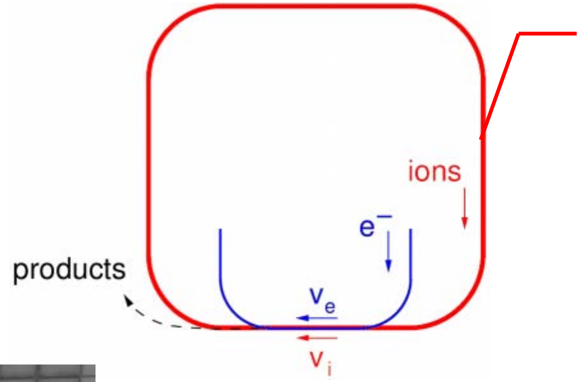
Upcoming Experiments at the Heidelberg Cryogenic Storage Ring

Claude Krantz

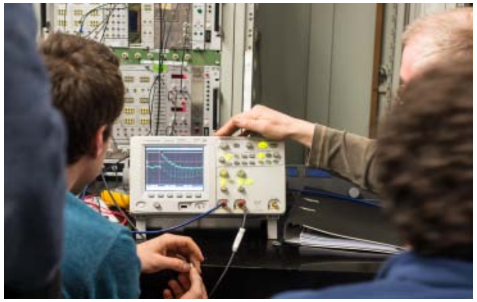
Max Planck Institute for Nuclear Physics



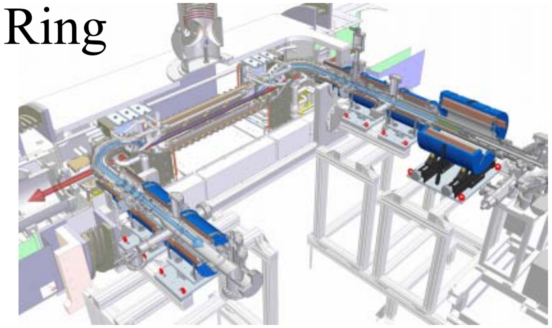
Atomic and Molecular Physics with **Storage Rings**

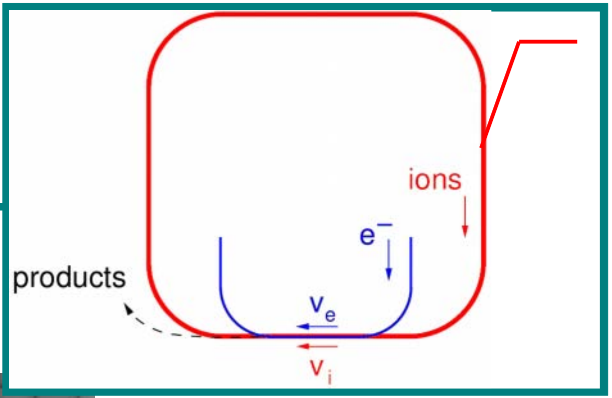
The **Cryogenic Storage Ring**

Commissioning and **First Experiments**



A look ahead: A Cryogenic **Electron Cooler** Storage Ring





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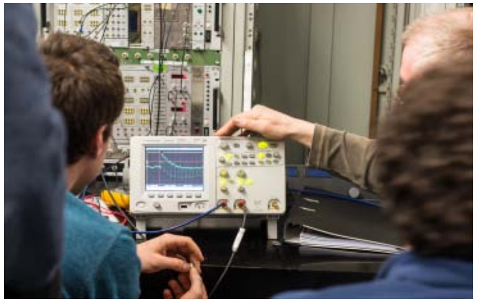

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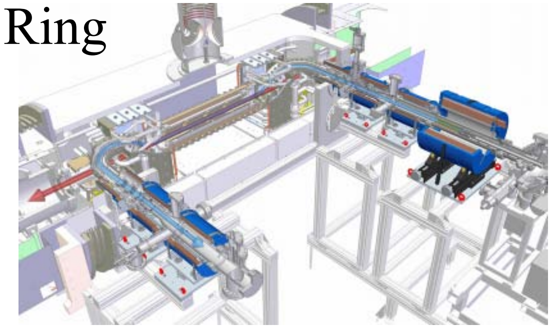
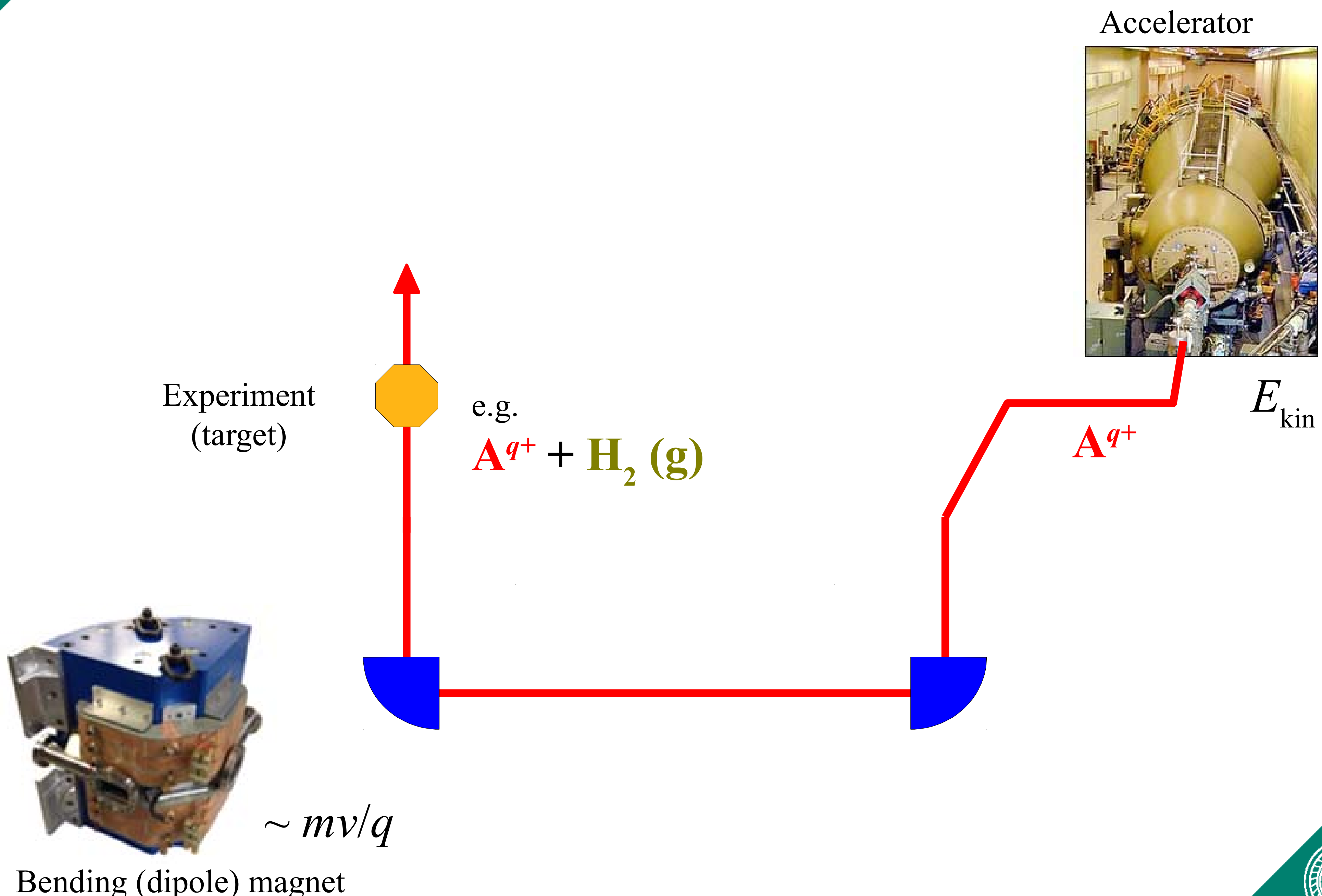


Atomic and Molecular Physics with Storage Rings



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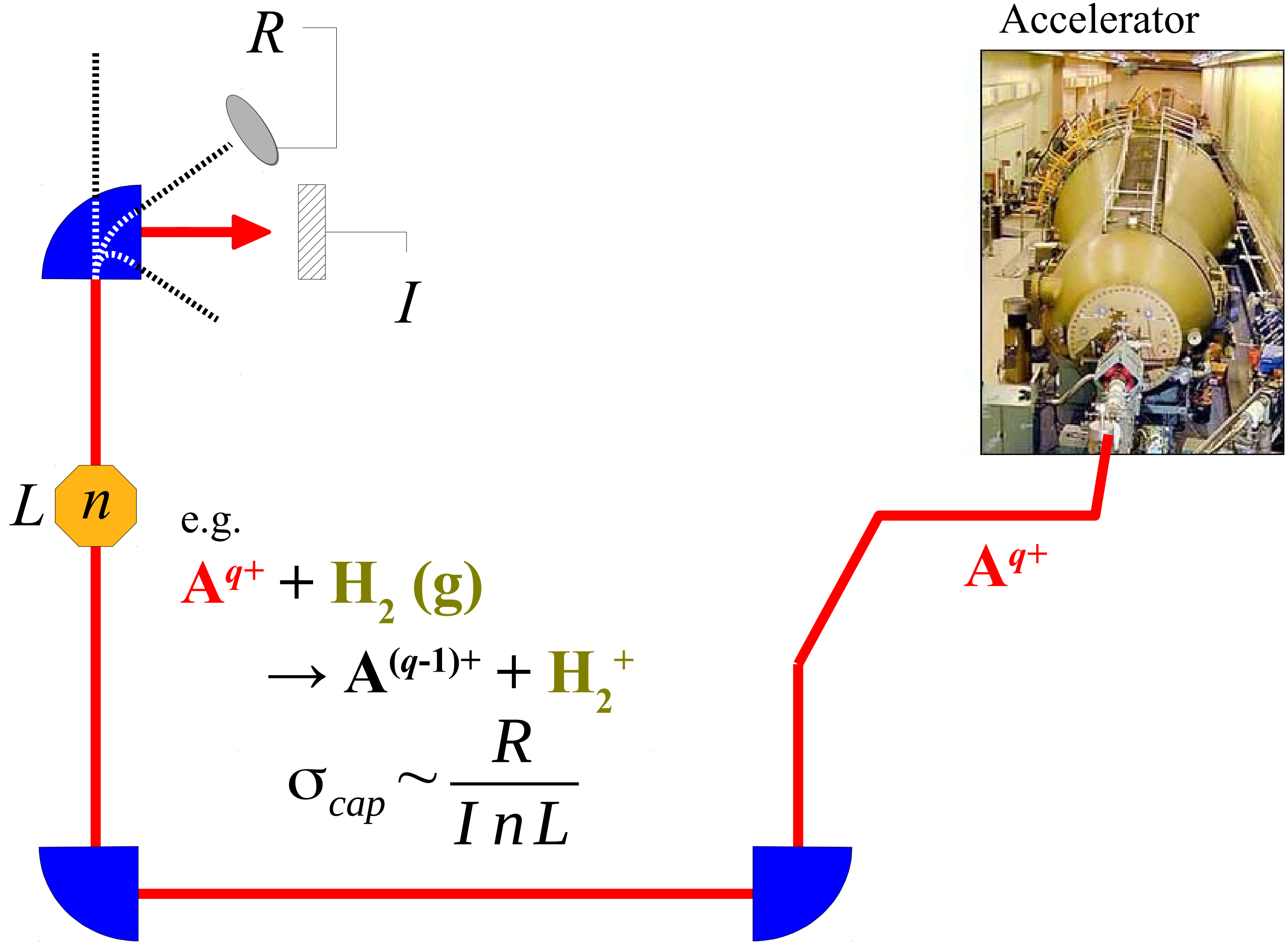


e.g.

$$\mathbf{A}^{q+} + \mathbf{H}_2\ \mathbf{(g)}$$

$$\rightarrow \mathbf{A}^{(q\text{-}1)+} + \mathbf{H}_2^{\ +}$$

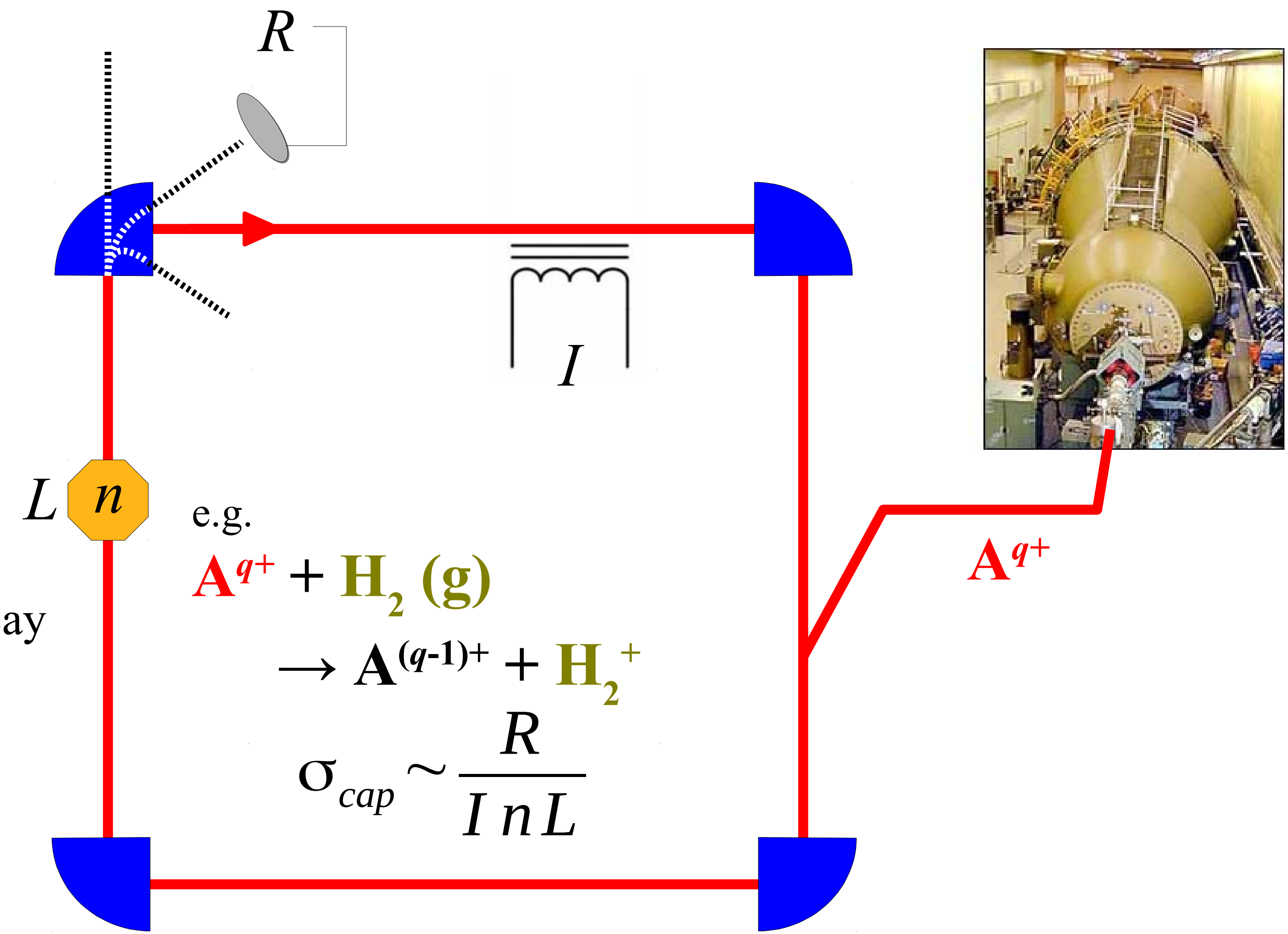
$$\sigma_{cap} \sim \frac{R}{I\,n\,L}$$

Bending (dipole) magnet

Atomic and Molecular Physics with Storage Rings

Ion Storage Ring

* **Recycle** ions
  (higher *I*)
* Increase **ToF**
  (µs to s)
  e.g. allow
  metastables to decay



e.g.

$$\mathbf{A}^{q+} + \mathbf{H_2\,(g)} \rightarrow \mathbf{A}^{(q-1)+} + \mathbf{H_2^{\,+}}$$

$$\sigma_{cap} \sim \frac{R}{I\,n\,L}$$

Atomic and Molecular Physics with Storage Rings

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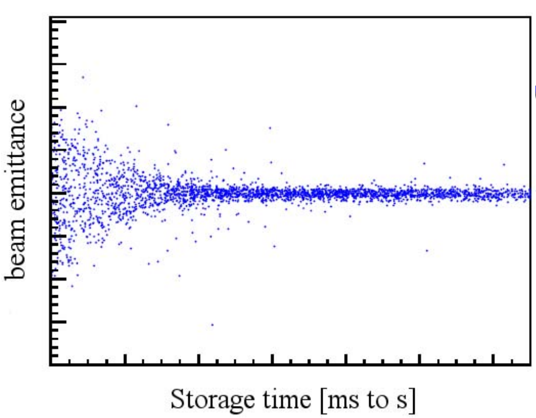
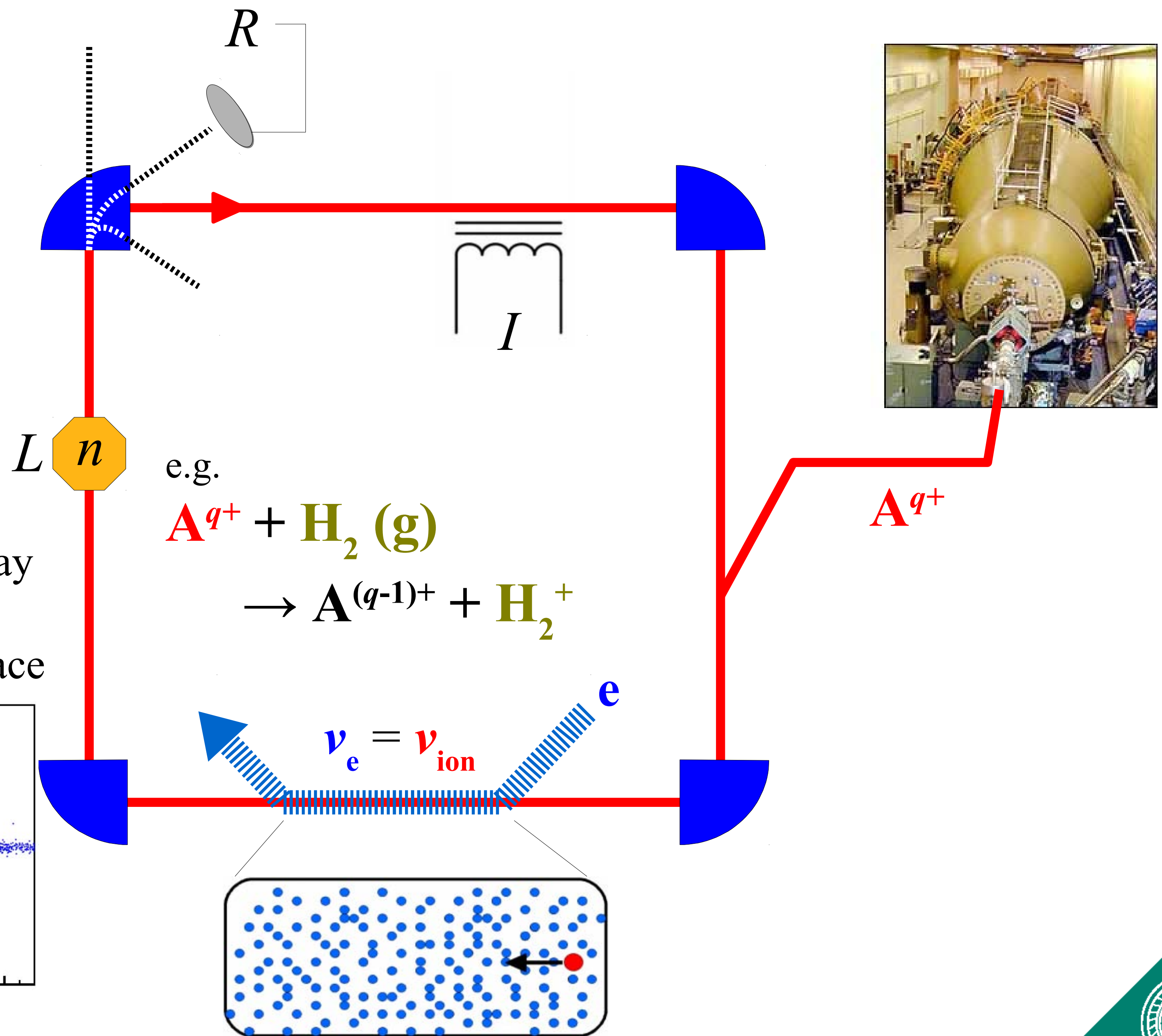
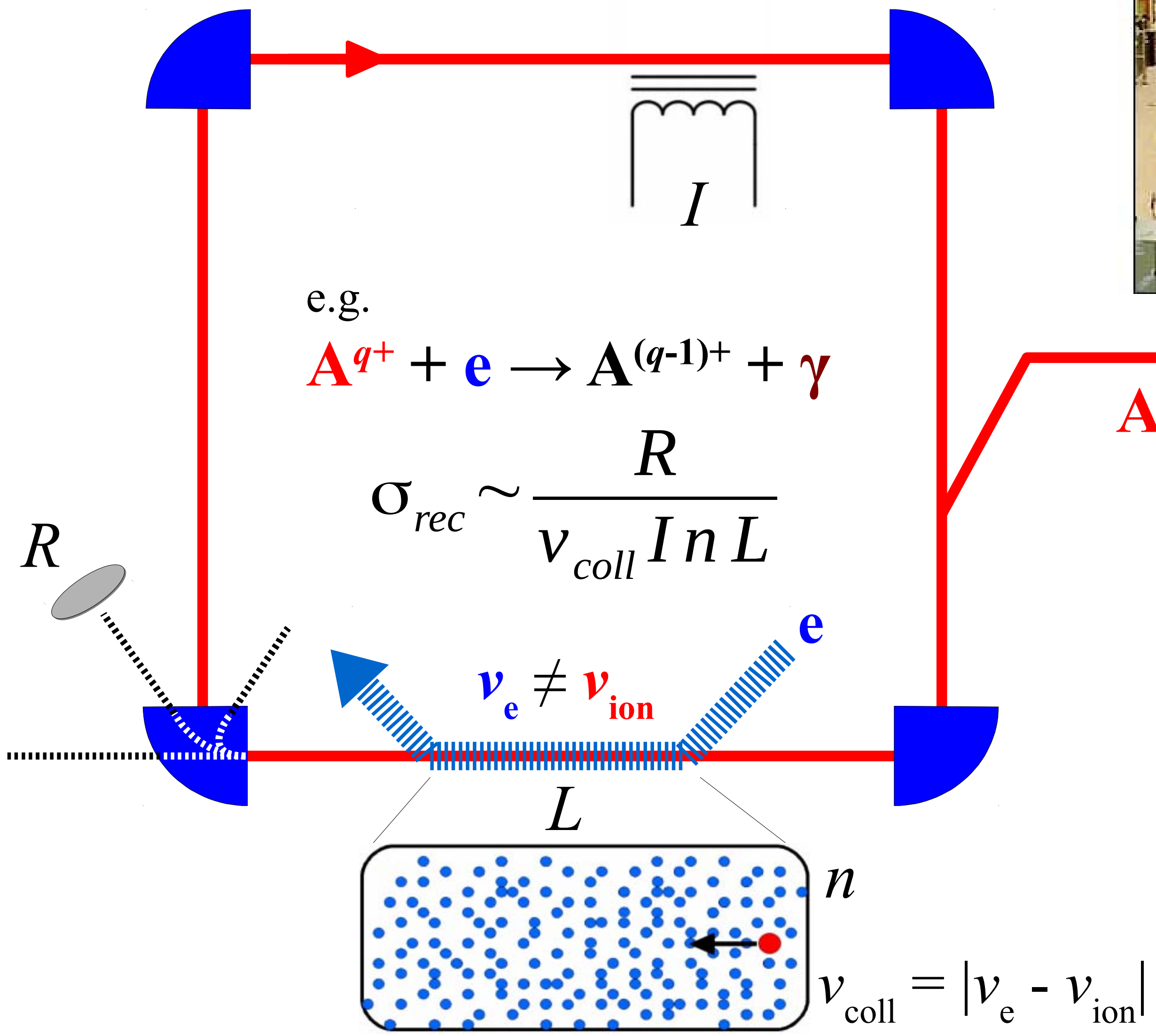
Ion Storage Ring
+ Electron Cooler

* **Recycle** ions (higher I)
* Increase **ToF** (µs to s) e.g. allow **metastables** to decay
* Decrease **ion beam spread** in phase space





Atomic and Molecular Physics with Storage Rings



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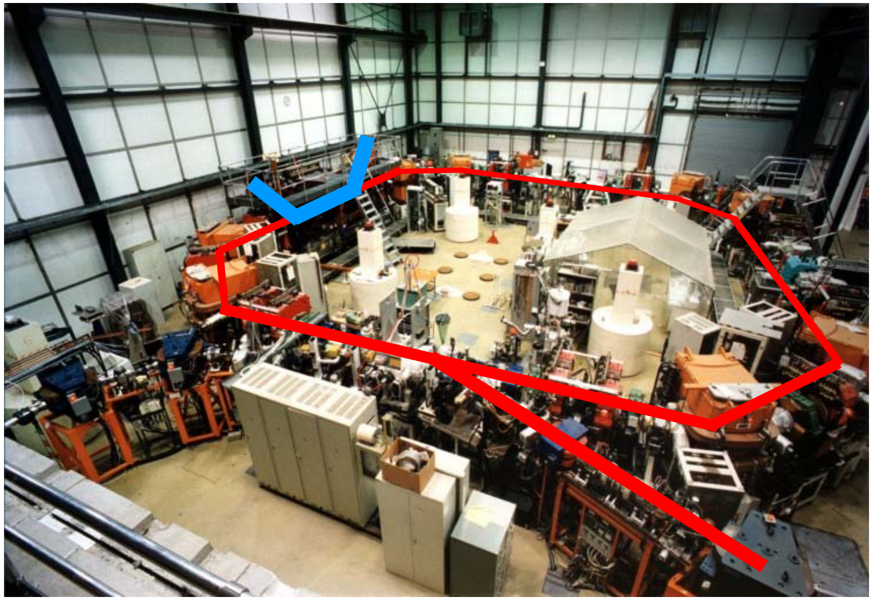
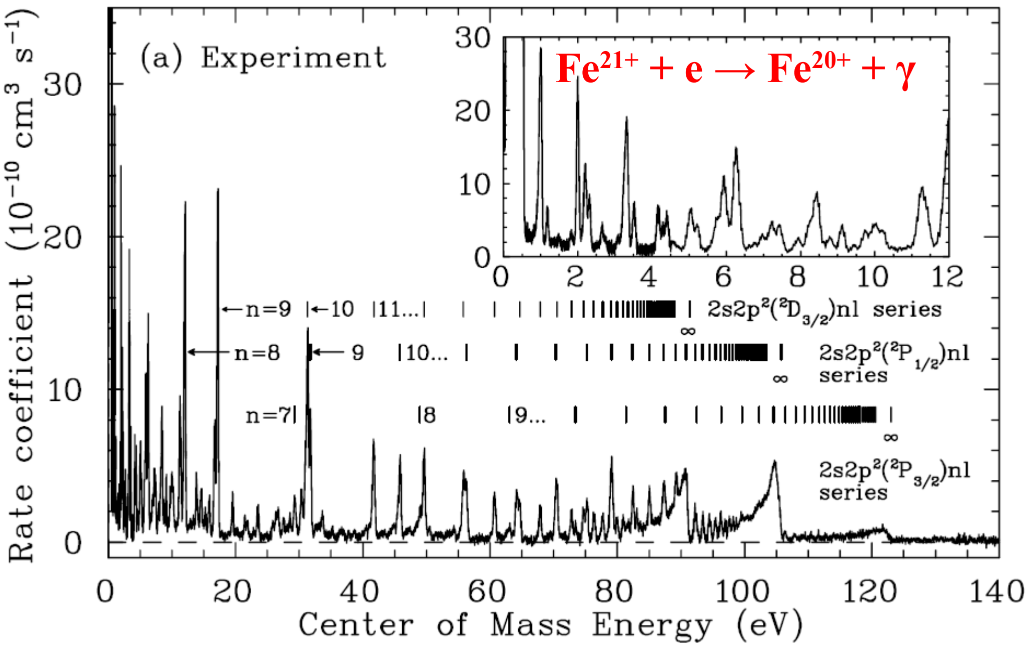
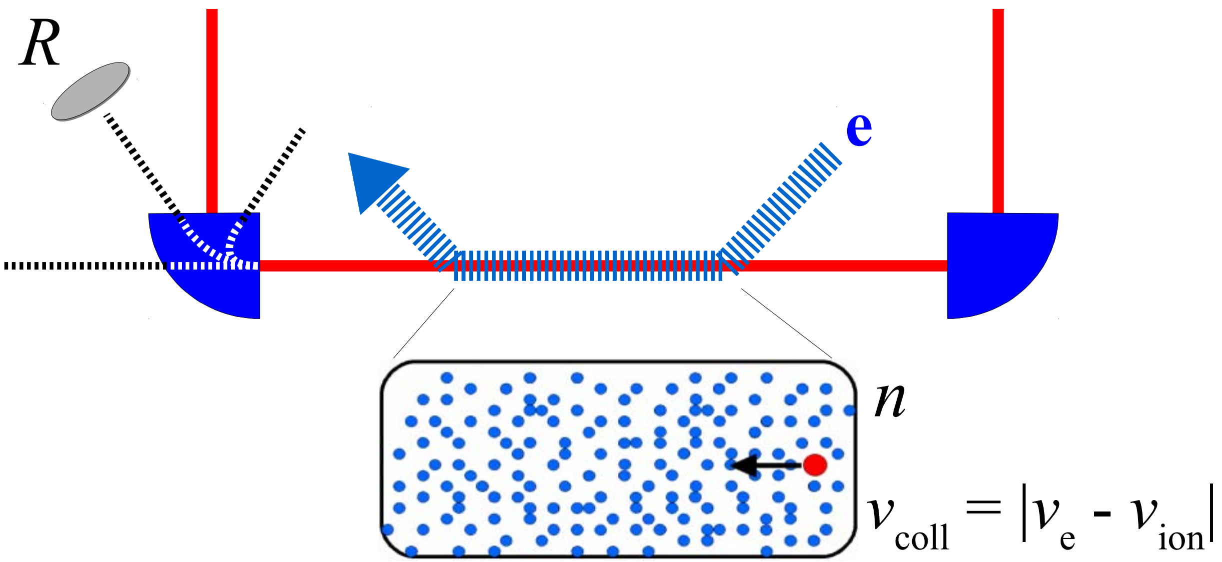
Atomic and Molecular Physics with Storage Rings



Storage Ring TSR (decom. end 2012)



[Savin, ApJ Suppl. Ser. 147 (2003)]



