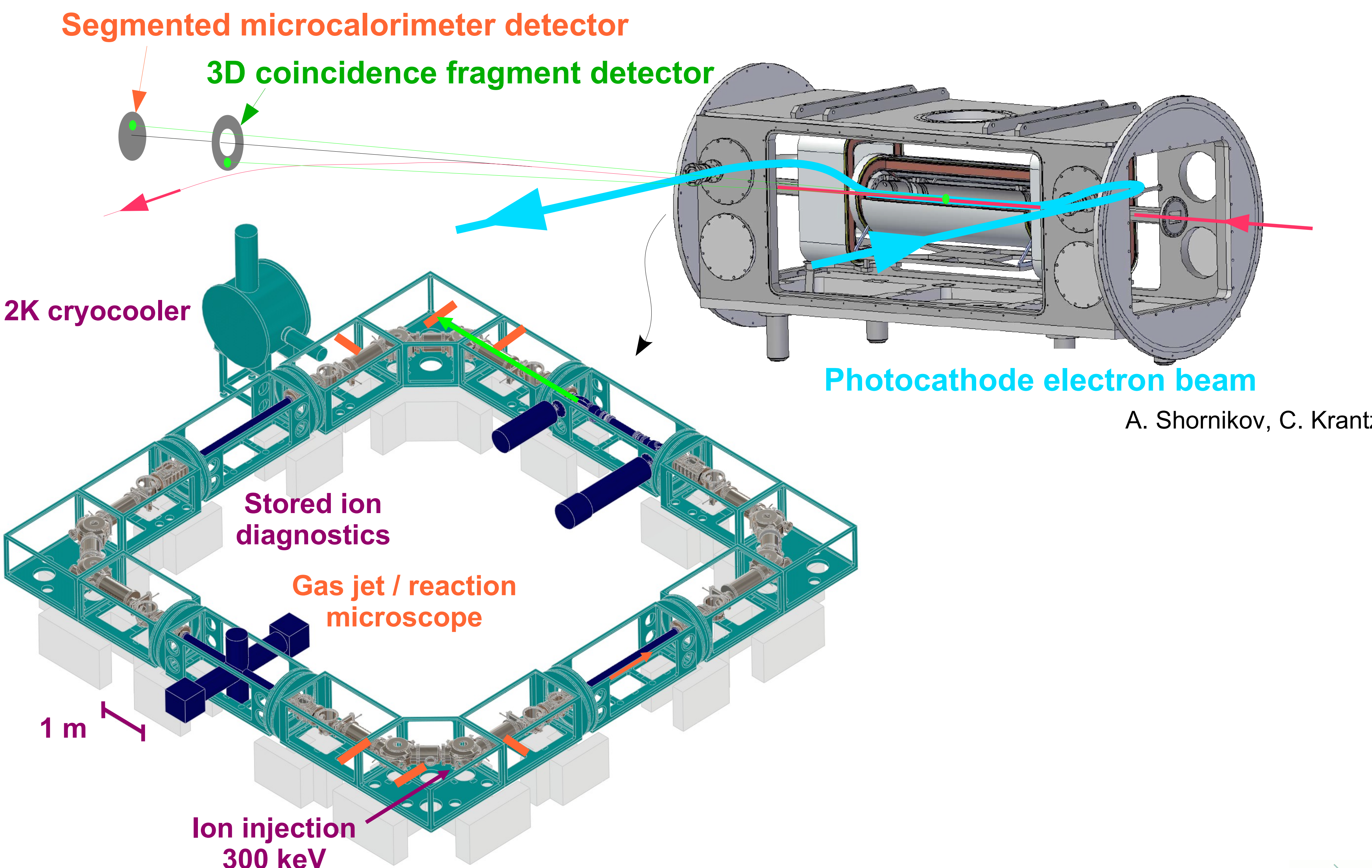




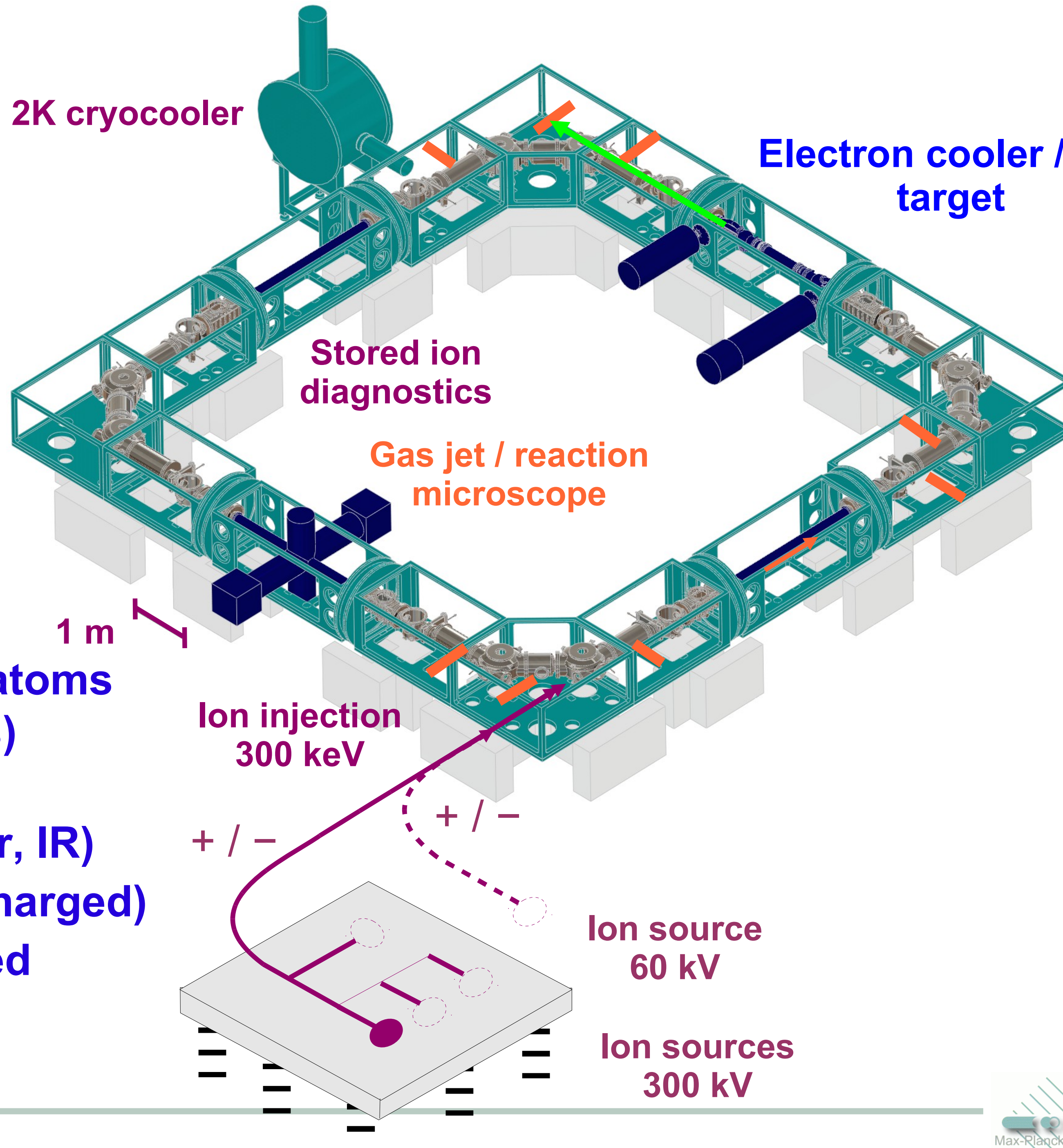
Rydberg capture resonances at low rotation

