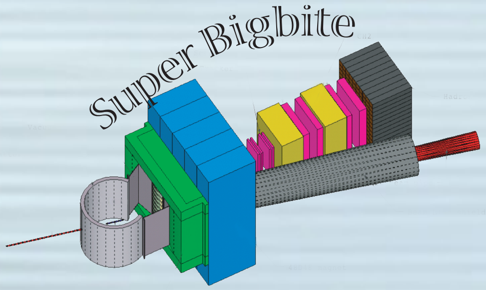
Target status for G_E^n and A_1^n

- SBS G_E^n target system
- Development of the SBS target cells
- Improving polarimetry
- Future steps



G. Cates – UVa
Friday, July 22, 2016

Jefferson Lab
EXPLORING THE NATURE OF MATTER

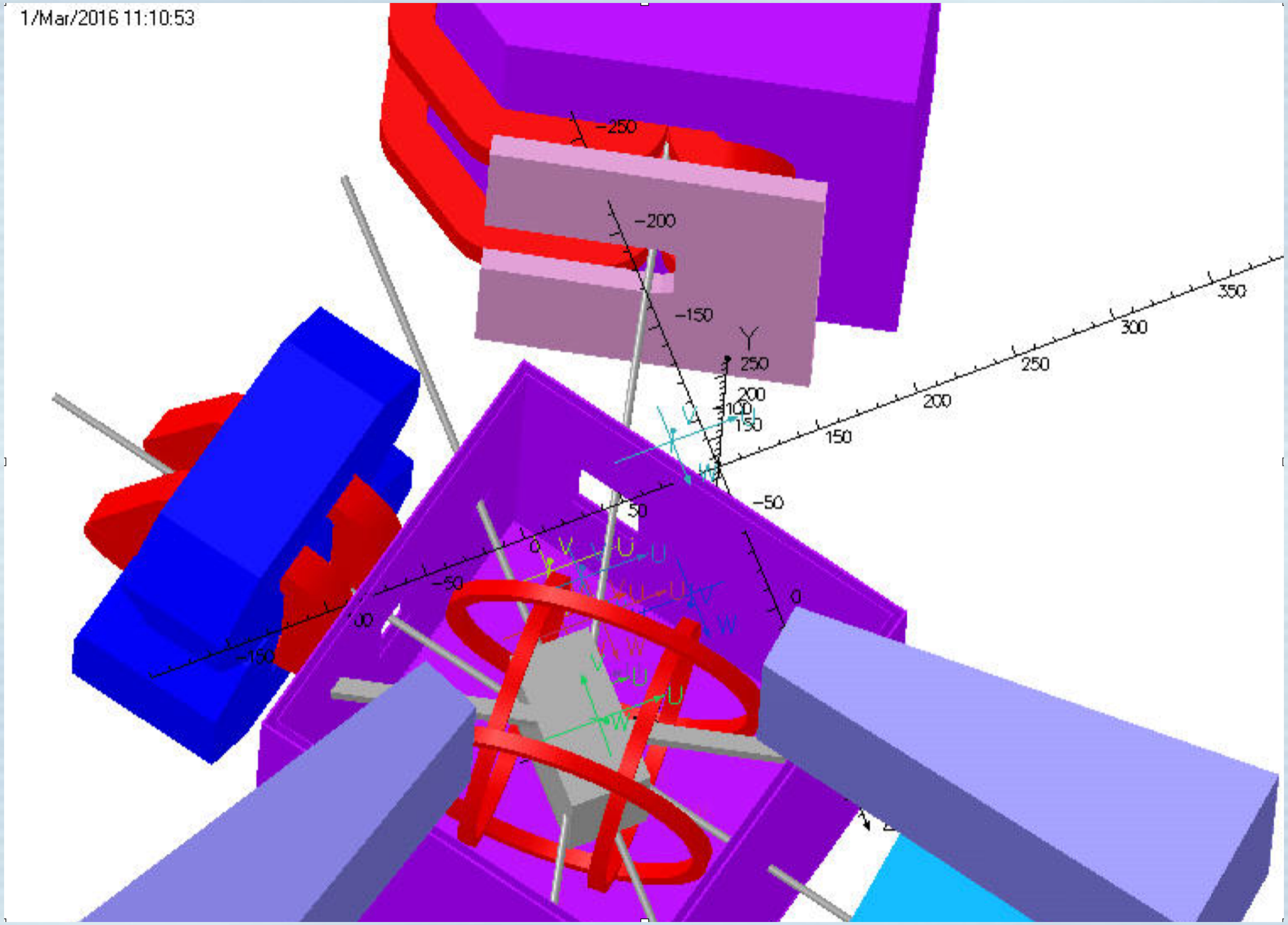
Progress during 2016

- March 17th: New coils arrive for κ_0 measurement and (some) of the tests of 6-liter SBS G_E^n target cells.
- March 28th: successful SBS G_E^n target CDR review.
- April 15th: dual-pumping-direction polarization test yields (local) record of 76%.
- May: with conceptual design frozen, engineering began.
- Week of July 4th: glass-and-metal development work completed.
- July 14th: Detailed (Bastille Day) design of 3-liter target cell released to Princeton glass blower Mike Souza. Should be ready to ship by Monday.

Conceptual design for the SBS G_E^n target

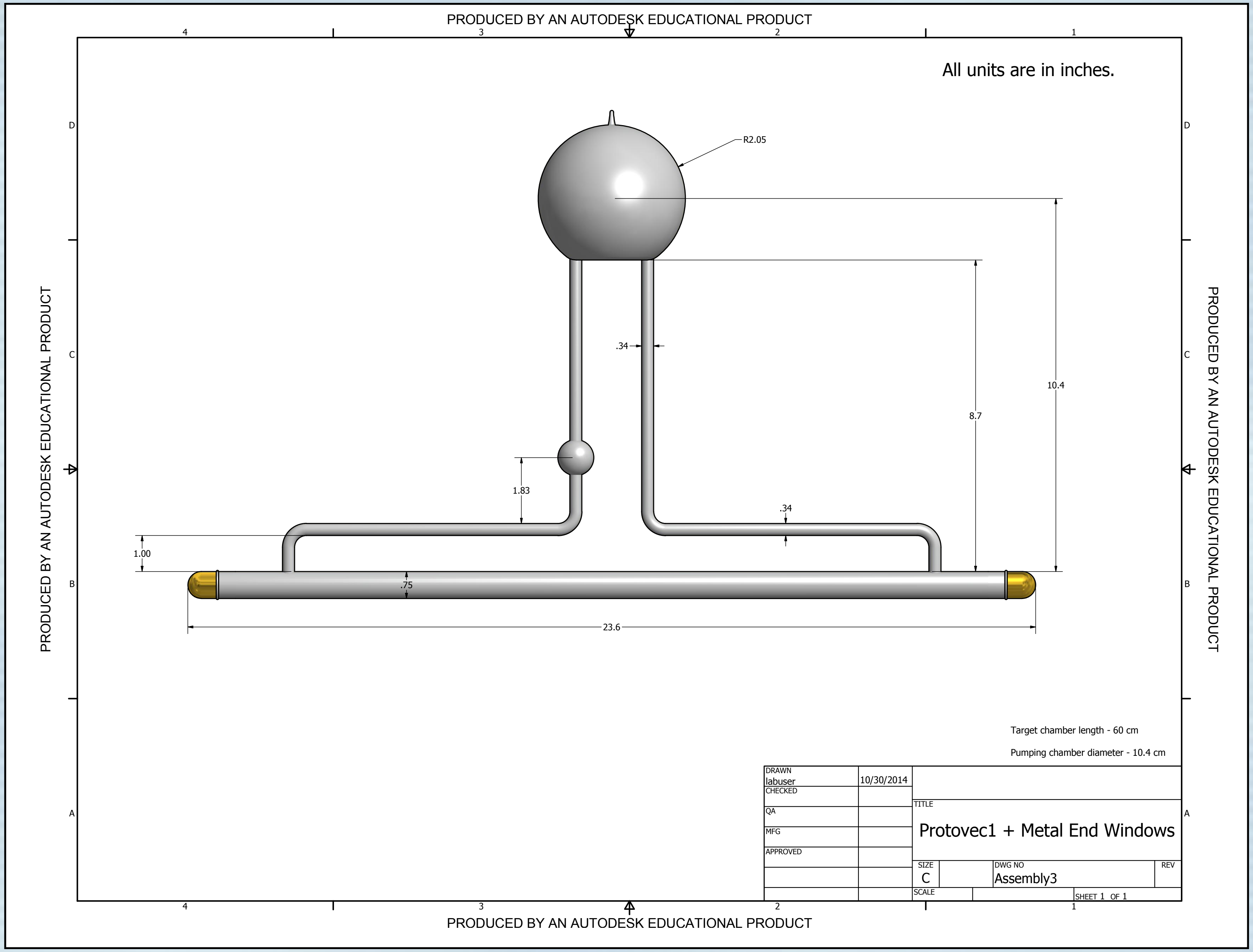
(now frozen)

Conceptual design for the SBS G_E^n target system



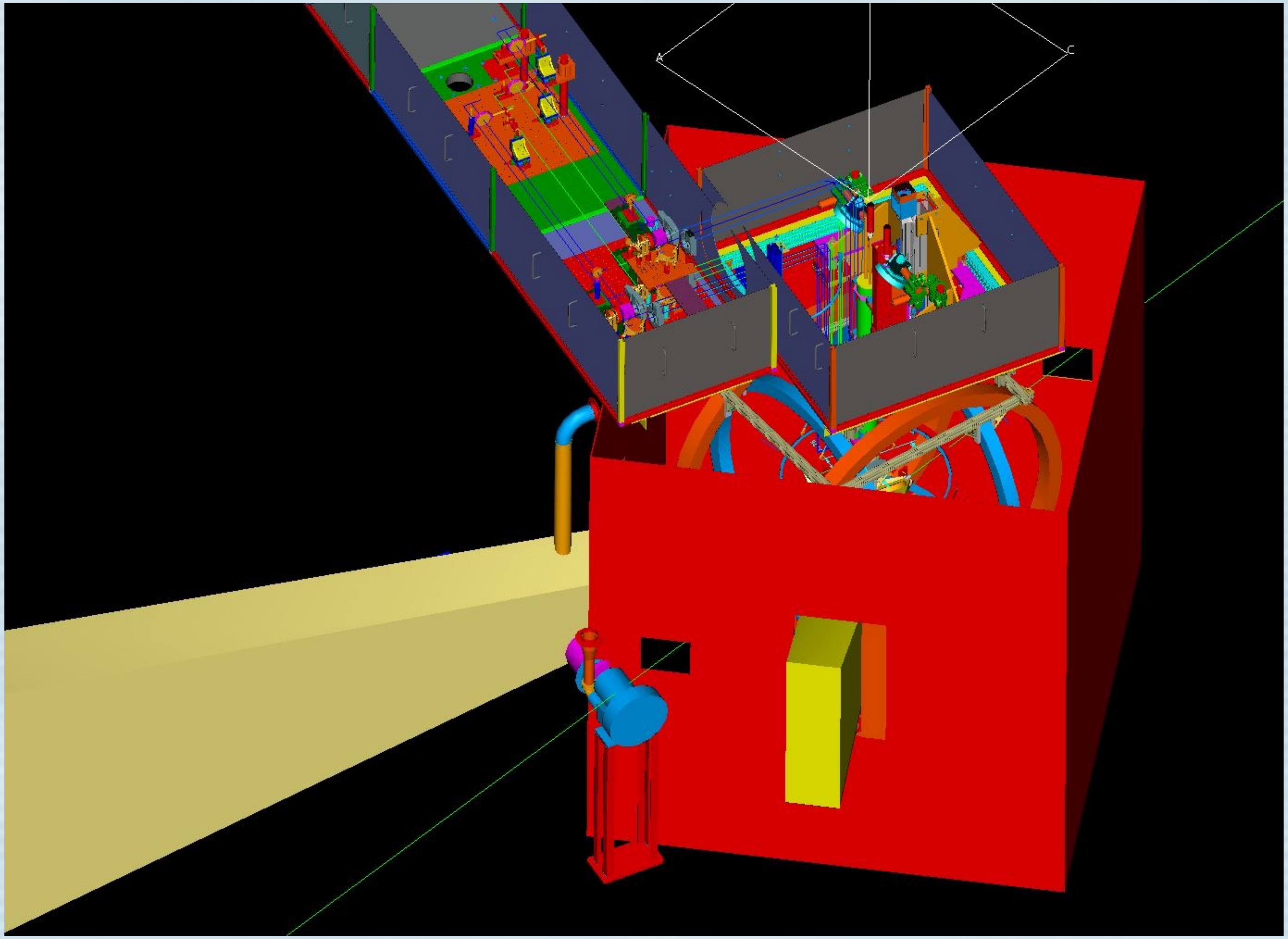
- Existing "Transversity coils", lifted by 15 cm.
- Soft iron box for shielding magnetic fields from SBS and BigBite magnets.
- Optics system will illuminate target from two directions.
- Magnetic field direction will be within a small range.

