Embedding Strong External Magnetic Fields In OMEGA Implosions—

An Experimental Reality With Applications To Fusion, Exotic Plasma States And More: The Designer And User Perspectives

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Abstract

The MIFEDS (Magneto-Inertial Fusion Electrical Discharge System) magnetic pulse generator represents a user-supplied, compact, and flexible extension of the OMEGA laser. It is the current enabling technology for magnetized target implosions on OMEGA. It has already been used for magnetic flux compression experiments in cylindrical D_2-filled plastic shells, achieving tens of megagauss compressed fields. The device and experiments are reviewed in the context of integrating in a flexible way and with minimum online testing a moderate-to-high complexity instrumentation into a production system like OMEGA. The execution logic, special considerations, extra measures of safety and support and the interaction with the people behind OMEGA before, durin, and after the experiments are discussed as a case study. Highlighted are the unique conditions and experimental observables in the fielding of the MIFEDS experiments on OMEGA, along with some firsts and records. Possible improvements and extensions of the infrastructure and the variety/quality of HEDP experiments involving external magnetic fields are considered.

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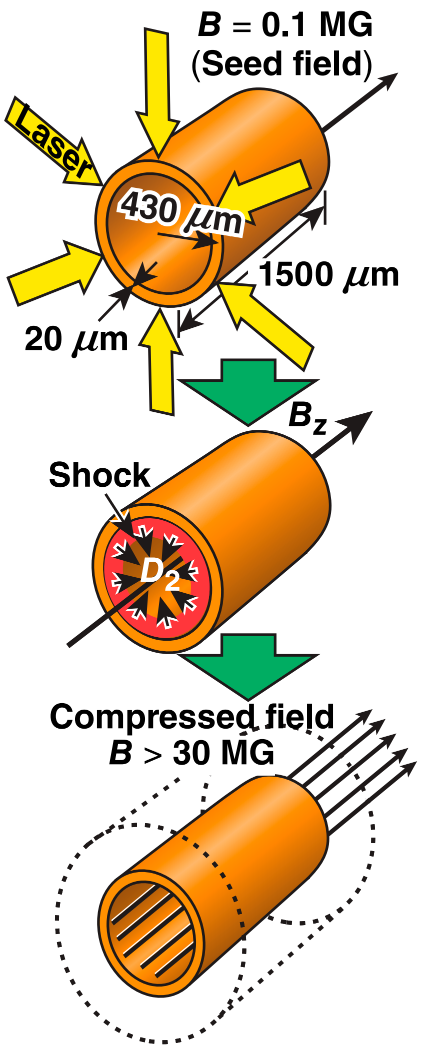
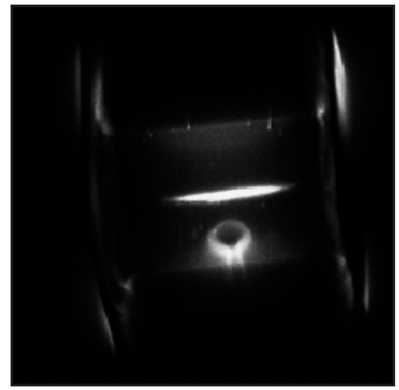
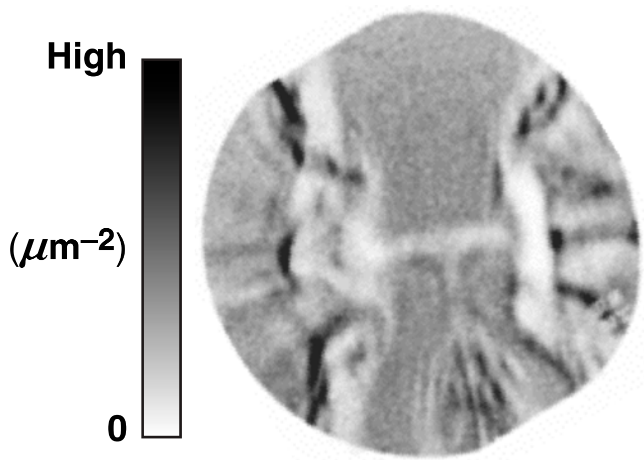
Embedding and compressing magnetic fields to record values has become an experimental reality