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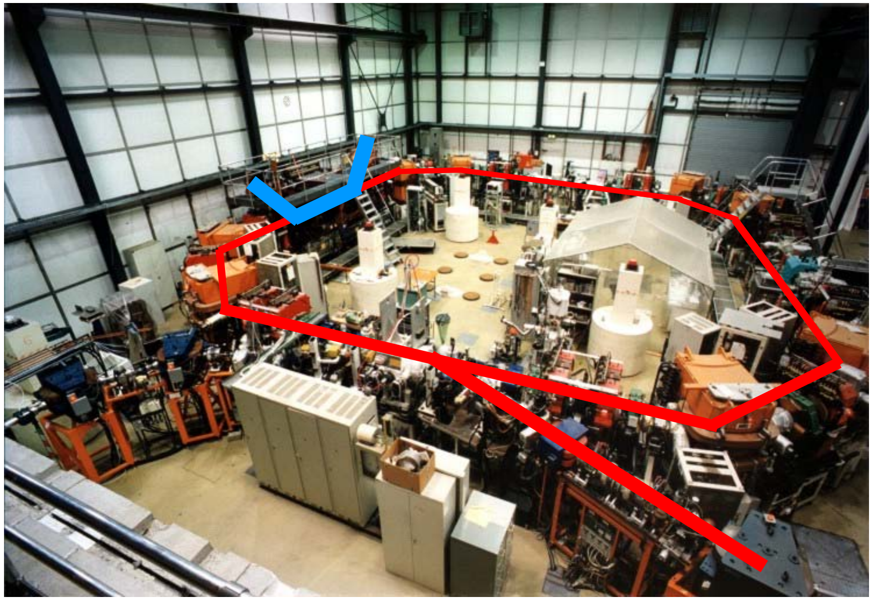

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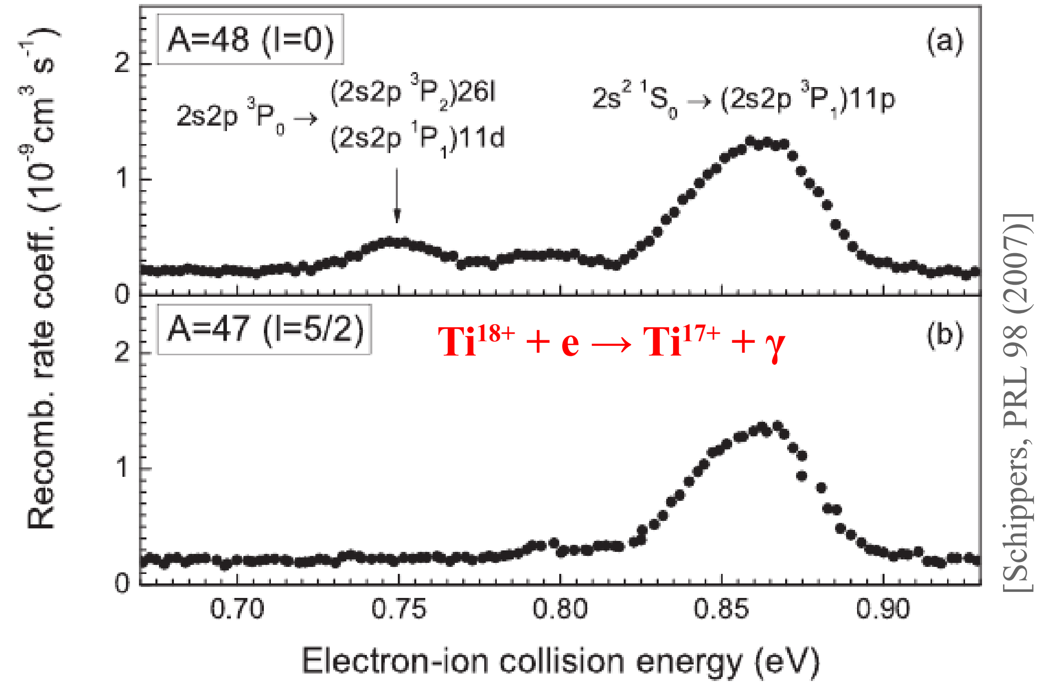

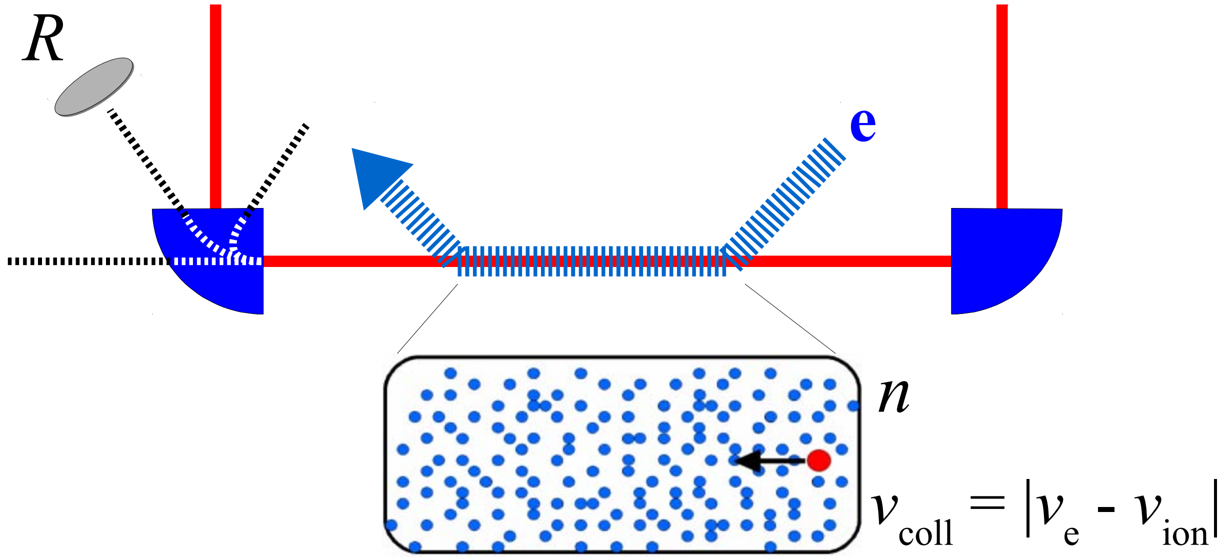

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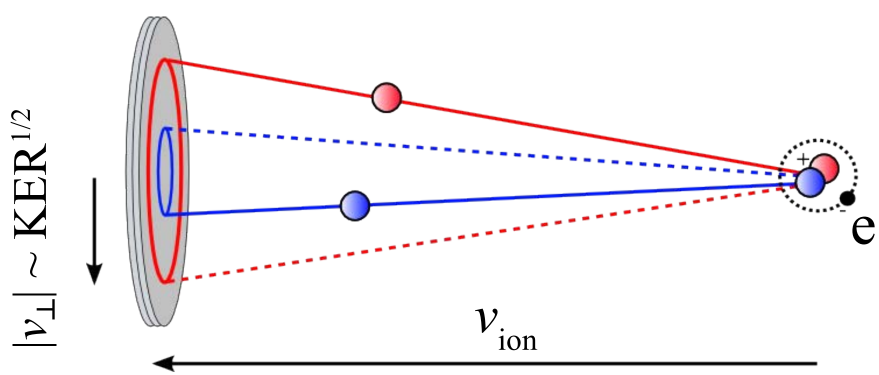
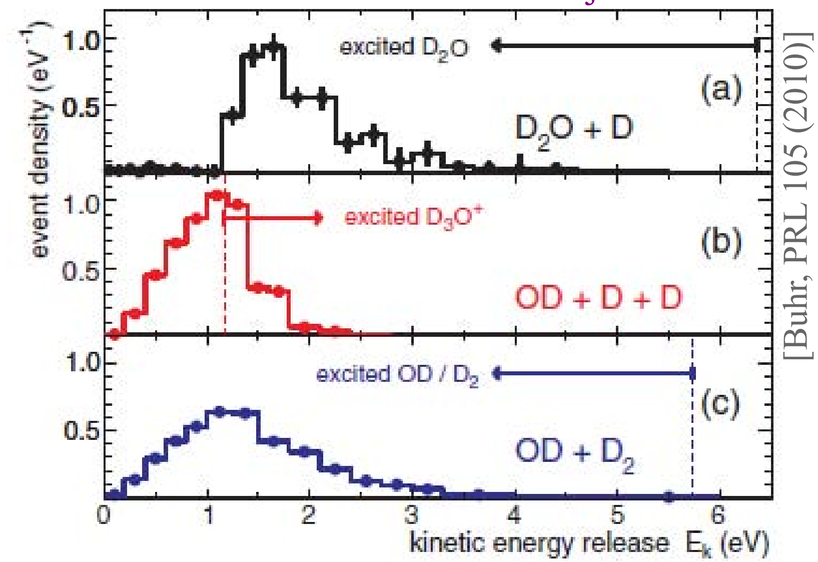
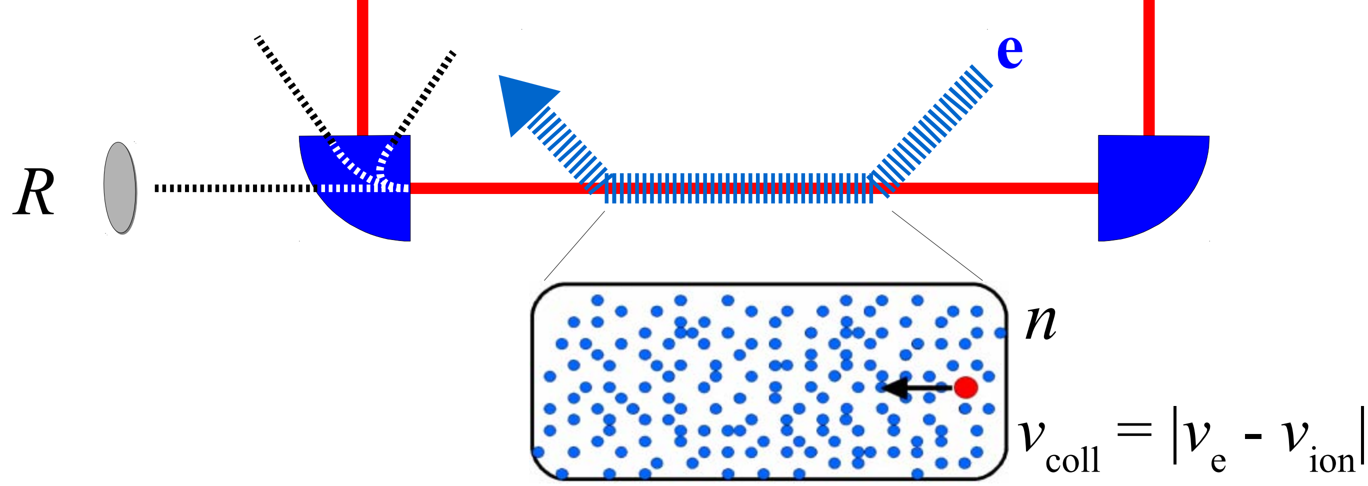


dissociative recombination of D_3O^+



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



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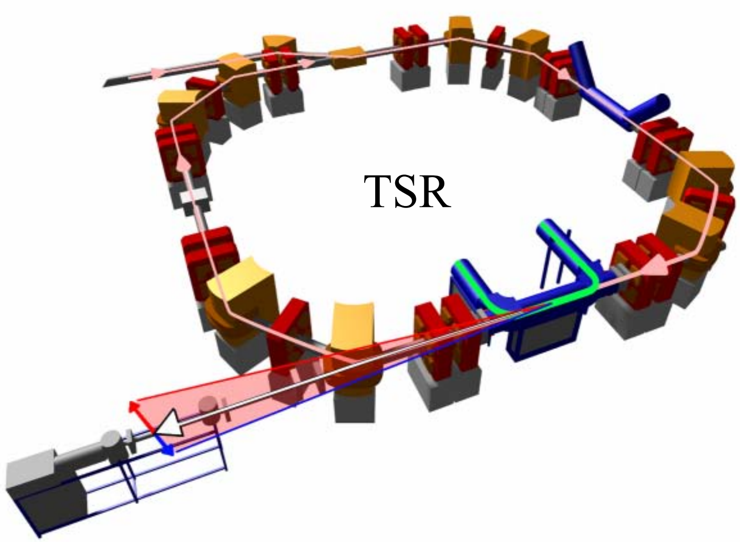
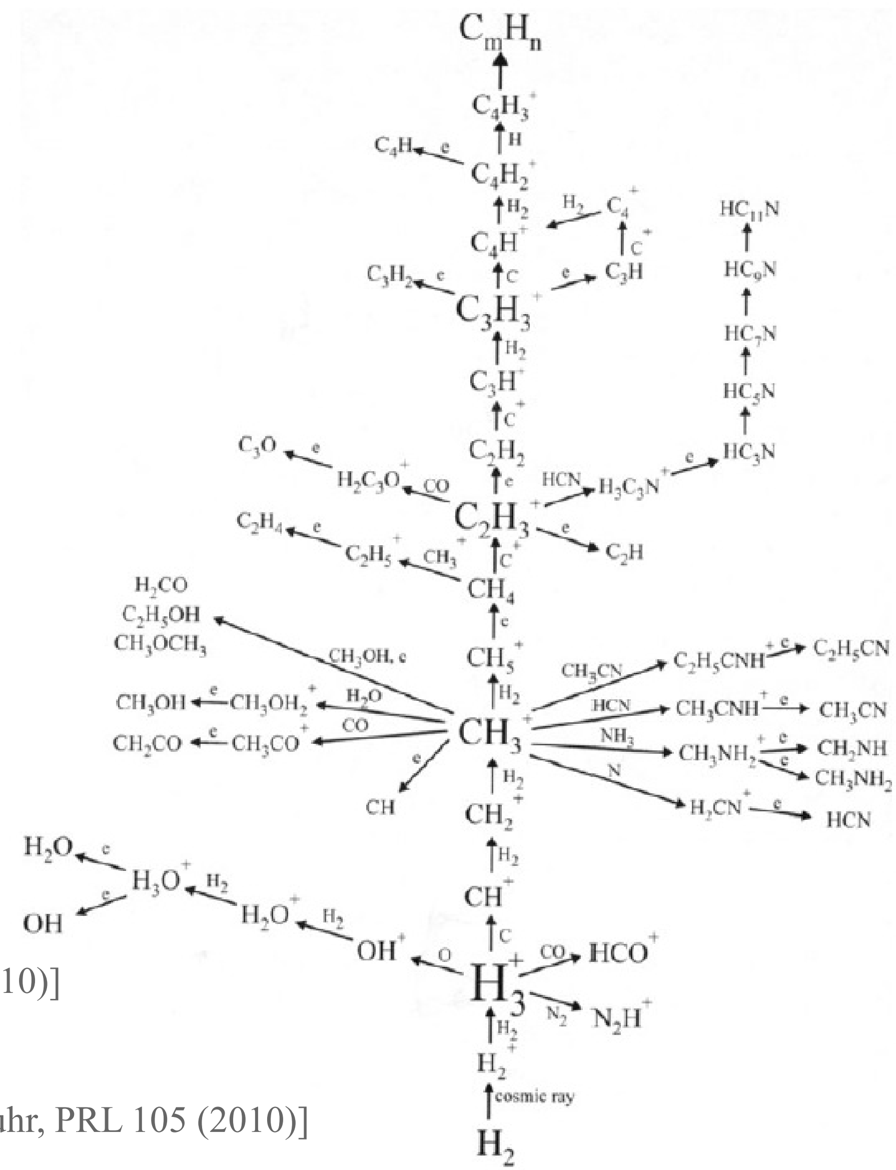
Atomic and Molecular Physics with Storage Rings





Gas-phase chemistry in ISM driven by H_3^+:

$$H_3^+ + e \rightarrow H + H + H$$

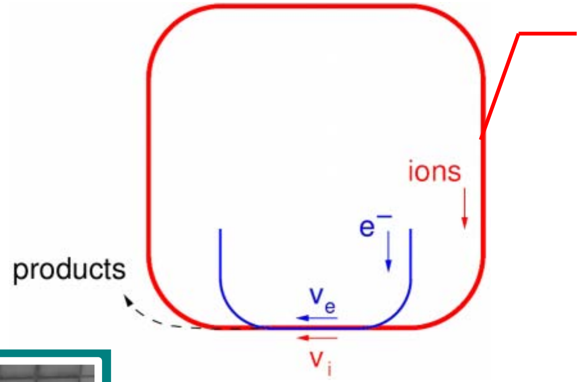
e.g. [Petrignani, PRA 83 (2011); Kreckel, PRA 82 (2010)]

Formation of neutral molecules

$$H_3O^+ + e \rightarrow H_2O^{**} + H$$ [Buhr, PRL 105 (2010)]

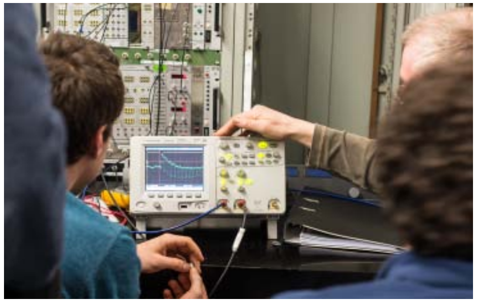
$$HCNH^+ + e \rightarrow HCN/CNH^{**} + H$$ [Mendes, ApJ Lett. 746 (2012)]

Atomic and Molecular Physics with **Storage Rings**



The **Cryogenic Storage Ring**

Commissioning and **First Experiments**



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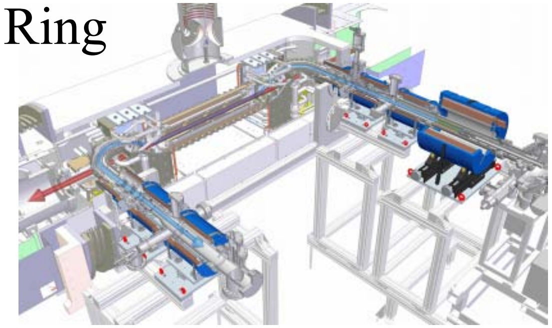

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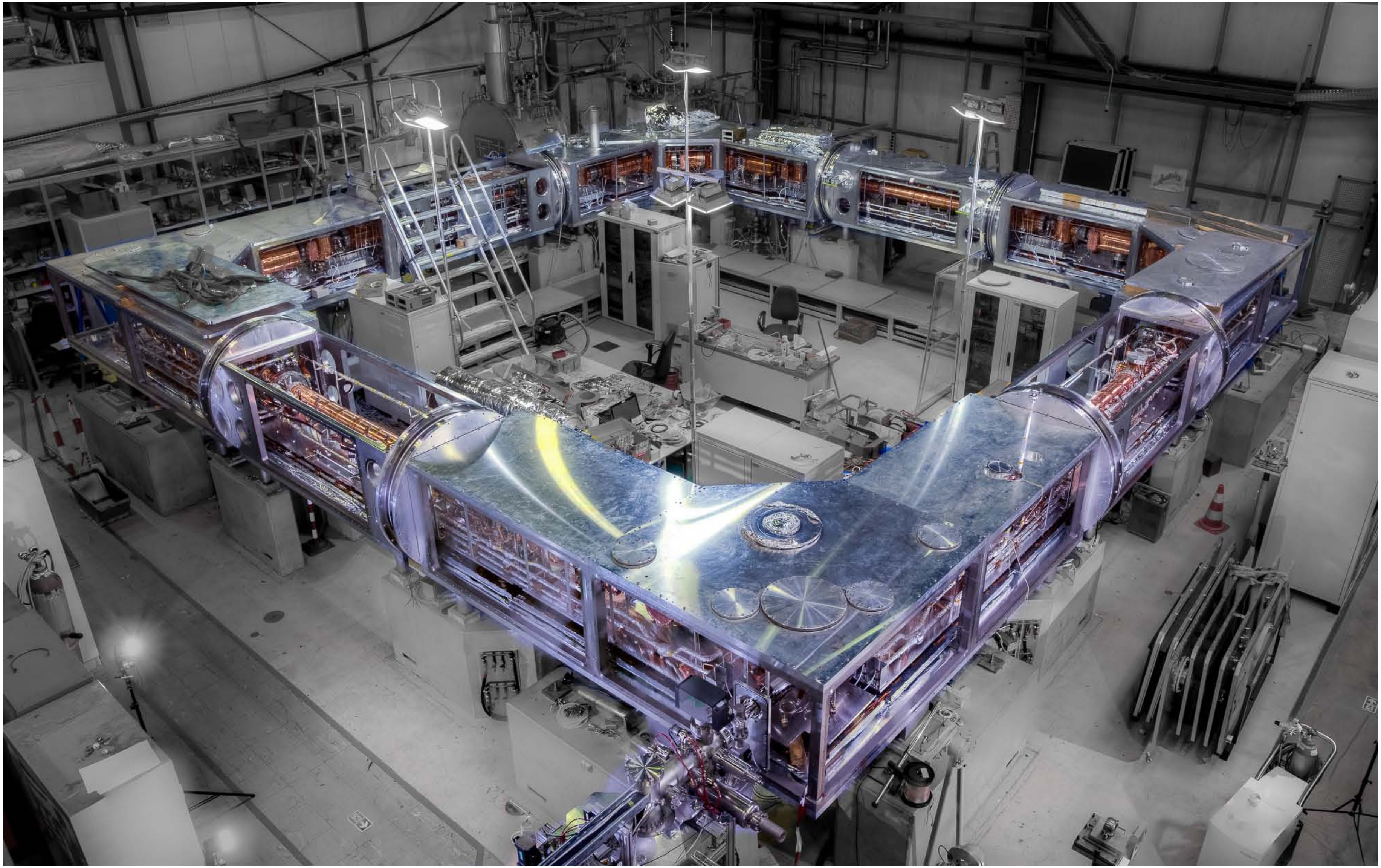

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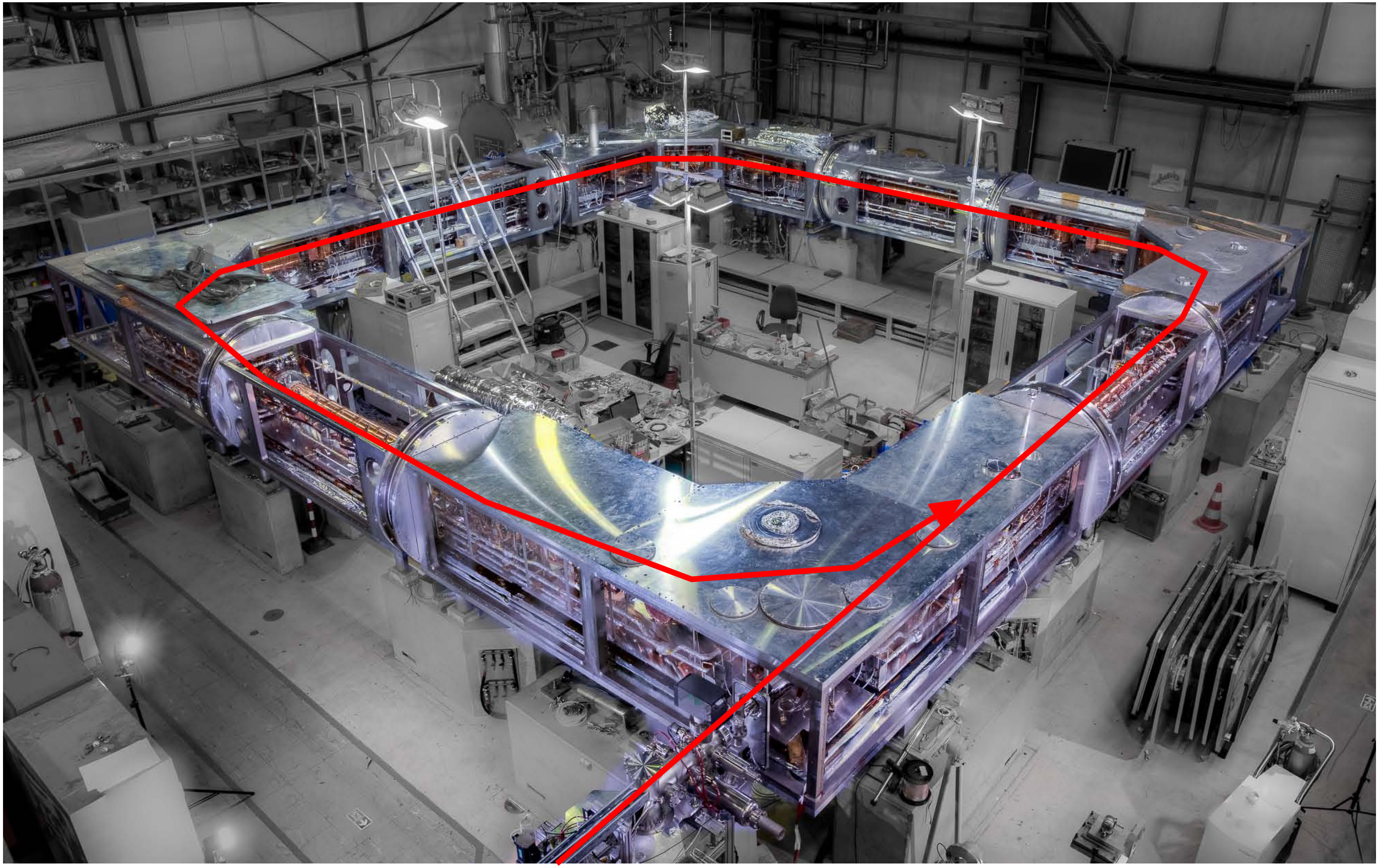
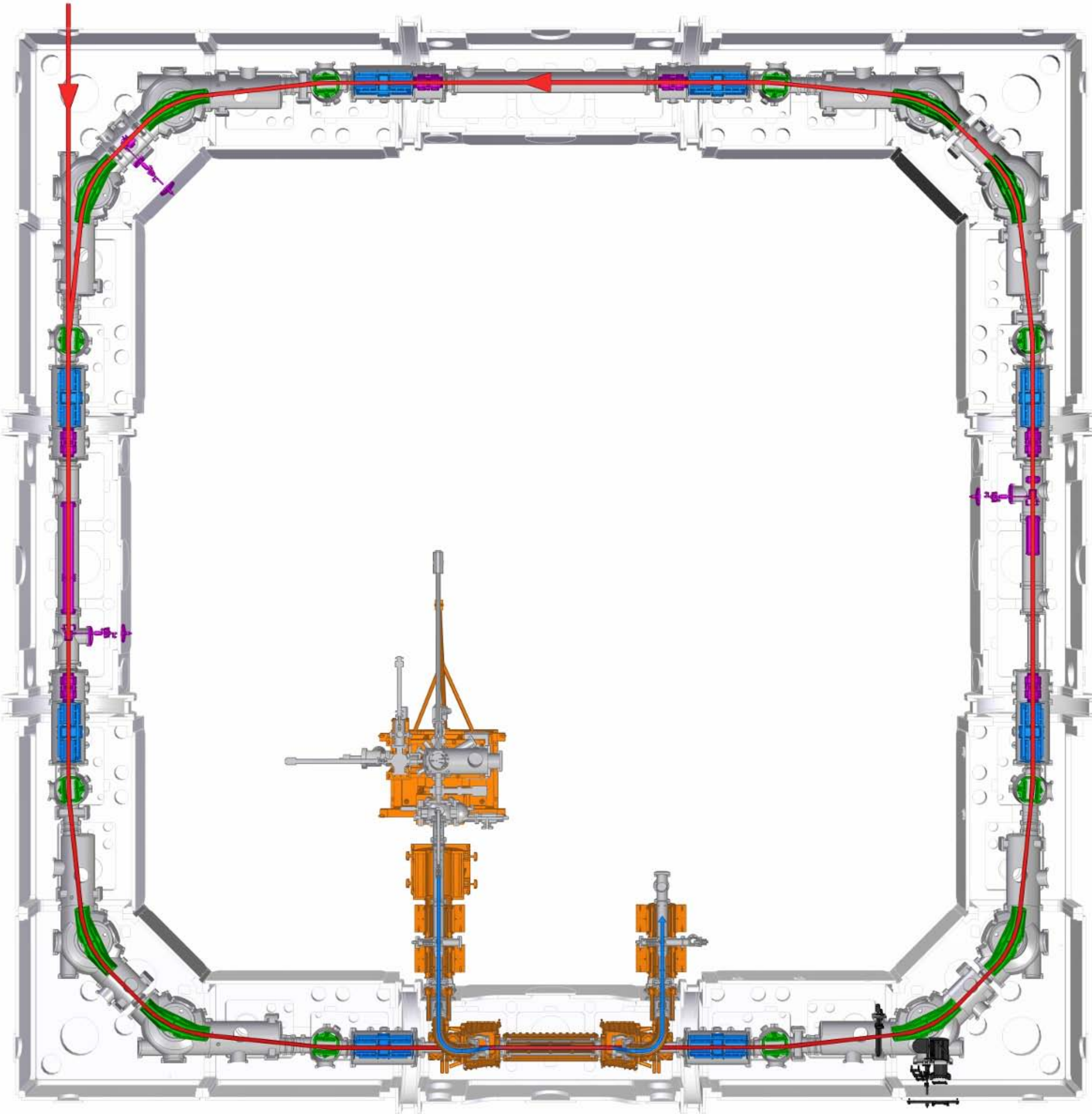
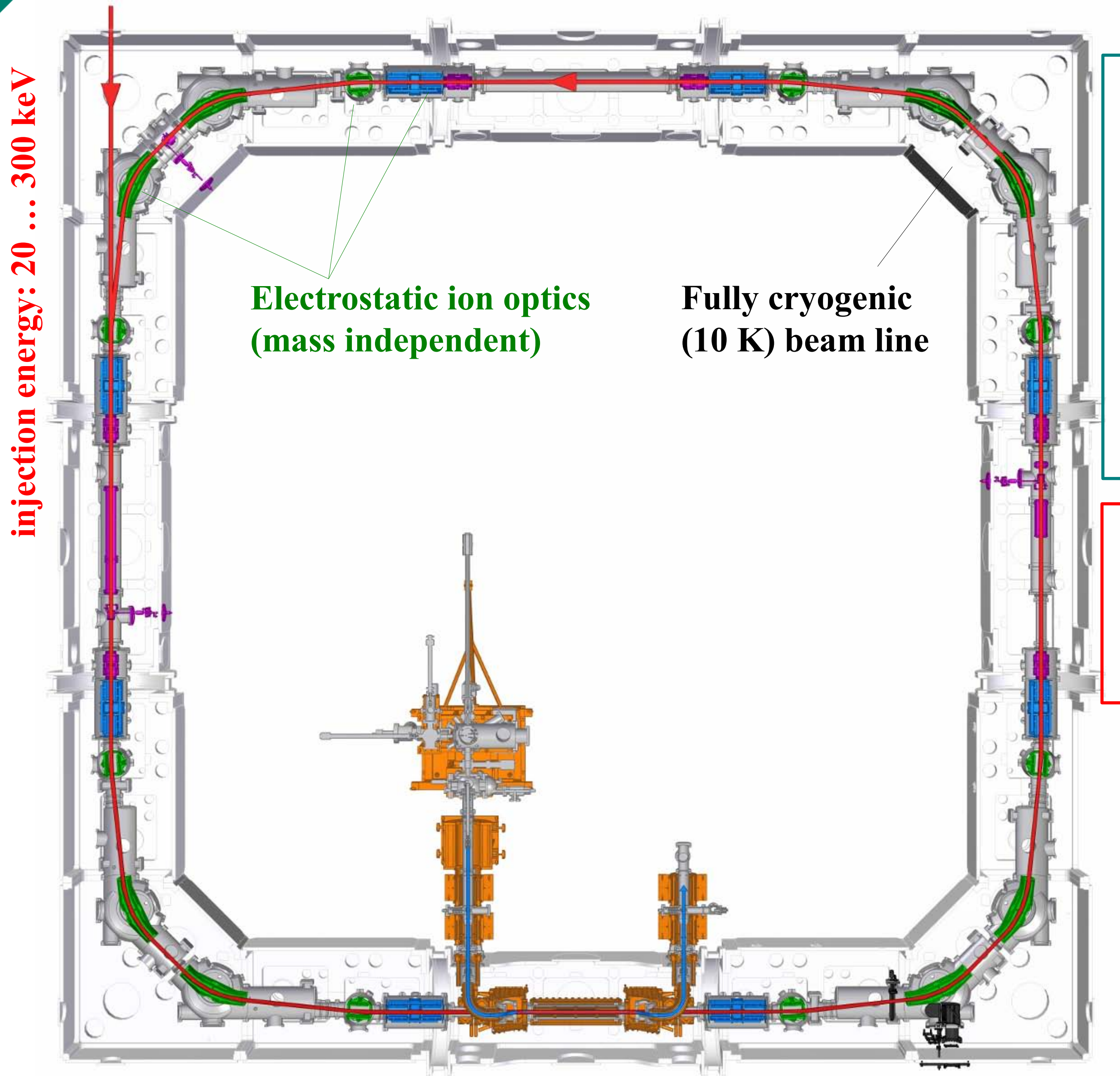


