Potential for $\vec{e}+\vec{HD}$ experiments with Frozen-Spin HD

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- $\vec{H}\vec{D}$ lifetimes with photon beams ~ 2 years :
  - PRL **102** (2009) 172002; PRL **118** (2017) 242002; …
  - NIM A**737** (2014) 107; NIM A**815** (2016) 31; …

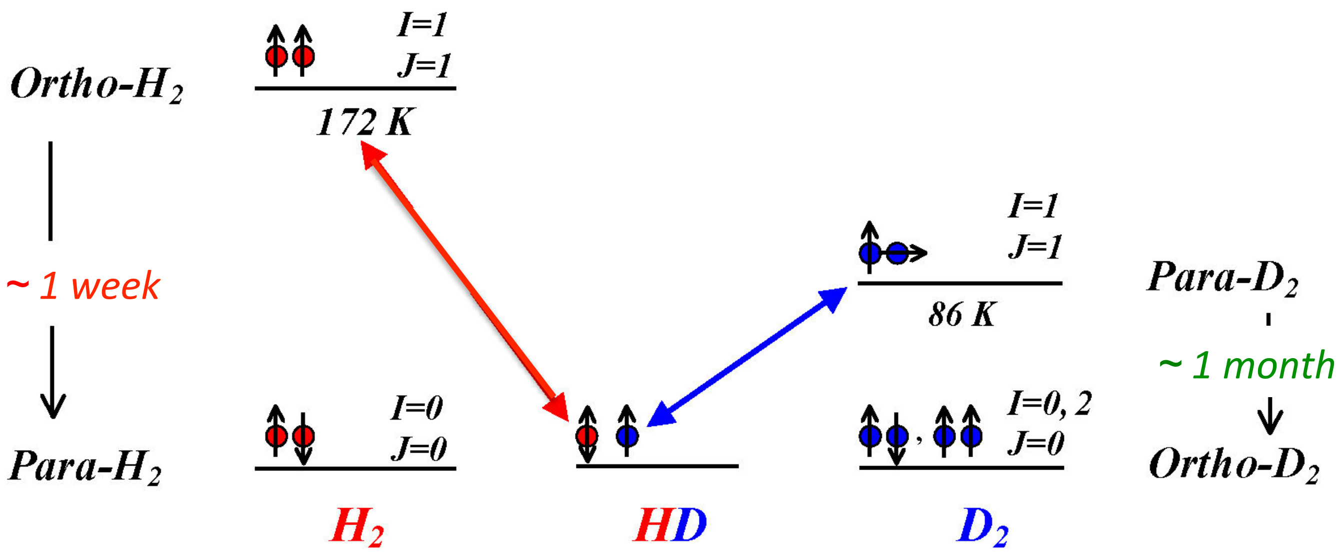
- next goal – viable transverse frozen-spin target with electron beams

- PAC 39:

	Scientific rating
◊ SIDIS, C12-11-111, M. Contalbrigo,…	A
◊ dihadron production, PR12-12-009, H. Avakian,…	A
◊ DVCS, PR12-12-101, L. Elouadrhiri,…	A

steps in polarizing solid HD - a brief overview

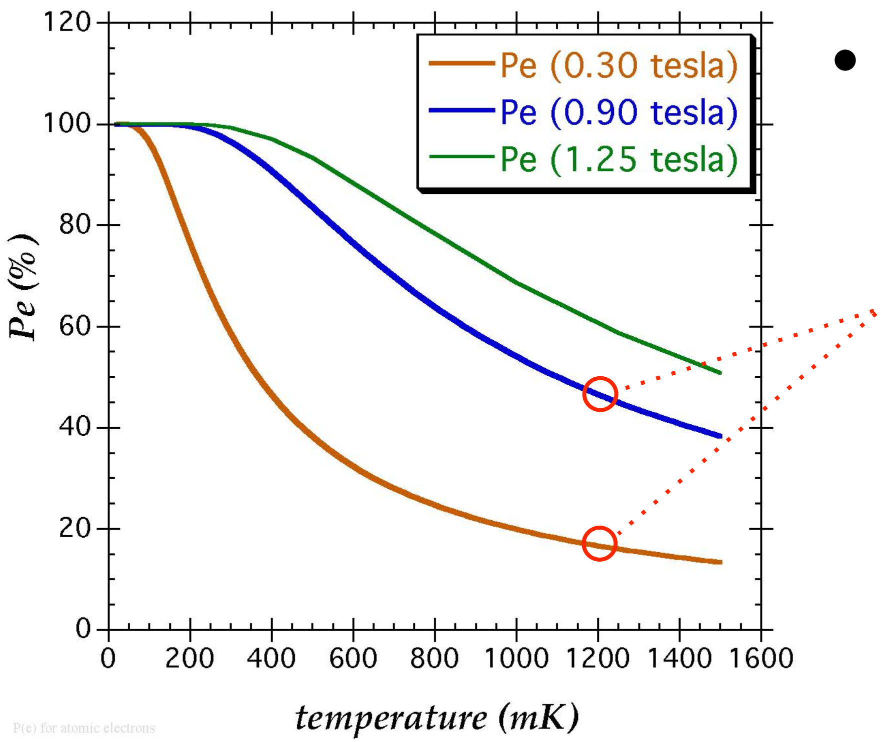
- HD gas distilled with impurity concentrations, c = 10^{-3} to 10^{-4} of H_2 & D_2
- condensed to a solid, ¾ of H_2 & ⅓ of D_2 are caught in their J=1 levels
- magnet field aligns 1st rotational states (J=1) of *Ortho-H_2* & *Para-D_2*
- H_2 (& D_2) spin exchange with HD, polarizing target to P(H) ~ 60%
- spin-exchange stops as J=1 states decay away ⇨ HD with frozen spin



e^- beam-induced depolarization mechanisms - I

I. e^- beam ionization unpairs *1s* molecular electrons of HD
- if residual *1s* electron is unpolarized (depends on temperature)

➔ flips with Fourier components at nuclear Larmor frequencies
➔ depolarizes the local HD
➔ depolarization diffuses out into the rest of the HD crystal



- T(HD) ~ 1.2K in 2012 test runs

➔ P(e) ~ 20-50%

➔ depolarization is expected

⇔ observed ~1 nA-day in tests

e⁻ beam-induced depolarization mechanisms –I– solutions

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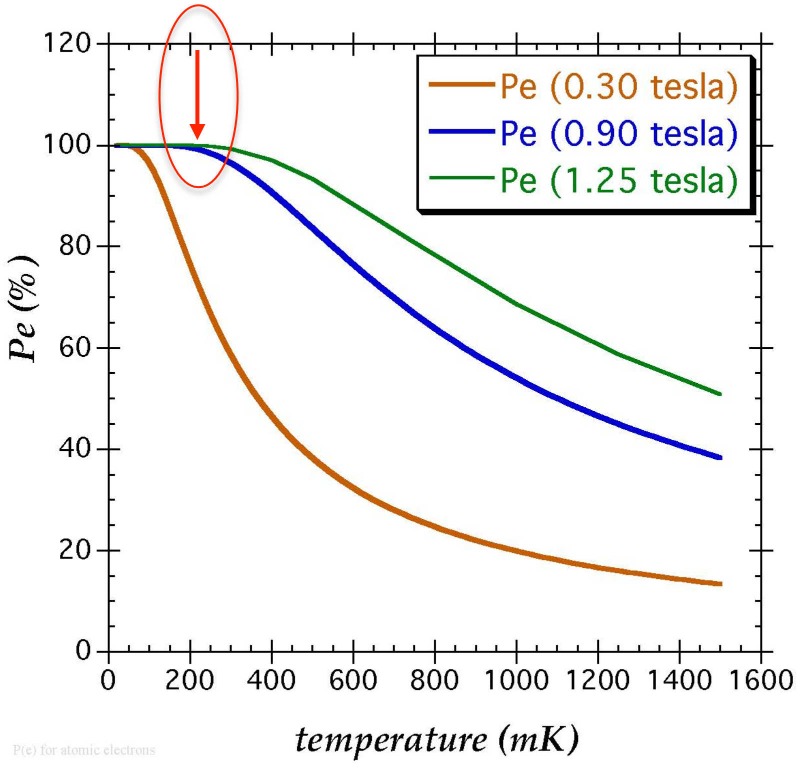


Solution:

- colder running temps (new cell, new fast raster):
- expected HDtemp ~ 210 ±70 mK
- B ~ 1 ¼ tesla

➔ will insure P(e) ~ 100 %

II. Hyperfine mixing of unpaired electrons with H spins

- $\mu(e)$ opposite in sign to that of H (or D)

➔ electrons polarized in the holding field have spins opposite to H

➔ total angular momentum projected along B is less than maximal

➔ Hyperfine mixing of |F, $m_F = m_H + m_e$> states with different m_H

$\Leftrightarrow \frac{1}{\sqrt{2}}\left\{\left|\Uparrow_H \downarrow_e\right\rangle + \left|\Downarrow_H \uparrow_e\right\rangle\right\}$ $\Leftrightarrow$ dilutes H polarization

➔ depolarization can diffuse out into the rest of the HD crystal

$\Rightarrow$ depolarization $\propto B^{-2}$ (& independent of temperature)

(should also have contributed to depolarization in 2012 tests)

Solutions:

- use RF flip of H (or D) to align nuclear and electron spins $\left|\Downarrow_H \downarrow_e\right\rangle$

➔ stretched state with maximal angular mom projection ← unique

➔ prevents depolarization through hyperfine mixing

III. Radiation-induced Chemical changes

(following parallel literature on tritium chemistry after beta decay)

- ionized HD^+ will be highly reactive
- $HD^+ + HD \Rightarrow H_2D^+ + D$

  or $\Rightarrow HD_2^+ + H$

  ↑ no effect on polarization (paired e^-), but highly mobile
- $H_2D^+ + e^- \Rightarrow H_2 + D$, ...

