MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

The Cryogenic Storage Ring CSR:

Present Status and Outlook

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Overview

- The CSR Project
- Electron Target
- Experimental Perspectives

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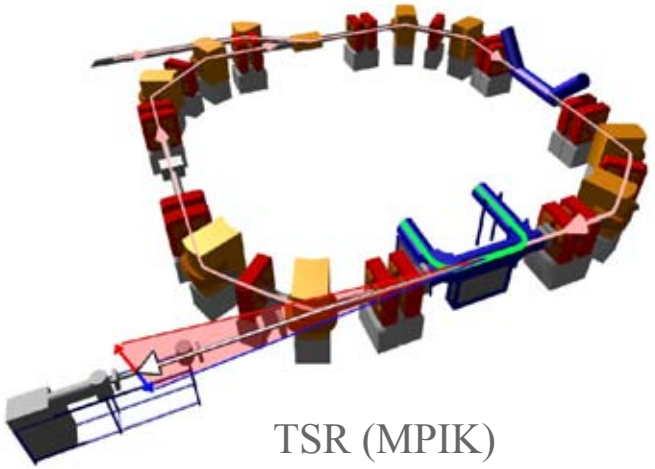
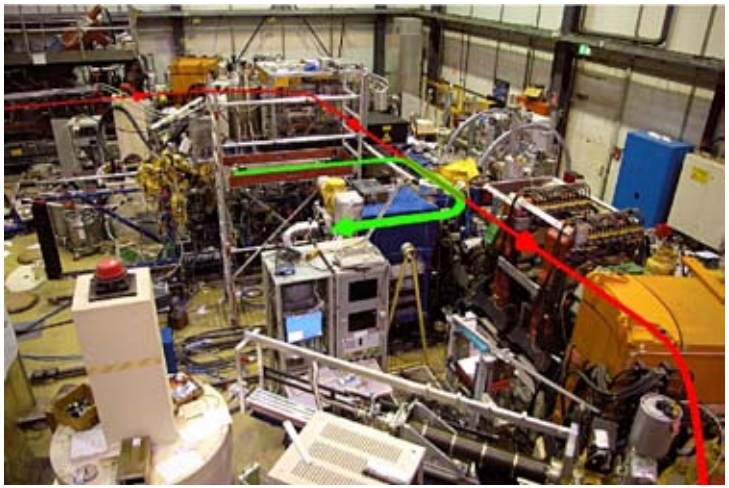
- Electron Target
- Experimental Perspectives

The CSR Project

- Today: Electron cooler storage rings



TSR (MPIK)



- Maximum beam rigidity: $r\,B_{max}$
  for TSR: ≈ 1.4 Tm
- Maximum velocity of stored beam:

$$v_{max} = \frac{q}{M}\, r\, B_{max}$$

- There is a **practical** maximum M
  Ion loss rate by residual gas collisions exceeds electron cooling rate ...

The CSR Project

- Why electrostatic storage rings?
  - Use static electric field to deflect ions:
    Deflecting force becomes velocity-independent.
    Momentum selective ↔ energy selective.

$$q\,v\,B \leftrightarrow q\,E$$

  - Higher velocities for very large M:
    Longer storage times

$$v_{max} \sim M^{-1} \quad \text{vs.} \quad v_{max} \sim M^{-1/2}$$

  - Economic
    Power consumption!
  - "Easy" to operate both at room and cryogenic temperature.

The CSR Project

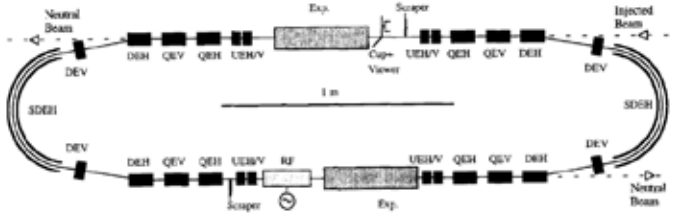
- First electrostatic storage rings

  - ELISA (Aarhus, 1998)
    Racetrack design,
    25 keV/q, room temp.

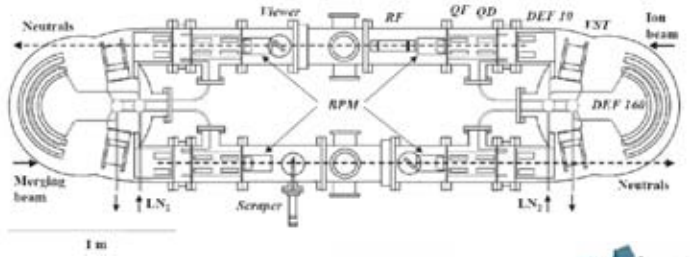
  - TMU Ring (Tokyo, 2004)
    ELISA design,
    77 K (LN_2)
    Electron target

  - DESIREE (Stockholm, *in constr.*)
    Double ring (ion-ion interact.),
    < 20 K,
    25 kV and 100 kV injectors

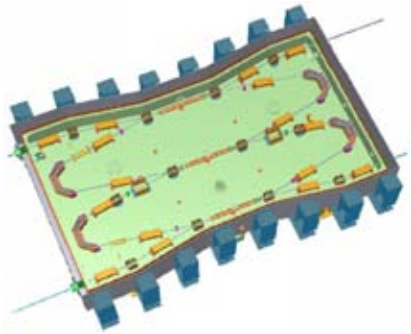
  - CSR (Heidelberg, *in constr.*)
    < 10 K,
    300 keV/q
    electron cooling



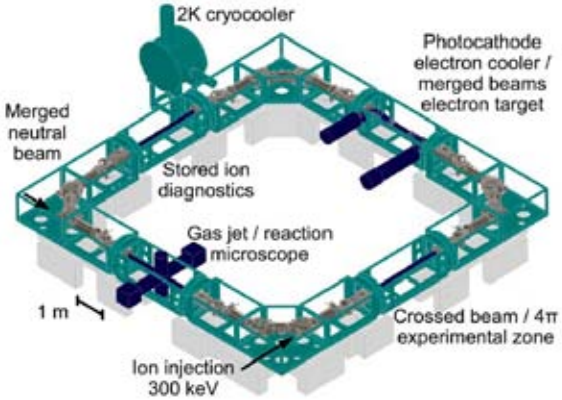
Møller, NIM A 394



Jinno, NIM A, 532



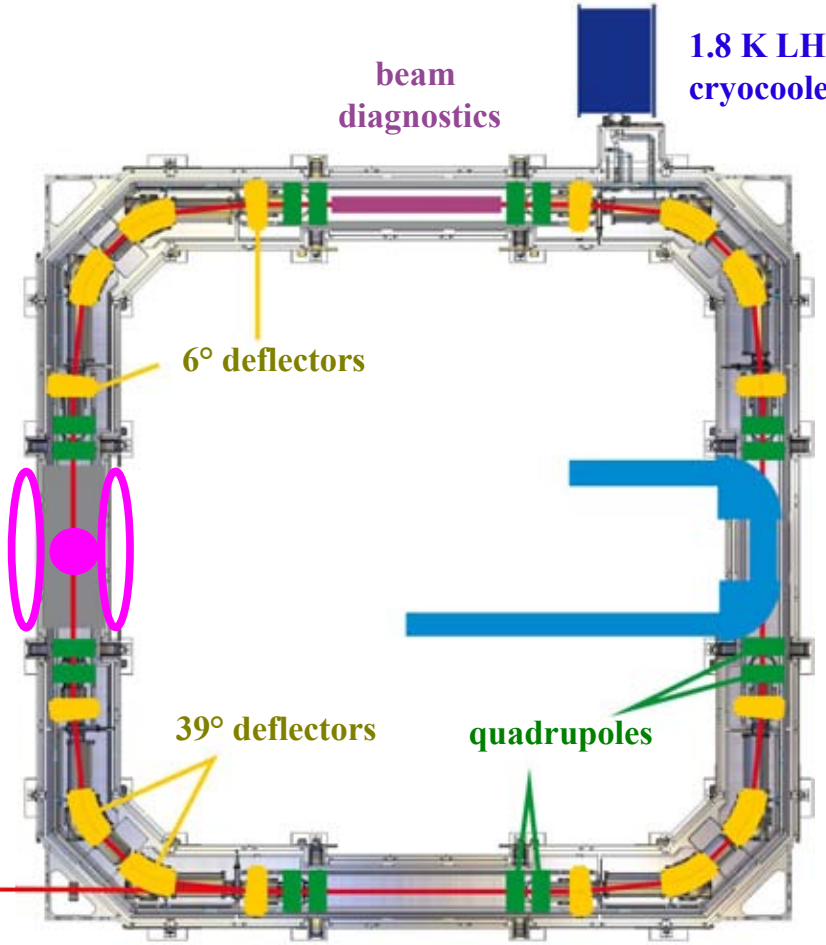
Löfgren, Proc. EPAC06



The CSR Project

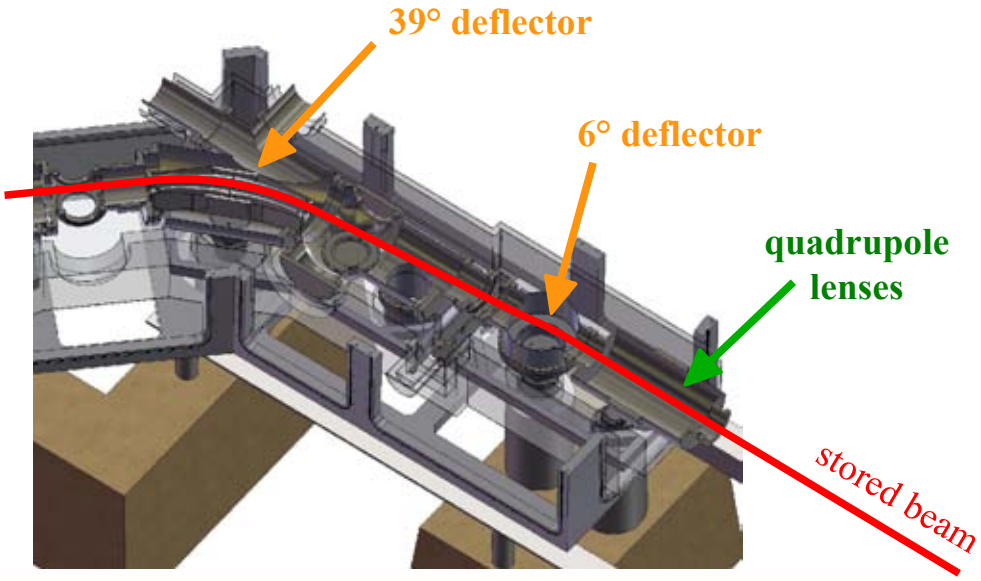
- CSR: a full-featured next generation storage ring

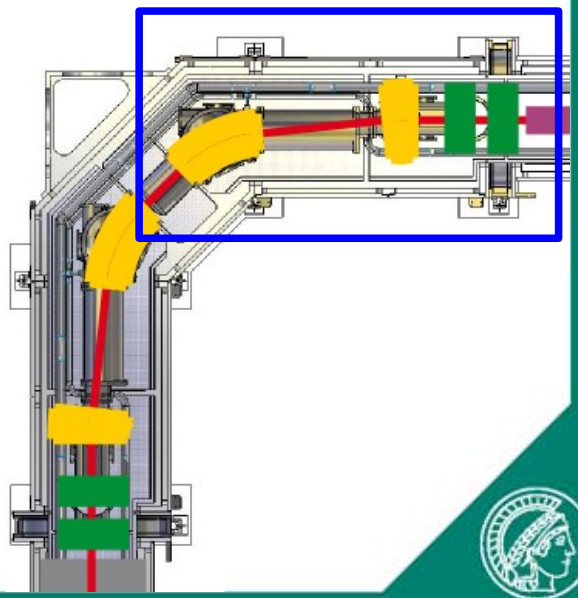
circumference:	35 m
beam energy:	300 keV/q
temperature:	10 … 300 K
res. gas press. (@ < 10 K):	10^{-13} mbar RTE (~ 1000 cm^{-3})
ion masses (for q = 1 e)	
no cooling:	1 … "∞" u
with cooling:	1 … 160 u



The CSR Project

- Electrostatic beam optics
  - 4-fold symmetric storage ring
    All CSR corner sections identical
  - 4 x 2 pairs of **focussing quadrupoles**
  - 4 x 2 **6°-deflector** electrodes (30 kV)
  - 4 x 2 **39°-deflector** electrodes (30 kV)
  - 4 free straight sections (2.6 m each)





