Heavy Molecular Ions in Electron Cooler Storage Rings

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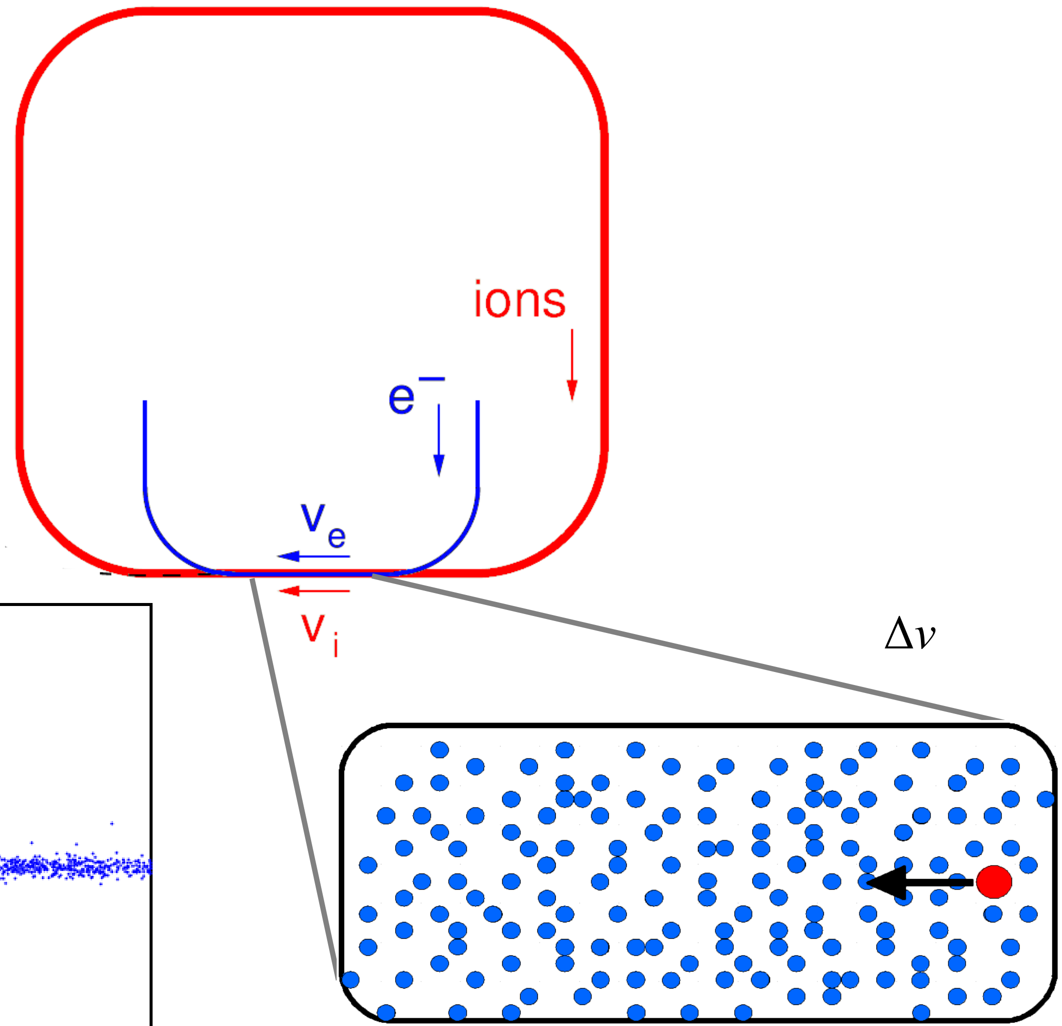
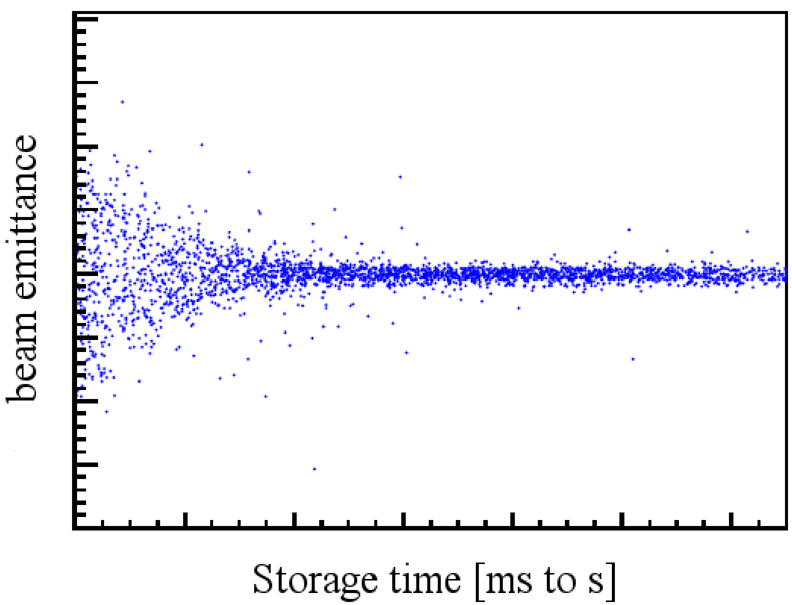
Max Planck Institute for Nuclear Physics

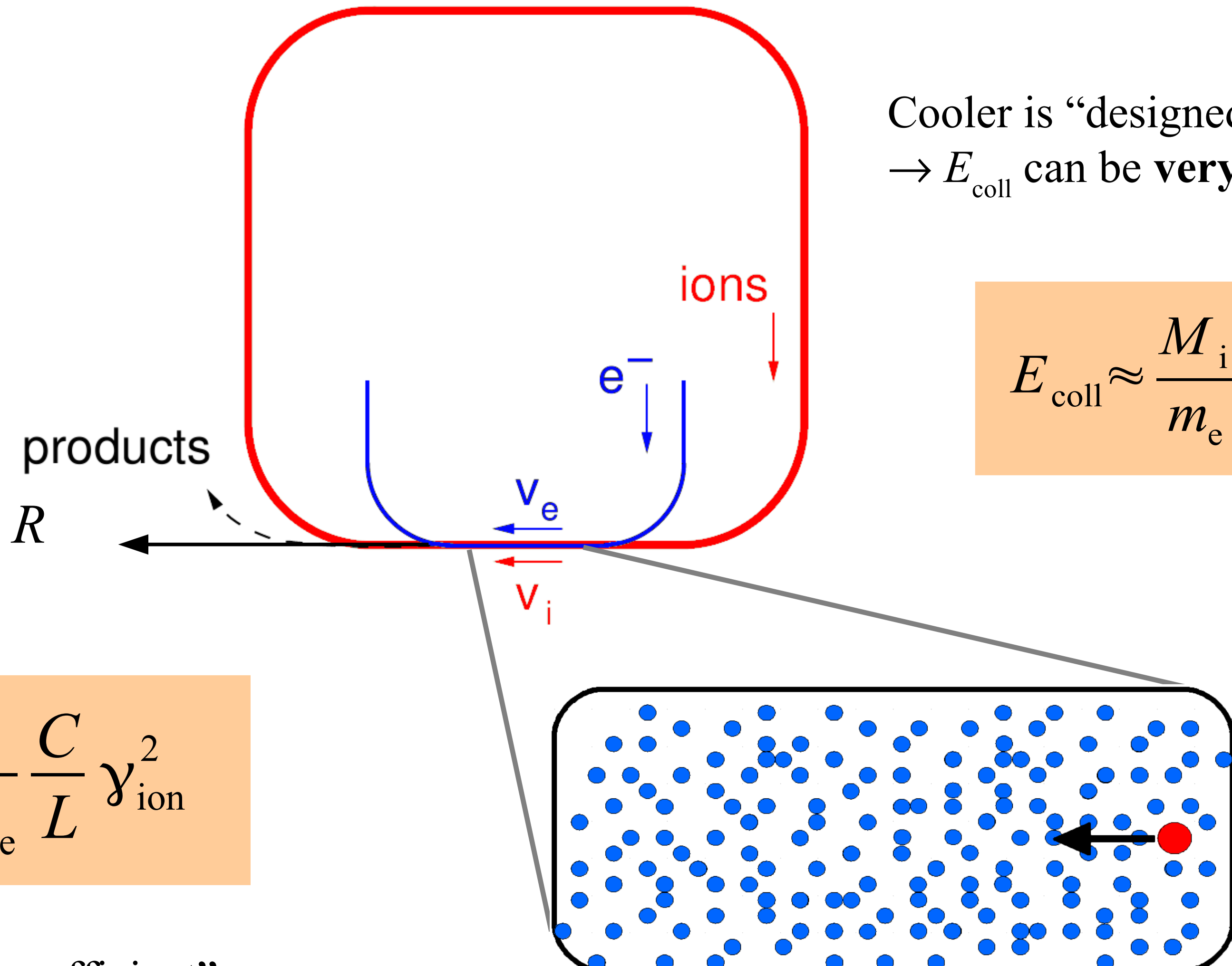
e-Coolers



"Electron cooling"



e-Cooler: Low energy electron-ion collider



Cooler is “designed” for $v = 0$
→ E_{coll} can be **very small** (meV!)

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

collision velocity $v = |v_i - v_e|$

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

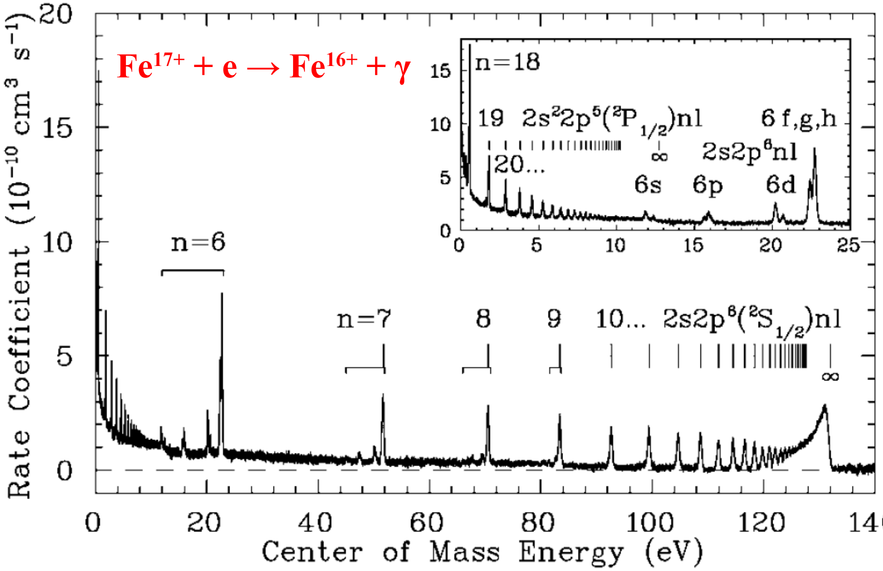
reaction “rate coefficient”

$$\alpha = \langle \sigma(v) v \rangle$$

e-Cooler: Low energy electron-ion collider

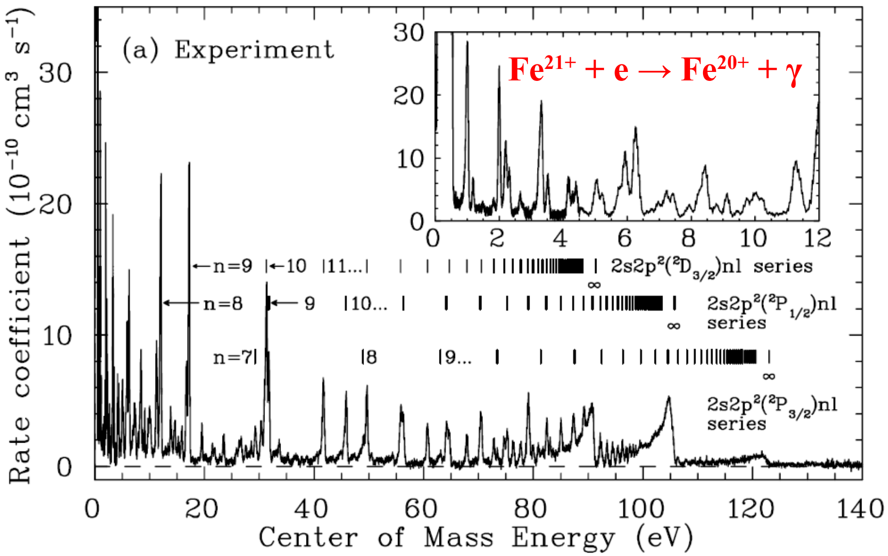
Recombination rates of HCI in astrophysical plasma

$$\alpha = \langle \sigma(v) v \rangle$$



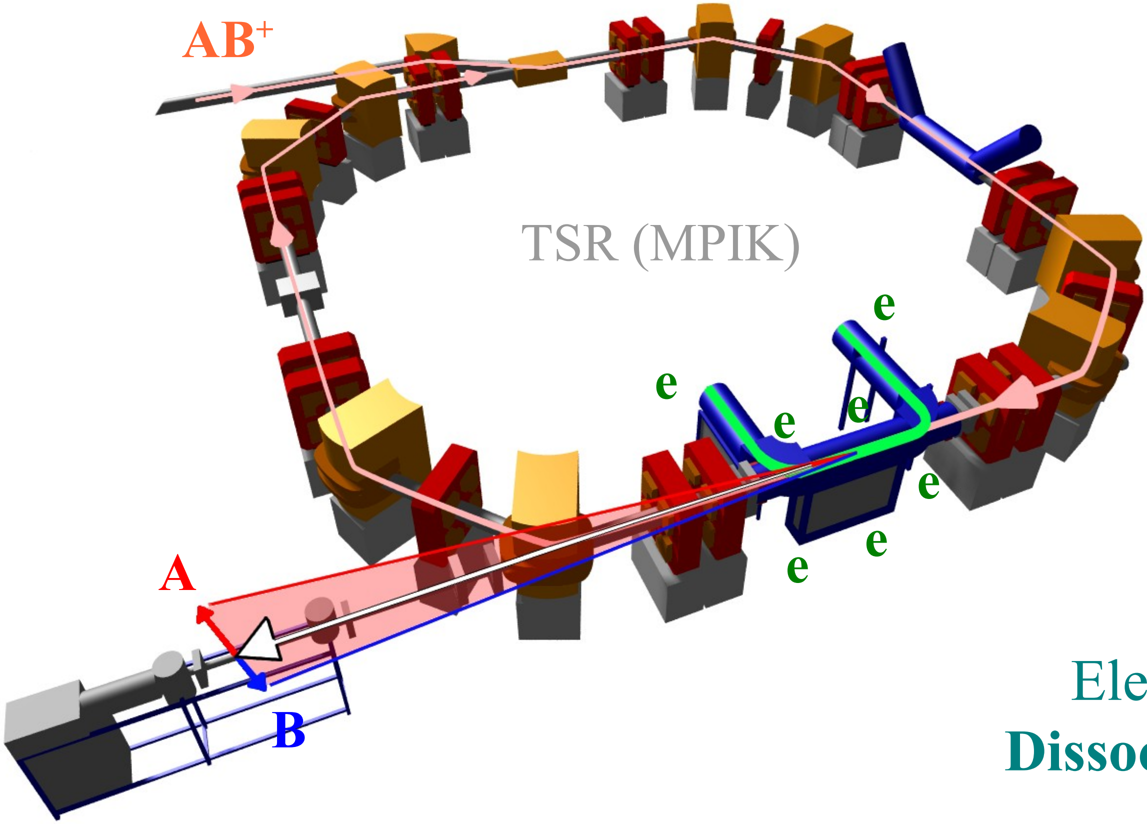
[Savin, ApJ 489 (1997)]

TSR (MPIK) 1988 - 2012



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

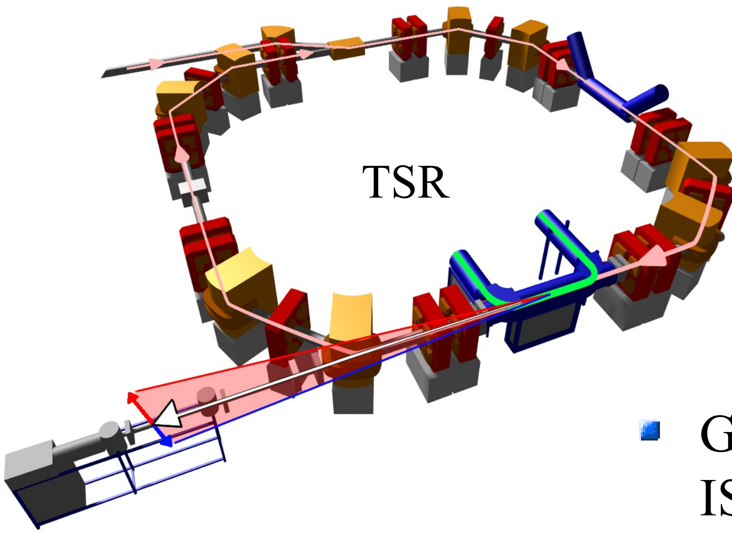
Recombination of molecular ions

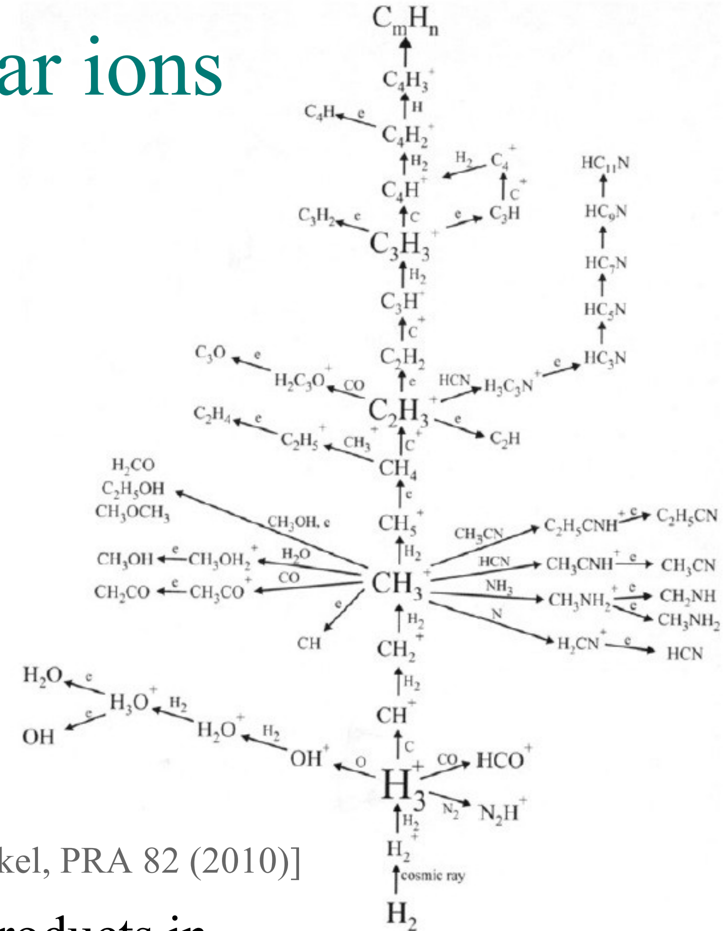


Electrons and molecular ions:
Dissociative Recombination (DR)

$$\mathbf{AB^+ + e + \mathit{E}_{coll} \longrightarrow A^{(*)} + B^{(*)} + \mathit{E}_{KER}}$$

DR of molecular ions

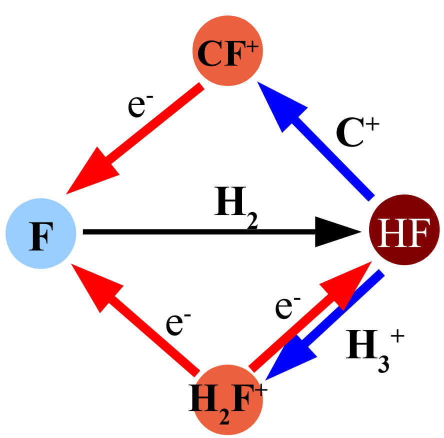




- Gas-phase chemistry in ISC:
  $H_3^+ + e \rightarrow H + H + H$

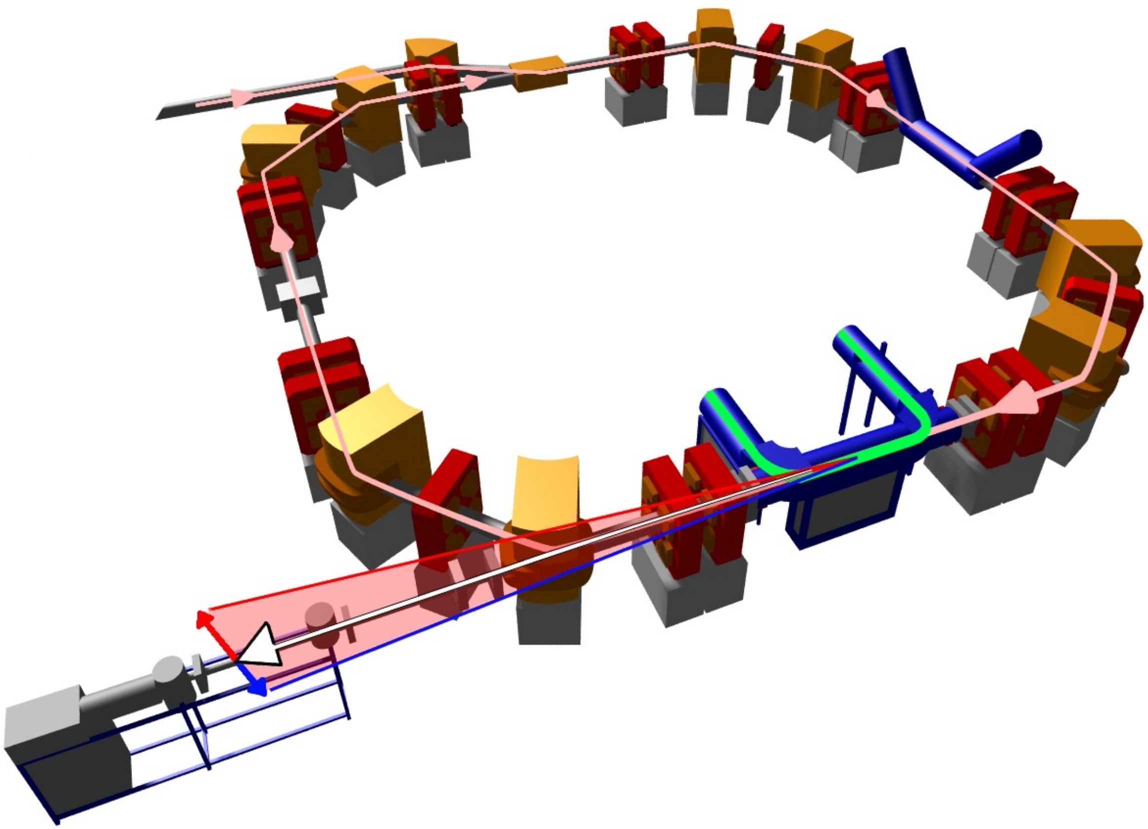
e.g. [Petrignani, PRA 83 (2011); Kreckel, PRA 82 (2010)]

- A source of energetic products in cold environments
  $H_3O^+ + e \rightarrow H_2O^{**} + H$ [Buhr, PRL 105 (2010)]
  $HCNH^+ + e \rightarrow HCN/CNH^{**} + H$ [Mendes, ApJ Lett. 746 (2012)]



- Molecular proxy for H_2: HF
  $H_2 + 2\,F \rightarrow 2\,HF + E$ [Novotný, t.b.p.]