  $\Rightarrow$ increased concentrations of (J=1) ortho-H_2 (para-D_2)

  ↑ polarization catalysts

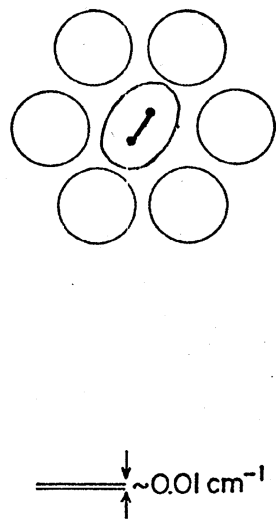
  $\Rightarrow$ could H (& D) loose their frozen spin state ?

Spin Transfer : eQQ and the role of J=1 pairs

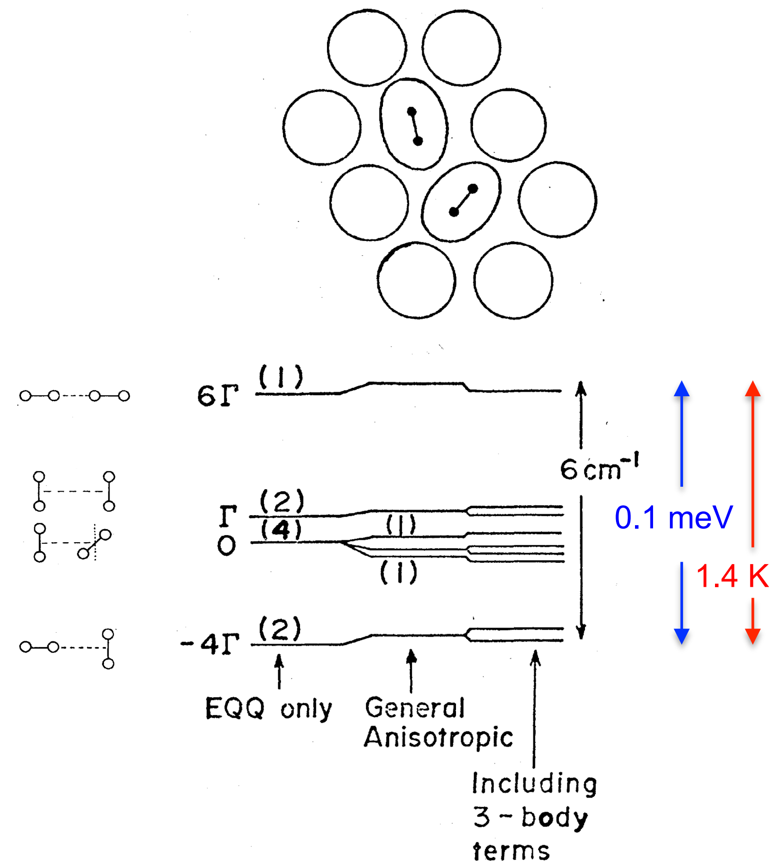
- molecular J=0 ground states are spherically symmetric,
- J=1 rotational excitations are NOT

*I. Silvera, Rev Mod Phys **52** (1980) 393*

spatial degeneracy of an isolated J=1 H_2 or D_2 molecule



very small energy splitting when a single J=1 is surrounded by other J=0 molecules



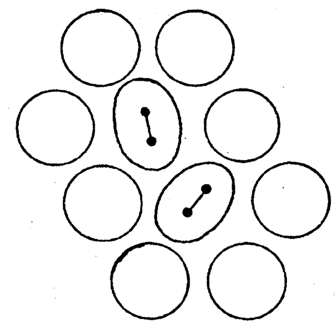
degeneracy Is lifted by large eQQ of a pair of J=1 molecule

spin transfer mechanism - through J=1 pairs

*I. Silvera, Rev Mod Phys **52** (1980) 393*

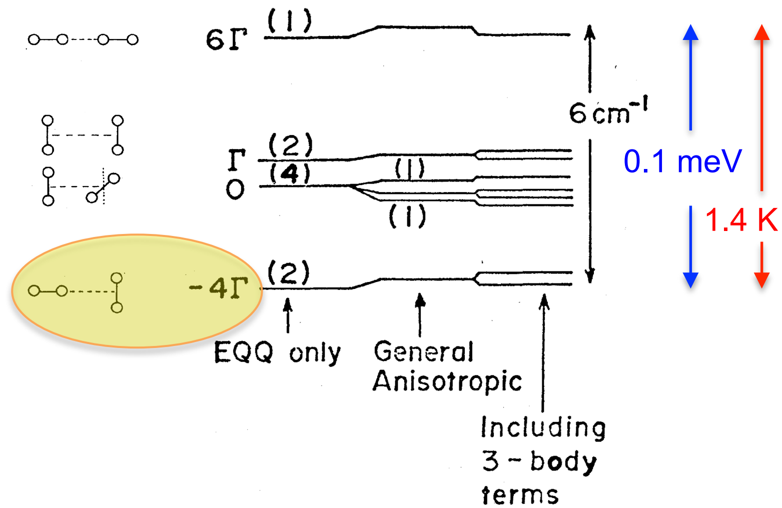
- in some orientations, the electric Quadrupole-Quadrupole (eQQ) interaction is attractive
  - — overwhelmed by collisions in the gas or liquid states
  - — but this binding can be a significant effect in a solid

⇔ a J=1 molecule at the solid-liquid boundary (triple pt) has a slightly increased probability of capturing another J=1



- phonons in the solid lattice scatters from eQ moments of J=1 x J=1 molecular pairs, causing sudden transitions between their 3 x 3 substates
  - — transitions ⇔ spatial reorientations
  - — the magnetic dipole moments of the J=1 rotating molecules follow the reorientation

⇔ there is a sudden change in the magnetic field in the vicinity of nearby a HD, with Fourier components at H and D Larmor frequencies



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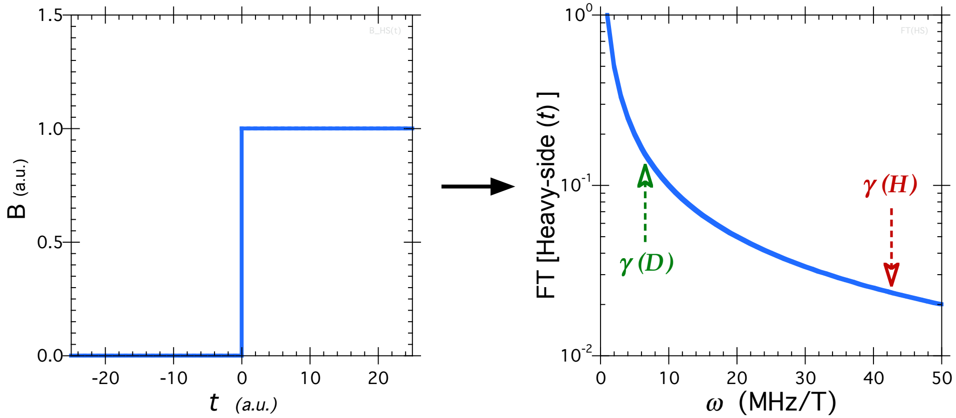
spin transfer mechanism



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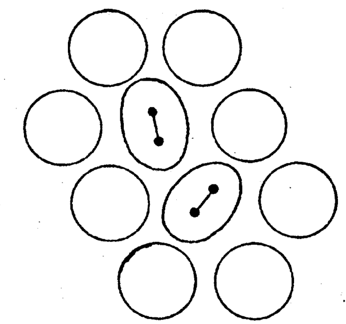
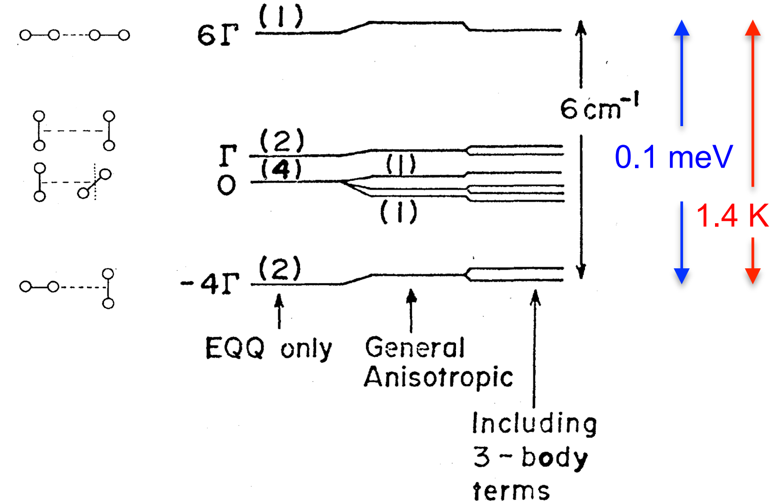


