Ultra Cold Electron Beams for the Heidelberg TSR and CSR

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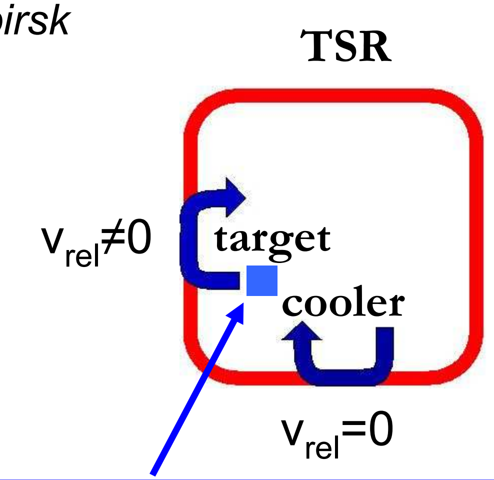
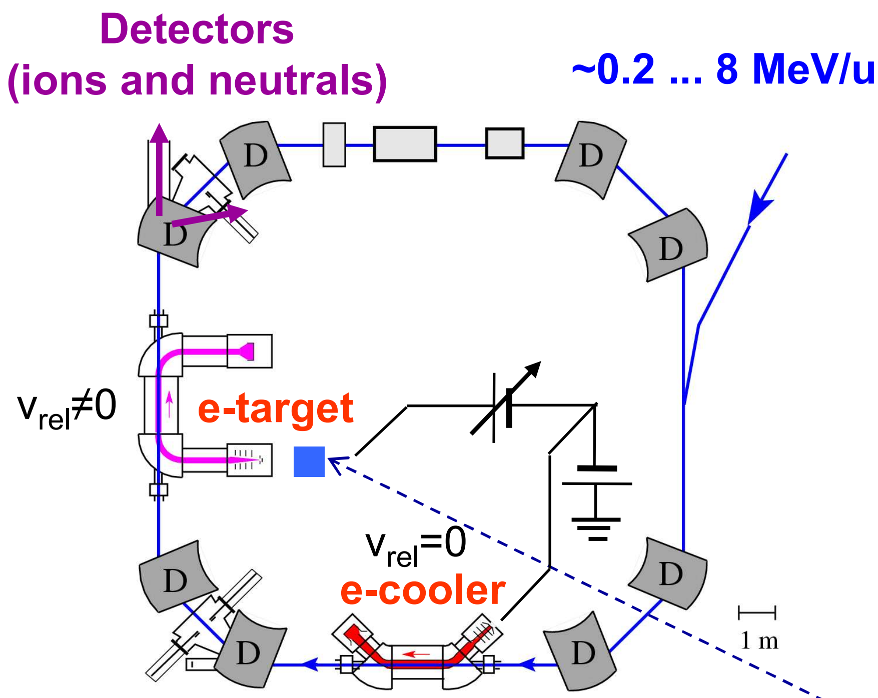
- Cold electron target for TSR
- Electron beam formation
- Cold electrons from cryogenic photocathodes
- Experimental: target, photocathode setup
- First results with photocathode-driven target
- Electron cooler with cryogenic photocathodes for low-energy electrostatic storage rings



Photocathode source at 90 K :
$kT_C \approx 10$ meV

$kT_\perp = 0.5$ meV ; $kT_\parallel = 0.02$ meV

TSR electron target - concept

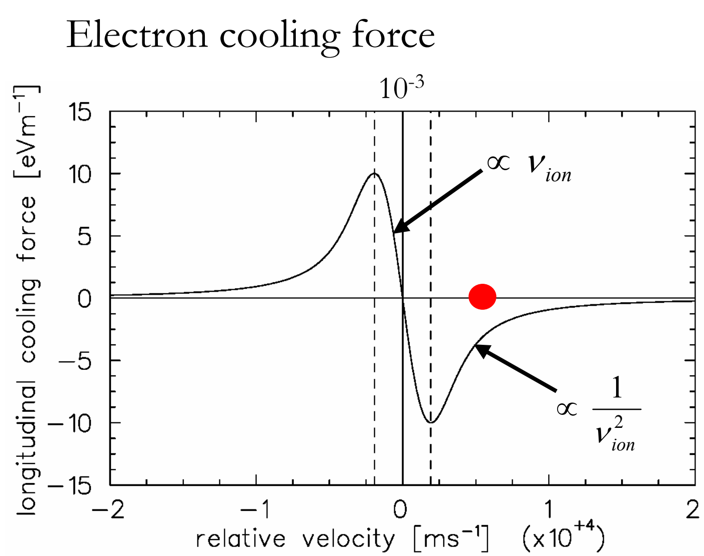


Enhanced experimental resolution:

- ❑ **separation of cooling and target operation:**
  - **- continuously cooled ion beam,**
  - **- no change of ion velocity**
- ❑ **adiabatic acceleration: lower $kT_{\parallel}$**
- ❑ **magnetic adiabatic expansion: lower $k\,T_{\perp}$**
  $k_B T_{\perp}$ = 3.5 meV ; $k_B T_{\parallel}$ = 0.02 meV

- ❑ **cold source of electrons: photocathode at 90 K**

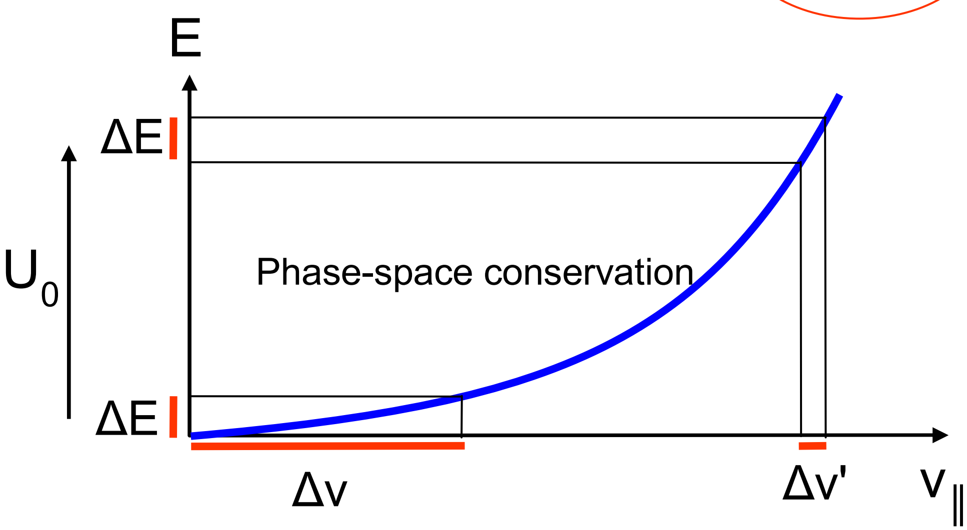
  $k_B T_{\perp}$ = 0.5 meV ; $k_B T_{\parallel}$ = 0.02 meV



Electron beam formation

Acceleration

$kT_\parallel$ reduction: $$k_B T_\parallel \cong \frac{k_B^2 T_C^2}{2eU} + C\frac{e^2}{4\pi\varepsilon_0} n_e^{1/3}$$



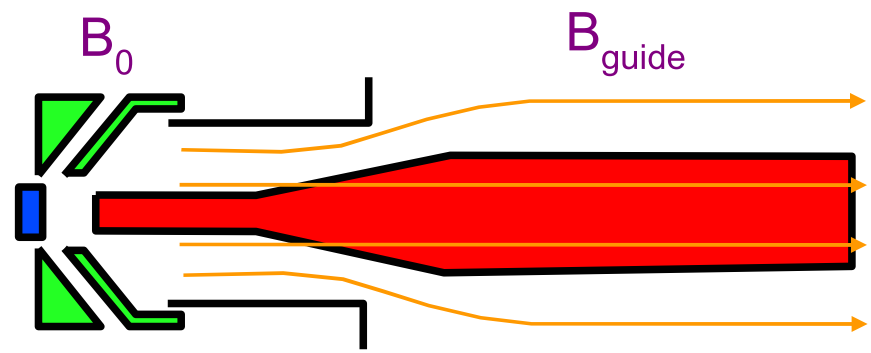
C = 1.9 - fast acceleration
C < 1.9 - slow (adiabatic) acceleration

$kT_\parallel$ = 0.1 meV

$$kT_\parallel \ll kT_\perp$$

Magnetic adiabatic expansion

adiabatic invariant: $E_\perp/B$=const.

