MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

# Photo Cathodes and Electron Cooling at low Beam Velocities

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# Overview

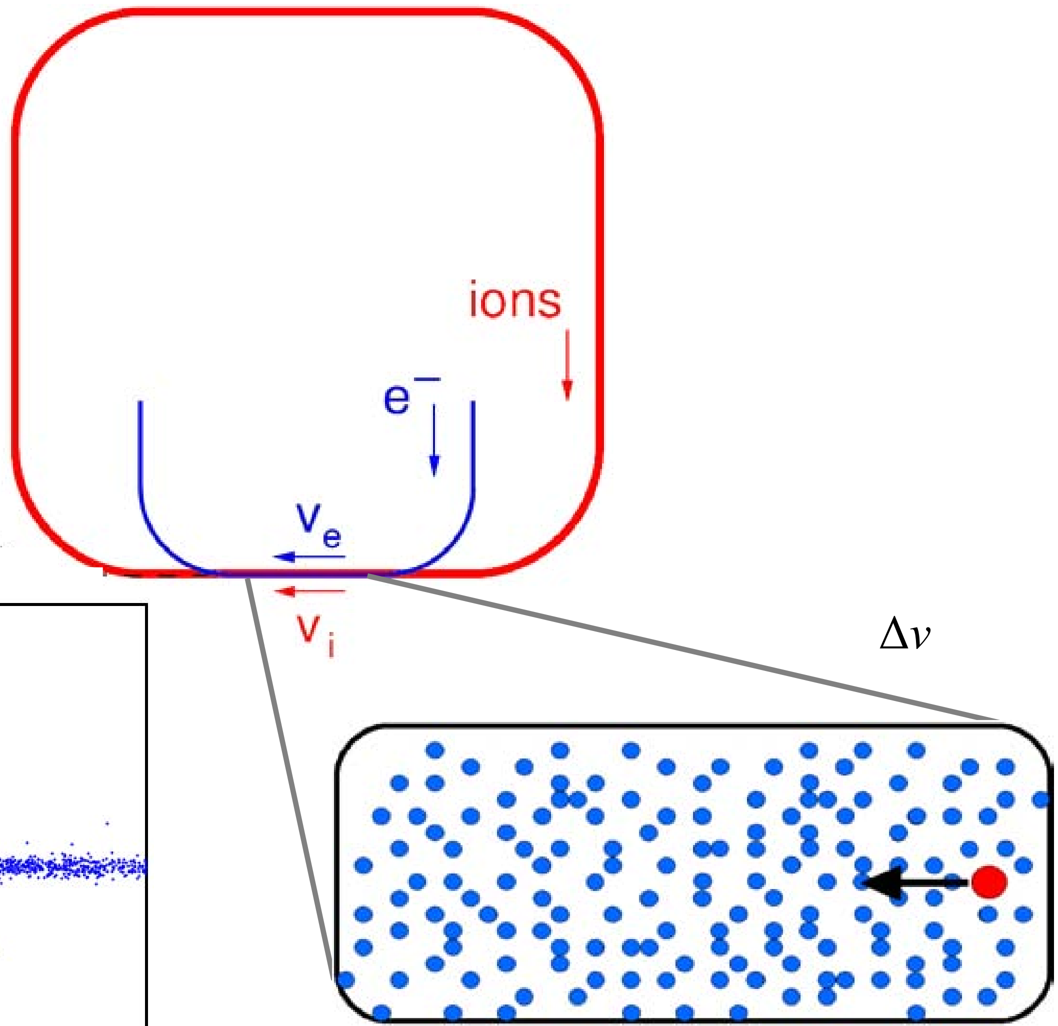
Electron cooler storage rings at low velocity

NEA photo cathodes as cooling electron sources

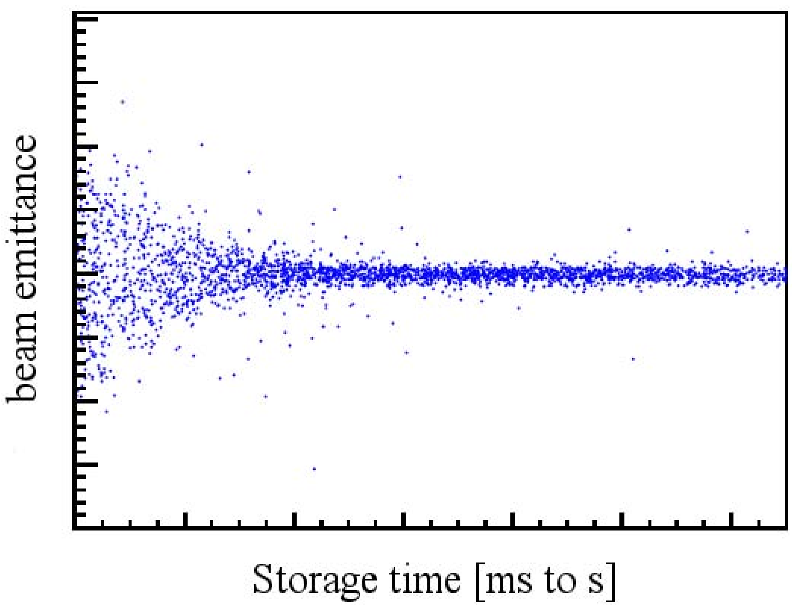
Present: Photo cathode electron cooler at TSR

Future: Photo cathode electron cooler at CSR

# Electron coolers



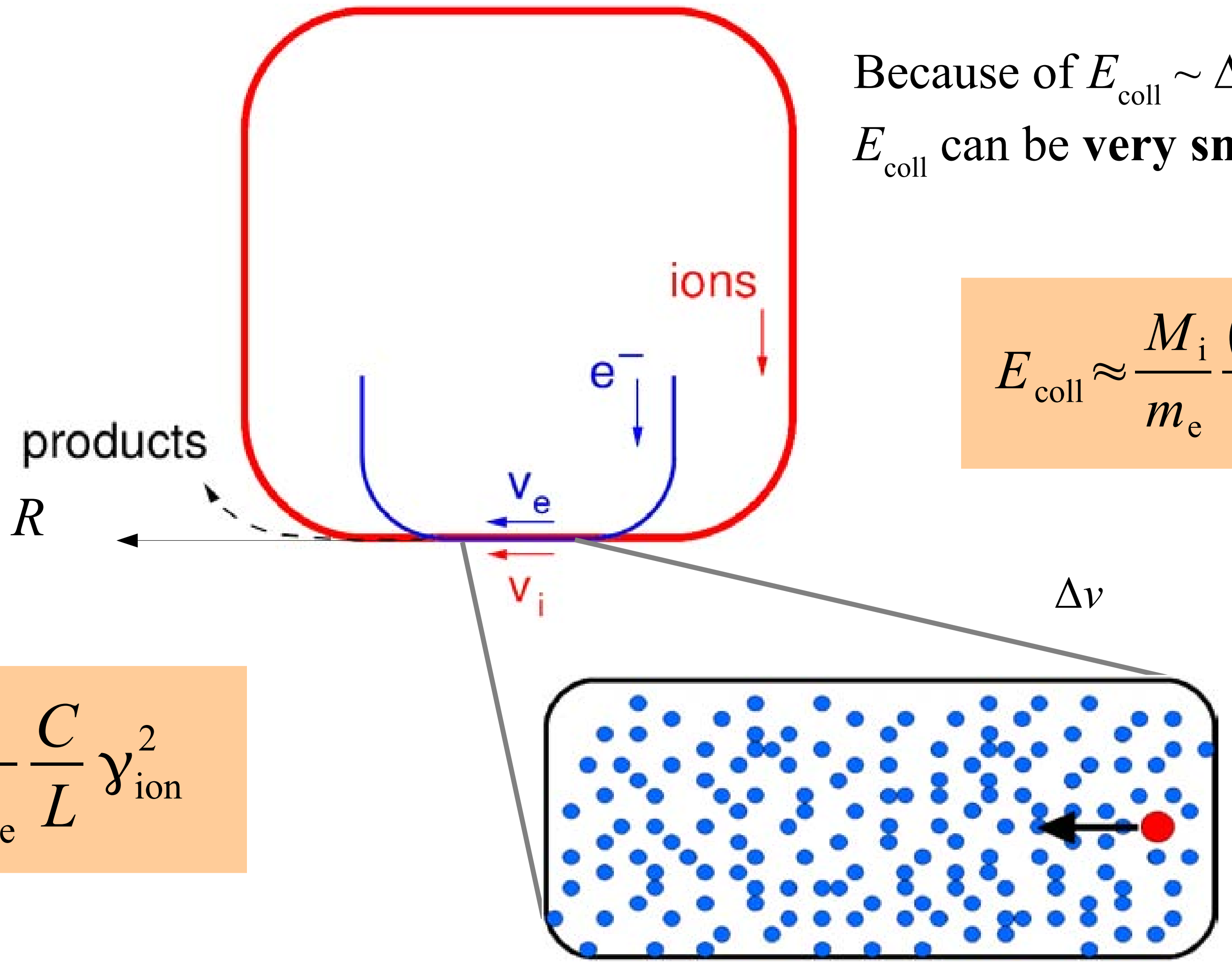

"Electron cooling"



# Recombination in electron coolers

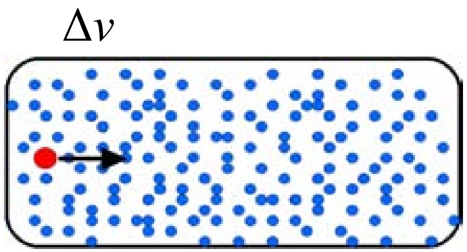
Because of $E_{coll} \sim \Delta U^2$,
$E_{coll}$ can be **very small** (meV!)

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

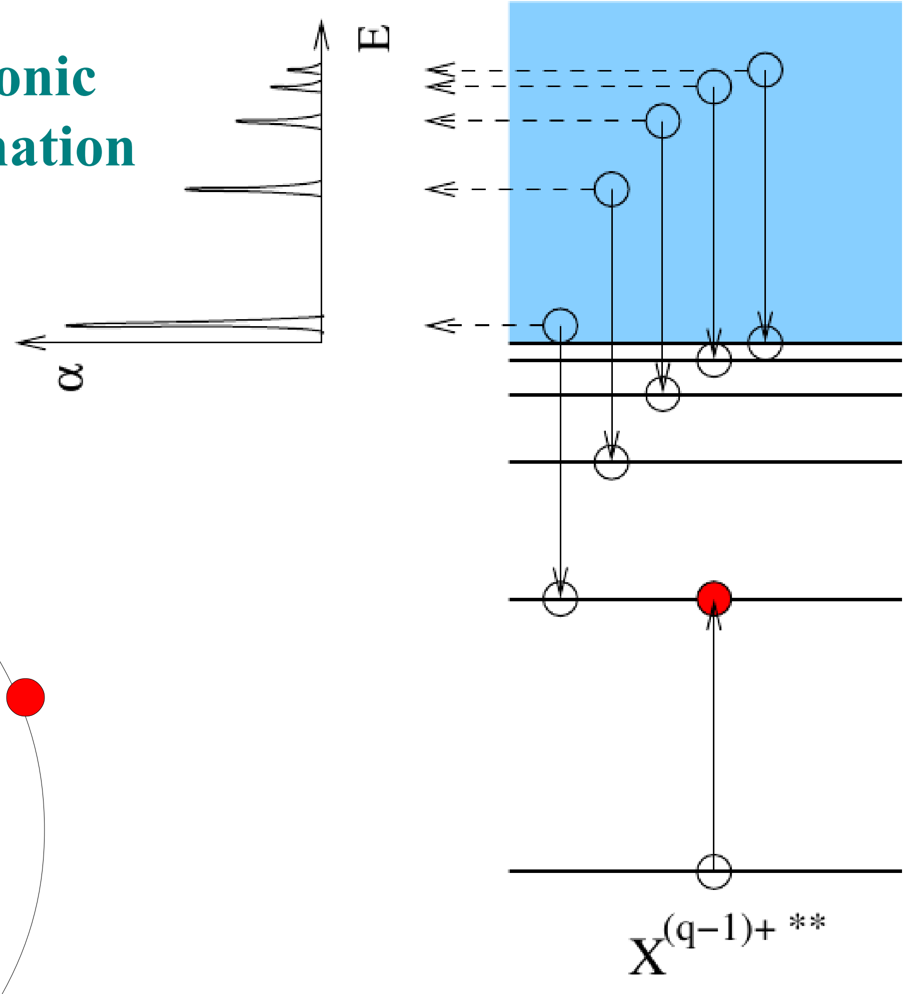


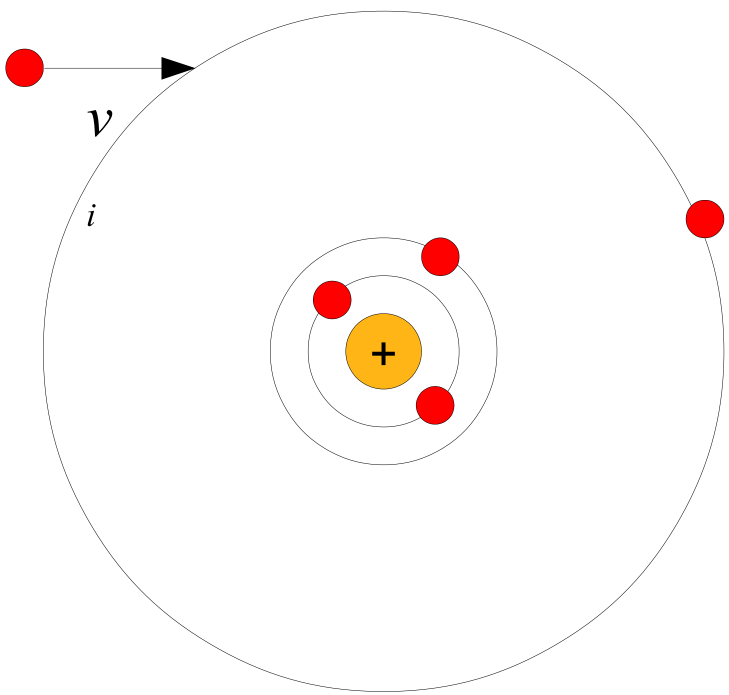

$$\alpha = \frac{R}{N_{ion} n_e} \frac{C}{L} \gamma_{ion}^2$$

# Recombination in electron coolers



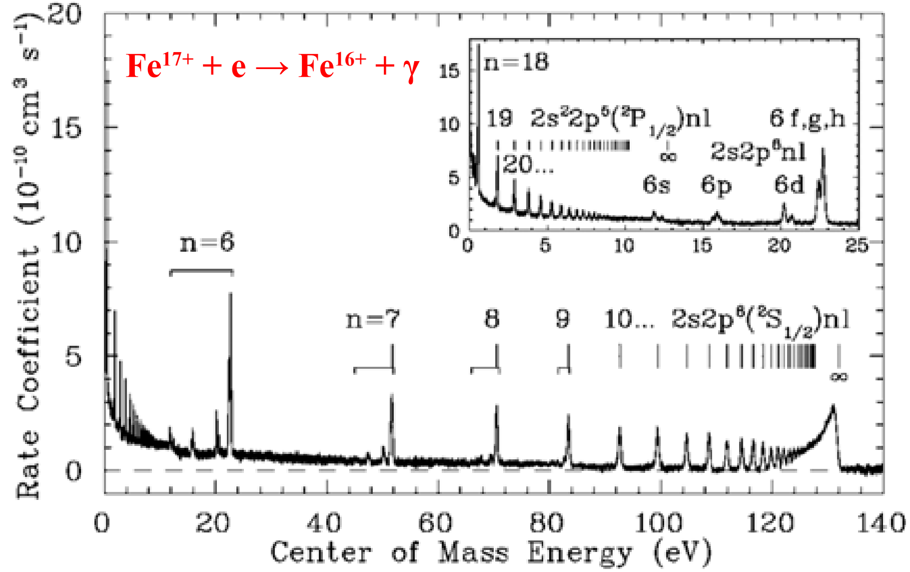

**Dielectronic Recombination**



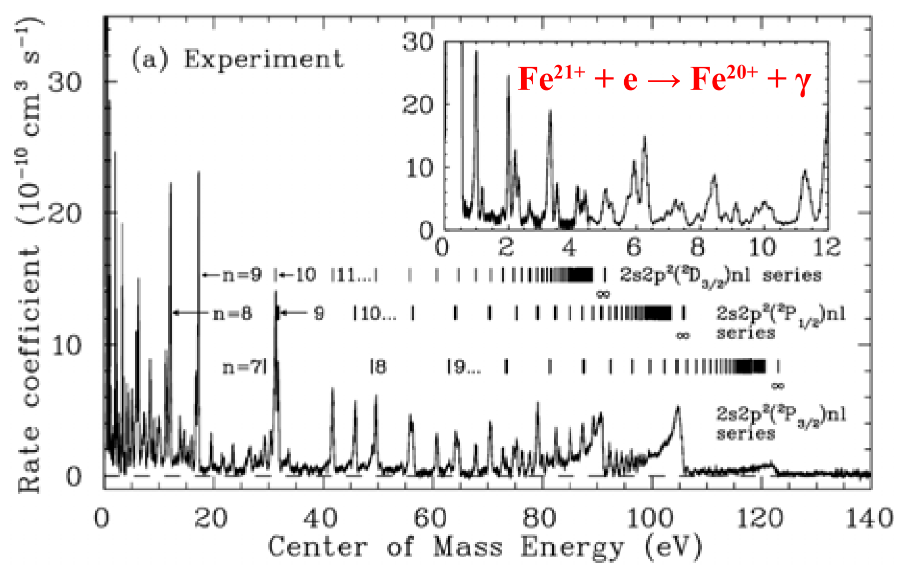



# Recombination in electron coolers

Recombination rates of
HCI in astrophysical plasma




[Savin, ApJ 489 (1997)]

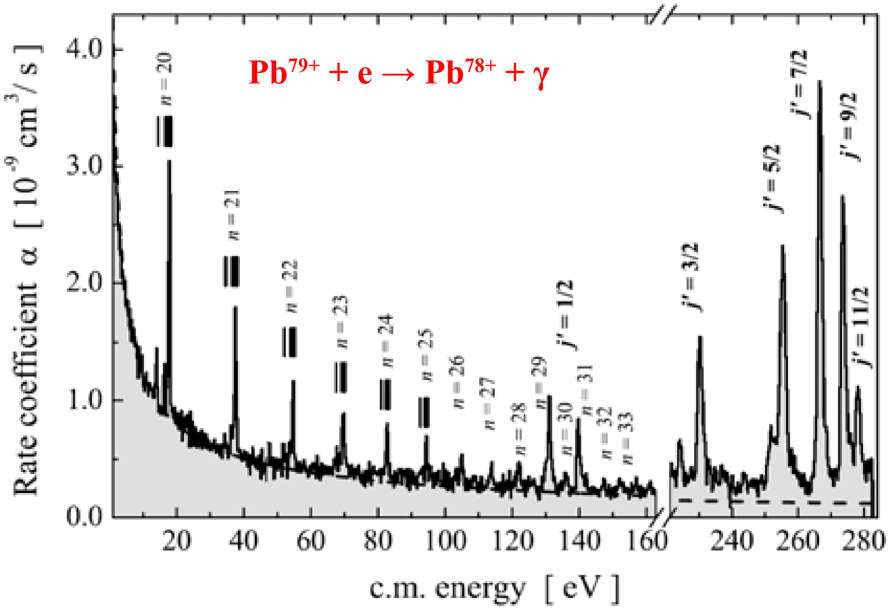



[Savin, ApJ Suppl. Ser. 147 (2003)]