Conceptual scheme of laser-driven flux compression



X-ray pinhole camera image

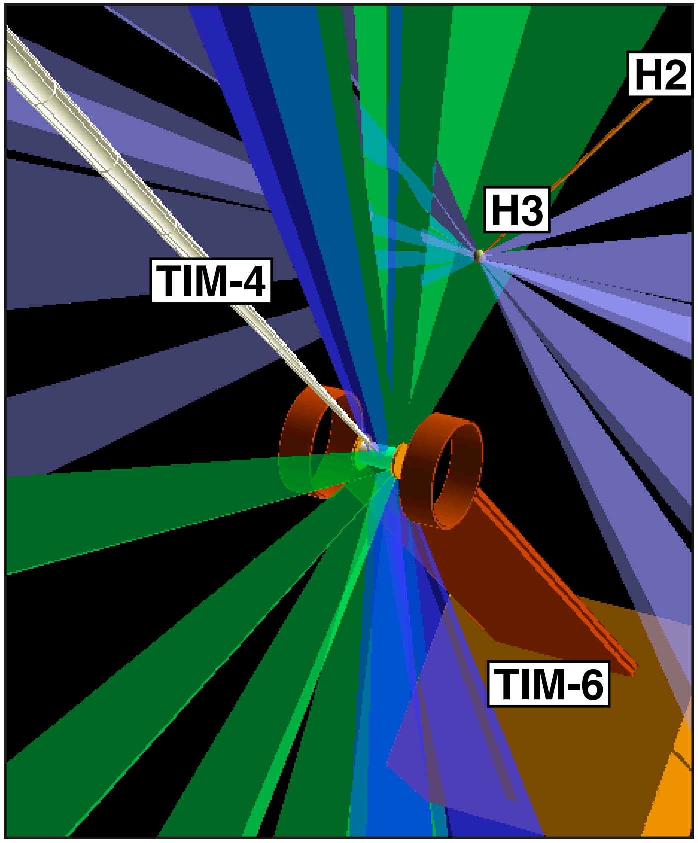


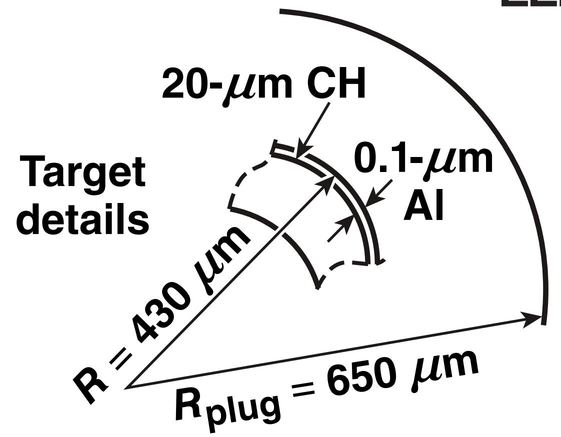
Proton density map

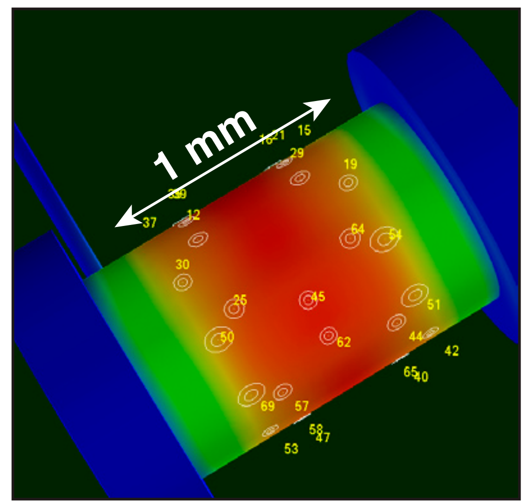
Experimental data from self-emission x rays and backlighter protons

E17764

Cylindrical target implosions have been performed with 1-ns square pulses from 40 OMEGA beams (~14 kJ)