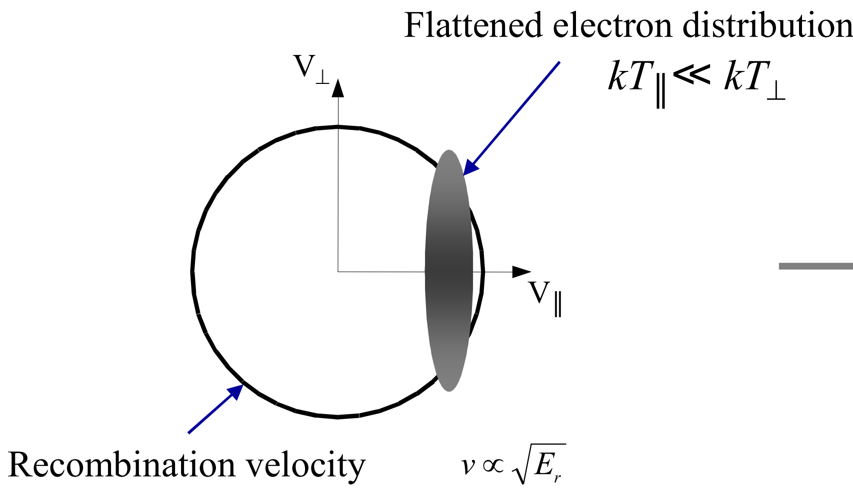


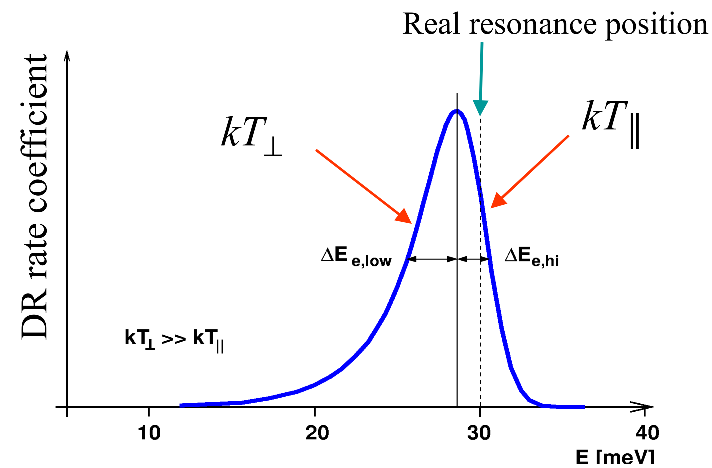
$$\alpha = \frac{B_0}{B_{guide}} \qquad kT_\perp = \frac{kT_C}{\alpha}$$

Thermocathode	kT_C = 110-120 meV
α = 20	$kT_\perp$ = 5-6 meV
α = 90	$kT_\perp$ = 2 meV (CRYRING)

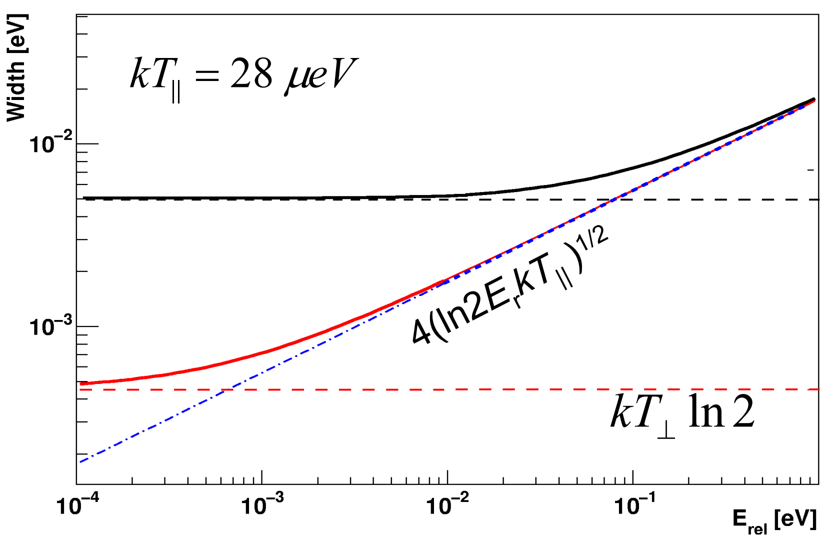
Photocathode	kT_C = 10 meV
α = 20	$kT_\perp$ = 0.5 meV