# Recombination in electron coolers

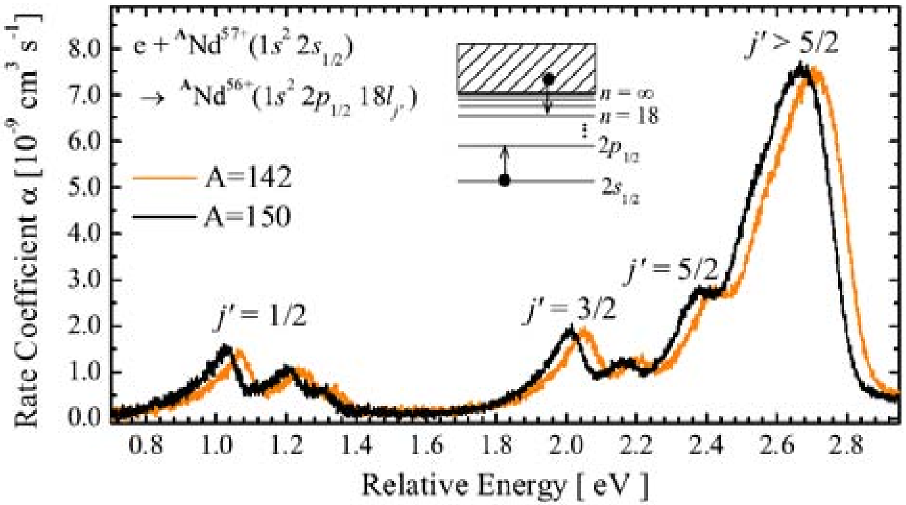
QED precision tests
with HCI

**FS splitting:**



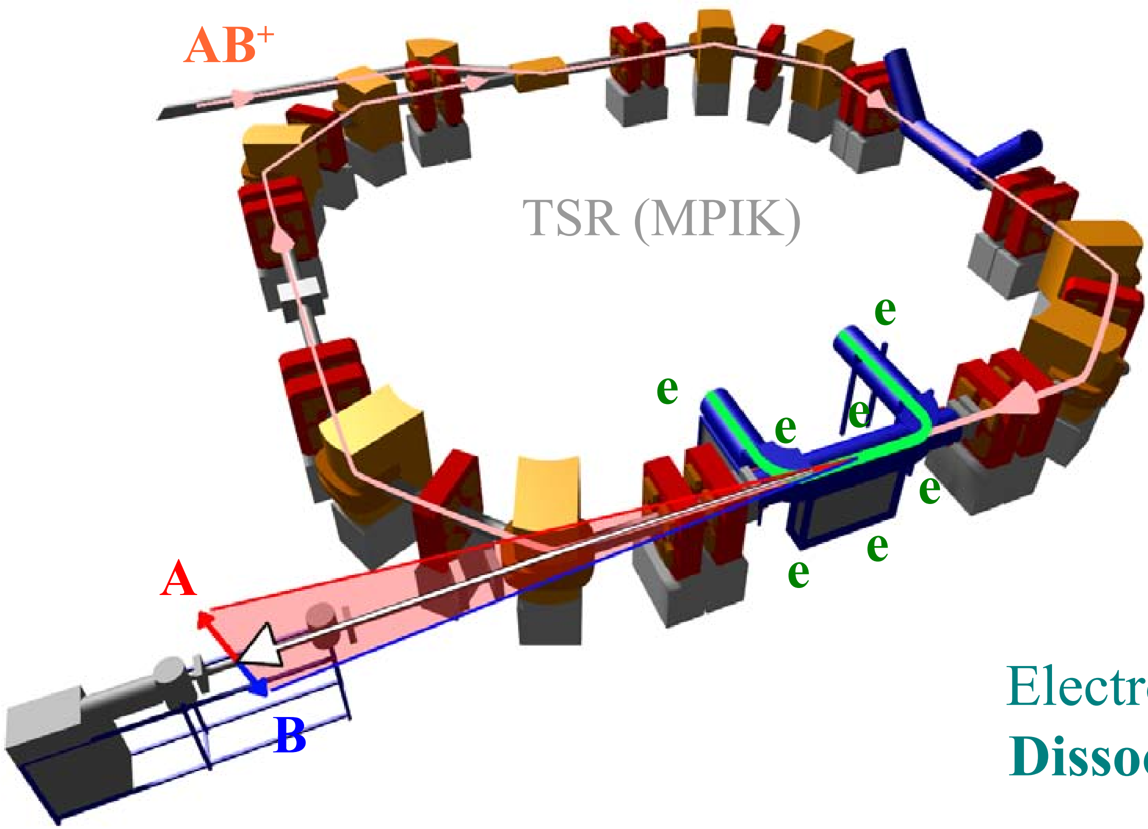

[Brandau, PRL 91 (2003)]

**Isotope shift:**




[Brandau, PRL 100 (2008)]

# Recombination of molecular ions

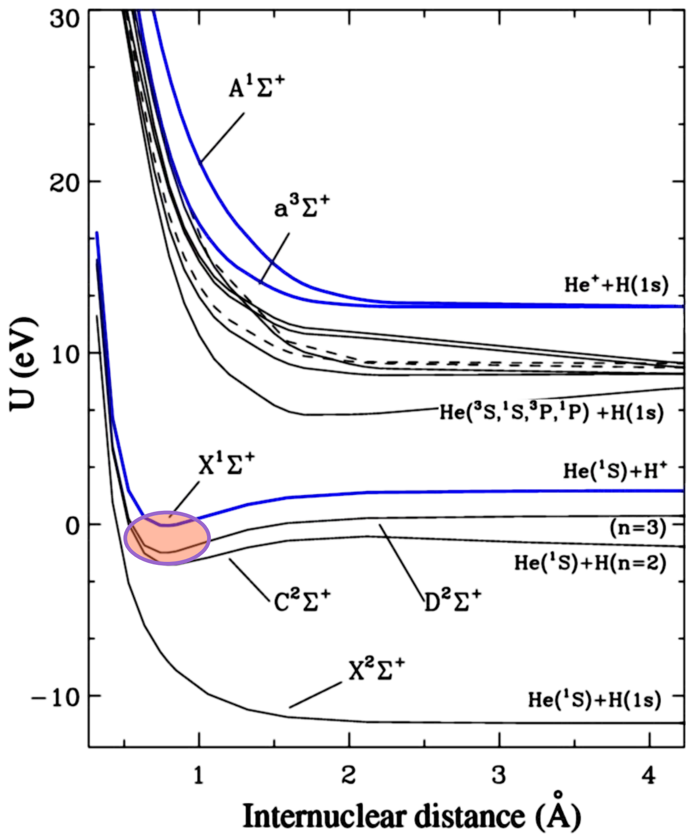


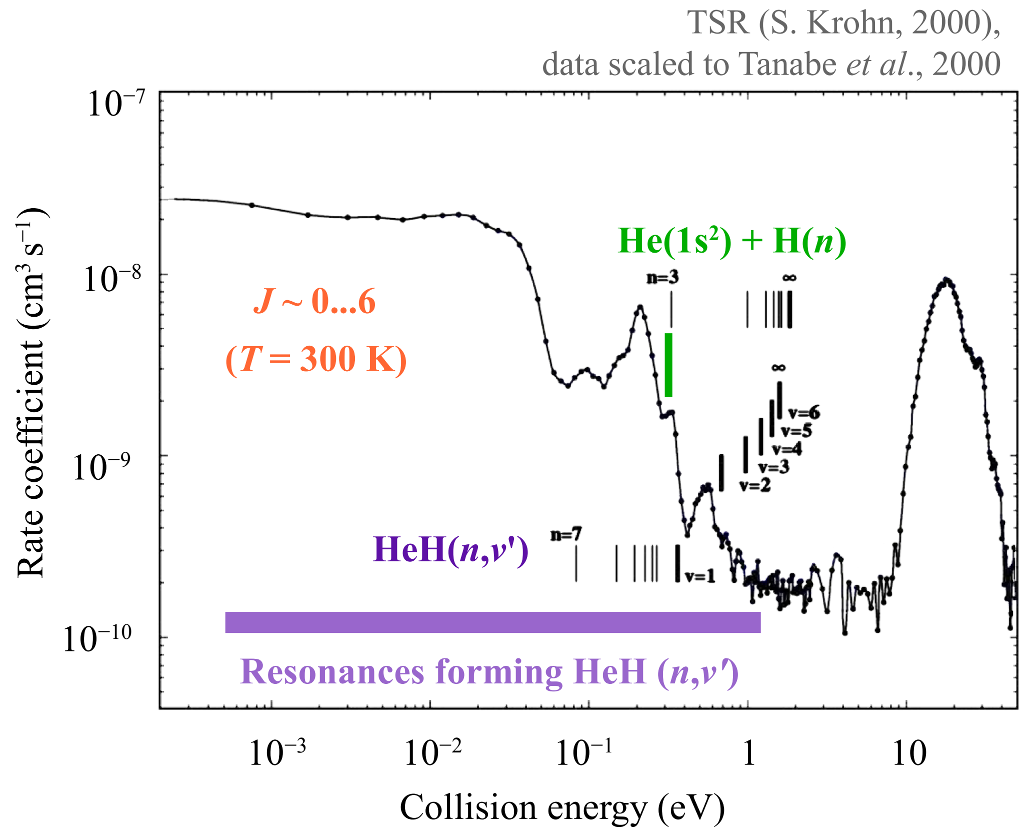

Electrons and molecular ions:
**Dissociative Recombination**

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

# Recombination of molecular ions

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

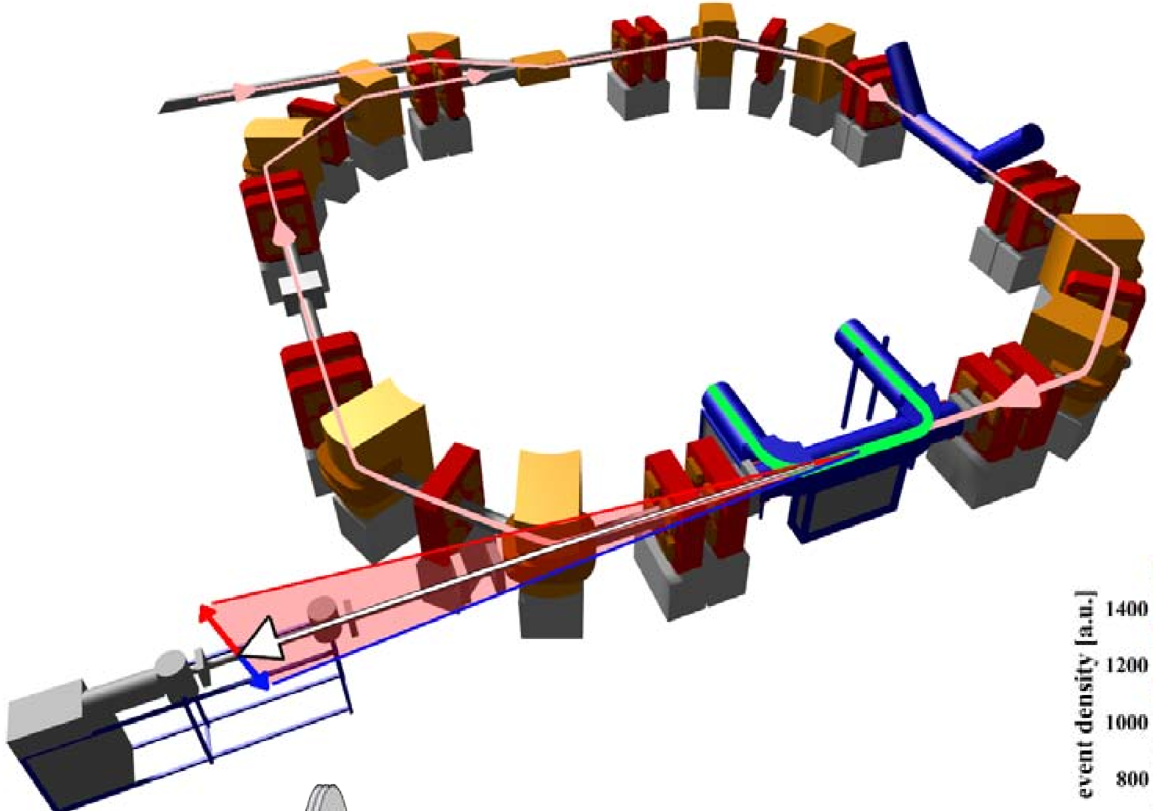


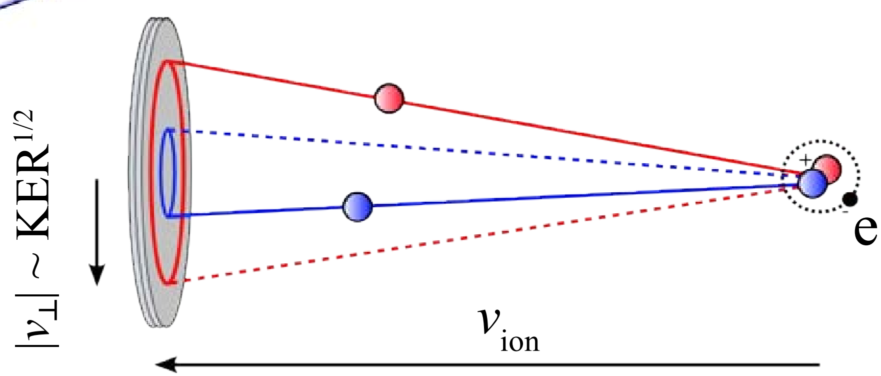




$$\alpha = \frac{R}{N_{\text{ion}}\, n_e} \frac{C}{L} \gamma_{\text{ion}}^2$$

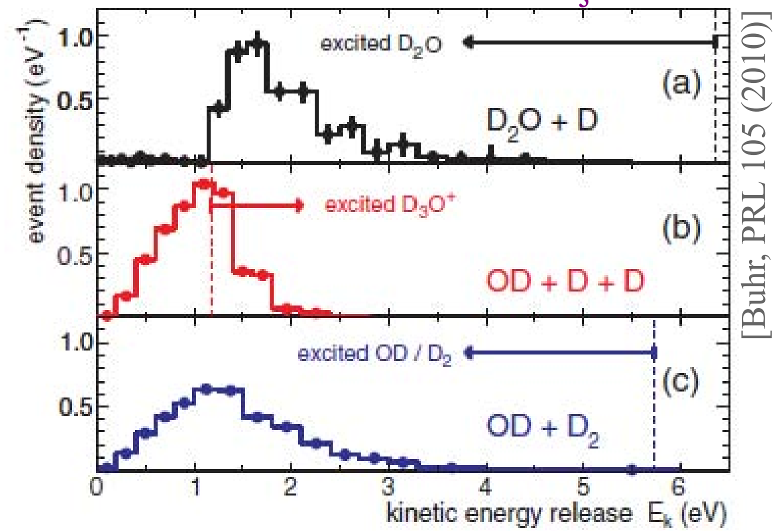
$$\mathbf{AB^+ + e + \mathit{E}_{coll} \longrightarrow A^{(*)} + B^{(*)} + \mathit{E}_{KER}}$$

# Recombination of molecular ions

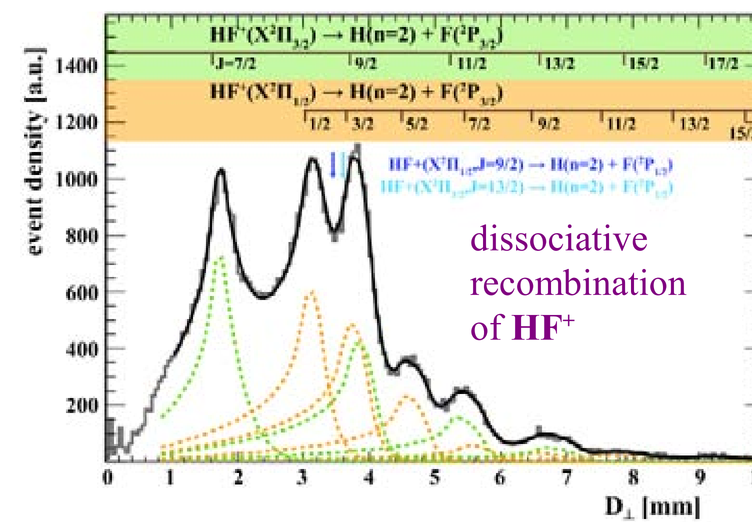





dissociative recombination of $D_3O^+$




[Buhr, PRL 105 (2010)]




[Stützel, in prep.]

