[redacted]

The Heidelberg CSR:

Low-Energy Ion Beams in a Cryogenic Environment

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Max-Planck Institute for Nuclear Physics, Heidelberg

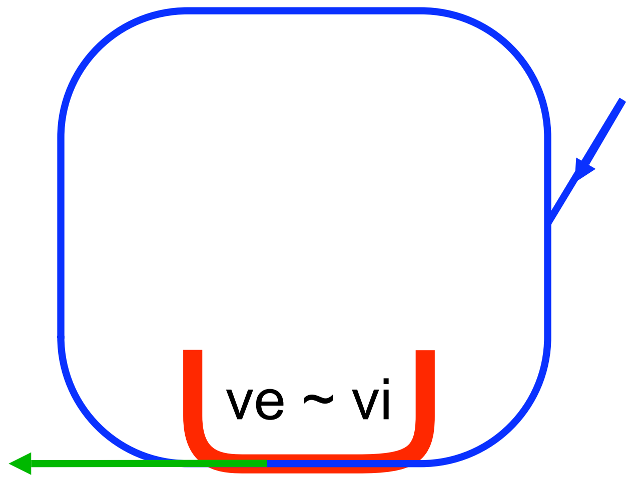
COOL05
Galena, Illinois, Sept. 21, 2005

High resolution merged beams experiments with molecular ions

CSR: Goals, layout, design status

Beyond CSR: Collision physics with low-energy antihydrogen beams

Collision experiments with fast merged beams

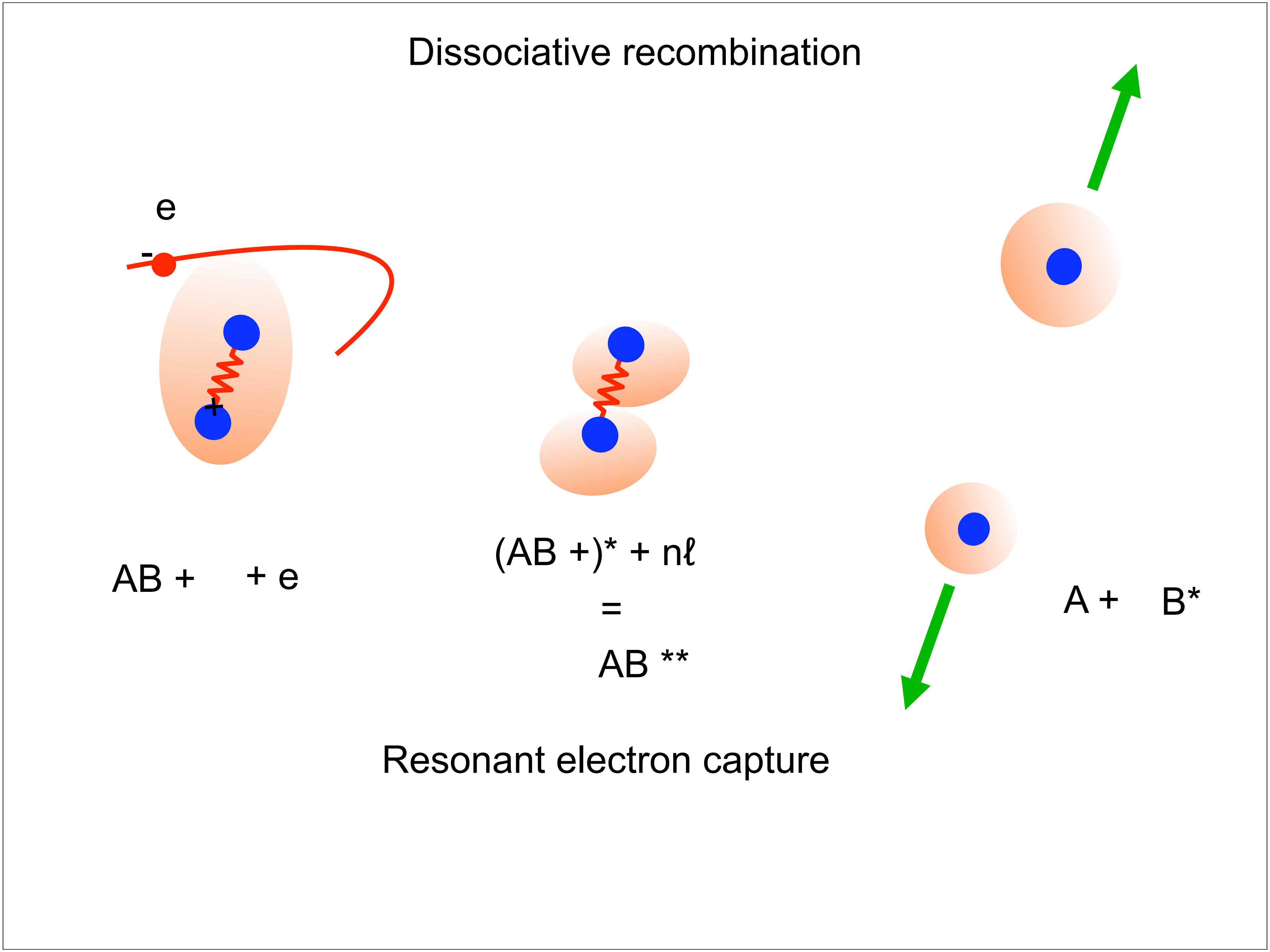


Electron cooling: $v_i \stackrel{!}{=} v_e$

Collision measurements: $v_e \stackrel{!}{\neq} v_i$

Þ collision energy:
~1 meV up to keV

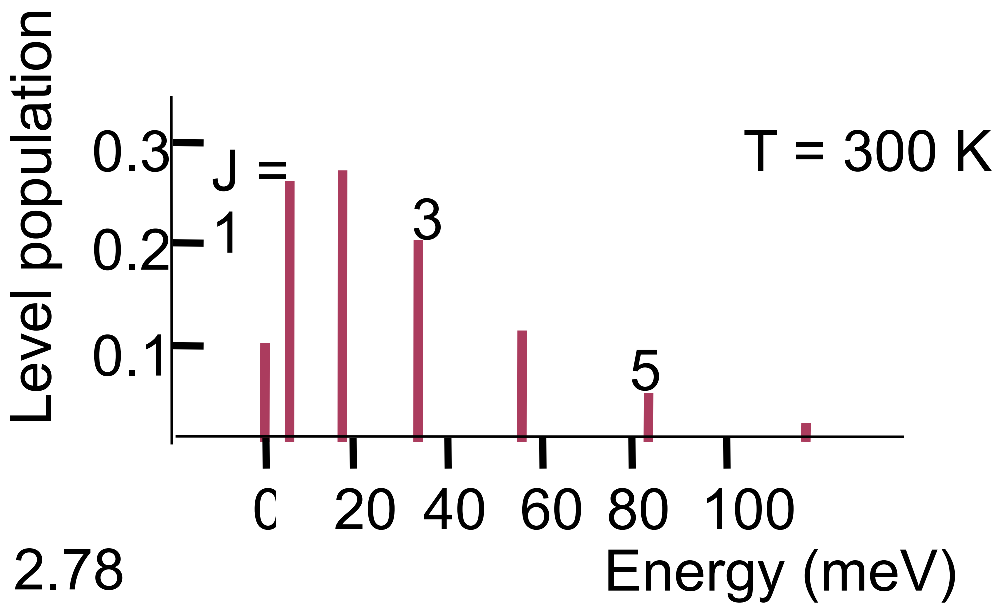
energy resolution: < 1 meV
(at collision energy < 100 meV)


Dissociative recombination
e
-
+
AB + + e
(AB +)* + nℓ
=
AB **
A + B*
Resonant electron capture

Dissociative recombination

Rotational resolution

HD+ (1sσ, v = 0, J) + e → HD** (1sσ nℓλ , v'J') → H + D

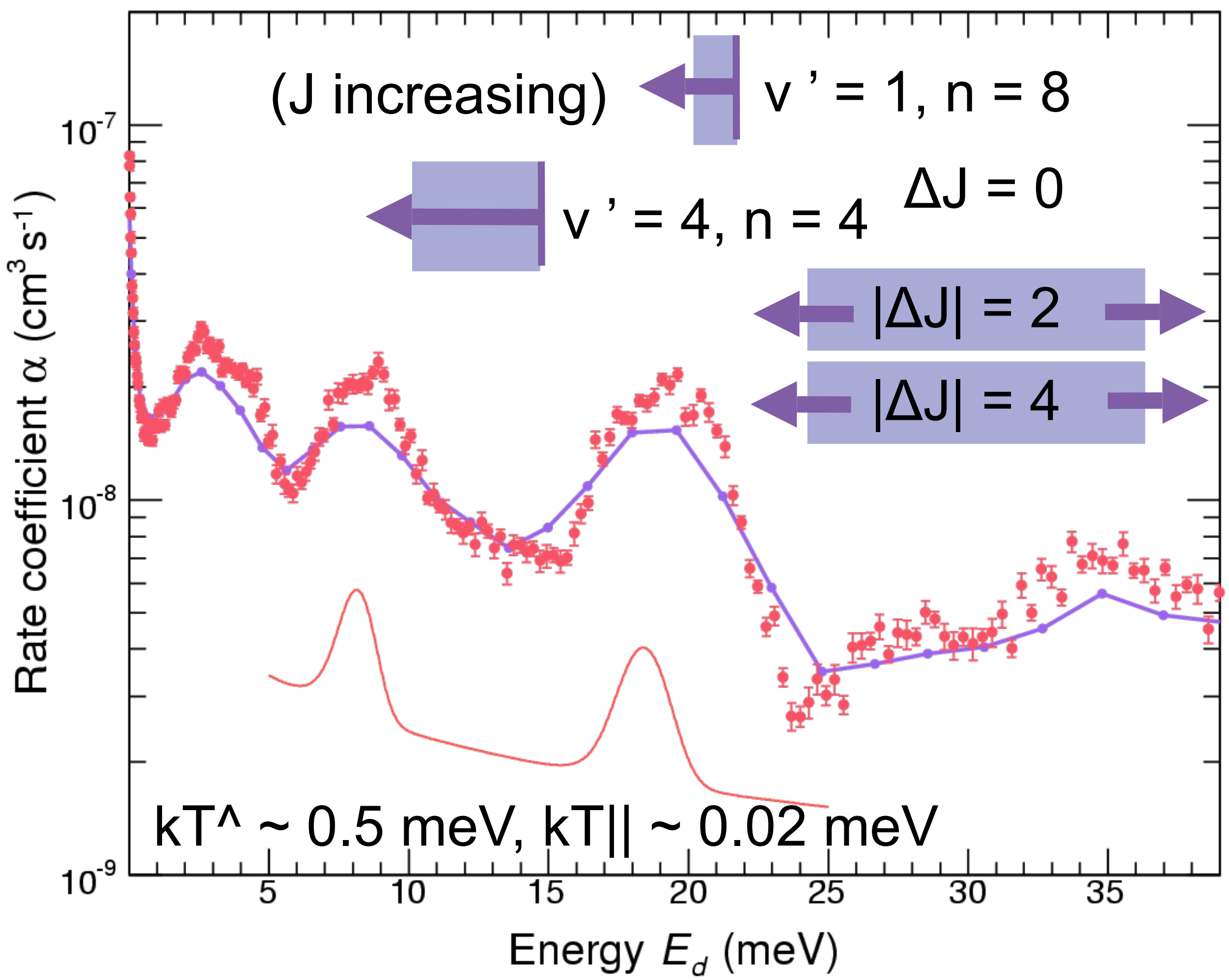


HD+ Be = 2.78 meV

Low-energy rovibrational resonances

Rotational resolution

HD+ (1sσ, v = 0, J) + e → HD** (1sσ nℓλ , v'J') → H + D



(ℓ = 0, 2)

CRYRING (2001)

kT_d ~ 2 meV

TSR
E-target and
photocathode
(2004)

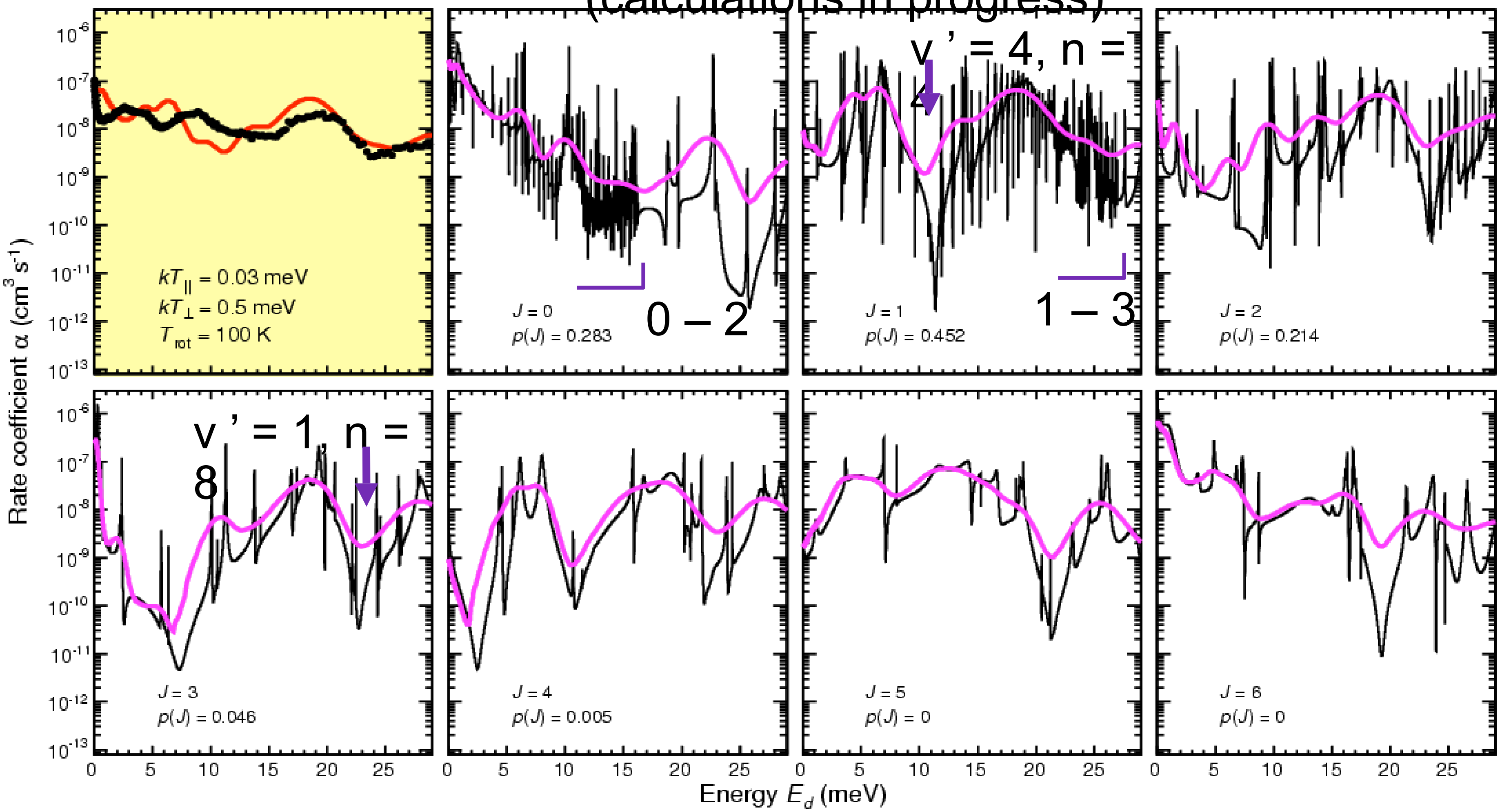
Low-energy rovibrational resonances

Rotational resolution

(ℓ = 0, 2 → ΔJ = 0, ± 2, ± 4)

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

MQDT: Ioan Schneider and F. O. Waffeu Tamo (LeHavre)
(calculations in progress)



