# *Preparations for Electron Beam Experiments with Transversely Polarized solid $\vec{H}\vec{D}$*


*Xiangdong Wei*

*Thomas Jefferson National Accelerator Facility*


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SPIN 2014

The 21st International Spin Physics Symposium

HDice

# *Preparations for Electron Beam Experiments with Transversely Polarized solid $\overrightarrow{H}\overrightarrow{D}$*

*X. Wei*
*SPIN2014, Oct. 24, 2014*

- *PAC39 C1-approved experiments with electrons*
- *lessons from the 2012 eHD test runs – preventing depolarization*
- *test runs at the new Upgraded Injector Test Facility ~ mid 2016*
- *R&D for a new "passive" in-beam transverse holding field*
- *R&D for the next generation target cell*

# *Collaborators*



- *Jefferson Lab*

H. Areti, G. Dezern, J. Grames, C. Hanretty, T. Kageya, M.M. Lowry, M. Poelker and A. M. Sandorfi, and **X. Wei** (*for HDice target & test beam*)

- *Universita di Ferrara and INFN di Ferrara*

M. Contalbrigo, P. Lenisa and M. Statera (*for the* $2^{nd}$ *generation magnets*)

- *Universita di Roma "Tor Vergata" and INFN-Sezione di Roma2*

A. D'Angelo (*for HD gas purification and analysis*)

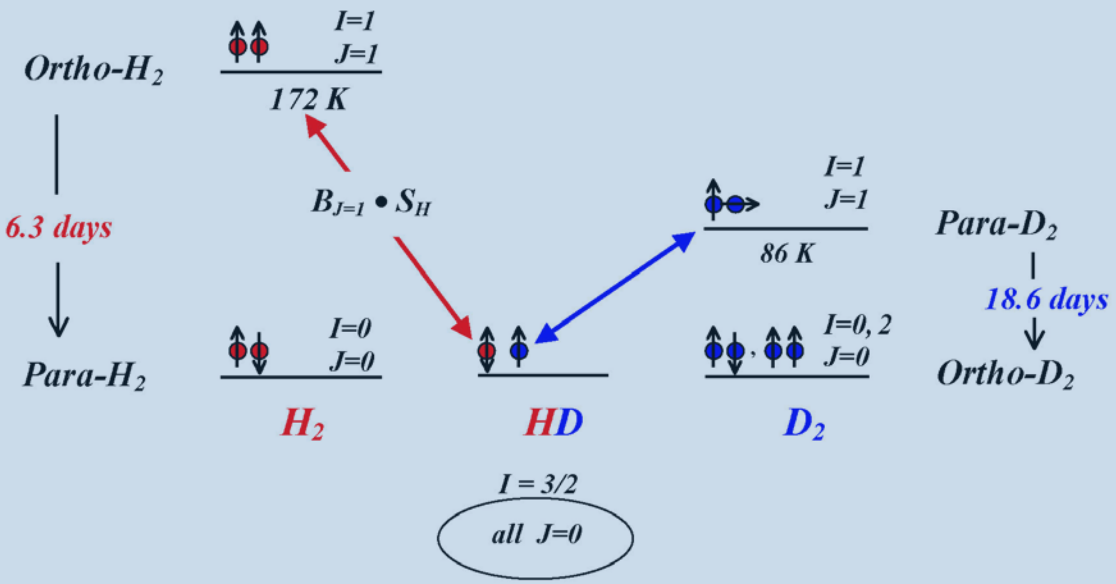
*George Washington University*

A. Afanasev and A. Kechiantz (*for the* $2^{nd}$ *generation target cell*)

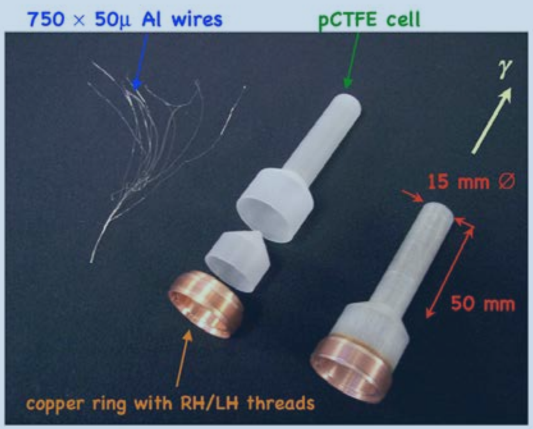
# Steps in polarizing HD – a brief refresher



- HD gas distilled with $10^{-3}$ to $10^{-4}$ impurities of $H_2$ & $D_2$ (catalysts)
- 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




- HDice target cells:




- material in the beam path:

77% HD + 17 % Al + 6% pCTFE (remove with vertex cuts)

# Electron experiments with transversely polarized $\overrightarrow{HD}$



- **$\overrightarrow{H}\overrightarrow{D}$ lifetimes with photon beams ~ 2 years ⇨ g14 run (Nov'11-May'12)**
- **next goal – viable transverse frozen-spin target with electron beams**
- **PAC 39:**

| | Sci rate | PAC decision |
|---|---|---|
| ◊ SIDIS, C12-11-111, Marco Contalbrigo,… | A | C1 |
| ◊ dihadron production, PR12-12-009, Harut Avakian,… | A | C1 |
| ◊ DVCS, PR12-12-101, Latifa Elouadrhiri,… | A | C1 |

- **PAC 41: Rated *high impact* for Jlab Hall B**
- C1 ⇨ successful demonstration to Lab management of viable performance in a subsequent eHD test run

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# Findings and solutions of the 2012 eHD test



**During the 2012 eHD run @1nA, P(H) dropped within ~1/2 day (but not immediately).**

Identified mechanisms for beam induced depolarization:

*I. e- beam ionization unpairs 1s molecular electrons of HD*

*II. Hyperfine mixing of unpaired electrons with H spins*

*III. Radiation-induced Chemical composition changes*

# $e^-$ beam-induced depolarization mechanisms –I– solutions



**I. $e^-$ beam ionization unpairs *1s* molecular electrons of HD**

- if residual *1s* electron is unpolarized (depends on temperature, which was peaked at 1.2 K along the beam path, due to a 1 Hertz slow raster and a 5cm long HD target)

➔ flips with Fourier components at nuclear Larmor frequencies

➔ depolarizes the local HD

➔ depolarization diffuses out into the rest of the HD crystal

**Solutions:**

- suppress flips with higher polarization of unpaired electrons from colder running temperatures (new cell—2.5cm, new fast raster—**1 kHz** pattern refresh rate):
  - expected T(HD) ~ **0.21 ±0.07 K**
  - B ~ **1 ¼ tesla**

➔ will insure P(e) ~ 100 %

➔ P(e) will not depolarize HD

# $e^-$ beam-induced depolarization mechanisms - II - solution



## II. Hyperfine mixing of unpaired electrons with H spins

- μ(e) opposite in sign to that of H (or D)

➔ electrons polarized in the holding field have spins opposite to H
➔ total angular momentum (F) projected along B is less than maximal
➔ Hyperfine mixing of $|F, m_F = m_H + m_e\rangle$ states with different $m_H$

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

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

⟶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 momentum projection 🡐 unique

