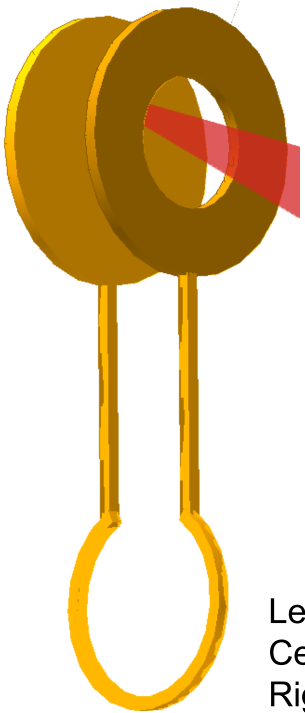
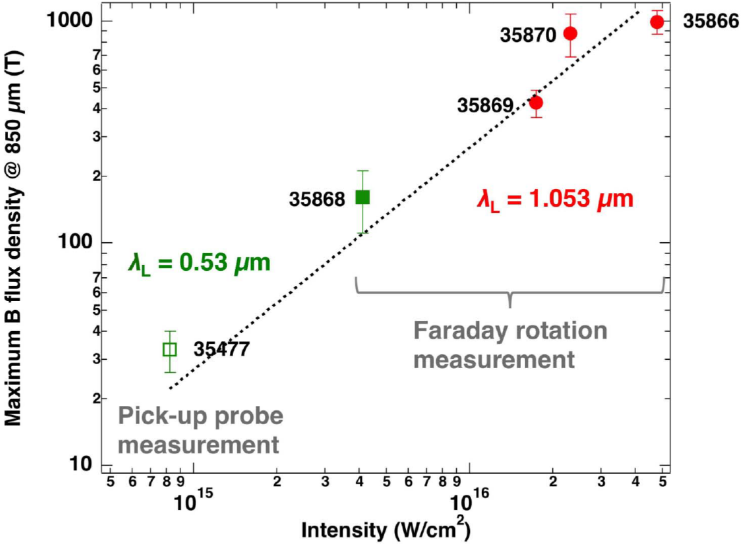
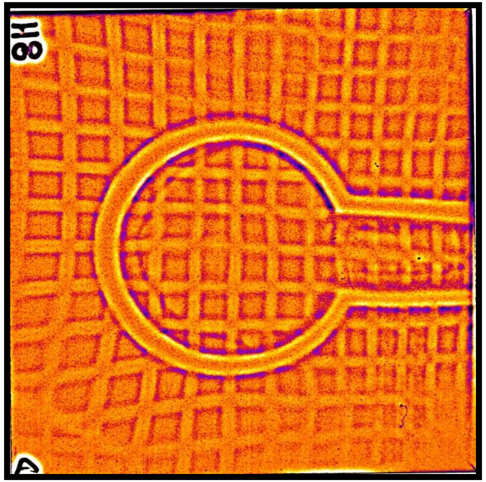
Laser-driven coils, how well do they work?







Left: General laser driven coil configuration
Center: Result from Fujioka *et al.* claiming impressive, kT magnetic fields
Right: Proton radiograph of the center of the laser driven coil

J. Peebles

April 1st, 2021
HEDS Seminar

Thanks to my collaborators

J. Davies, D. Barnak, M. Bonino, G. Brent, T. Cracium, R. Betti

Laboratory for Laser Energetics
University of Rochester

Thanks to the Office of Fusion Energy Sciences for supporting this work and the Center of Excellence for Advanced Nuclear Diagnostics and Platforms for ICF and HED Physics at OMEGA, NIF and Z

This material is based upon work supported by the Department of Energy Office of Fusion Energy Sciences under Award Number DE-SC0021072 and the National Nuclear Security Administration under Award Numbers DE-NA0003856 and DE-NA0003868.

Outline

- Laser driven coils (LDC) overview
- How well do LDCs work?
- Electric and magnetic field diagnostics
- Calibrating and validating diagnostics
- Overview of initial and follow up experimental results
- Discussion and conclusions

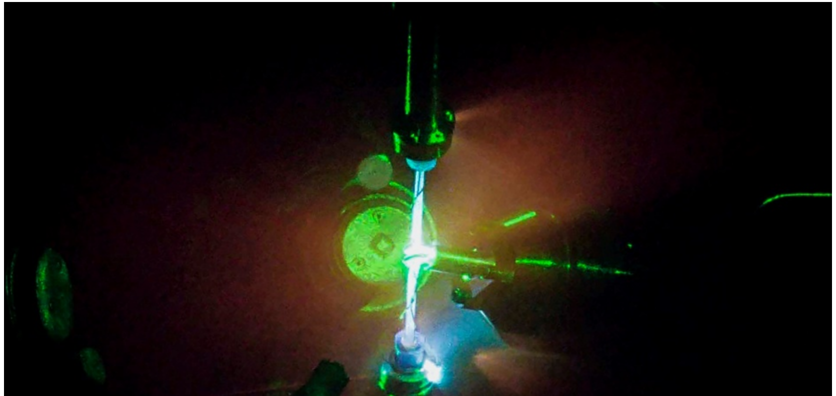
Outline

- Laser driven coils (LDC) overview
    - Motivation
    - Principles of operation
- How well do LDCs work?
- Electric and magnetic field diagnostics
- Calibrating and validating diagnostics
- Overview of initial and follow up experimental results
- Discussion and conclusions

Strong magnetic fields open new avenues of research in high energy density physics and are highly desirable for inertial confinement fusion research

- LLE's magnetic field generator MIFEDS is heavily subscribed for shots on OMEGA and EP, despite complications in brings to campaigns (~8 shot days in Q4 FY20 alone)
- LLNL is pursuing a project to create its own pulsed power device for NIF to be compatible with their cryogenic system and debris requirements
- Pulsed power systems produce debris that are incompatible with many high performing laser systems and experiments

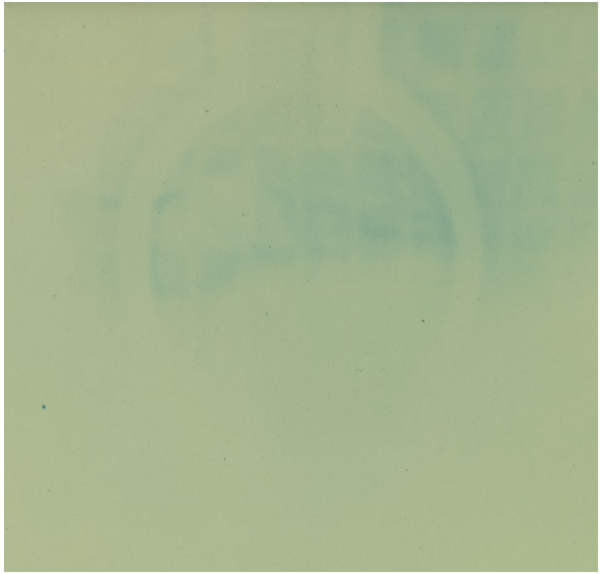
Single shot MIFEDS debris



Quick shot of Z. Barfield's LatHeatTrans Campaign
Credit: Eugene Kowaluk

The Catch-22 with magnetized experiments

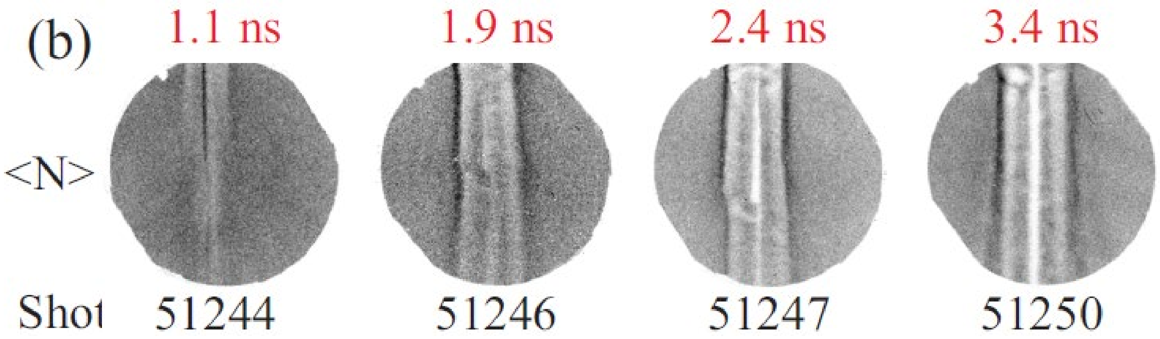
- Magnetized experiments use high intensity lasers to generate energetic particles for physics goals or to probe magnetic fields
  - **I_{laser} > 10^{19} W/cm^2, pulse length = best compression**
- Pulsed power devices such as MIFEDS can potentially damage optics, debris shields are required which drop laser intensities
  - **I_{laser} < 10^{18} W/cm^2 at BC, ~10^{19} W/cm^2 at 10 ps**
- Coils are bulky and can block beams preventing physics goals. Magnetic fields are generated at the expense of the rest of the experiment



Not sure there's enough here for a paper…

Laser driven coils are target based platforms used to generate strong magnetic fields without a pulser

- **Early laser experiments measured current traveling through target support structures and the chamber wall***
- **While current was low, it was hypothesized that electrons ejected from targets lead to a neutralizing return current through the target**

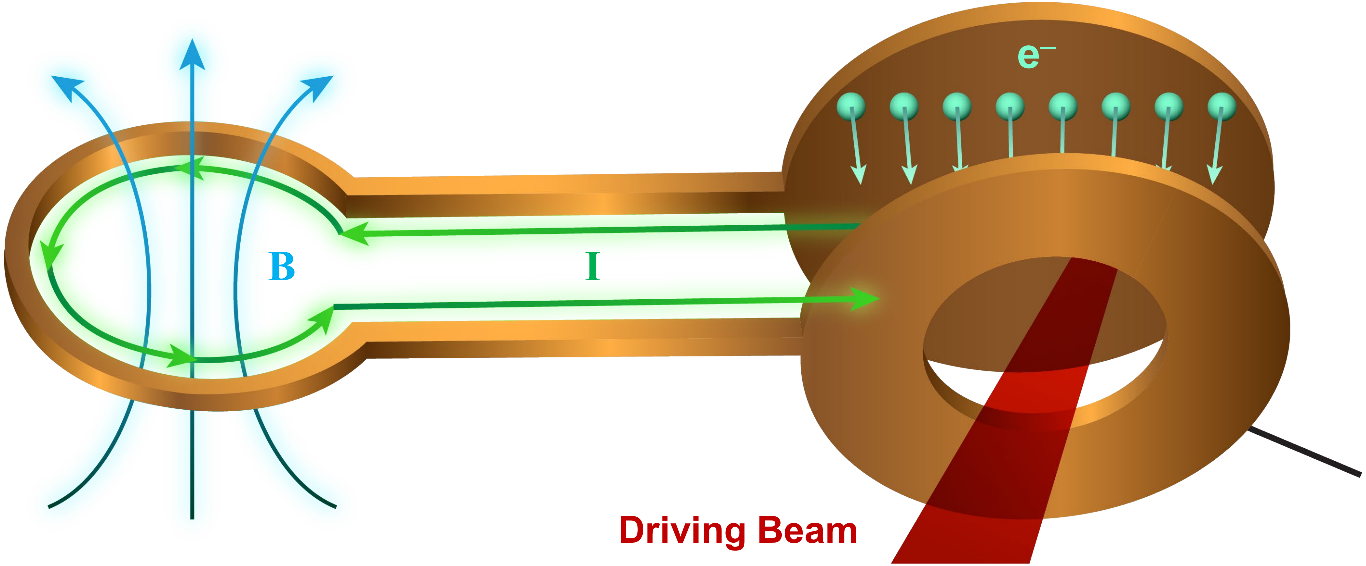


Proton radiographs taken of a target stalk at different stages of a direct drive laser implosions by M. Manuel inferred a stalk current of 7 kA with large electric field

*R. F. Benjamin et al., Phys Rev Lett **42** (1978)
M. Manuel et al., Appl. Phys. Lett. **100**, 203505 (2012)

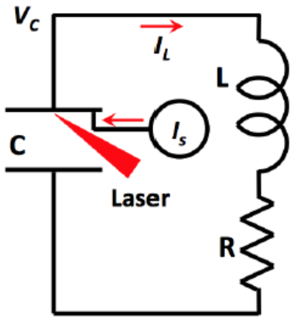
Laser driven coils are target based platforms used to generate strong magnetic fields without a pulsed power device

- Conventional laser driven coils (LDCs) use a laser to drive charge separation, which draws a current to create a field in a loop of wire*
- This solves many problems by limiting debris is generated and providing magnetic fields to facilities with no pulser



*H. Daido, *et al.*, Phys. Rev. Lett. **56** 846 (1986)

LDC experiments are often modeled after electronic circuits and are frequently referred to as “capacitor coils”



$$\frac{dI_L}{dt} = -I_L\frac{R}{L} + \frac{V_C}{L}$$

$$\frac{dV_C}{dt} = -\frac{I_L}{C} + \frac{I_S}{C}$$

C. Goyon, et al., Phys. Rev. E **95,** 033208 (2017)

thermal electrons that are escaping the potential barrier [30, 31]. A fraction of them are captured by the opposite disk. The target reacts like an RL-circuit to the potential difference between the disks and the subsequent discharge current through the coil-shaped wire. The laser-driven target charging and the discharge current process simultaneously (steady-state regime), during the laser-pulse irradiation, establishing a quasi-static

J. J. Santos et al., New J. Phys., 17 083051 (2015)

B. J. Zhu *et al.,* Appl. Phys. Lett. 107, 261903 (2015)

With the establishment of an initial potential V_0 between the two disks, the target behaves toward the potential like a resistor–inductor (RL) electrical circuit. The time evolution of the current $I(t)$ can be treated using an RL model:

$$V_0(t) = L\frac{\mathrm{d}I(t)}{\mathrm{d}t} + RI(t), \qquad (5)$$

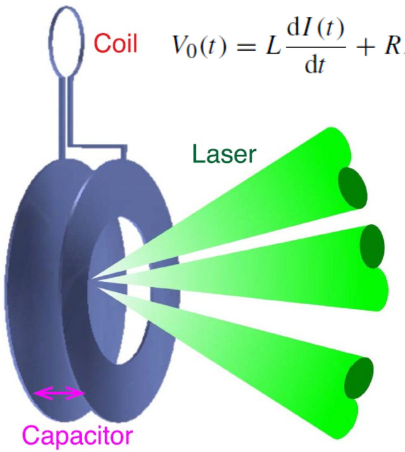


Figure 1. Basic geometry of the capacitor–coil target.

LDC experiments are often modeled after electronic circuits and are frequently referred to as "capacitor coils"

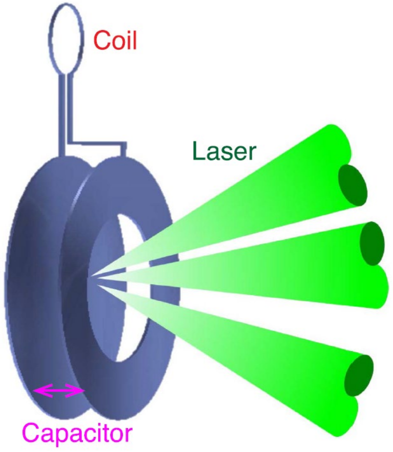


Figure 1. Basic geometry of the capacitor–coil target.

"Capacitor coils" are a misnomer

The physical dimensions of this plate have no basis on the "capacitance" of this target

$$C = \frac{\varepsilon A}{d} \approx 0.1\text{pF}$$

$$\text{Capacitor Energy} = {}^{1}\!/_{2}\, CV^2 = \mathbf{0.5\ mJ}\ \text{for } 100\ \text{kV charge}$$

The plates are considered "current sources"

Circuit theory also makes certain assumptions, such as current uniformity, truncated circuit size and Ohm's law

Outline

- Laser driven coils (LDC) overview:
- How well do LDCs work?
- Electric and magnetic field diagnostics
- Calibrating and validating diagnostics
- Overview of initial and follow up experimental results
- Discussion and conclusions

Ongoing research shows interest in laser driven coils (LDCs), in particular with coils producing kiloTesla fields

hit the front target. Strong currents are driven in the two parallel coils connected to the target due to the voltage between the two targets. A magnetic field is generated around the coils through Ampere's law. Experiments show that the magnetic field generated by this method can reach a kilotesla [14–17]. There is a spacer between the coils and the target to prevent the laser-produced high-energy plasma from affecting reconnection, the reconnection plasma is generated by irradiating another laser beam to a foam target. In this setup, the plasma beta can reach a low value (~0.1).

Kai Huang et al., Plasma Phys. Control. Fusion 63 015010 (2021)

As already stated, a strong magnetic field that can confine the relativistic electrons is required to realize this scheme experimentally. A laser-driven capacitor-coil [25], [26], [27], [28], [29], [30] can produce a 1-kT-level magnetic field. The pulse duration of this magnetic field is about 1 ns, sufficiently long relative to the time scale of proton acceleration. It was confirmed in the previous experiments that the magnetic field generated by a laser-driven magnetic field can indeed radially confine relativistic electrons within a small spot [31], [32].

H. Morita, et al., High Energy Density Physics 37 1008742 (2020)

All samples from articles released in 2020

A numerical study on the pulse duration dependence of a magnetic field generated using a laser-driven capacitor-coil target

Toru Sasaki [a], Kazumasa Takahashi [a], Takashi Kikuchi [a], Atsushi Sunahara [b], Hideo Nagatomo [c], Shinsuke Fujioka [c]

Show more

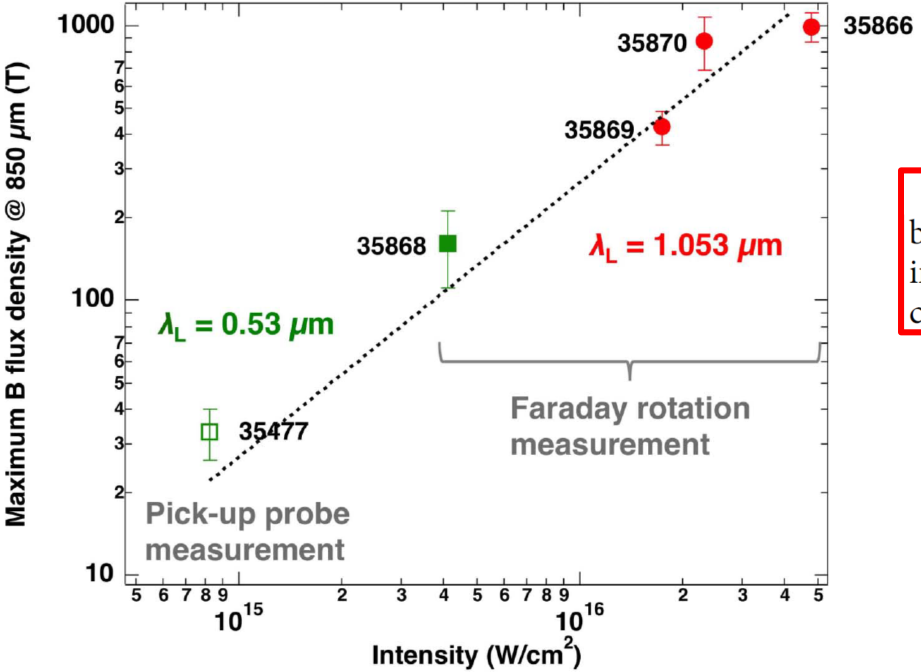
Though kT numbers are often cited, it is only one measurement in a sea of experiments that have been performed

	Driving Laser				Coil Design			Field (T)	+	[τ_p (ns)]
Ref	E (kJ)	t (ns)	λ (nm)	I (10^{15}W/cm^2)	d (mm)	Mat.	r (mm)	PRad	B-Dot	Faraday Rot
Daido (1986)	0.1	1.0	10000	0.13	0.3, 0.5	Cu	1.0	–	15, 28	–
Daido (1986)	0.1	1.0	10000	0.13	0.7, 1.0	Cu	1.0	–	41, 16	–
Santos(2015)	0.5	1.0	1057	100	0.9	Cu, Ni, Al	0.25	–, 95 [0.35], –	800, 600, 150	–, 450 [0.2], –
Fujioka (2013) 2 @ (0.095, 0.27)		1.3	526	4, 0.8	0.78	Ni	0.25	–,–	–,33	160, –
Fujioka (2013) 2 @ (0.37, 0.5)		1.3	1053	16, 43	0.78	Ni	0.25	–	–	480, 1100
Law (2016)	0.54	2.0	1053	21	0.5	Unknown	0.25	610 [2.3]	620 [2.0]	–
Courtois (2005)	0.3	1.0	1053	40	0.5	Cu	1.25	–	7.5	–
Courtois (2005)	0.022	0.08	526	40	0.5	Cu	1.25	–	7.5	–
Tarifeño (2008)	0.0005	7.0	1064	0.0007	1.3	Cu	1.0	–	0.001	–
Gao (2016)	2 @ 1.25	1.0	351	30	0.6	Cu	0.3	45 [4.1]	–	–
Goyon (2017)	2 @ 0.375	0.75	351	4	0.5	Au + CH	0.25	200 [1.0]	–	–
Wang (2018)	0.01	3×10^{-5}	800	1000	0.5	Ni	0.5	20 [0.05]	–	–
Zhu (2015)	0.18	2.0	527	0.14	Inf	Cu	0.55	50 [unk.]	–	–
Zhu (2015)	8 @ (0.063, 0.125)	2.0	351	1.4, 2.8	Inf	Cu	0.55	–	45, 73	–
Zhu (2015)	8 @ (0.222, 0.246)	2.0	351	5.0, 7.7	Inf	Cu	0.55	–	102, 205	–
Matsuo (2017)	1.3	1.2	351	1.5	0.5	Ni	0.45	–	219	206
Korobkin (1979)	0.001	20	1053	–	0.1	Cu	0.7	–	2	–
Ivanov (2020)	0.022	2.8	532	8	0.5	Cu	0.5	–	–	6.4
Ivanov (2020)	0.022	0.07	532	25	0.5	Cu	0.5	–	–	12.4

Though kT numbers are often cited, it is only one measurement in a sea of experiments that have been performed