The CSR



circumference:	**35 m**
beam energy:	**20 keV × q ... 300 keV × q**
temperature:	**10 … 300 K**
res. gas press. (@ < 10 K):	**10^{-13} mbar (~ 1000 cm^{-3})**

The CSR



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m/q range:	**1 ... "∞" u/e**
lowest rigidity	**p^+, H^- @ 20 keV**

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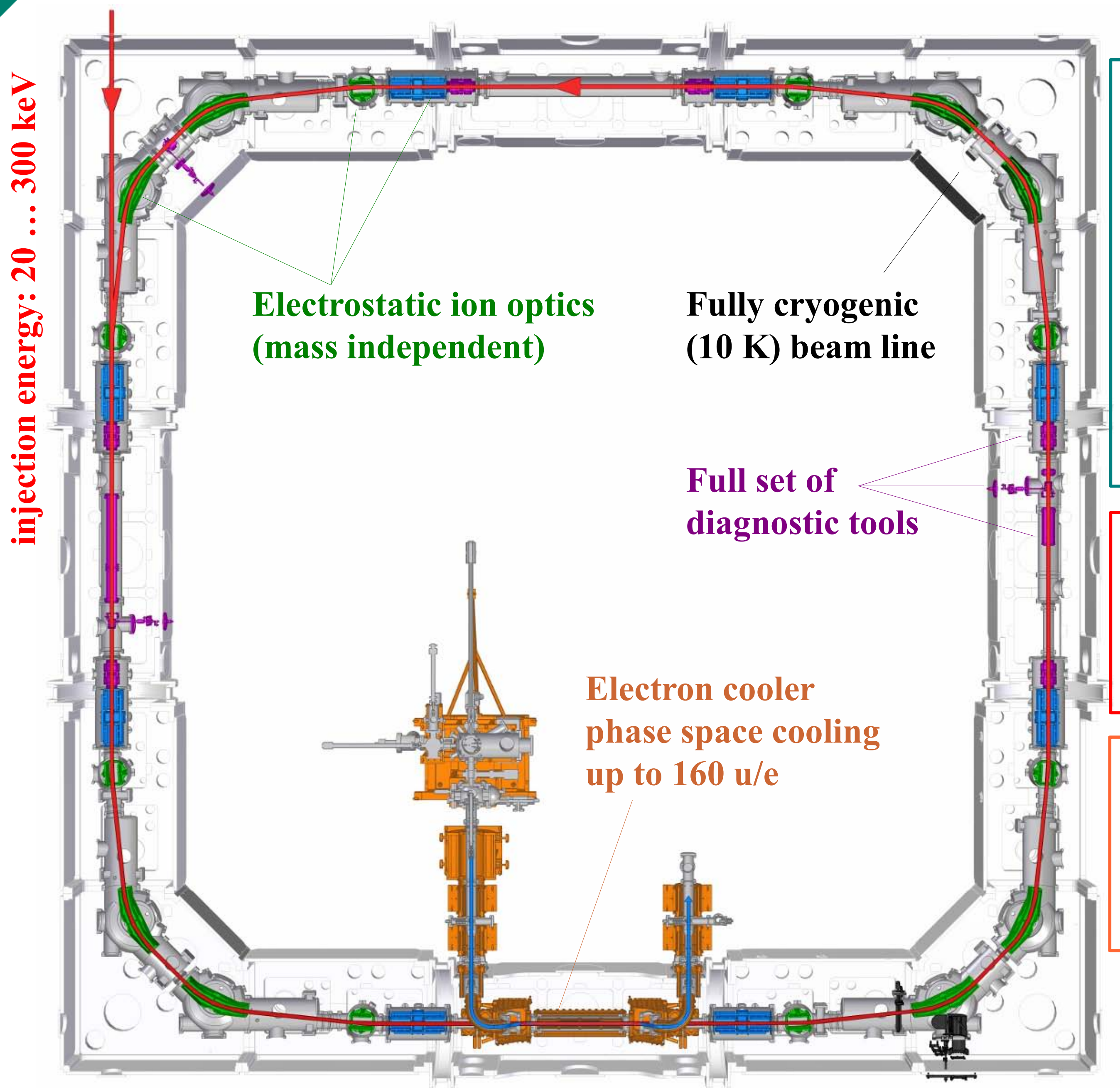
The CSR



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m/q range:	**1 ... "∞" u/e**
lowest rigidity	**p^+, H^- @ 20 keV**

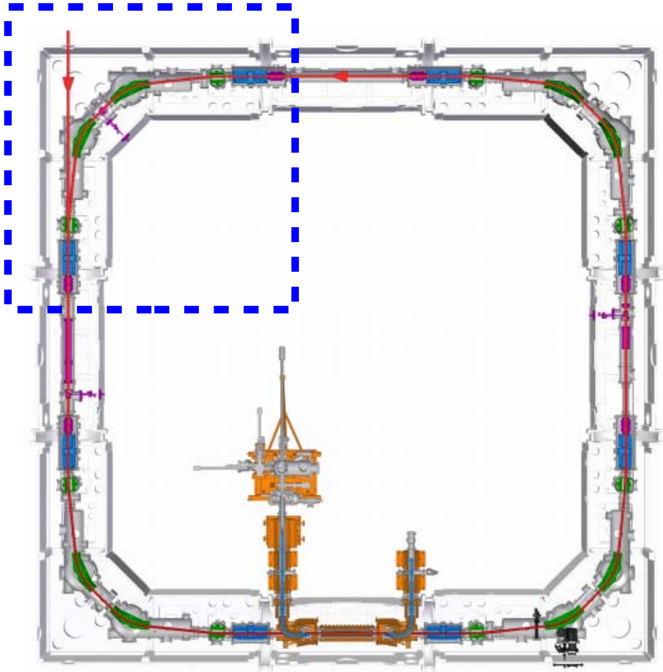
... with electron cooling

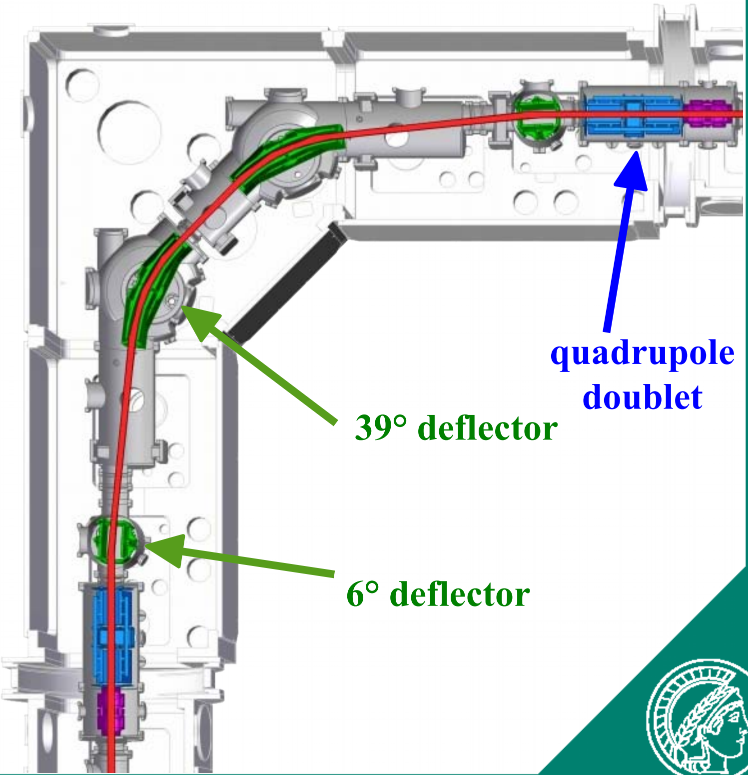
m/q range:	**1 ... 160 u/e (@ 300 kV)**
lowest rigidity	**p^+, H^- @ 20 keV**

The CSR

Electrostatic beam optics

- 4-fold symmetric
  - 4 identical "corner" lattice sectors
- 4 x 2 pairs of **focussing quadrupoles**
- 4 x 2 **6°-deflector** electrodes (20 kV)
- 4 x 2 **39°-deflector** electrodes (20 kV)
- 4 free straight sections (2.4 m each)





The CSR

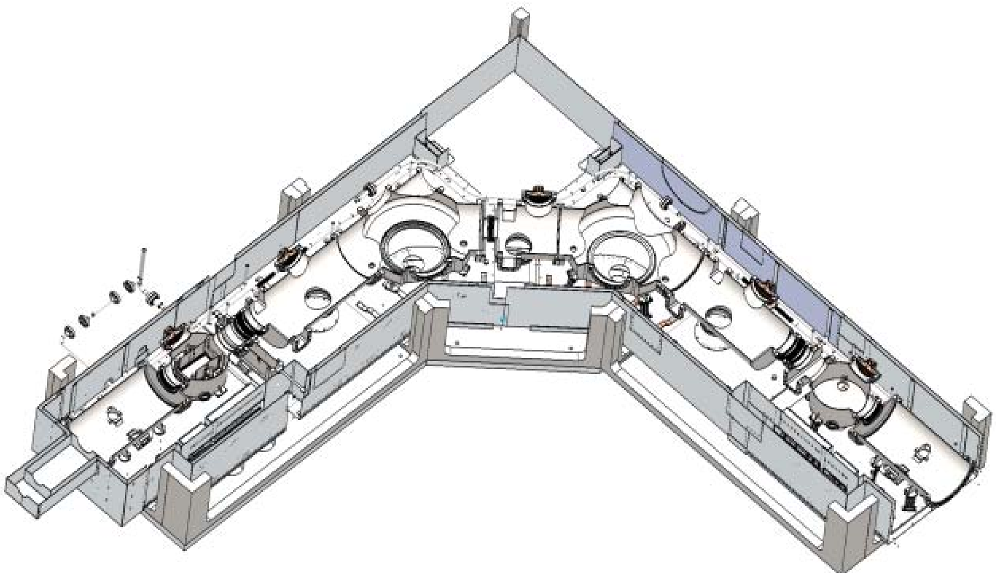
Cryogenics

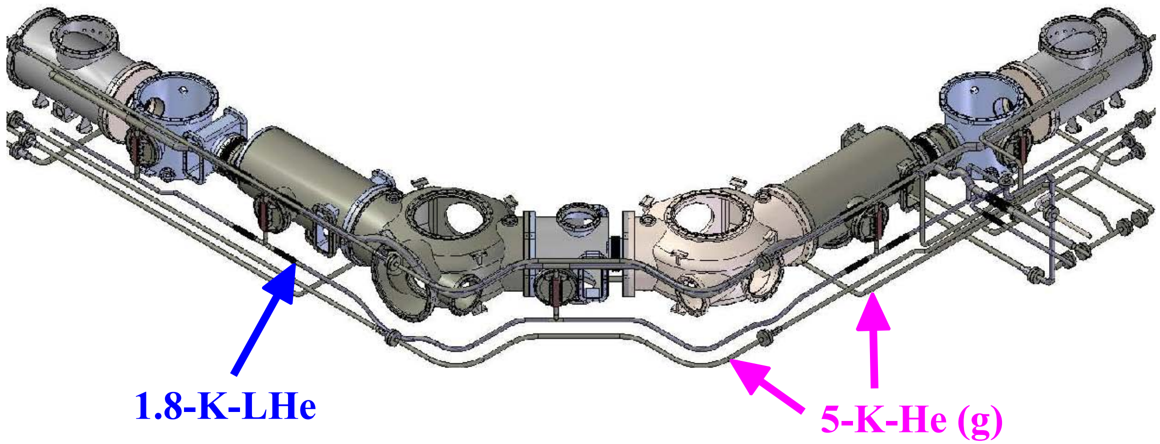
Inner vacuum chamber ($\leq$ 10 K)
cooled by superfluid He (20 W).

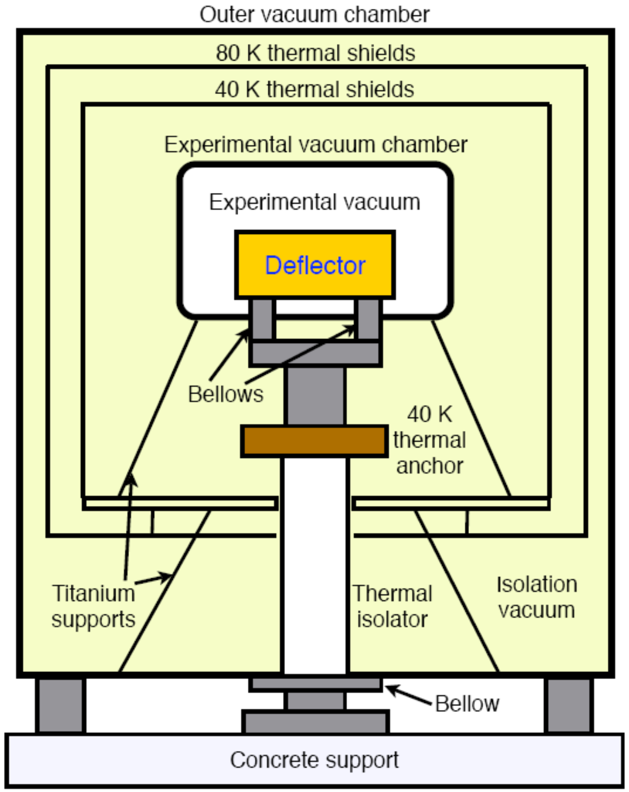
2 radiation shields (40 and 80 K)
cooled by 5-K He (600 W)

Multi-Layer Insulation

Isolation vacuum chamber







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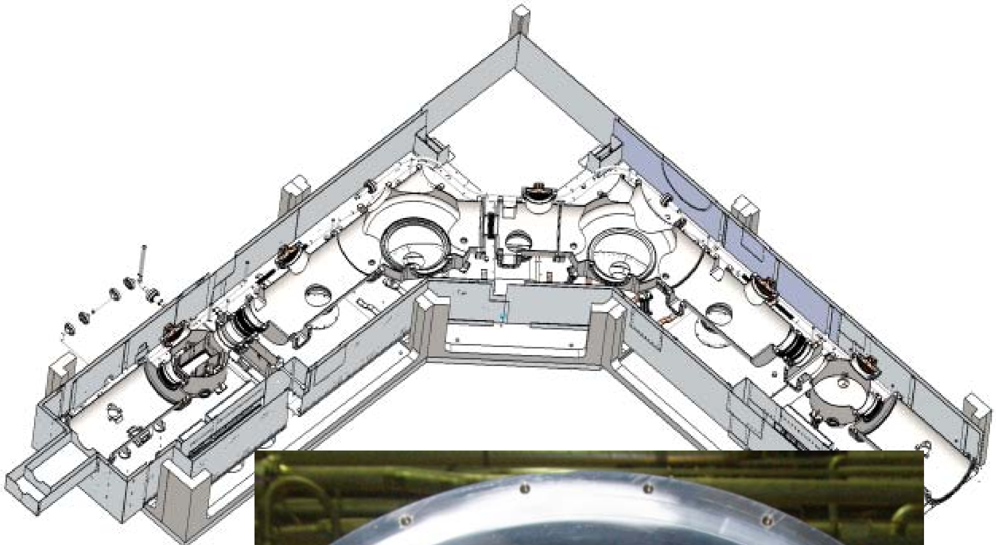
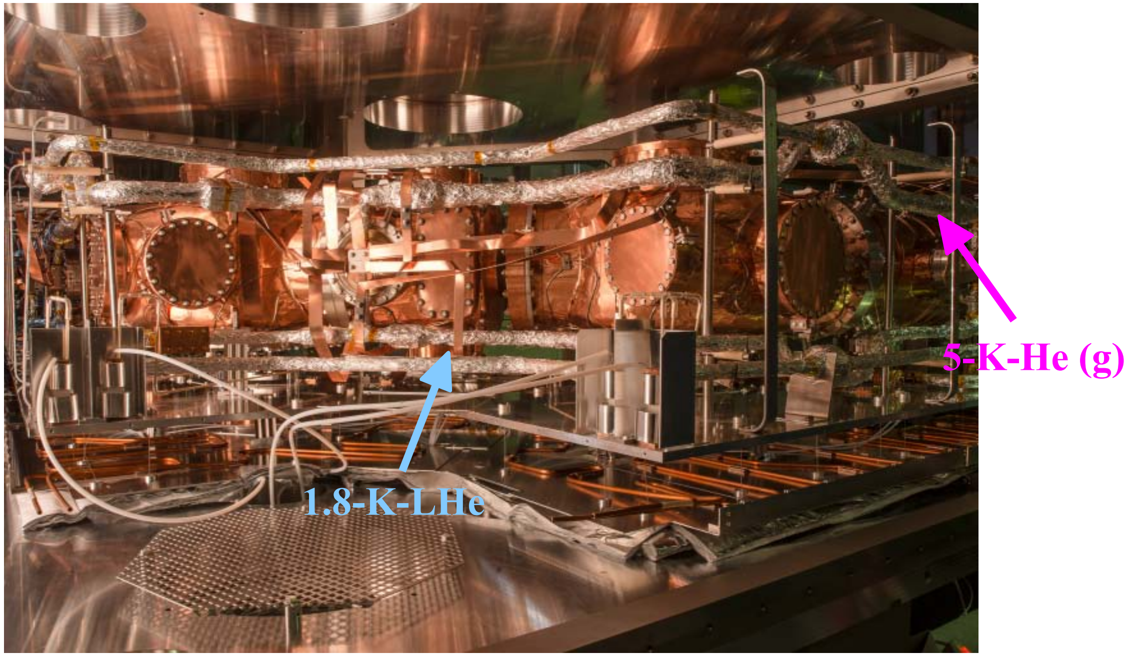
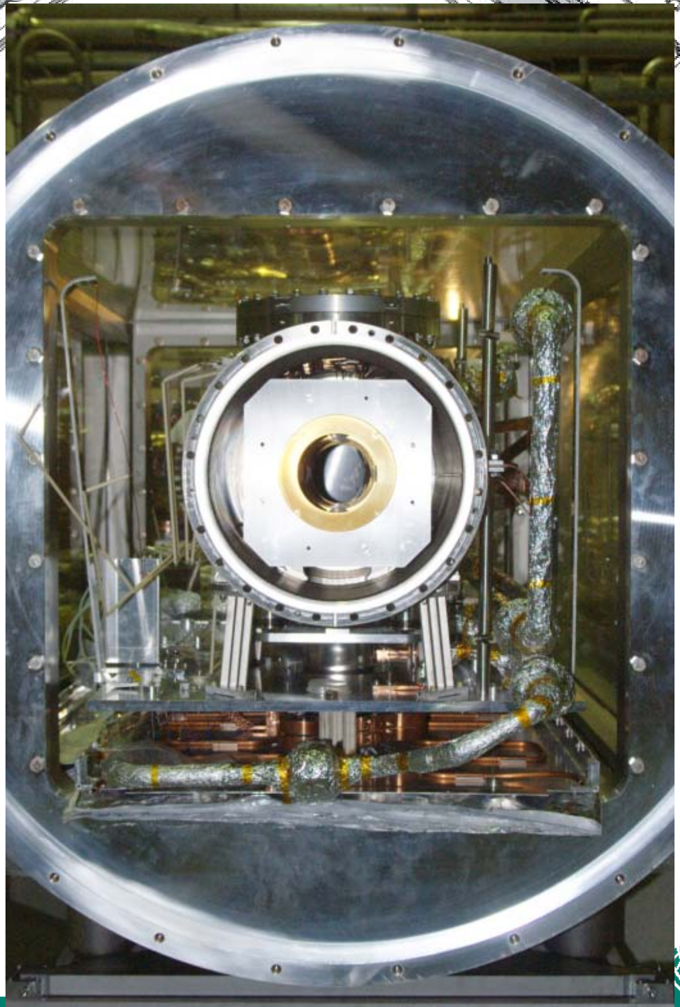




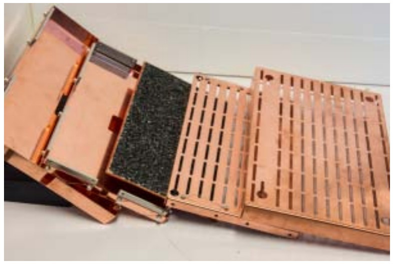


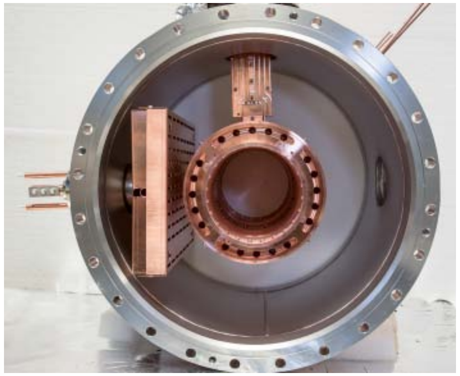
The CSR

XHV: Extremely High Vacuum

In 300-K-operation: **~ 10^{-11} mbar**

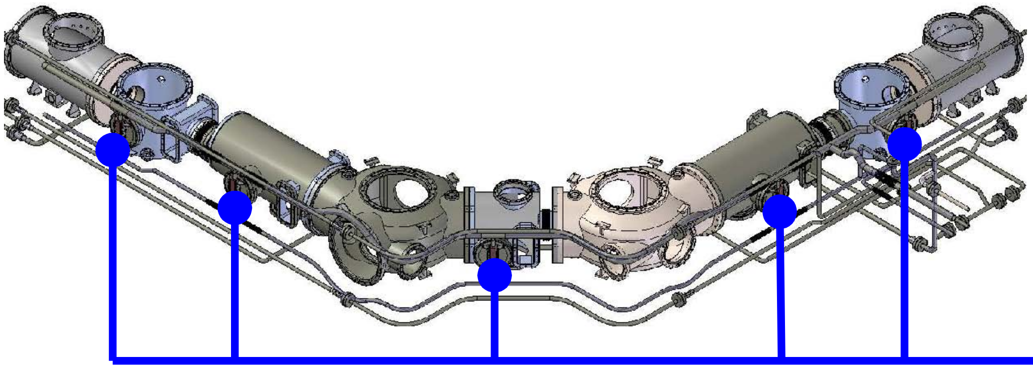
250°C bakeout,
5 ion-getter pumps,
16 active NEG pumps (~ 3 m²),
8 bakeable charcoal cryopumps





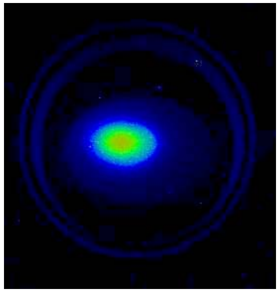
In 10-K-operation: **≈ 10^{-13} mbar RTE**

cryoadsorption at 10-K-walls,
20 2-K cryocondensation pumps

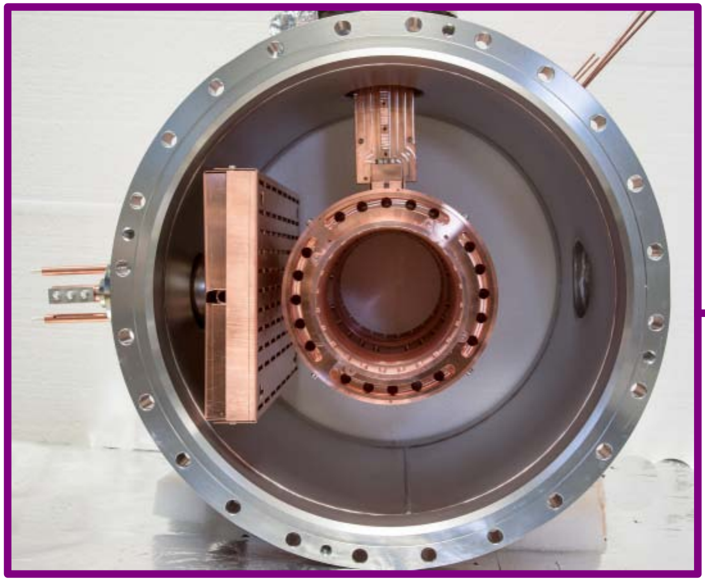


The CSR

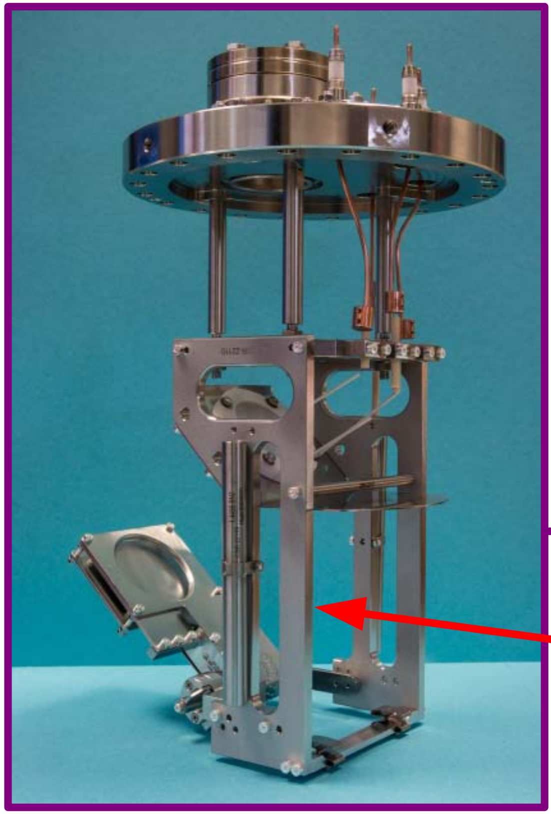
Beam diagnostics:

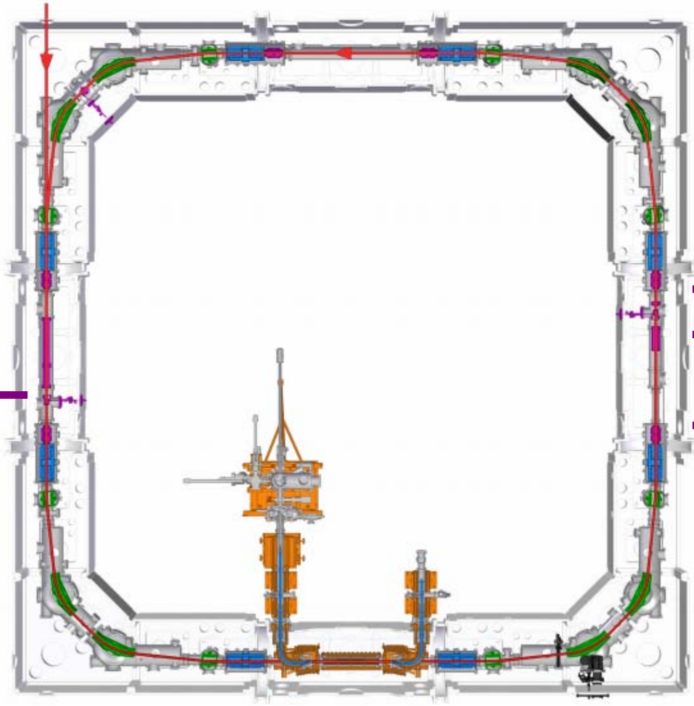


Position-, Schottky-, and ion current-pickup electrodes



Beam Imaging System

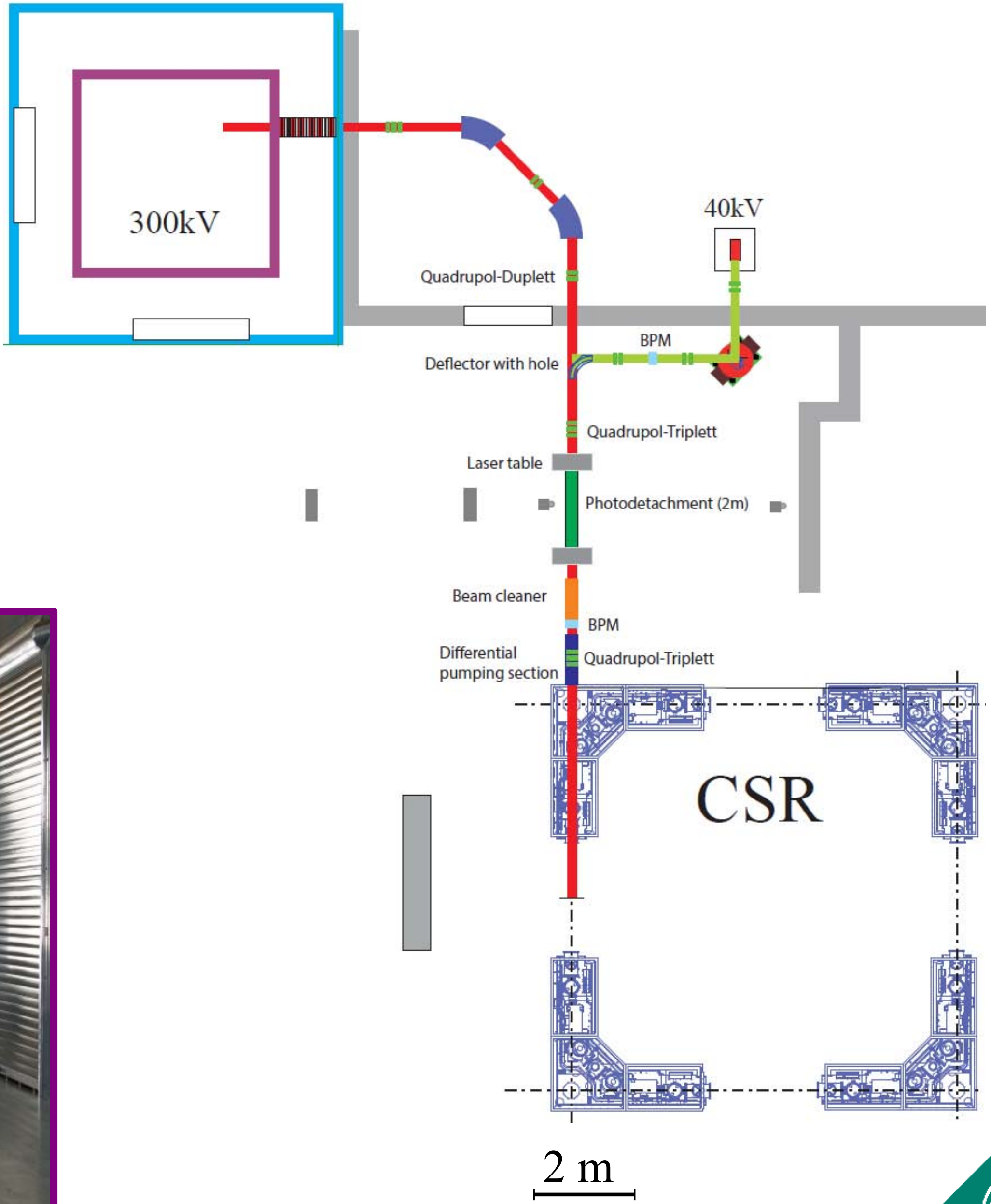




The CSR

Accelerators:

± 300 kV Main Injector



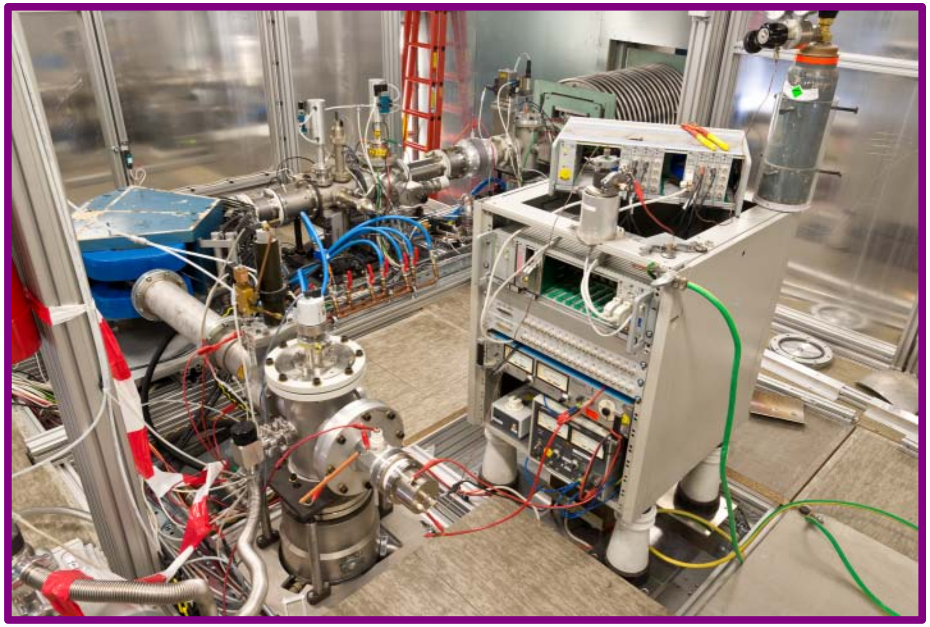
The CSR

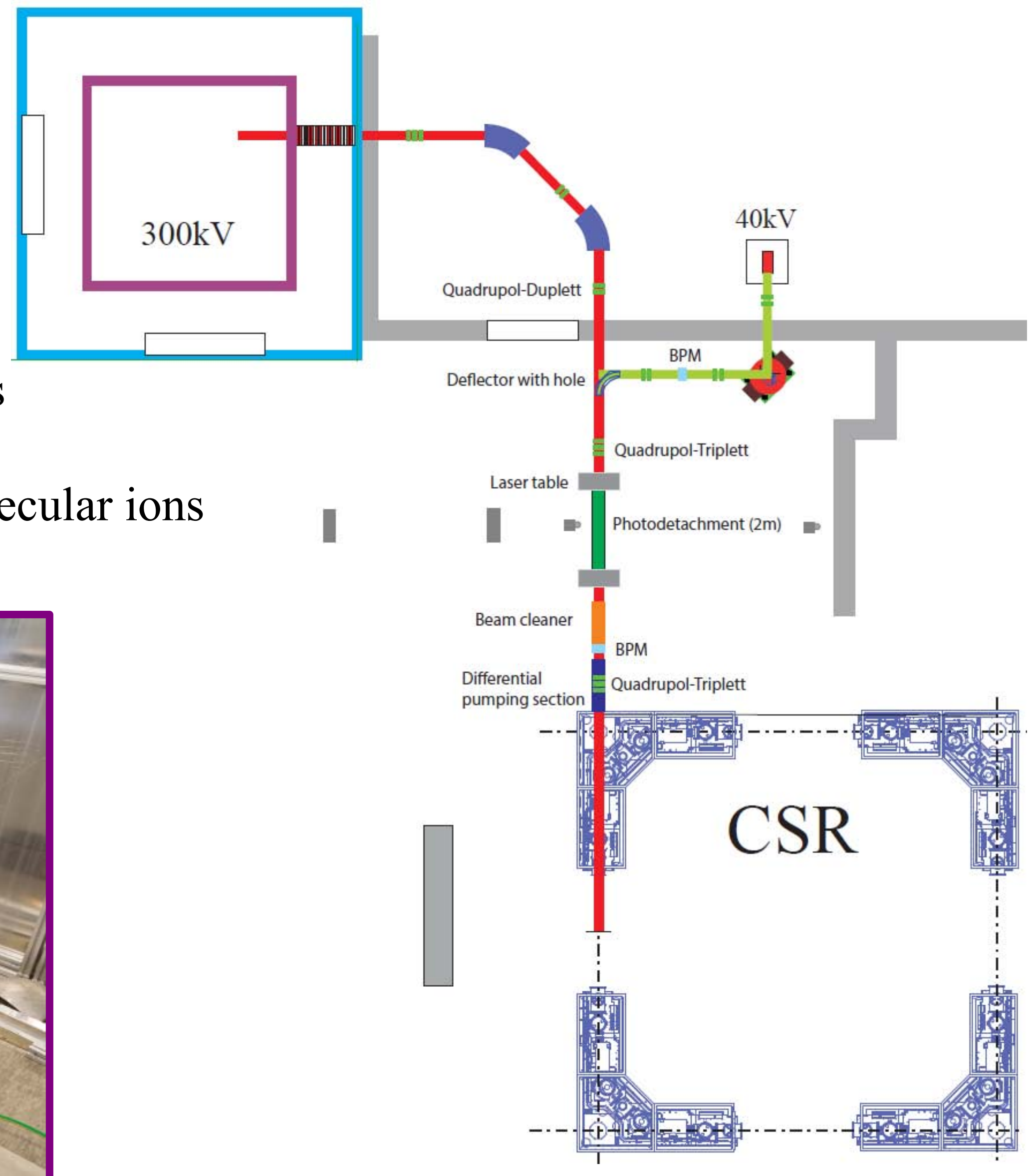
Accelerators:

± 300 kV Main Injector

Planned **ion source array**:

* Sputter ion source for negative molecular and cluster ions
* ECR ion source (HCI)
* E-spray ion source for organic molecular ions
* Buffer-gas cooled rf-traps ...



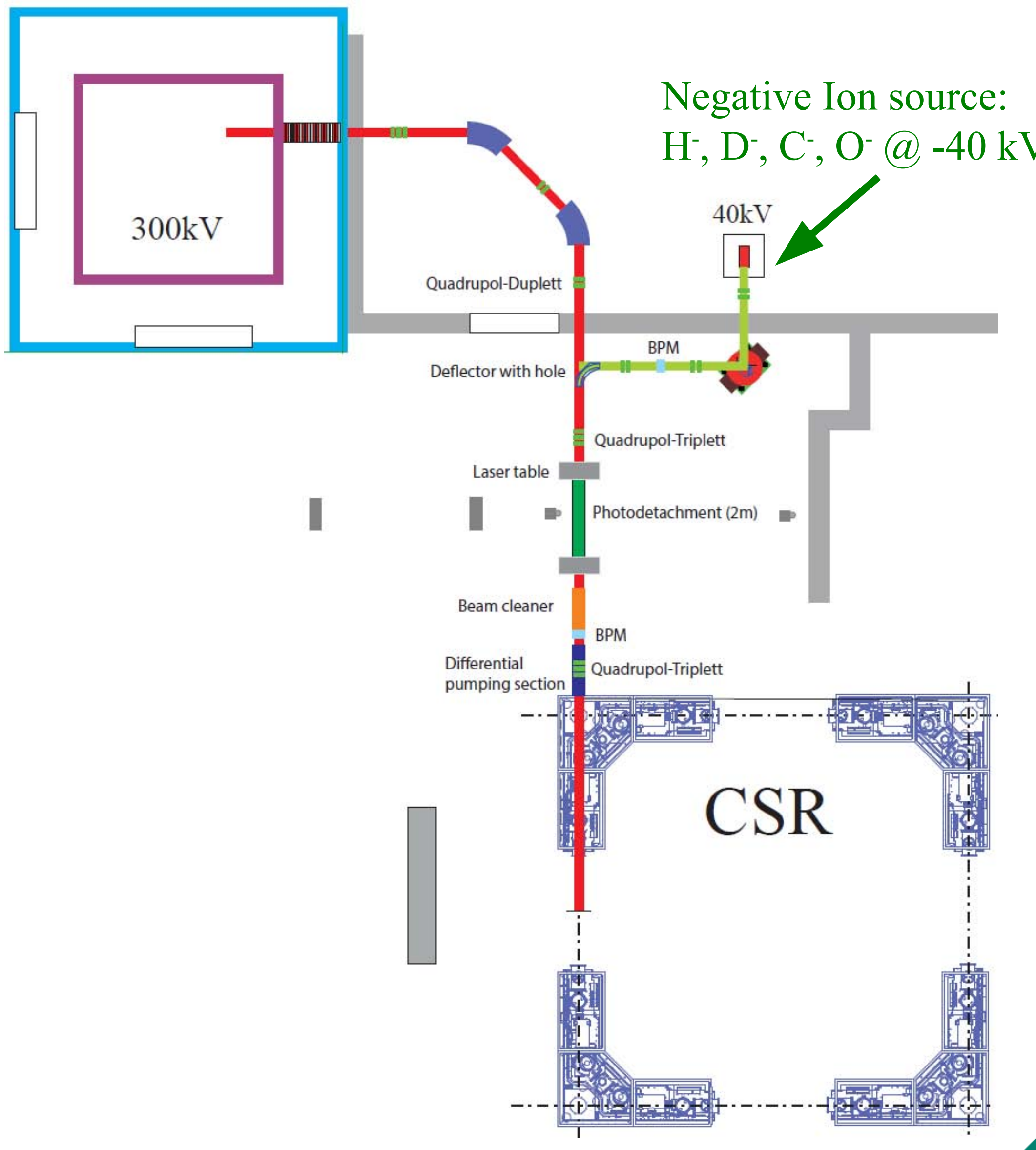


The CSR

Accelerators:

± 300 kV Main Injector

– 40 kV Secondary Injector



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± 300 kV Main Injector

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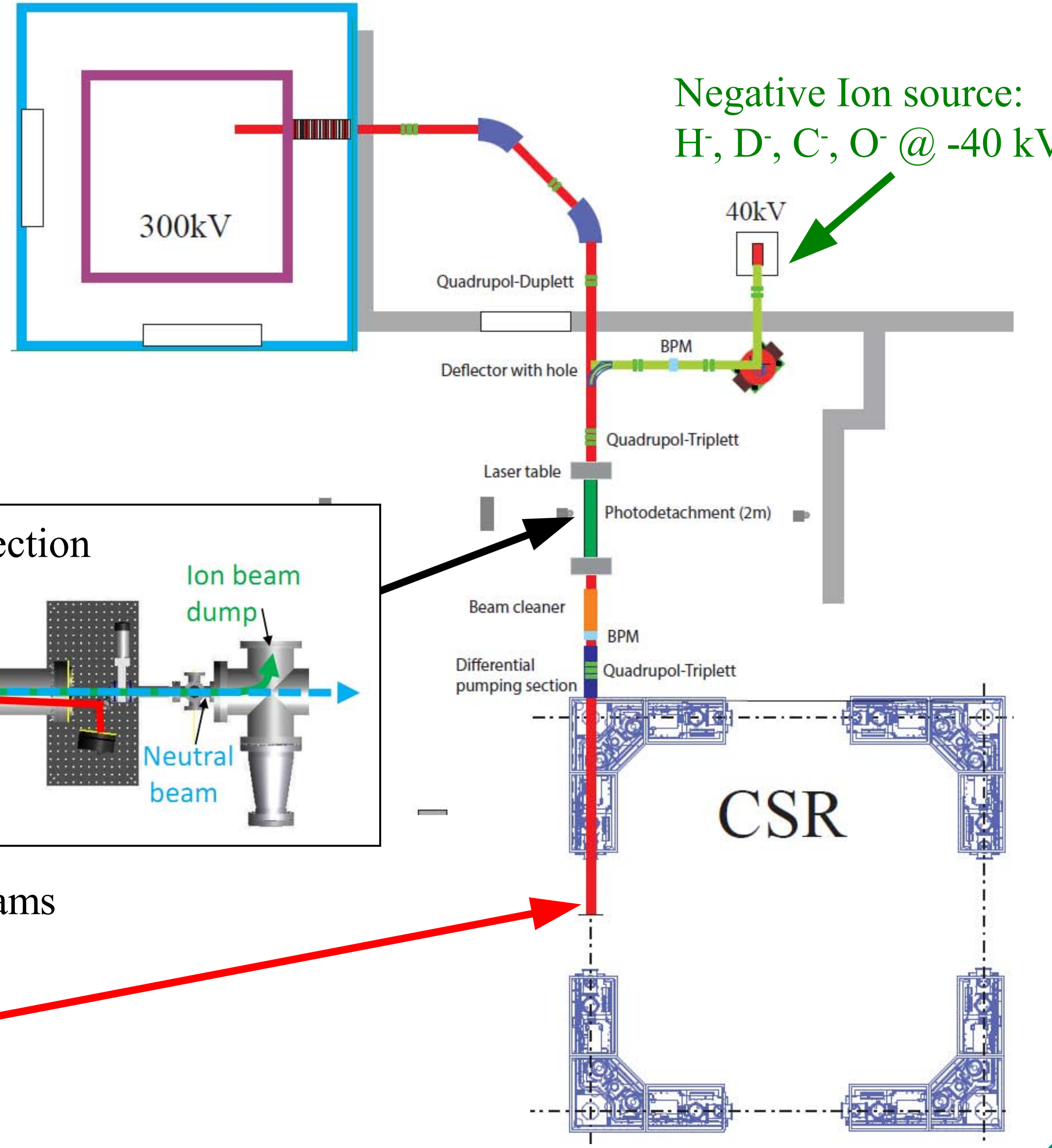
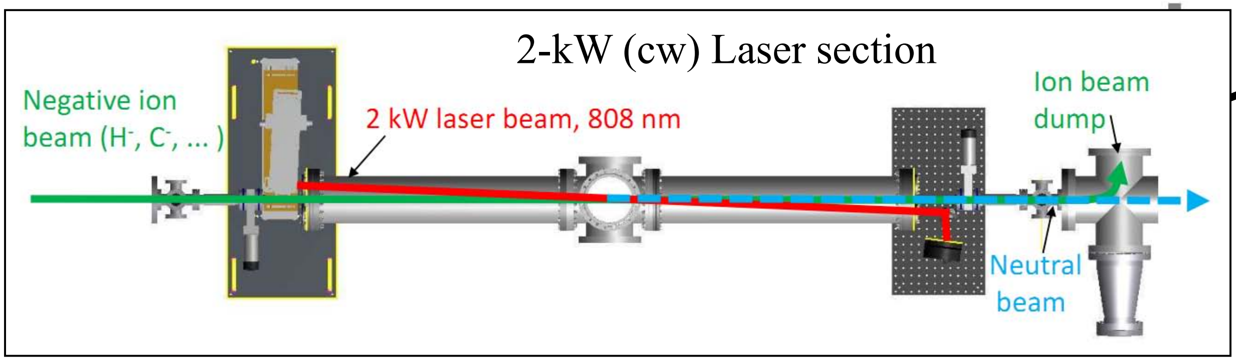


H. Kreckel et al.

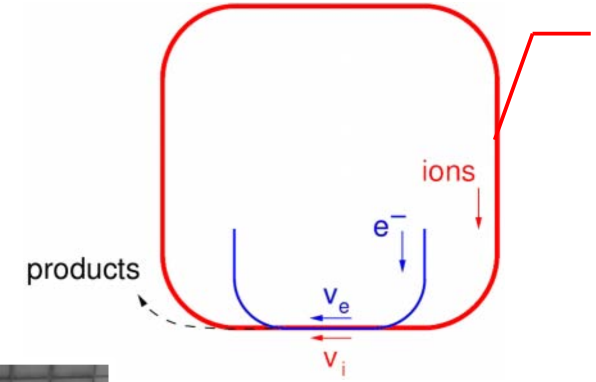


Create ground-state **H, D, C, O neutral** beams by photo-detachment

superimpose the to the **stored ions**

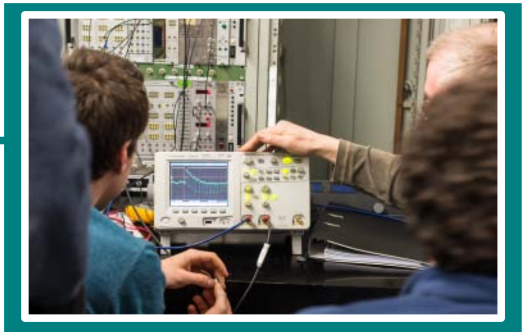
e.g. $\mathbf{C + H_3^+ \rightarrow CH^+ + H_2}$

Atomic and Molecular Physics with **Storage Rings**



The **Cryogenic Storage Ring**

Commissioning and **First Experiments**



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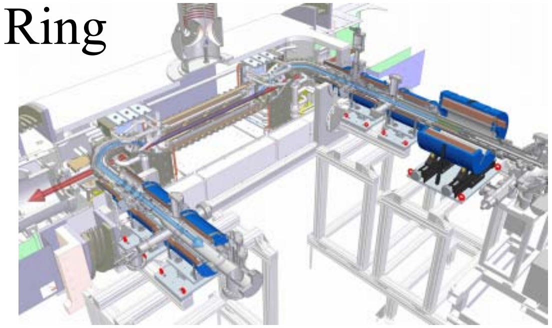

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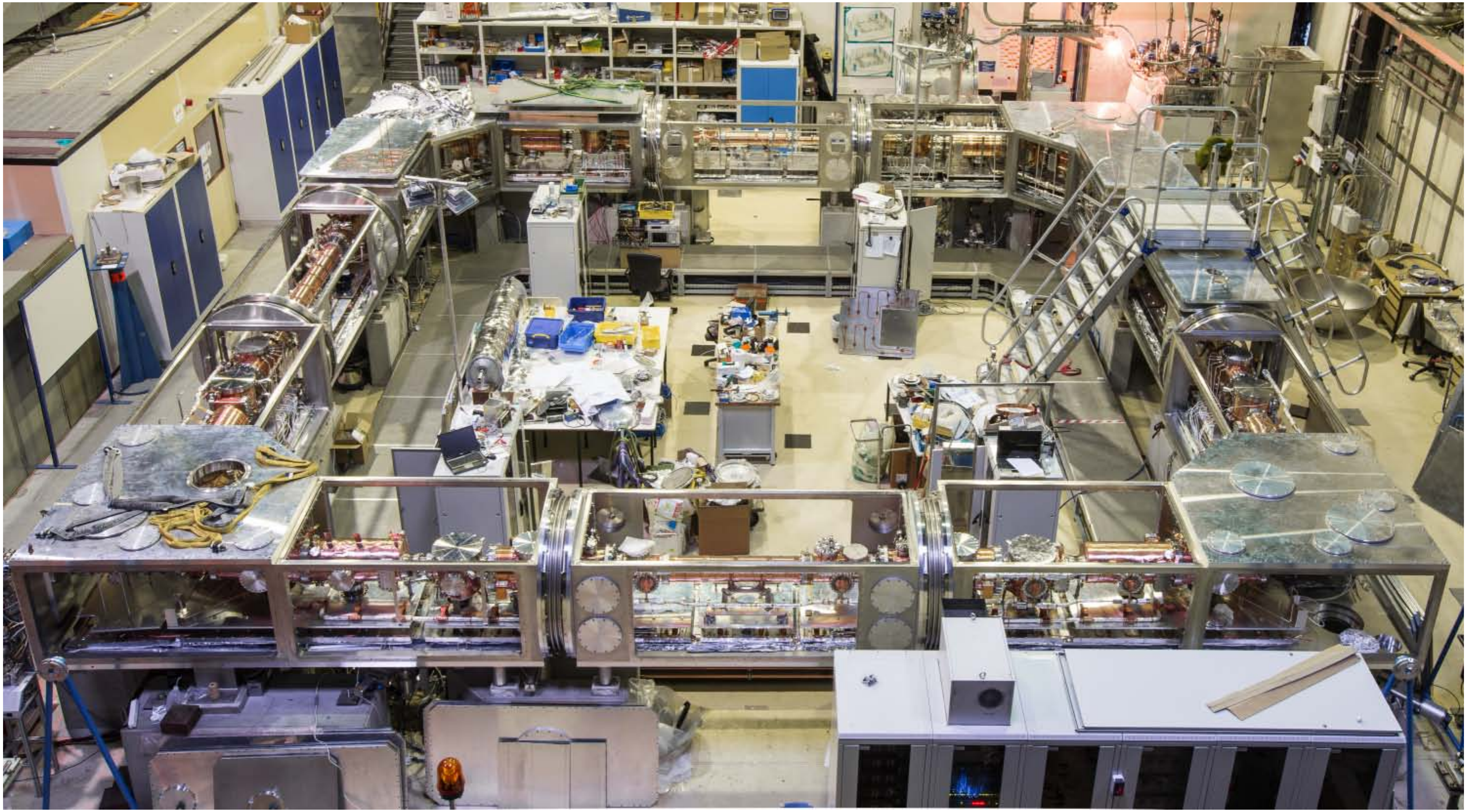
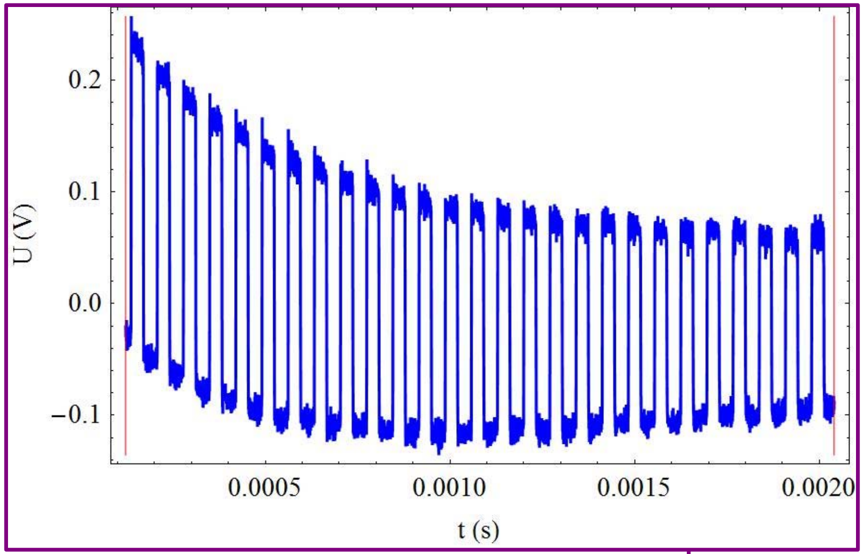


The CSR in March 2014

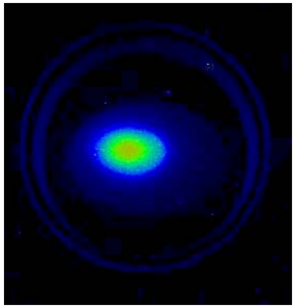
Commissioning ...

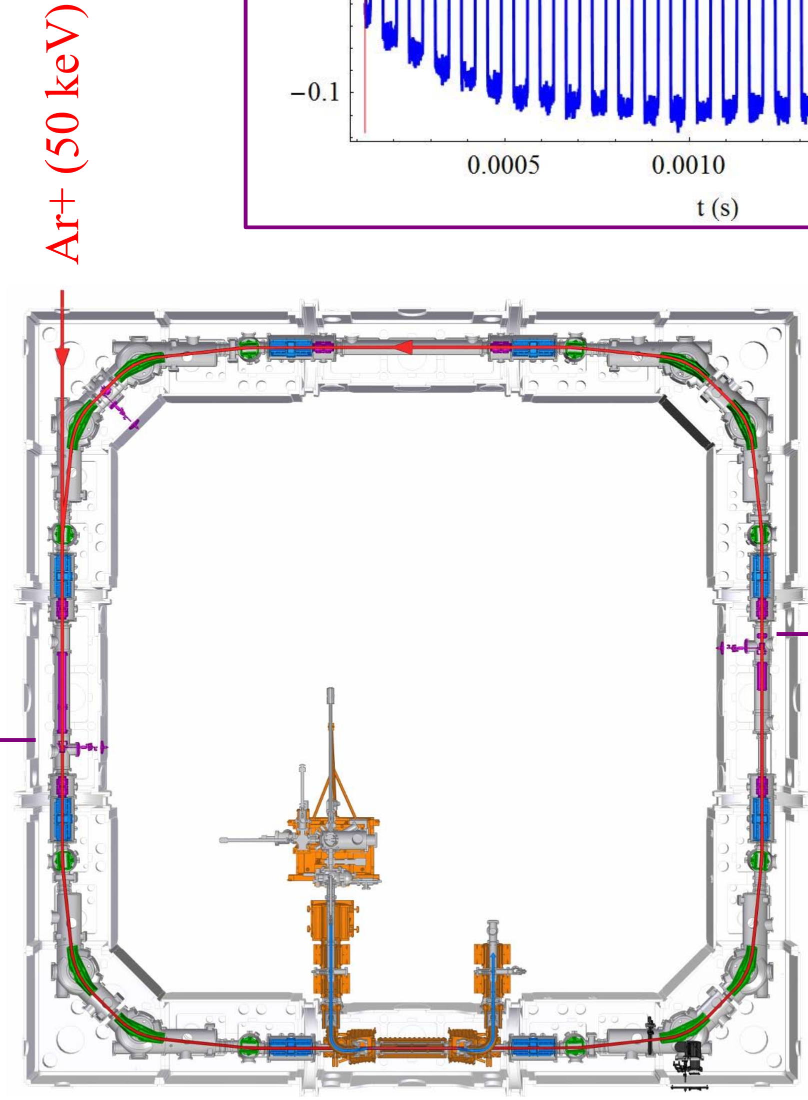


Spring 2014:

Commissioning

at room temperature, $^{40}Ar^{+}$ at 50 keV





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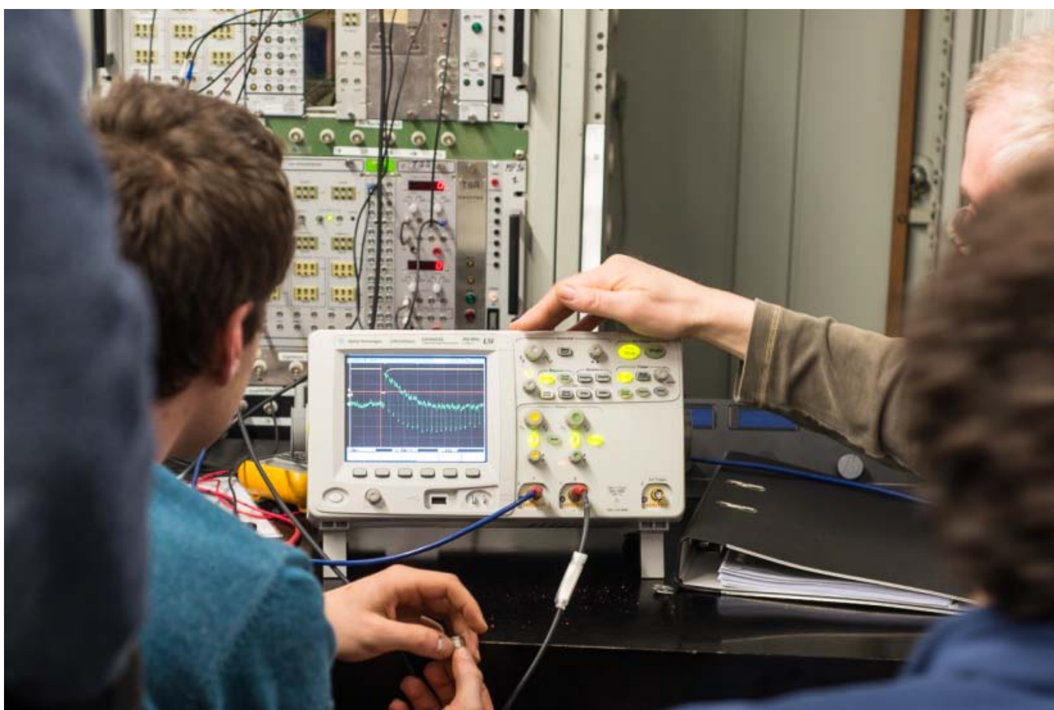
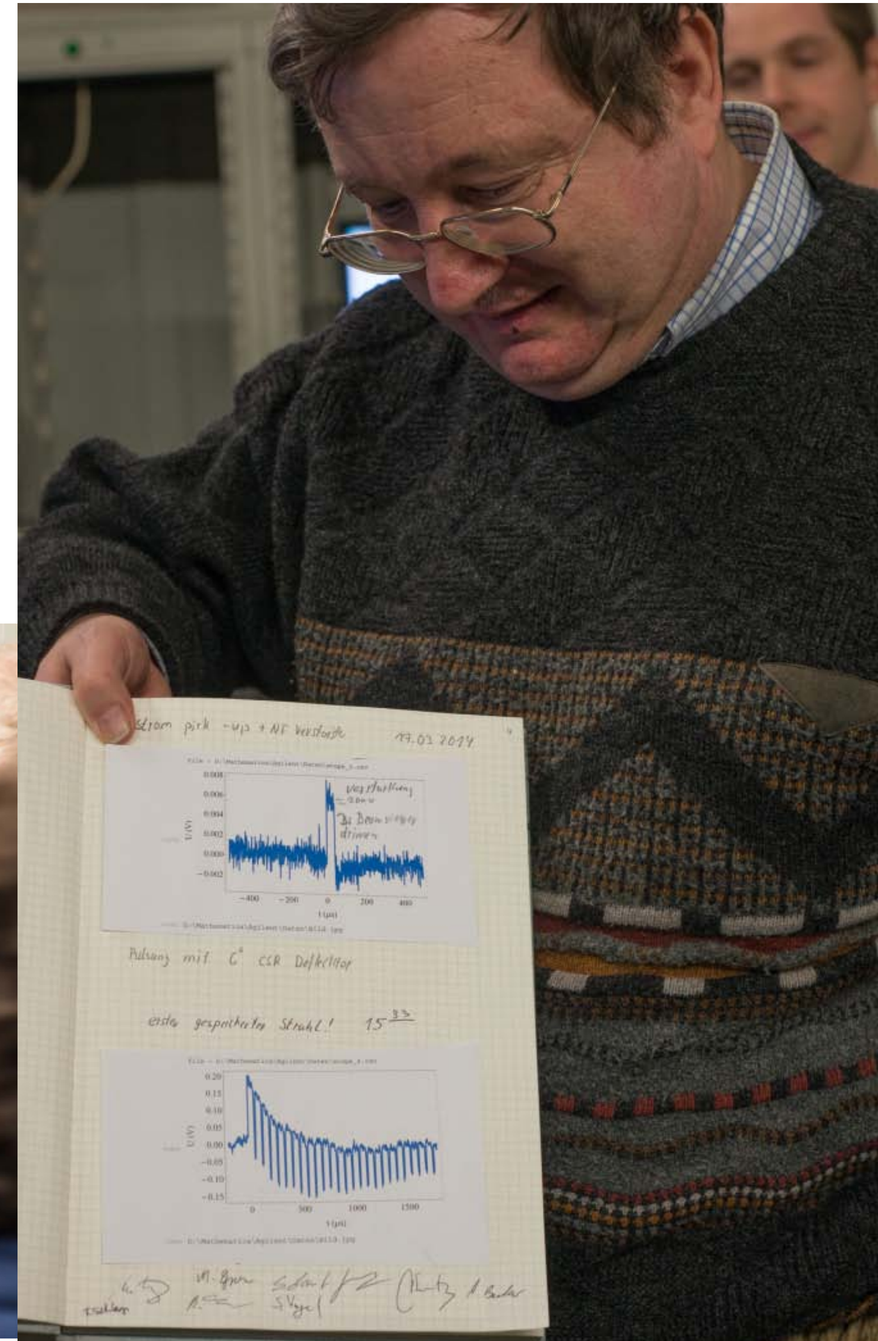
Commissioning ...