Electron-ion collision resolution





$$\delta E = \sqrt{(kT_\perp \ln 2)^2 + 16 \ln 2\, E_r kT_\parallel}$$

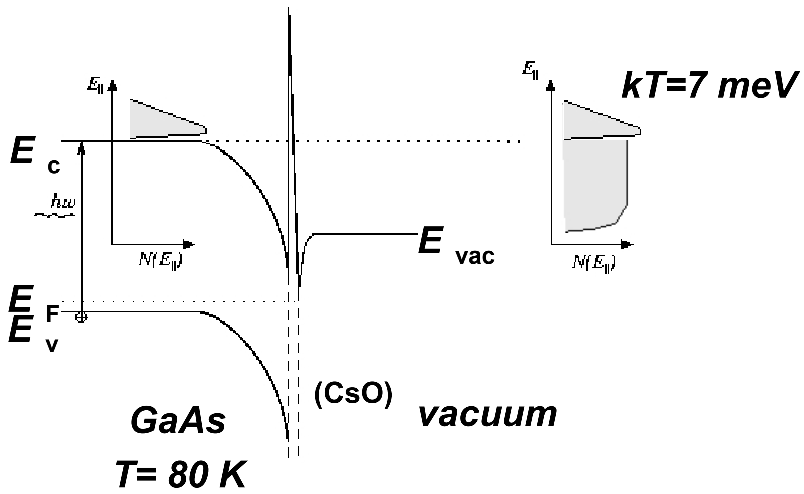


$kT_\perp = 5\ meV$ Thermocathode $kT_C = 110\text{-}120$ meV

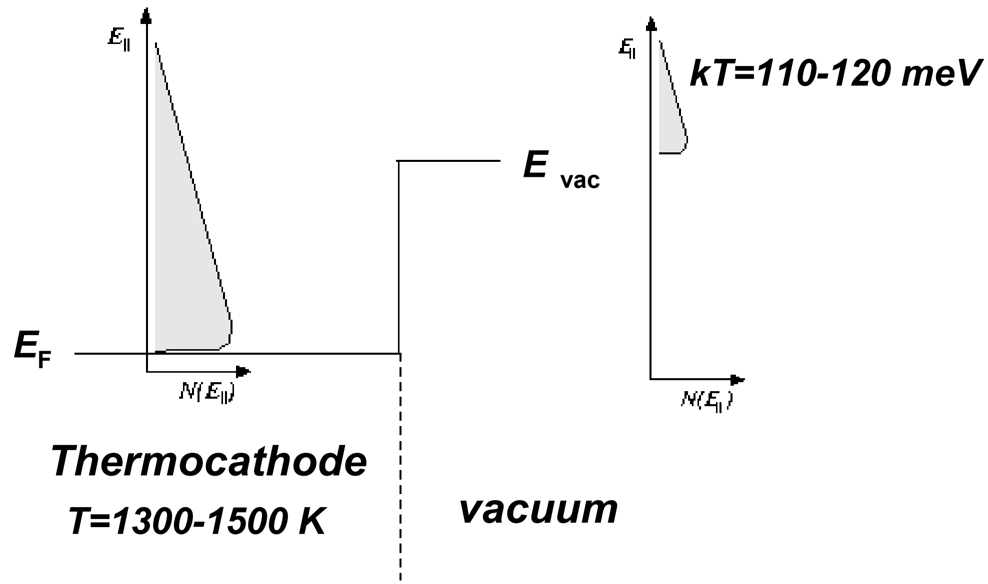
$kT_\perp = 0.45\ meV$ **Photocathode** **$kT_C = 10$ meV**

Electron beam from photocathode

Photocathode principle



Thermocathode principle

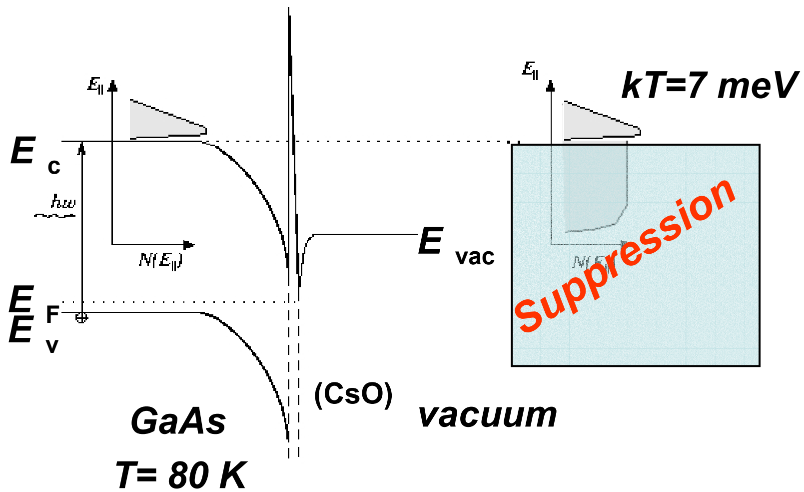


Strong energy and impulse relaxations enlarge electron energy spreads in vacuum

Fully activated cathode: QY= 20-30%

Electron beam from photocathode

Photocathode principle



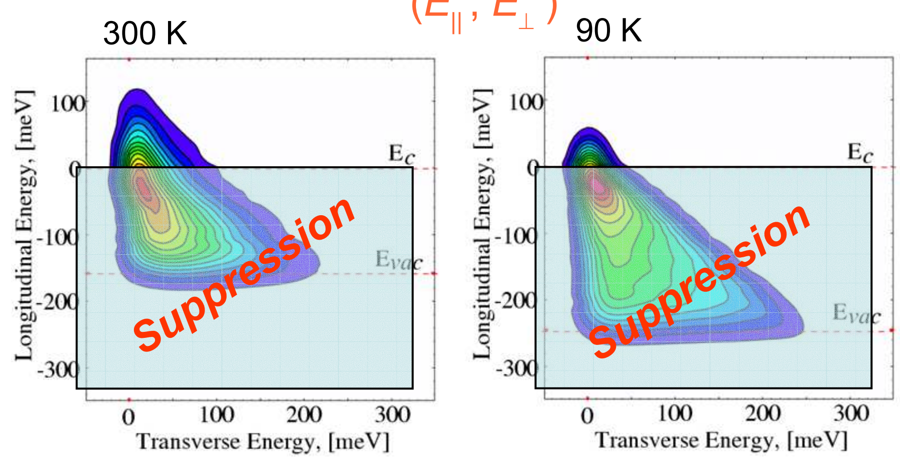
Strong energy and impulse relaxations enlarge electron energy spreads in vacuum