	Driving Laser				Coil Design			Field (T)	+	[τ_p (ns)]
Ref	E (kJ)	t (ns)	λ (nm)	I (10^{15}W/cm^2)	d (mm)	Mat.	r (mm)	PRad	B-Dot	Faraday Rot
Daido (1986)	0.1	1.0	10000	0.13	0.3, 0.5	Cu	1.0	–	15, 28	–
Daido (1986)	0.1	1.0	10000	0.13	0.7, 1.0	Cu	1.0	–	41, 16	–
Santos(2015)	0.5	1.0	1057	100	0.9	Cu, Ni, Al	0.25	–, 95 [0.35], –	800, 600, 150	–, 450 [0.2], –
Fujioka (2013)	2 @ (0.095, 0.27)	1.3	526	4, 0.8	0.78	Ni	0.25	–,–	–,33	160, –
Fujioka (2013)	2 @ (0.37, 0.5)	1.3	1053	16, 43	0.78	Ni	0.25			480, 1100
Law (2016)	0.54	2.0	1053	21	0.5	Unknown	0.25	610 [2.3]	620 [2.0]	–
Courtois (2005)	0.3	1.0	1053	40	0.5	Cu	1.25	–	7.5	–
Courtois (2005)	0.022	0.08	526	40	0.5	Cu	1.25	–	7.5	–
Tarifeño (2008)	0.0005	7.0	1064	0.0007	1.3	Cu	1.0	–	0.001	–
Gao (2016)	2 @ 1.25	1.0	351	30	0.6	Cu	0.3	45 [4.1]	–	–
Goyon (2017)	2 @ 0.375	0.75	351	4	0.5	Au + CH	0.25	200 [1.0]	–	–
Wang (2018)	0.01	3×10^{-5}	800	1000	0.5	Ni	0.5	20 [0.05]	–	–
Zhu (2015)	0.18	2.0	527	0.14	Inf	Cu	0.55	50 [unk.]	–	–
Zhu (2015)	8 @ (0.063, 0.125)	2.0	351	1.4, 2.8	Inf	Cu	0.55	–	45, 73	–
Zhu (2015)	8 @ (0.222, 0.246)	2.0	351	5.0, 7.7	Inf	Cu	0.55	–	102, 205	–
Matsuo (2017)	1.3	1.2	351	1.5	0.5	Ni	0.45	–	219	206
Korobkin (1979)	0.001	20	1053	–	0.1	Cu	0.7	–	2	–
Ivanov (2020)	0.022	2.8	532	8	0.5	Cu	0.5	–	–	6.4
Ivanov (2020)	0.022	0.07	532	25	0.5	Cu	0.5	–	–	12.4

The authors of the > 1 kT result declare it breaks energy conservation throwing suspicion on the Faraday results

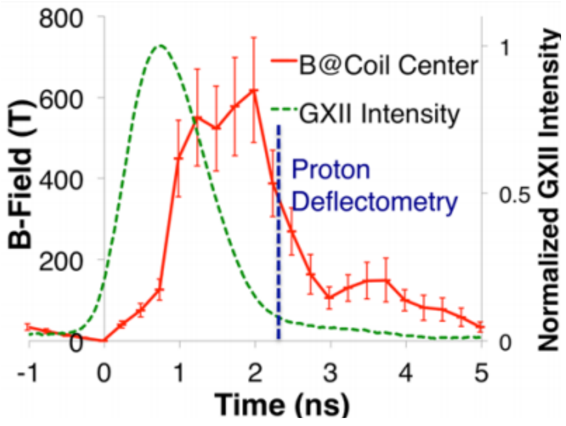


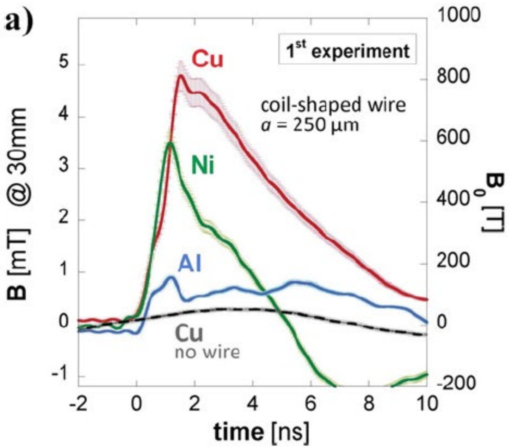
The field energy was obtained by integrating magnetic field energy (B^2/μ_0) at the field peak timing in the calculation space ($2 \times 4 \times 5$ mm^3). The total energy is inconceivable, because 15 kJ is much larger than the laser energy (1 kJ).

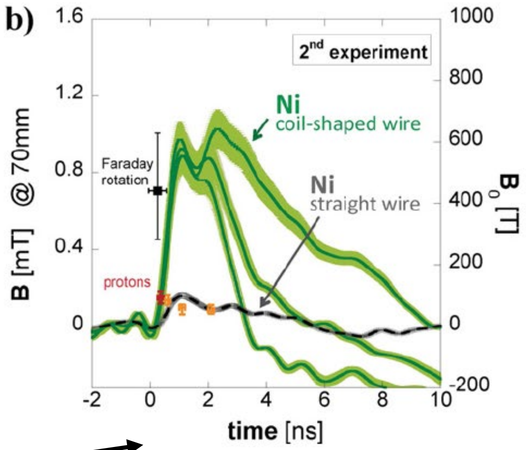
S. Fujioka *et al.*, Scientific Reports, 3:1170 (2013)

<u>We should not use 1 kT as a reasonable achievable field, differences of 100s of Tesla are not insignificant in terms of field energy!</u>

1 kT is not feasible, what about the 600+ T measurements from other experiments?







Experiments by Law et al. and Santos et al. measured fields of > 600 T

For reference, MIFEDS (480 J stored energy) currently reaches 100 T, with coils made as small as possible (~2 mm^3 magnetized volume)

K. F. F. Law *et al.*, Appl Phys Lett., **108** 091104 (2016)
J. J. Santos *et al.*, New J. Phys., **17** 083051 (2015)

Field energy density provides some insight into whether quoted field values and applications are reasonable

- Energy in the field is absolutely limited by the energy in the driving laser

$$Field\ Energy\ Density = \frac{|B|^2}{2\mu_0} + \frac{|E|^2}{2\varepsilon_0}$$

$$Energy\ in\ B = \frac{1}{2\mu_0}\int \boldsymbol{B}^2 dV = \frac{LI^2}{2}$$

- Lasers deliver comparable energy as pulsed power capacitors (~< 1 kJ)
- To be competitive with pulsed power, LDCs have one advantage for generating higher peak fields

Field energy density provides some insight into whether quoted field values and applications are reasonable

- Energy in the field is absolutely limited by the energy in the driving laser

$$Field\ Energy\ Density = \frac{|B|^2}{2\mu_0} + \frac{|E|^2}{2\varepsilon_0}$$

$$Energy\ in\ B = \frac{1}{2\mu_0}\int \boldsymbol{B}^2 dV = \frac{LI^2}{2}$$

This relationship can also help validate calculations of L

- Lasers deliver comparable energy as pulsed power capacitors (~< 1 kJ)
- To be competitive with pulsed power, LDCs have one advantage for generating higher peak fields
- Magnetized volume can be made much smaller in LDCs

Field energy density provides some insight into whether quoted field values and applications are reasonable

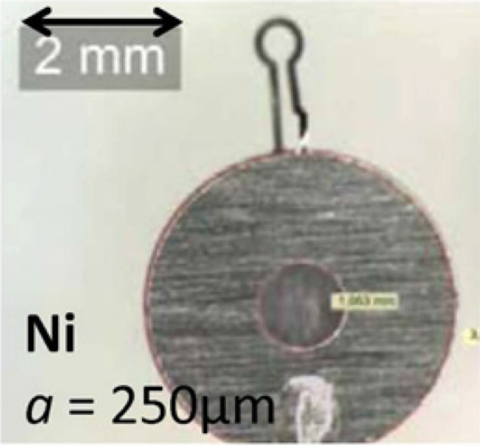
- MIFEDS for example can typically have a efficiency of 60% (peak field energy/stored energy), due mainly to not being critically damped
- Finding the peak conversion efficiency of a laser driven coil is not so simple:
  - Fraction of laser energy converted to hot electrons **(~ 30%)**
  - Fraction of electrons that escape the plate
  - Fraction of electrons that escape backwards towards the undriven plate*
  - Fraction of electrons are absorbed by the undriven plate*
- With less energy available, **magnetizing large volumes (such as implosions) is not an option**

For this reason nearly all laser driven coil experiments have coils with a diameter < 1 mm

Energy estimates indicate that some scrutiny should be applied to 600+ T results

I = 290 kA for 610 T in loop as described
Magnetic Field Energy > 200 J
Laser Energy < 540 J
Conversion laser to field > 37%

K. F. F. Law *et al.*, Appl Phys Lett., **108** 091104 (2016)

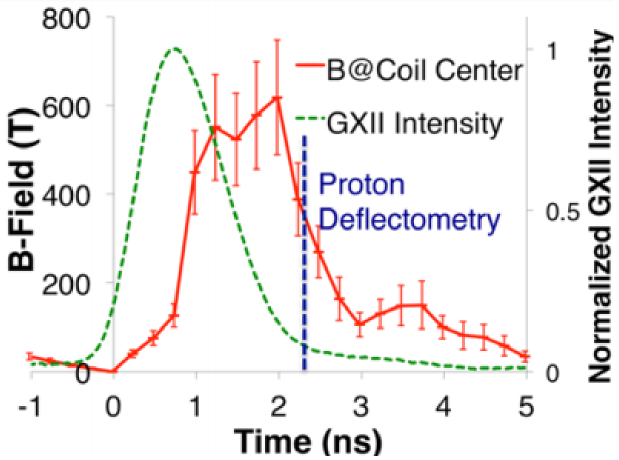


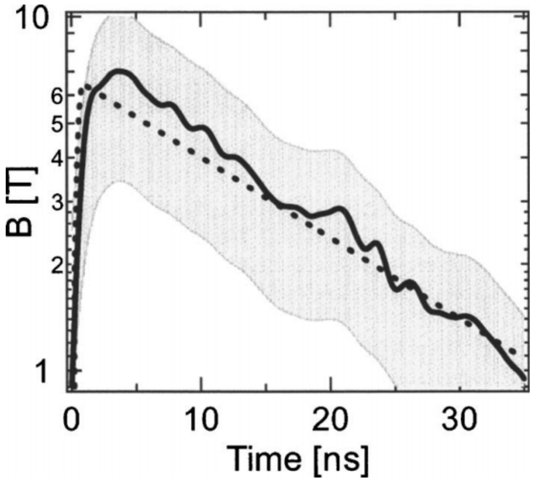
I = 375 kA for 800 T in loop as described
Magnetic Field Energy > 250 J
Laser Energy < 500 J
Conversion laser to field > 50%

J. J. Santos *et al.*, New J. Phys., **17** 083051 (2015)

The range of results have large differences between similar experiments

- Experiments by Law et al.[1] and Courtois et al.[2], give very different results using similar diagnostics and driving laser parameters (same Iλ^2)



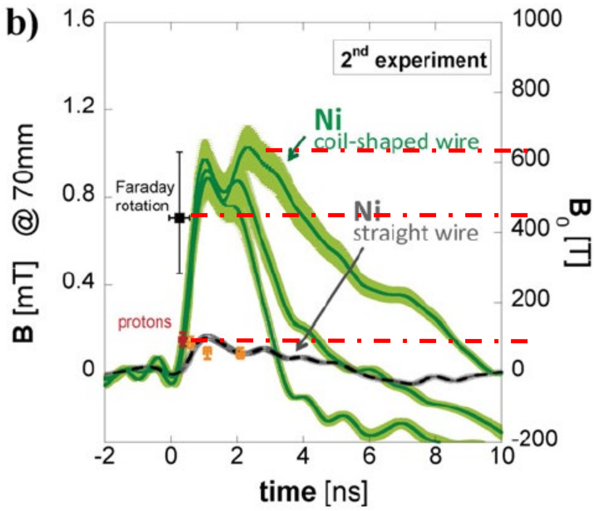


Courtois' loop was 5 times larger, but this does not account for nearly 100 times less field

[1]K. F. F. Law, *et al.*, Appl. Phys. Lett. **108**, 091104 (2016)
[2]C. Courtois, *et al.*, J. of Appl. Phys **98**, 054913 (2005)

The range of results, even within a single experiment, indicate that they can't all be true

- Santos et al.[3] measured fields of 95, 450, 600 T for the same type of coil using radiography, Faraday rotation and b-dot probes respectively



A more thorough investigation and comparison of diagnostic techniques is required

[3] J. J. Santos, *et al.*, New. J. Phys **17,** 083051 (2015)

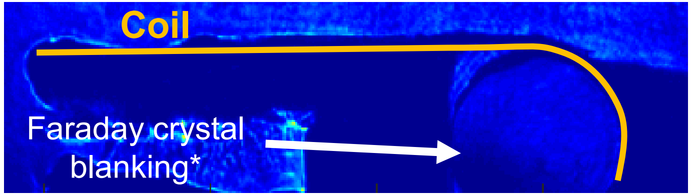
Outline

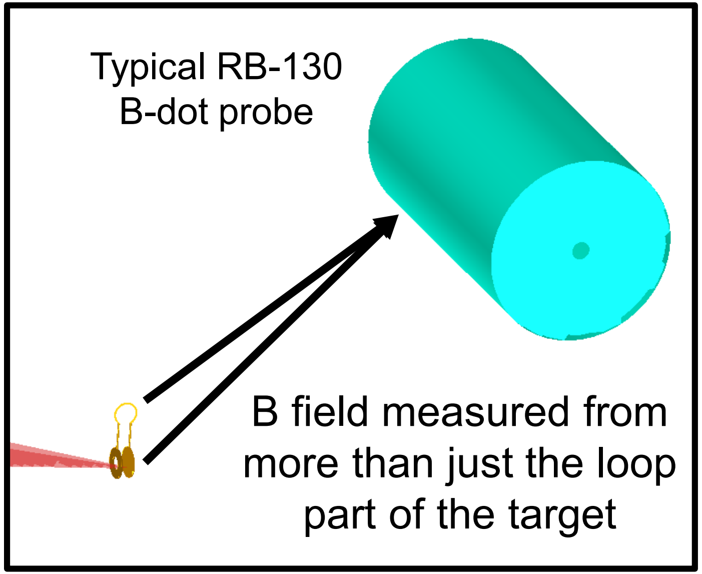
- Laser driven coils (LDC) overview:
- How well do LDCs work?
- Electric and magnetic field diagnostics
    - B-dot probes and Faraday rotation
    - Transverse proton radiography
    - Axial proton radiography
- Calibrating and validating diagnostics
- Overview of initial and follow up experimental results
- Discussion and conclusions

Certain diagnostics have difficulty in providing precise measurements of magnetic fields in the region of interest

- Probe diagnostics such as Faraday rotation and B-dot probes require material to be placed in the vicinity of the coil

- These diagnostics often fail due to blanking and EMI so peak fields can rarely be measured
- These tools also inadvertently measure fields from the laser interacting with the disk and other sources

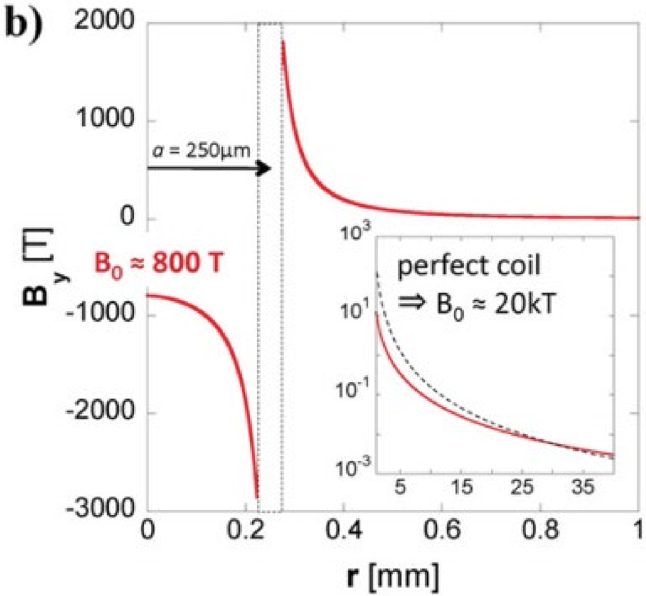




*Data from J. Moody and B. Pollock campaign on EP

Certain diagnostics have difficulty in providing precise measurements of magnetic fields in the region of interest

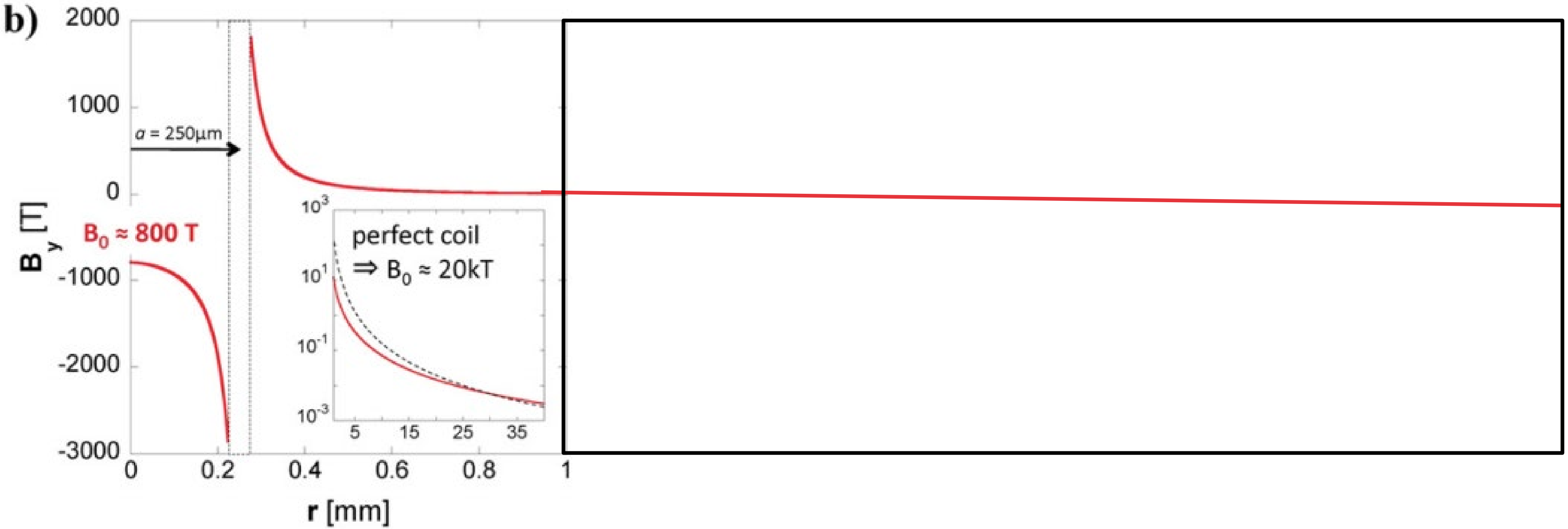
- Placing the diagnostic far from the coil requires a significant degree of extrapolation and assumption on field geometry (5 orders of magnitude)



J. J. Santos *et al.*, New J. Phys., **17** 083051 (2015)

Certain diagnostics have difficulty in providing precise measurements of magnetic fields in the region of interest

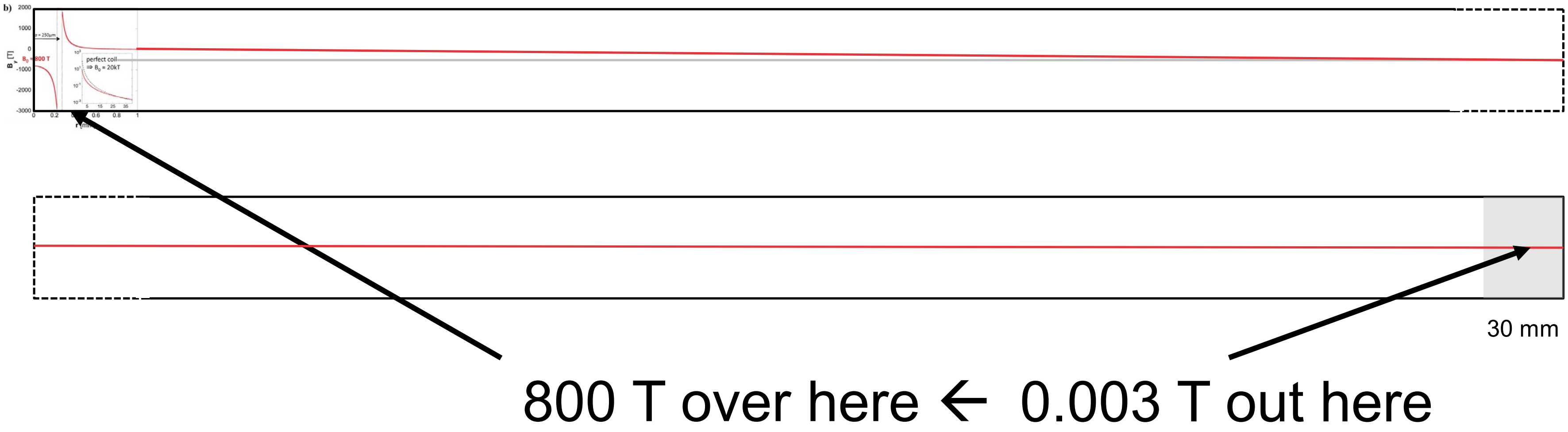
- Placing the diagnostic far from the coil requires a significant degree of extrapolation and assumption on field geometry (5 orders of magnitude)



J. J. Santos *et al.*, New J. Phys., **17** 083051 (2015)

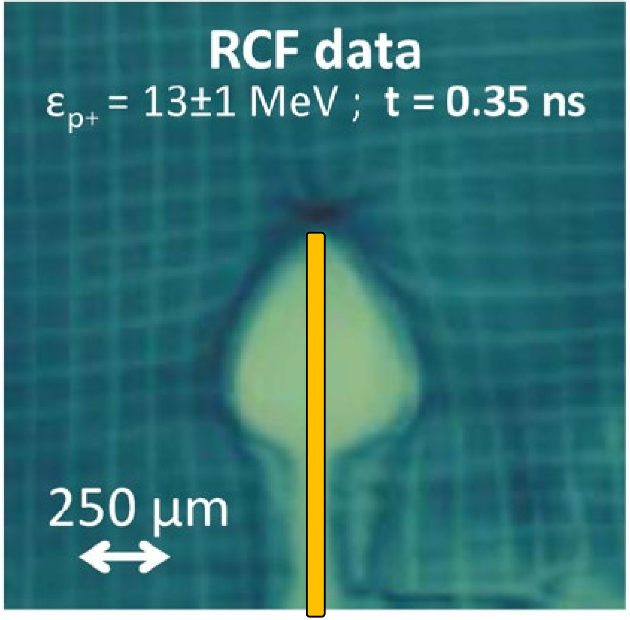
Certain diagnostics have difficulty in providing precise measurements of magnetic fields in the region of interest

- Placing the diagnostic far from the coil requires a significant degree of extrapolation and assumption on field geometry (5 orders of magnitude)
- It also assumes current is perfectly uniform along the wire and no other sources of voltage



Transverse proton radiography fails to probe the region of interest due to the strength of magnetic and electric fields

- Protons traveling transverse to the coil should be deflected by the axial field and create a void
- There is ambiguity in what field causes the creation of a proton void, electric and magnetic fields can both duplicate features seen
- The void actually significantly decreases the information gained about conditions in the center of the loop