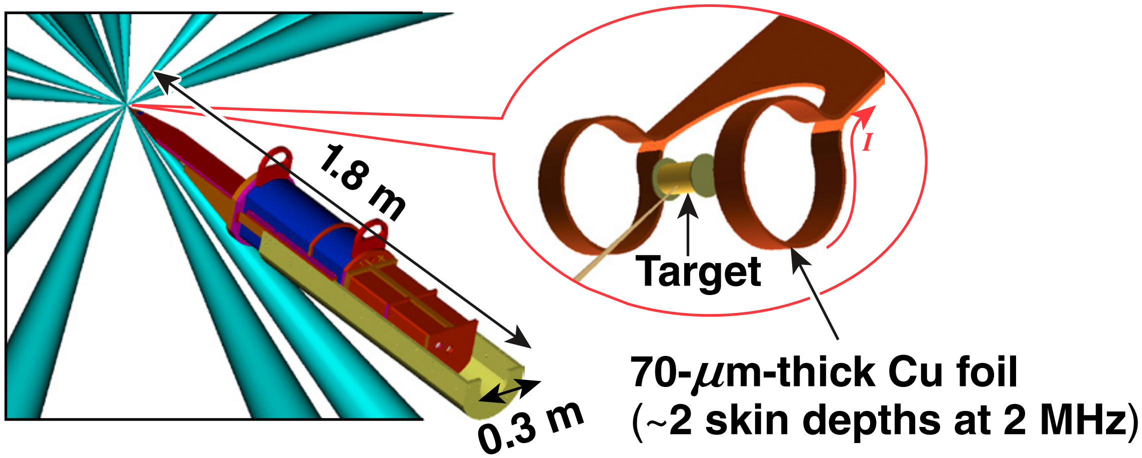




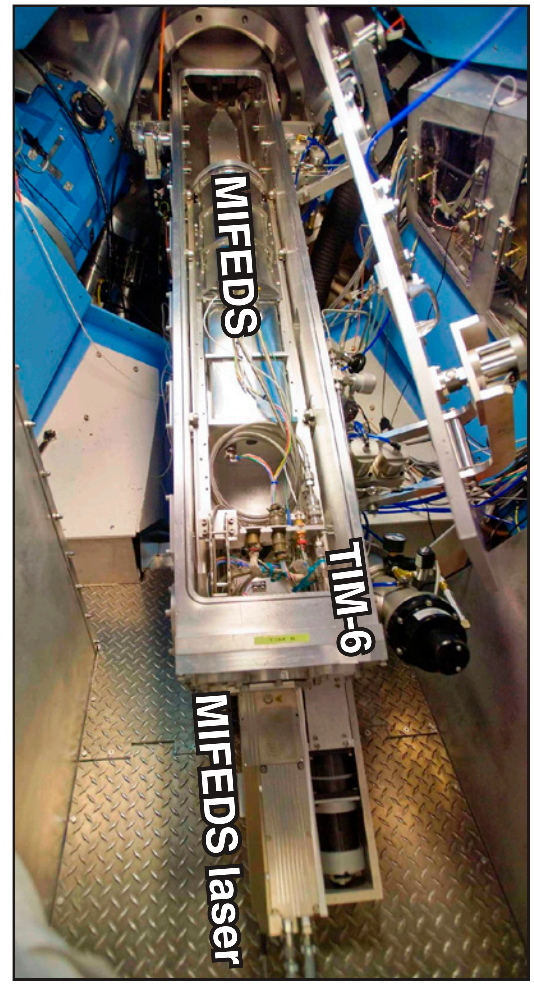
- D_2-filled CH cylinder (40 beams)
- D^3He-filled SiO_2 microballoon, 9 mm away from cylinder (20 beams)
- Average on-target intensity ~3.5×10^{14} W/cm^2

E17765

The seed magnetic field is generated in a double-coil configuration optimized for OMEGA implosions



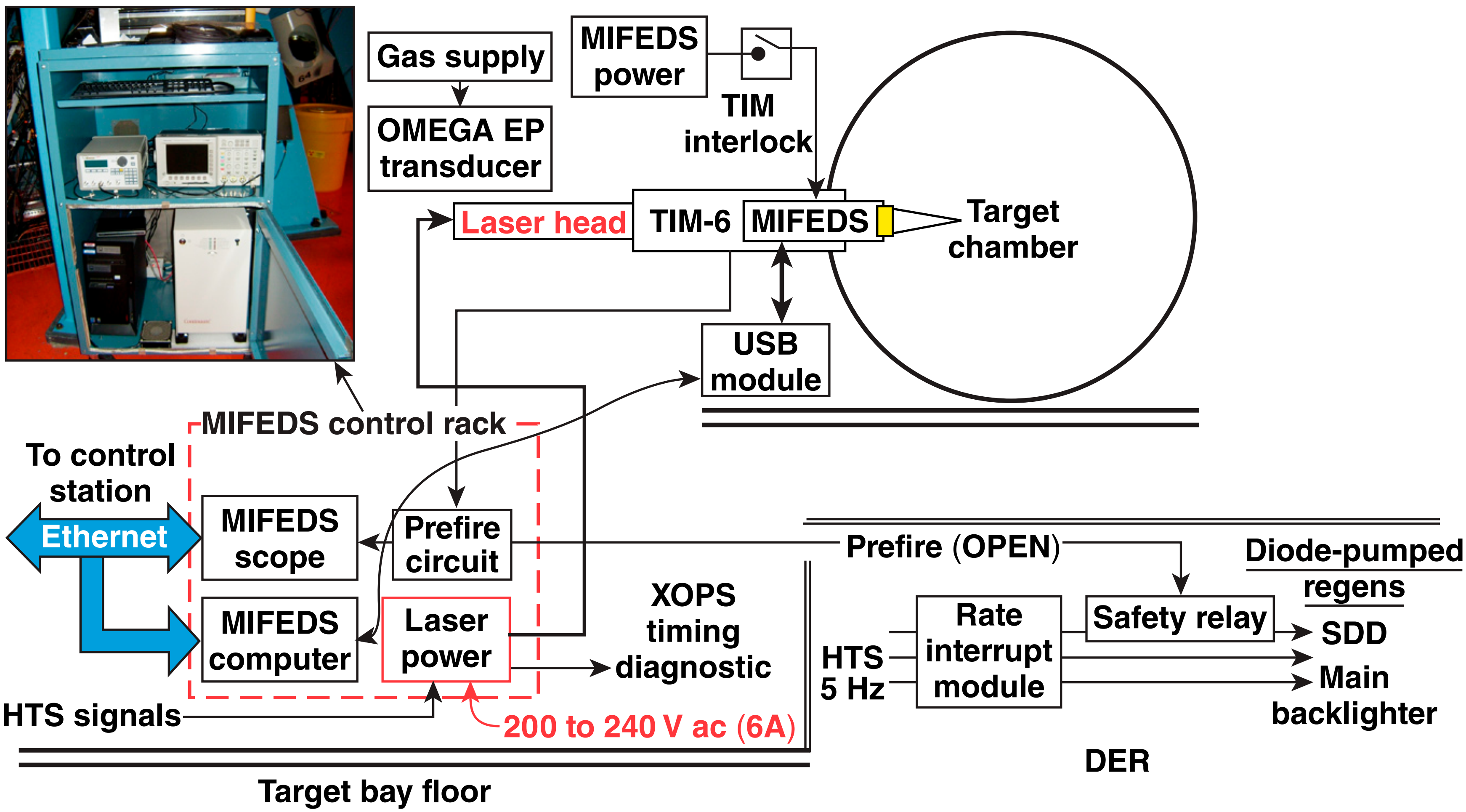
- A TIM-based, self-contained system, MIFEDS stores <100 J and is low-voltage powered
- Yet, it delivers ~100-kA peak current to the coil in a 350-ns pulse
- The SG trigger laser delivers 65 mJ in an ~5-ns UV (266 nm) pulse for a fast, reliable discharge



