# The Cryogenic Storage Ring CSR and its Application to Molecular Recombination Physics

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# Overview

- The CSR Project
  - Limits of present-day storage rings
  - Electrostatic storage
  - Low-temperature XHV
- DR @ CSR
  - Electron cooler
  - Detector concept
- Experimental Perspectives
  - DR with cold molecules
  - DR with heavy molecules

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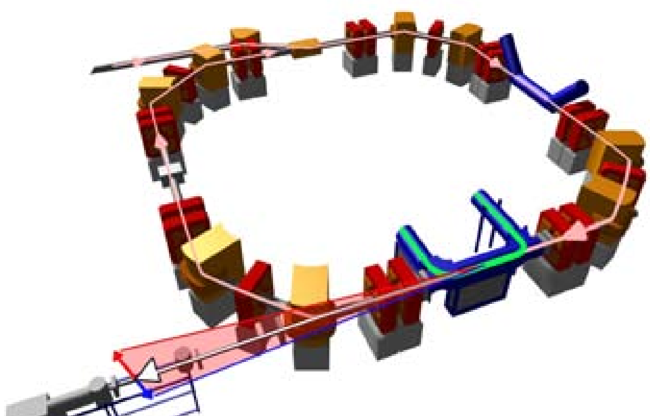
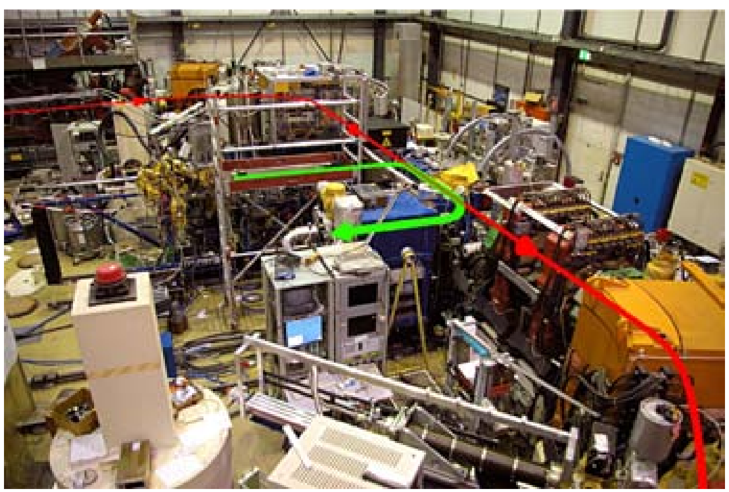
# The CSR Project

- Today: Electron cooler storage rings for DR studies



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.

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

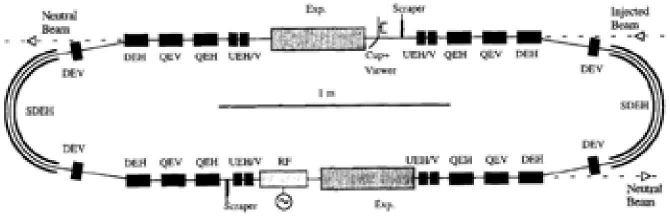
  - Higher velocities for very large *M*:
    Longer storage times

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

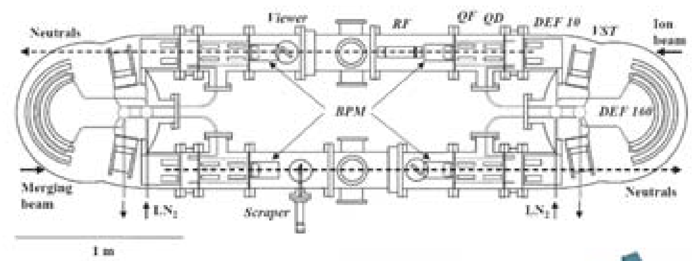
  - Economic
    Power consumption!
  - "Easy" to operate both at room and cryogenic temperature.

# The CSR Project

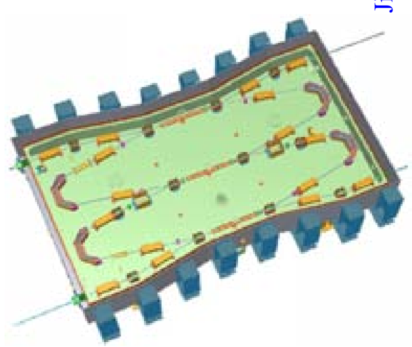
- First electrostatic storage rings
  - ELISA (Aarhus, 1998)
    Racetrack design,
    25 keV/q, room temp.
  - TMU Ring (Tokyo, 2004)
    ELISA design,
    77 K ($LN_2$)
  - DESIREE (Stockholm, *in constr.*)
    Double ring (ion-ion interact.),
    < 20 K,
    25 kV and 100 kV injectors
  - CSR (Heidelberg, *in constr.*)
    < 10 K,
    300 keV/q
    electron cooling (→ DR !)