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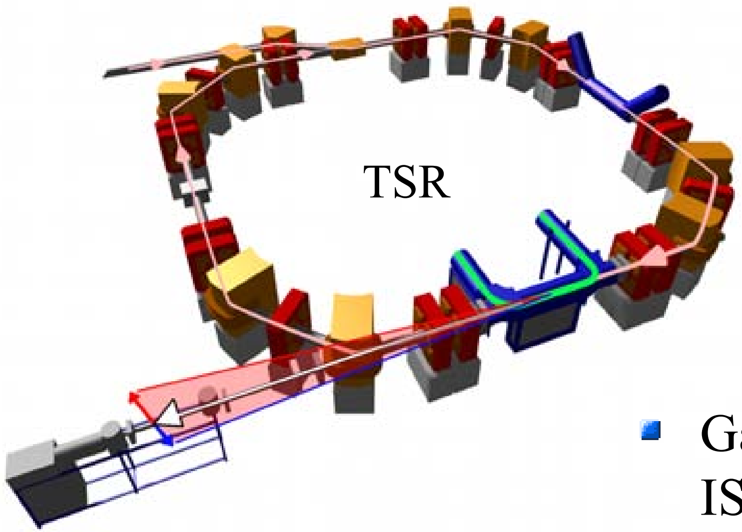
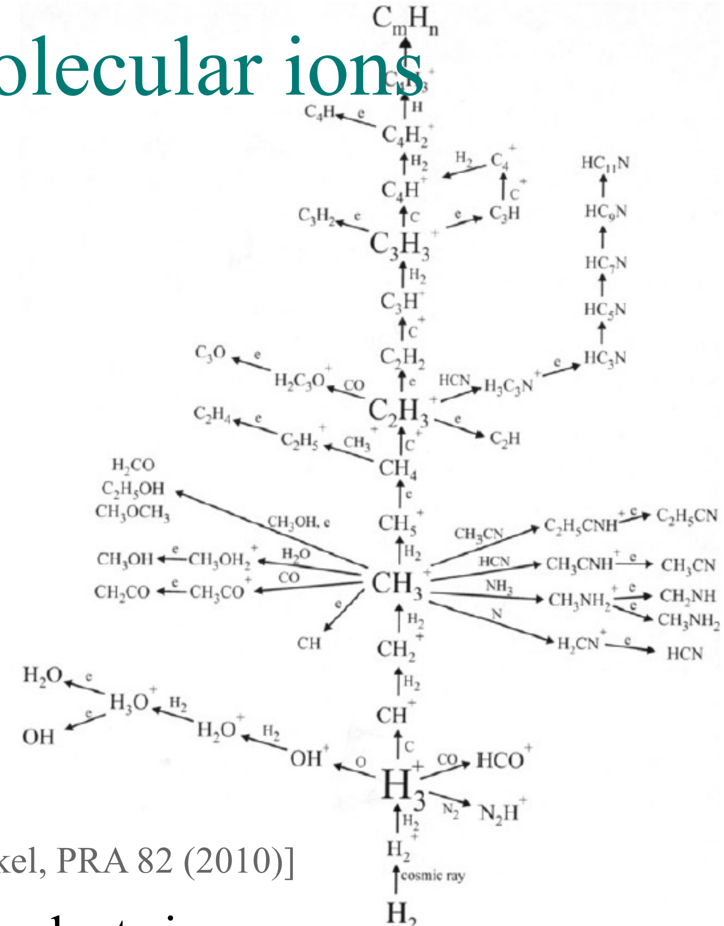
# Recombination of molecular ions

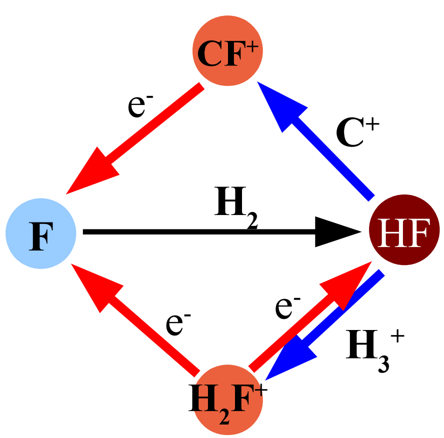



- Gas-phase chemistry in ISC:
  $H_3^+ + e \rightarrow H + H + H$

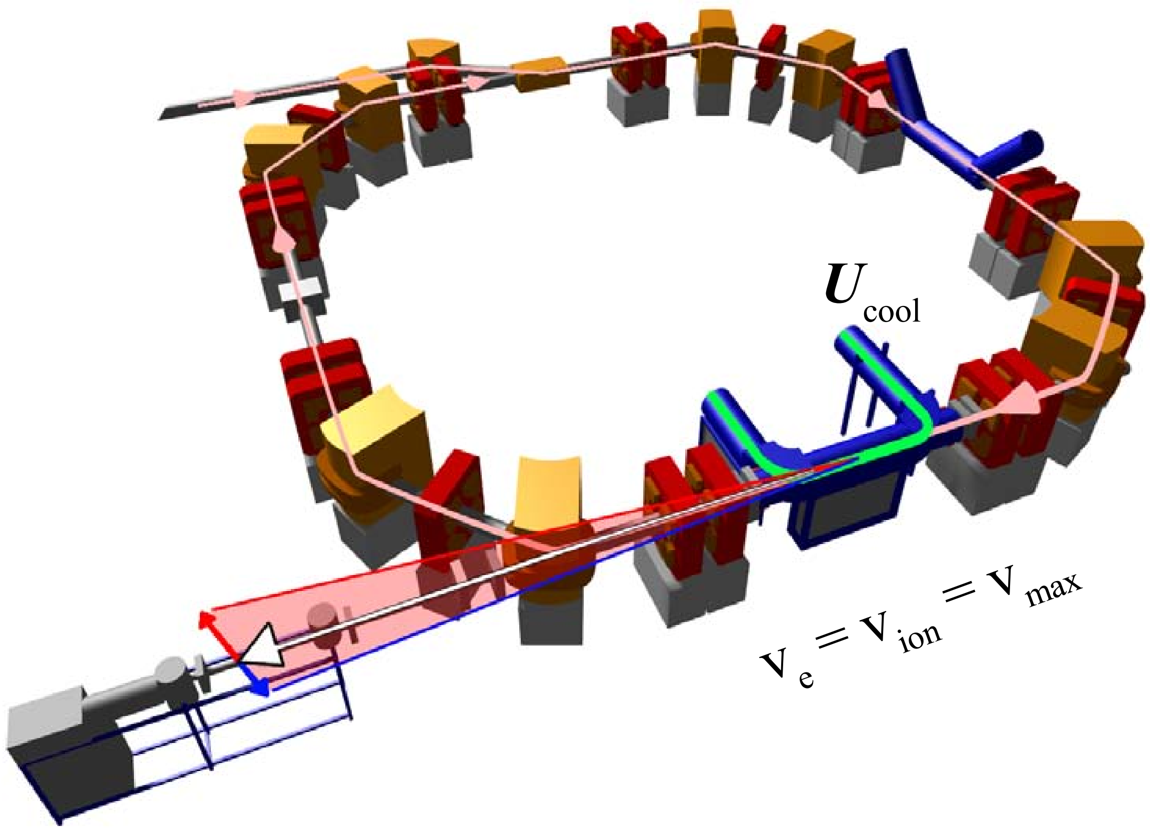
e.g. [Petrignani, PRA 83 (2011); Kreckel, PRA 82 (2010)]

- 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.]

# Electron cooling molecular ions




- Maximum rigidity: $r\,B_{max}$

  for TSR: ≈ 1.4 Tm

- Maximum velocity:

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

  **e.g. $CHD^+$ (15 u) : $U_{cool}$ ~ 230 V**

  **$D_3O^+$ (22 u) : $U_{cool}$ ~ 110 V**

  **$DCND^+$ (30 u) : $U_{cool}$ ~ 55 V**

- But: $I_e \sim U_{cool}^{3/2}$ !

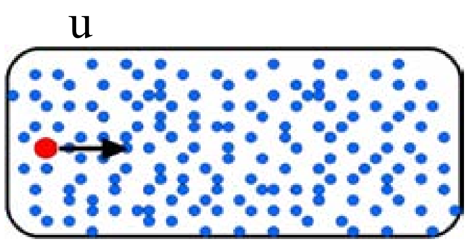
  electron density **degrades**

  ion beam lifetime **degrades**

- There is a **practical $M_{ion,max}$**

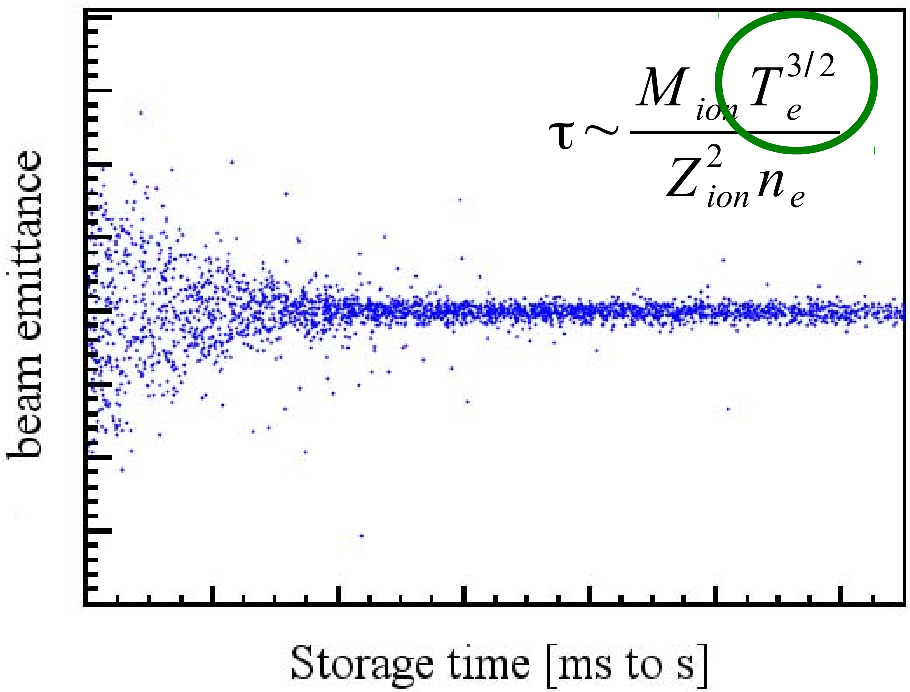
  Ion loss rate exceeds electron cooling rate ...

# Cooling force



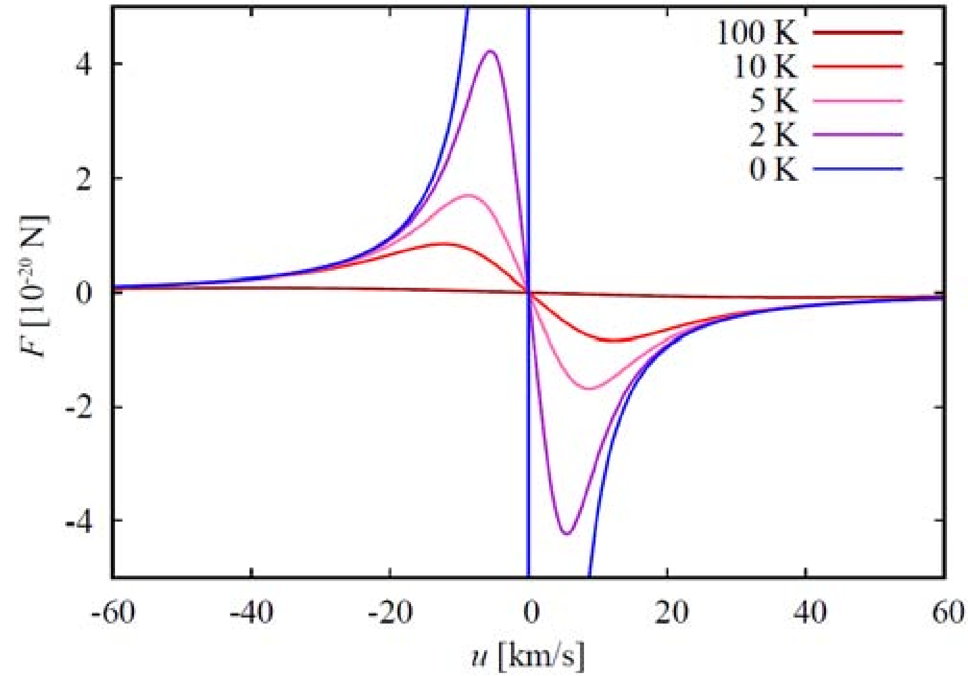

$$\vec{F} \sim -\frac{Z_{ion}^2 n_e}{u^2} \frac{\vec{u}}{|u|}$$

Cooling time




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

Electron temperature



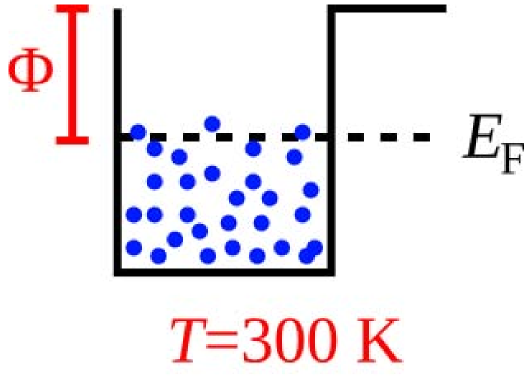

Molecular ions:

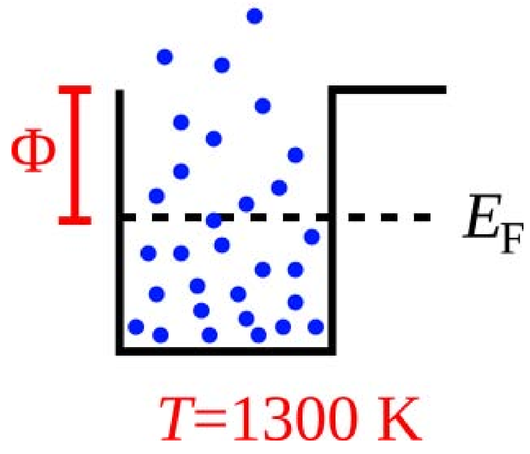
**$M_{ion}$ → large**
**$Z_{ion}$ → 1**
**$n_e$ → limited ($I \sim U^{3/2}$)**
**$T_e$ → ??**

# Electron temperature

## Thermionic cathodes:

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



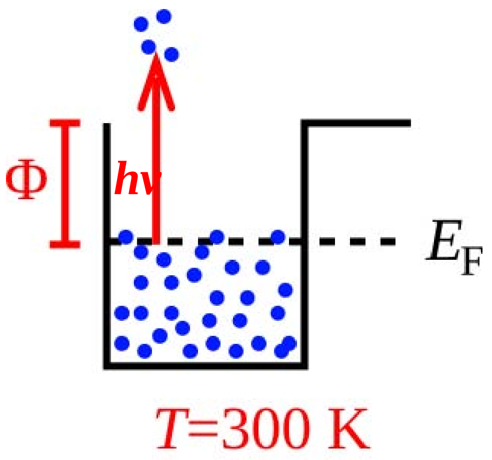

established technology
high $J$ are possible …

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

# Electron temperature

Photocathodes:

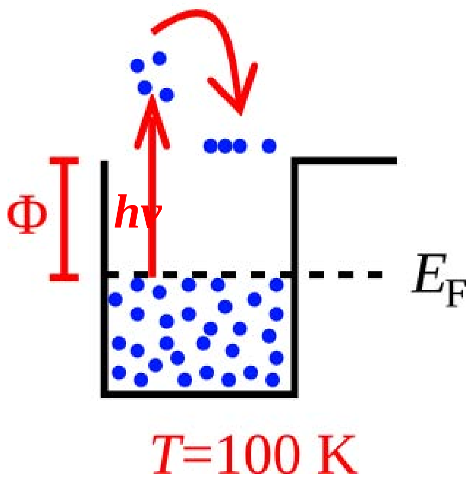
- Electrons overcome Φ by **absorbtion of photons** ($h\nu > \Phi$)




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

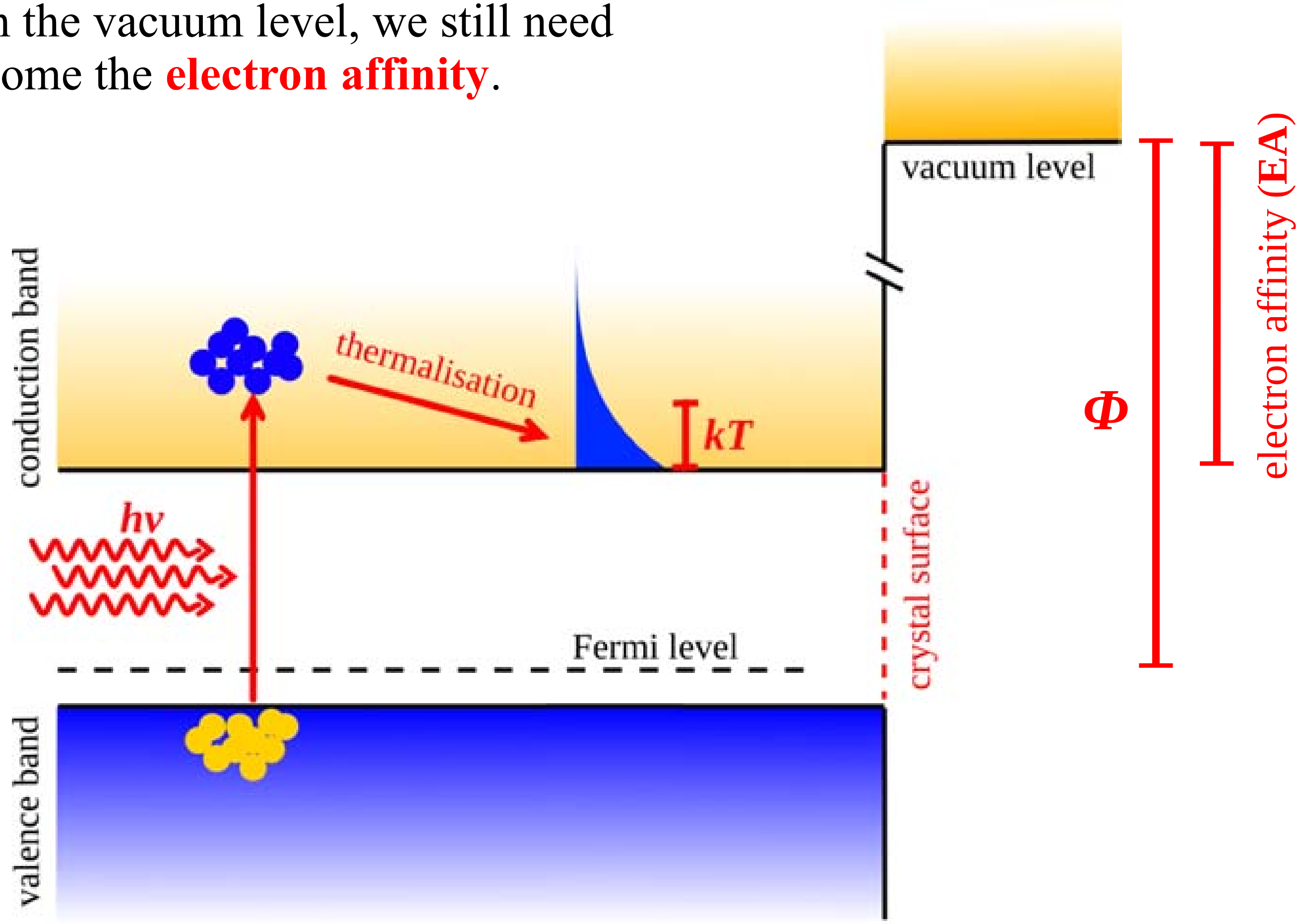
$T_e \sim T_{cath}$

($k_B T \approx 10$ meV)