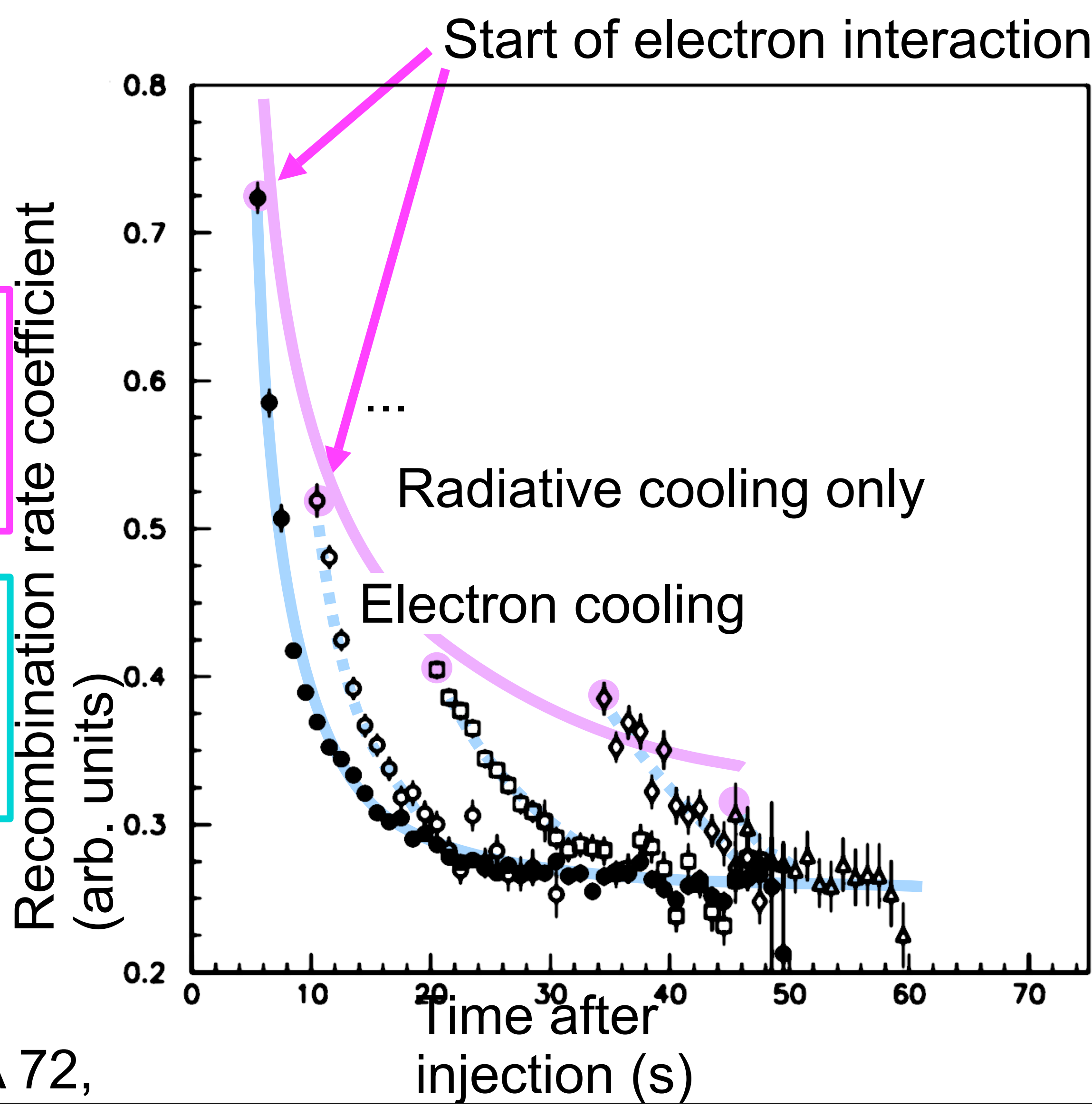
Inelastic electron collisions

Rotational dependence of 3He4He+ recombination rate

Vibrational cooling by radiation: < 5 s

Rotational cooling by radiation: > 40 s

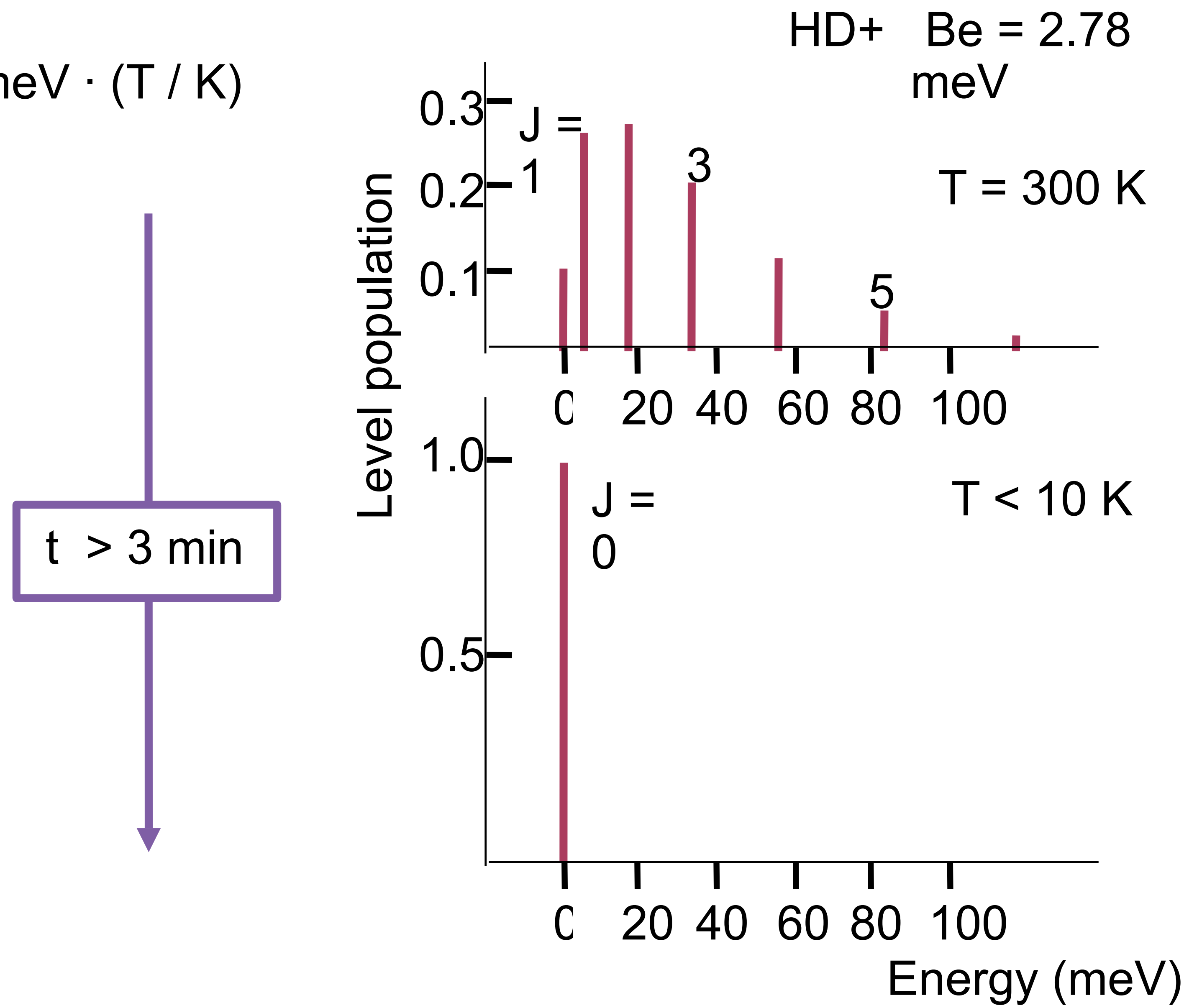
Rotational cooling by electron collisions: ~ 10 s



H. B. Pedersen et al., PRA 72,

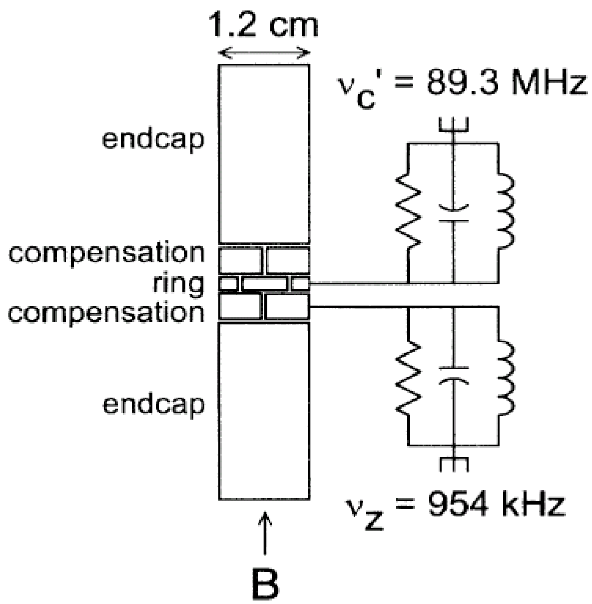
Cryogenic low-density environment for ion storage

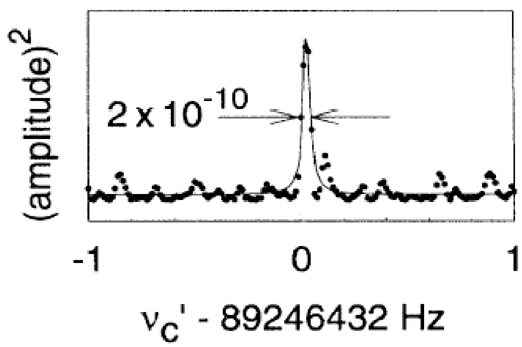
$kT = 0.086\ \mathrm{meV} \cdot (T / K)$



Cryogenic low-density environment for ion storage

Cryogenic (4.2 K) Penning trap for antiprotons:
Storage lifetime $\tau > 3.4$ months





G. Gabrielse et al., PRL 65, 1317 (1990)
PRL 74, 3544 (1995)

Small, hermetically closed system

From low-energy $\bar{p}$ annihilation cross section:
p (4.2 K) < 5 x 10-17 mbar

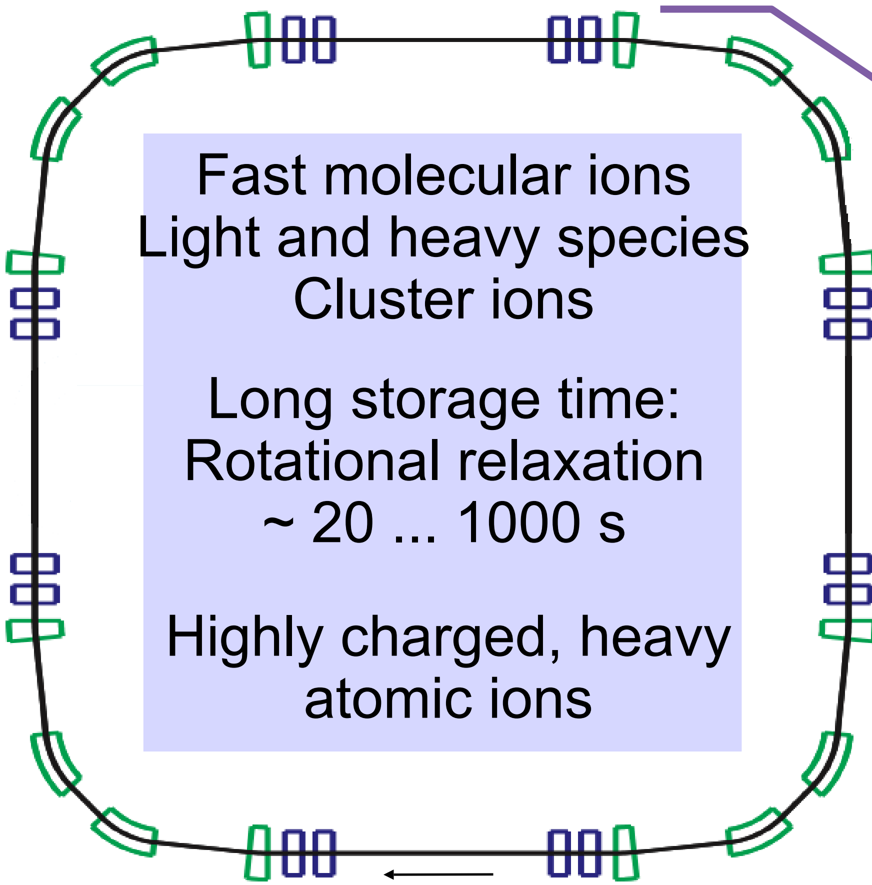
The CSR project

Electrostatic storage ring

20 … 300 keV·q

Cryogenic vacuum ≤ 10-15 mbar

Wall temperature ~ 2 K



Cryopumping of H2

Fast molecular ions
Light and heavy species
Cluster ions

Long storage time:
Rotational relaxation
~ 20 ... 1000 s

Highly charged, heavy atomic ions

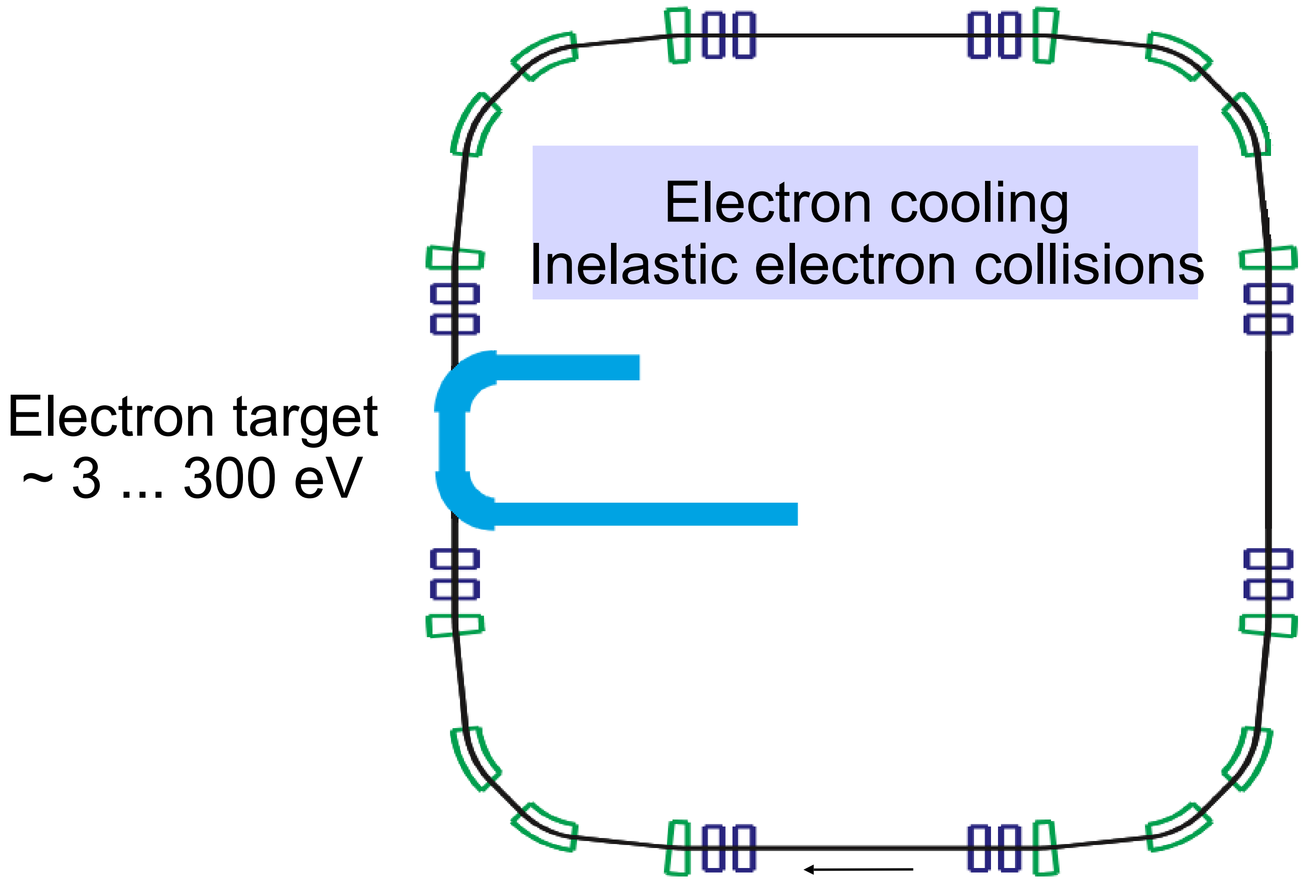
The CSR project

Electrostatic storage ring

20 … 300 keV·q

Cryogenic vacuum ≤ 10-15 mbar

Wall temperature ~ 2 K



The CSR project

Electrostatic storage ring

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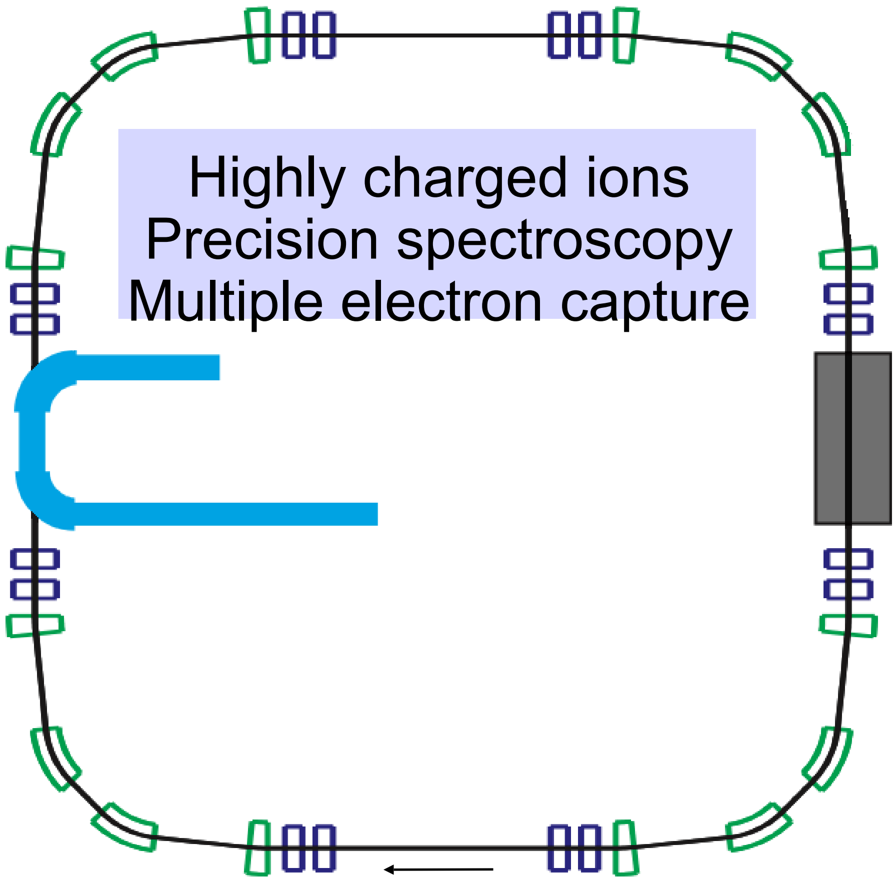
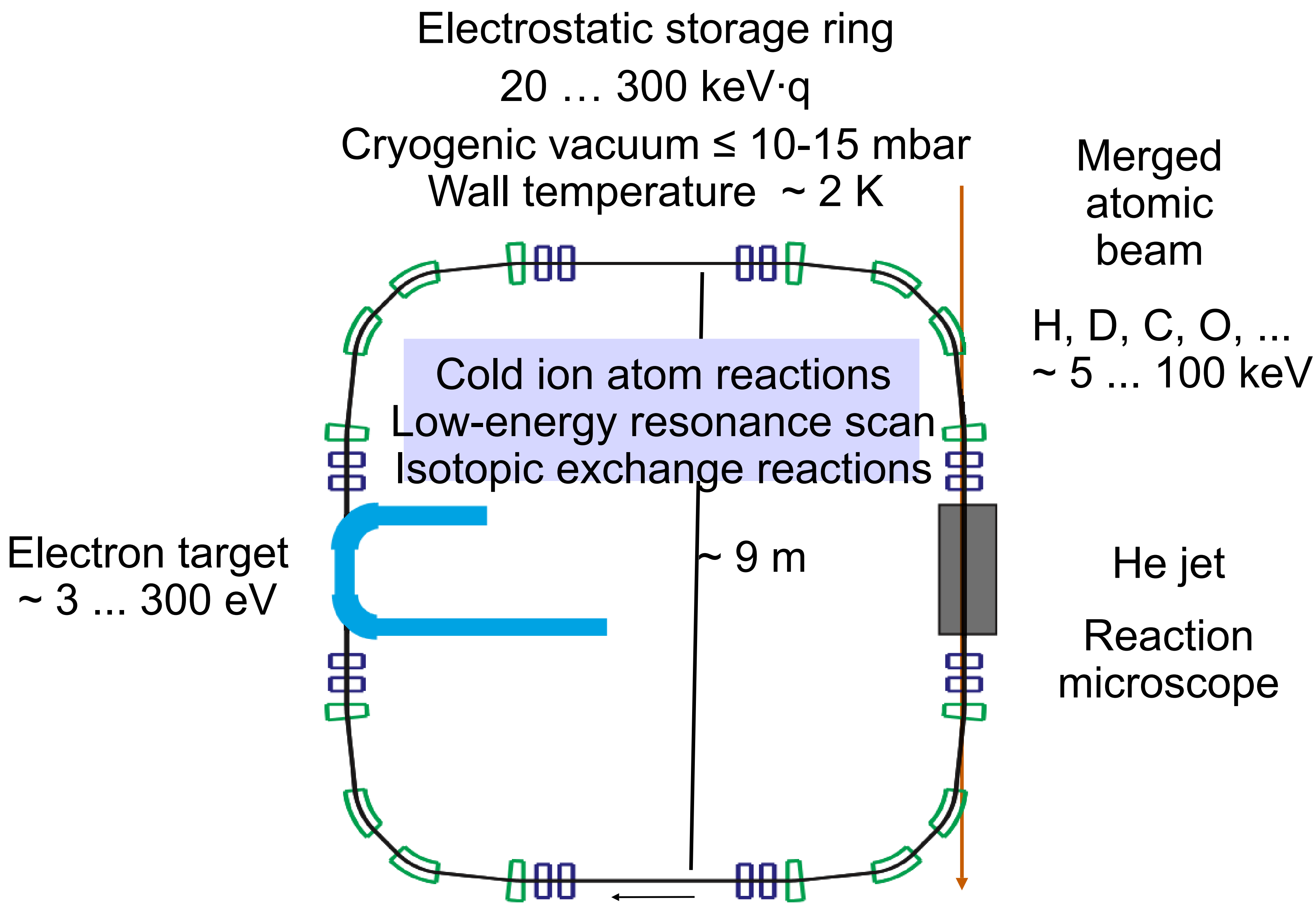