17th March 2014 (15:33):
First stored beam in CSR
$^{40}Ar^{+}$ (50 keV)

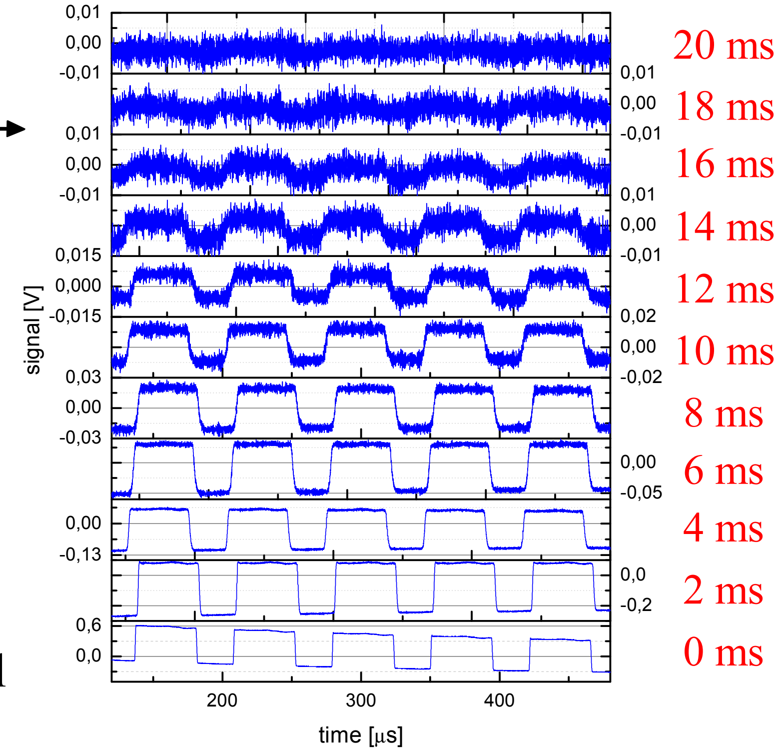




Commissioning ...

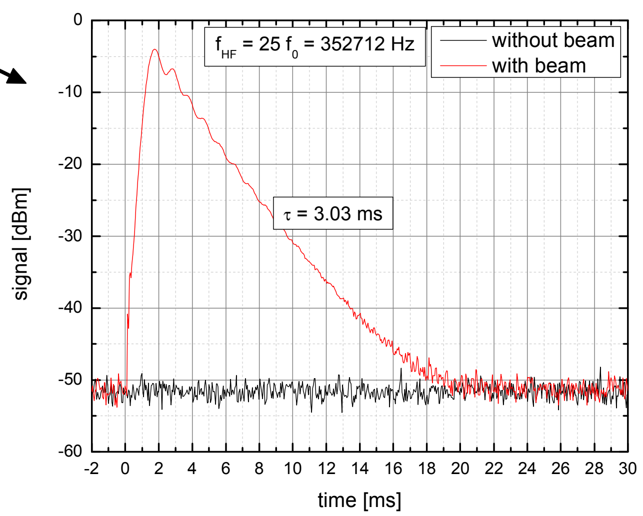
17th March 2014 (15:33):
First stored beam in CSR
$^{40}Ar^{+}$ (50 keV)

Beam lifetime from pickup electrodes ...

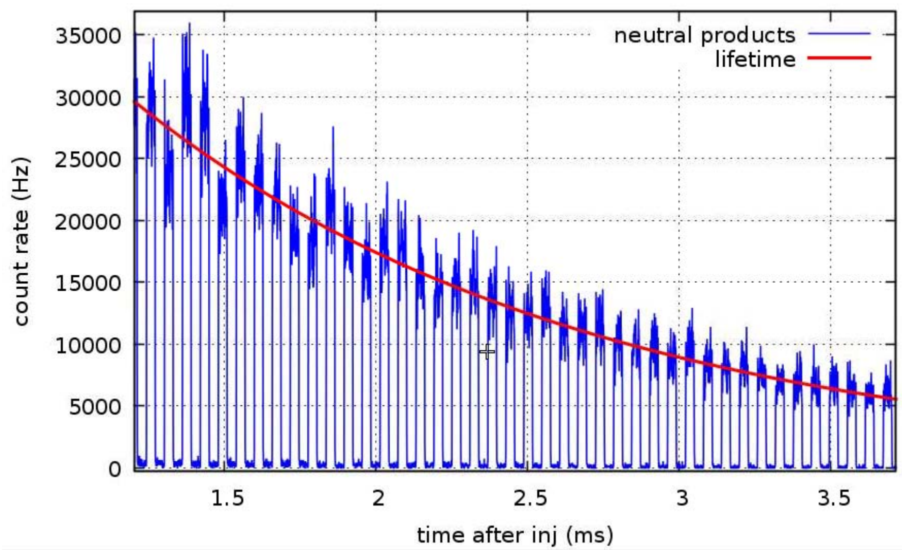


~ 300 revolutions (10 km)

First rf-bunching.



... and from experimental detectors



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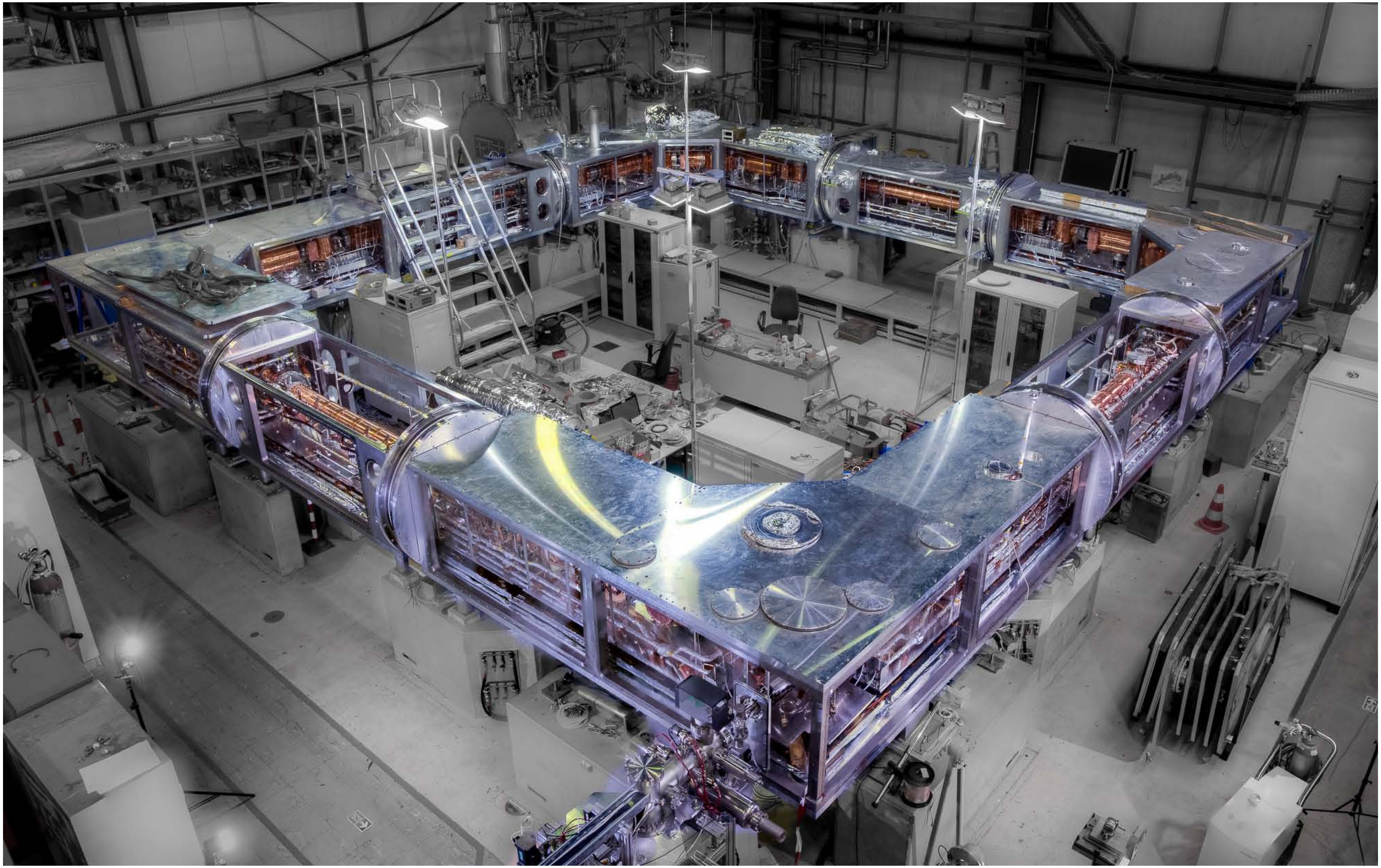
... and towards first experiments.



The CSR, end of 2014

... and towards first experiments.

Next goal (**March 2015**): Cryogenic operation

... and towards first experiments.

Electrostatic ion optics

Characterise **ring lattice**

(betatron fuctions, tune,
momentum compactation, etc.)

Extremely High Vacuum (10^{-13} mbar)

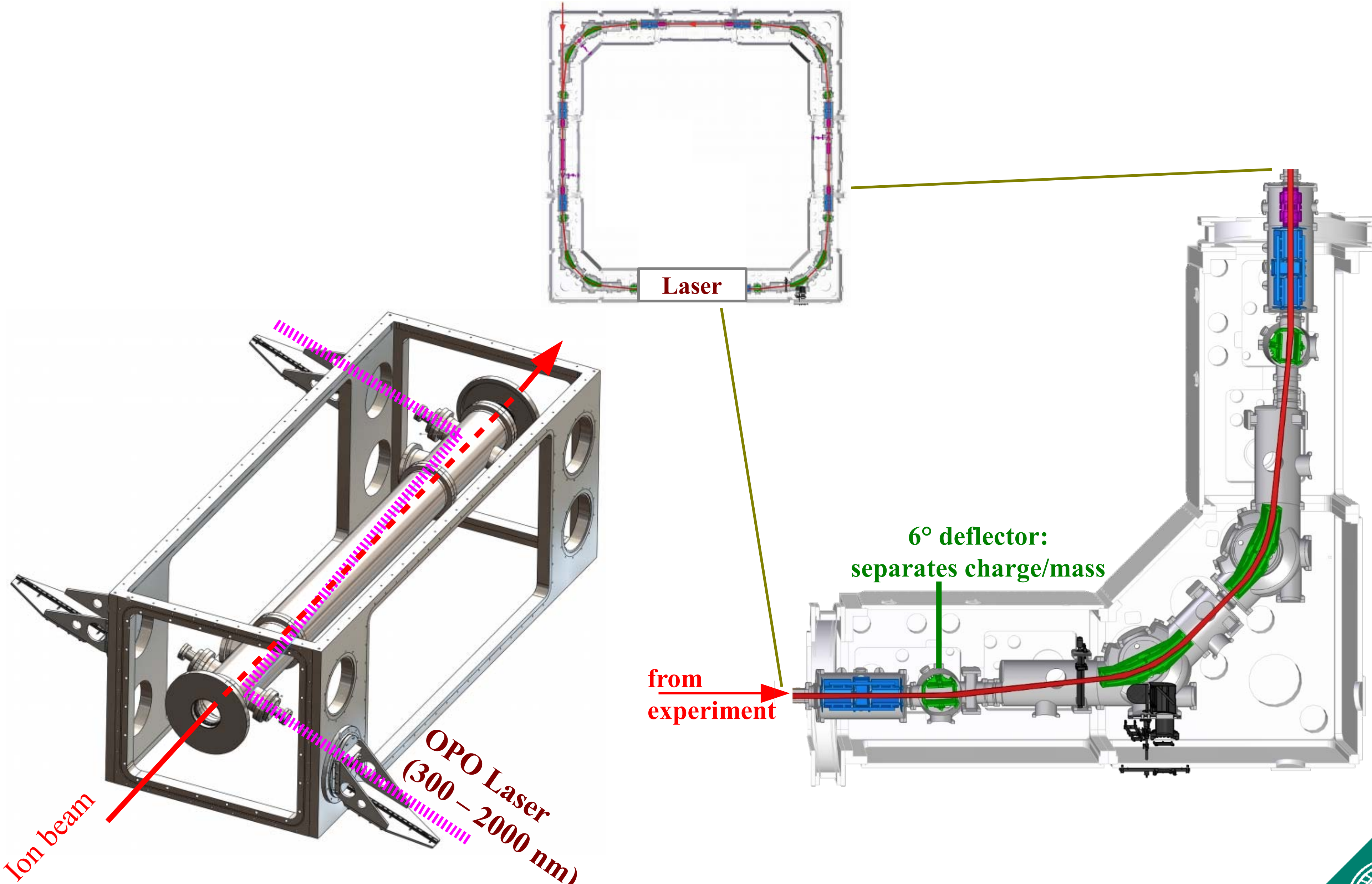
Storage of heavy (= slow)
ions for **very** long times (~ 1000 s)

Cold molecular ions

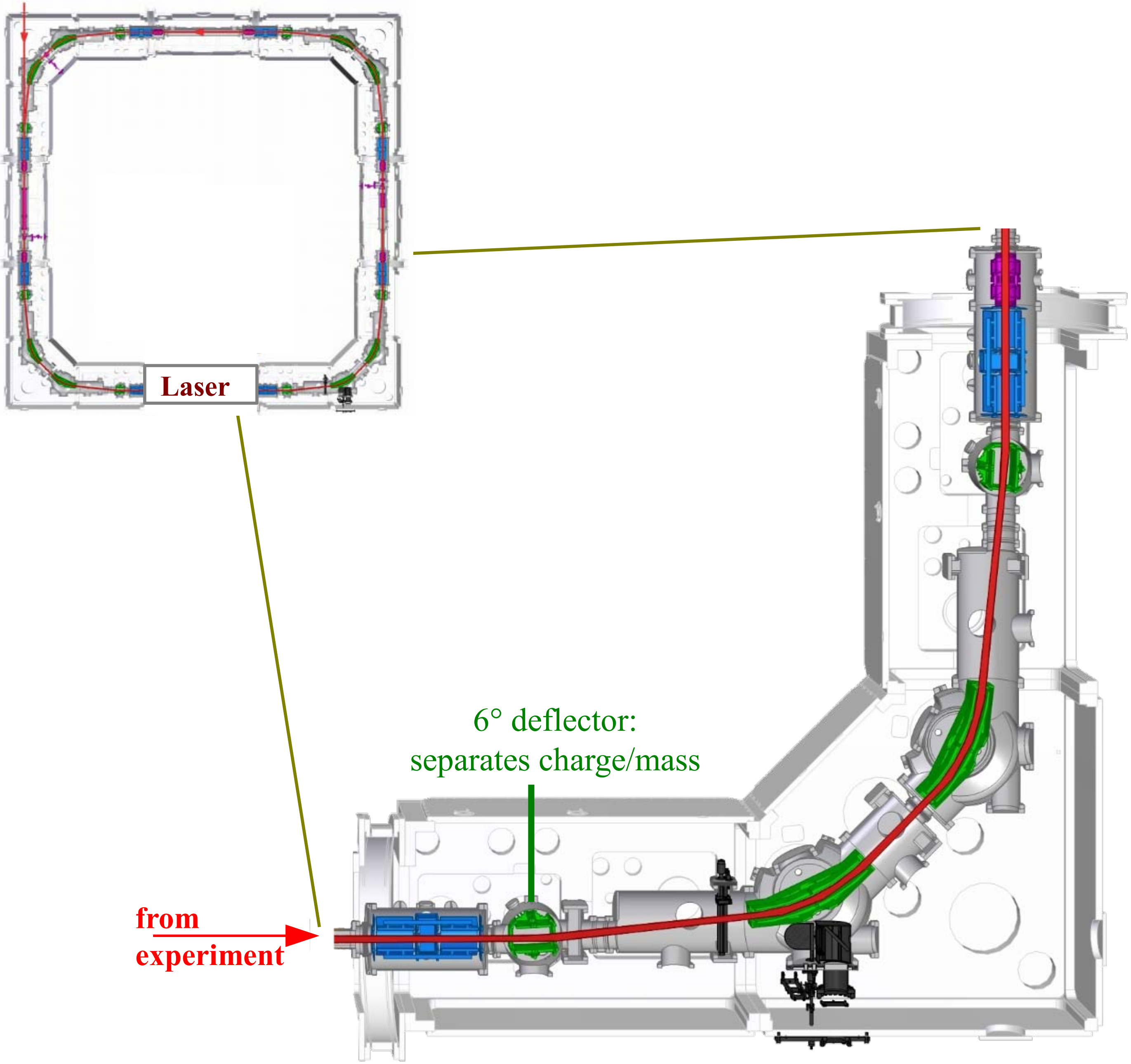
10 K environment:

Rovibrational cooling of molecules

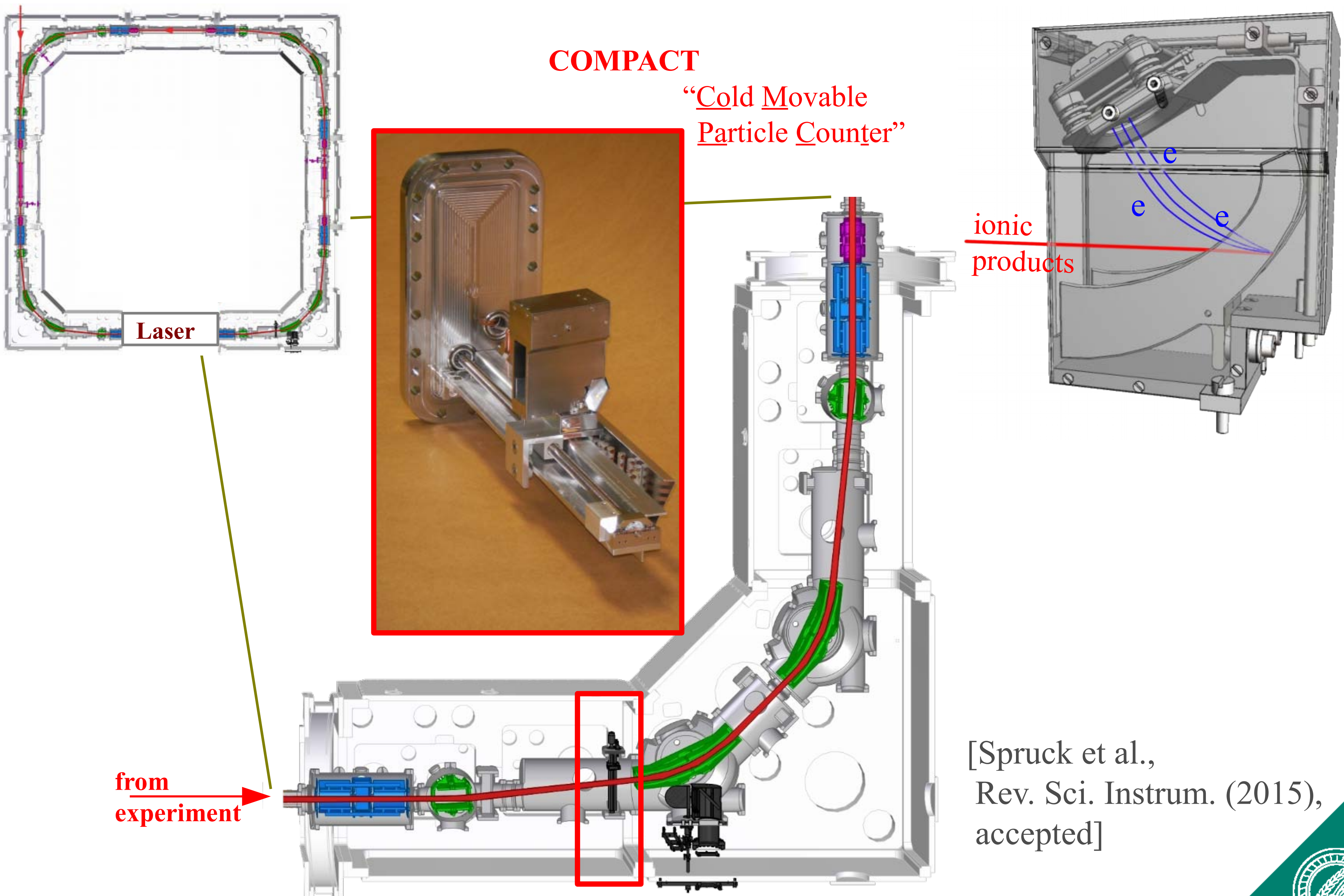
... and towards first experiments



... and towards first experiments

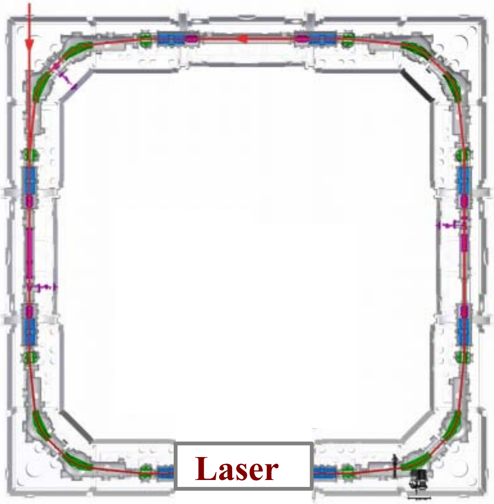


... and towards first experiments



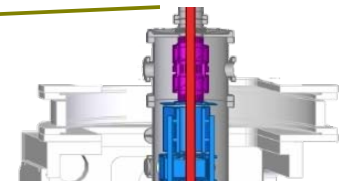
[Spruck et al.,
Rev. Sci. Instrum. (2015),
accepted]

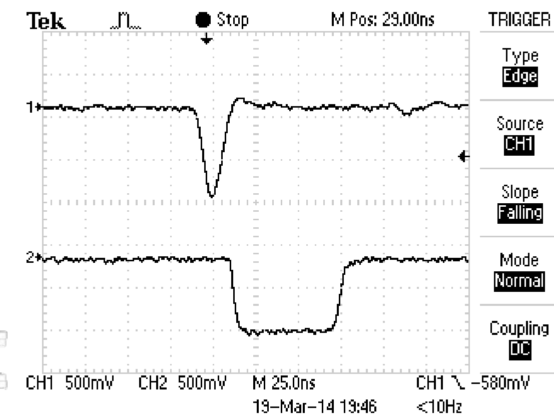
... and towards first experiments

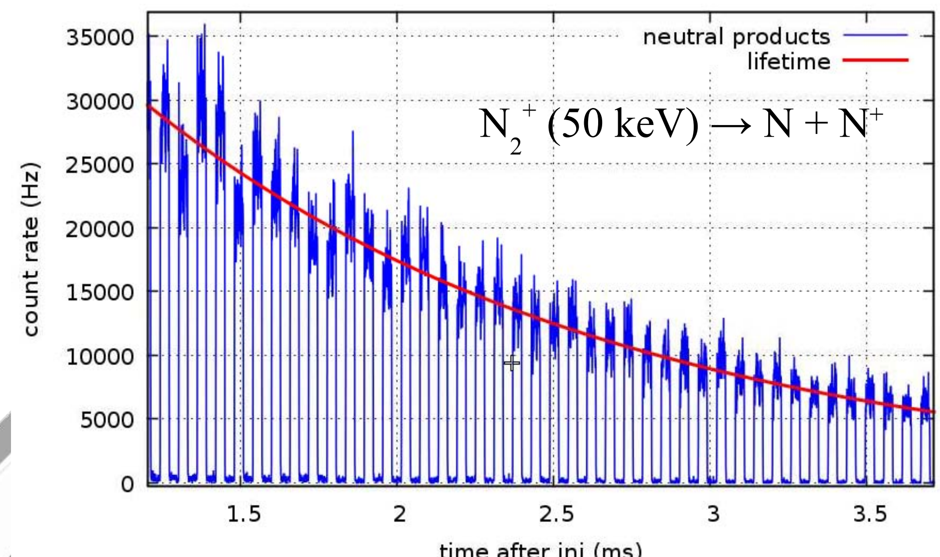


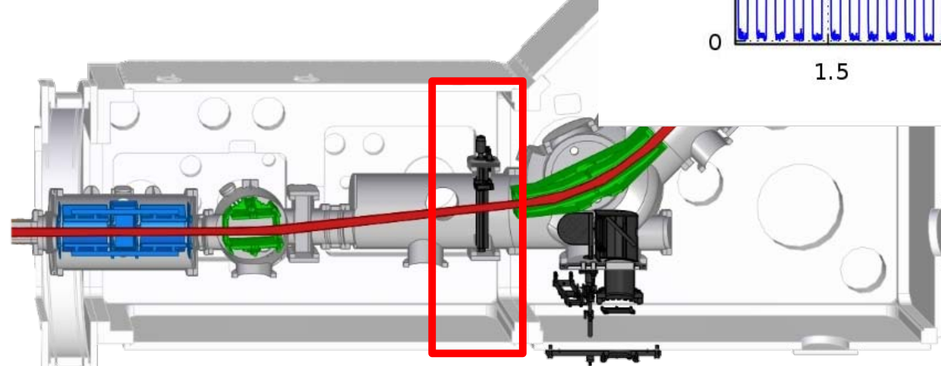
COMPACT

"Cold Movable Particle Counter"



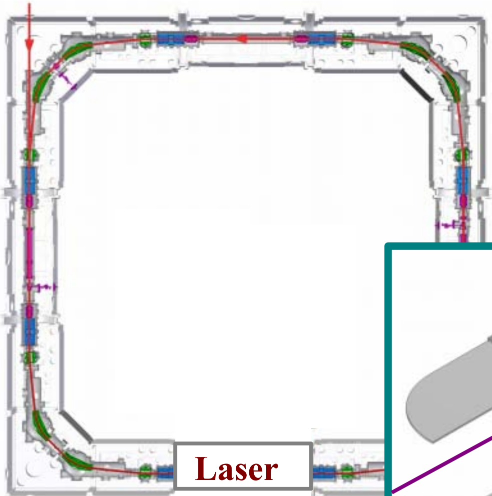




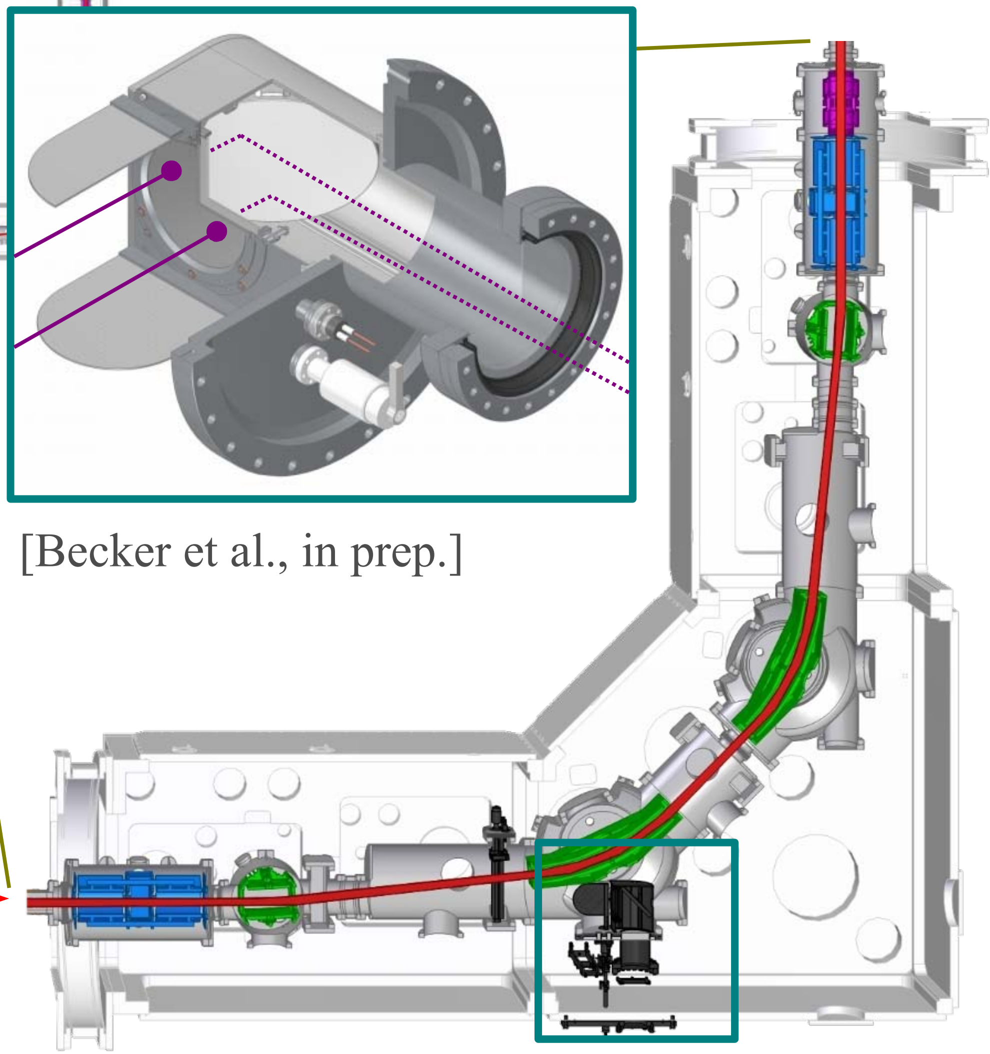


[Spruck et al., Rev. Sci. Instrum (2015), accepted]

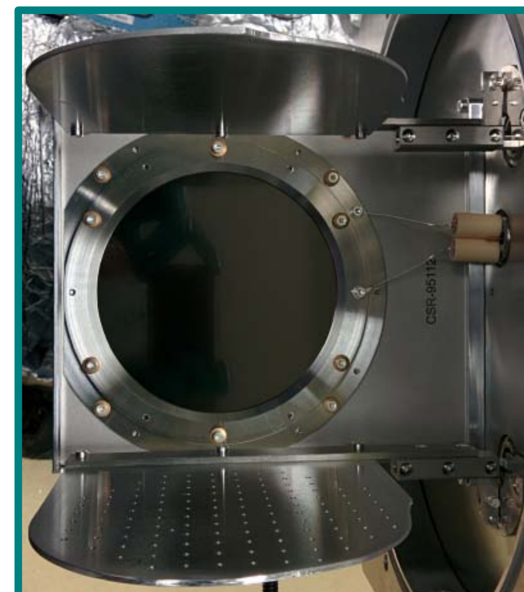
... and towards first experiments



NICE "Neutral Imaging in Cryogenic Environment"



[Becker et al., in prep.]