MIFEDS seed-field generator

E17122b

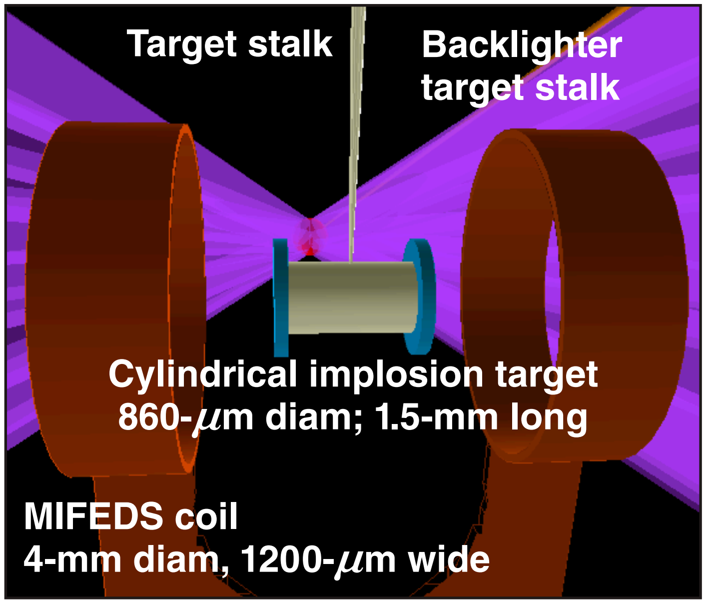
MIFEDS is a multicomponent system that, while portable, requires careful integration with OMEGA

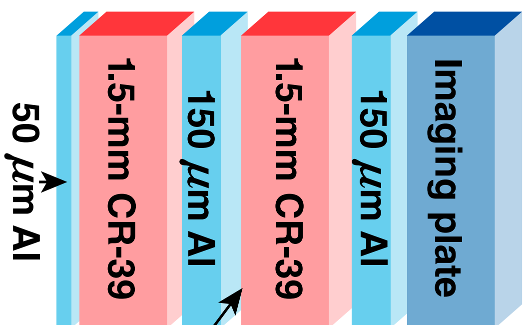


- The flexibility of a TIM-based instrument is weighted against significant installation and a setup effort prior to and during a shot day.

E17766

Charged-particle (proton) deflectometry is used as the magnetic-field diagnostic





- The proton source is the D^3He fusion reaction in a glass microballoon filled with D^3He mix and driven as an exploding pusher

  $$D + {}^3He \rightarrow {}^4He + p \text{ (14.7 MeV)}$$

- This source is:[1]
  - monoenergetic ($\Delta E/E < 0.03$)
  - time gated (~150-ps FWHM)
  - point-like (size/object distance ~ $6 \times 10^{-3} << 1$)

- The detector is a CR-39 nuclear track media, which, after processing, can resolve individual particle tracks and their incident energy.[2]