- ⬄ these induces spin flips of H or D in nearby HD
- ⬄ depolarization resonantly hops outward through the HD (a Quantum crystal)



- eQQ interaction energies are almost the same for all combinations of J=1 pairs:
  (oH_2) x (oH_2)
  (oH_2) x (pD_2)
  (pD_2) x (pD_2)

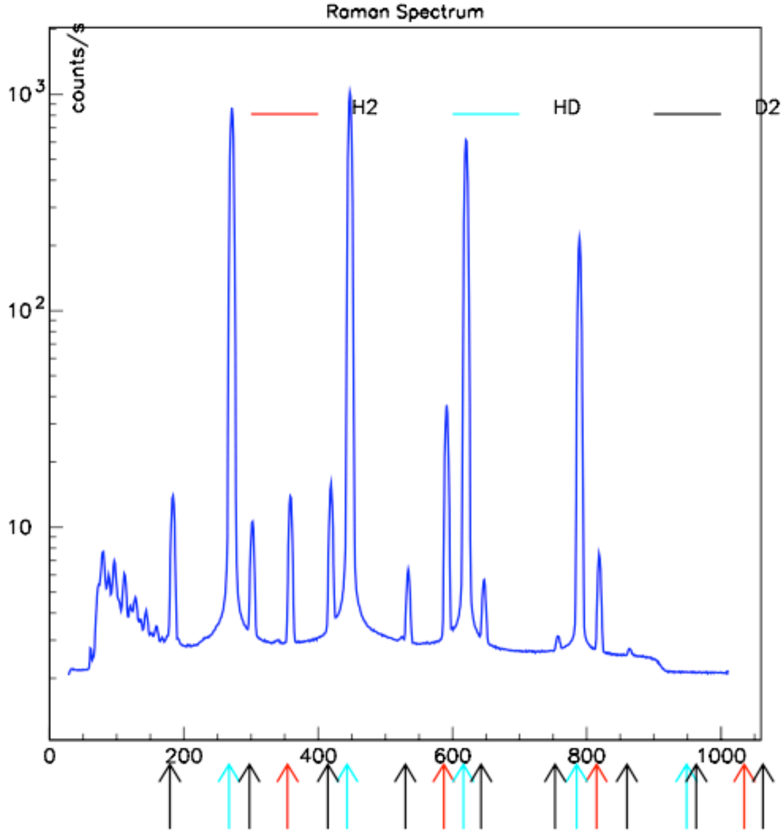
degeneracy
Is lifted by large eQQ of a pair of J=1 molecule

- number of J=1 x J=1 clusters is proportional to:

$c(oH_2) \bullet c(oH_2) + 2 \bullet c(oH_2) \bullet c(pD_2) + c(pD_2) \bullet c(pD_2)$

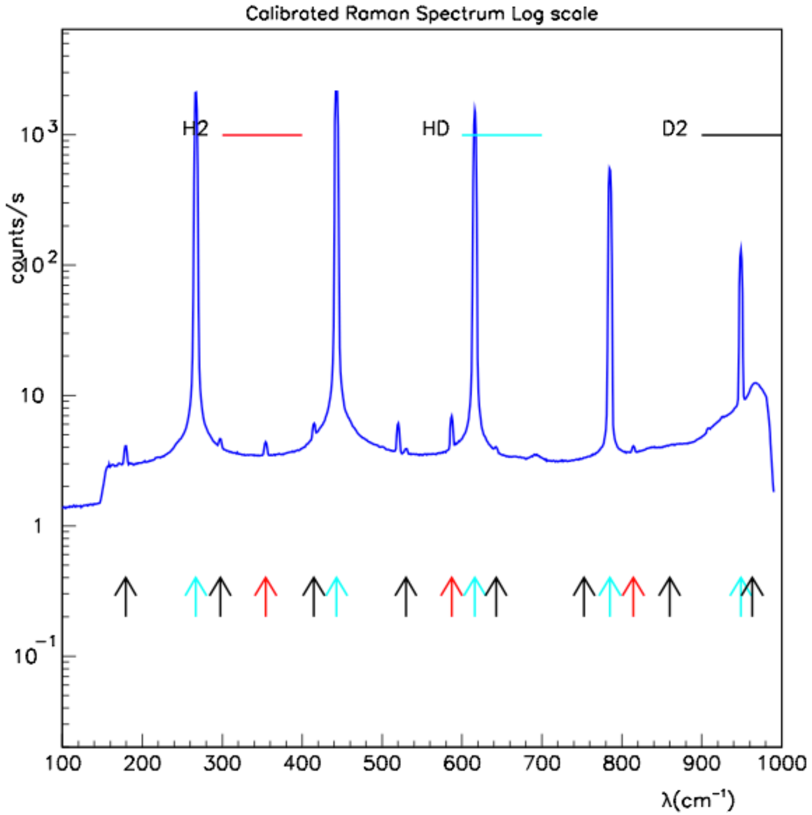
Purity analysis through Raman scattering (U Roma-II)

Reference gas (used for tune-up)



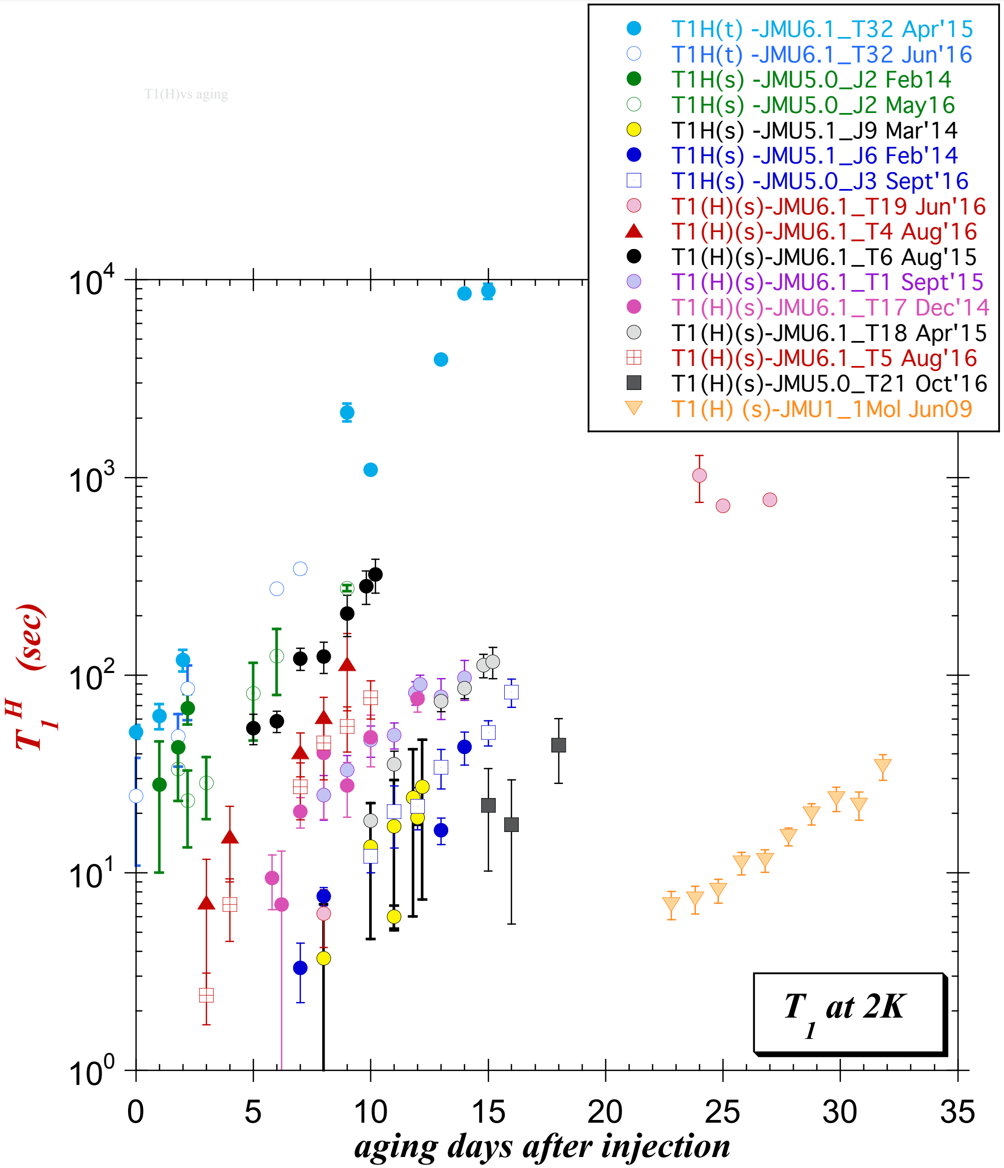
$c(H_2)$ = H_2/HD = 0.01874 ±0.00005
$c(D_2)$ = D_2/HD = 0.01533 ±0.00012