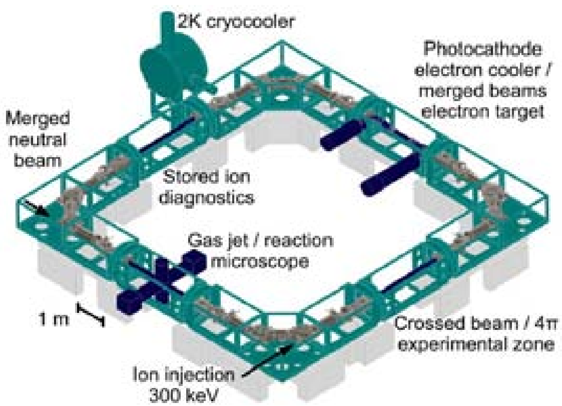
Møller, NIM A 394



Jinno, NIM A, 532



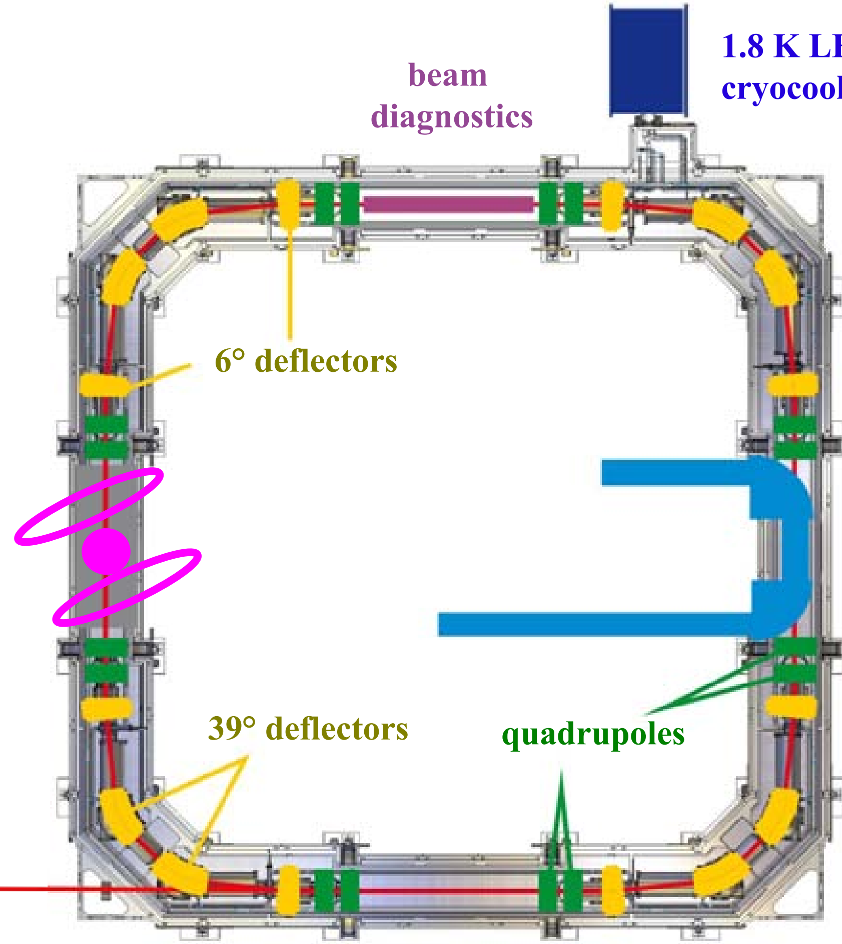
Löfgren, Proc. EPAC06



# 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 |

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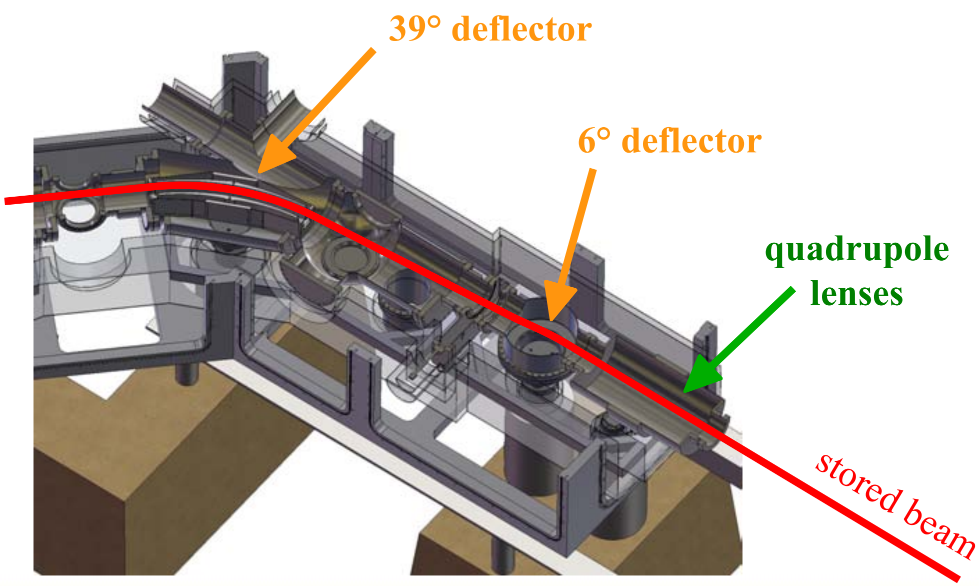
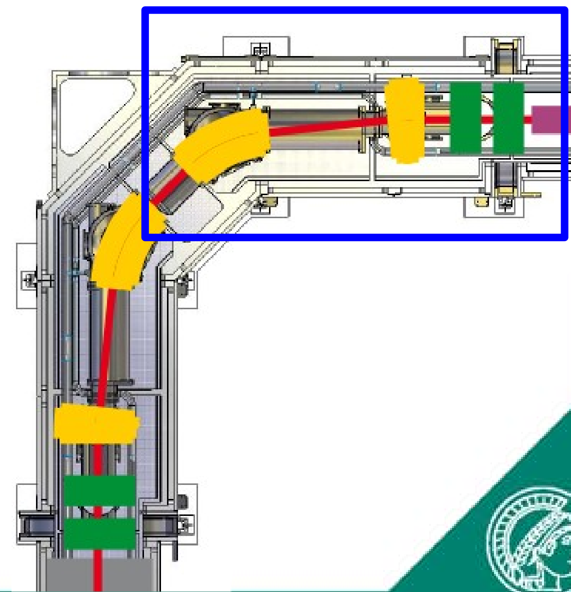
# The CSR Project

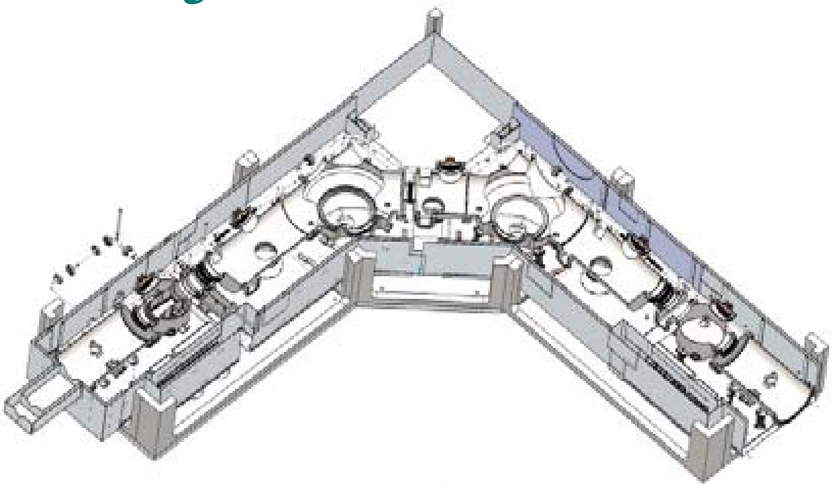
- Electrostatic beam optics
  - 4-fold symmetric storage ring
    All CSR corner sections identical
  - 4 x 2 pairs of **focussing quadrupoles**
  - 4 x 2 **6°-deflector** electrodes (30 kV)
  - 4 x 2 **39°-deflector** electrodes (30 kV)
  - 4 free straight sections (2.6 m each)

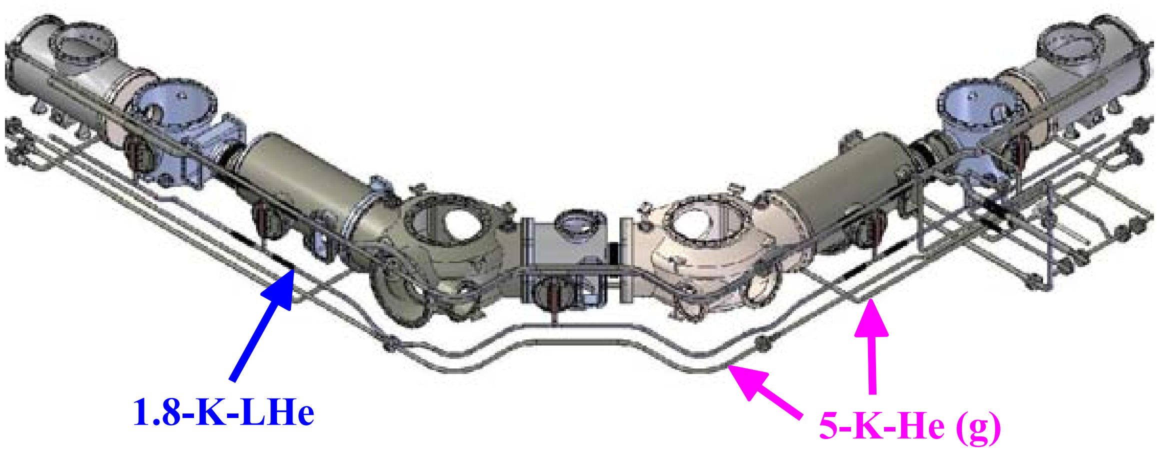


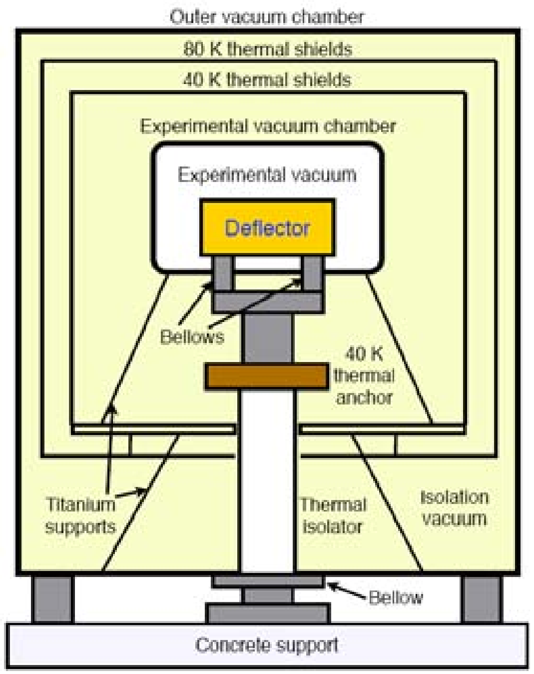



# The CSR Project

- 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 return line (600 W)
  - Superinsulation
  - Isolation vacuum chamber