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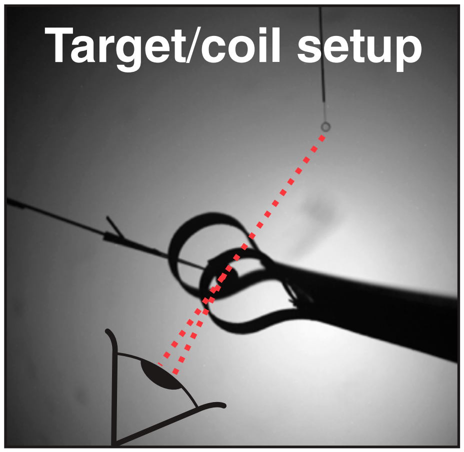
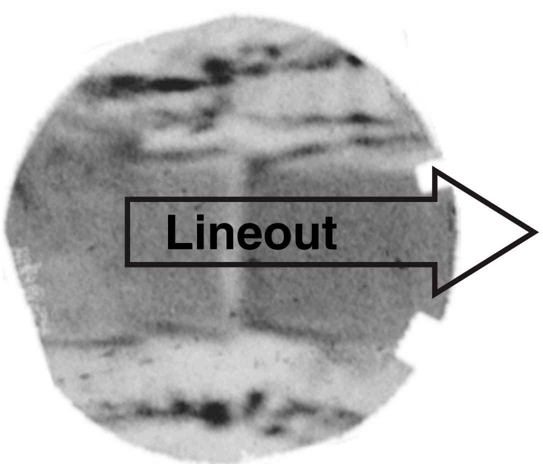
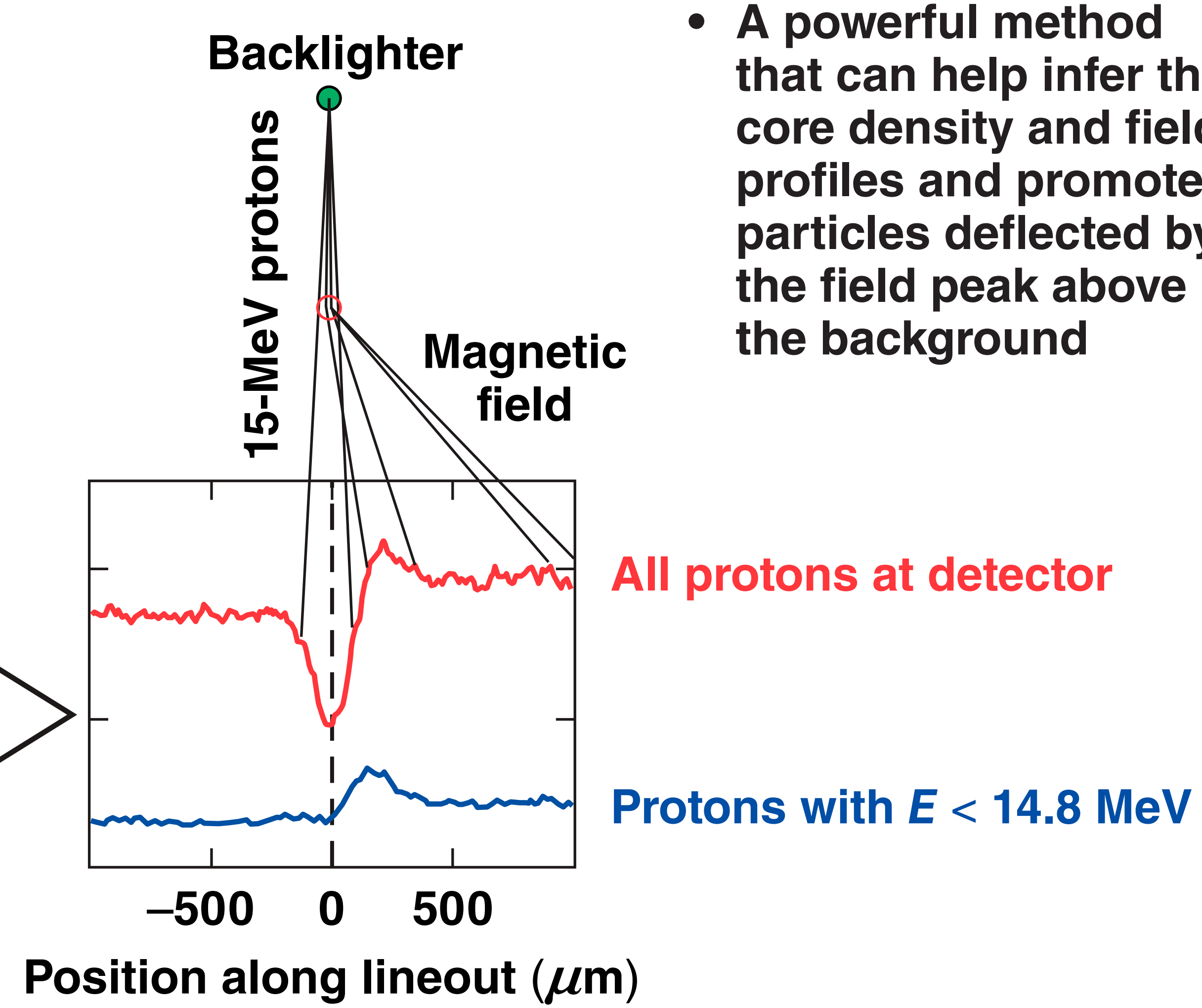
[1] C. K. Li *et al*., Rev. Sci. Instrum. 77, 10E725 (2006).
[2] F. H. Séguin *et al*., Rev. Sci. Instrum 74, 975 (2003).

E17767

Selection of tracks by diameter (energy) is used to expose the particles deflected in the amplified field







- A powerful method that can help infer the core density and field profiles and promote particles deflected by the field peak above the background