DR of molecular ions



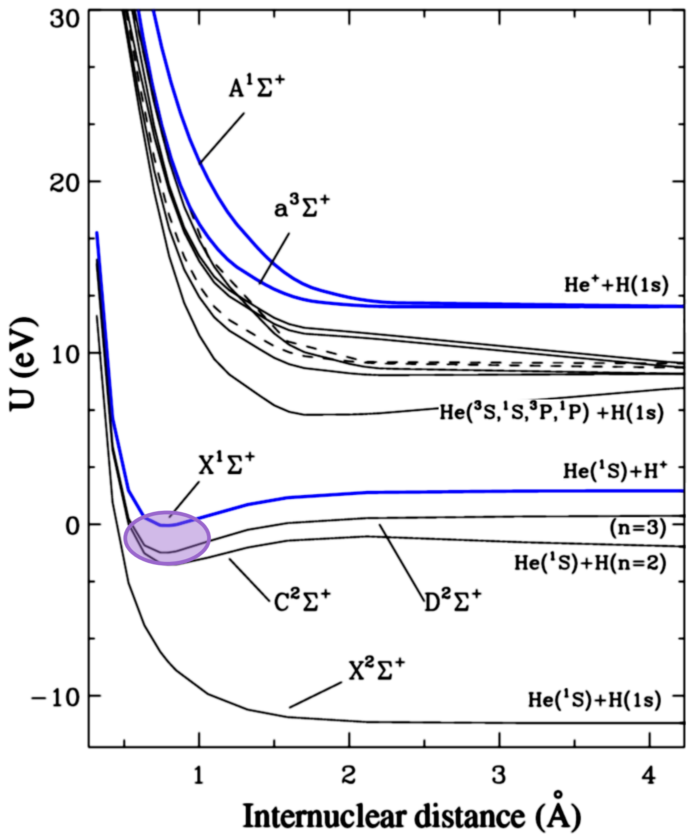
reaction “rate coefficient”

$$\alpha = \langle \sigma(v) v \rangle$$

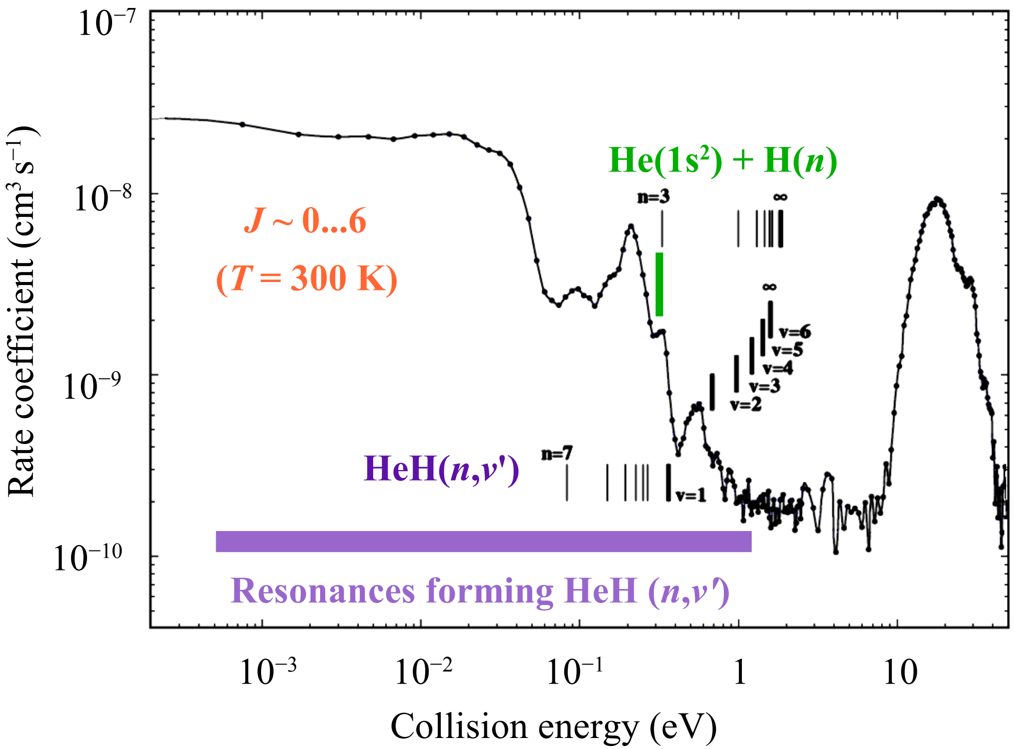
$$\mathbf{AB^+ + e + \mathit{E}_{coll} \longrightarrow A^{(*)} + B^{(*)} + \mathit{E}_{KER}}$$

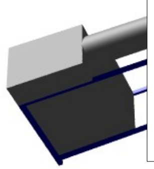
DR of molecular ions

$HeH^+\ (v = 0) + e \rightarrow He\ (1s^2) + H\ (n \geq 2)$



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



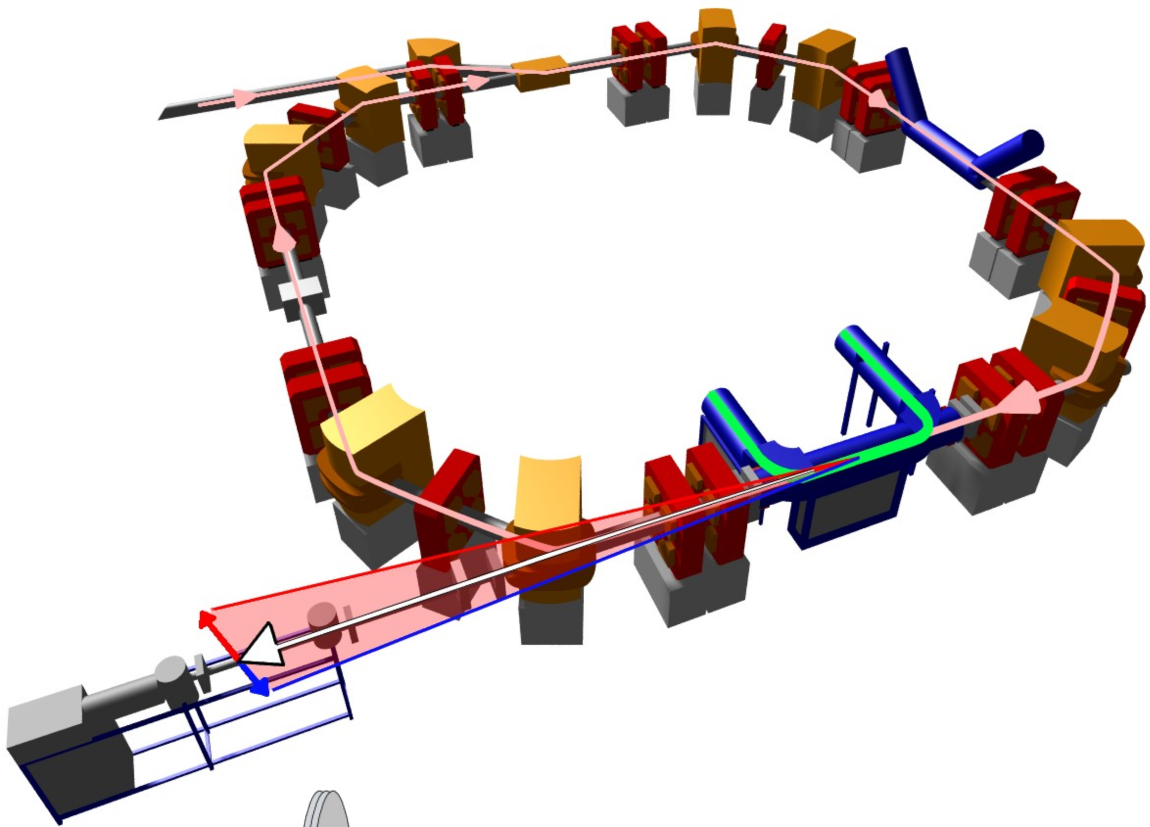


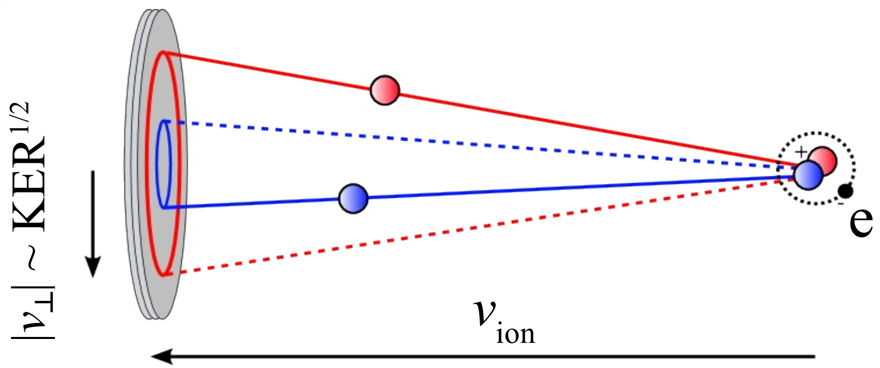
reaction "rate coefficient"

$$\alpha = \langle \sigma(v) v \rangle$$

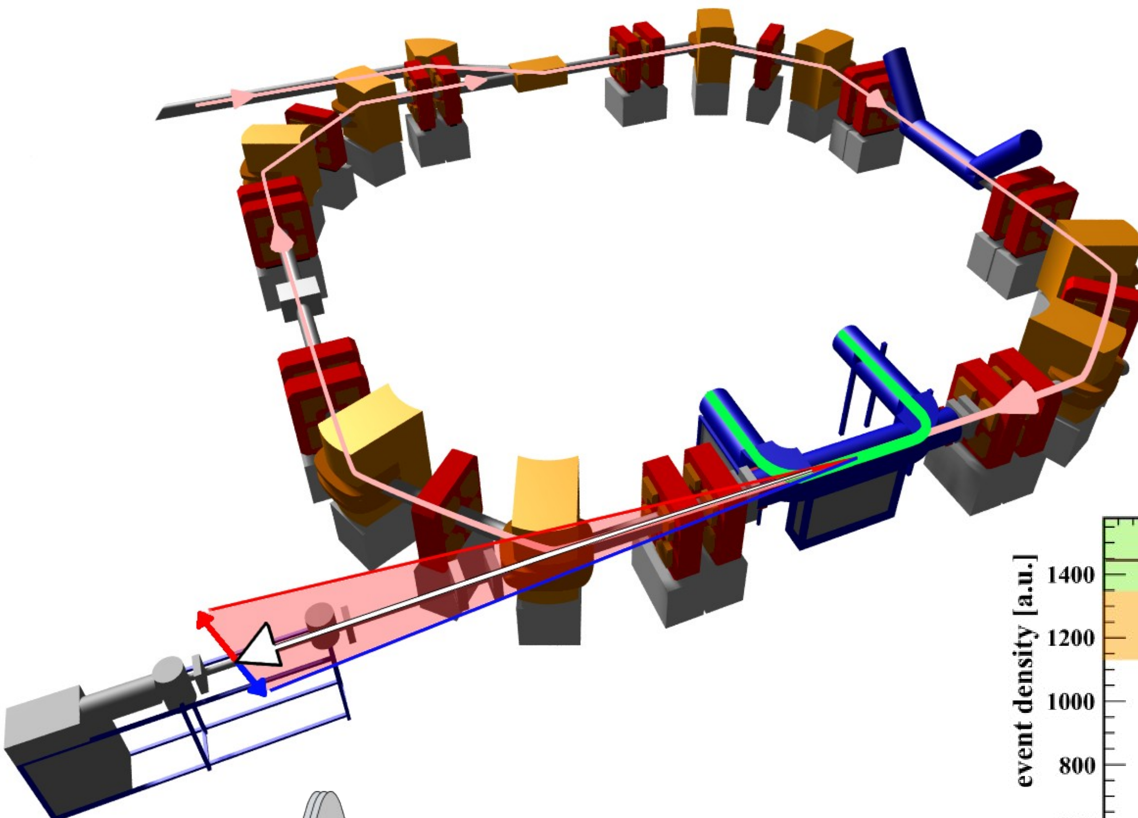
$$\mathbf{AB^+ + e +} E_{\mathbf{coll}} \mathbf{\longrightarrow A^{(*)} + B^{(*)} +} E_{\mathbf{KER}}$$

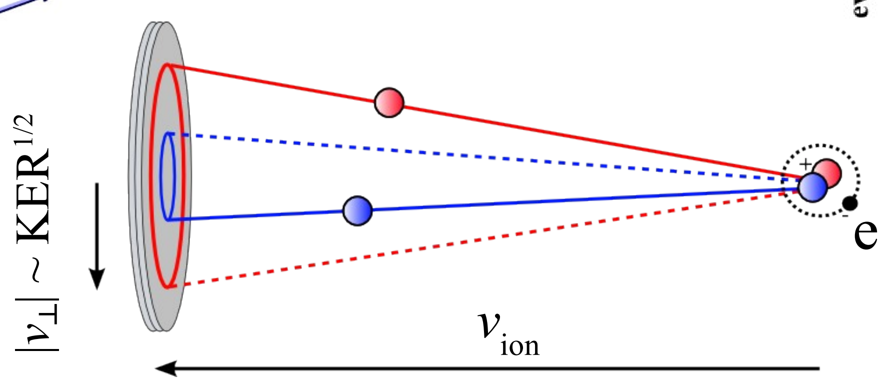
DR of molecular ions



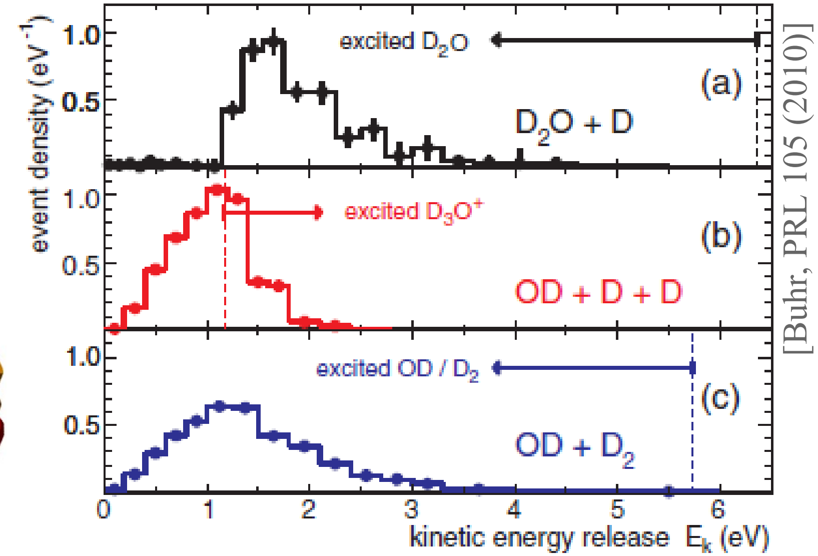


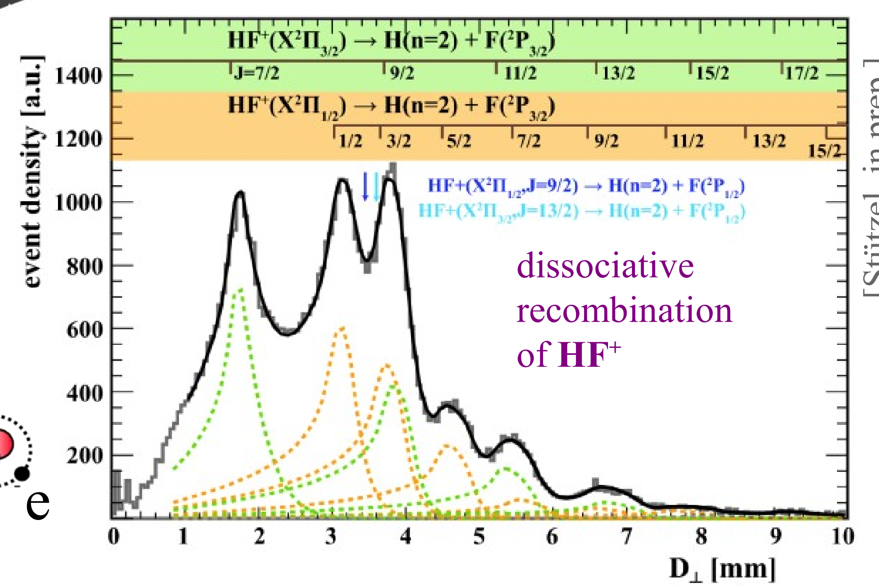
DR of molecular ions





dissociative recombination of **D_3O^+**





dissociative recombination of **HF^+**

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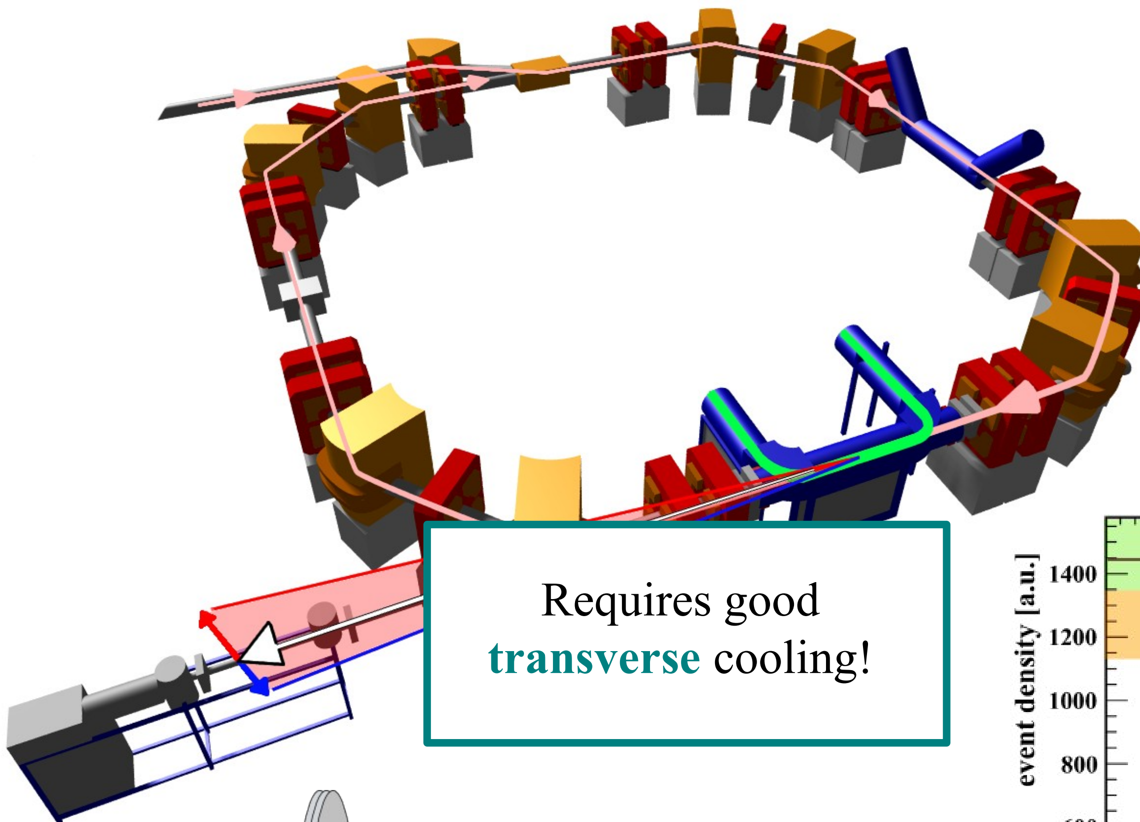
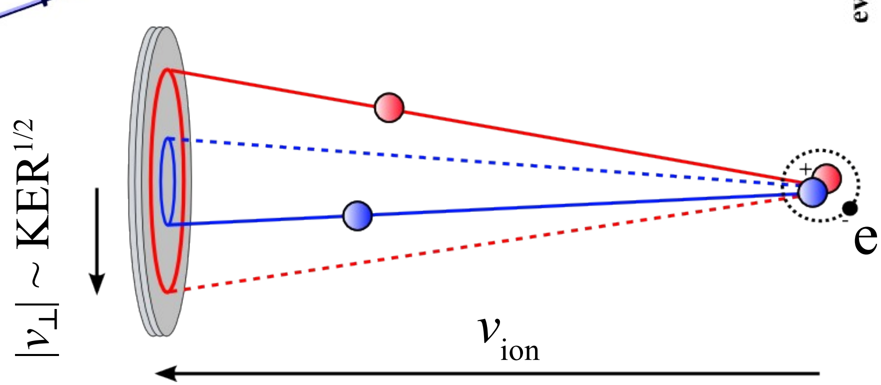
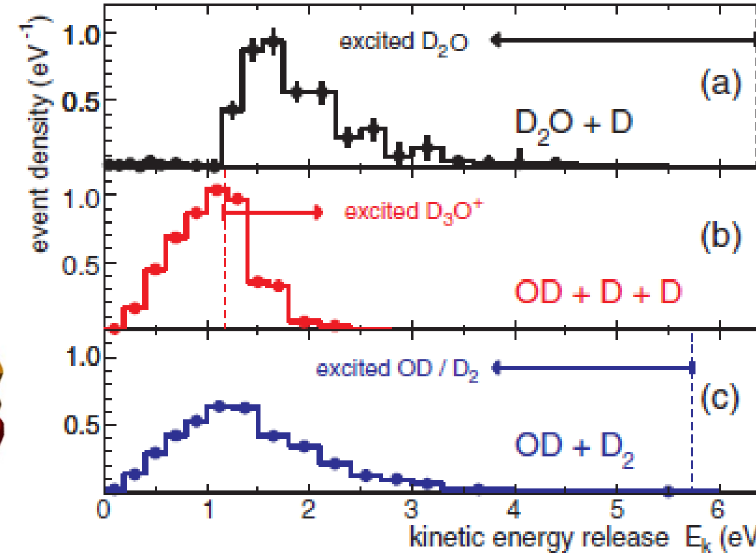
DR of molecular ions



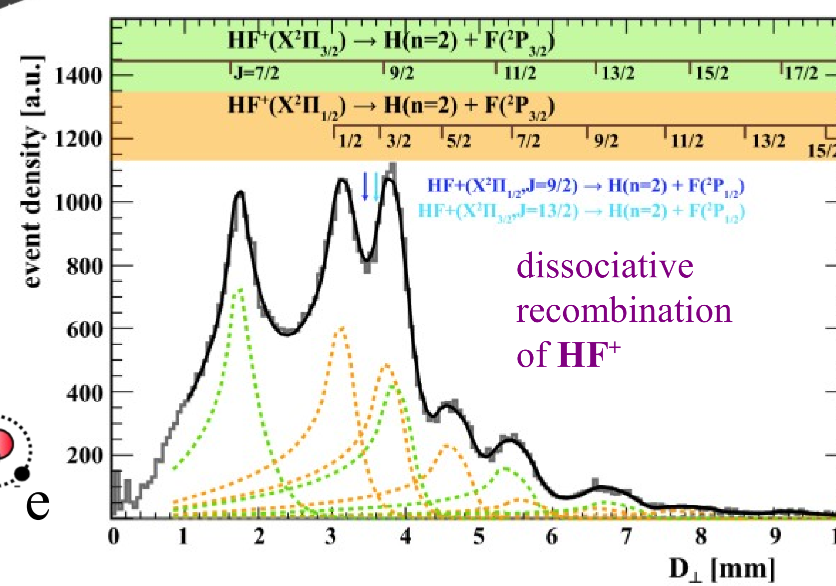
Requires good **transverse** cooling!



dissociative recombination of D_3O^+



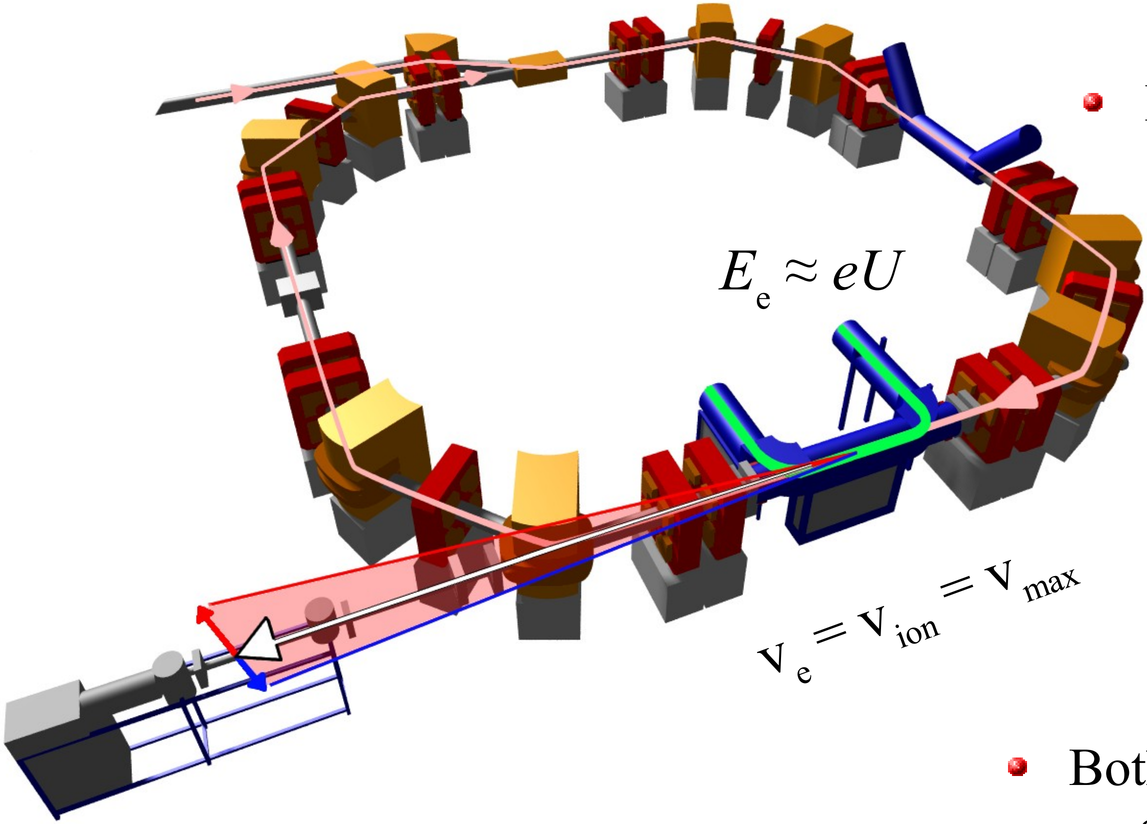
[Buhr, PRL 105 (2010)]



dissociative recombination of **HF$^+$**

[Stützel, in prep.]