# GaAs photo cathodes

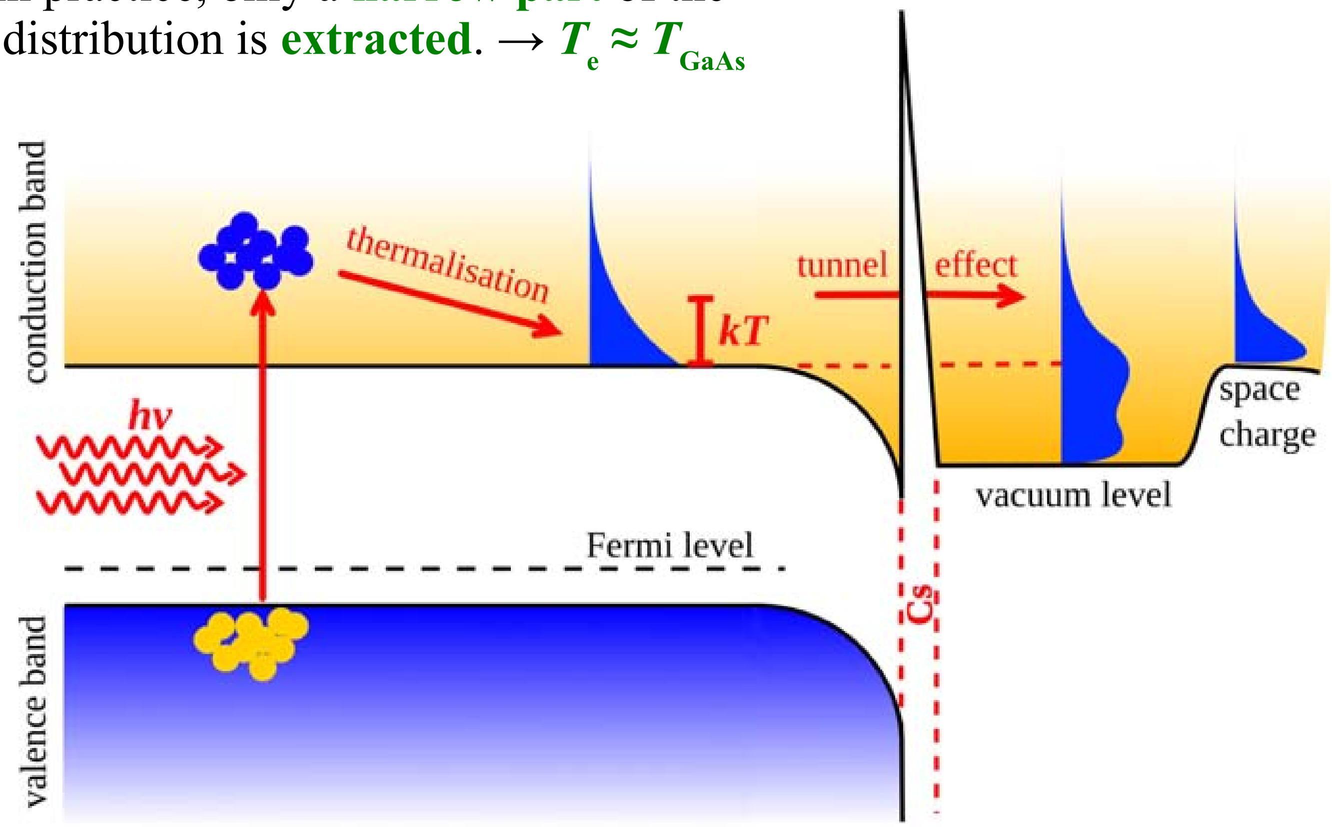
- Negative Electron Affinity:
  - To reach the vacuum level, we still need to overcome the **electron affinity**.




*p*-GaAs

# GaAs photo cathodes

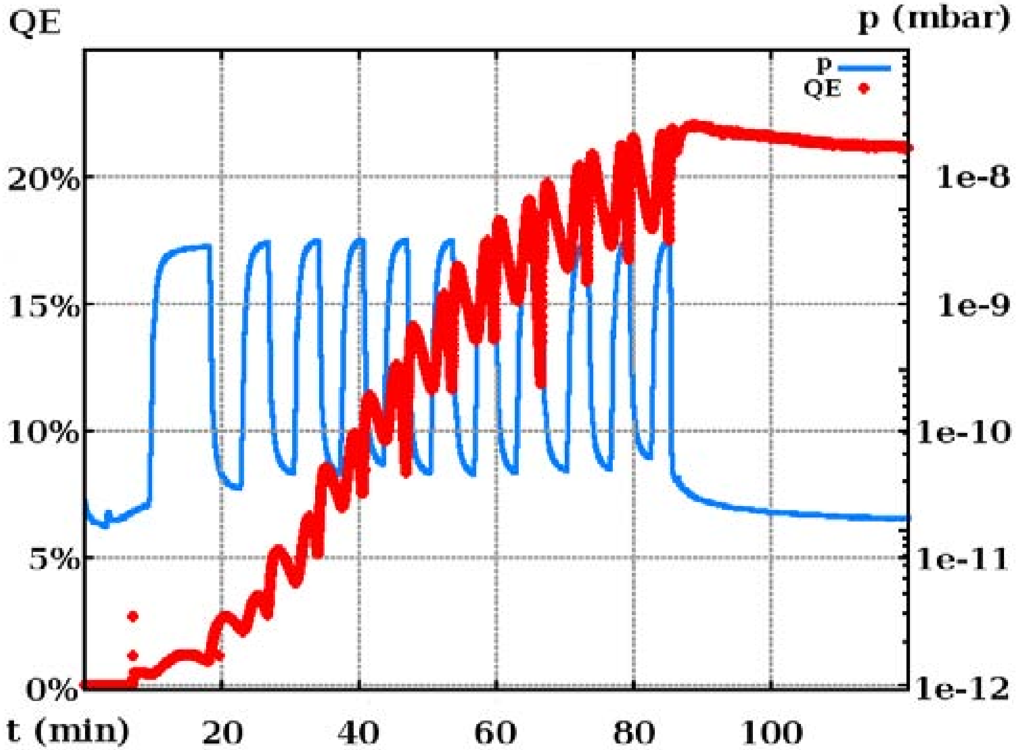
- Negative Electron Affinity:
  - electron-phonon **scattering broadens** the electron energy distribution ...
  - … but in practice, only a **narrow part** of the energy distribution is **extracted**. → $T_e \approx T_{GaAs}$

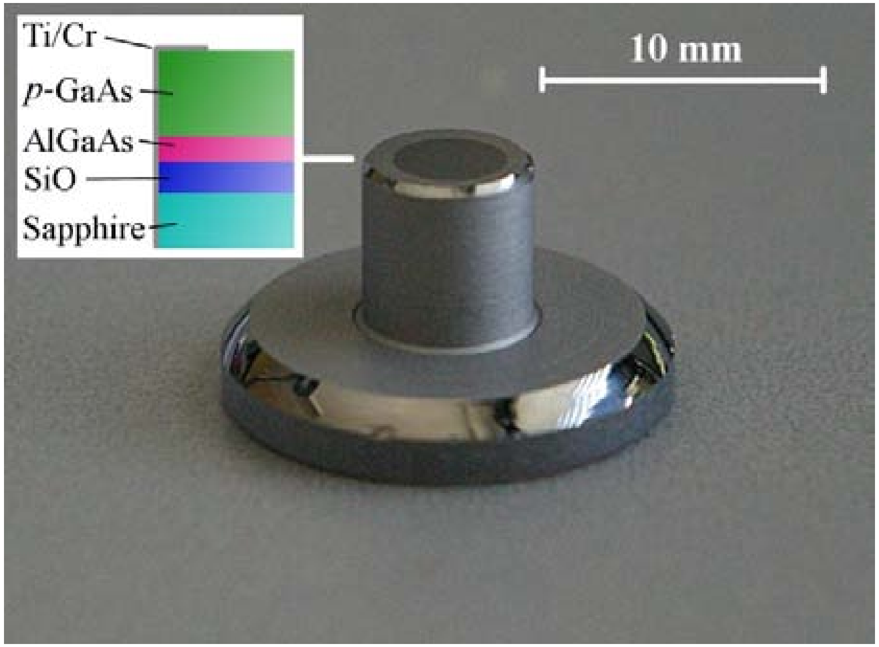



*p*-GaAs

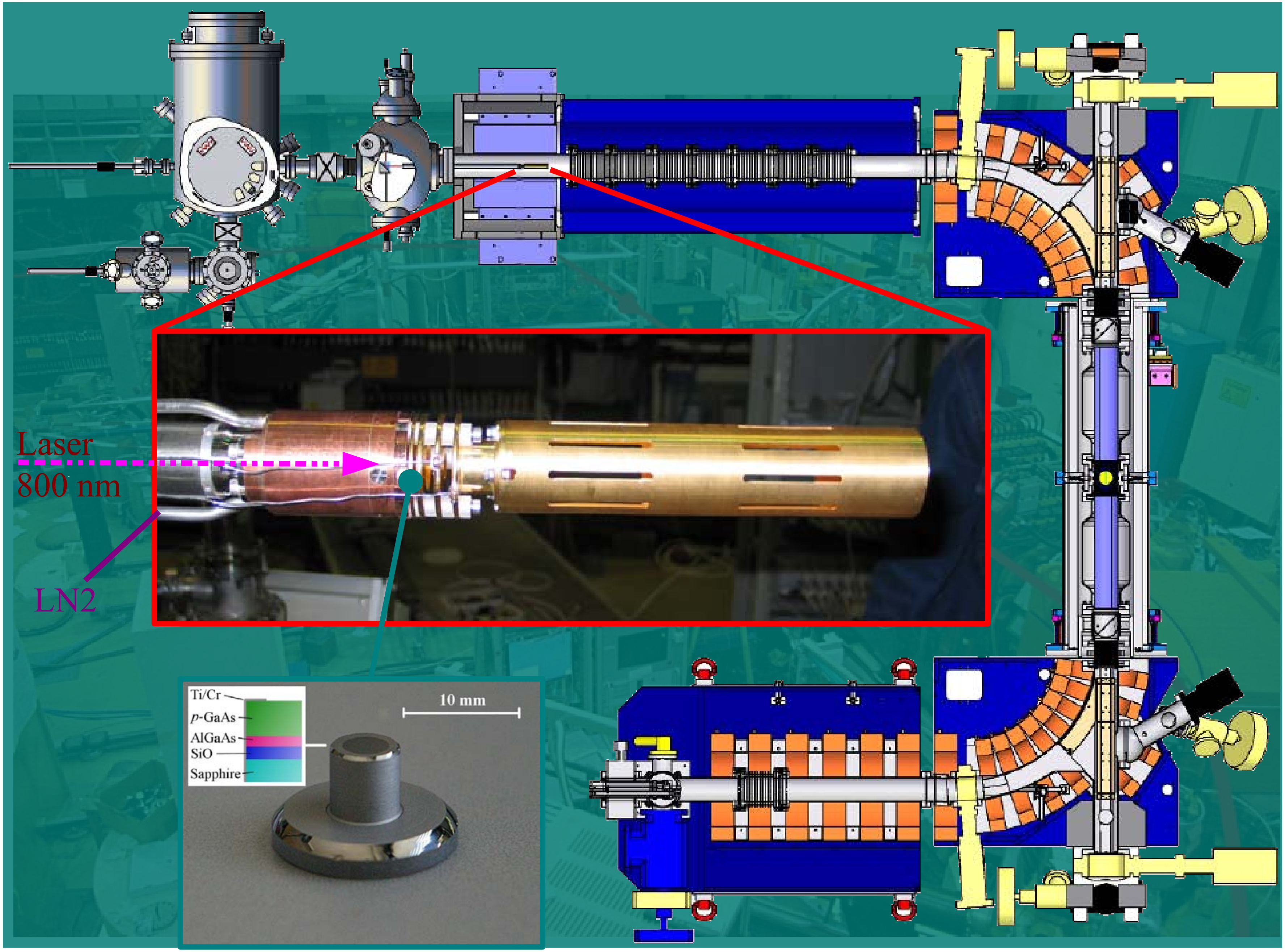
# GaAs photo cathodes

NEA-activation by exposure to Cs and $O_2$.