The CSR project

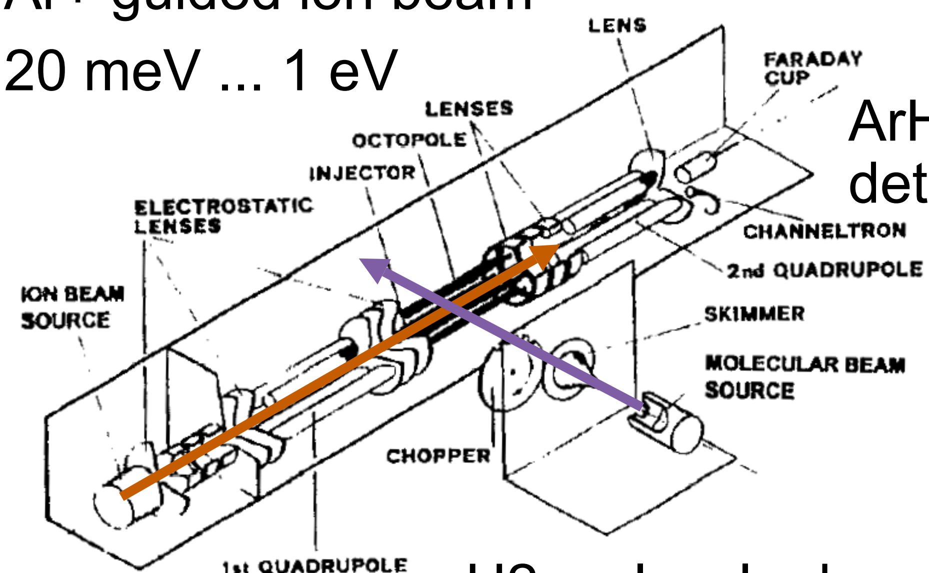


Energy resolved ion reaction studies

$Ar^+ + H_2 \rightarrow Ar + H_2^+ \rightarrow ArH^+ + H$

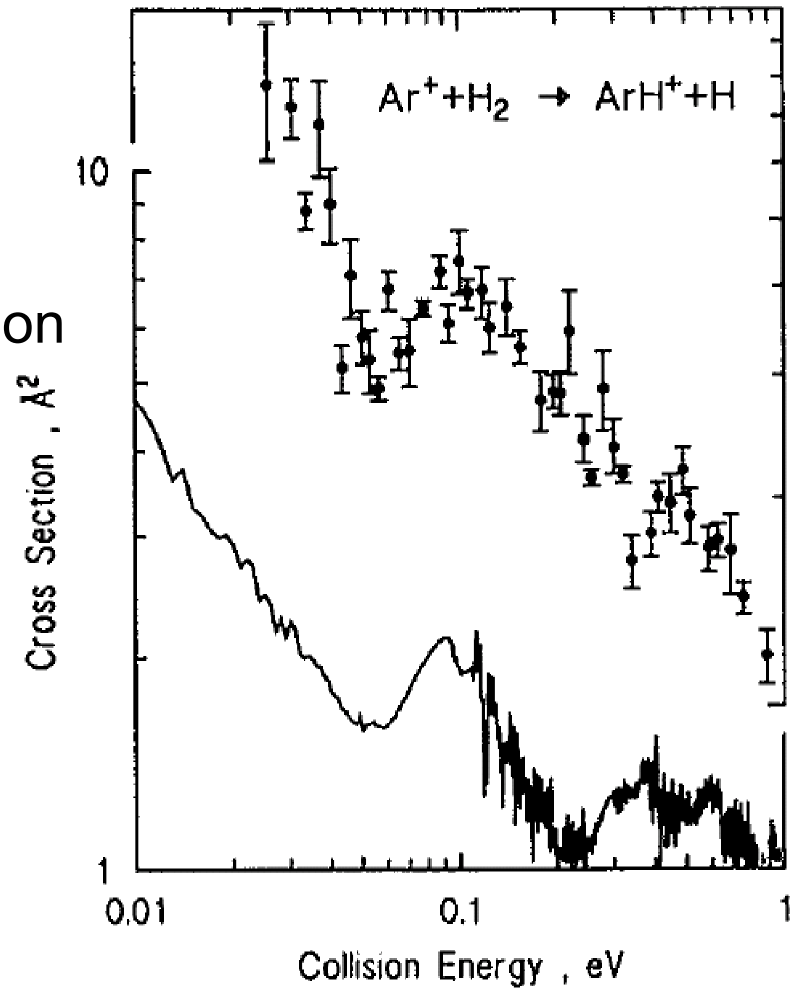
Ar+ guided ion beam

20 meV ... 1 eV



ArH+ detection

H2 molecular beam



Energy resolution ~ 10 meV

P. Tosi et al. (Trento/Perugia)

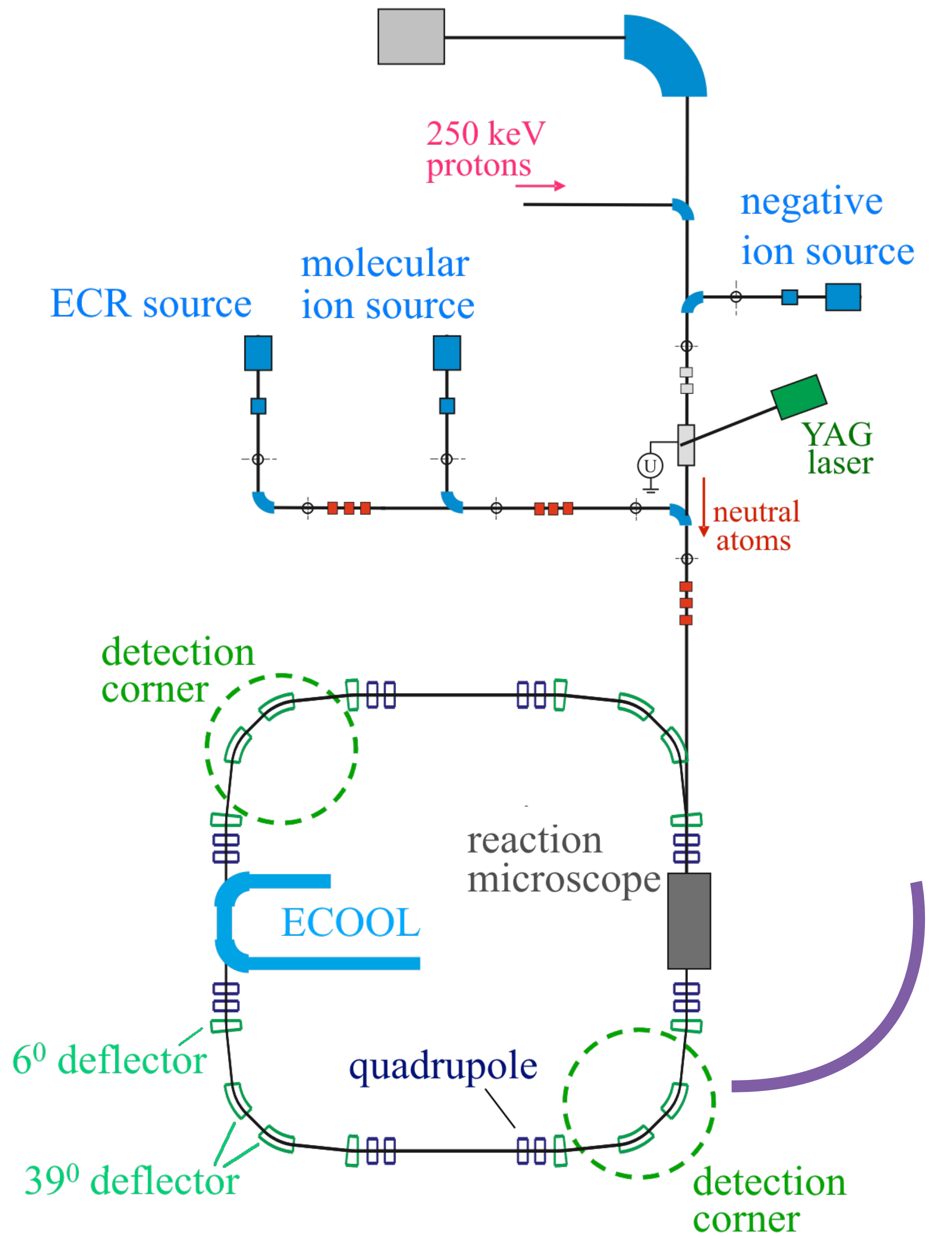
J. of Chemical Physics 99, 985 (1993)

The CSR project

Accelerator physics with low-energy ion beams

Acceleration, short pulses, loss mechanisms ...
Diagnostic using sensitive cryogenic electronics
(amplifiers, current probes, SQUID sensors ...)
Beam noise and stochastic cooling
Single-ion measurements ? ...

Layout of the Heidelberg CSR



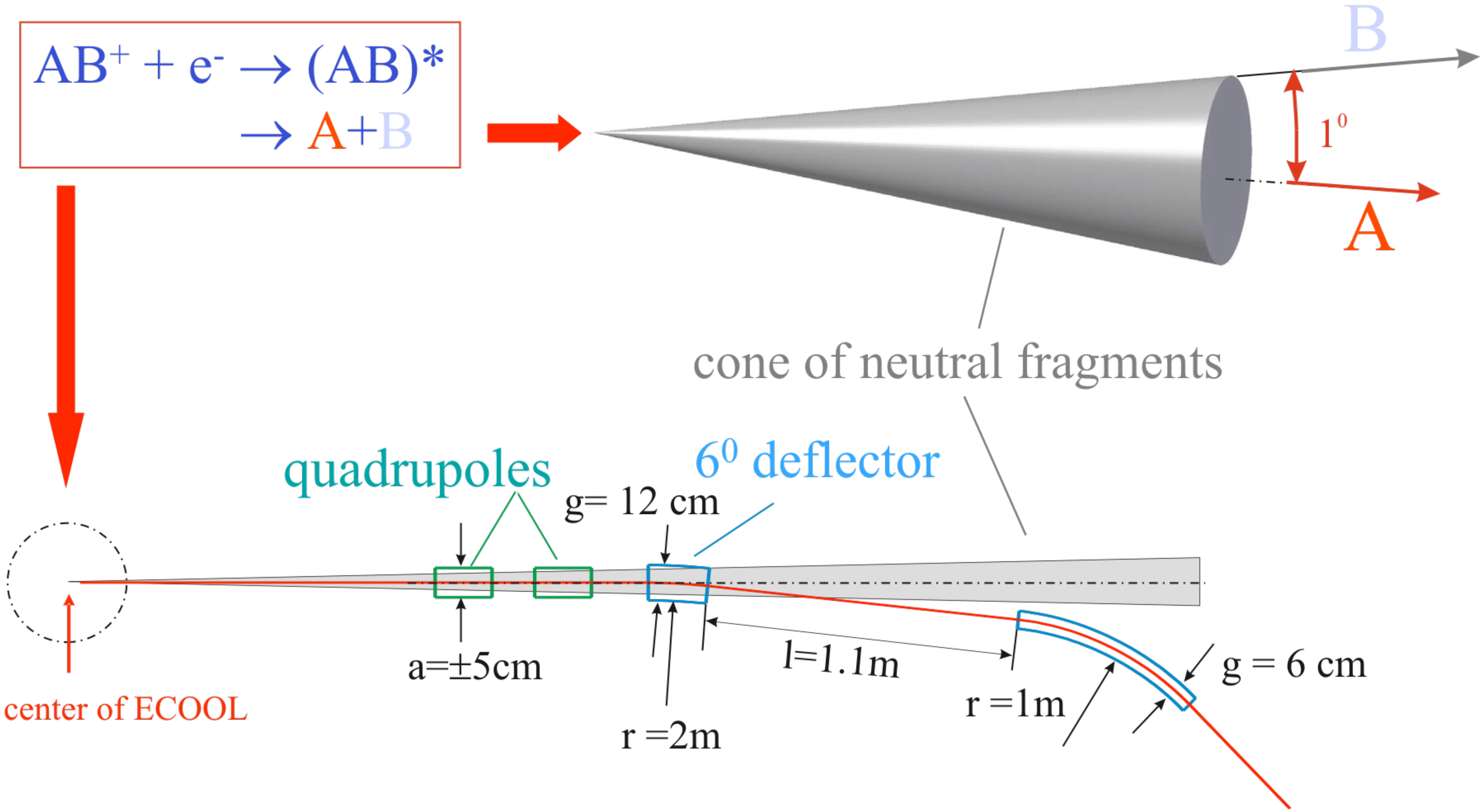
Lattice,
electron cooling:

Poster by
H. Fadil
today

Layout of the Heidelberg CSR

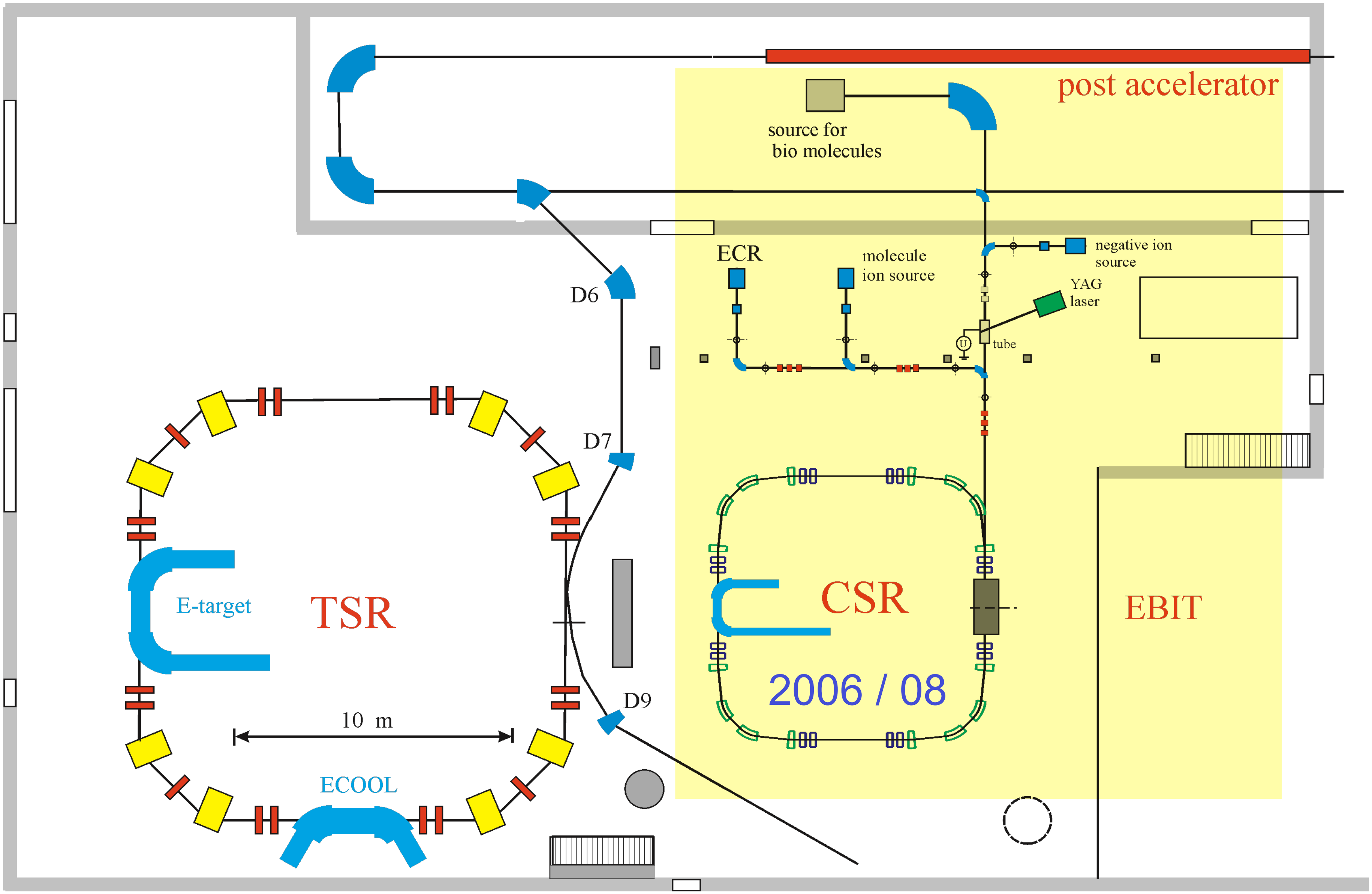
Deflector layout and molecular fragment detection