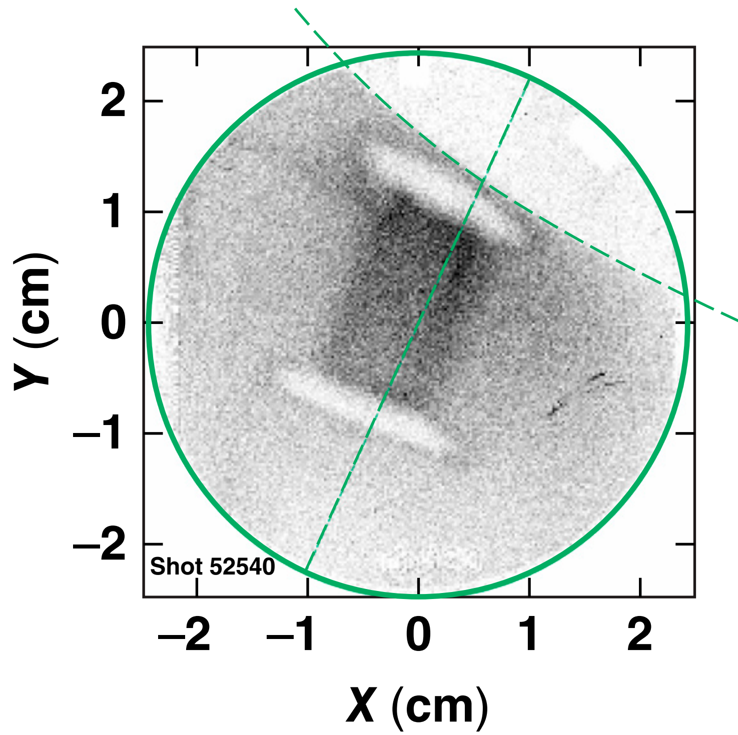
E17353a

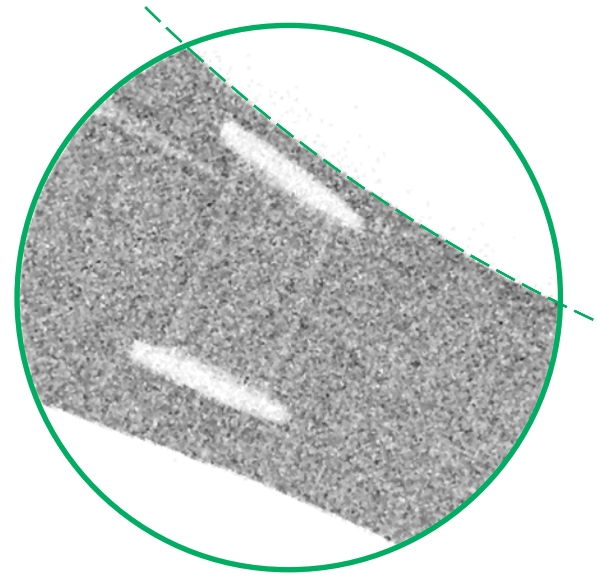
GEANT4 is instrumental for correct data interpretation

- A C++ framework for particle transport in matter where a multitude of physical processes can be switched on demand
- In the application created for proton deflectometry, the equation of motion is solved for the protons while tracking energy loss and scattering events
- Multiple scattering model based on the theory of Lewis
- The Bethe–Bloch model in combination with tabulated stopping powers from ICRU'49 are used for the ionization energy loss
- The code uses the hydro-simulation profiles as a starting point to match the experiment under the constraint of flux and mass conservation

Data for a backlit unimploded target show a seed-field deflection consistent with simulations

$B_{seed} = 5.6$ T



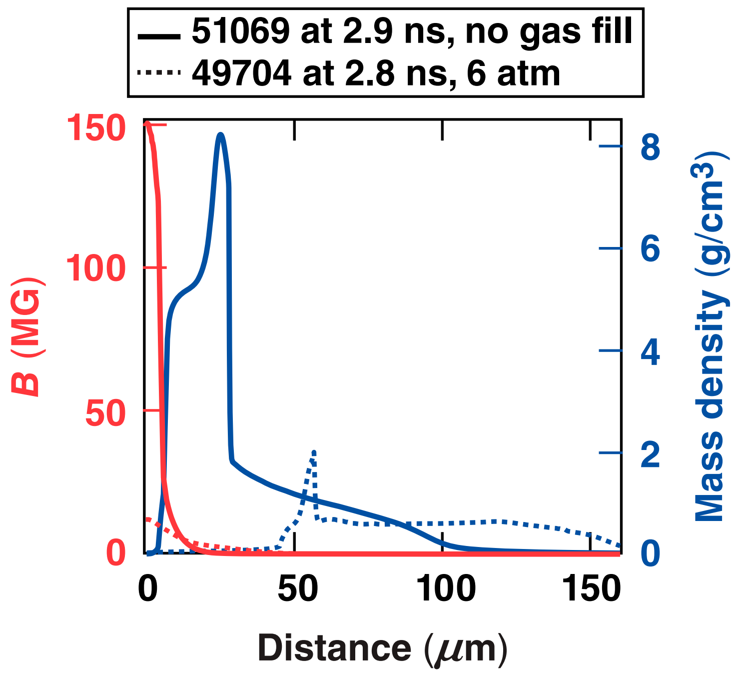


- Density map of all detected protons after traversing the target area

- The non-axial field near the coils distorts the *p* beam
- An offset was introduced to match the apparent offset in the experimental data