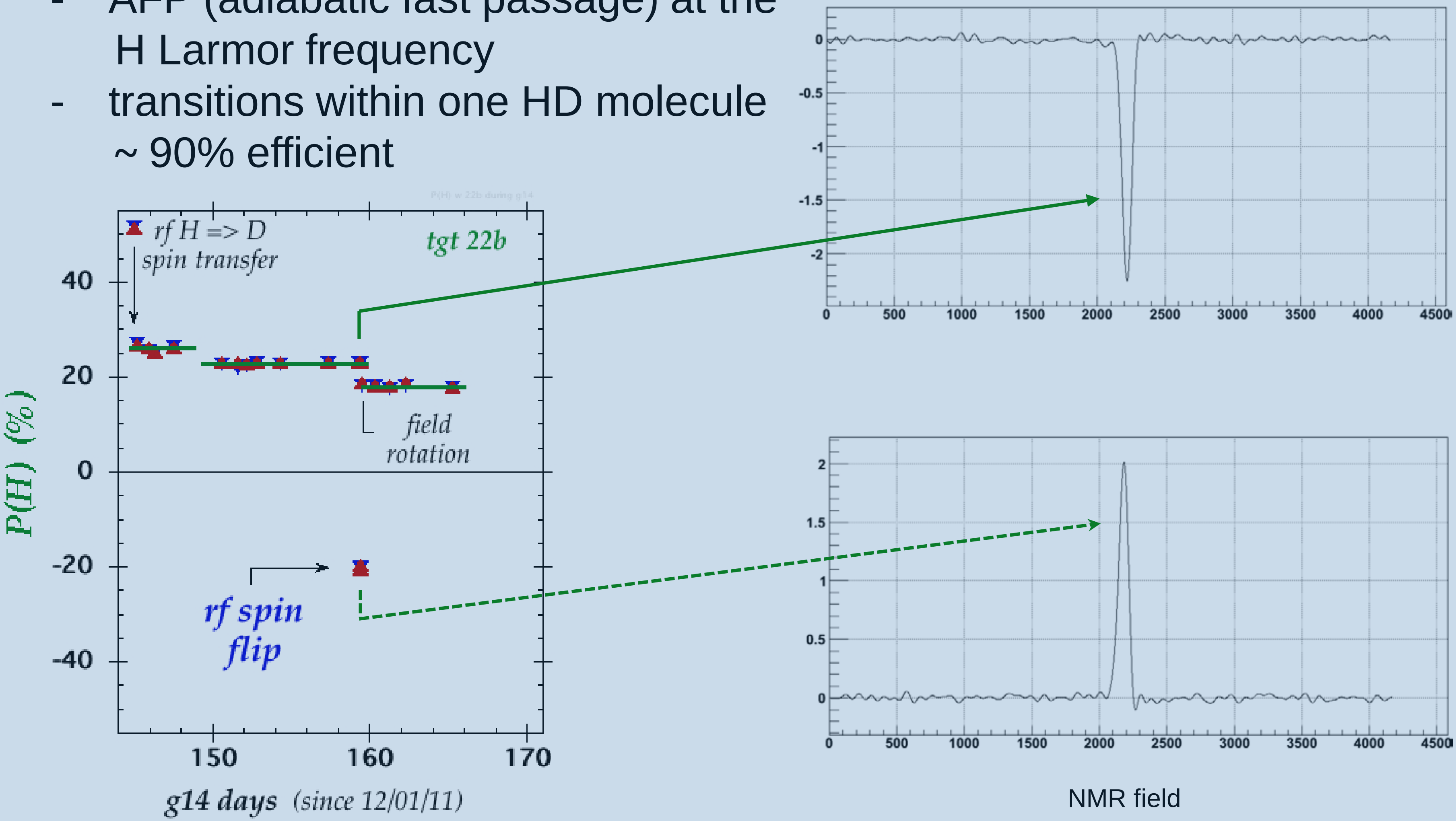
➔ prevents depolarization through hyperfine mixing

# *Flipping H spins with RF (adiabatic fast passage)*



Allowed *RF* flips during g14:

- AFP (adiabatic fast passage) at the H Larmor frequency
- transitions within one HD molecule ~ 90% efficient



# $e^-$ beam-induced depolarization mechanisms - III



## III. Radiation-induced Chemical changes

(following parallel literature on tritium chemistry after beta decay)

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

  *or* ⇨ $HD_2^+ + H$

  ↥ no effect on polarization (paired $e^-$), but highly mobile
- $H_2D^+ + e^-$ ⇨ $H_2 + D$ , …

  ⇨ increased concentrations of ortho-$H_2$ (para-$D_2$)

  ↥ polarization catalysts

  ⇨ H (& D) could lose their frozen spin state

## Evidence ?

- chemical recombination is a function of concentration and mobility
- energy release raises local temp

  ⇨ increases mobility

  ⇨ can produce a chain reaction, a *recombination flash*

HD gas analyzed with Raman scattering (in Rome) after eHD test

⇨ no significant increase in $H_2$ , $D_2$ after ~ 1 nA-day dose

***while encouraging, limitations need further study with test beams***

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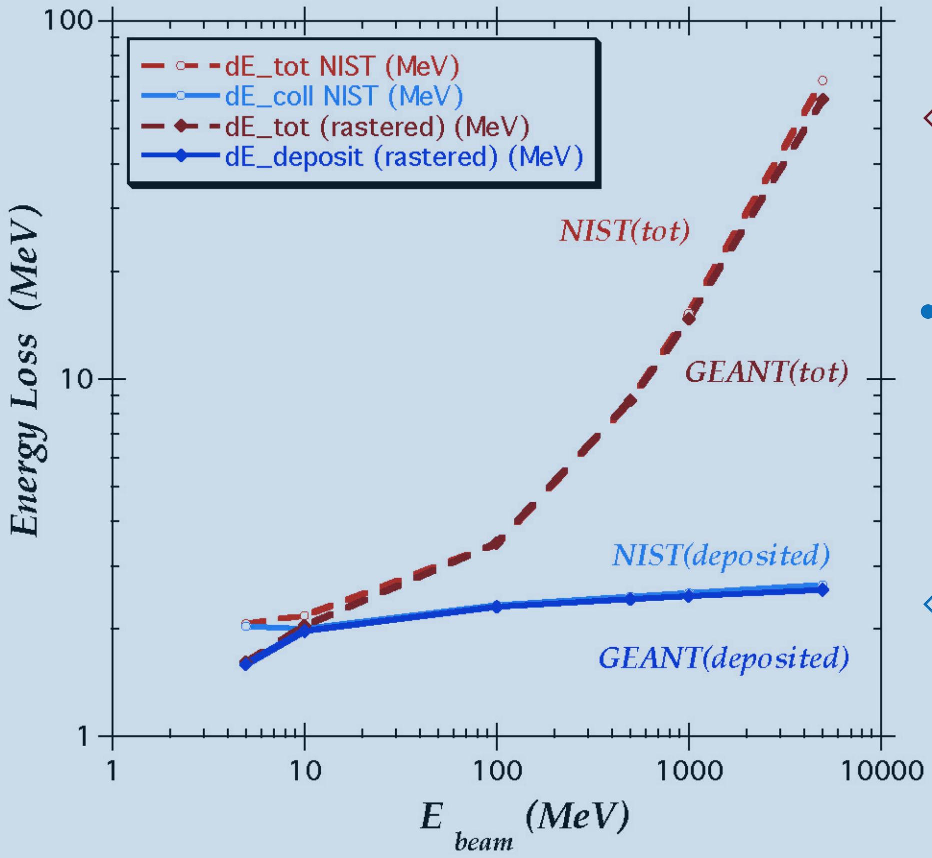
# R&D at the Upgraded Injector Test Facility



Electron energy loss in 5 cm of HD:



