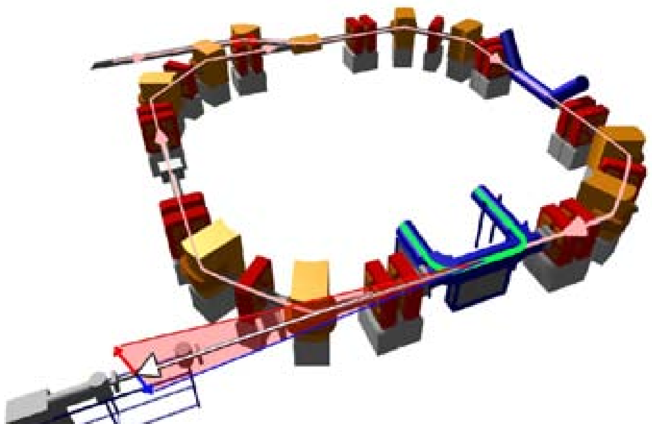
The Cryogenic Storage Ring CSR: Present Status and Outlook

Claude Krantz
Max-Planck-Institute for Nuclear Physics

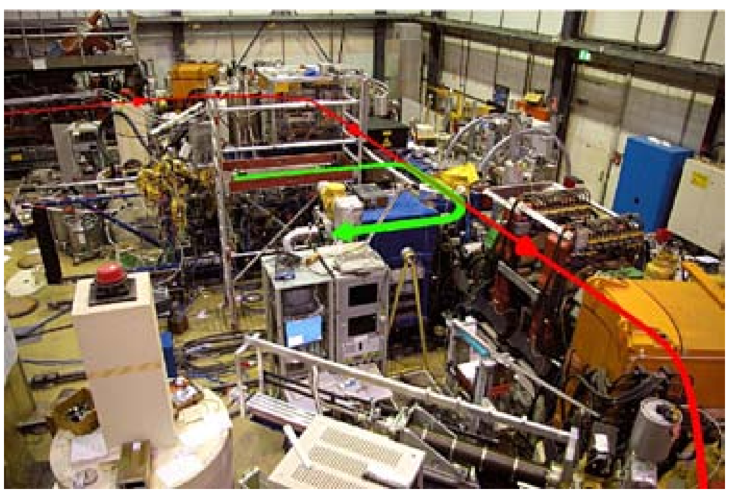
- Status of the CSR Project
- Outlook: Experimental Facilities

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:

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

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

The CSR Project

- Why electrostatic storage rings?

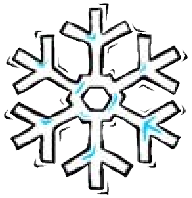
  - Use static electric field to deflect ions:
    Deflecting force becomes velocity-independent.
    Momentum selective ↔ energy selective.

    $$\boxed{q\,v\,B \leftrightarrow q\,E}$$

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

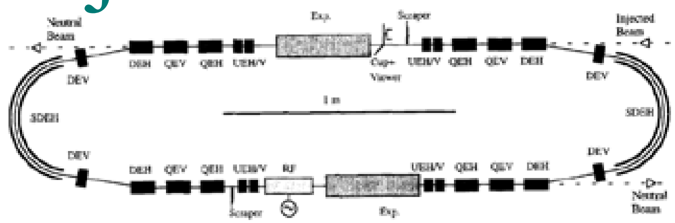
    $$\boxed{v_{\max} \sim M^{-1} \quad \text{vs.} \quad v_{\max} \sim M^{-1/2}}$$

  - Easy to operate at room and cryogenic temperature.
    Vast improvement of residual gas density. → **Much longer** storage times!
    Control of IR background radiation.



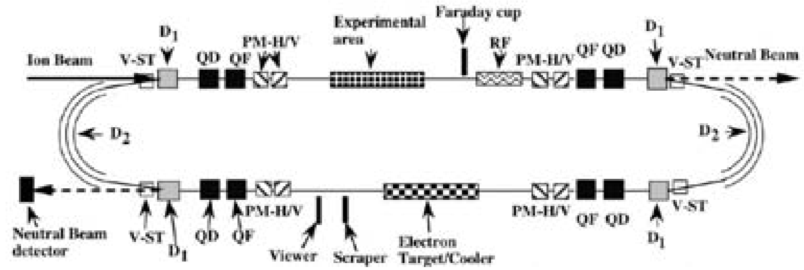
The CSR Project

- First electrostatic storage rings

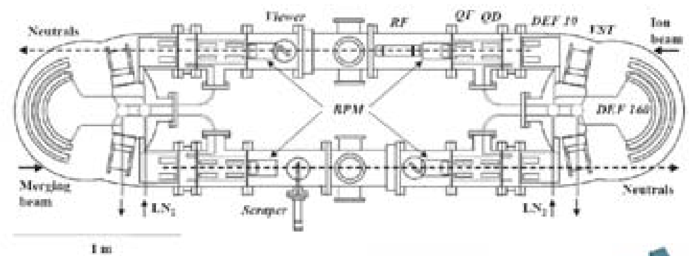


Møller, NIM A 394

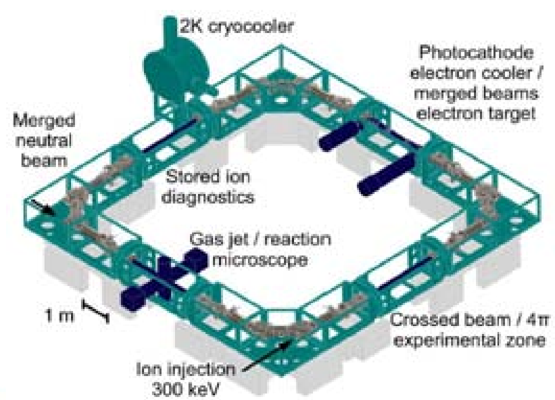
  - ELISA (Aarhus, 1998)
    Racetrack design,
    25 keV/q, room temp.
  - KEK Ring (Tsukuba, 2001)
    ELISA design,
    Electron target
  - TMU Ring (Tokyo, 2004)
    77 K (LN_2)
  - DESIREE (Stockholm, *in constr.*)
    Double ring (ion-ion interact.),
    < 20 K,
    25 kV and 100 kV injectors
  - CSR (Heidelberg, *in constr.*)
    < 10 K,
    300 keV/q
    electron cooling

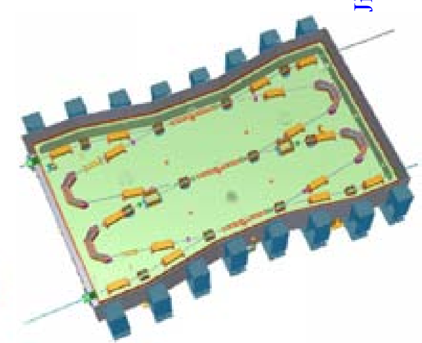


Tanabe, NIM A 482



Jinno, NIM A, 532



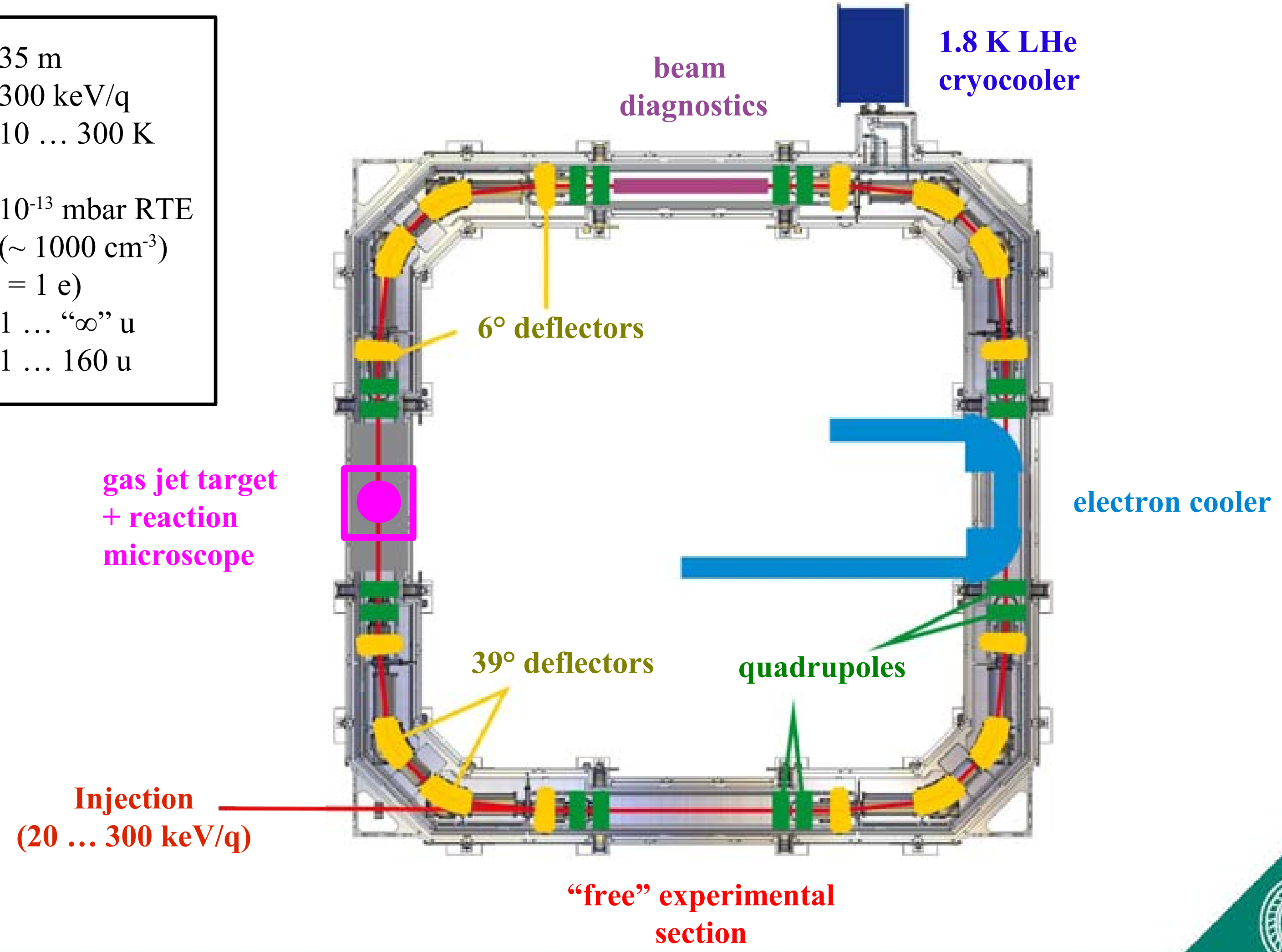


Löfgren, Proc. EPAC06

The CSR Project

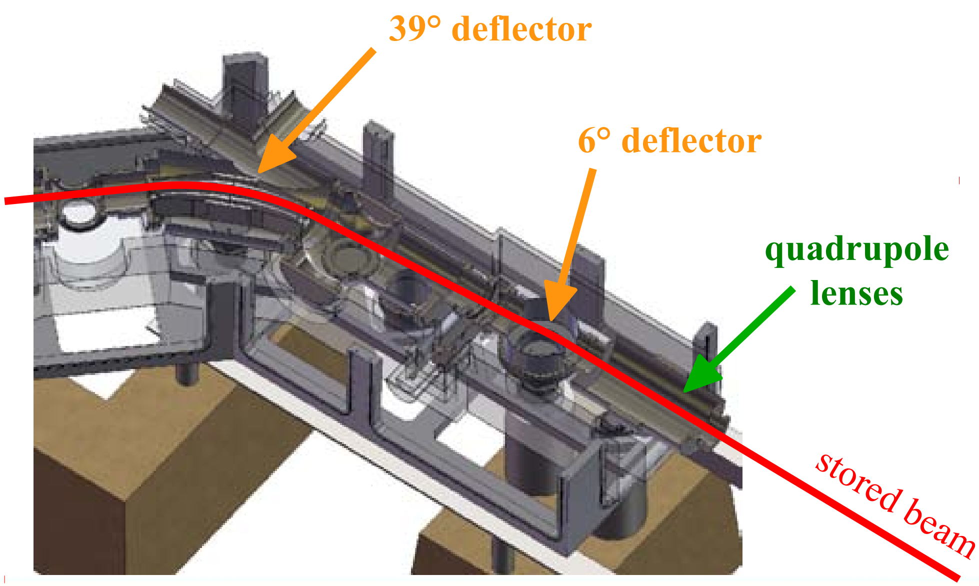
- CSR: a full-featured next generation storage ring

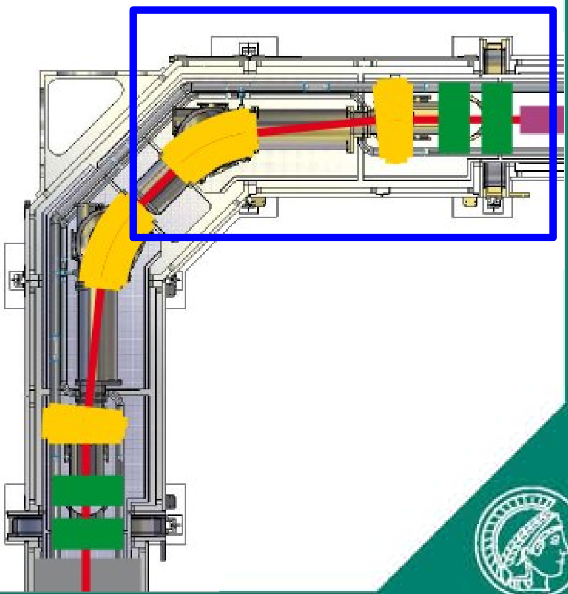
circumference:	35 m
beam energy:	300 keV/q
temperature:	10 … 300 K
res. gas press.	
(@ < 10 K):	10^{-13} mbar RTE
	(~ 1000 cm^{-3})
ion masses (for q = 1 e)	
no cooling:	1 … "∞" u
with cooling:	1 … 160 u