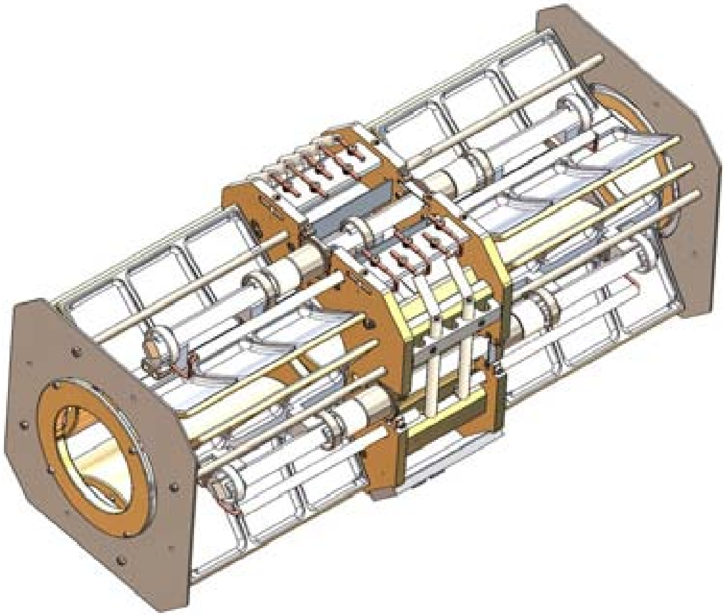


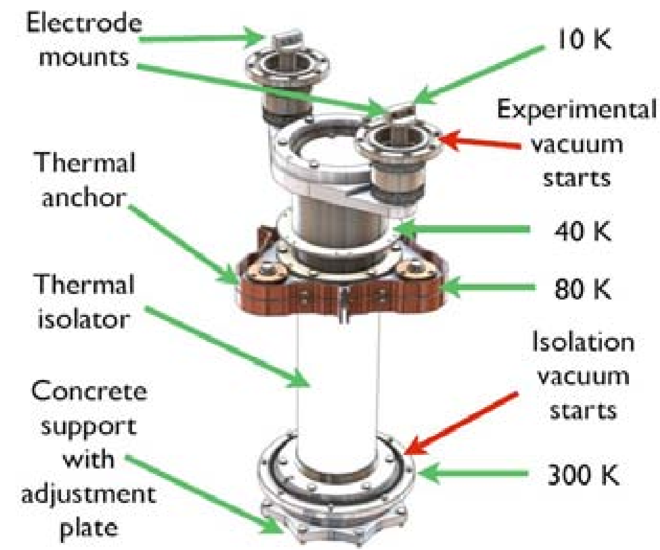


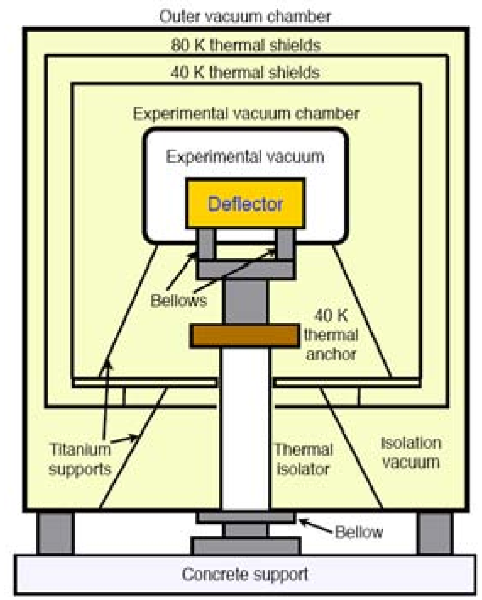



# The CSR Project

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



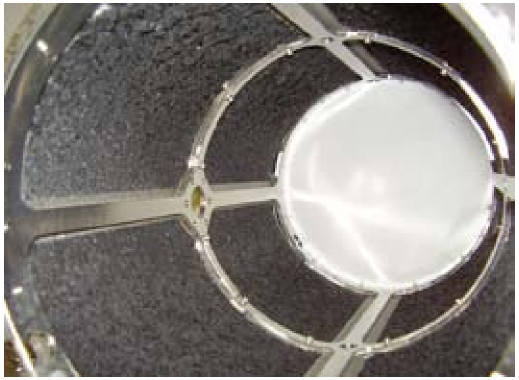


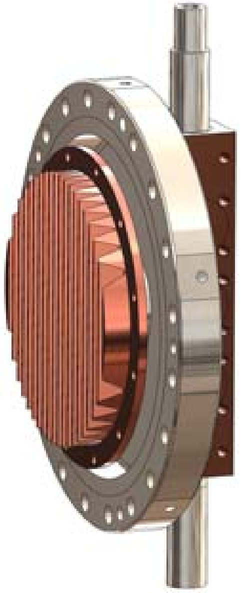
# The CSR Project

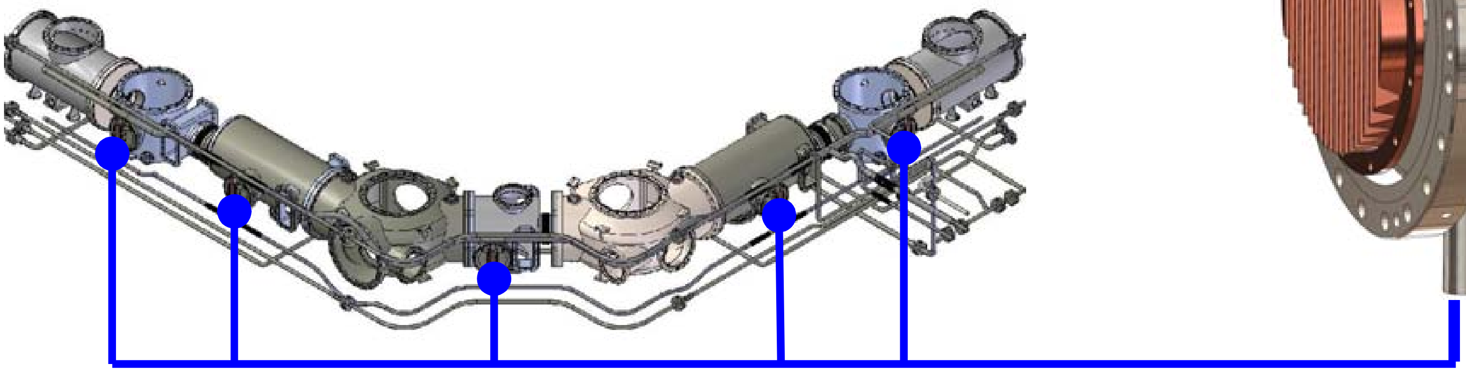
- XHV: Extremely High Vacuum

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



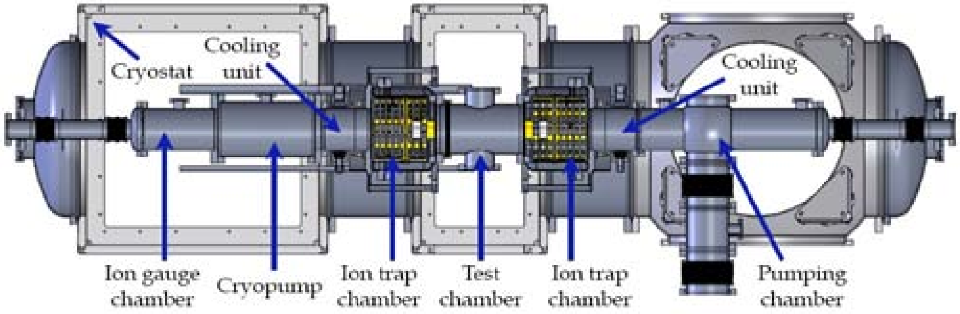
  - In < 10-K-operation: **≈ $10^{-13}$ mbar RTE**
    cryoadsorption at 10-K-walls,
    2-K cryocondensation pumps



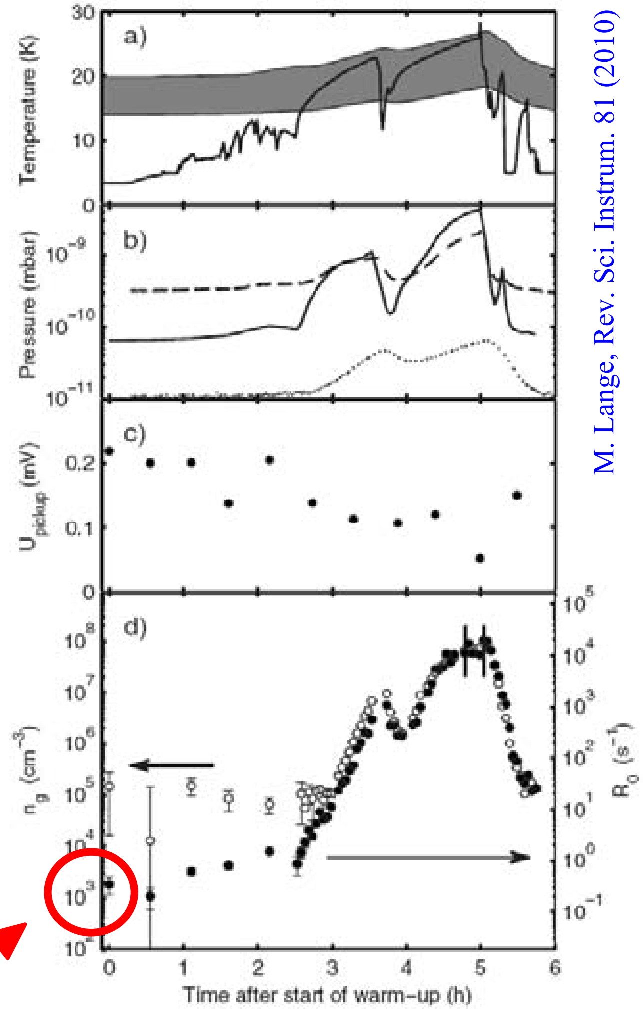


# The CSR Project

- 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**



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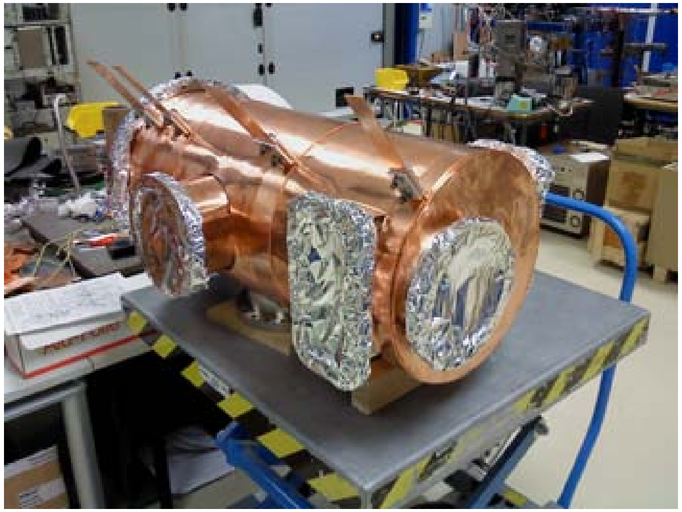
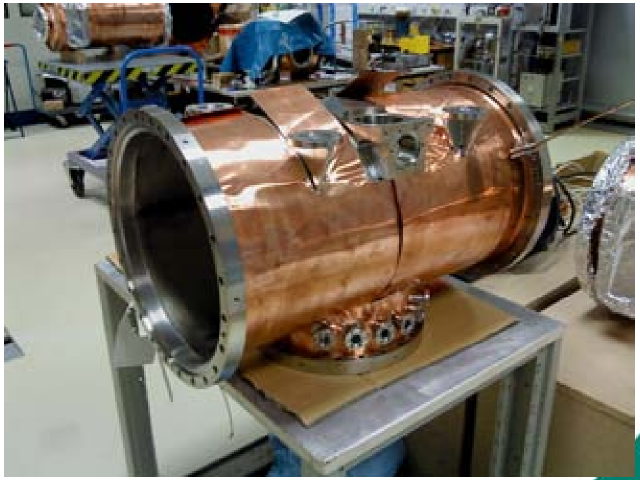
# The CSR Project