Fully activated cathode: QY= 20-30%

Energy distributions of photoelectrons

"2D"-measurement

$(E_{||}, E_{\perp})$



Suppression

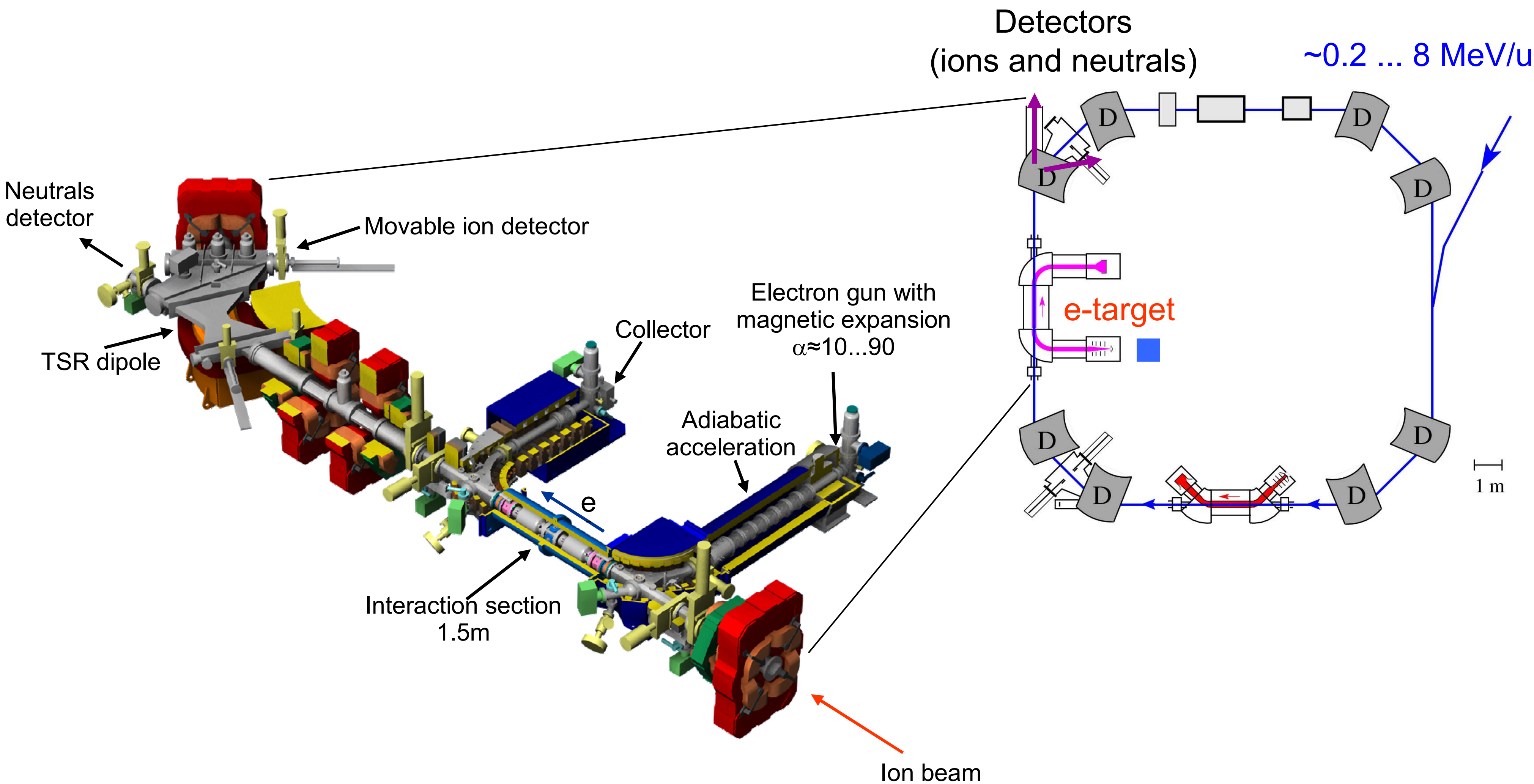
Energy spreads about kT

QY_{eff}=1 %

Laser power (800 nm) for 1 mA: < 1 W
Efficient heat transfer from the cathode

D. A. Orlov et al., Appl. Phys. Lett. 78 (2001) 2721

TSR electron target section - overview

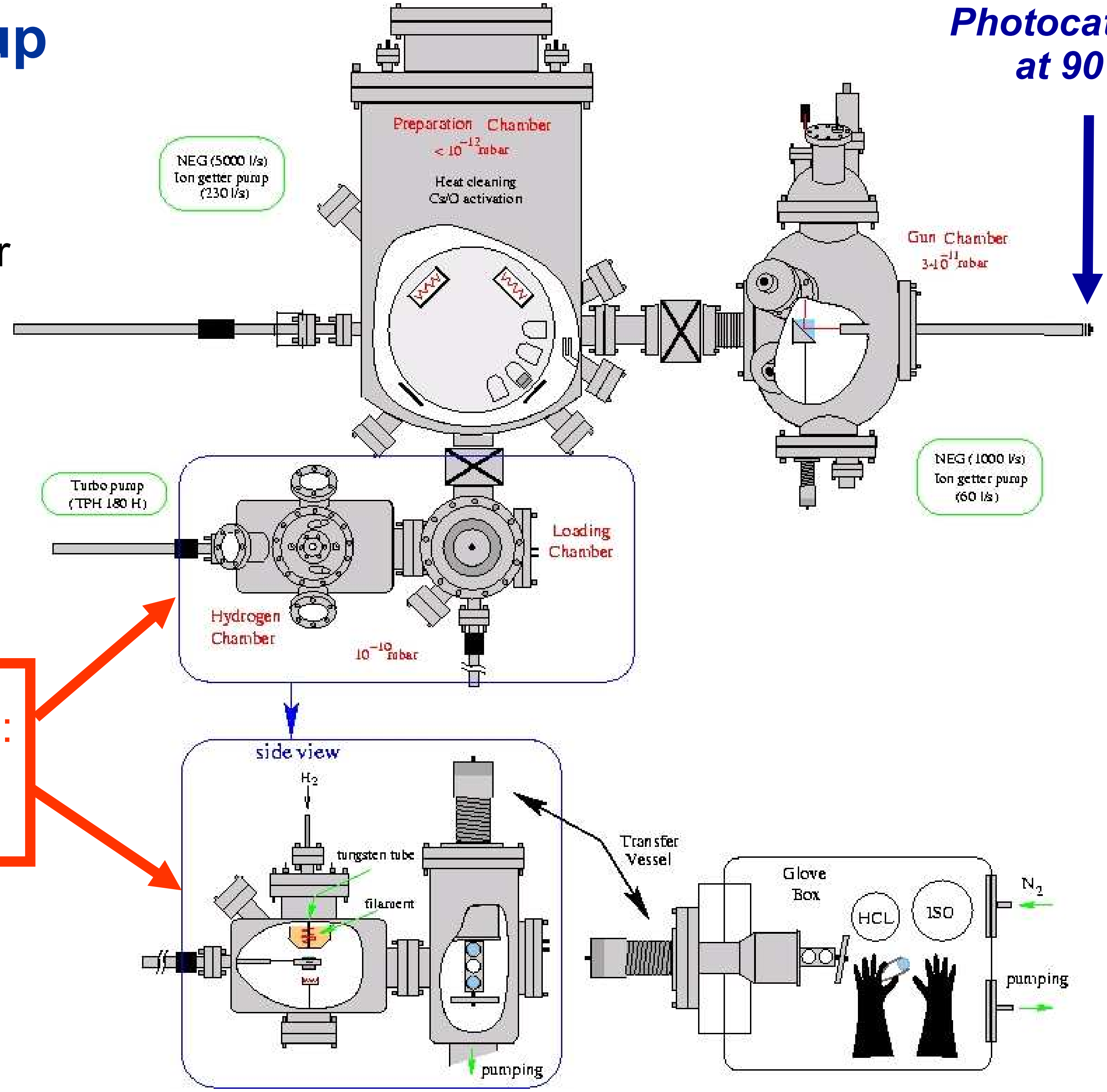


Photocathode setup

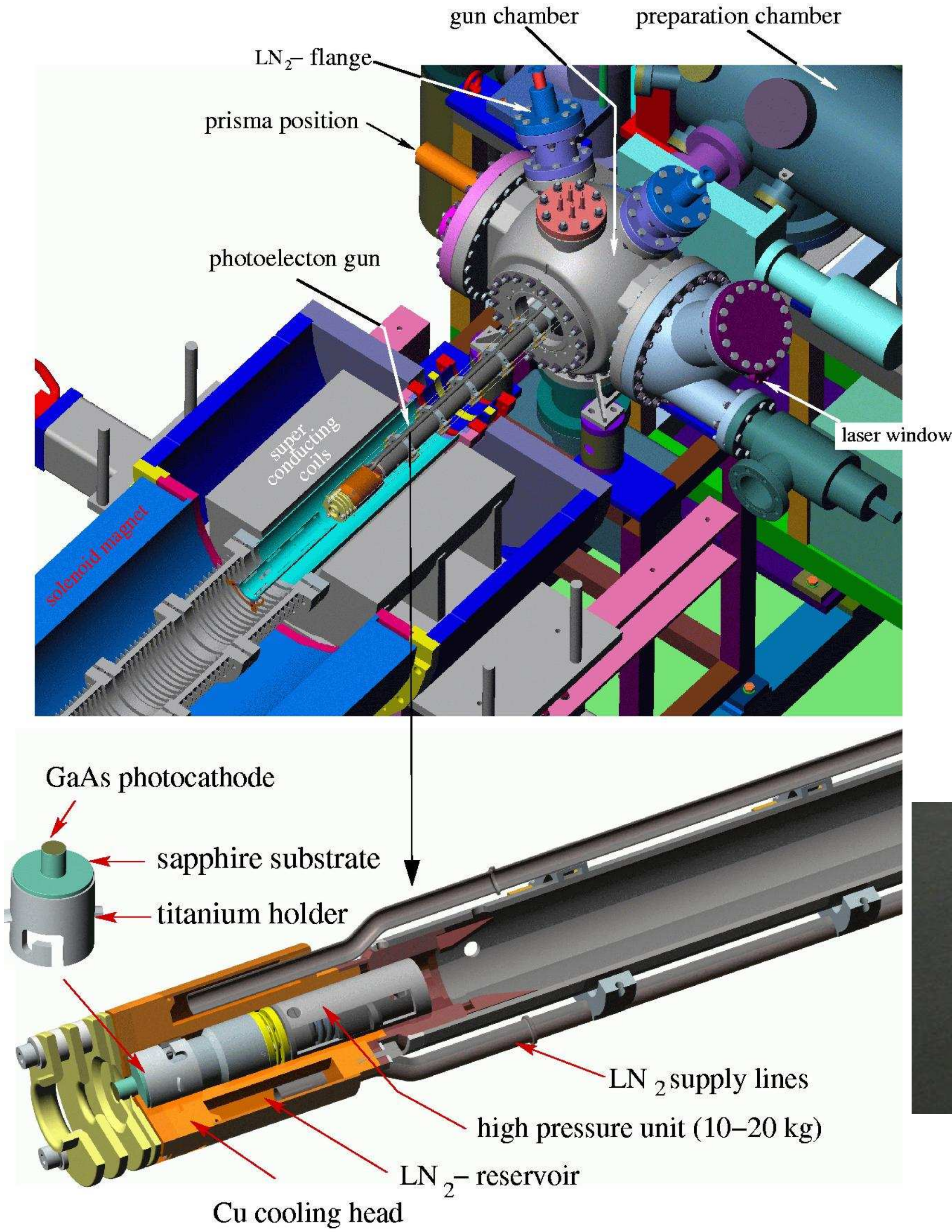
Vacuum conditions:
UHV (10^{-12} mbar)
$H_2O + O_2 + CO_2 < 10^{-14}$ mbar