Conceptual design for SBS G_E^n target cells



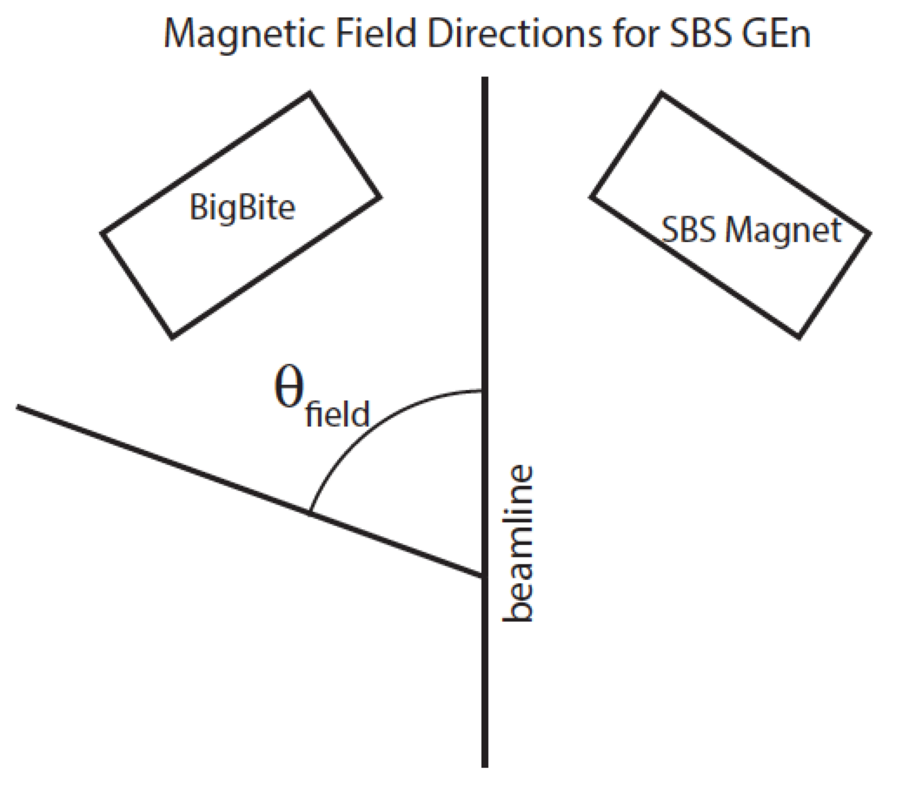
- 60 cm target-chamber length will deliver desired luminosity with 60 μA electron beam.
- Convection-based design, now well tested in Protovec-series cells.
- Contains 6 STP liters of ^{3}He in 750 cm^3 volume cell.
- Will use copper or aluminum metal end windows with gold electroplating on inner surface.

Engineering model is becoming increasingly refined.



Kinematic settings for SBS G_E^n target

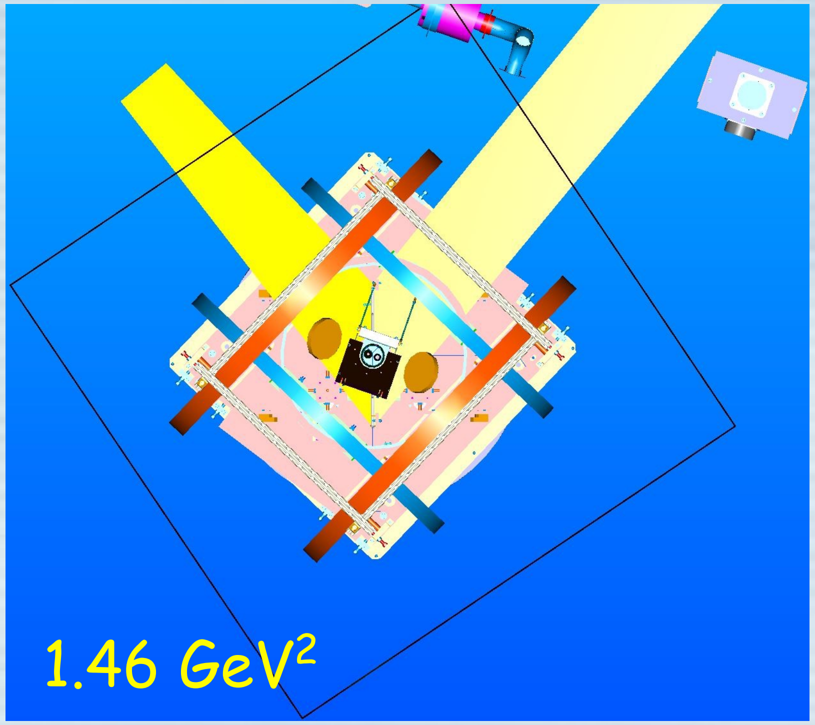
Our plan is to keep the magnetic field direction (as defined at right) at something close to 70°. **In general, we will try to make the experimental asymmetry as close to zero as possible.**

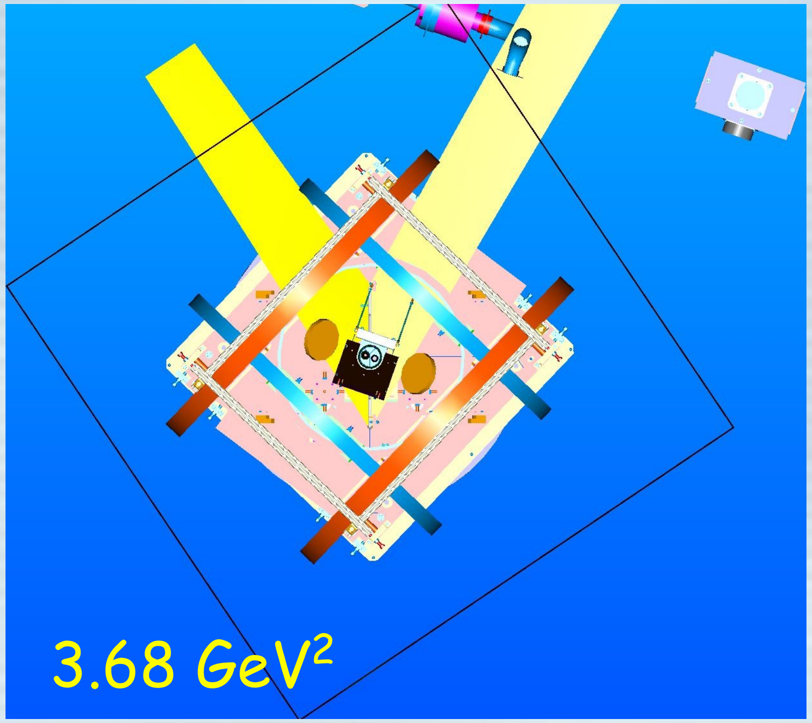


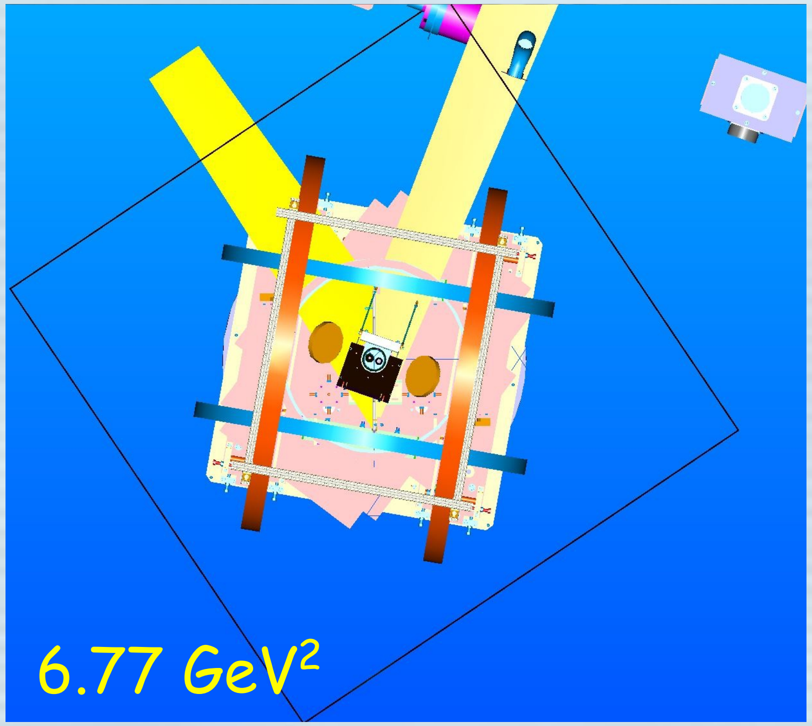
Kinematics and field direction

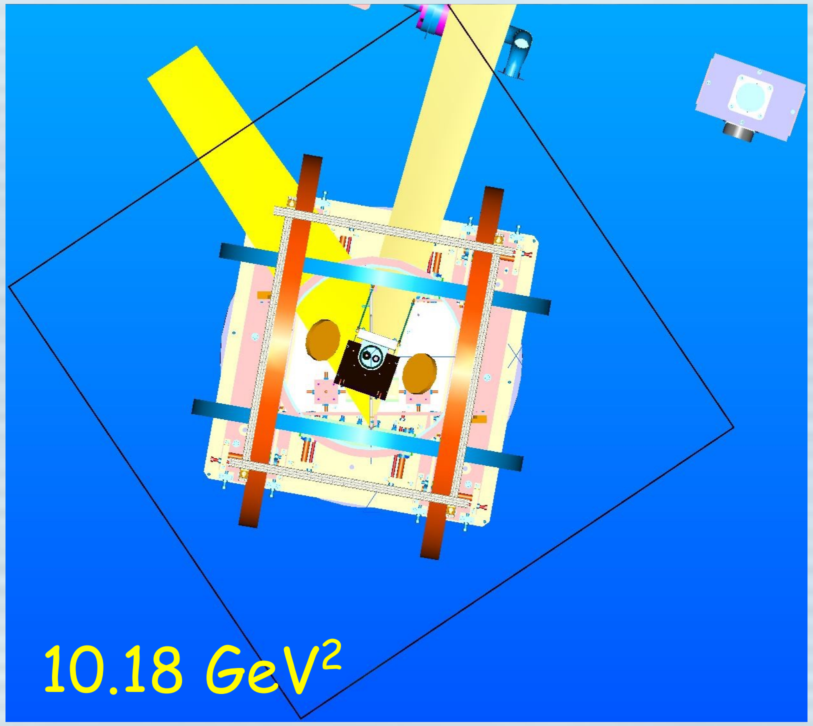
Q^2	θ_{BigBite}	θ_{SBS}	θ_{field}	$g_n(Q^2)$ assumed
1.46	40 degrees	39.4 degrees	70.6 - 50.6	0.3
3.68	34 degrees	29.9 degree	69.1 - 60.1	0.49
6.77	34 degrees	22.2 degrees	70.8 - 67.8	0.50
10.18	34 degrees	17.5 degrees	74.4 - 72.5	0.6