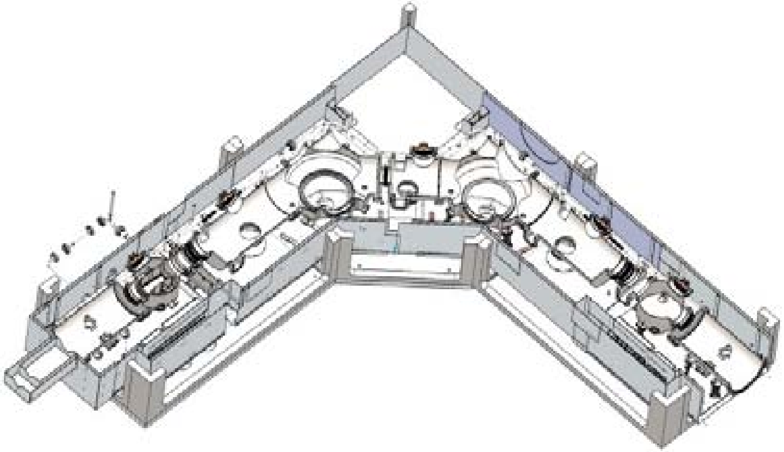
- Present status
  - Prototype (CTF) test:
    Successful. ✓
  - Isolation vacuum chamber:
    Complete. ✓
  - Inner chambers
    Available for
    1st corner section. ✓





# The CSR Project

- Present status
  - Prototype (CTF) test:
    Successful. ✓
  - Isolation vacuum chamber:
    Complete. ✓
  - Inner chambers
    Available for
    1st corner section. ✓
  - Thermal radiation shields:
    Being manufactured …
  - Cooling lines:
    Being manufactured …
  - First corner section:
    To be complete by end of 2010



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  - Limits of present-day storage rings
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  - Electron cooler
  - Detector concept
- Experimental Perspectives
  - DR with cold molecules
  - DR with heavy molecules

# DR @ CSR

- Benefits
  - **Extremely High Vacuum:**

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

    Phase-space cooling with CSR electron cooler

  - **Cold Environment:**

    State-selective experiments on IR-active species

# DR @ CSR

- Experimental challenges

  - **Electron cooler/target**

    Low ion velocities → low cathode potential

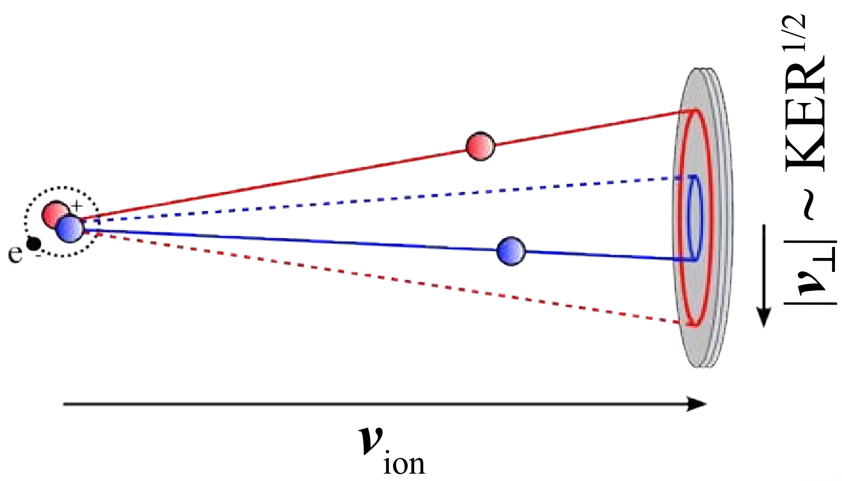
    e.g. for $M = 160$ u @ 300 keV : $\boldsymbol{E_e \approx 1}$ **eV (!)**


  - **DR fragment detectors**

    Low-energetic particles difficult to detect

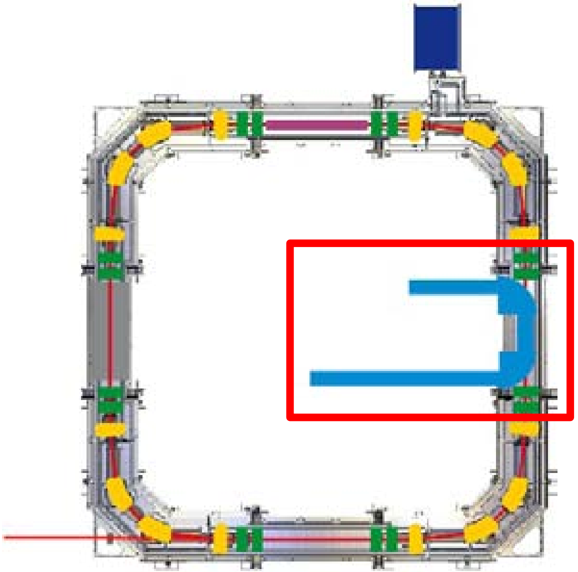
    Wide fragmentation cones for light fragments / large KER

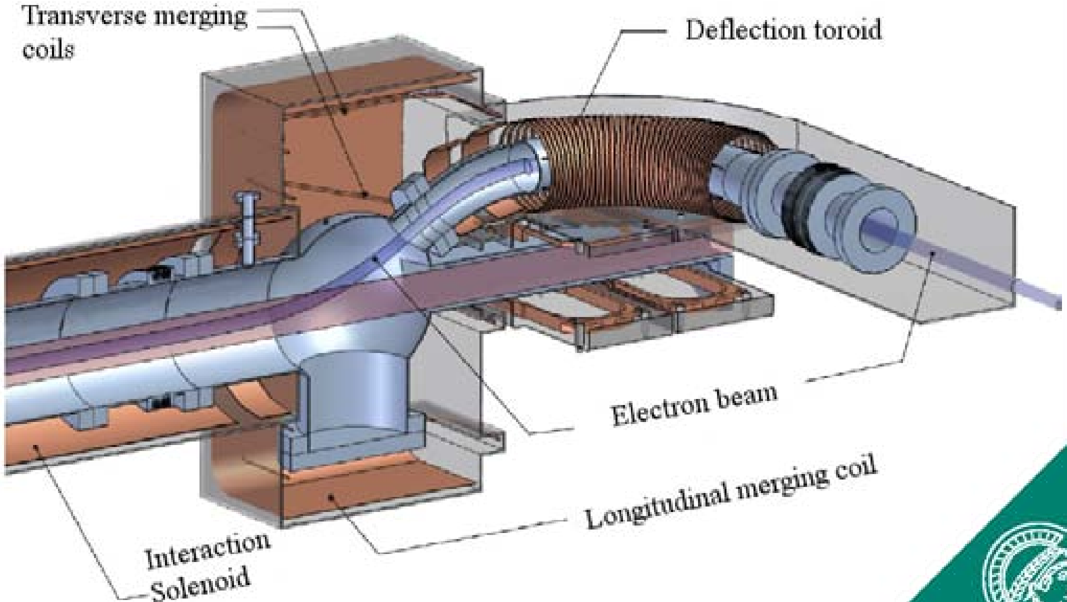
    Extreme requirements on materials (10 … 600 K, $10^{-13}$ mbar, ...)



# DR @ CSR

- Electron cooler
  - Low energy electron beam:
    **~ 1000 eV … 1 eV**
  - "parallel beams" merging scheme
    less disturbance of stored CSR beam.
  - Photocathode e-source
    superior temperature,
    vacuum compatibility





# DR @ CSR

- 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:

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

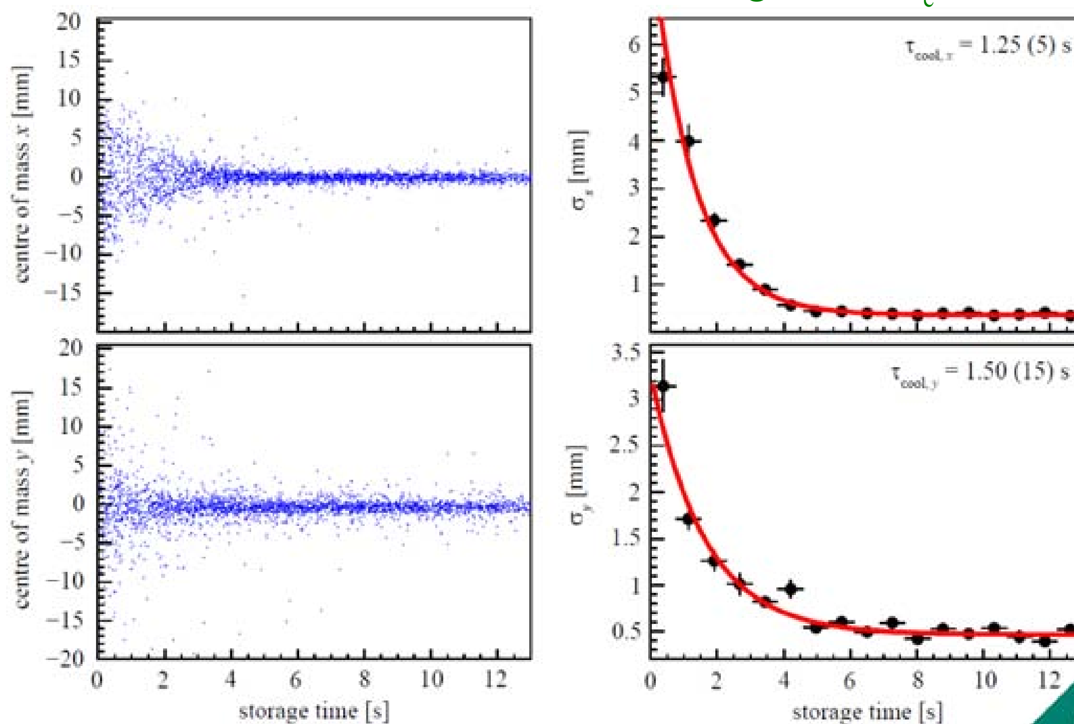
  - At low $E_e$:

    $n_e$ limited
    by e-gun
    perveance!