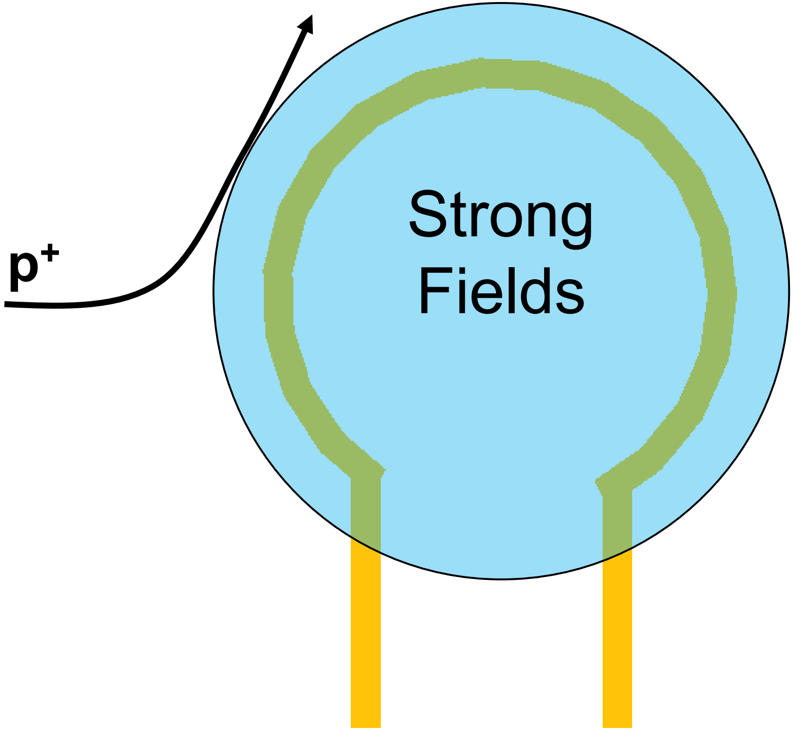


*Santos *et al* NJP 17, 083051 (2015)

Transverse proton radiography fails to probe the region of interest due to the strength of magnetic and electric fields

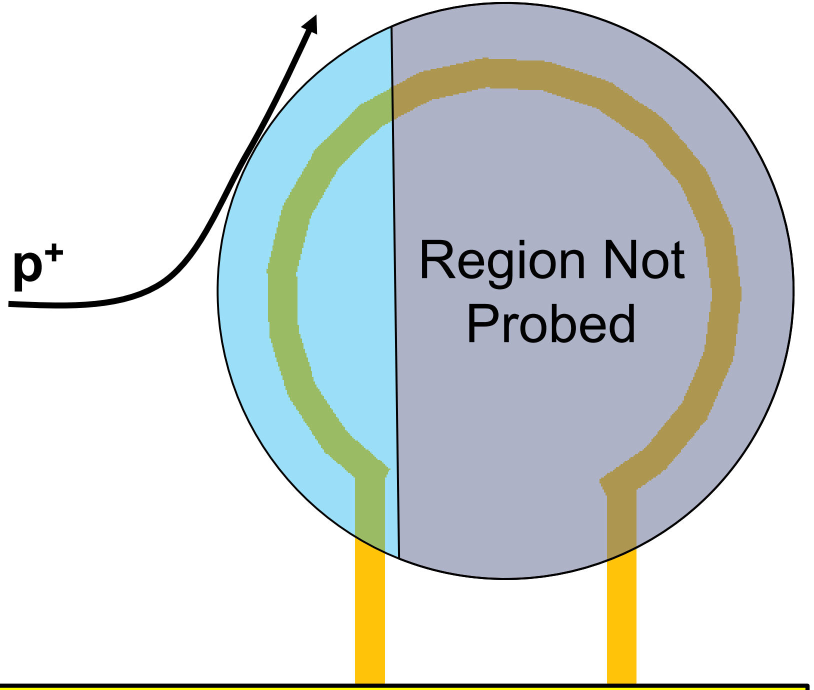
- Protons traveling transverse to the coil should be deflected by the axial field and create a void

- There is ambiguity in what field causes the creation of a proton void, electric and magnetic fields can both duplicate features seen
- The void actually significantly decreases the information gained about conditions in the center of the loop



Transverse proton radiography fails to probe the region of interest due to the strength of magnetic and electric fields

- Protons traveling transverse to the coil should be deflected by the axial field and create a void
- There is ambiguity in what field causes the creation of a proton void, electric and magnetic fields can both duplicate features seen
- The void actually significantly decreases the information gained about conditions in the center of the loop

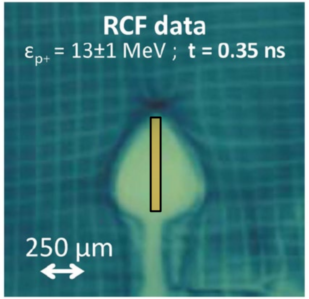


Another way to view it is the transverse probe is too sensitive for 100s of Tesla

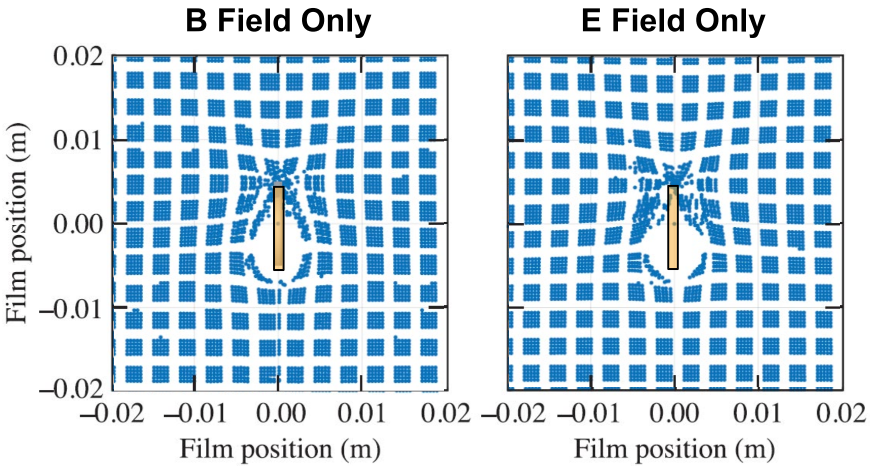
Transverse proton radiography fails to probe the region of interest due to the strength of magnetic and electric fields

- Protons traveling transverse to the coil should be deflected by the axial field and create a void

- There is ambiguity in what field causes the creation of a proton void, electric and magnetic fields can both duplicate features seen
- The void actually significantly decreases the information gained about conditions in the center of the loop

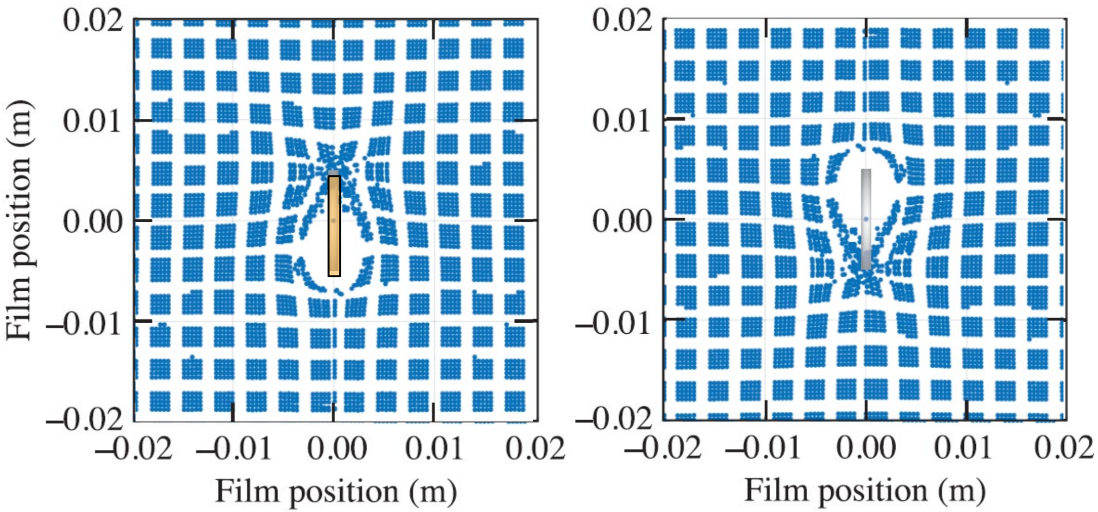


*Santos *et al* NJP 17, 083051 (2015)



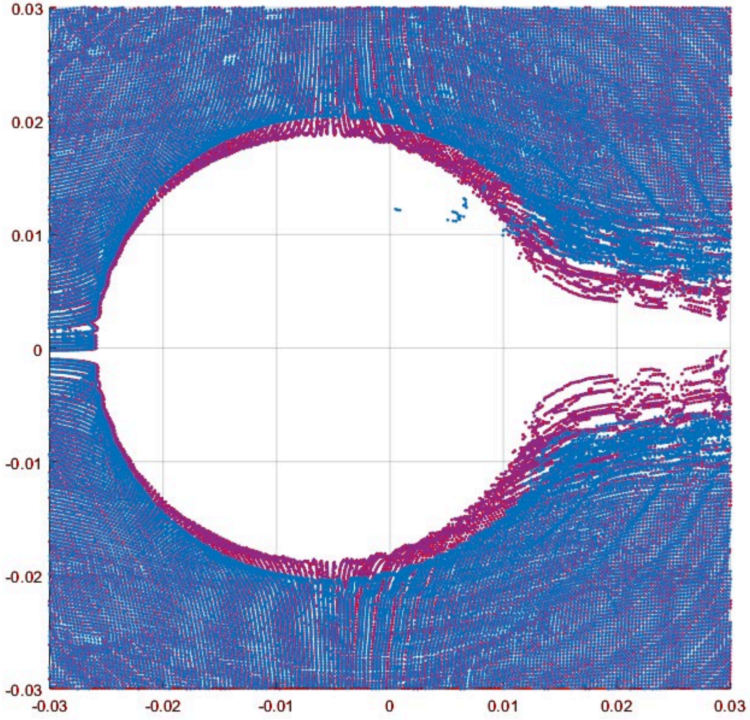
An obvious experiment would be to reverse the current on the coil

- The transverse probe deflection is asymmetric, if the current is reversed by switching a wire the pattern should flip!
- This would demonstrate how much deflection is from the B field vs E field
- Nothing has been <u>published</u> attempting this simple experiment



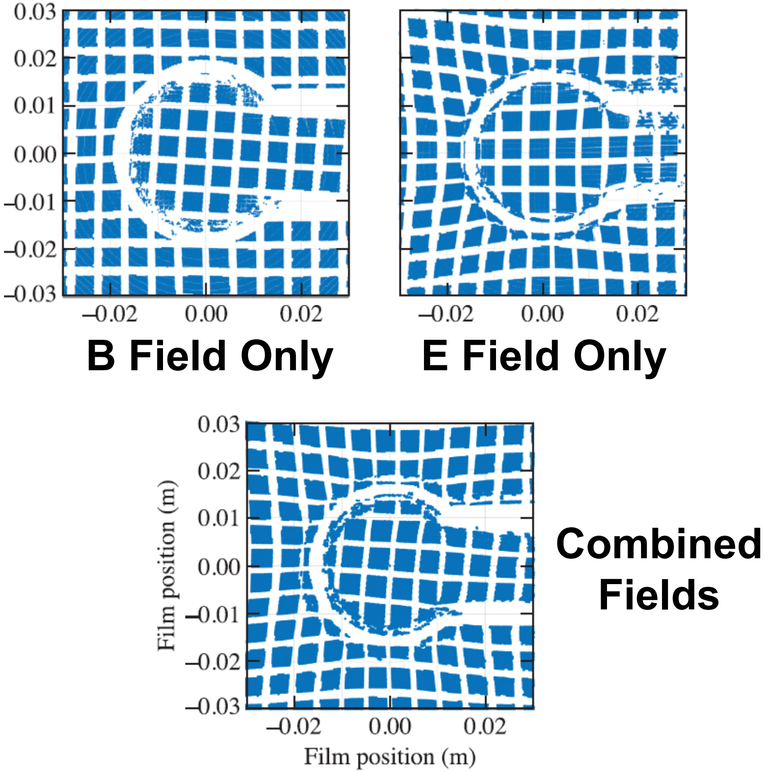
Magnetic fields typically require much more field energy to create proton voids than electric fields

- Some experiments, especially with high intensity lasers, produce very large voids
- Simulating a void around a coil with electric fields (blue) required 25 J of energy, with magnetic fields (magenta) 183 J, 7 times the energy!
- Attributing all the deflection to magnetic fields often produces an unreasonable energy conversion



Axial proton radiography can address all of the concerns for transverse radiography for laser driven coils

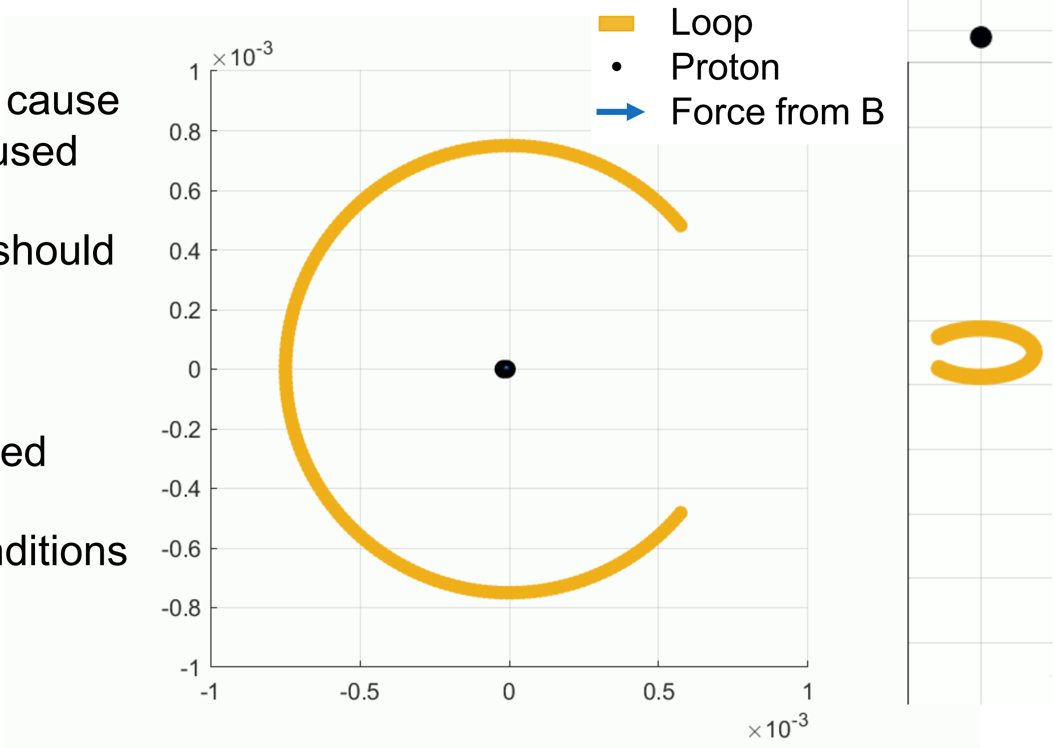
- Electric fields along the coil will cause protons to be focused or defocused
- Weaker, radial magnetic fields should cause a rotation in the mesh
- Even when the two effects are combined, they can be decoupled
- Information is gained about conditions inside the center of the coil



*J. Peebles et al., PoP 27, 063109 (2020)

Axial proton radiography can address all of the concerns for transverse radiography for laser driven coils

- Electric fields along the coil will cause protons to be focused or defocused
- Weaker, radial magnetic fields should cause a rotation in the mesh
- Even when the two effects are combined, they can be decoupled
- Information is gained about conditions inside the center of the coil

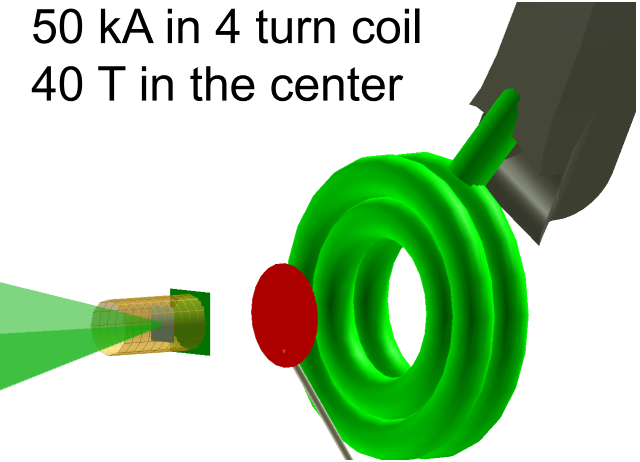


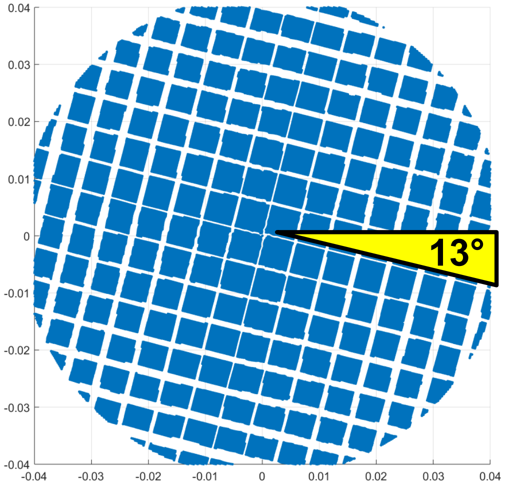
Outline

- Laser driven coils (LDC) overview:
- How well do LDCs work?
- Electric and magnetic field diagnostics
- **Calibrating and validating diagnostics**
- Overview of initial and follow up experimental results
- Discussion and conclusions

Axial probing of a MIFEDS coil confirms functionality and provides information on the proton energy spectrum

50 kA in 4 turn coil
40 T in the center



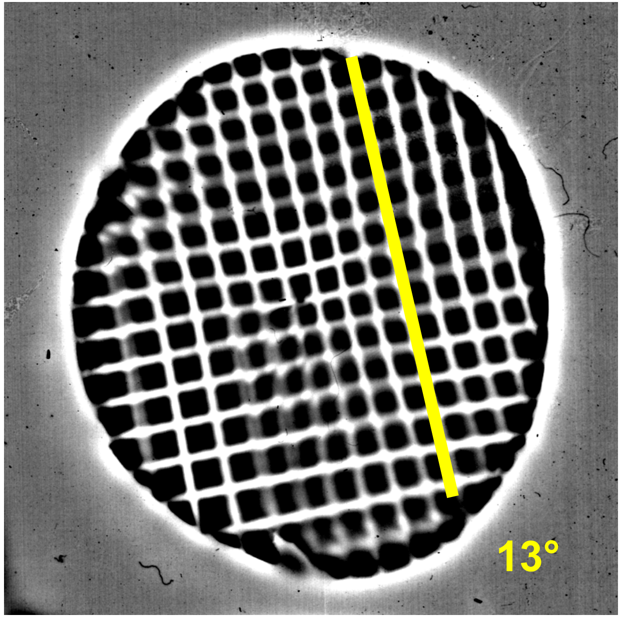


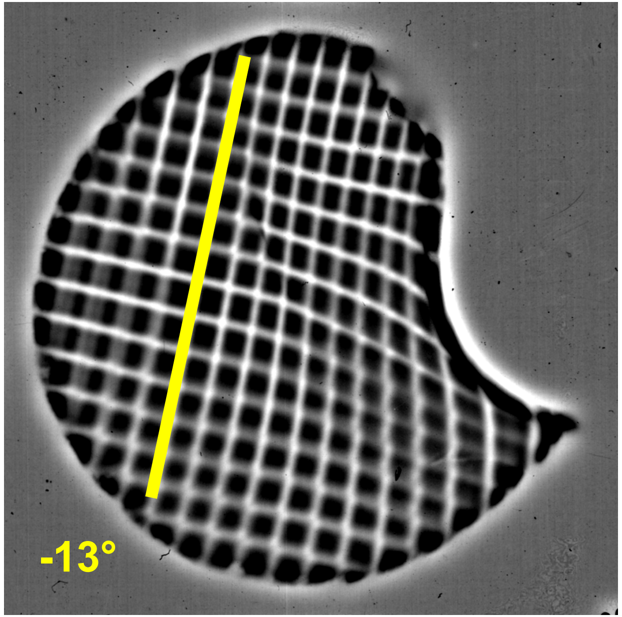
9 MeV Protons

Layer	Energy (MeV)	Angle
1	5	18.0
2	7	15.0
3	9	13.0
4	10.5	12.0
5	14.5	10.5
6	20	8.0

Angle of rotation was calculated for the expected coil and current for each proton energy
Reversing current with MIFEDS is trivial

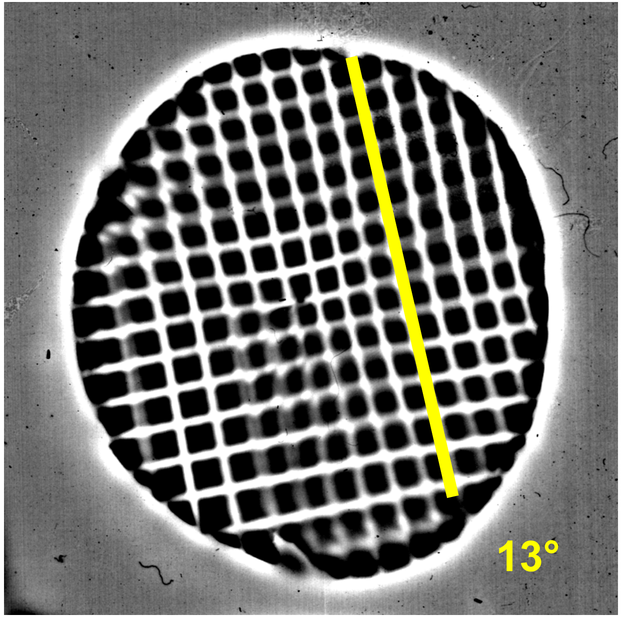
Radiographs of coil and inverted current measure anticipated rotation