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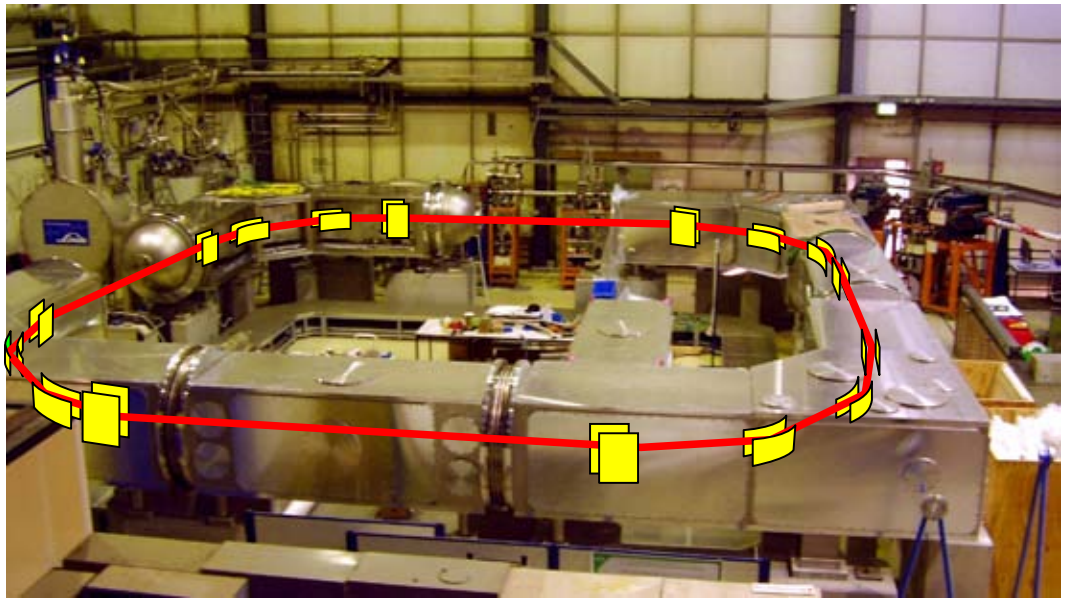
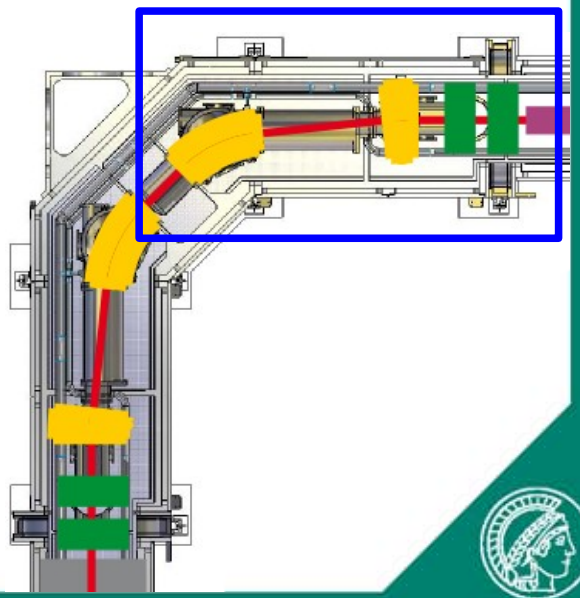
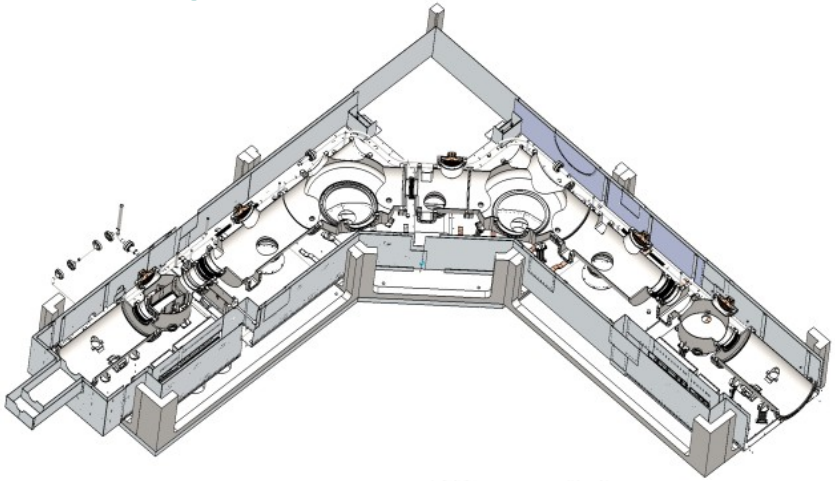
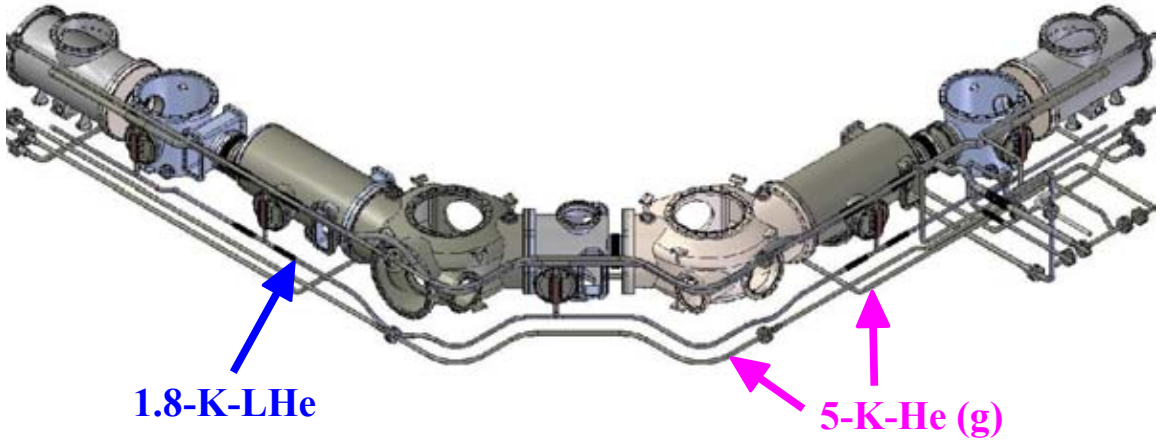


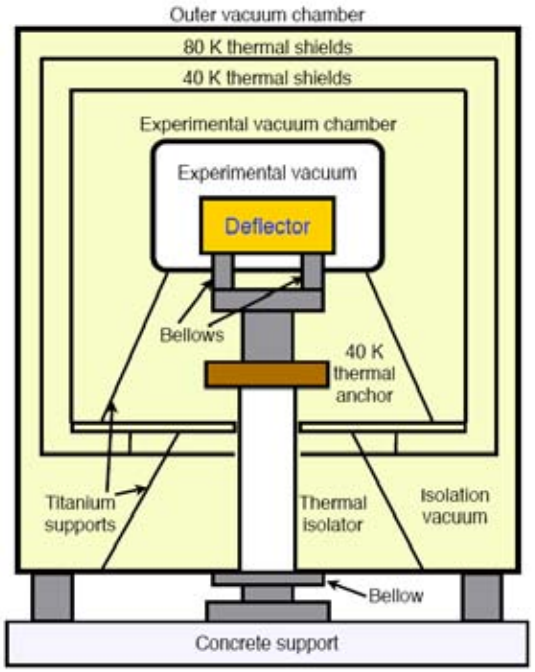


The CSR Project

- Cryogenics
  - Multi-layer cryostat
  - Inner vacuum chamber (≤ 10 K)
    cooled by superfluid He (20 W).
  - 2 radiation shields (40 and 80 K)
    cooled by 5-K He (600 W)
  - Superinsulation
  - Isolation vacuum chamber

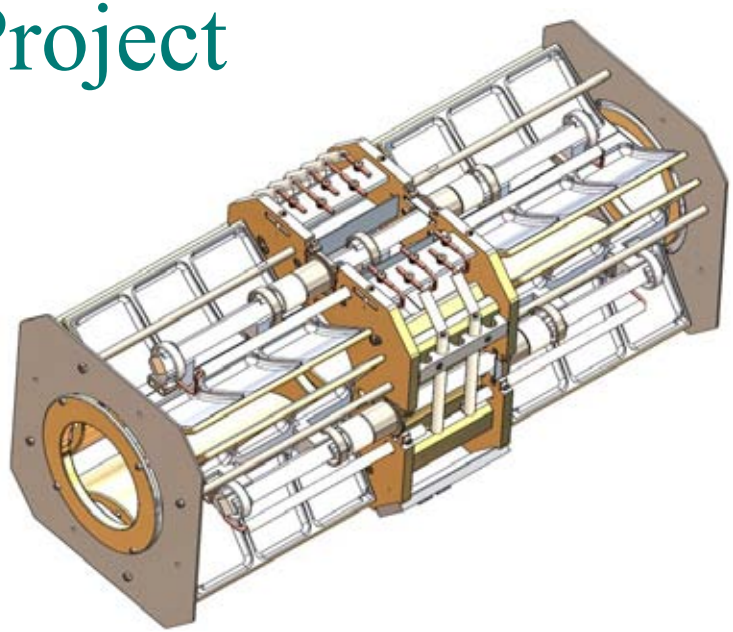


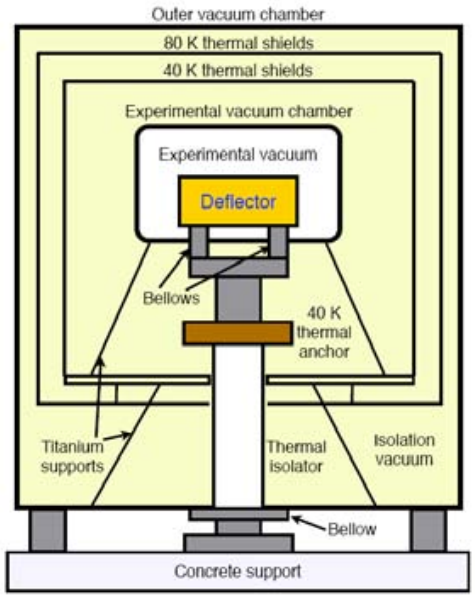


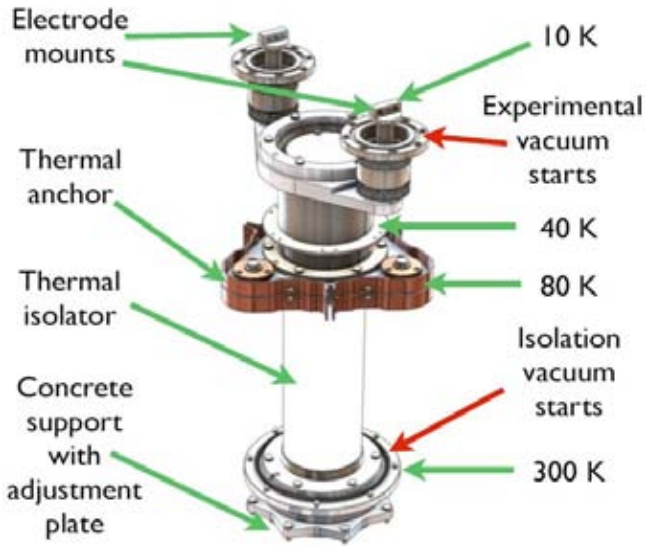


The CSR Project

- Electrostatic beam optics
  - Electrodes thermally anchored to cold chamber walls (≤ 10 K) …
  - … but mechanically decoupled from them.
    (thermal shrinking of beam pipe!)







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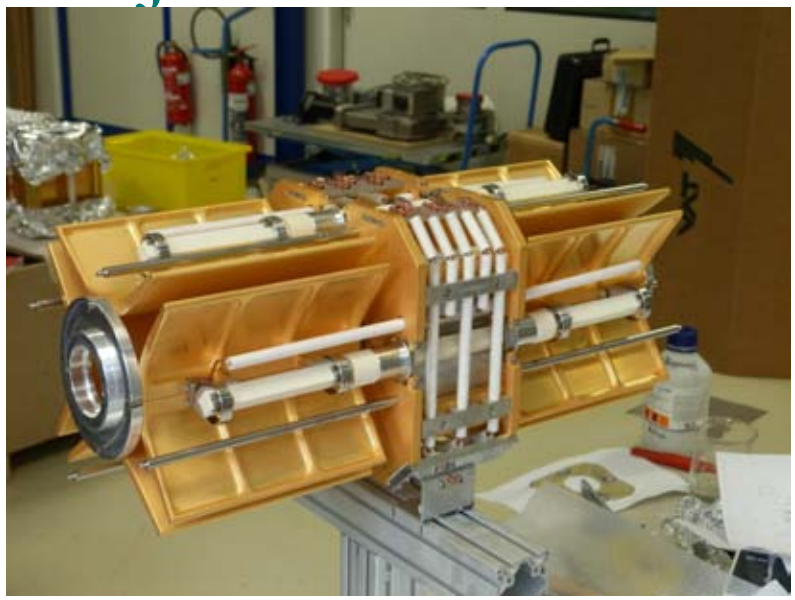
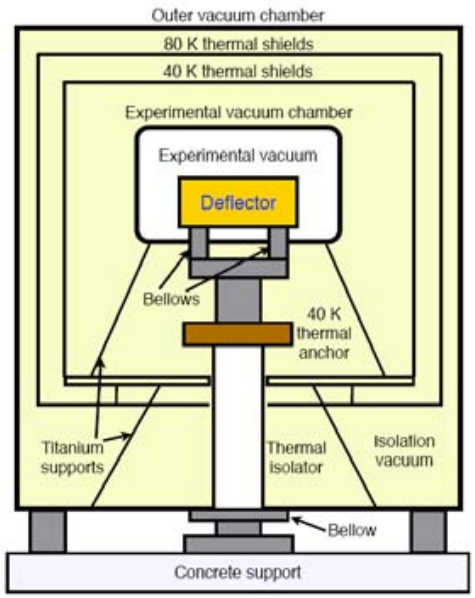
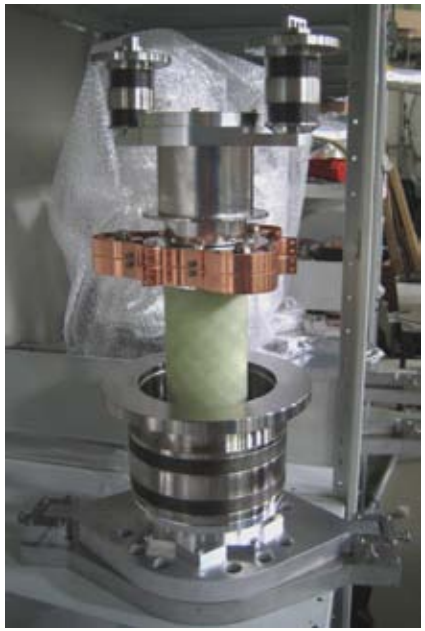
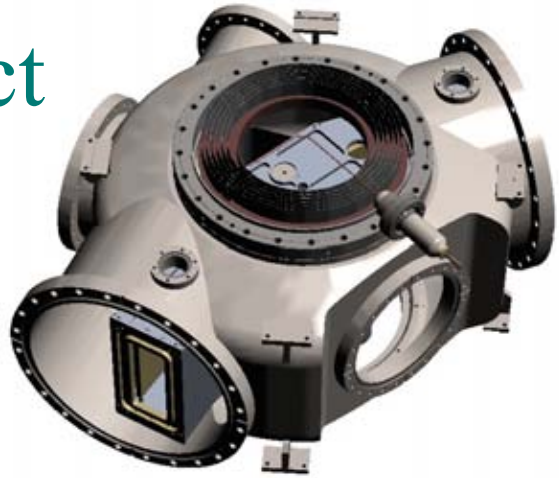




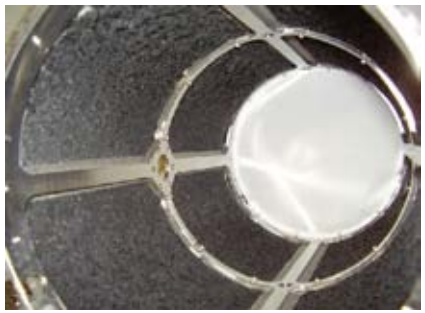


The CSR Project

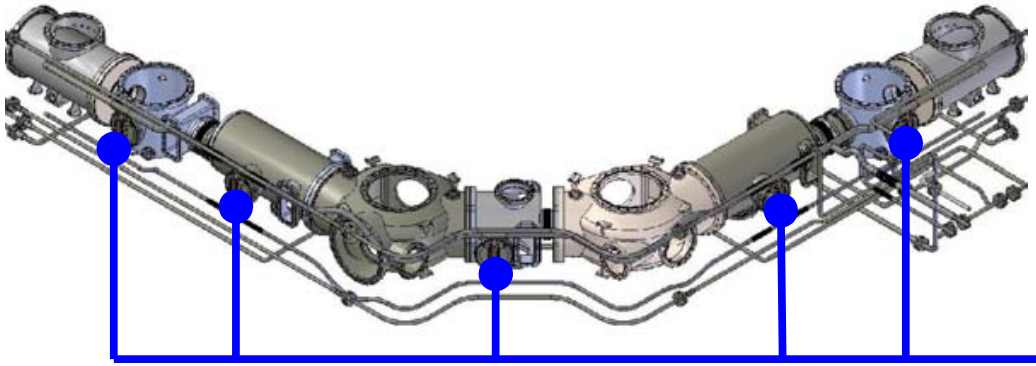
- XHV: Extremely High Vacuum



  - In 300-K-operation: **~ 10^{-11} mbar**
    200°C – 300°C bakeout,
    Ion-getter pumps,
    NEG surfaces,
    bakeable charcoal cryopumps