Electron cooling molecular ions



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

- Maximum velocity:

$$v_{ion} = \frac{Z_{ion}}{M_{ion}} r\,B_{max} \rightarrow U \sim \frac{Z_{ion}^2}{M_{ion}^2}$$

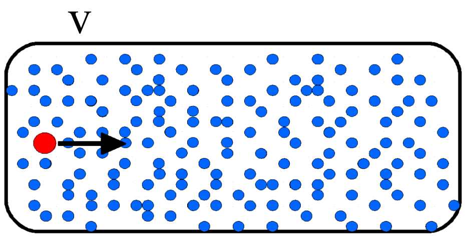
e.g. CHD^+ (15 u) : $v_{ion} \sim 0.030$ c , $U \sim 230$ V
D_3O^+ (22 u) : $v_{ion} \sim 0.020$ c , $U \sim 110$ V
$DCND^+$ (30 u) : $v_{ion} \sim 0.015$ c , $U \sim 55$ V
HCl^+ (36 u) : $v_{ion} \sim 0.012$ c , $U \sim 40$ V
D_2Cl^+ (39 u) : $v_{ion} \sim 0.010$ c , $U \sim 31$ V

- Both storage and electron cooling of molecular ions are difficult!

... short storage times
(res. gas losses)

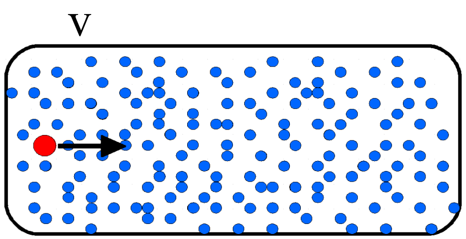
... long e-cooling times

Cooling force



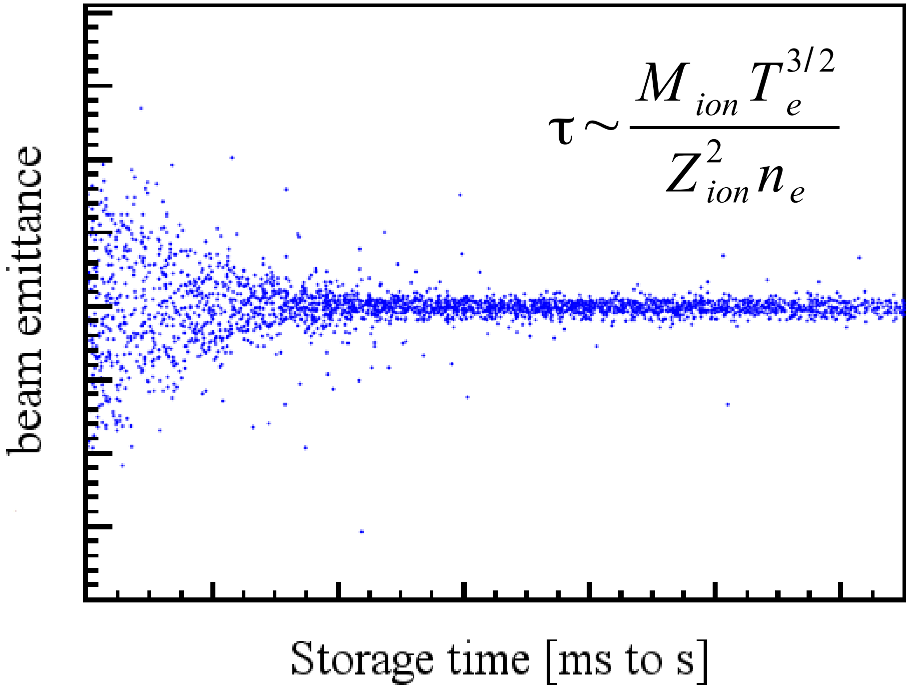
$$\vec{F} \sim -\frac{Z_{ion}^2 n_e}{v^2}\frac{\vec{v}}{|v|}$$

Cooling force

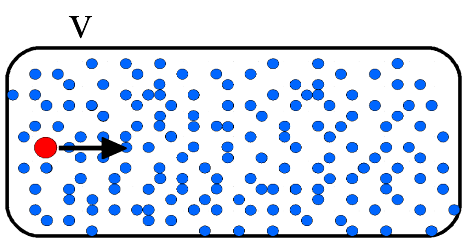


$$\vec{F} \sim -\frac{Z_{ion}^2 n_e}{v^2} \frac{\vec{v}}{|v|}$$

Cooling time

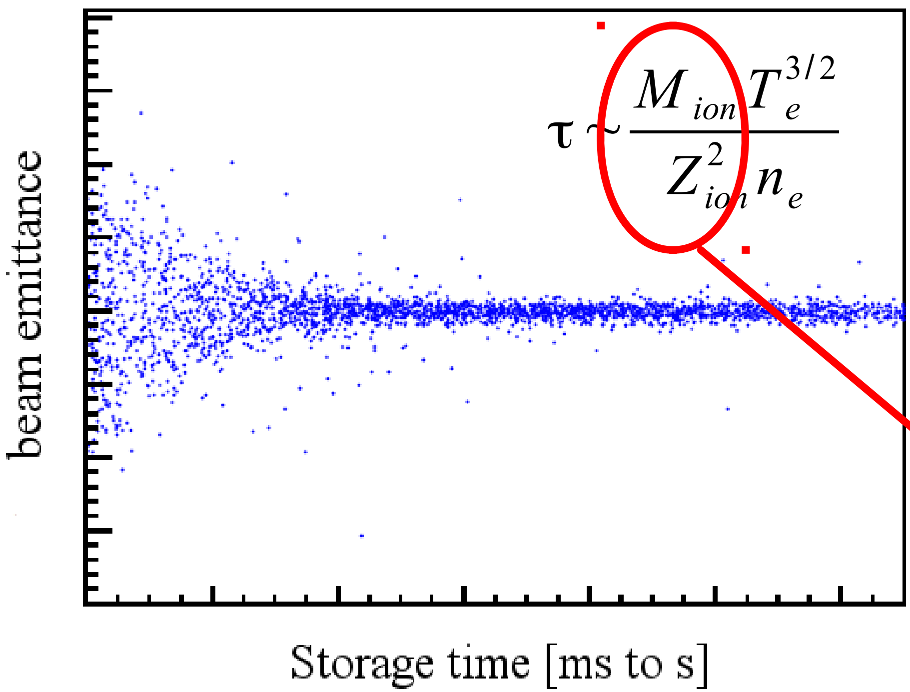


Cooling force



$$\vec{F} \sim -\frac{Z_{ion}^2 n_e}{v^2}\frac{\vec{v}}{|v|}$$

Cooling time

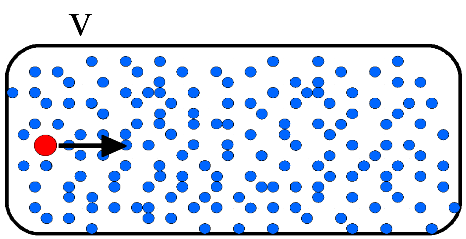


For molecular ions:

$M_{\text{ion}} \gg 10\,\text{u}$

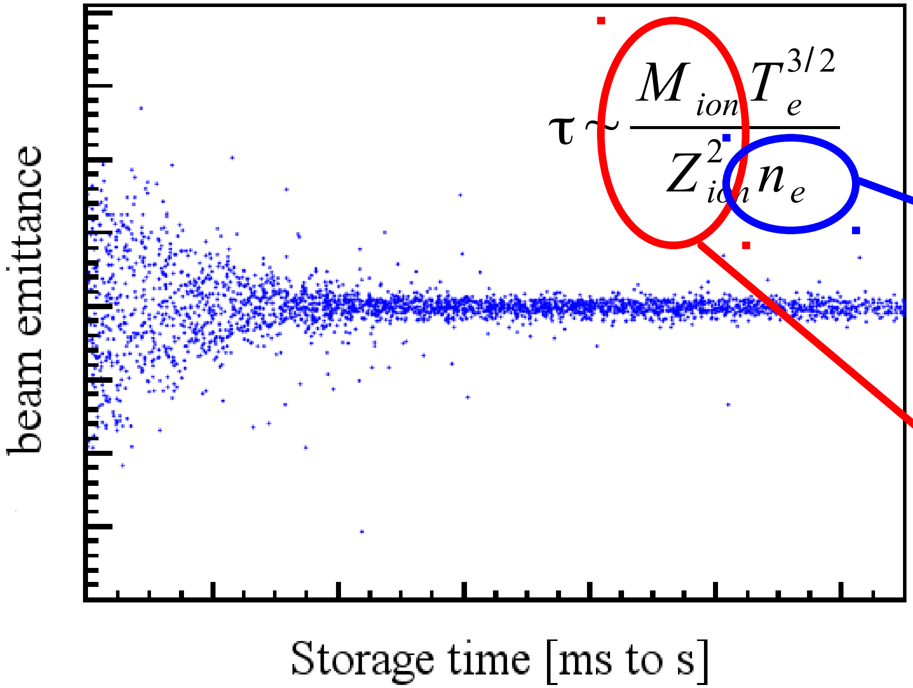
$Z_{\text{ion}} = 1$

Cooling force



$$\vec{F} \sim -\frac{Z_{ion}^2 n_e}{v^2}\frac{\vec{v}}{|v|}$$

Cooling time



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

High beam rigidity (low v_{ion}):

→ low electron energy (~Ue)

→ low n_e ($I_{max} \sim U^{3/2}$)

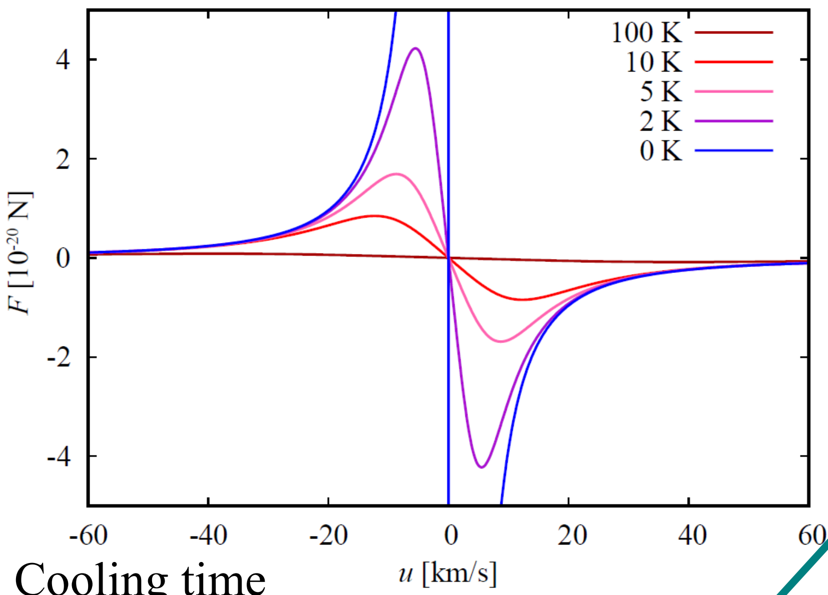
For molecular ions:

$M_{\rm ion} \gg 10\,{\rm u}$

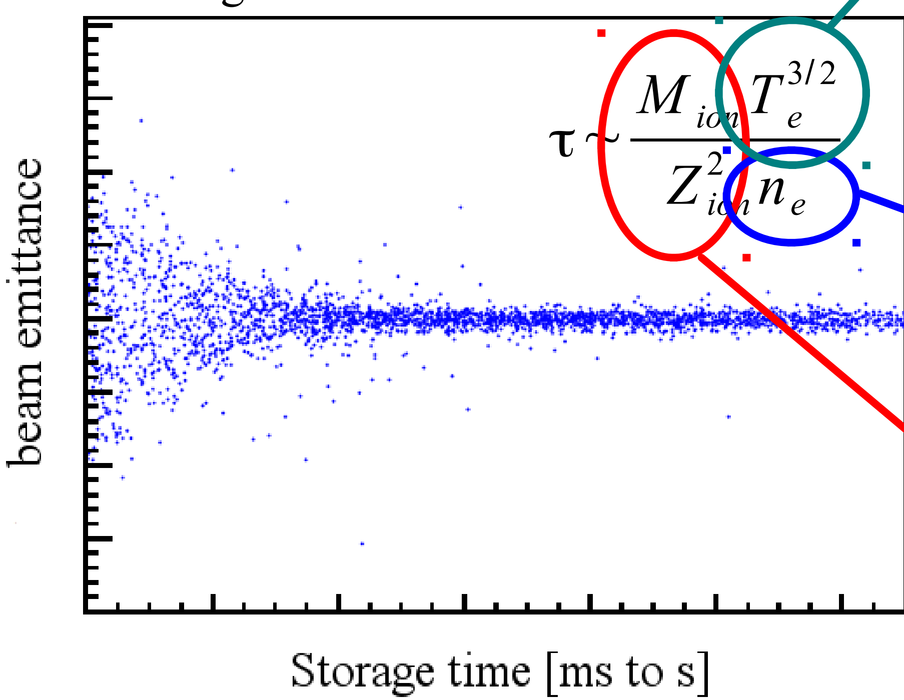
$Z_{\rm ion} = 1$

Cooling force

effective electron temperature



Cooling time



Major impact on cooling force

for transverse cooling (DR imaging!):

$$T_\mathrm{e} \approx T_\perp$$

Improvement: Magnetic expansion

$$T_\perp \approx T_\mathrm{cath} \frac{B_\mathrm{f}}{B_\mathrm{i}}$$

but: decreases also n_e!

Better: Start with **low T_{cath}** directly!

High beam rigidity (low v_{ion}):

→ low electron energy (~Ue)

→ low n_e ($I_{max} \sim U^{3/2}$)

For molecular ions:

$$M_\mathrm{ion} \gg 10\,\mathrm{u}$$

$$Z_\mathrm{ion} = 1$$

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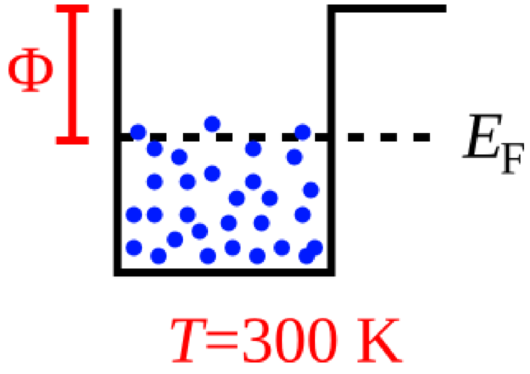
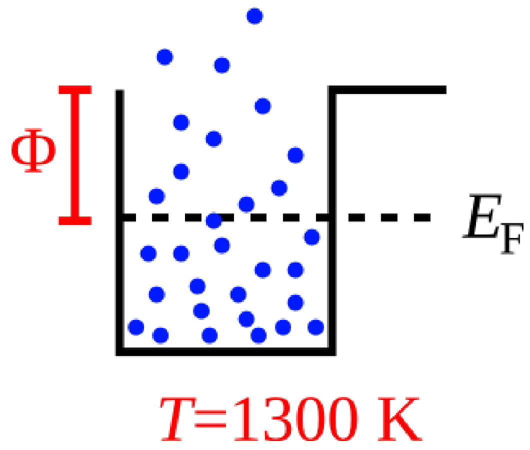
Electron temperature

Thermionic cathodes:

$$J \sim T^2 \exp\left(\frac{-\Phi}{k_B T}\right)$$





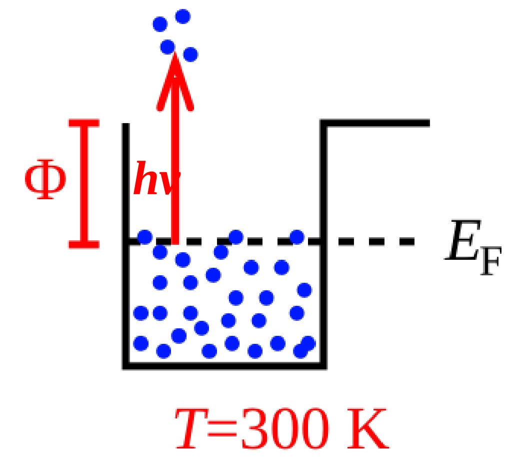
established technology
high J are possible …

high electron-T
($k_B T$ > 100 meV)

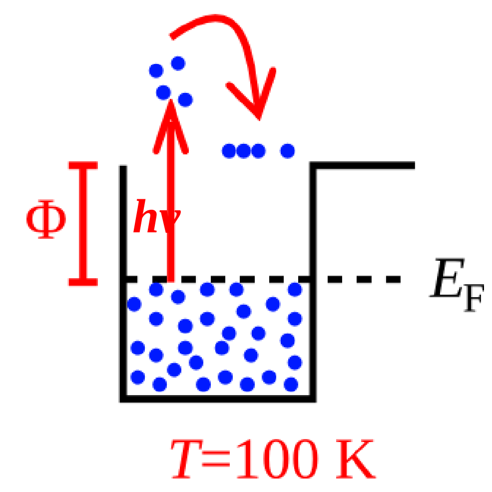
Electron temperature

Photocathodes:

- Electrons overcome Φ by **absorbtion of photons** ($h\nu > \Phi$)



- Semiconductor *Negative Electron Affinity* (**NEA**) photocathodes: e's can **thermalise to states close to vacuum energy**.

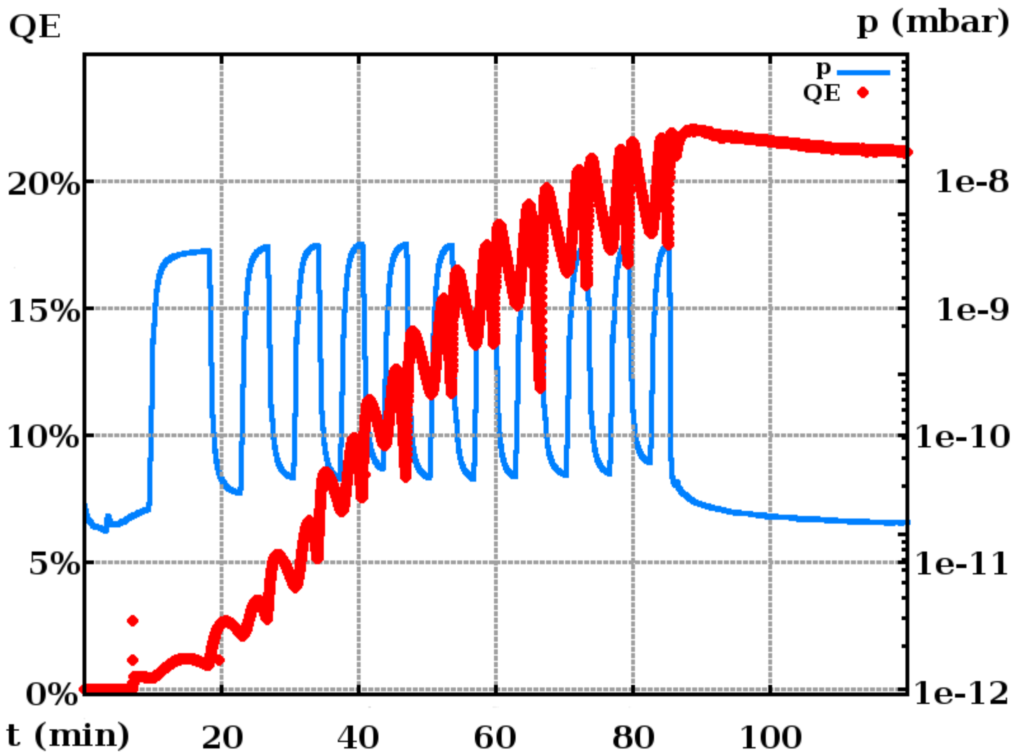


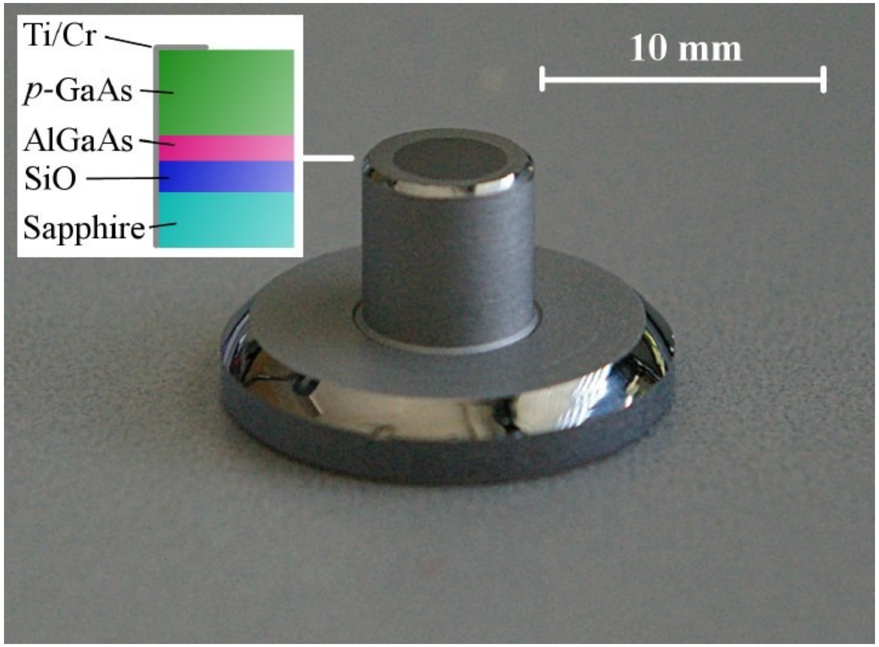
$T_e \sim T_{cath}$

($k_B T \approx 10 \ldots 24$ meV)

GaAs photo cathodes

NEA-activation by exposure to Cs and O_2.