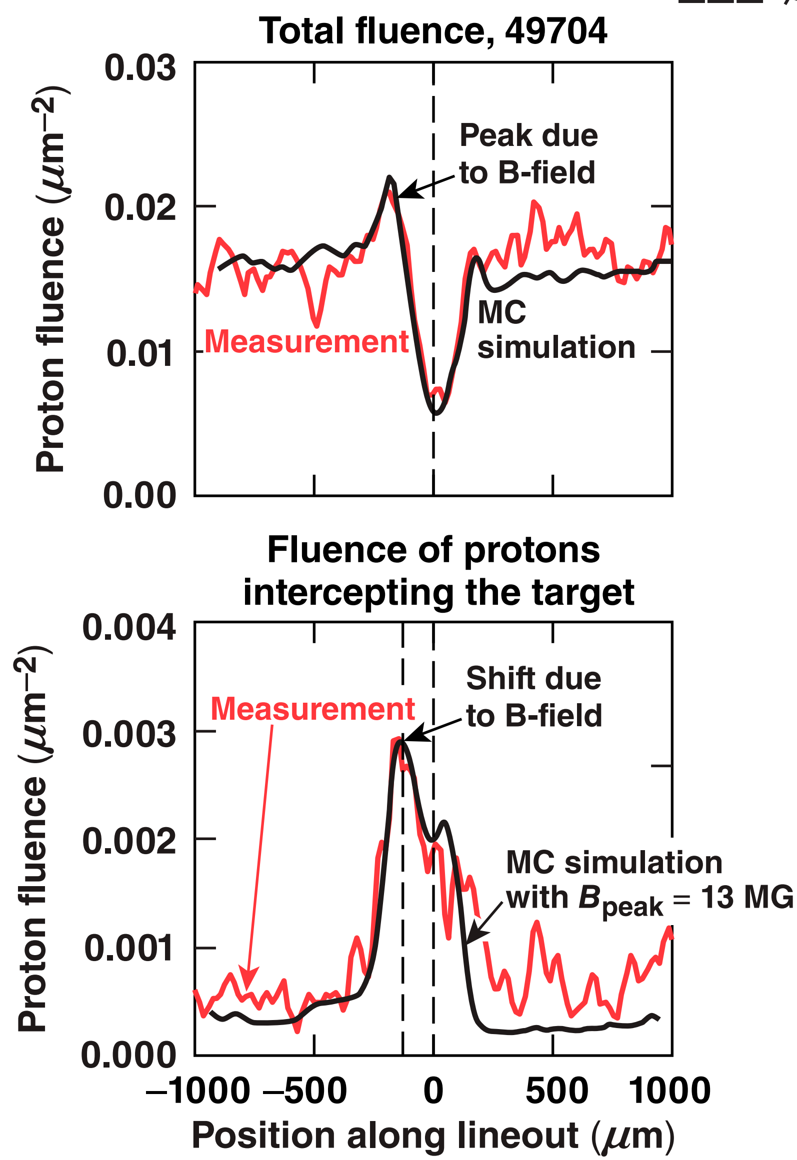
Field amplification has been observed in all the magnetized implosions probed by protons

Density and field profiles from *LILAC*-MHD
(~60% of the initial flux retained)



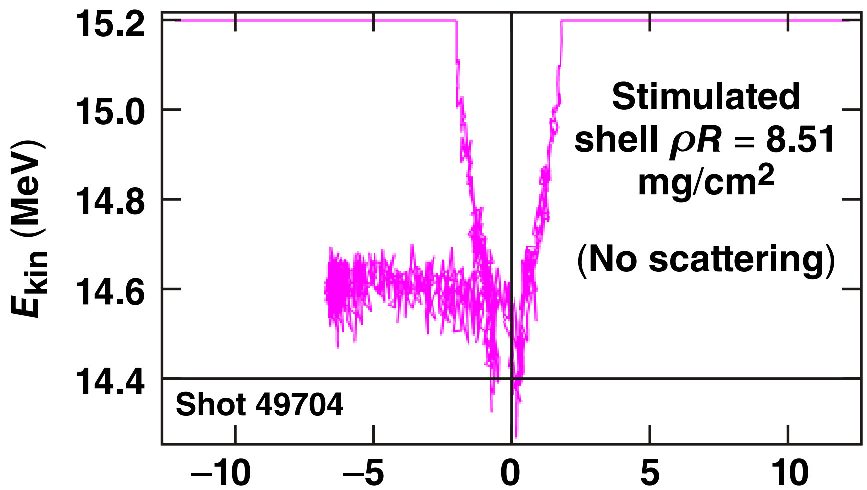
Shot number	49704	51069
Bang time (ns)	3.2	2.8

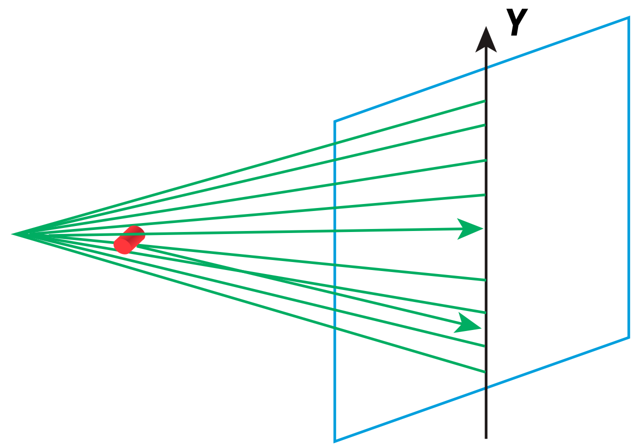
Initial flux	3.48×10^{-6}	T m^2
Final flux	2.25×10^{-6}	T m^2

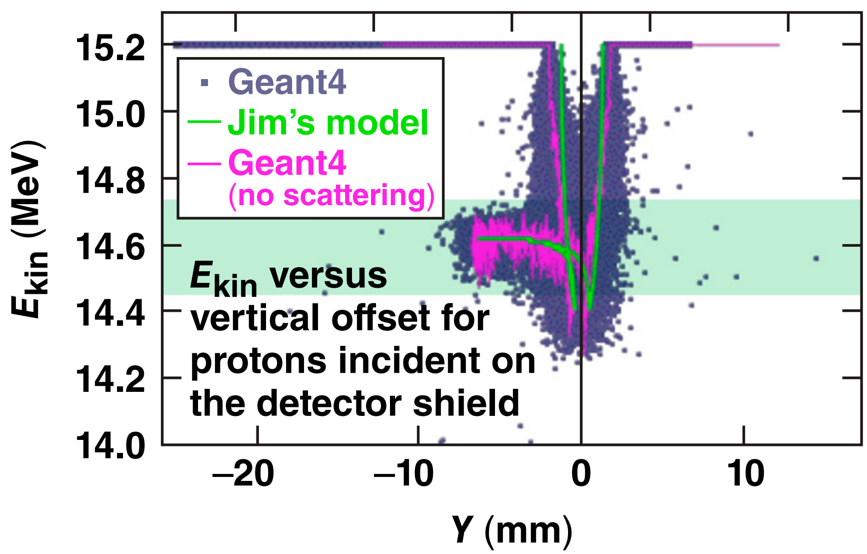


E17460a

Removing physics processes and looking at only a single vertical fan of protons can help simplify the picture