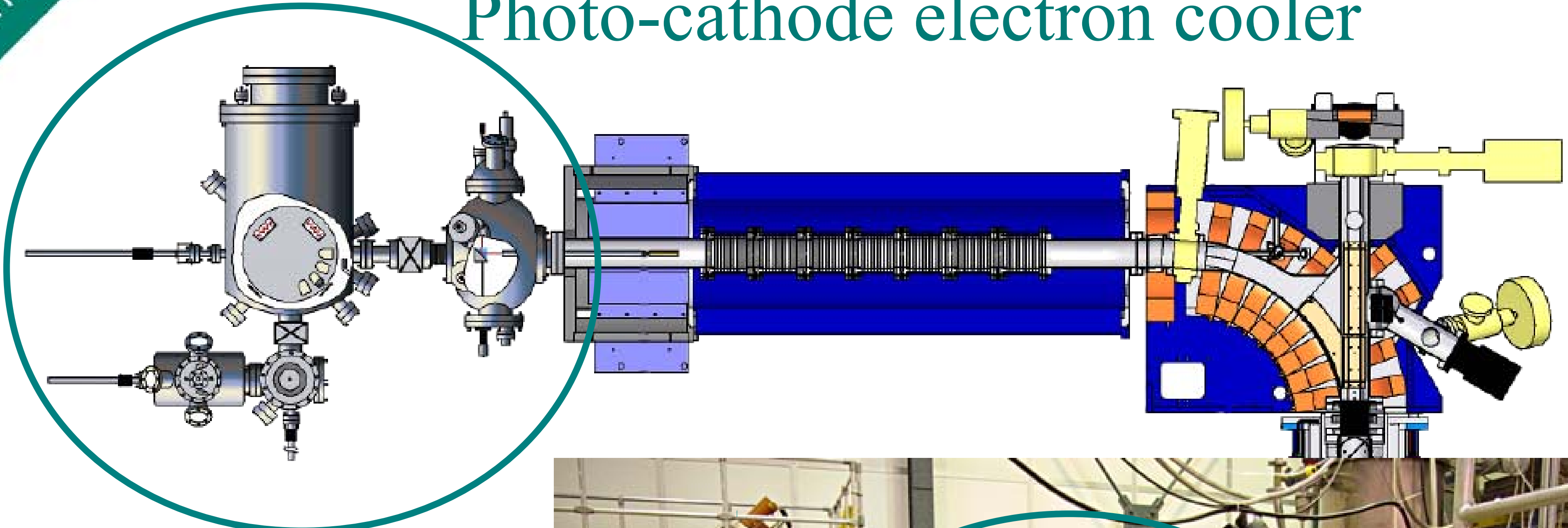


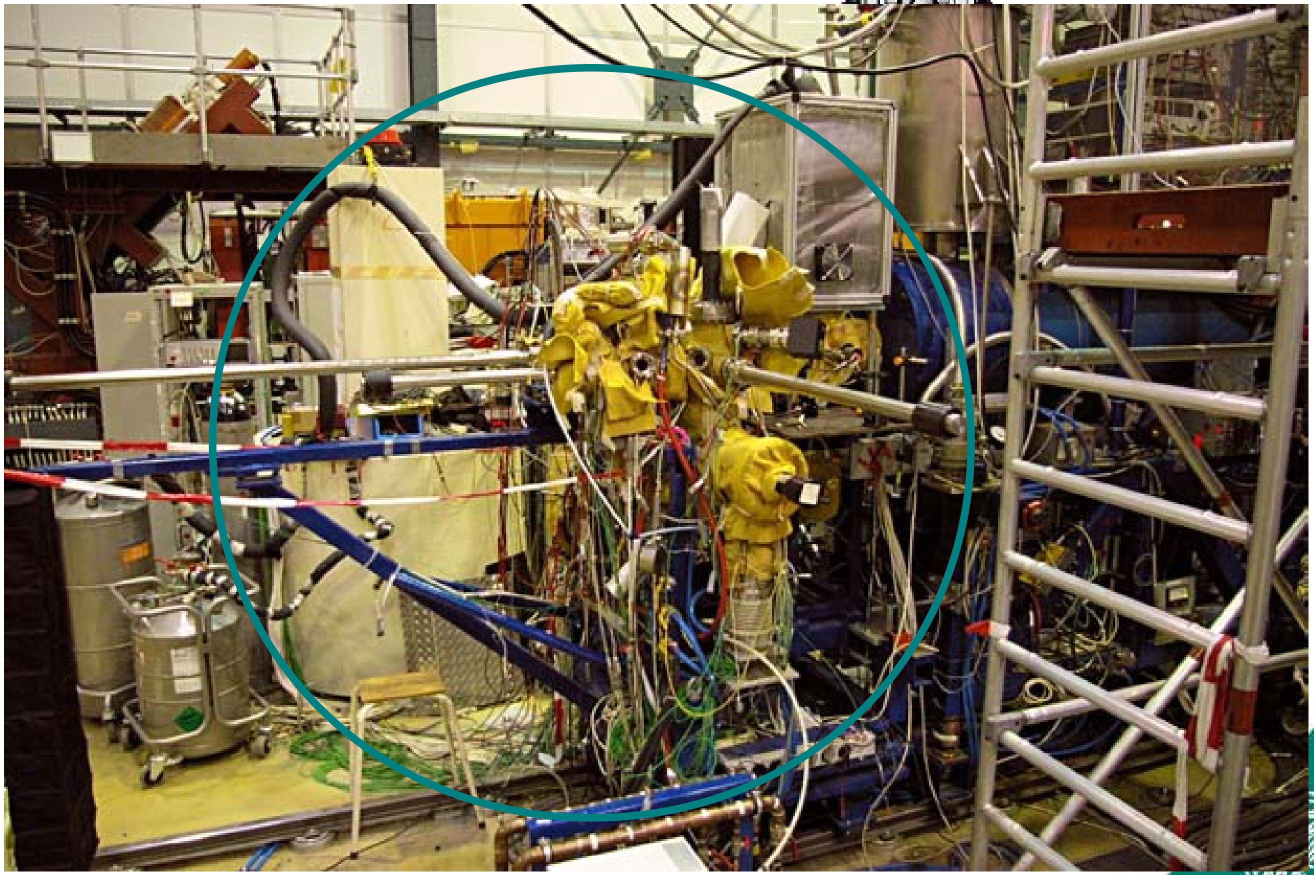



# Photo-cathode electron cooler



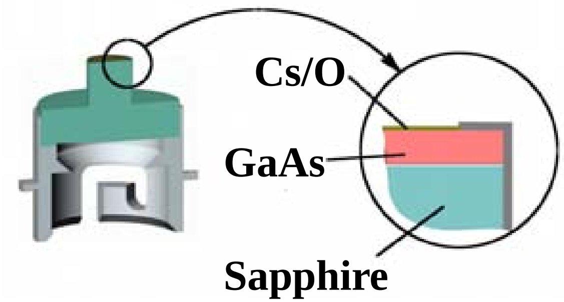
# Photo-cathode electron cooler



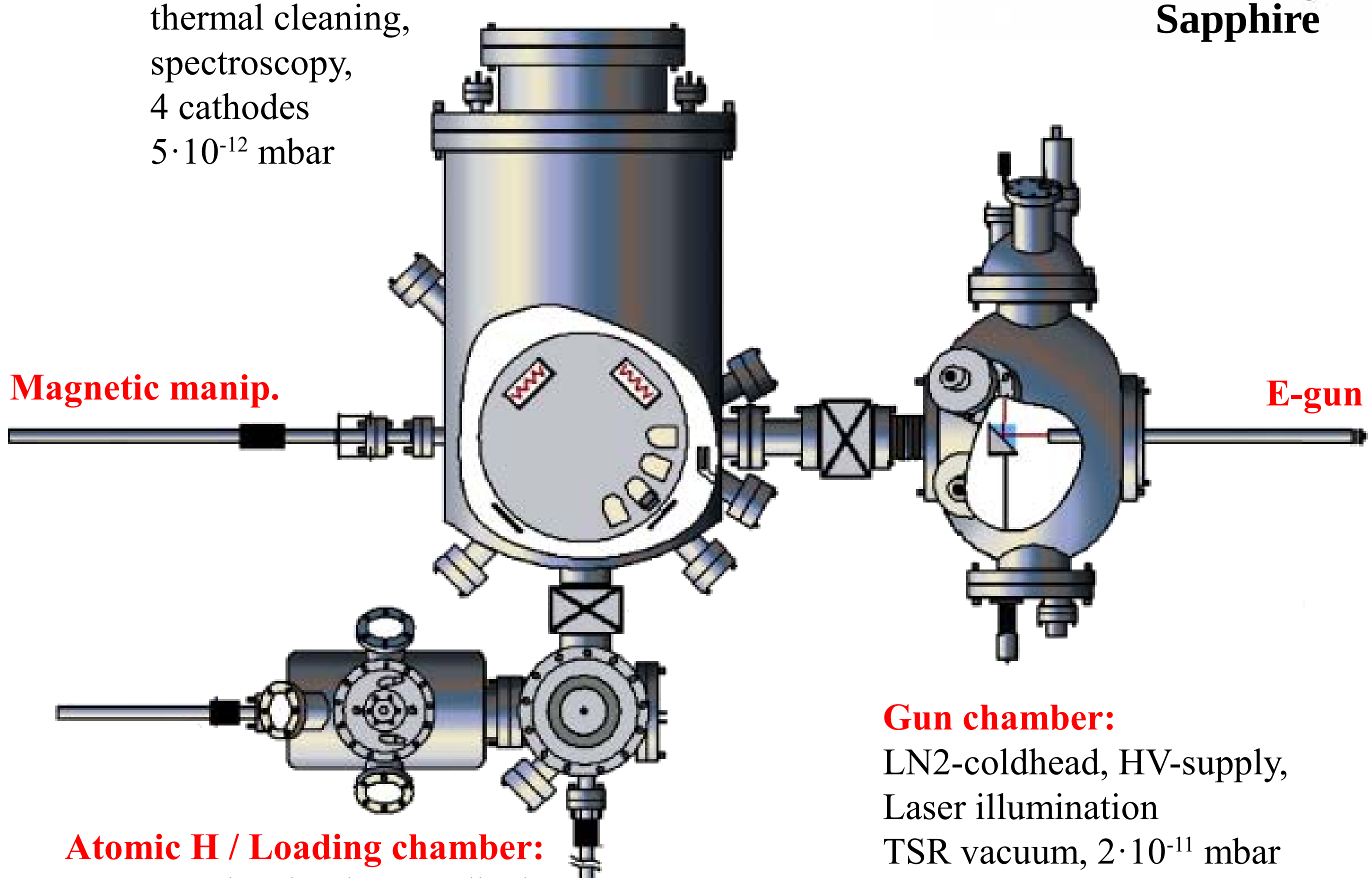


# Photo-cathode electron cooler

## 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

# Photo-cathode electron cooler

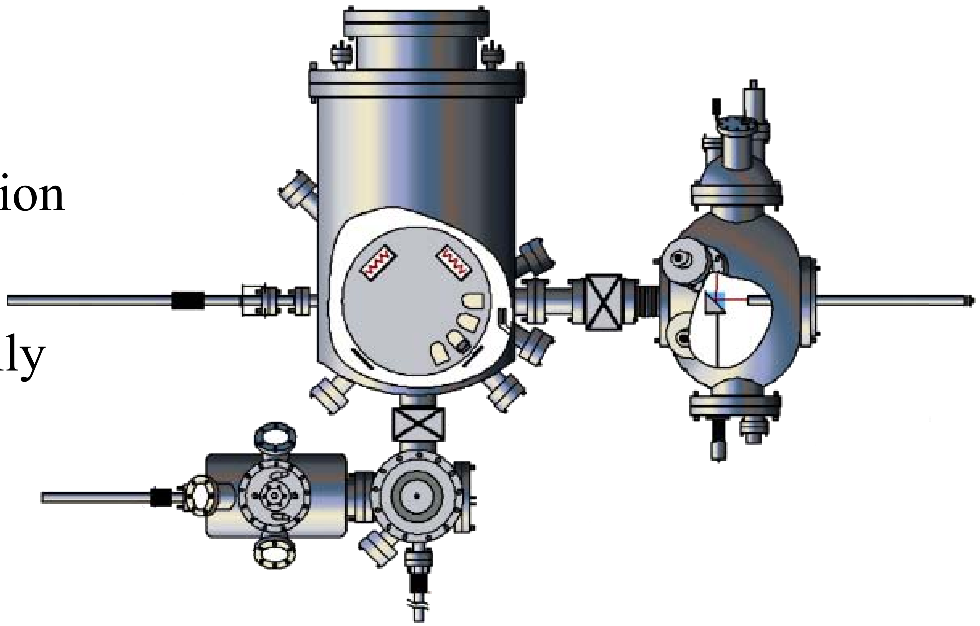
## Electron beam performance

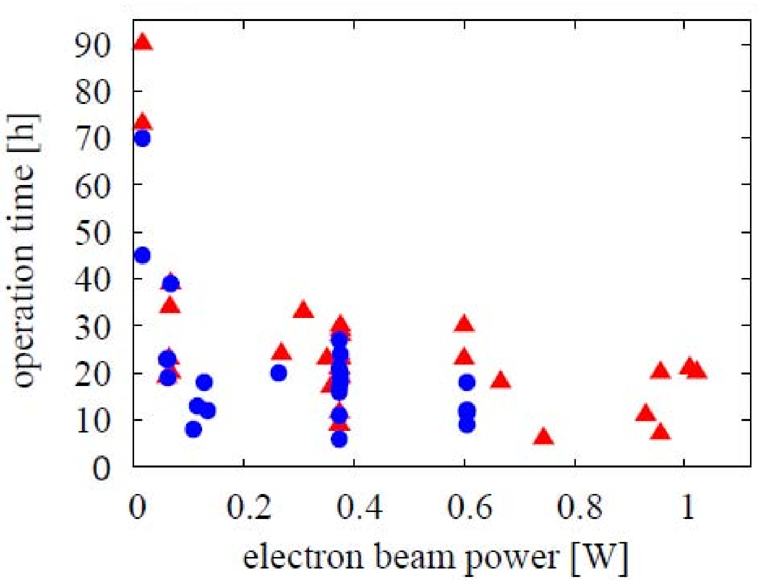
- In vacuum **closed-cycle** operation

- re-activation of cathode typically
  after 1 day of operation
  (for molecular ion beams)

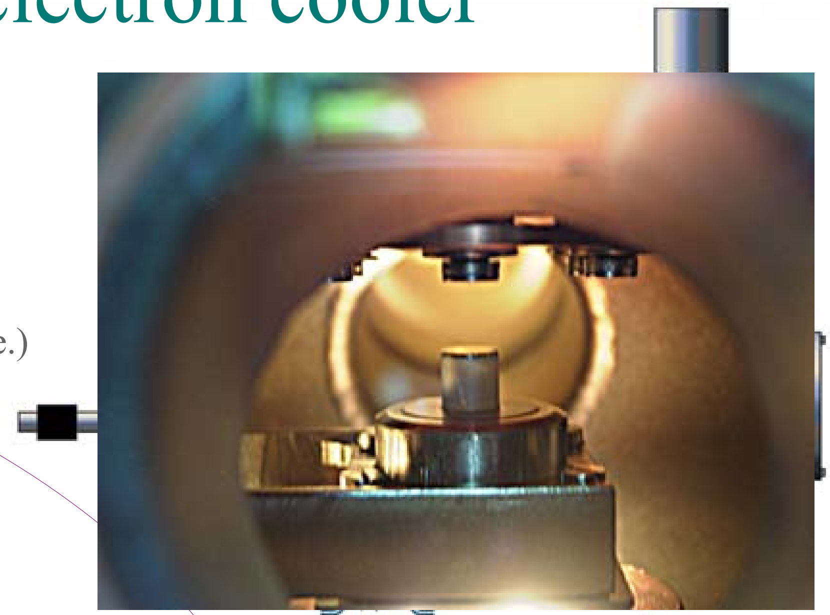
- typical $n_e \sim 10^6$ cm$^{-3}$

- cathode **lifetime** $\sim (I_e U_{cool})^{-1}$
  vacuum degradation ...





# Photo-cathode electron cooler



[Orlov, J. Appl. Phys. 106 (2009)]

## Surface cleaning by H radicals

- Cathode **cleaning by bakeout** can be done **3-4 times**.
  (non-volatile Ga- and As-oxides accumulate on the surface.)
  → **Gradual decrease of the quantum efficiency**.

- Ga-oxides can be removed by

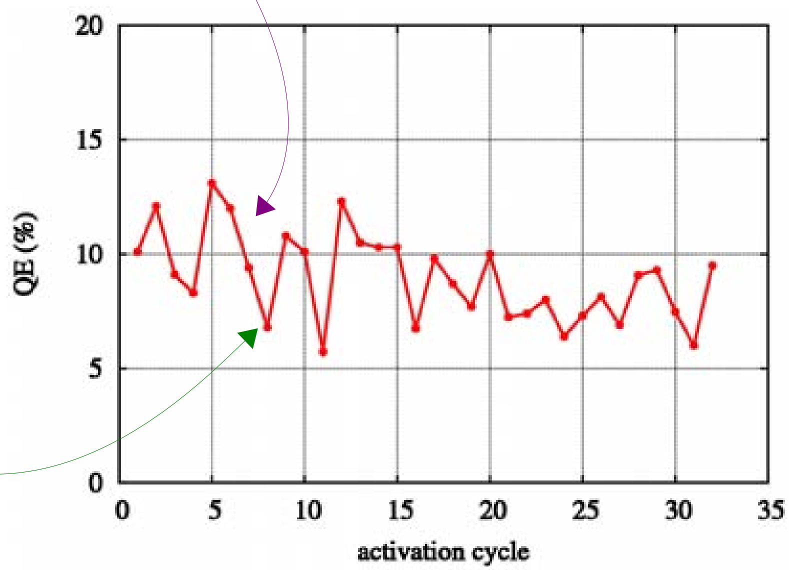
1. etching in HCl solution.
   → **Requires removal of cathode from setup**. ☹

2. Exposure to **H• radicals** in vacuum

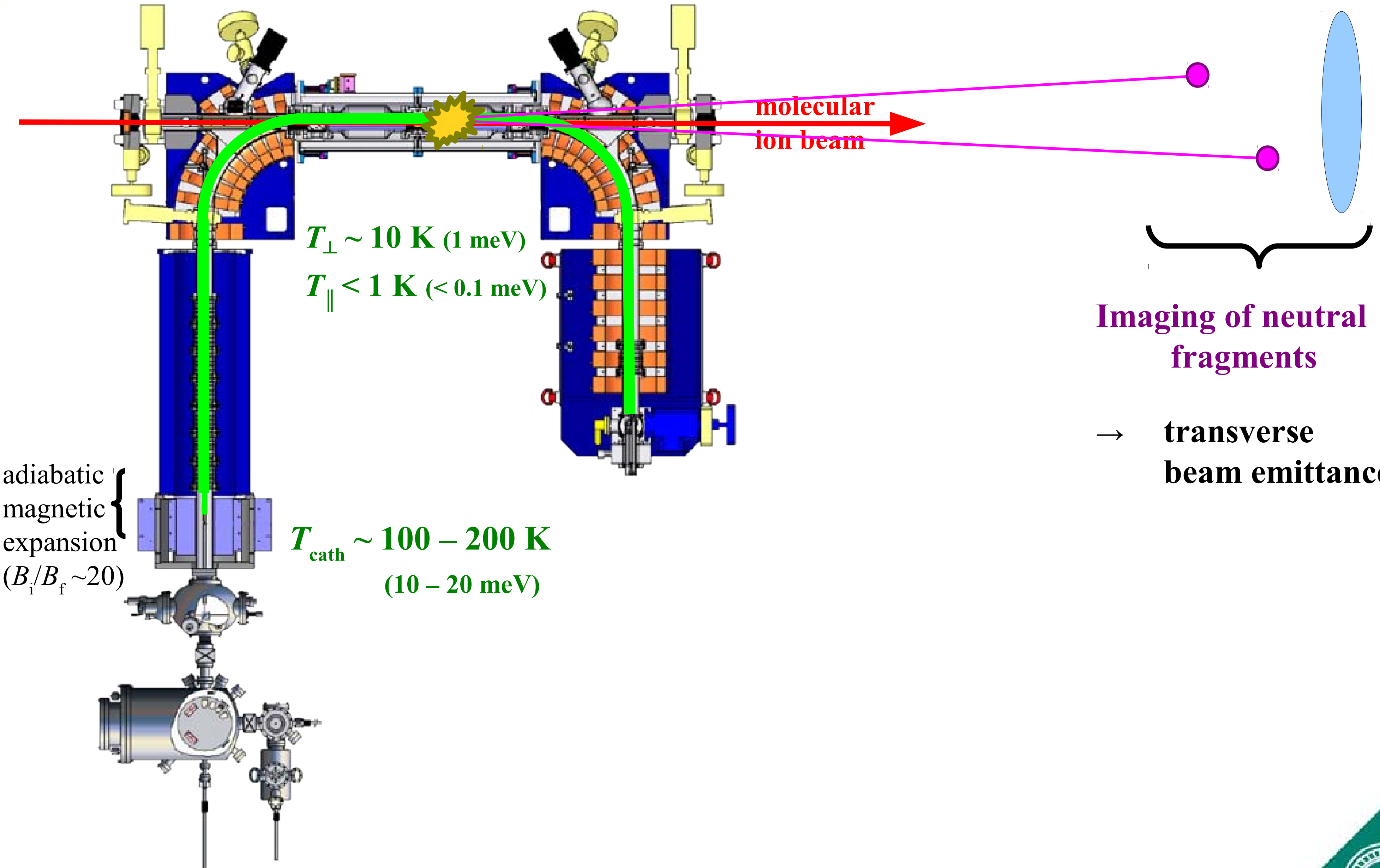
$$\mathrm{Ga_2O_3 + 4\ H \rightarrow Ga_2O + 2\ H_2O}\ ,$$

$$\mathrm{As_2O_3 + 6\ H \rightarrow 3\ H_2O + As_2} \left(\frac{1}{2}\ \mathrm{As_4}\right)$$

→ **Cathode can stay in vacuum.** ☺



# Electron cooling at low velocity



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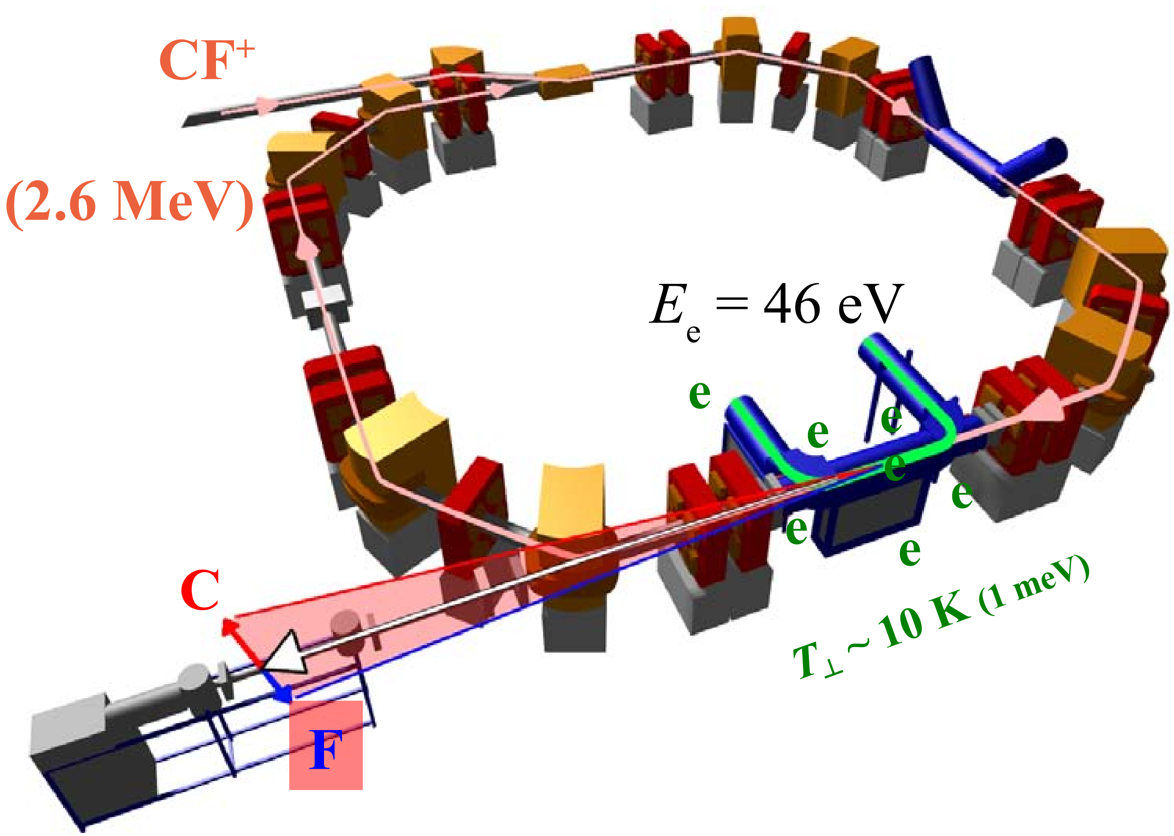