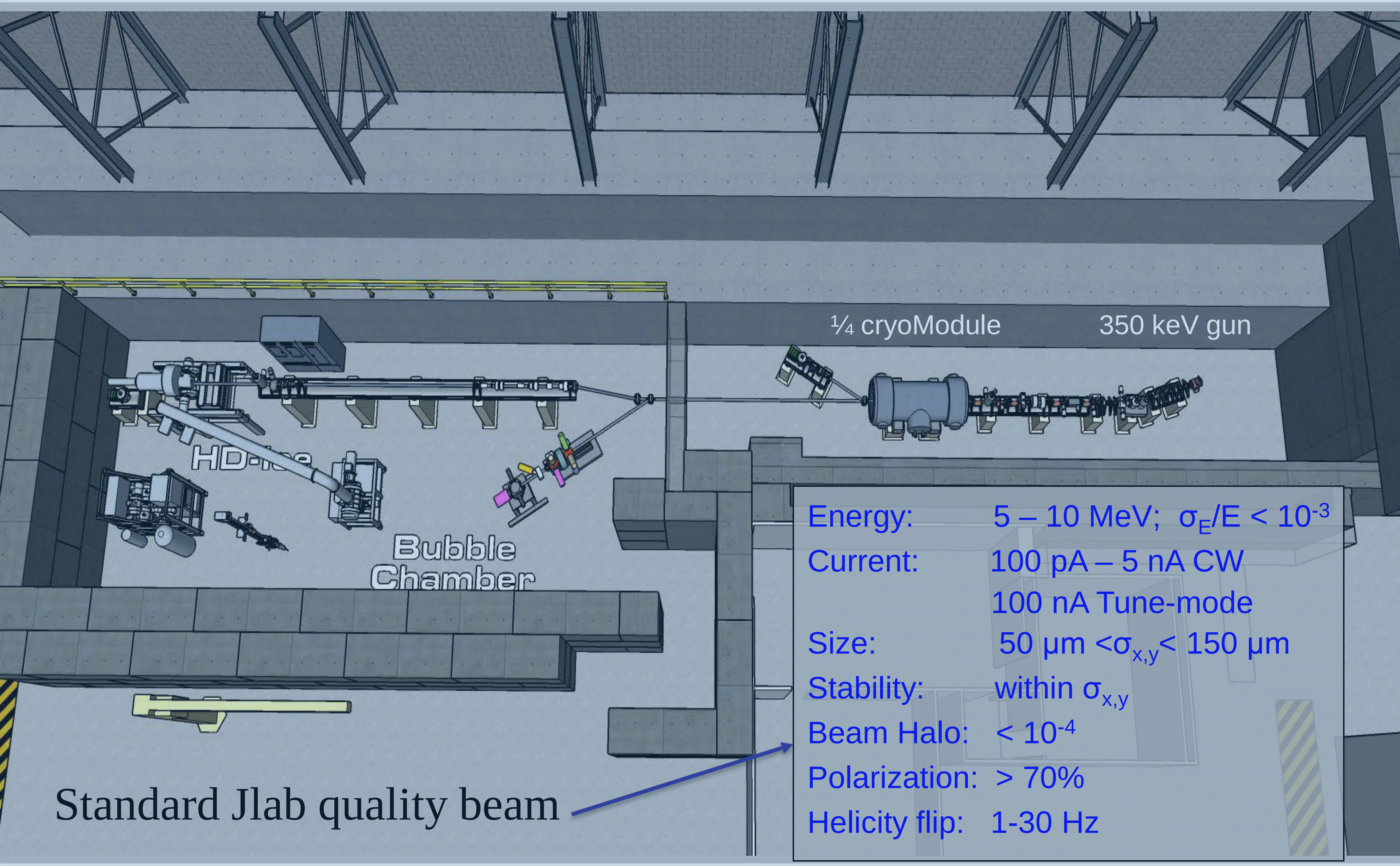

⇦ loss dominated by bremsstrahlung

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

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

⇨ **~10 MeV beams will test the HD performance at 11 GeV !**

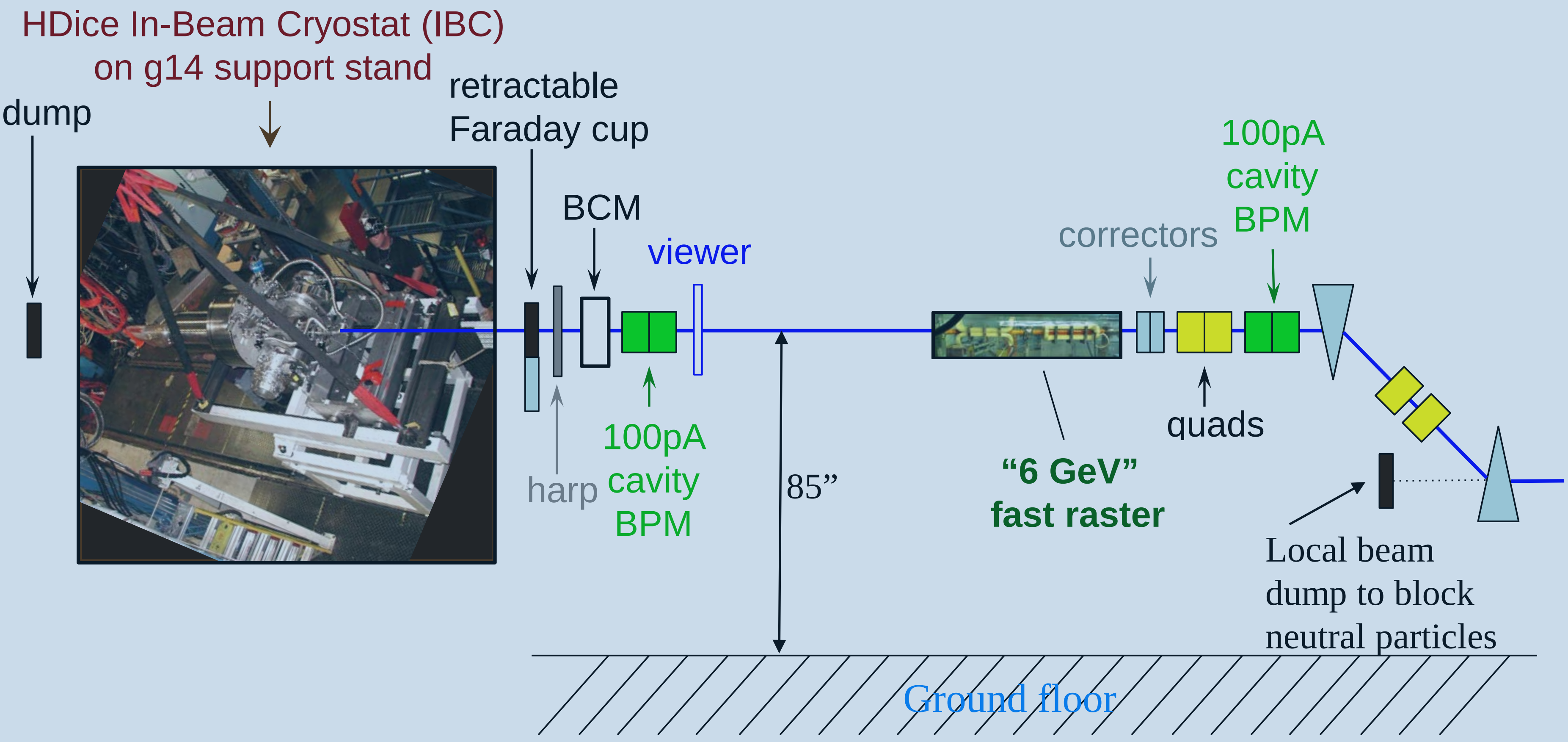
# UITF layout in the Test Lab




| | |
|---|---|
| Energy: | 5 – 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 |

Standard Jlab quality beam

# HDice beam line at the UITF




**1st beam ~2/2016**

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# Diamagnetic shielding with bulk high-$T_c$ superconductor

***II. SC magnetic shell generated by perfect diamagnetism:***

- perfect diamagnetism in SC can be used to trap any desired field
- bulk high-$T_c$ SC recently available in ~ any shape

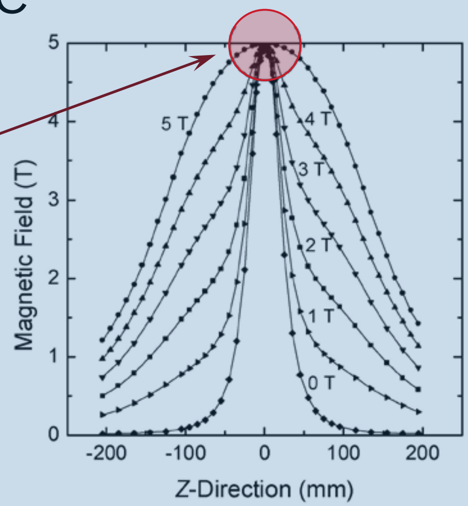
*eg.* – external magnet generates **5 Tesla**