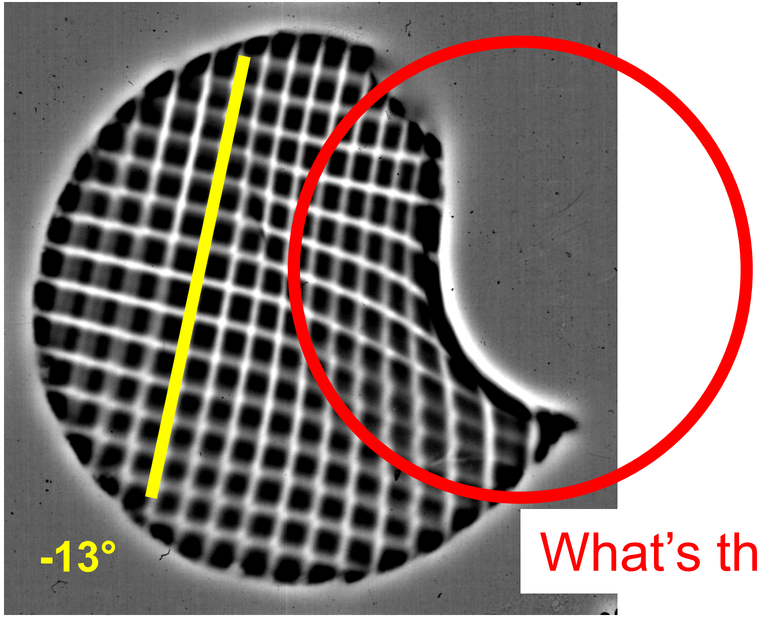




Overall mesh rotation is the same for the same proton energies, simply inverted

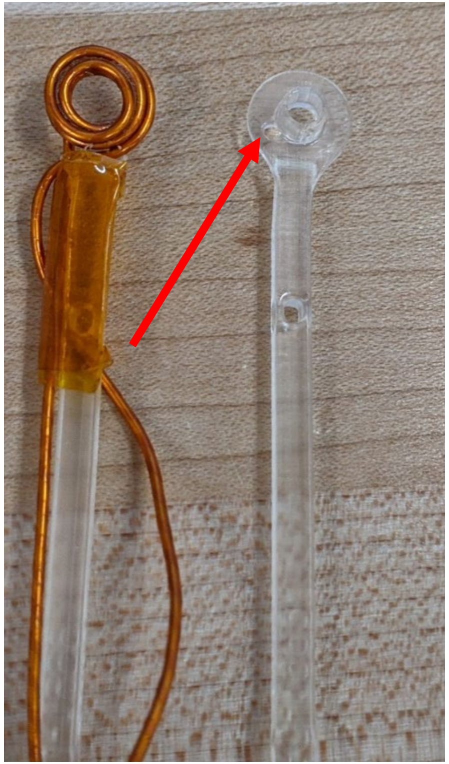
Radiographs of coil and inverted current measure anticipated rotation

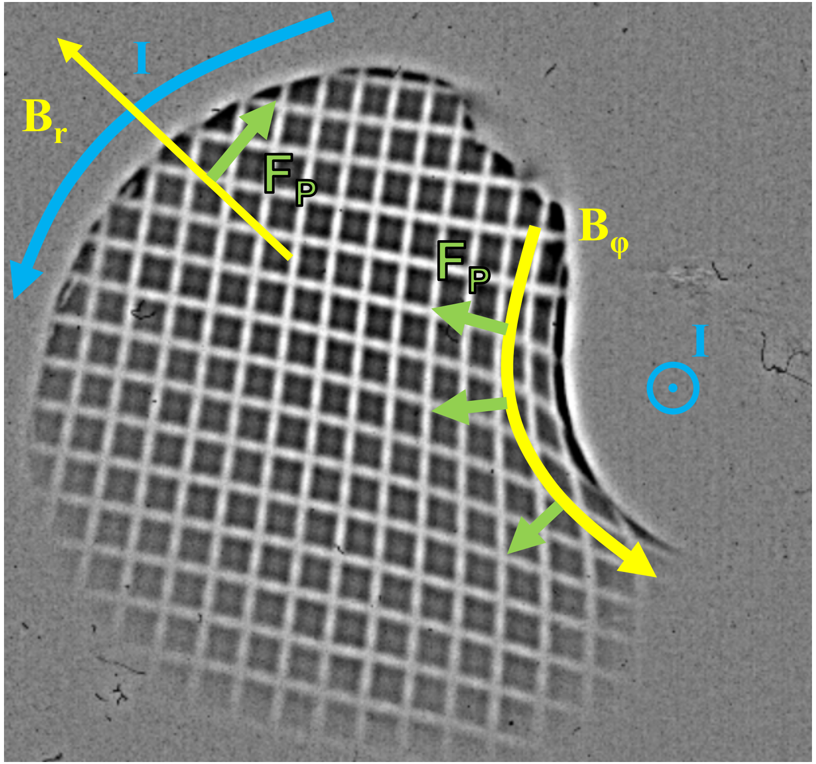




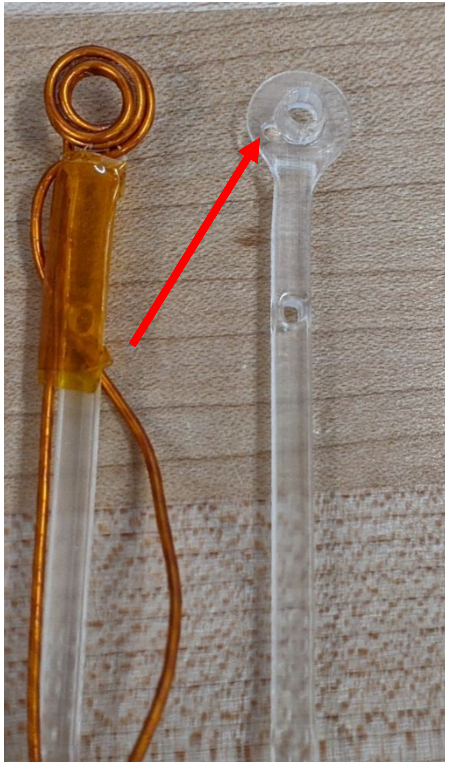
Overall mesh rotation is the same for the same proton energies, simply inverted

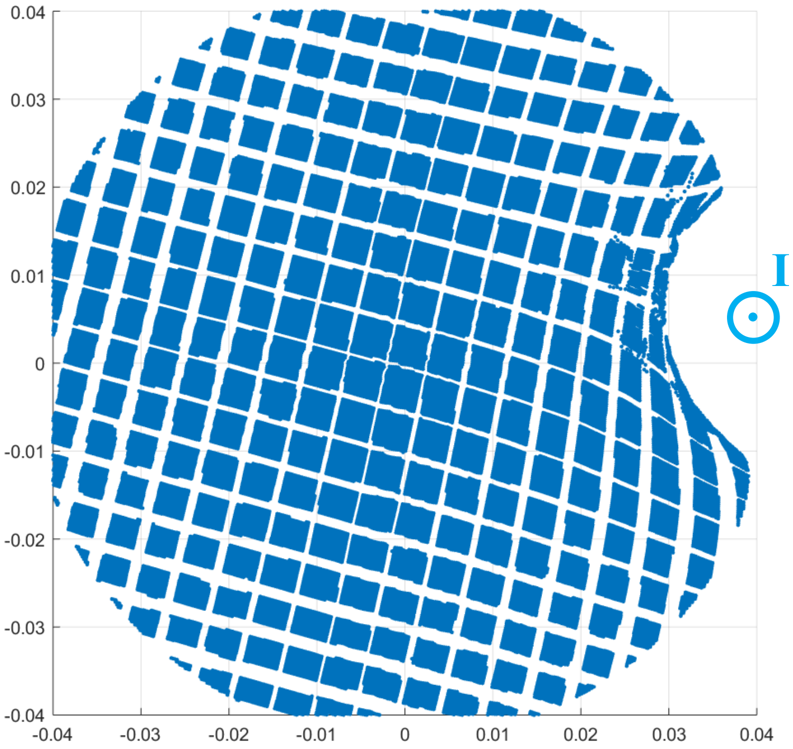
Bulging feature is a consequence of coils not being perfect (requiring an ingress and egress)



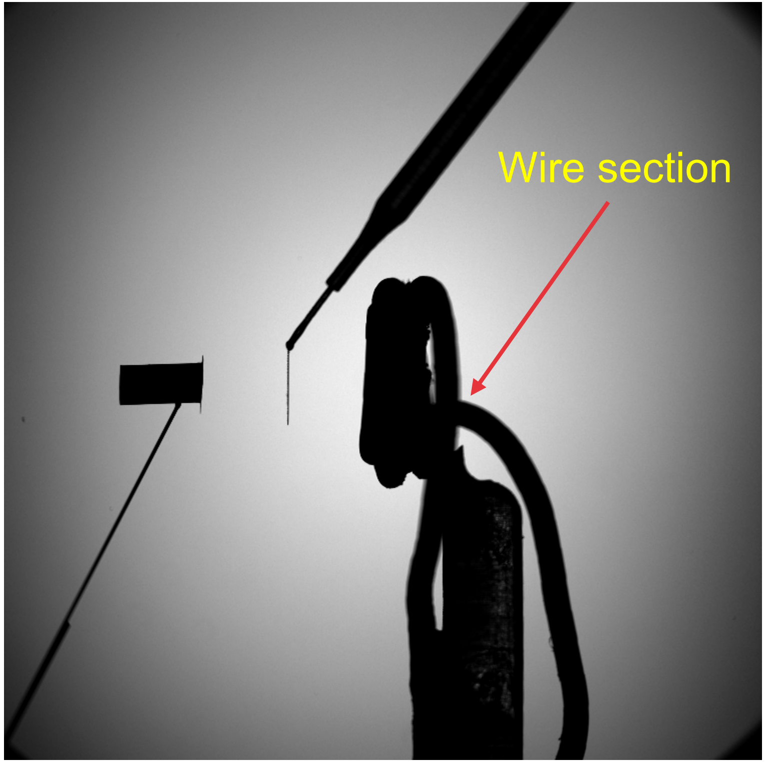


Bulging feature is a consequence of coils not being perfect (requiring an ingress and egress)

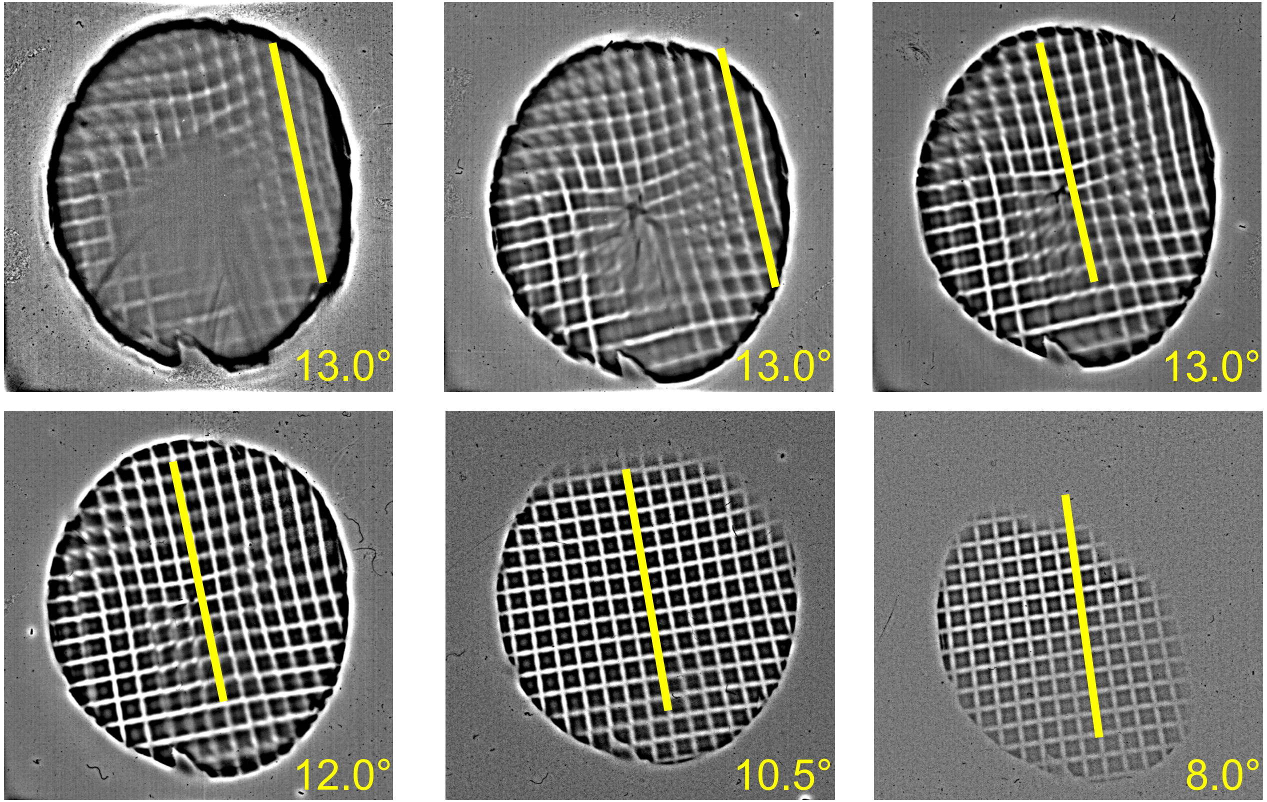




Bulging feature is a consequence of coils not being perfect (requiring an ingress and egress)



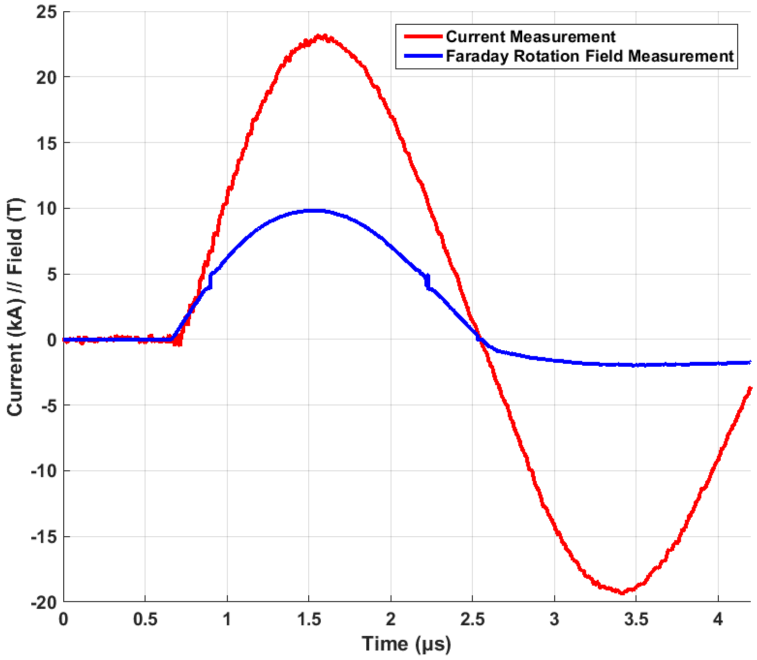
We can compare rotation changes based on proton energy to simulations



Energy (MeV)	Angle
5	**18.0 X**
7	**15.0 X**
9	**13.0 ✓**
10.5	**12.0 ✓**
14.5	**10.5 ✓**
20	**8.0 ✓**

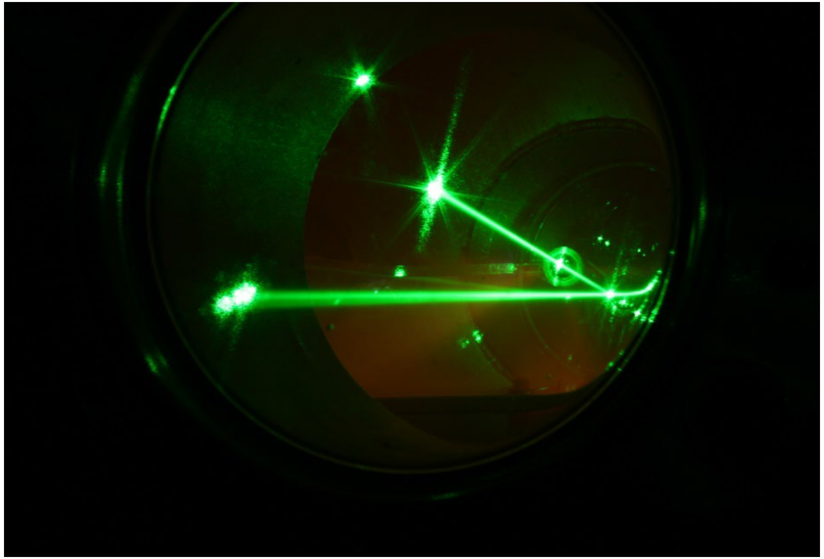
Axial radiography is accurate enough to tell us that the first 2 films are dominated by shadowing from the 3rd

Faraday rotation has been tested in the lab as a technique to verify fields from MIFEDS

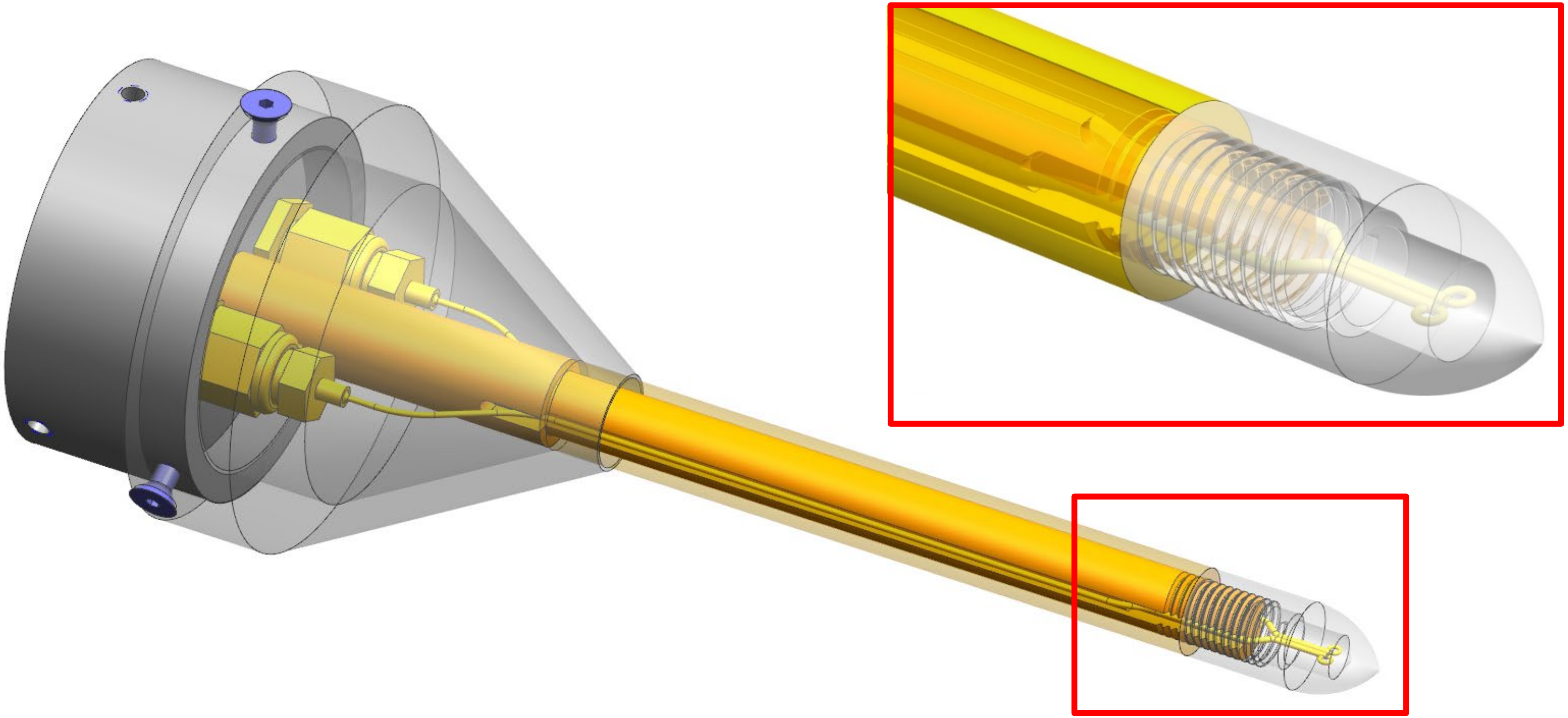


Coil designed for 9 T in the center

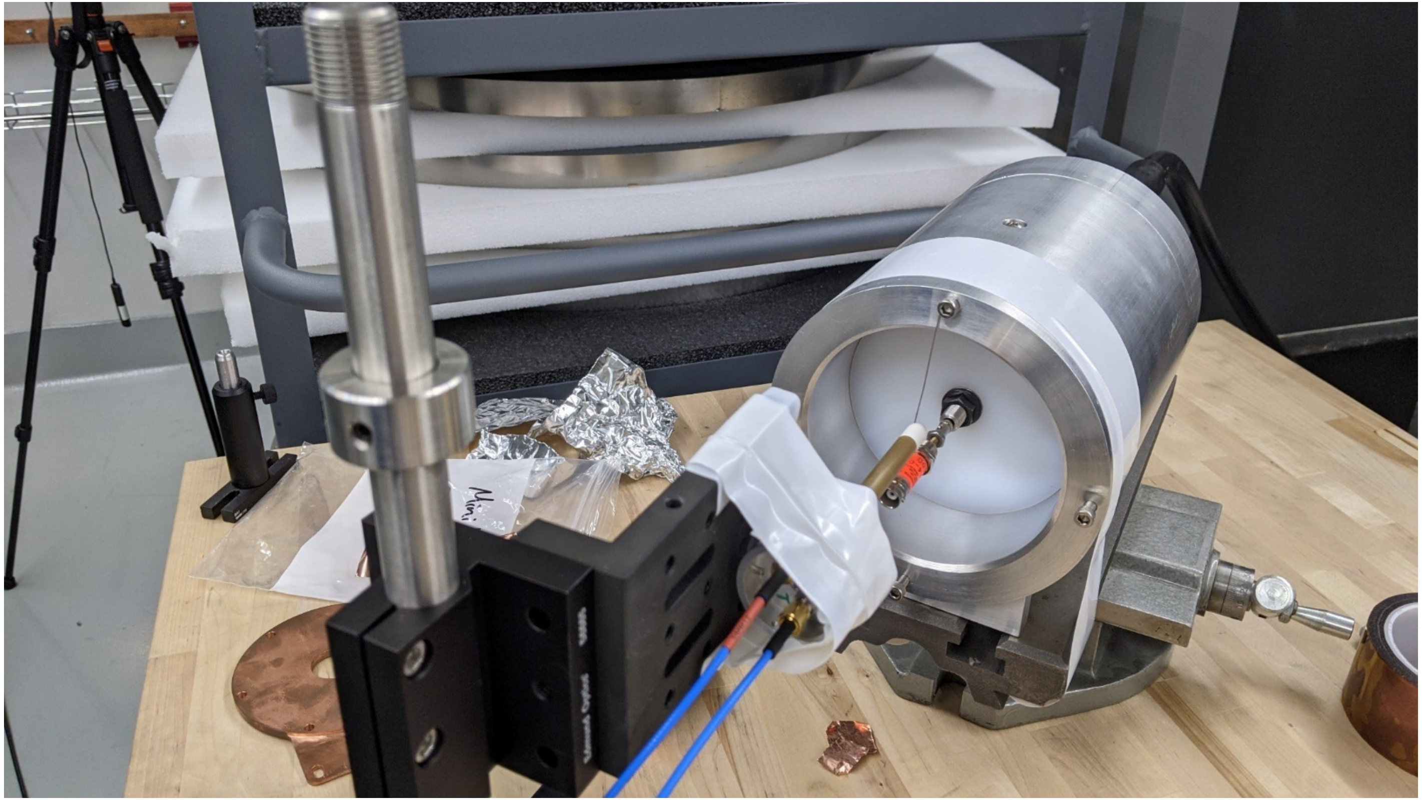
Original TGG crystal performed well but blanks quickly in a laser environment



