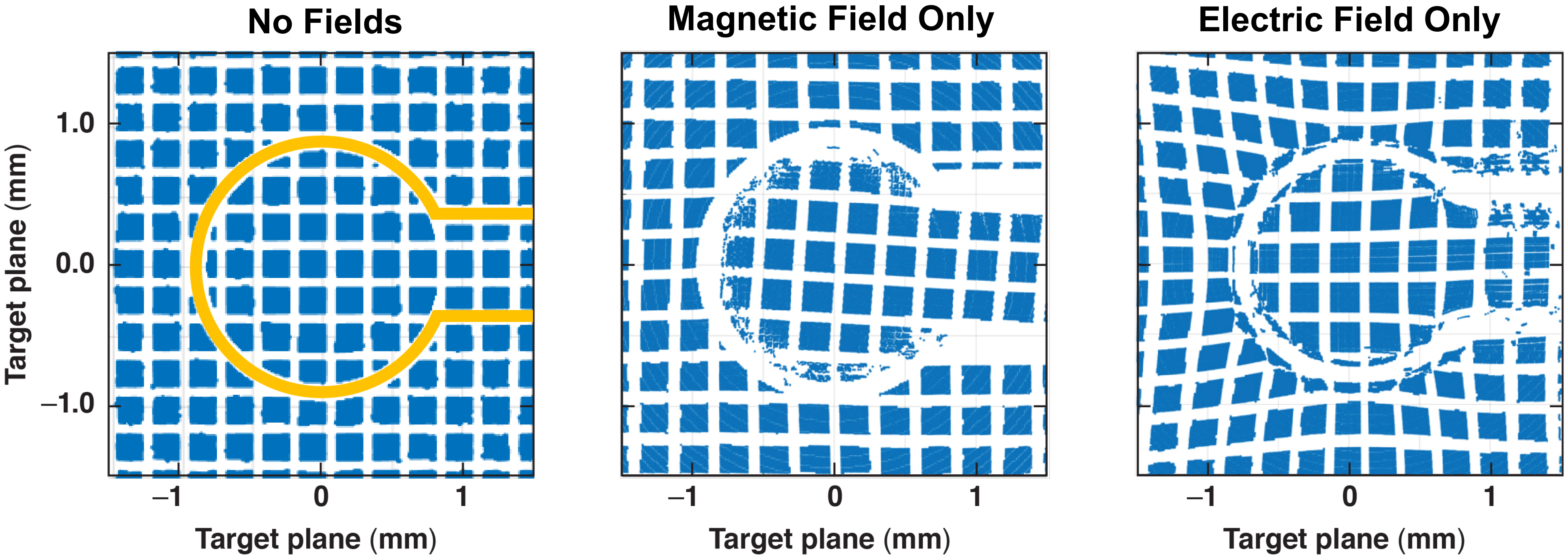
Axial Proton Radiography of Electric and Magnetic Fields Inside Laser-Driven Coils



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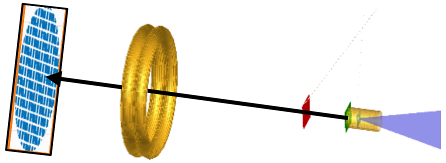

J. L. Peebles
University of Rochester
Laboratory for Laser Energetics

62nd Annual Meeting of the
American Physical Society
Division of Plasma Physics
9–13 November 2020

Summary

A deeper understanding of electric and magnetic fields in laser-driven coils (LDC's) has been gained by using axial proton radiography

- Axial proton radiography is demonstrated to provide field information in critical regions around the LDC with excellent time and spatial resolution
- Synthetic proton radiography reconstruction helps remove degeneracy between electric and magnetic fields in LDCs
- Single- and double-plate versions of LDC's were diagnosed on OMEGA EP
  - double-plate coils showed no significant magnetic field
  - single-plate coils showed an asymmetric, fast rising 80-T field along with a strong electric field

Thanks to my collaborators

J. R. Davies, D. H. Barnak, M. J. Bonino, T. Cracium, and R. Betti

Laboratory for Laser Energetics
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Institute of Space and Plasma Sciences,
National Cheng Kung University, Taiwan

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Outline

- Laser-driven coils overview
- Electric- and magnetic-field diagnostics
- Double- and single-plate laser-coil–driven coil experiments
- Discussion, future directions, and conclusions

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- Laser-driven coils overview
  - principles of operation
  - previous experimental results
- Electric- and magnetic-field diagnostics
- Double- and single-plate laser-coil–driven coil experiments
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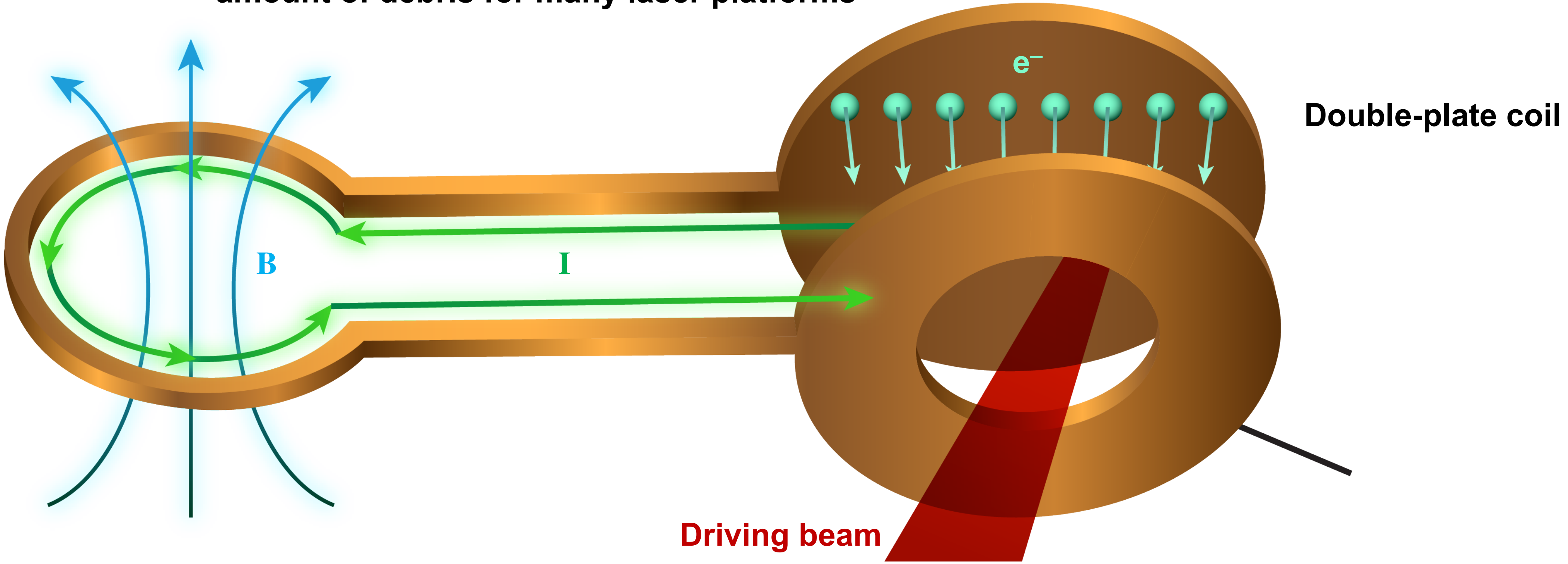
Laser-driven coils are platforms to generate strong magnetic fields without a pulser*

- In theory, laser-driven coils use a laser to drive charge separation, which draws a current to create a field in a loop of wire
- Pulsed-power magnetic field sources created a detrimental amount of debris for many laser platforms



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

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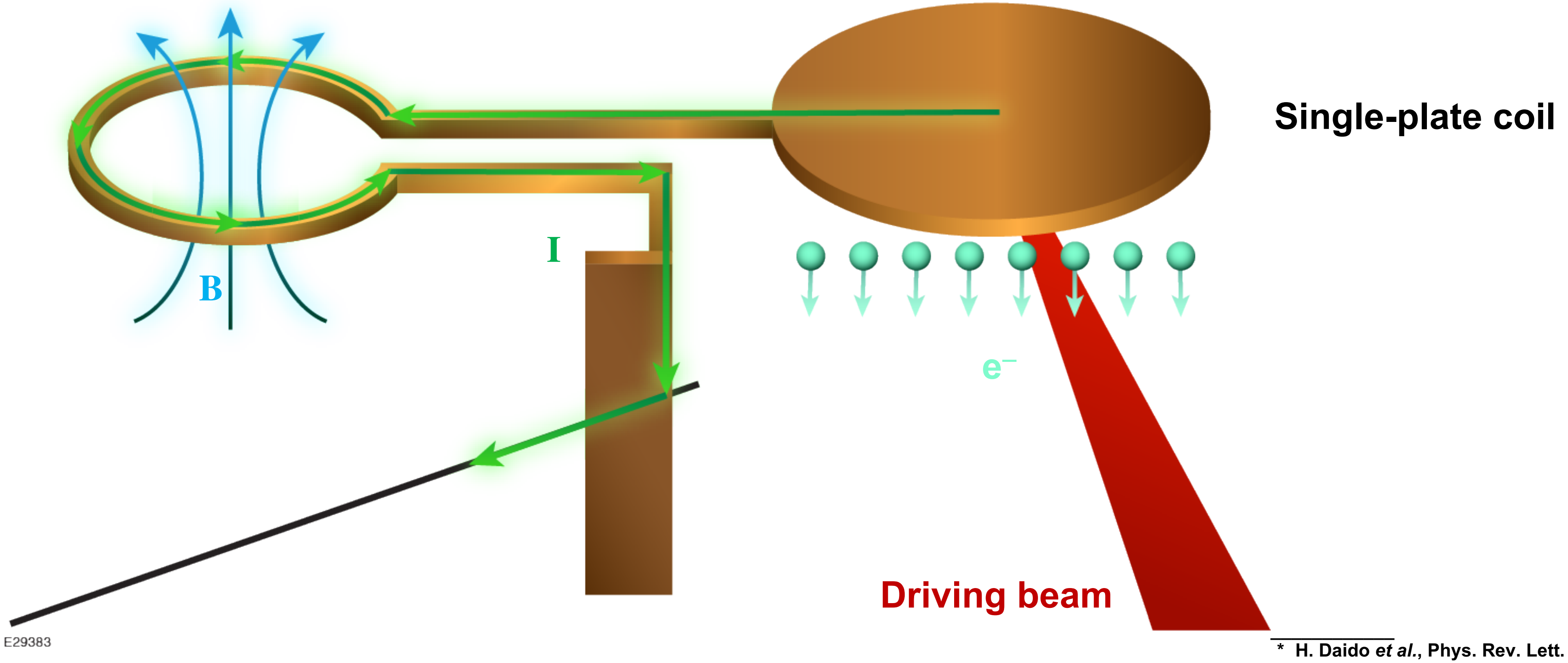

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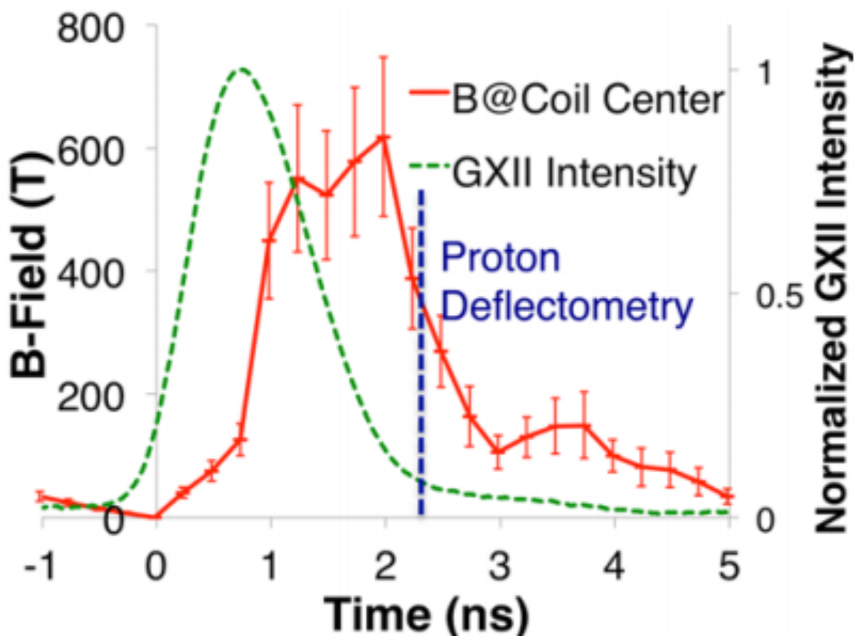
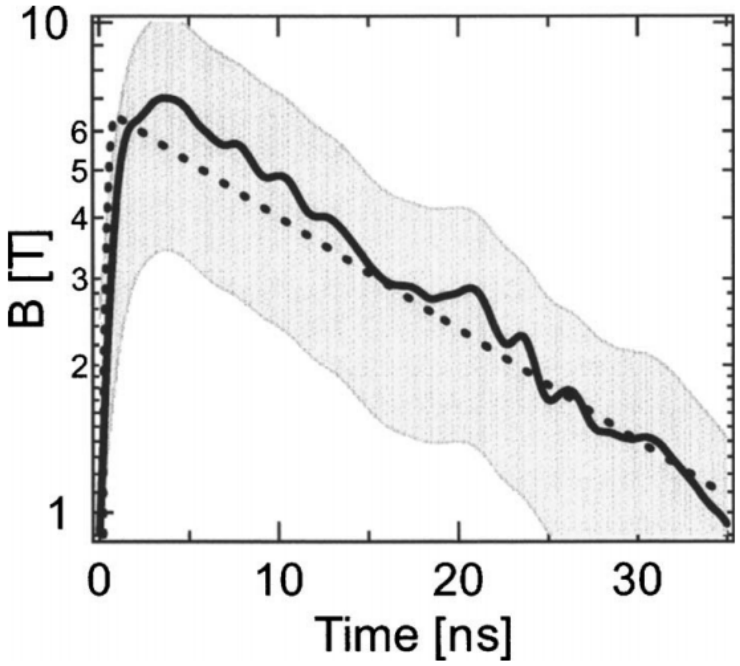
Current diagnostics give conflicting and ambiguous measurements of magnetic fields inside LDC's

- **Experiments by Law *et al.*[1] and Courtois *et al.*[2] give very different results using similar diagnostics and driving laser parameters**



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

600 T, $I\lambda^2 \sim 2\times10^{16}$ (μm^2 W/cm^2)
0.25 mm radius coil

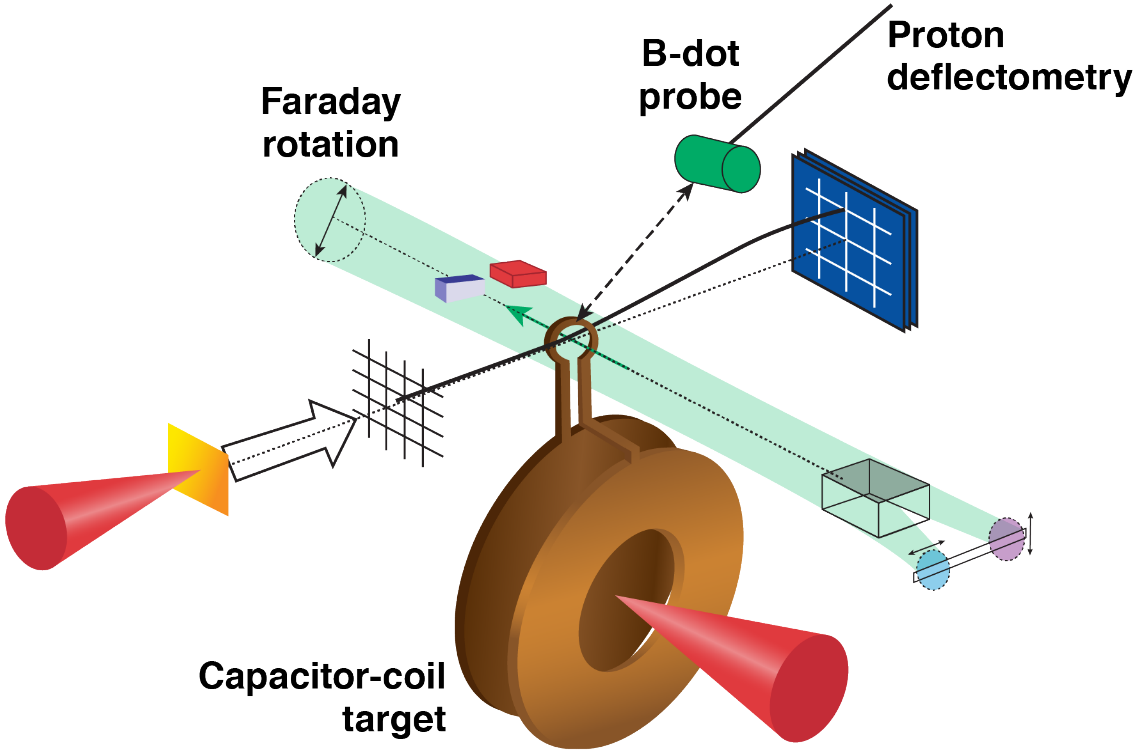


[2]C. Courtois *et al.*, J. Appl. Phys. 98, 054913 (2005).