  - Beam temperature

    becomes the
    decisive factor!

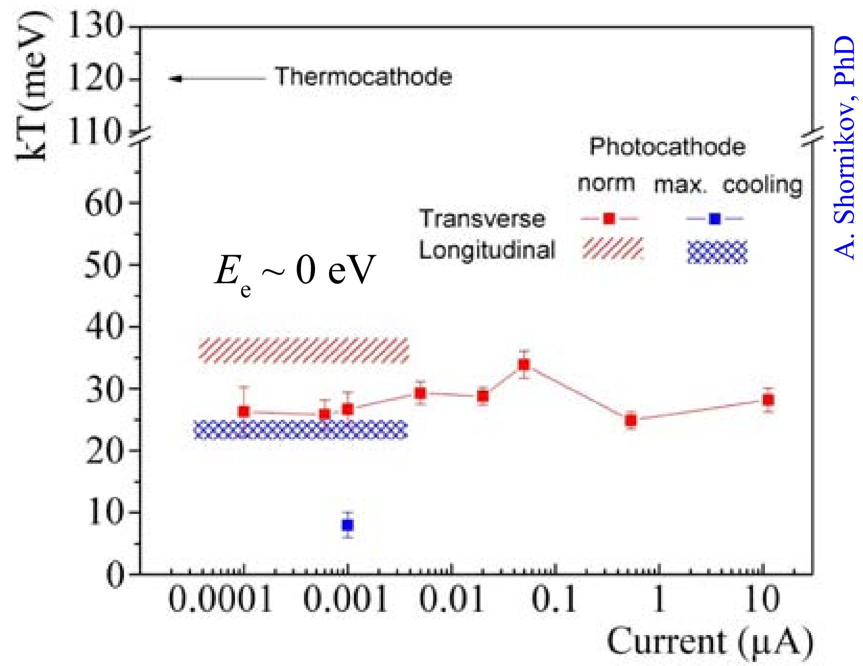
TSR: Cooling $CF^+$ at $E_e$ = 46 eV

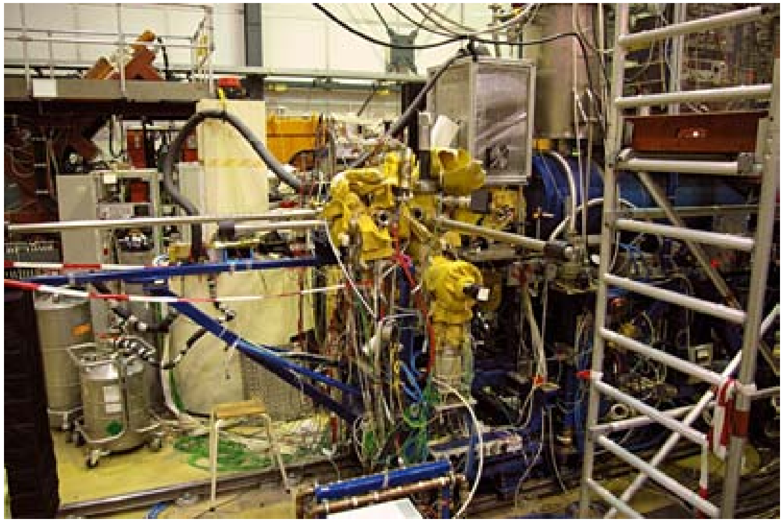


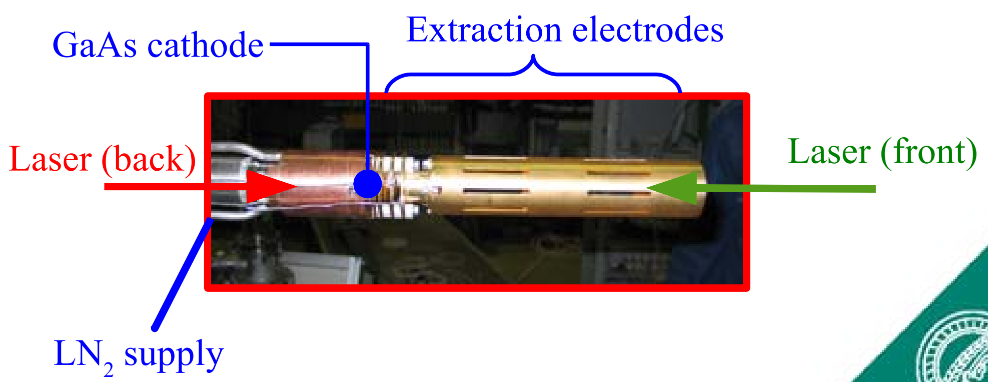
# DR @ CSR

- Electron temperature
  - TSR photocathode electron gun:

    ~ 10 times lower $T_e$ than thermionic electron gun



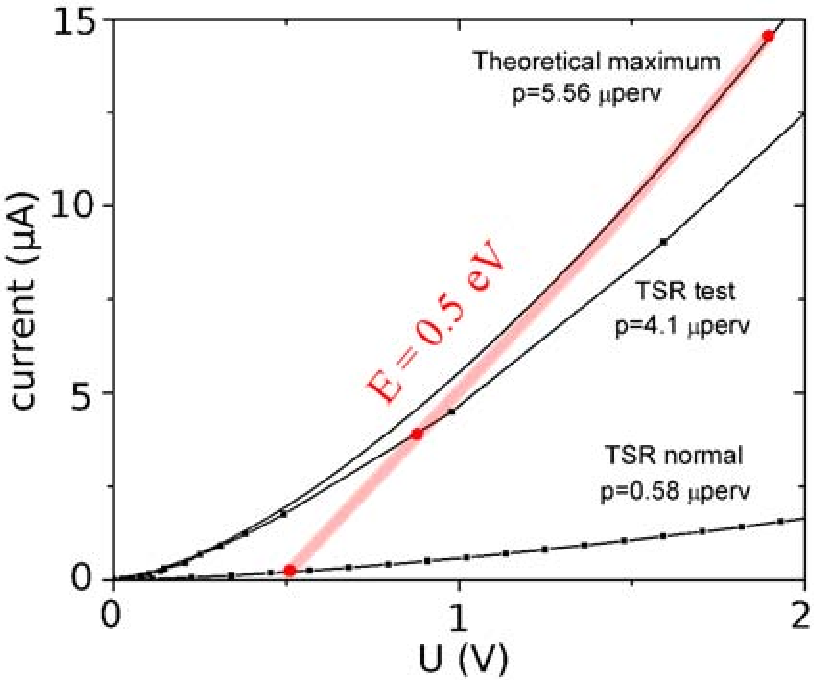





# DR @ CSR

- Electron energy
  - Calibration of $E_e$ against cathode potential
    taking beam space charge and
    work function differences into account
  - Current:
    few µA at $U_{cath} = 1$ V