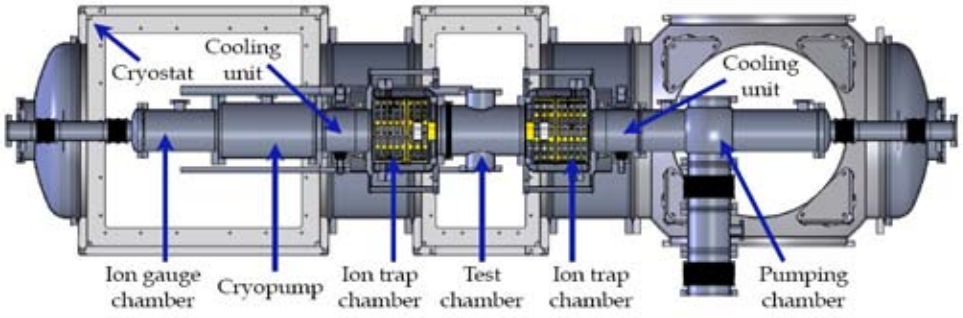


  - In < 10-K-operation: **≈ 10^{-13} mbar RTE**
    cryoadsorption at 10-K-walls,
    2-K cryocondensation pumps

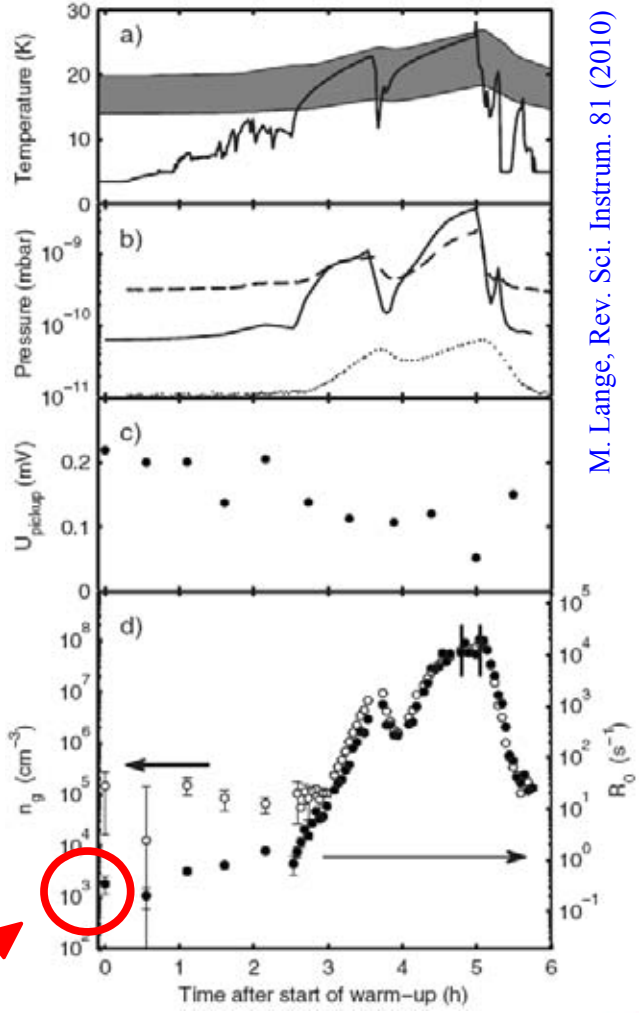


The CSR Project

- Present status
  - Prototype (CTF) test:
    Successful. ✓



M. Froese, PhD (2010)

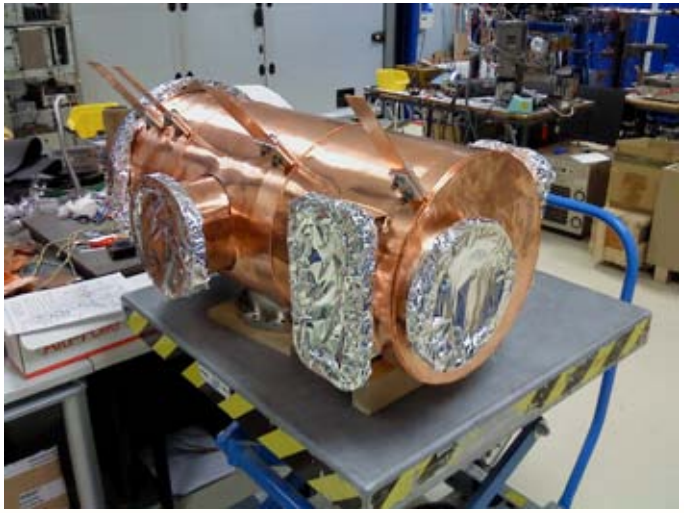


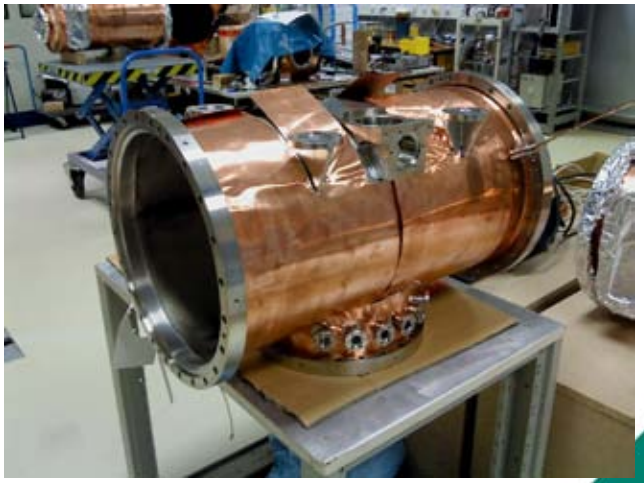
M. Lange, Rev. Sci. Instrum. 81 (2010)

$2\,(1) \cdot 10^3$ cm^{-3}
$= 8\,(4)\ 10^{-14}$ mbar RTE

The CSR Project

- Present status
  - Prototype (CTF) test:
    Successful. ✓
  - Isolation vacuum chamber:
    Complete. ✓
  - 1st corner section:
    Inner chambers ✓





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The CSR Project

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  - Prototype (CTF) test:
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  - Isolation vacuum chamber:
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  - 1st corner section:
    Inner chambers ✓
    Thermal shields ✓

The CSR Project

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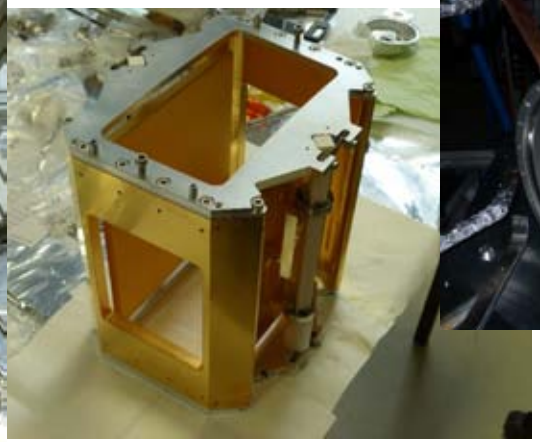
  - Prototype (CTF) test:
    Successful. ✓
  - Isolation vacuum chamber:
    Complete. ✓
  - 1st corner section:
    Inner chambers ✓
    Thermal shields ✓
    Ion optics ✓



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  - Prototype (CTF) test:
    Successful. ✓
  - Isolation vacuum chamber:
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  - 1st corner section:
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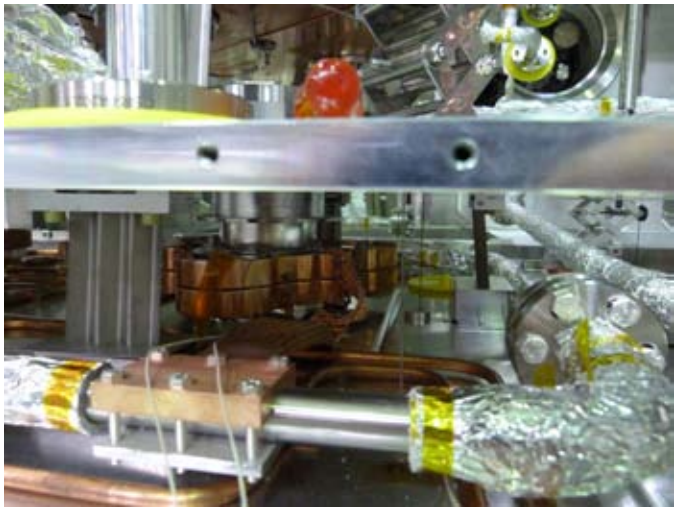
    Thermal shields ✓
    Ion optics ✓
  - Ongoing (1st corner) ...
    Electrode alignment
    Installation of cooling lines



The CSR Project

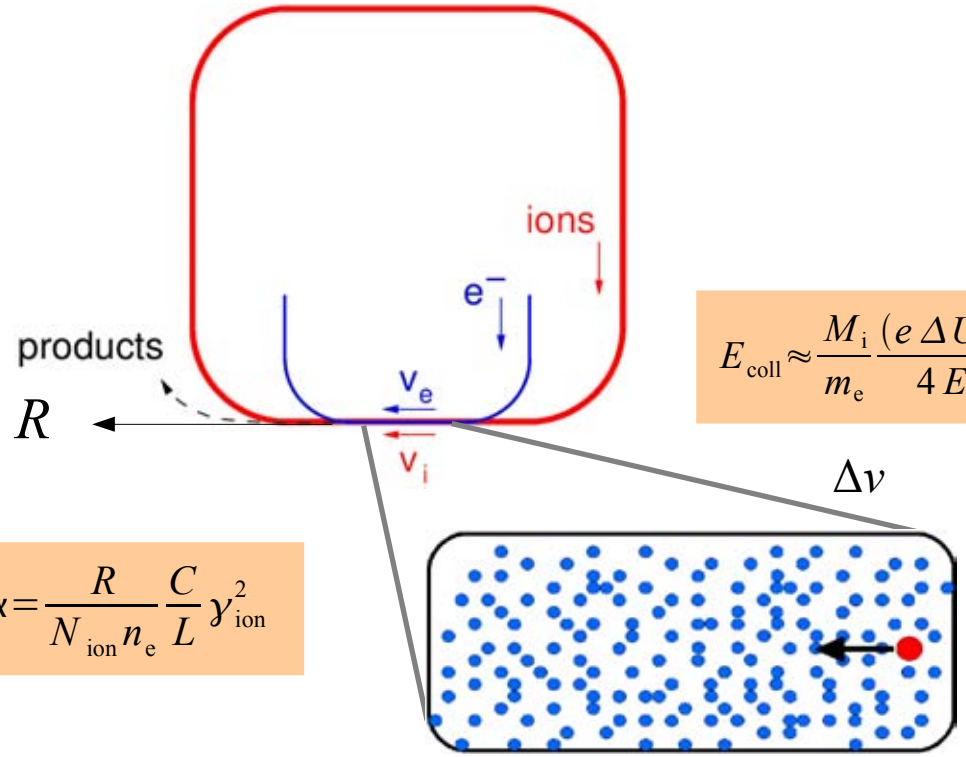
- Present status
  - Prototype (CTF) test:
    Successful. ✓
  - Isolation vacuum chamber:
    Complete. ✓
  - 1st corner section:
    Inner chambers ✓
    Thermal shields ✓
    Ion optics ✓
  - Ongoing (1st corner) ...
    Electrode alignment
    Installation of cooling lines
  - Next:
    Cooling tests
    of 1st corner

Overview

- The CSR Project
- Electron Target
- Experimental Perspectives

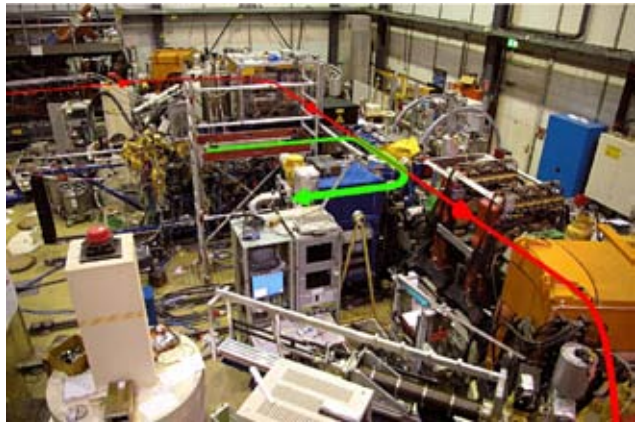
Electron Target

- Electron cooler (with $v_e \neq v_{ion}$)

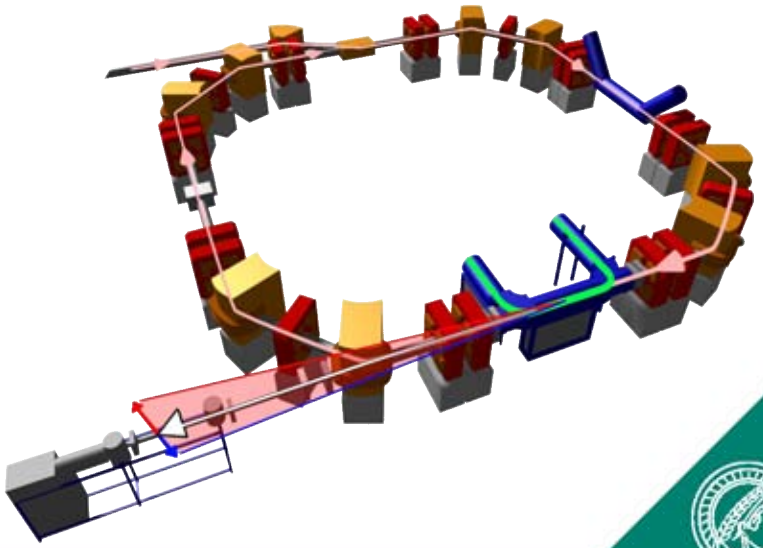


$$E_{coll} \approx \frac{M_i}{m_e} \frac{(e\,\Delta U)^2}{4\,E_i}$$

$$\alpha = \frac{R}{N_{ion} n_e} \frac{C}{L} \gamma_{ion}^2$$



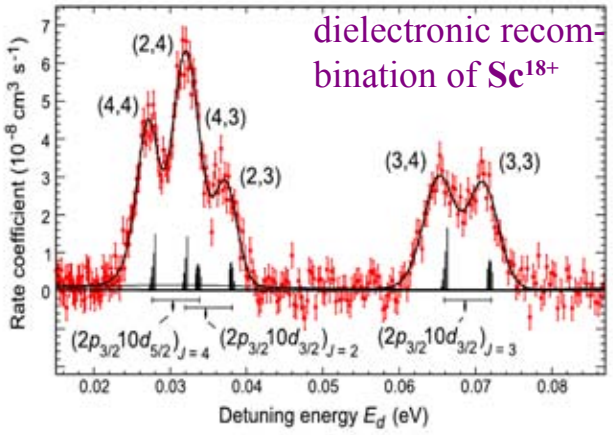
TSR



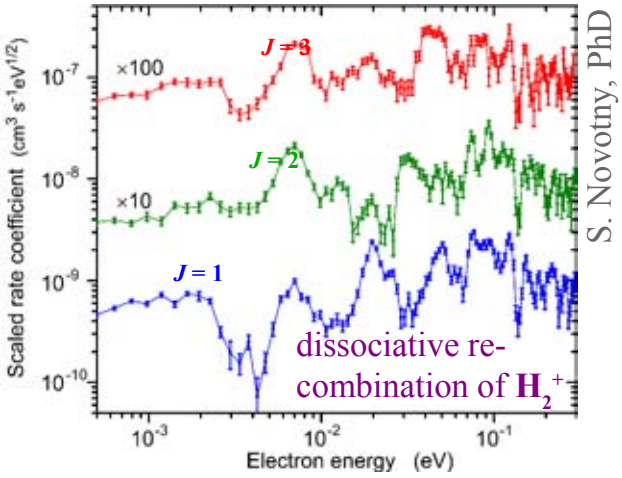
Because of $E_{coll} \sim \Delta U^2$,
E_{coll} can be **very small** (meV!)