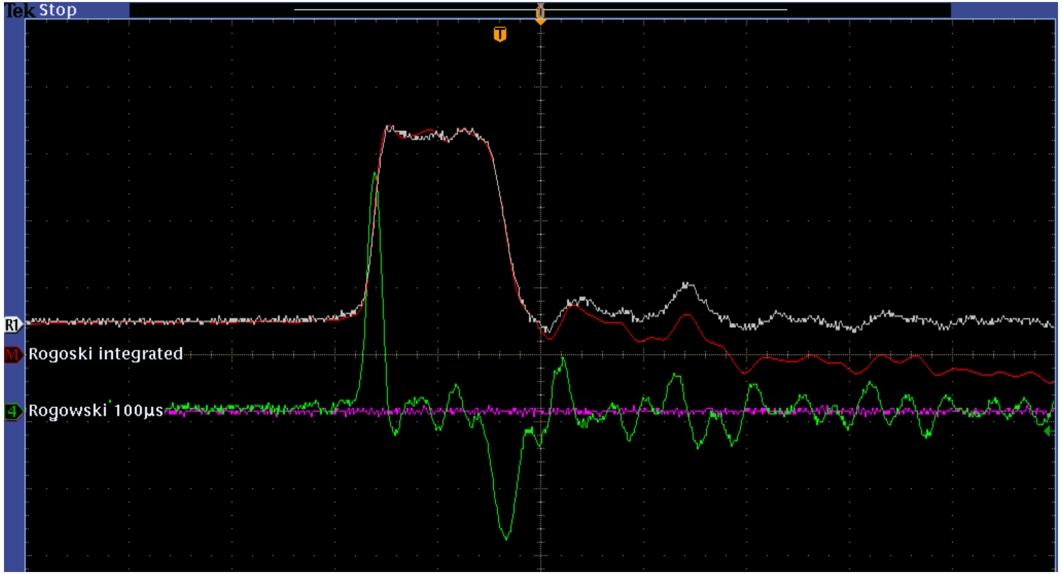
A custom B-dot probe was designed, constructed and calibrated for multiple shots on OMEGA-EP



A custom B-dot probe was designed, constructed and calibrated for multiple shots on OMEGA-EP



A custom B-dot probe was designed, constructed and calibrated for multiple shots on OMEGA-EP



1 kA pulser through a straight wire with 20 ns flat top, 3 ns rise time

White: CVR (direct current measurement)

Red: Scope integrated B-dot

Green: Raw B-dot data

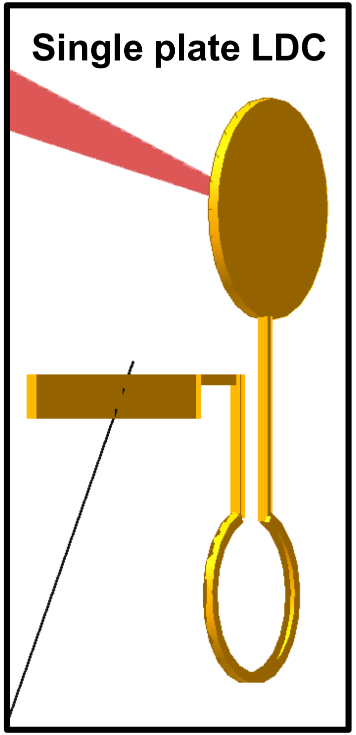
The B-dot is looking at an assumed time derivative of B field

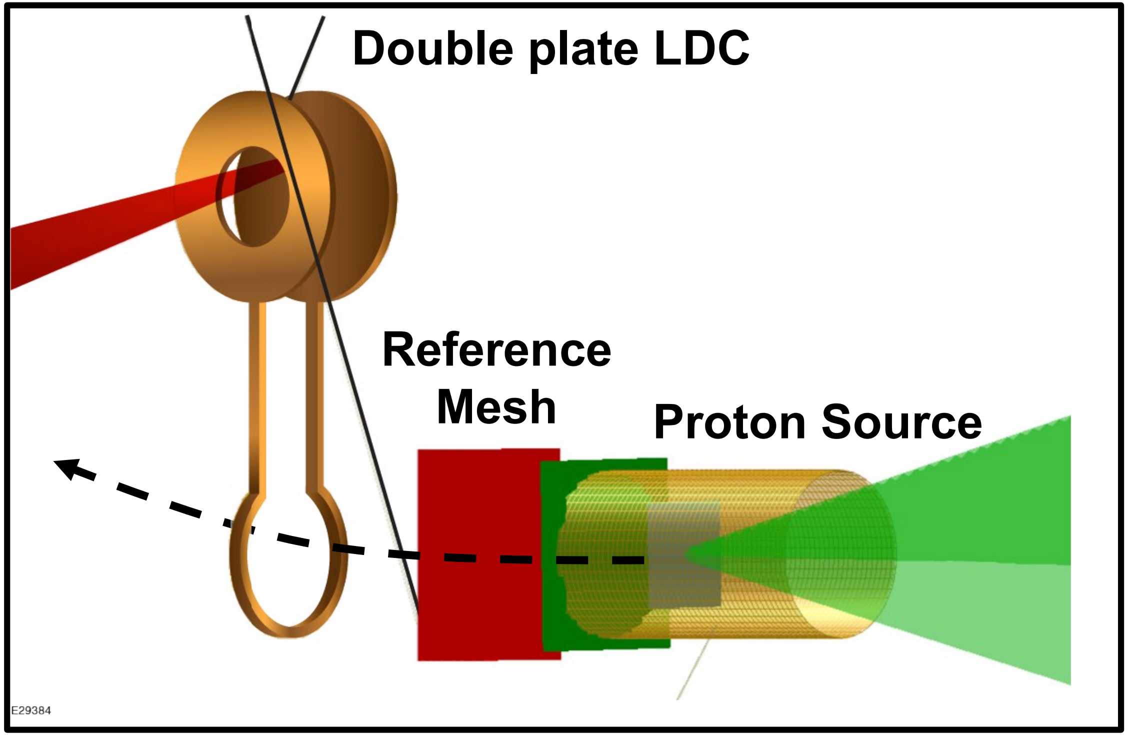
An E field imparting a signal is not the derivative w.r.t. time (not an E-dot probe!). Time integrating the signal and attributing it to changing B field would lead to significant error

Outline

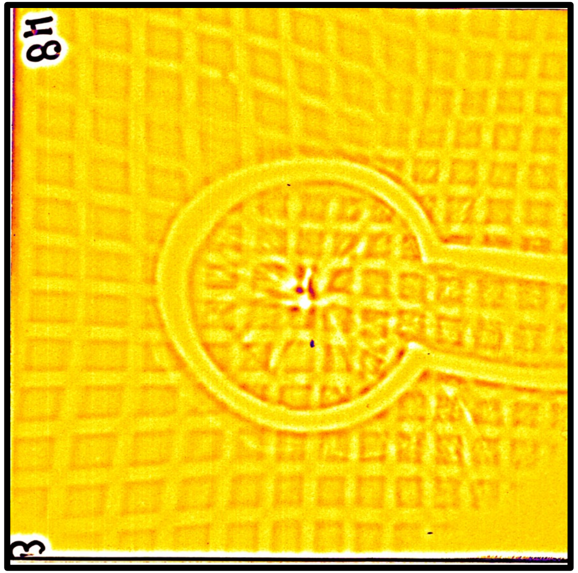
- Laser driven coils (LDC) overview:
- How well do LDCs work?
- Electric and magnetic field diagnostics
- Calibrating and validating diagnostics
- **Overview of initial and follow up experimental results**
- Discussion and conclusions

Initial experiments only tested the axial probe on different types of LDCs



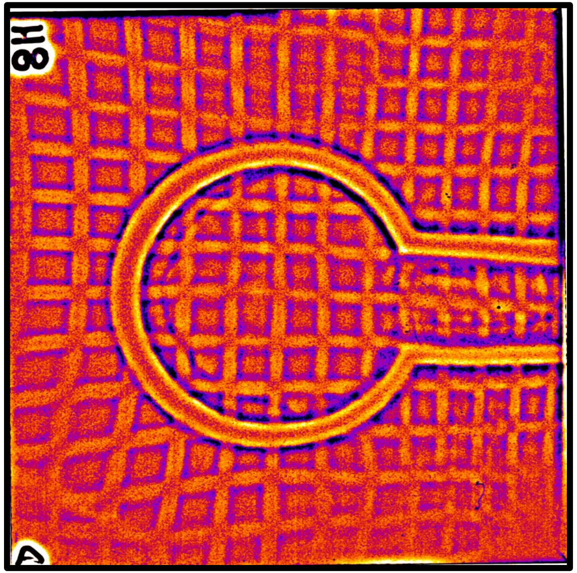


Initial experiments only tested the axial probe on different types of LDCs



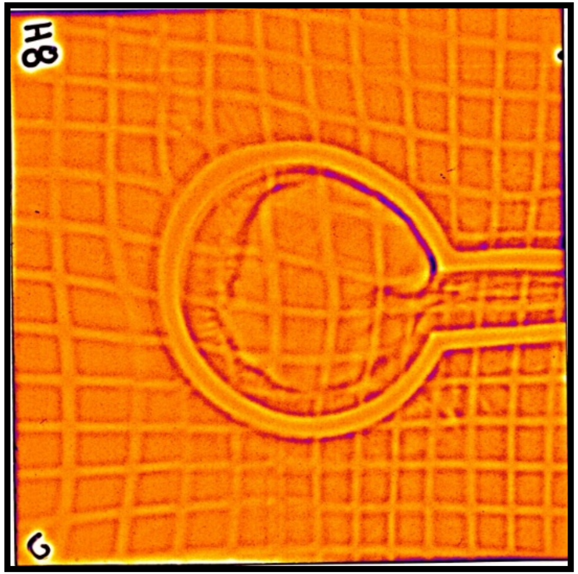
Double plate

No measurable B field



Double plate reversed
Stalk on driven plate

No measurable B field



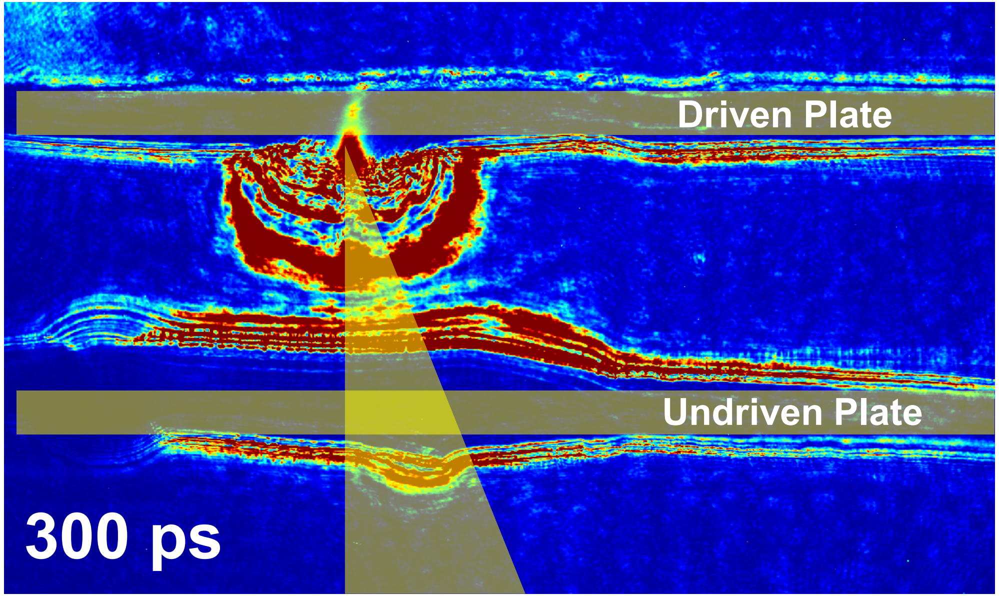
Single plate

Asymmetric B and E fields

*J. Peebles et al., PoP 27, 063109 (2020)

The lack of current for the double-plate coil is explained by expanding plasma from both plates measured by 4ω angular filter refractometry* (AFR)

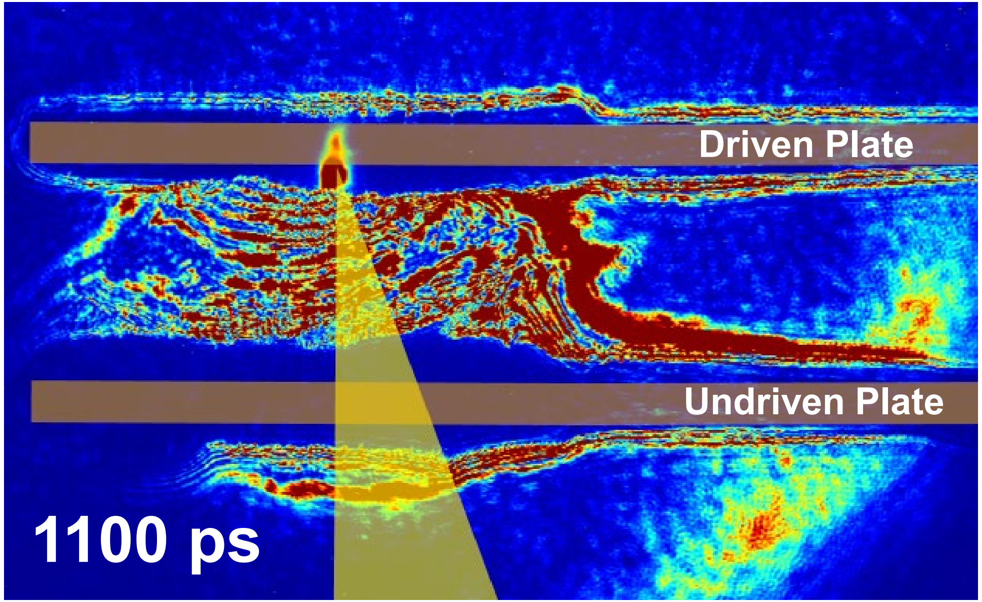
- X-rays from the driven plate indirectly drive the other plate
- From a voltage perspective: equal charge displacement leads to no voltage difference and no current
- From a circuit perspective: any current would jump the gap between plates as a "short-circuit" since plasmas are conductors



*D. Haberberger *et al.*, CLEO Technical Digest, Paper ATu3M.3

The lack of current for the double-plate coil is explained by expanding plasma from both plates measured by 4ω angular filter refractometry* (AFR)

- **X-rays from the driven plate indirectly drive the other plate**
- **From a voltage perspective: equal charge displacement leads to no voltage difference and no current**
- **From a circuit perspective: any current would jump the gap between plates as a "short-circuit" since plasmas are conductors**

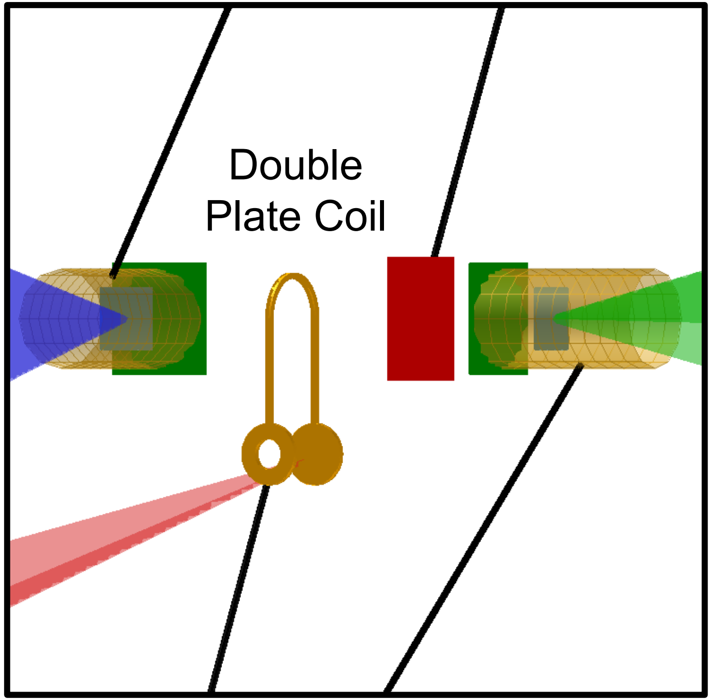


*D. Haberberger *et al.*, CLEO Technical Digest, Paper ATu3M.3

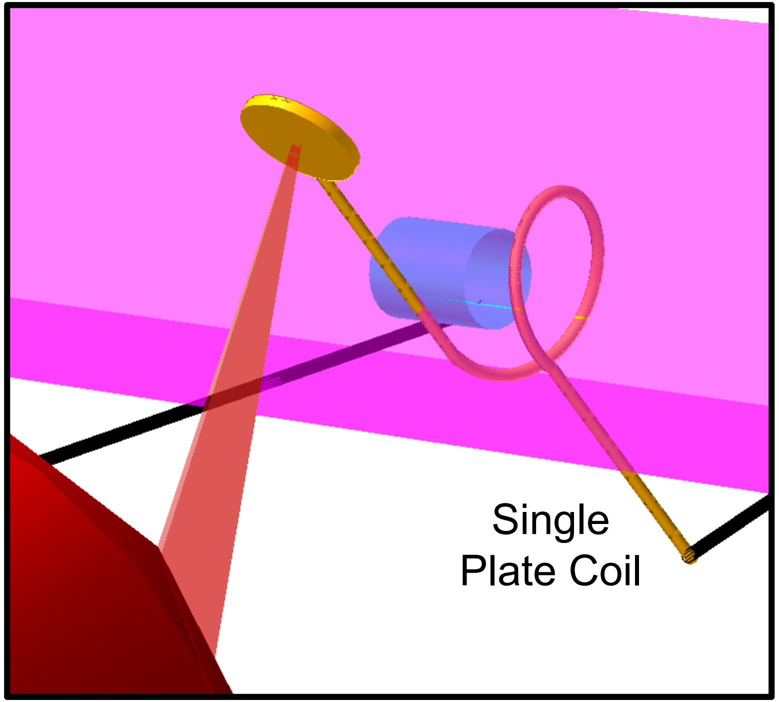
New experimental goals as a consequence

- Verify axial proton probing results by using multiple diagnostics on the same shot
- Try to remove as many sharp corners and burrs from the target as possible to reduce E field enhancement
  - Previously laser cut from foil, move to smooth magnet wire and foils
  - Previously used a 5/6 loop with bends, switch to U shaped 1/2 loop to have no bends
  - Place the stalk of the target on the opposite side of the loop from the plate on the single plate targets
  - Measure current in both directions on a single shot

Two configurations with two types of targets were used on the subsequent experimental campaign



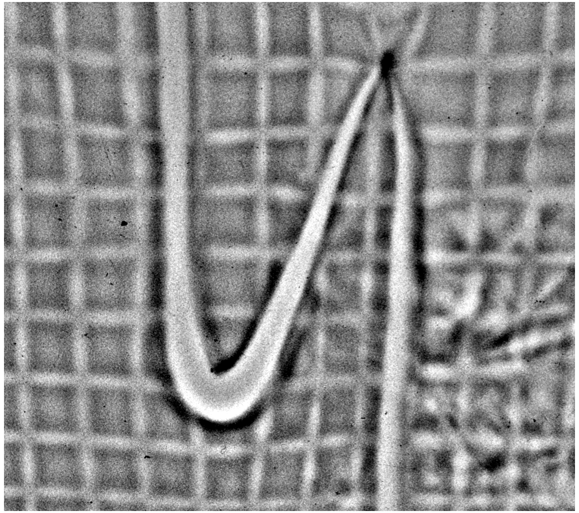
Double radiography configuration



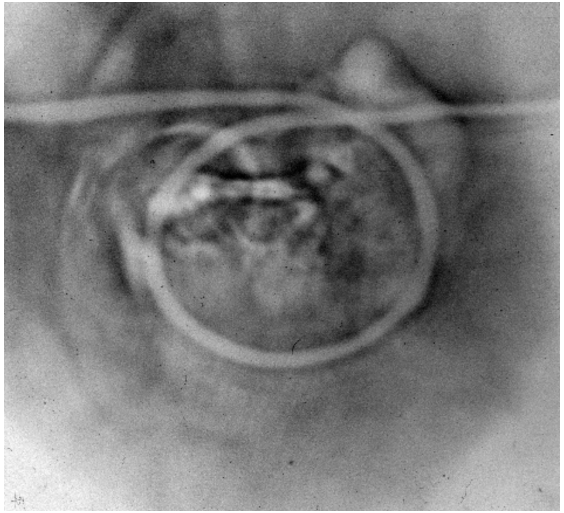
B-dot + Faraday rotation

Transverse proton radiography on the single plate coils provided a very accurate current measurement

- Single plate coils are really just a coiled stalk in this experiment, the helix provides two half loops in one target for transverse probe purposes
- Effectively we get to see the effect of current and if the current were reversed



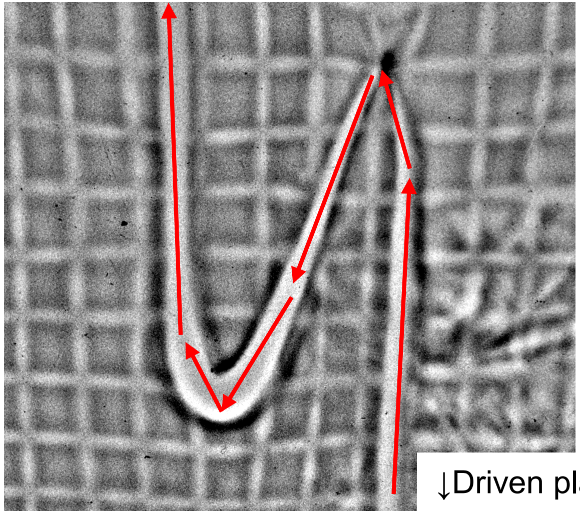
Transverse



Axial (no mesh)

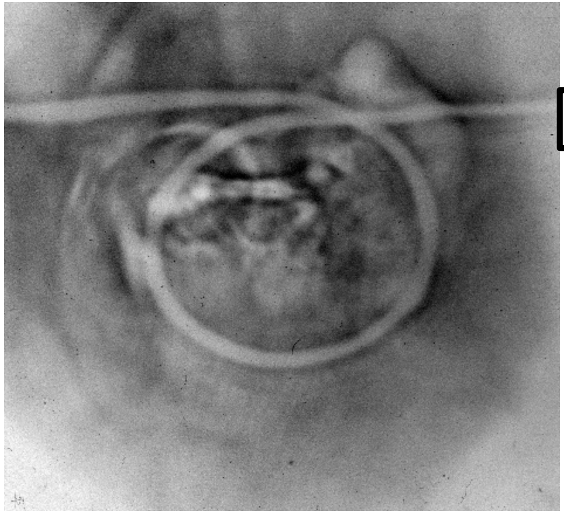
Transverse proton radiography on the single plate coils provided a very accurate current measurement

- Single plate coils are really just a coiled stalk in this experiment, the helix provides two half loops in one target for transverse probe purposes
- Effectively we get to see the effect of current and if the current were reversed