Kinematic settings for SBS G_E^n target

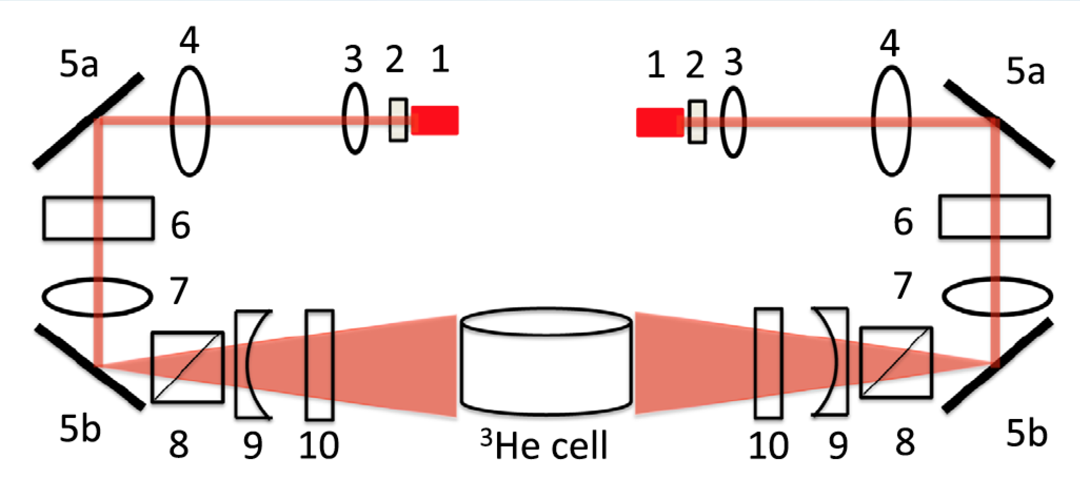

1.46 GeV^2


3.68 GeV^2


6.77 GeV^2


10.18 GeV^2

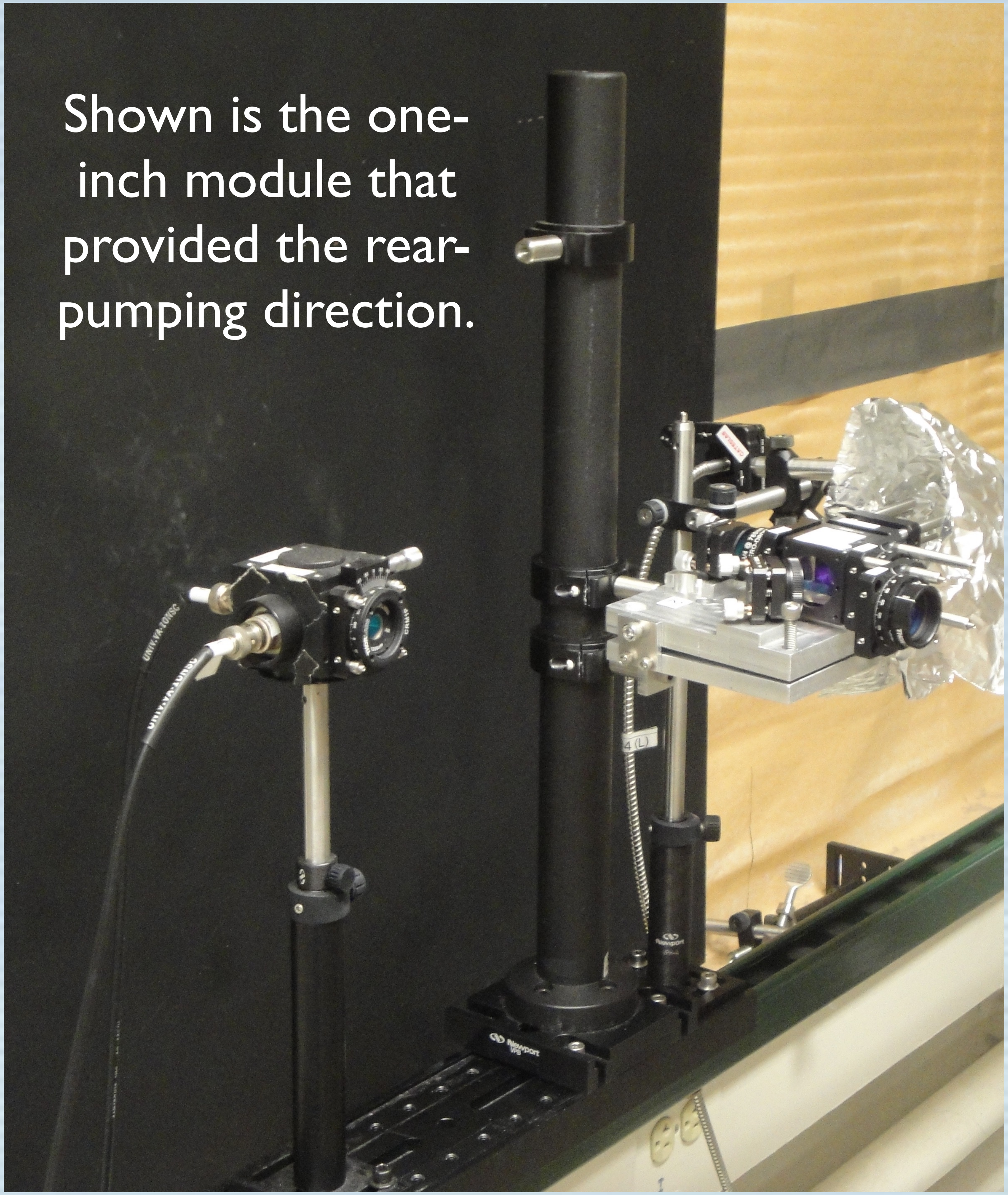
First test of dual-direction optical pumping



At left: the NIST system, from "On the limits of spin-exchange optical pumping of ^{3}He", W. C. Chen, T. R. Gentile, Q. Ye, T. G. Walker, and E. Babcock, Journal of Applied Physics vol. 116, pg. 014903 (2014).

First test of dual-direction pumping

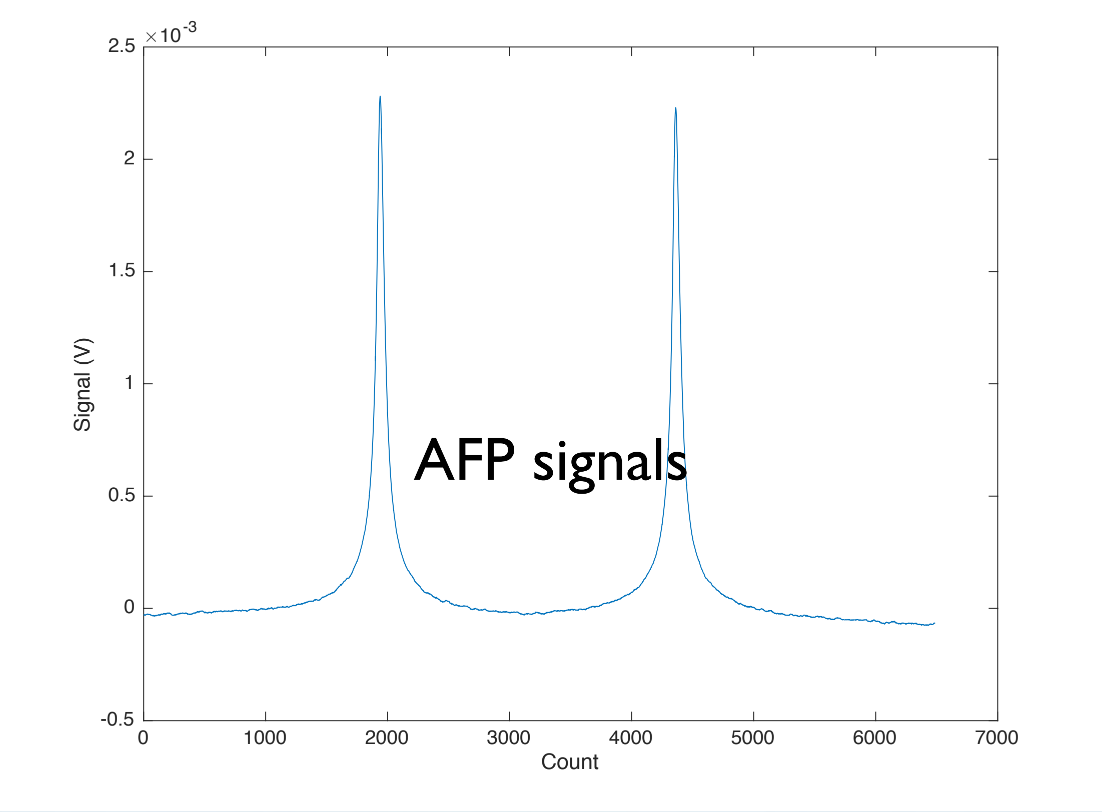
- Spherical cell, 3.25 inches outside diameter.
- Pressure just under one atmosphere.
- 40 Watts from three lasers combined with five-to-one combiner from the "front" pumping direction.
- 40 Watts from single one-inch module from the "back" pumping direction.

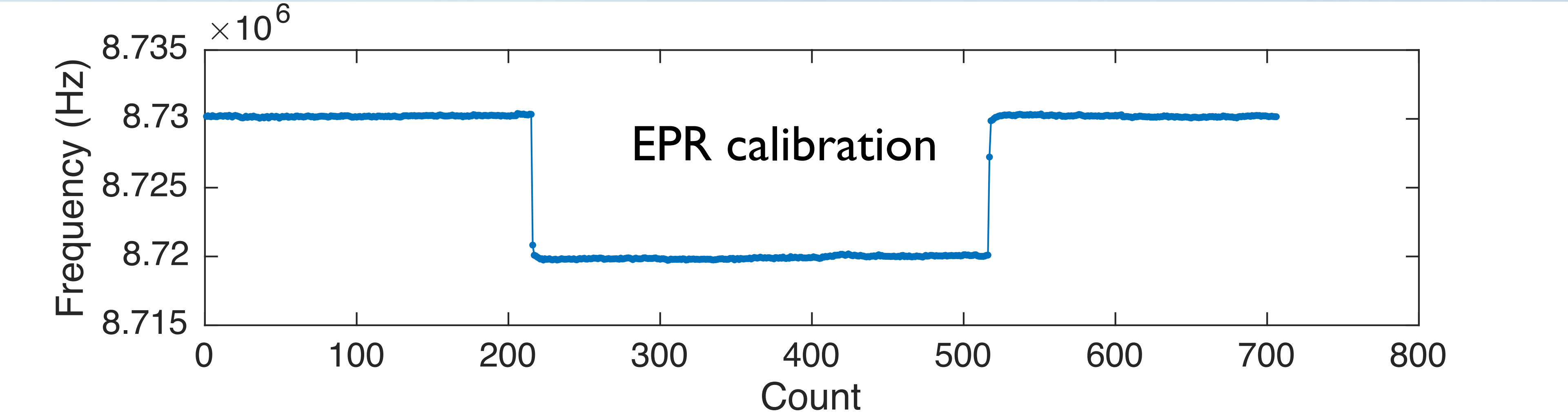


Shown is the one-inch module that provided the rear-pumping direction.