Electron Target

- High-resolution recombination rate coefficients:



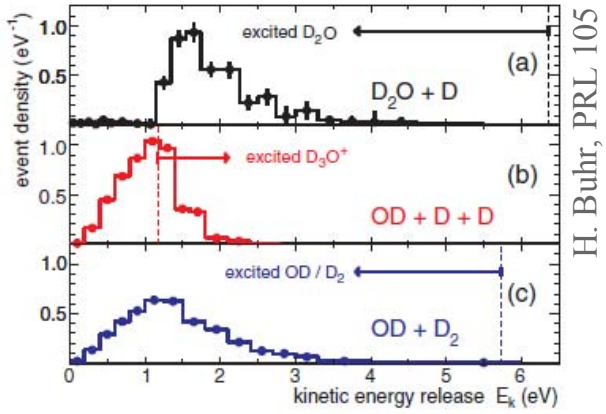
M. Lestinsky, PRL 100



S. Novotny, PhD

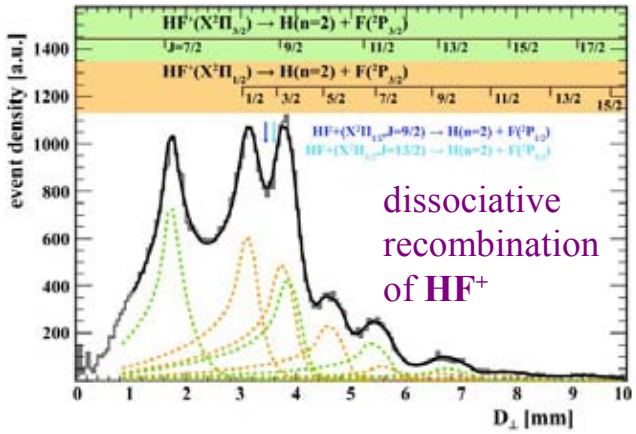
$$\alpha = \frac{R}{N_{\mathrm{ion}} n_{\mathrm{e}}} \frac{C}{L} \gamma_{\mathrm{ion}}^2$$

- Fragmentation dynamics:

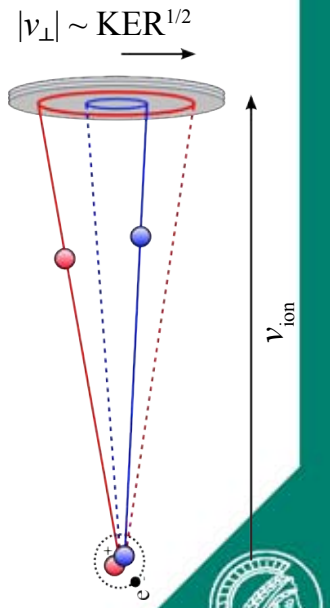


H. Buhr, PRL 105

dissociative recombination of D_3O^+



J. Stützel, in prep.



Electron Target

- CSR benefits
  - **Electrostatic optics**

    Well-suited for low charge/mass-ratio
    (e.g. complex molecules, clusters,
    low-charge atomic ions)

  - **Extremely high vacuum**

    Storage of large or heavy (= slow)
    ions/molecules for long times.

    Phase-space cooling with
    CSR electron cooler

  - **Cold environment**

    State-selective experiments
    on IR-active species

Electron Target

- CSR challenges
  - **Electron cooler/target**

    Low ion velocities → low cathode potential

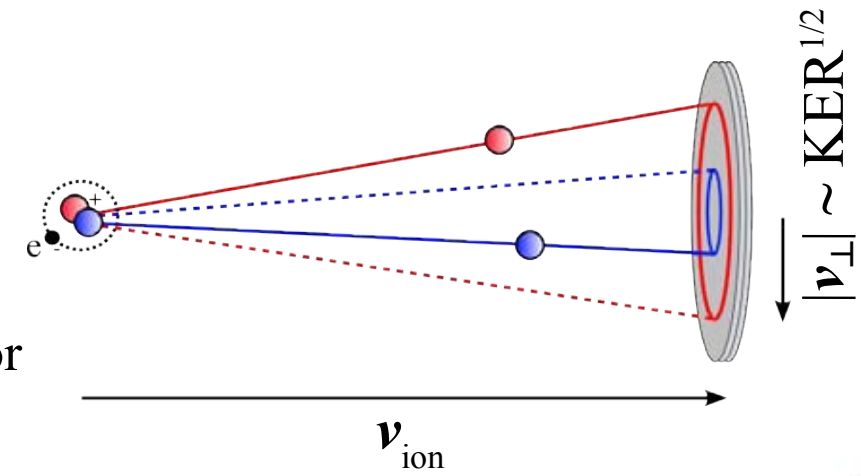
    1 eV electrons ↔ 160 u ions @ 300 keV

  - **Product detectors**

    Low-energetic particles
    → **No dead layers allowed!**
    (e.g. no semiconductor detectors!)

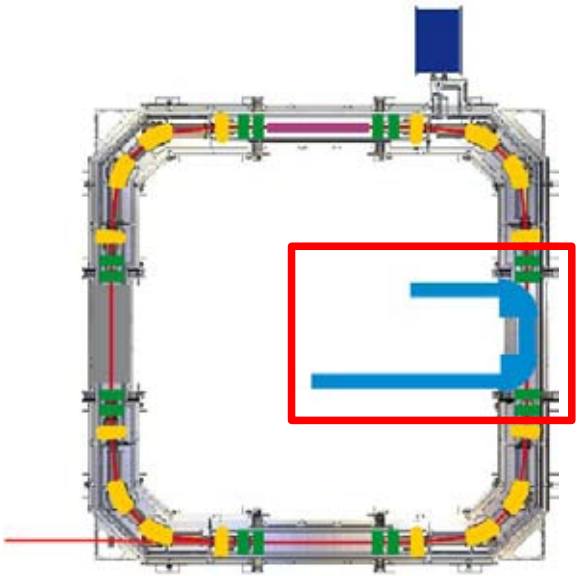
    Wide **fragmentation cones** for light fragments / large KER

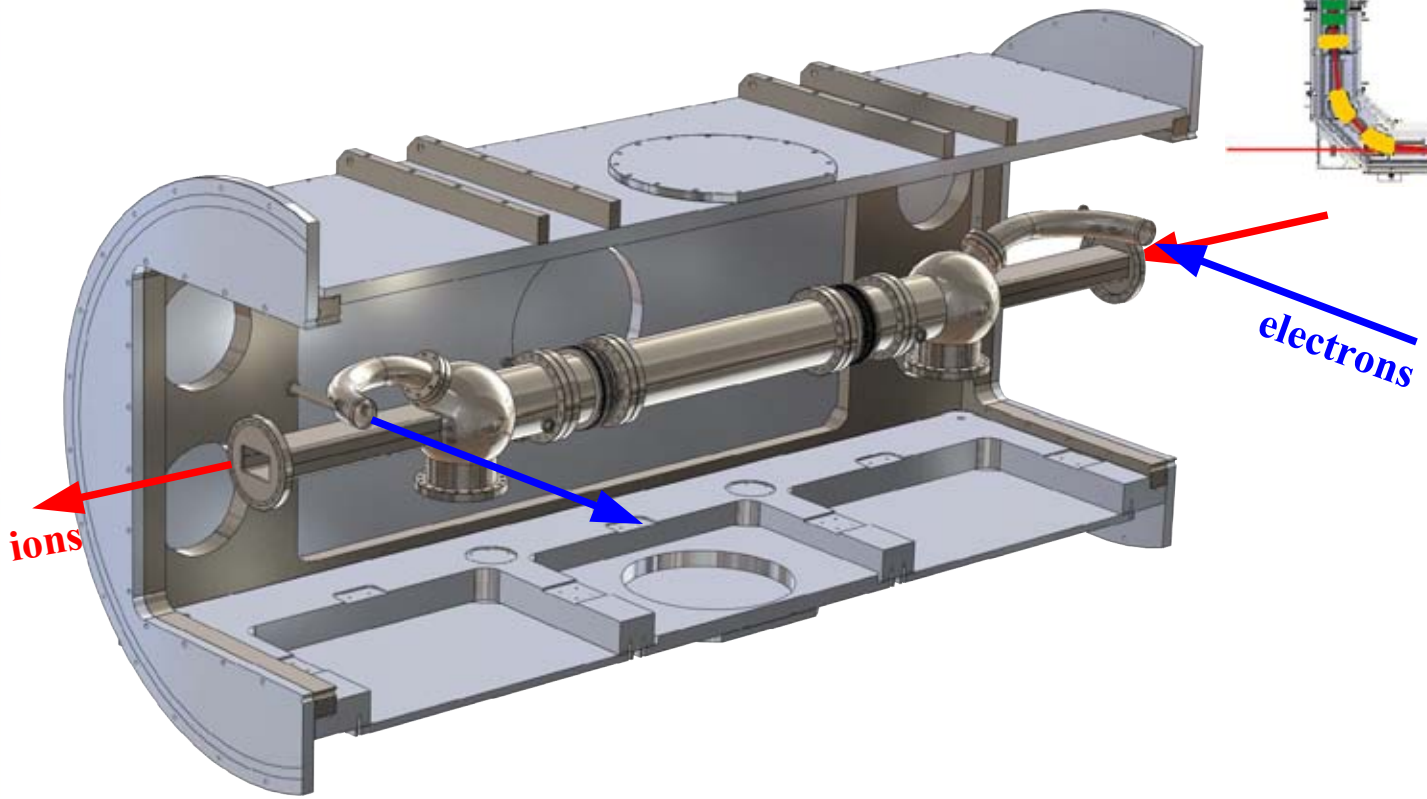
    Extreme requirements on **materials** (10 … 600 K, 10^{-13} mbar, ...)



Electron Target

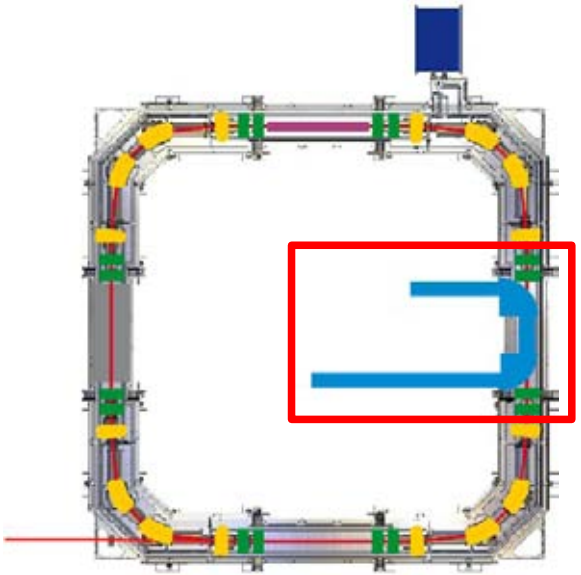
- Electron cooler
  - Low energy electron beam:
    ~ 1000 eV … 1 eV

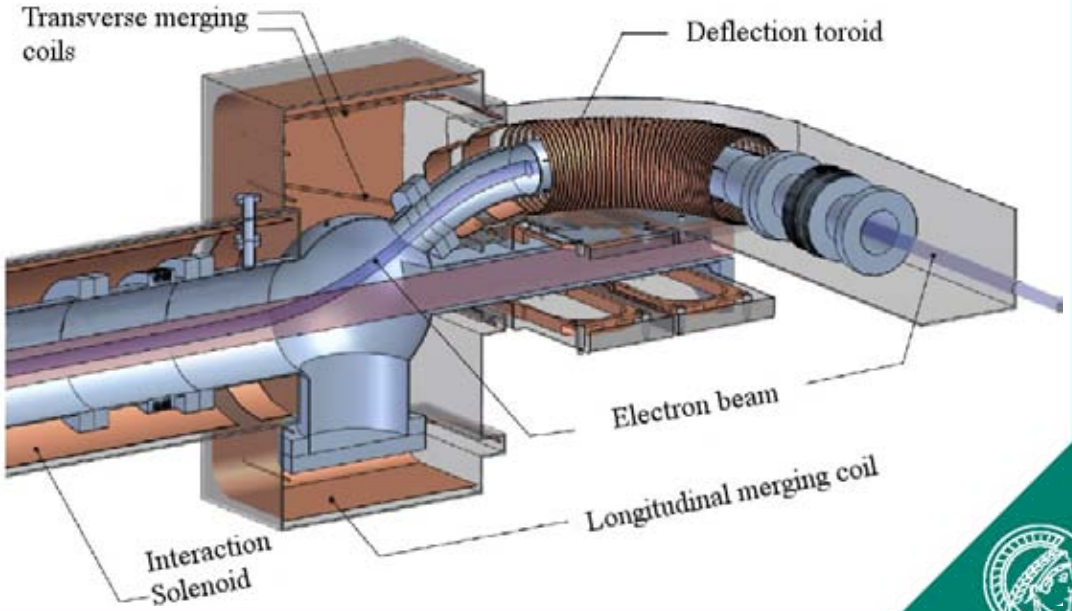




Electron Target

- Electron cooler
  - Low energy electron beam:
    ~ 1000 eV … 1 eV
  - Magnetic guiding field
    ~ 150 G for adiabatic transport
  - Coils must be cooled!
    Too much for
    CSR cryocooler.