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



Outlook to experiments at CSR



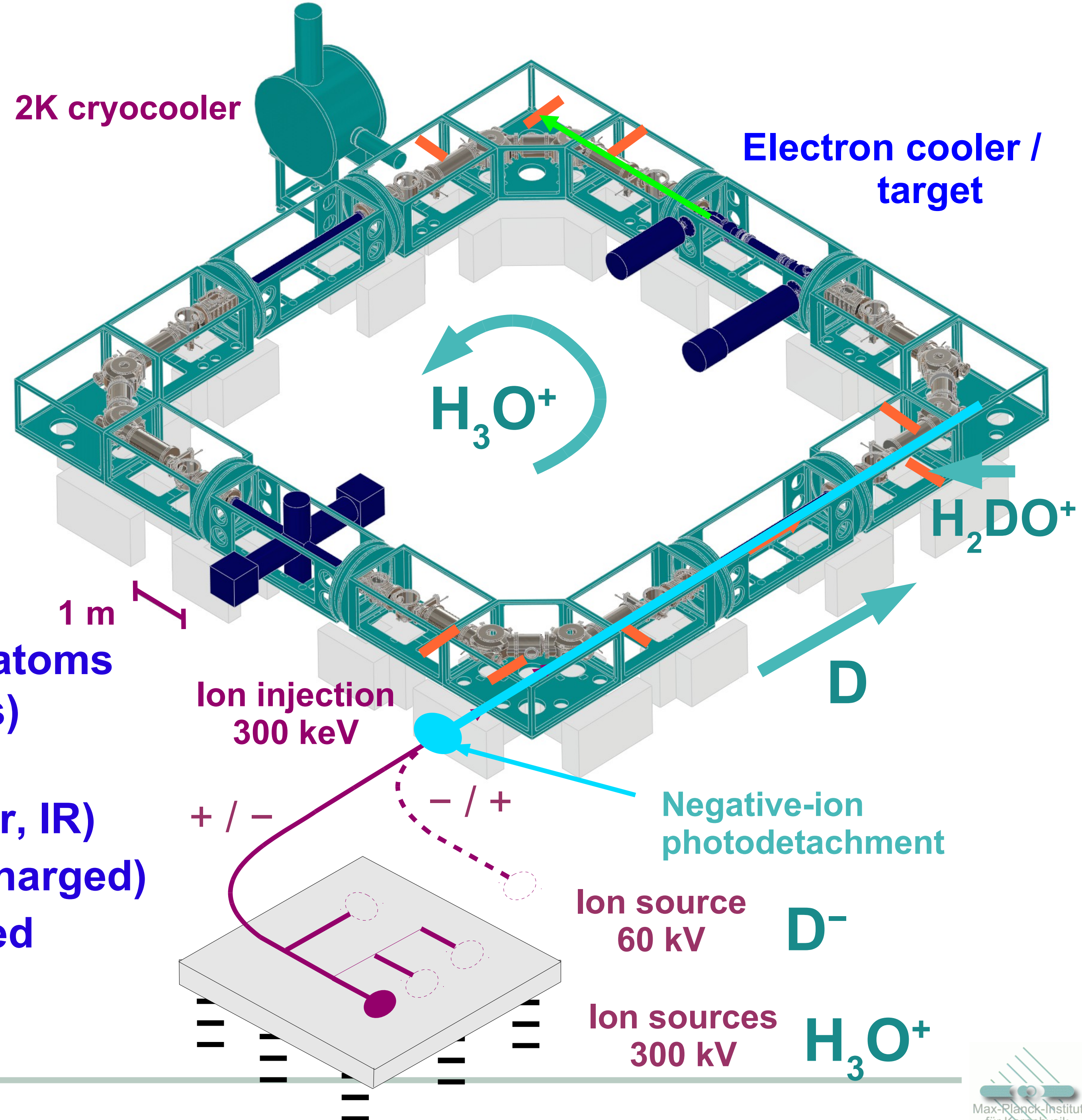
- Stored ion beams at 10 K internal temperature
- Organic molecules, heavy atoms (300 keV for all masses)
- Rotationally resolved ion spectroscopy (laser, IR)
- Negative ions (also multi-charged)
- Cluster systems, H_2O-loaded

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
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- Negative ions (also multi-charged)
- Cluster systems, H_2O-loaded

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Max-Planck Institute for Nuclear Physics,
Heidelberg, Germany

Stored and Cooled Ions (K. Blaum)

Atomic and molecular quantum dynamics

Atomic and molecular physics

Electron target

Photocathode

A. W.
O. Novotný (**)
H. Buhr (*)
C. Krantz
A. Petrignani (*)
B. Jordon-Thaden (*)
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

Collaborations

Weizmann Institute of Science
Rehovot, Israel

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

Univ. Giessen, Germany

S. Schippers
A. Müller

IAMP

Columbia Univ., NYC

D. Savin
O. Novotný (**)

COLUMBIA UNIVERSITY

Univ. Stockholm

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

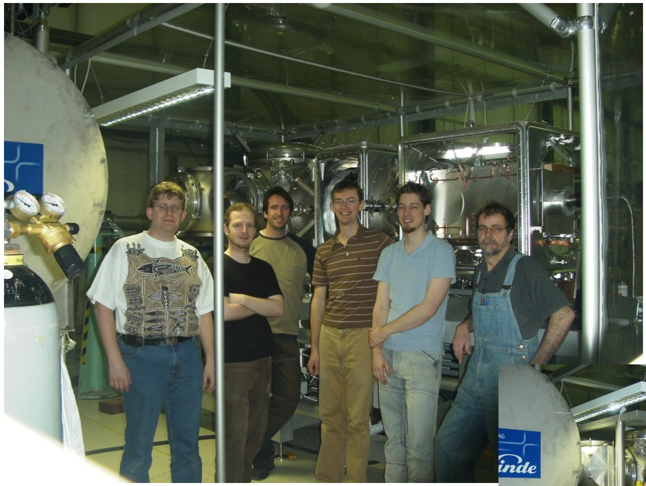
Univ. Louvain-La-Neuve, Belgium

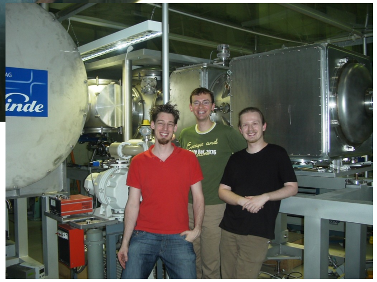
X. Urbain

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

Max-Planck Institute for Nuclear Physics,
Heidelberg, Germany

Stored and Cooled Ions (K. Blaum)

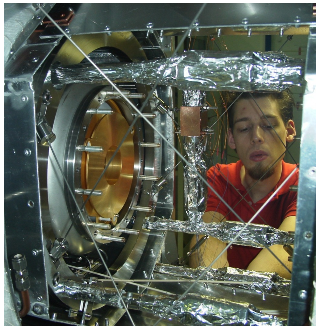




CSR and CTF

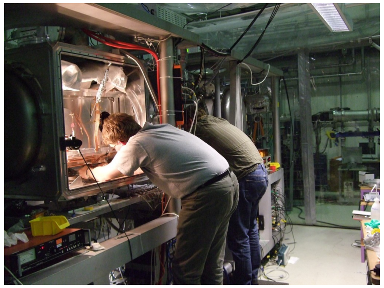
K. Blaum
R. von Hahn
M. Grieser
R. Repnow
M. Froese
M. Lange
D. A. Orlov (*)

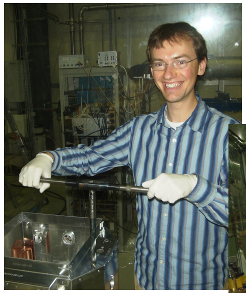
F. Fellenberger
S. Menk
F. Laux
T. Sieber (*)
J. Varju
F. Berg
R. Bastert (*)