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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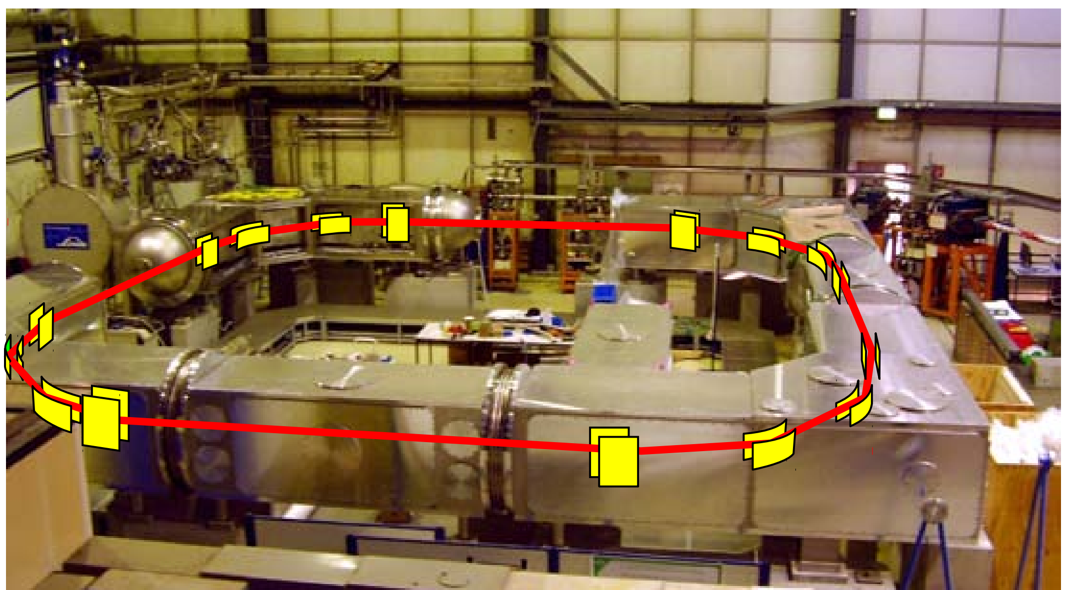
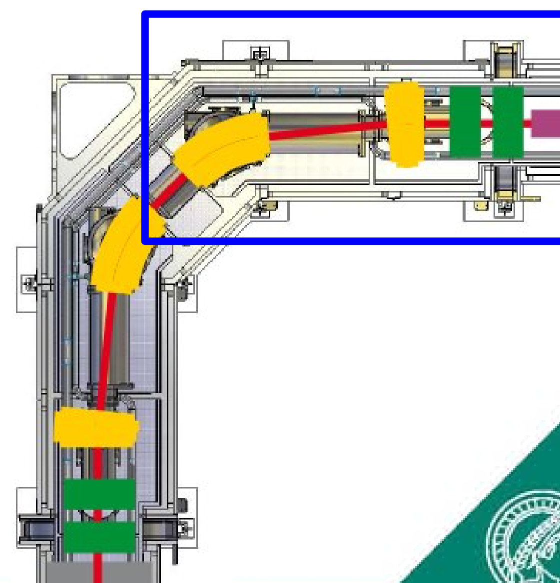
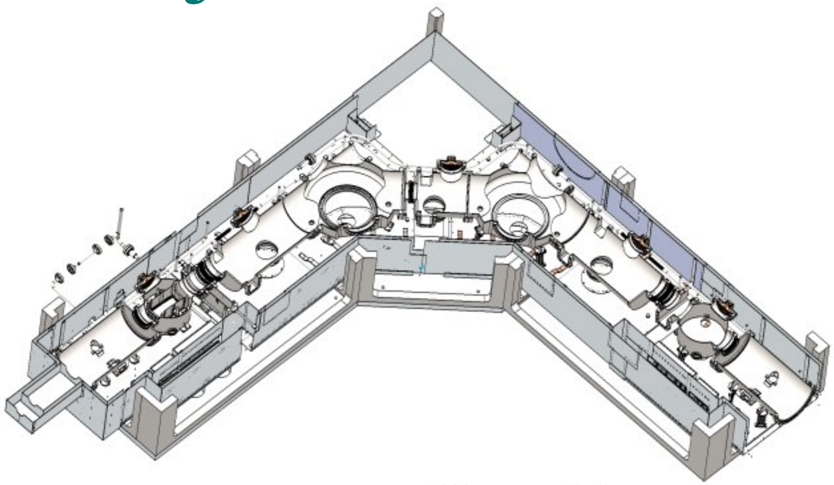
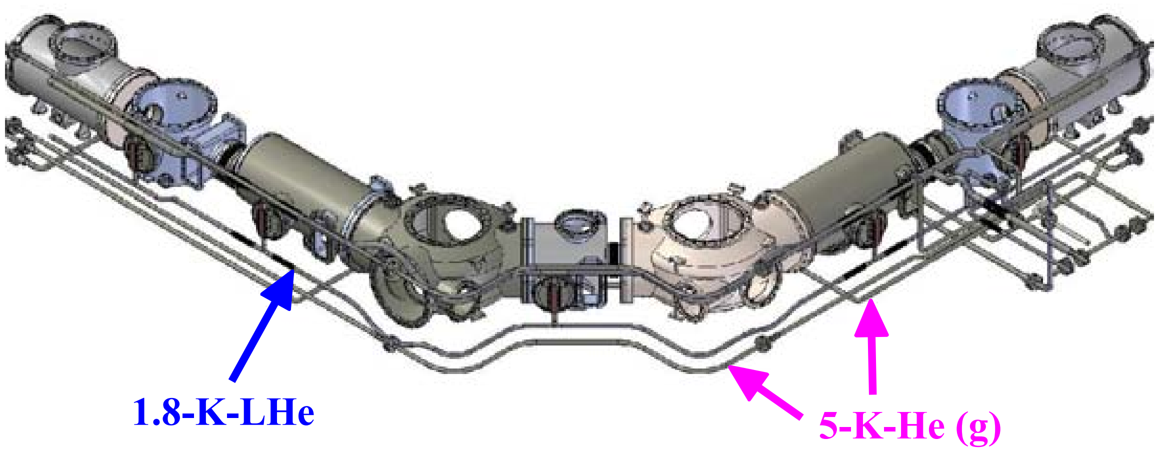


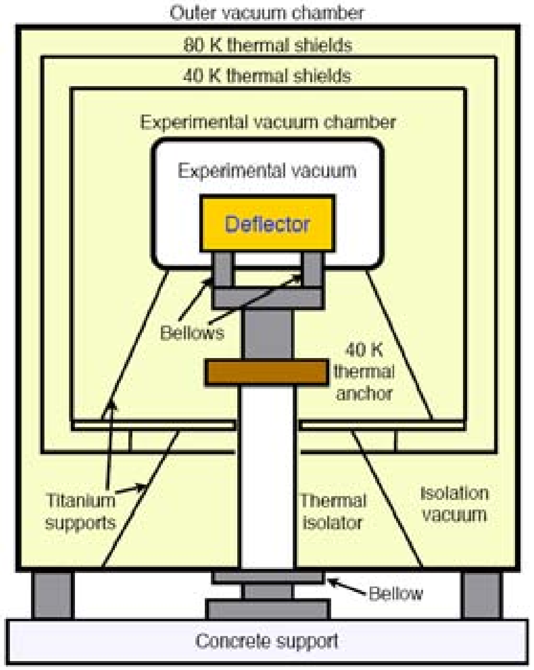


The CSR Project

- 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

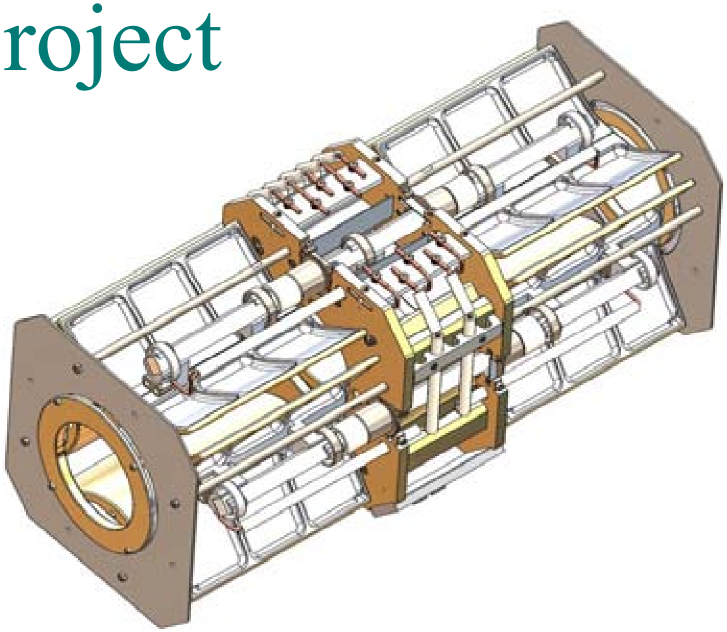


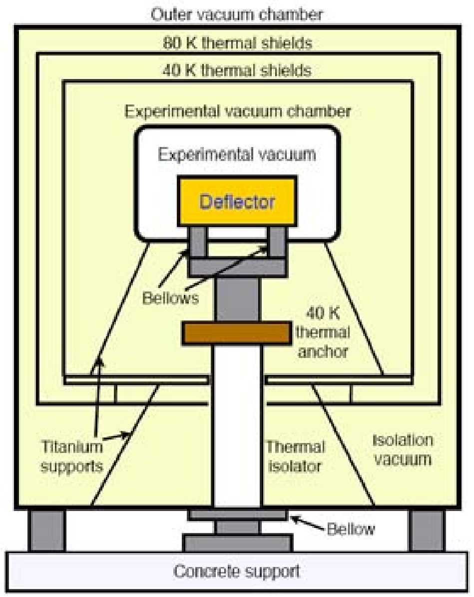


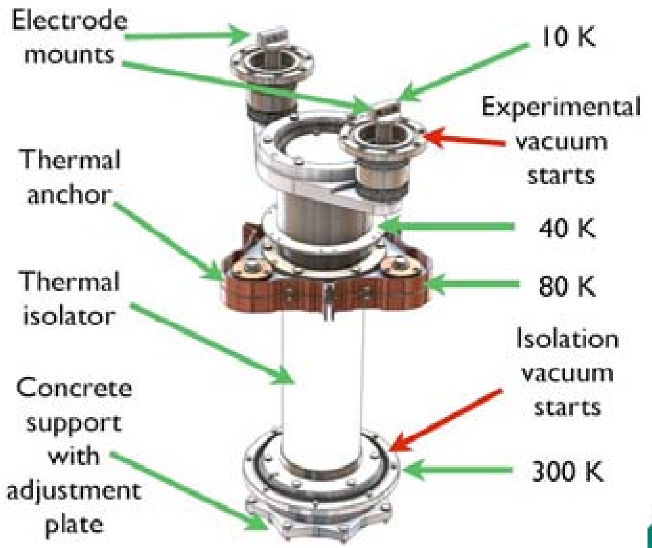


The CSR Project

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







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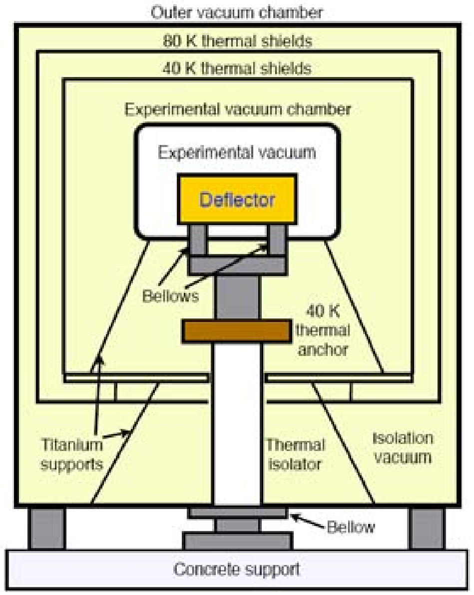

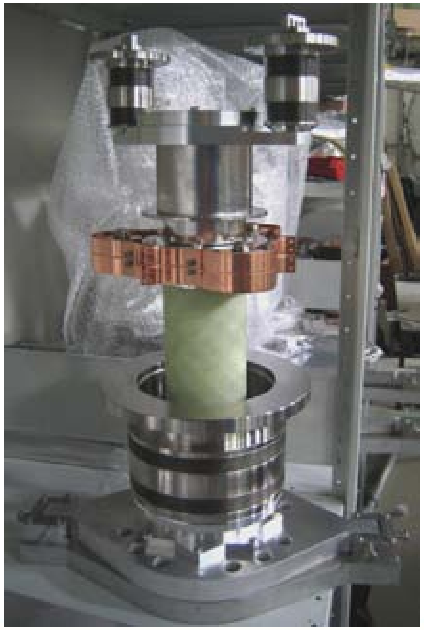

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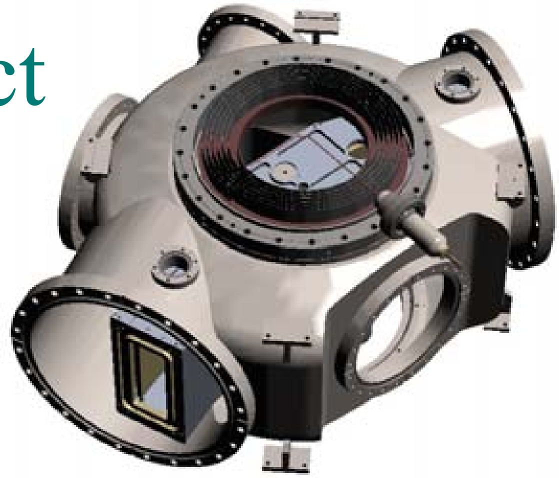
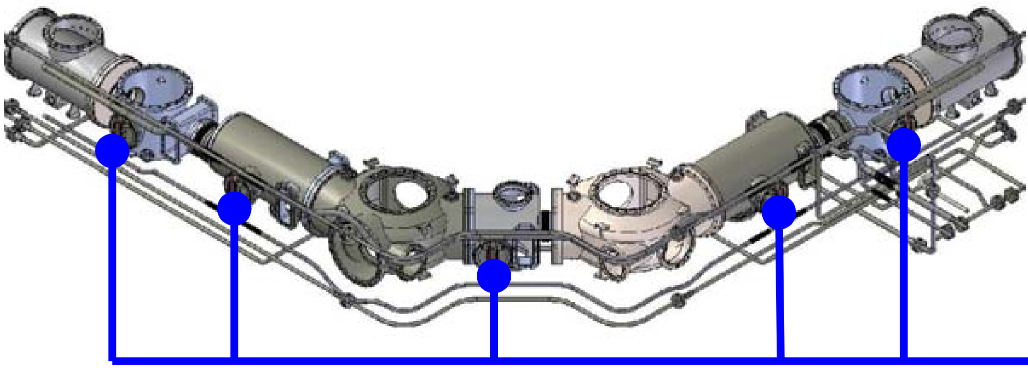