7 T, $I\lambda^2 \sim 4\times10^{16}$ (μm^2 W/cm^2)
1.25 mm radius coil

Current diagnostics give conflicting and ambiguous measurements of magnetic fields inside LDC's

- Santos *et al.*[3] measured fields of 95, 450, and 600 T for the same types of coils using radiography, Faraday rotation, and B-dot probes, respectively



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

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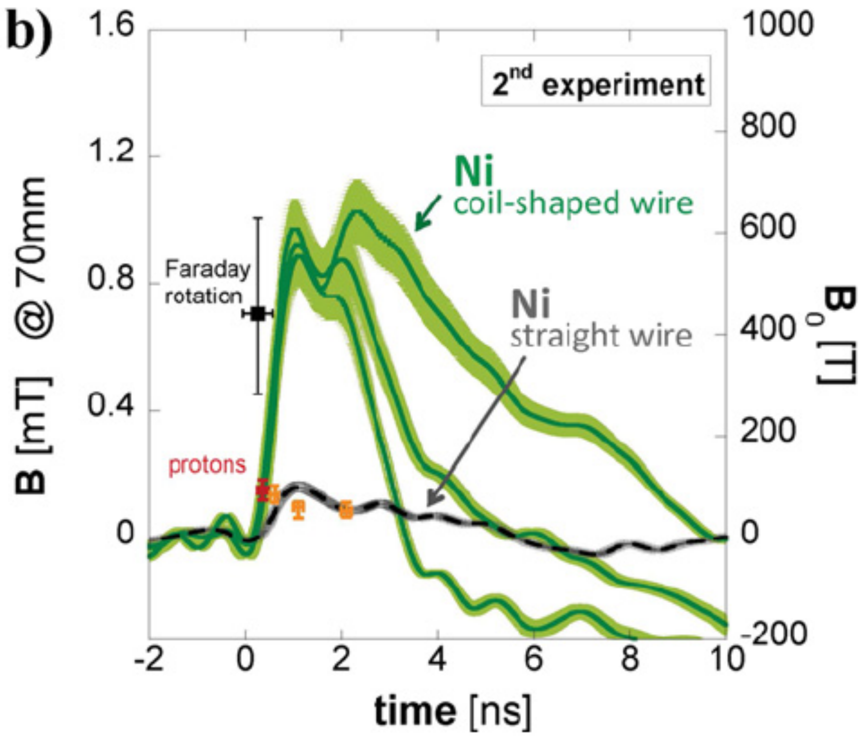

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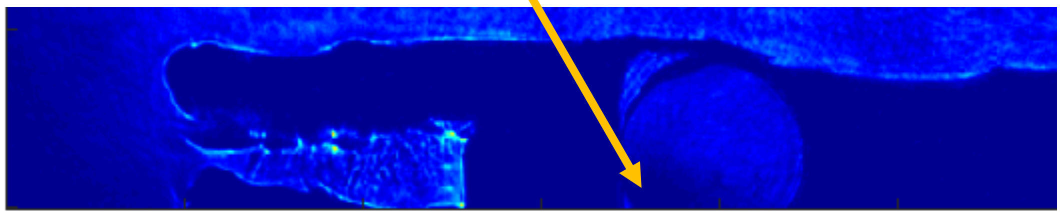
Outline

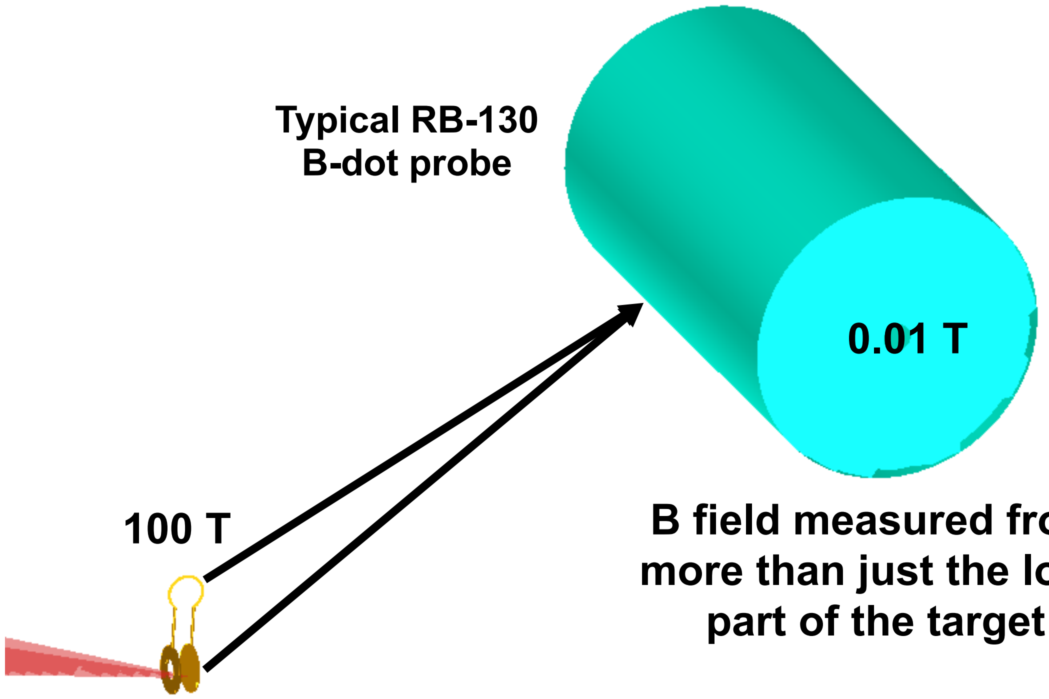
- Laser-driven coils overview
- **Electric- and magnetic-field diagnostics**
  - **B-dot probes and Faraday rotation**
  - **transverse proton radiography**
  - **axial proton radiography**
- Double- and single-plate laser-coil–driven coil experiments
- Discussion, future directions, and conclusions

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 inadvertently measure fields from the laser interacting with the disk and other sources

Faraday crystal blanking inside LDC*





B field measured from more than just the loop part of the target

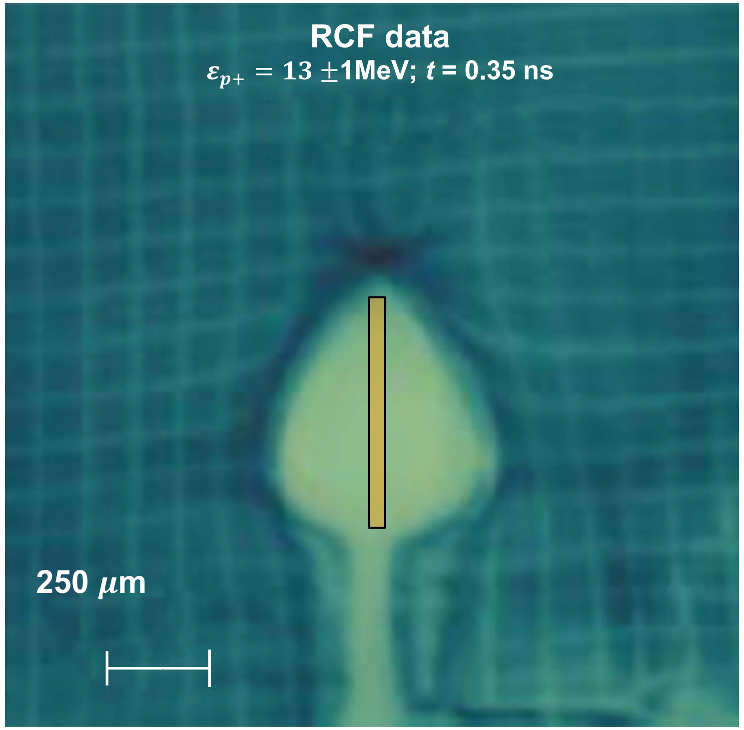
* Data from J. Moody and B. Pollock campaign on OMEGA EP

Transverse proton radiography fails to probe the region of interest in the presence of strong magnetic and electric fields

- Protons traveling transverse to the coil should see the greatest deflection from the axial field and create a void

- The void significantly decreases the information gained about conditions in the center of the loop

- There is ambiguity in what field causes the creation of a proton void; electric and magnetic fields can both duplicate the features seen



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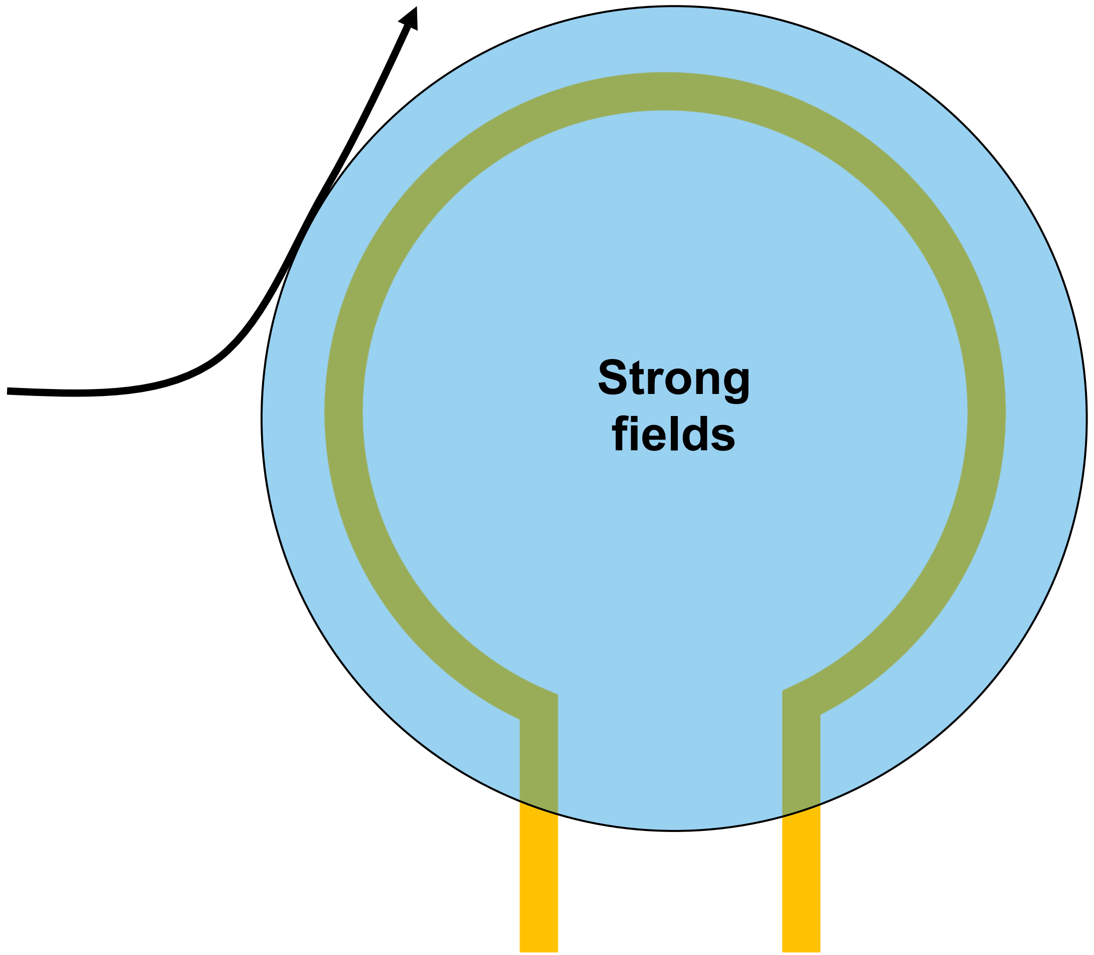

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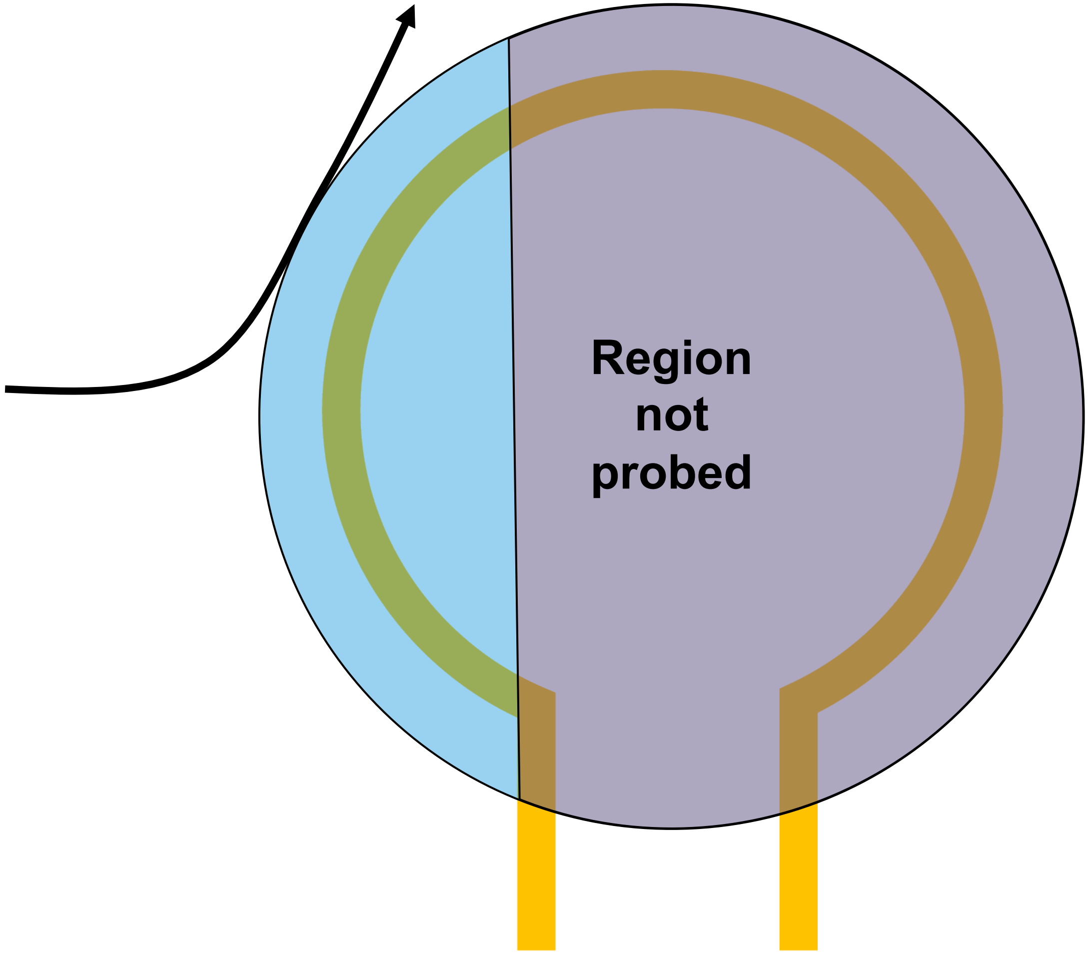

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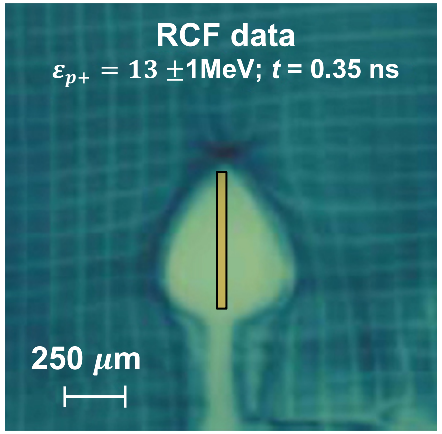

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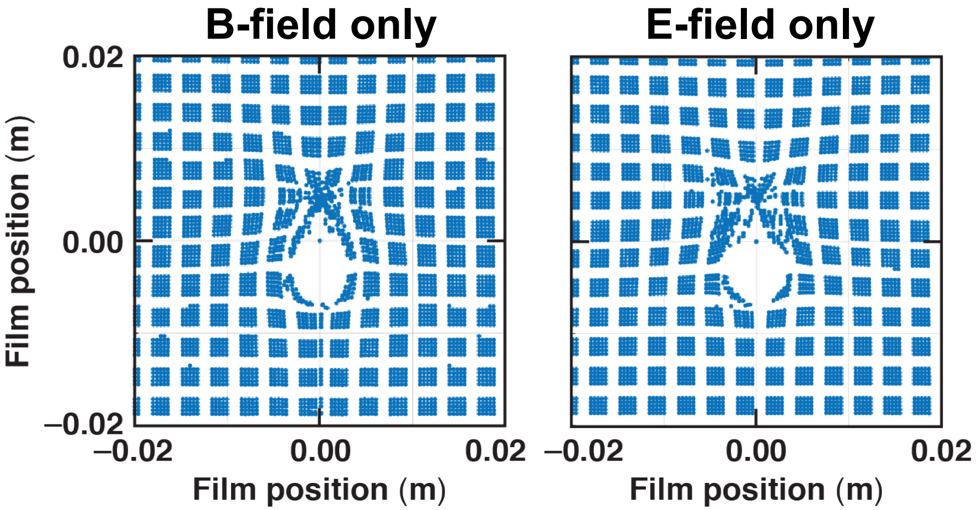