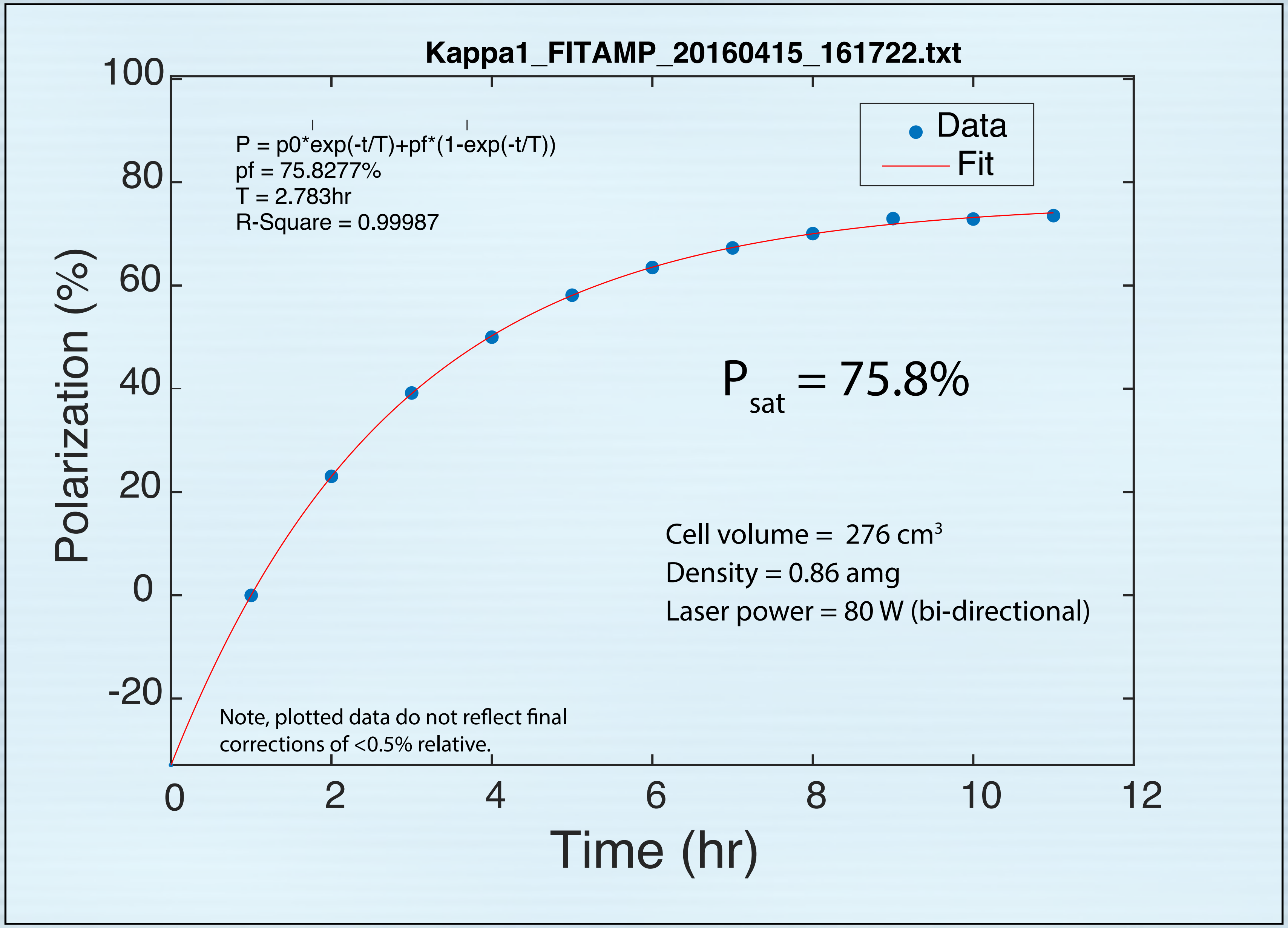
First test of dual-direction pumping

- AFP monitoring of polarization.
- EPR for absolute calibration of polarization.
- Multiple calibrations to establish reproducibility (which REQUIRE knowledge of the atomic parameter κ_0, which is poorly known for the operating conditions of alkali-hybrid target cells.


AFP signals

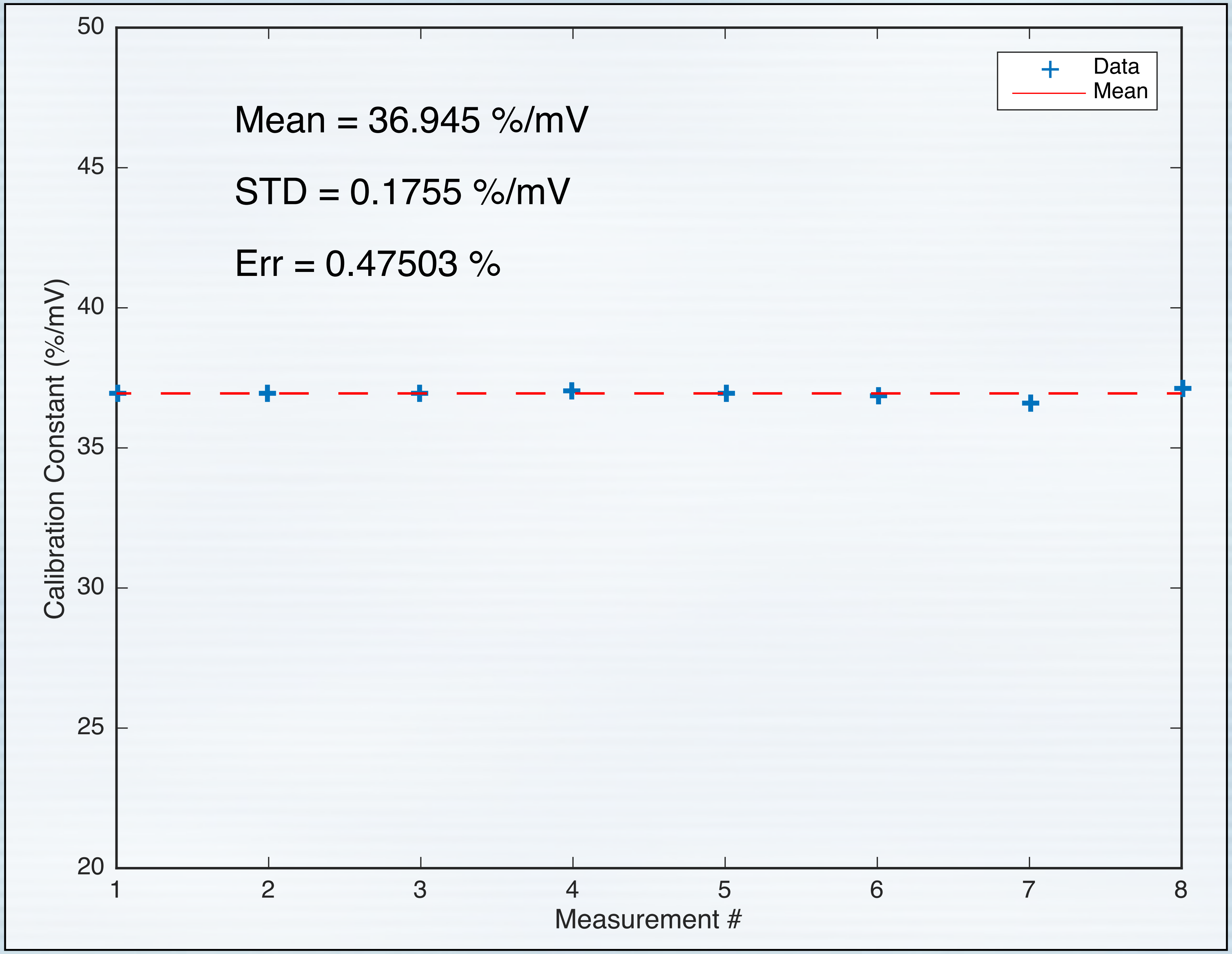

EPR calibration

First test of dual-direction pumping



This cell is a low-pressure spherical (i.e. simple geometry) cell, so it is unclear how this translates to a target cell. Even so, the ratio of (laser power)/(cell volume) in this test is the same as the ratio planned for the SBS G_E^n target.

Reproducibility of calibrations



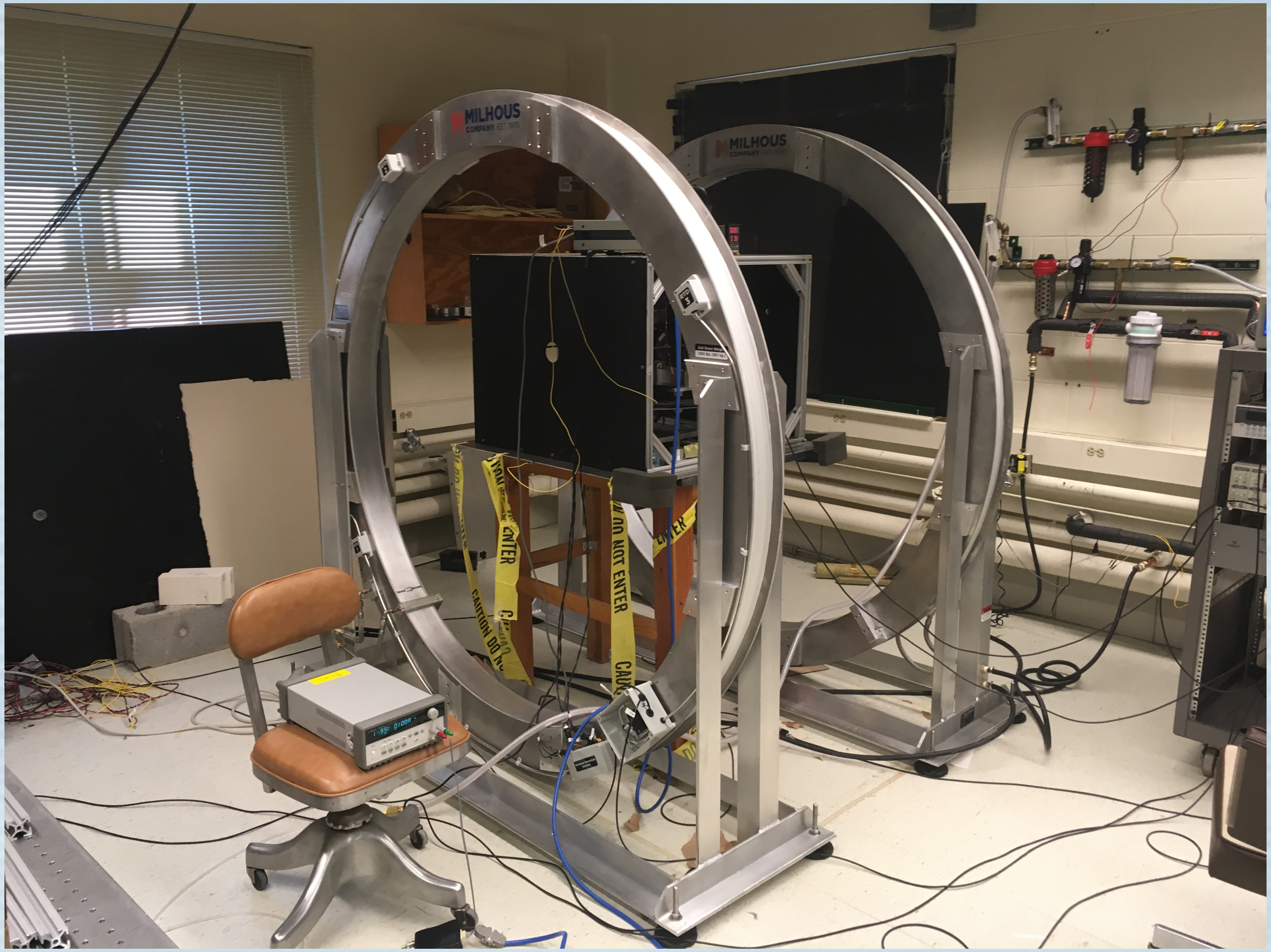
Better than 0.5% STD on multiple calibrations shows precision of the technique, but for absolute accuracy better than 3%, we need improved knowledge of the atomic parameter κ_0.

Measurements of the atomic parameter κ_0

The atomic parameter κ_0. characterizes the enhancement of the wave functions of Rb and K valence electrons at the location of the ^{3}He nucleus during collisions, and is the only unknown parameter describing EPR frequency shifts used for polarimetry.