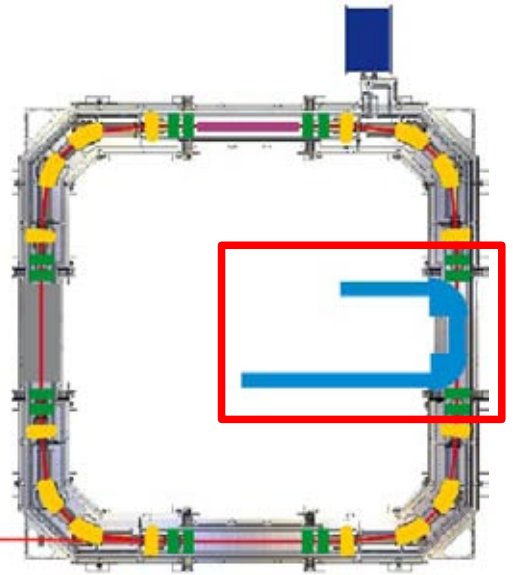


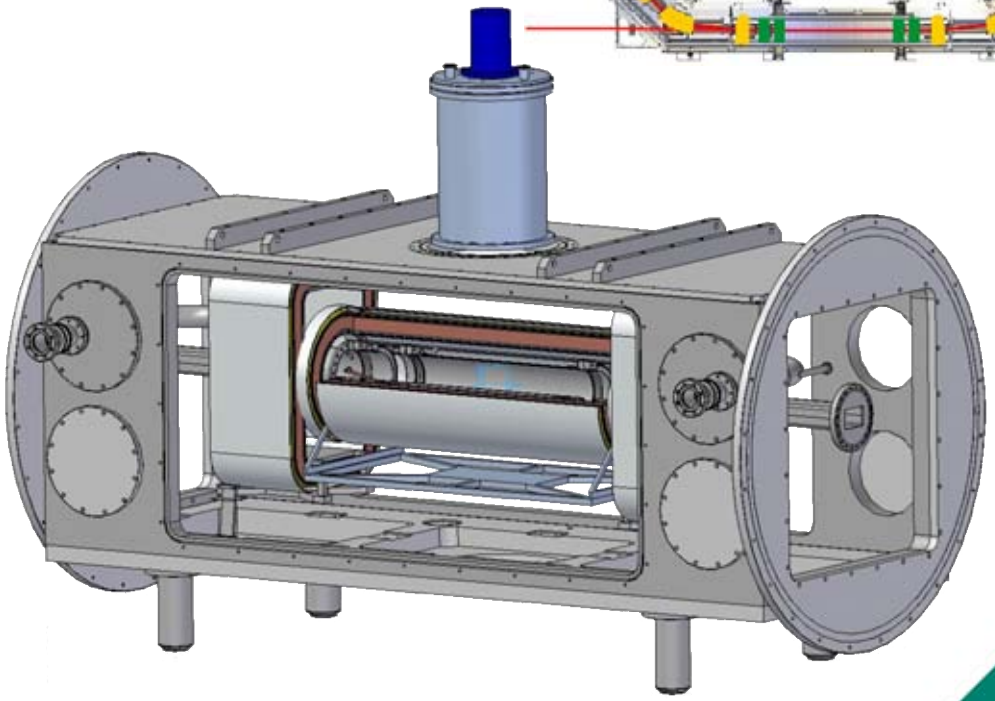


Electron Target

- Electron cooler
  - Low energy electron beam:
    ~ 1000 eV … 1 eV
  - Magnetic guiding field
    ~ 150 G for adiabatic transport
  - Coils must be cooled.
    Independent
    LNe cryocooler
    (~ 30 K)

→ stable low R
→ HTSC
→ approx. 17 W





A. Shornikov

Electron Target

- Low energy electron cooling
  - Experience from TSR

    CF^+ (31 u, 2.6 MeV) : $E_e = 46$ eV
    $DCND^+$ (30 u, 3.1 MeV): $E_e = 56$ eV
    NO^+ (30 u, 2.0 MeV) : $E_e = 34$ eV

  - Cooling time:

$$\tau \sim \frac{M\, T_e^{3/2}}{q^2\, n_e}$$

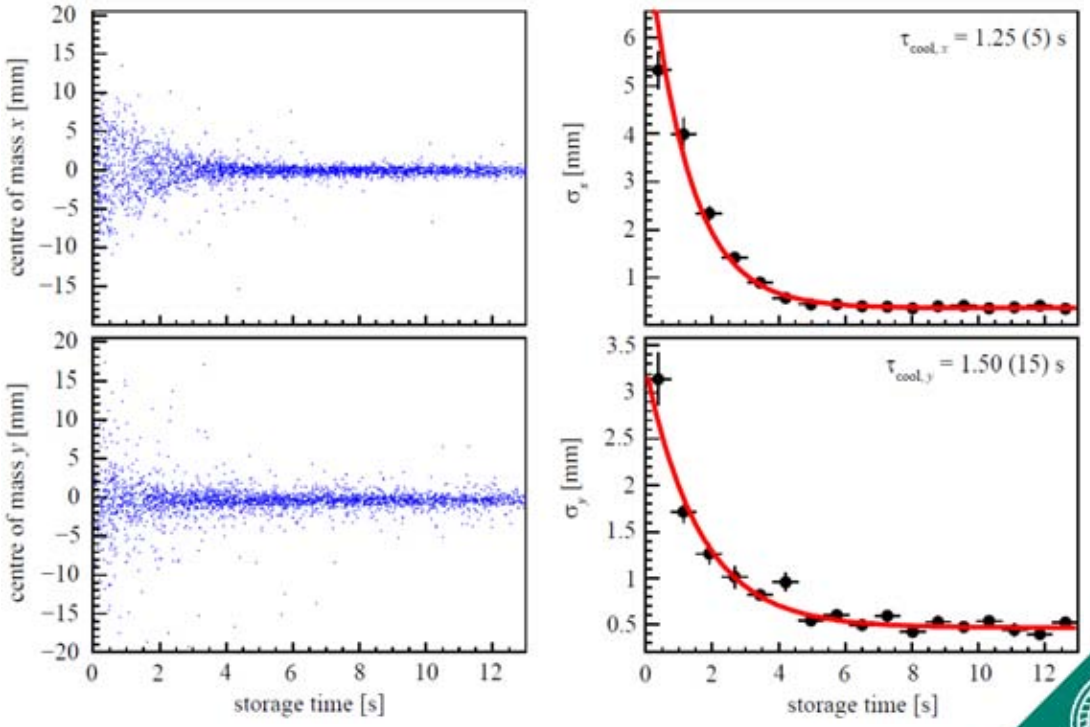
  - At low E_e:

    n_e limited by e-gun perveance!

  - Beam temperature becomes the decisive factor!

TSR: Cooling CF^+ at $E_e = 46$ eV

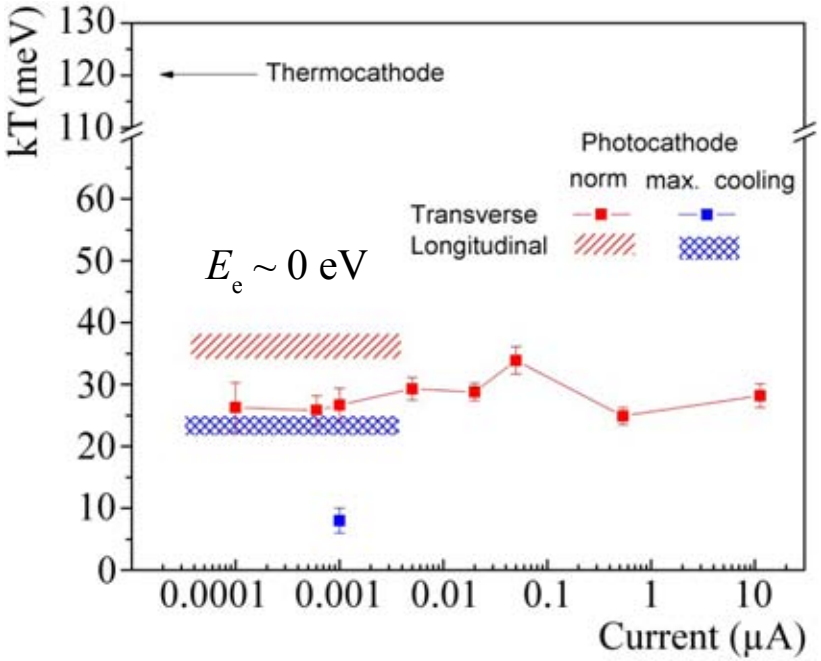
ε ~ 0.01 mm mrad
(< 1 mm @ 12 m)

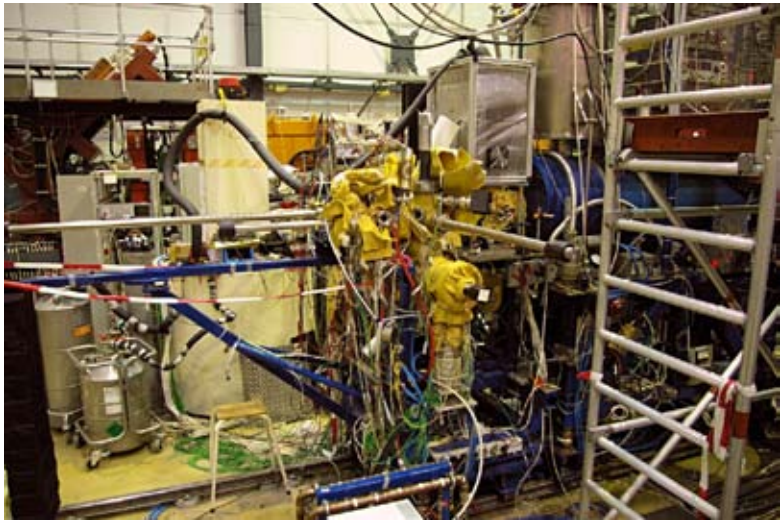


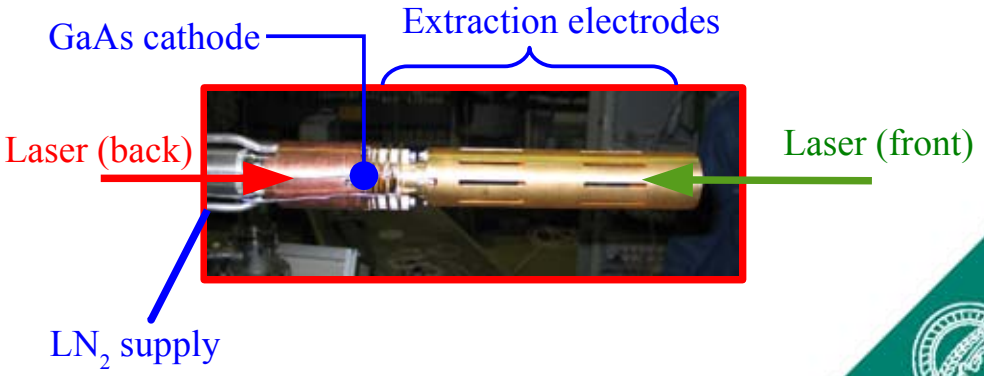
Electron Target

- Electron temperature
  - TSR photocathode electron gun:

    ~ 10 times lower T_e than thermionic electron gun

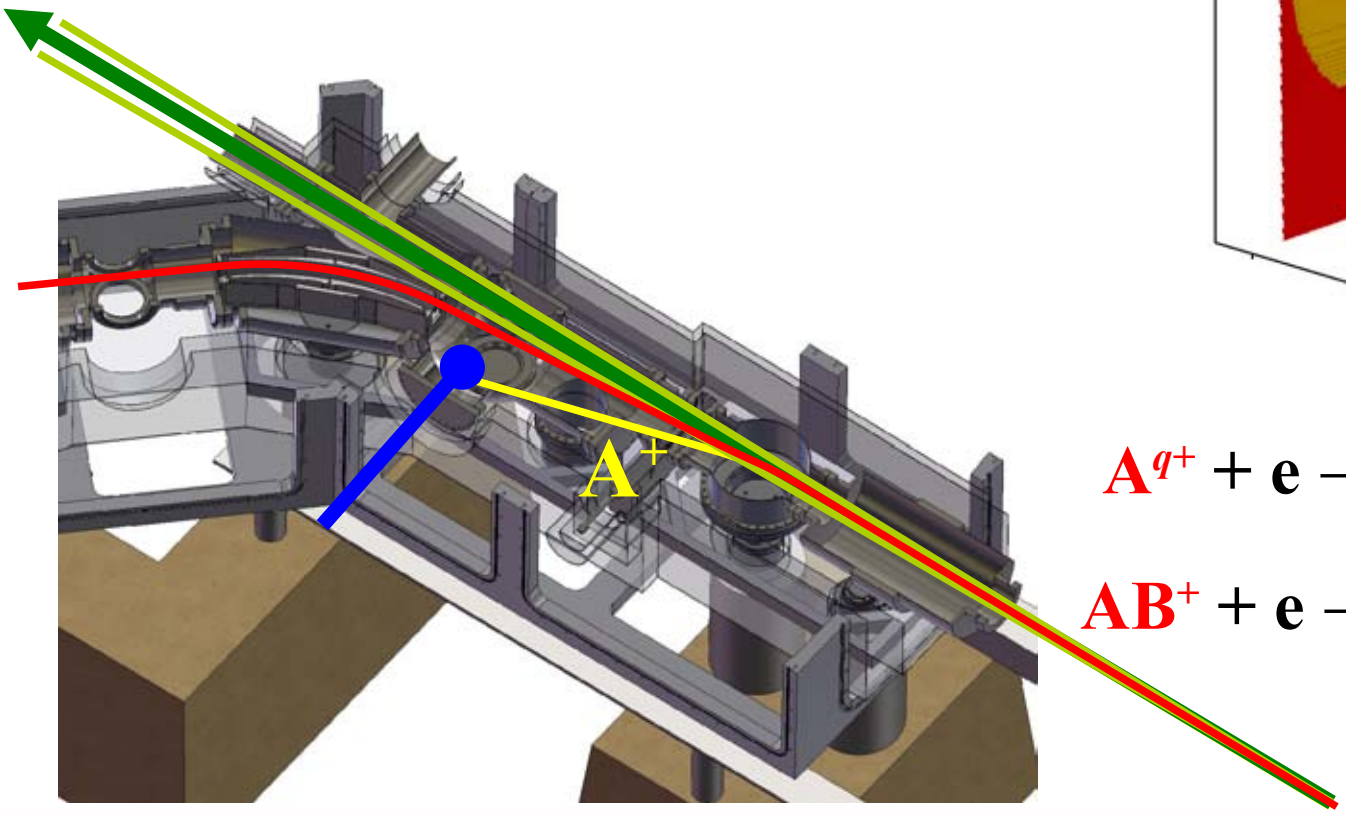


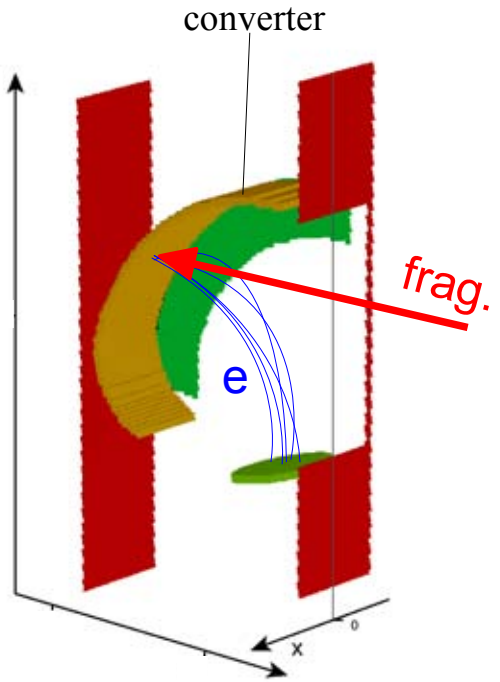




Electron Target

- Detectors for charged products
  - Placed after bending/focussing elements
  - Open, secondary-electron converter for good efficiency at low energies.