High requirements for surface preparation

Photocathode at 90 K



Atomic hydrogen cleaning:
Closed cycle of operation



Photocathode gun

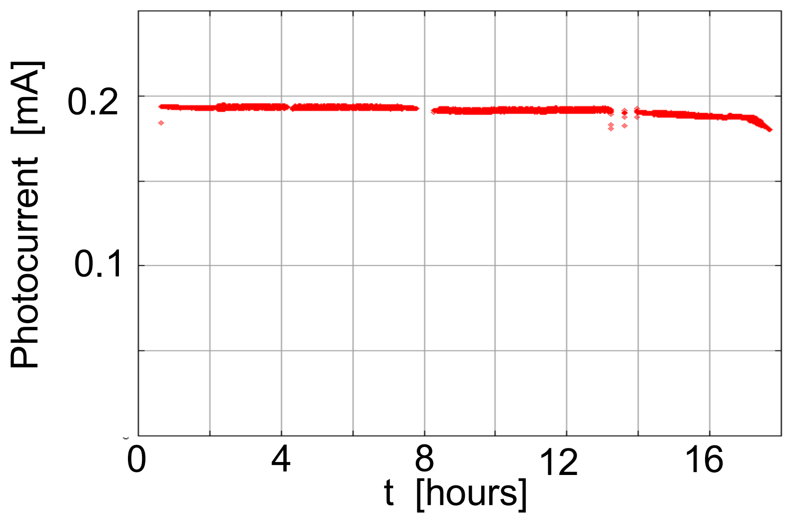
Laser illumination up to 1 W

Temperature rise 15-20 K/W at 90 K

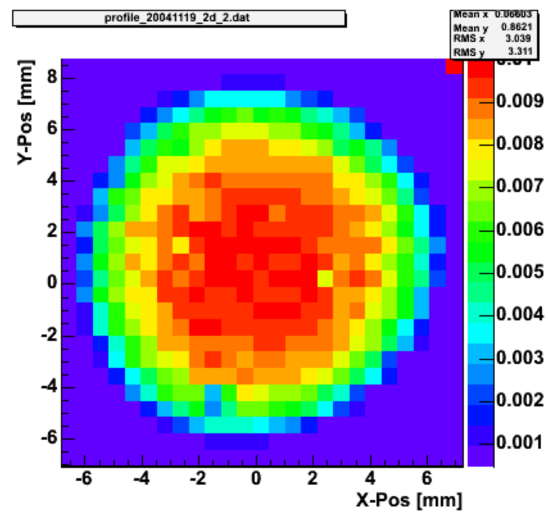
U. Weigel et al., NIM A 536 (2005) 323

Photocathode performance at the TSR target

Lifetime data



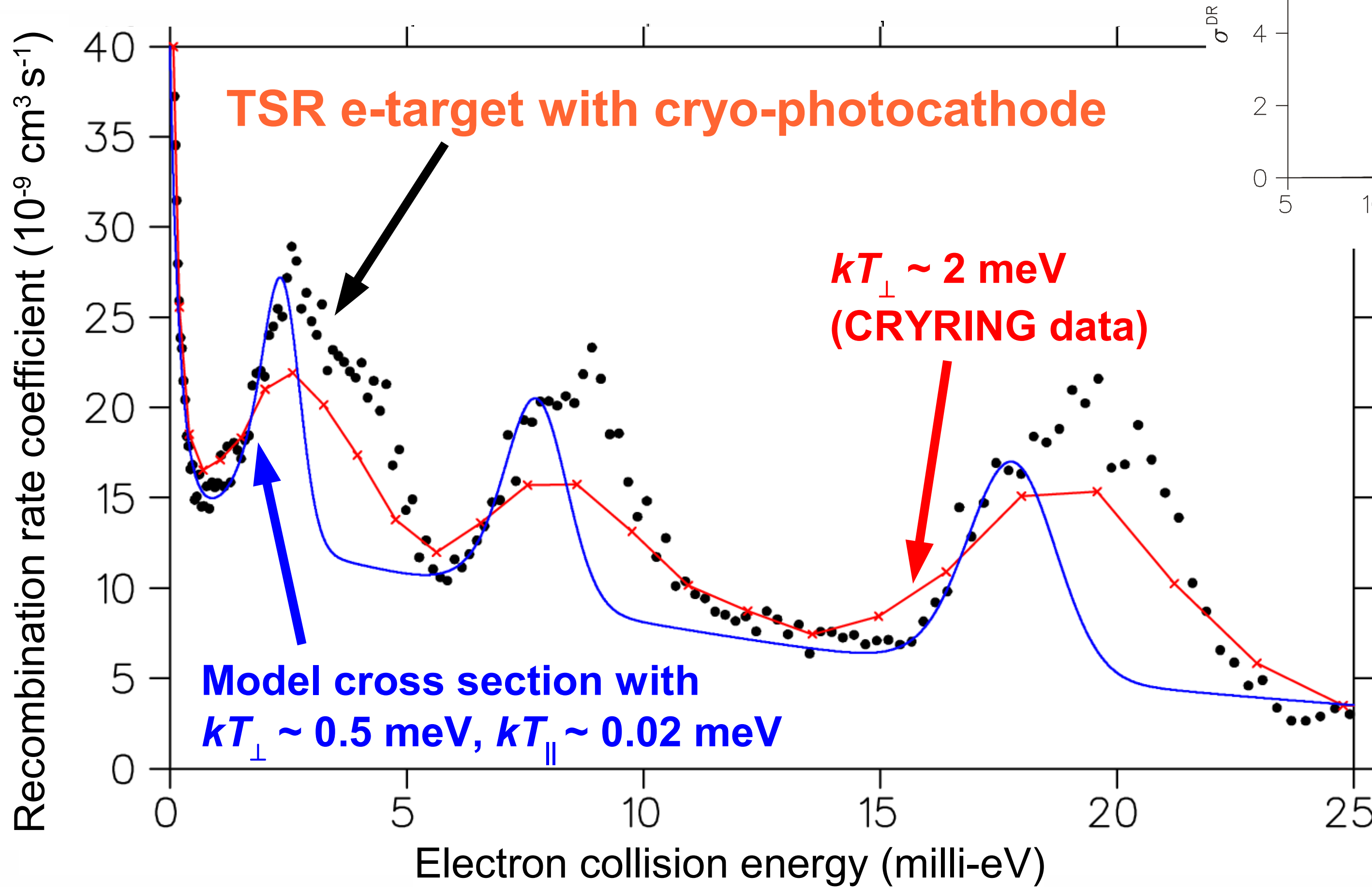
Beam profile

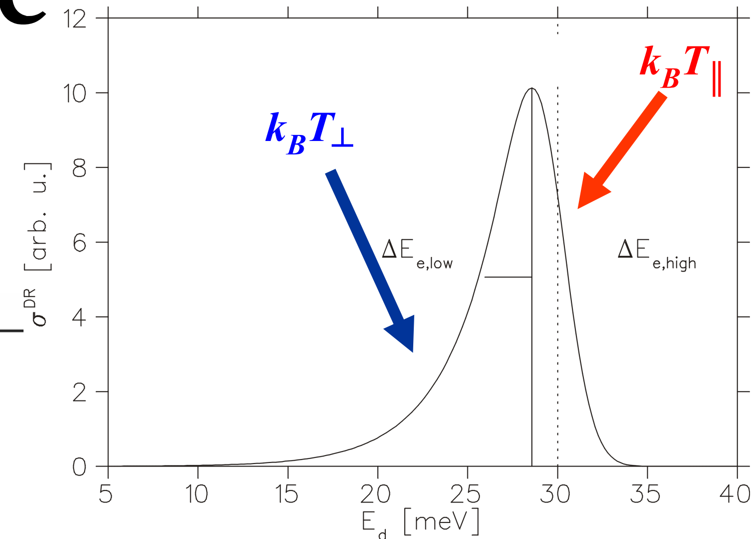


- ❑ **Lifetimes 7-15 hours at 0.15-0.2 mA**
- ❑ **Non-stop operation**
- ❑ **Closed cycle of operation**
- ❑ $k_B T_\perp$ **= 0.5 meV** $k_B T_\parallel$ **= 0.02 meV**

Photocathode performance at the target

$HD^{+}(1s\sigma, v = 0, J) + e \rightarrow HD^{**}(1s\sigma\, n\ell\lambda,\ v'J') \rightarrow H(n) + D(n')$