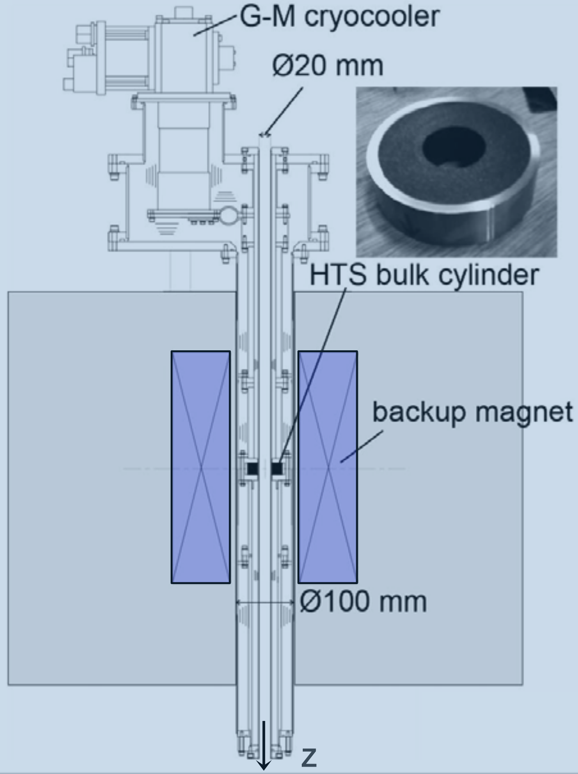
- GdBaCuO cylinder cooled below $T_c$
- external field lowered to <u>zero</u>

⇨ surface currents spontaneously flow to maintain original field in SC

- field at cylinder axis

⇨ 4.9 Tesla



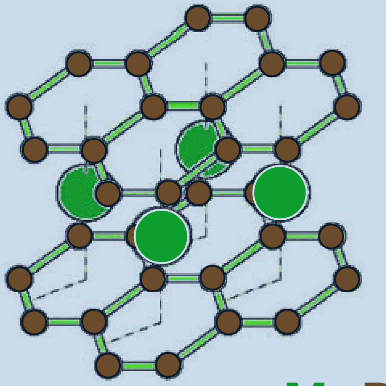




T. Kiyoshi *et al*,
IEEE Trans Appl SC **17** (2007) 2274

# Trapping fields with bulk $MgB_2$



- $T_c$ = 39 K for crystaline $MgB_2$ discovered in Japan
  - Nagamatsu *et al*, Nature **410**, 6824 (2001)
- bulk production developed by Edison-S.p.A.-Milan
  - G. Giunchi, IEEE Trans Appl SC **13**, 3060 (2003)
- "type 1.5 SC" - 1st BCS SC with two band gaps
  - Moshchalkov *et al*, PRL 102, 117001 (2009)
- high current densities at 4K : up to 1000 A/mm$^2$ !!!

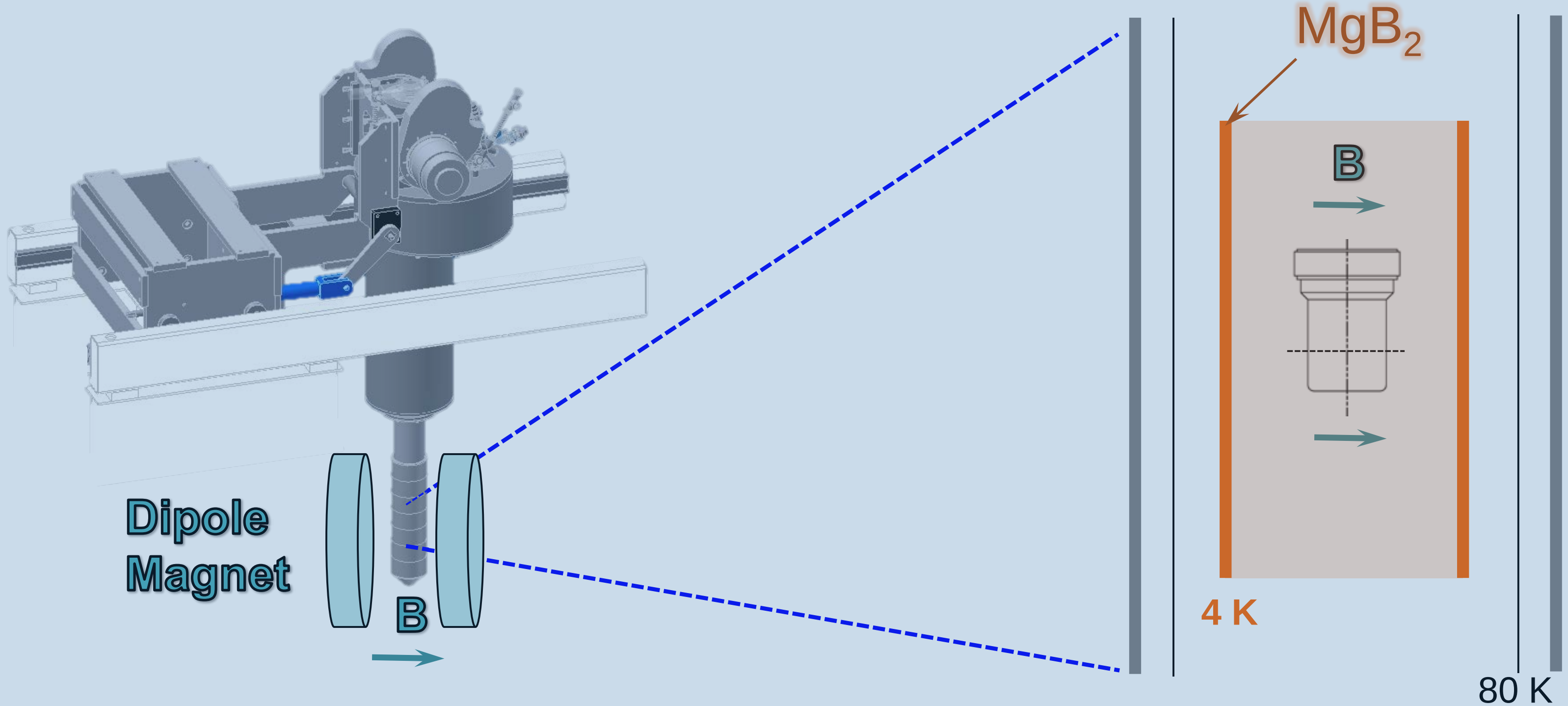


# *Diamagnetic $MgB_2$ transverse shell*



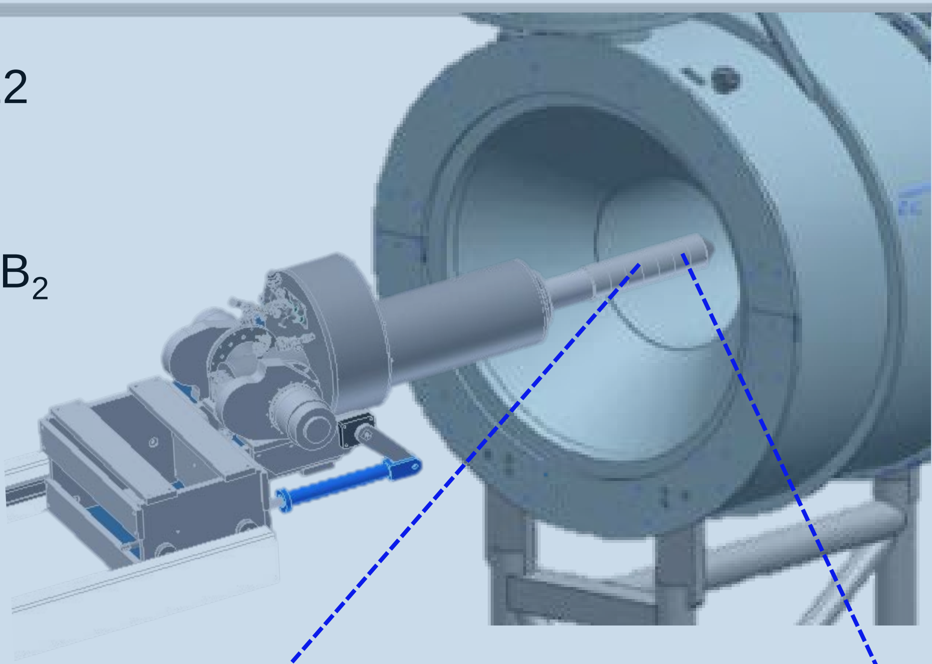
- energize 1¼ T external Dipole magnet
- cool $MgB_2$ shell within the HDice IBC to 4K ($T_c$ = 39 K)
- load polarized $\vec{HD}$ into the IBC, within an $MgB_2$ shell
- lower External Dipole field → 0