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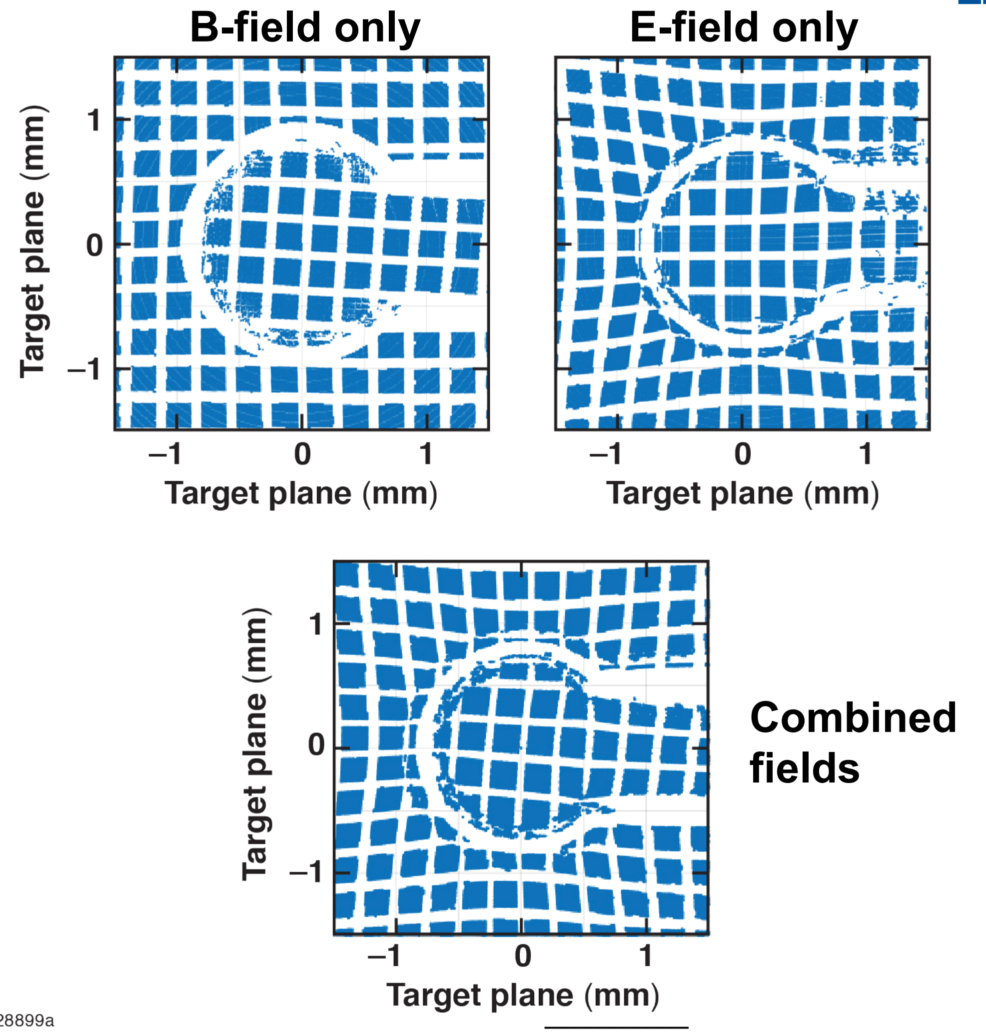
Axial proton radiography can answer all of the concerns for transverse radiography

- Electric fields along the coil will cause protons to be focused or defocused
- Magnetic fields generated by a current 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
- See reference* for generating synthetic radiographs



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*J. L. Peebles *et al.*, Phys. Plasmas 27, 063109 (2020).

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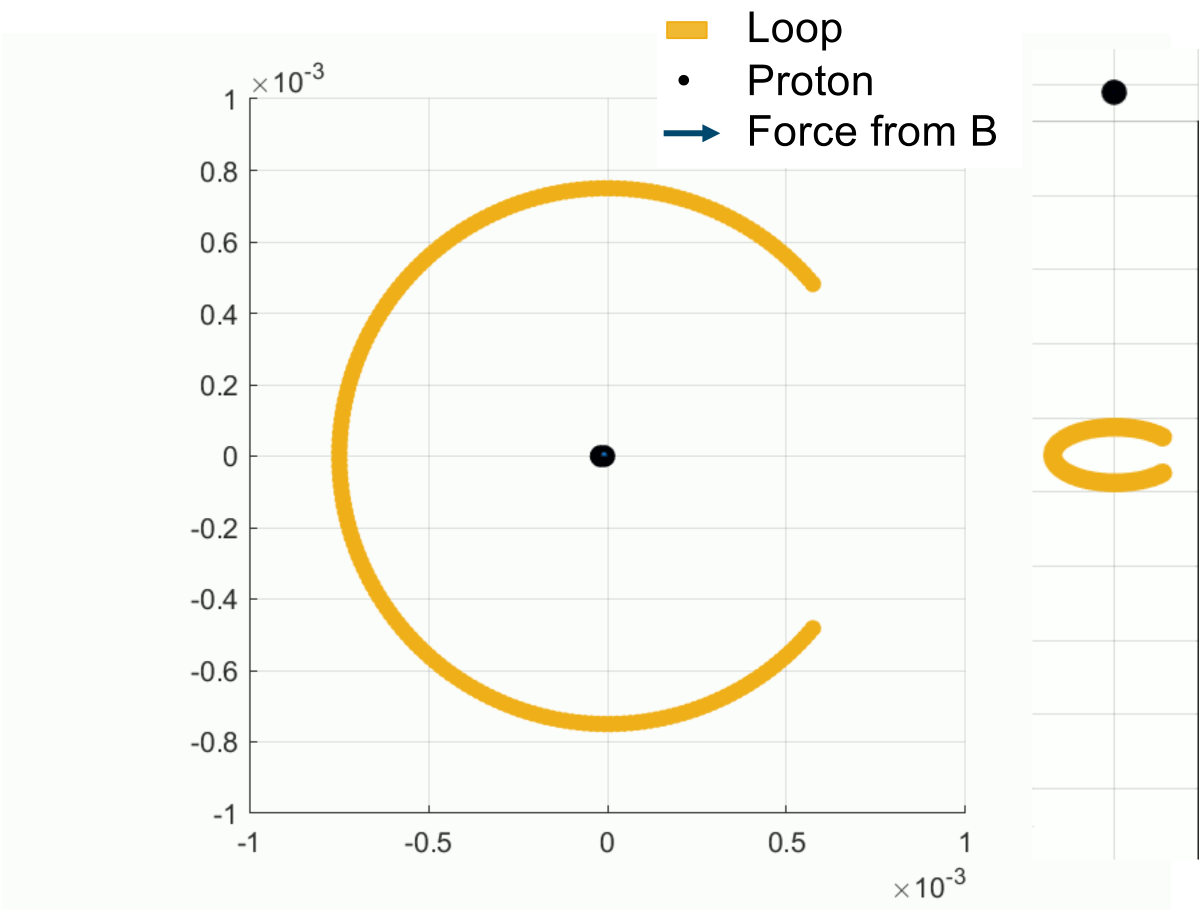

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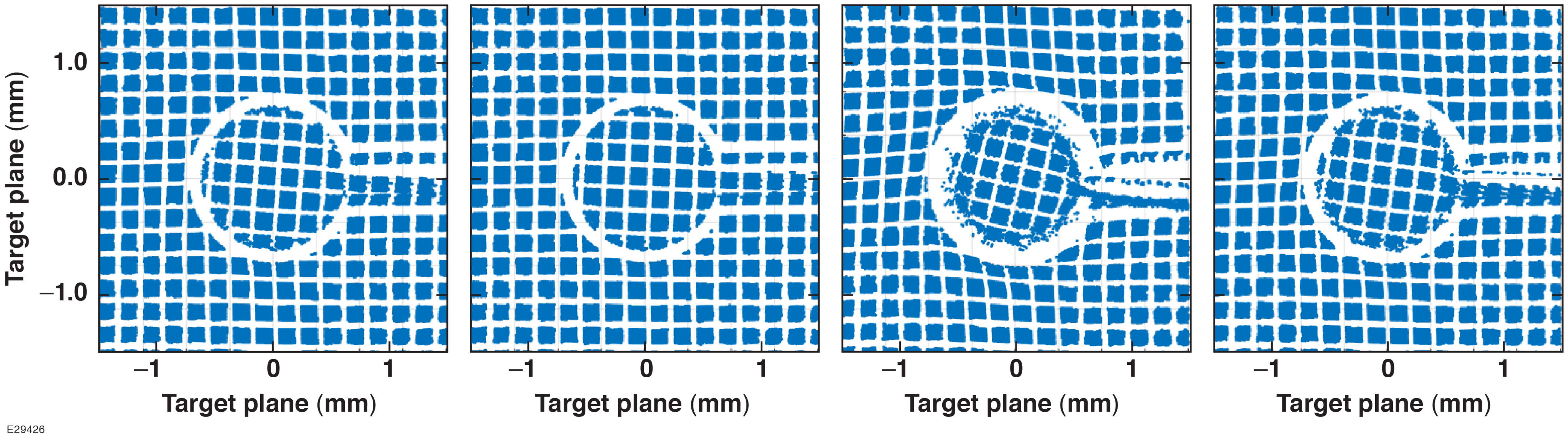
Given uniform fields and limited electric fields, axial radiography has potential to resolve a wide range of field strengths



10 MeV protons
50 T Field

30 MeV protons
50 T Field

10 MeV protons
150 T Field

30 MeV protons
150 T Field

Rotation of the mesh given a uniform current around a loop could be distinctly measured at 100s of T given sufficient proton energy

$$\theta^{\circ}_{\mathrm{rot.}} \approx \frac{0.23 I_{\mathrm{kA}}}{r_{\mathrm{mm}}^{0.27}\sqrt{\mathcal{E}_{\mathrm{MeV}}}}$$

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Outline

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- Electric- and magnetic-field diagnostics
  - B-dot probes and Faraday rotation
  - transverse proton radiography
  - axial proton radiography
- **Double- and single-plate laser-coil–driven coil experiments**
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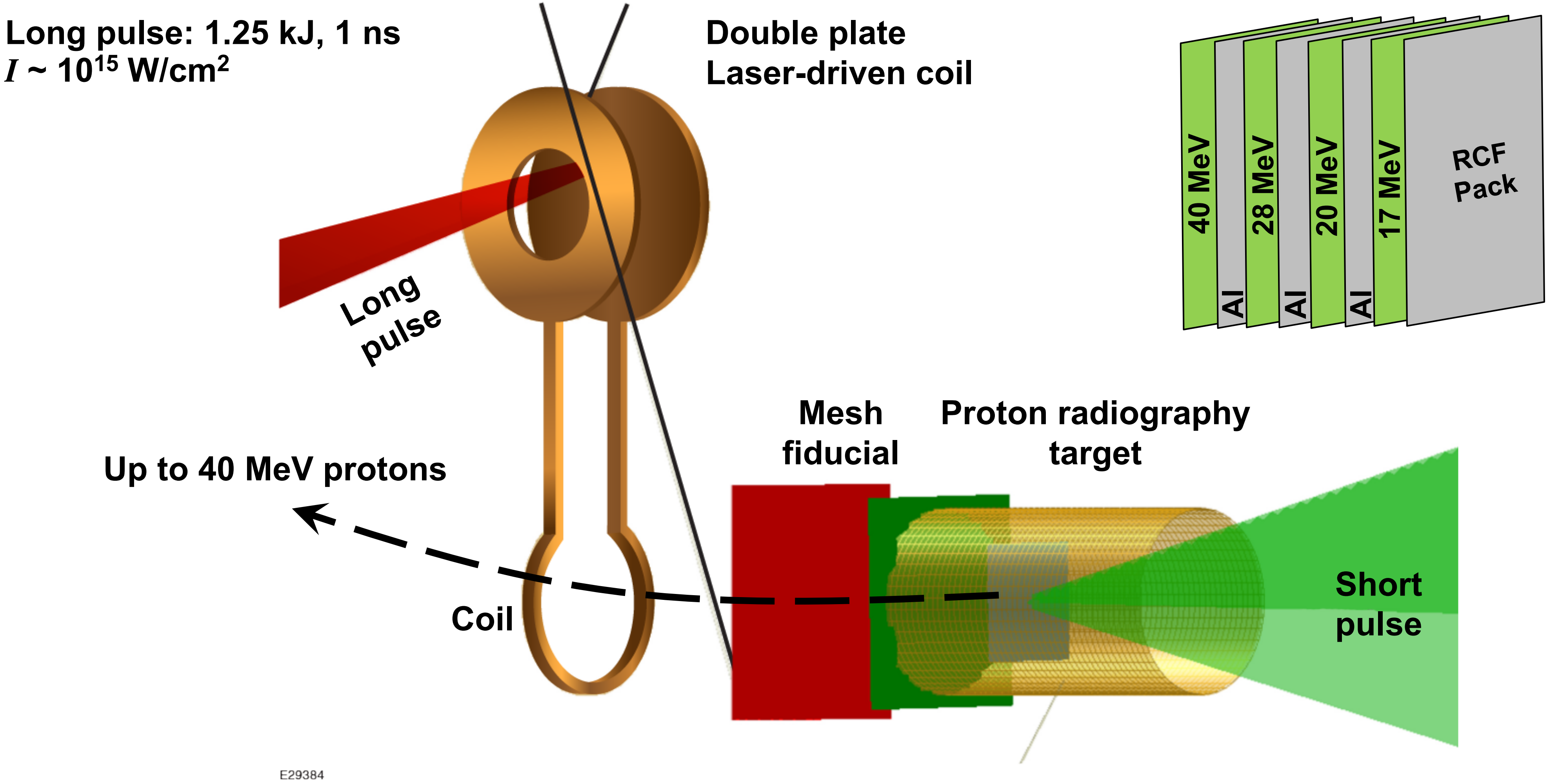
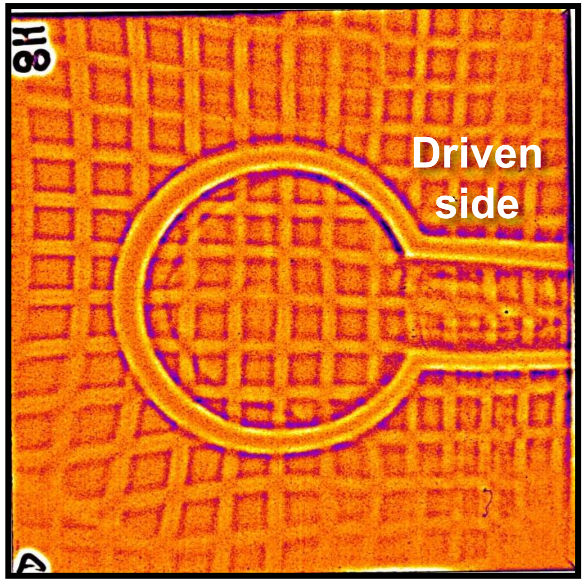
Double-plate LDC's were tested with a larger (0.75-mm) radius coil for easier probing



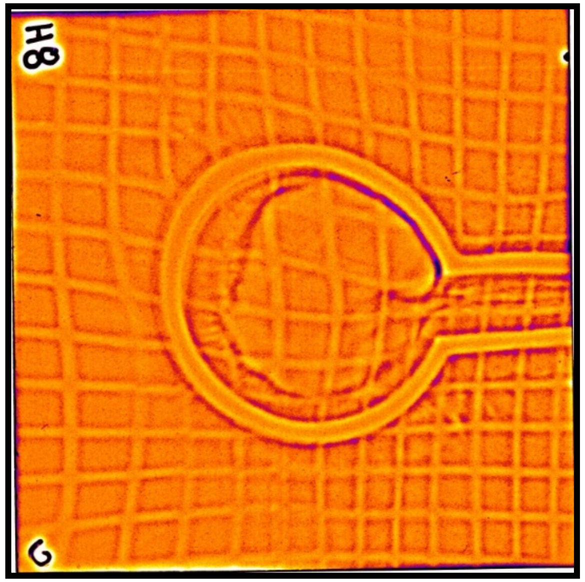
Radiographs consistently showed no notable magnetic field in the loop for the double plate coil types