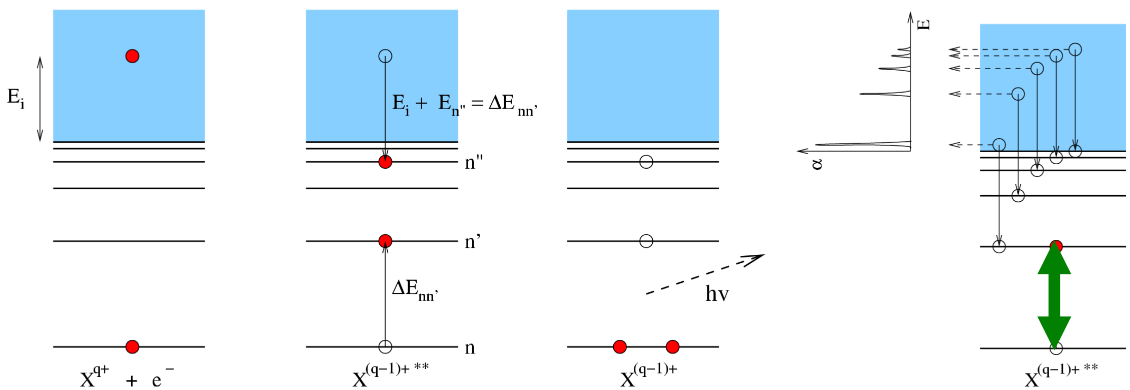


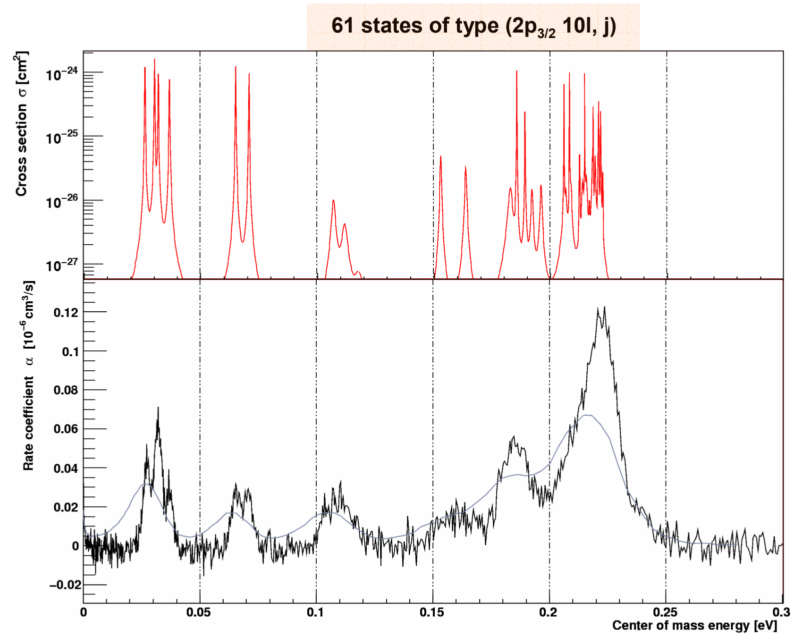
H. Buhr et al., work in progress

D. A. Orlov et al., J. Phys.: Conf. Ser. 4 (2005) 290.

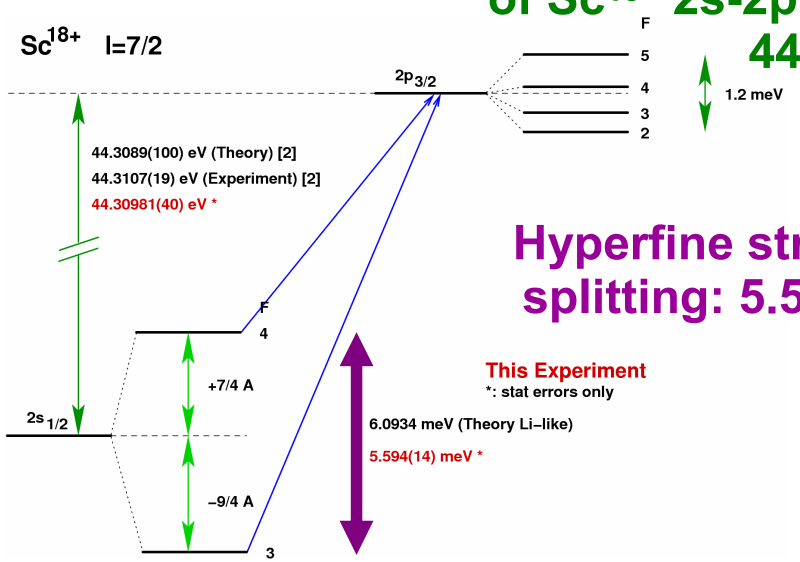
Photocathode performance at the target

$Sc^{18+} (2s_{1/2}) + e^- \rightarrow Sc^{17+} (2p_{3/2}10d_{3/2})_3$

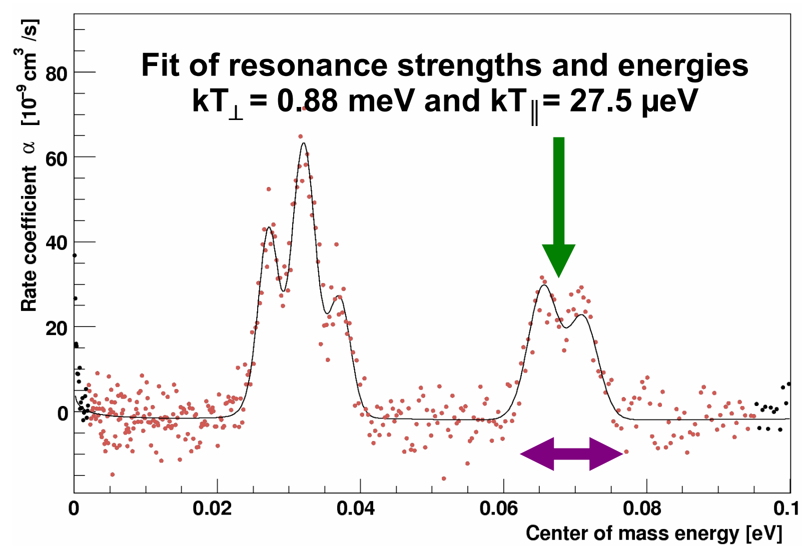




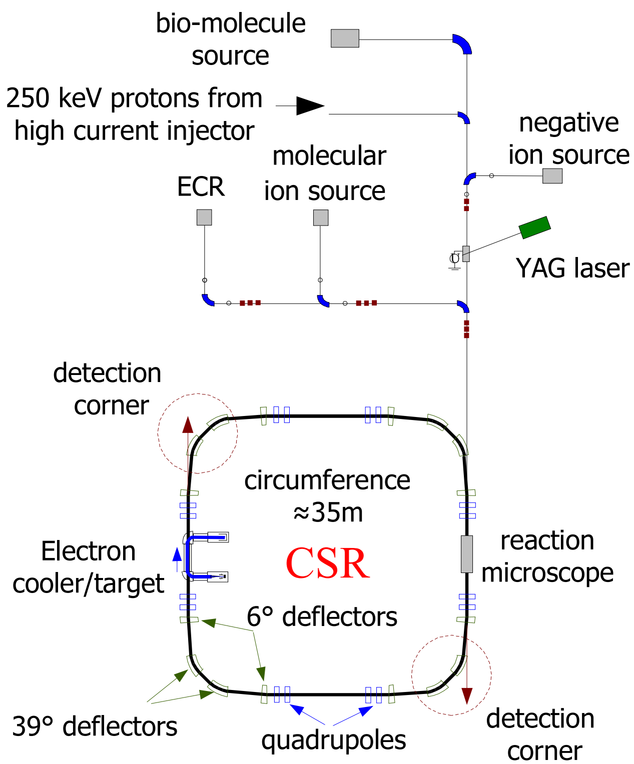
Radiative corrections of Sc^{18+} 2s-2p splitting: 44.3107 eV



Hyperfine structure splitting: 5.59 meV



Ultra-low energy electron cooler for the Heidelberg CSR



Low energy ions

↓

Strong ion deflection in toroid

$$\Delta y \propto R_{tor}^2 \frac{B\,eZ}{\sqrt{E_i M_i}}$$

↙ ↘

Low magnetic field | *Toroid optimization*

Low energy electrons

↓

Adiabaticity ☺ *!*

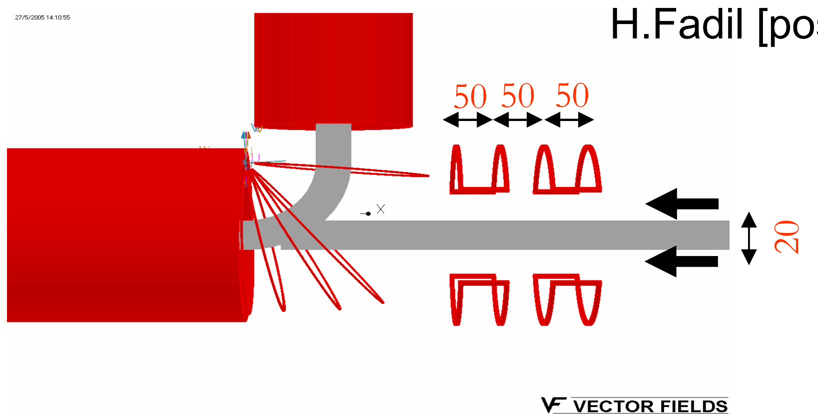
↓

Toroid – simple solution ☺ *!*

$R_{tor}\downarrow,\ B\uparrow$

Ion mass [amu]	Ion energy [keV]	Electron energy [eV]	Bmax [Gauss]
1	10	5.5	15
1	300	165	60
3	300	54	100
32	300	5.1	>300
100	300	1.6	>300

H.Fadil [poster]



Ultra-low energy electron cooling

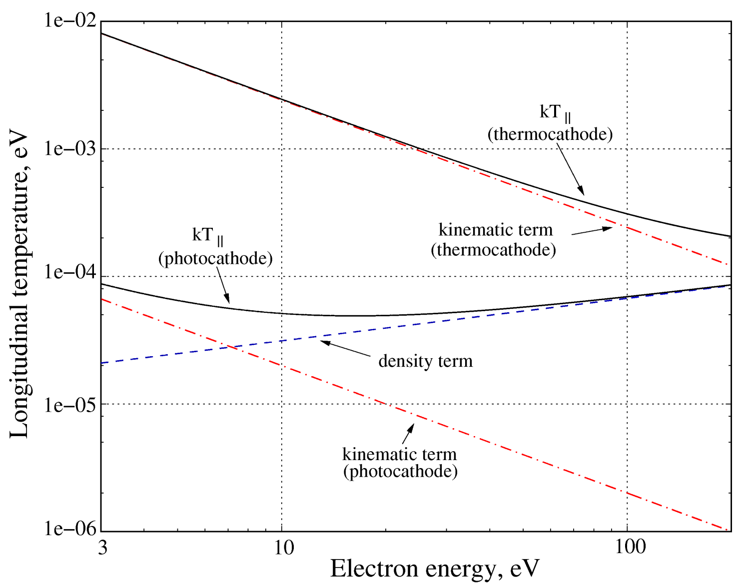