[A. S. Terekhov *et al.*, ISP Novosibirsk]

$k_B T_e$ = 10 … 24 meV
I_e ≤ 1 mA
Q_{max} ~ 100 C

Photo cathode electron cooler

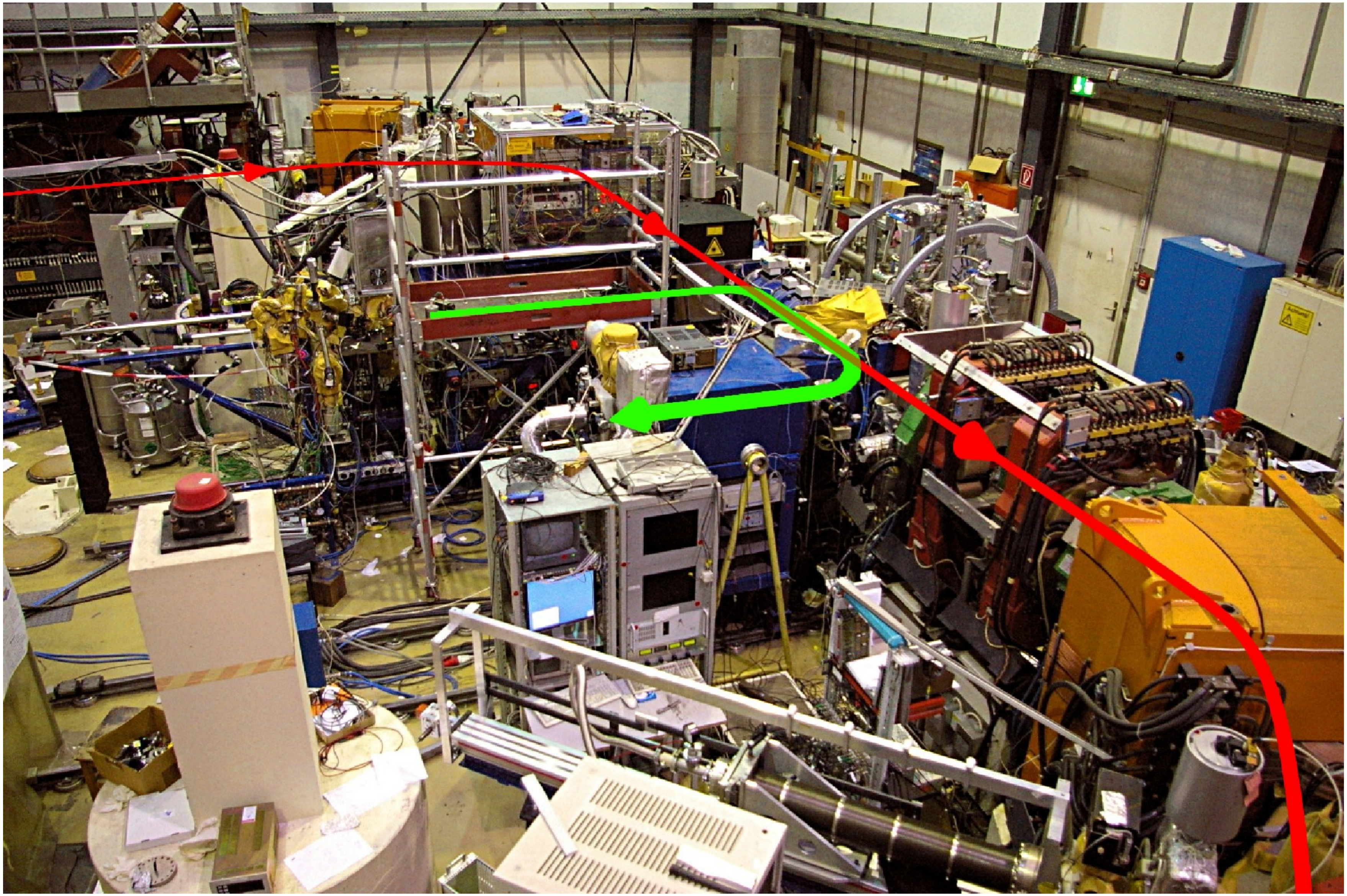
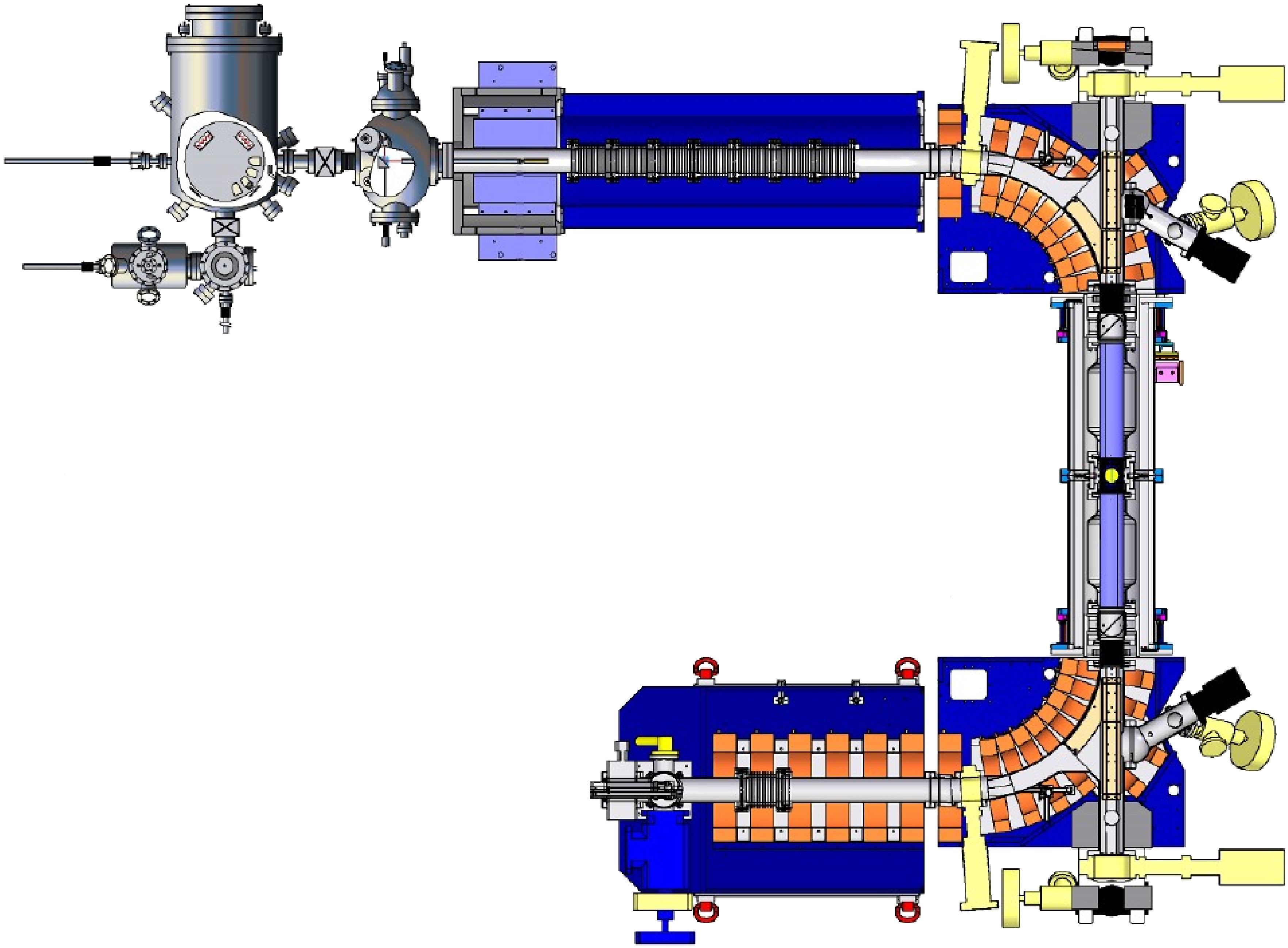


Photo cathode electron cooler



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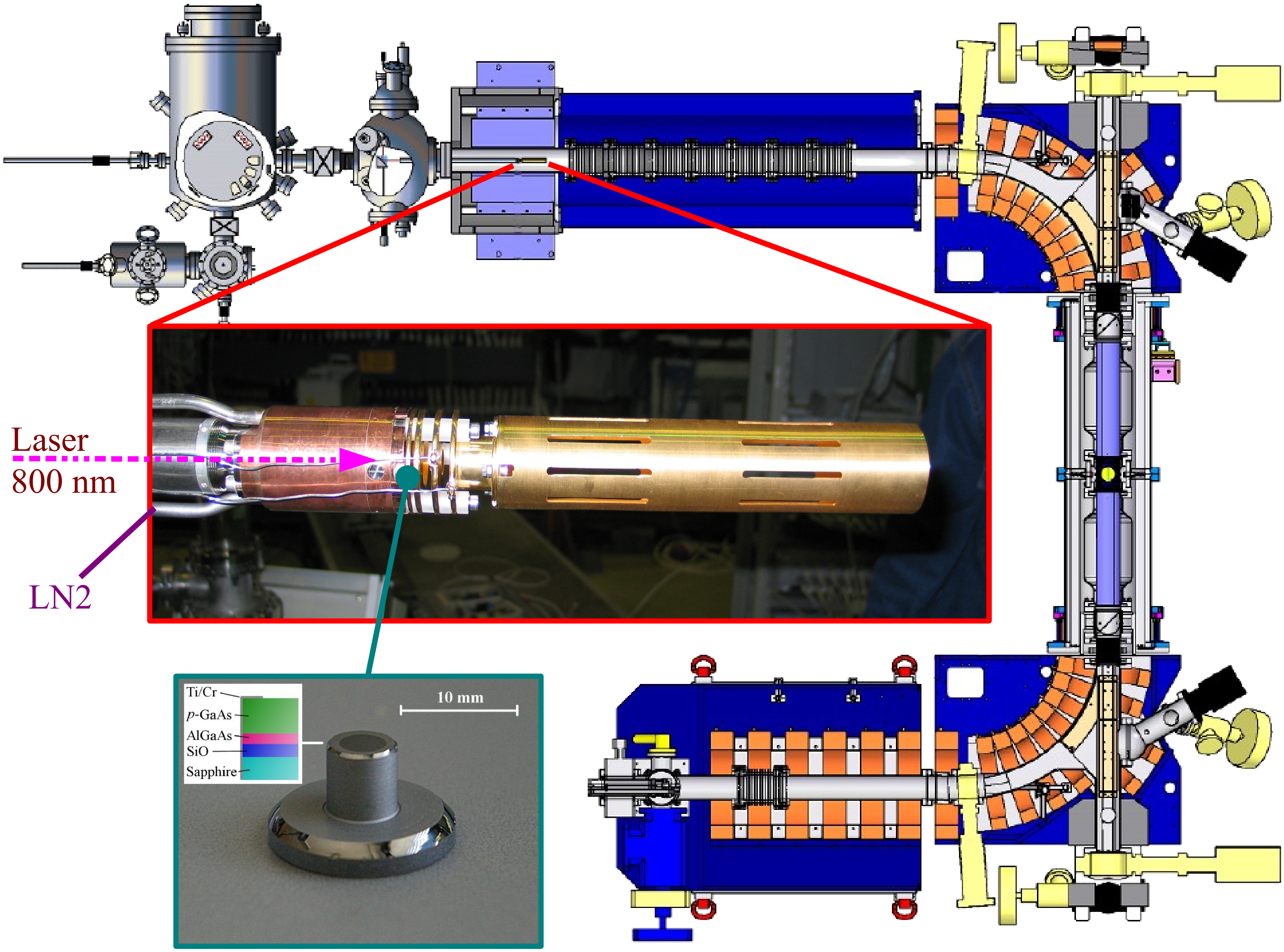

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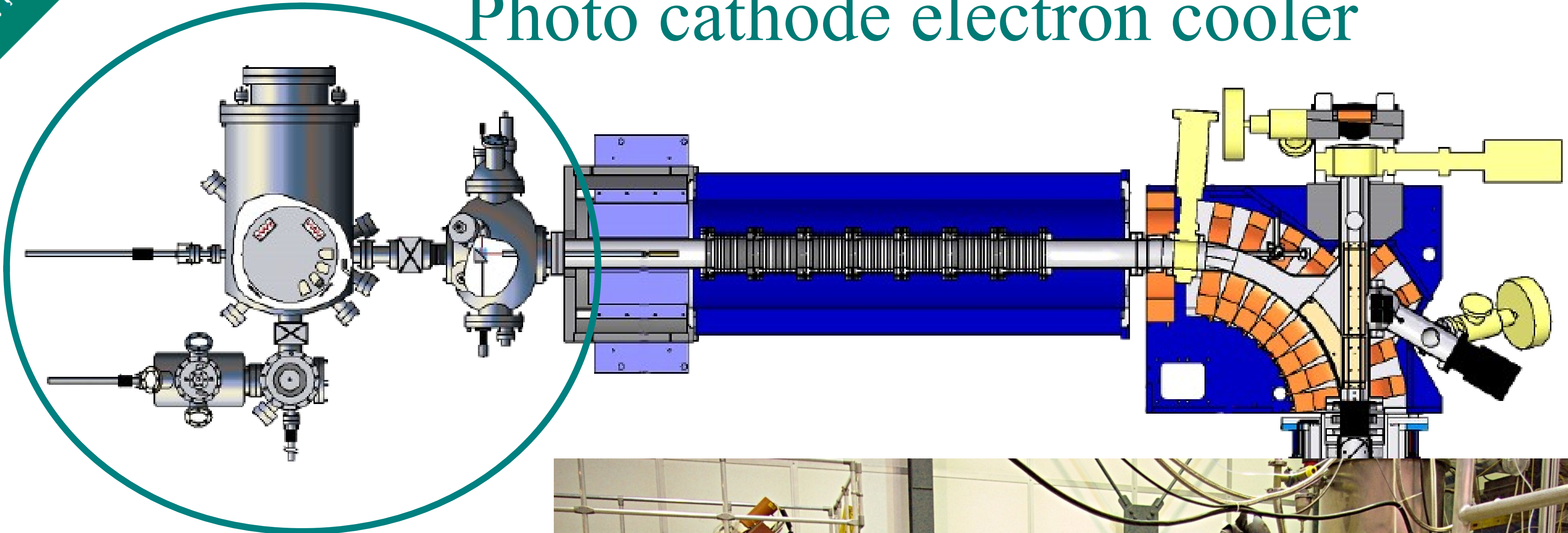
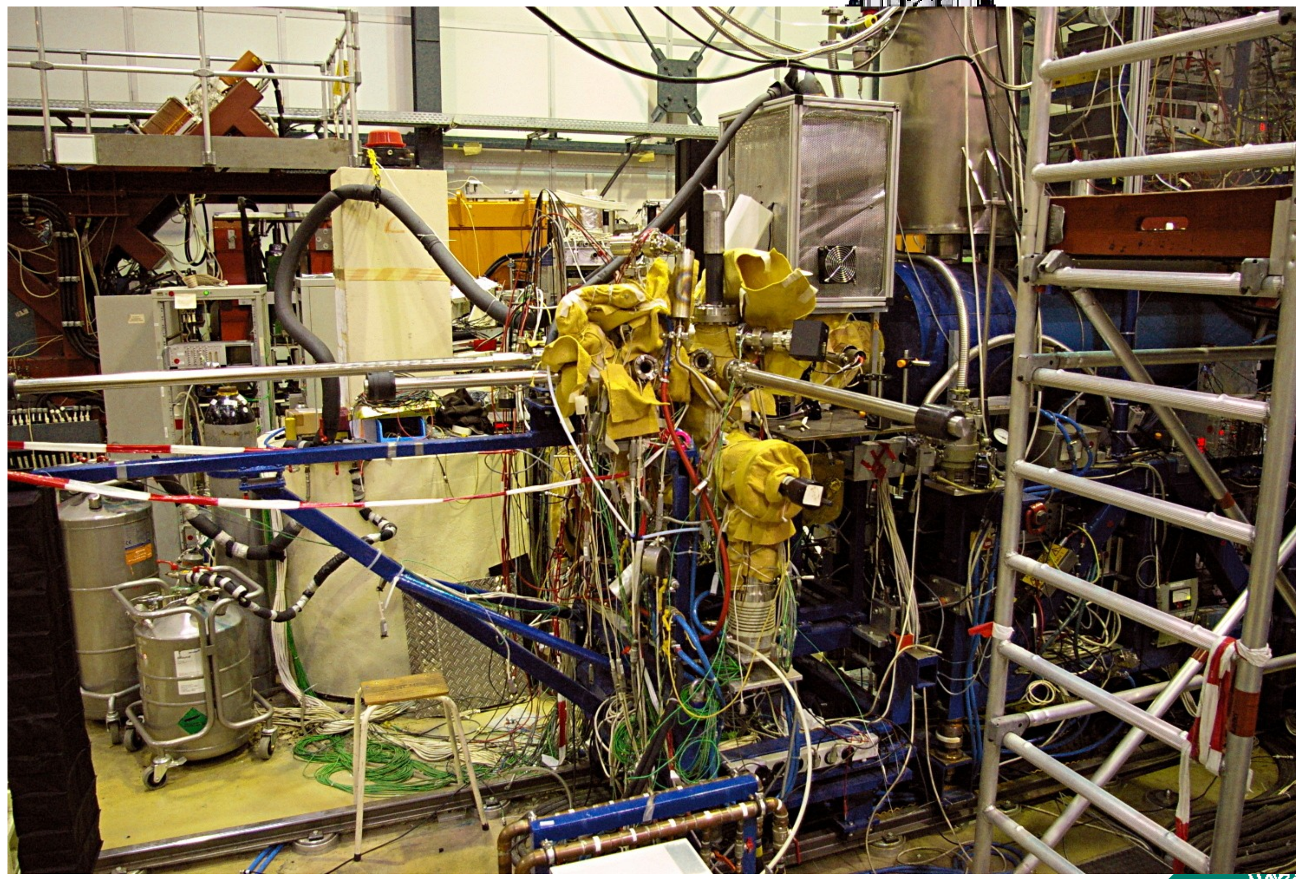
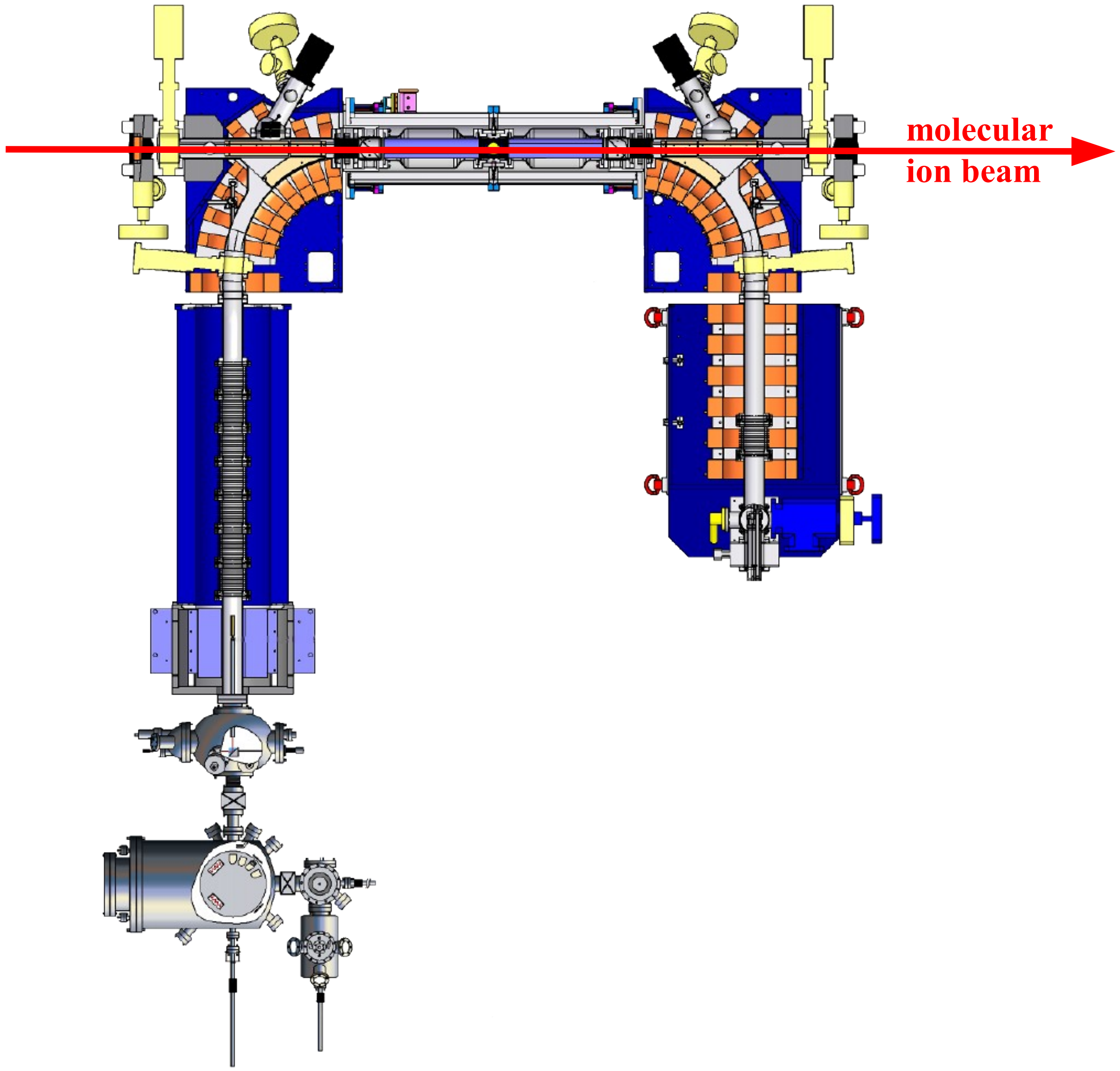




Electron cooling at low velocity



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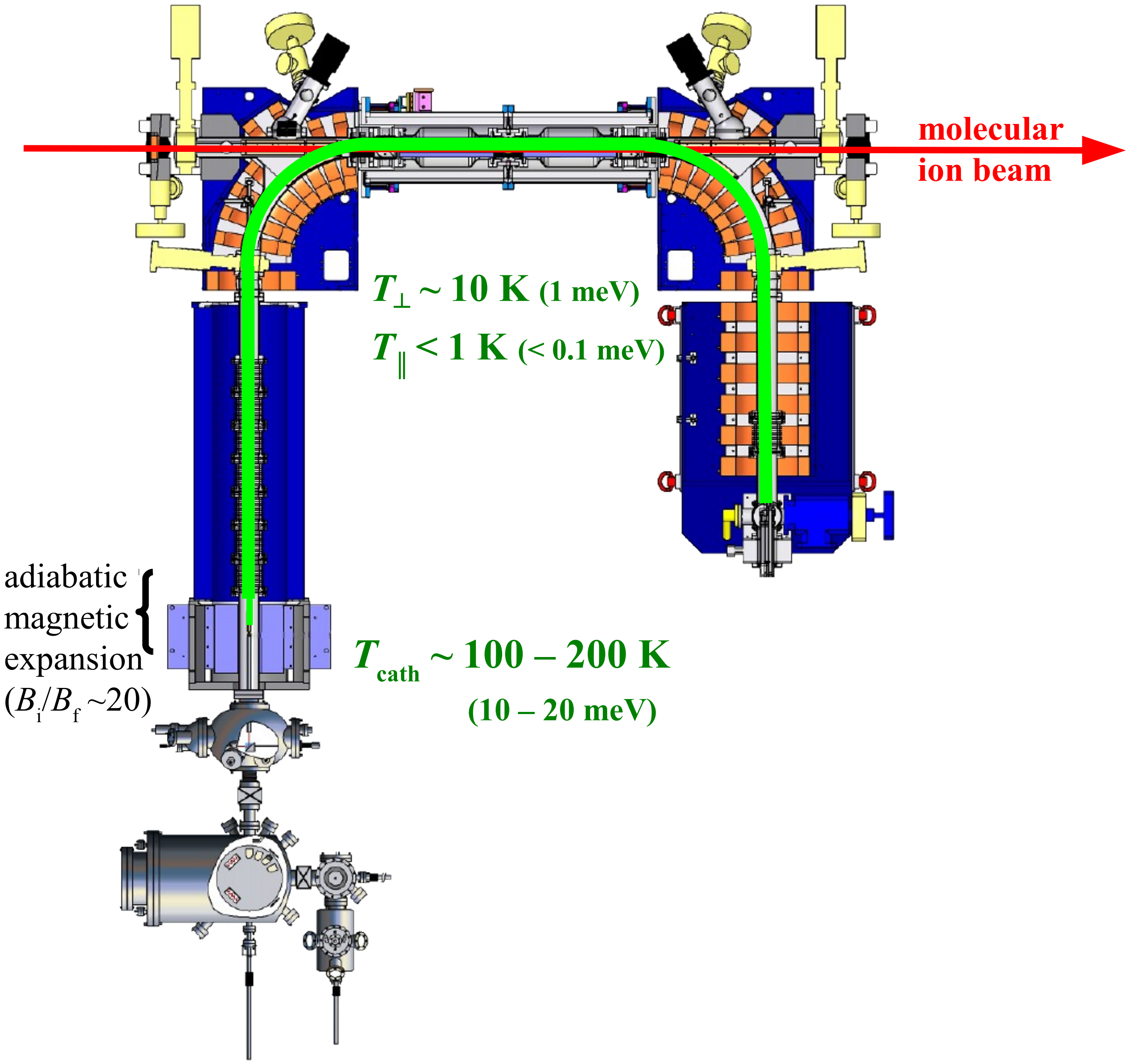