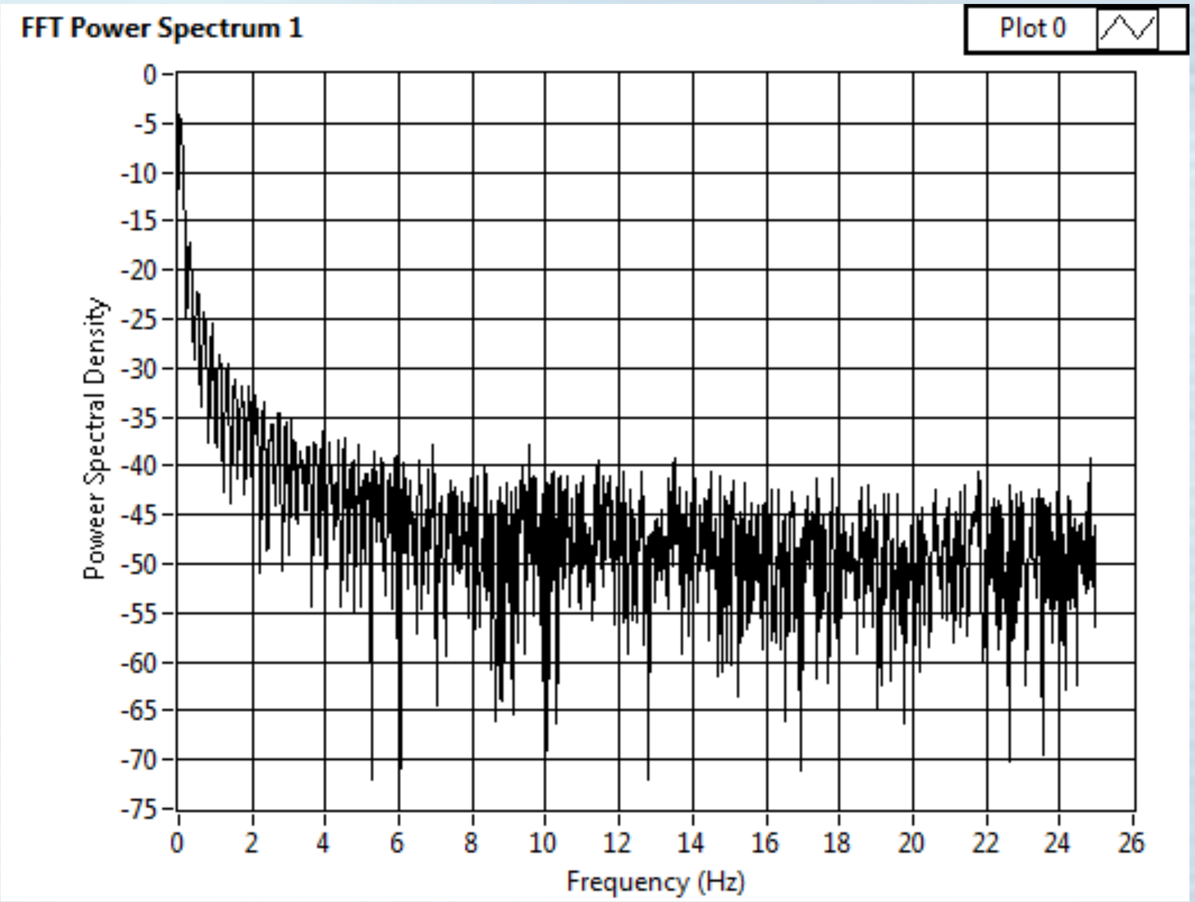
Apparatus for κ_0 measurement

Shown at right are our new coils, just under 2 meters in diameter, along with evolving components of the κ_0 measurement.

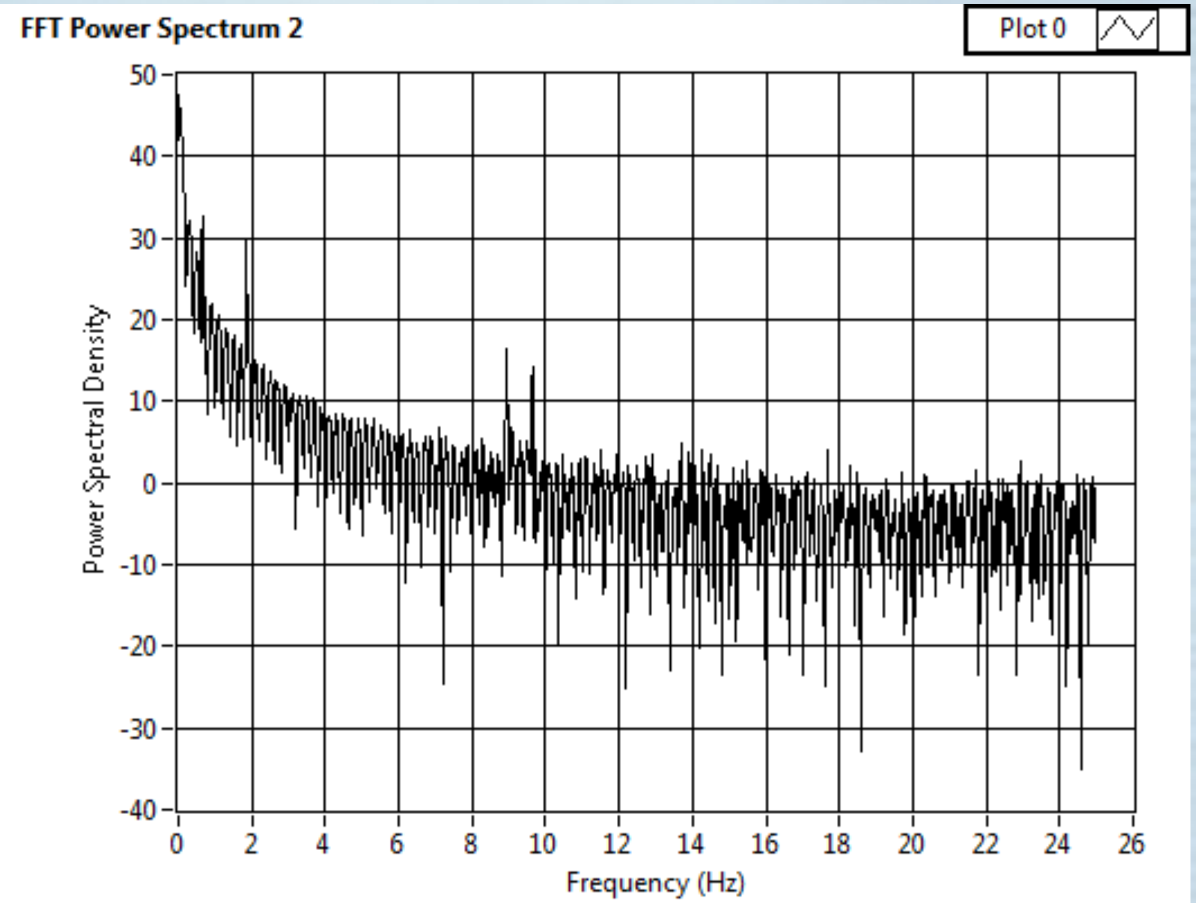


- Make precise NMR measurements of spherical ^{3}He cells using adiabatic fast passage (AFP).
- Interleave with EPR measurements of Rb and K frequency shifts.
- Calibrate NMR system with extremely-well-understood thermally polarized water samples.

Noise studies for κ_0 apparatus



FFT of velocimeter



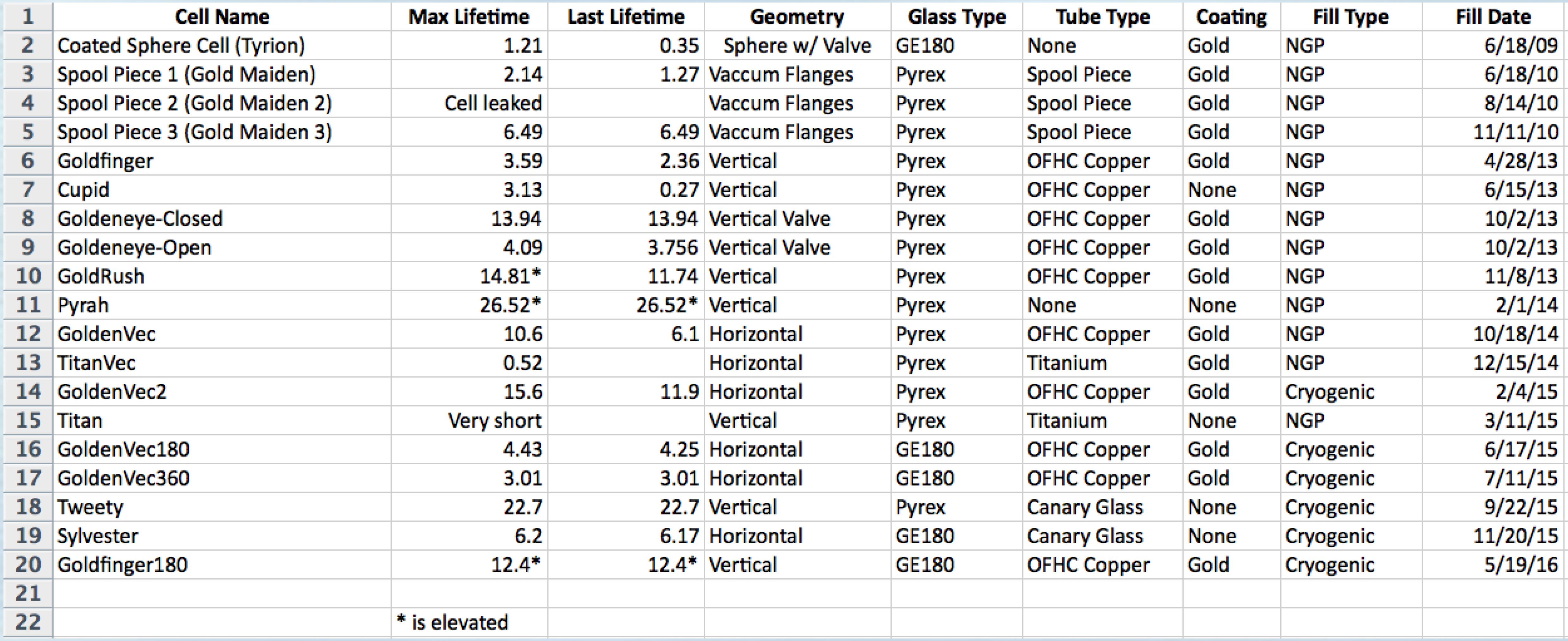
FFT of RF post-lockin

These measurements suggest that microphonic indeed contribute to the NMR AFP signals that are central to the κ_0 measurement.

Completion of glass-and-metal technology development

A huge effort has gone into identifying materials and fabrication techniques that do not cause excessive spin relaxation

Summary of glass-and-metal studies



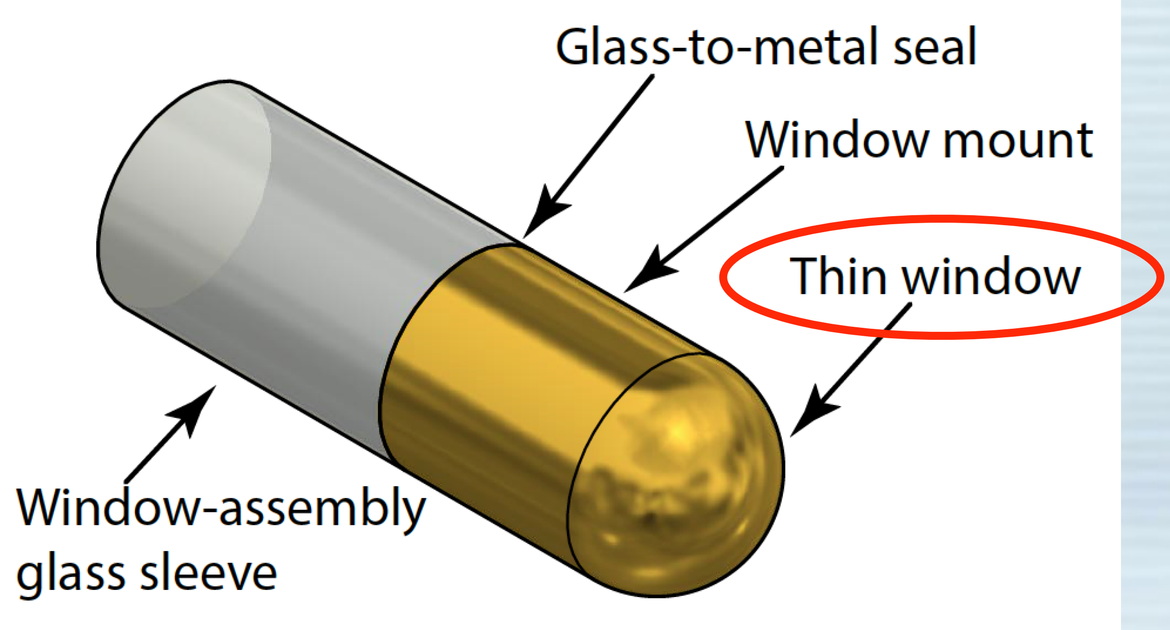
1	Cell Name	Max Lifetime	Last Lifetime	Geometry	Glass Type	Tube Type	Coating	Fill Type	Fill Date
2	Coated Sphere Cell (Tyrion)	1.21	0.35	Sphere w/ Valve	GE180	None	Gold	NGP	6/18/09
3	Spool Piece 1 (Gold Maiden)	2.14	1.27	Vaccum Flanges	Pyrex	Spool Piece	Gold	NGP	6/18/10
4	Spool Piece 2 (Gold Maiden 2)	Cell leaked		Vaccum Flanges	Pyrex	Spool Piece	Gold	NGP	8/14/10
5	Spool Piece 3 (Gold Maiden 3)	6.49	6.49	Vaccum Flanges	Pyrex	Spool Piece	Gold	NGP	11/11/10
6	Goldfinger	3.59	2.36	Vertical	Pyrex	OFHC Copper	Gold	NGP	4/28/13
7	Cupid	3.13	0.27	Vertical	Pyrex	OFHC Copper	None	NGP	6/15/13
8	Goldeneye-Closed	13.94	13.94	Vertical Valve	Pyrex	OFHC Copper	Gold	NGP	10/2/13
9	Goldeneye-Open	4.09	3.756	Vertical Valve	Pyrex	OFHC Copper	Gold	NGP	10/2/13
10	GoldRush	14.81*	11.74	Vertical	Pyrex	OFHC Copper	Gold	NGP	11/8/13
11	Pyrah	26.52*	26.52*	Vertical	Pyrex	None	None	NGP	2/1/14
12	GoldenVec	10.6	6.1	Horizontal	Pyrex	OFHC Copper	Gold	NGP	10/18/14
13	TitanVec	0.52		Horizontal	Pyrex	Titanium	Gold	NGP	12/15/14
14	GoldenVec2	15.6	11.9	Horizontal	Pyrex	OFHC Copper	Gold	Cryogenic	2/4/15
15	Titan	Very short		Vertical	Pyrex	Titanium	None	NGP	3/11/15
16	GoldenVec180	4.43	4.25	Horizontal	GE180	OFHC Copper	Gold	Cryogenic	6/17/15
17	GoldenVec360	3.01	3.01	Horizontal	GE180	OFHC Copper	Gold	Cryogenic	7/11/15
18	Tweety	22.7	22.7	Vertical	Pyrex	Canary Glass	None	Cryogenic	9/22/15
19	Sylvester	6.2	6.17	Horizontal	GE180	Canary Glass	None	Cryogenic	11/20/15
20	Goldfinger180	12.4*	12.4*	Vertical	GE180	OFHC Copper	Gold	Cryogenic	5/19/16
21									
22		* is elevated							