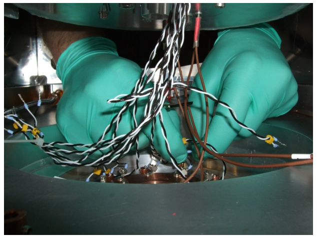


Photocathode electron beams and cooled molecular beams

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







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

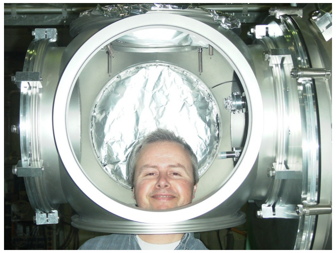
Collaborations

Weizmann Institute of Science
Rehovot, Israel

Y. Toker
O. Heber
M. Rappaport

D. Schwalm
D. Zajfman

X. Urbain — Louvain-la-Neuve, Belgium
A. Terekhov — ISP Novosibirsk, Russia

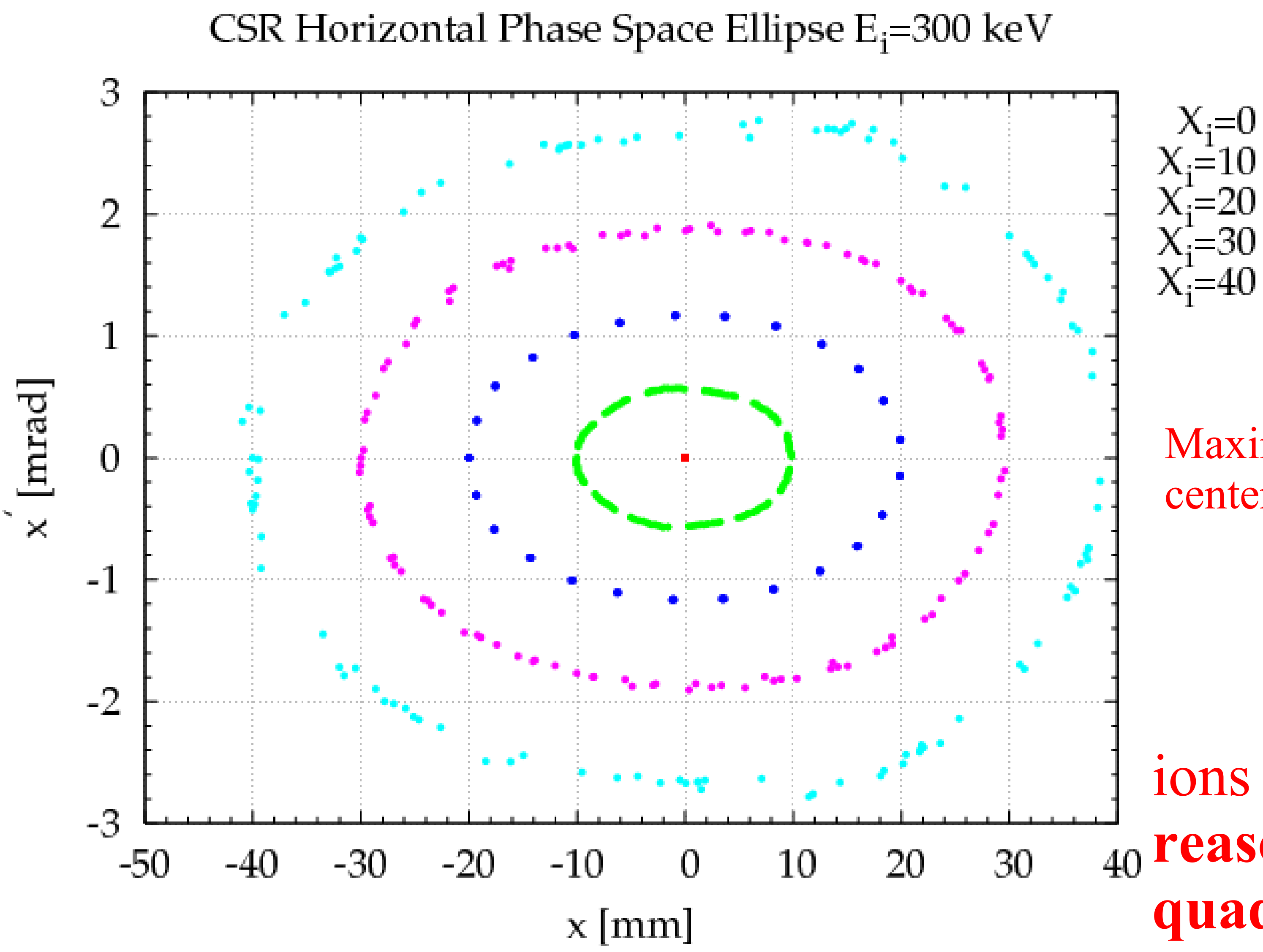


www.mpi-hd.mpg.de/blaum/molecular-qd
storage-rings