distilled NP grade gas



$c(H_2)$ = H_2/HD = 0.00067 ±0.00002
$c(D_2)$ = D_2/HD = 0.00064 ±0.00004

Correlations between T_1 (2K) and $c(H_2)$,$c(D_2)$ from Raman



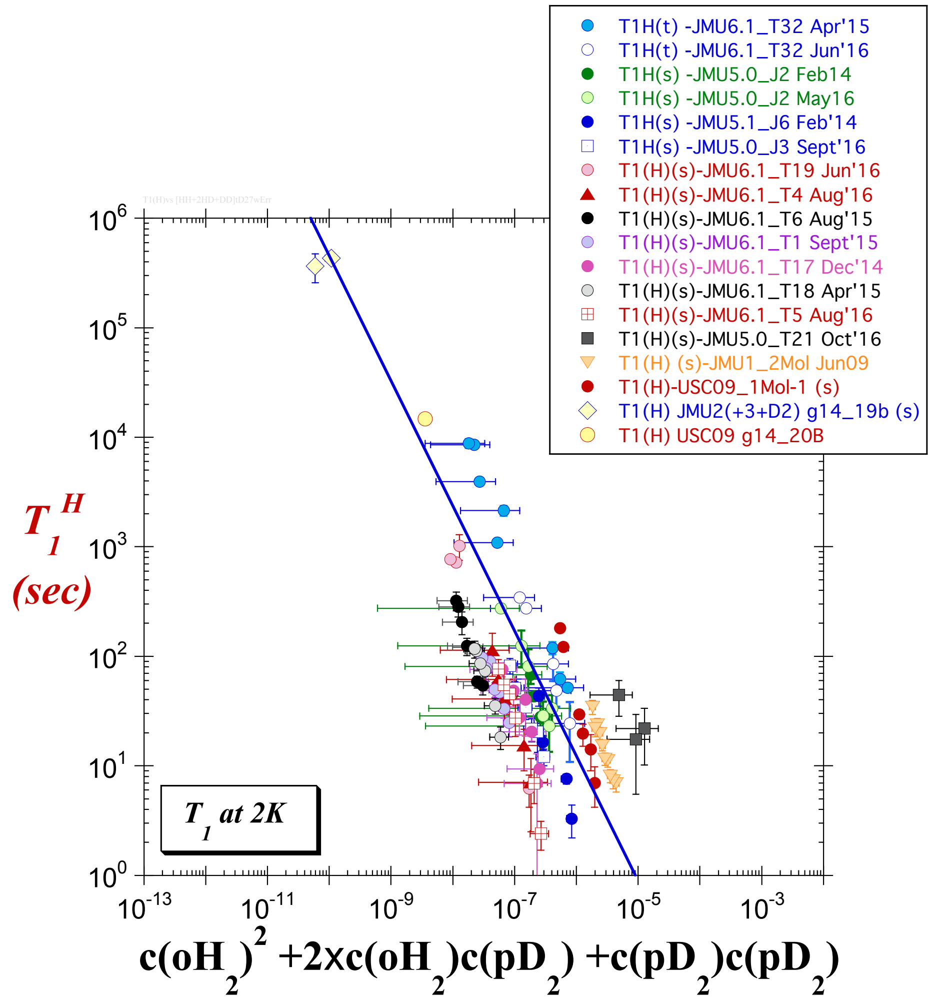
Measurements on a large number of distilled HD gas samples over the last decade:

- T_1 (2K) measurements, &
- Raman measurements of $c(H_2)$, $c(D_2)$

- T_1 increases with time as $c(\text{ortho-}H_2)$ and $c(\text{para-}D_2)$ drop

- $c(oH_2) = \frac{3}{4}\, c(H_2) \exp(-t/6 \text{ days})$
- $c(pD_2) = \frac{1}{3}\, c(D_2) \exp(-t/27 \text{ days})$

Polarization decay (T_1) correlated with number of J=1 pairs



III. Radiation-induced Chemical changes

(following parallel literature on tritium chemistry after beta decay)

- ionized HD^+ will be highly reactive
- $HD^+ + HD \Rightarrow H_2D^+ + D$

  or $\Rightarrow HD_2^+ + H$

  ↑ no effect on polarization (paired e^-), but highly mobile
- $H_2D^+ + e^- \Rightarrow H_2 + D$, ...

  ⇨ increased concentrations of (J=1) ortho-H_2 (para-D_2)

  ↑ polarization catalysts

  ⇨ could H (& D) loose their frozen spin state ?

Solution:

- chemical processes will **NOT** produce J=1 species <u>in pairs</u> !

$\vec{e}$ + $\vec{HD}$ performance goals

e^- beam-induced depolarization mechanisms :

I. production of paramagnetic, unpaired electrons
⇔ should no be an issue at colder temperatures where they are fully polarized

II. polarization dilution through hyperfine splitting (HFS)
⇔ eliminate by operating with target and electron spins aligned

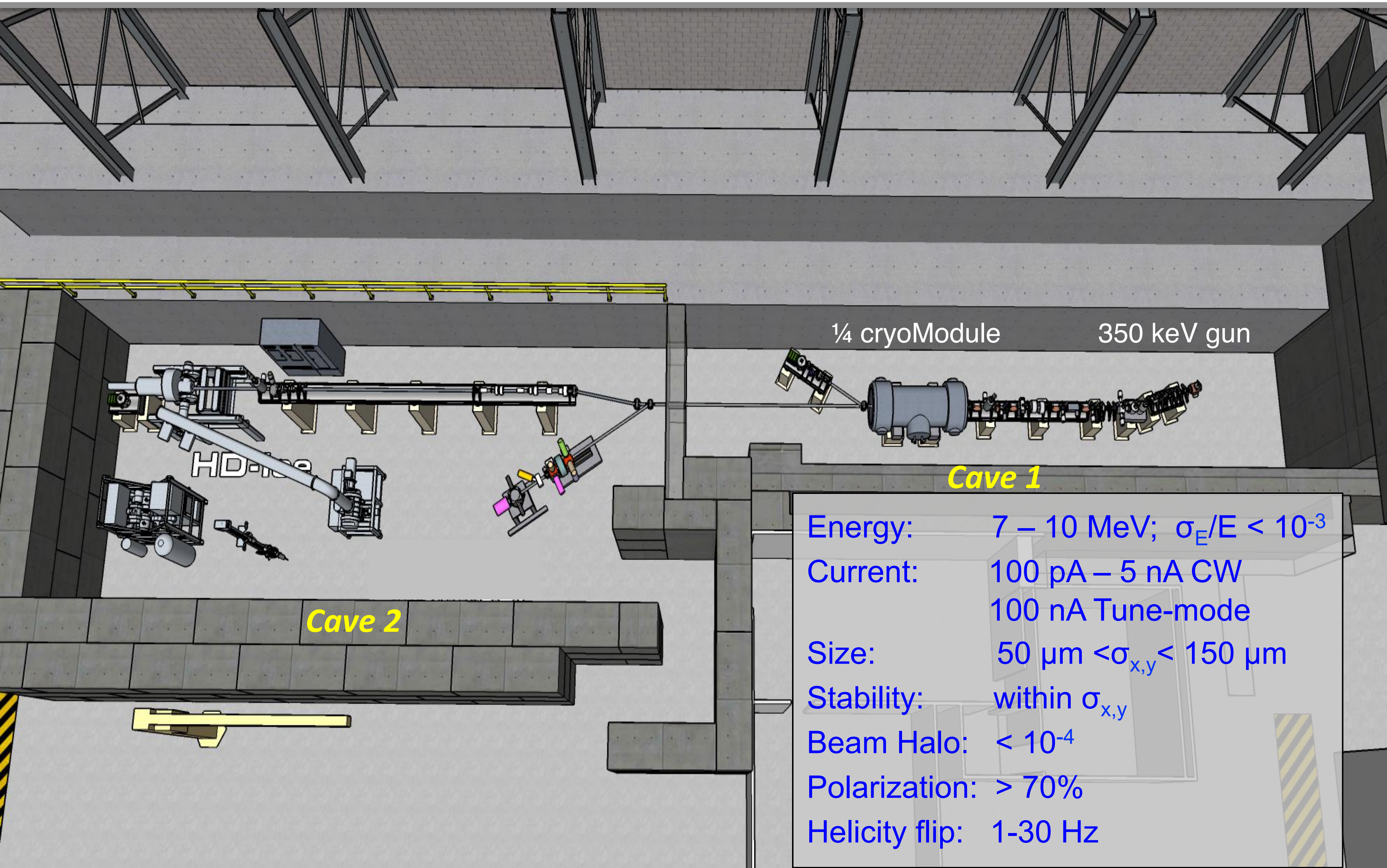
III. regeneration of J=1 rotational states through chain reactions
⇔ cannot generate the *pairs* of J=1 molecules that generate spin flips