    = few $10^5$ cm$^{-3}$



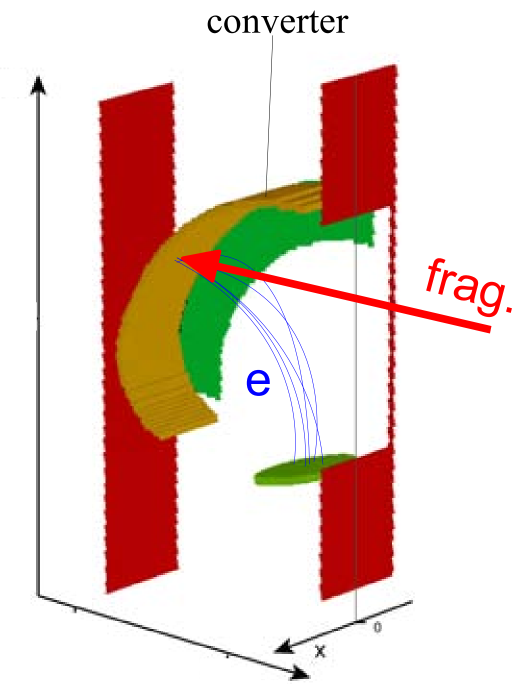

A. Shornikov, to be published

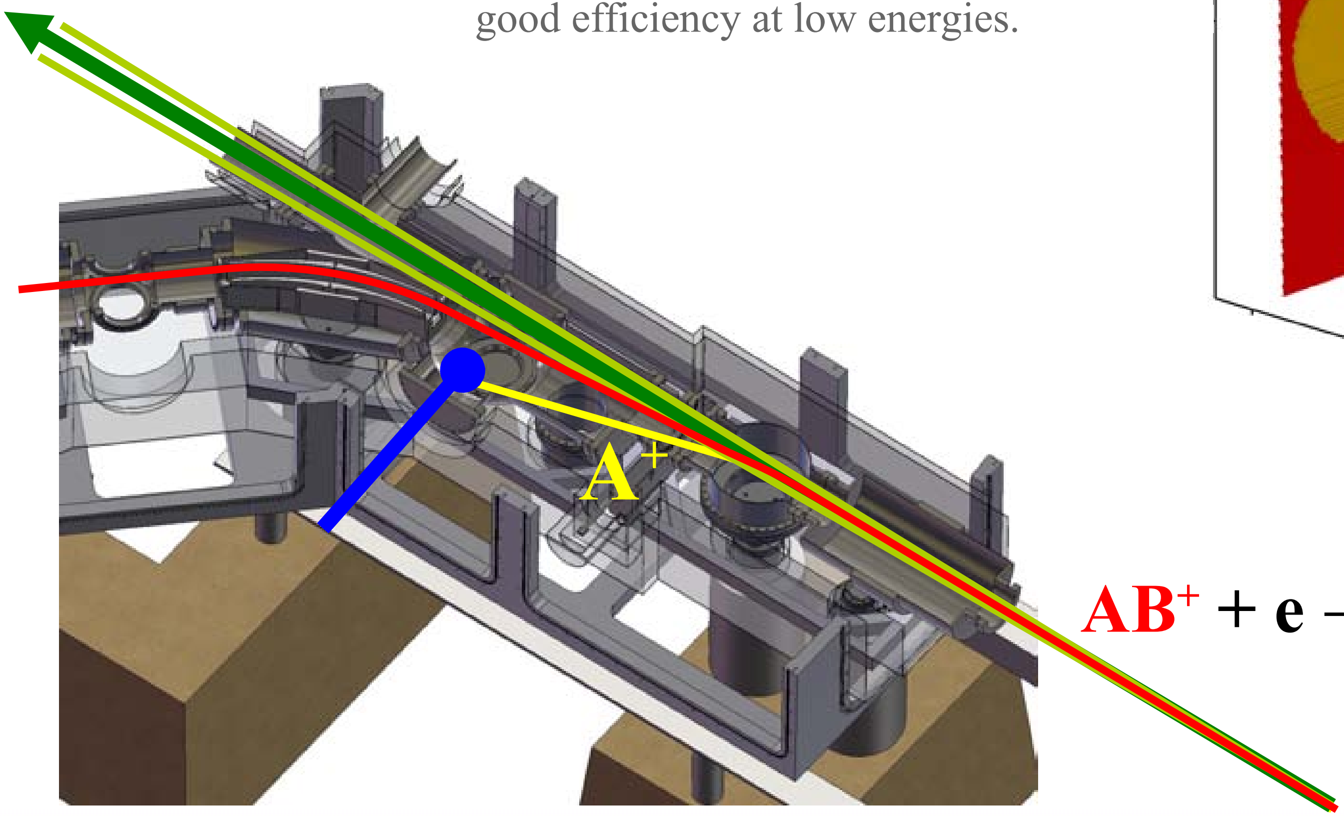
# DR @ CSR

- DR fragment detectors
  - Detectors for charged fragments:

    Placed after bending elements.

    Open, secondary-electron converter for good efficiency at low energies.




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

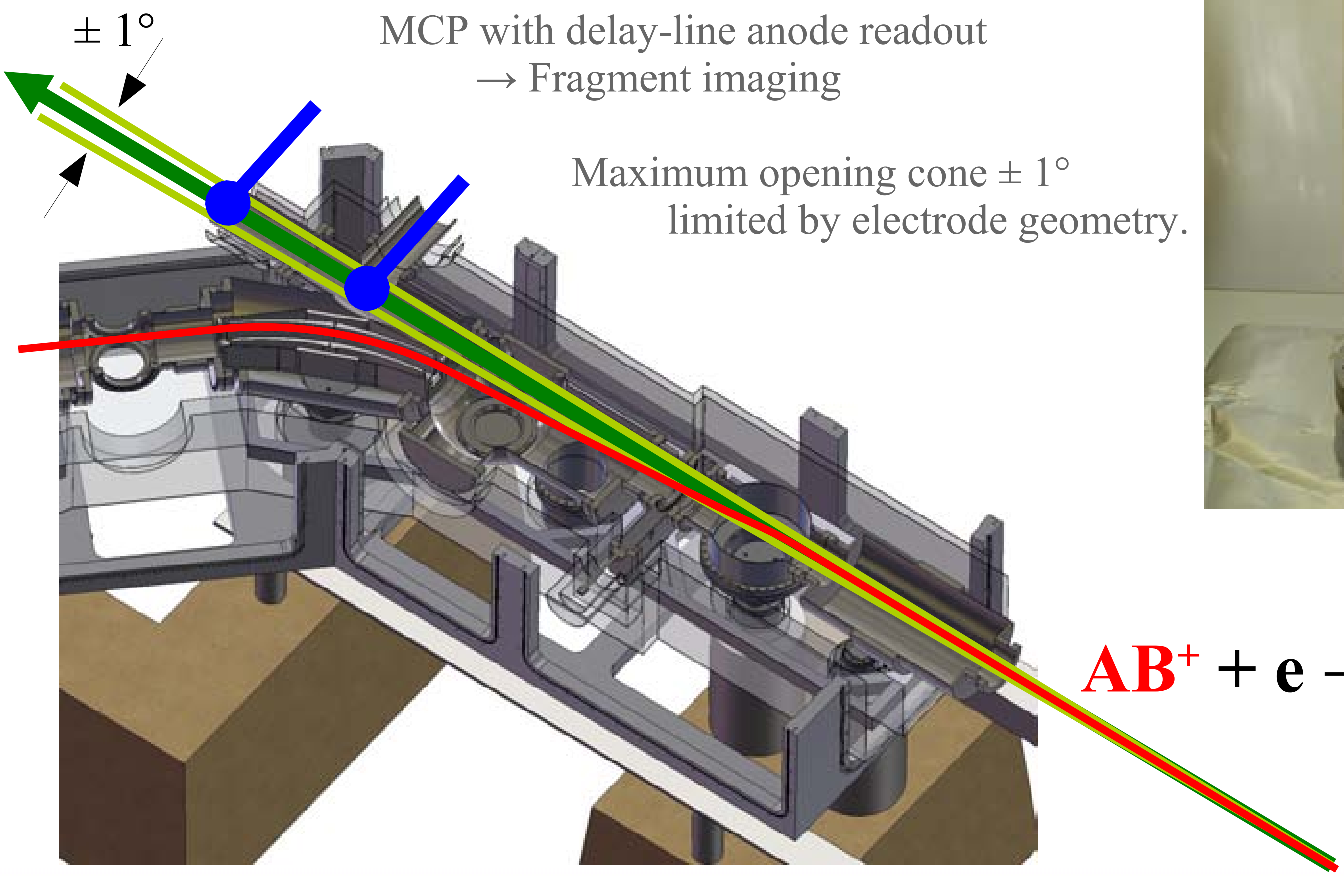
# DR @ CSR

- DR fragment detectors
  - Detectors for neutral fragments:

Placed in chambers of 39° bending elements

MCP with delay-line anode readout
→ Fragment imaging

Maximum opening cone ± 1°
limited by electrode geometry.