After thousands of hours of data taking, the take-away messages:

- We have technology that consistently produces a low-relaxivity metal surface.
- Degradation of metal surfaces with exposure to Rb is modest.
- Annealing effects are very important when working with GE-180.
- “Canary” or “Uranium” glass, a transition glass, is NOT very relaxing and can be safely incorporated into our cells.

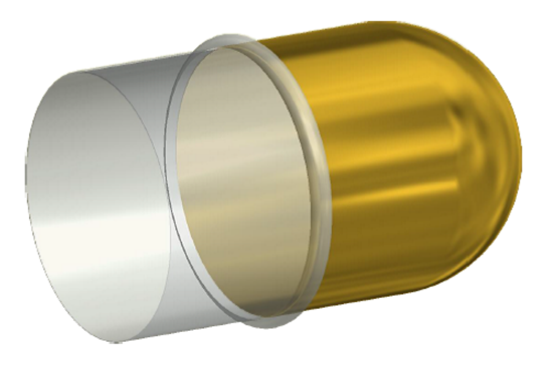
Next steps

Window development



- OFHC Copper, by itself, would require too many radiation lengths to achieve the required strength.
- Several promising approaches have been identified, and we will be testing the different possibilities.
- In-beam testing would be HIGHLY desirable, as the character and strength of the metal is likely to change with radiation exposure.
- We may have the opportunity to test 3-liter (stage 1) target cells with metal windows during early ^{3}He experiments (A_1^n in Hall C?)

Window development

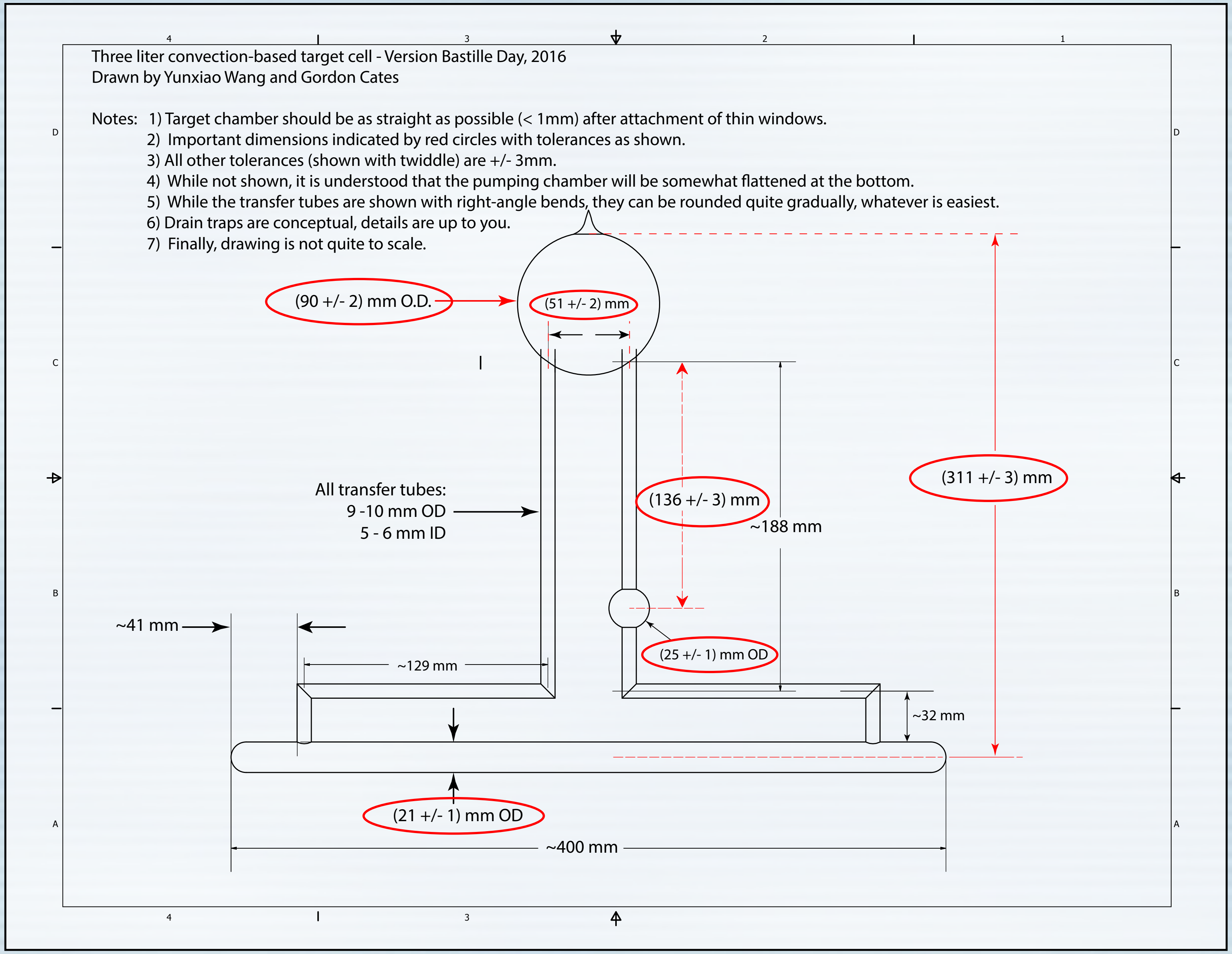


Material	Min. thickness (microns)	Rad. lengths
GE 180	139.7 (actual)	0.0028
OFHC	172.1	0.0123
Glidcop Al-60	20.4	0.0019
Al	153	0.0026

Current plan is to try aluminum first.

Production of 3-liter target cells is beginning

Bastille Day Design (below) released to glass blower on July 14th



Three liter convection-based target cell - Version Bastille Day, 2016
Drawn by Yunxiao Wang and Gordon Cates

Notes:
1) Target chamber should be as straight as possible (< 1mm) after attachment of thin windows.
2) Important dimensions indicated by red circles with tolerances as shown.
3) All other tolerances (shown with twiddle) are +/- 3mm.
4) While not shown, it is understood that the pumping chamber will be somewhat flattened at the bottom.
5) While the transfer tubes are shown with right-angle bends, they can be rounded quite gradually, whatever is easiest.
6) Drain traps are conceptual, details are up to you.
7) Finally, drawing is not quite to scale.

Mike Souza, the glass blower, expects to finish the first cell on Monday, July 25th.

Summary

- Engineering is proceeding.
- SBS G_E^n target cell development will now focus on windows.
- Production of 3-liter (stage 1) target cells is underway, and may provide an opportunity to test the final window design.
- Simulated-beam tests will resume soon with actual 3-liter target cells.

Backup Slides

Remaining challenges

Material	Density (g/cm^3)	Melting Point (^{0}C)	Yield Strength (MPa)	Min. Thickness Needed (um)	Min. Thickness Needed (mg/cm^2)	Radiation Length (mg/cm^2)	Number of radiation lengths
OFHC	8.9	1065	49	172.09	153.16	$1.247*10^4$	0.0123
Cartridge Brass	8.53	916	441	19.12	16.31	$9.439*10^3$	0.0017
Glidcop Al-60	8.81	1083	413	20.42	17.99	$9.693*10^3$	0.0019
GE 180	2.76	1015		139.7 (thickness used)	38.56 (thickness used)	$1.388*10^4$	0.0028
Al	2.7	~ 600	55	153	41.40	$1.591*10^4$	0.0026

Backup Slides

Existing laser/optics system

The current system must be upgraded to deliver the required power

- Each pumping direction would use two-inch optics with a five-to-one combiner.
- With 25 Watt limit per channel => 125 watts max per pumping direction
- Assuming 80% transmission => 200 Watts maximum - not enough.
- Need to add more power - should have 300 Watts available in order to be safe.

Two obvious solutions

Solution #1:

- Bring light in from the top as is done now.
- Use existing five-to-one combiners to utilize existing lower power lasers.
- Add one-inch modules (40-50 Watts each) to provide remaining power to bring total to 300 Watts.

Solution #2:

- Mount 3 one-inch modules with 50 Watt lasers on the magnetic shielding box for each pumping direction.
- Translate or tip modules to follow the target ladder motion.

Key points from CDR

- Target cell design has been settled for over a year.
- With hopefully minor caveats, the Transversity/Temple coils can do the job if elevated by 15cm.
- The double-walled box design of Vladimir (or possibly even simpler variants), can provide the necessary magnetic shielding.
- Approach to polarimetry with the glass-and-metal cells is largely settled.
- Laser and optics system, as it exists, needs upgrading.

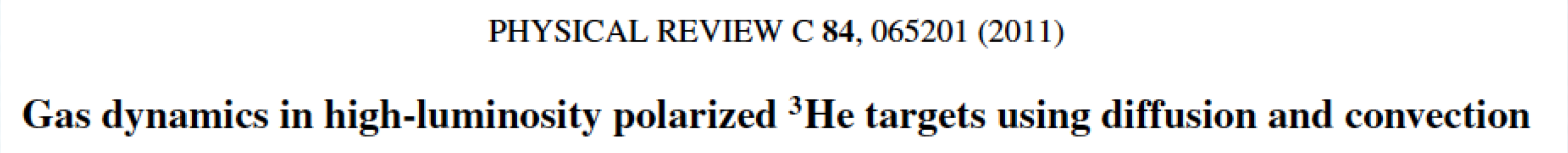
Laser power requirements

The SBS GEn target will have a figure of merit roughly nine times higher than was the case for Transversity. How do we compute the required laser power?

- Scale from Transversity: with 6 STP liters versus 2 STP liters, we need 3x80 Watts, or 240 Watts.
- Use the results of the benchmarked simulations in the Jaideep Singh's target-development paper (PRC v91, 055205 (2015)): indicates 237 Watts.
- Consider the NIST targets, with similar volumes but less gas. They are based on two 100 Watt laser bars. Conclusion? Greater than 200 Watts.