Extrapolations from 2012 e+HD tests:

⇔ if the higher temperatures during the 2012 tests were the only source of loss, via the 1^{st} mechanism, then we anticipate that our improvements would give

~ 400 nA-hr lifetimes, … and possibly longer if HFS was an issue

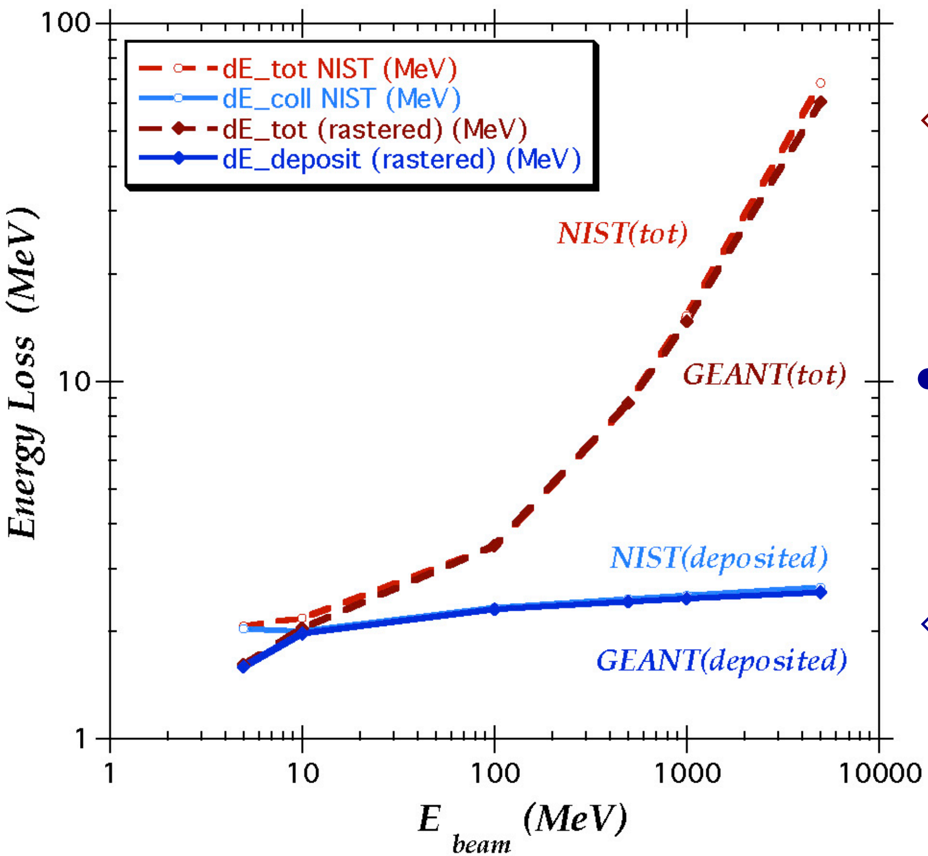
*Testing eHD at Jlab's **Upgraded Injector Test Facility** (UITF)*



Energy:	7 – 10 MeV; $\sigma_E/E < 10^{-3}$
Current:	100 pA – 5 nA CW 100 nA Tune-mode
Size:	50 μm $< \sigma_{x,y} <$ 150 μm
Stability:	within $\sigma_{x,y}$
Beam Halo:	$< 10^{-4}$
Polarization:	> 70%
Helicity flip:	1-30 Hz

energy deposited in HD

Electron energy loss in 5 cm of HD:



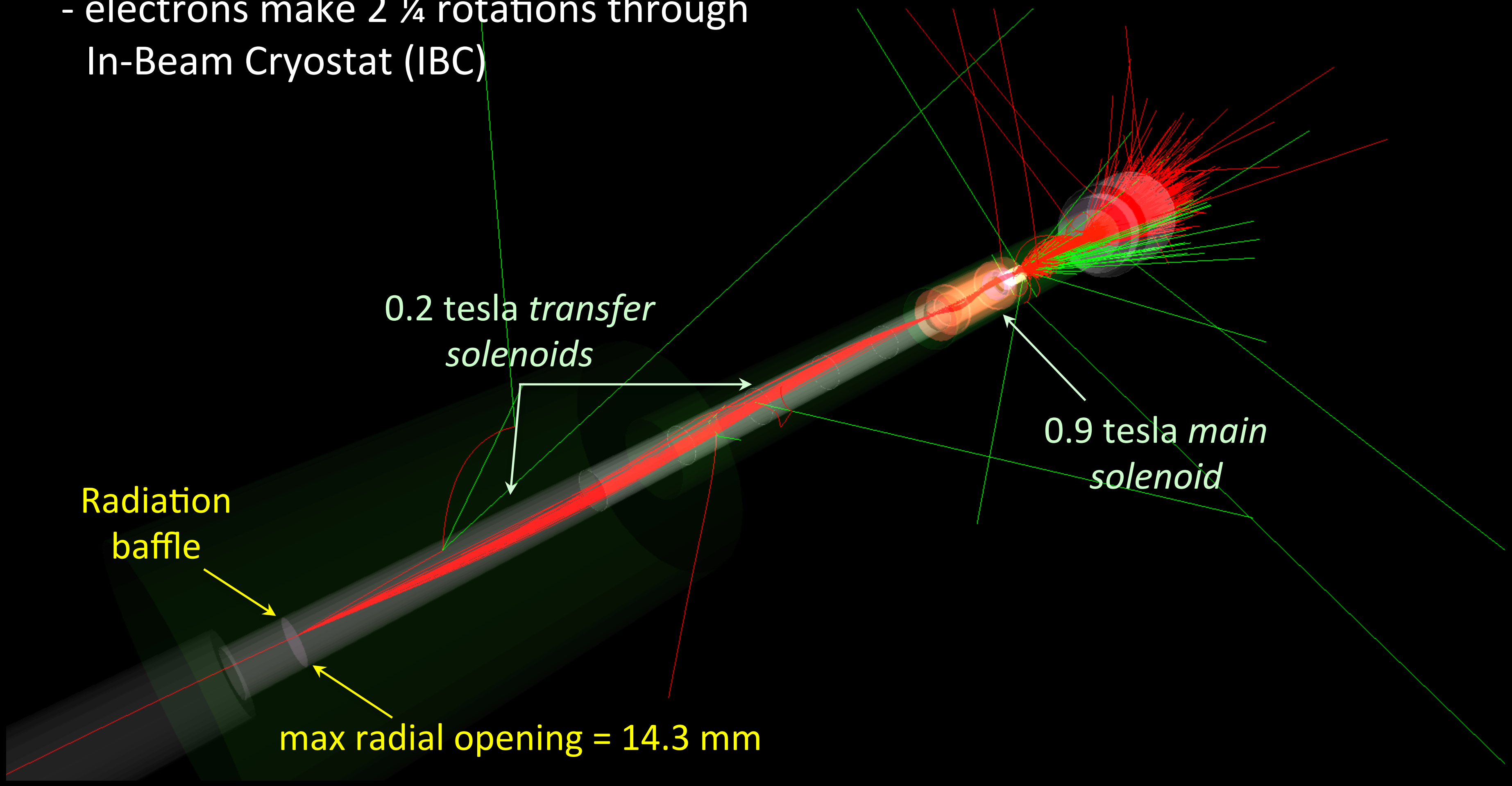
⇦ loss dominated by bremsstrahlung

- deposition dominated by Møllers
  $\sigma_{Møller} \sim (1 + 1/\gamma)^2$
  ~ independent of beam energy