↓Driven plate

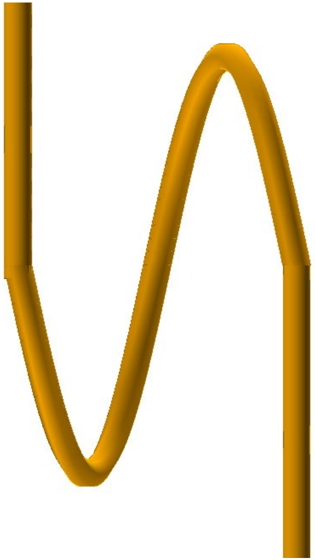
Transverse

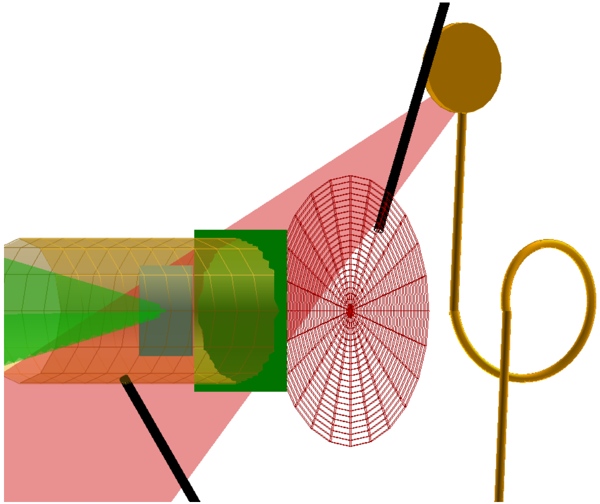


Driven plate

Axial (no mesh)

Simulated radiographs match very well with experimental radiographs, though only indicate a very low current

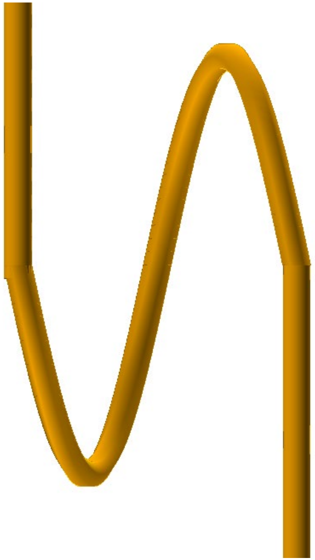




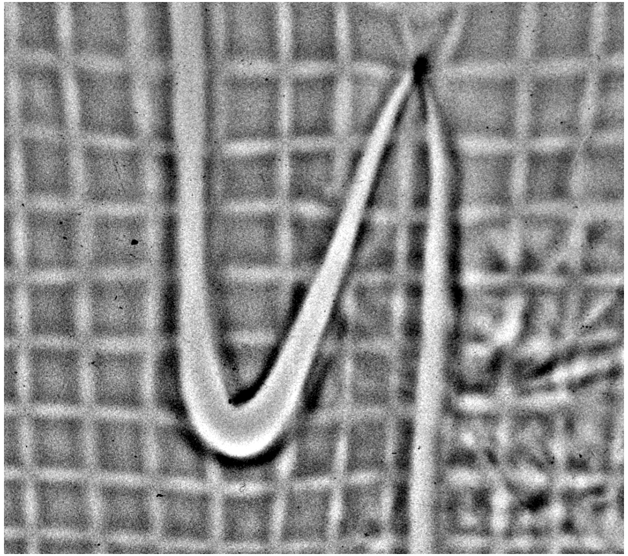
Orientation of transverse proton probe

Radiographs show one turn of the loop defocuses and one focuses

Simulated radiographs match very well with experimental radiographs, though only indicate a very low current



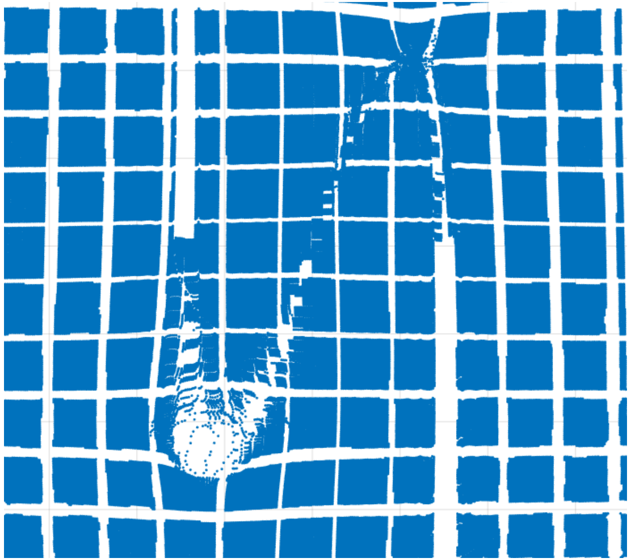
Orientation of transverse proton probe



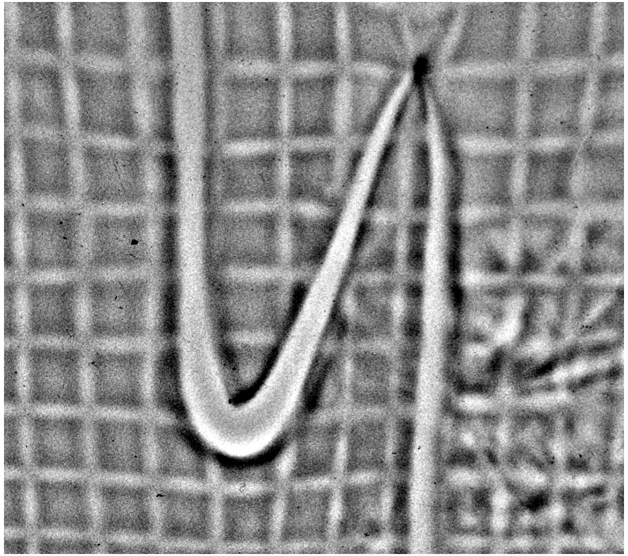
20 MeV experimental radiograph

Radiographs show one turn of the loop defocuses and one focuses

Simulated radiographs match very well with experimental radiographs, though only indicate a very low current



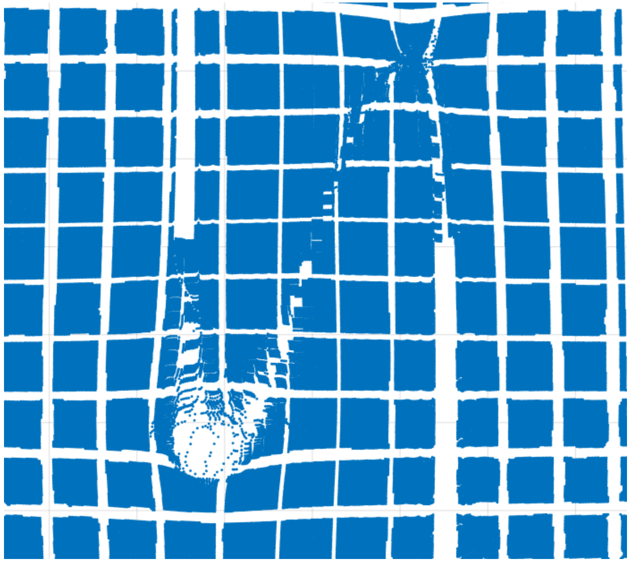
10 kA, 20 MeV synthetic radiograph



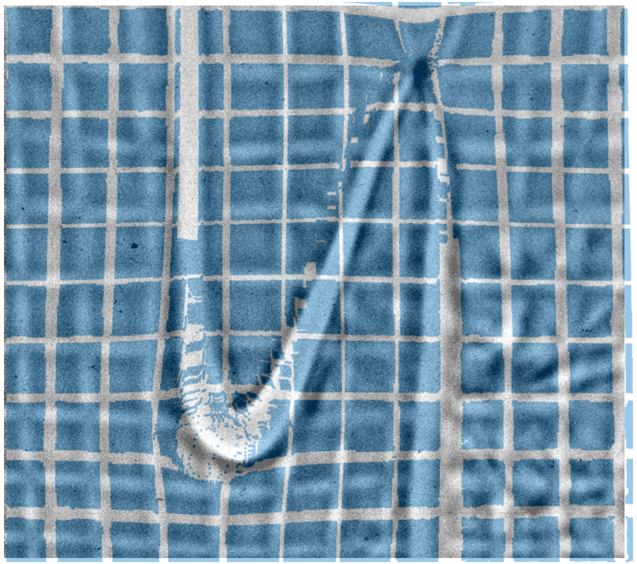
20 MeV experimental radiograph

Radiographs show one turn of the loop defocuses and one focuses

Simulated radiographs match very well with experimental radiographs, though only indicate a very low current



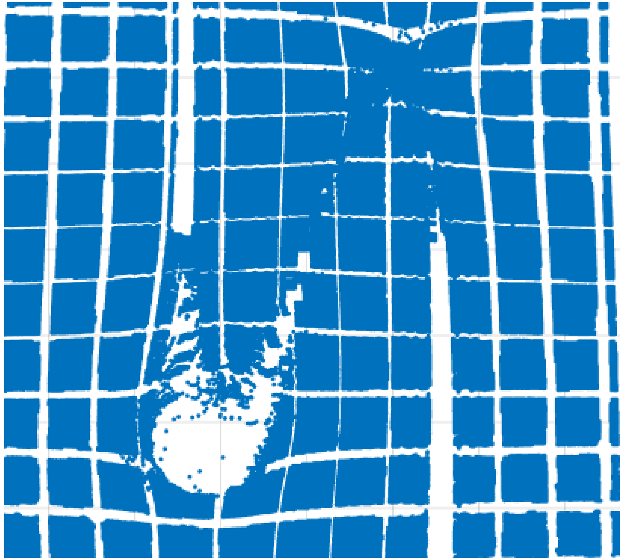
10 kA, 20 MeV synthetic radiograph



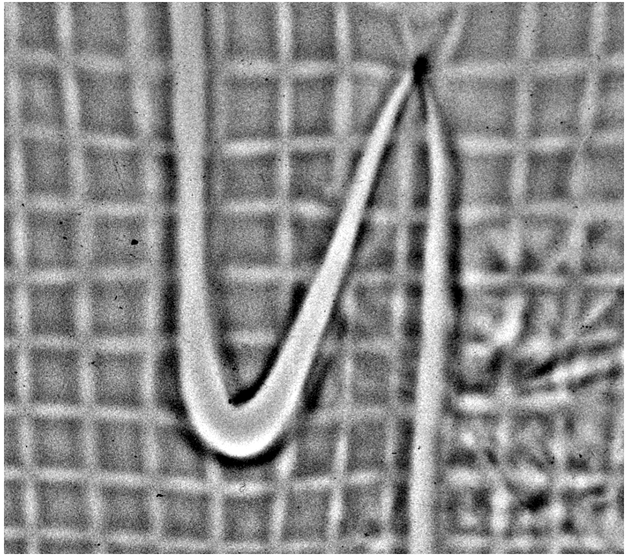
20 MeV experimental radiograph

Radiographs show one turn of the loop defocuses and one focuses

20 kA is beyond the upper limit for current measured by proton radiography



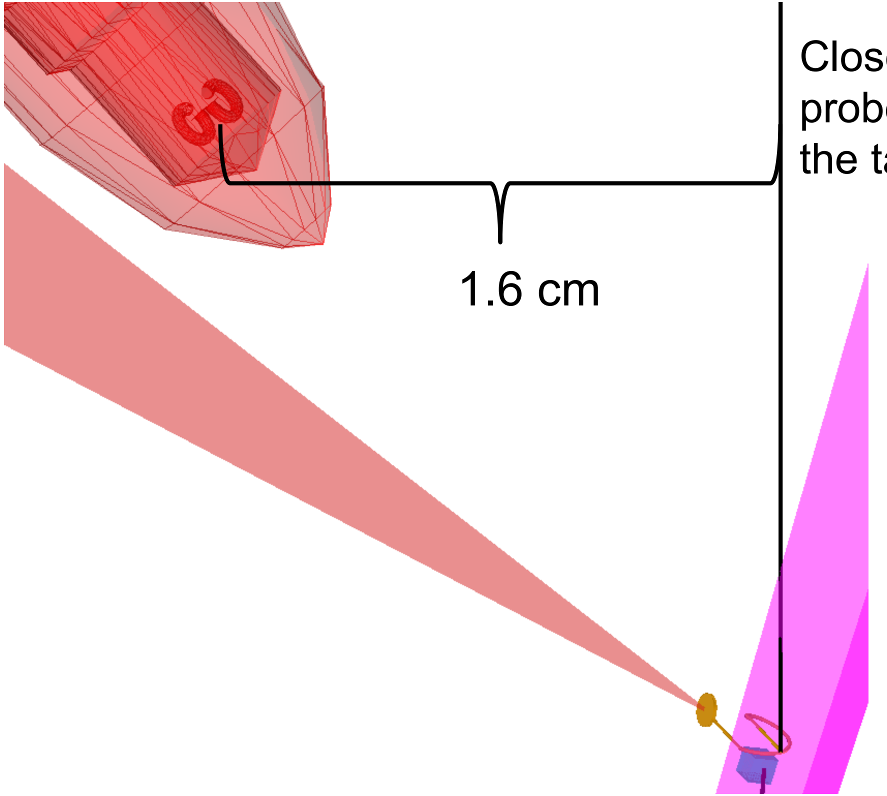
20 kA, 20 MeV synthetic radiograph



20 MeV experimental radiograph

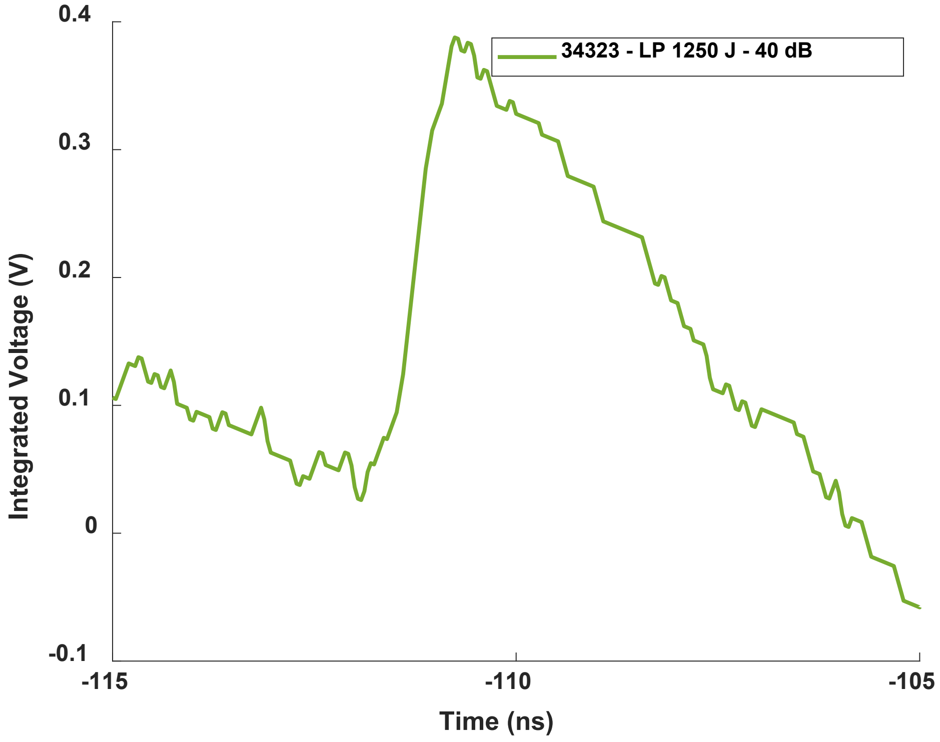
20 kA current bulges and focuses more than in experiment

Estimating current passing through the target and stalk ("infinite wire") using the B-dot probe



Closest approach to B-dot probe is actually the stalk, not the target

If we attributed all signal close to t0 to dB/dt, what is the field?



Back of the envelope calculation

In the lab 2.5 V measured with probe 1.6 cm from 1 kA wire (should be ~0.0117 T)

Equivalent to 30-40 V at 20 dB (lab attenuation)

Coil is tilted ~45° relative to stalk

Assume some attenuation due to system bandwidth (30%)

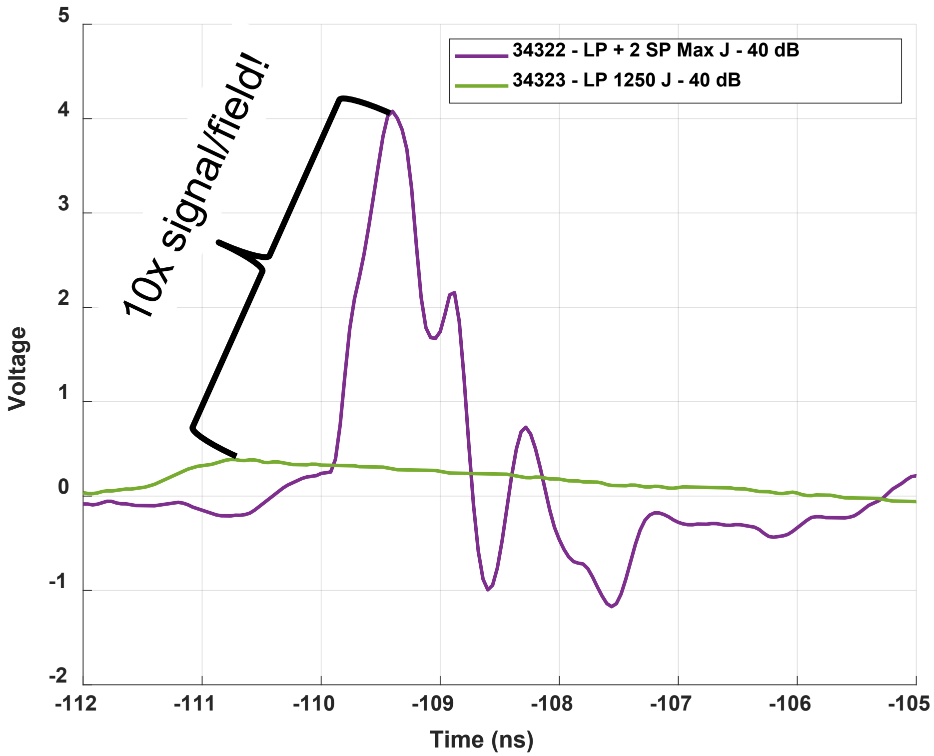
(40/2.5)*sqrt(2)*1.4*0.0117 T ≈ 0.4 T

Using $B = \mu_0 I/2\pi$, $\underline{I_{stalk} < 30\ \text{kA}}$

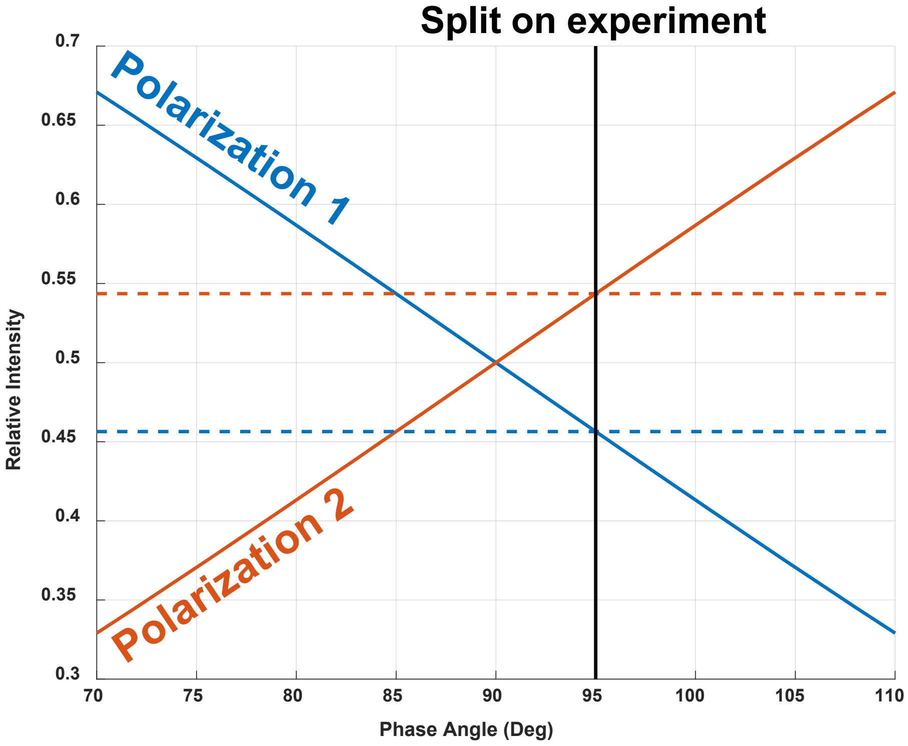
Adding the short pulses for proton radiography introduces significant signal that cannot be magnetic field

On shots with the short pulses the B-dot probe measured significantly higher spikes in signal ~1 ns after the long pulse

It is unlikely that this is due to magnetic field since 300 kA through a stalk would be more energy than the short pulse laser

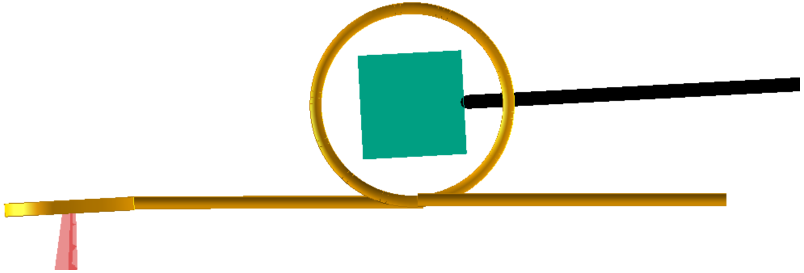


Faraday rotation measured no significant rotation in fused silica media compared to other regions in the probe



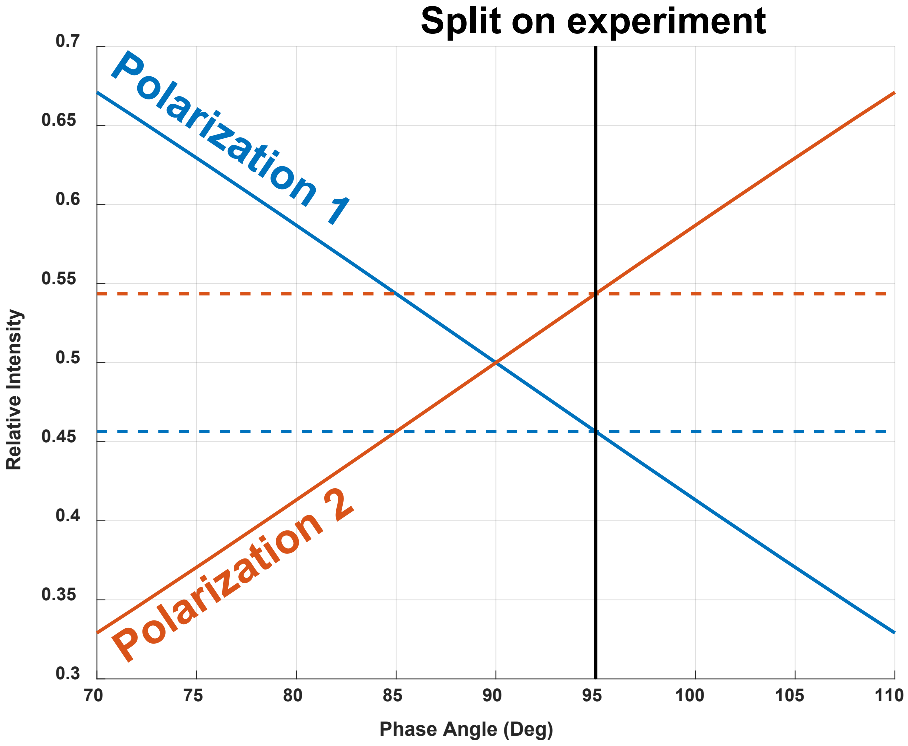
Light is split into || and ⊥ polarizations