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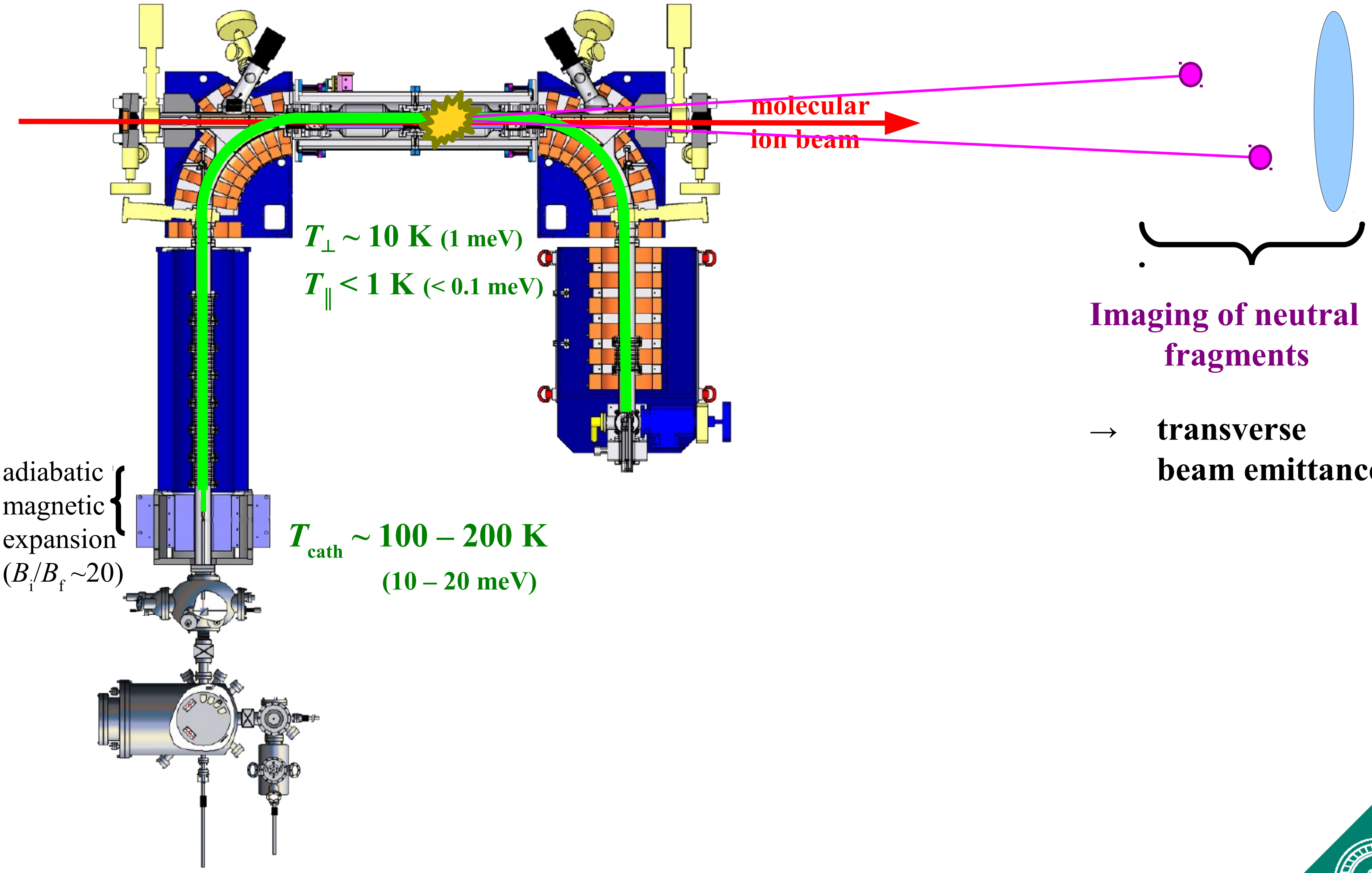
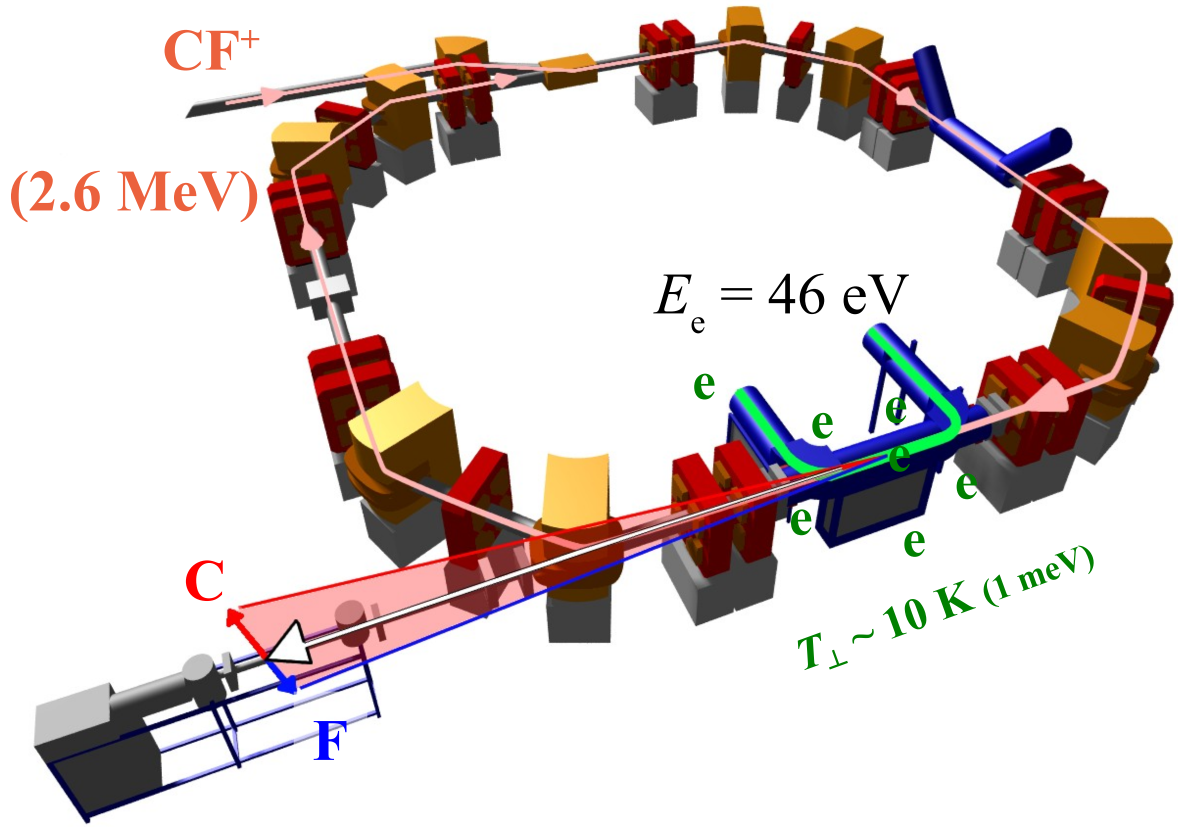
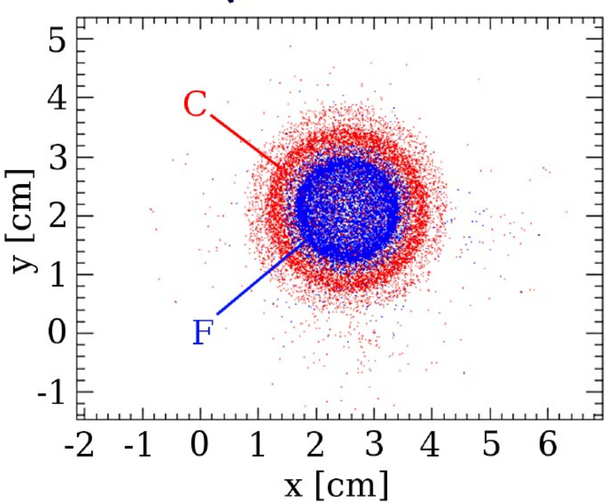
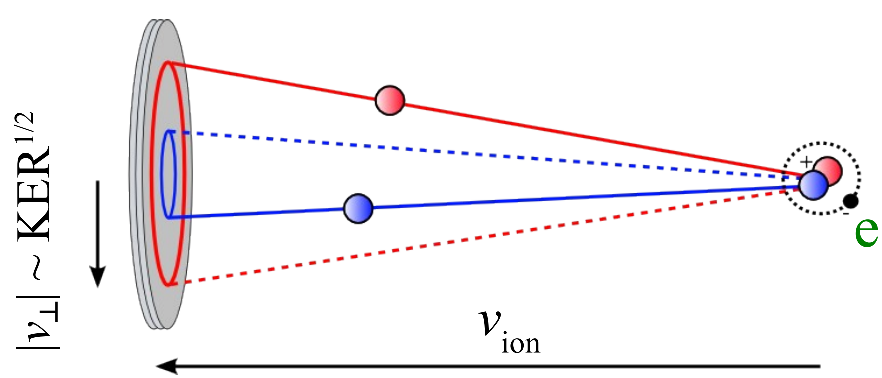


→ **transverse beam emittance**

Electron cooling at low velocity







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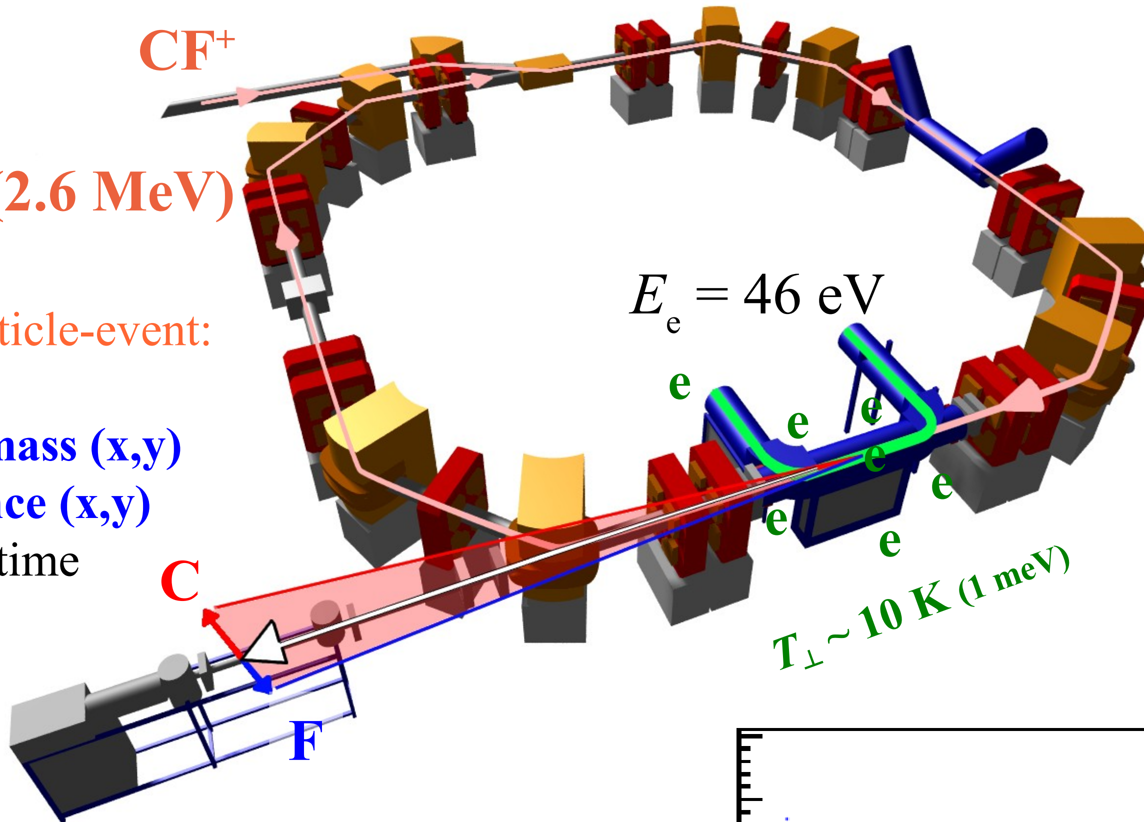
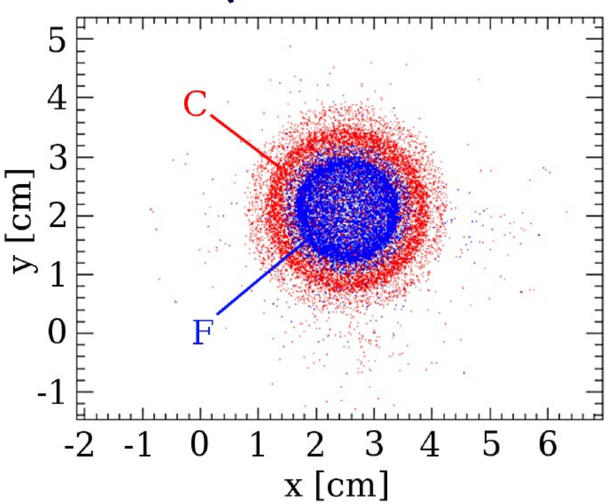
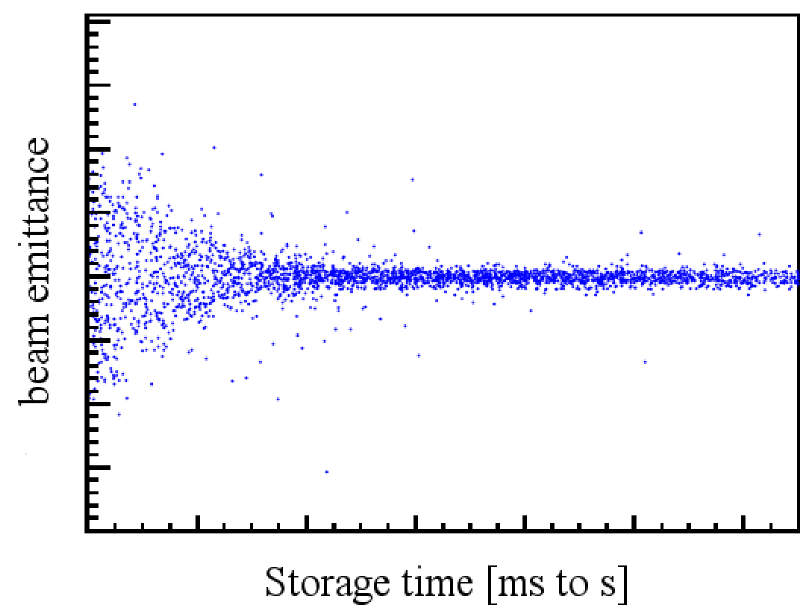
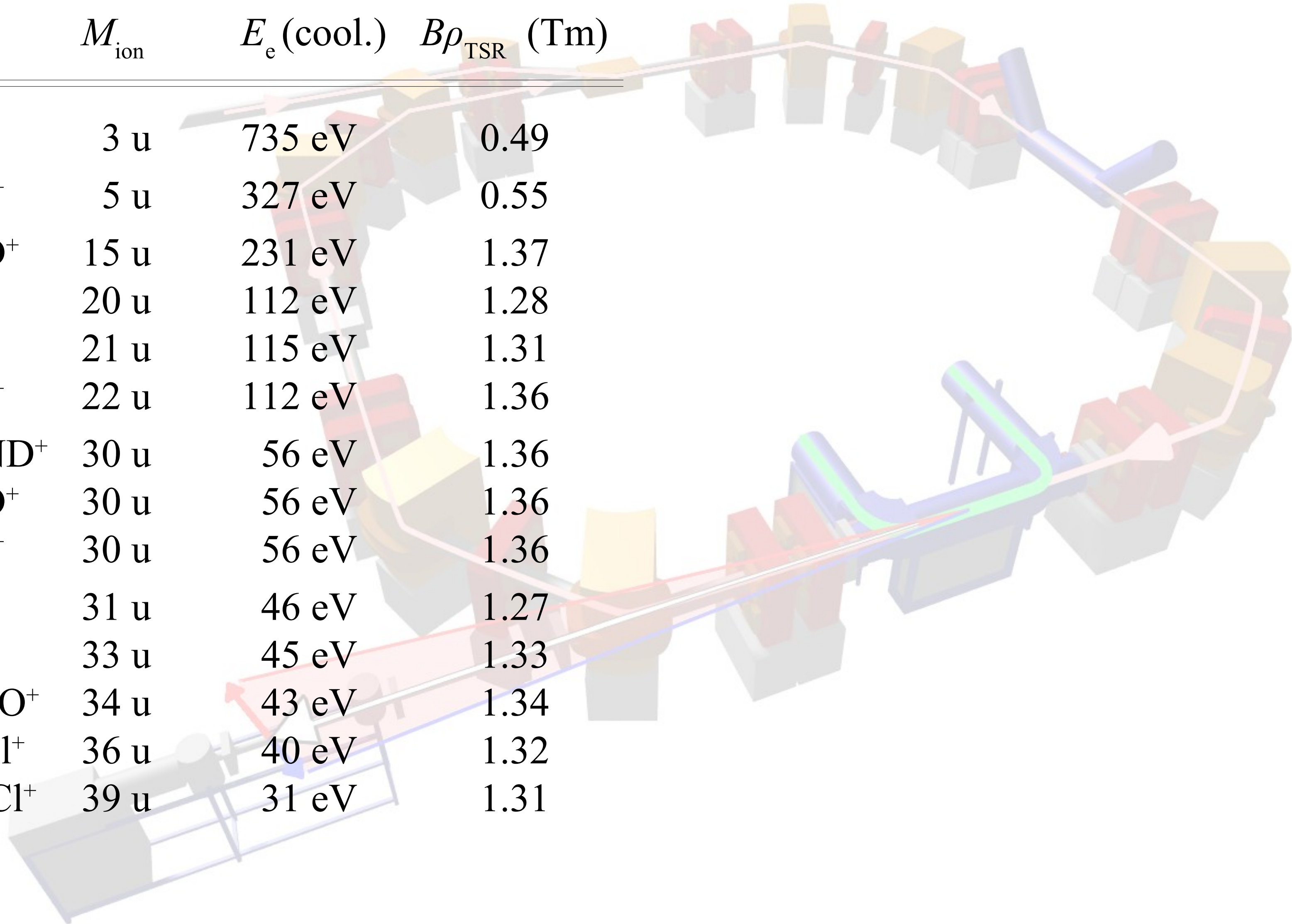


For each 2-particle-event:
→ reconstruct **centre-of-mass (x,y)**
→ get **emittance (x,y)** vs. storage time





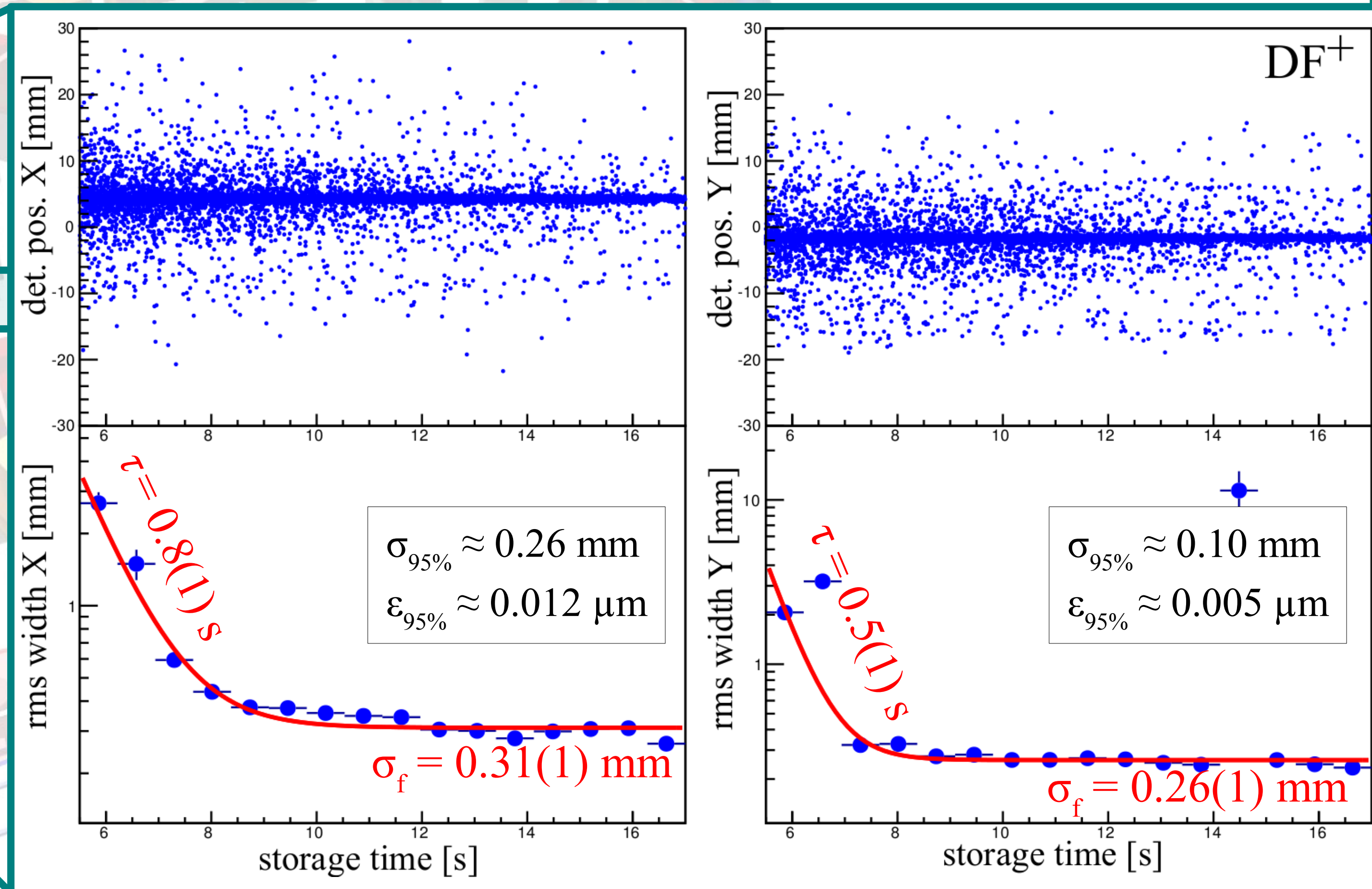
Electron cooling at low velocity



Ions	M_{ion}	E_e (cool.)	$B\rho_{TSR}$ (Tm)
...			
H_3^+	3 u	735 eV	0.49
HD_2^+	5 u	327 eV	0.55
CHD^+	15 u	231 eV	1.37
HF^+	20 u	112 eV	1.28
DF^+	21 u	115 eV	1.31
D_3O^+	22 u	112 eV	1.36
$DCND^+$	30 u	56 eV	1.36
DCO^+	30 u	56 eV	1.36
N_2D^+	30 u	56 eV	1.36
CF^+	31 u	46 eV	1.27
HS^+	33 u	45 eV	1.33
$^{18}O^{16}O^+$	34 u	43 eV	1.34
$H^{35}Cl^+$	36 u	40 eV	1.32
$D_2{}^{35}Cl^+$	39 u	31 eV	1.31

Electron cooling at low velocity

Ions	M_{ion}	E_e (cool.)	$B\rho_{TSR}$ (Tm)
…			
H_3^+	3 u	735 eV	
HD_2^+	5 u	327 eV	
CHD^+	15 u	231 eV	
HF^+	20 u	112 eV	
DF^+	21 u	115 eV	
D_3O^+	22 u	112 eV	
$DCND^+$	30 u	56 eV	
DCO^+	30 u	56 eV	
N_2D^+	30 u	56 eV	
CF^+	31 u	46 eV	
HS^+	33 u	45 eV	
$^{18}O^{16}O^+$	34 u	43 eV	
$H^{35}Cl^+$	36 u	40 eV	
$D_2^{35}Cl^+$	39 u	31 eV	



Preliminary!