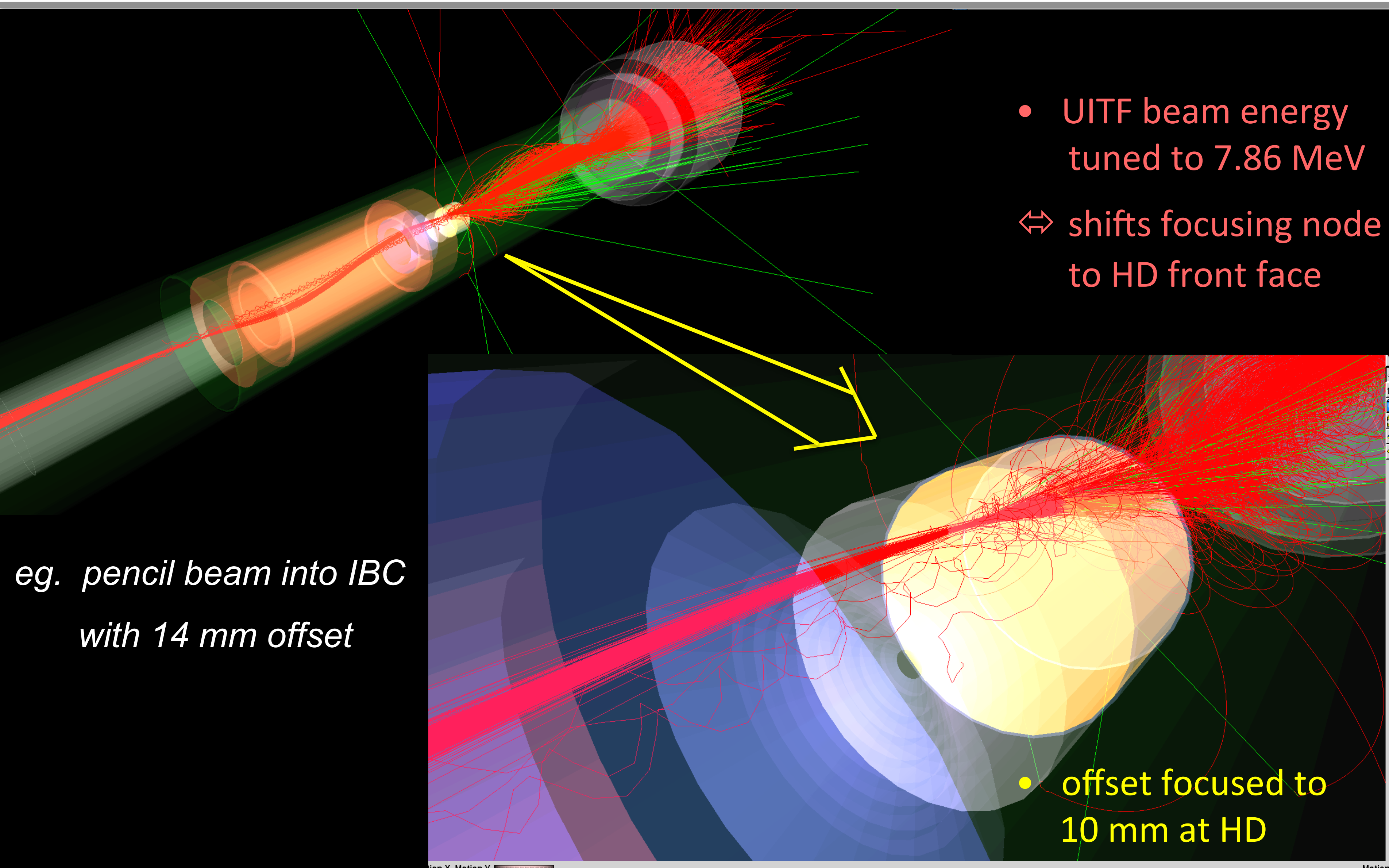
⇦ deposition: 2 Mev/e^- = 1 mW/ ½ nA
  ~ independent of beam energy

*electron transport studied with **G4BeamLine**©*

eg. pencil beam offset 14 mm at launch
- significant edge focusing from solenoids
- electrons make 2 ¼ rotations through In-Beam Cryostat (IBC)