  ⇨ currents spontaneously flow in $MgB_2$ to maintain original internal field

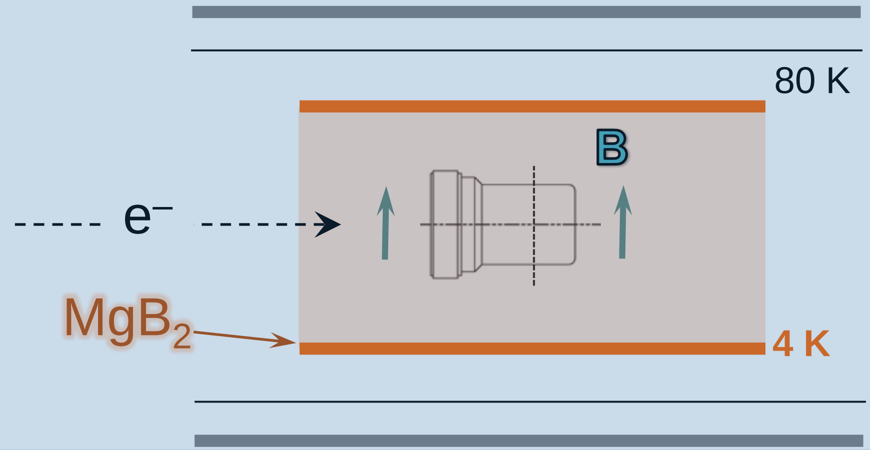


# $MgB_2$ transverse shell in the CLAS12 solenoid

- 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

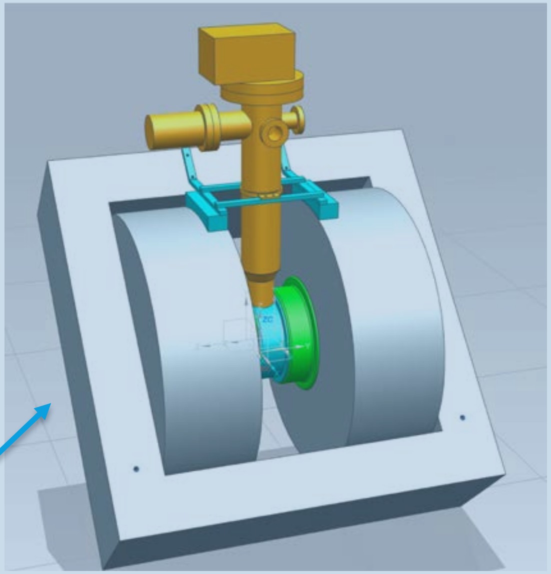


# Transverse field trapping in a prototype $MgB_2$ cylinder

Q1. What's the field droop rate ?

Q2. Can $MgB_2$ survive a quench ?

## Prototype tests in Ferrara



- 1 Tesla H-dipole, 4K cryo-cooler
  (M. Stratera, M. Contalbrigo, P. Lenisa)
- $MgB_2$ cylinder from Edison-S.p.A. (Giunchi)
  39 mm OD x 2 mm wall x 97 mm length

⇨ begin tests by ~ early 2015

Q3. Does open tube geometry work?
(Even though diamagnetic "memory" of external field is perfect for complete enclosed can, BUT, openings are needed for target loading and beam exit)

## Modeling Studies at JLab

- TOSCA, CST-Studio calculations for realistic geometry under way (M. Lowry)

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# The 2$^{nd}$ generation target cell development



**The feasibility study:**

Utilizing carbon nanotube filled target cell is underway with George Washington University and Jefferson Lab. (Replacing aluminum cooling wires with carbon nanotubes while keeping cooling material with the same mass)

Pro:

*I. Very high longitudinal thermal conductivity*

*6x better than ETP copper*

*(phonons travel inside the nanotube at ballistic speed)*

*I. Low transverse electrical conductivity*

*less RF shielding*

*II. Can be arranged to grow in parallel for low density bundle, "Carbon Nano Forest"*

*trapping HD inside the carbon nanotube gaps*

*shortening the maximum distance between HD and cooling tube ~100nm*

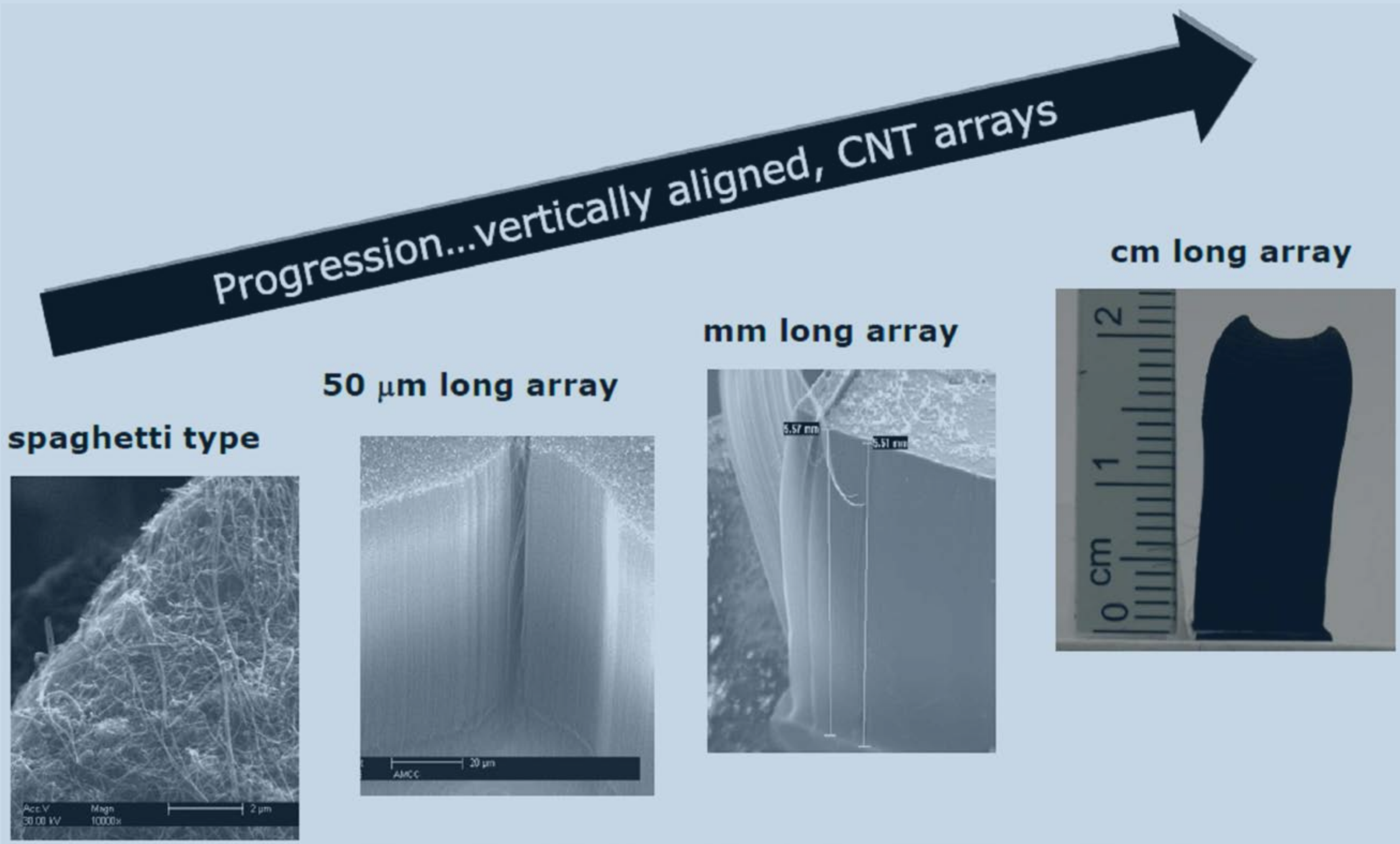
Con:

*I. New material*

*no data below 4K*

*II. A lot of development work has to be done*

# The $2^{nd}$ generation target cell development



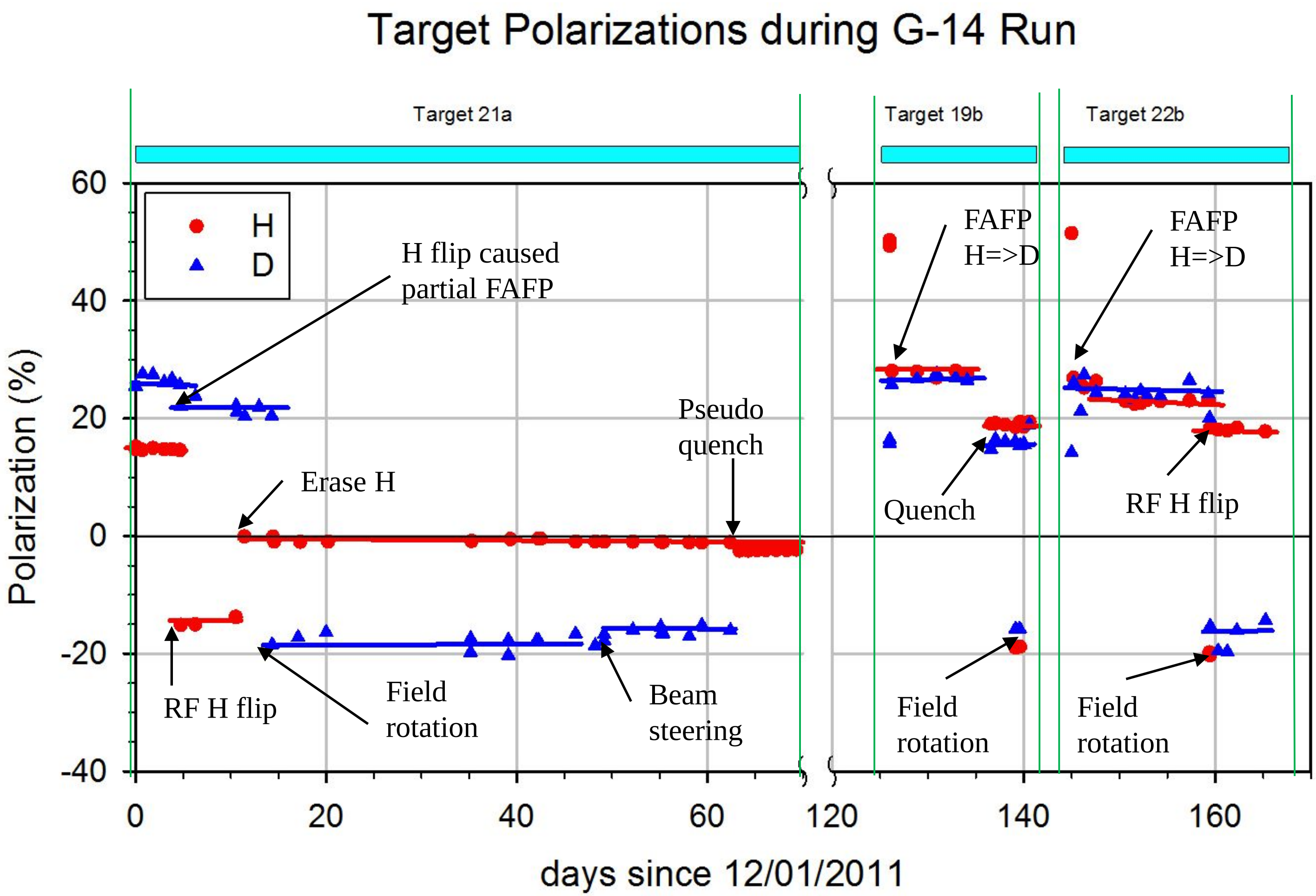
# Conclusions



**Looking forward to eHD tests in 2016**

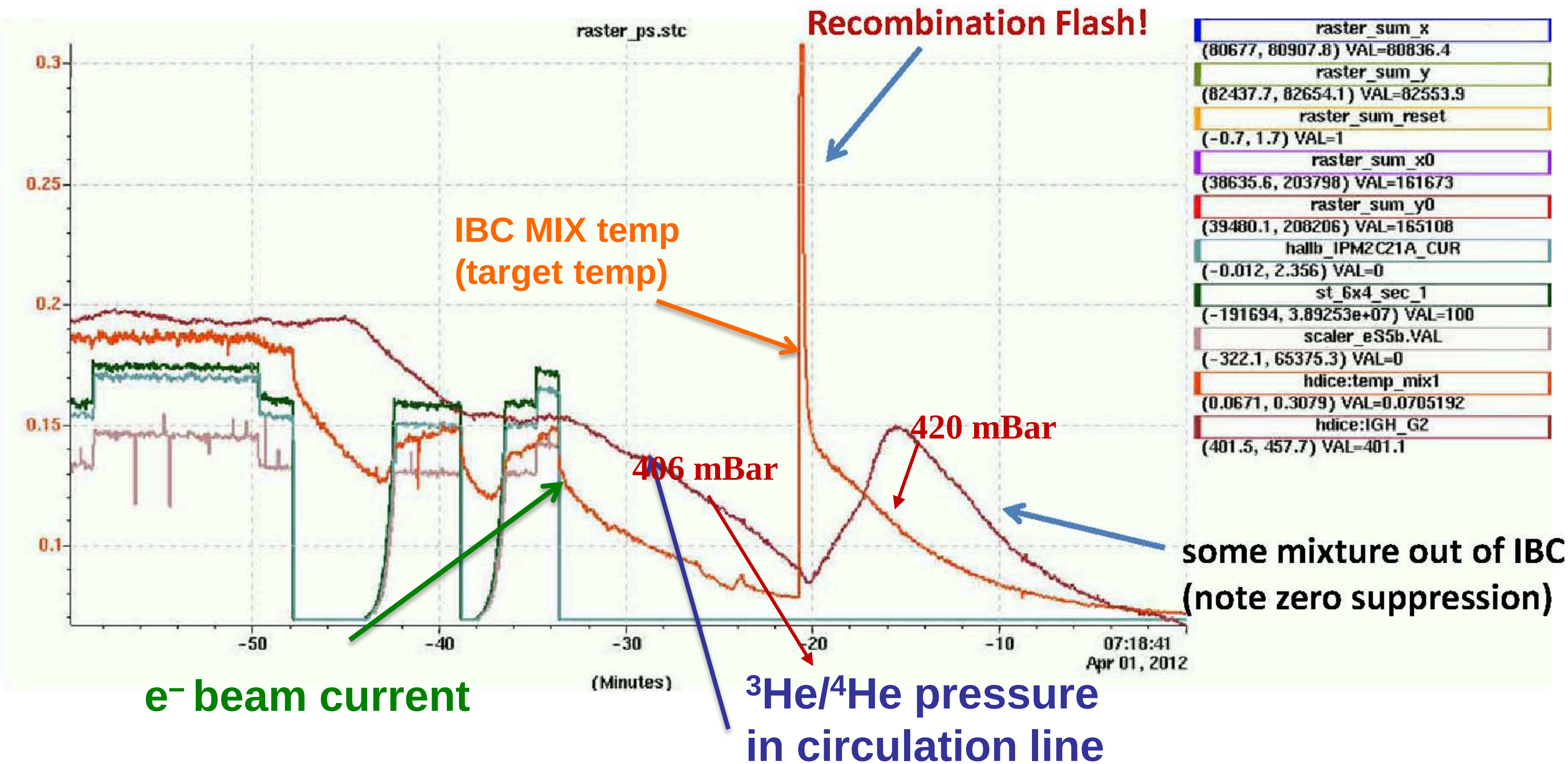
# extras

# Target Performance during G-14 Run




HDice targets used in frozen spin mode during E06-101/g14 run.
Relaxation times were longer than a year at B=0.9T and T<100mK .