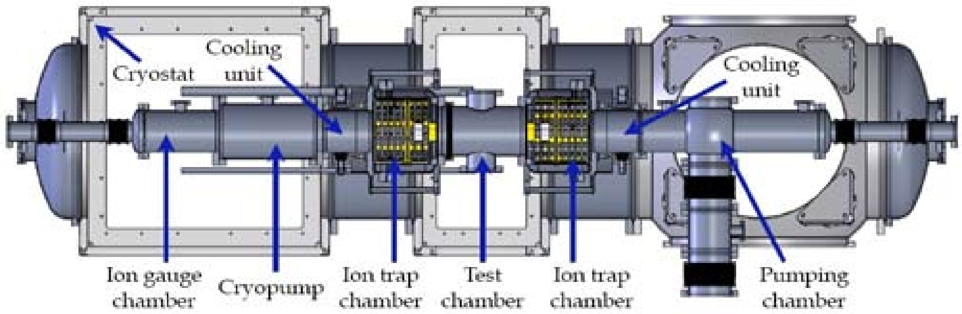
- XHV: Extremely High Vacuum
  - In 300-K-operation: **~ 10^{-11} mbar**
    200°C – 300°C bakeout,
    Ion-getter pumps,
    NEG surfaces,
    bakeable charcoal cryopumps

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

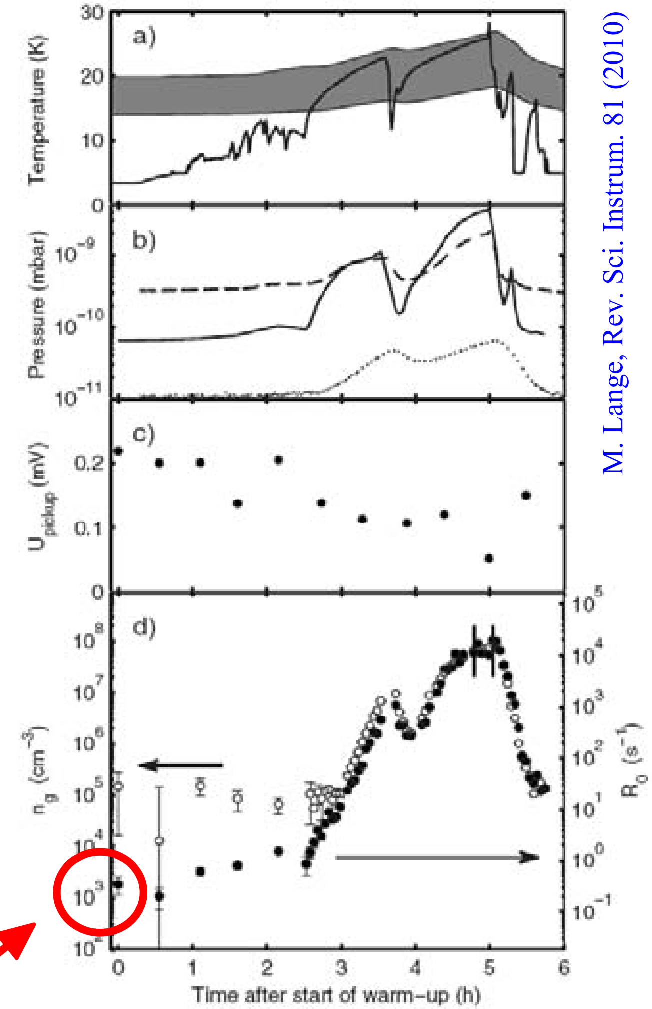


The CSR Project

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



M. Froese, PhD (2010)



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

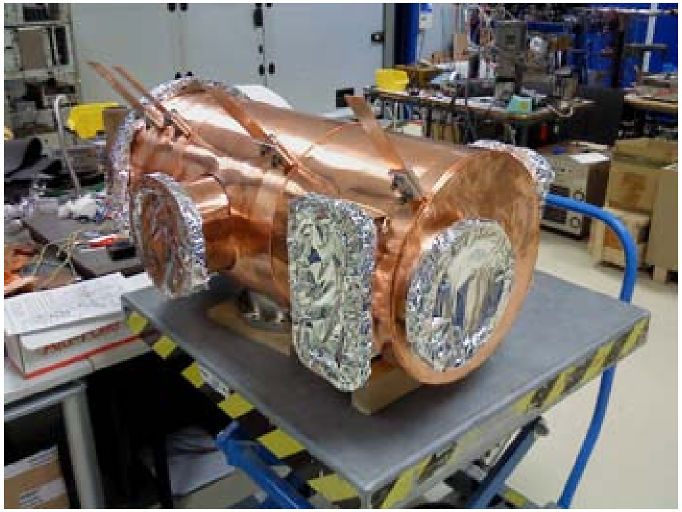
Experiments @ CTF:
Talk by M. Lange
Fri, 11:00

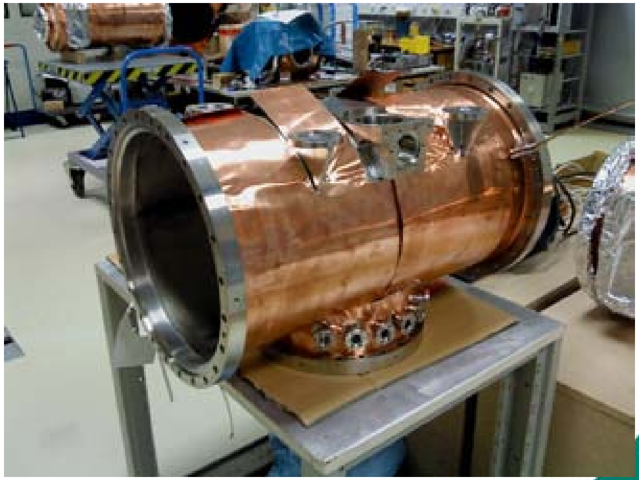
$2\,(1) \cdot 10^{3}$ cm^{-3}
$= 8\,(4)\ 10^{-14}$ mbar RTE

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

The CSR Project

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





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  - 1^{st} corner section:
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    Thermal shields ✓

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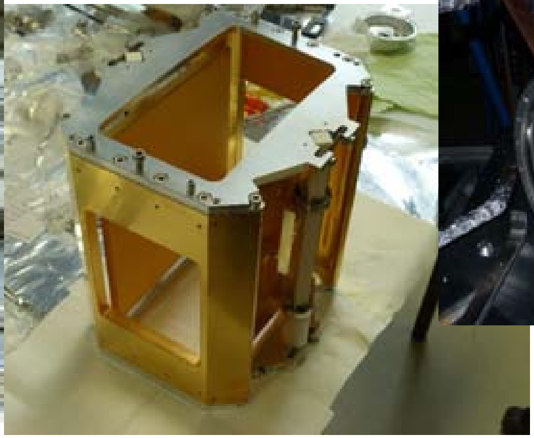
    Ion optics ✓



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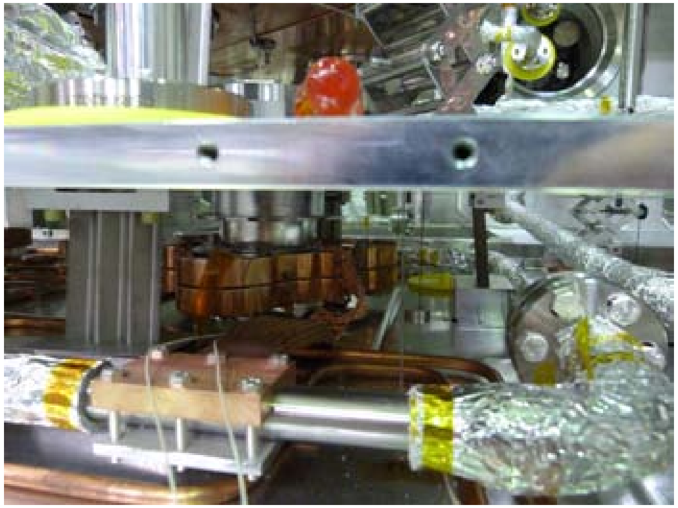
  - Ongoing (1st corner) ...
    Electrode alignment
    Installation of cooling lines