electron transport studied with **G4BeamLine**©



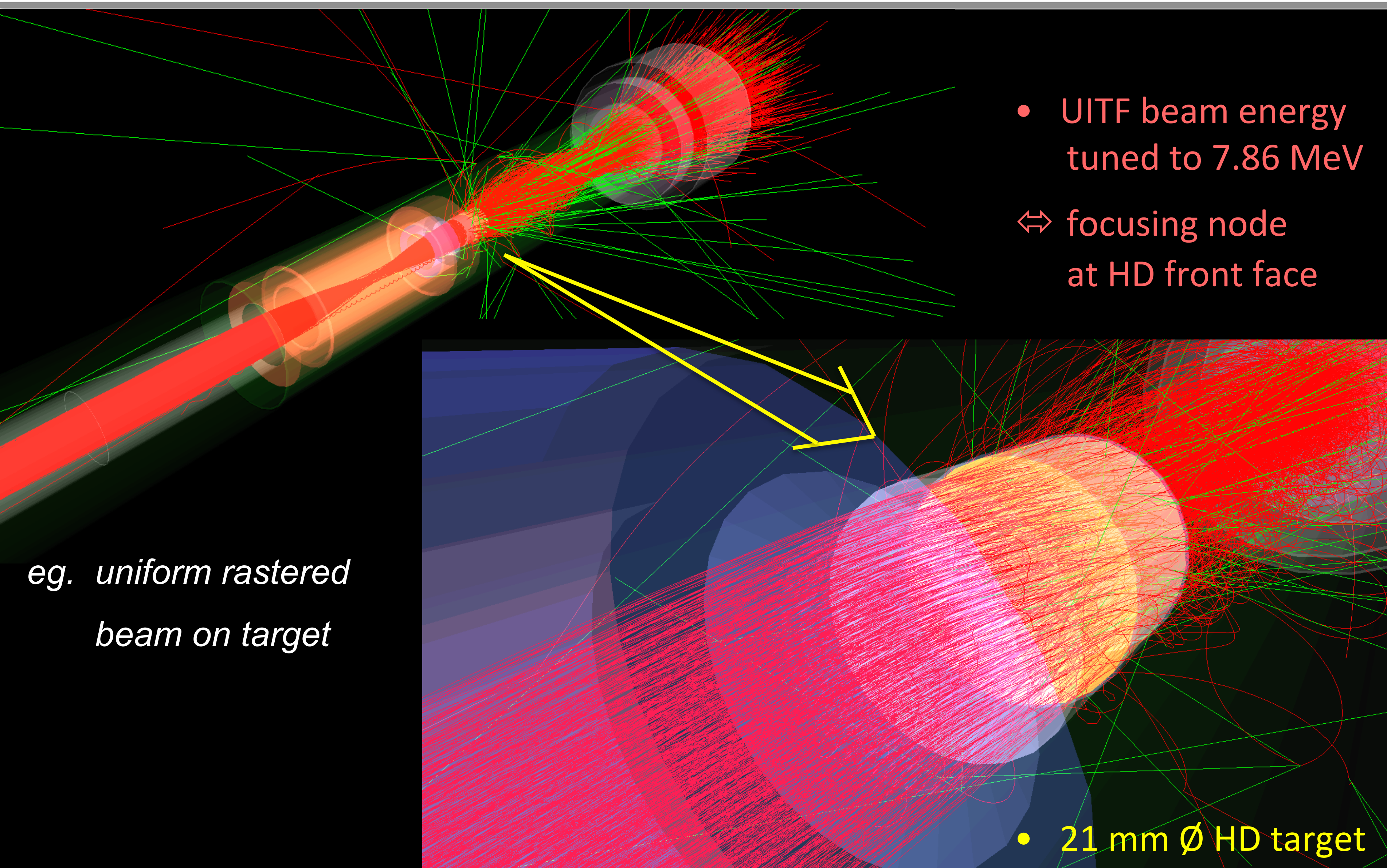
- UITF beam energy tuned to 7.86 MeV

⇔ shifts focusing node to HD front face

eg. pencil beam into IBC with 14 mm offset

- offset focused to 10 mm at HD

electron transport studied with ***G4BeamLine©***



Heat load ➔ polarization of molecular electrons

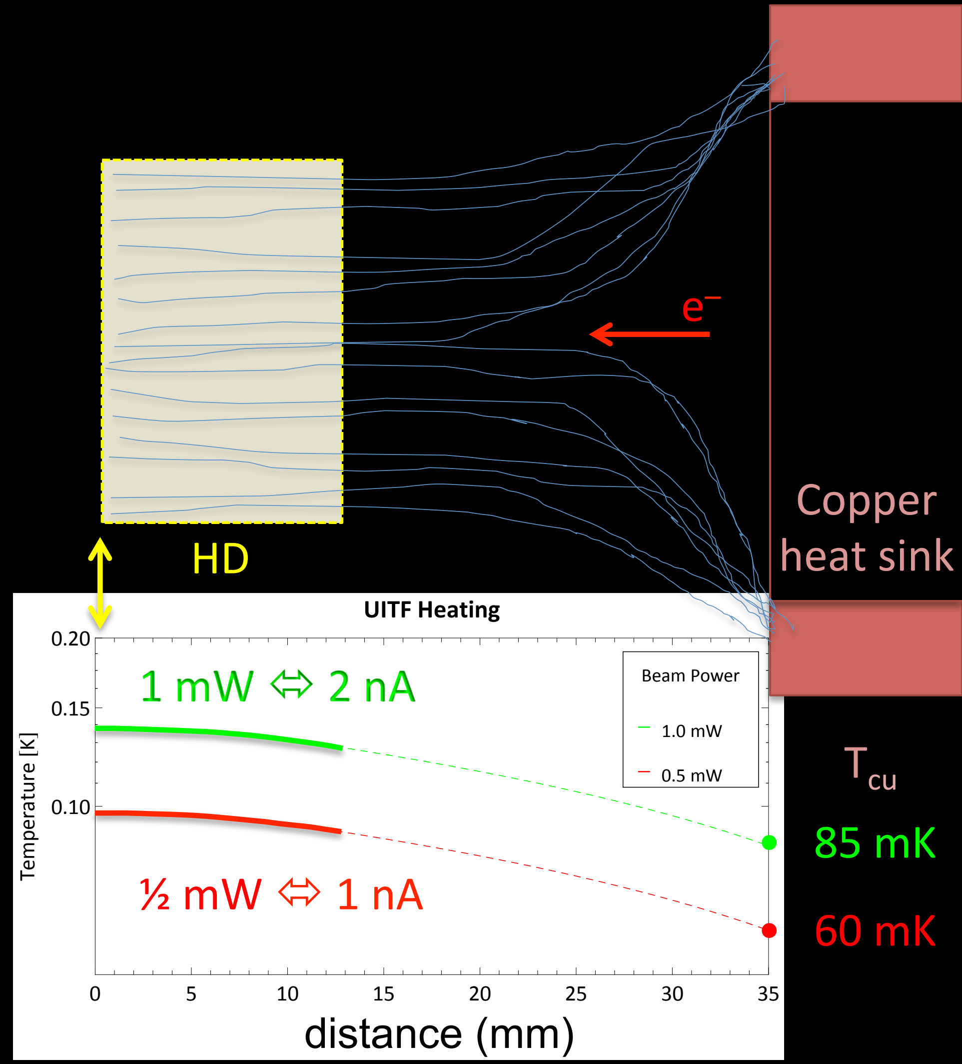
- beam will ionize HD, breaking paired *1s* electrons
- unpaired electrons will be inert
  if they polarize in the 0.9 T IBC field

⇔ polarization depends on temperature

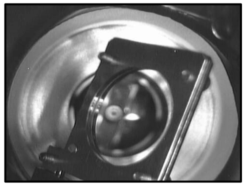
- HD temp depends on deposited
  beam power & temp of Cu heat sink
  (⇔ cooling pwr of IBC refrigerator)

P_e	I_e	Q_{HD}	T_{HD}^{max}
0.99977	2 nA	1 mW	138 mK
0.99999	1 nA	½ mW	98 mK

🡅 very promising !

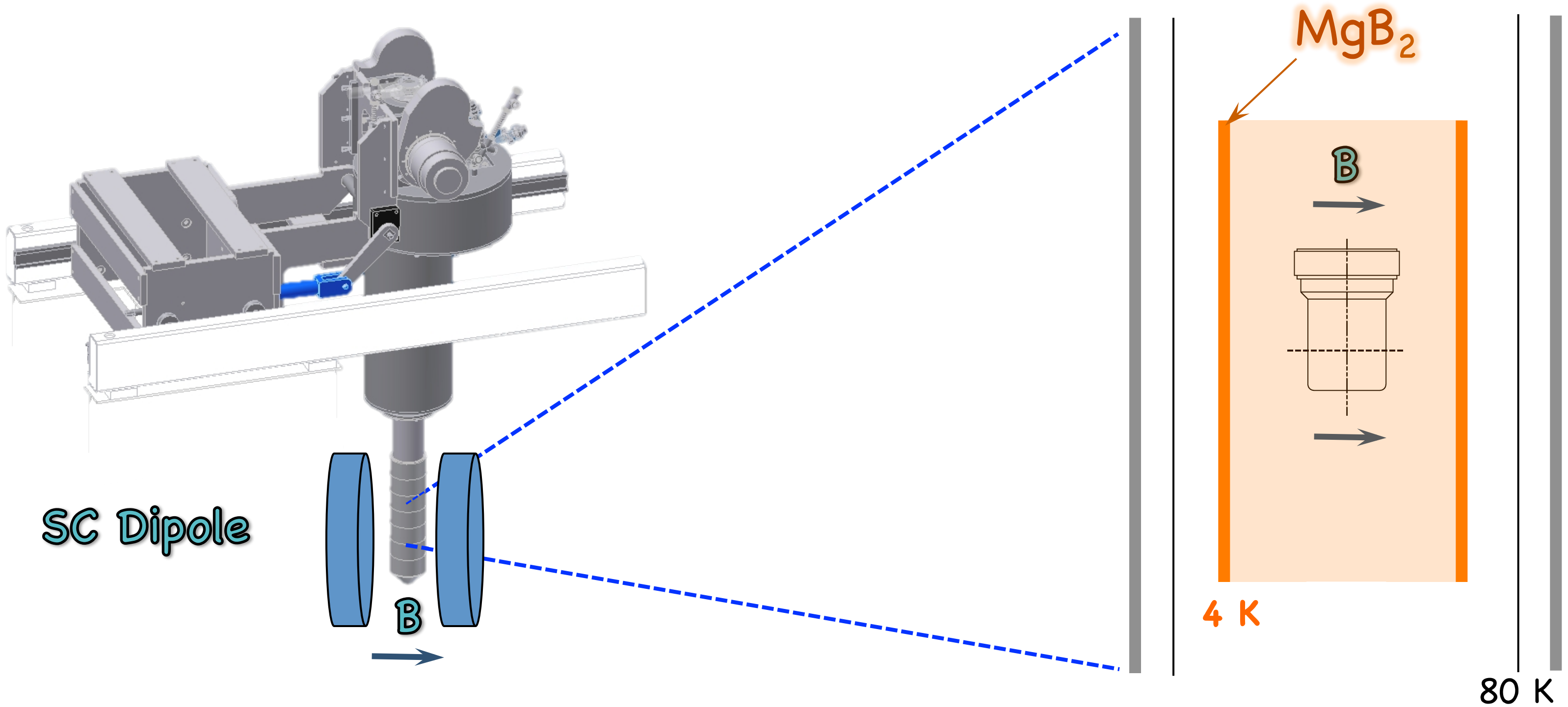


eHD testing schedule

- beam up to ¼ CryoModule in cave-1  ✔
- 10 MeV OPS - waiting for the completion of safety reviews, expected ~ Dec/2018
- 1st beam into In-Beam Cryostat to study transport ~ Feb/2019
- beam on unpolarized HD ~ April/2019
- 1st beam on polarized $\vec{HD}$ ~ June/2019

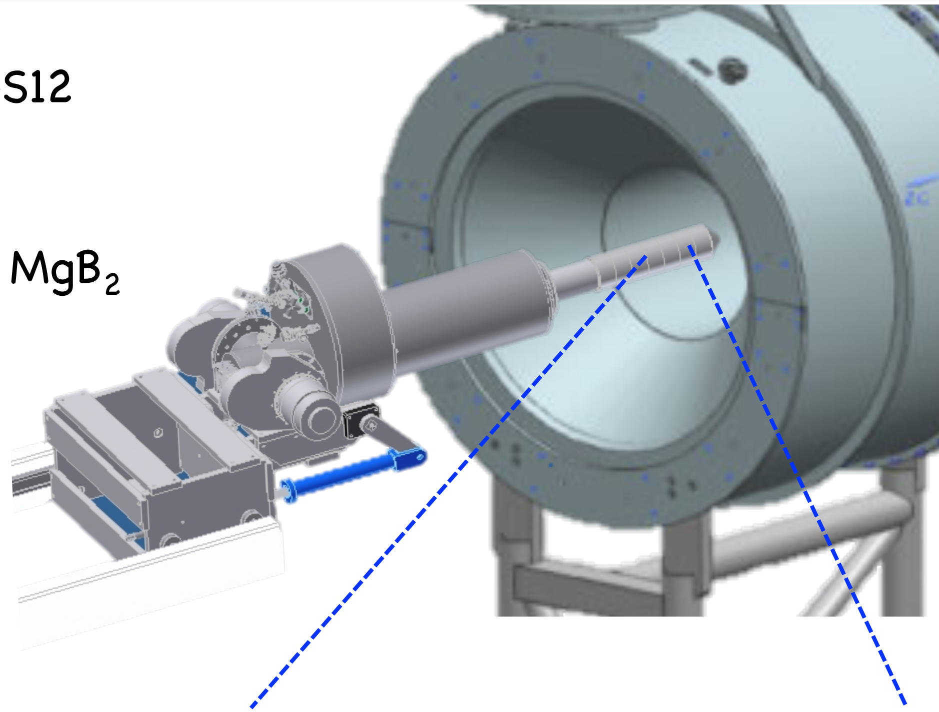
Trapping a transverse field in an MgB_2 diamagnetic shell

- energize 1¼ T external Dipole magnet
- cool MgB_2 shell within the HDice IBC to 4K (T_c = 39 K)
- load polarized $\vec{HD}$ into the IBC, within the MgB_2 shell
- lower external Dipole field → 0
  - ⇨ currents spontaneously flow in MgB_2 to maintain original internal field
  - ⇨ talk by Marco Statera