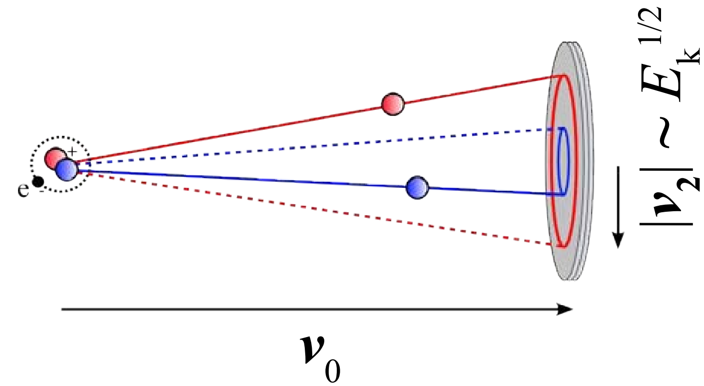


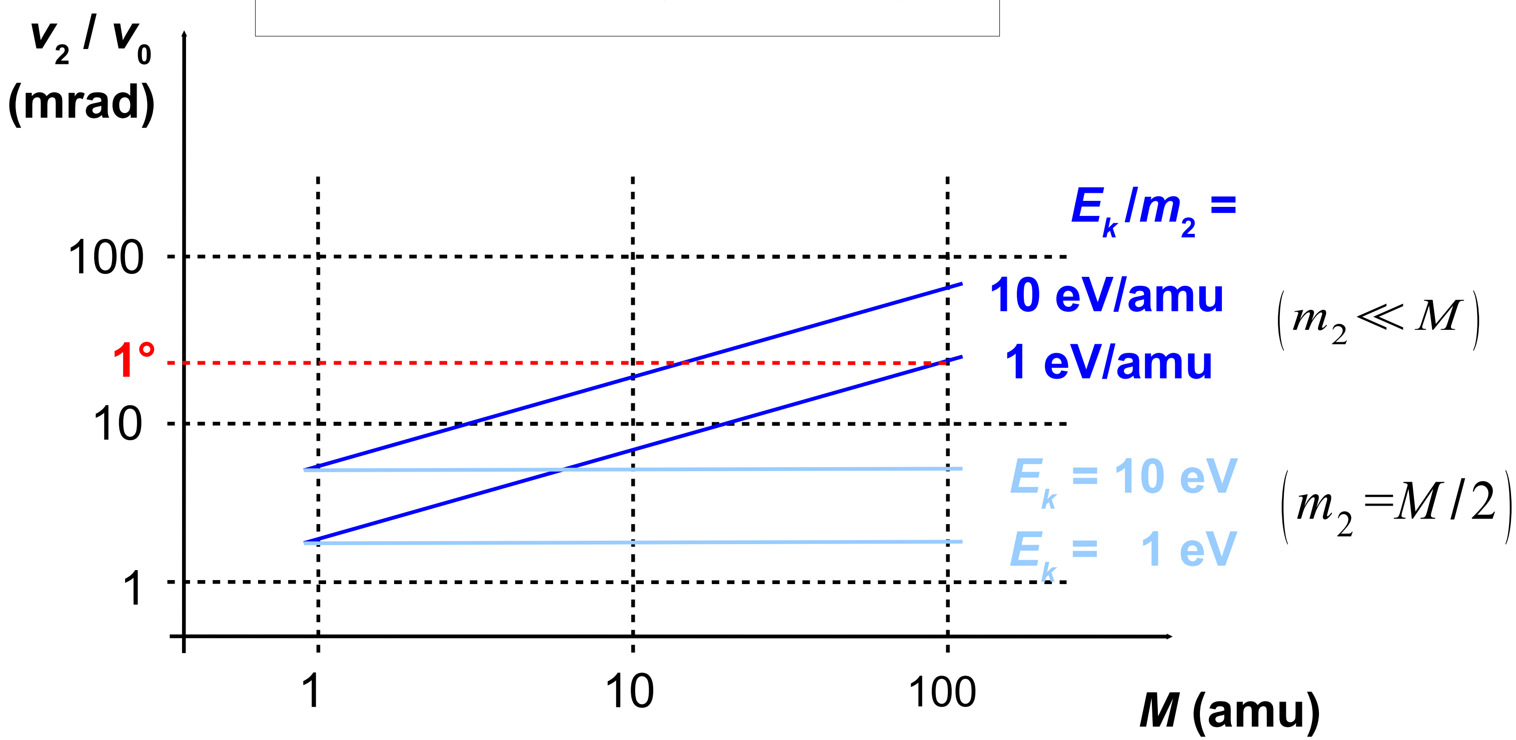

$AB^+ + e \rightarrow A + B$

# DR @ CSR

- Neutral fragment acceptance

$$
\begin{aligned}
v_2/v_0 &= \sqrt{E_k/E_0}\sqrt{Mm_r}/m_2 \\
&\approx \sqrt{E_k/m_2 E_0} \quad (m_2 \ll M) \\
&= \sqrt{E_k/E_0} \quad (m_2 = M/2)
\end{aligned}
$$

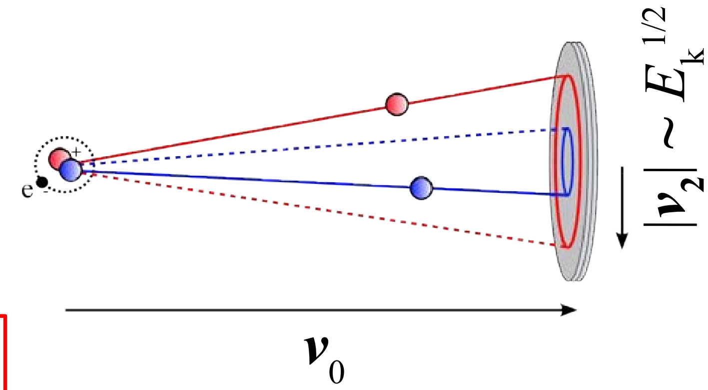


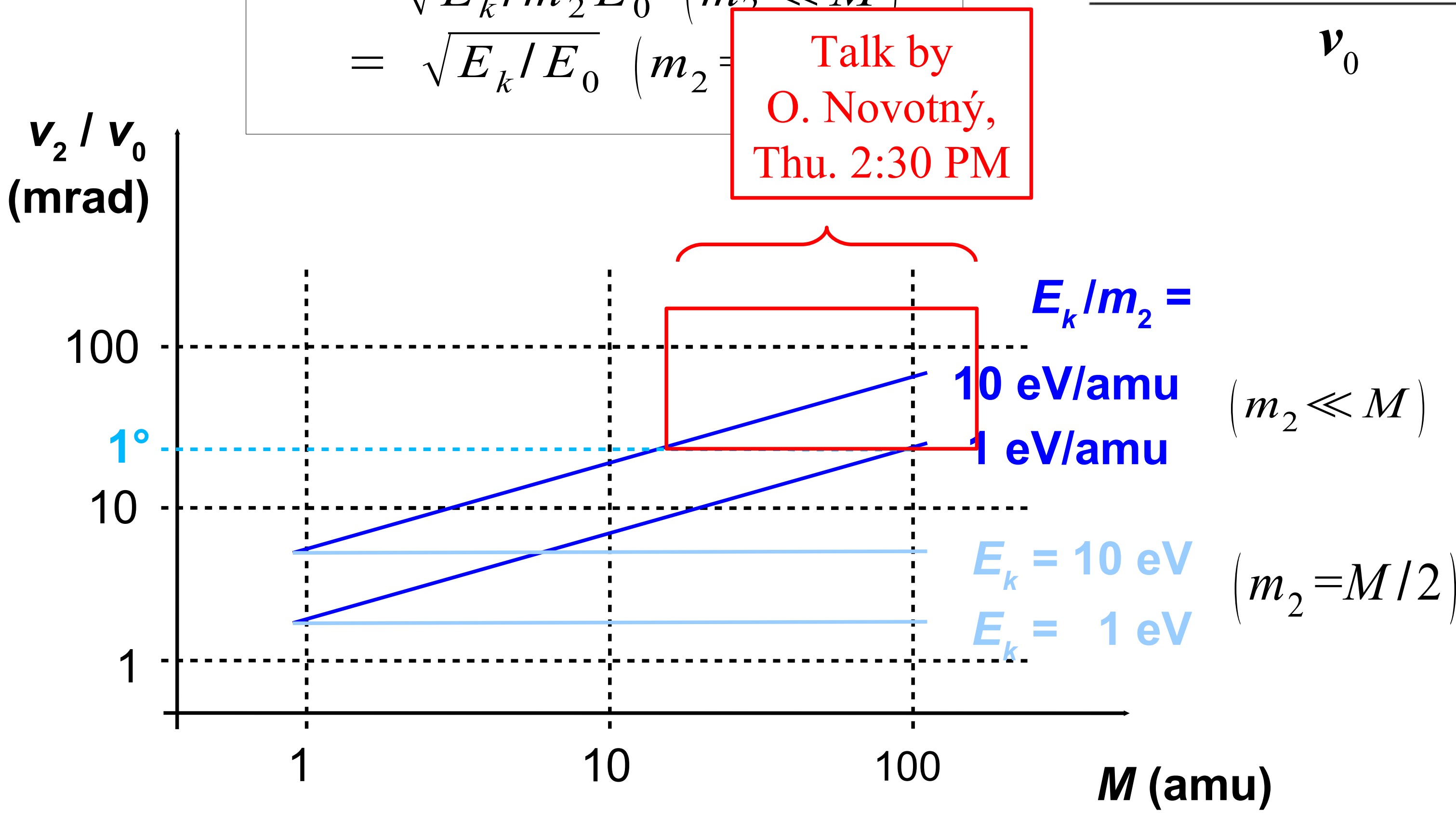



# DR @ CSR

- Neutral fragment acceptance

$$\begin{aligned} v_2/v_0 &= \sqrt{E_k/E_0}\sqrt{Mm_r}/m_2 \\ &\approx \sqrt{E_k/m_2 E_0} \quad (m_2 \ll M) \\ &= \sqrt{E_k/E_0} \quad (m_2 = \end{aligned}$$



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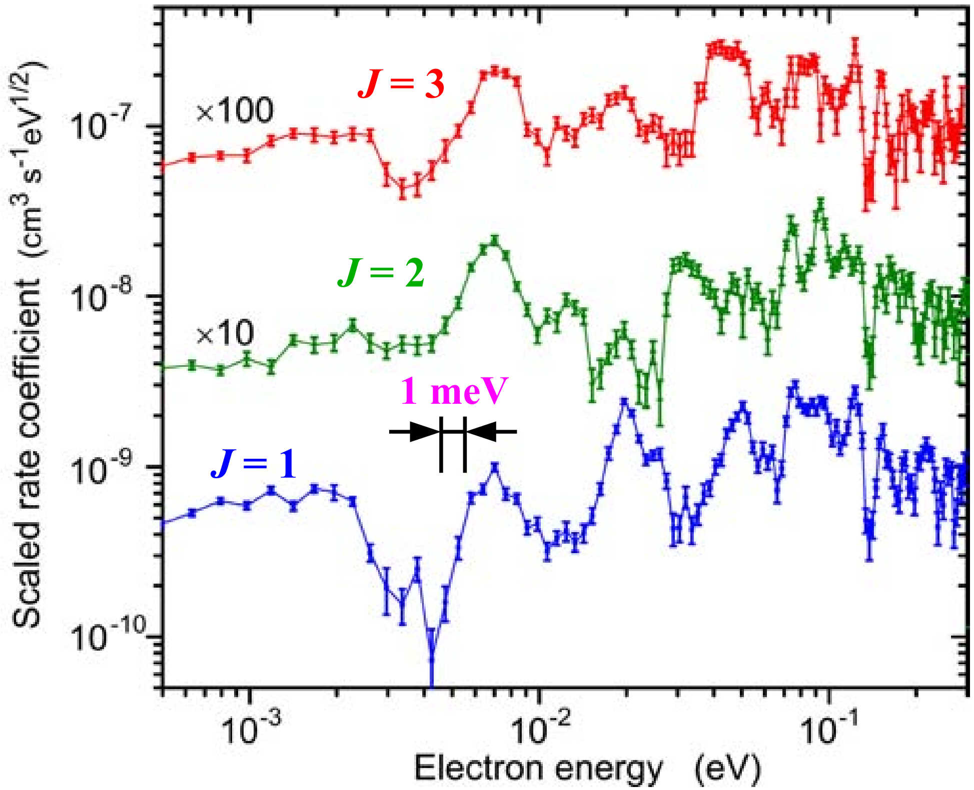
# Outlook: first DR experiments

- State selective DR
  - $H_2^+$ produced in rotational state-selective ion source: $v \in \{0, 1\}$ , $J \in \{0, 1, 2\}$ ("LISE", X. Urbain et al.)
  - Storage in TSR (300 K) possible due to missing dipole moment.
  - IR active species ($HD^+$) need cryogenic environment to reach and preserve lowest rovibrational states.