Very low B (10-50 G)

Strong TLR

$$kT_{\parallel} \cong kT_{\perp} \cong kT_C / \alpha$$

$$\tau_{cool}^{\perp} \propto \frac{T_{\perp}^{3/2}}{n_e} \qquad \tau_{cool}^{\parallel} \propto \frac{T_{\perp} T_{\parallel}^{1/2}}{n_n}$$

$$\tau_{cool} \propto \frac{T_C^{3/2}}{n_e}$$



High B

TLR suppressed

$$\tau_{cool} \propto \frac{T_{\parallel}^{3/2}}{n_e}$$

$$k_B T_{\parallel f} \cong \frac{k_B^2 T_C^2}{2eU} + C \frac{e^2}{4\pi\varepsilon_0} n_e^{1/3}$$

$$\tau_{cool} \propto \frac{T_C^3}{n_e}$$

Cold cathode

Photocathode at 90 K
kT_C = 10 meV

Ultra-low energy electron cooling

$P = 2\mu A / U^{3/2}$ $\qquad$ $k_B T_C \cong 10\, meV$

Ion mass [amu]	Ion energy [keV]	Electron energy [eV]	Electron current [mA]	Electron density [10^6 cm $^{-3}$]	Cooling time (cold beam) [s]	Cooling time (hot beam) [s]
1	300	165	4.2	20	0.005	0.05
1	10	5.5	0.02	0.7	0.16	1.6
3	300	54	0.8	6.4	0.5	0.5
32	300	5.1	0.02	0.6	5	50
100	300	1.6	0.004	0.2	50	500

$k_B T_e$ = 0.5 meV

L_C = 3.3

η_C = 0.028

S_{el} = 0.1 S_{ion} (hot beam)

$$\tau_{cool} = C_0 \frac{M_{ion}}{n_e \cdot Z^2 \cdot L_C} \cdot \left(\frac{k_B T_e}{M_e c^2} \right)^{3/2}$$