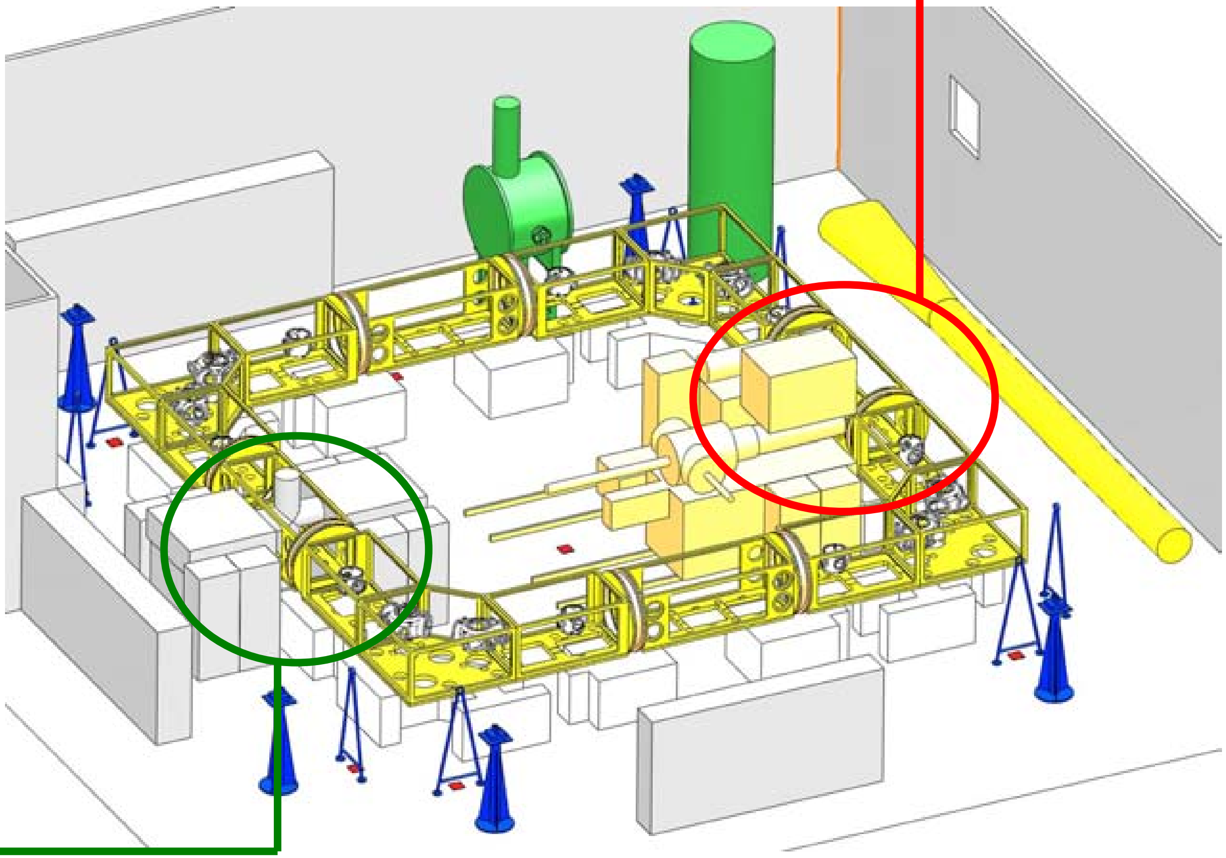
Max-Planck-Institut für Kernphysik

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

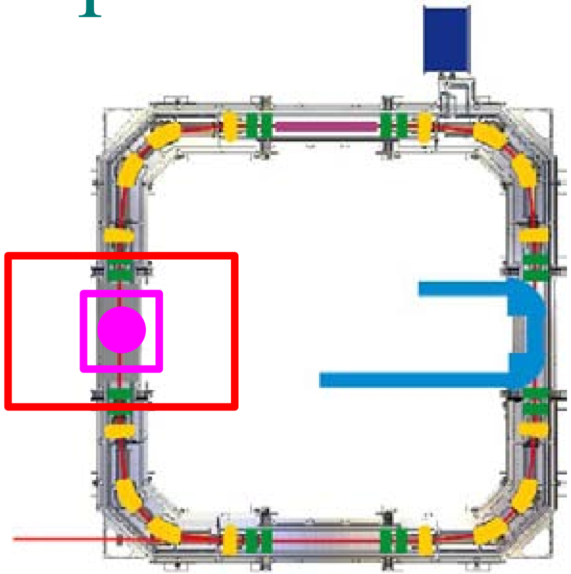
Experimental Sections

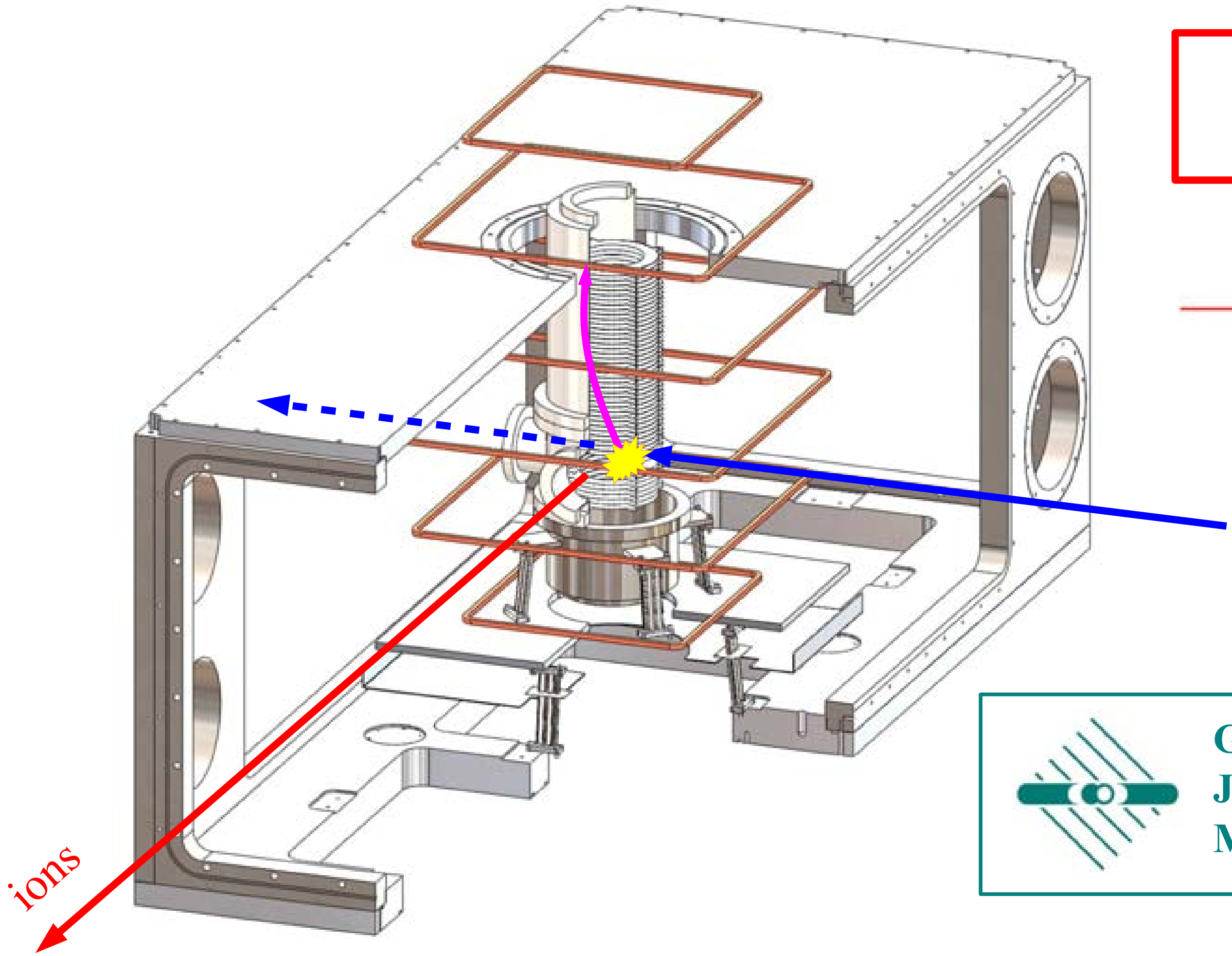
- Electron cooler / electron target
- Gas-jet target / reaction microscope



Reaction Microscope

- Interaction section

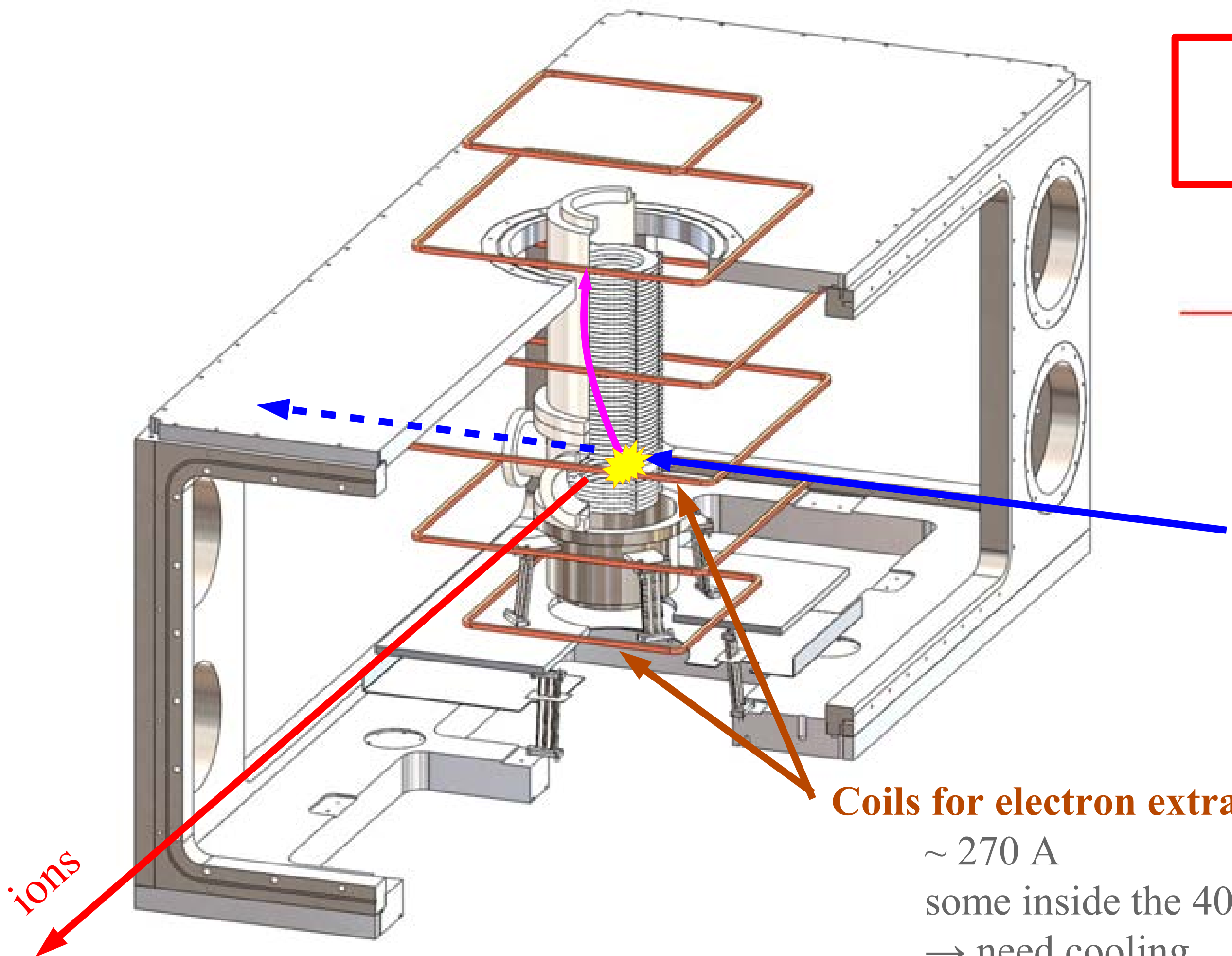


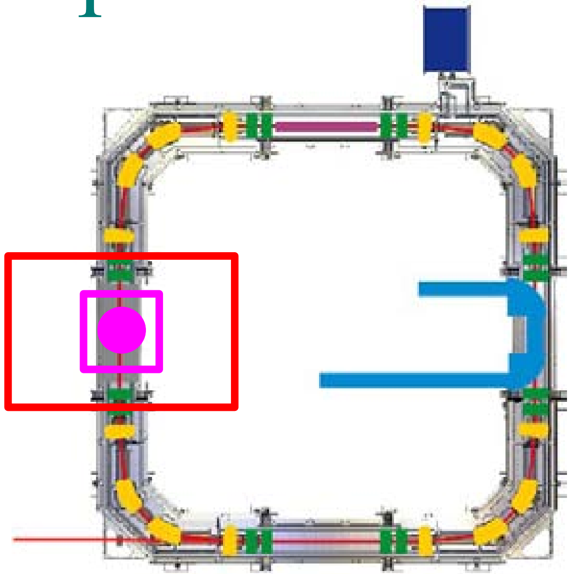


Group of
J. Ullrich,
MPIK

Reaction Microscope

- Interaction section



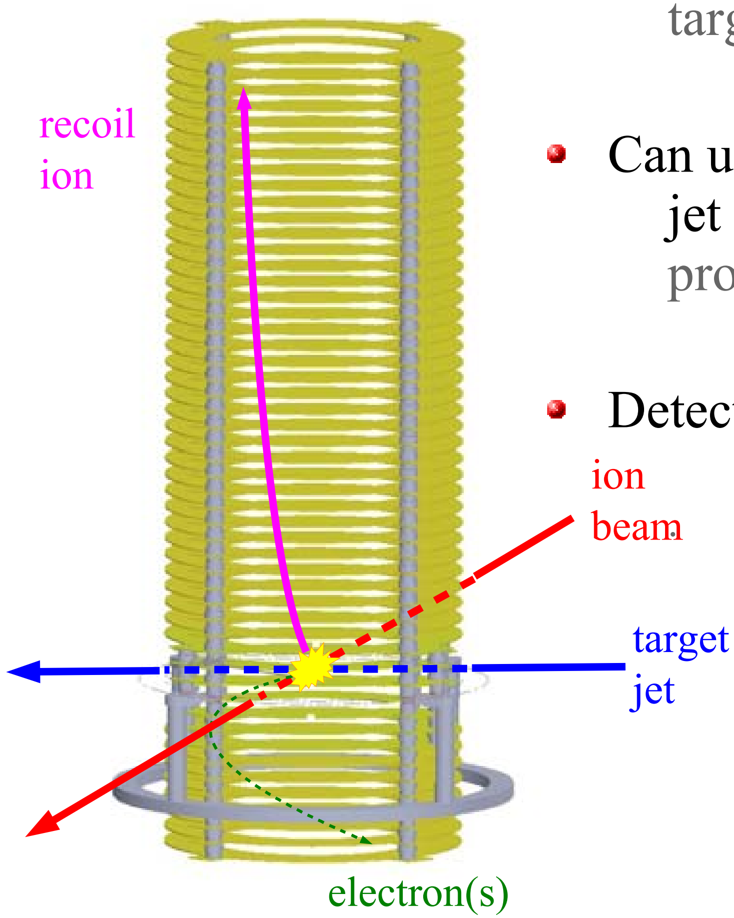


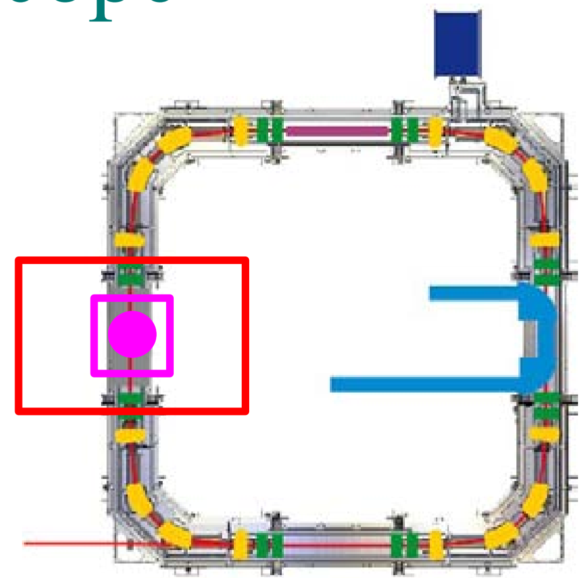
Coils for electron extraction

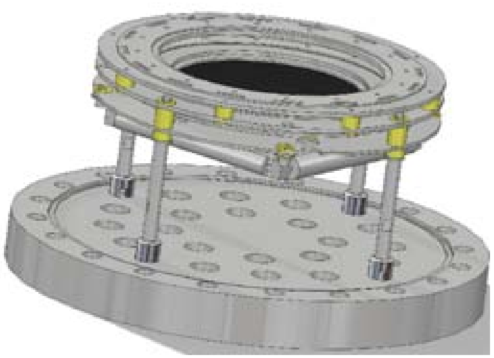
~ 270 A
some inside the 40 K shield
→ need cooling

Reaction Microscope

- COLTRIM Spectrometers
  - Two spectrometers
    for atomic / molecular
    target gas.
  - Can use a "curtain" like
    jet to be used as beam
    profile monitor for CSR.
  - Detectors: 120-mm MCP / delay-line