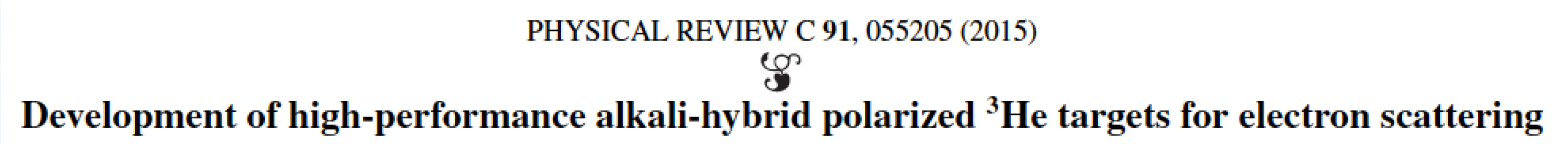
Backup Slides

We have quantified our understanding of the targets or lack thereof



PHYSICAL REVIEW C **84**, 065201 (2011)

Gas dynamics in high-luminosity polarized ^{3}He targets using diffusion and convection



PHYSICAL REVIEW C **91**, 055205 (2015)

Development of high-performance alkali-hybrid polarized ^{3}He targets for electron scattering

Where are the uncertainties?

- The unexplained temperature/alkali-density relaxation characterized by the so-called X-factor.
- The “cold” spin-relaxation time of the cell
- Alkali vapor polarization (uncertain at the 5% level)
- Polarization reduction associated with convection (not yet well-studied or optimized).
- Metal-end-window contribution to relaxation.

The best we can do is look at a reasonable range of parameters based on hard data.

Beam relaxation is well understood (and a limiting issue)

$$\Gamma^{\mathrm{av}}_{\mathrm{beam}} = \mathrm{f_{tc}}\,\Gamma_{\mathrm{beam}} = \mathrm{f_{tc}}\left(5 \times 10^{-3}\,\frac{\mathrm{cm}^2}{\mu\mathrm{A\,hr}}\right) \mathrm{I}/\mathrm{A_{tc}}$$

- Relaxation due to the beam has been well understood since 1989.*
- The above equation has been verified during electron scattering by multiple theses at better than the 20% level.
- The only way to reduce it at high currents is reducing the fraction of gas in the target chamber, f_{tc}.
- It is worth noting that while convection cells address the problem of "polarization gradients", they do nothing to help with overall suppression of cell-averaged polarization.

---

* K.P. Coulter, A.B. McDonald, G.D. Cates, W. Happer, and T.E. Chupp, *Measurement of* ^{3}He *depolarization rates during bombardment with a* ^{4}He *beam*, Nucl. Inst. and Meth. in Phys. Res. **A276**, 29 (1989).

Simple model benchmarked to cell "Brady" and average values

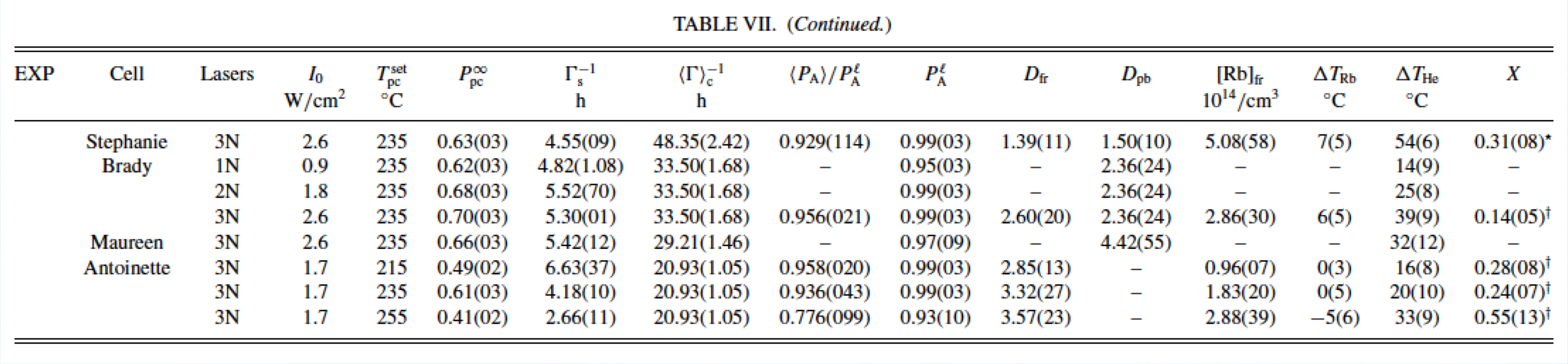


TABLE VII. (*Continued.*)

EXP	Cell	Lasers	I_0 W/cm^2	$T_{\mathrm{pc}}^{\mathrm{set}}$ °C	P_{pc}^{∞}	Γ_{s}^{-1} h	$\langle\Gamma\rangle_{\mathrm{c}}^{-1}$ h	$\langle P_{\mathrm{A}}\rangle / P_{\mathrm{A}}^{\ell}$	P_{A}^{ℓ}	D_{fr}	D_{pb}	$[\mathrm{Rb}]_{\mathrm{fr}}$ $10^{14}/\mathrm{cm}^3$	ΔT_{Rb} °C	ΔT_{He} °C	X
	Stephanie Brady	3N	2.6	235	0.63(03)	4.55(09)	48.35(2.42)	0.929(114)	0.99(03)	1.39(11)	1.50(10)	5.08(58)	7(5)	54(6)	0.31(08)*
		1N	0.9	235	0.62(03)	4.82(1.08)	33.50(1.68)	–	0.95(03)	–	2.36(24)	–	–	14(9)	–
		2N	1.8	235	0.68(03)	5.52(70)	33.50(1.68)	–	0.99(03)	–	2.36(24)	–	–	25(8)	–
		3N	2.6	235	0.70(03)	5.30(01)	33.50(1.68)	0.956(021)	0.99(03)	2.60(20)	2.36(24)	2.86(30)	6(5)	39(9)	0.14(05)†
	Maureen Antoinette	3N	2.6	235	0.66(03)	5.42(12)	29.21(1.46)	–	0.97(09)	–	4.42(55)	–	–	32(12)	–
		3N	1.7	215	0.49(02)	6.63(37)	20.93(1.05)	0.958(020)	0.99(03)	2.85(13)	–	0.96(07)	0(3)	16(8)	0.28(08)†
		3N	1.7	235	0.61(03)	4.18(10)	20.93(1.05)	0.936(043)	0.99(03)	3.32(27)	–	1.83(20)	0(5)	20(10)	0.24(07)†
		3N	1.7	255	0.41(02)	2.66(11)	20.93(1.05)	0.776(099)	0.93(10)	3.57(23)	–	2.88(39)	–5(6)	33(9)	0.55(13)†

- Extract spin-exchange rate to be 1/6.4 hours (from Brady)
- Assume that $0.14 < X < 0.25$
- Assume that 1/35 hrs < Cold spin-relaxation rate < 1/30 hrs
- Assume that reduction is polarization is 10% (absolute) for a 3 liter cell and 5% absolute for a 6 liter cell.

$$P_{He} = 0.95(alkali\ pol) * \frac{\gamma_{se}}{\gamma_{se}(1+X) + \Gamma_{cold} + \Gamma_{beam}}$$

Beam relaxation for different cell geometries and overly simple model for polarization

Cell	Brady f_{tc}=0.38 Length: 40 cm	Protovec f_{tc}=0.26 Length: 40 cm	Protovec-D f_{tc}=0.20 Length: 60 cm	Protovec-D-S f_{tc}=0.14 Length: 40 cm
τ (12μA)	84 hrs 63%/58% (3% high)	125 hrs	161 hrs	225 hrs
τ (30μA)	33 hrs	50 hrs	65 hrs	90 hrs
τ (60μA)	17 hrs 41%/32%	25 hrs 55%-60%	32 hrs 57%-62%	45 hrs 59-65 %

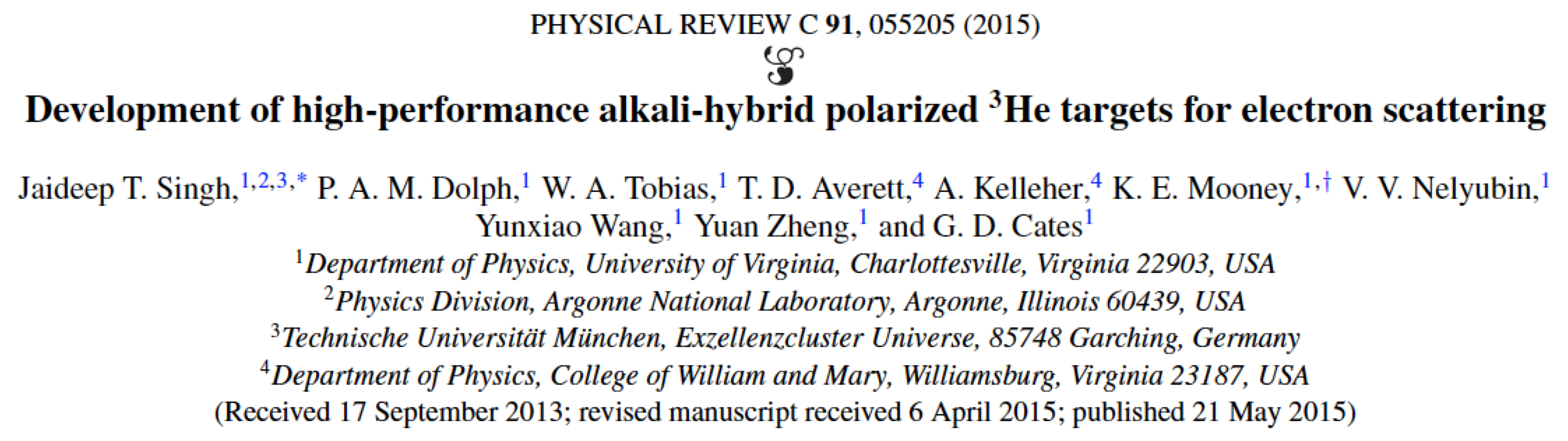
- Brady was run during Transversity and is well studied at both UVa and JLab.
- A simple model using Brady as a benchmark predicts Brady's performance to be about 3% higher (absolute) than was the case.
- Provides a reasonable starting point for predictions.

Performance expectations at 60μA

Cell	simple model at 60 microA	adjusted for Brady benchmark	+ adjust for convection	adjusted for sim. beam benchmark
Protovec	55-60 %	52 - 57%	42 - 47 %	49 % from sim. beam test
Protovec-D	57-62 %	54 - 59 %	49 - 54%	51 - 56 %
Protovec-D-S	59-65 %	56 - 62 %	51 - 57%	53 - 59%

- Brady was run during Transversity and is well studied at both UVa and JLab.
- A simple model using Brady as a benchmark predicts Brady's performance to be about 3% higher (absolute) than was the case.
- Provides a reasonable starting point for predictions.
- Pumping from two sides, and slightly higher spin-exchange rates in 6 liter cells may result in small increases

A quick aside



PHYSICAL REVIEW C **91**, 055205 (2015)

Development of high-performance alkali-hybrid polarized ^{3}He targets for electron scattering

Jaideep T. Singh,[1,2,3,*] P. A. M. Dolph,[1] W. A. Tobias,[1] T. D. Averett,[4] A. Kelleher,[4] K. E. Mooney,[1,†] V. V. Nelyubin,[1]
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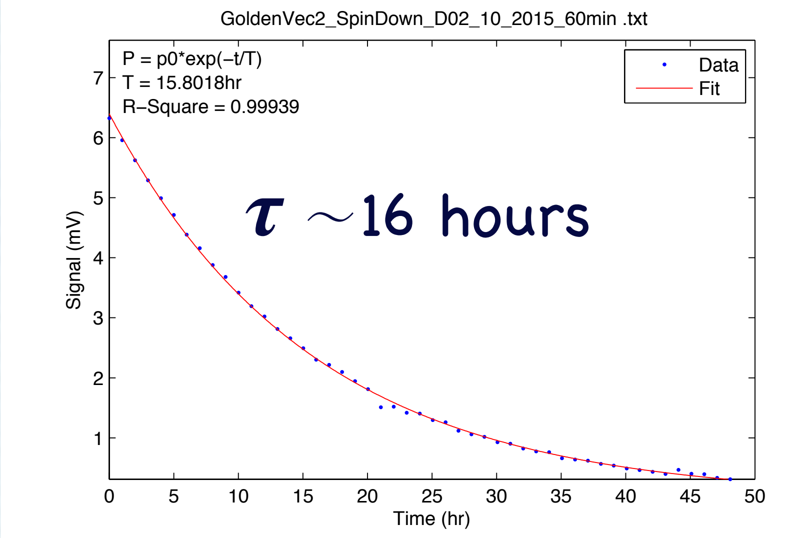
Editor’s choice!

The work underlying the high luminosity targets we are developing is now published.