- The double-plate LDC seemed to generate no significant magnetic field
- The single-plate LDC generated an ambiguous deflection that required more analysis
- Electric fields are generated by electrons being ejected, forming a sheath, and leaving behind a positively charged coil

Double plate



Single plate



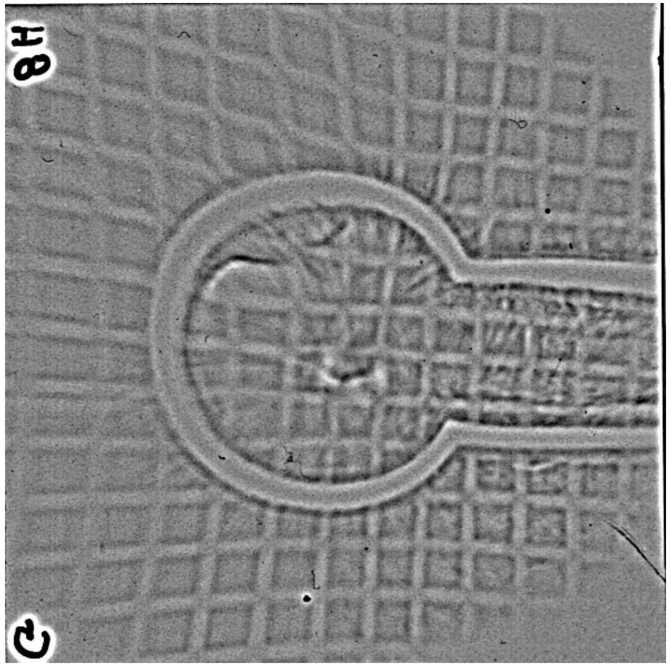
Both targets driven with 1.25 kJ, probed at 1.1 ns, just after the 1-ns driving laser

J. L. Peebles *et al.*, Phys. Plasmas 27, 063109 (2020).

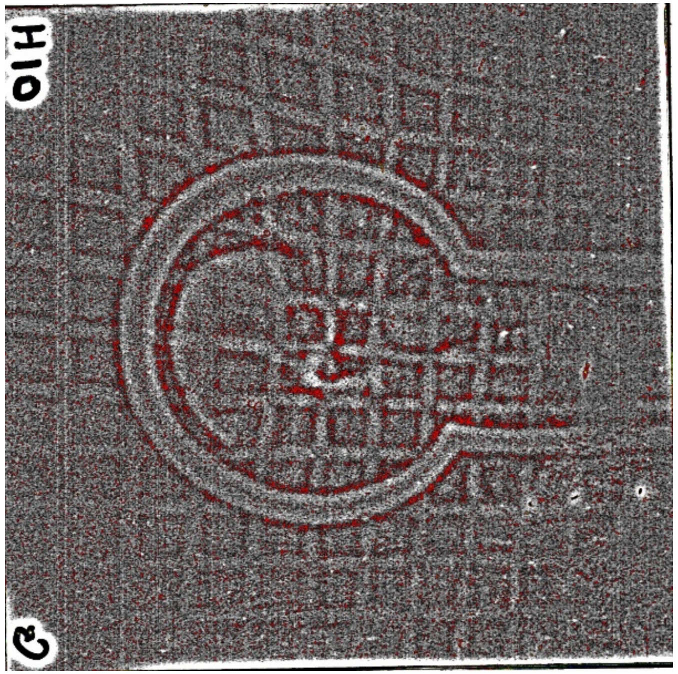
Radiographs consistently showed no notable magnetic field in the loop for the double plate coil types

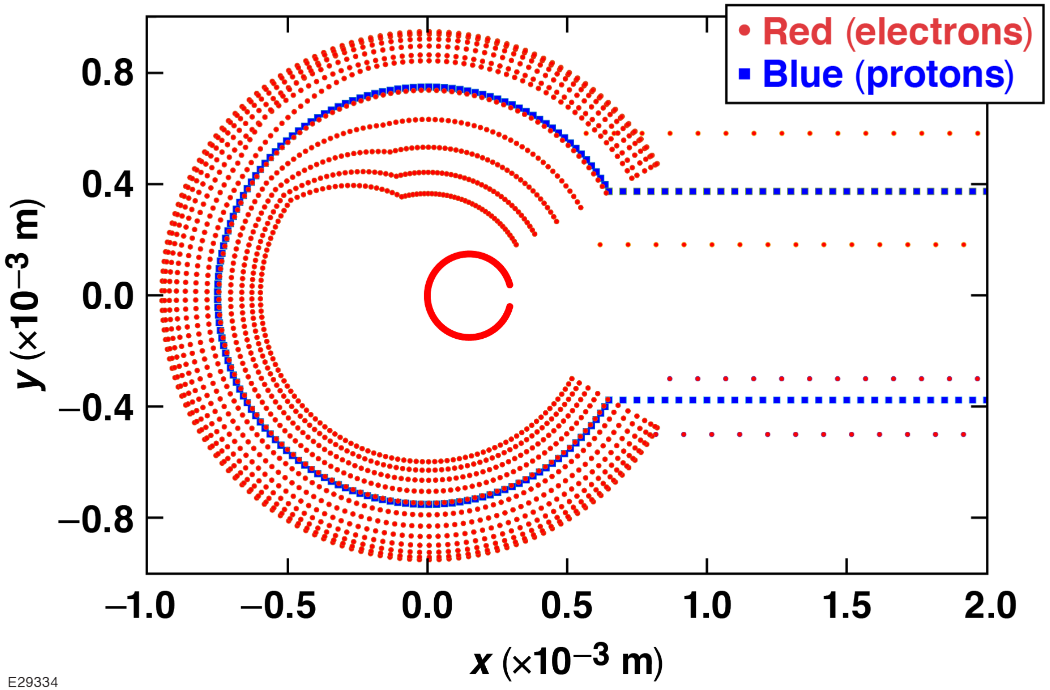
- Reproduction of the radiographs at multiple proton energies required no magnetic field
- Electric field is calculated by explicitly placing charge in the simulation

20 MeV



40 MeV





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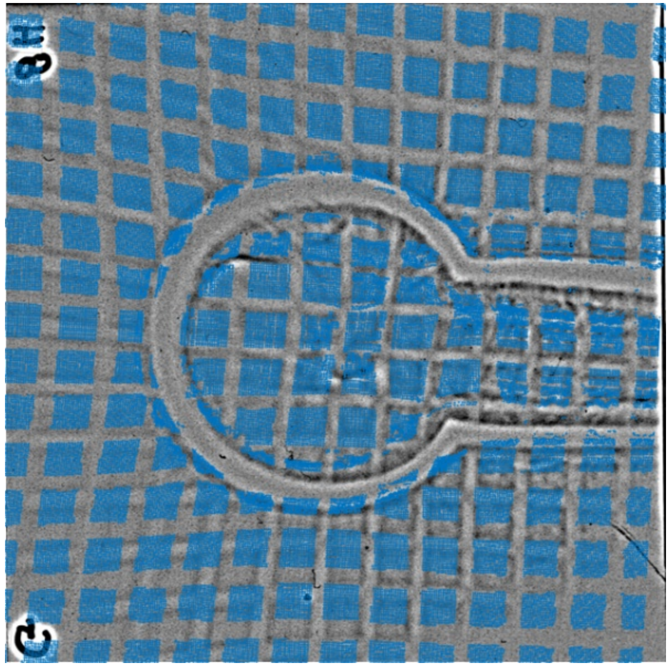

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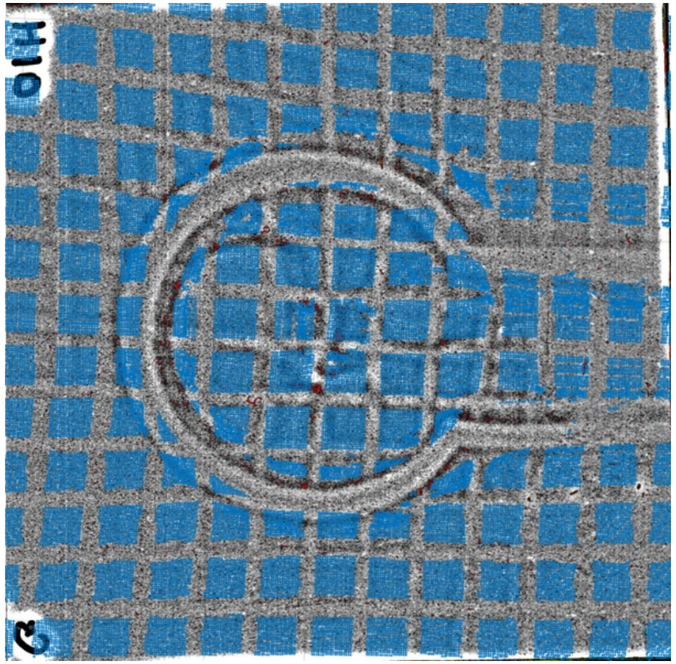
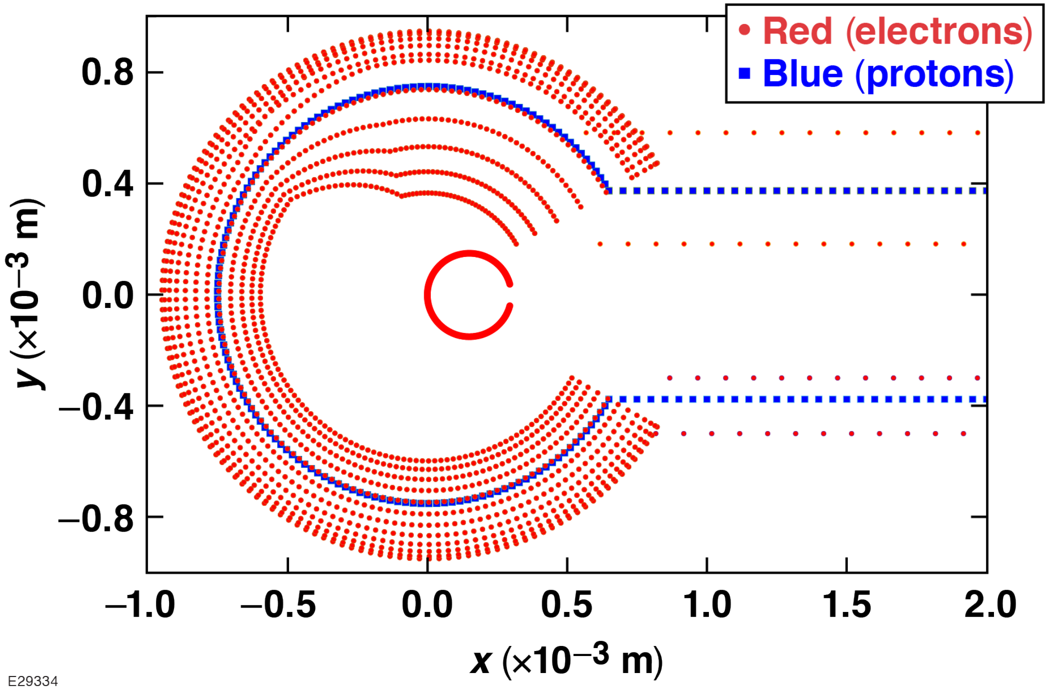
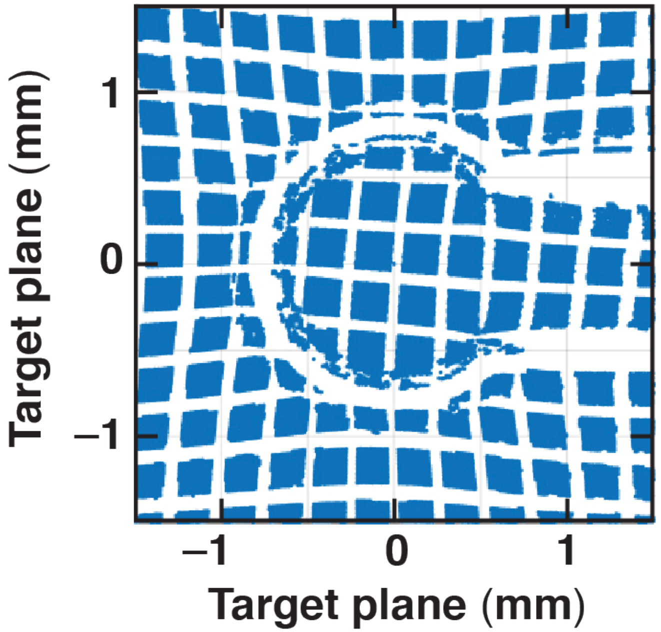


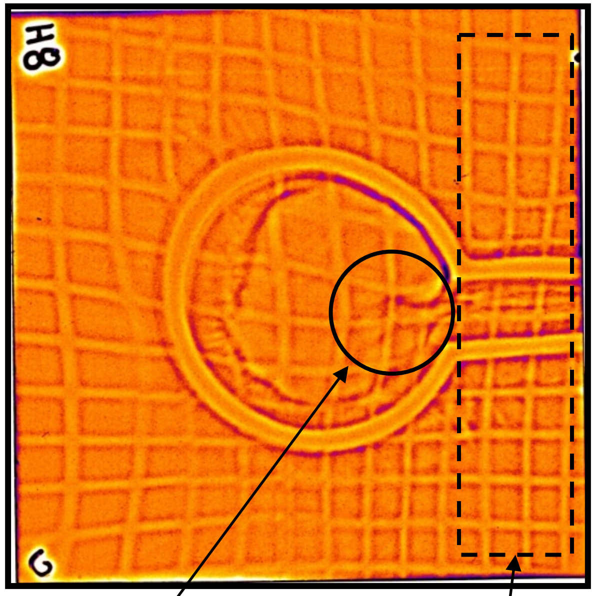


E29334

Single plate coils showed an unusual radiograph, which was not reproducible using assumed field symmetry

- The original assumptions of uniform current and uniform sheath field cannot reproduce the experimental data
- Some aspects of magnetic and electric fields are subjectively present
- It should be noted that this data directly contradicts many assumptions of symmetry used in analyzing a transverse probe



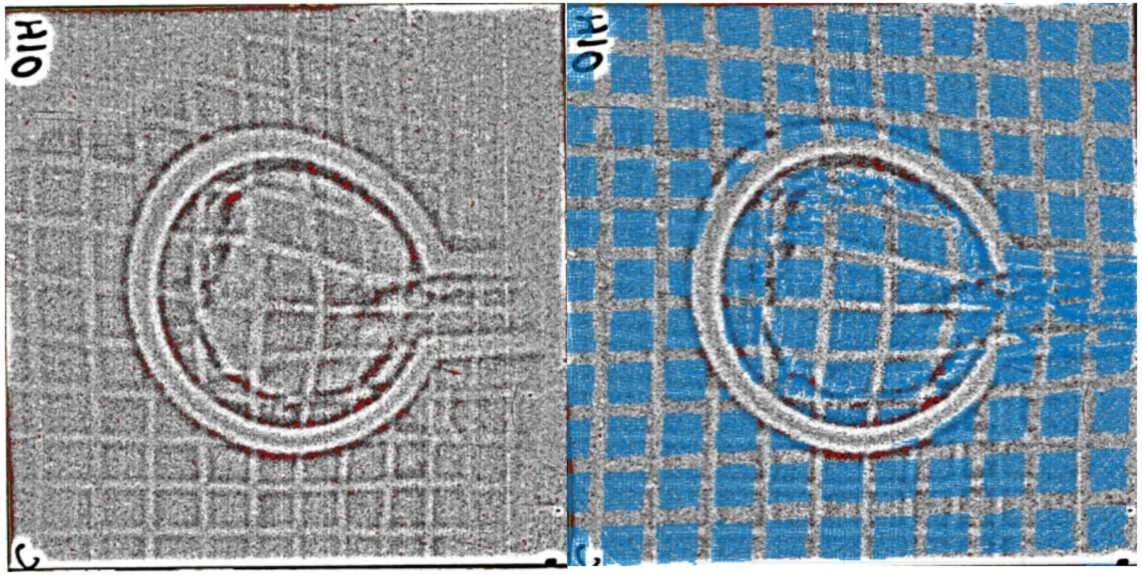


Pinching indicative of E field

Mesh twist indicative of B field

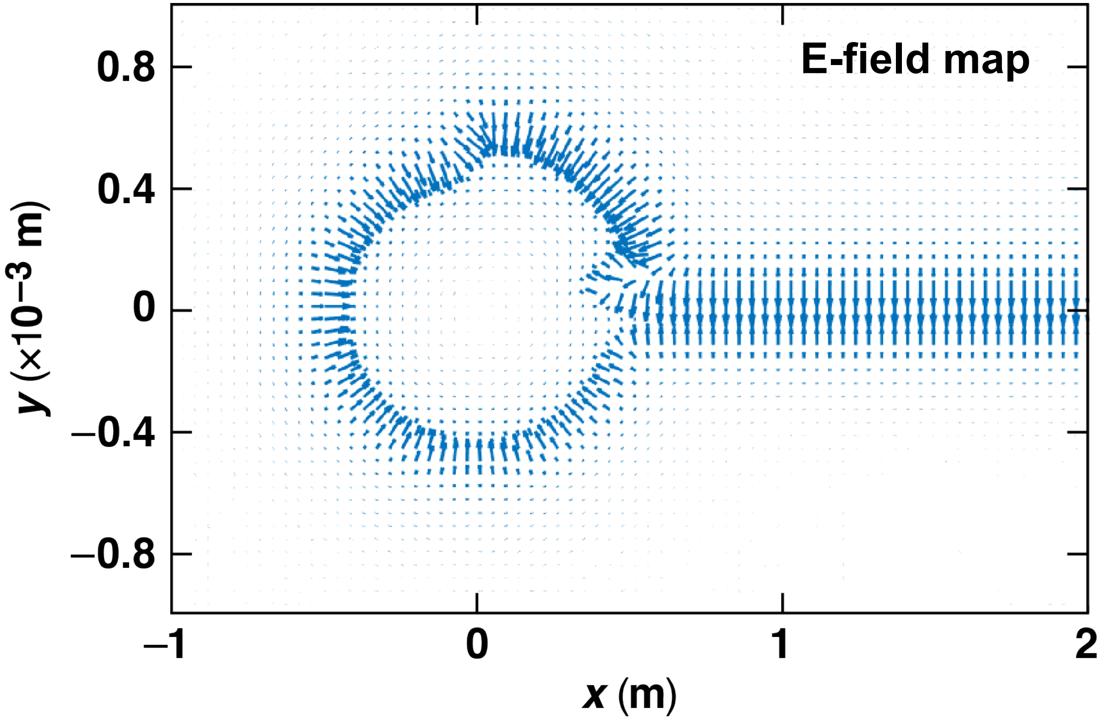
*J. L. Peebles *et al.*, Phys. Plasmas 27, 063109 (2020).