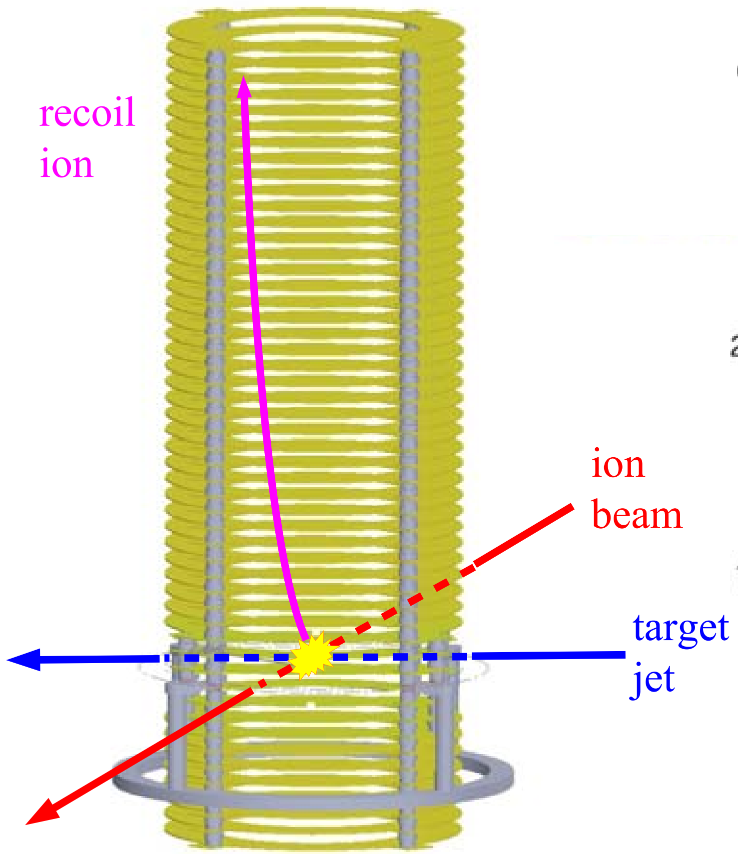


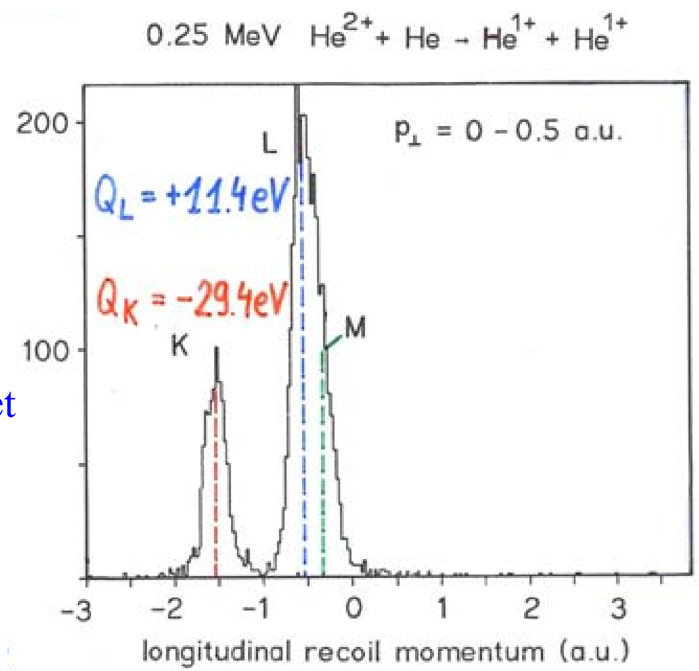


Reaction Microscope

- COLTRIM Spectrometers
  - Charge exchange reactions

$$\mathrm{d}P_{\mathrm{RI}} \sim \frac{Q}{v_{\mathrm{p}}}$$





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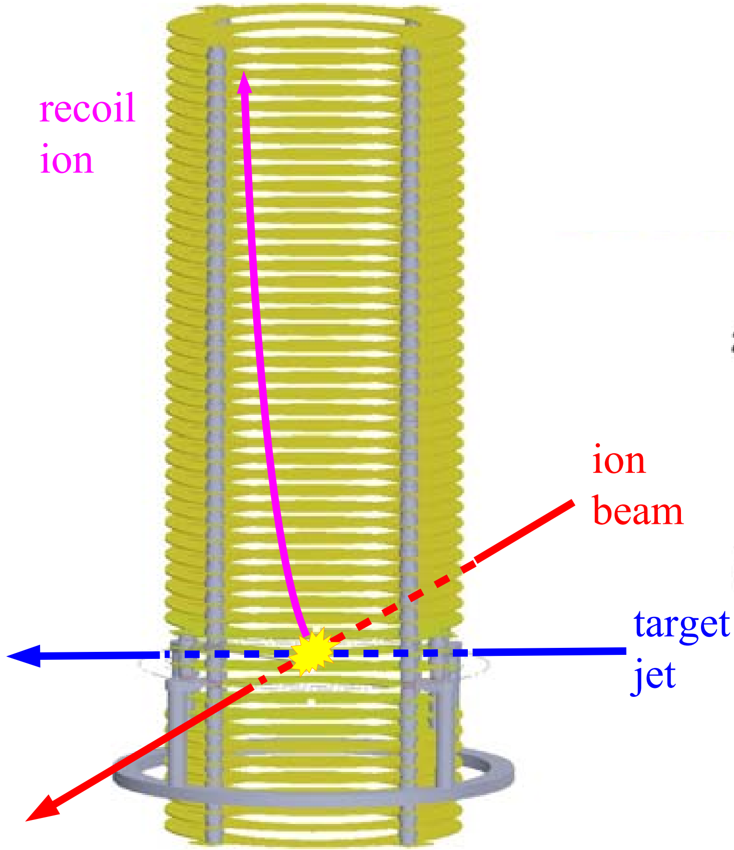
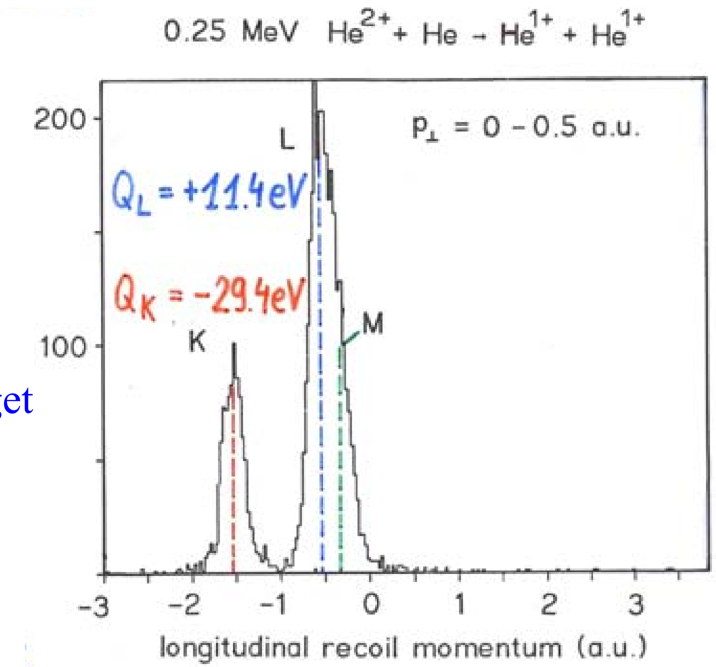


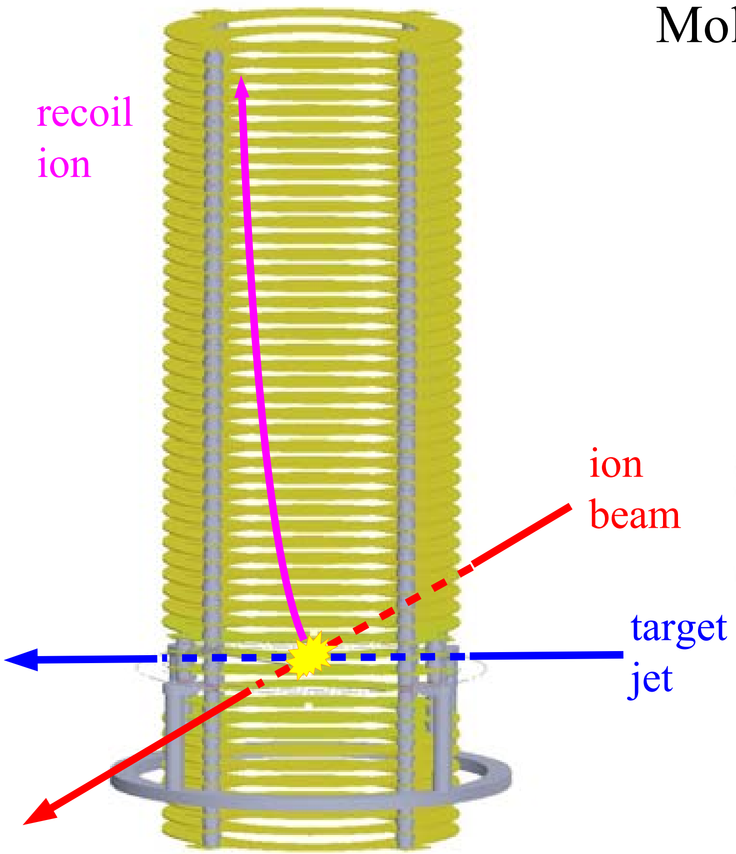


CSR @ 20 keV:
low-velocity,
electron-cooled
projectile

→ higher
resolution!

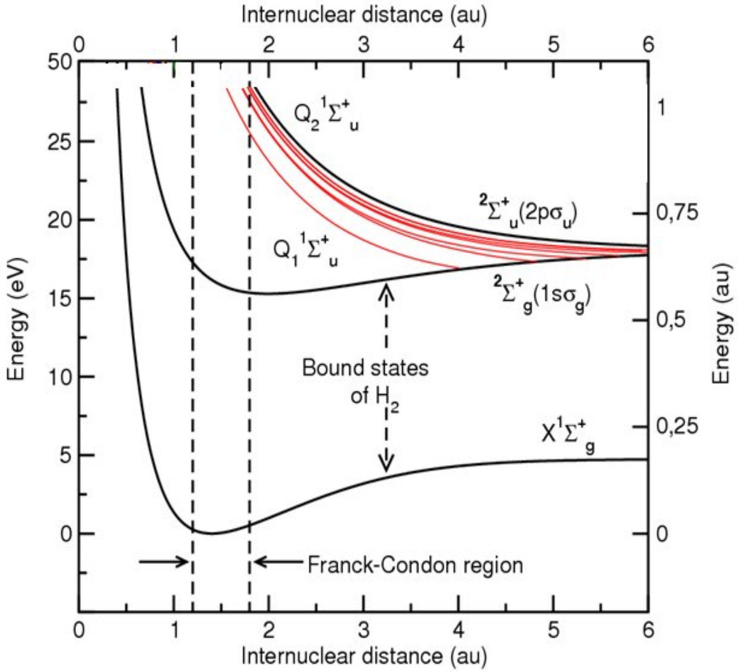
Reaction Microscope

- COLTRIM Spectrometers
  - Charge exchange reactions



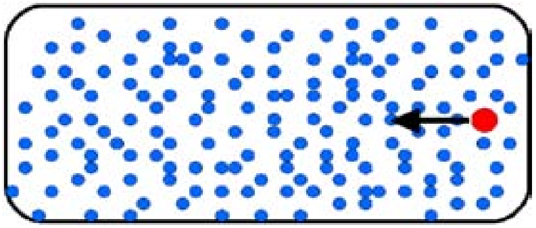
Molecular targets/projectiles: e.g. $H_2 + H_2^+ \rightarrow H_2^+ + H_2$