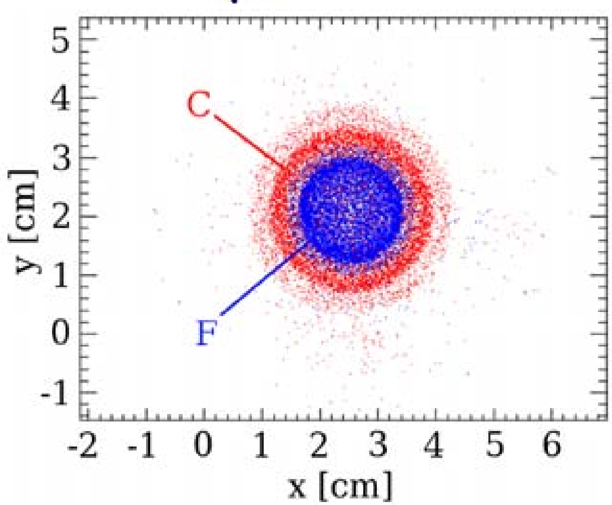


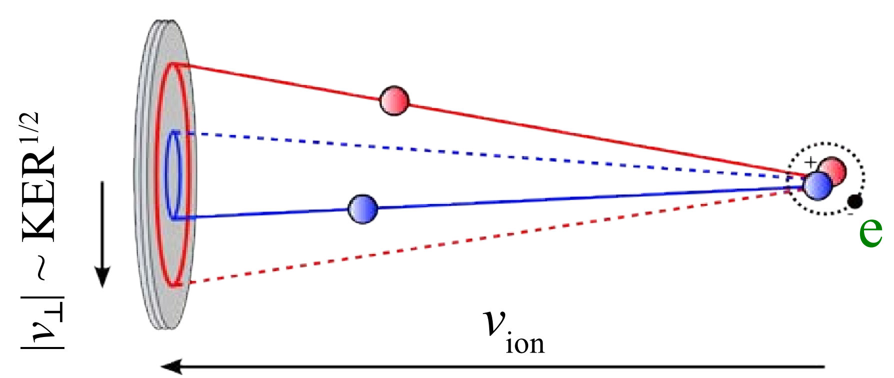

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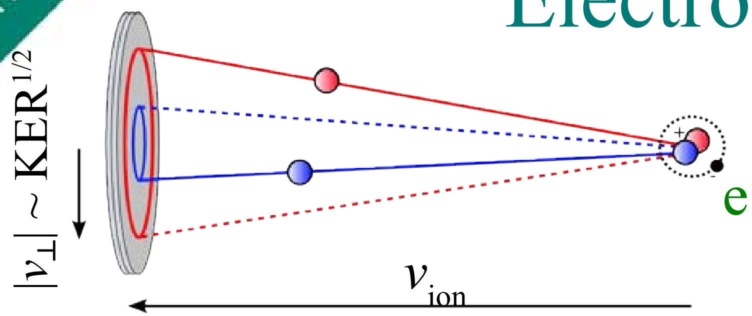


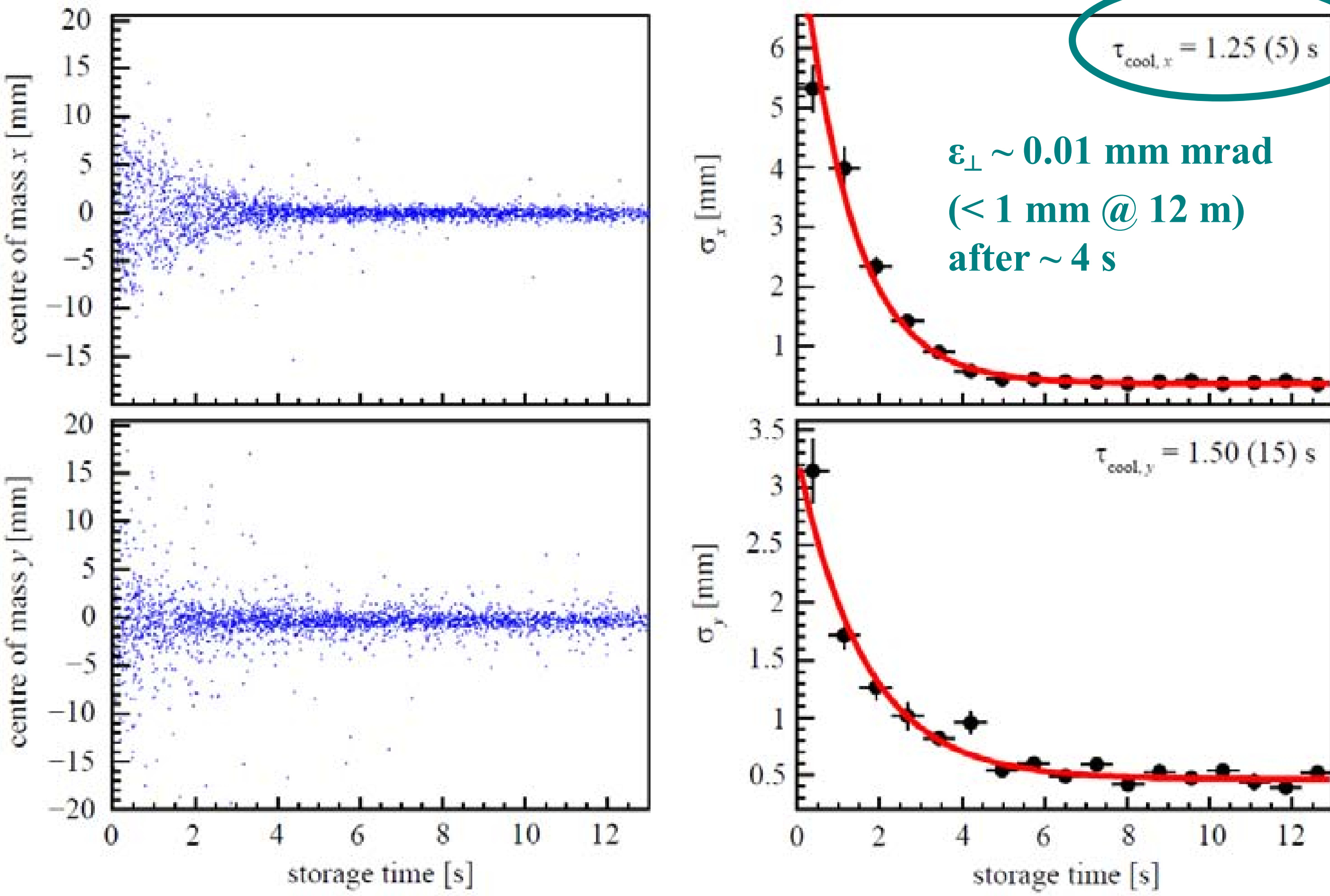

$$\tau \sim \frac{M_{ion} T_e^{3/2}}{Z_{ion}^2 n_e}$$

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:~~

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

~~**τ ~ 30 s**~~

~~(longer than ion lifetime)~~

# Electron cooling at low velocity

| | |
|---|---|
| $H_3^+$ | $E_e = 735$ eV |
| $HD_2^+$ | $E_e = 327$ eV |
| $CHD^+$ | $E_e = 231$ eV |
| $HF^+$ | $E_e = 125$ eV |
| $D_3O^+$ | $E_e = 112$ eV |
| $DCND^+$ | $E_e = 56$ eV |
| $N_2D$ | $E_e$ = [illegible] eV |
| $HS^+$ | $E_e = 47$ eV |
| $CF^+$ | $E_e = 46$ eV |
| $^{18}O^{16}O^+$ | $E_e = 43$ eV |
| $HCl^+$ | $E_e = 40$ eV |
| $HCl^+$ | $E_e = 37$ eV |
| $D_2Cl^+$ | $E_e = 30$ eV |

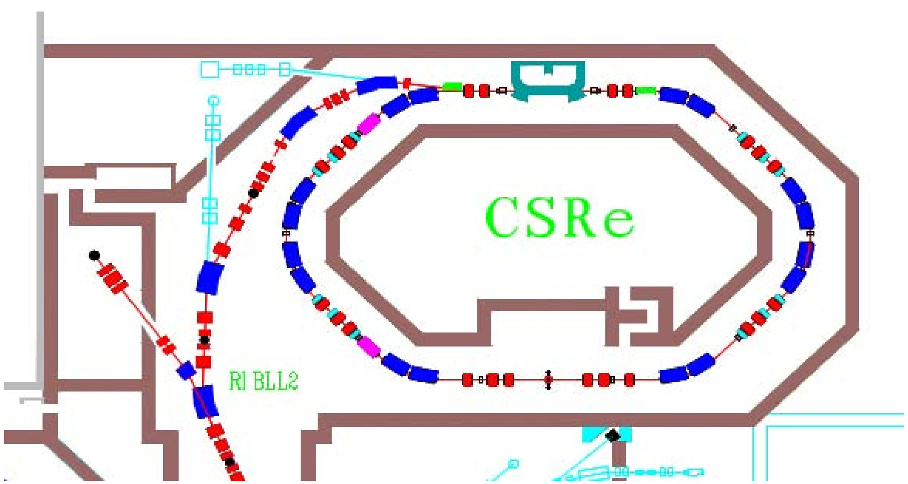
We are approaching the limit of our storage ring.

# Solutions?

## Solution 1: Use a bigger storage ring

CSRe ("Cooler Storage Ring")

**9.4 Tm**



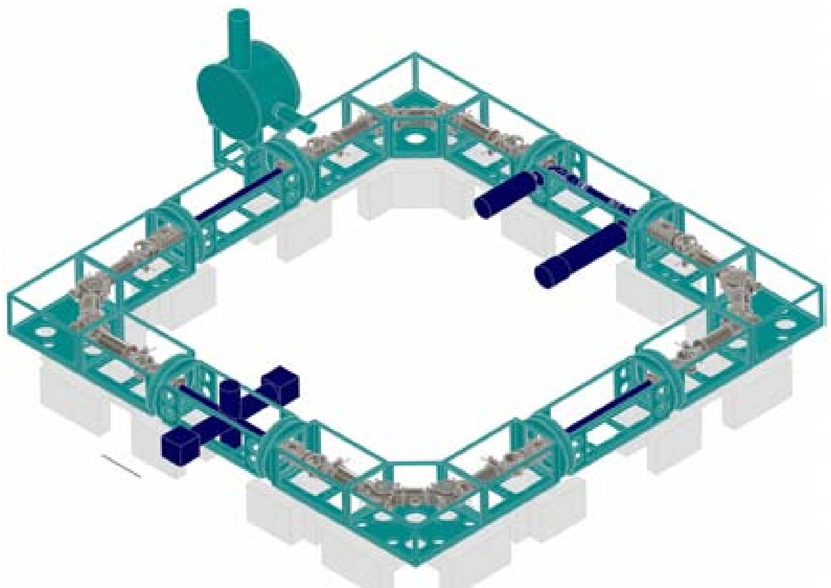

Molecular ions research facility, Lanzhou, China.

→ $M_{ion}/Z_{ion} \sim 200$

## Solution 2: Store (much!) longer

CSR ("Cryogenic Storage Ring")

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



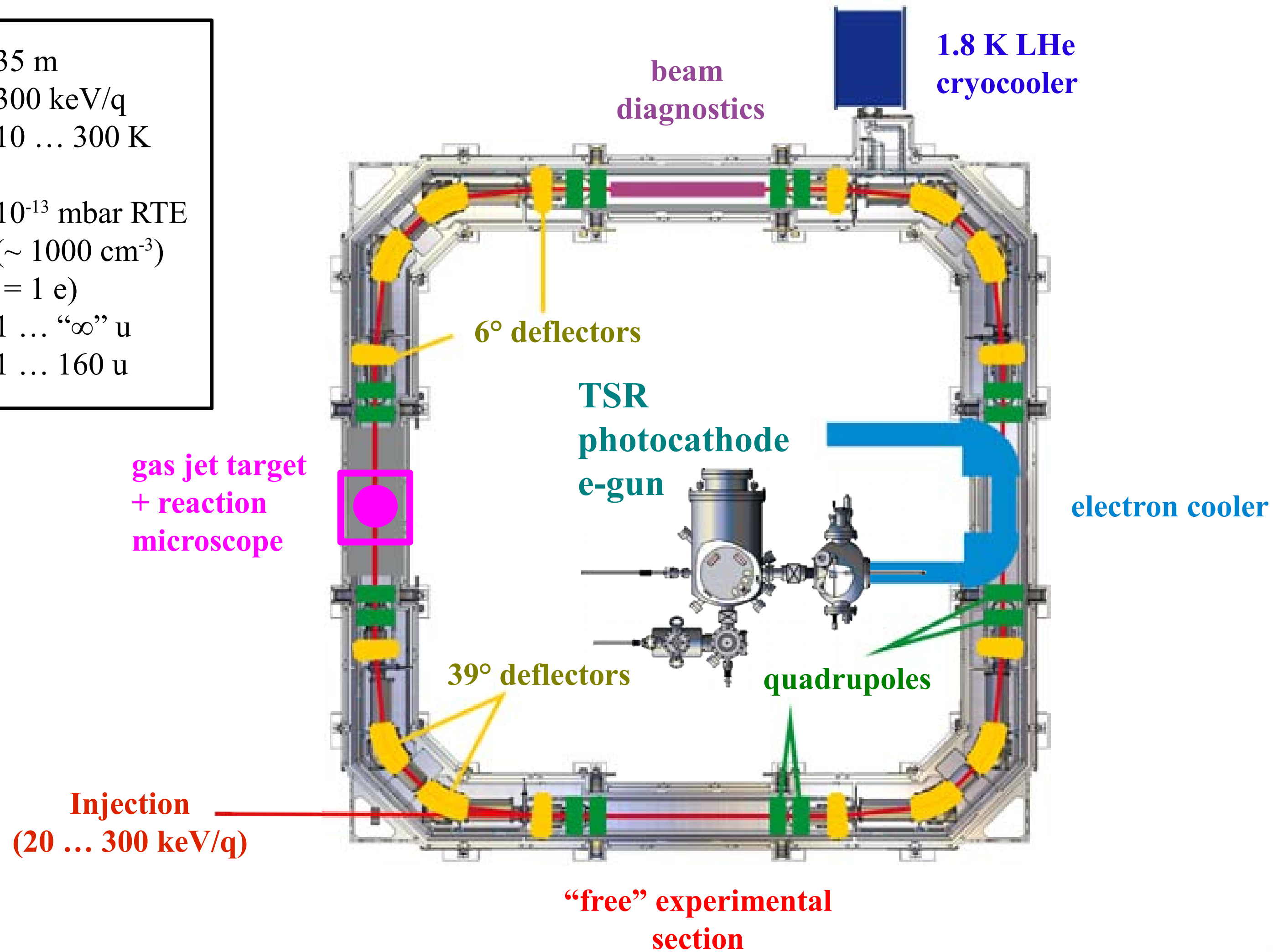
$M_{ion}/Z_{ion} \geq 160$ (with e-cooling!)