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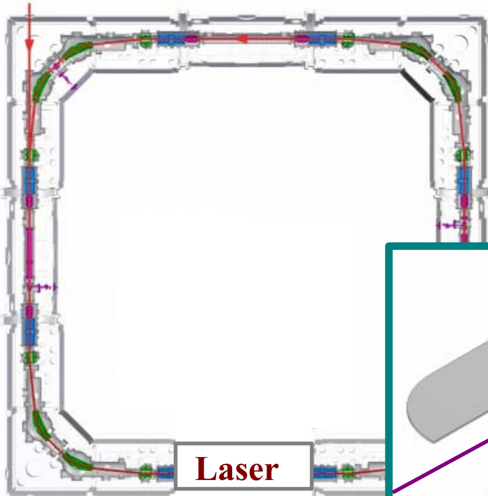
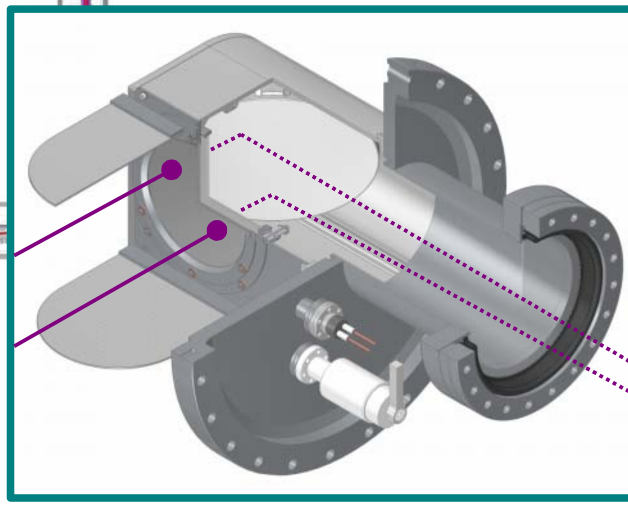
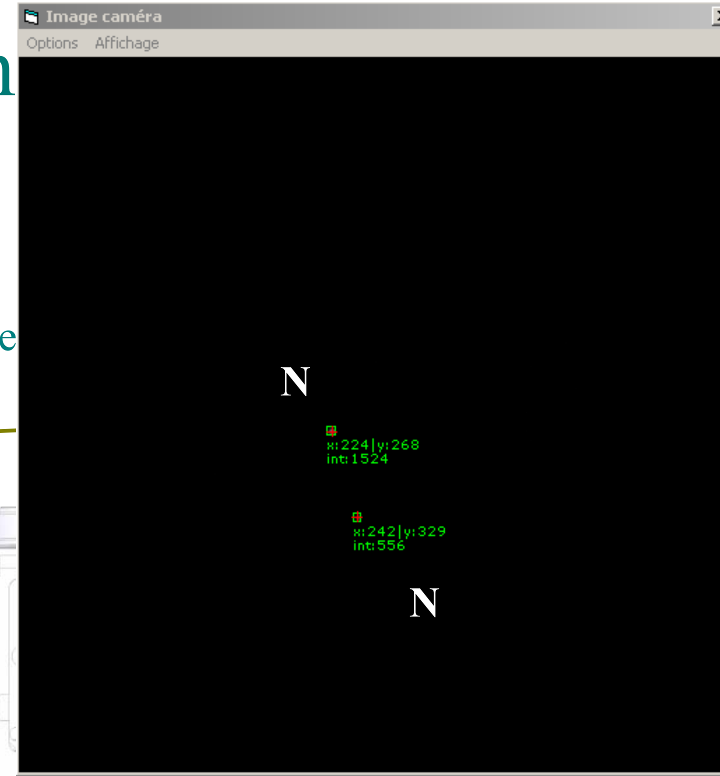
... and towards first experimen

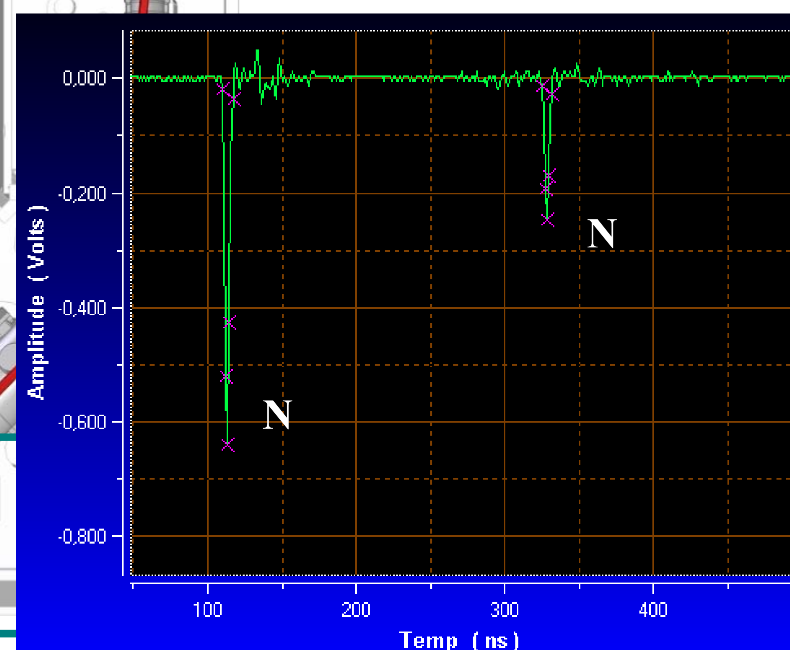
NICE “Neutral Imaging in Cryogenic Environme



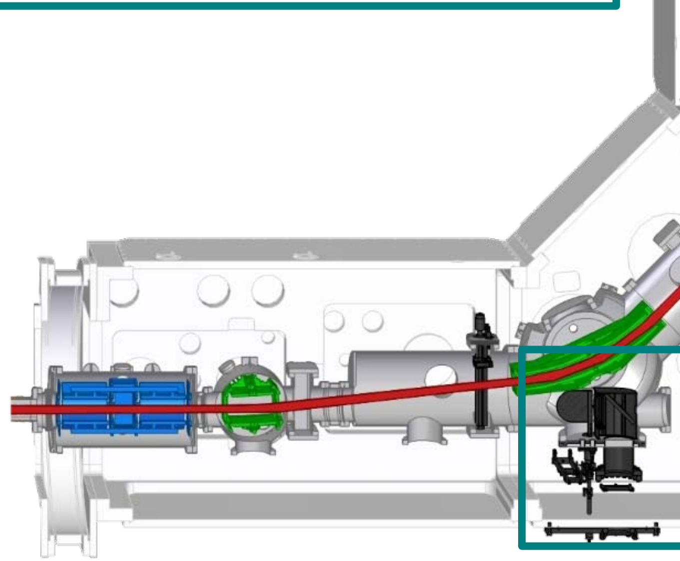




X. Urbain, A. Becker et al.

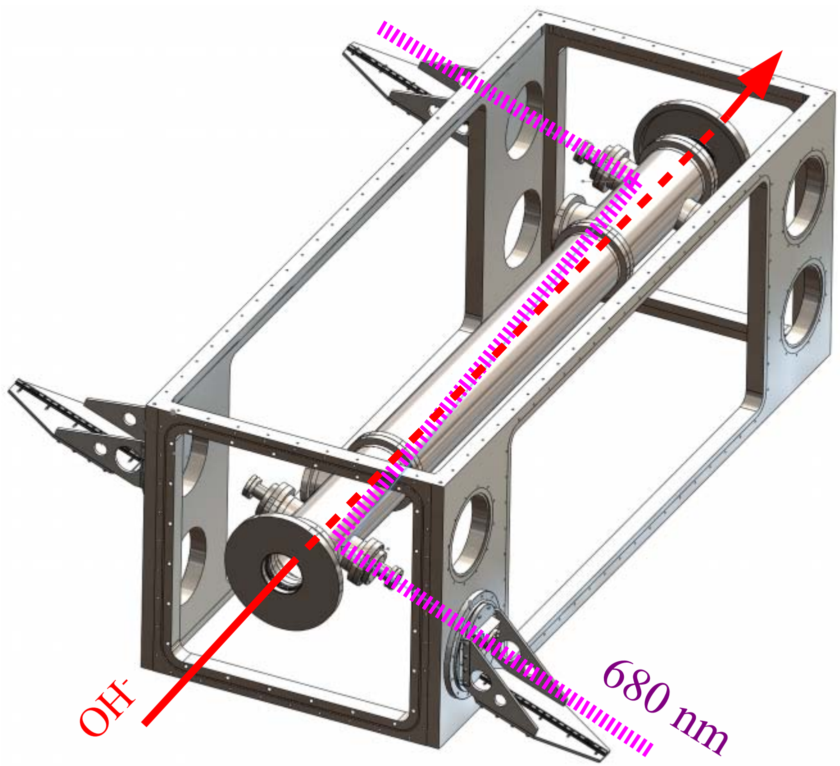


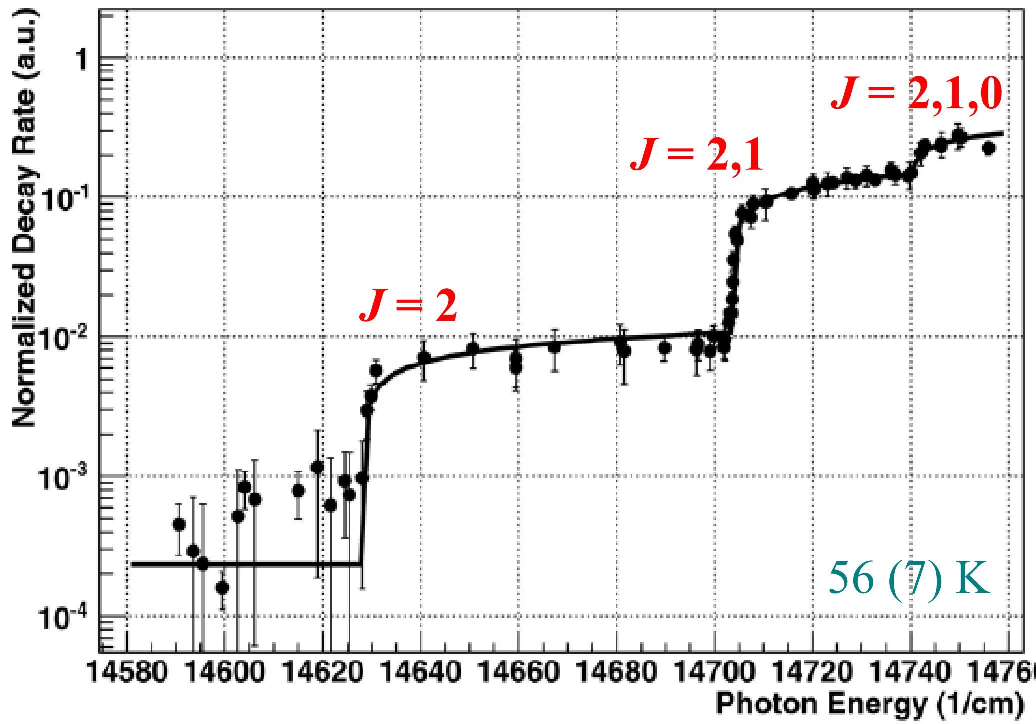
X. Urbain, A. Becker et al.



... and towards first experiments.

$OH^- + \gamma \rightarrow OH + e$

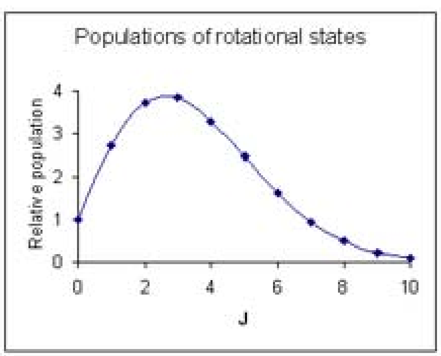




[Otto et al. Phys. Chem. Chem. Phys. 15 (2013)]

Detachment rate depends on rotational quantum number J

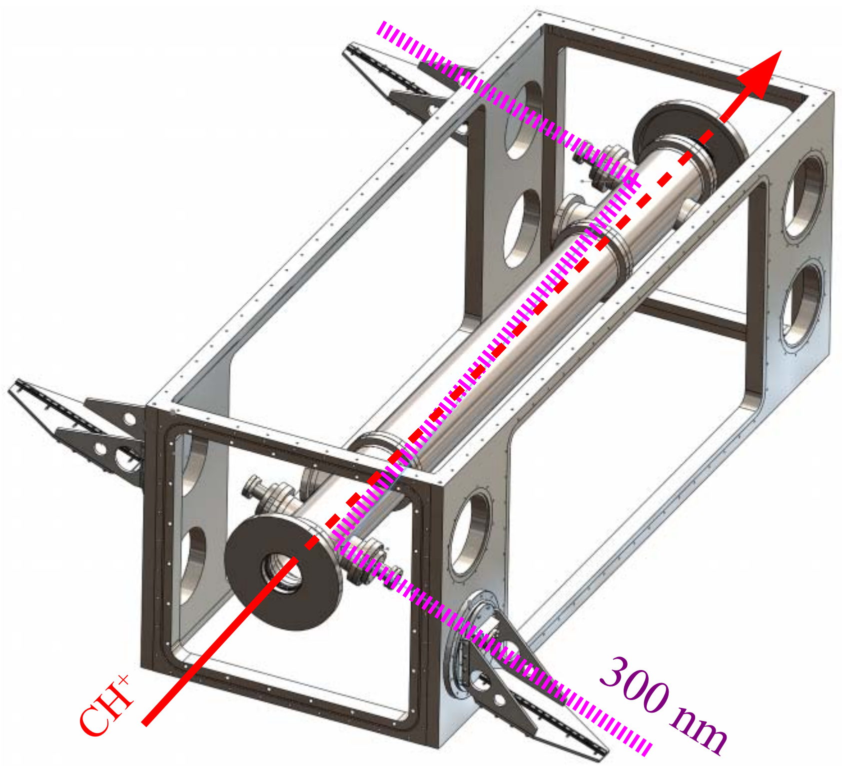
A molecular thermometer!

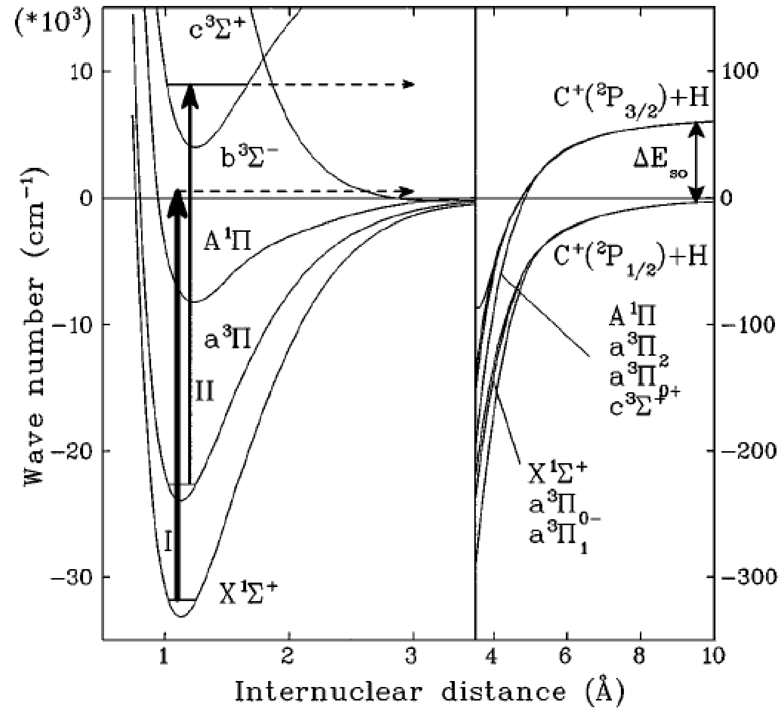


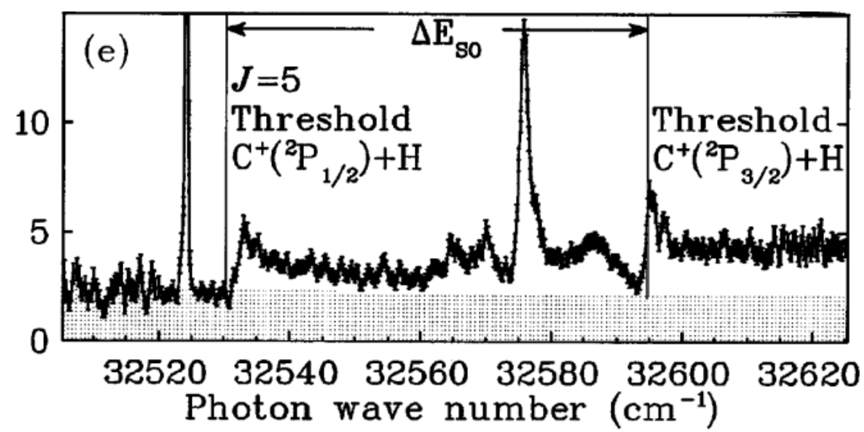
... and towards first experiments.

$CH^+ + \gamma \rightarrow C^+ + H$

Rotational state spectroscopy (*J* population)
Reverse process of CH^+ formation in ISM







[Hechtfischer et al.PRL 80 (1998)]

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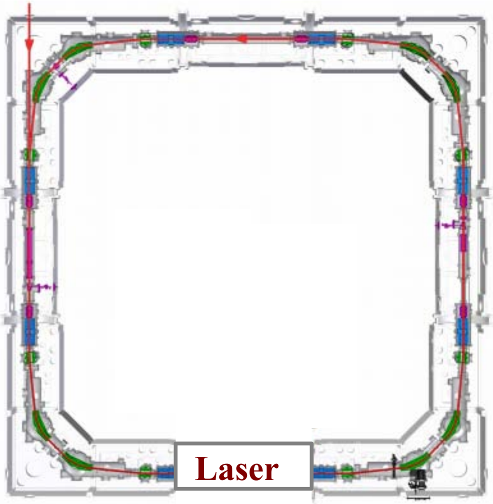
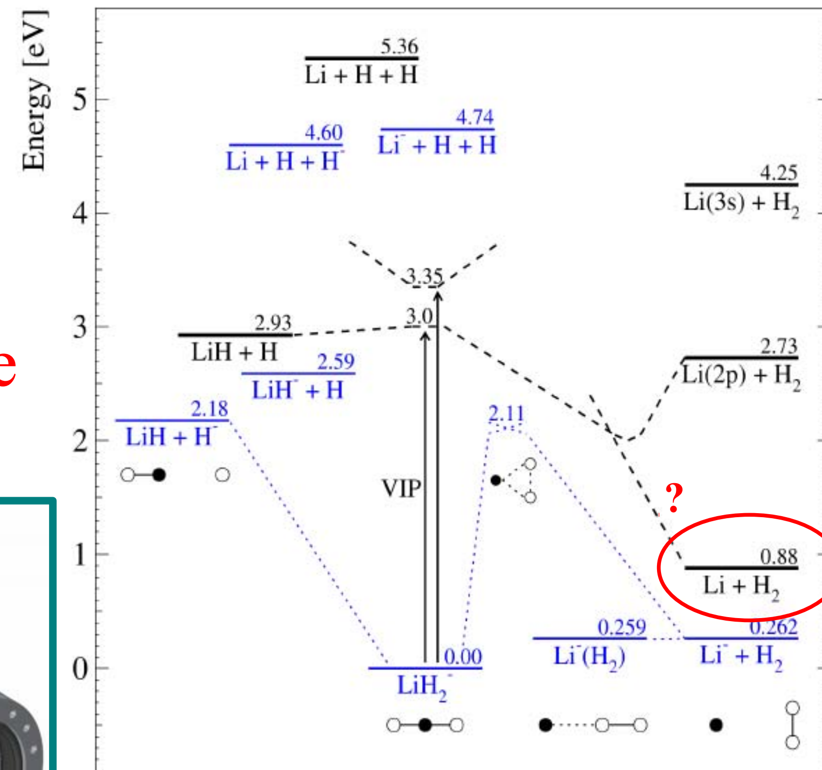
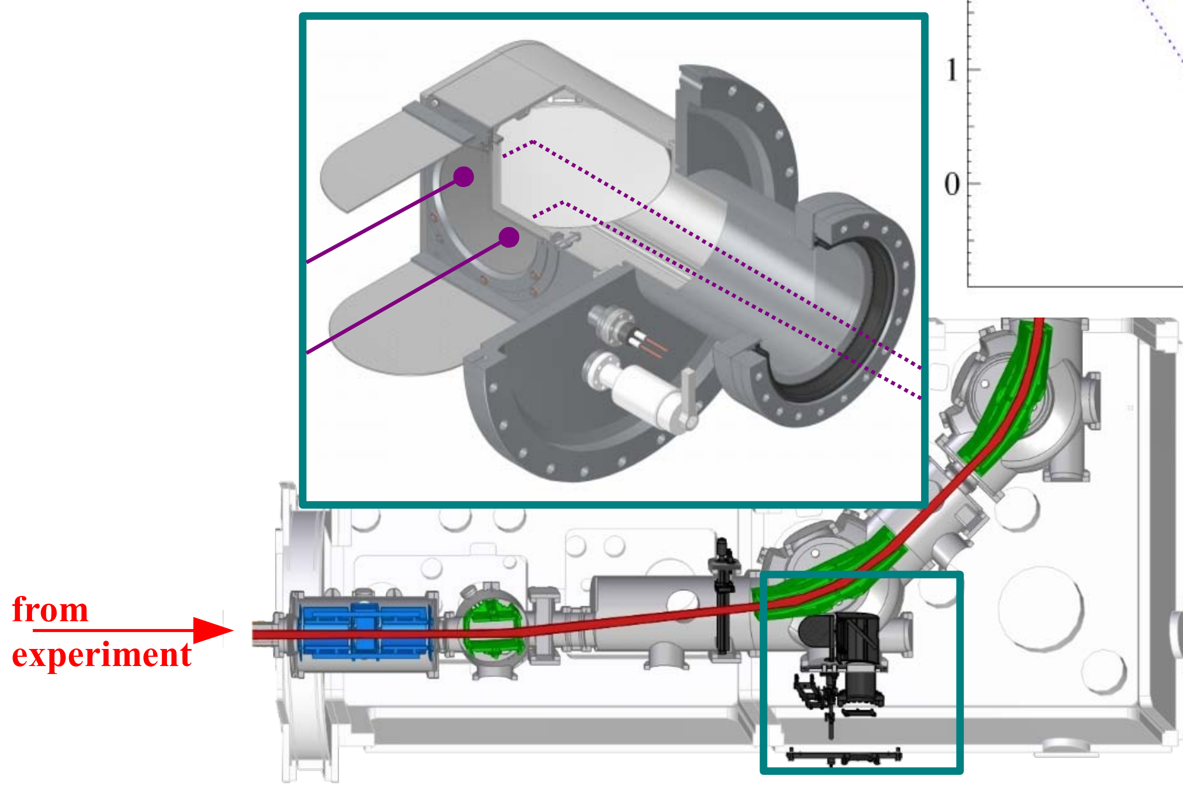
... and towards first experiments.



$$LiH_2^- + \gamma \rightarrow LiH + H + e$$

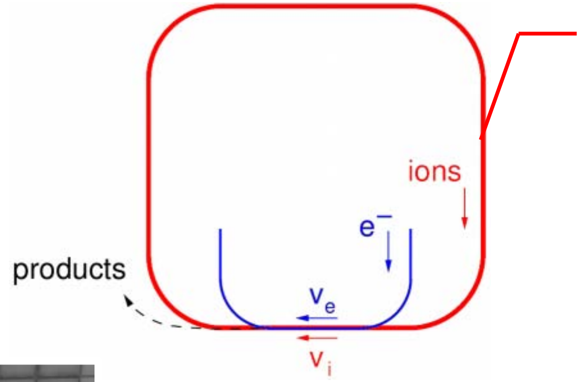


[Lammich et al. Eur. Phys. J. D 41 (2007)]



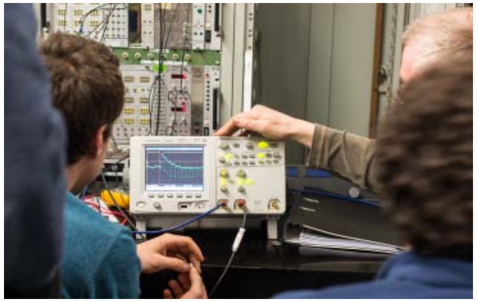
threshold?
dissociation channels?
$Li + H_2 \leftrightarrow LiH + H$

Atomic and Molecular Physics with **Storage Rings**

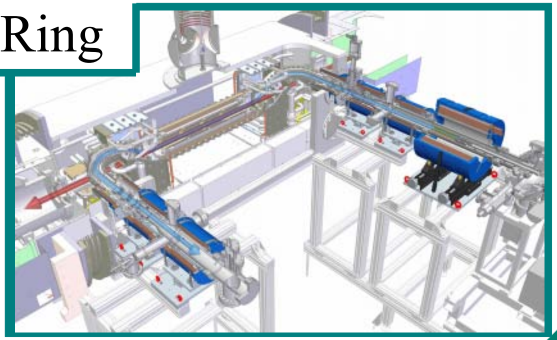


The **Cryogenic Storage Ring**

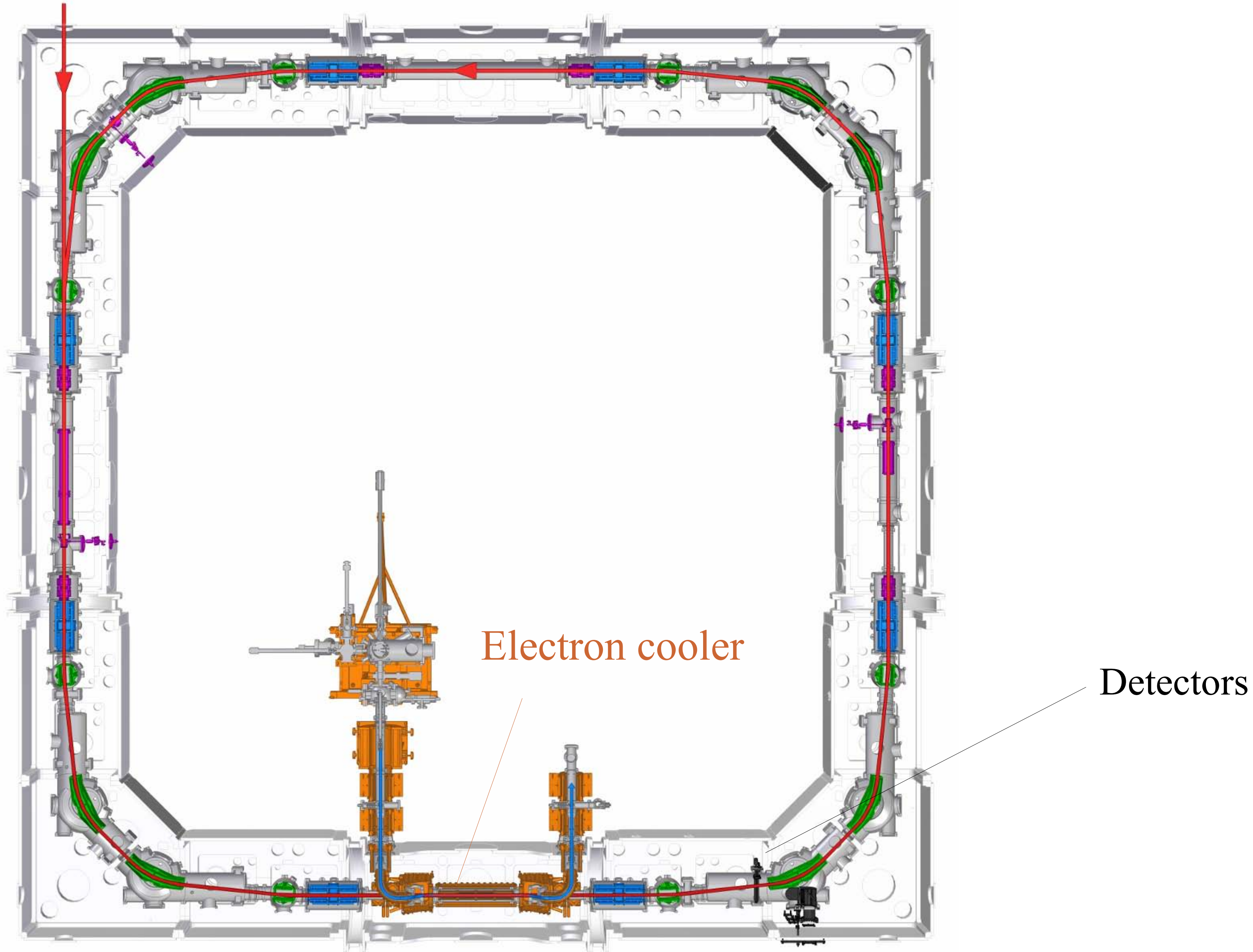
Commissioning and **First Experiments**



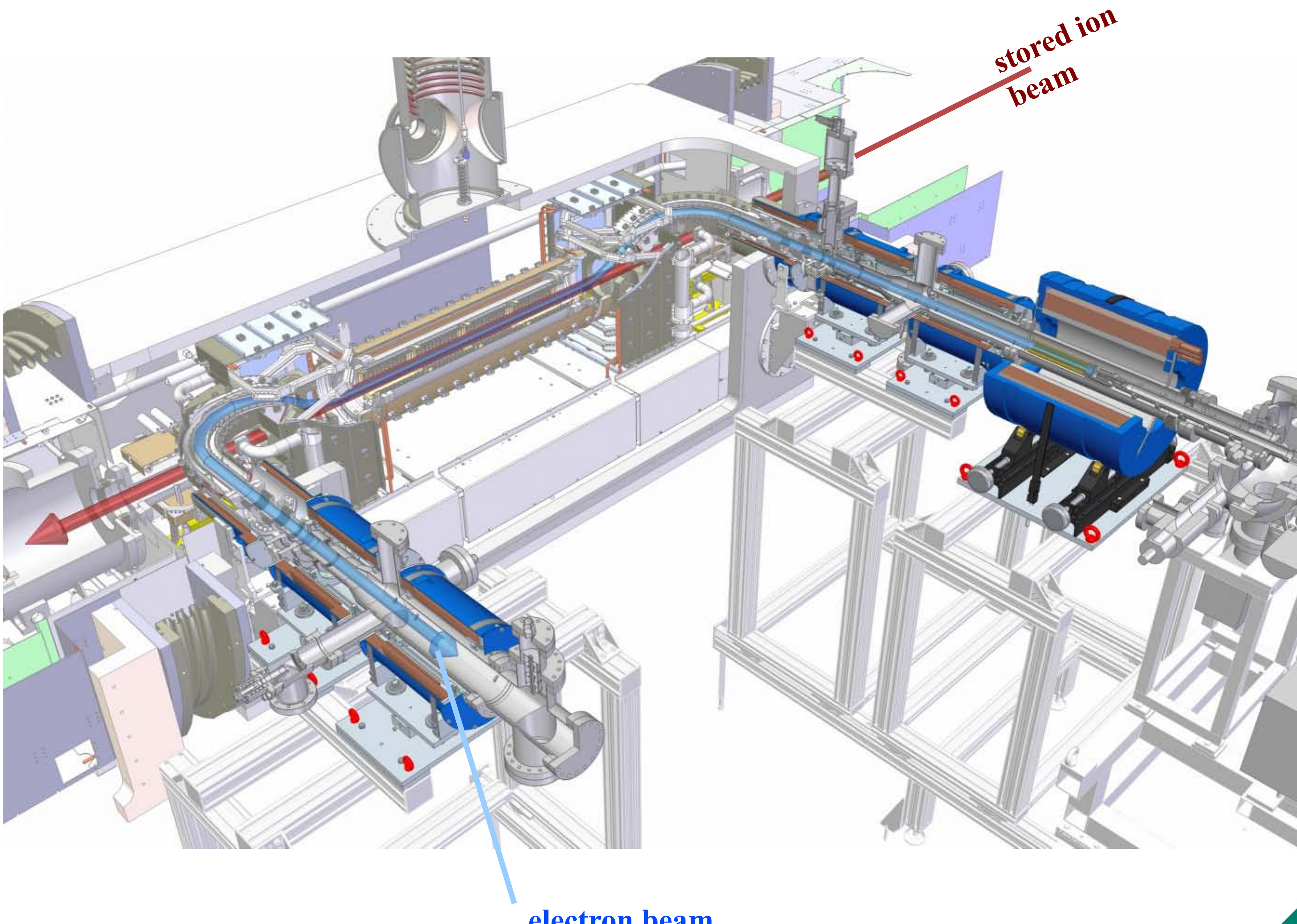
A look ahead: A Cryogenic **Electron Cooler** Storage Ring