Sensitive to vibrational states (~ 0.1 eV) ✓

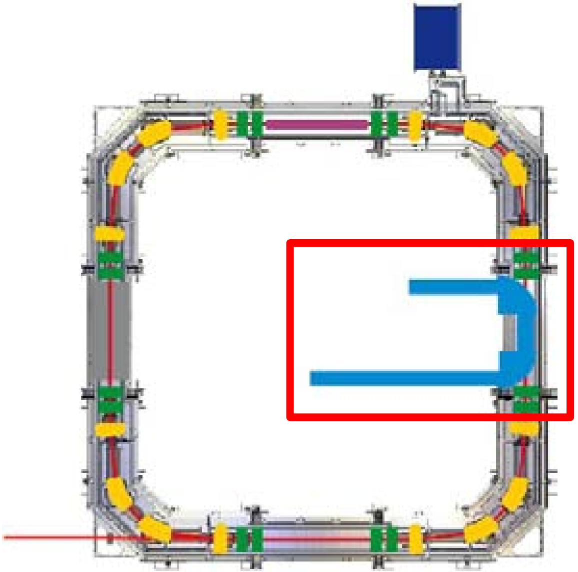


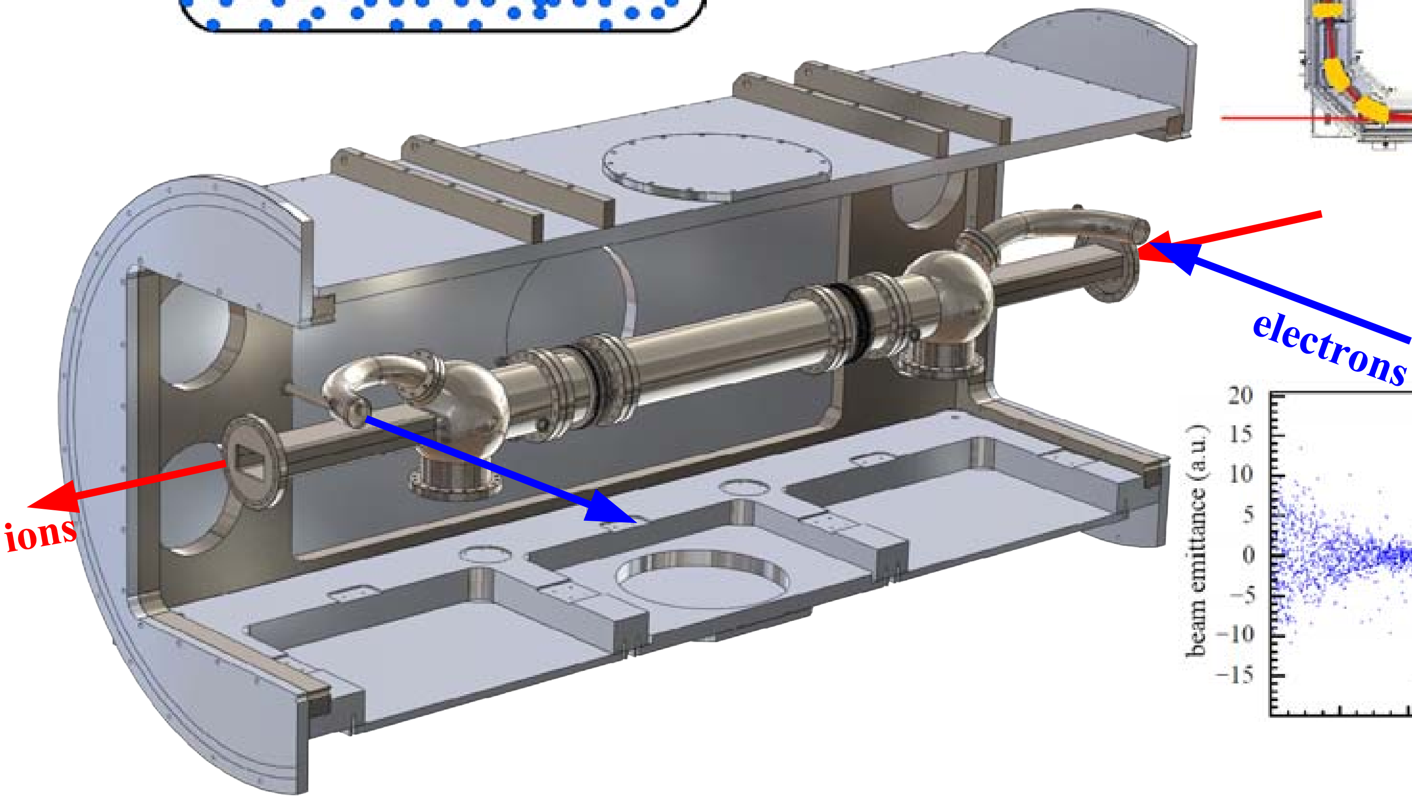
Electron Cooler

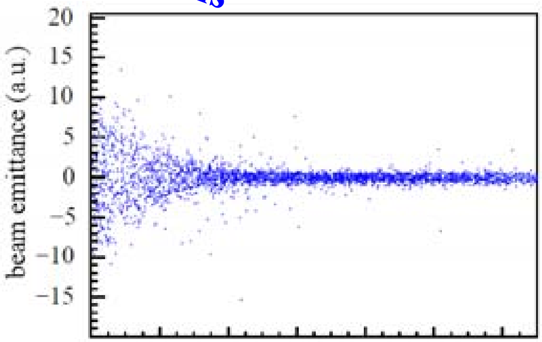
- Interaction Section



"electron cooling":
$T_{\text{ion}} \rightarrow T_{\text{e}}$



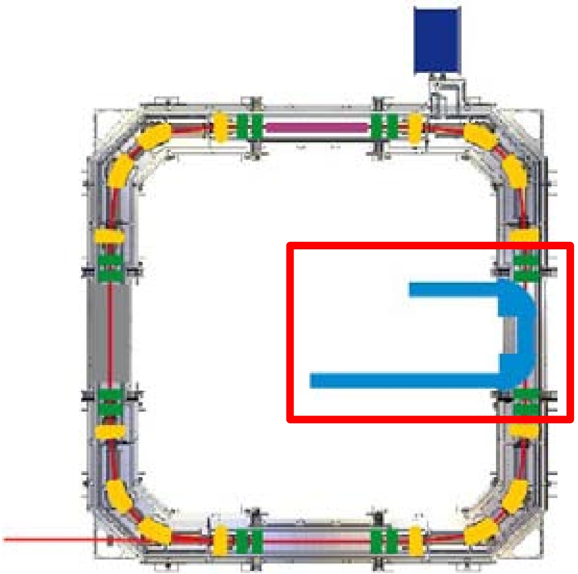


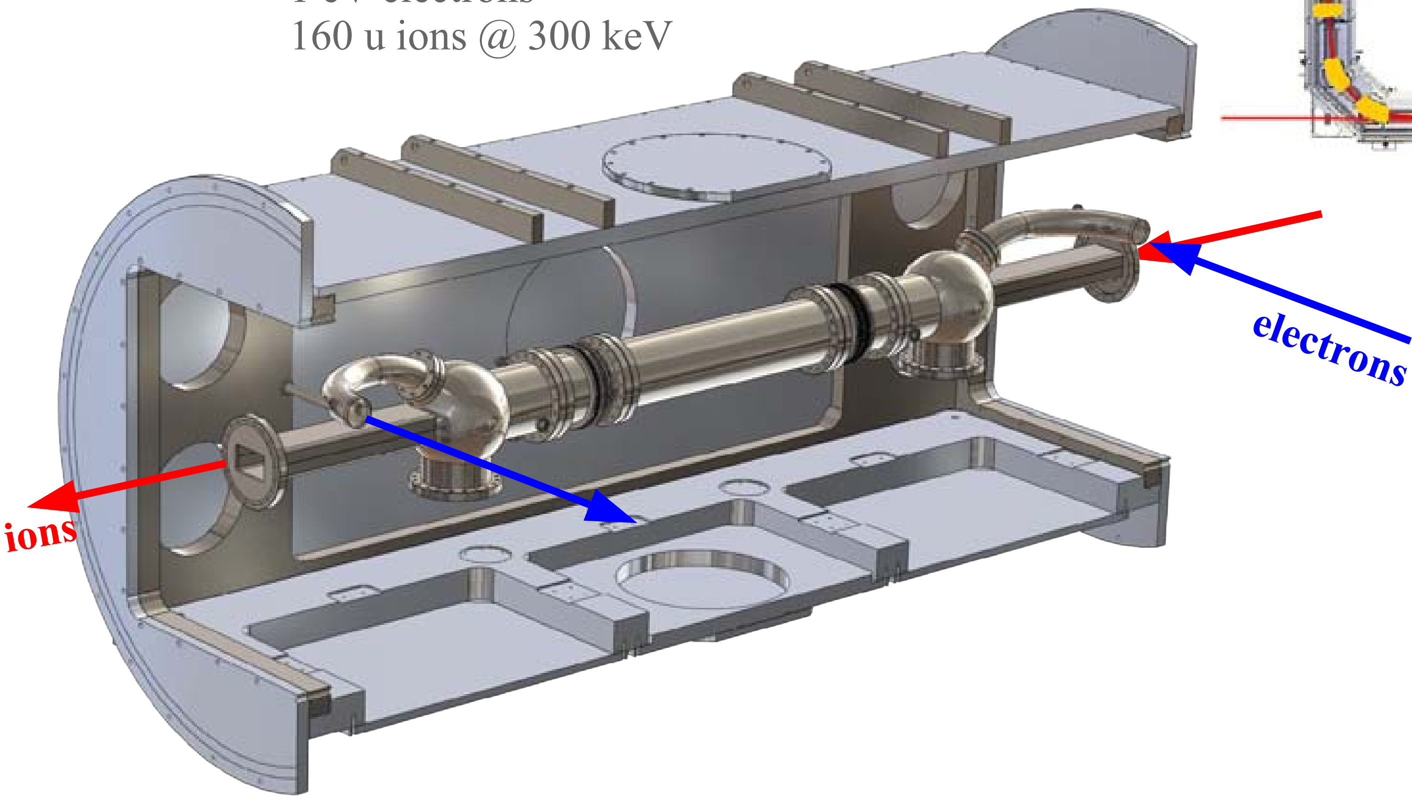


Electron Cooler

- Interaction Section
  - Low energy electron beam:
    ~ 1000 eV … 1 eV

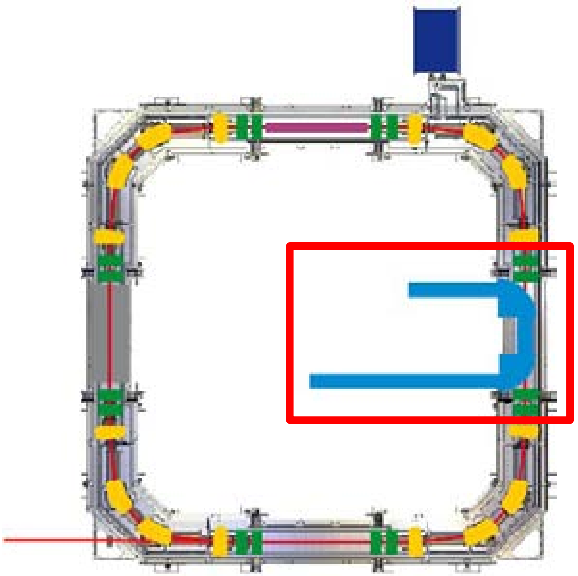
    1 eV electrons ↔
    160 u ions @ 300 keV

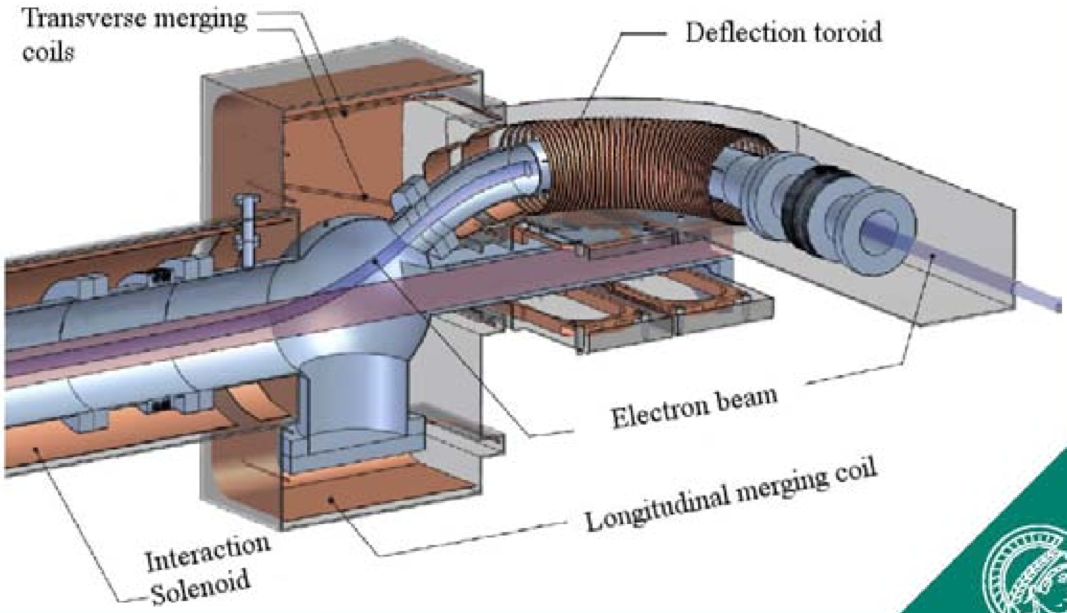




Electron Cooler

- Interaction Section
  - 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.

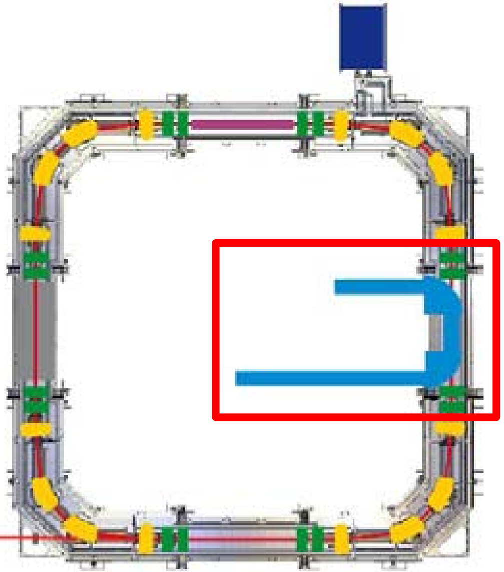


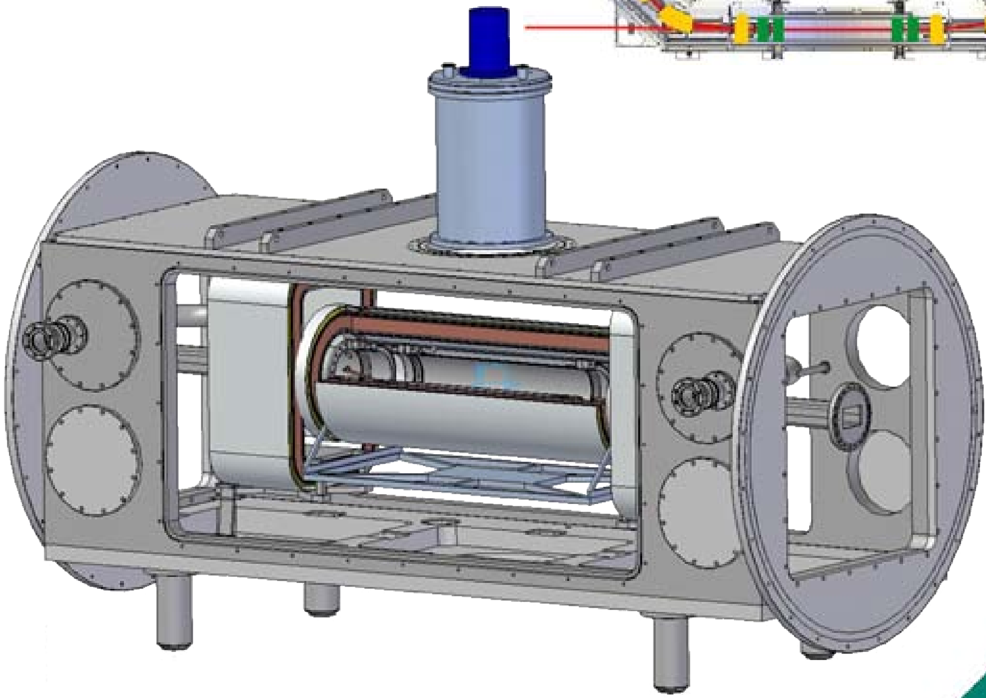


Electron Cooler

- Interaction Section
  - 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 Cooler

- 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

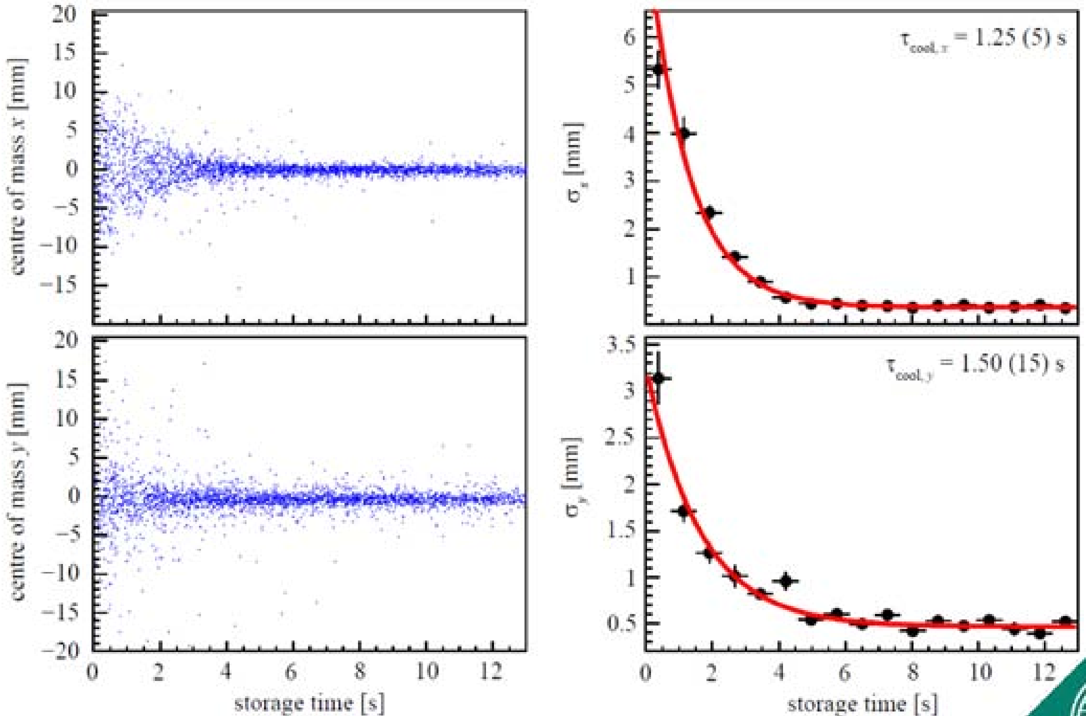
TSR: Cooling CF^+ at $E_e = 46$ eV
$\varepsilon \sim 0.01$ mm mrad
(< 1 mm @ 12 m)

  - 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!