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

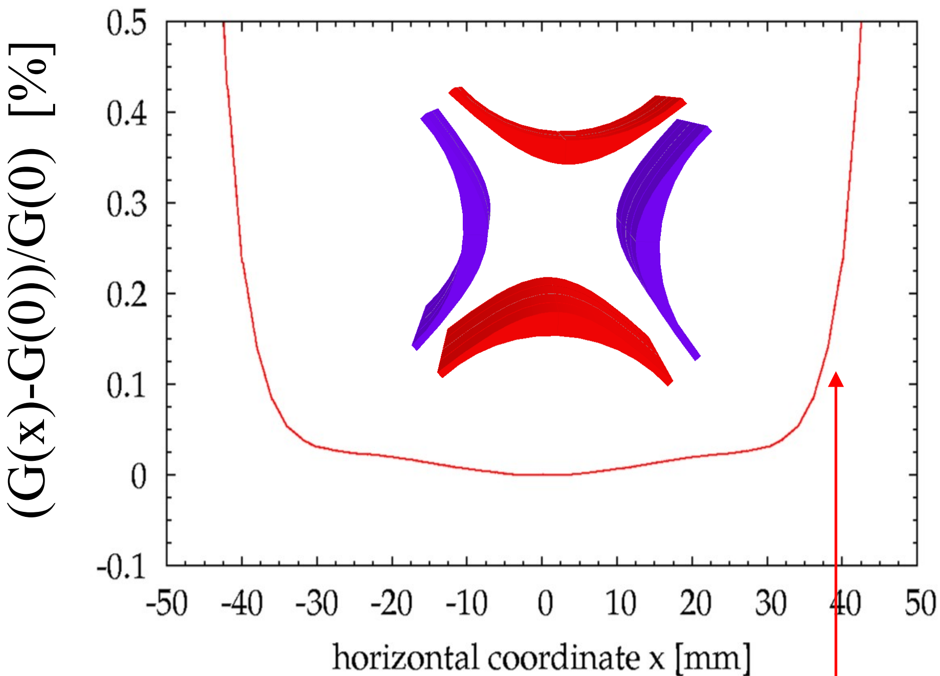
reason: property of the quadrupole

M. Grieser, H. Fadil

Horizontal acceptance and quadrupole gradient

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

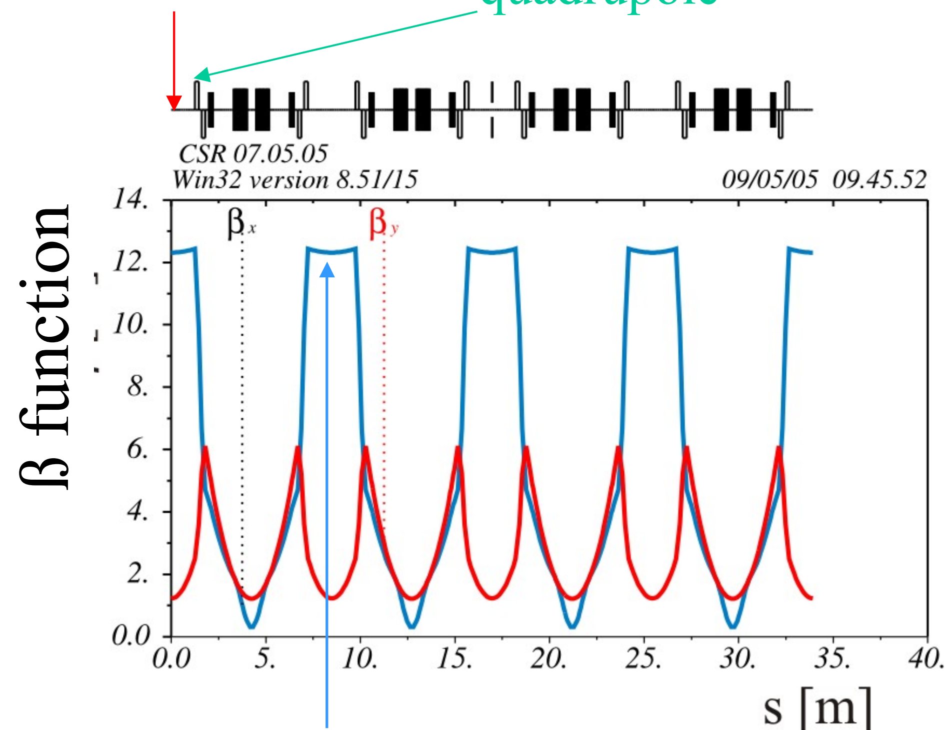
gradient G(x) deviation in quadrupole



x = 4 cm

observation point

quadrupole



horizontal β_x function

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

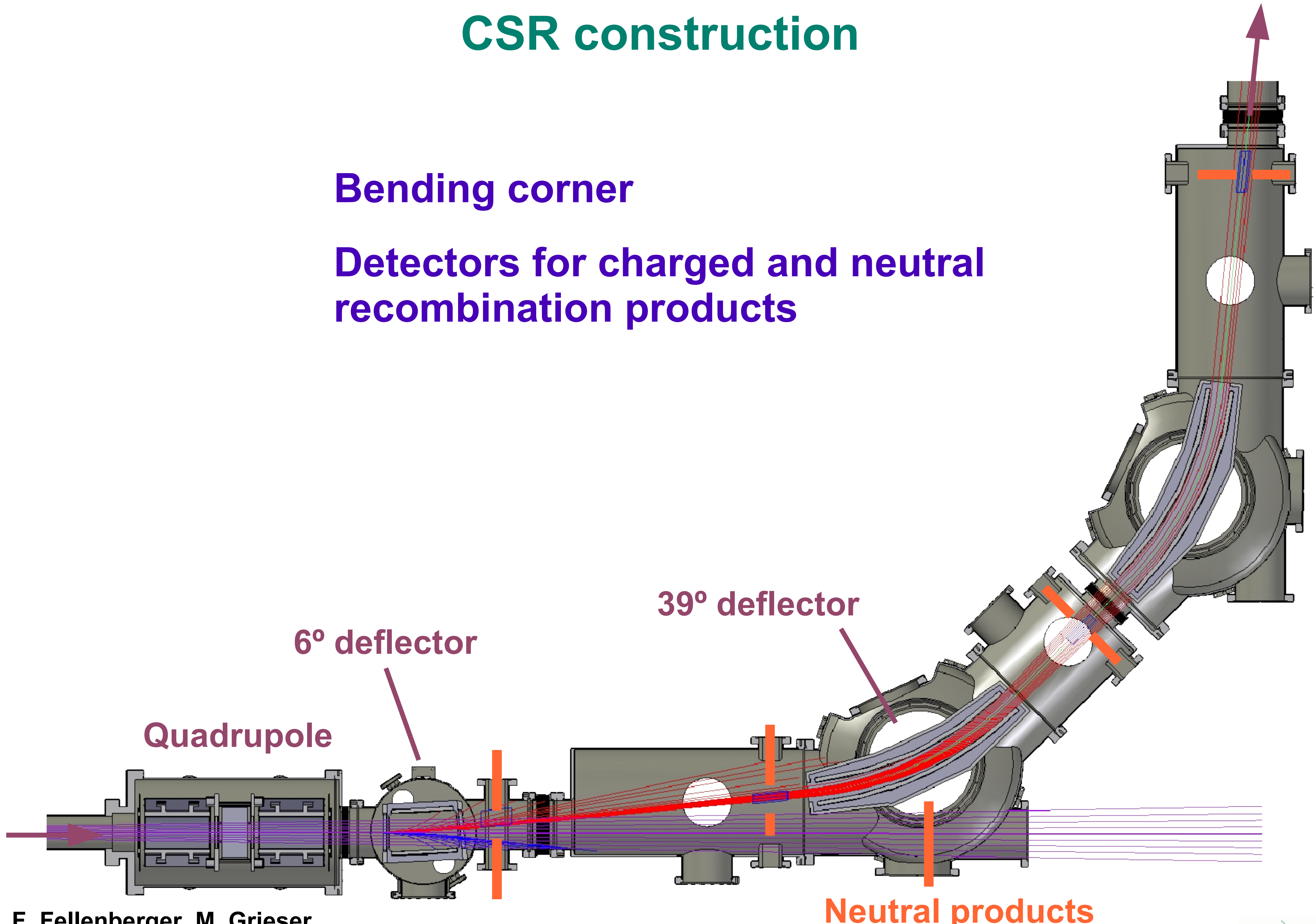
horizontal beam size
centre straight section
≈ beam size in quadrupole