Proton tracing was able to reproduce the single-plate experimental data reasonably well



Original radiograph (bandpassed)

Synthetic overlay



E29374

Electric and magnetic fields were calculated using explicitly placed charges and currents

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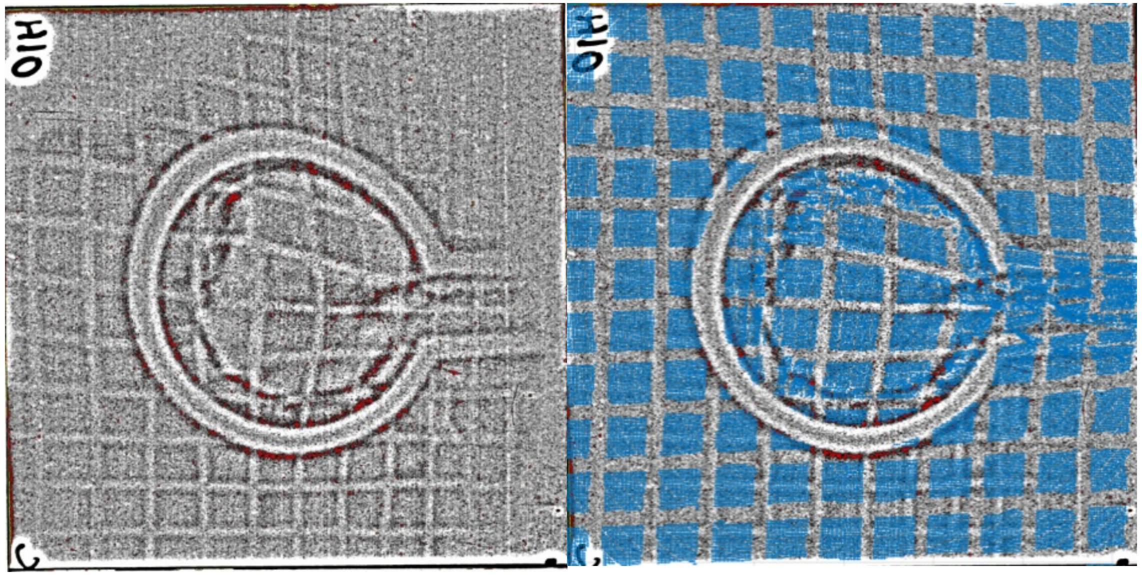

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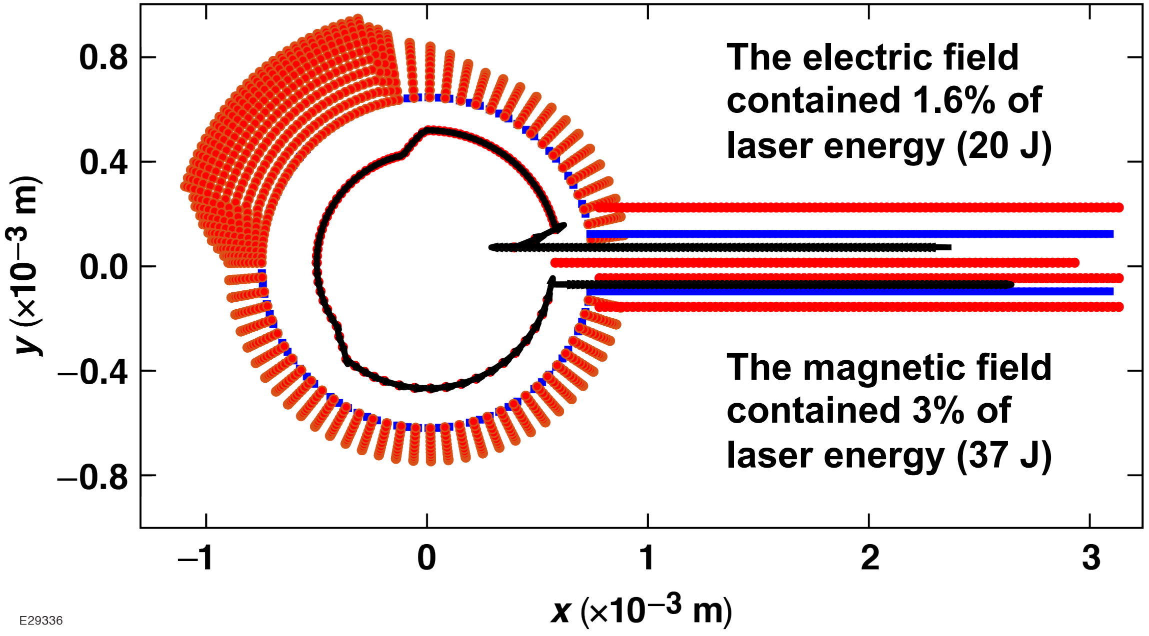

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Charge (red and blue dots) and current (black) was explicitly placed in the experimental geometry to produce fields used in creation of the synthetic radiographs

A nonuniform current leading to a 80±13 T field in the center of the loop was inferred from the radiographs.*

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  - transverse proton radiography
  - axial proton radiography
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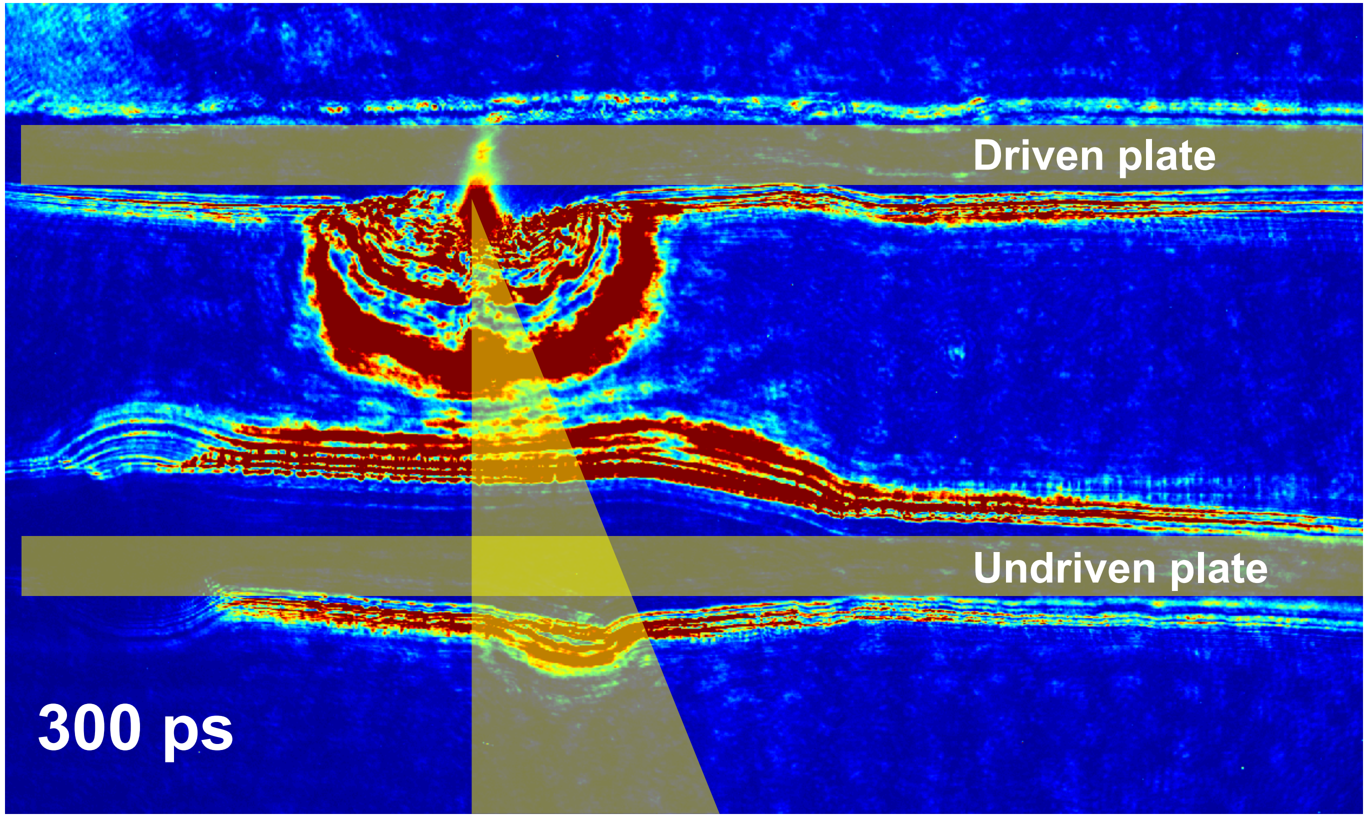
The lack of current for the double-plate coil is explained by expanding plasma from both plates and is diagnosed using 4ω angular filter refractometry* (AFR)

- 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.*, in *CLEO: 2013*, OSA Technical Digest (online) (Optical Society of America, Washington, DC, 2013), Paper ATu3M.3.

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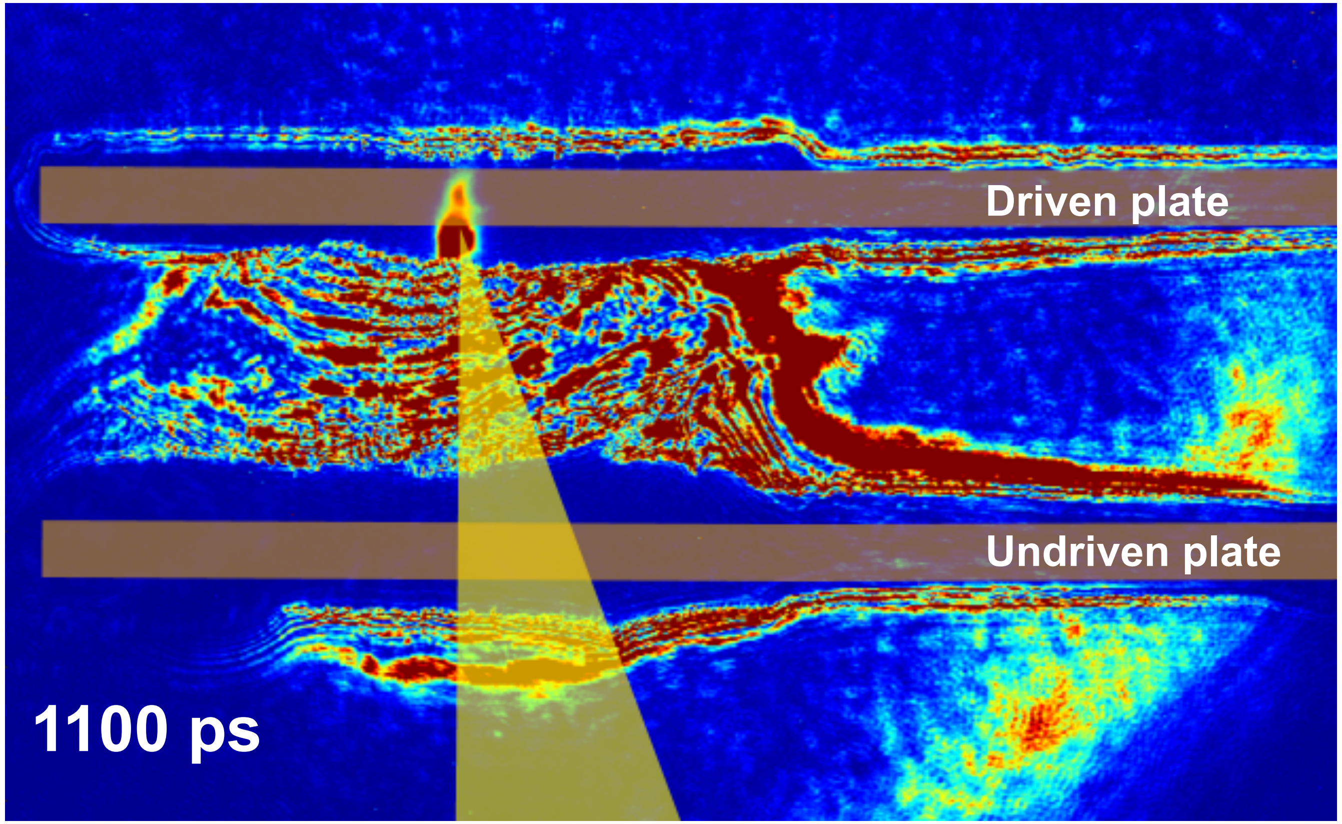

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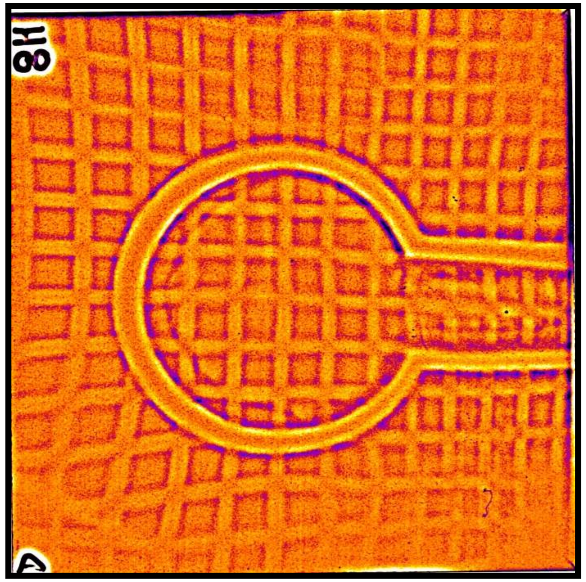
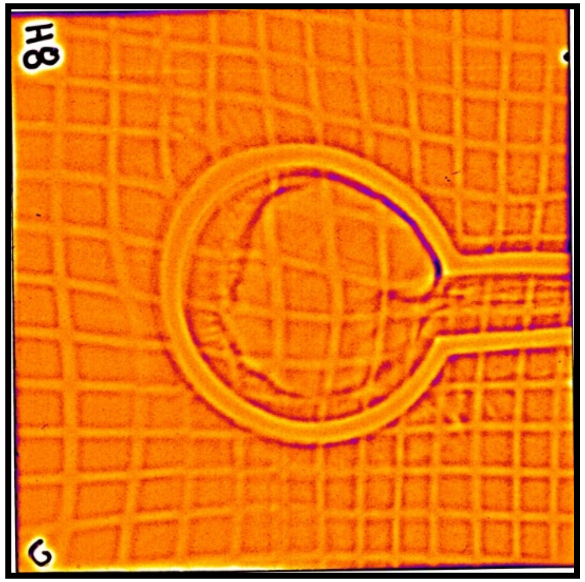
The single-plate system had an anomalous current that appeared to rise *after* the laser turned off

- Experiments measuring up to 0.8 ns into a 1-ns laser pulse showed no significant magnetic field
- Time evolution is contrary to previous publications