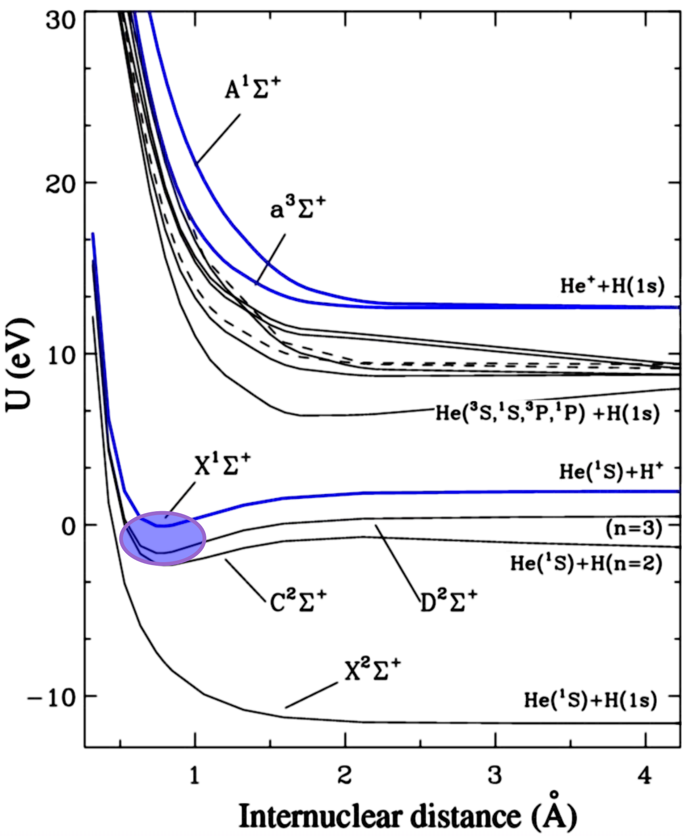
$H_2^+(v = 0) + e \rightarrow H\,(1s) + H\,(n = 2)$

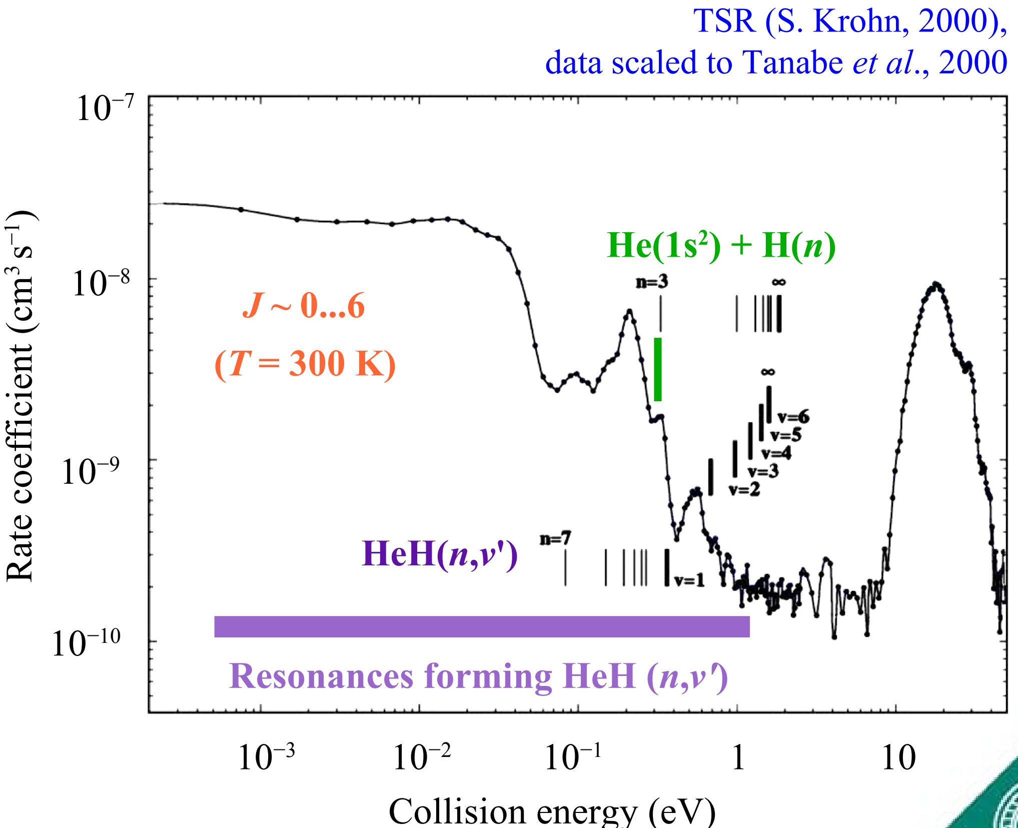



S. Novotny, PhD (2008)

# Outlook: first DR experiments

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



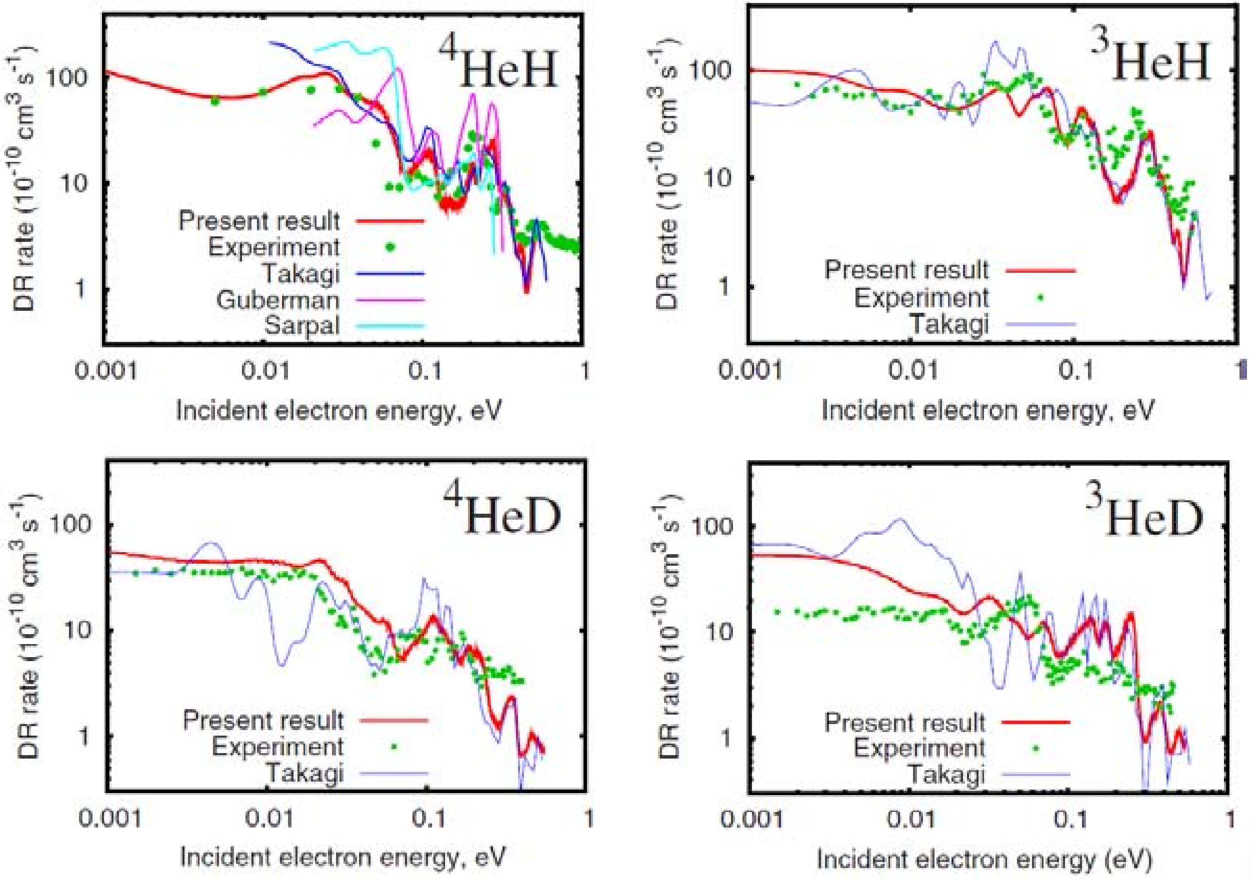
# Outlook: first DR experiments

- 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 → $J$ = 0**




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

# Outlook: first DR 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-DR background, …
  - … but CSR has:
    - Extremely High Vacuum
    - Long storage times
    - Electron cooling
    - Good recombination/collision signal ratio

# Outlook: first DR experiments

- Slow heavy ions
  - Heavy noble gas dimers: $Ar_2^+$, …
  - Large organic molecules $C_xH_y$, ...
  - Fluorines $CF_n^+$
    Industrially important
    CF+ heaviest ion studied at TSR
  - Cluster ions …
    Dependence of rate coefficients on cluster temperature ...

# Summary

- CSR, a next-generation storage ring is in construction.
- The first corner of the ring will be finished by end 2010.
- Its low-energy electron cooler makes the CSR the first electrostatic ring suitable for precision DR studies.
- Extremely high vacuum, cryogenic environment and ability to store large-mass ions provide unique new experimental opportunities for DR.

# Thank you!

Klaus Blaum
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Roland Repnow
Andrey Shornikov
Andreas Wolf
C. K.

# Thank you!