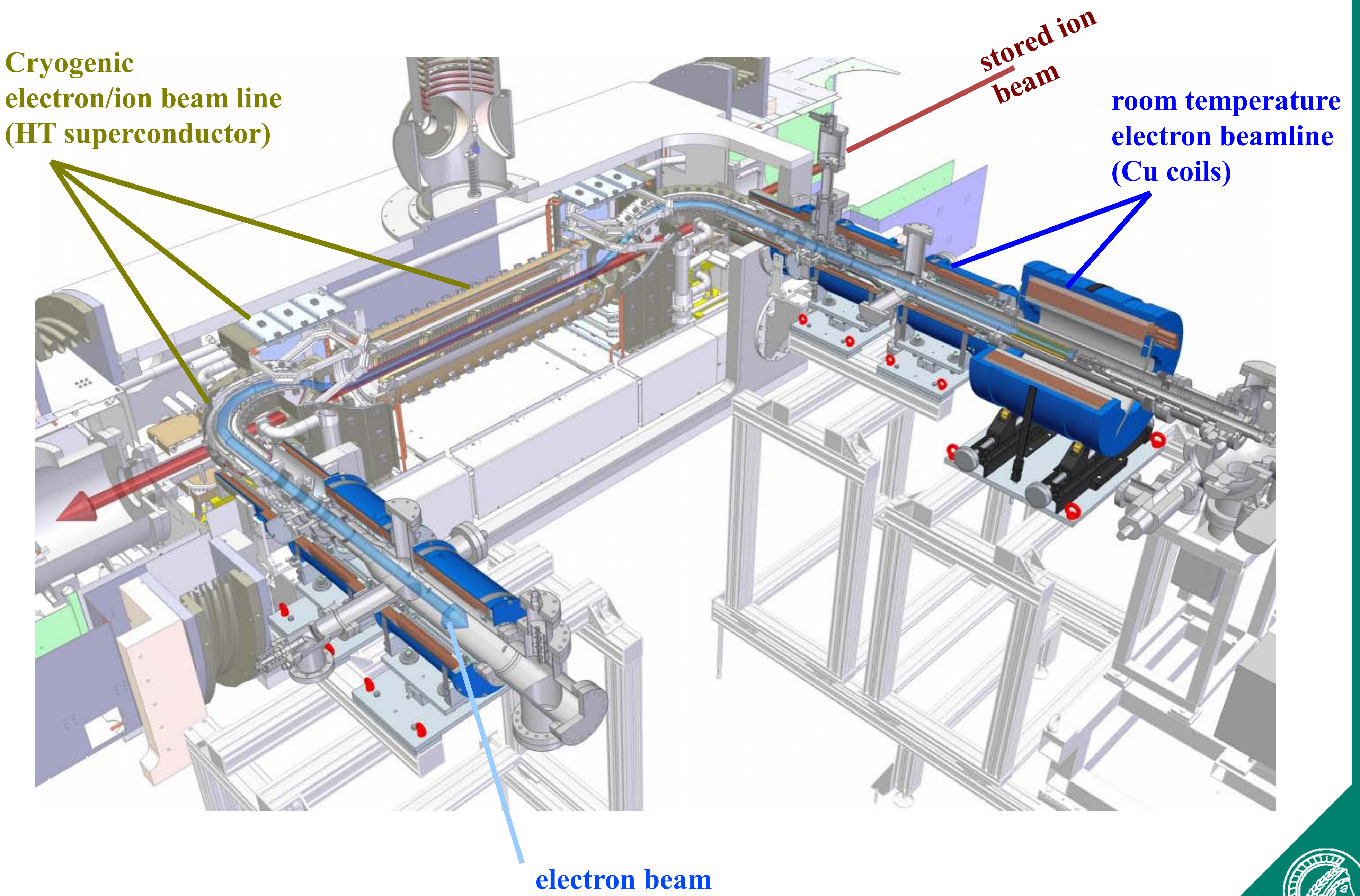
Electron Cooler



Electron Cooler



Electron Cooler



Electron Cooler

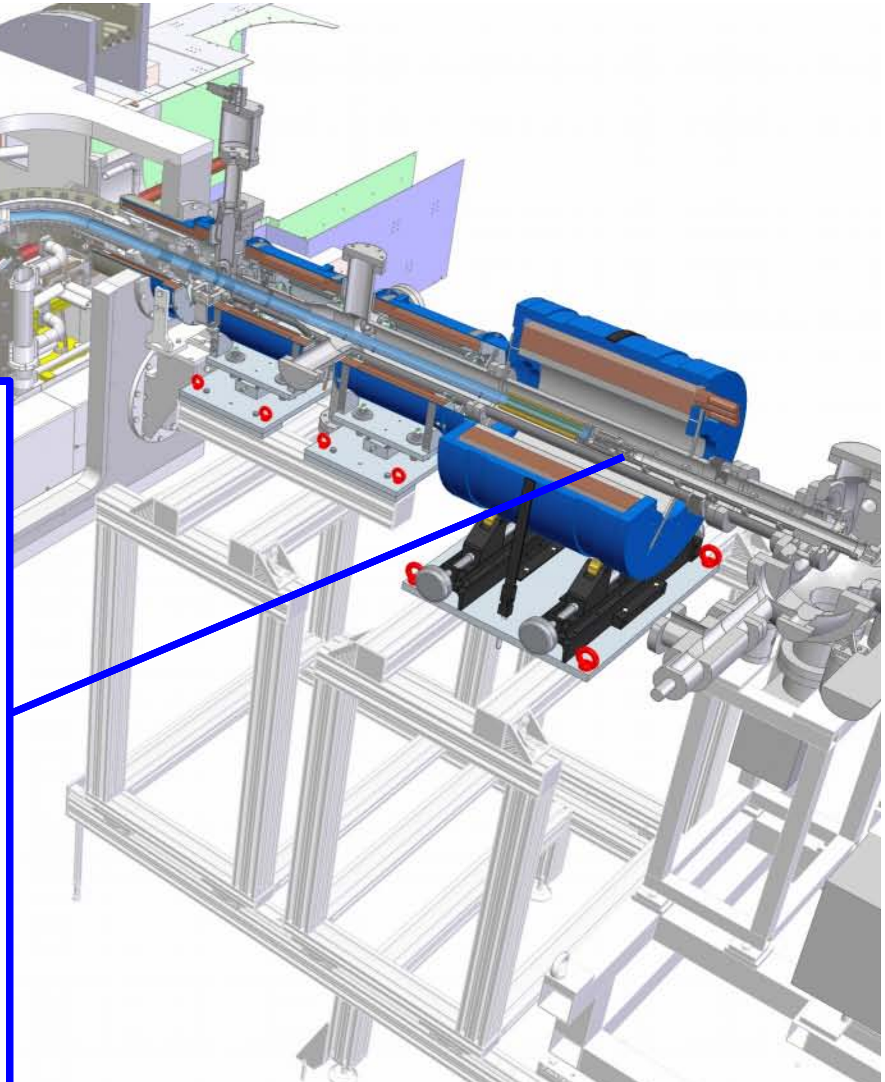
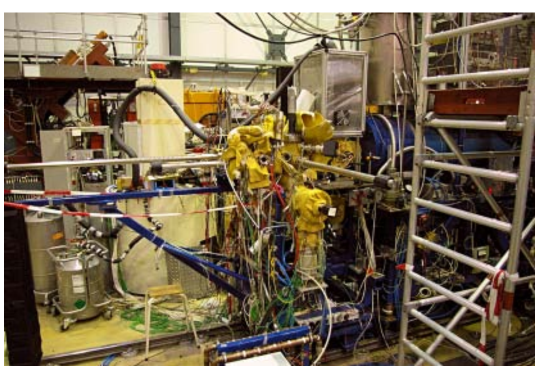


Photo cathode electron source (TSR) :

~ 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

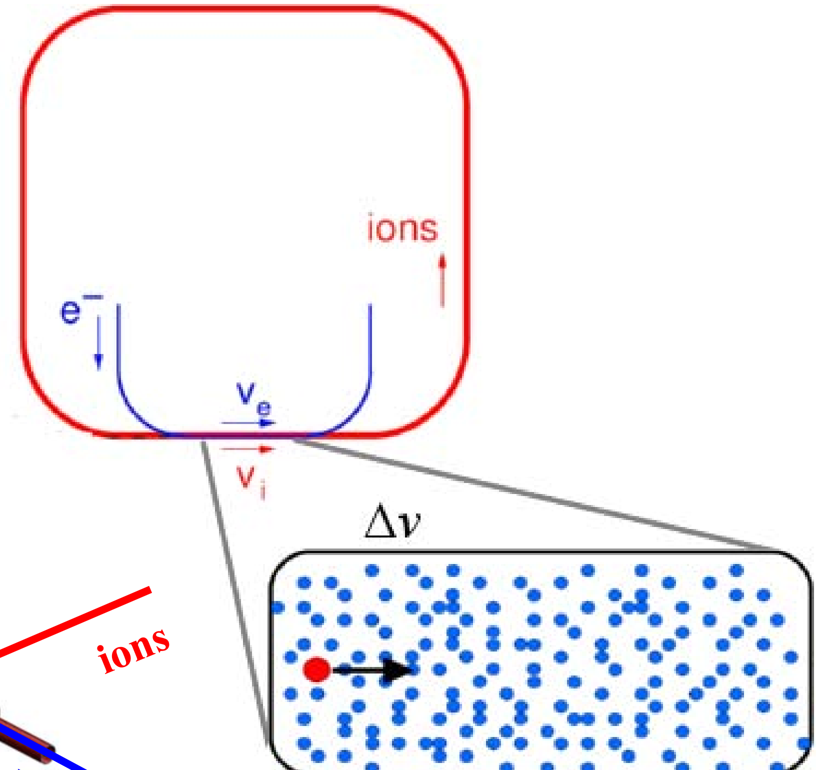
Electron Cooler

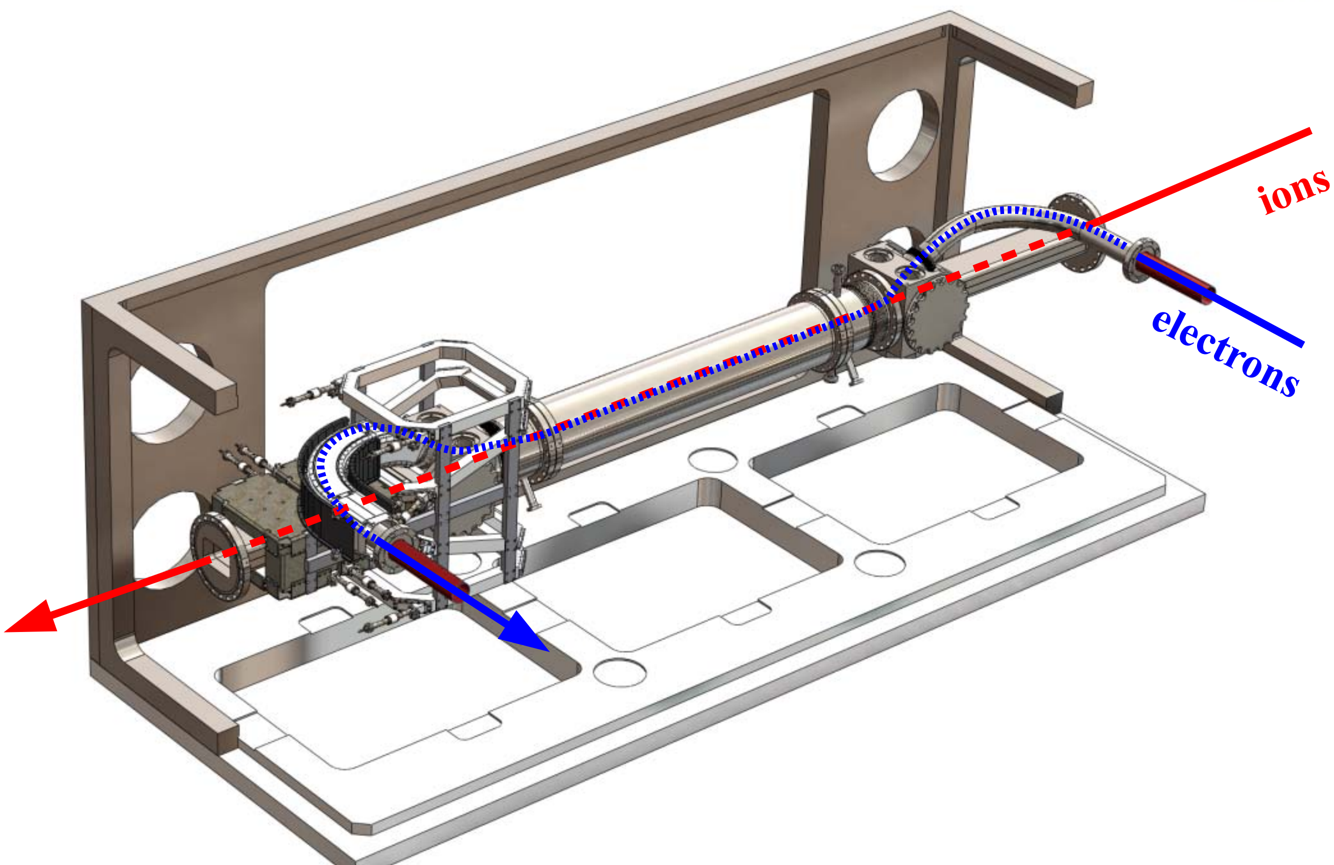
Principle of ecooling: $\boldsymbol{v}_{\mathbf{electron}} = \boldsymbol{v}_{\mathbf{ion}}$

CSR energy limit: $E_{\mathrm{ion}}/Z_{\mathrm{ion}} = 300$ keV

→ Need **very** slow electrons

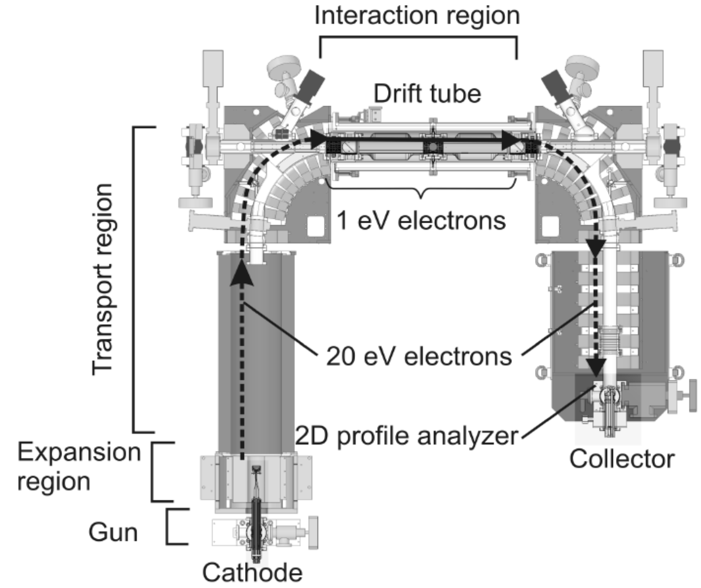
160 eV	for p^+
< 20 eV	for most ions
1 eV	for $M_{\mathrm{ion}} = 160$ u





Electron Cooler

Electron energy: towards 1 eV and below …



Calibration of E_e against cathode potential
taking beam **space charge** and
work function differences into account

Current:
few µA at $E_{cool} = 1$ eV

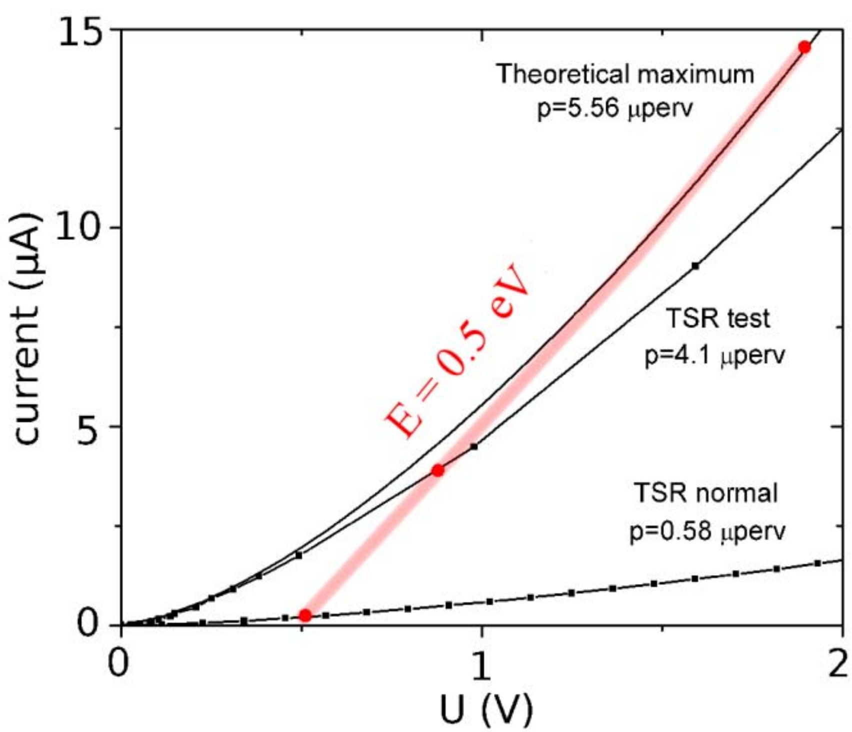
$n_e \sim 10^5$ cm^{-3}

Cooling times

$$\tau \sim \frac{M_{ion} T_e^{3/2}}{Z_{ion}^2 n_e}$$

up to ~ 100 s …

… but: ion lifetime ~ 1000 s



A. Shornikov et al., Phys. Rev. ST Accel. Beams 17 (2014) 042802

Electron Cooler

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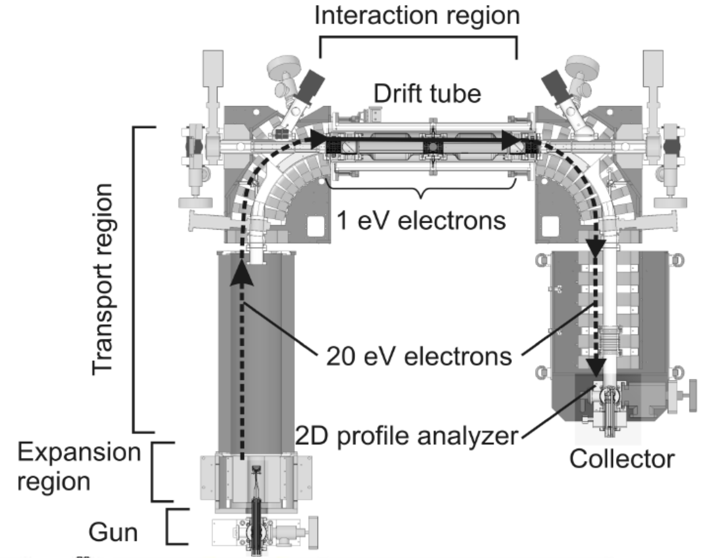
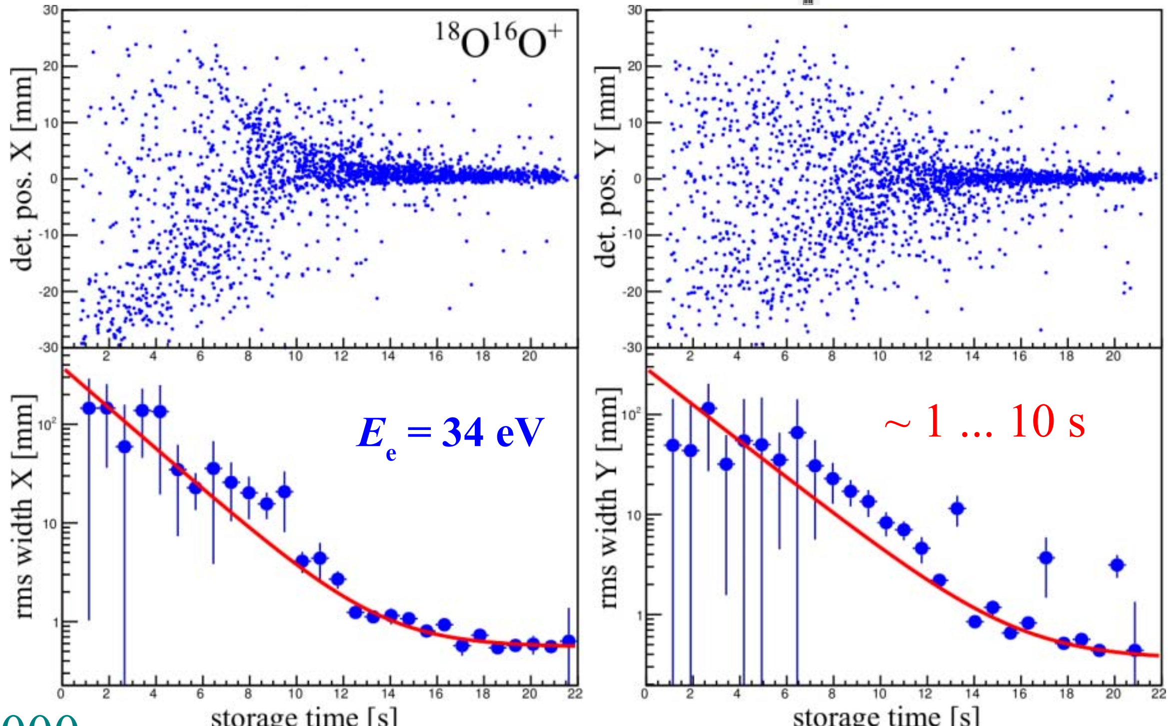


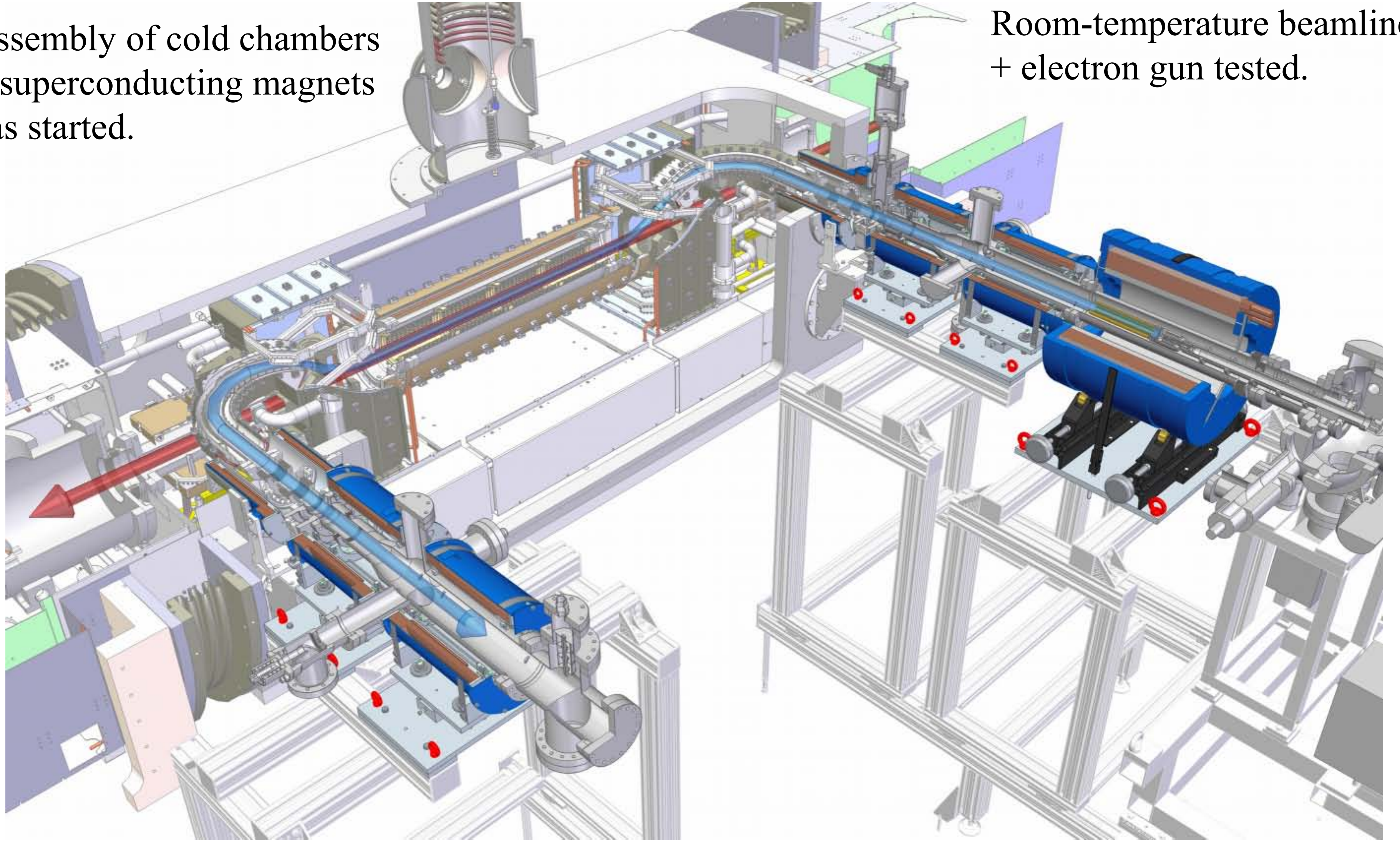


TSR data, C. K. et al., in prep.

Electron Cooler

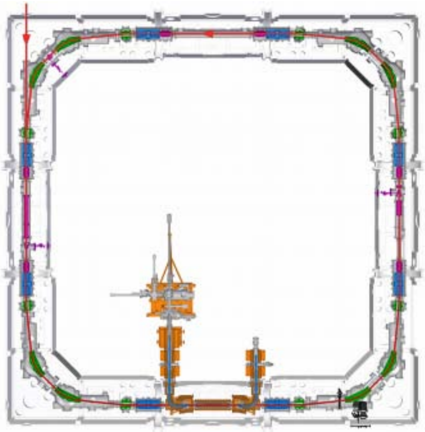
Assembly of cold chambers
+ superconducting magnets
has started.

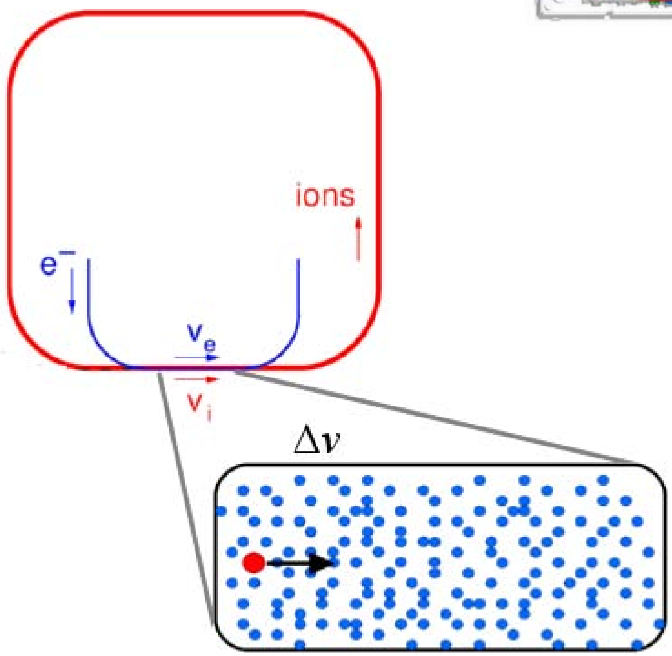
Room-temperature beamlines
+ electron gun tested.