$AB^+ + e^- \rightarrow (AB)^*$
$\rightarrow A + B$



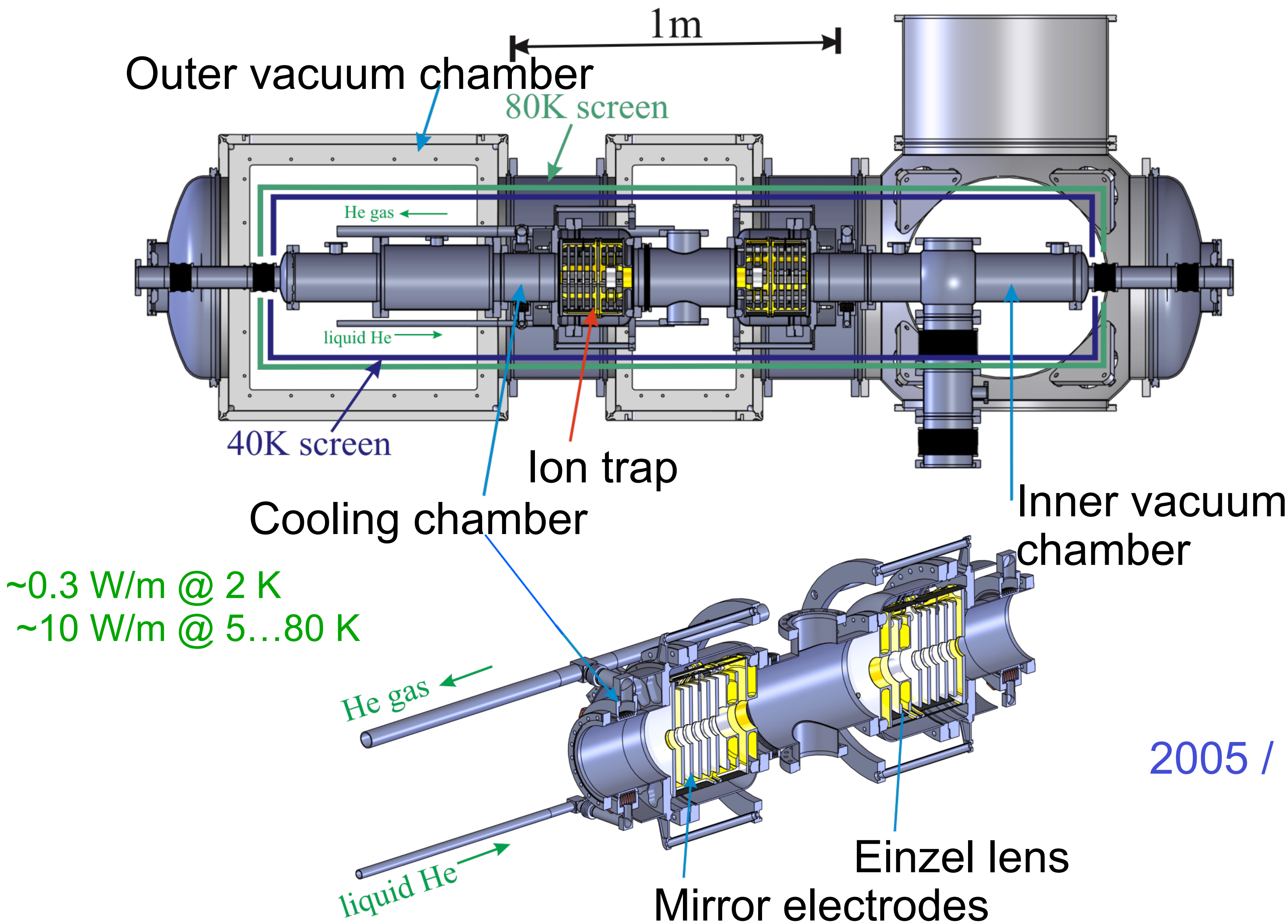
M. Grieser, C. Welsch

Layout of the Heidelberg CSR



Prototype for cryogenic CSR components

Heidelberg cryogenic ion beam trap



2005 / 06

CSR project team

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Infrared experiments
at cryogenic ion trap
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X. Urbain
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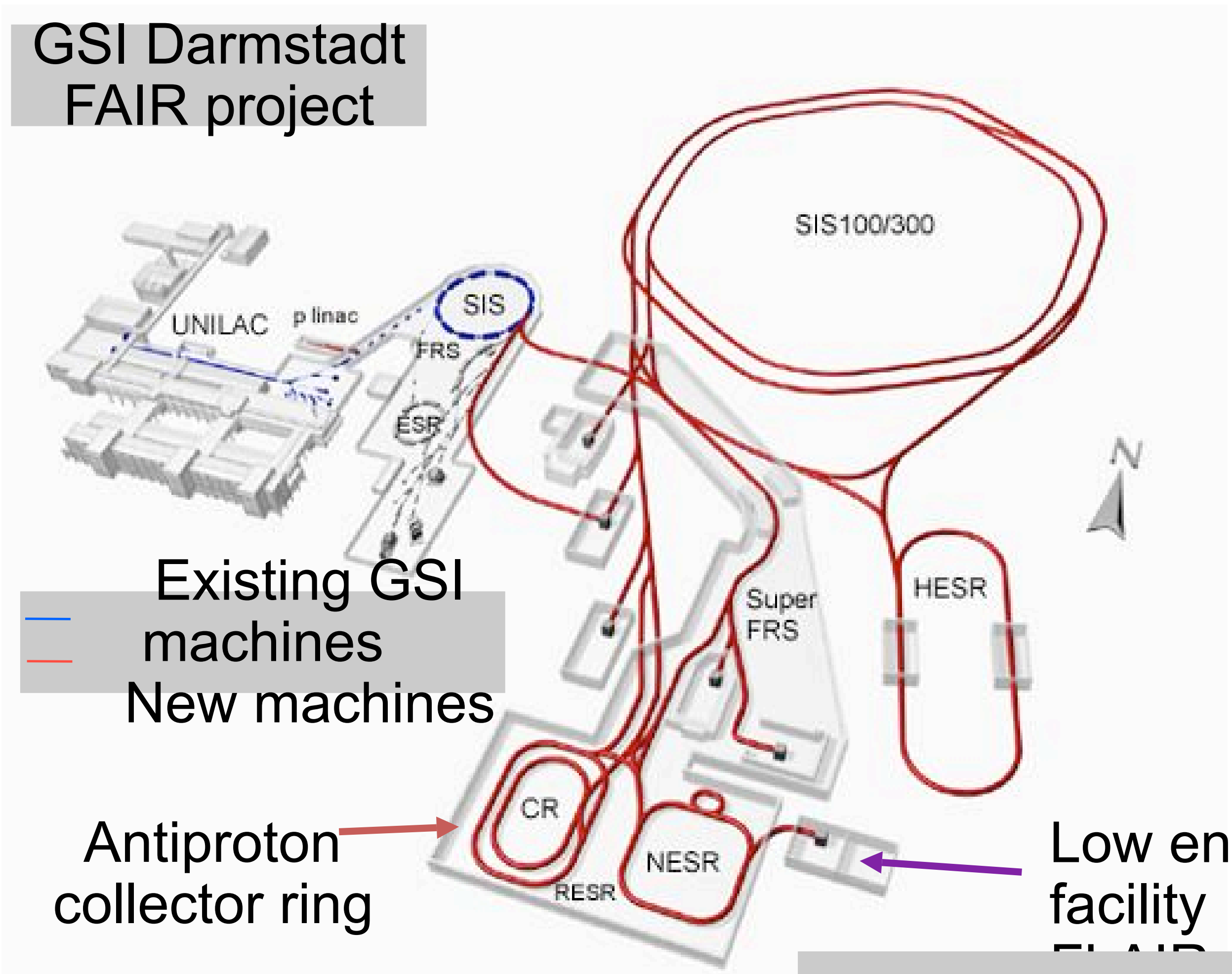
Cryogenic
consulting

Stored antiproton beams at keV energies

GSI Darmstadt
FAIR project



Existing GSI machines
New machines

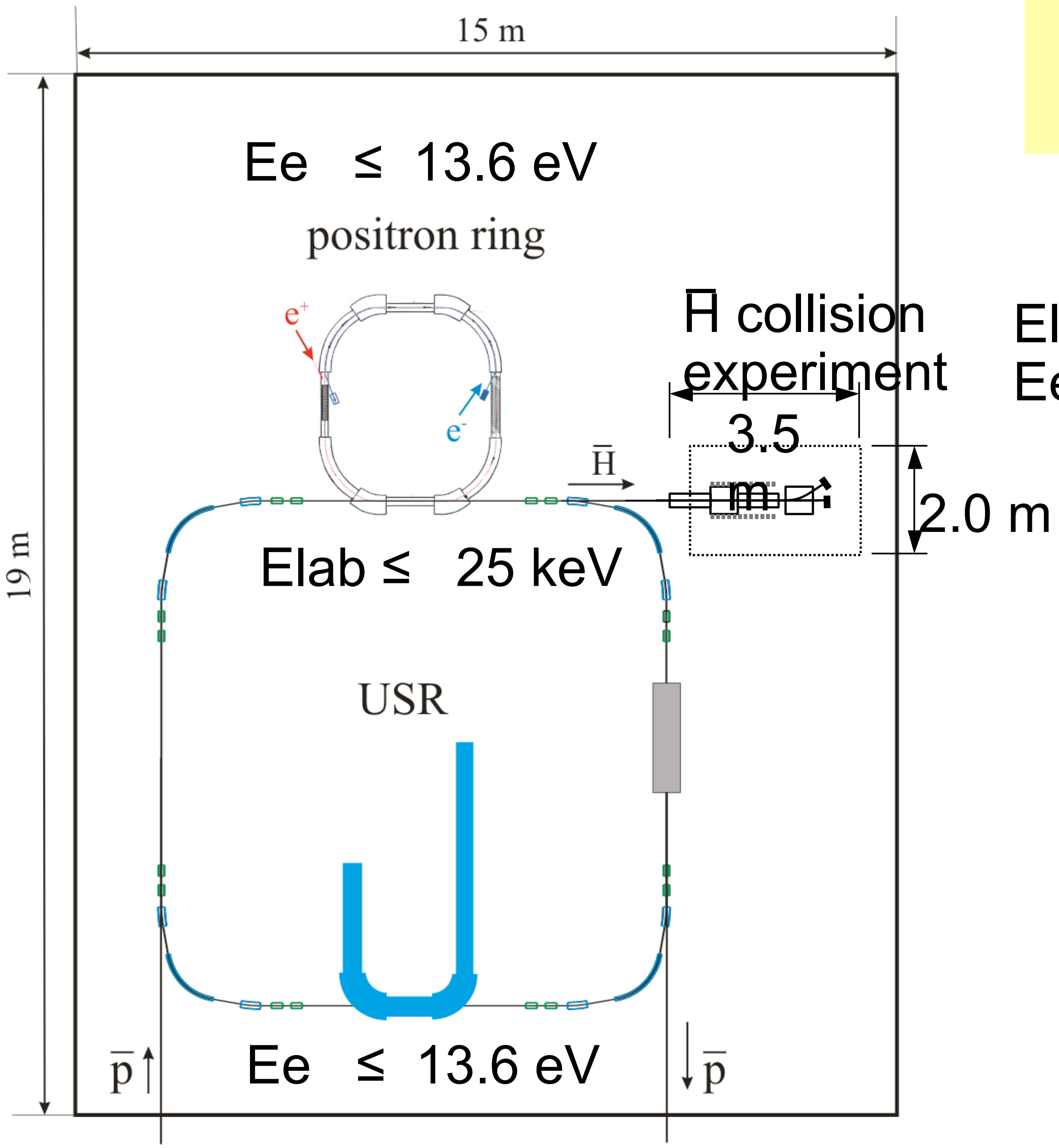
Antiproton collector ring

Low energy antiproton facility

> 2010

30 MeV ... 300 keV: LSR (magnetic)
300 keV ... 20 keV: USR (electrostatic)

Antihydrogen collision experiment



$$H + \bar{H} \rightarrow e^+ + e^- + p + \bar{p}$$
$$\rightarrow Ps + \bar{p} + p$$

Antihydrogen formation

Elab ≤ 25 keV
Ee ≤ 13.6 eV

Np = 107
ne = 107 cm-3
Te = 1 meV

→ 200 $\bar{H}$/s

Summary

Low-energy ion beams
in a cryogenic electrostatic storage ring (CSR)

Physics opportunities

- Rotationally controlled, high-resolution, low energy reaction studies
- Merged beams of electrons and atoms (meV resolution)
- Sensitive detection of electronic signals and infrared radiation
- Ultrahigh vacuum: long-time storage of highly charged ions
- Fixed target collisions with velocities around 1 a.u.
- Low-energy ion beam physics (cooling, diagnostic)

Experimental challenges

- Extreme vacuum requirements – 2 K cryogenic cooling
- Low energy electron beams (eV range laboratory energy)
- Imaging and mass sensitive detectors
- Control and diagnostic of rotational cooling

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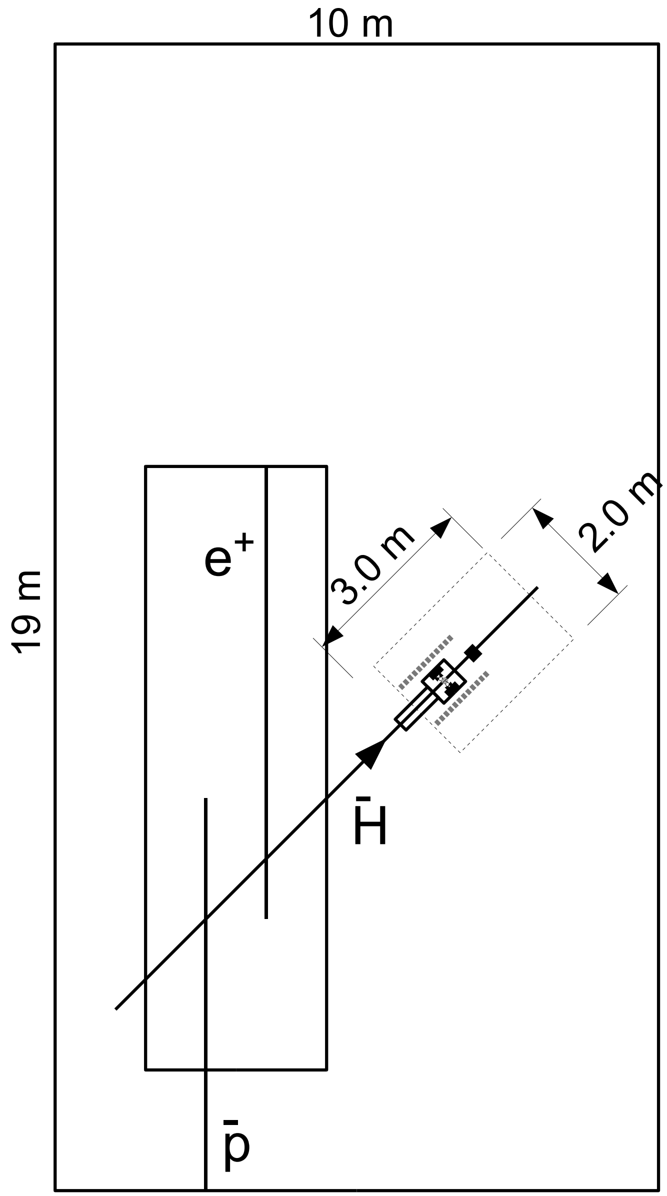
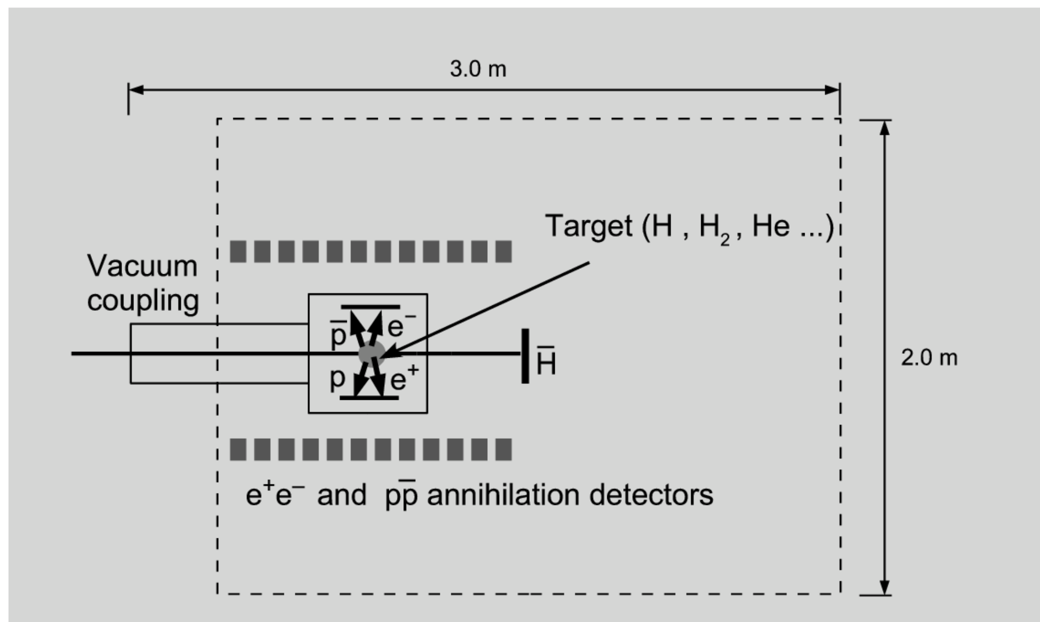
Hydrogen–antihydrogen rearrangement at eV energies