Max-Planck-Institut für Kernphysik

Electron cooling at low velocity

Ions	M_{ion}	E_e (cool.)	$B\rho_{TSR}$ (Tm)
…			
H_3^+	3 u	735 eV	
HD_2^+	5 u	327 eV	
CHD^+	15 u	231 eV	
HF^+	20 u	112 eV	
DF^+	21 u	115 eV	
D_3O^+	22 u	112 eV	
$DCND^+$	30 u	56 eV	
DCO^+	30 u	56 eV	
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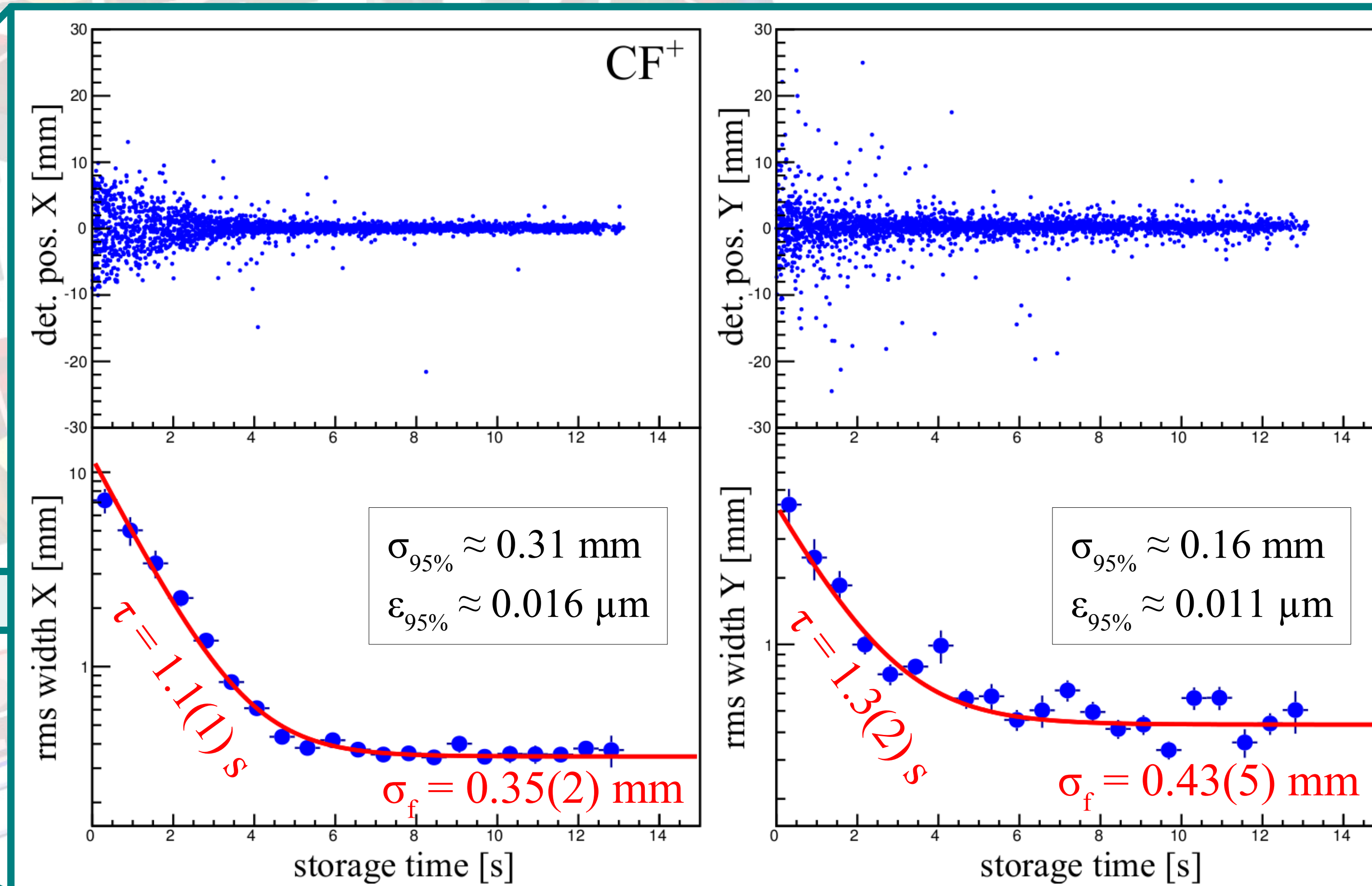

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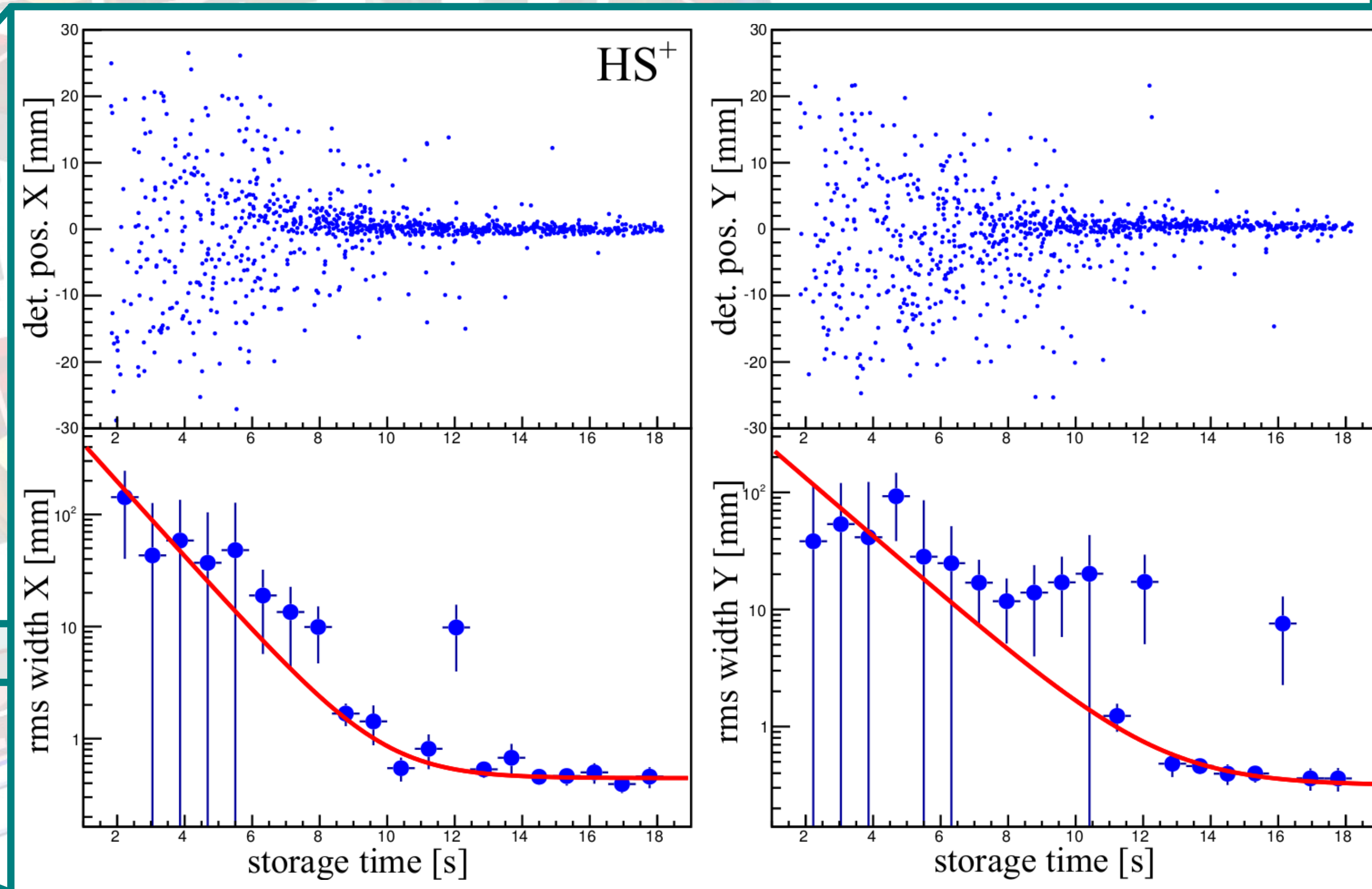

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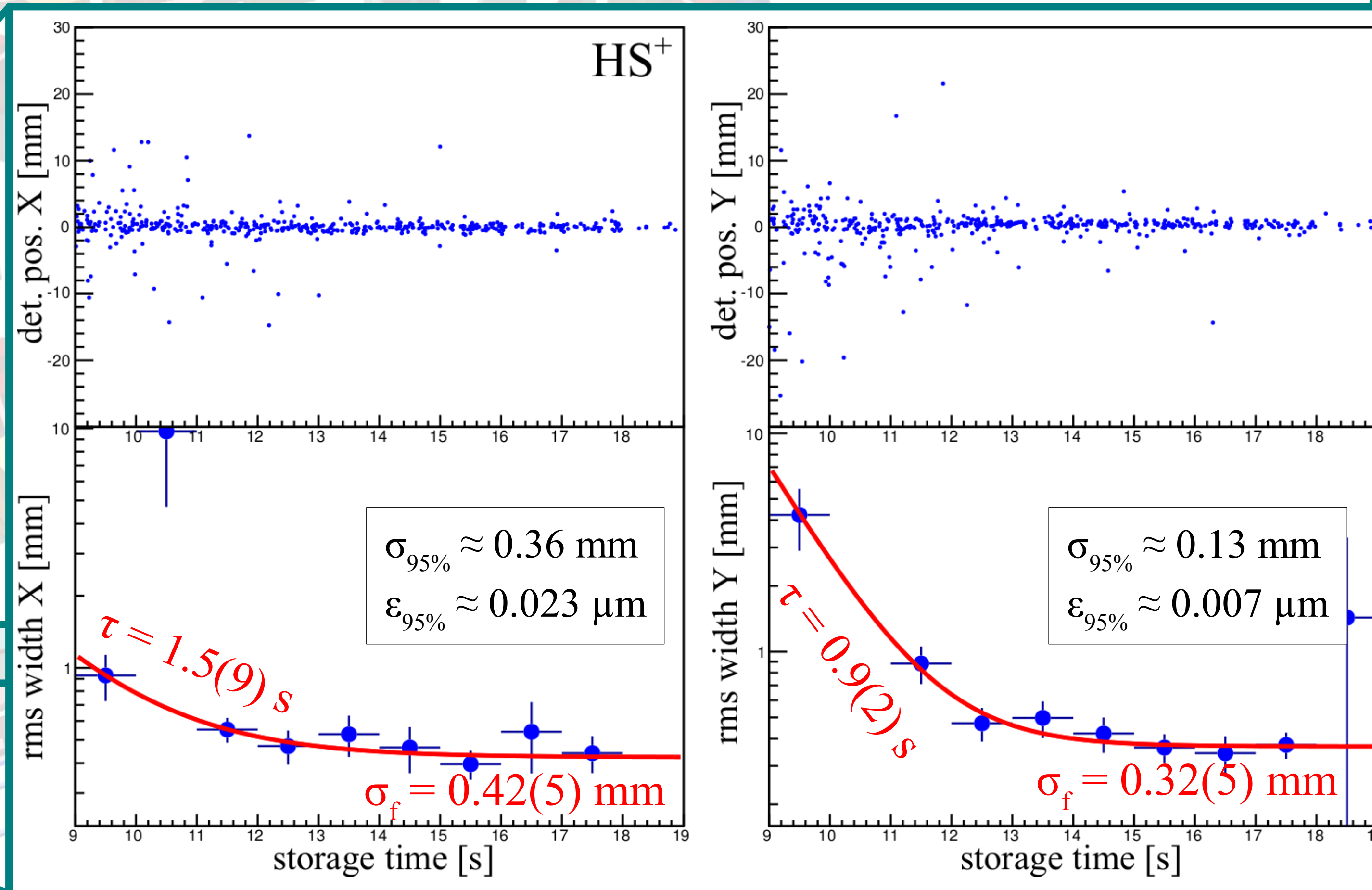

Preliminary!

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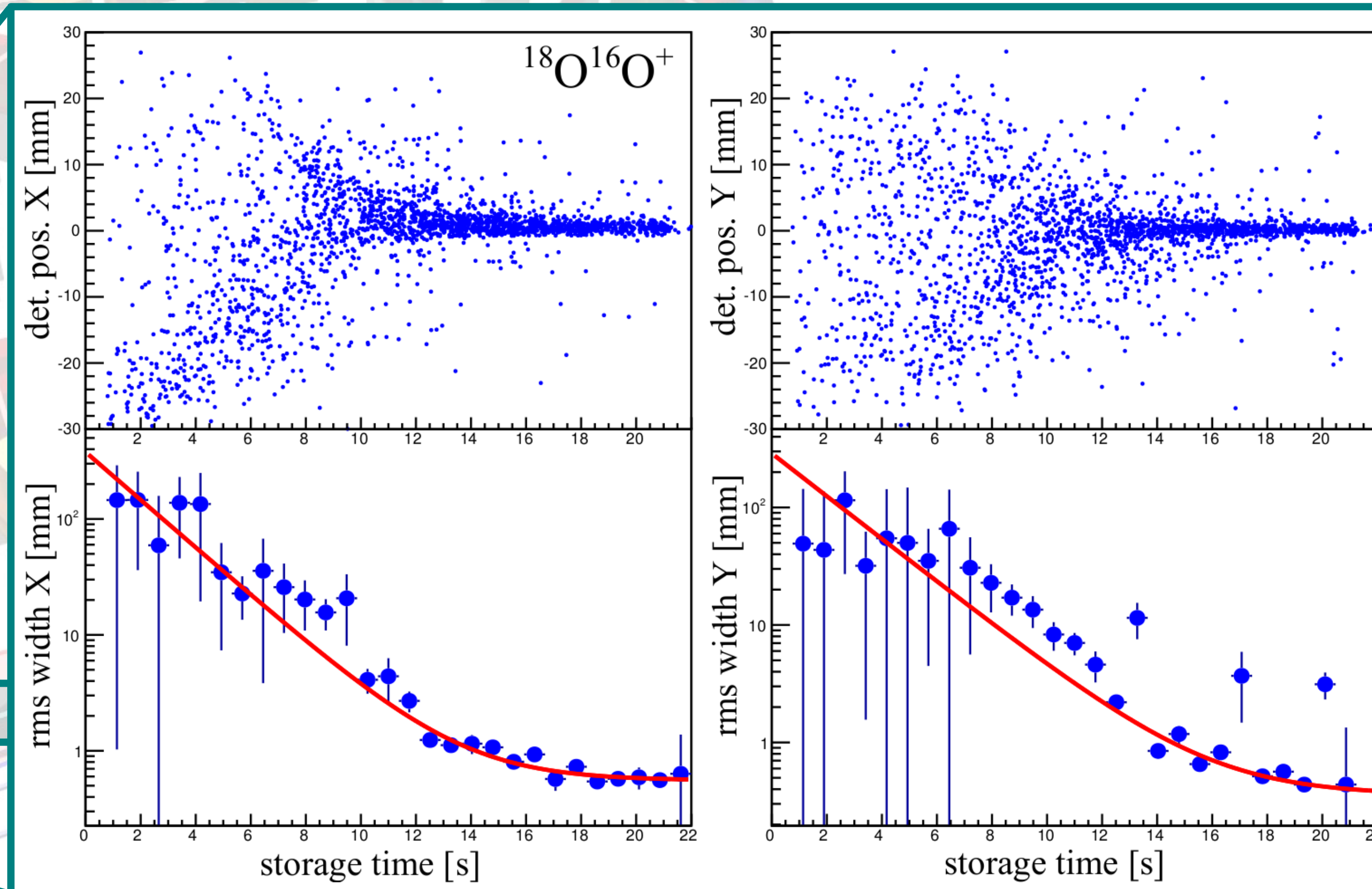

Preliminary!

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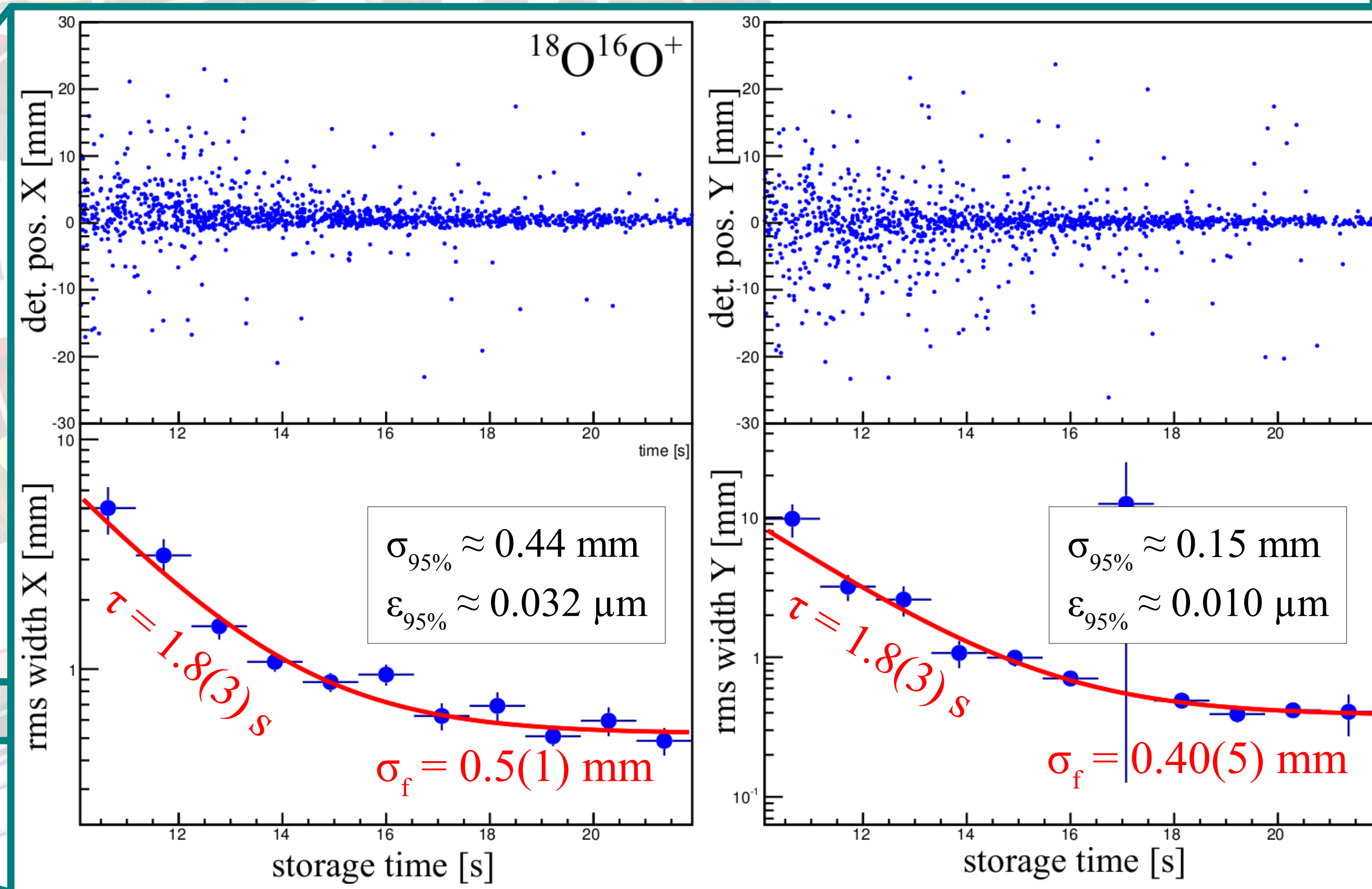

Preliminary!

Electron cooling at low velocity

Ions	M_{ion}	E_e (cool.)	$B\rho_{TSR}$ (Tm)	I_e (mA)	n_e (cm^{-3})	τ_{cool} (s)	"t_{cold}" (s)	ε_{fi} (μm)
…								
H_3^+	3 u	735 eV	0.49					
HD_2^+	5 u	327 eV	0.55					
CHD^+	15 u	231 eV	1.37					
HF^+	20 u	112 eV	1.28	0.3	$2.1\cdot10^6$	1.4(1)	3	≤ 0.008
DF^+	21 u	115 eV	1.31	0.3	$2.1\cdot10^6$	0.7(2)	3	≤ 0.012
D_3O^+	22 u	112 eV	1.36					
$DCND^+$	30 u	56 eV	1.36					
DCO^+	30 u	56 eV	1.36	0.3	$3.0\cdot10^6$		4	
N_2D^+	30 u	56 eV	1.36	0.2	$2.0\cdot10^6$		8	
CF^+	31 u	46 eV	1.27	0.27	$3.0\cdot10^6$	1.2(2)	4	≤ 0.016
HS^+	33 u	45 eV	1.33	0.24	$2.7\cdot10^6$	1.4(3)	10	≤ 0.023
$^{18}O^{16}O^+$	34 u	43 eV	1.34	0.22	$2.5\cdot10^6$	1.8(3)	8	≤ 0.032
$H^{35}Cl^+$	36 u	40 eV	1.32	0.22	$2.6\cdot10^6$		12	
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Preliminary!

Electron cooling at low velocity

Ions	M_{ion}	E_e			… (cm^{-3})	τ_{cool} (s)	"t_{cold}" (s)	ε_{fi} (µm)
…								
H_3^+	3 u	73[illegible]						
HD_2^+	5 u	32[illegible] eV	[illegible]					
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We are able to **cool** even the **heaviest** (slowest) molecular ions within **~ 10 s**.

Preliminary!

Electron cooling at low velocity

Ions	M_{ion}	E_e (co…		…)	n_e (cm^{-3})	τ_{cool} (s)	"t_{cold}" (s)	ε_{fi} (μm)
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Cooling rates agree with
T_e = 10 … 20 K
(lots of uncertainties …)

Preliminary!

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Electron cooling at low velocity

Ions	M_{ion}	E_e (e		A)	n_e (cm^{-3})	τ_{cool} (s)	"t_{cold}" (s)	ε_{fi} (μm)
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Transverse momentum spread corresponds to **~ 40 … 70 K**

(roughly what one expects from IBS modeling at given τ_{cool}.)

Preliminary!

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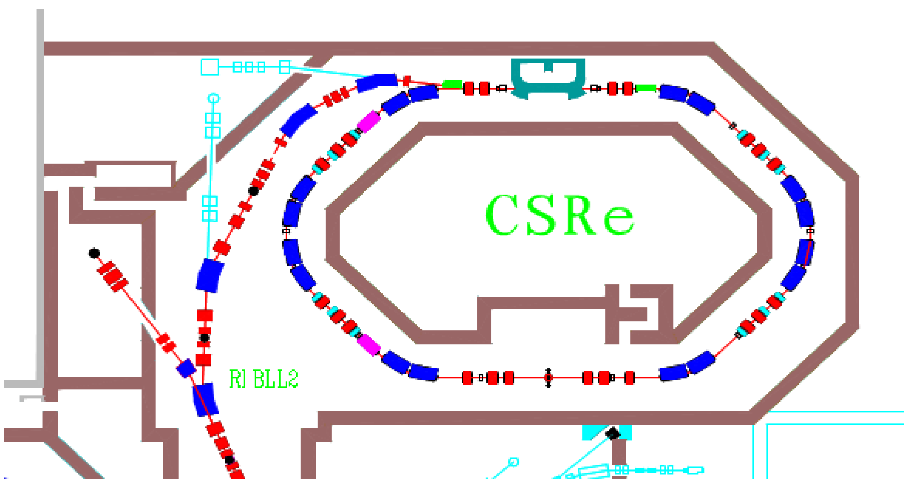
How to reach even higher mass?

Solution 1: Use a bigger storage ring

CSRe ("Cooler Storage Ring", IMP)

9.4 Tm



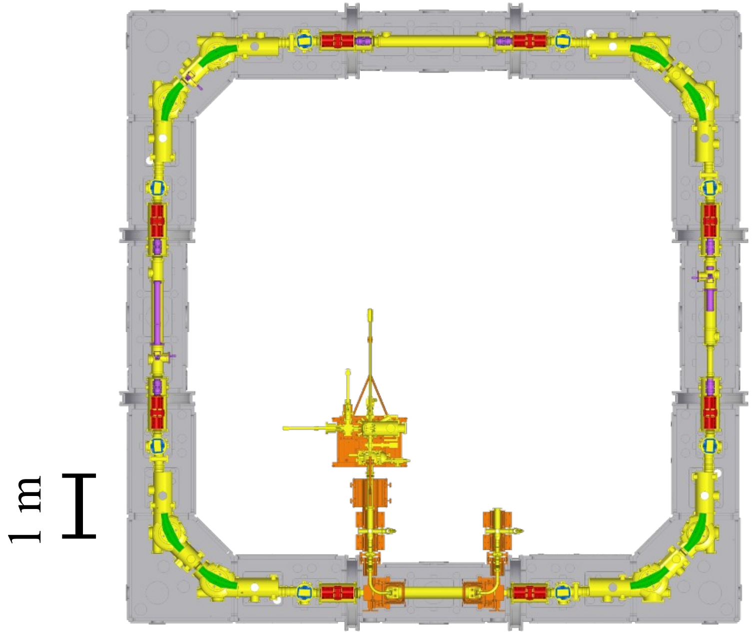
Molecular ions research facility, Lanzhou, China.

→ $M_{ion}/Z_{ion} \sim 200$

Solution 2: Store (much!) longer

CSR ("Cryogenic Storage Ring", MPIK)

beam line at ~ 10 K
→ 10^{-13} mbar
→ 100 × longer ion lifetimes



$M_{ion}/Z_{ion} \geq 160$ (with e-cooling!)

Added value: IR-radiation-free!