M. Grieser

CSR construction

Bending corner

Detectors for charged and neutral recombination products



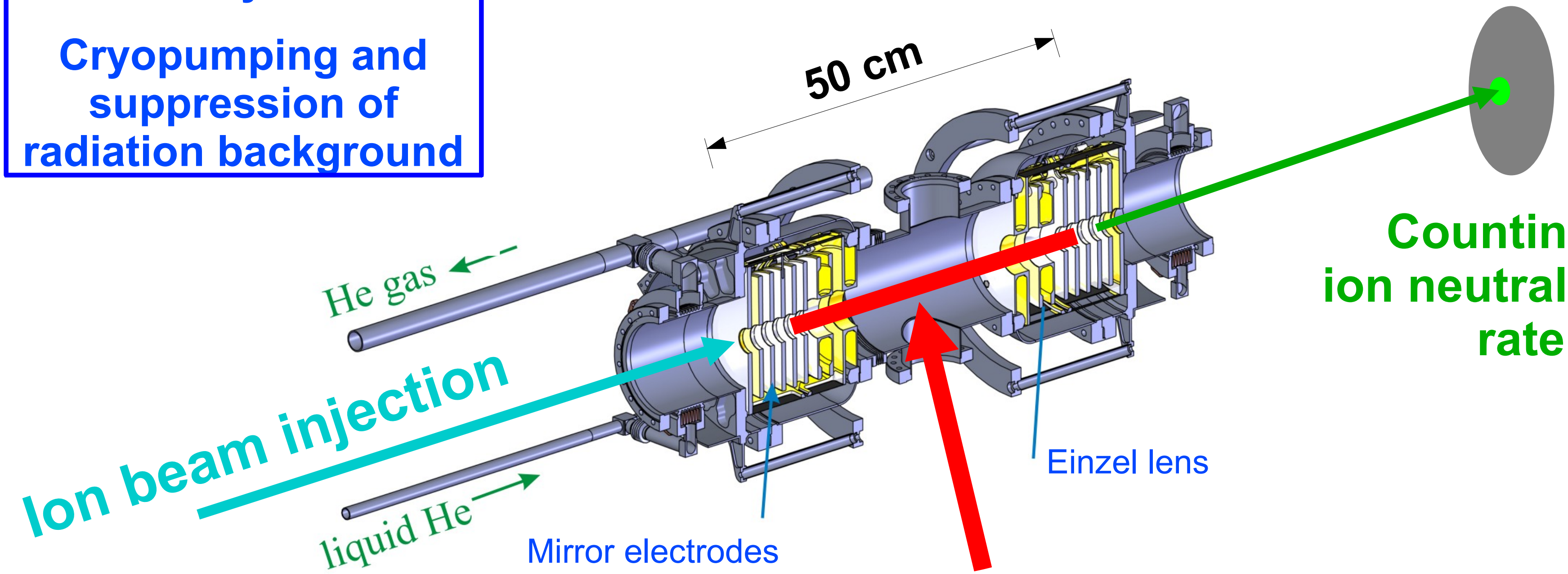
F. Fellenberger, M. Grieser

Cryogenic electrostatic ion storage

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

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

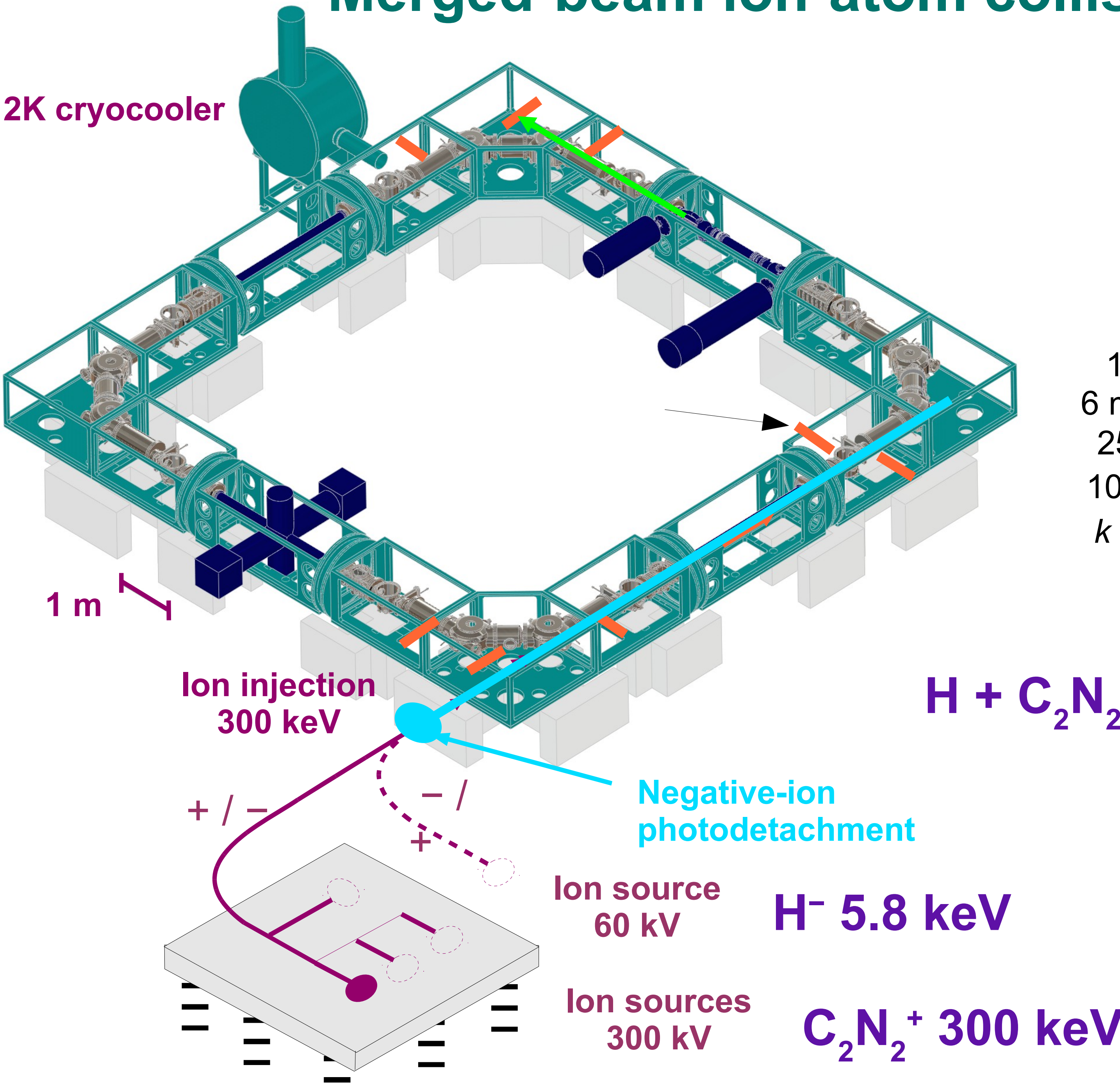
Cryopumping and suppression of radiation background



Storage of ~ 5 keV ion beam

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

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**

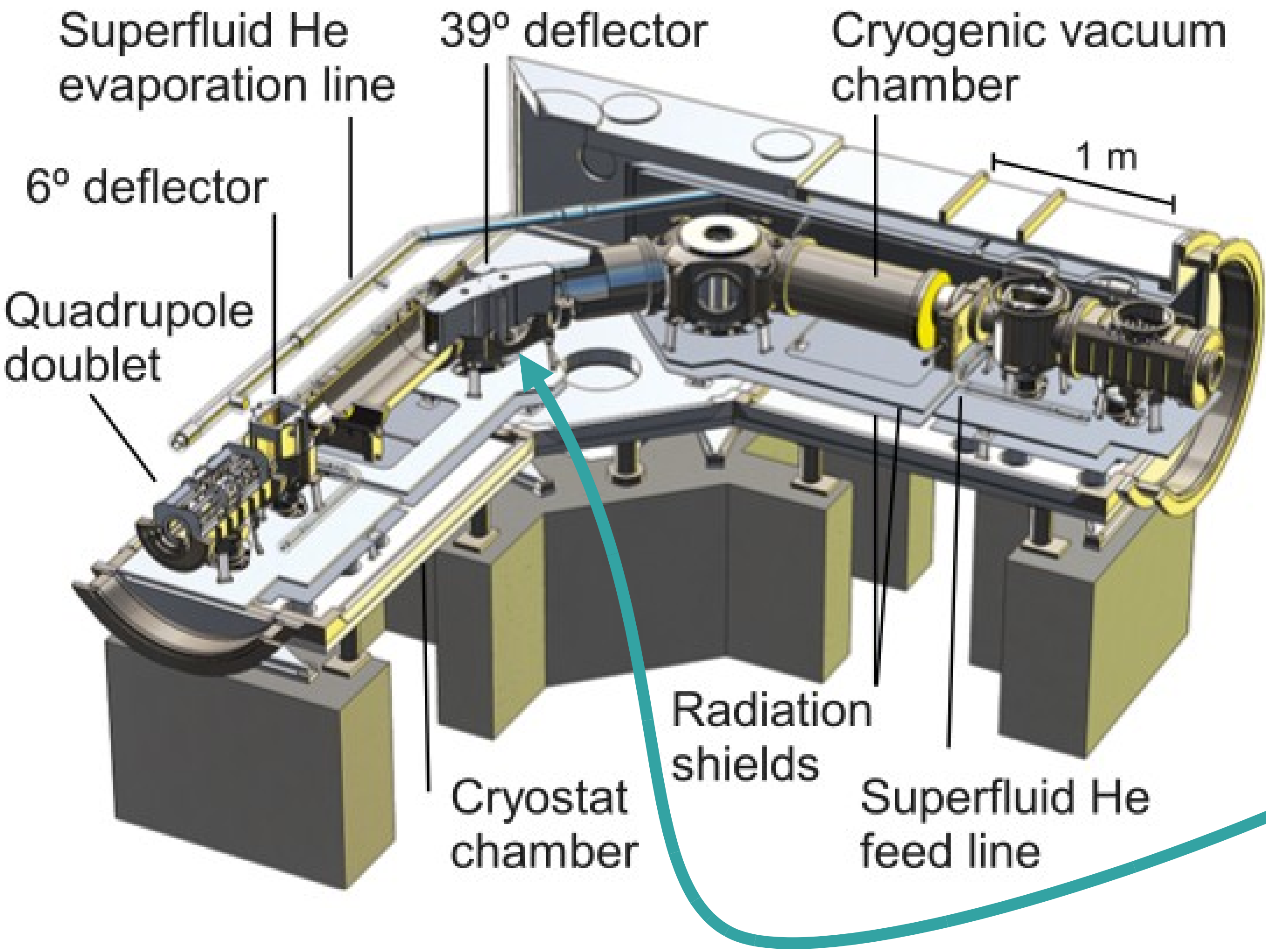
$$H + C_2N_2^+ \rightarrow \begin{cases} N_2 + C_2H^+ \\ CN + HCN^+ \end{cases}$$