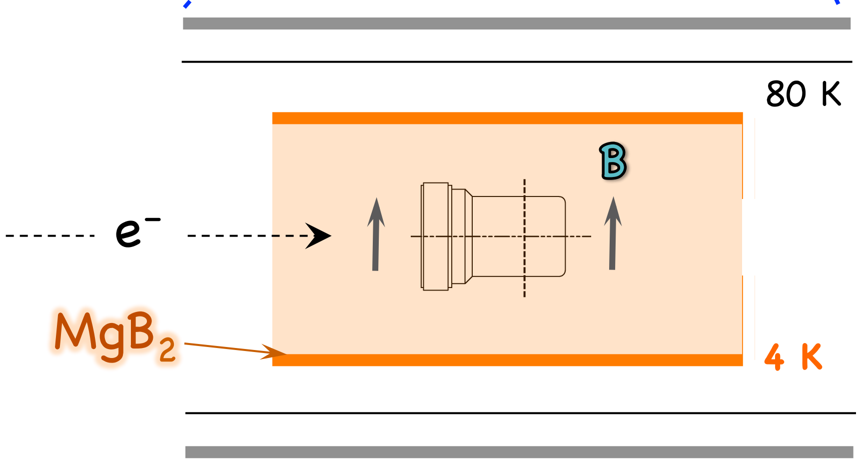


Expelling solenoid fields from the MgB_2 transverse shell

- rotate IBC horizontal and roll into CLAS12
- ramp up field in CLAS12 solenoid
  ⇨ additional currents begin to flow in MgB_2 to maintain original transverse field



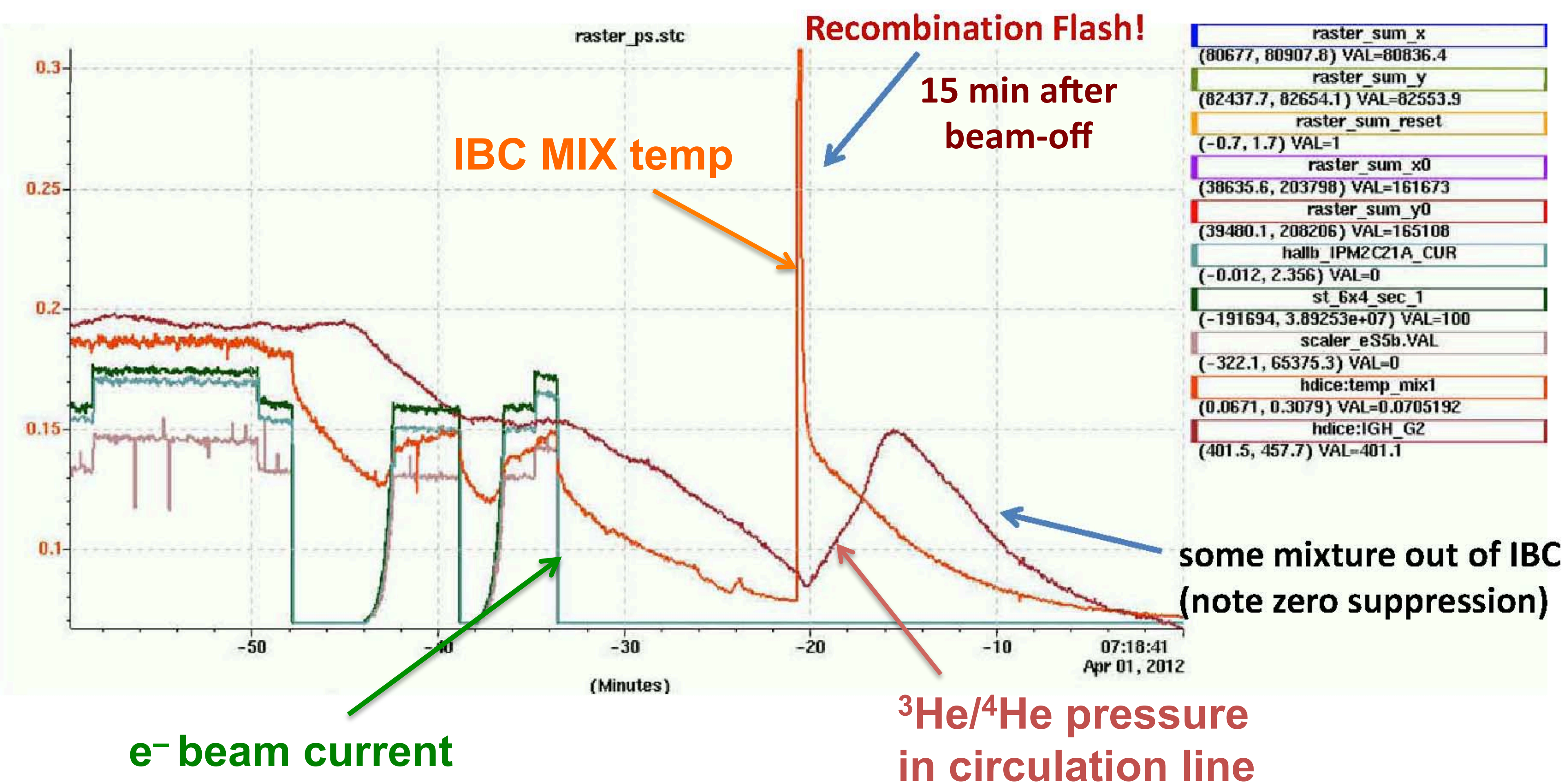
- MgB_2 retains the "memory" of fields present when it was cooled below T_c and became a diamagnetic SC
- as CLAS12 solenoid is energized, complex currents develop in the MgB_2 that are much more intricate than could be realized with an electromagnet



extras

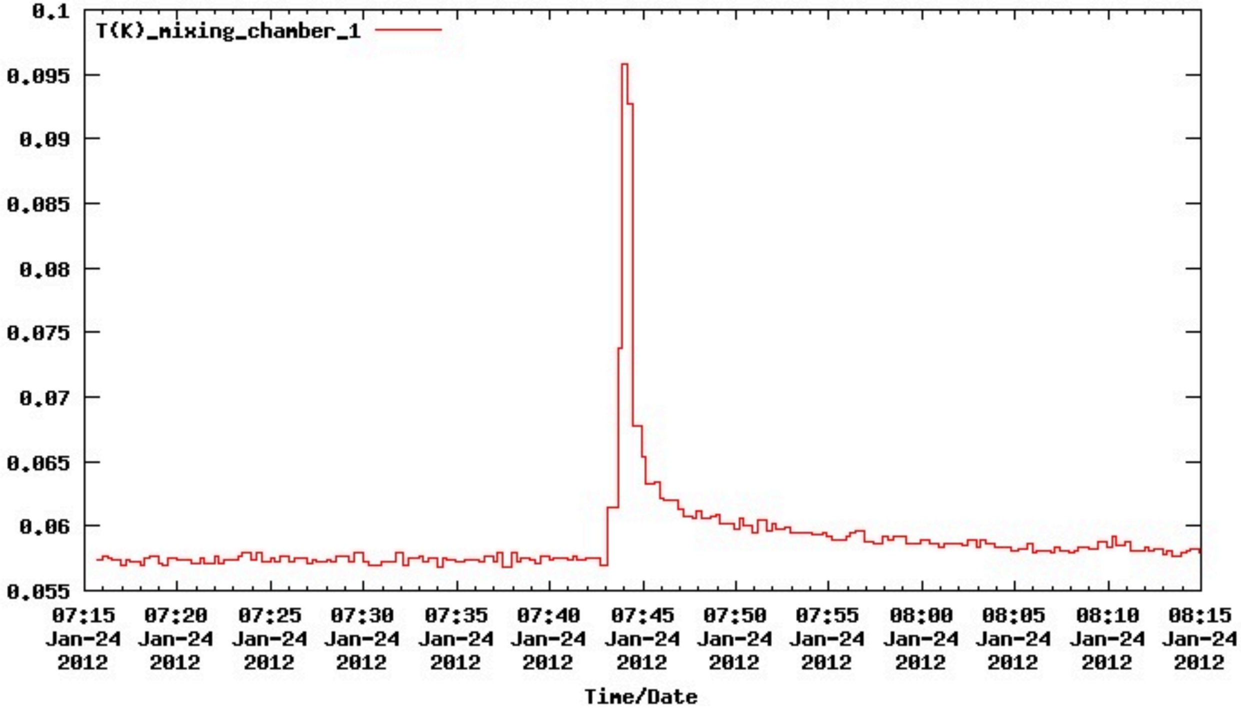
e⁻ beam-induced depolarization mechanisms – III

- chemical recombination is a function of concentration and mobility
- energy release raises local temp ⇨ increases mobility
  ⇨ can produce a chain reaction, a *recombination flash*



chemically driven recombination flashes during g14

- g14 *flash* events: about 1/week (from $\gamma \rightarrow e^{\pm}$ pair production)



Effect on polarization ?

- most (as above example from Jan 24/12) had no effect on g14 targets
- but events will be more frequent with e^- beams

Polarization decay (T_1) correlated with number of J=1 pairs