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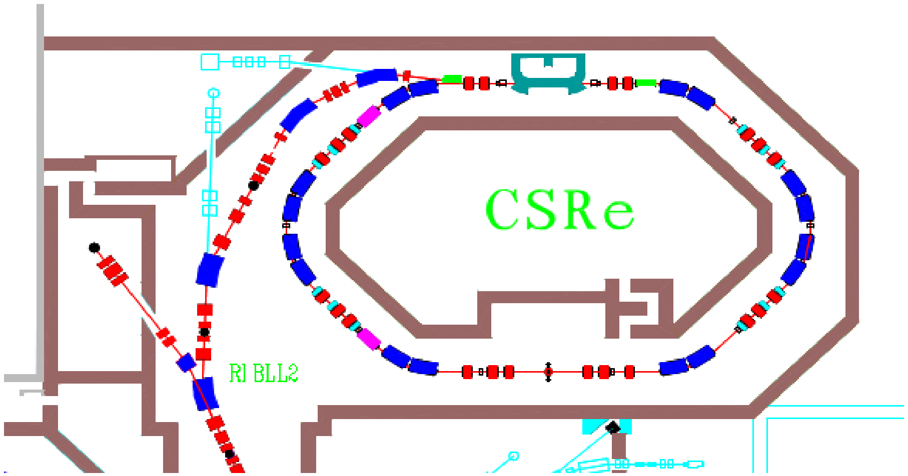

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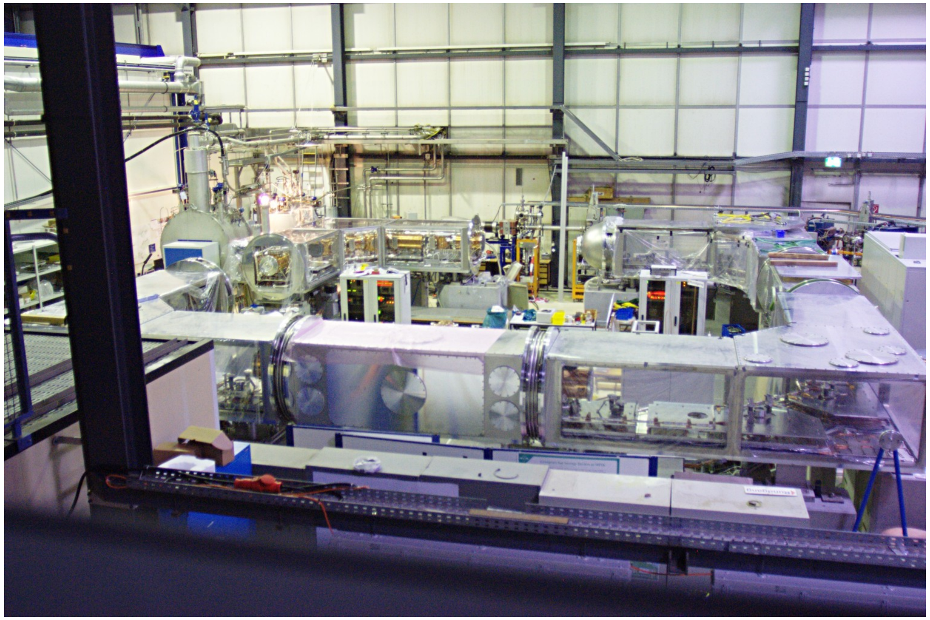

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Added value: IR-radiation-free!

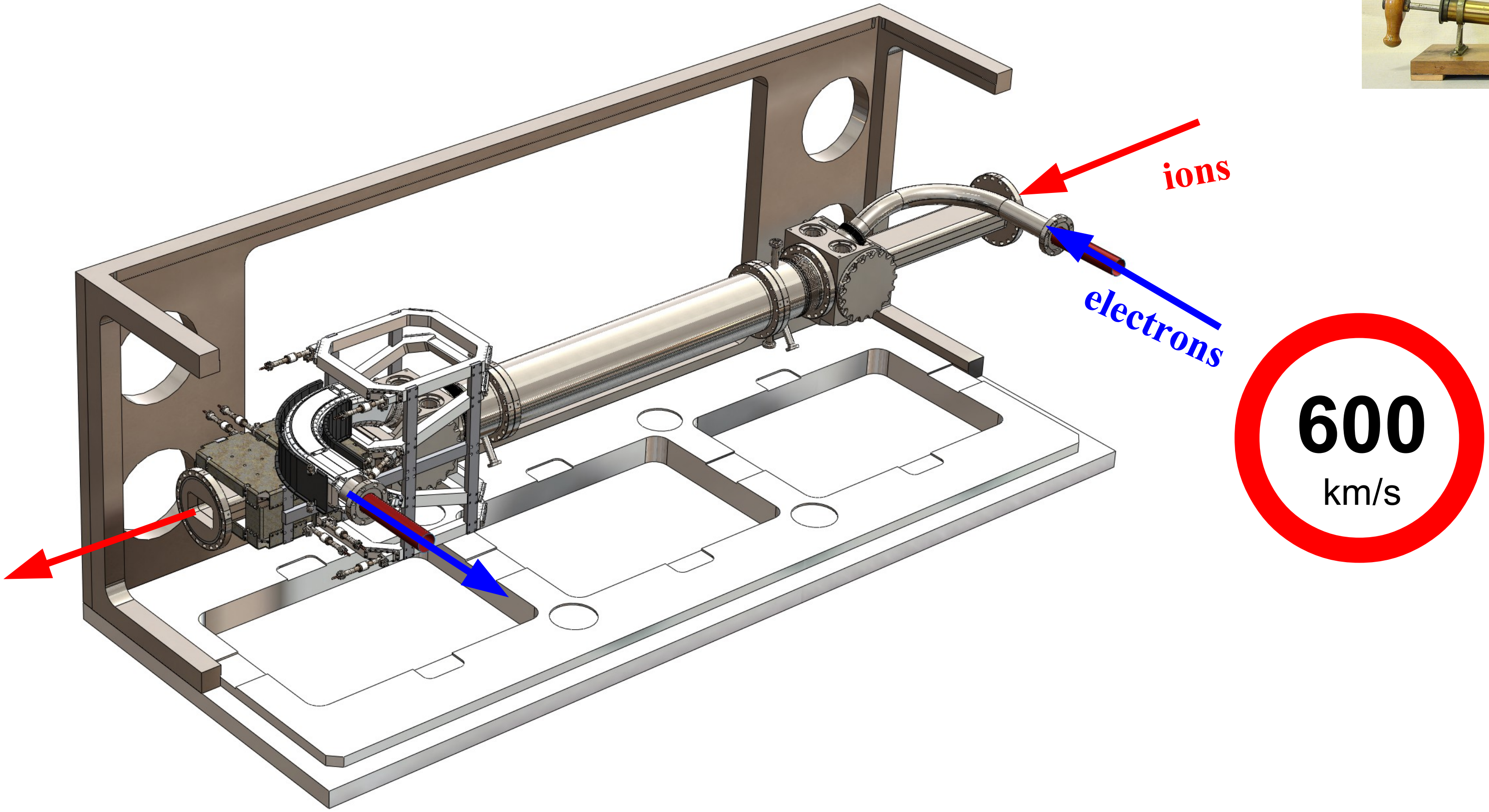
CSR Electron Cooler

Technically challenging: Cooler must be contained in the **CSR cryostat**
(bakeable, 10^{-13} mbar, 10 K)

CSR energy limit: → Need **very slow** electrons

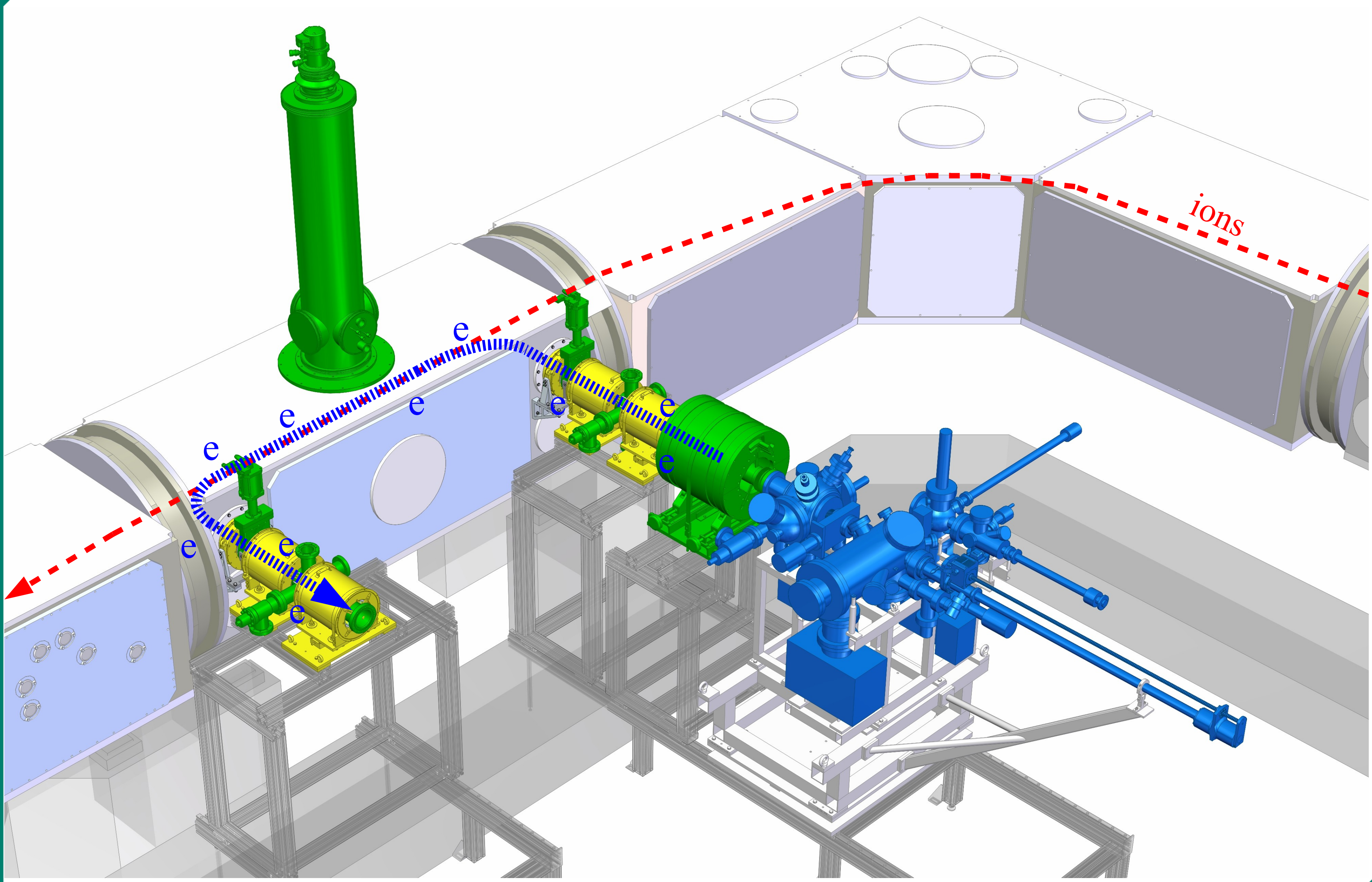
E_{ion}/Z_{ion} **= 300 keV**

160 eV	for p^+
< 20 eV	for most mol. ions
1 eV	for M_{ion} = 160 u



Max-Planck-Institut für Kernphysik

CSR Electron Cooler



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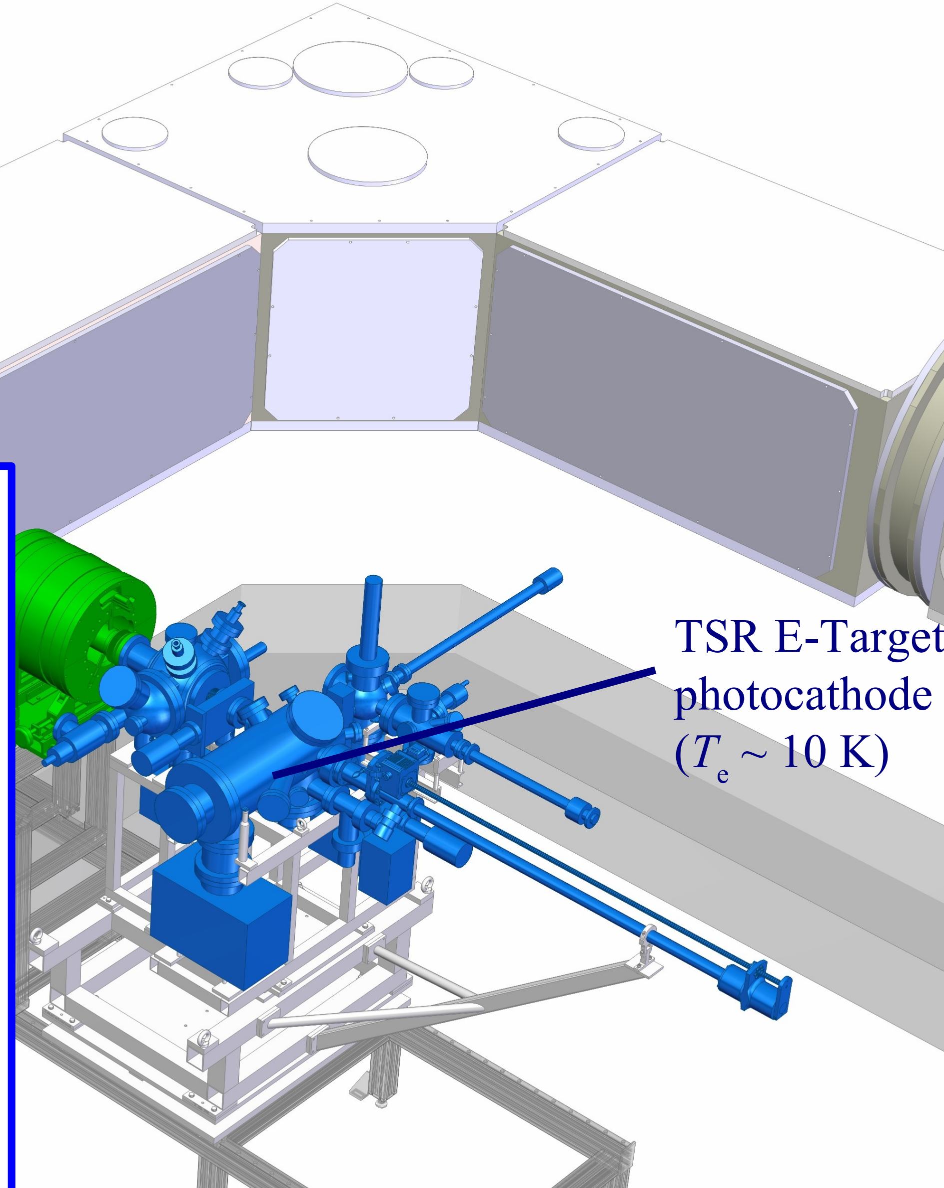
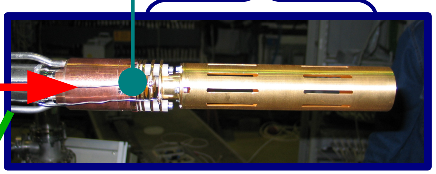
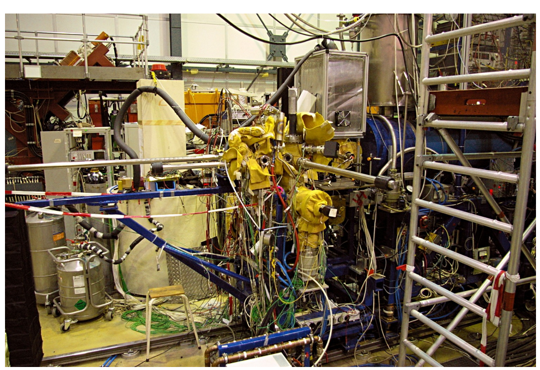


Photocathode electron source (TSR) :

~ 10 x lower T_e compared to thermionic emission





$k_B T_e$ ~ 1 meV

n_e ~ 10^5 cm^{-3} @ 1 eV

Summary

Slow molecular ion beams are fun but challenging.

---

e-cooling of them requires cold, slow electron beams.
GaAs photo-cathodes are ideal sources.

The photocathode e-cooler at TSR has cooled molecular ions up to mass 39 to emittances of ~0.01 μm in a few seconds.

A low energy (1 eV) e-cooler based on the same emitter is being build for the electrostatic Cryogenic Storage Ring.

Thank you!

Max-Planck-Institut für Kernphysik, Heidelberg

Andrey Shornikov

Arno Becker

Stephen Vogel

Manfred Grieser

Andreas Wolf

C. K.

Institute of Semiconductor Physics, Novosibirsk

Aleksandr Terekhov

Aleksandr Jaroshevich

Columbia Astrophysics Lab, New York

Oldřich Novotný

Daniel W. Savin

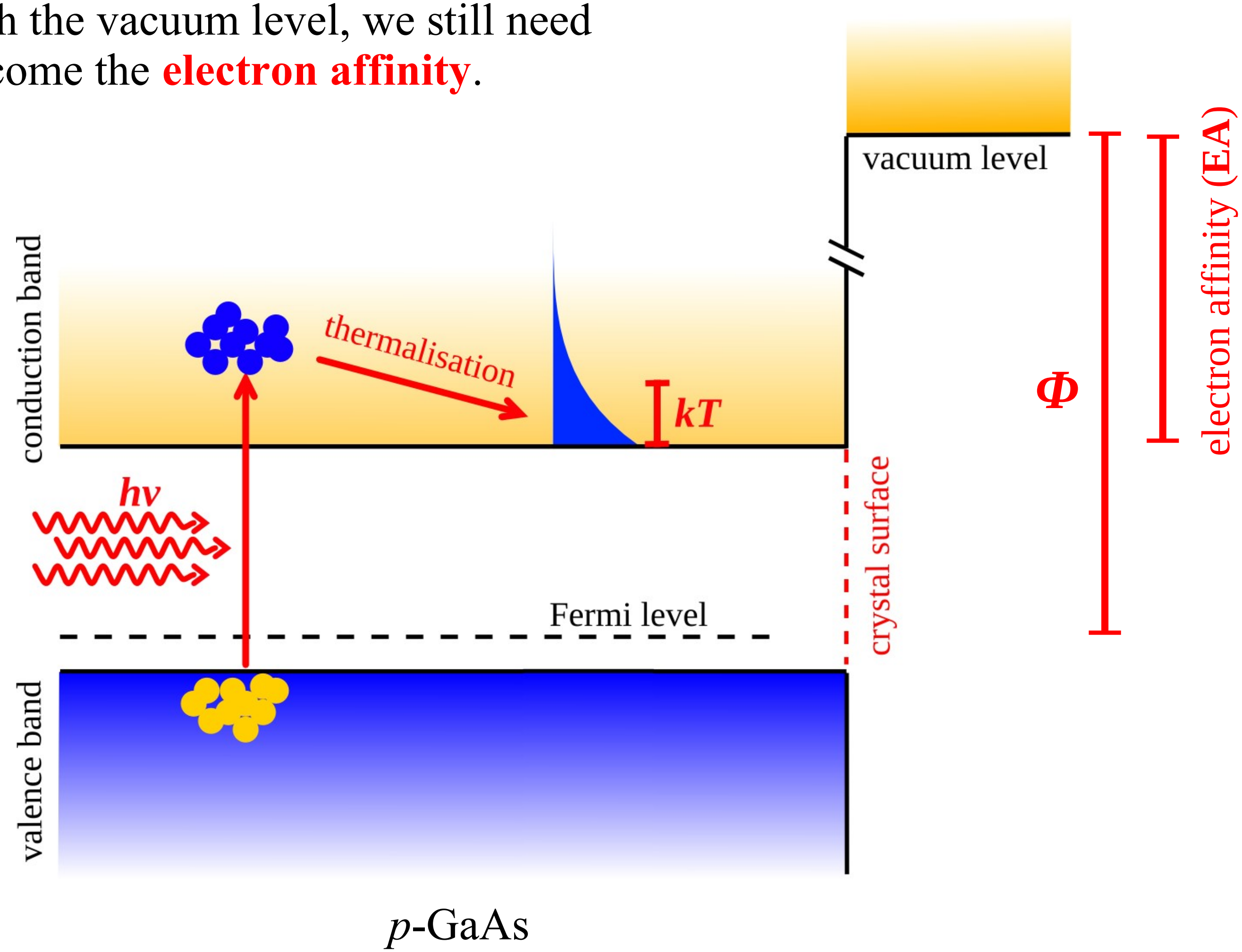
Justus-Liebig Universität, Gießen

Kaija Spruck

Stefan Schippers

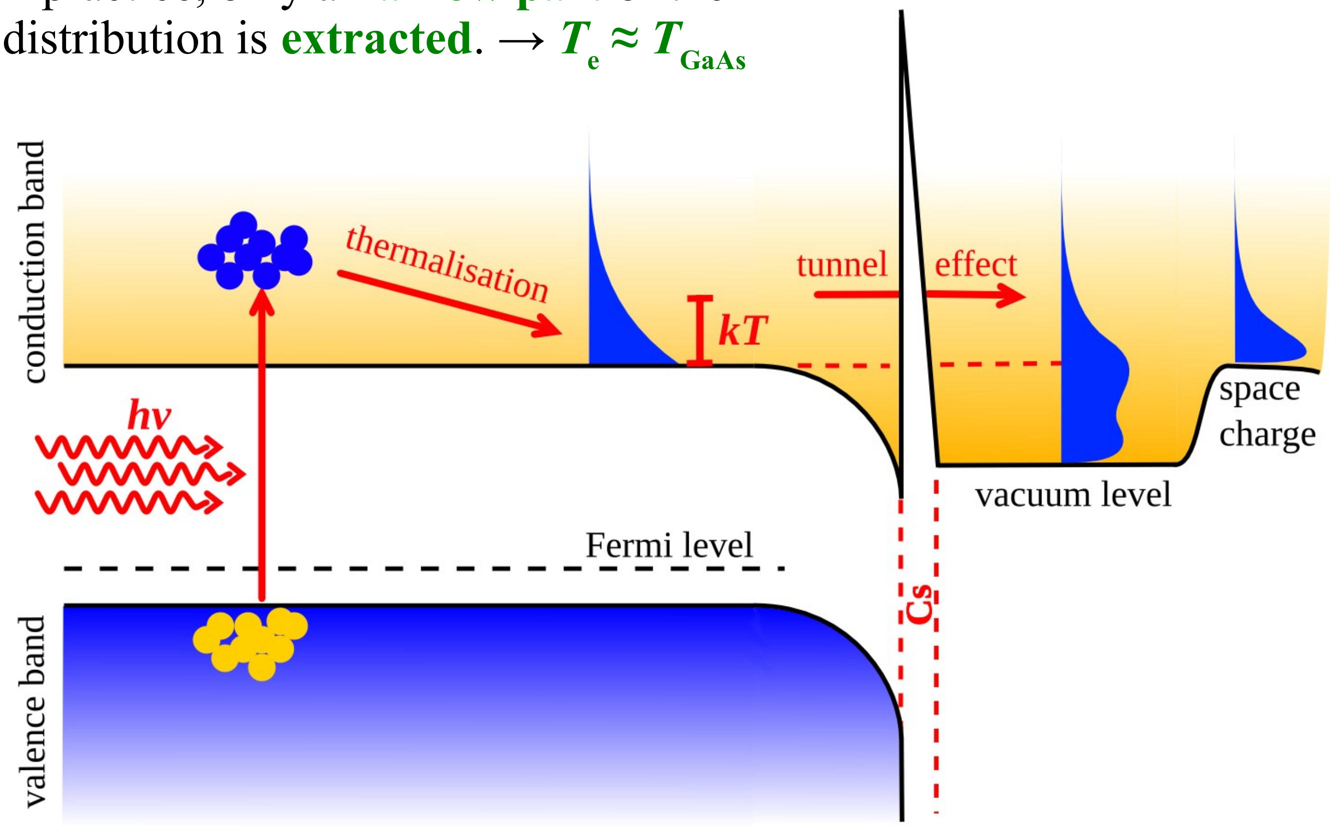
GaAs photo cathodes

- Negative Electron Affinity:
  - To reach the vacuum level, we still need to overcome the **electron affinity**.