Δx ~ 3 mm

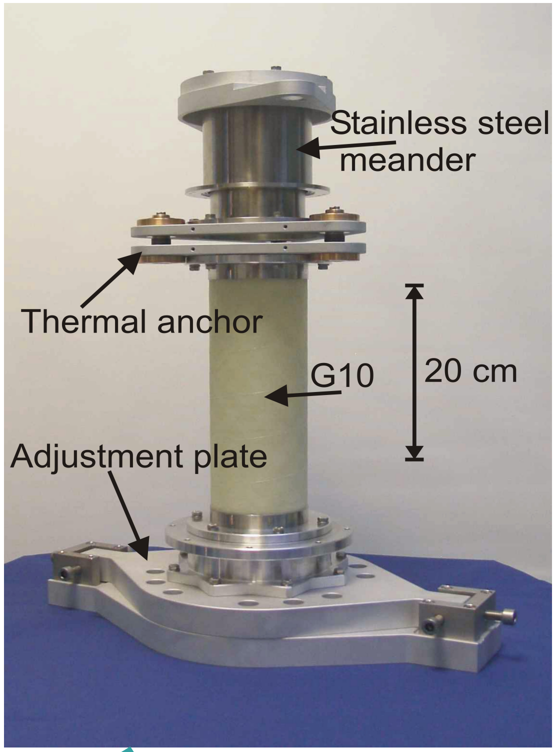
$\Delta E/E = 10^{-3}$ → ~3 meV

CSR construction

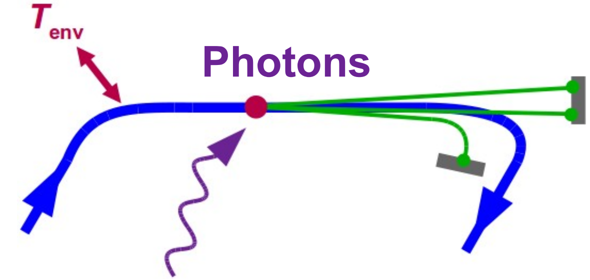
CSR ion optics and deflection cell



Ion optics support



Water cluster photofragmentation

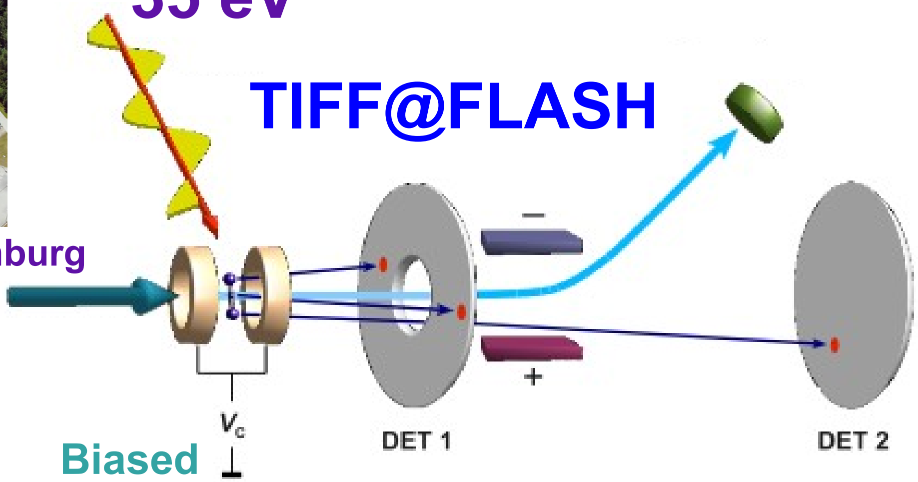


Fragmention following valence ionization

FLASH FEL, DESY, Hamburg

35 eV

TIFF@FLASH

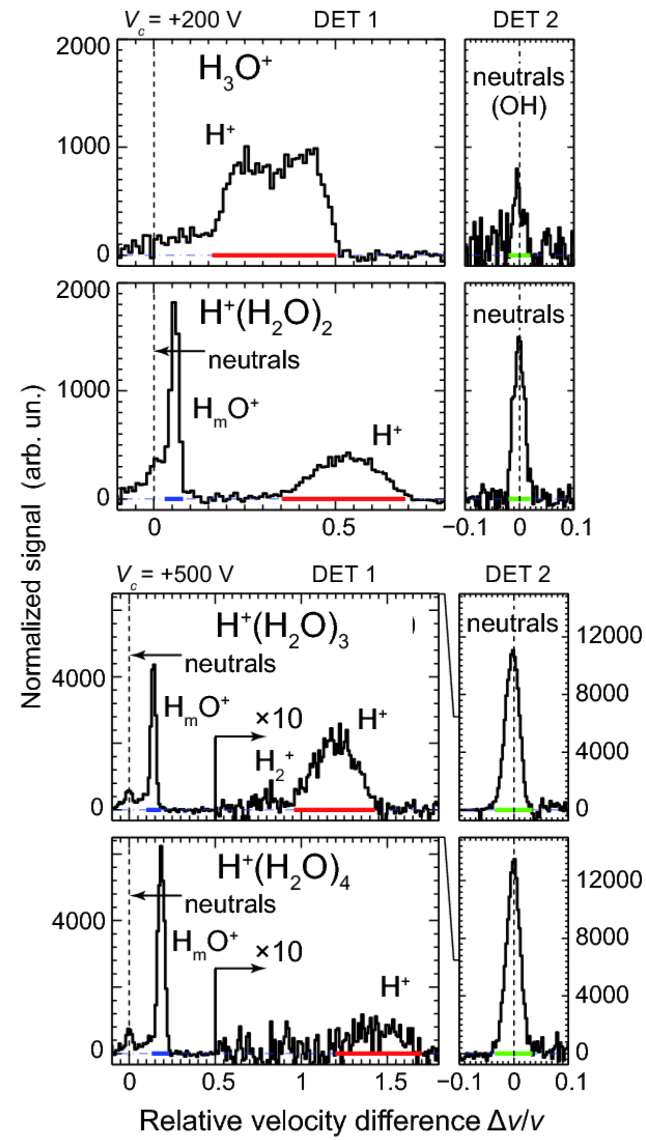


TIFF ion beam
(~4 keV)
pulsing, trapping

Biased interaction zone

Fragment time-of-flight, imaging

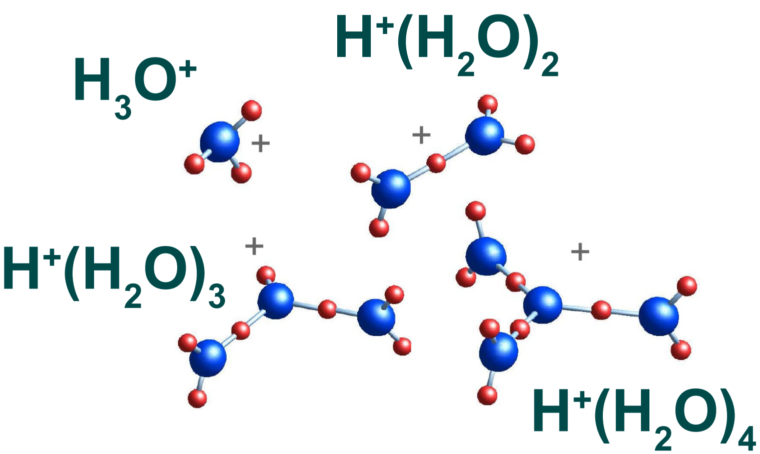