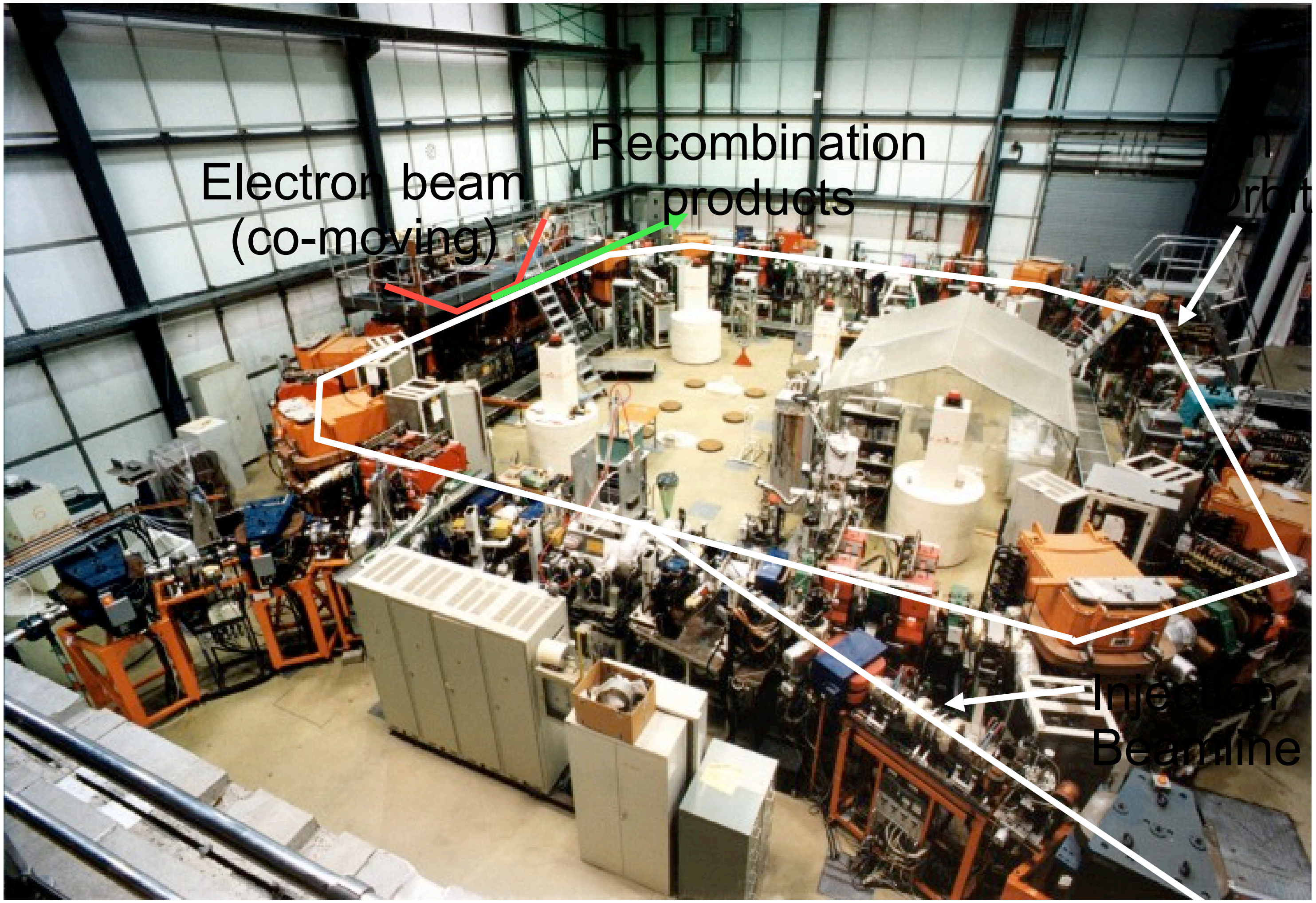
Parameters:

Elab ≤ 0.3 eV (nested traps)
Elab ≤ 50 eV (modif. nested traps)

Required production rate ~ 100 $\bar{H}$/s



Ion Storage Ring TSR

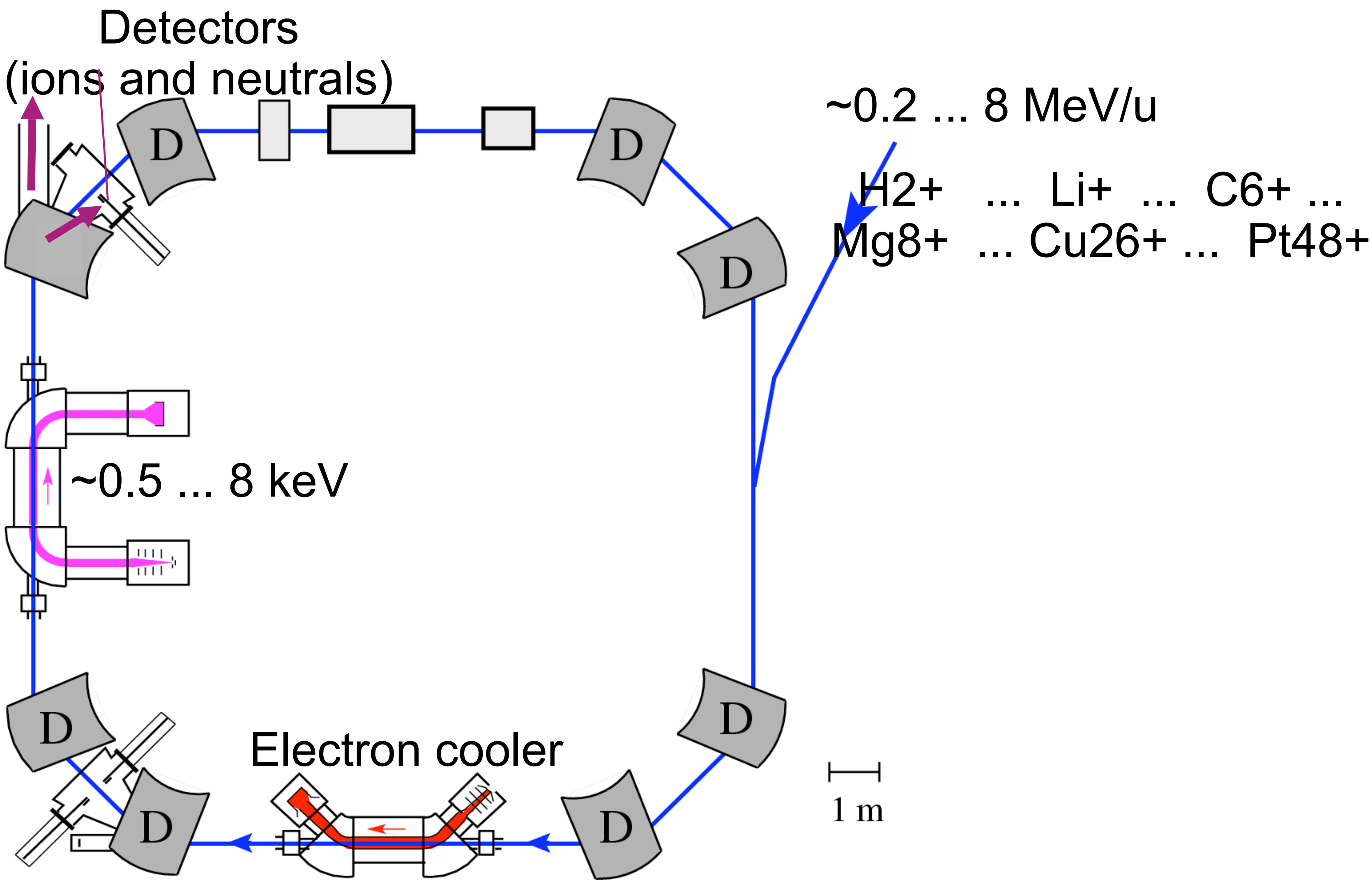


MPI-K Heidelberg

Ion accelerator ~0.2 ... 8 MeV/u

H2+ ... Li+ ... C6+ ... Mg8+ ... Cu26+ ... Pt48+

High resolution electron target at TSR

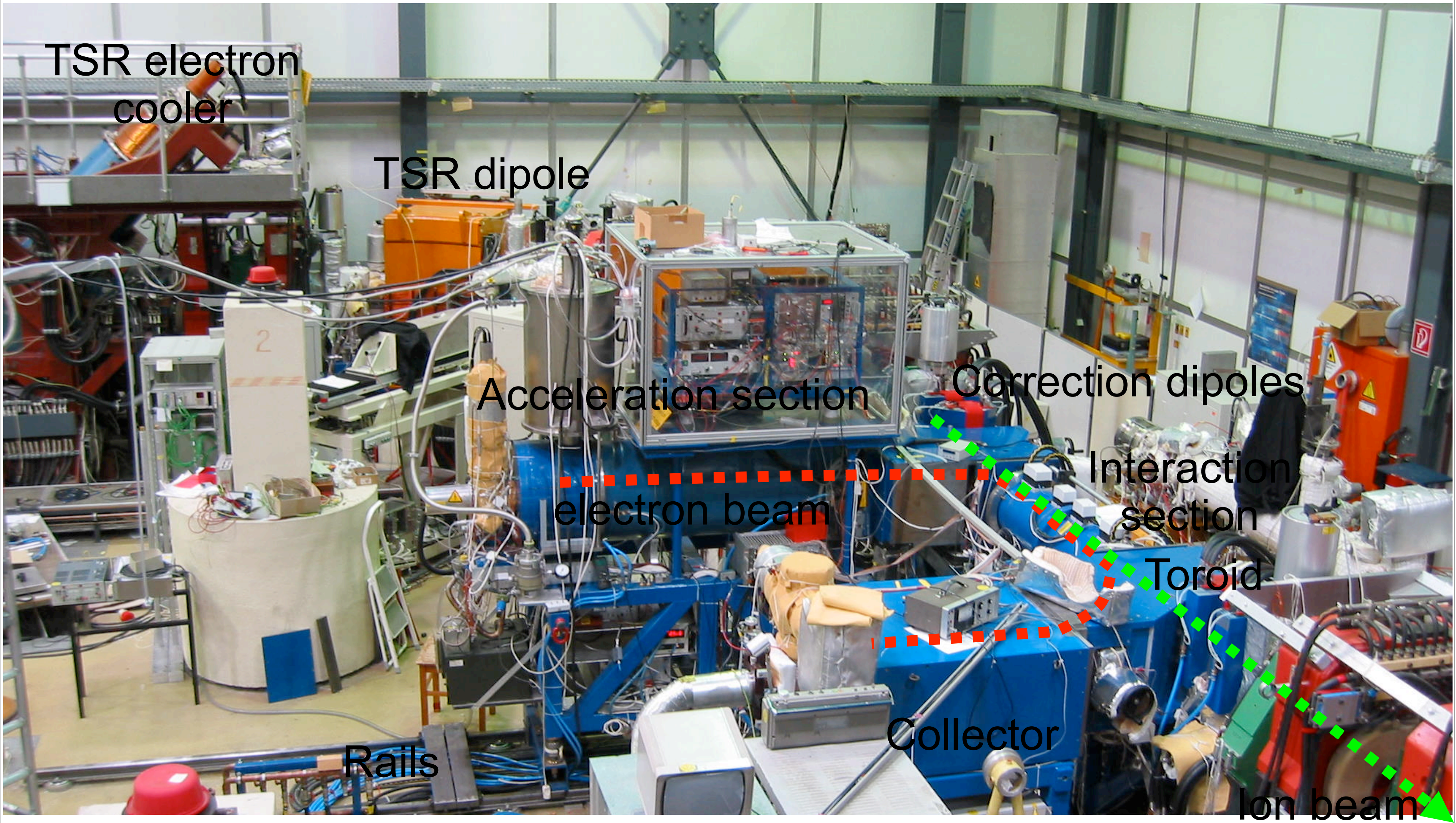


Continuously cooled ion beam

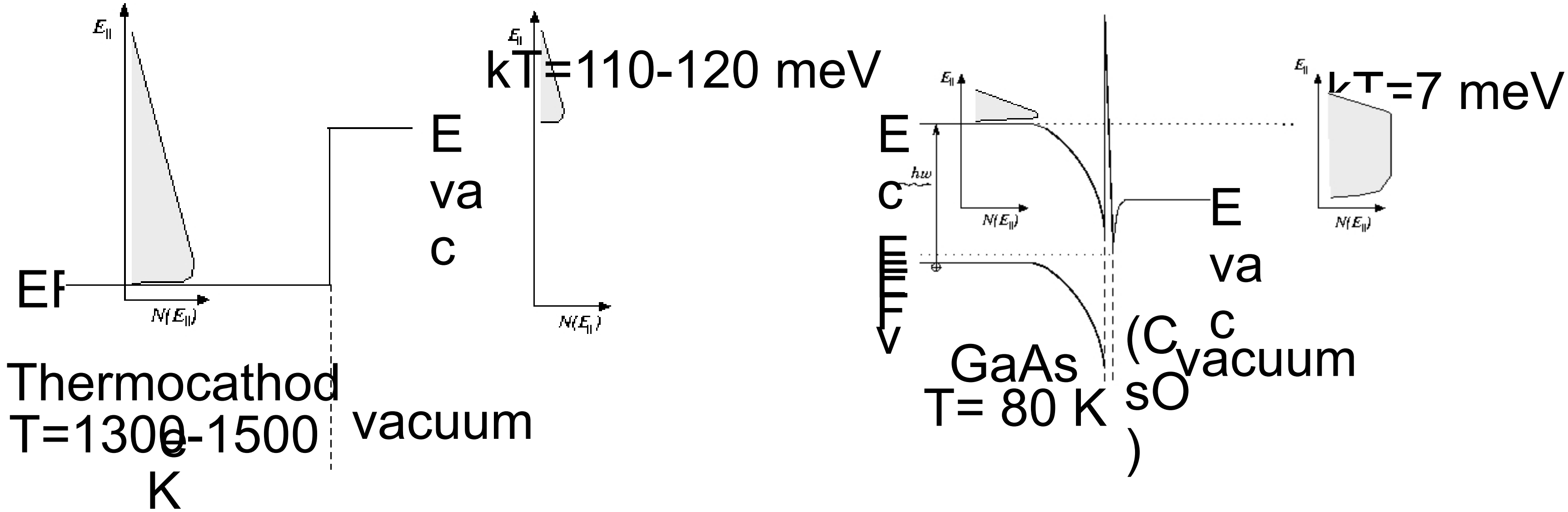
Avoided during DR measurement:
- Self-heating of ion beam
- Ion velocity shift by electron drag

High resolution electron target at TSR

Installation: Summer 2003



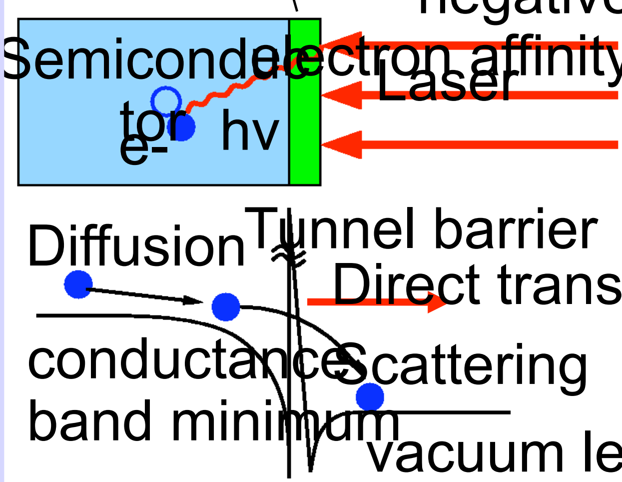
Cryogenic photocathode



Cryogenic photocathode

Photocathode principle

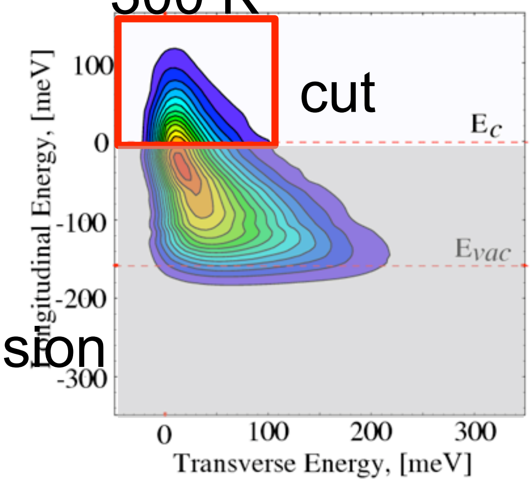
Cs/O deposition for negative electron affinity

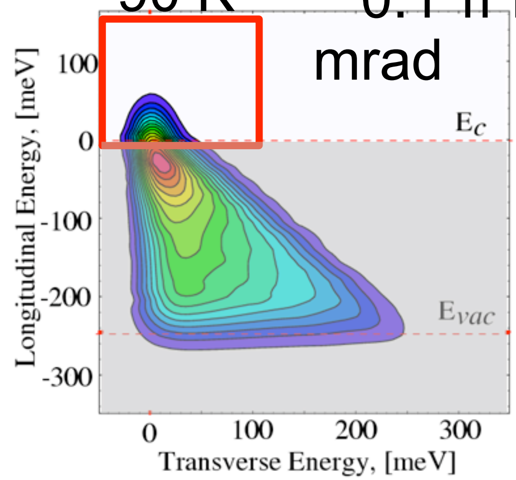


Energy distributions of photoelectrons

"2D"-measurement (E|| , E^)

E⊥n ~ 0.1 π mm mrad





D. A. Orlov et al., Appl. Phys. Lett. 78,

Fully activated cathode
Quantum yield: 31%
Space charge limited
Thermalized e –:

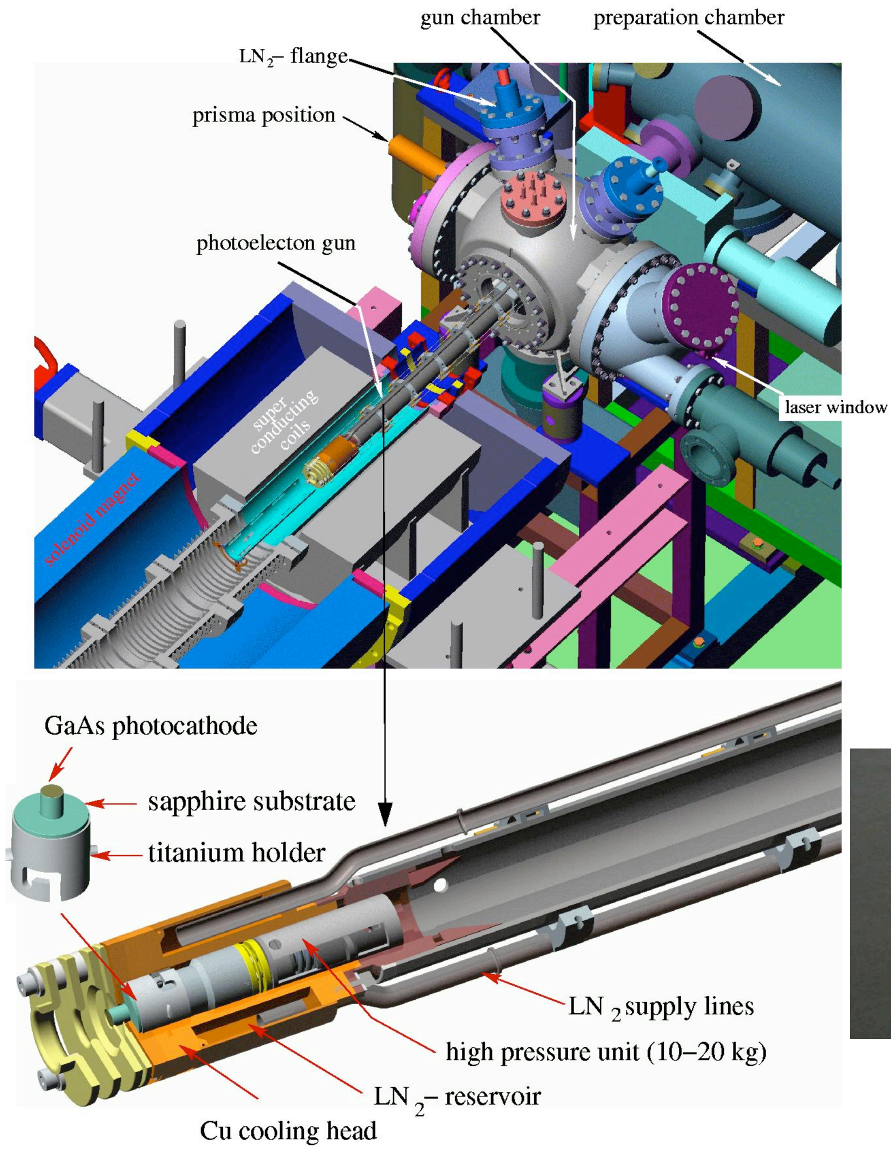
Laser power (800 nm) for 1 mA: <

Þ 90 K electron source

Extracted current reached: ~0.25 mA (10-16 hrs)

(mA currents may become possible)

Cryogenic photocathode



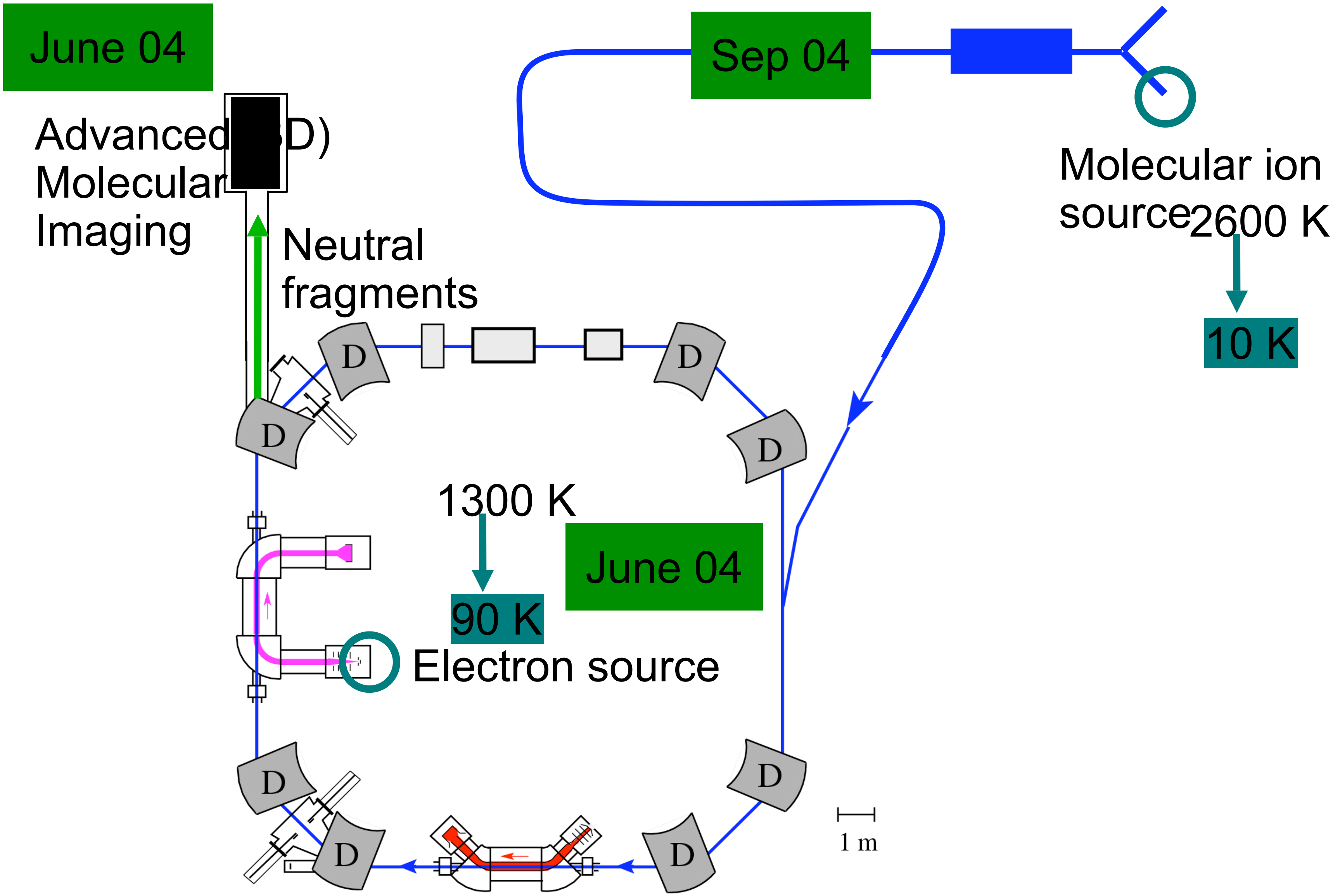
Photocathode gun

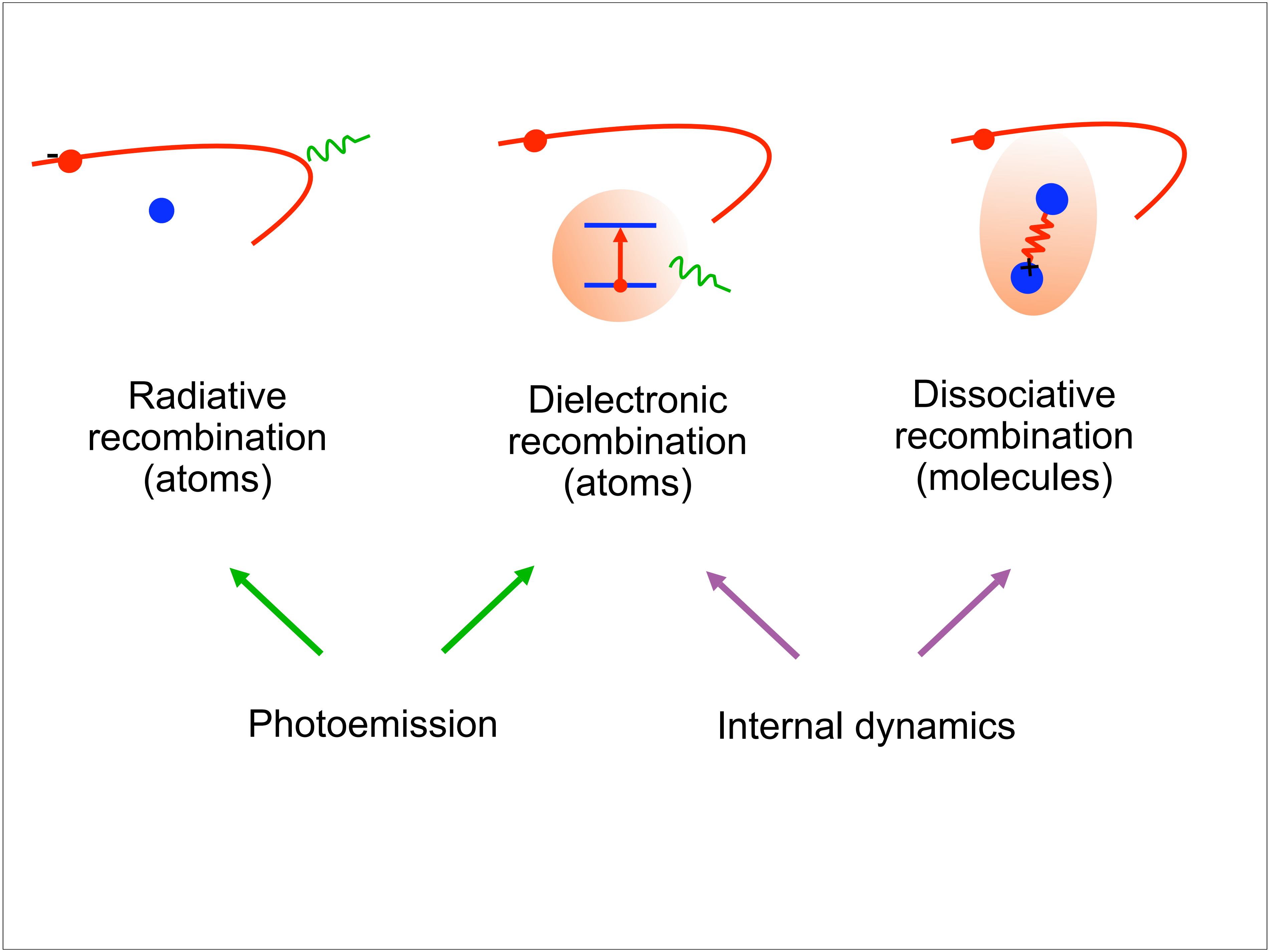
Laser illumination up to 1 W

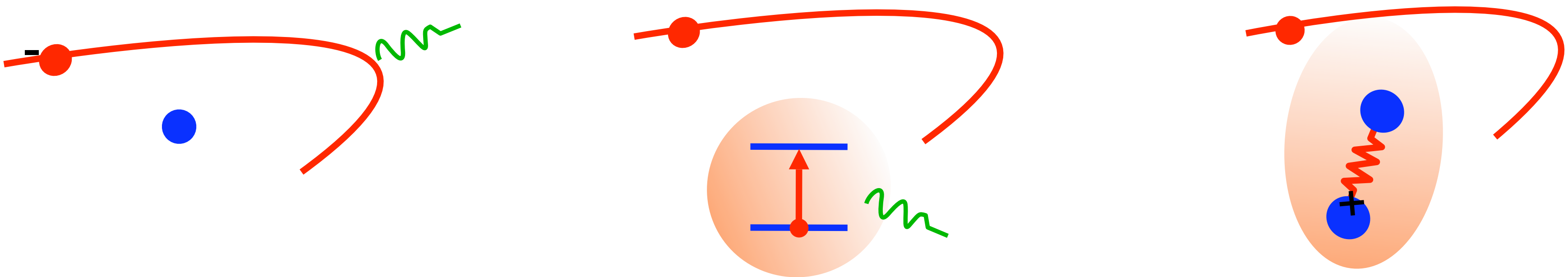
Temperature rise 15-20 K/W at 90 K

U. Weigel et al., NIM A 536

New instrumentation at TSR in 2004




Radiative recombination (atoms)
Dielectronic recombination (atoms)
Dissociative recombination (molecules)
Photoemission
Internal dynamics



Importance of low-energy electron-ion recombination

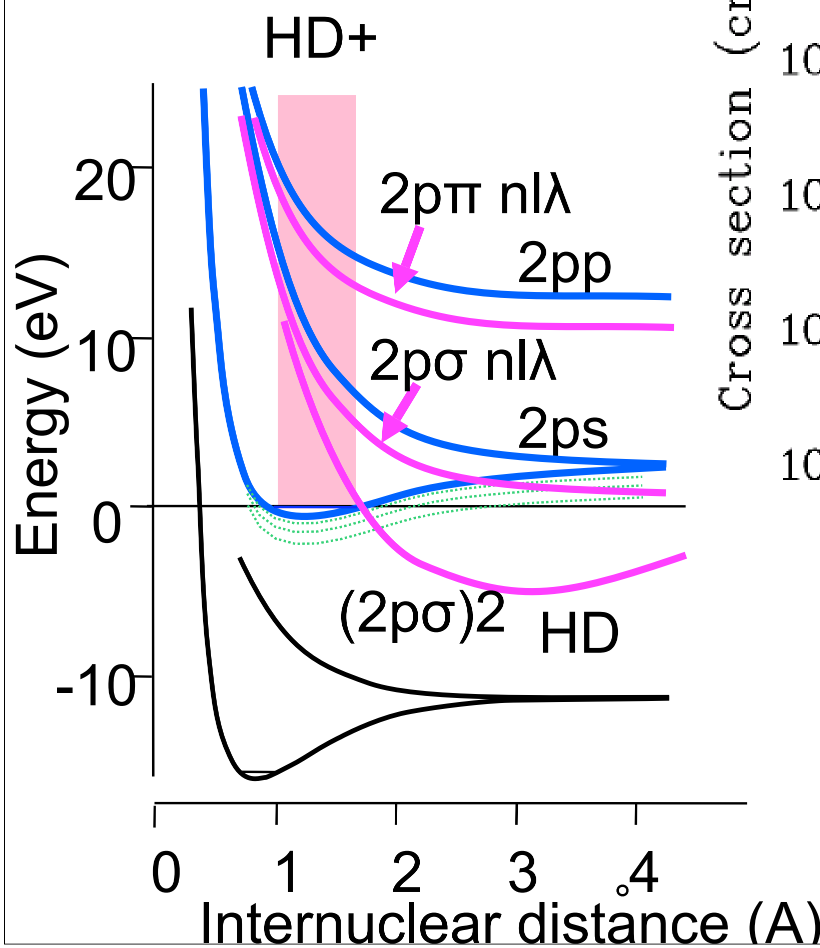
“Recombination phase” in cosmology

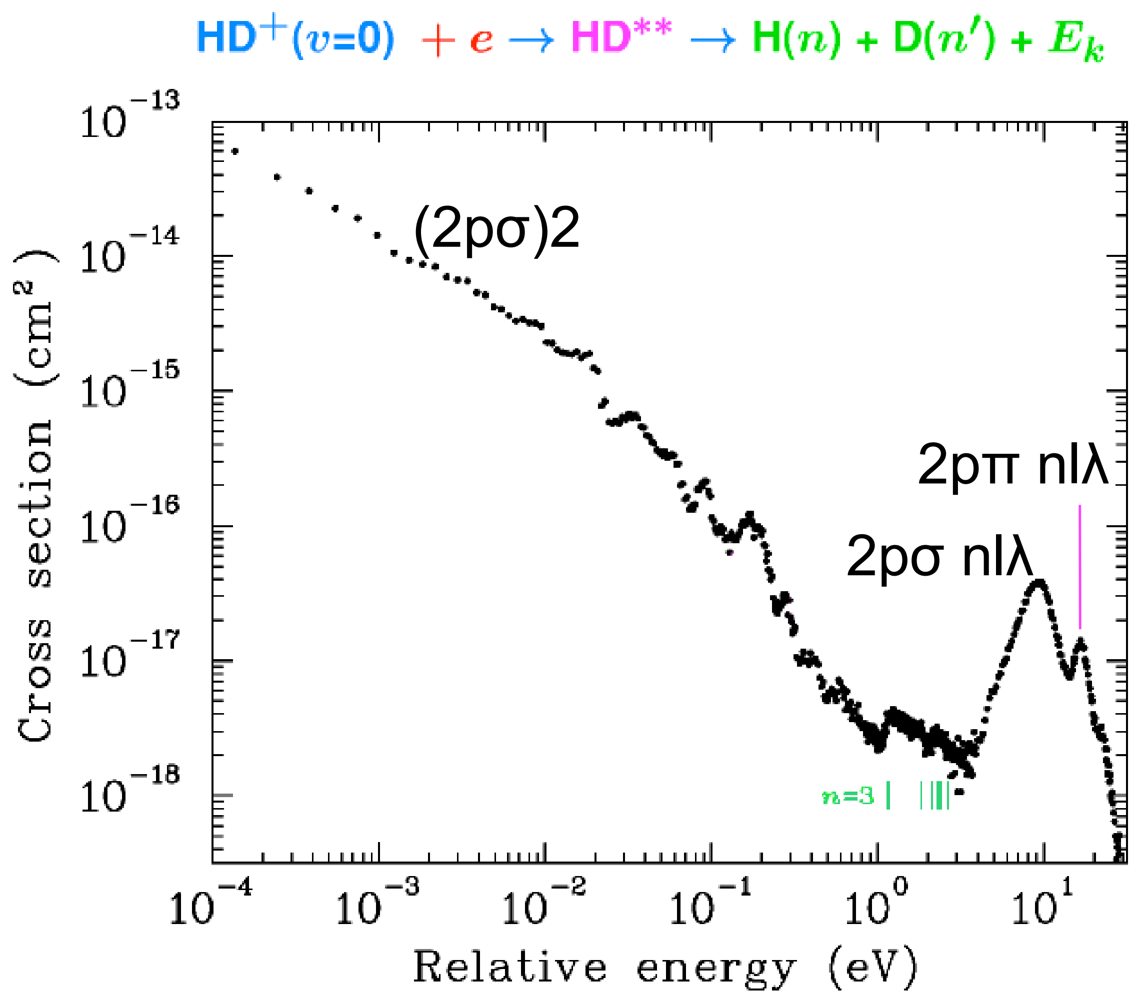
Interstellar plasma
- Photoionized interstellar gas
- Molecular clouds, star forming regions

Excited states for highly charged few-e systems
- Ground state Lamb shift in, e.g., U^{91+}

Atoms from elementary particles:
$e^+ \bar{p}$ (antihydrogen) (e^+e^- , $p\bar{p}$)