Electron Cooler

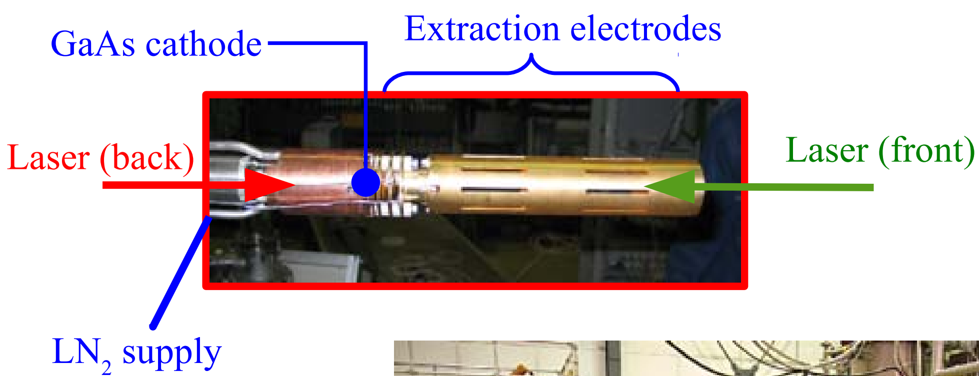
- Low energy electron cooling
  - Experience from TS
    - CF^+ (31 u, 2.6 MeV) :
    - $DCND^+$ (30 u, 3.1 Me
    - NO^+ (30 u, 2.0 MeV)
  - Cooling time:

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

  - At low E_e:
    - n_e limited by e-gun perveance!
  - Beam temperature becomes the decisive factor!

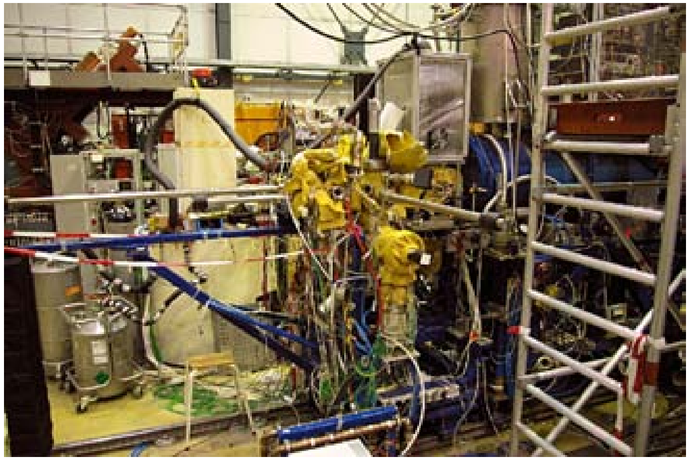
Photocathode electron source (TSR) :

~ 10 x lower T_e compared to thermionic emission



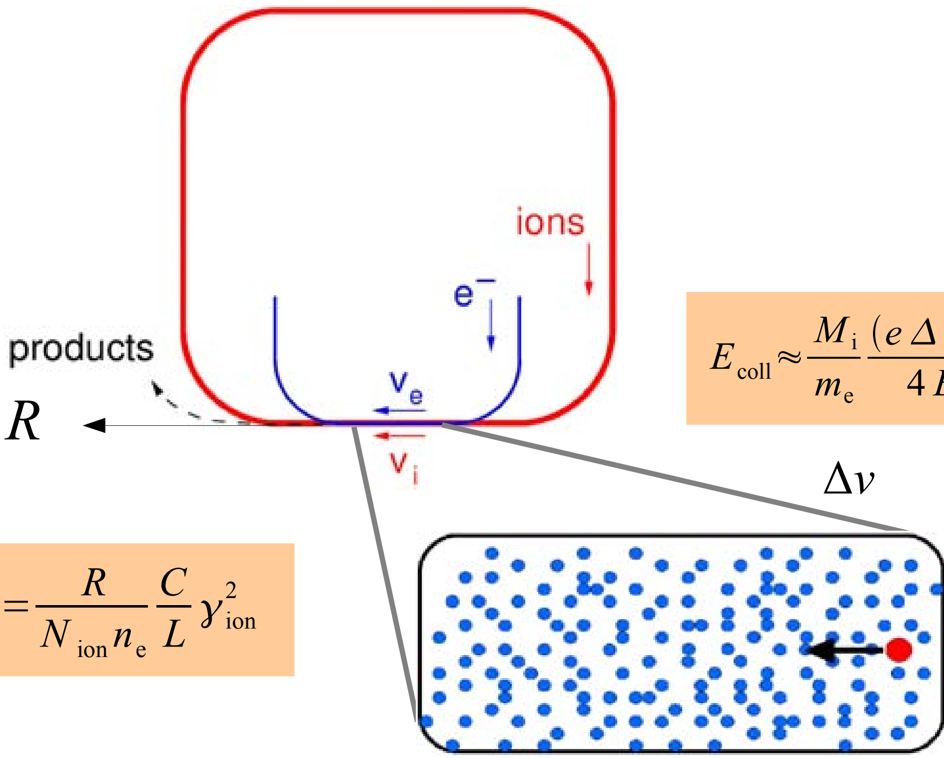
$k_B T_e \sim 1$ meV

$n_e \sim 10^5$ cm^{-3} @ 1 eV



Electron Target Experiments

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



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

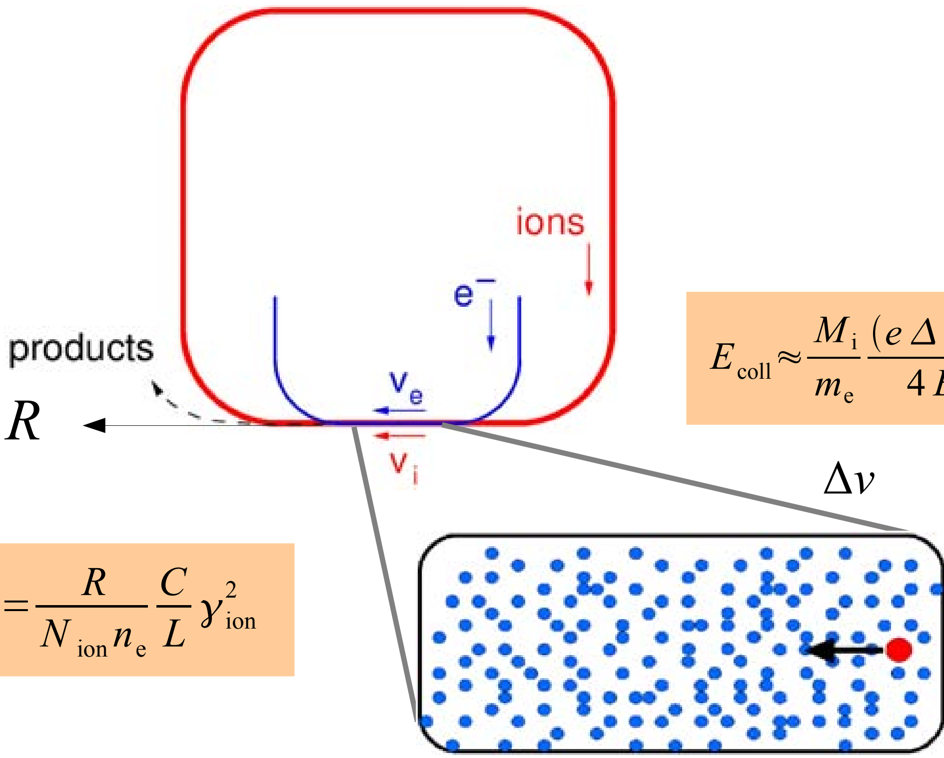
$$\alpha = \frac{R}{N_{ion} n_e} \frac{C}{L} \gamma_{ion}^2$$

Because of $E_{coll} \sim \Delta U^2$,

E_{coll} can be **very small** (meV!)

Electron Target Experiments

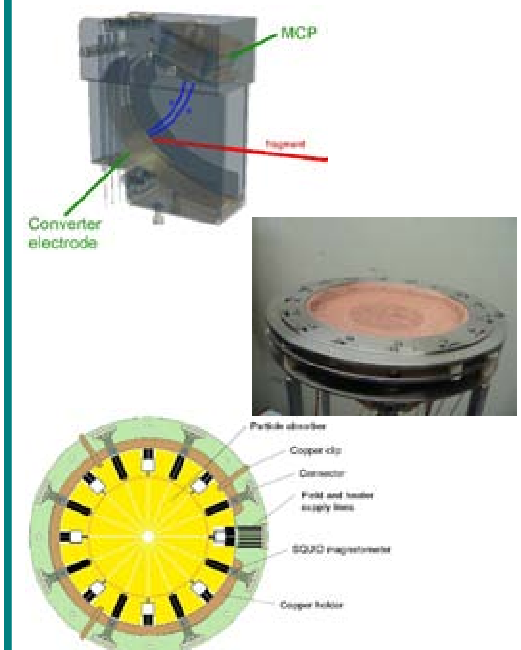
- Electron cooler (with $v_{\mathrm{e}} \neq v_{\mathrm{ion}}$)



$$E_{\mathrm{coll}} \approx \frac{M_{\mathrm{i}}}{m_{\mathrm{e}}} \frac{(e\,\Delta U)^2}{4\,E_{\mathrm{i}}}$$

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

Product detectors: Posters #6 and #8



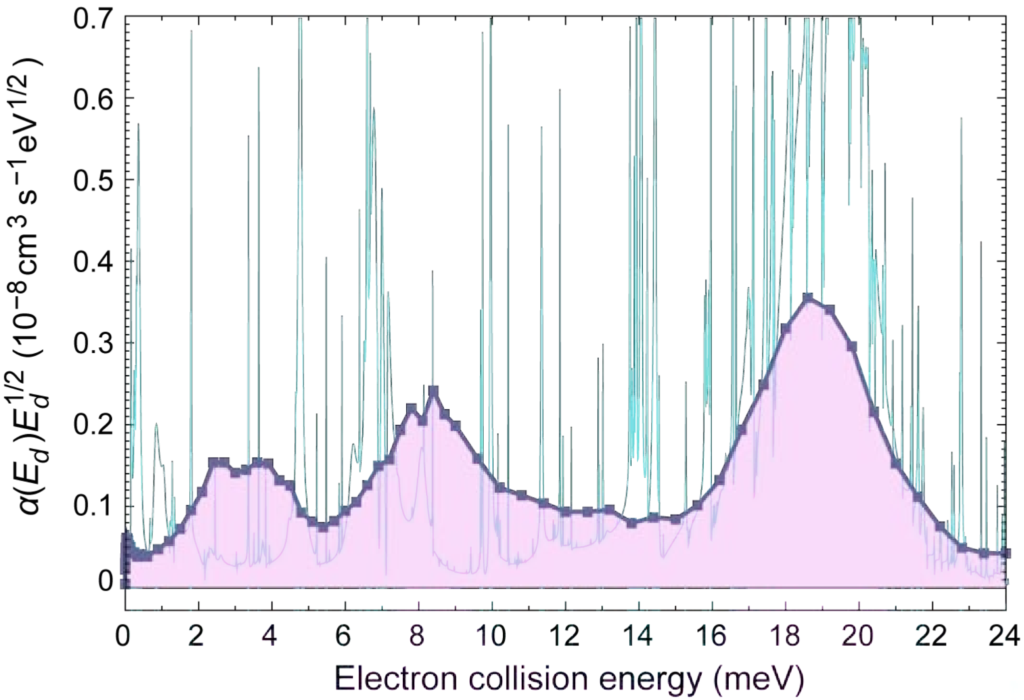
Because of $E_{\mathrm{coll}} \sim \Delta U^2$,

E_{coll} can be **very small** (meV!)