Fragment time-of-flight spectra

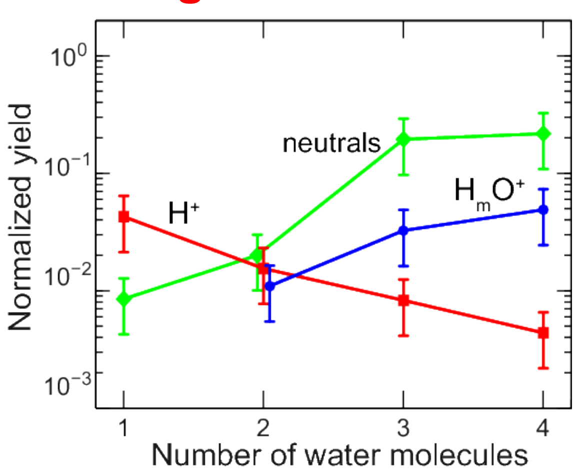


2009: Strong channel of H_2O^+ + H_3O^+ from $H^+(H_2O)_2$

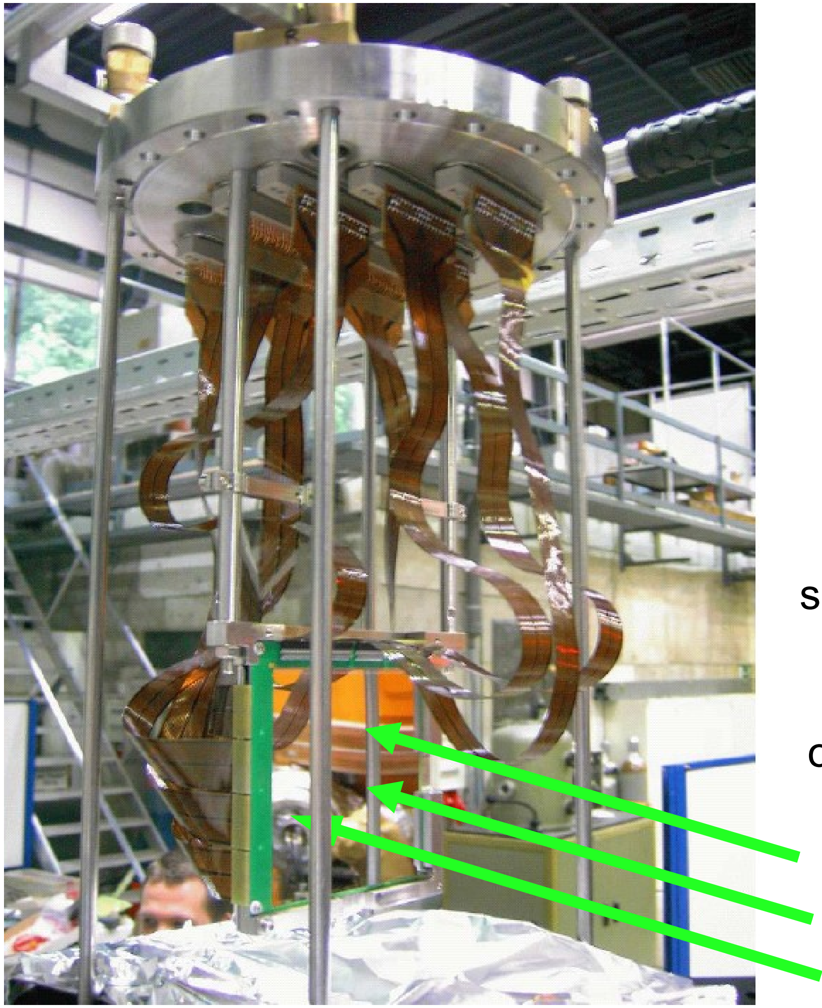
L. Lammich et al., PRL 105, 253003 (2010)

2010: Strong suppression of proton fragments for n > 2



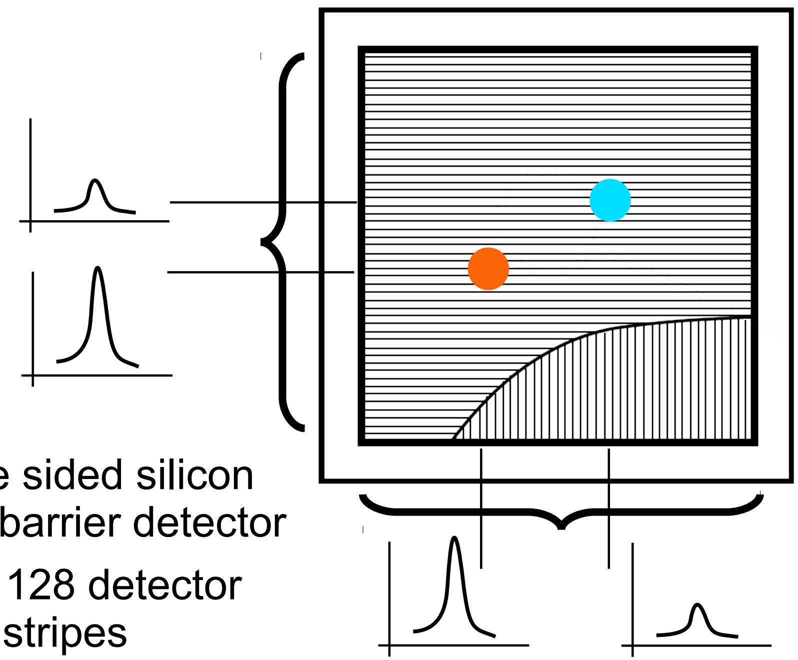


Multistrip silicon detector for fast-beam imaging



2008

Energy-sensitive MUlti-strip detector



Double sided silicon surface-barrier detector

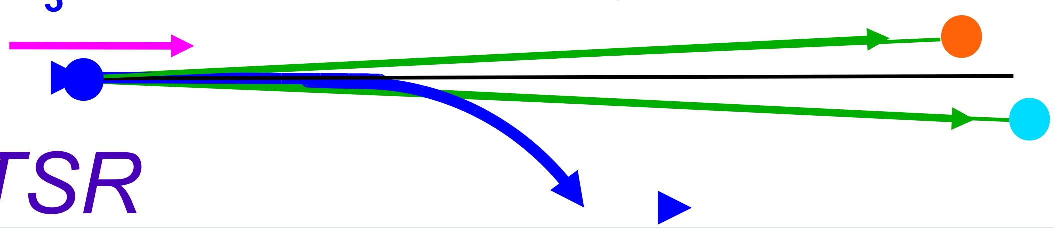
128 x 128 detector stripes on 100 x 100 mm area