0.6 ns



1.1 ns



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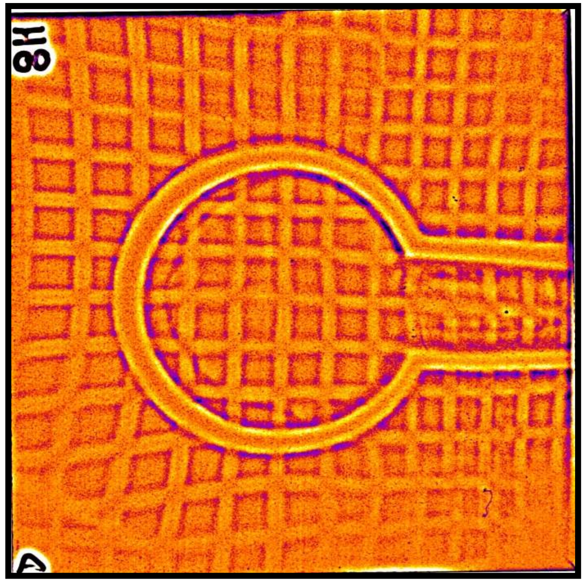

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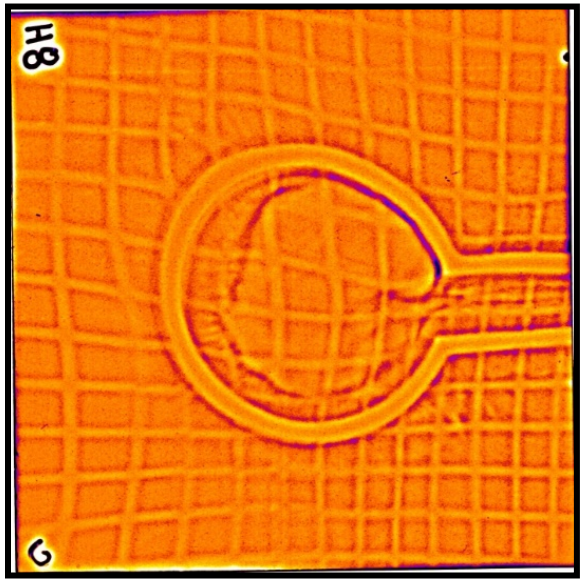

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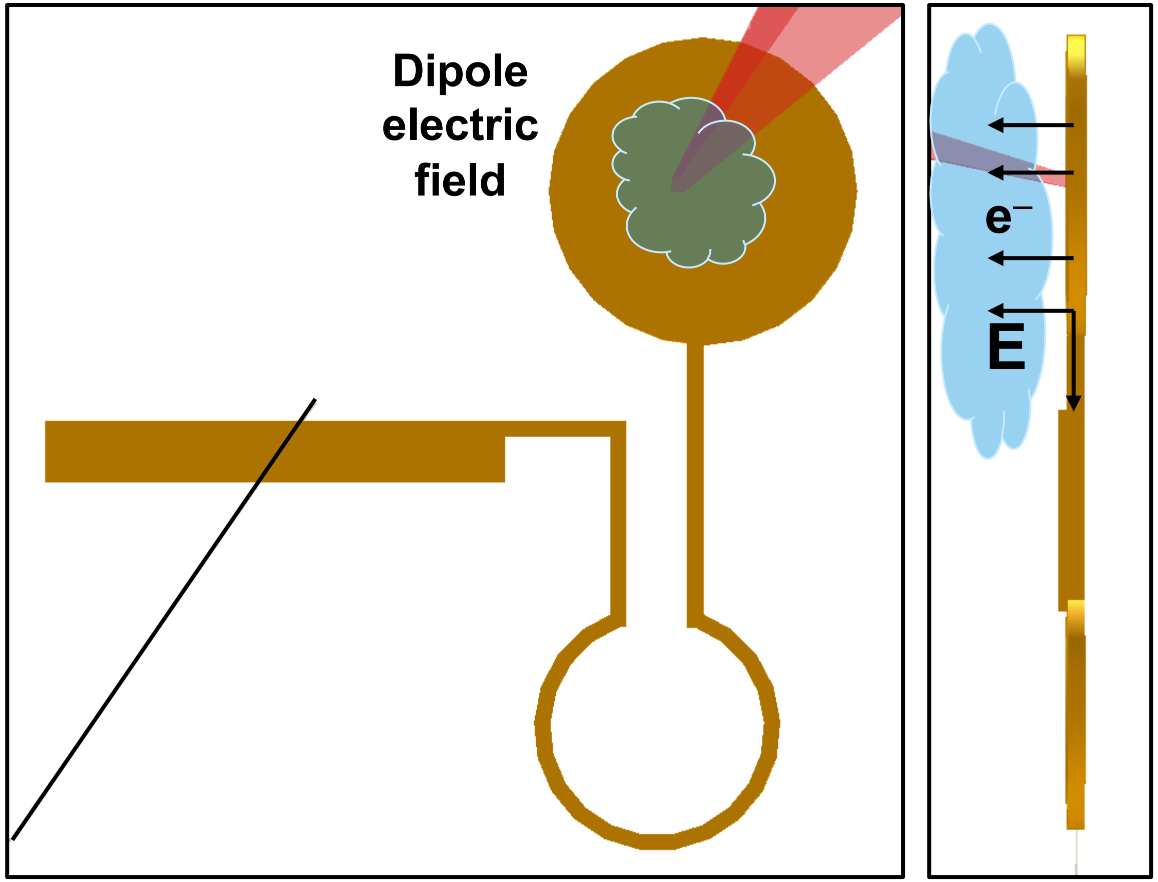
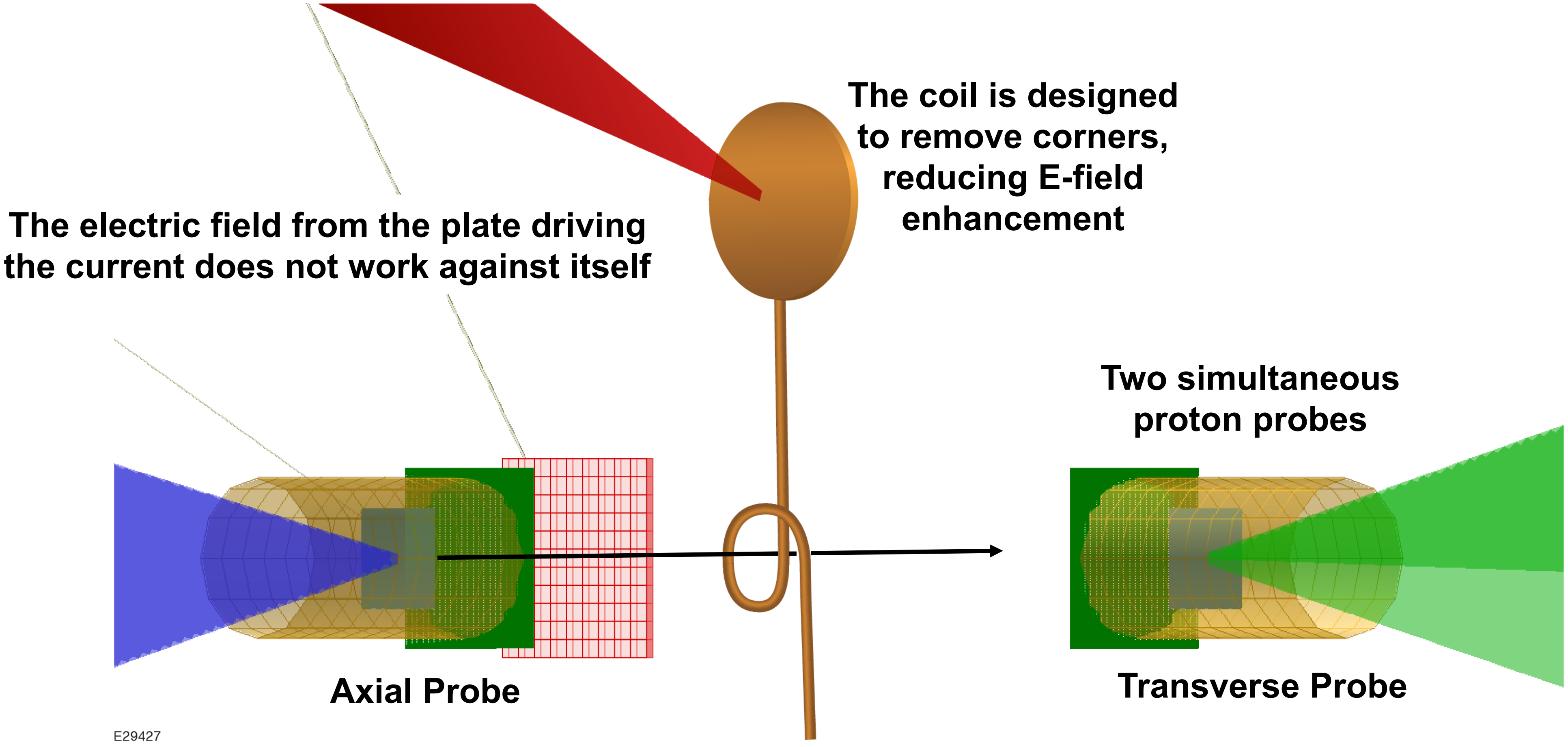
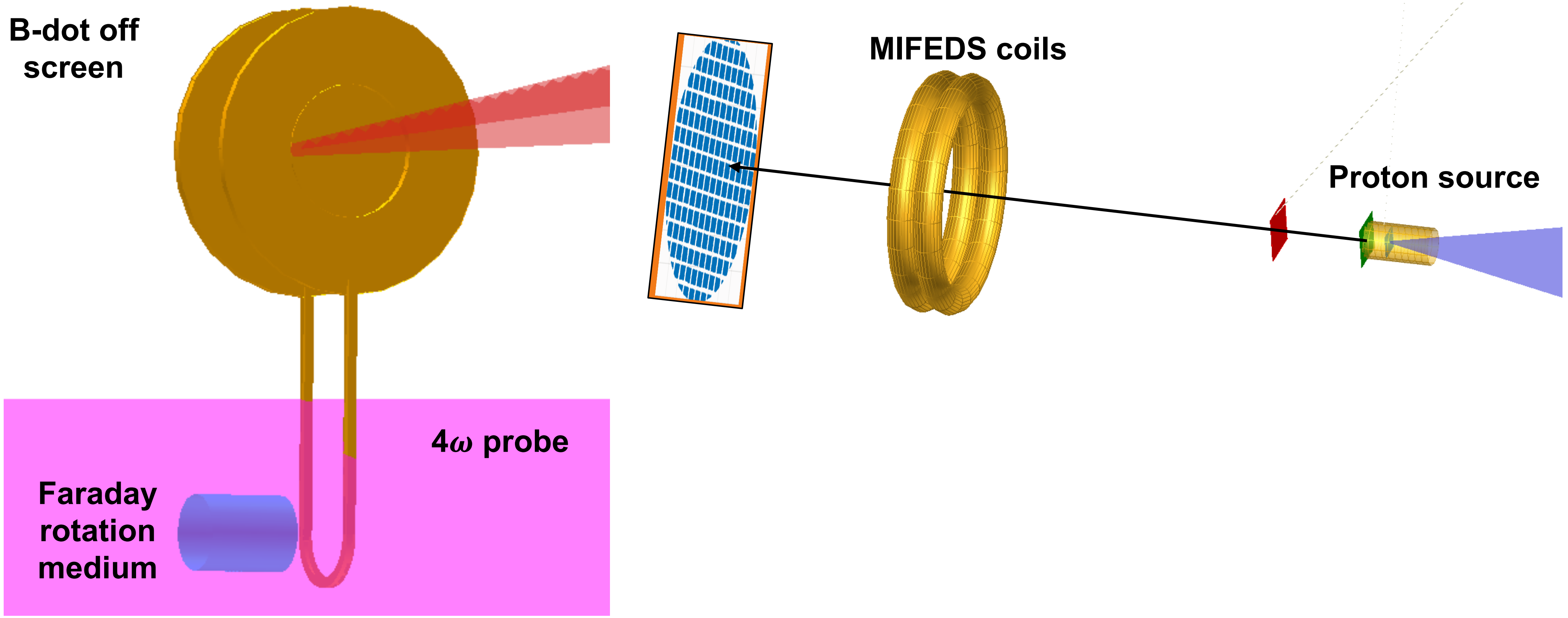
- Time evolution is contrary to previous publications
- An initial explanation for no field during the laser pulse is that both wires effectively see the same dipole electric field
- Electrons only begin to equalize potential after the laser turns off



Future experiments will take lessons learned to better understand proton radiography and diagnose the 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.

MIFEDS: magneto inertial fusion electrical discharge system

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- Synthetic proton radiography reconstruction helps remove degeneracy between electric and magnetic fields in LDCs
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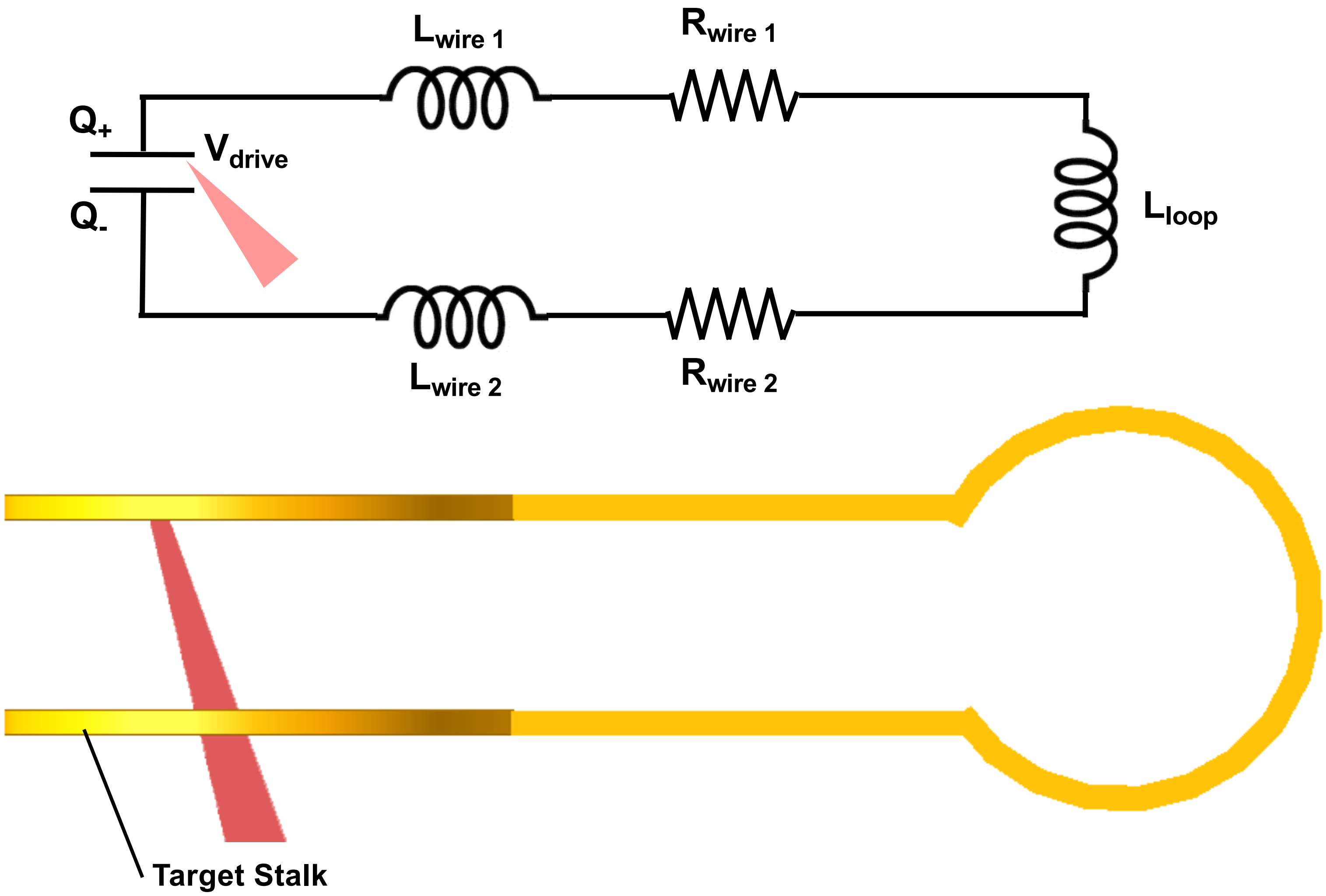
Backup

A few problems in circuit assumptions for LDCs, what defines the circuit?