The Faraday effect in a medium with a refractive index causes polarization rotation



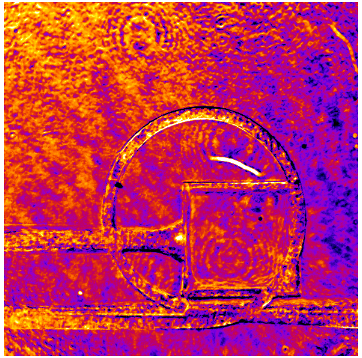
Only 500 J drive used due to blanking

Faraday rotation measured no significant rotation in fused silica media compared to other regions in the probe

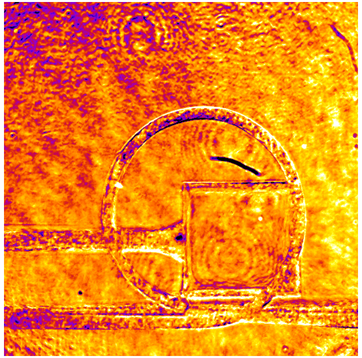


Light is split into || and ⊥ polarizations

The Faraday effect in a medium with a refractive index causes polarization rotation

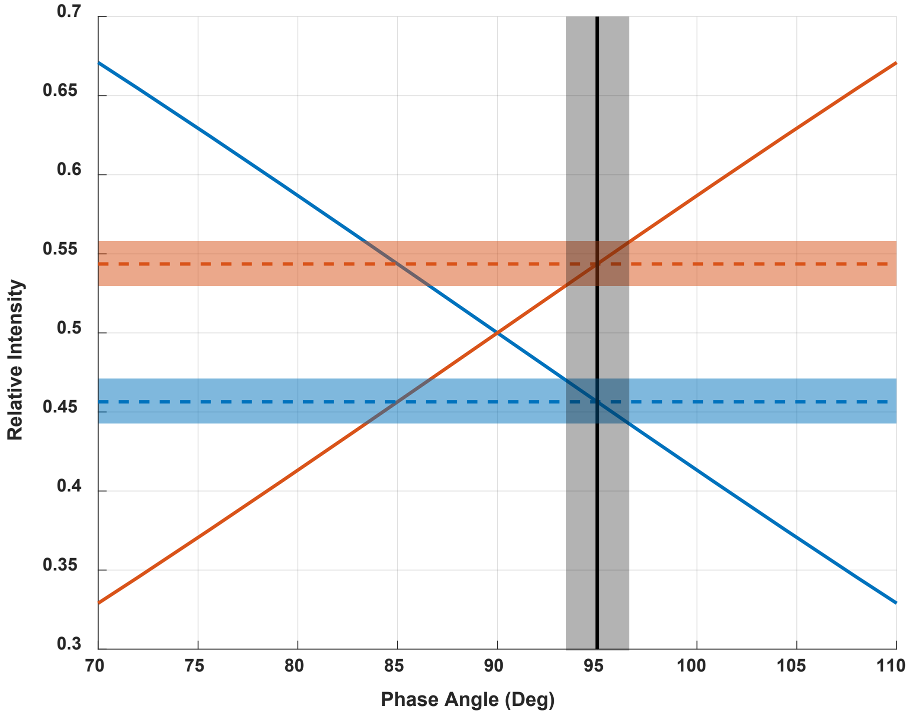


<u>Polarization 1</u>
Summed image



<u>Polarization 2</u>
Summed image

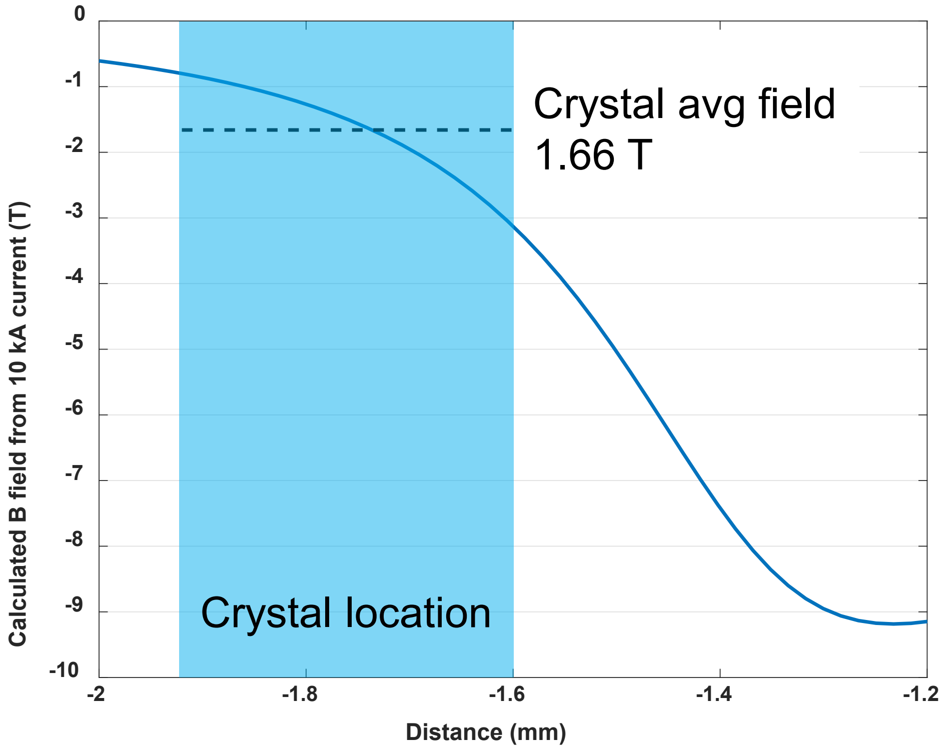
If no significant rotation is measured, how sensitive is the diagnostic?



Edges of Faraday medium showed changes of ± 2%

If attributed to field this corresponds to a rotation of ± 1.5° or ± 1.23 T integrated over the 800 μm Faraday medium

If no significant rotation is measured, how sensitive is the diagnostic?



Edges of Faraday medium showed changes of ± 2%

If attributed to field this corresponds to a rotation of ± 1.5° or ± 1.23 T integrated over the 800 μm Faraday medium

Faraday estimates at most 7.5 kA, with significant assumptions

Single plate current estimates

Proton radiography: **I = 10 ± 2.5 kA**

- Still could use more work on introducing E fields, but opposing loops restricts this condition

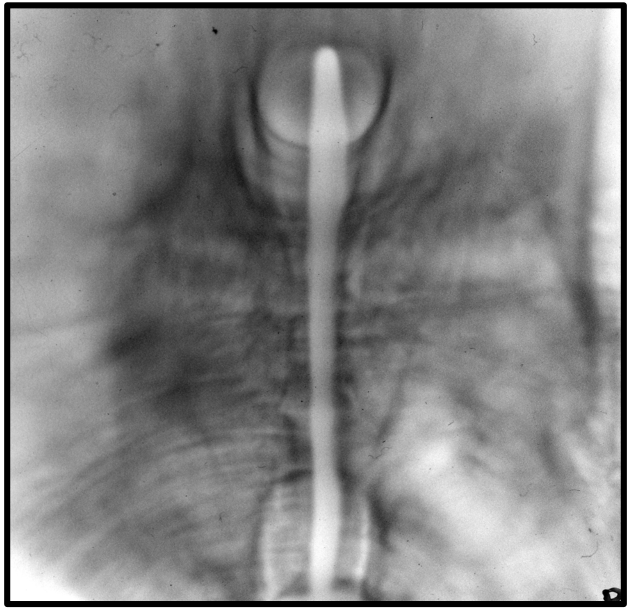
B-Dot probe: **I < 30 kA** (unknown how much is from electric field)

- Nothing is currently known about electric field coupling on ns timescales to the probe so this can only impose an upper limit

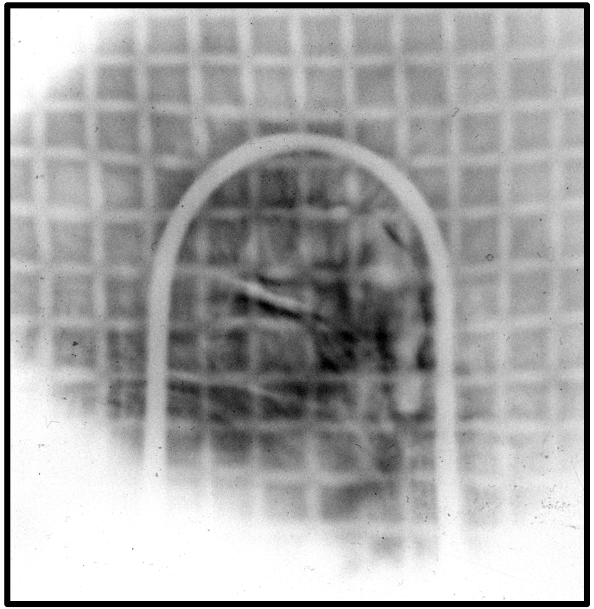
Faraday rotation: **I = 0 - 7.5 kA (for lower energy shots)**

- Depending on where you measure in the Faraday glass there is either no rotation or very slight rotation, likely due to noise

Double plate proton radiography does not make a convincing argument for high current



Two bulges at the loop can be seen in the 36 MeV transverse radiograph, though bulge size is consistent with ~ 5 kA current



Rotation should be apparent with > 10 kA current
No rotation measured

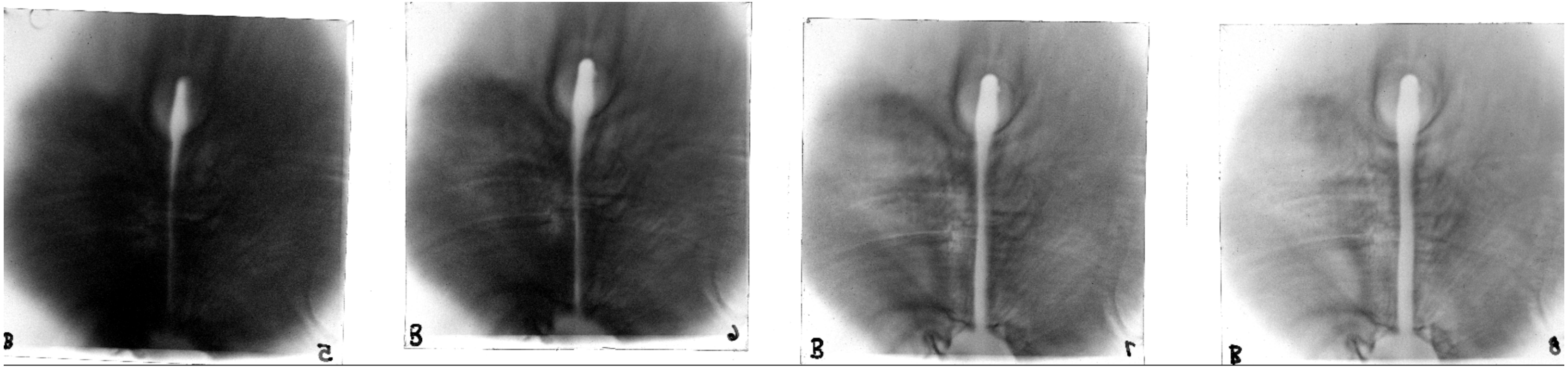
Transverse radiographs still require more analysis

E < 15 MeV protons are focused by net negative charge (E ~10^7 V/m), obscuring the coil

E = 20-30 MeV protons have a void at the tip, caused primarily by small E and B field

E > 30 MeV protons are not significantly affected by either field around the coil

15 MeV | 19 MeV | 24 MeV | 28 MeV



Transverse radiographs still require more analysis

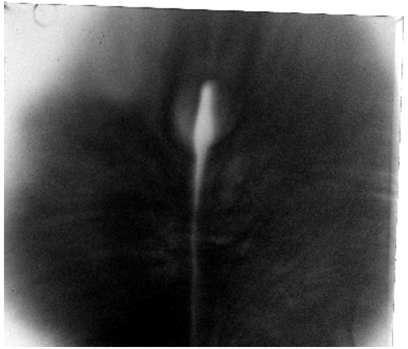
E < 15 MeV protons are focused by net negative charge (E ~10^7 V/m), obscuring the coil

E = 20-30 MeV protons have a void at the tip, caused primarily by small E and B field

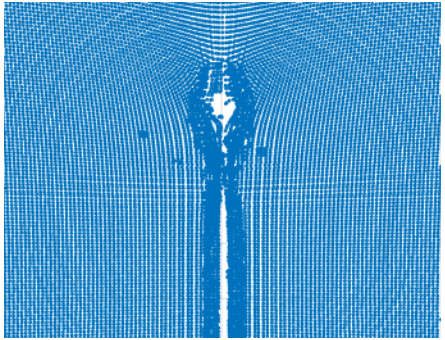
E > 30 MeV protons are not significantly affected by either field around the coil

15 MeV

Experiment

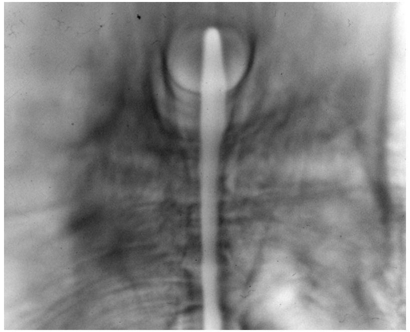


Simulation

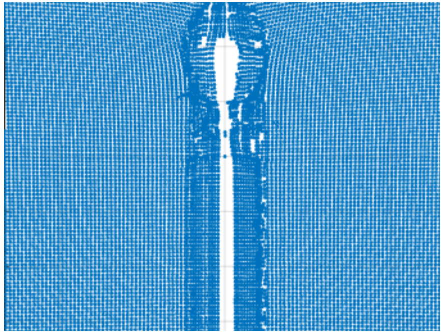


36 MeV

Experiment



Simulation



Transverse radiographs still require more analysis

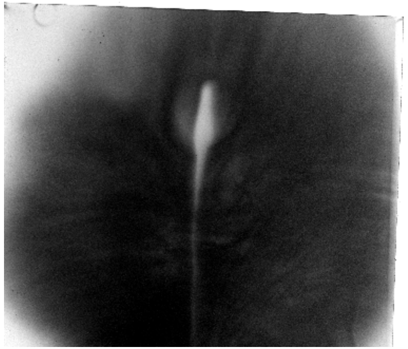
E < 15 MeV protons are focused by net negative charge (E ~10^7 V/m), obscuring the coil

E = 20-30 MeV protons have a void at the tip, caused primarily by small E and B field

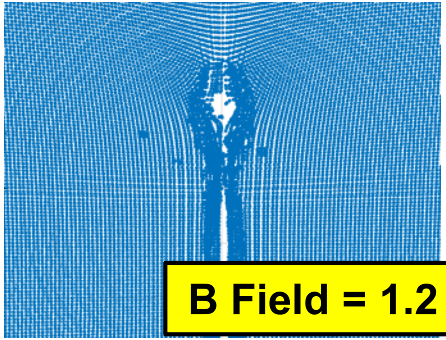
E > 30 MeV protons are not significantly affected by either field around the coil

15 MeV

Experiment

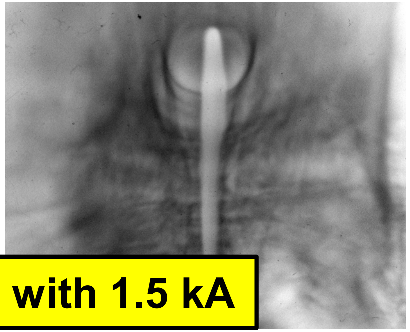


Simulation

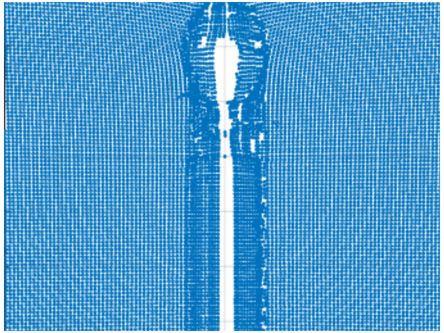


36 MeV

Experiment

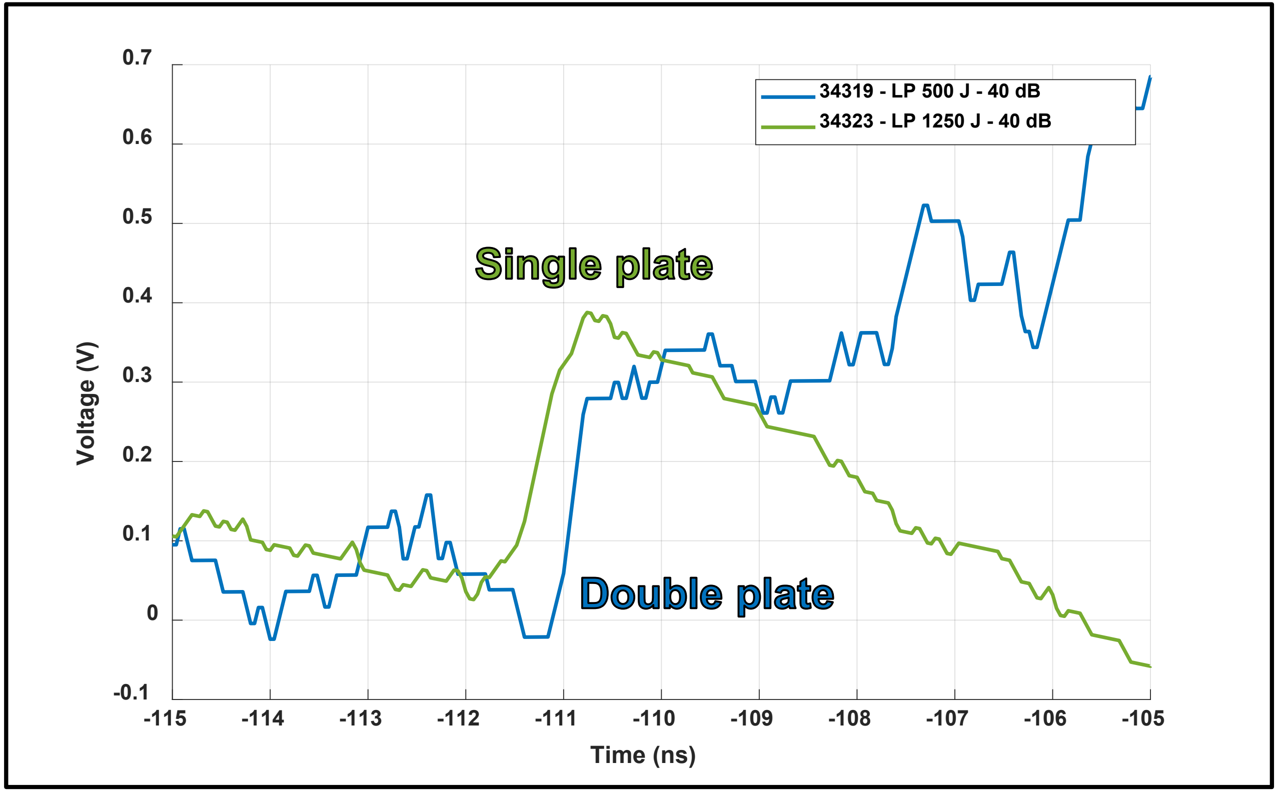


Simulation

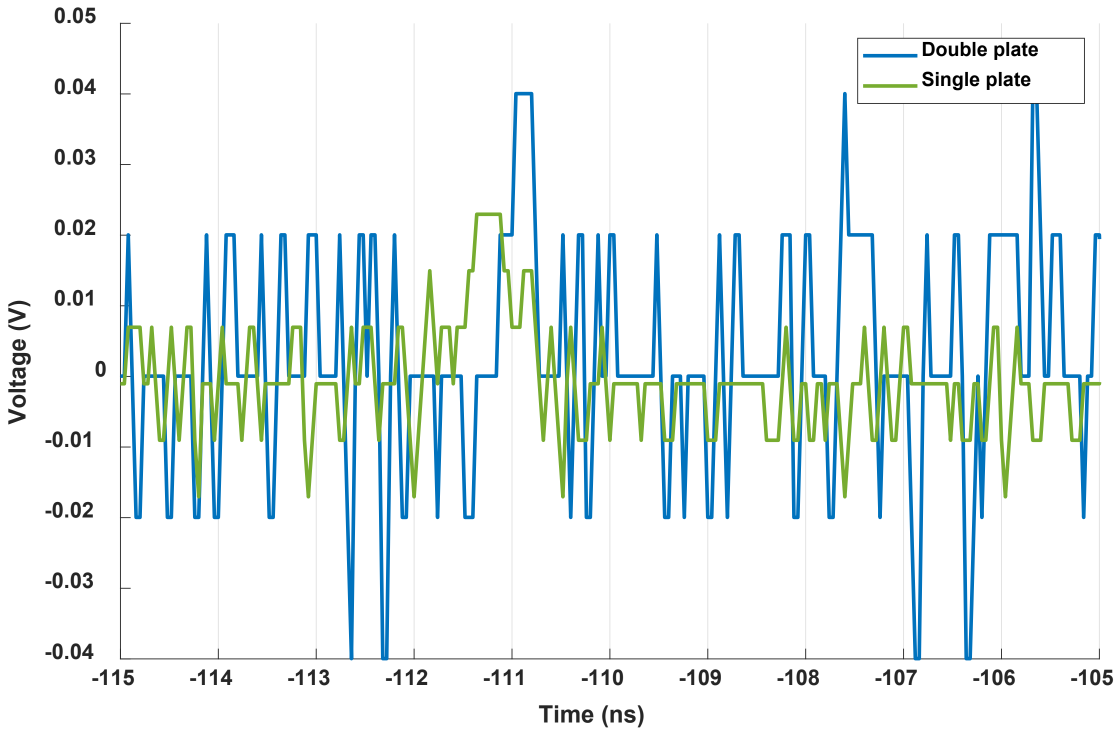


B Field = 1.2 T with 1.5 kA

B-dot probe measurements of the double plate showed similar results to the single plate, with less energy



Integration makes the B-dot probe look a little more convincing than raw data



Double plate current estimates

UR LLE

Proton radiography: **I = 1.5 ± 5 kA**

- Axial probe restricts this to < 10 kA, transverse probe suggests 1.5 kA, but the shape mismatch suggests more electric field involvement

B-Dot probe: **I < 30 kA** (unknown how much is from electric field)