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*

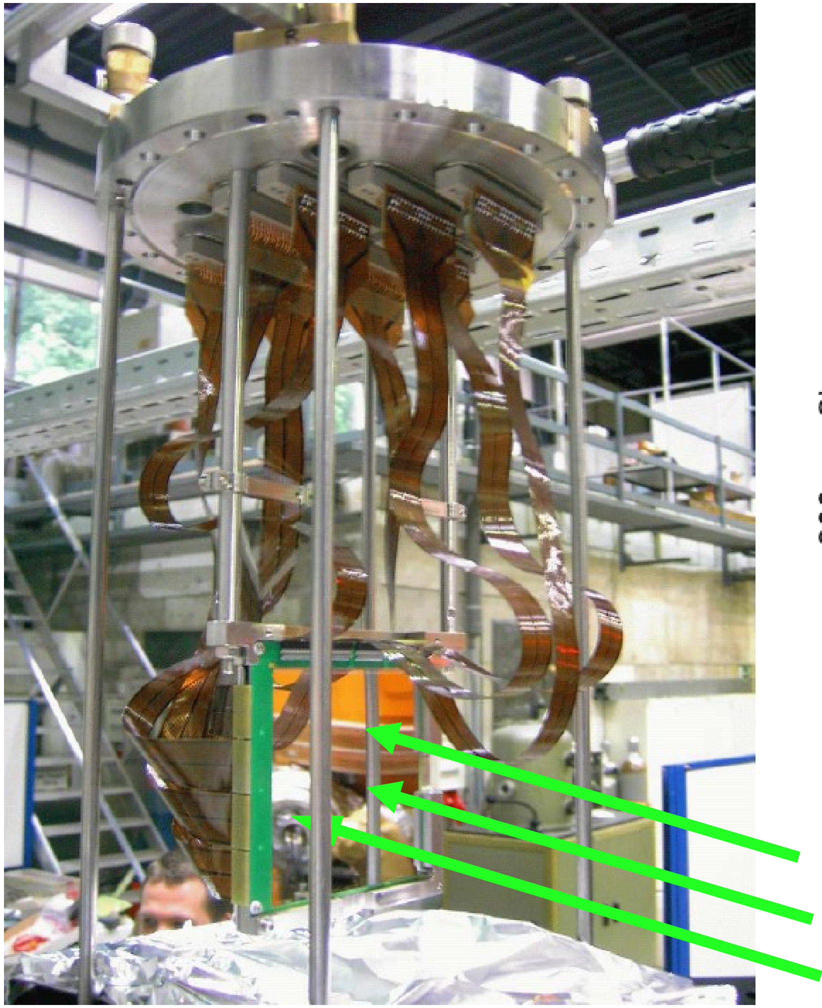


TSR

EMU imaging system @ TSR

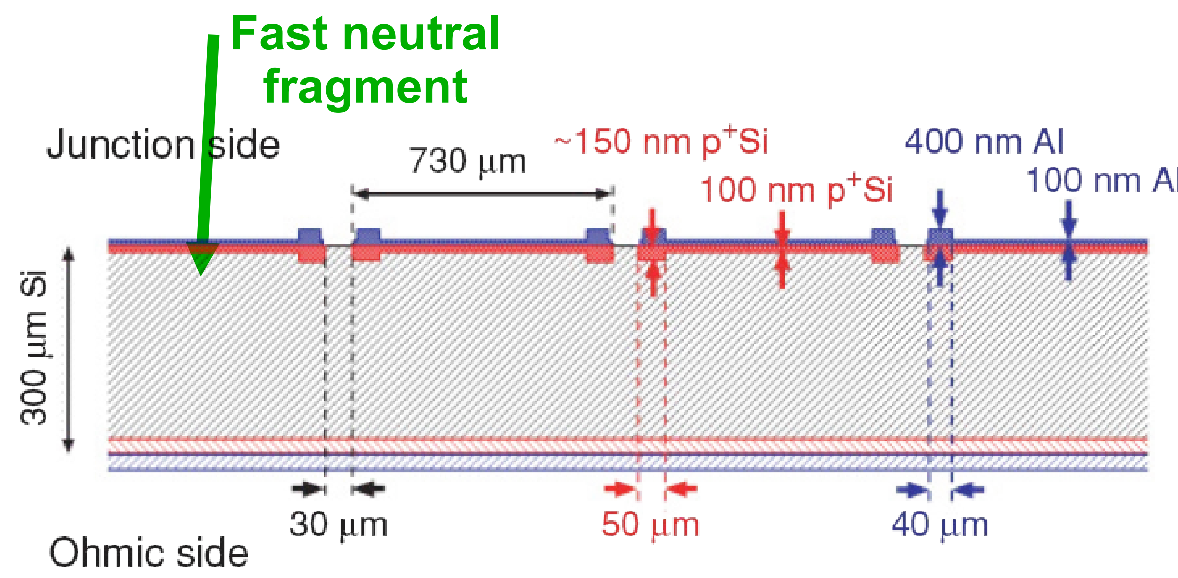
H. Buhr et al., Phys. Rev. A 81, 062702 (2010)
MPIK, Heidelberg + Weizmann Institute, Rehovot

Multistrip silicon detector for fast-beam imaging



2008

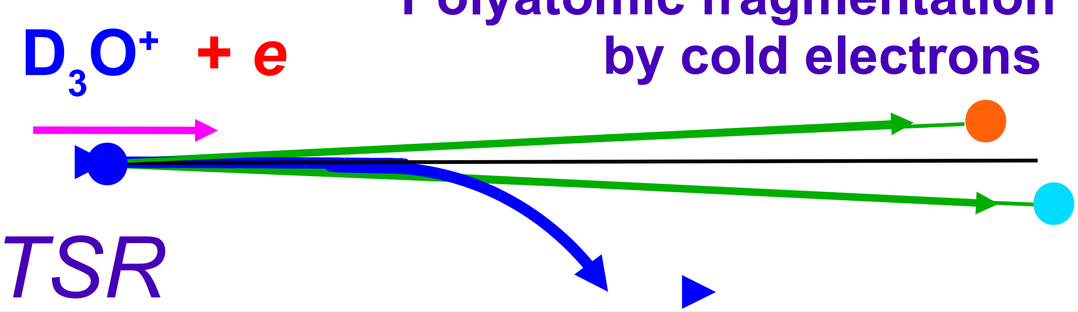
Energy-sensitive MUlti-strip detector



Energy readout →
fragment channel identification

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

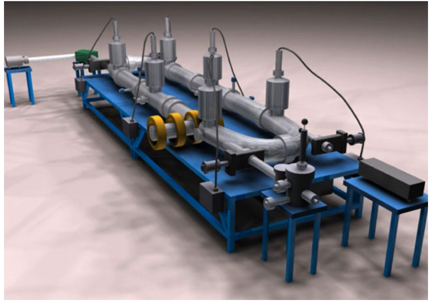
Polyatomic fragmentation by cold electrons



EMU imaging system @ TSR

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

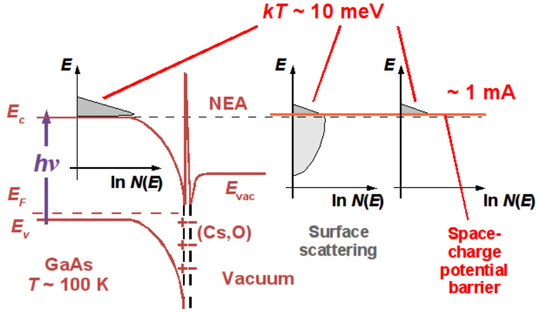
Summary



Storage-rings as tools for molecular physics

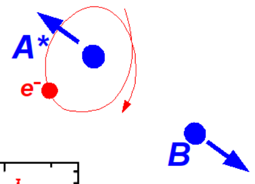
Electron-induced chemistry:

- photocathode electron beam
  10 K, $10^6 \ldots 10^7$ cm^{-3}
- electron cooling of slow ion beams



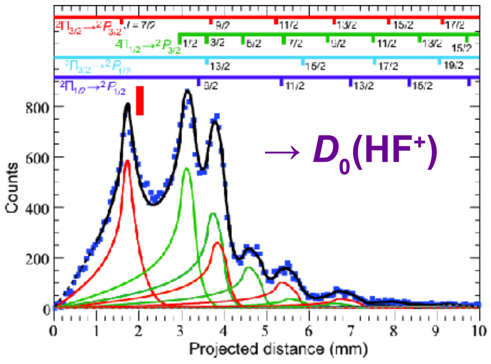
Feshbach electron capture resonances

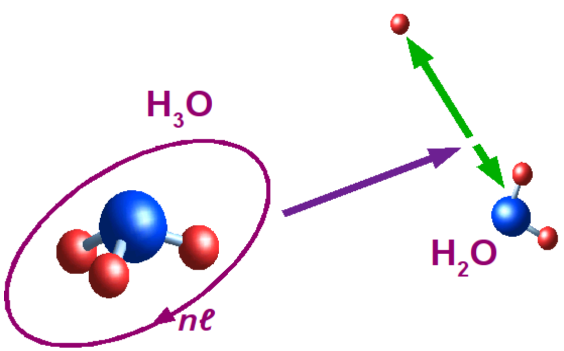
exciting molecular vibration
and rotation – 1 meV energy resolution

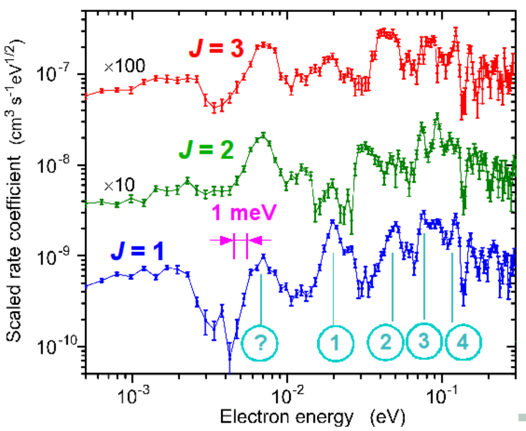


Fragment spectroscopy: molecular

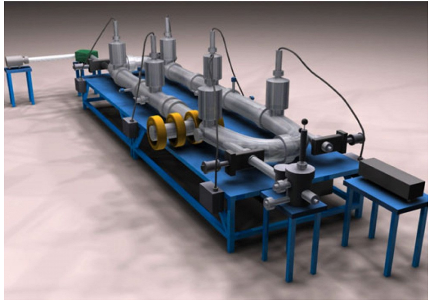
binding energies, reaction channels







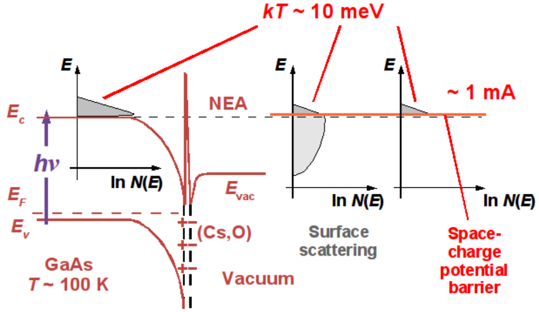
Summary



Storage-rings as tools for molecular physics

Electron-induced chemistry:

- photocathode electron beam
  10 K, $10^6 ... 10^7$ cm^{-3}
- electron cooling of slow ion beams



Cryogenic electrostatic storage ring CSR