**Added value: IR-radiation-free!**

# 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 |



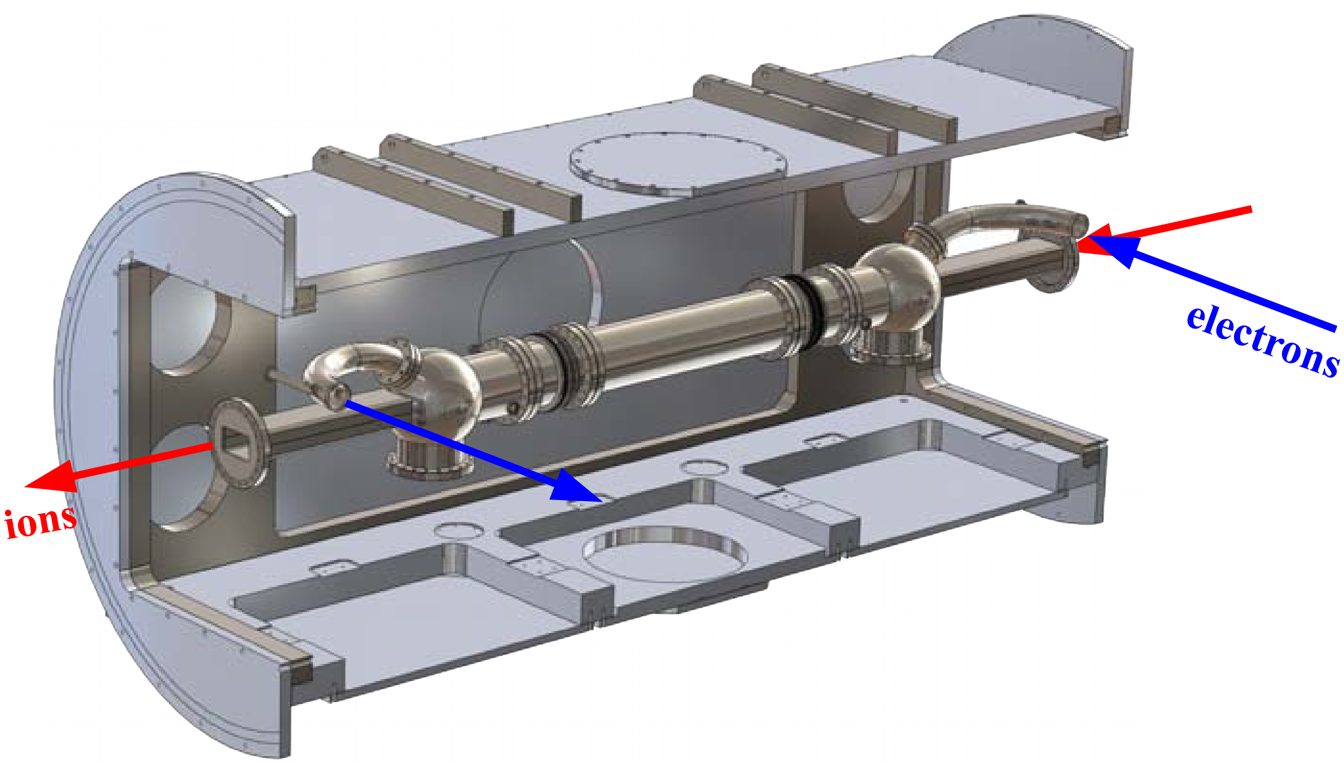
# The CSR electron cooler

**Cryogenic beam line** → Cooler has to be **contained in an isolating cryostat.**

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

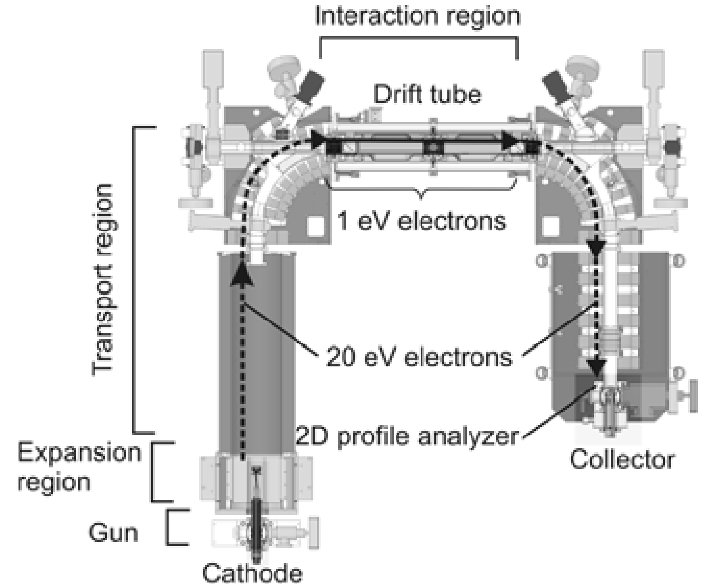
→ Need **very** slow electrons

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




# 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

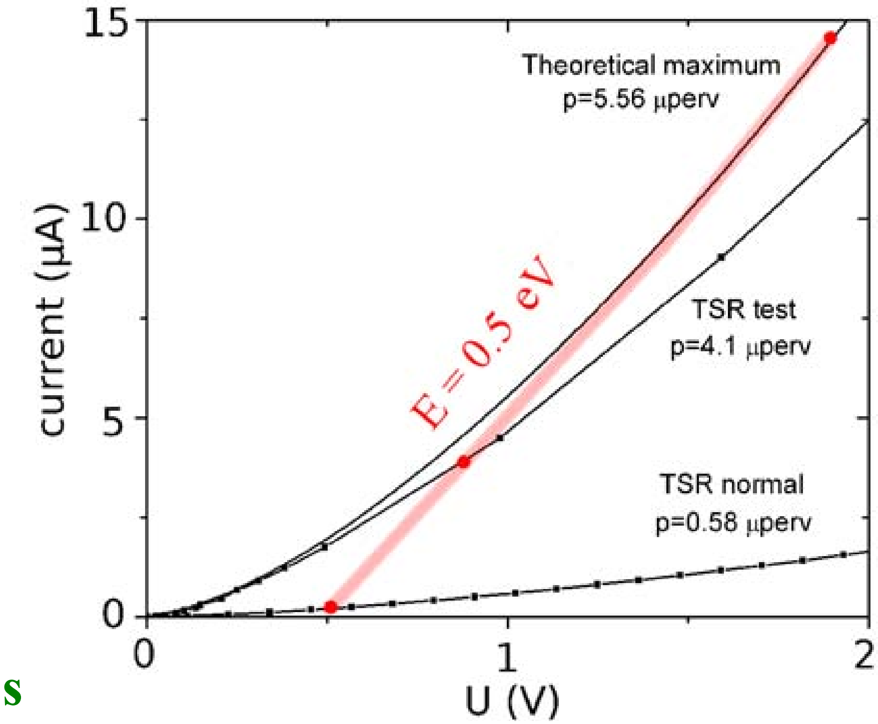
  $\boldsymbol{n_e \sim 10^5\ \mathrm{cm}^{-3}}$

- Cooling times

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

**up to ~ 100 s …**

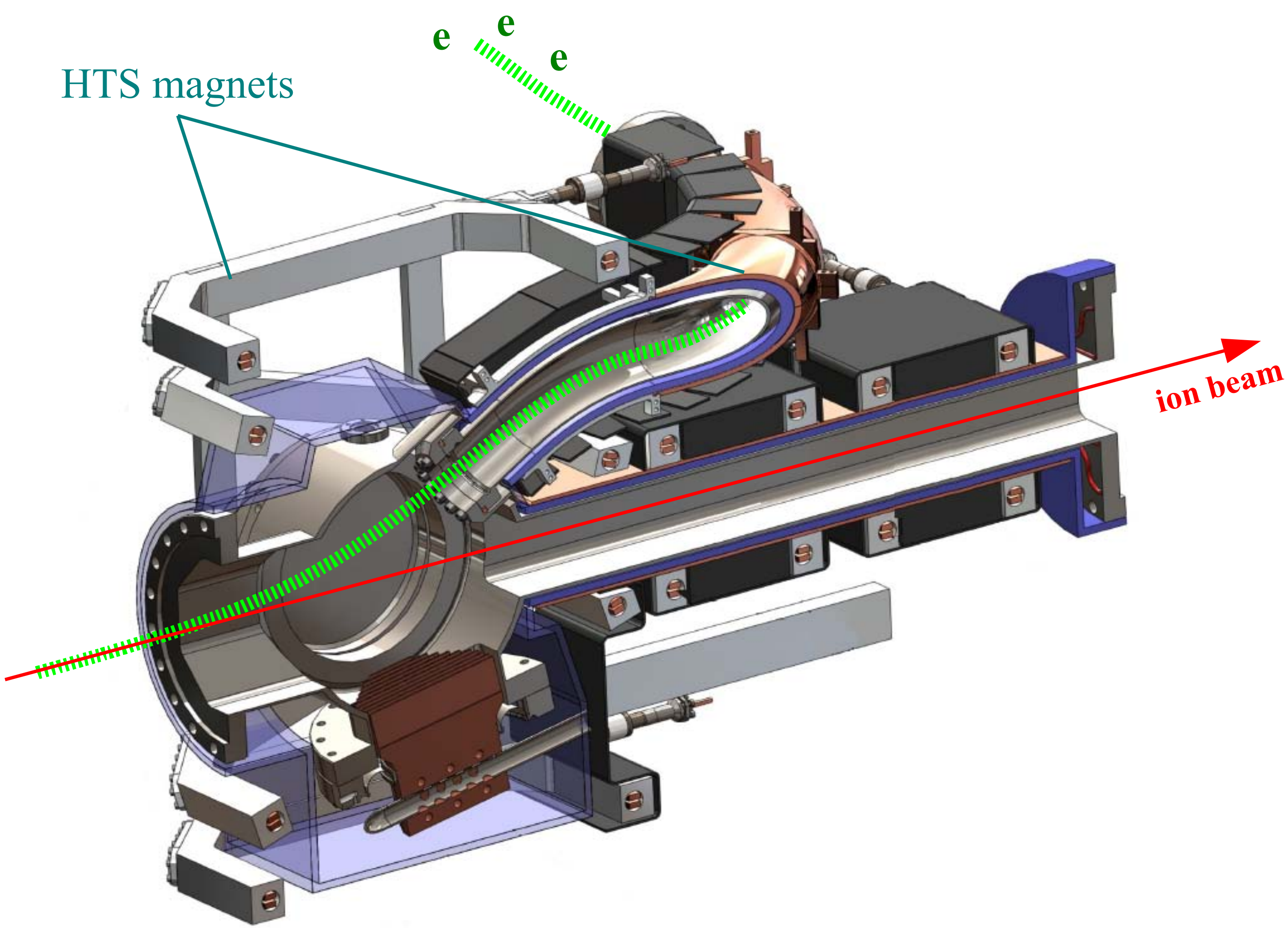
**… but: ion lifetime ~ 1000 s**




[Shornikov, t.b.p.]

# The CSR electron cooler

Magnetic guiding field




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

Magnets + chambers **cryogenic**

**HT superconductors**

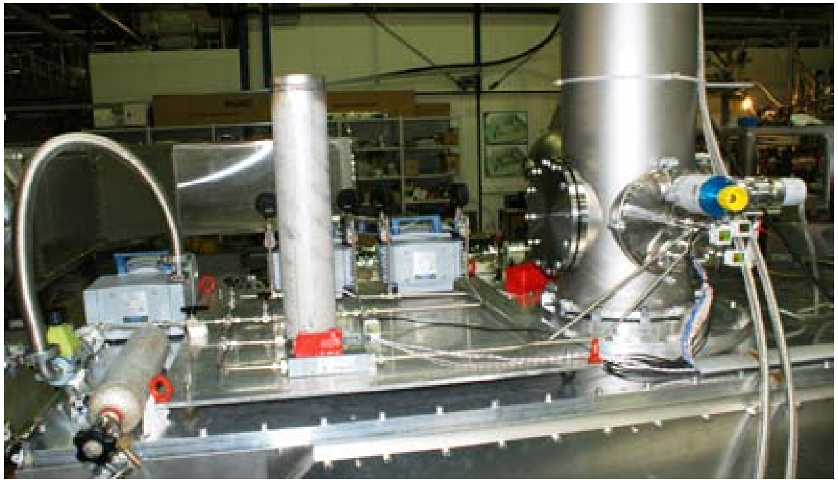
**(no heating of CSR)**

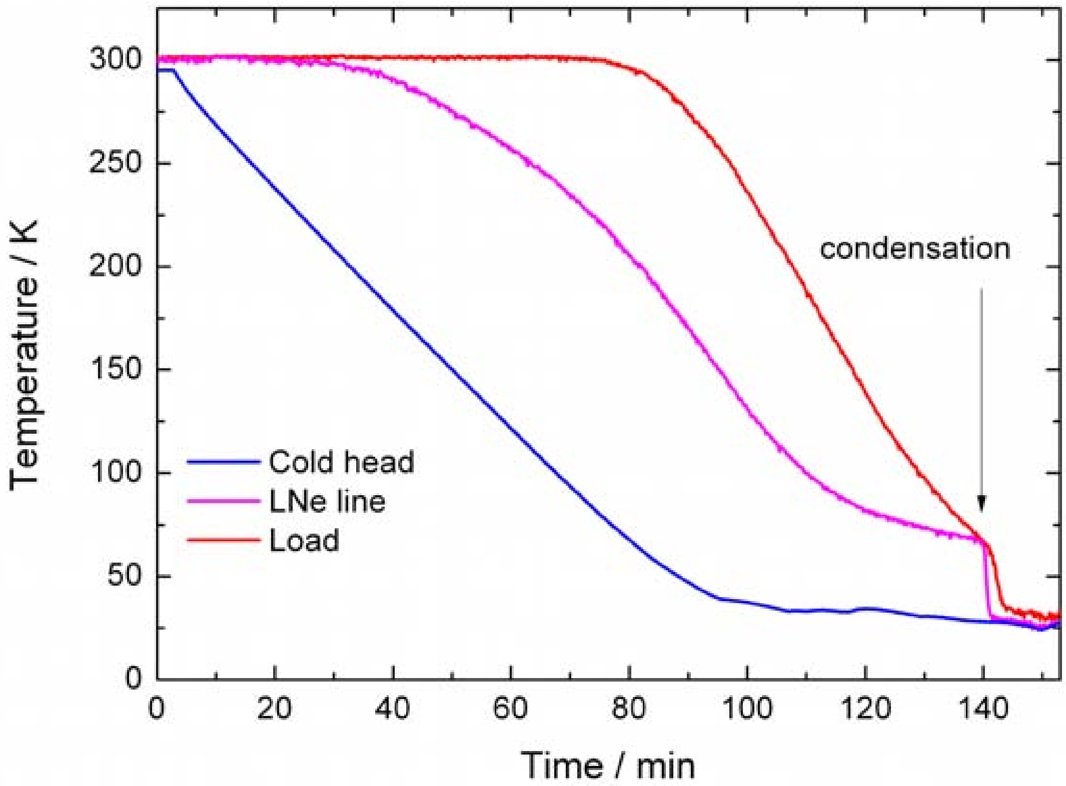
Cryogen: **LNe**

# The CSR electron cooler

Magnet cooling system (LNe)

**25 W at 32 K**






HTS magnet prototype

# The CSR electron cooler

Design phase complete

Cryo-cooling system and HTS magnet tested

Final construction design of cold vacuum chambers

Ordering of vacuum and magnet components

2012: Assembly of cold chambers and magnets

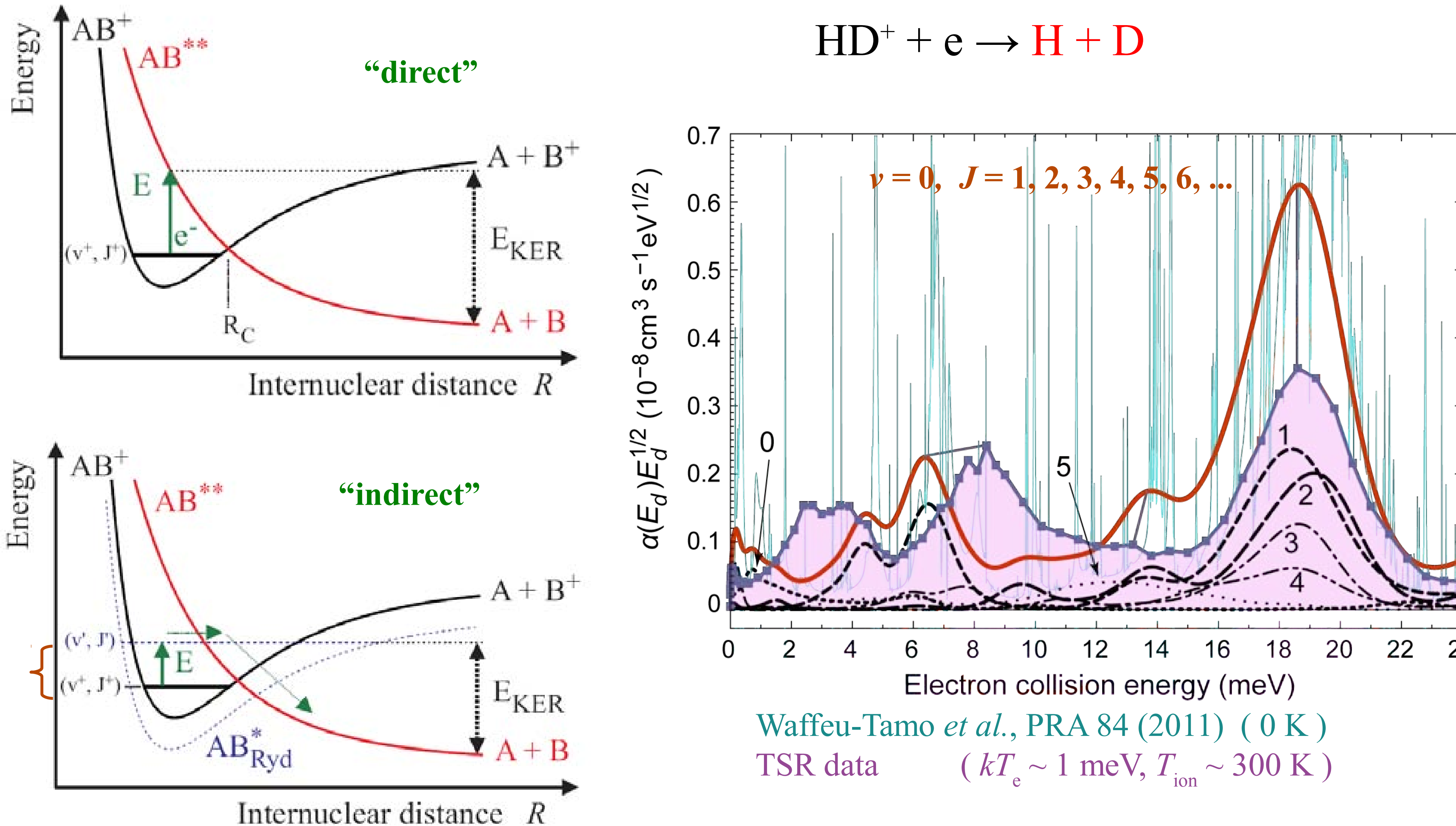
2012: Assembly of outer beam lines

2013: TSR photo cathode setup → CSR

…

first electron cooling at CSR

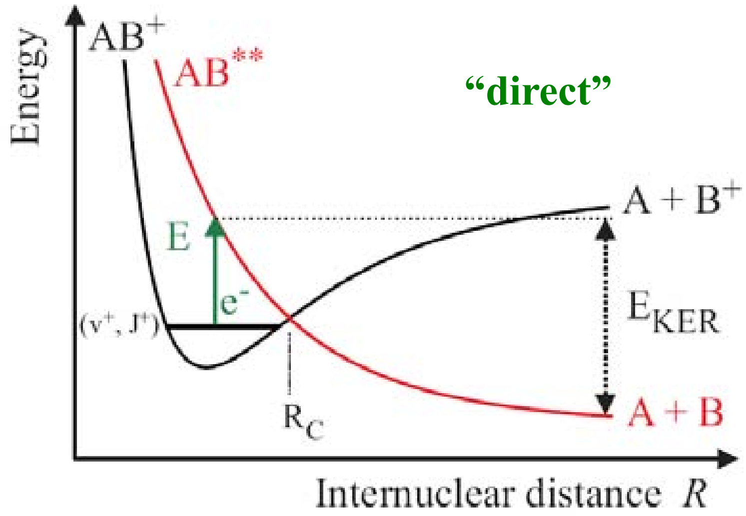
# Outlook: Molecular physics at CSR

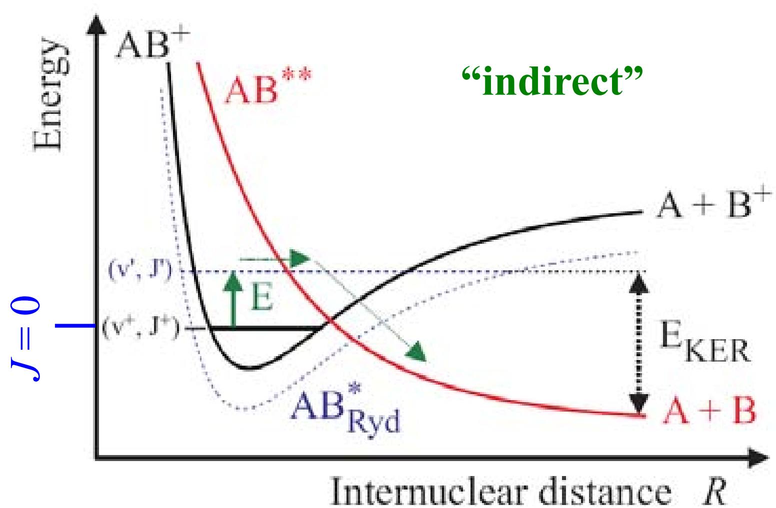



Waffeu-Tamo *et al.*, PRA 84 (2011) ( 0 K )