- **Assume the laser drives a potential difference with a certain amount of charge separation (capacitance)**



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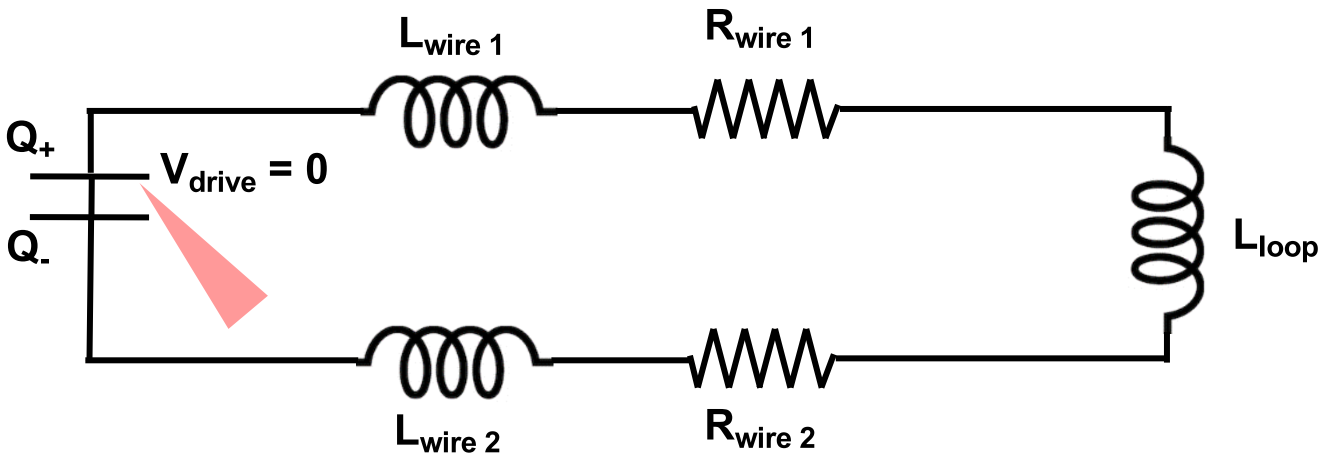
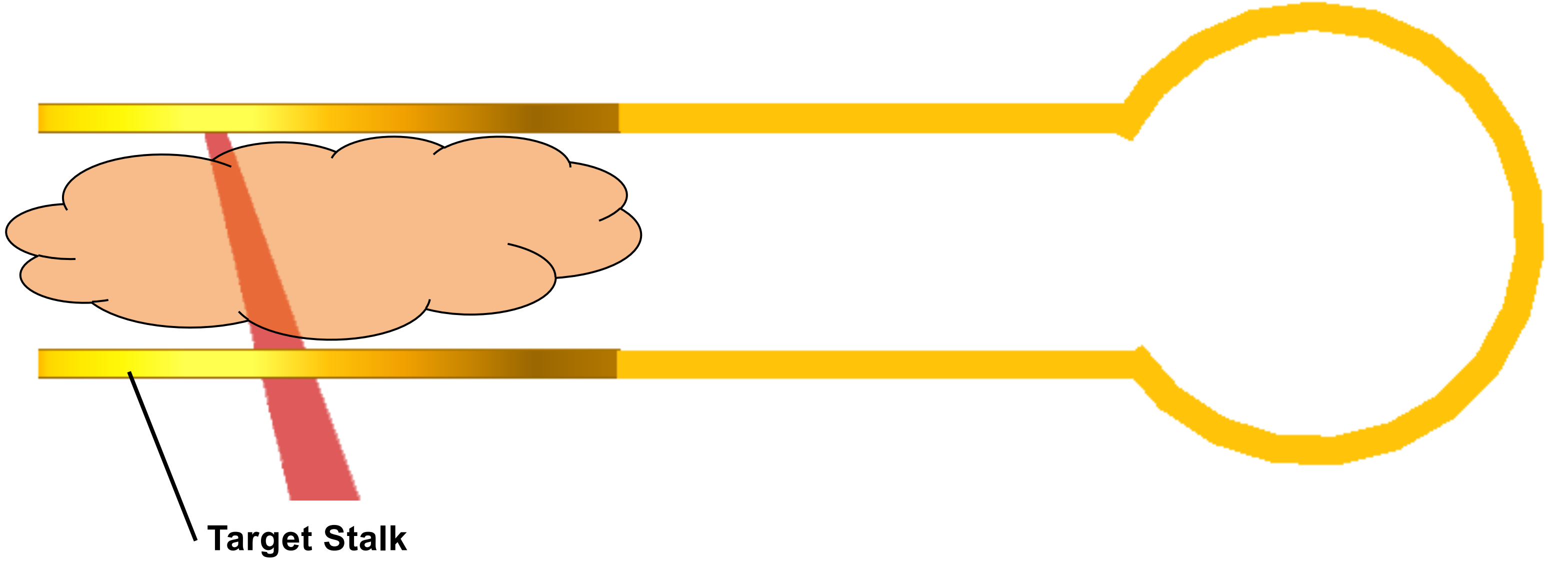
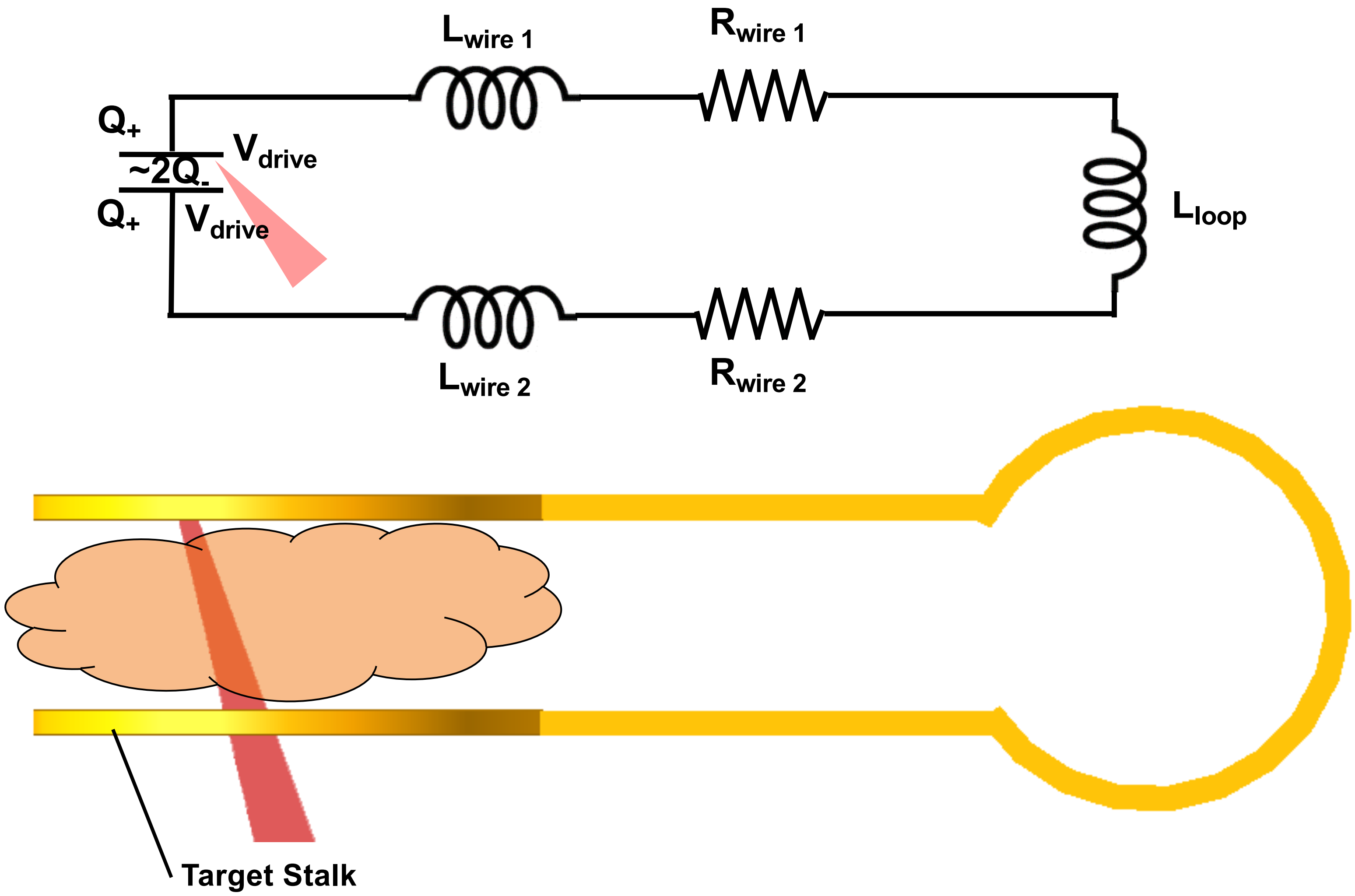
- Assume the laser drives a potential difference with a certain amount of charge separation (capacitance)
- A conductive plasma bridging the gap with > 100 kV potential would cause a clear short circuit





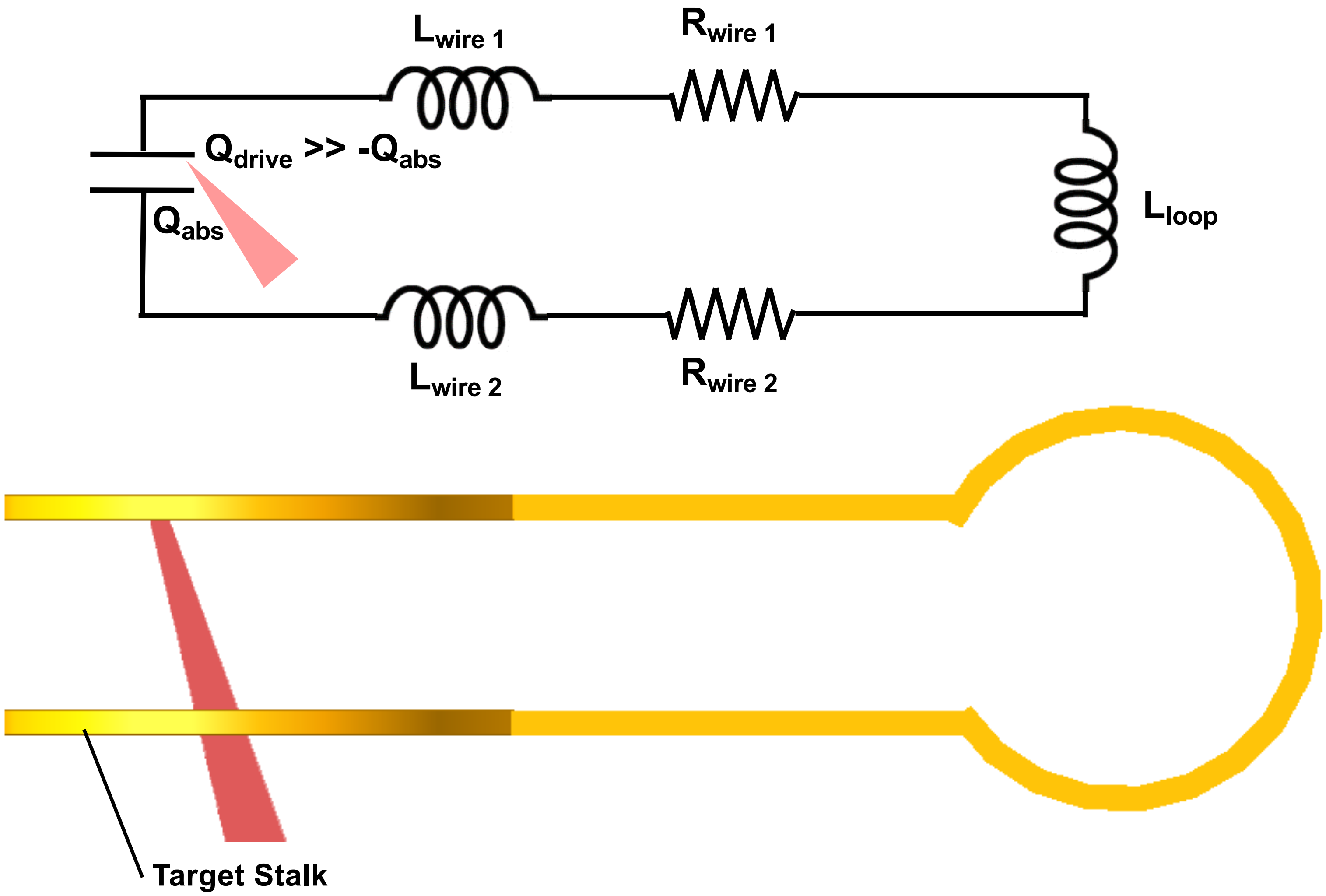
A few problems in circuit assumptions for LDCs, what defines the circuit?

- Assume the laser drives a potential difference with a certain amount of charge separation (capacitance)
- Even without a short circuit, the indirect drive of the second plate causes there to be no voltage difference



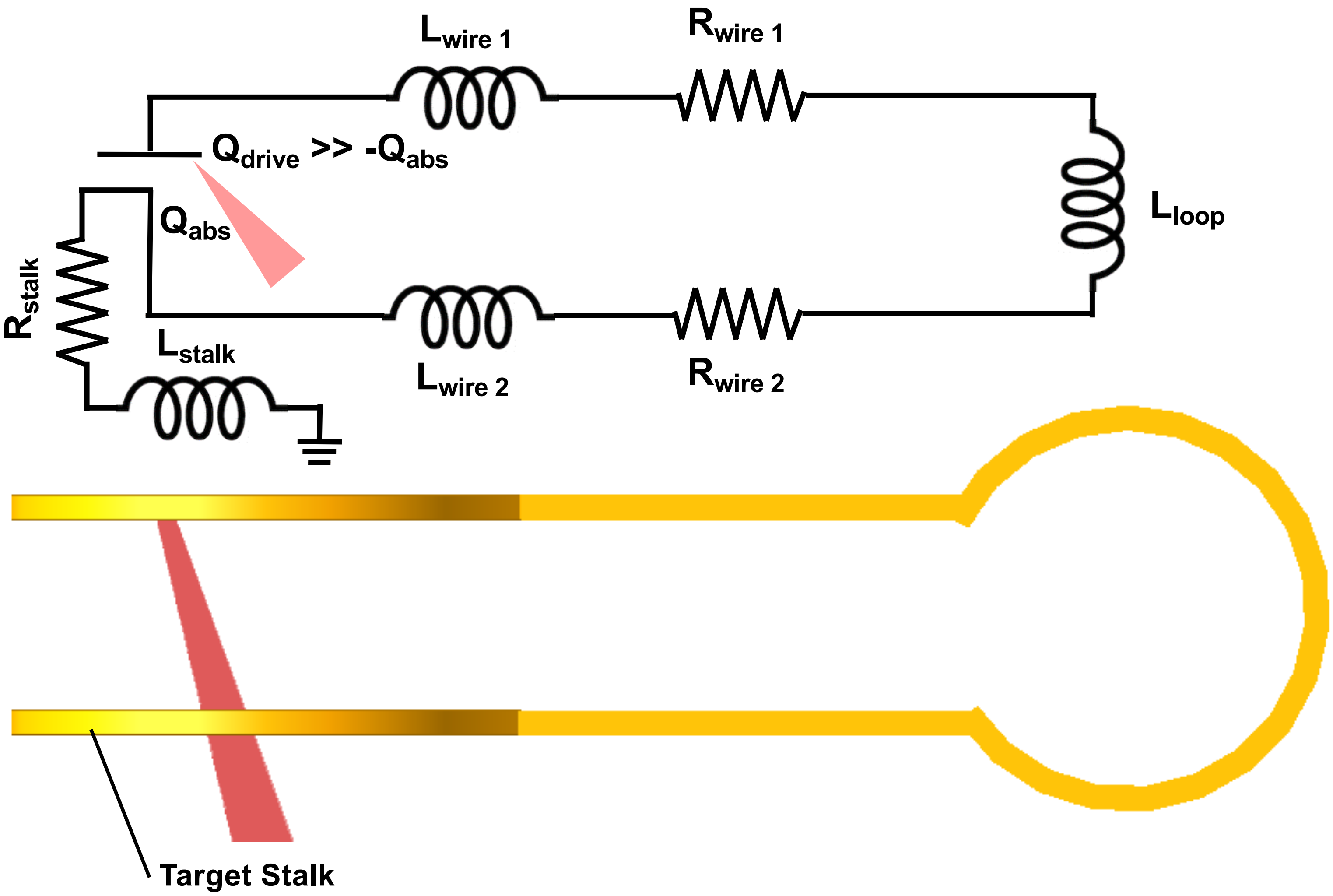
A few problems in circuit assumptions for LDCs, what defines the circuit?

- **Assume the laser drives a potential difference with a certain amount of charge separation (capacitance)**
- **Let's pretend those aren't problems, what if the absorbed charge is not 100% on the undriven plate?**



A few problems in circuit assumptions for LDCs, what defines the circuit?