Dissociative recombination

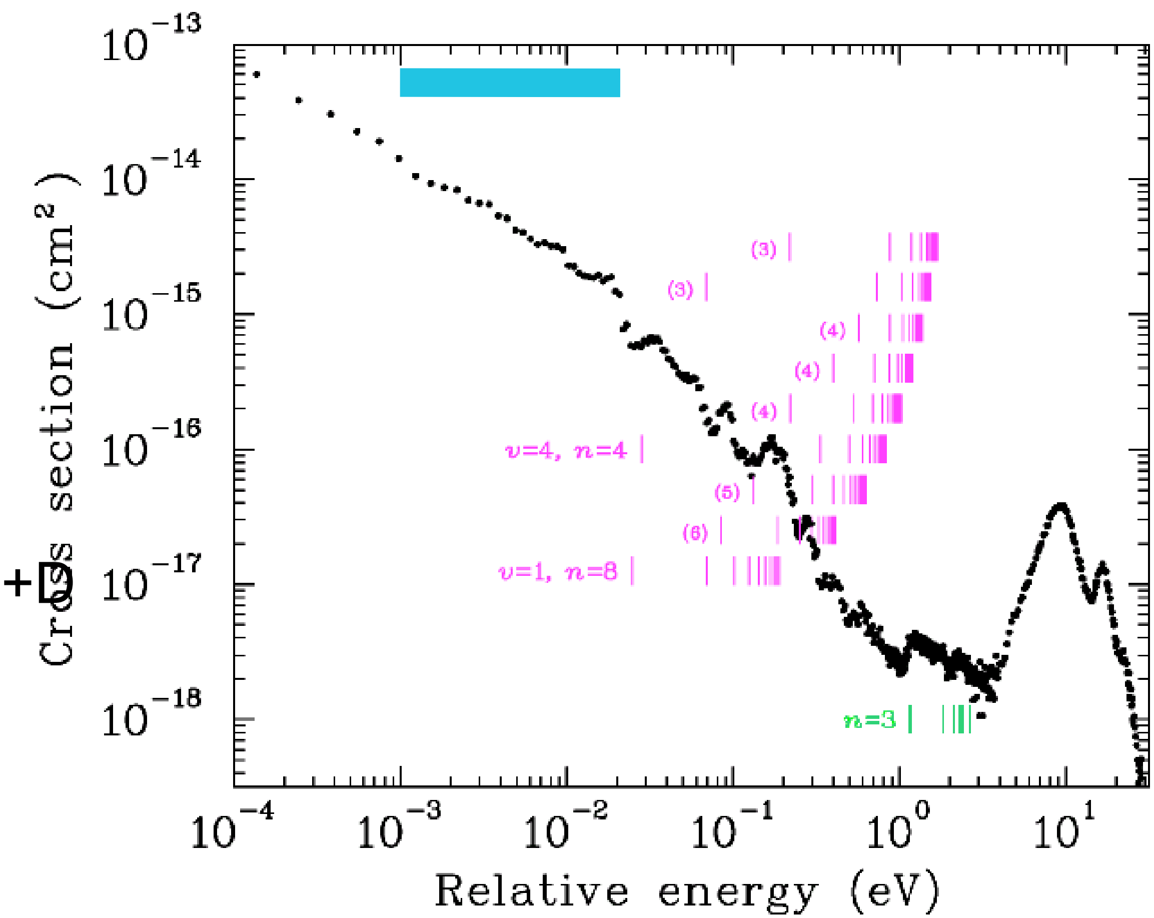


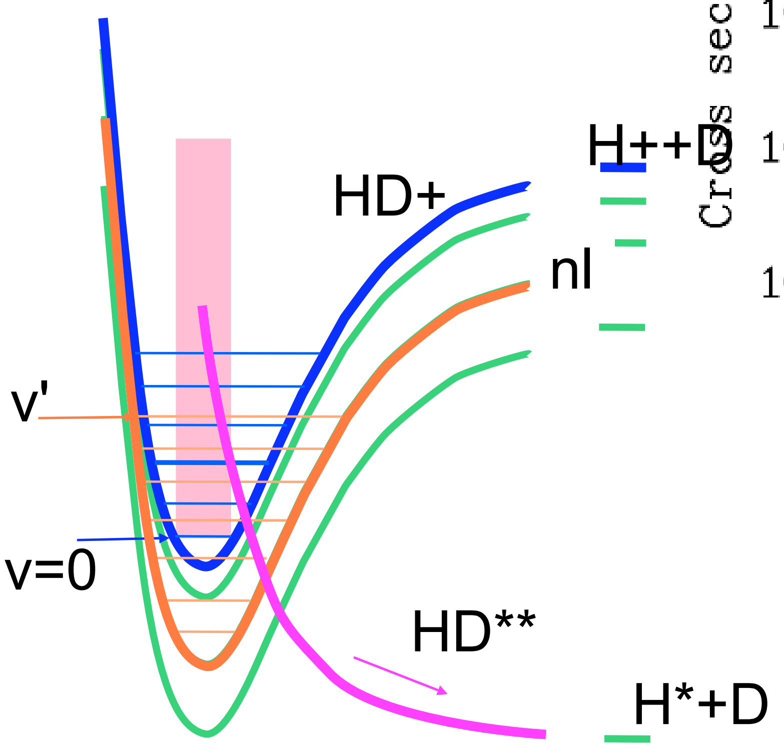


TSR: M. Lange et al., PRL 83 (1999) 4979;
Al-Khalili et al., PRA (2003)

Dissociative recombination

$$\mathrm{HD}^{+}(v{=}0) + e \rightarrow \mathrm{HD}^{**} \rightarrow \mathrm{H}(n) + \mathrm{D}(n') + E_k$$



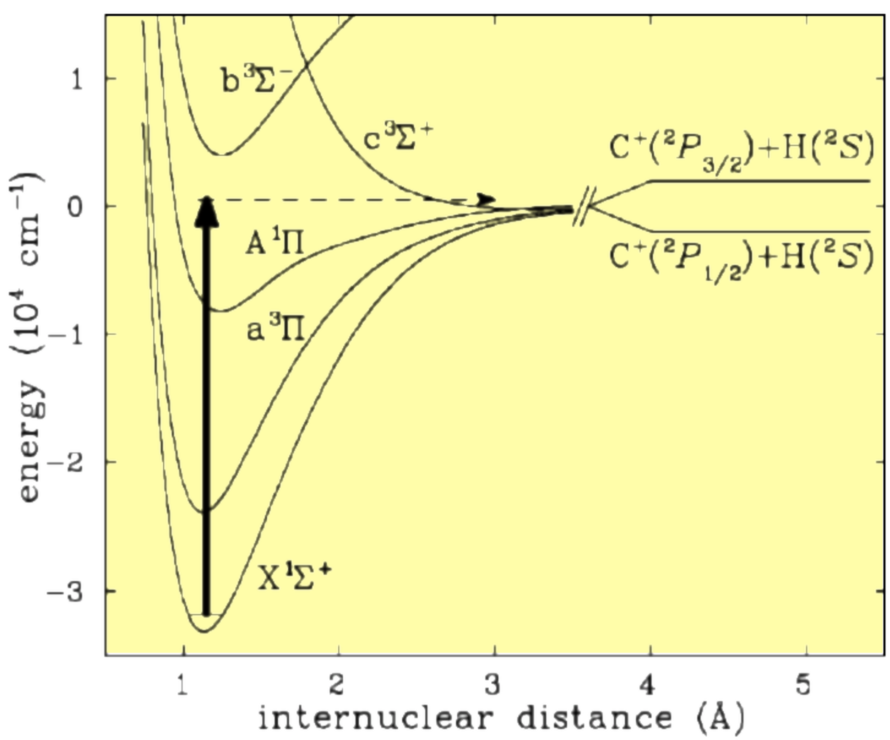


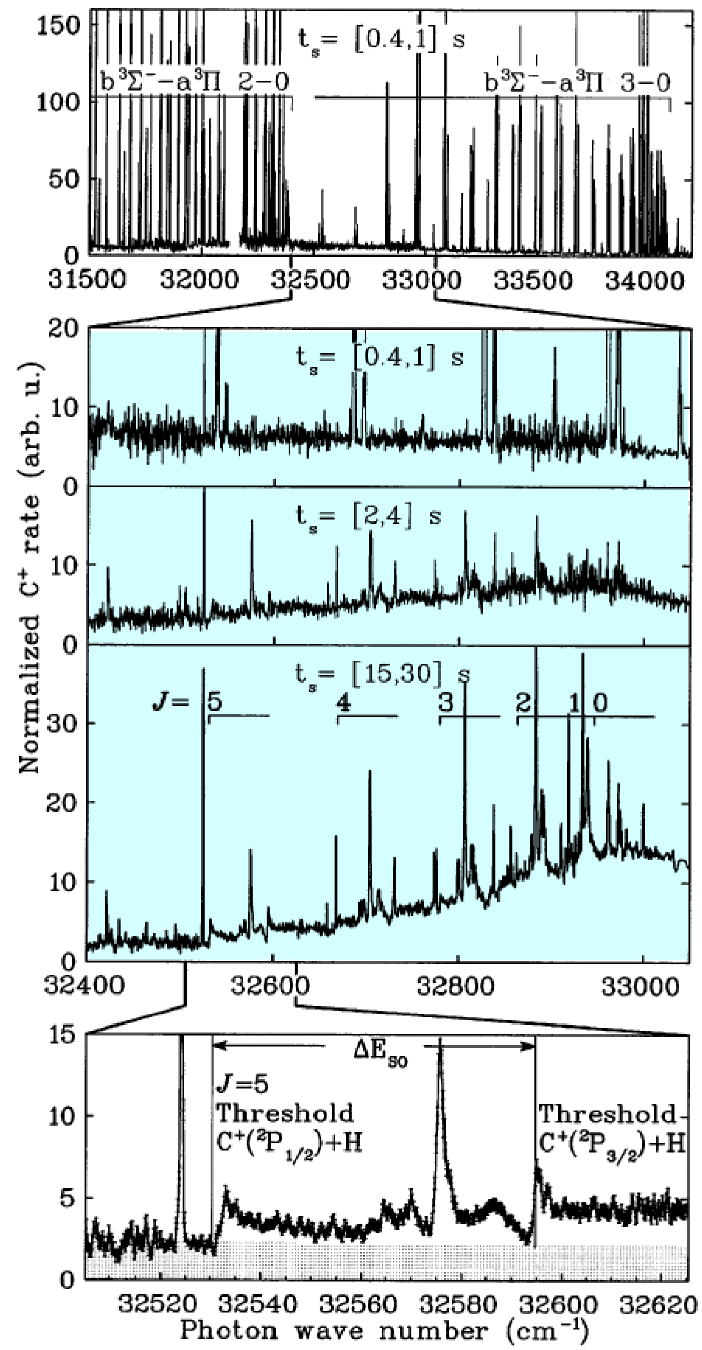
TSR: M. Lange et al., PRL 83 (1999) 4979;
Al-Khalili et al., PRA (2003)