$$A^{q+} + e \rightarrow A^{(q-1)+} + \gamma$$

$$AB^{+} + e \rightarrow \begin{cases} A^{+} + B + e \\ A^{+} + B^{-} \end{cases}$$

Electron Target

- Detectors for charged products
  - Placed after bending/focussing elements
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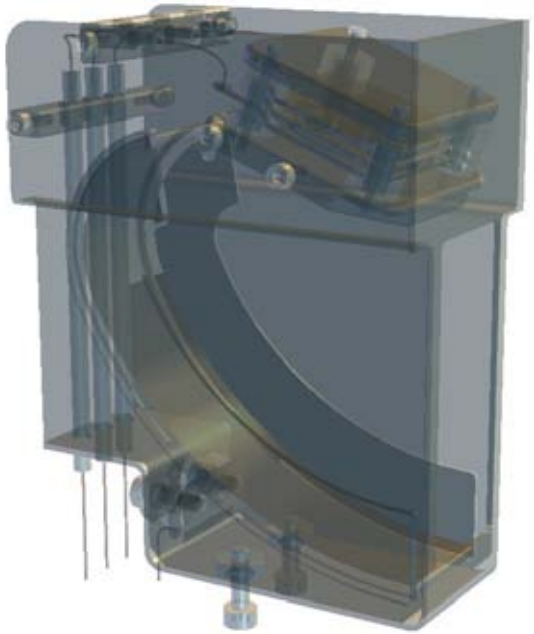
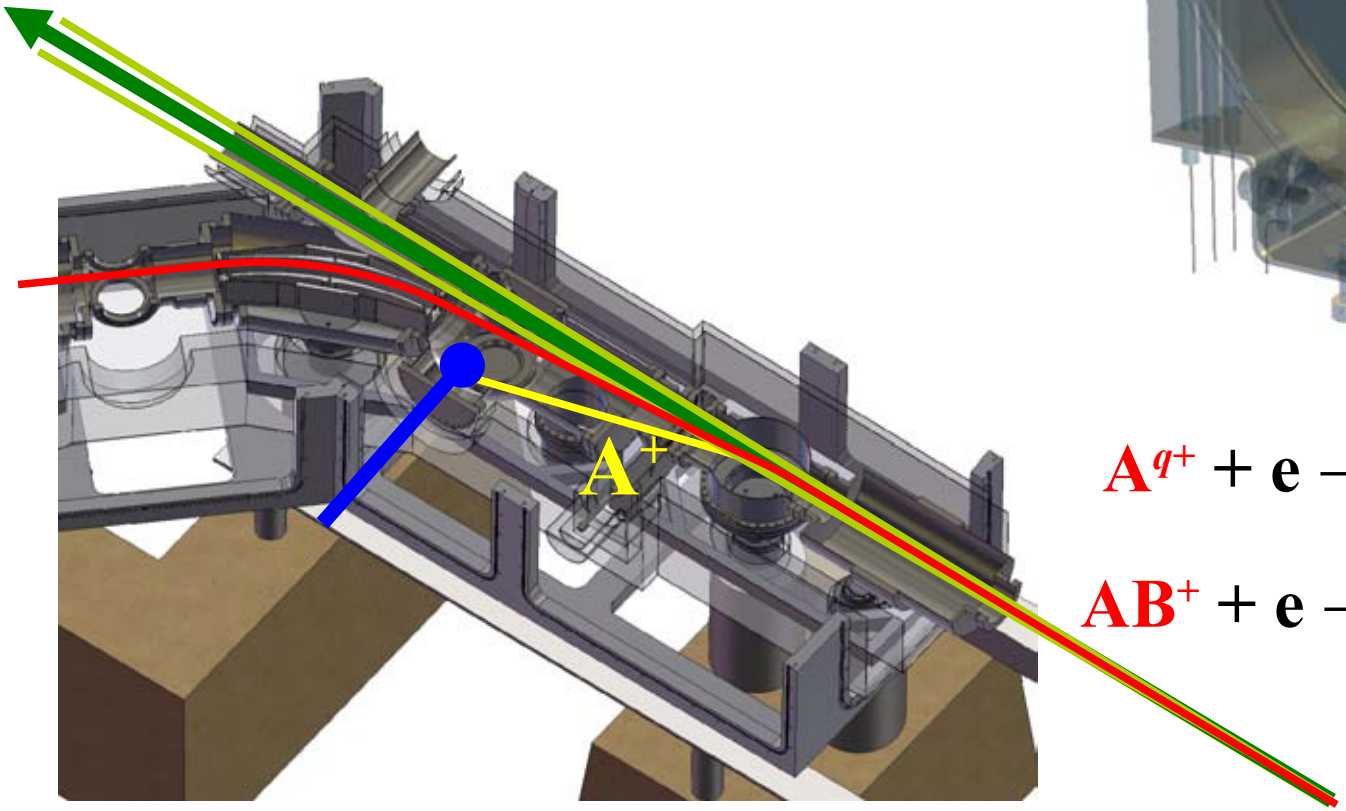


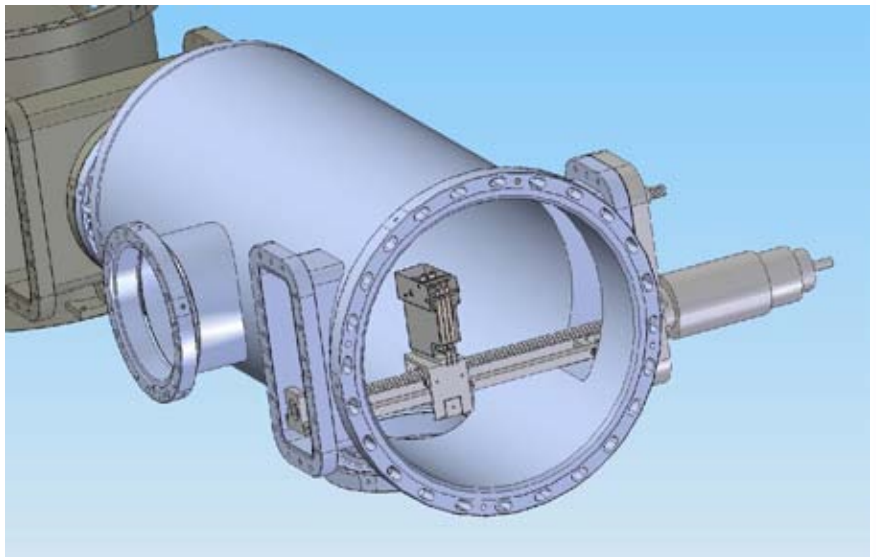


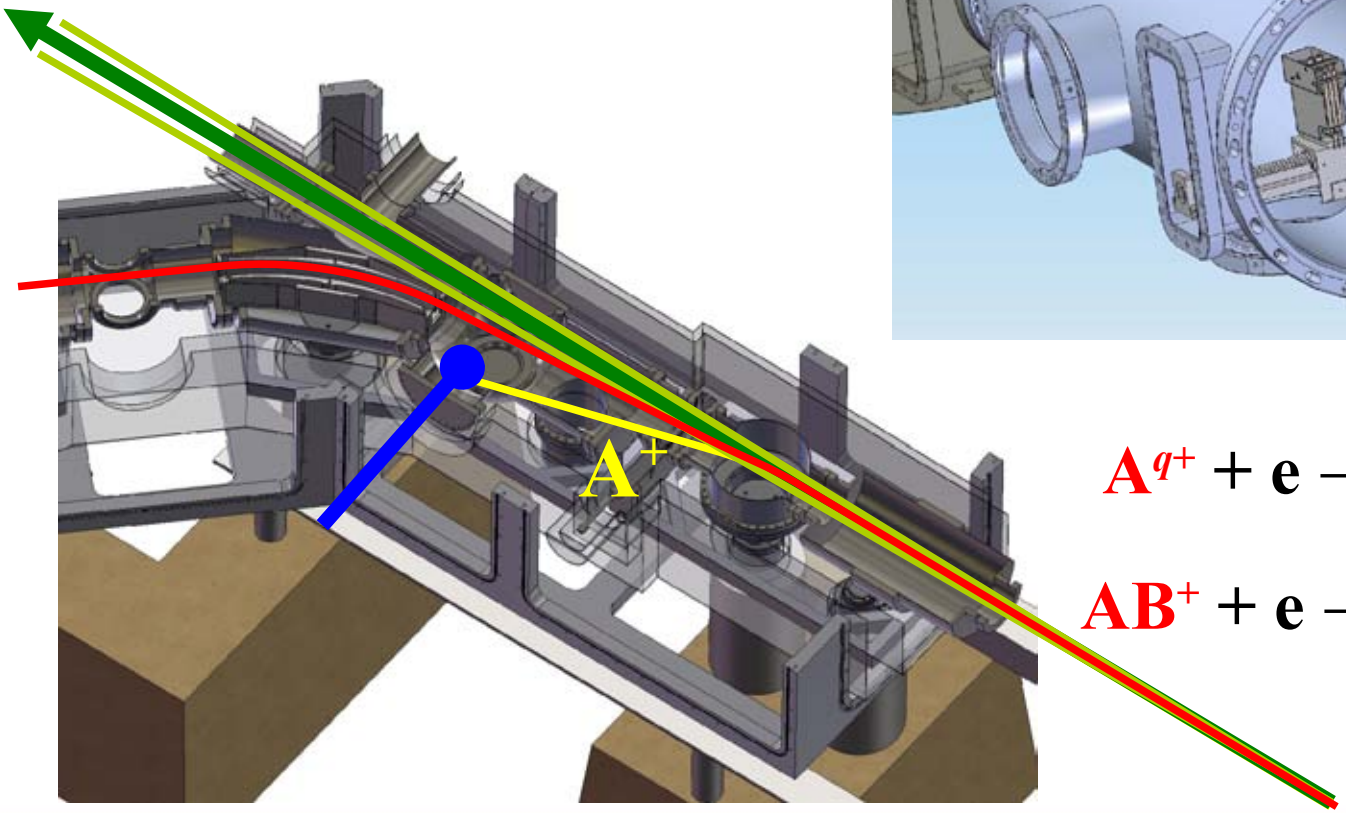
$$A^{q+} + e \rightarrow A^{q'+} + \gamma$$

$$AB^{+} + e \rightarrow \begin{cases} A^{+} + B + e \\ A^{+} + B^{-} \end{cases}$$

Electron Target

- Detectors for charged products
  - Placed after bending/focussing elements
  - Open, secondary-electron converter for good efficiency at low energies.



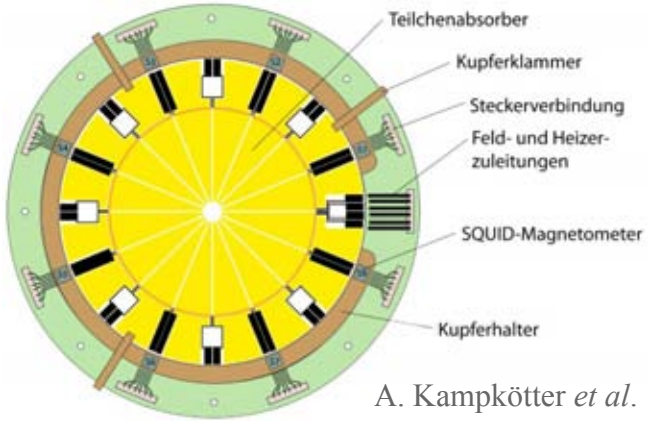


$$A^{q+} + e \rightarrow A^{q'+} + \gamma$$

$$AB^{+} + e \rightarrow \begin{cases} A^{+} + B + e \\ A^{+} + B^{-} \end{cases}$$

Electron Target

- Detectors for neutral products
  - Placed in chambers of 39° bending elements
  - Maximum opening cone ± 1°
    limited by electrode geometry.