# Recombination flash – 15 min after e-beam turned off

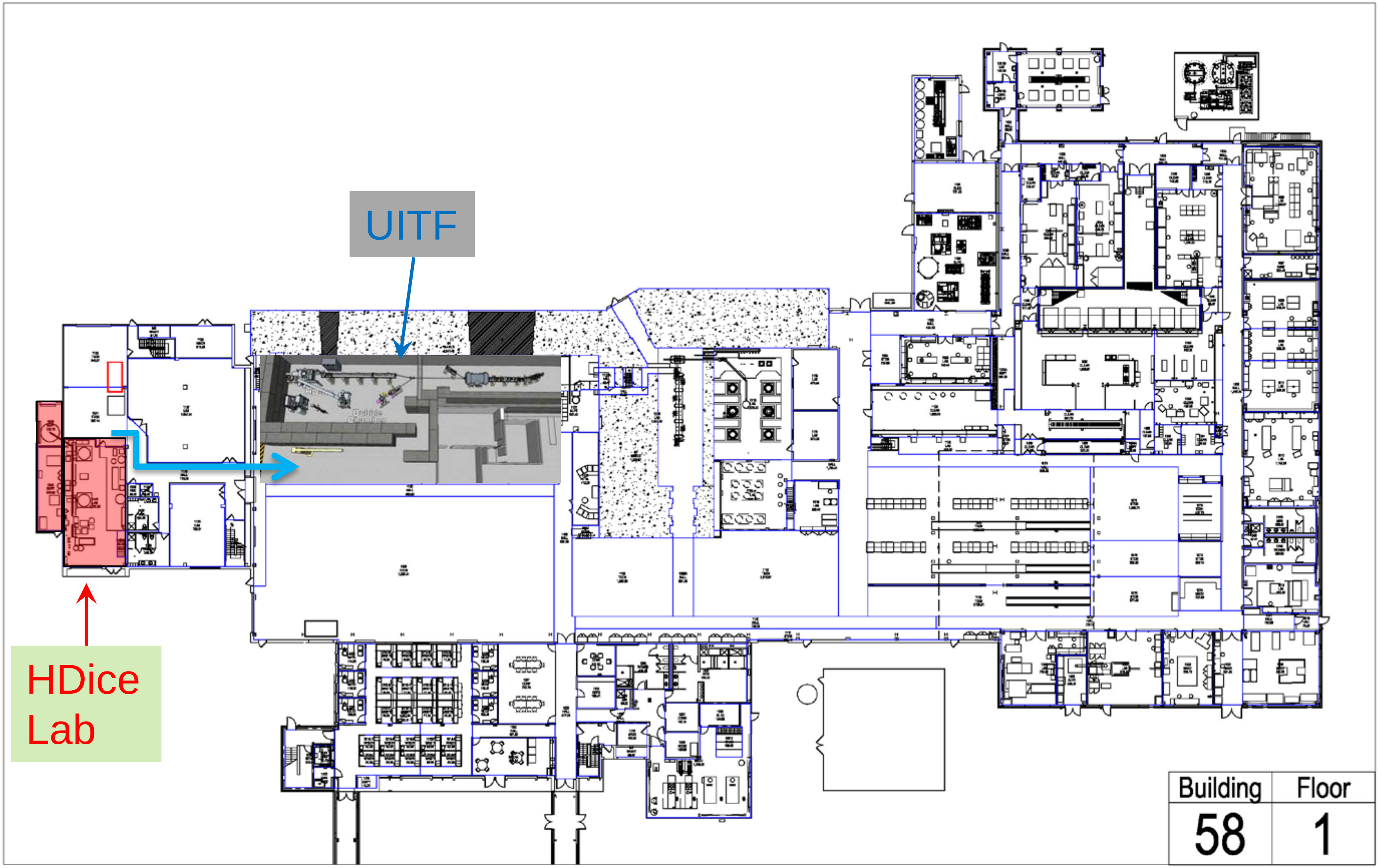



Effect on polarization ?

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

# *Upgraded Injector Test Facility (UITF) in the Test Lab*

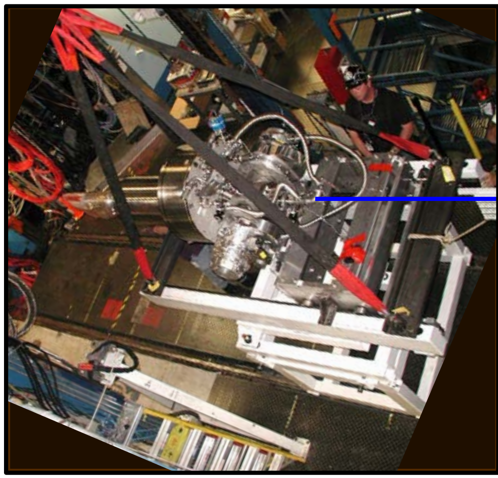


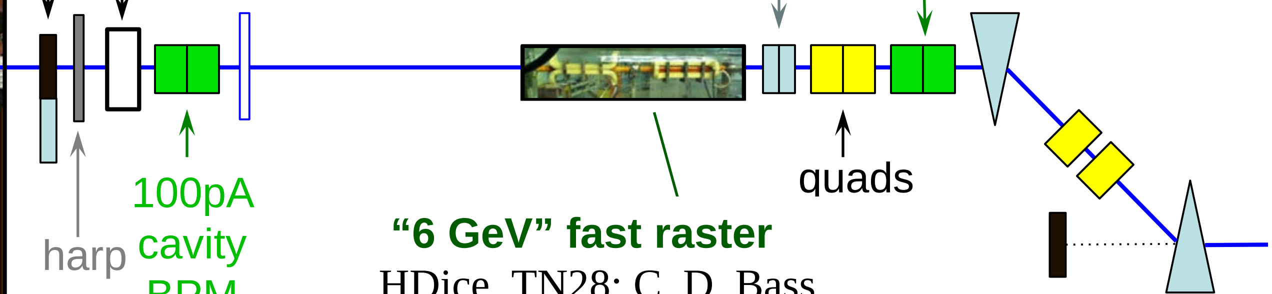


# HDice beam line at the UITF

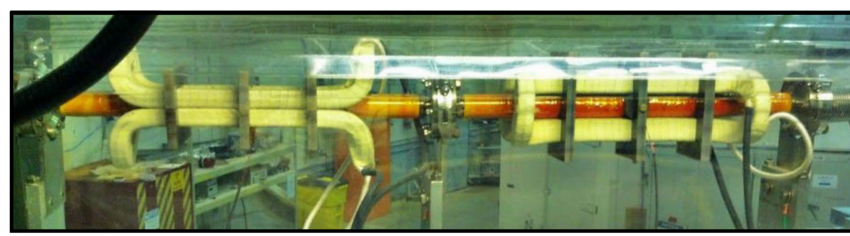


HDice In-Beam Cryostat (IBC)
on g14 support stand



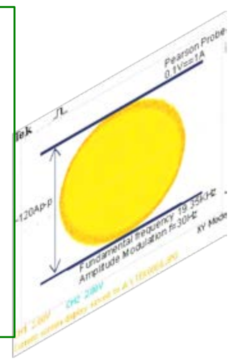



**"6 GeV" fast raster**
HDice_TN28: C. D. Bass, Development of fast rasters for eHD test runs and experiments)



**Fast AM Raster** - C. Cuevas
- resonant circular pattern at 19 KHz ✓
- 30 Hz amplitude modulation

⇨ need AM at ~ 1 KHz (~ early 2015)