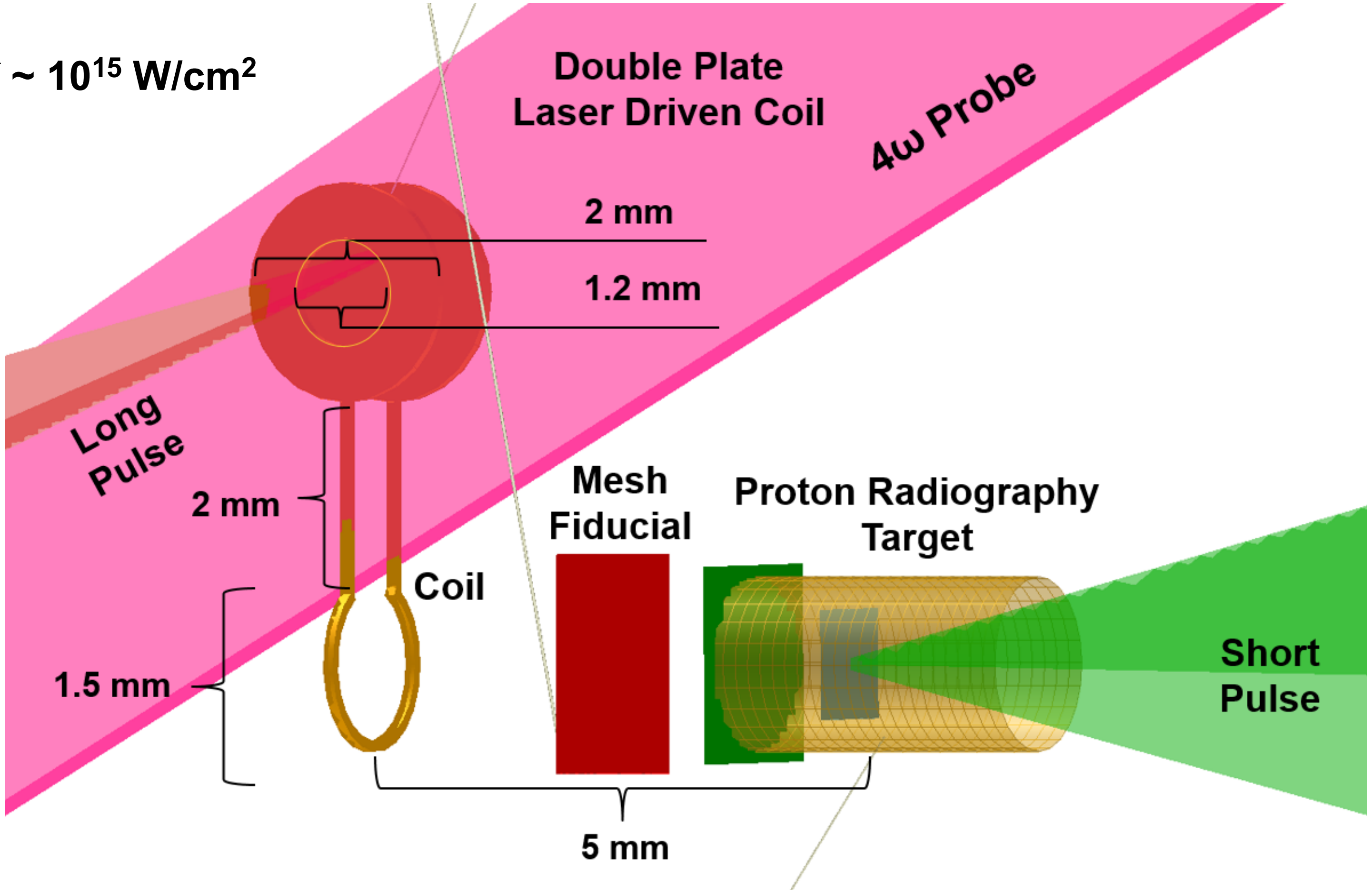
- Assume the laser drives a potential difference with a certain amount of charge separation (capacitance)
- Let's pretend those aren't problems, what if the absorbed charge is not 100% on the undriven plate?
- The circuit is not "closed" until it reaches sufficient ground
- Therefore what is considered the "circuit" will expand to include more of the stalk until a sufficient ground is reached



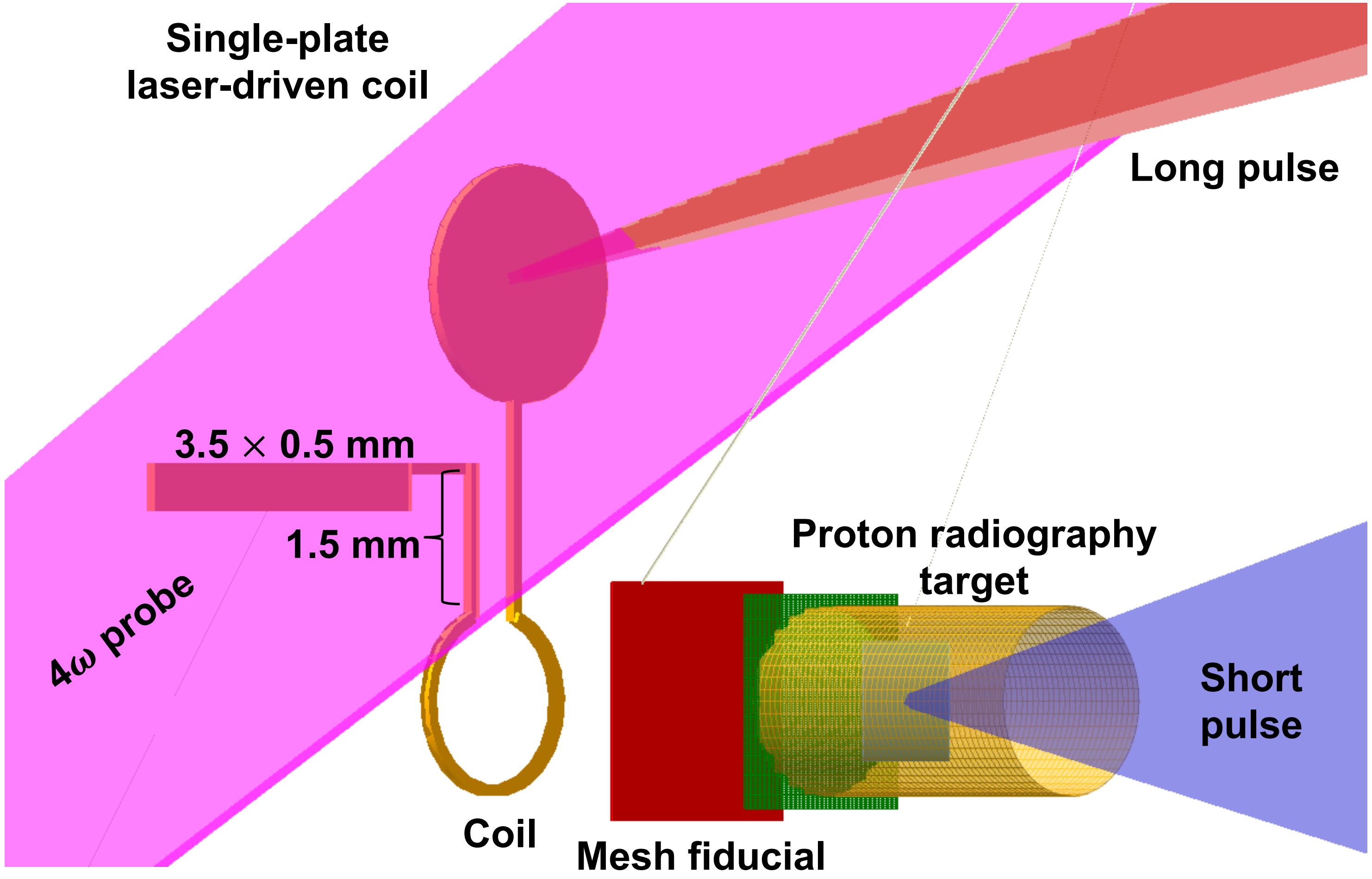
Driving Laser				Coil Design			Field (T)	+	[τ_p (ns)]	
E (kJ)	t (ns)	λ (nm)	I (10^{15}W/cm^2)	d (mm)	Mat.	r (mm)	PRad	B-Dot	Faraday Rot	(kA/T)
0.1	1.0	10000	40	0.3, 0.5	Cu	1.0	–	15, 28	–	1.47
0.1	1.0	10000	40	0.7, 1.0	Cu	1.0	–	41, 16	–	1.47
0.5	1.0	1057	100	0.9	Cu, Ni, Al	0.25	–, 95 [0.35], –	800, 600, 150	–, 450 [0.2], –	0.42
2 @ (0.095, 0.27)	1.3	526	4, 0.8	0.78	Ni	0.25	–,–	–,33	160, –	5.73
2 @ (0.37, 0.5)	1.3	1053	16, 43	0.78	Ni	0.25	–	–	480, 1100	5.73
0.54	2.0	1053	21	0.5	Unknown	0.25	610 [2.3]	620 [2.0]	–	0.42
0.3	1.0	1053	40	0.5	Cu	1.25	–	7.5	–	1.6
0.022	0.08	526	40	0.5	Cu	1.25	–	7.5	–	1.6
0.0005	7.0	1064	0.0007	1.3	Cu	1.0	–	0.001	–	1.6
2 @ 1.25	1.0	351	30	0.6	Cu	0.3	45 [4.1]	–	–	0.44
2 @ 0.375	0.75	351	4	0.5	Au + CH	0.25	200 [1.0]	–	–	1.2
0.01	3×10^{-5}	800	1000	0.5	Ni	0.5	20 [0.05]	–	–	0.89
0.18	2.0	527	0.14	Inf	Cu	0.55	50 [unk.]	–	–	0.97
8 @ (0.063, 0.125)	2.0	351	1.4, 2.8	Inf	Cu	0.55	–	45, 73	–	0.97
8 @ (0.222, 0.246)	2.0	351	5.0, 7.7	Inf	Cu	0.55	–	102, 205	–	0.97
1.3	1.2	351	1.5	0.5	Ni	0.45	–	219	206	1.02
0.001	20	1053	–	0.1	Cu	0.7	–	2	–	1.0
0.022	2.8	532	8	0.5	Cu	0.5	–	–	6.4	1.56
0.022	0.07	532	25	0.5	Cu	0.5	–	–	12.4	1.56

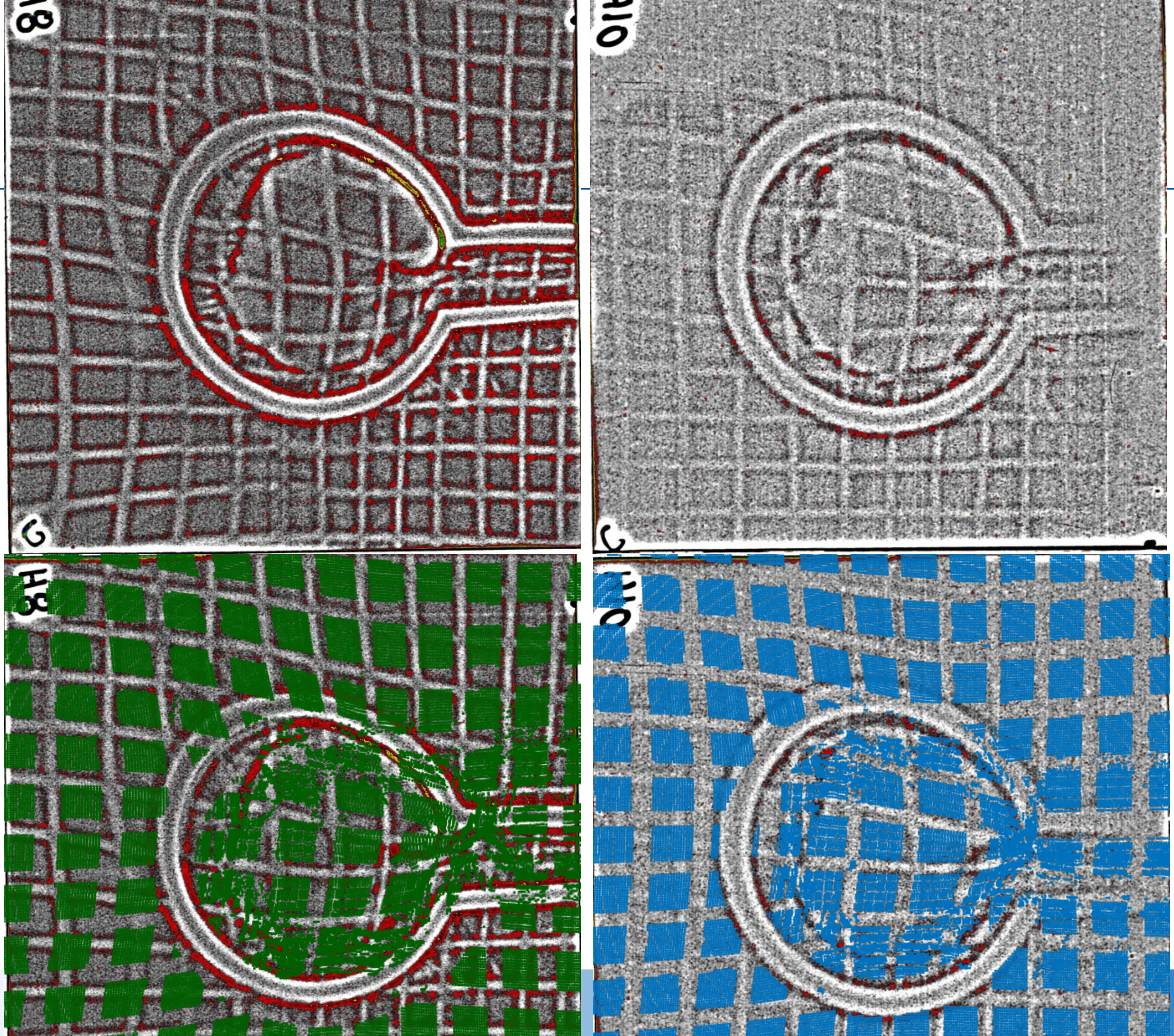
Experimental setup—examining two types of coils: double plate

Long pulse:
up to 1.25 kJ, $I \sim 10^{15}$ W/cm^2



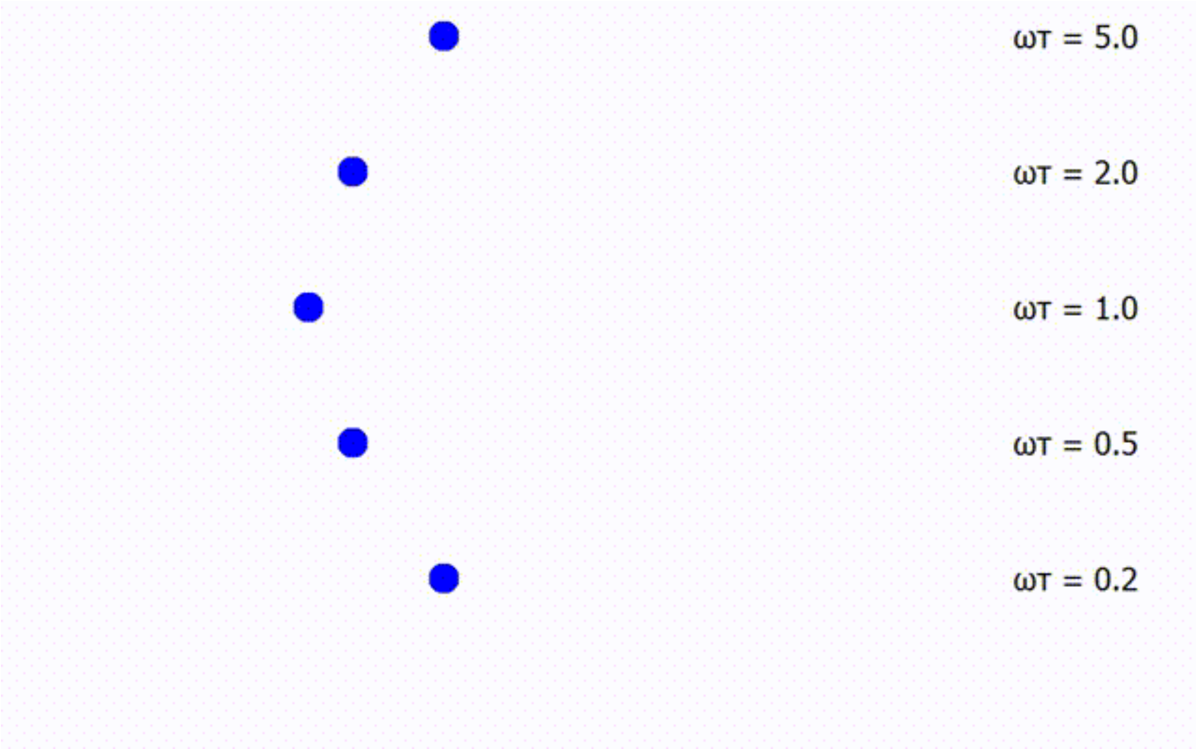
Experimental setup—examining two types of coils: single plate





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?

- 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