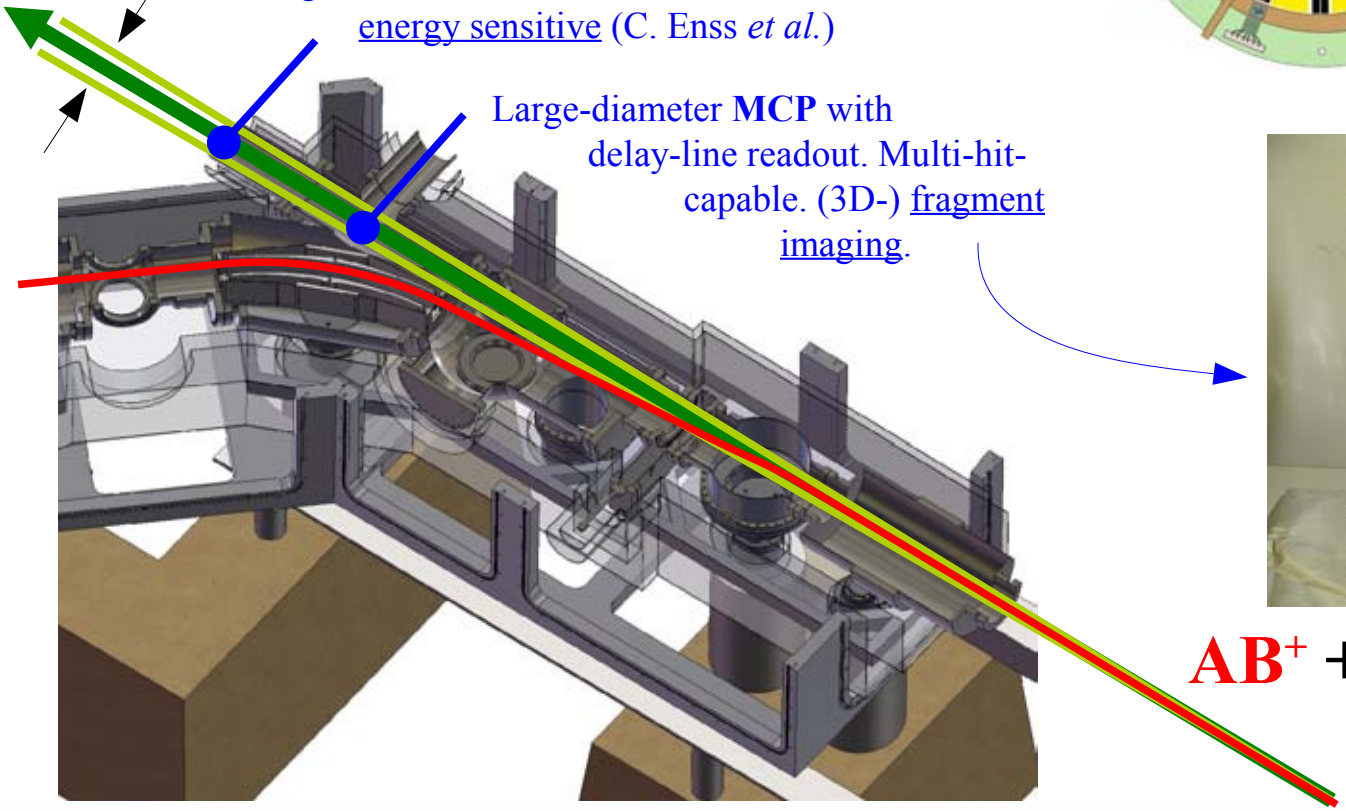


A. Kampkötter *et al.*

± 1°

Segmented **microcalorimeter**, energy sensitive (C. Enss *et al.*)

Large-diameter **MCP** with delay-line readout. Multi-hit-capable. (3D-) fragment imaging.



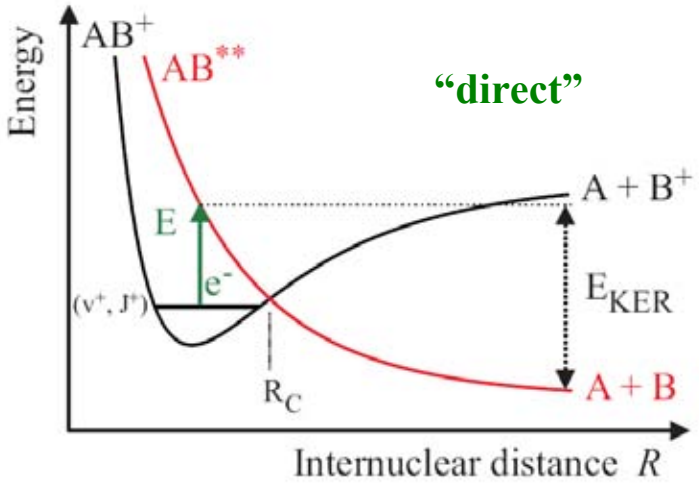
$$AB^+ + e \rightarrow A + B$$

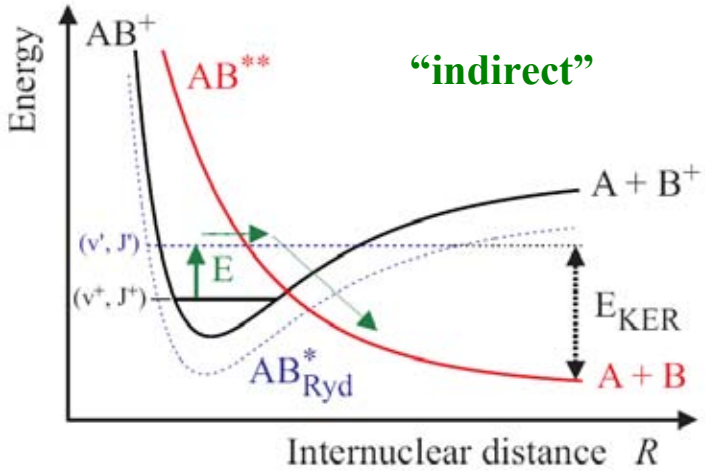
Overview

- The CSR Project
- Electron Target
- Experimental Perspectives

Outlook: recombination experiments

- State selective DR



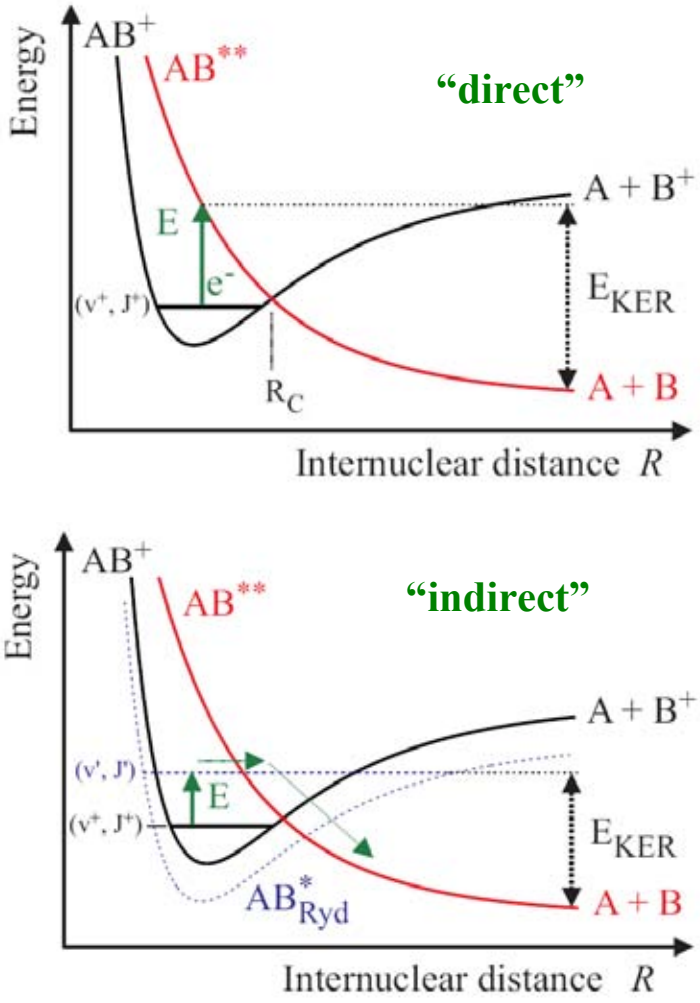


$$e^-(E) + AB^+ \rightarrow A + B + E_{KER}$$

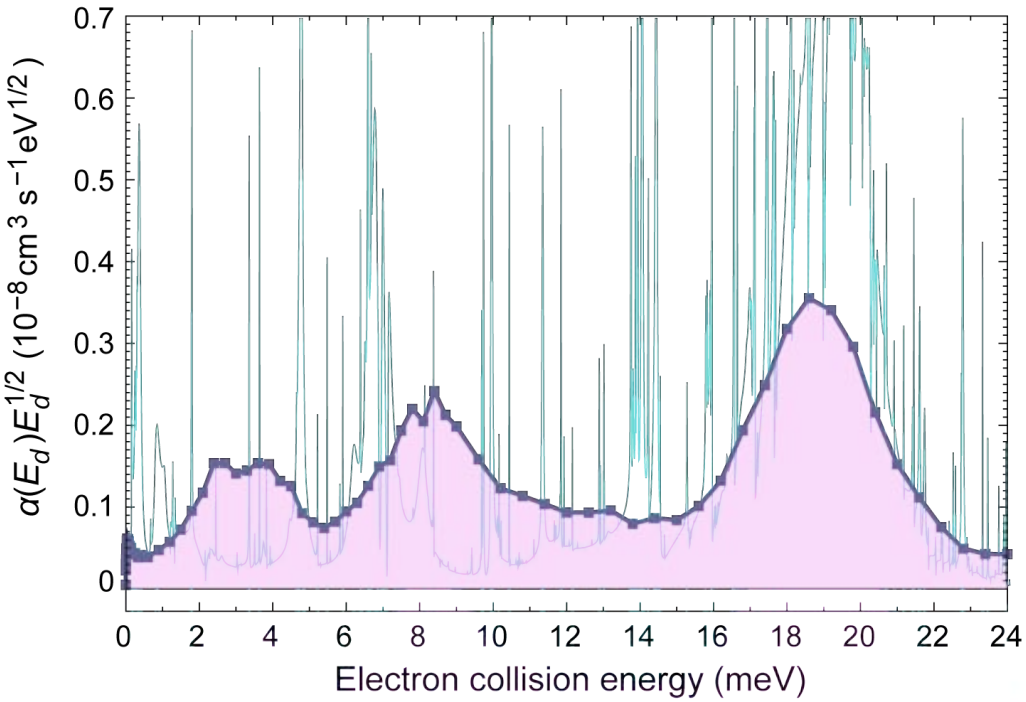
Leads to sharp resonances in the recombination cross-section.

Outlook: recombination experiments

- State selective DR



$e^-(E) + HD^+ \rightarrow H + D + E_{KER}$

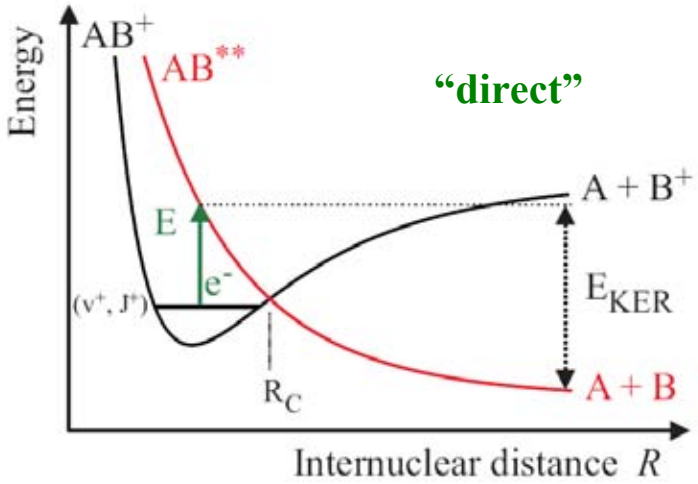


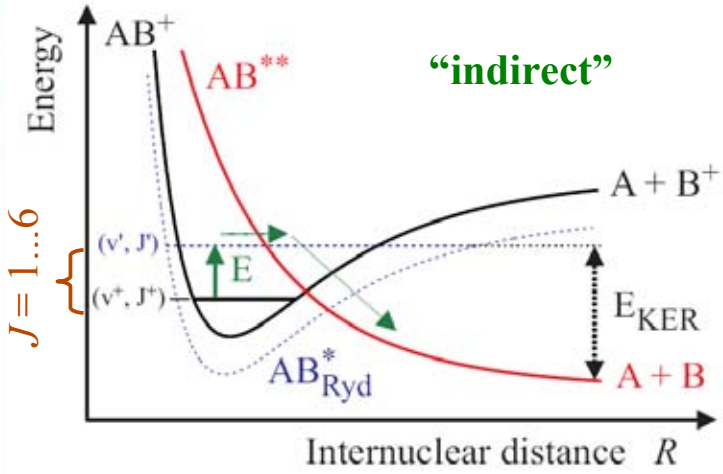
Waffeu-Tamo *et al.*, submitted (0 K)

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

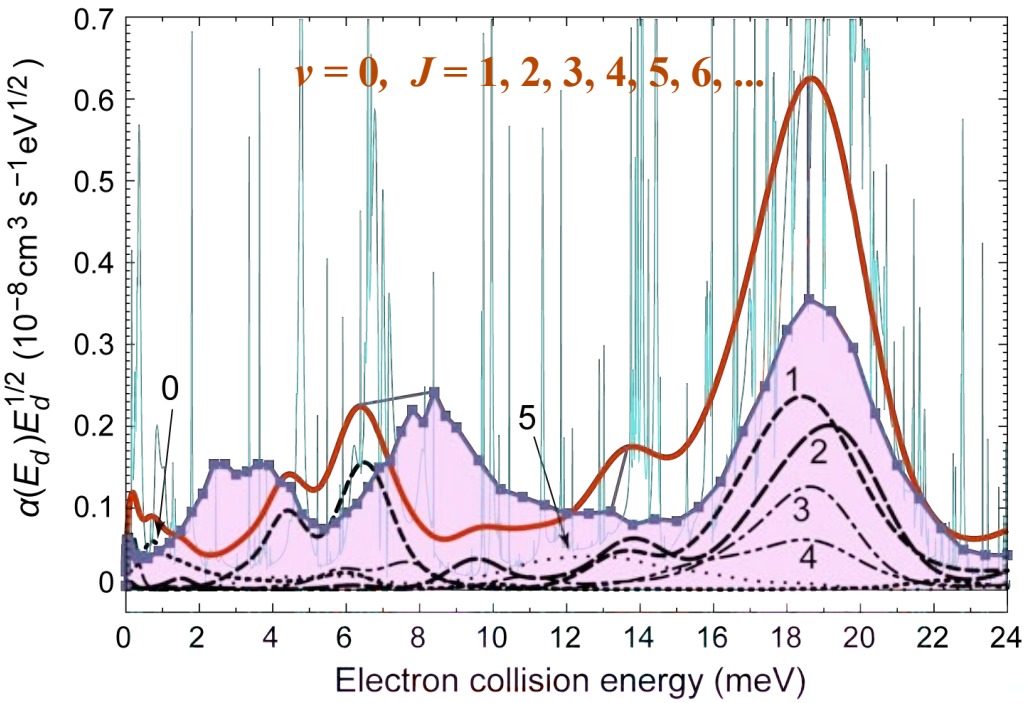
Outlook: recombination experiments

- State selective DR





$e^-(E) + HD^+ \rightarrow H + D + E_{KER}$



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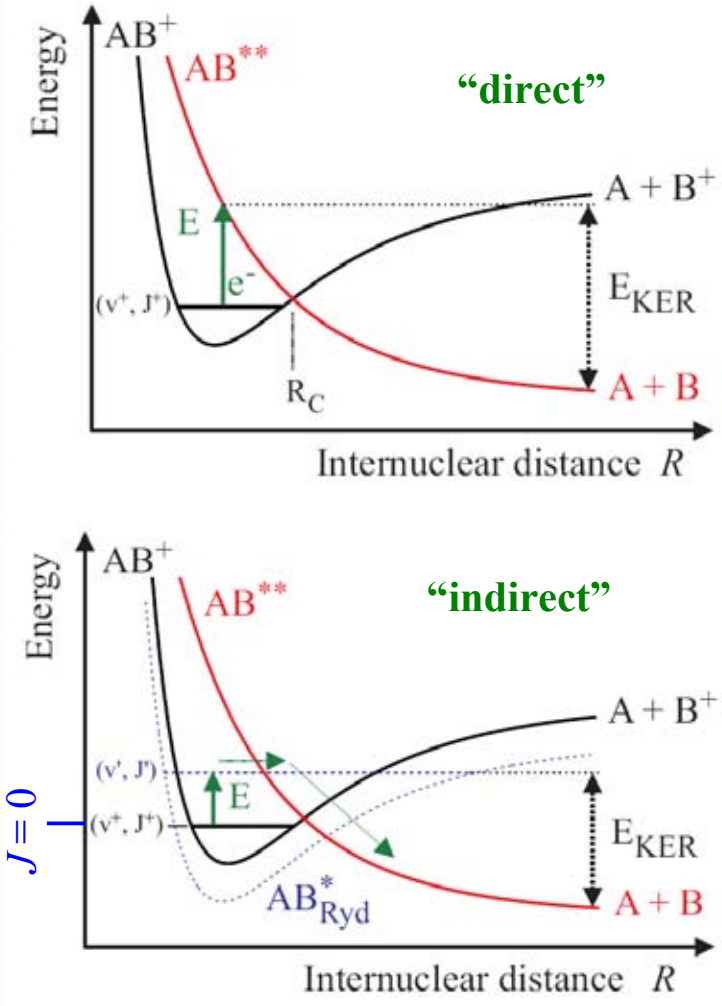
Outlook: recombination experiments