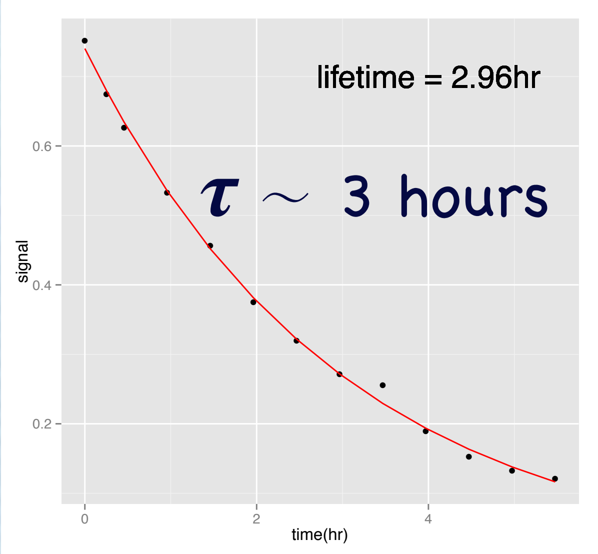
Where we stand right now

GoldenVec-II



$\tau \sim 16$ hours

GoldenVec-180



$\tau \sim 3$ hours

GoldenVec-I and GoldenVec-II were constructed of Pyrex, with the metal portion being made of OFHC Copper with a 5 micron gold coating on the inside.

GoldenVec- 180 (and GoldenVec-360) were constructed of GE-180 along with a transition glass between the GE-180 and the metal tube, which again was made of OFHC Copper with a 5 micron gold coating on the inside.

Major victory with Pyrex, complications moving to GE-180

The implications of the GoldenVec-180 tests

(the first tests using metal + aluminosilicate glass)

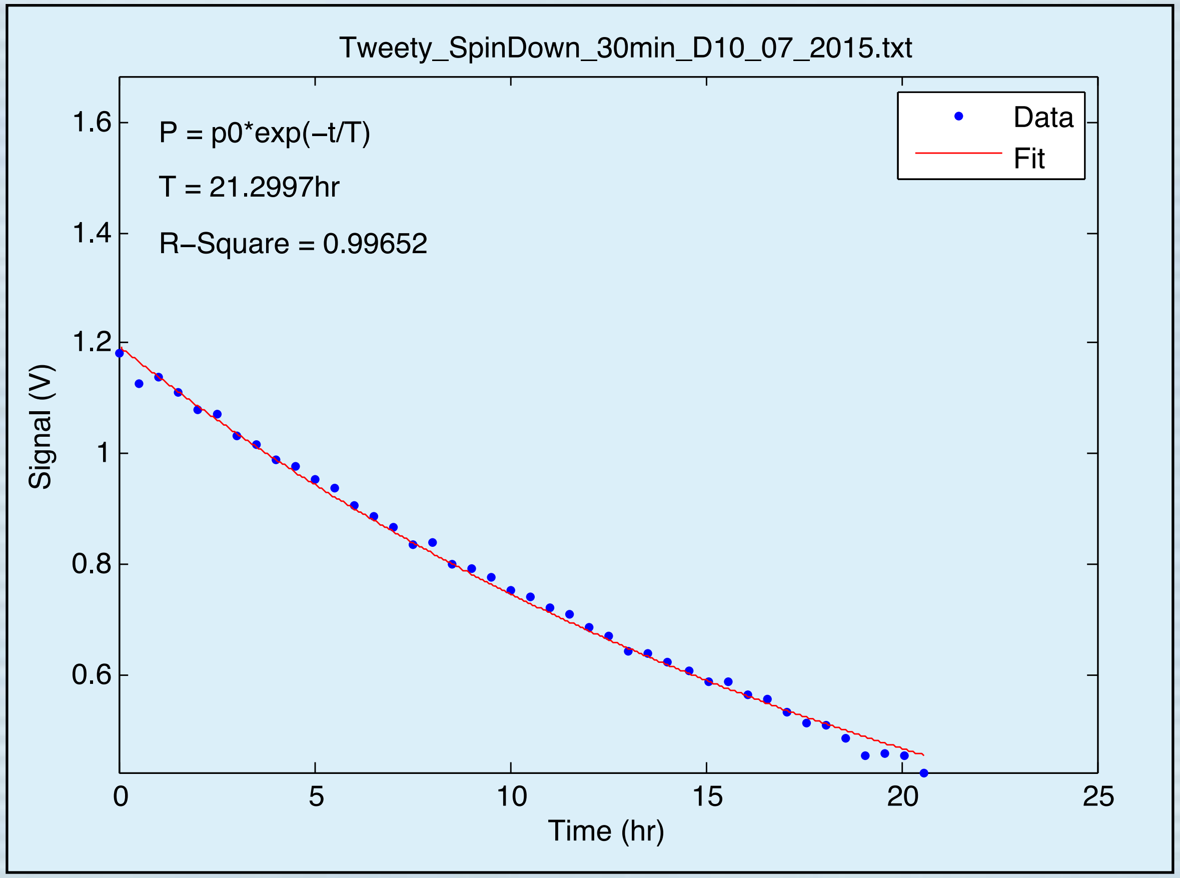
The tests of GoldenVec-180 and GoldenVec-360 were meant to be the final tests before producing prototype windows but the tests failed (yielded short lifetimes).

Possible hypotheses as to why the tests failed

- The transition glass caused excessive spin relaxation.
- The annealing process (which was different from that used with all-glass cells), while sufficient for Pyrex, was not sufficient for the aluminosilicate glass GE-180

Test of different transition glass: canary glass

- Canary glass contains uranium, which is paramagnetic.
- Expectations among those working with polarized noble gases were that canary glass would cause excessive spin relaxation.
- We decided to see if those expectations were justified.
- We found the spin-relaxation properties of canary glass to be similar to those of Pyrex.



Comparison of different copper alloys with GE-180 Glass

In all cases below, we assumed that the thickness was sufficient for the “yield point” to occur at 50% greater than the operating pressure.

Material	Density (g/cm^3)	Melting Point (^0C)	Yield Strength (MPa)	Min. Thickness Needed (um)	Min. Thickness Needed (mg/cm^2)	Radiation Length (mg/cm^2)	Number of radiation lengths
OFHC	8.9	1065	49	172.09	153.16	$1.32*10^4$	0.0116
Cartridge Brass	8.53	916	441	19.12	16.31	$1.31*10^4$	0.0012
Glidcop Al-60	8.81	1083	413	20.42	17.99	$1.33*10^4$	0.0013
GE 180	2.76	1015		139.7 (thickness used)	38.56 (thickness used)	$1.96*10^4$	0.0020

- OFHC copper would need to be way too thick.
- Cartridge brass melts at too low a temperature for the process in which the metal and the glass are sealed to each other.
- Glidcop Al-60 (a copper/aluminum/other stuff alloy) looks reasonable.

Summary of ongoing work

Four parallel efforts, three full-time graduate students

- We are running tests to isolate the problem in moving to GE-180.
- We are preparing to test different approaches to fabricating the window itself.
- We are beginning the construction of two or three Stage 1 target cells (3 liter all-glass convections cells with thin glass windows).
- Again in parallel, we are constructing an experiment to measure the parameter κ_0, which is needed for polarimetry.

Backup Slides

Polarized ^{3}He target requirements: past and future

Experiment	Current (μA)	Polarization	Luminosity
SLAC E142	3.3	33%	$1.5x10^{35}$
GDH	12.5	35%	$1.0x10^{36}$
GEn	8	47%	$6.1x10^{35}$
Transversity	12	55%	$9.0x10^{35}$
Hall A A1n	30	65%	$3.3x10^{36}$
SBS GEn	60	62%	$6.6x10^{36}$
Hall C A1n	60	60%	$6.6x10^{36}$

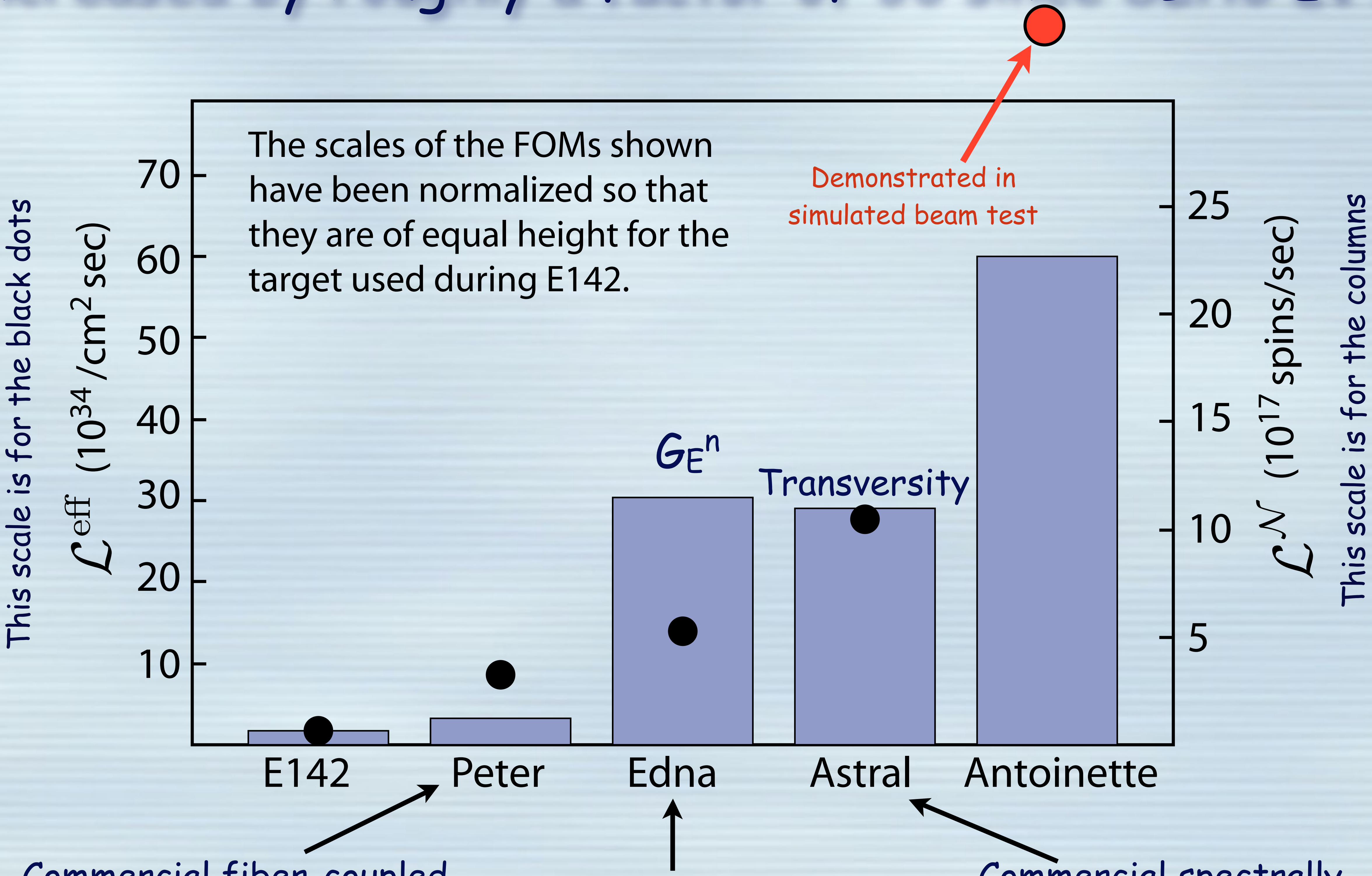
Past

Future

Important technology

- High-power diode-laser arrays (SLAC E154/JLab E-94-010 (GDH))
- Careful selection through full-power tests (E-99-117 (A1n))
- Alkali-hybrid spin-exchange optical pumping (GEn)
- Spectrally-narrowed high-power diode-laser arrays (Transversity)
- Convection-driven cells (demonstrated in bench tests)
- Metal end windows (in development)

The performance of polarized ^{3}He targets have increased by roughly a factor of 30 since SLAC E142



The scales of the FOMs shown have been normalized so that they are of equal height for the target used during E142.

Demonstrated in simulated beam test

Commercial fiber-coupled high-power diode laser arrays: early JLab

Alkali-hybrid SEOP

Commercial spectrally narrowed high-power diode laser arrays