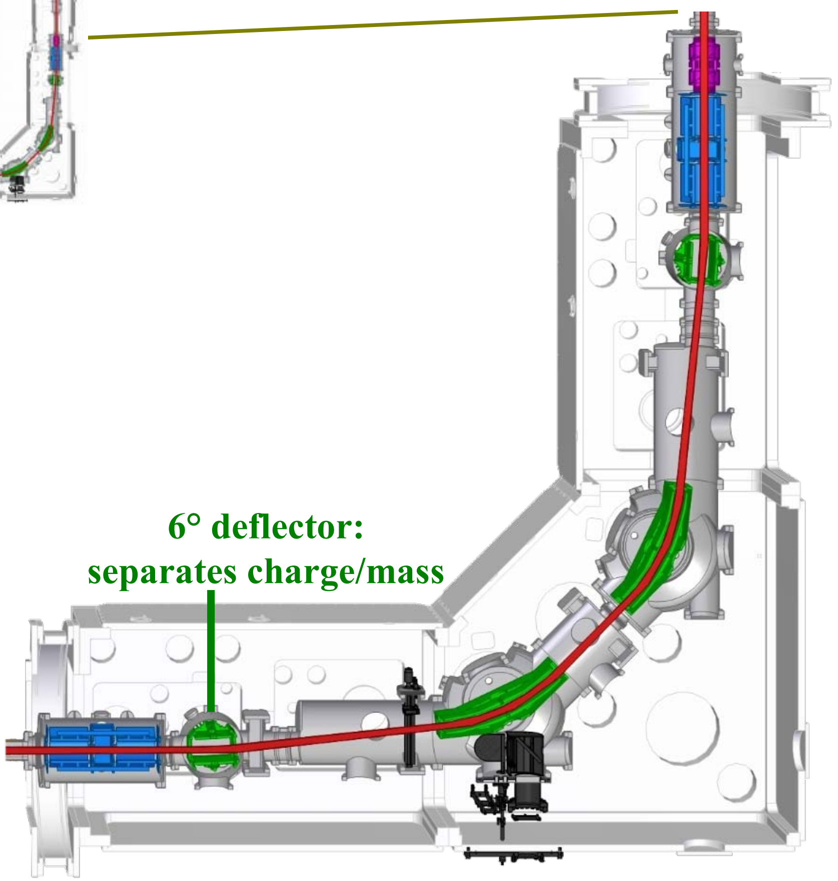


Installation of electron cooler into CSR: Fall 2015

Electron Cooler – Experiments







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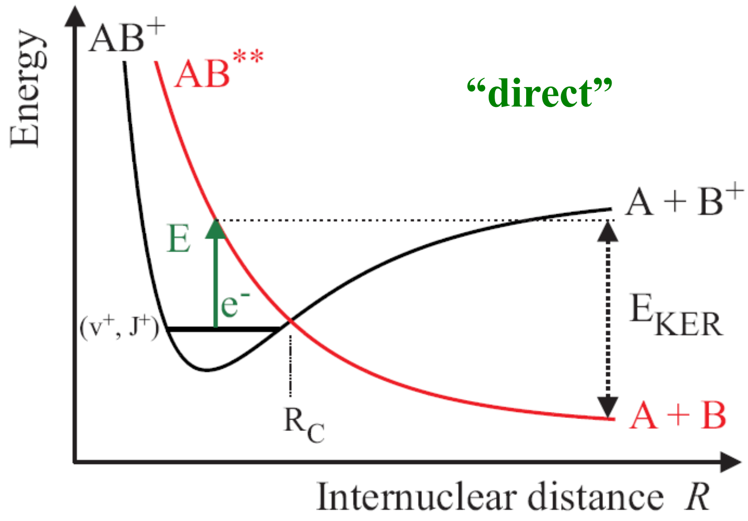
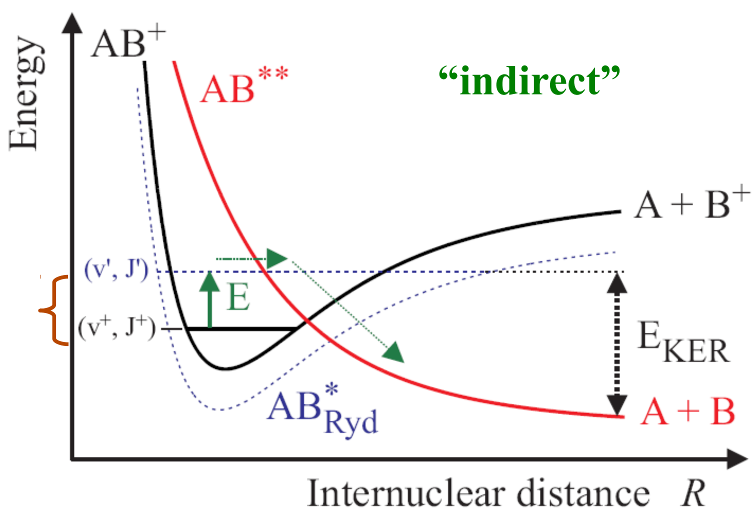
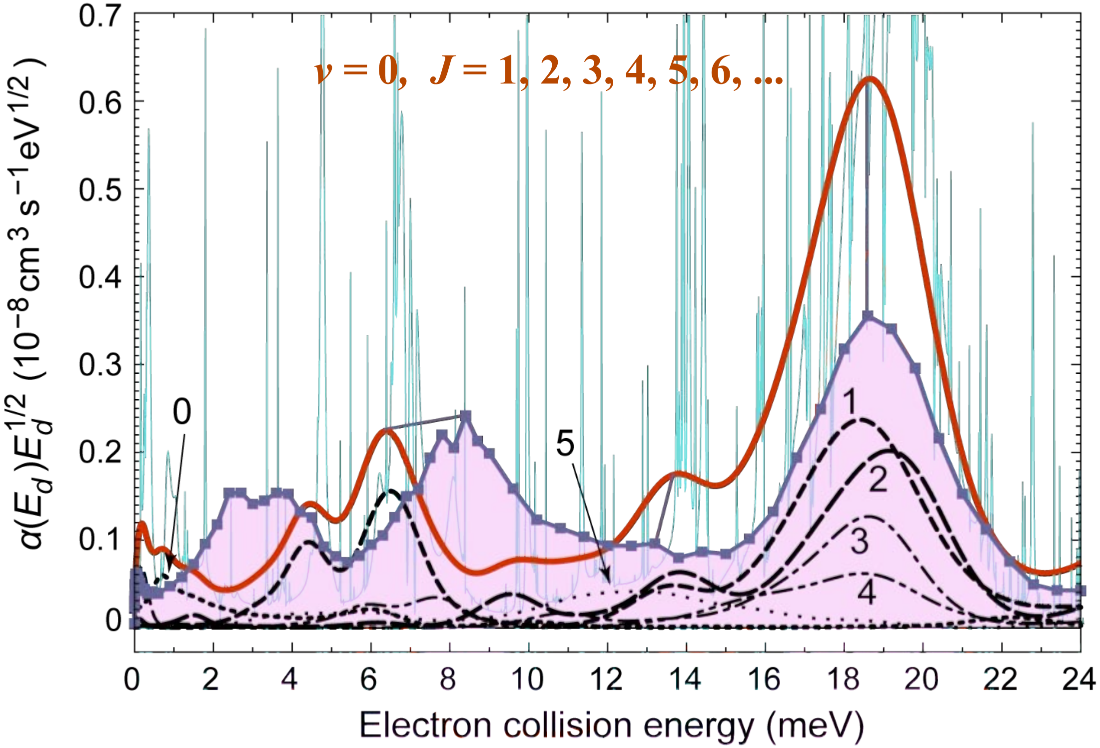
Electron Cooler – Experiments





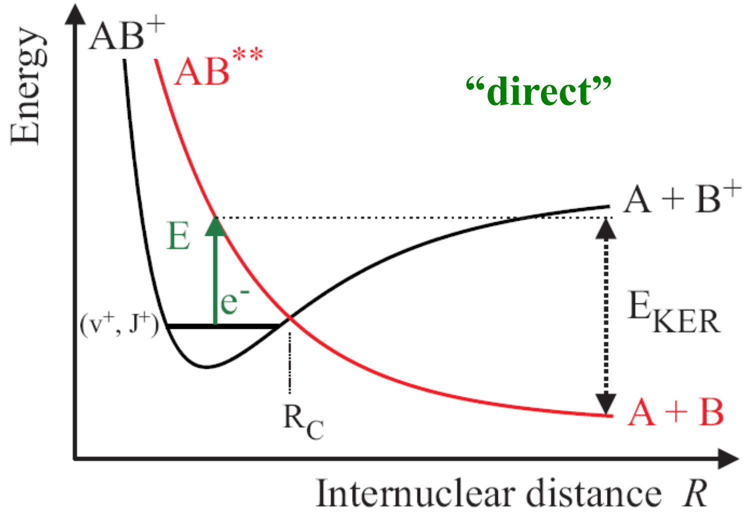
$HD^+ + e \rightarrow H + D$

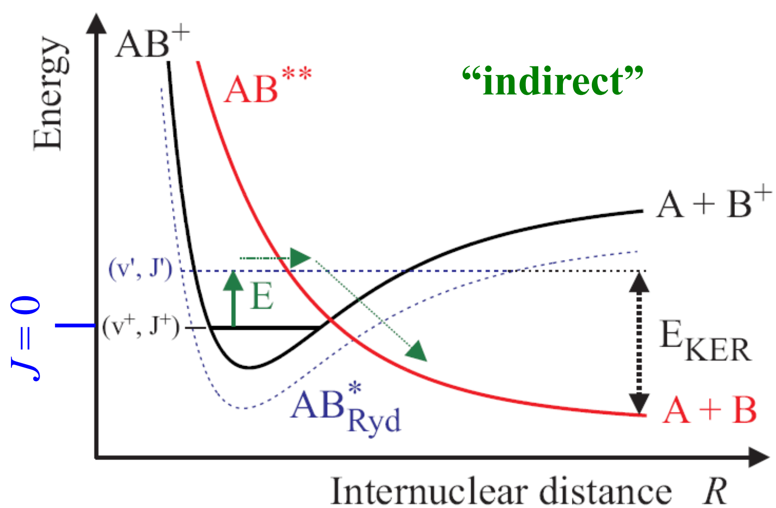


Waffeu-Tamo *et al.*, PRA 84 (2011) (0 K)

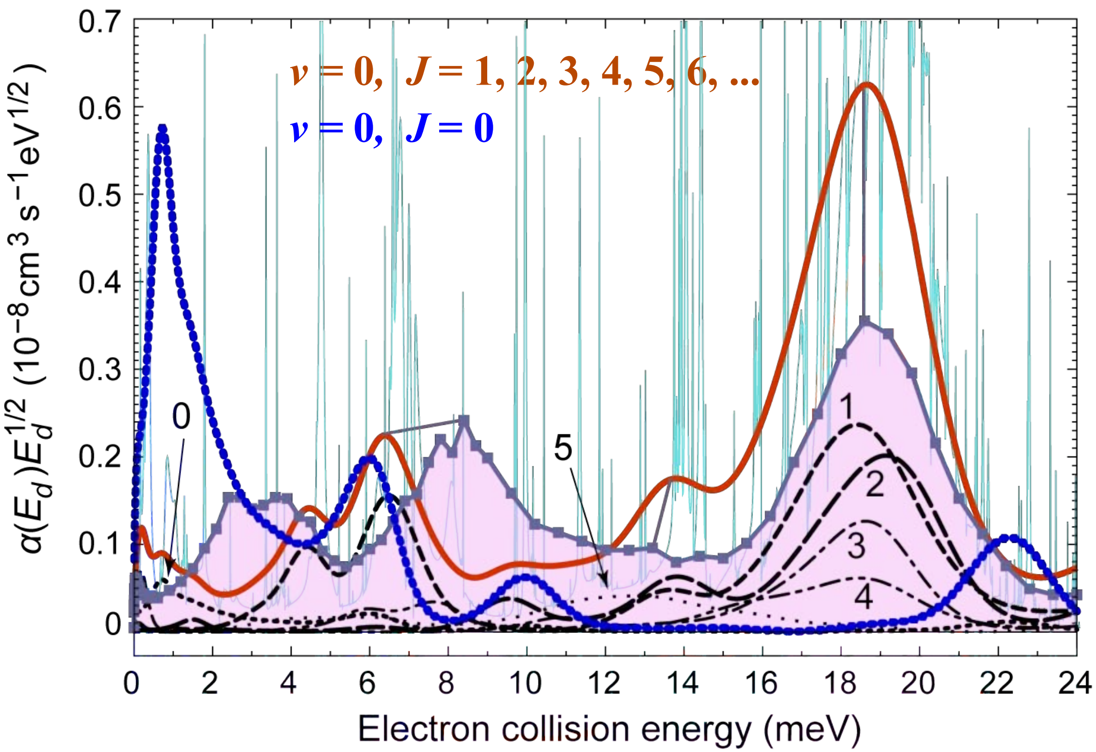
TSR data ($kT_e \sim 1$ meV, $T_{ion} \sim 300$ K)

Electron Cooler – Experiments





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



Waffeu-Tamo *et al.*, PRA 84 (2011) (0 K)

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

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

at CSR: $E_{cool} = 54$ eV

10 K → $J = 0$

Electron Cooler – Experiments

Polyatomics: $\mathbf{H_3^+}$, $\mathbf{HD_2^+}$, $\mathbf{H_3O^+}$, $\mathbf{HNO^+/HON^+}$, $\mathbf{CCN^+/CNC^+}$ ...

Dielectronic Recombination of atomic **monocations**: C^+, N^+, F^+, Si^+, P^+, Cl^+, Fe^+

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

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

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

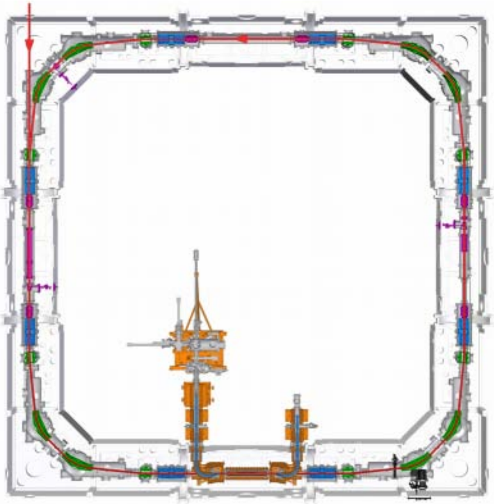
Electron cooled **cluster anions** (detachment, fragmentation …)

Ion-neutral collisions with cooled/cold ions: $C + H_3^+ \rightarrow CH^+ + H_2$

Recombination of large **organic molecules** $C_xH_y^+$, $C_xH_yOH^+$ …

(Transition to **non-dissociative** recombination)

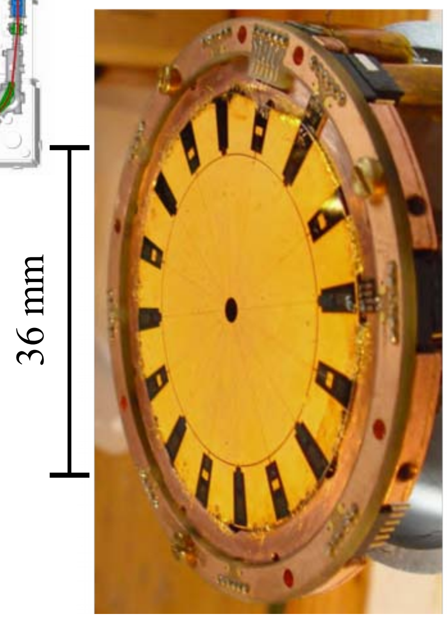
Electron Cooler – Experiments

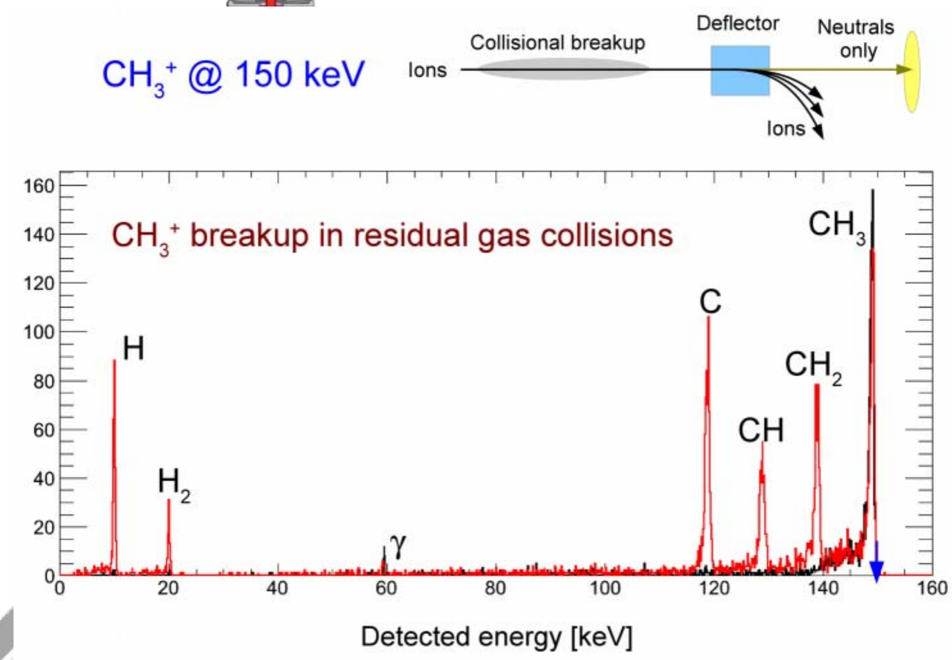


future Detector upgrade:

A. Fleischmann, C. Enss et al.
KIP, University of Heidelberg

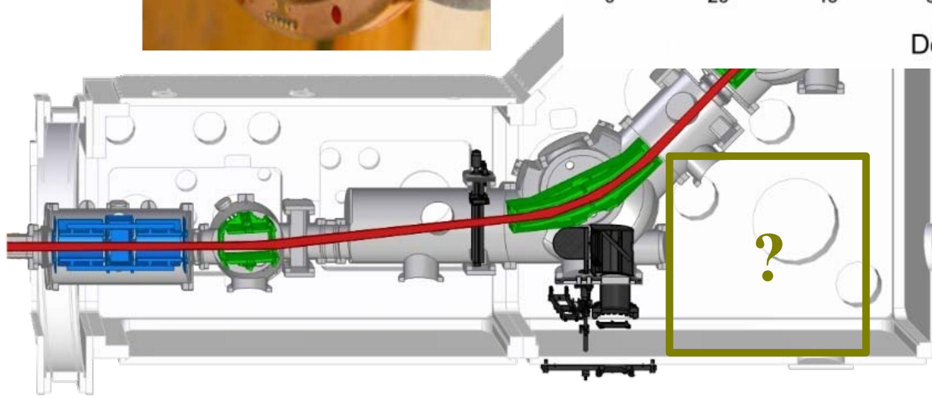
"PIZZA"
segmented microcalorimeter
Fragment **energy (= mass)** sensitive





[O. Novotny, in prep.]

from experiment



Summary

The **Cryogenic Storage Ring** has passed all **basic functional tests** in room temperature operation.

The first beamtimes in **cryogenic operation** should start in March 2015.

After addition of an **electron cooler** in late 2015, CSR will be the world-leading facility for precision experiments on extremely heavy stored ions.

There is a rich experimental program ahead, on (at least) **molecular, atomic, and astrophysics**.

Thank You!

Max Planck Institute for Nuclear Physics, Heidelberg

Klaus Blaum
Robert von Hahn
Florian Fellenberger
Sebastian George
Svenja Lohmann
Christian Meyer

Holger Kreckel
Florian Grussie
Philipp Herwig
Sebastian Menk
Arno Becker
C. K.

Aodh O'Connor
Stephen Vogel
Robert Repnow
Manfred Grieser
Andreas Wolf

Université Catholique, Louvain-la-Neuve

Xavier Urbain

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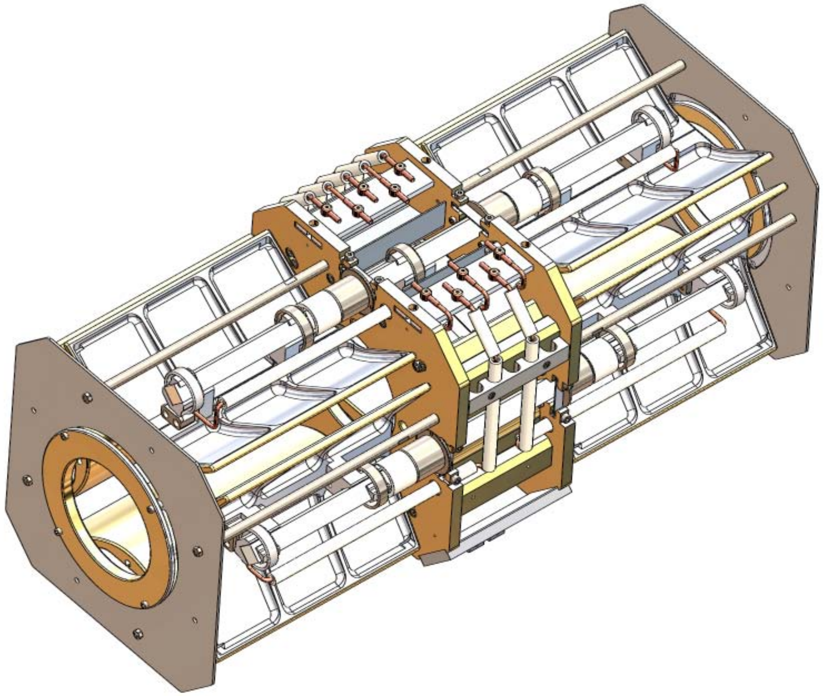
Daniel W. Savin

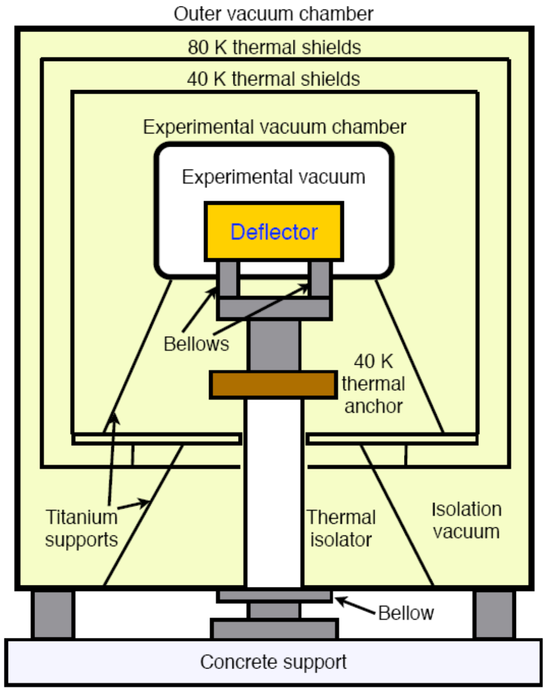
The CSR

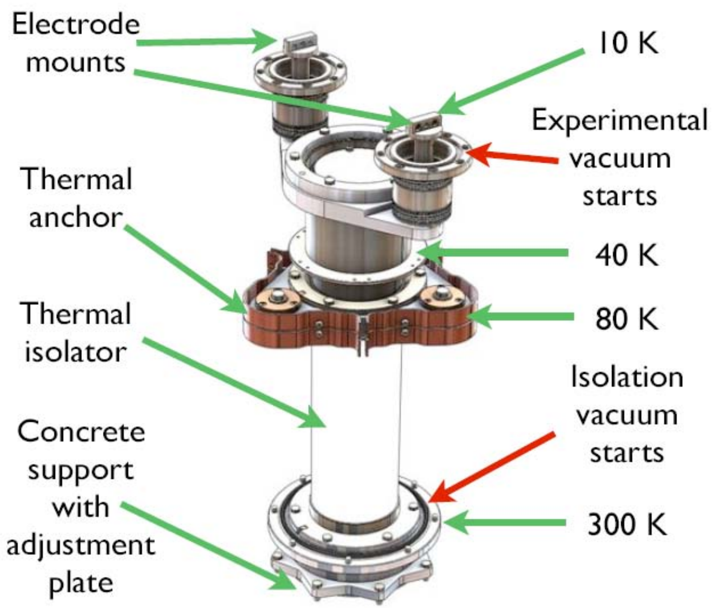
Electrostatic beam optics

Thermally anchored to cold chamber walls (~ 10 K) …

… but mechanically decoupled
(thermal shrinking of beam pipe)

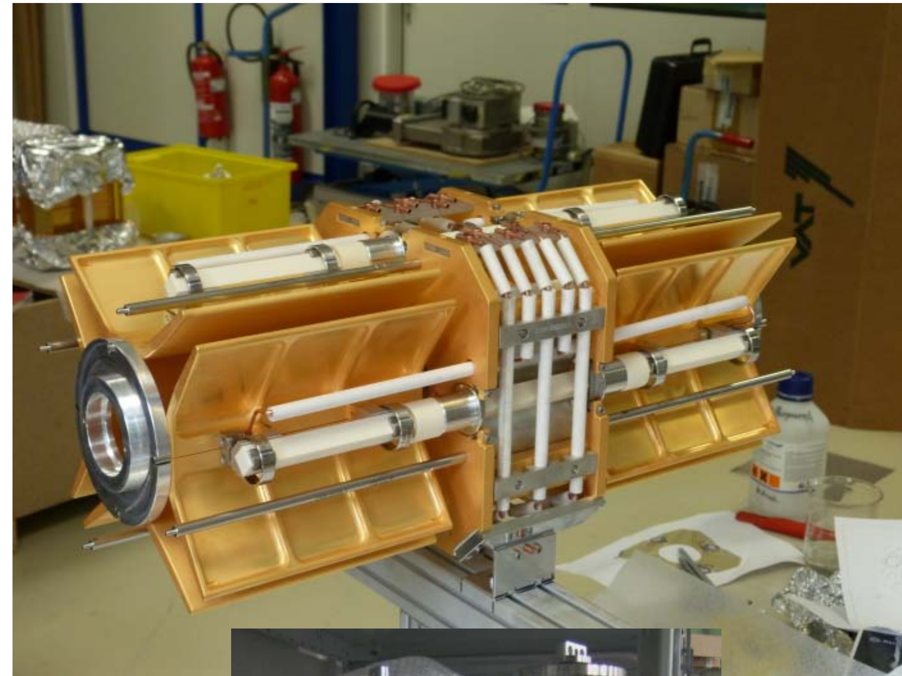






The CSR

Electrostatic beam optics



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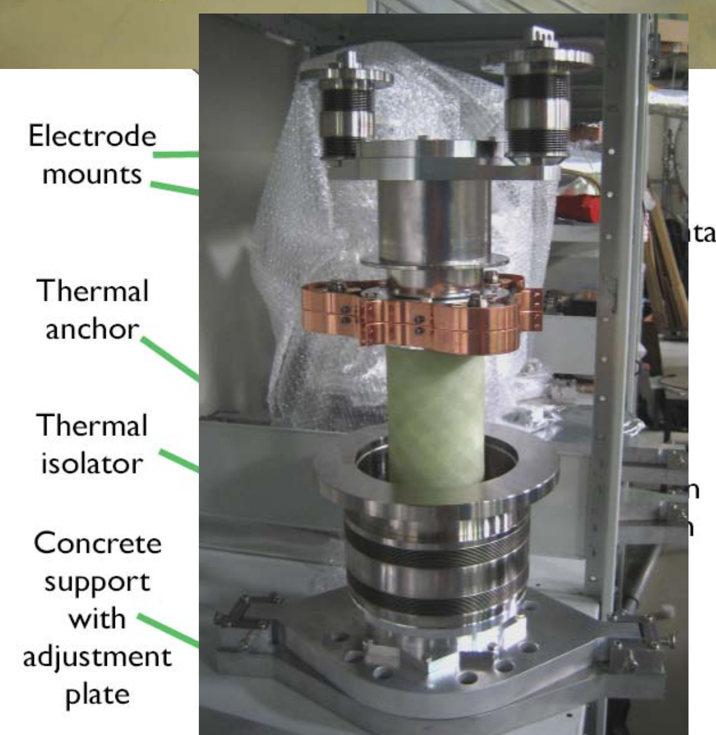
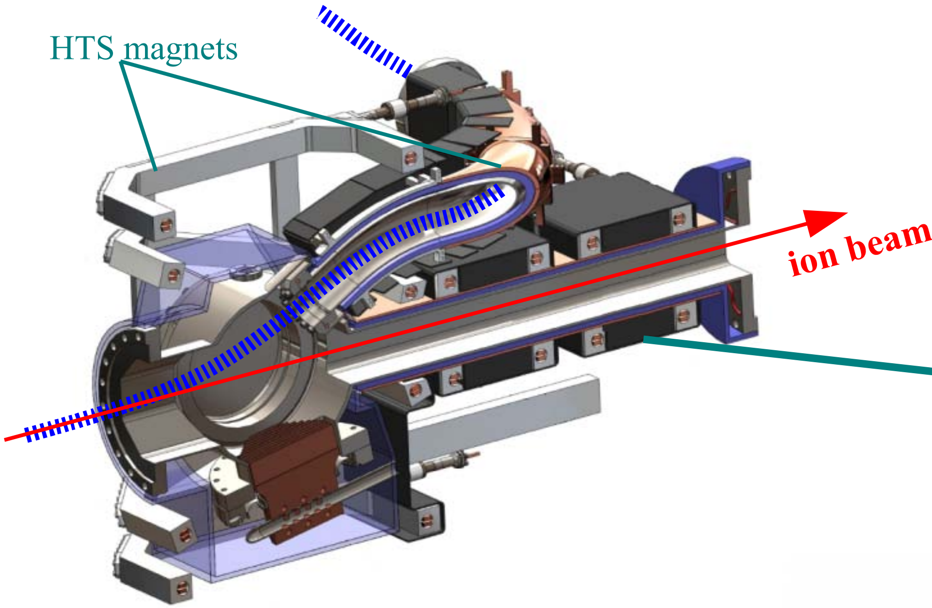
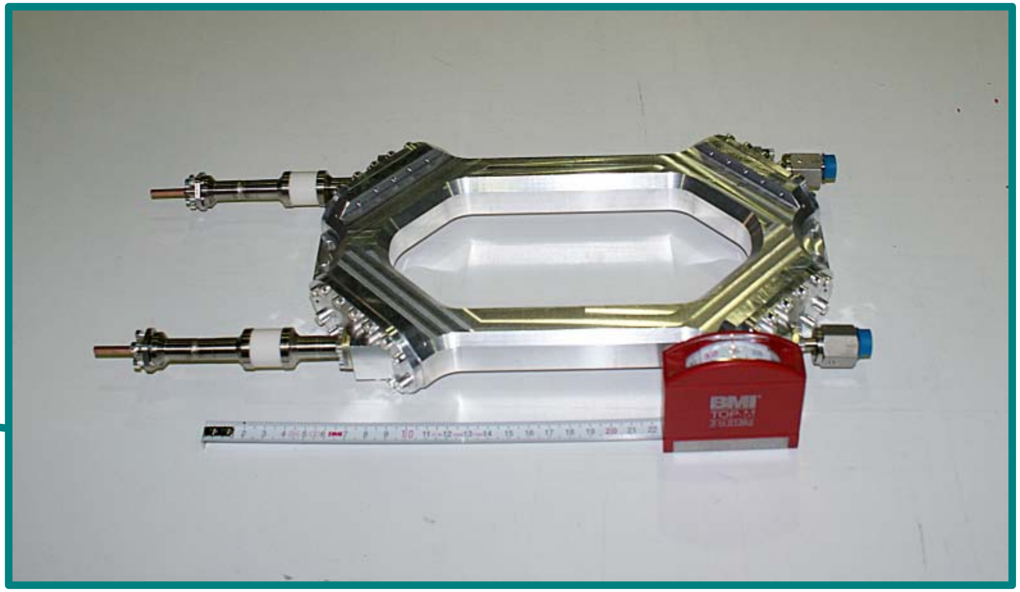


Electron Cooler





Superconducting ring coils have been built and tested

(LNe, approx. 30 K)

10-K vacuum chambers are in manufacturing process ...