- State selective DR



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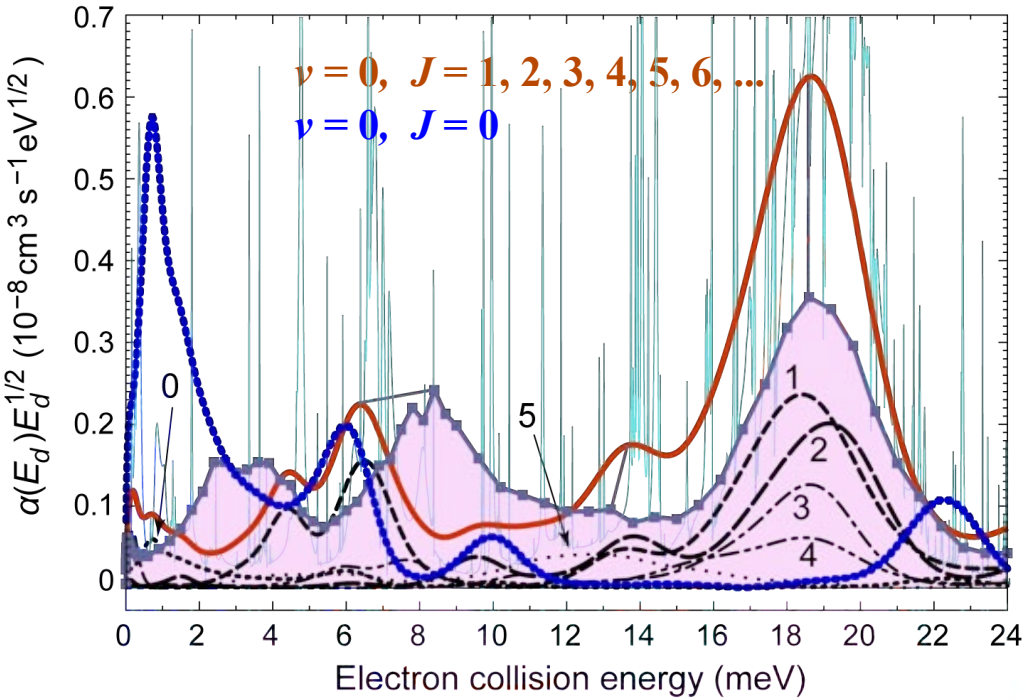


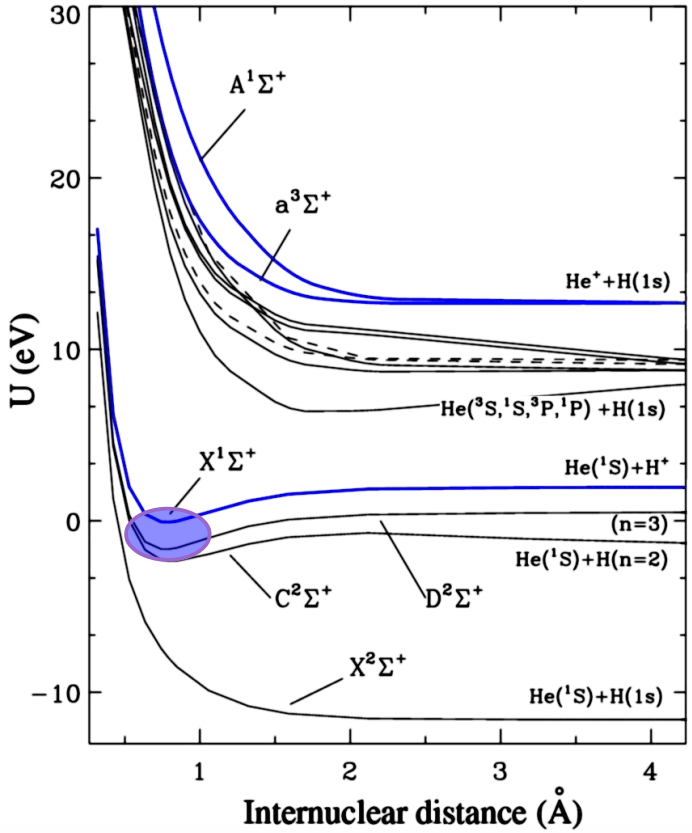
Waffeu-Tamo *et al.*, submitted (0 K)

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

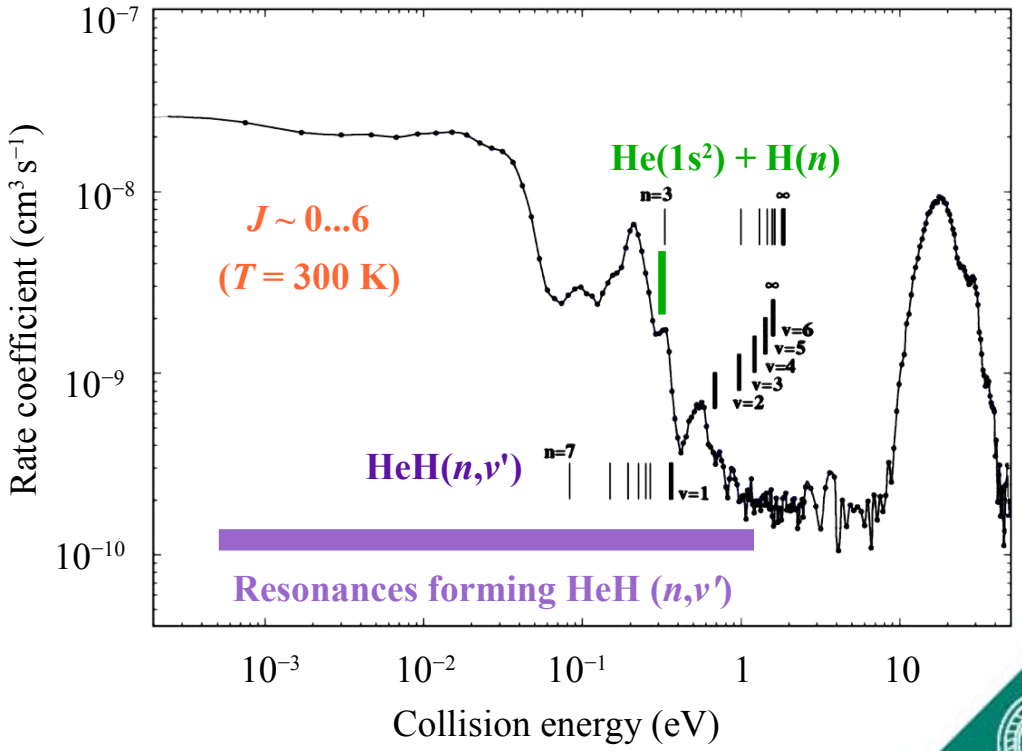
CSR prediction ($T_{ion} = 10$ K)

Outlook: recombination experiments

- IR active species (e.g.)
  - HeH^+ ($v = 0$) + e $\rightarrow$ He ($1s^2$) + H ($n \geq 2$)



TSR (S. Krohn, 2000),
data scaled to Tanabe *et al.*, 2000



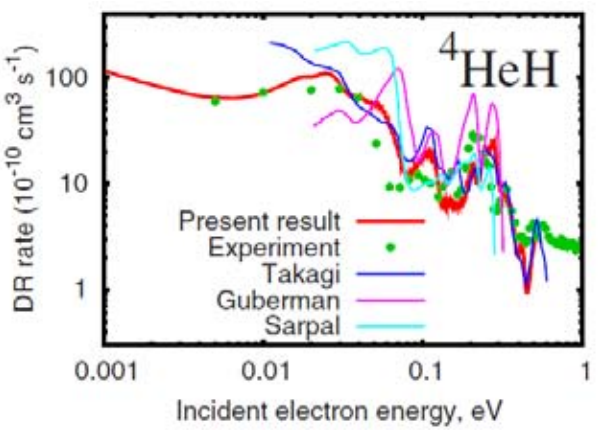
Outlook: recombination experiments

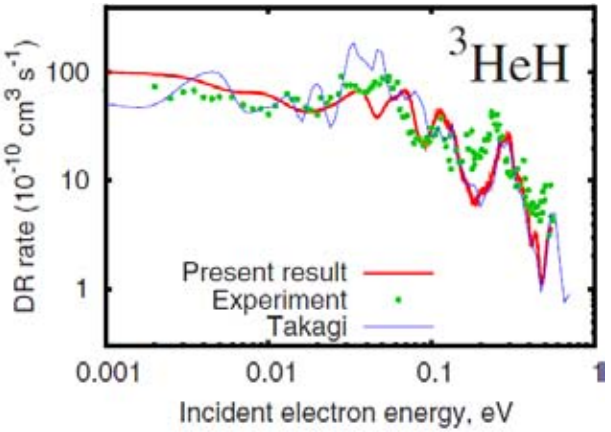
- IR active species (e.g.)
  - HeH^+ ($v = 0$) + e $\rightarrow$ He ($1s^2$) + H ($n \geq 2$)

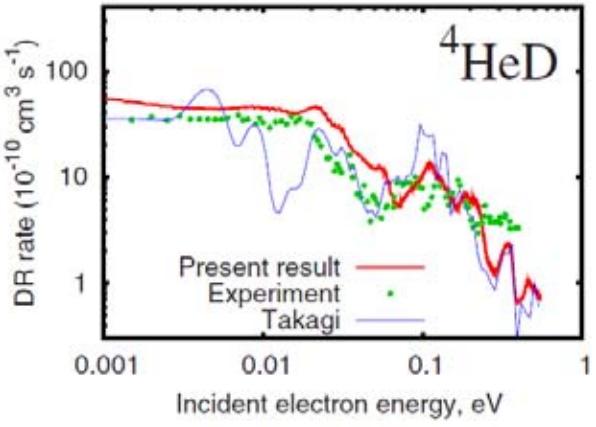
convolved with
$T = 800$ K !

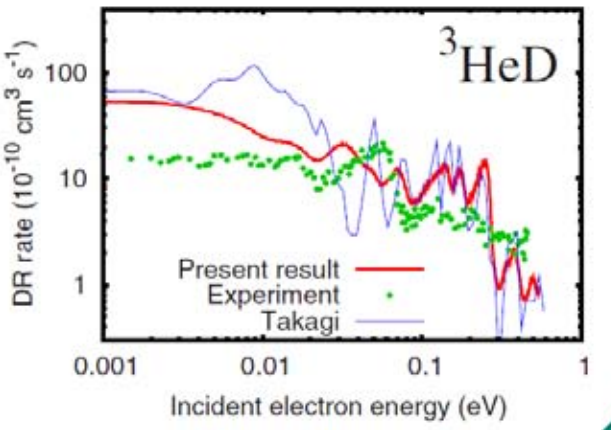
@ CSR:

10 K $\rightarrow$ $J = 0$









D. J. Haxton, C. H. Greene, Phys. Rev. A 79, 022701 (2009)

Outlook: recombination experiments

- Slow heavy ions
  - … difficult to study because of technical limits:
    - Slow ions
    - short storage times
    - no electron cooling
    - high residual gas collision rate i.e. high non-electron background, …
  - … but CSR has:
    - Extremely High Vacuum
    - Long storage times
    - Electron cooling
    - Good recombination/collision signal ratio

Outlook: recombination experiments

- Slow, heavy/complex ions

  - Singly-charged atomic ions: C^+, N^+, F^+, Si^+, P^+, Cl^+, Fe^+

    Contribute to cold astrochemistry [Bryans et al., ApJ 694 (2009)]

    Dielectronic recombination via fine-structure excitation

    $$C^+ (^2P_{1/2}) + e^- (< 8\ meV) \rightarrow C^{**} (^2P_{3/2}, nl) \rightarrow C^* + \gamma$$

    Not measurable in TSR due to field ionisation and non-DR background!

  - Cluster / fullerene ions …

    Dependence of rate coefficients on internal excitations ?

  - DR of large organic molecules $C_xH_y^+$, $C_xH_yOH^+$ ...

    Complex chemistry in cold interstellar media

  - Transition to non-dissociative recombination?

    Recombination by non-destructive intramolecular energy repartitioning.

    .

Summary

- CSR, a next-generation electrostatic storage ring is in construction.
- It will feature a fully-functional electron cooler.
- It will be all-cryogenic, providing very low residual gas density and IR background radiation.
- Besides other applications, it will be the platform of choice for electron-ion collision experiments with molecular and low-charged heavy ions.

Thank you!

Klaus Blaum
Florian Fellenberger
Michael Froese
Manfred Grieser
Robert von Hahn
Michael Lange

Felix Laux
Sebastian Menk
Roland Repnow
Andrey Shornikov
Andreas Wolf
C. K.

… and many more ...

Thank you!