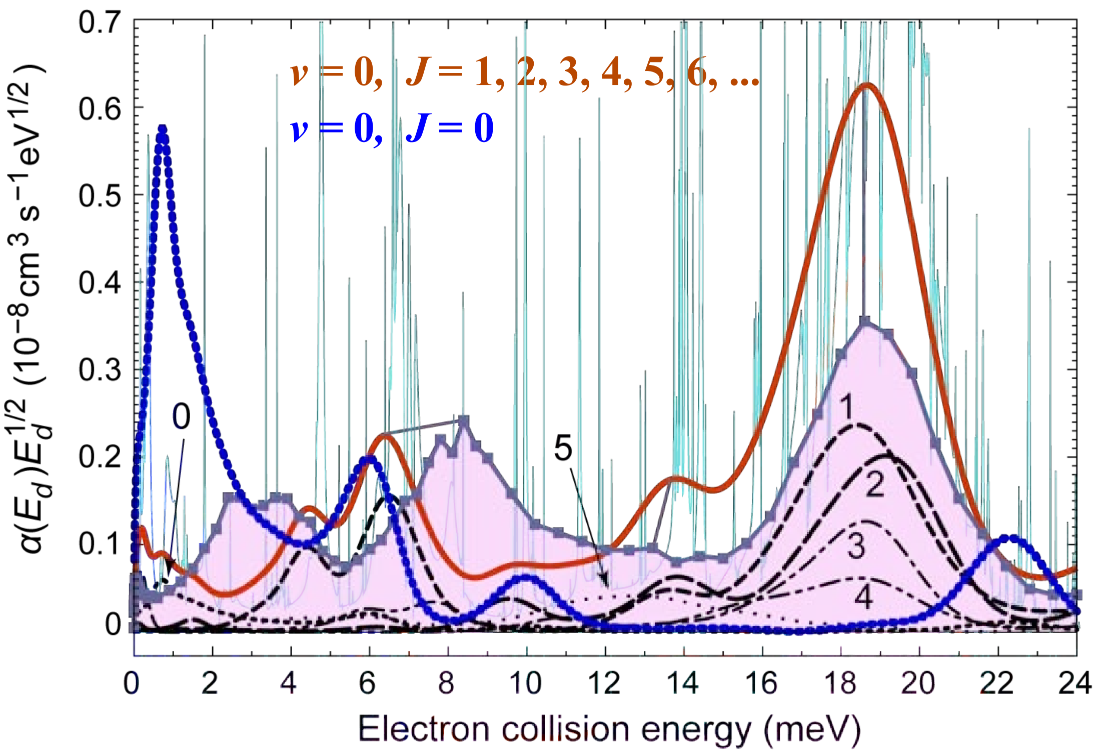
TSR data ( $kT_e \sim 1$ meV, $T_{ion} \sim 300$ K )

# Outlook: Molecular physics at CSR




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



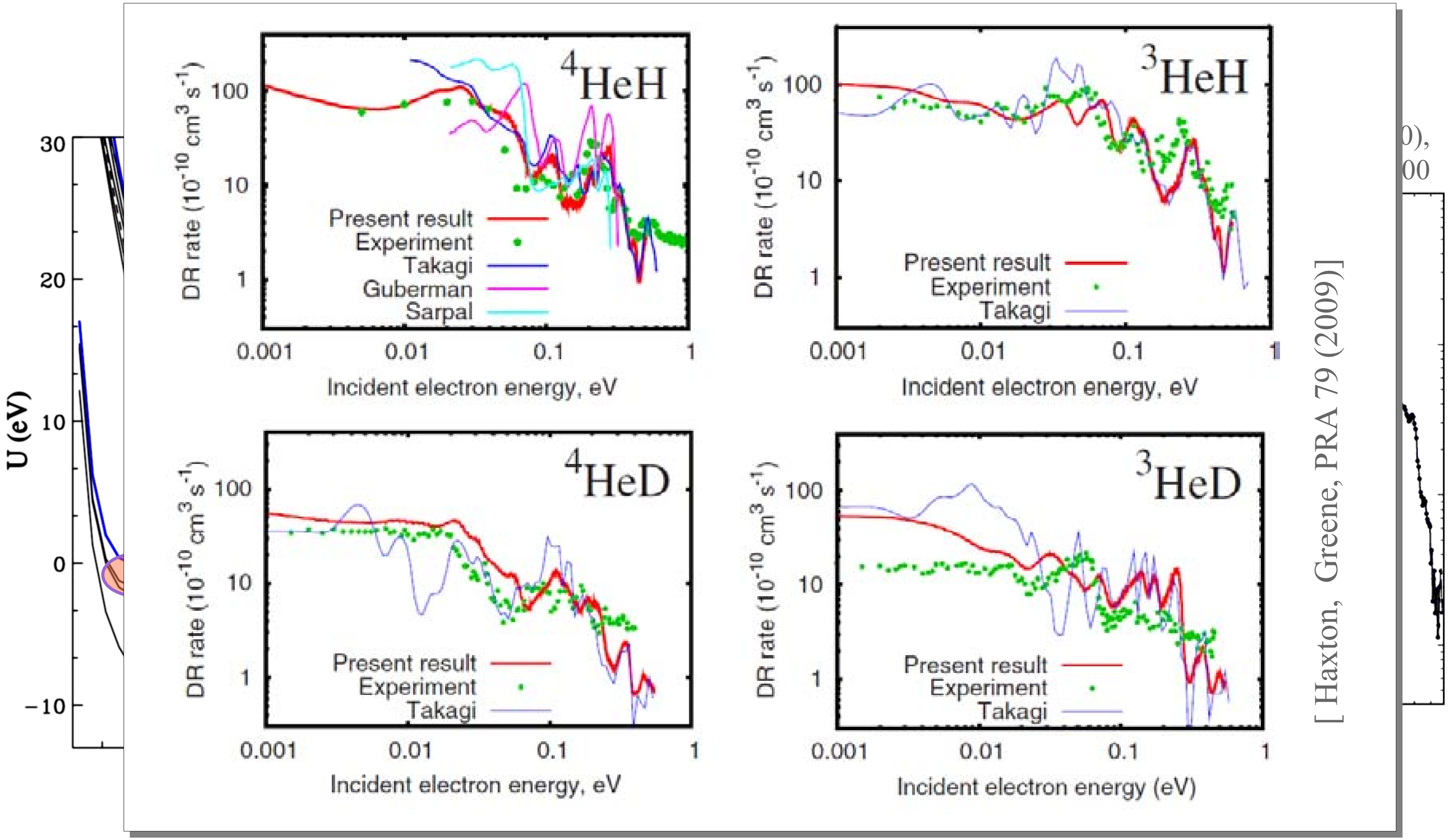

Waffeu-Tamo *et al.*, PRA 84 (2011) ( 0 K )

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 → $J = 0$**

# Outlook: Molecular physics at CSR




[ Haxton, Greene, PRA 79 (2009)]

**at CSR: $E_{cool} = 32$ eV**
**10 K $\rightarrow J = 0$**

# Summary

Slow molecular ion beams are fun but challenging.

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e-cooling of them requires cold emitter cathodes.

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NEA photo cathodes can be ideal cold electron sources.

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A photo cathode e-cooler is being build for the Heidelberg CSR.

# Thank you!

**Max-Planck-Institut für Kernphysik, Heidelberg**

Andrey Shornikov

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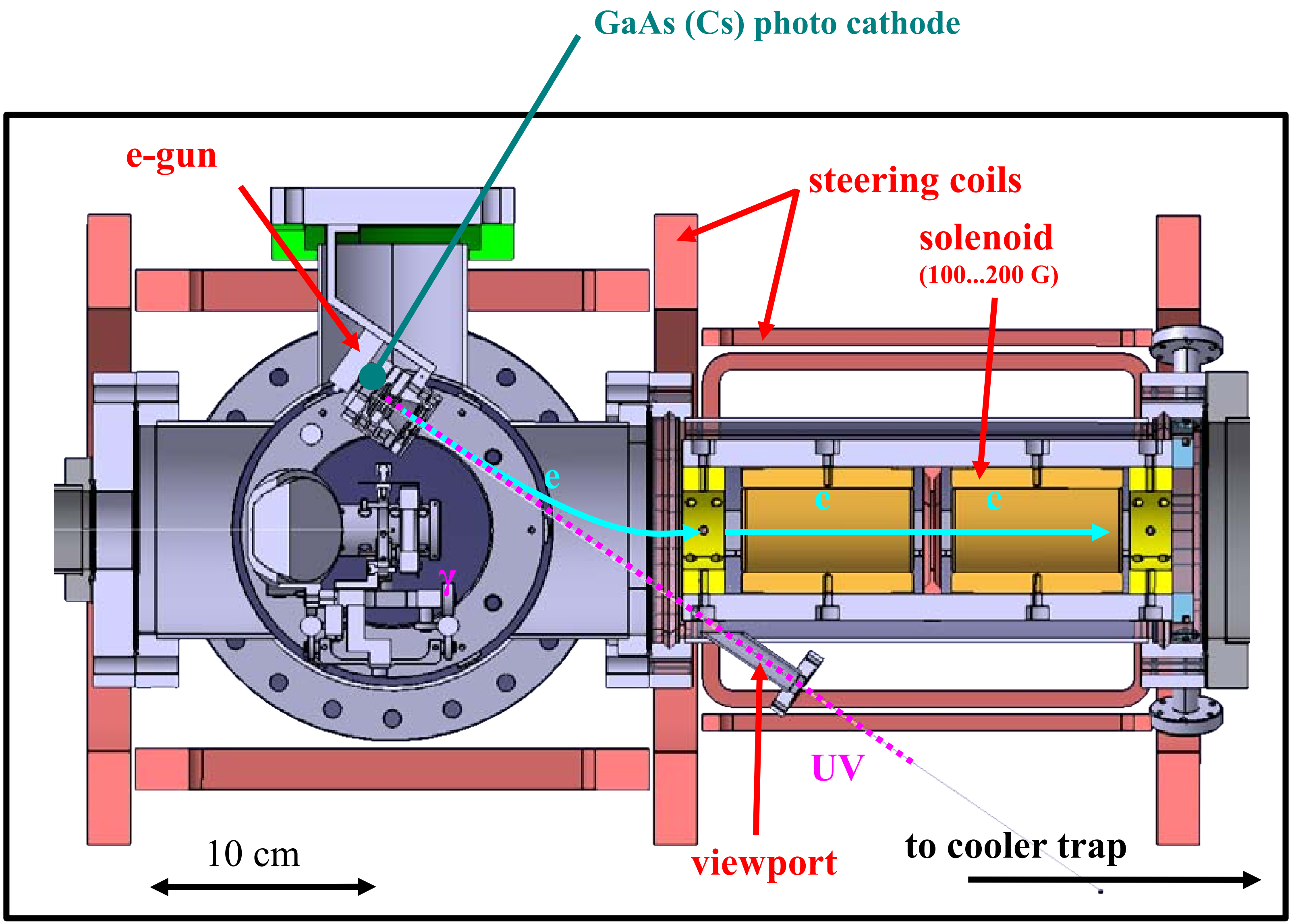
Daniel W. Savin

**Justus-Liebig Universität, Giessen**

Kaija Spruck

Stefan Schippers

# Spin-off project: HITRAP e-gun



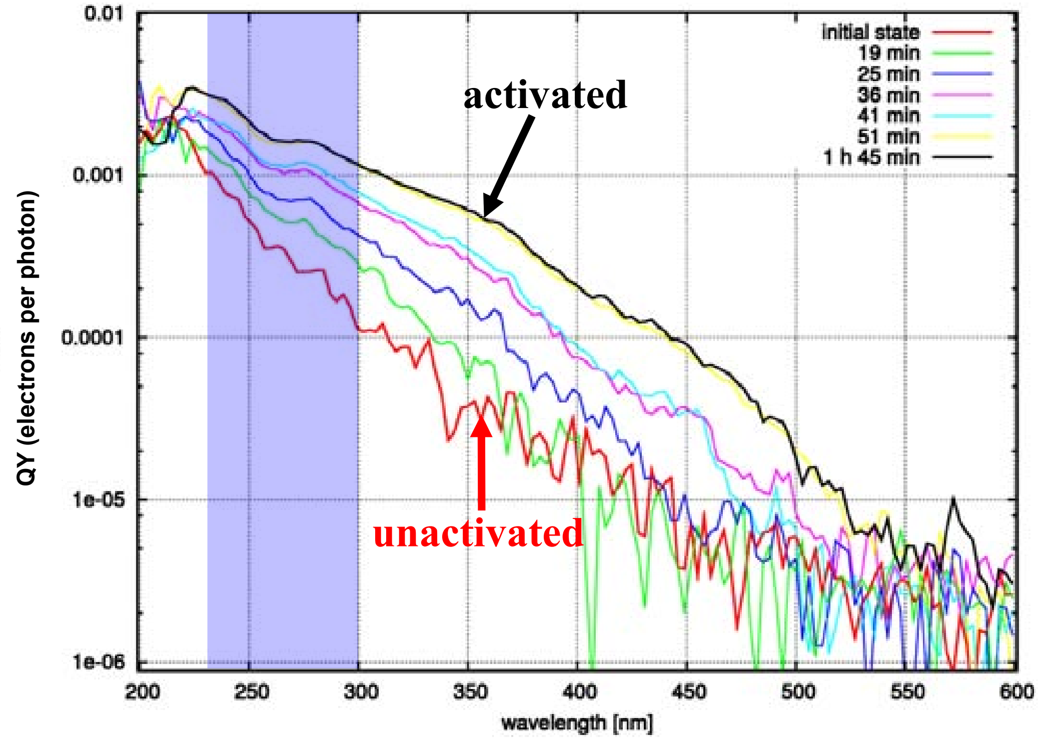
# Spin-off project: HITRAP e-gun

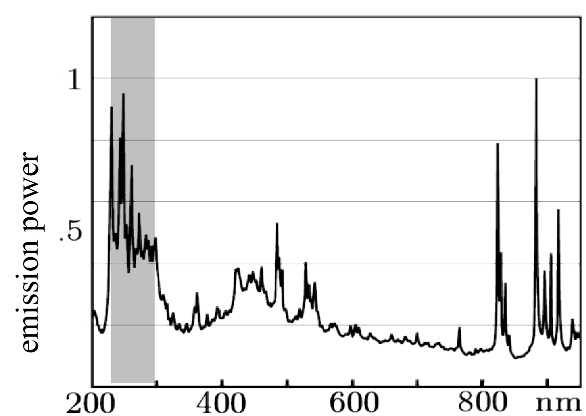
## GaAs photocathode:

- “minimally” activated **GaAs(Cs)** cathode.
- **QY > 0.1%** for 230 nm ≤ λ ≤ 300 nm
- UV efficiency low, but **robust** (and still higher than e.g. metal)
- UV light provided by *Hamamatsu L9455* **Xe flashlamp**.

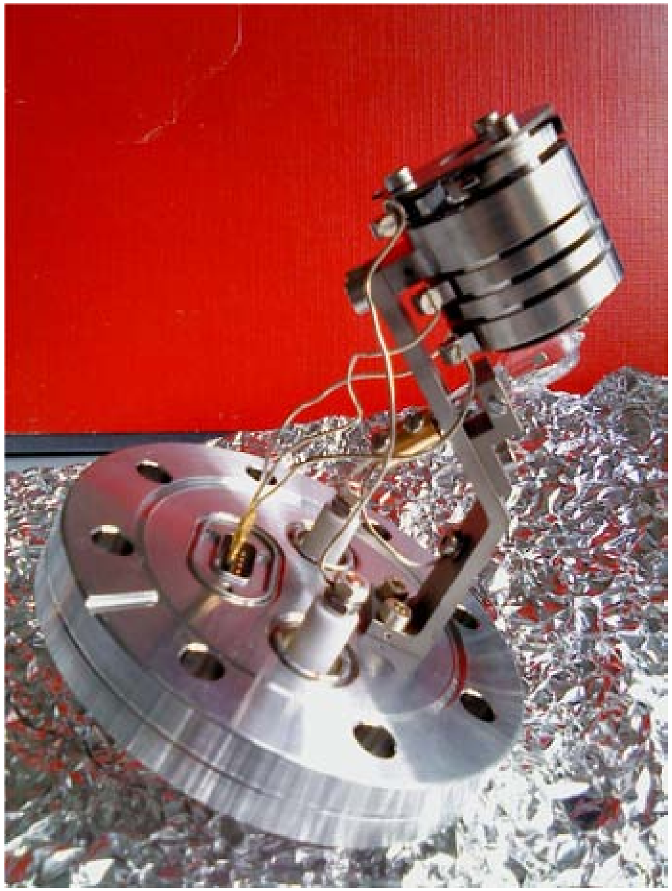
**FWHM: 300 ... 500 ns**
**few µJ in UV**
**rate 0 ... 150 Hz**
**“cheap”**

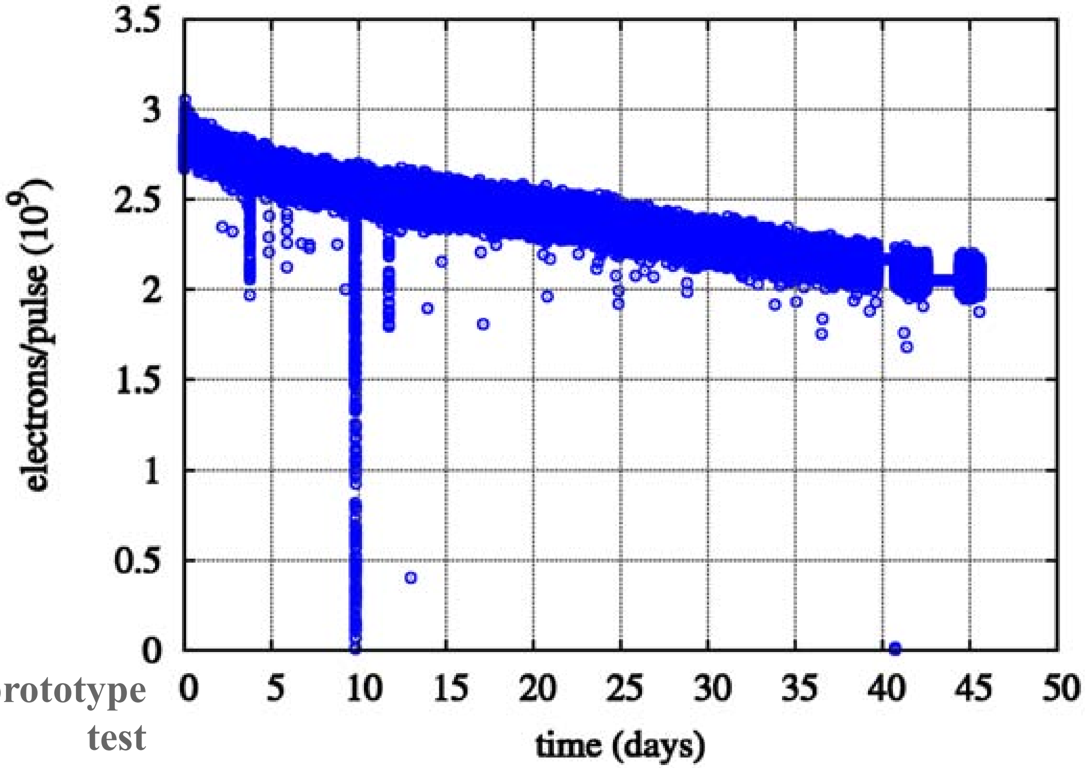
**Cs activation:**



# Spin-off project: HITRAP e-gun






prototype test