Summary and outlook

- ❑ Cold photocathode source works close to design parameters
- ❑ Electron target + photocathode:
  Strong gain in energy resolution and accuracy at meV collision energy
- ❑ Work to improve currents, lifetimes and energy spreads in progress

  - ❑ Cold photocathode source beneficial
    for low-energy electron cooling (CSR, low-energy ion beams)

Atomic hydrogen treatment

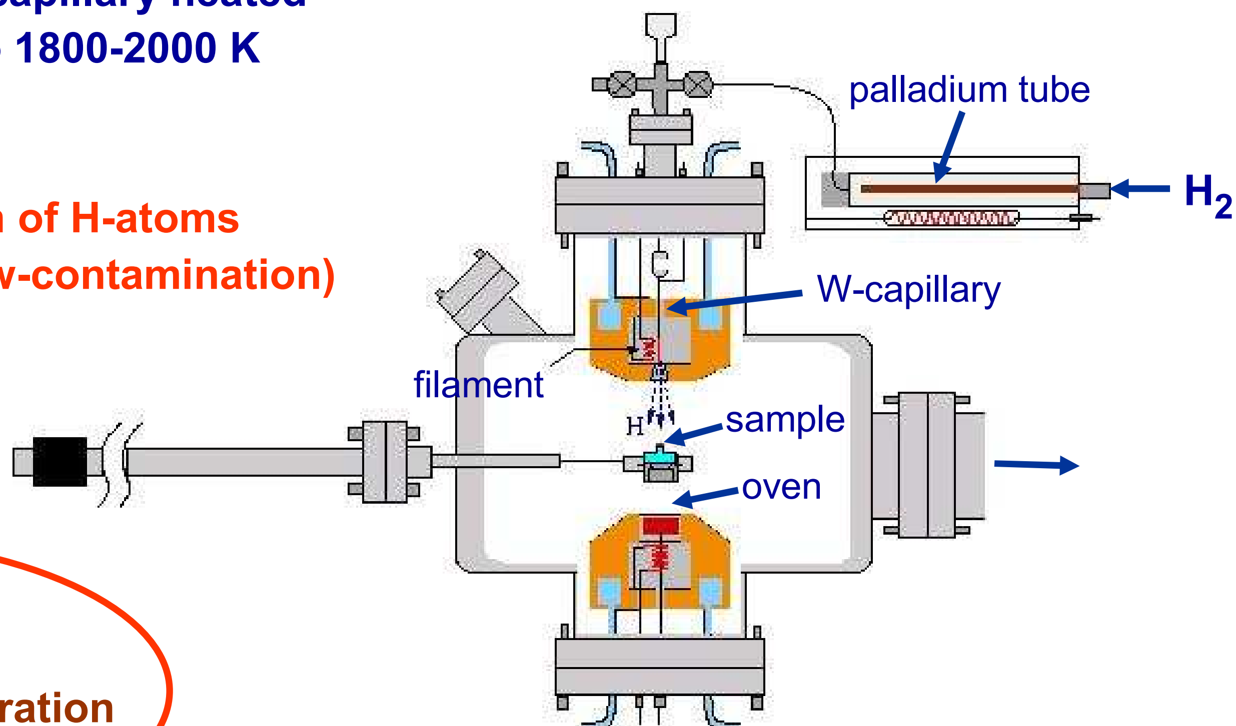
Hot capillary source

It is basically consists of a W-capillary heated by electron bombardment to 1800-2000 K

Efficient

Narrow angular distribution of H-atoms

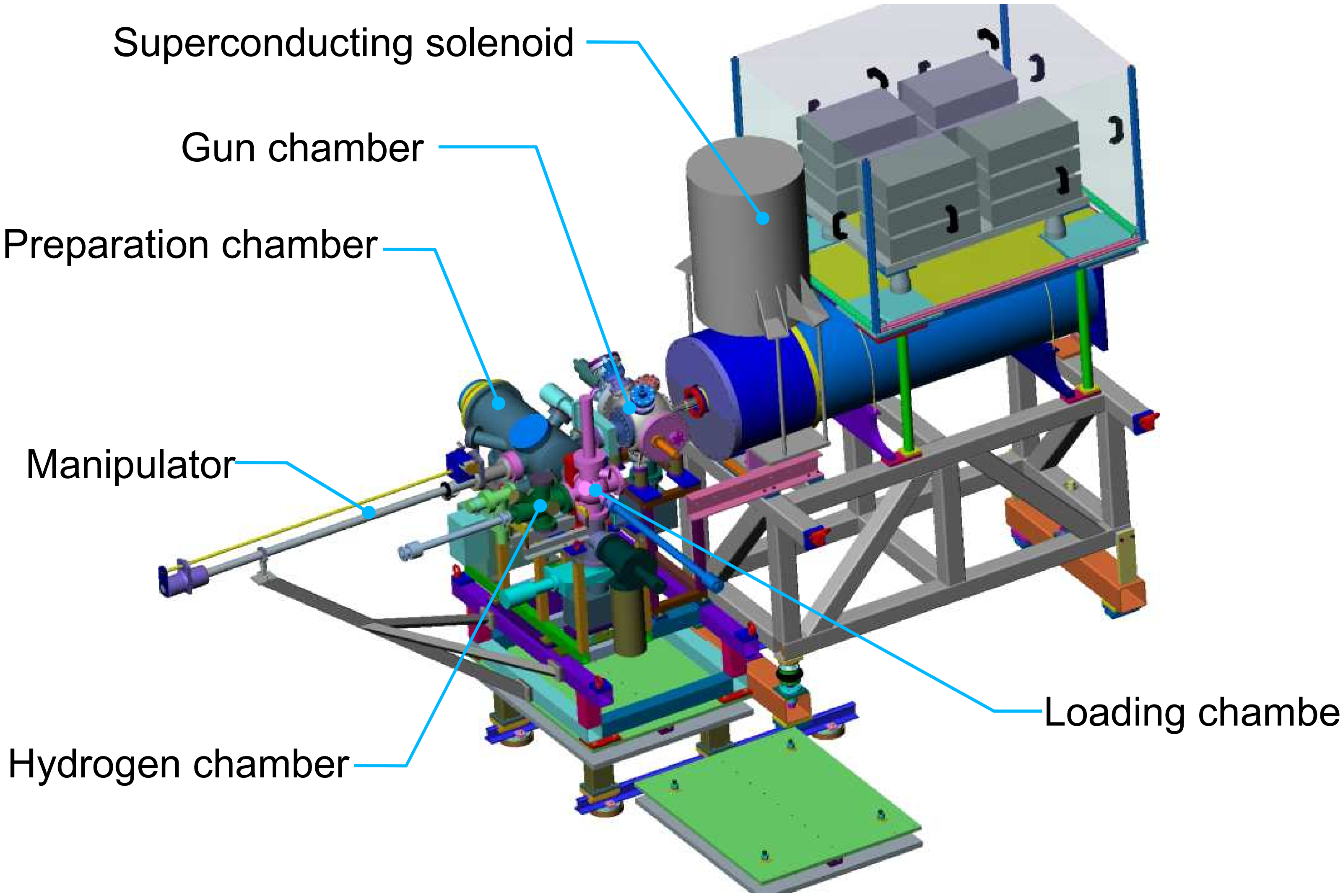
Low capillary temperature (no w-contamination)



Closed cycle

of the photocathode operation

Photocathode section - overview



Photocathode setup at the TSR