- A similar voltage was measured to the single plate though with less drive energy

Faraday rotation: **N/A**

- Faraday glass blanked on shots with 1250 J

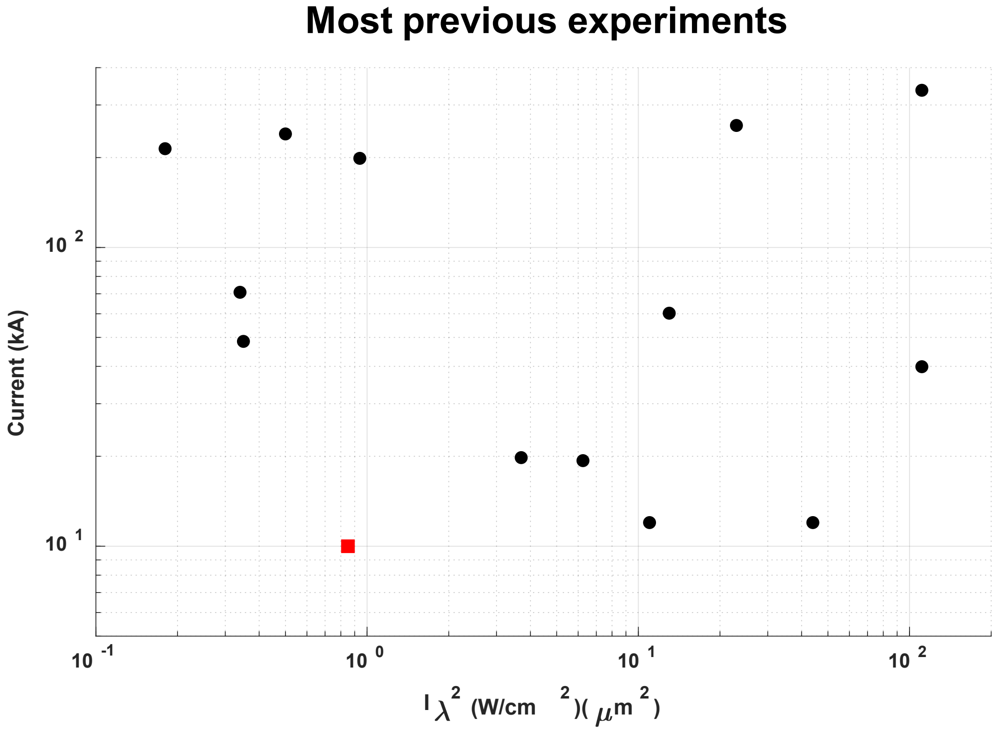
Outline

- Laser driven coils (LDC) overview:
- How well do LDCs work?
- Electric and magnetic field diagnostics
- Calibrating and validating diagnostics
- Overview of initial and follow up experimental results
- Discussion and conclusions

There are a few key differences between these experiments and others

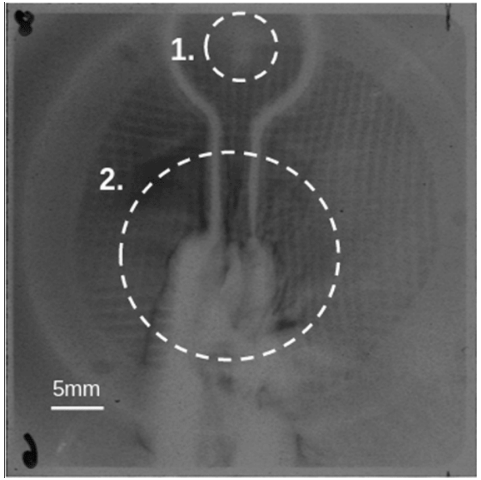
$I\lambda^2$ (W/cm^2)·(μm^2) is lower for these experiments than those with very high field measurements

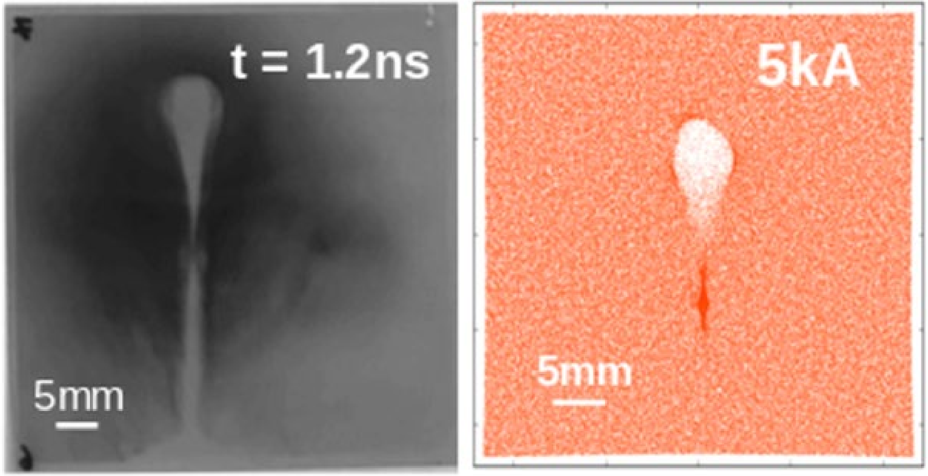
Comparing $I\lambda^2$ across most experiments there appears to be little correlation with current or field



Very recent experiments on the Vulcan laser corroborated our result on OMEGA-EP

- P. Bradford *et al.* performed experiments with a similar dual proton probe geometry and intensity but with **1 μm** light
- Axial radiographs found no rotation and a limited current was inferred from transverse radiography

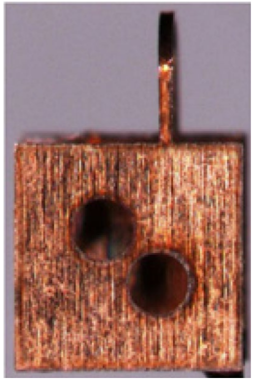




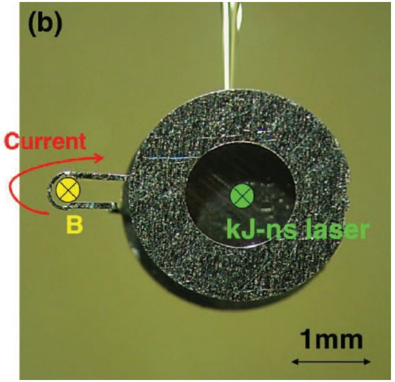
Target construction and target stalk placement vary across experiments

Initial motivation stemmed from drawing a current through the target stalk, what happened to target stalks for these experiments? Most designs place it on the driven plate (acting as a current divider), or do not specify

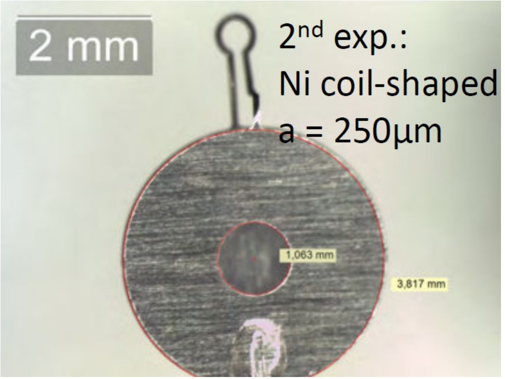
Targets have varying degrees of smoothness in their construction geometry



Gao (2016)



Fujioka (2013)



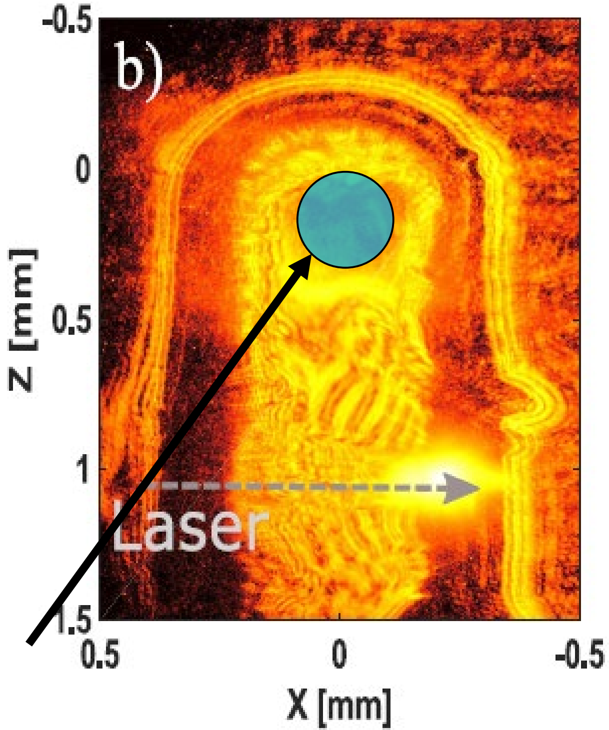
Santos (2015)

Law (2016)

Peebles (2021)

Finally, the ultimate problem with LDCs: magnetizing an experiment

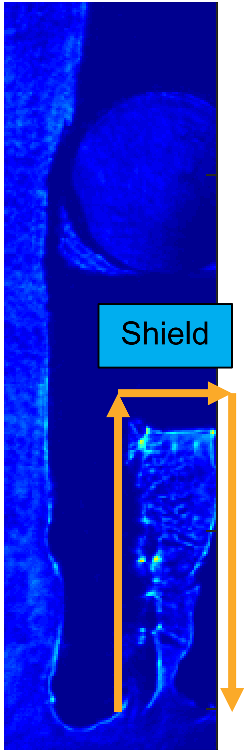
- The laser driven coil is not independent from the experiment it is magnetizing
- Driving the LDC creates a huge x-ray source that irradiates the target
- To keep fields high and inductance low, experiments must be placed close to the driving plate



C. Goyon, *et al.*, Phys. Rev. E ***95,*** *033208 (2017).*

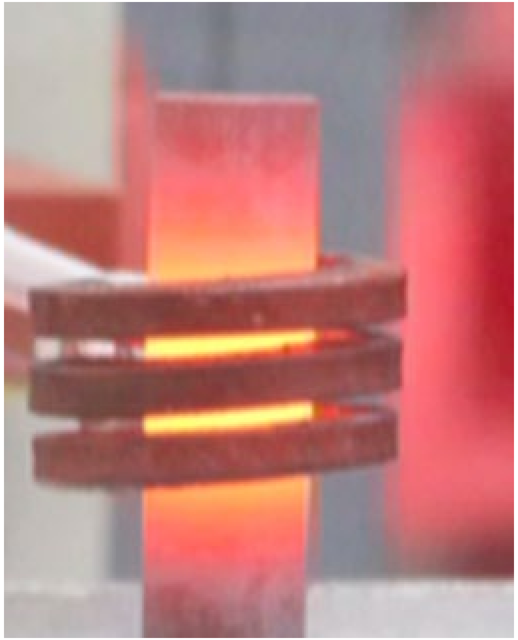
Finally, the ultimate problem with LDCs: magnetizing an experiment

- The laser driven coil is not independent from the experiment it is magnetizing
- Driving the LDC creates a huge x-ray source that irradiates the target
- To keep fields high and inductance low, experiments must be placed close to the driving plate
- Shielding the experiment is completely ineffective as it provides a clear short circuit path if any current was present
- Should be noted that any experiments that magnetize a target with an LDC likely significantly preheat the target



Even if LDCs functioned as well as the most optimistic publication suggests, there are limitations

- Since laser driven coils have a rise time on the order of the laser pulse, dB/dt is extremely high, leading to a high EMF
- Conductive targets will generate opposing currents very quickly to stop field penetration
- These induced currents coupled with resistive heating will cause the target to blow up before an experiment can be performed



Let’s revisit the question:
How well do laser driven coils work?

How well do laser-driven coils work?

<u>Not very well, and you have to jump through these hoops:</u>

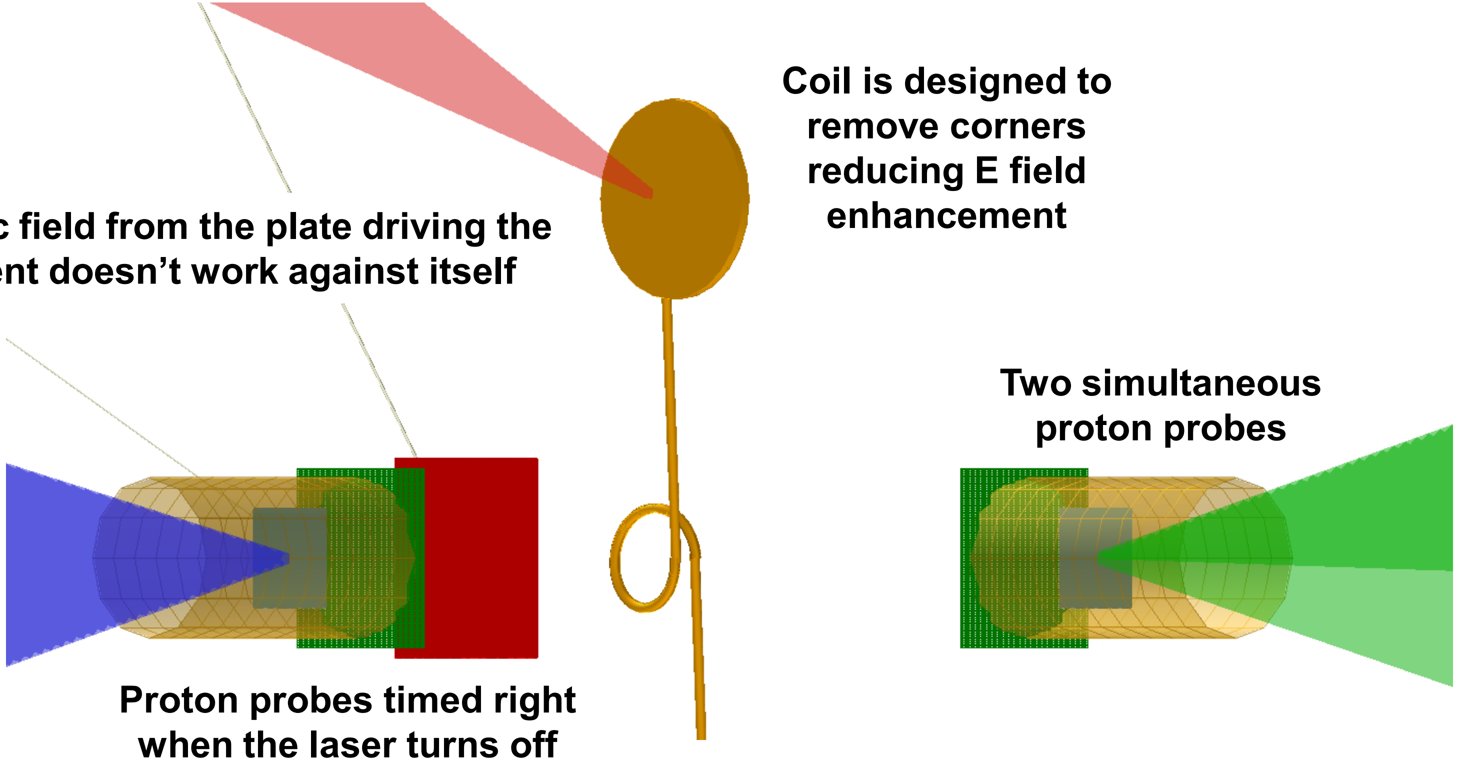
- Have very efficient (>30%) coupling to electrons
- Make a <u>single</u> plate LDC small enough so that inductance is kept low
- Since the inductance must be kept low, the main experiment must be shielded from x-rays generated by a kJ laser 1-2 mm away
- Make sure your shielding is < 1 mm in size and doesn't become part of the circuit
- Make sure your main experimental target is < 1 mm in size and non-conductive
- Have an experiment where you don't mind if the field is non-uniform and don't mind if the experiment is preheated

Extra Slides

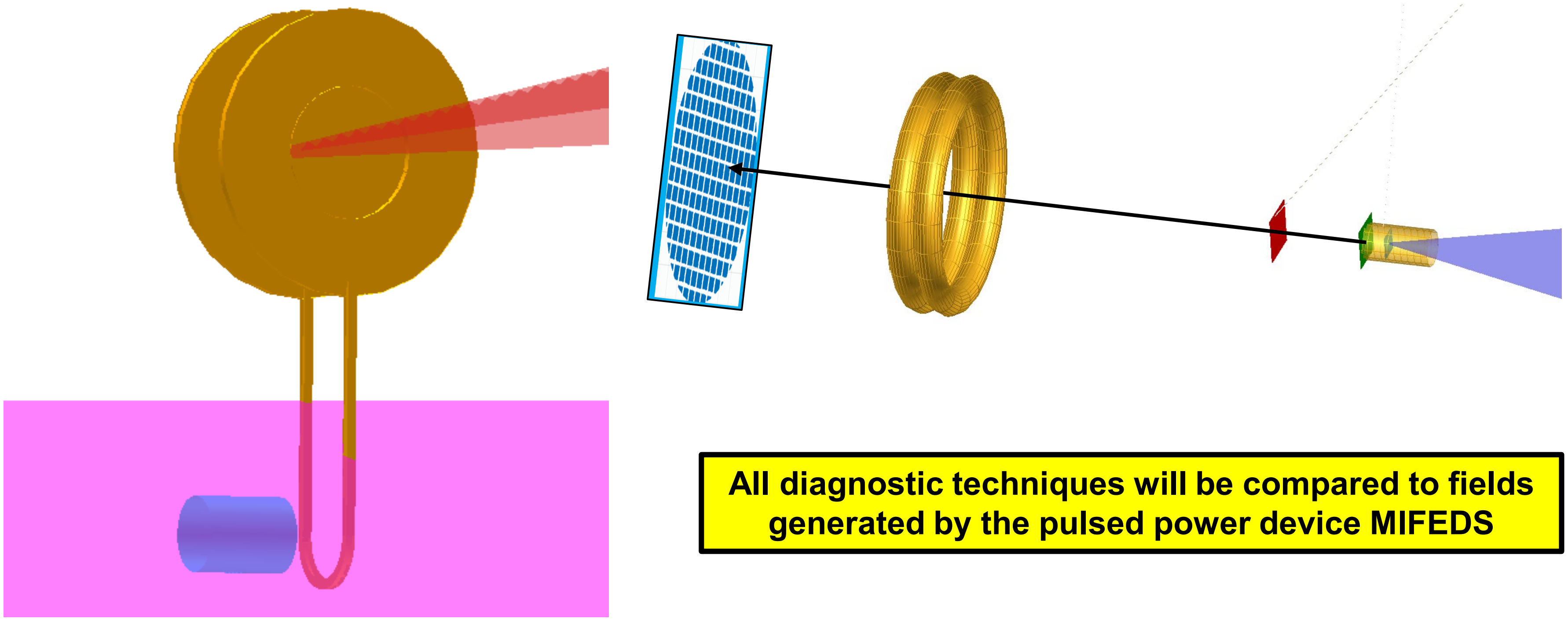
Future experiments and goals

- Measure the current and electric field from short pulse driven stalks using a mesh fiducial (has been done in the past but somewhat inconclusive)
- Faraday rotation using 4ω polarimetry for a MIFEDS coil
- Measure EMI from different material targets and stalk designs

Future experiments will take lessons learned to better understand proton radiography and diagnosing fast rising current



B-dot and Faraday rotation diagnostics will be compared concurrently on the same shot



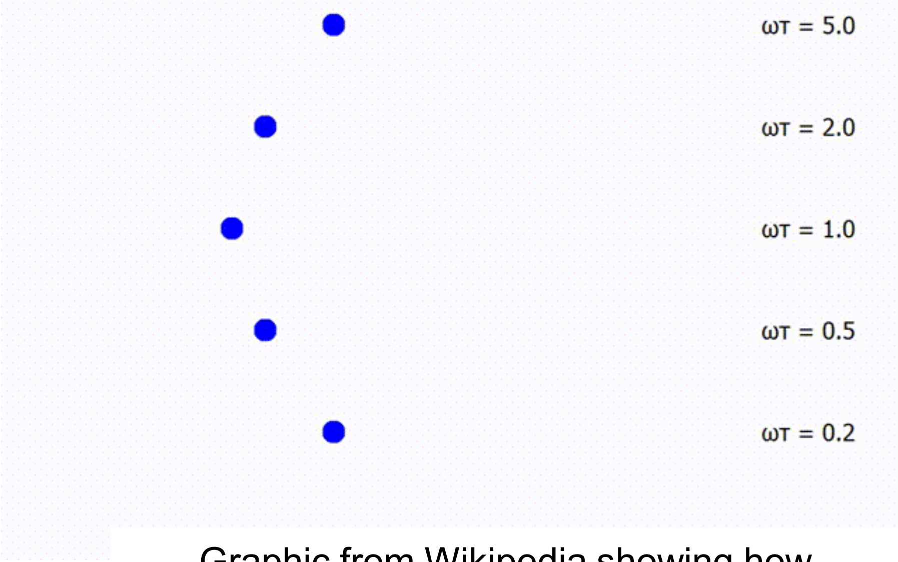
All diagnostic techniques will be compared to fields generated by the pulsed power device MIFEDS

Synthetic radiographs were constructed with a leap-frog particle pusher in Matlab

- Current and charge are explicitly placed to allow for convoluted current geometries
- A 3D field map for the entire simulation box (6x6x10 mm) is explicitly calculated using Coulomb and Biot-Savart laws
- Particles are uniformly sent from the proton source with a given energy towards the target
- Particles that overlap with a reference mesh grid, with the coil material or leave the box are removed
- Particles that reach the end of the box have their trajectory extrapolated to the film
- Small magnification changes are made afterwards due to varying location of film in the RCF stack

Revisiting assumptions: does the assumption of Ohm’s law and steady state current apply to LDCs?

- **A non-uniform current leads to charge build up in the coil**
- **Ohm’s law is frequently used to justify that current in the coil must be uniform, but our experiment data indicates otherwise**
- **Ohm’s law is an empirical law, which is not necessarily true in all circumstances**
- **The Drude model of electron transport indicates how Ohm’s law comes from electron-ion collisions in conductors**
- **In an AC spatially uniform field the Drude model shows material tends toward plasma like behavior (response time is that of an electron plasma period)**



Graphic from Wikipedia showing how electron inertia impacts current development in a fast rising E field

What does the Drude model say about the LDC environment?

UR LLE

- An electric field is generated at the plate which propagates at the speed of light
- Electrons in the wire material will be accelerated by the electric field
- Inertia causes the electron response to have a rise time, rather than be instantaneous
  - The rise time is on the time scale of an electron plasma period
- Electrons accelerated – collide – accelerate – collide, until an equilibrium is reached, several plasma periods long
- These current transients in our system should generally travel several mm/ns
- The electric field is not steady temporally or spatially in the LDC, further complicating the establishment of a steady state current

It seems likely that LDCs are transient dominated systems which would be difficult to model due to system size

The single plate system had anomalous, asymmetric current which appeared to rise after the laser turned off

- The dipole electric field established by the laser affects both wires due to coil geometry leading to at least 2 current transients
- Turning the laser off may change the conditions seen by the wires leading to a change in current flow and new transients forming