GaAs photo cathodes

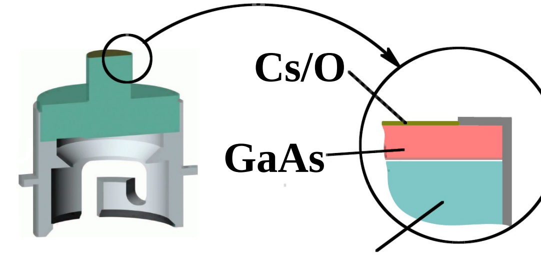
- Negative Electron Affinity:
  - electron-phonon **scattering broadens** the electron energy distribution ...
- … but in practice, only a **narrow part** of the energy distribution is **extracted**. → $T_e \approx T_{GaAs}$



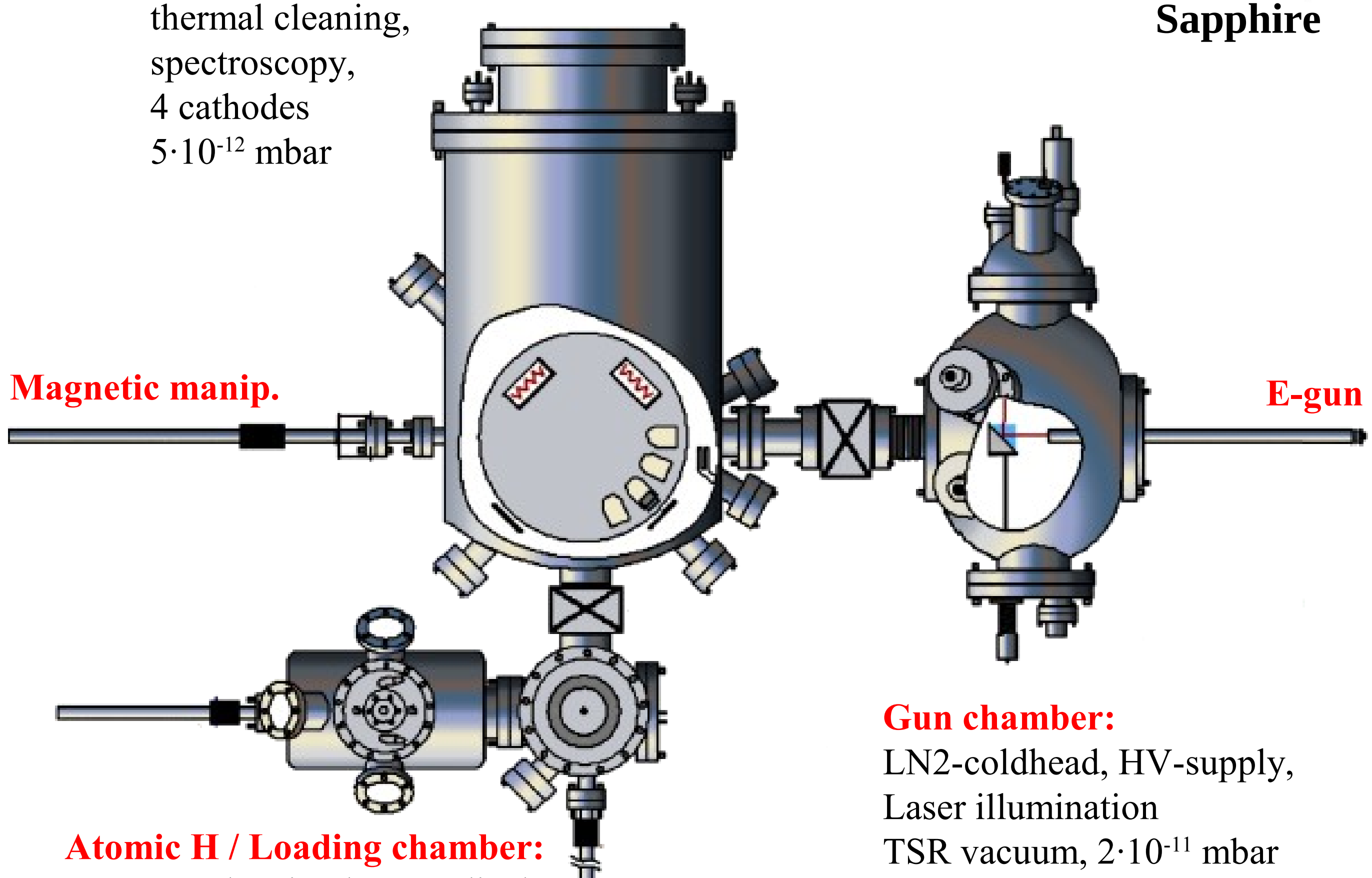
p-GaAs

Photo-cathode electron cooler

Photocathode setup



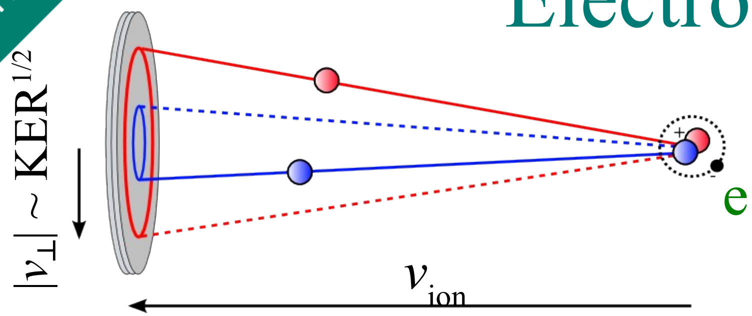
Preparation chamber:
Cs/O activation,
thermal cleaning,
spectroscopy,
4 cathodes
$5 \cdot 10^{-12}$ mbar



Gun chamber:
LN2-coldhead, HV-supply,
Laser illumination
TSR vacuum, $2 \cdot 10^{-11}$ mbar

Atomic H / Loading chamber:
In-vacuo cleaning by H radicals,
air-lock for cathode loading,
10^{-9} mbar

Electron cooling at low velocity



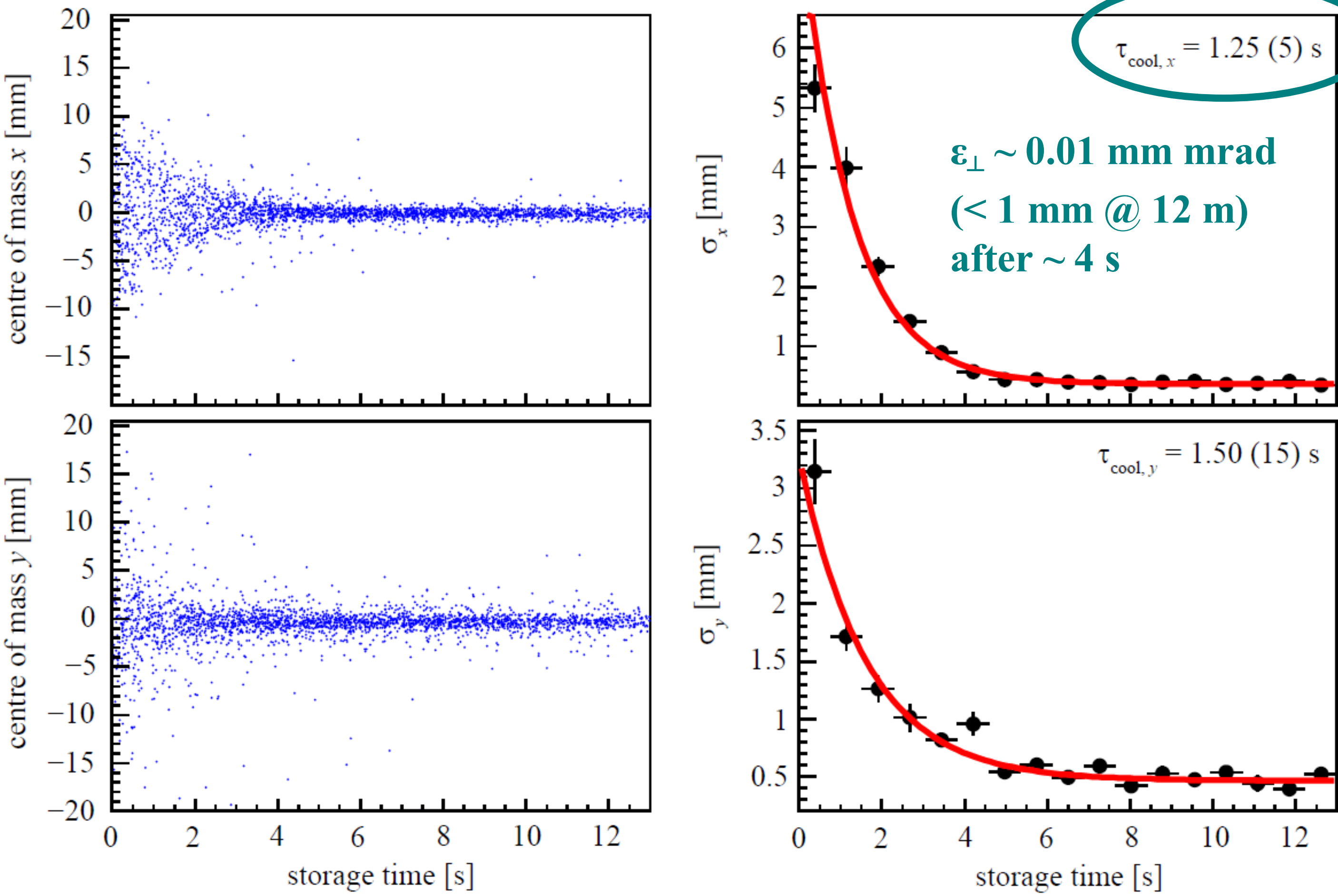
$$\tau \sim \frac{M_{ion} T_e^{3/2}}{Z_{ion}^2 n_e}$$

fits with

$T_{e,\perp}$ = 15 (3) K

We **need** a cold electron source!

Cooling CF^+ at E_e = 46 eV



~~expected for thermionic electron cooler:~~

~~($T_\perp$ ~ 100 K)~~

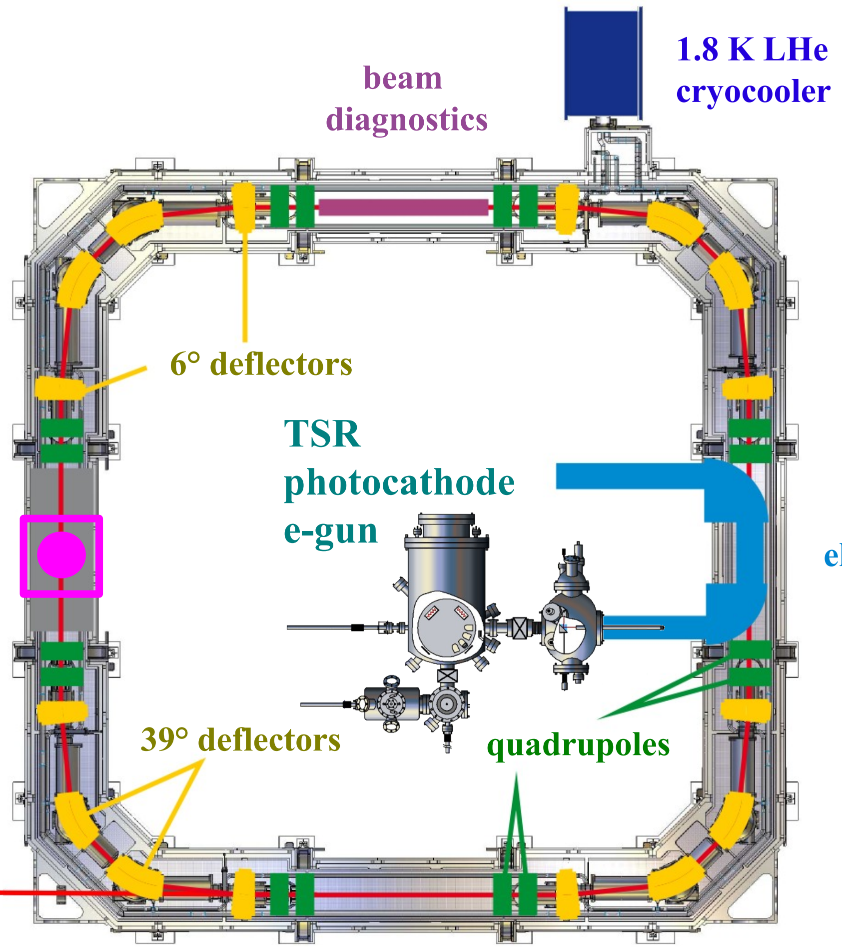
~~**τ ~ 30 s**~~

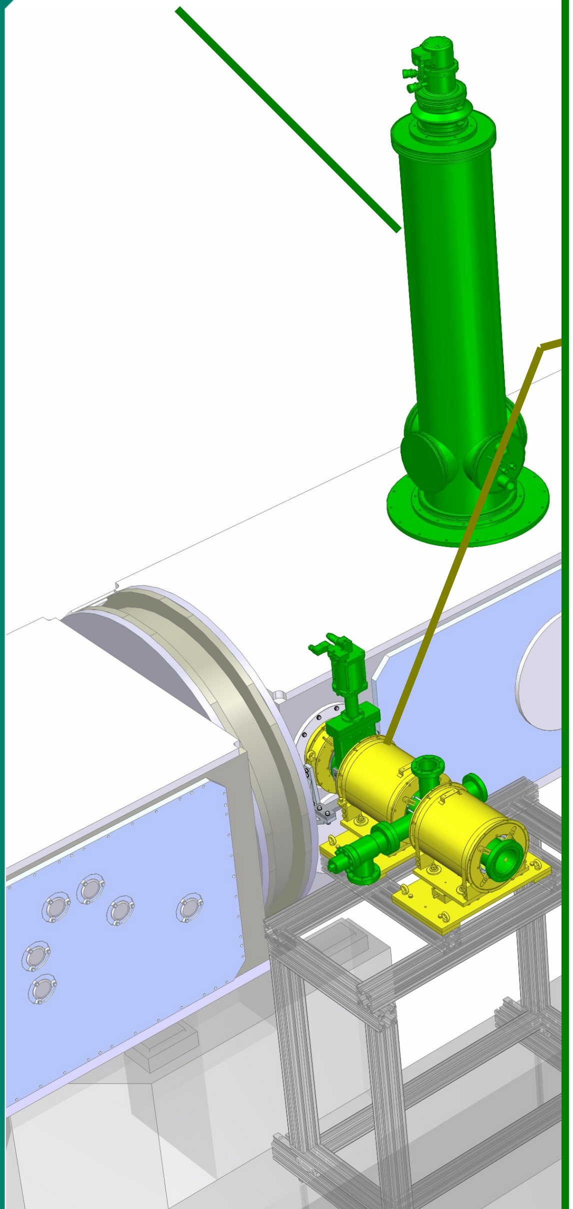
~~(longer than ion lifetime)~~

The Cryogenic Storage Ring

A fully-featured next generation storage ring

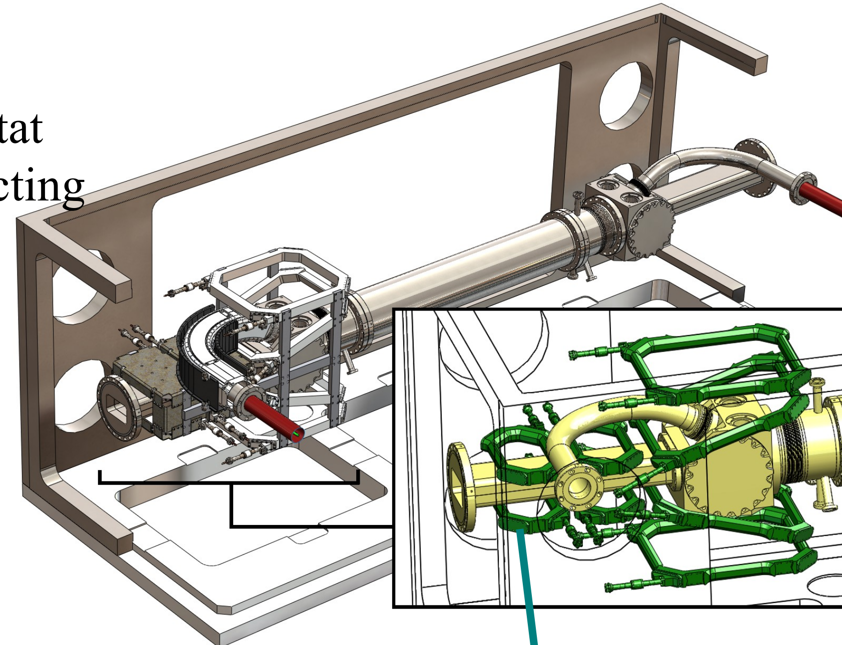
circumference:	35 m
beam energy:	300 keV/q
temperature:	10 … 300 K
res. gas press.	
(@ < 10 K):	10^{-13} mbar RTE
	(~ 1000 cm^{-3})
ion masses (for q = 1 e)	
no cooling:	1 … "∞" u
with cooling:	1 … 160 u



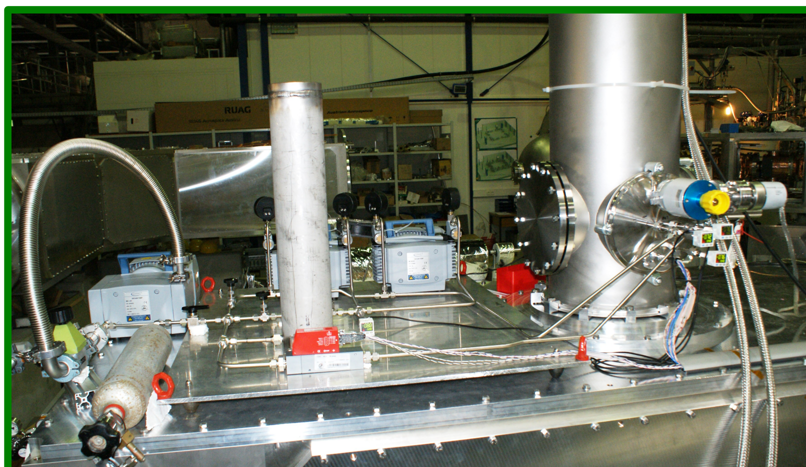


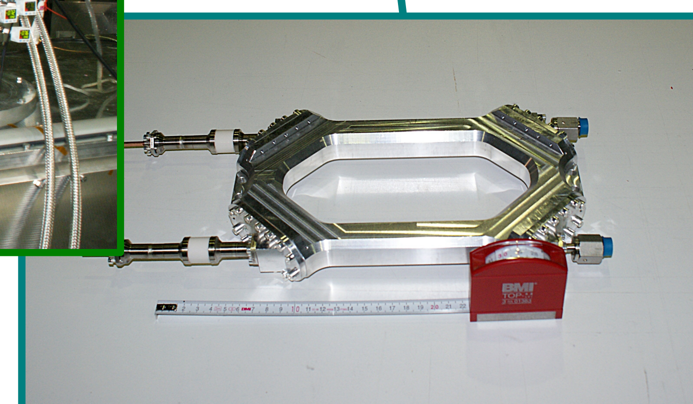
LNe Cooler:

Guiding field inside cryostat is provided by superconducting (HTS) coils.



A ~32 K LNe cooler for the HTS coils to has





The HTS coils have been suc

The CSR electron cooler

Electron energy: towards 1 eV an 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

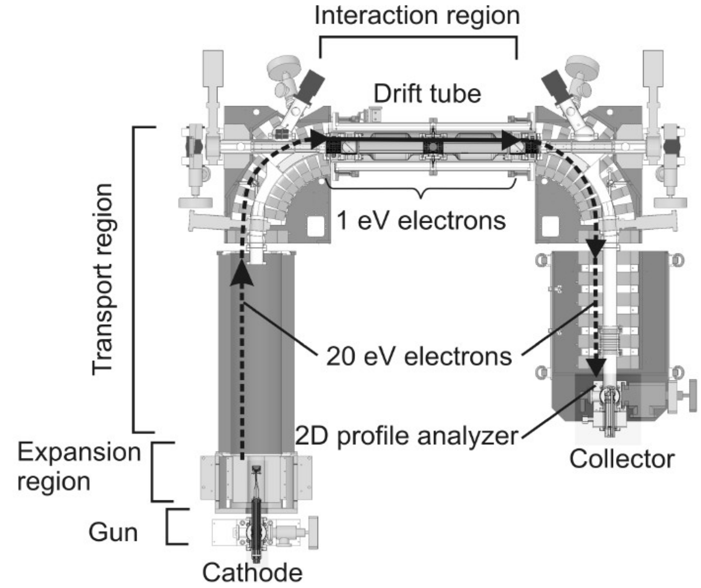
  $n_e \sim 10^5$ cm^{-3}

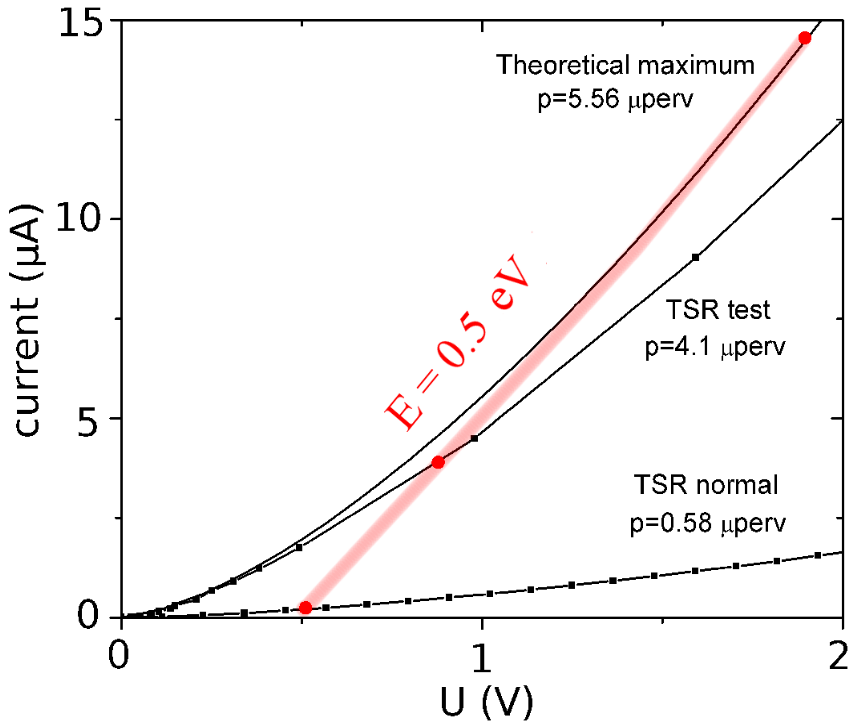
- Cooling times

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

up to ~ 100 s …

… but: ion lifetime ~ 1000 s

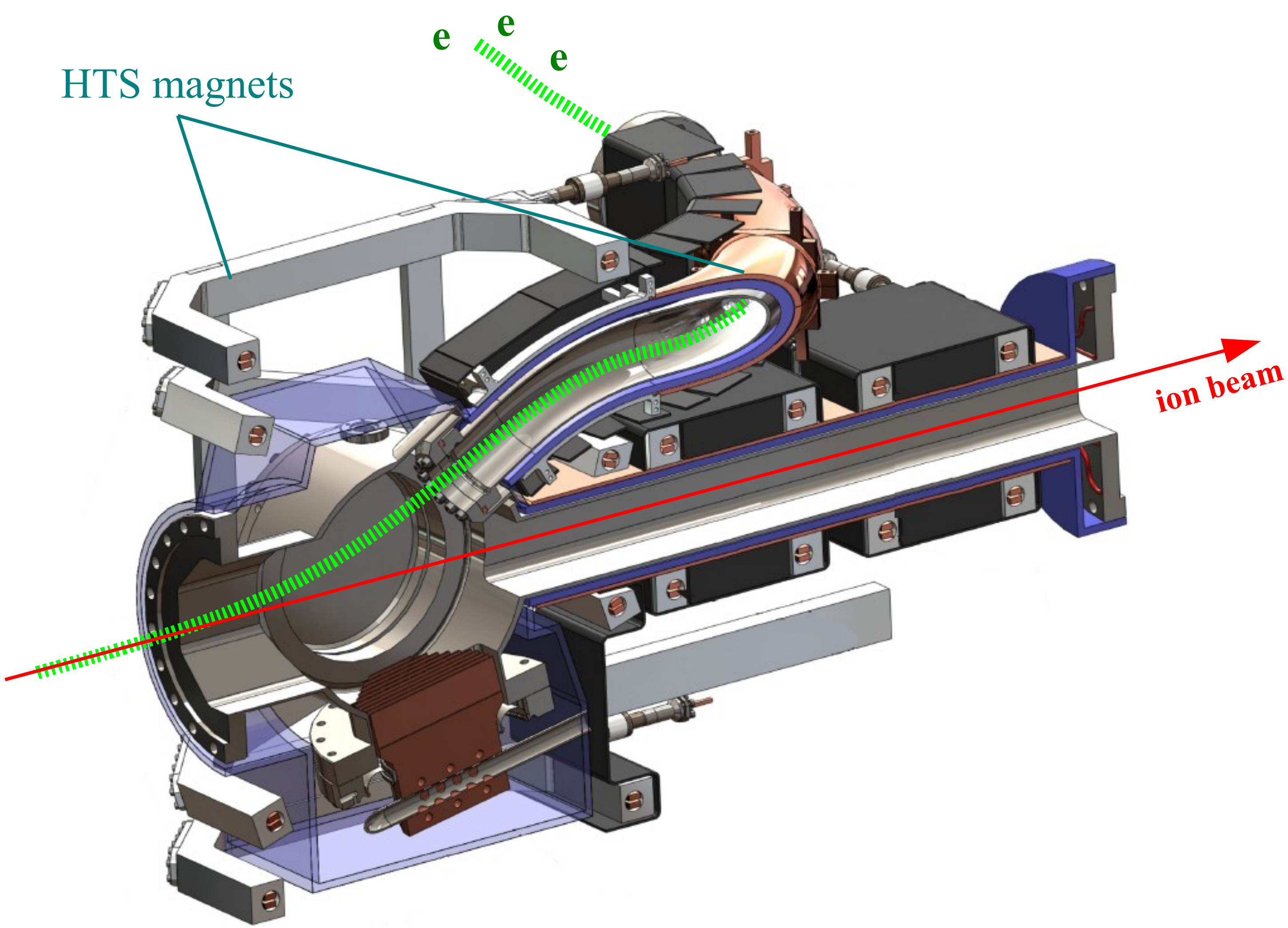




[Shornikov, t.b.p.]

The CSR electron cooler

Magnetic guiding field



Need ***B* = 250 G** for adiabatic transport

Magnets + chambers **cryogenic**

HT superconductors

(no heating of CSR)

Cryogen: **LNe**