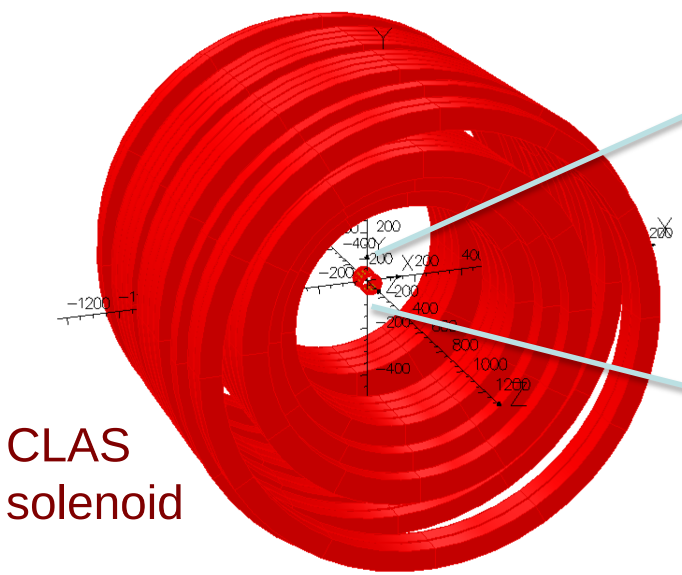


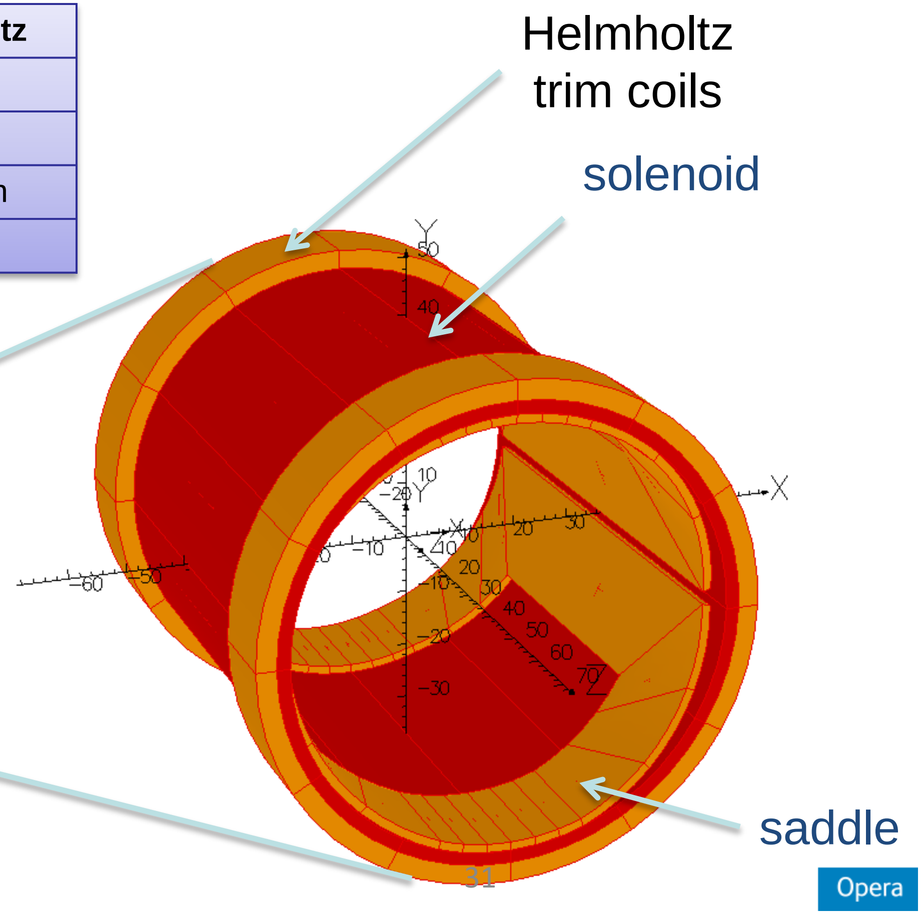
# Magnets to hold transverse spins $\vec{HD}$ at the CLAS12

***I. Brute-force solution:*** cancelling *Solenoid* and *Helmoltz* coils + inner *Saddle* coil
- possible, in principle, but lots of challenges

| PARAMETER | Saddle | Solenoid | Helmoltz |
|---|---|---|---|
| inner radius mm | 35.7 | 37.2 | 39.4 |
| outer radius mm | 37.2 | 39.4 | 42.8 |
| length mm | 100 | 100 | 15 each |
| $J_e$ A/mm$^2$ | 730 | 730 | 730 |

M. Stratera, U Ferrara



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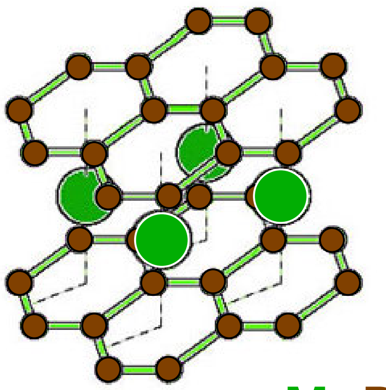



## ADVANTAGES

◊ reliability of a passive device

◊ uniform transverse field determined by exterior dipole
⇨ minimum B•dL
⇨ minimum beam deflection

◊ <Z> ~ 7 ⇨ minimal dE/dx

## DISADVANTAGES

◊ less flexible (fixed field)

⇨ NMR must sweep frequency at fixed B (some complications)

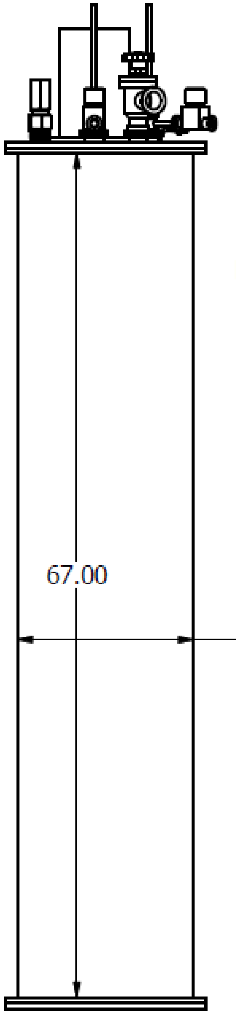
◊ flipping $\vec{H}$ spin is quite complicated

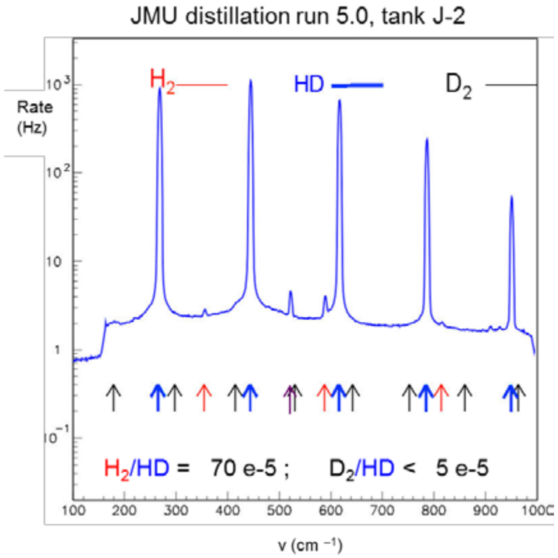
# *The 2nd distillation apparatus*



- The 2nd generation of HD distiller, utilizing a pulsed tube refrigerator for low vibration cooling, has been designed at Jlab.
- The pulsed tube cold head and compressor have been ordered from Cryomech, Inc.
- The cryostat, gas handling system, instrumentations and finally assembling will be done at Jlab.
- It will be integrated with a Raman scattering device at University of Rome 2.

$\Rightarrow$ purified HD factory!!!




The impurities will be monitored periodically with a desktop Raman scattering device while purifying and collecting HD.

# Schedule



2014:

- assemble infrastructure (civil work, AC, LCW, Power)
- install laser system and 350 keV gun
- order pulsed tube refrigerator
- test HDice IBC
- study "nano forest" properties @GWU & @JLab

2015:

- install cryo-systems, RF system & ¼ cryomodule
- construct shielding walls
- install and commission *fast Raster*
- install HDice beamline components
- install HDice IBC and recommission *in situ*

- construct HD distiller @JLab
- study "nano forest" properties @GWU & @JLab
- re-commission HD distiller and start purify HD @Rome

2016:

- commission with *tune mode* and *nA CW* beams

⇨ first beam on HD ~ Summer/2016