Rotational cooling and diagnostic

$CH^+ + h\nu \rightarrow C^+ + H$

Feshbach resonances through
C+ fine structure splitting



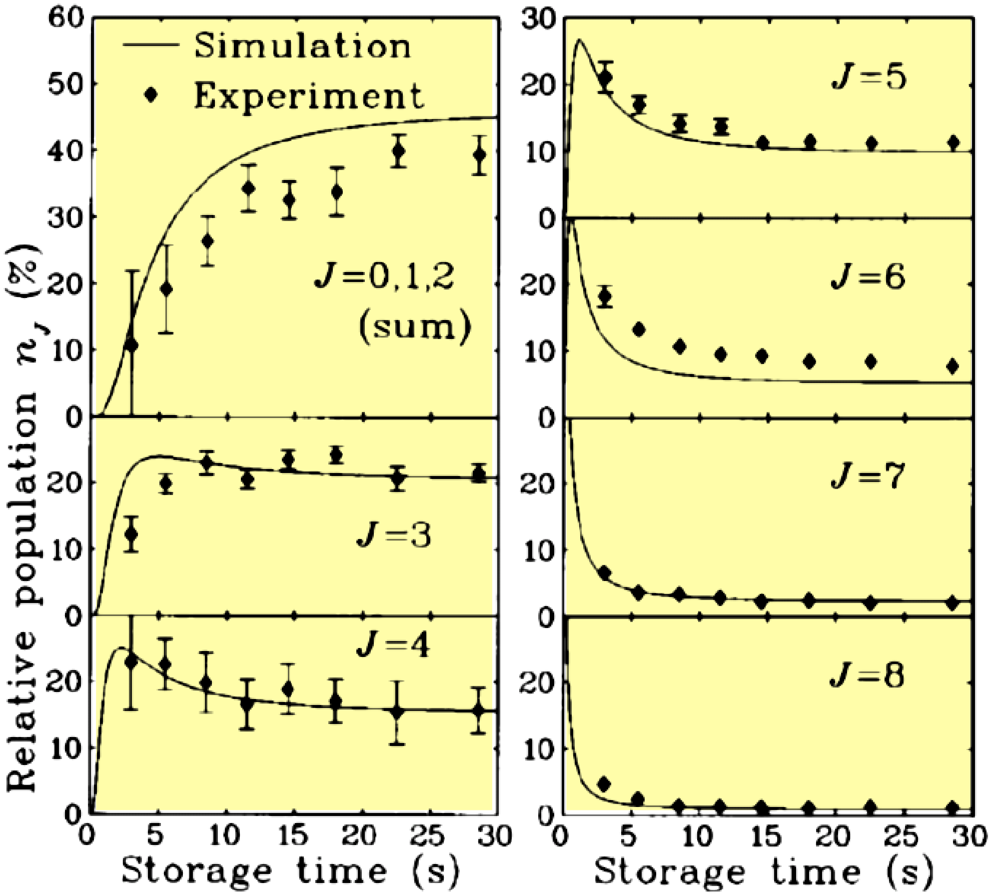


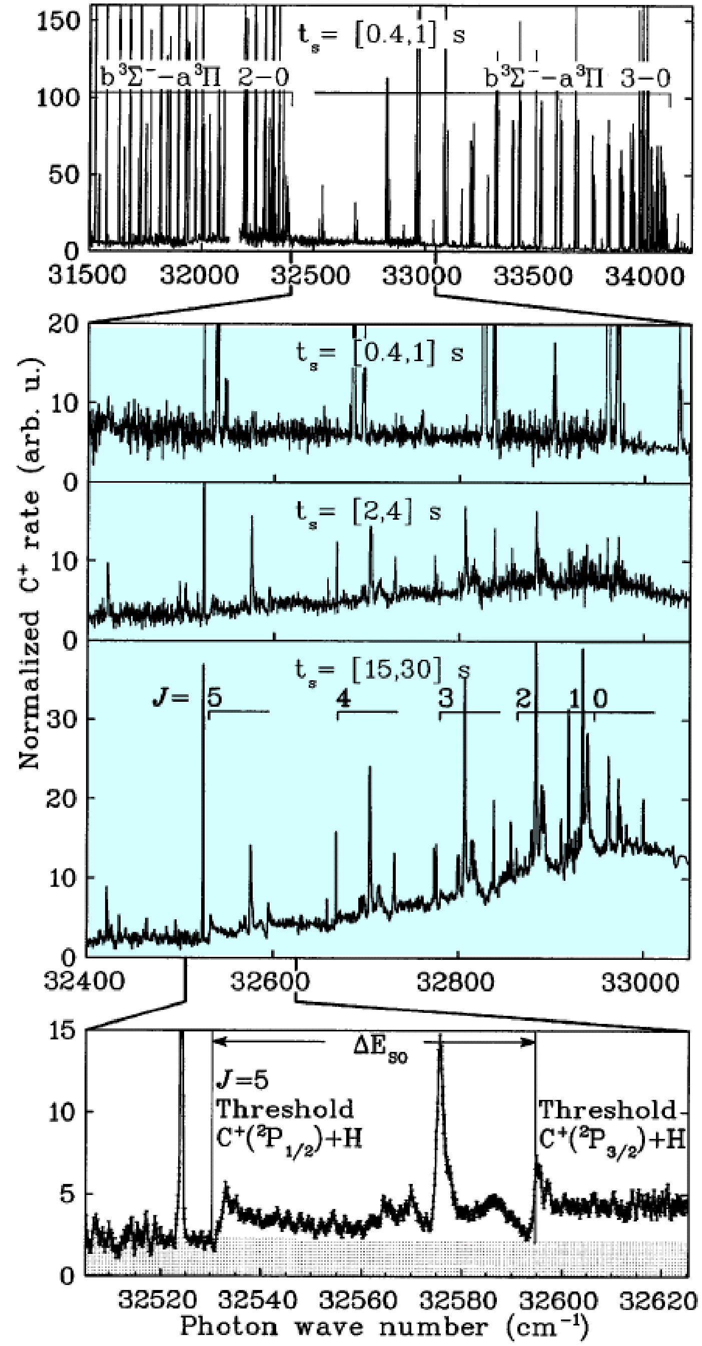
U. Hechtfischer et al., PRL 80,

Rotational cooling and diagnostic

CH+ + hv → C+ + H

Rotational cooling to ~ 300 K





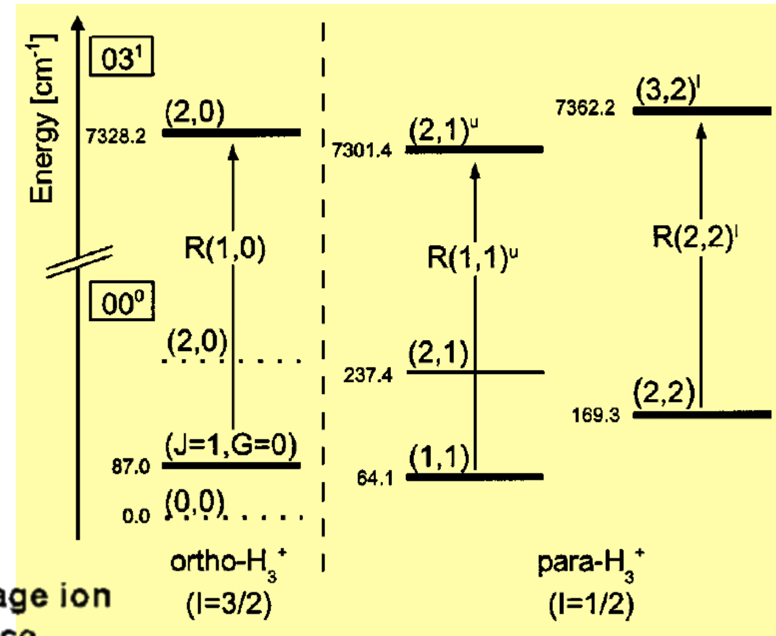
U. Hechtfischer et al., PRL 80,

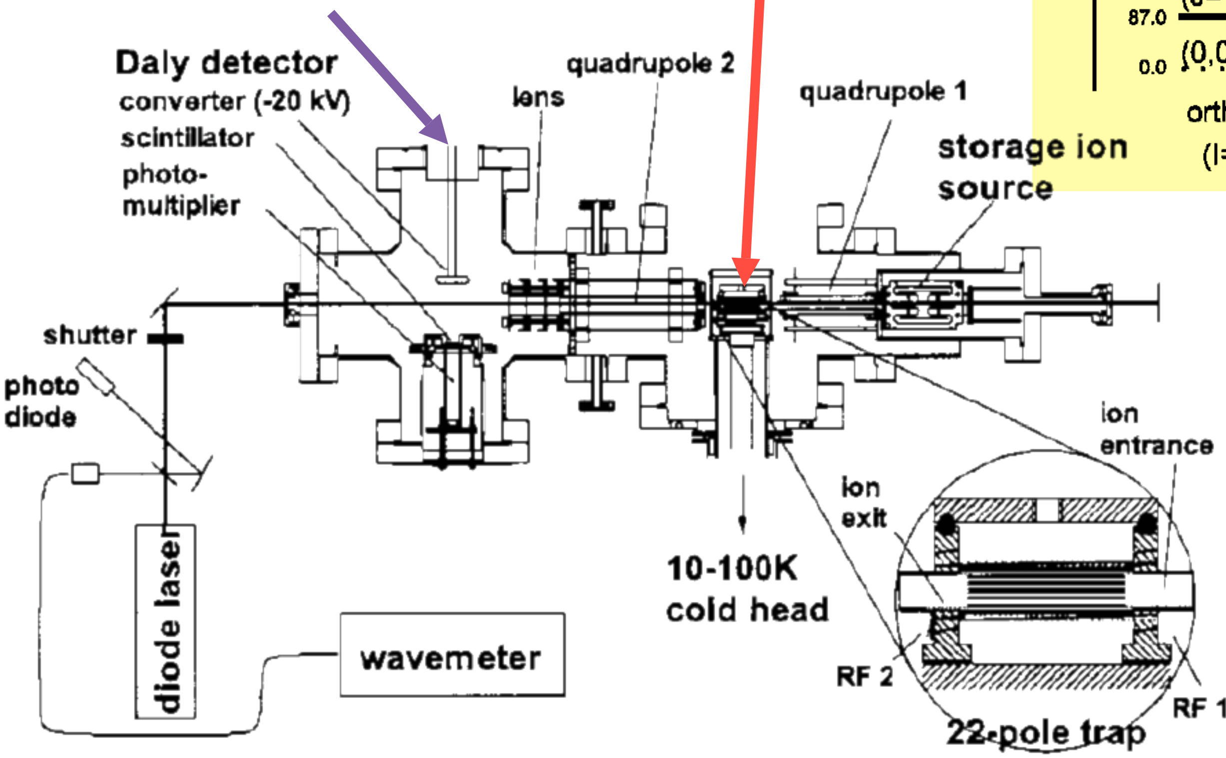
Rotational cooling and diagnostic

Ro-vibrational spectroscopy with
mass spectrometric probing

(H3+)* + Ar
→ ArH+ + H2

~ 300 H3+ ions



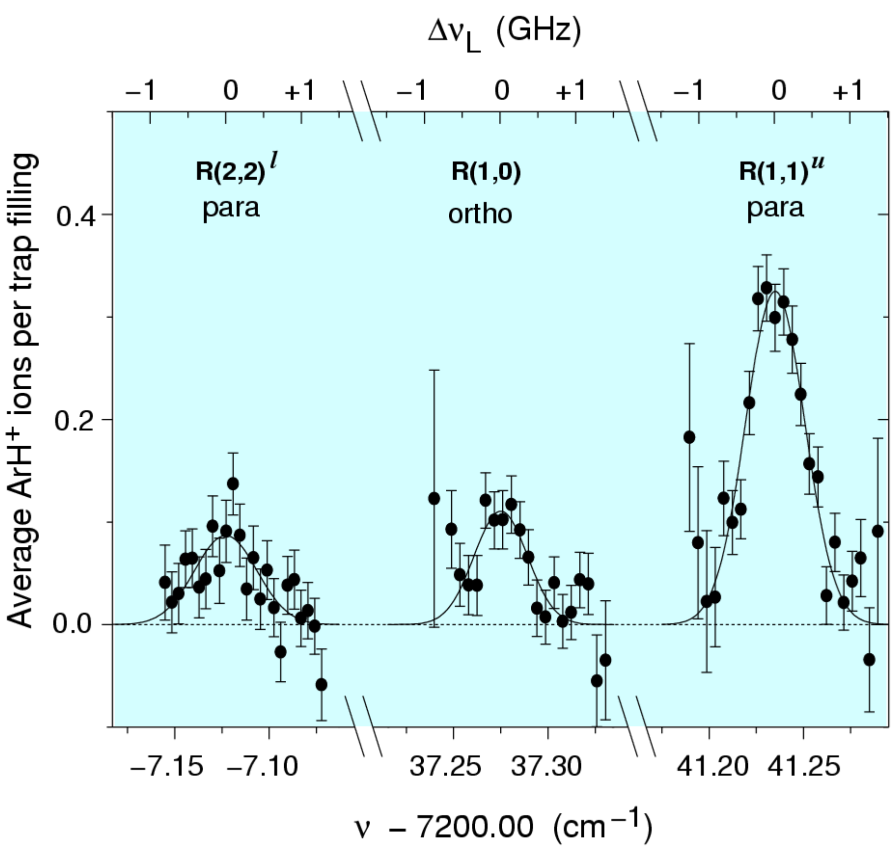


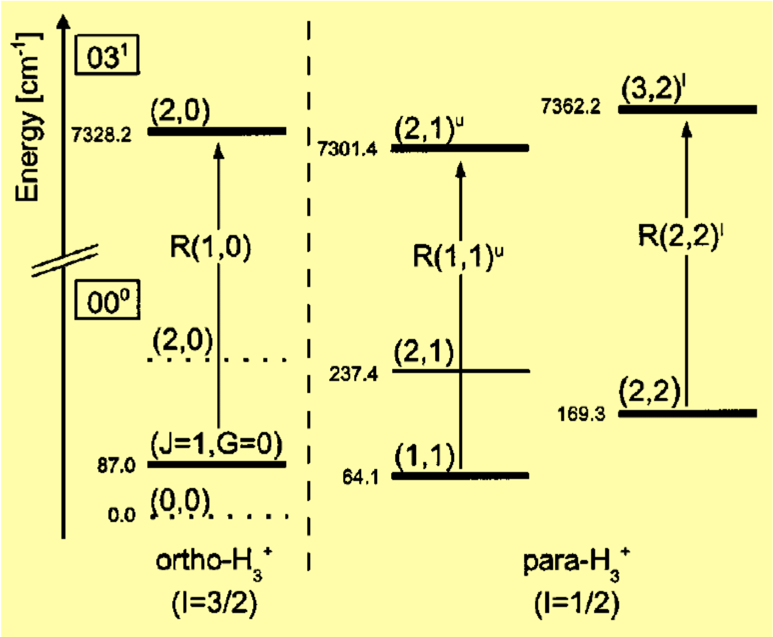
H. Kreckel
in collaboration with
J. Glosik, R. Plasil
(Prague)
R. Wester, J. Mikosch
(Freiburg)
D. Gerlich (Chemitz)

Rotational cooling and diagnostic

Ro-vibrational spectroscopy with mass spectrometric probing

~ 300 H3+ ions





H. Kreckel

in collaboration with

J. Glosik, R. Plasil (Prague)

R. Wester, J. Mikosch (Freiburg)

D. Gerlich (Chemitz)

J. Mikosch et al., JCP 121,

Stored antiproton beams at keV energies

Hydrogen-Antihydrogen collision experiments

Systems: $\bar{H}$ on H, H2, He, ...

Collision energy regimes and dynamics:

Collision velocity matched to bound leptons
e+e- formation dynamics – Lepton rearrangement

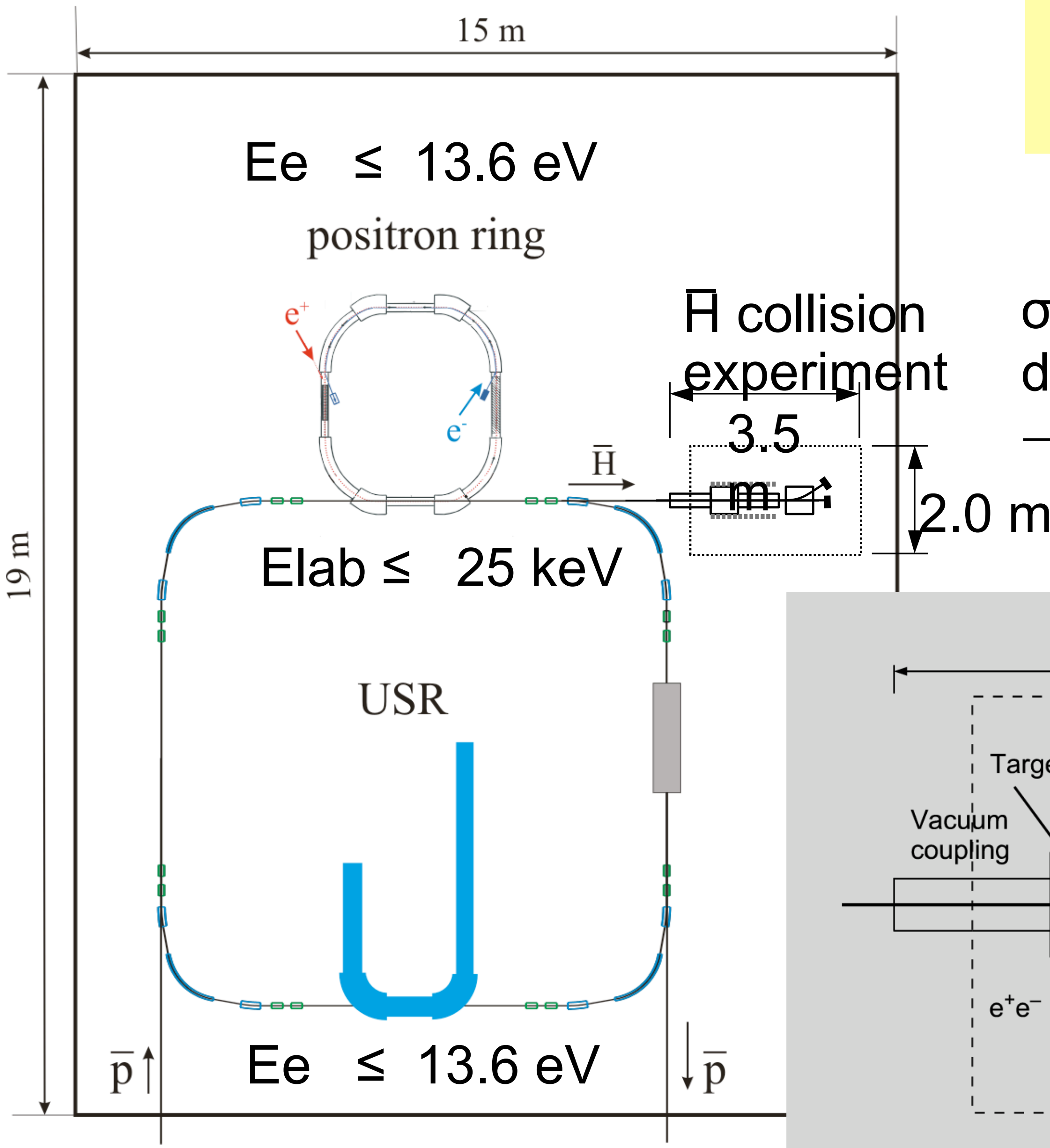
v ≤ 1 a.u. EH ≤ 25 keV

Collision velocity matched to bound hadrons
$p\bar{p}$ formation dynamics – Hadron rearrangement

v < 0.046 a.u. EH ≤ 54 eV

Antihydrogen collision experiment

$$H + \bar{H} \rightarrow e^+ + e^- + p + \bar{p}$$
$$\rightarrow Ps + \bar{p} + p$$



Antihydrogen collisions

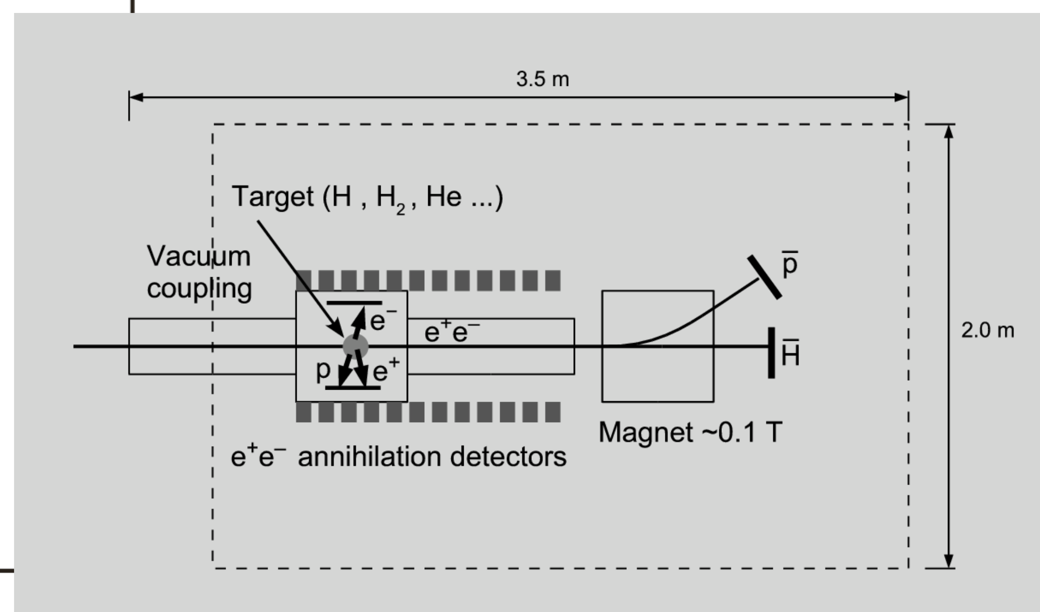
σ ~ 10-16 cm2 (from H+H collisions)

dnt = 1014 cm-2

→ Event rate

~ 1/s for 200 H̄/s

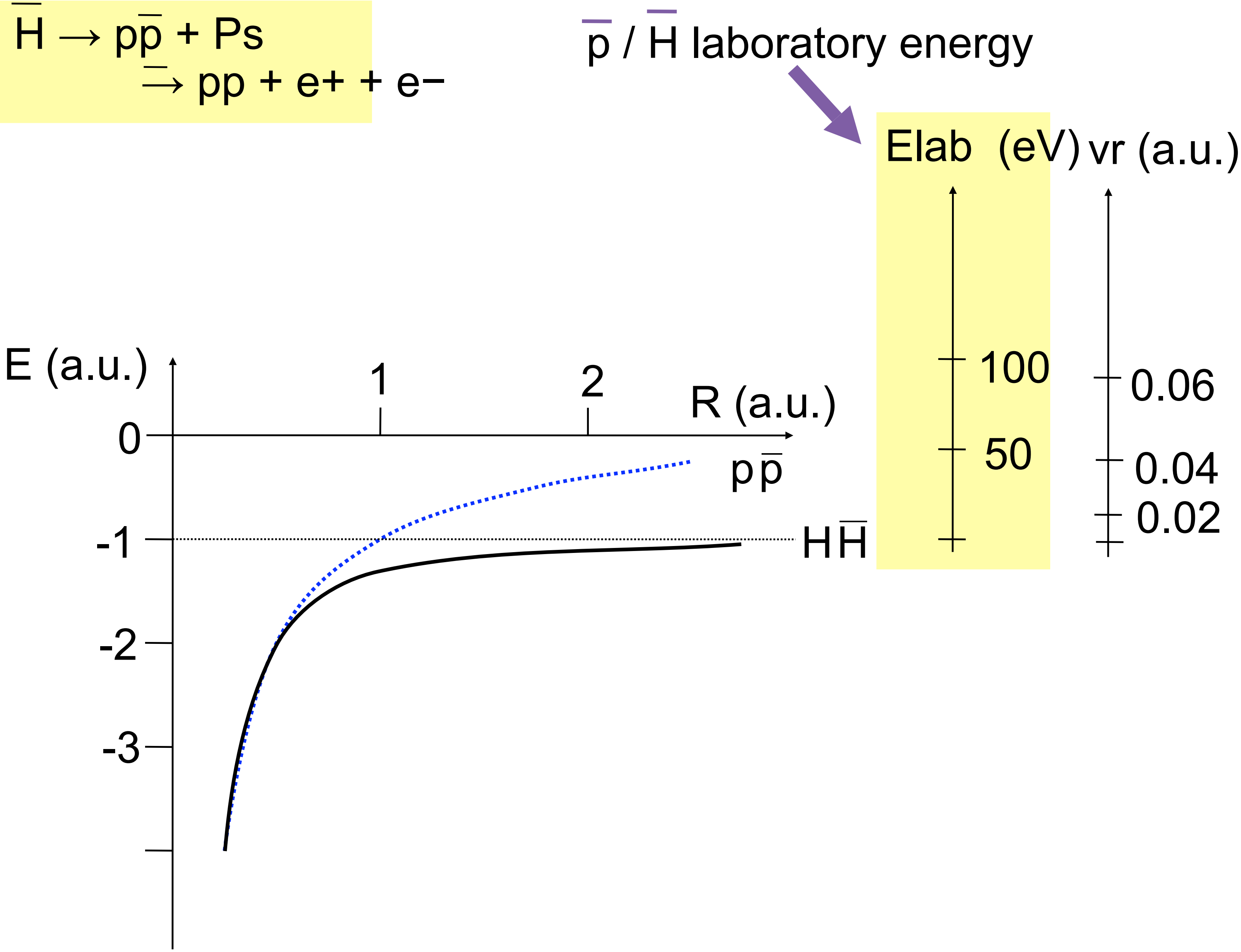
s)



Hydrogen–antihydrogen rearrangement at eV energies

$H + \bar{H} \to p\bar{p} + Ps$

$\to p\bar{p} + e^+ + e^-$



Hydrogen–antihydrogen rearrangement at eV energies

$$H + \bar{H} \rightarrow p\bar{p} + Ps$$
$$\rightarrow p\bar{p} + e+ + e-$$