Electron Target Experiments

- State selective dissociative recombination

$e^{-}(E_{coll}) + HD^{+} \longrightarrow H + D + E_{KER}$

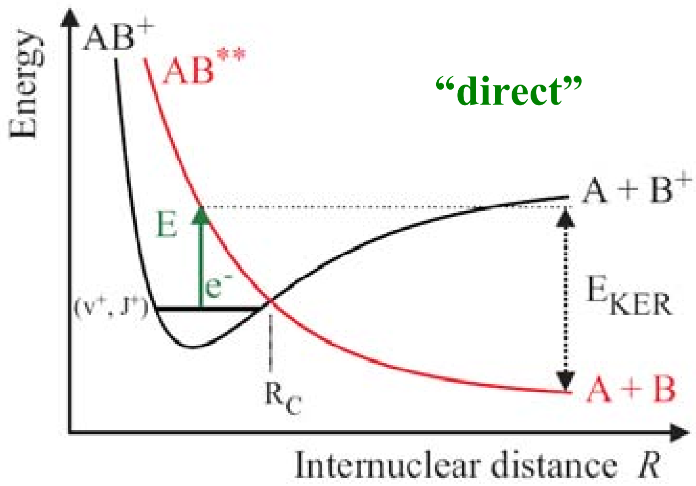


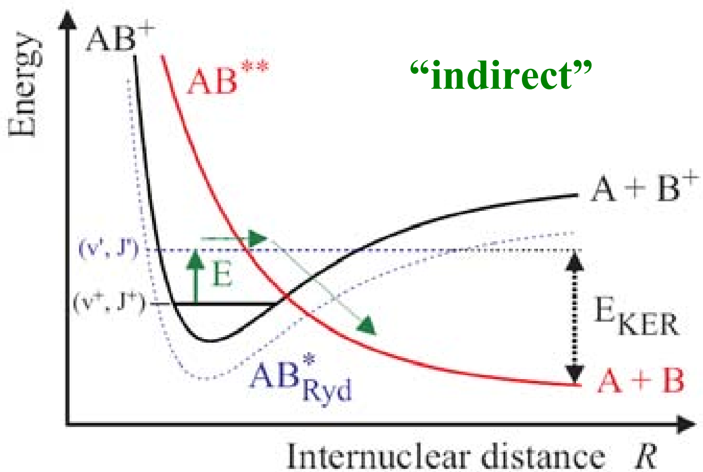
Waffeu-Tamo *et al.*, submitted (0 K)

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

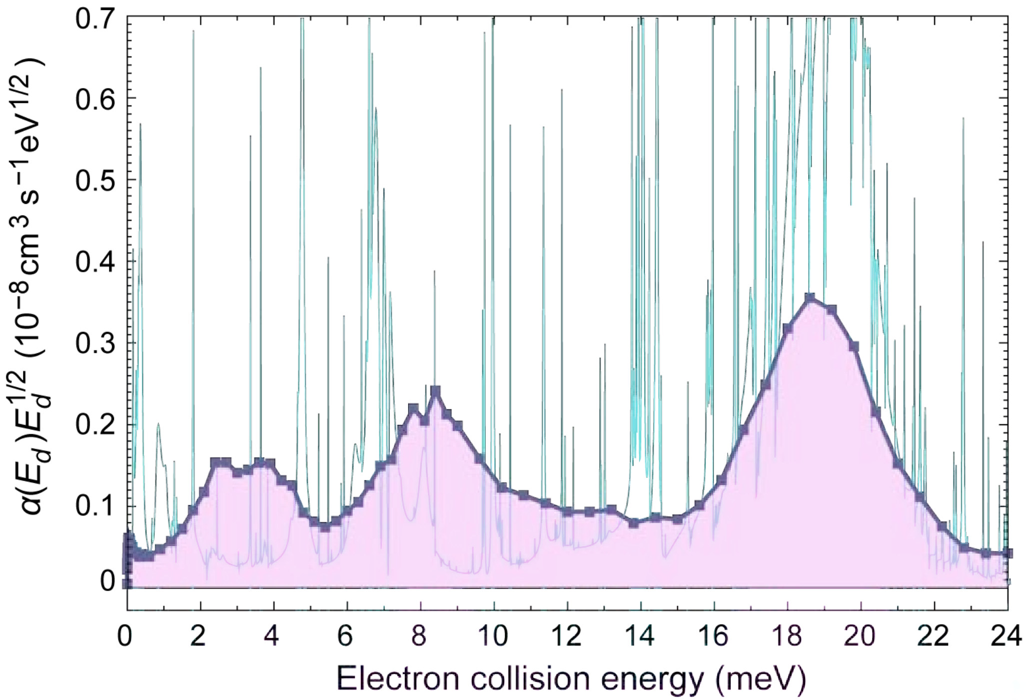
Electron Target Experiments

- State selective dissociative recombination





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



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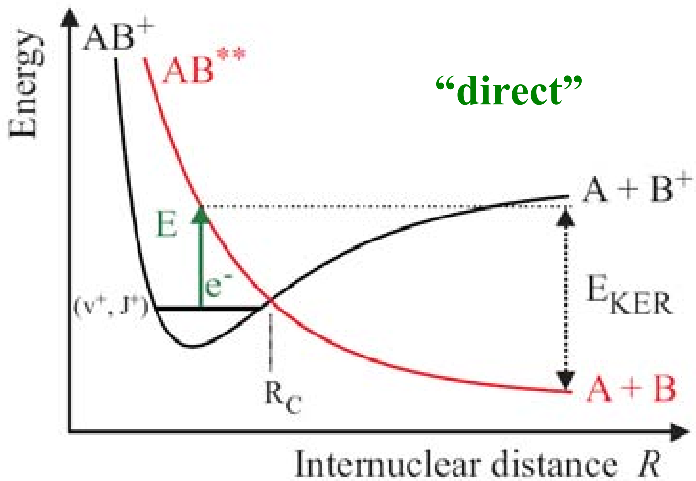
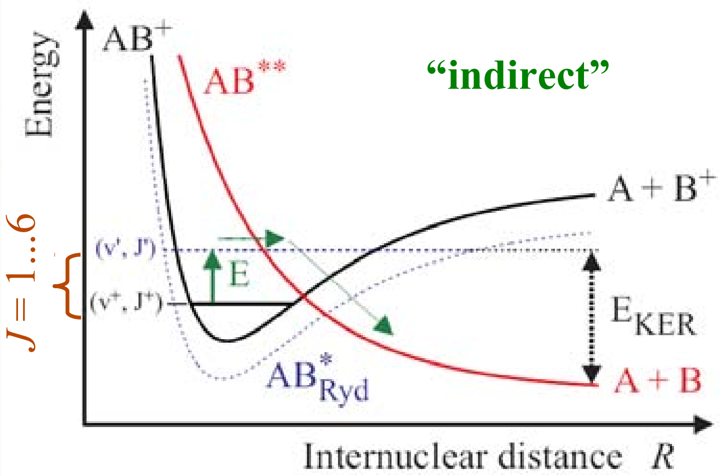
Electron Target Experiments

- State selective dissociative recombination





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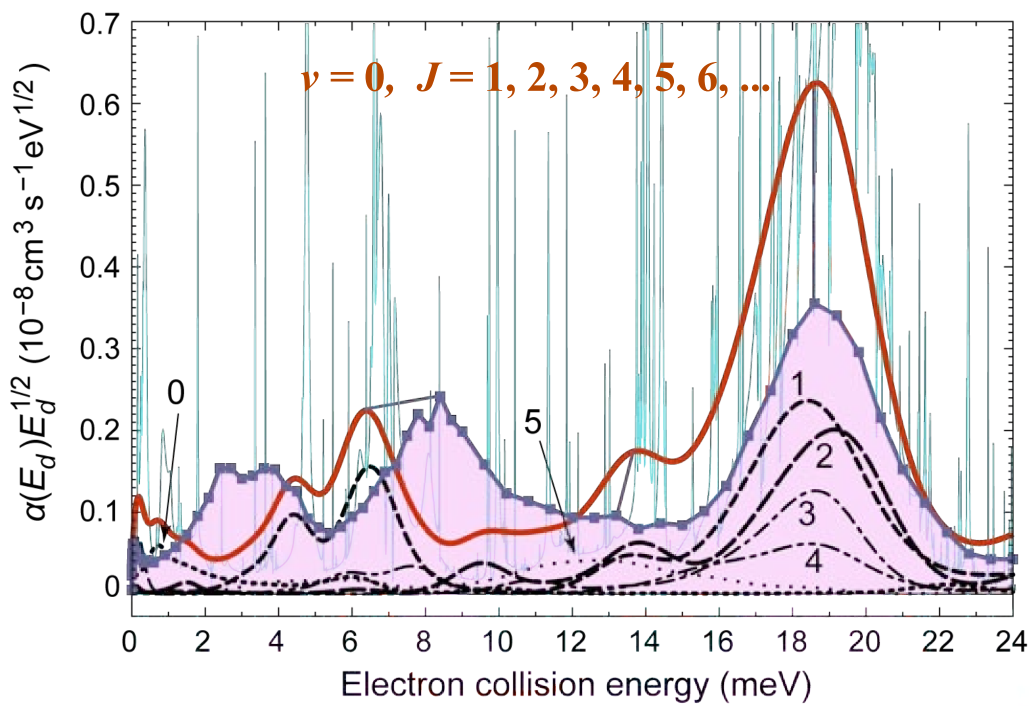

Waffeu-Tamo *et al.*, submitted (0 K)

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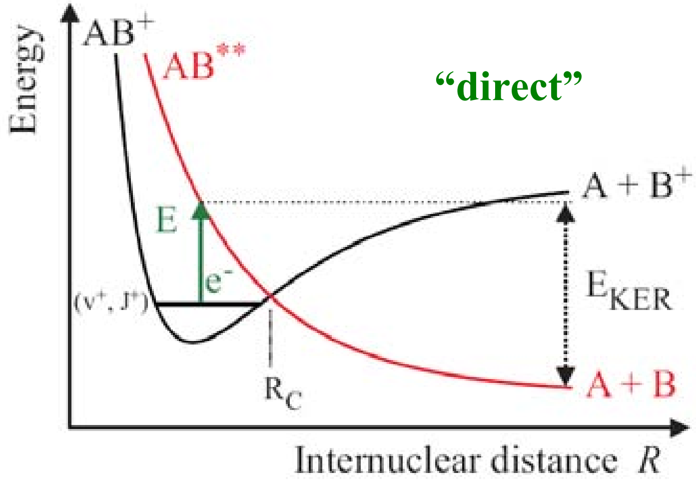
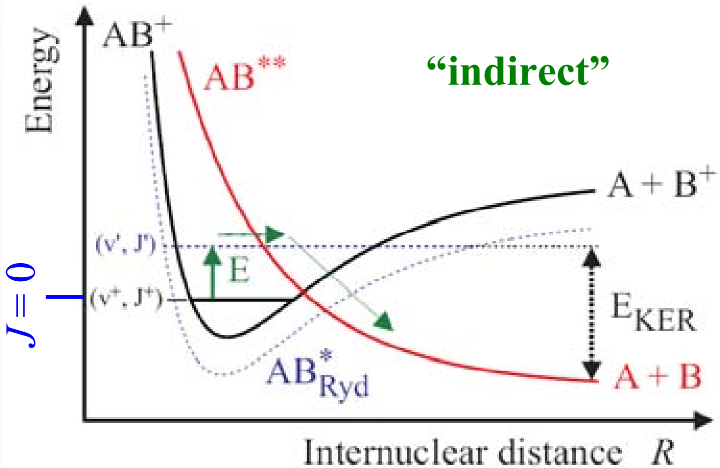
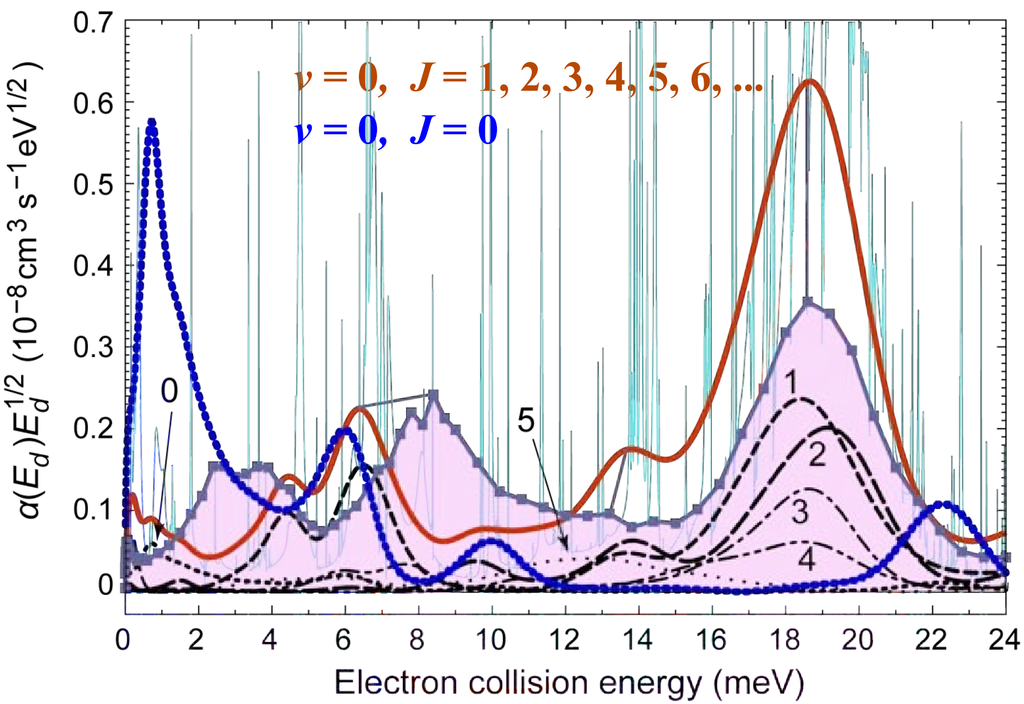
Electron Target Experiments

- State selective dissociative recombination





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



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

TSR data (kT_e ~ 1 meV, T_{ion} ~ 300 K)

CSR prediction (T_{ion} = 10 K)

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Electron Target 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

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

    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 be all-cryogenic, providing very low residual gas density and IR background radiation.
- It will feature a fully-functional electron cooler.
- It provides unique opportunities for electron exchange and free electron collision experiments molecular and low-charged heavy ions.

Thank you!

K. Blaum
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Thank you!