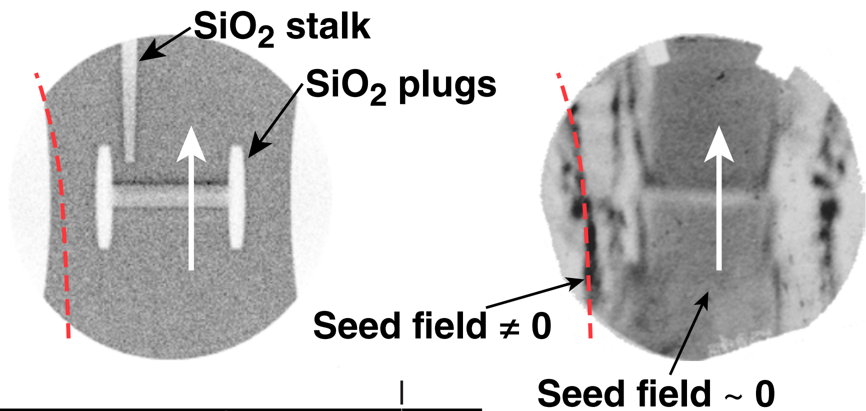


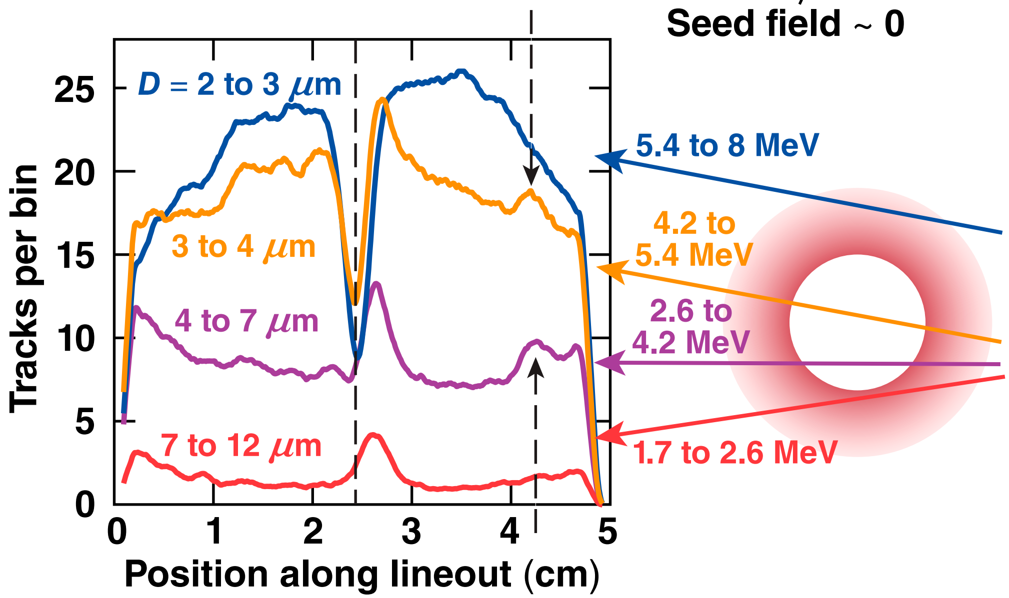
- The width, depth, and shape of the deflected pattern depend on ρR and B.
- To promote the protons traversing the high field above the background, the tracks with diameter outside the "green" energy band should be filtered.

E17770

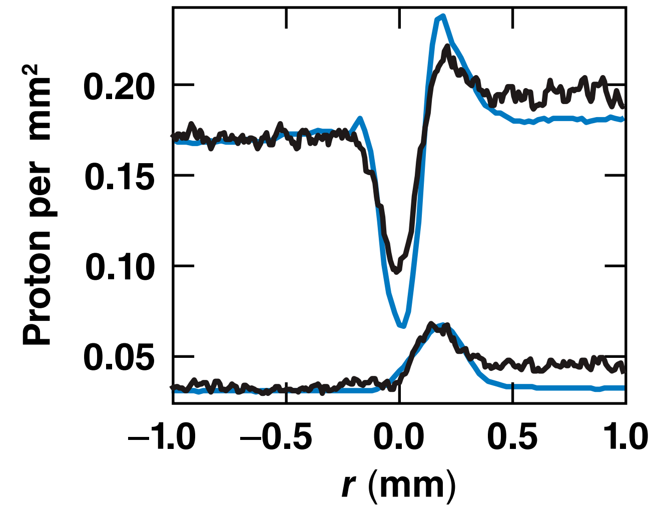
A strong magnetic field (B > 30 MG) is present in the compressed core in low-fill-pressure shot 51069

Proton maps at T_0 + 2.9 ns (shot 51069), deflection toward stalk





Experimental data at various energy bands (paths through the target)



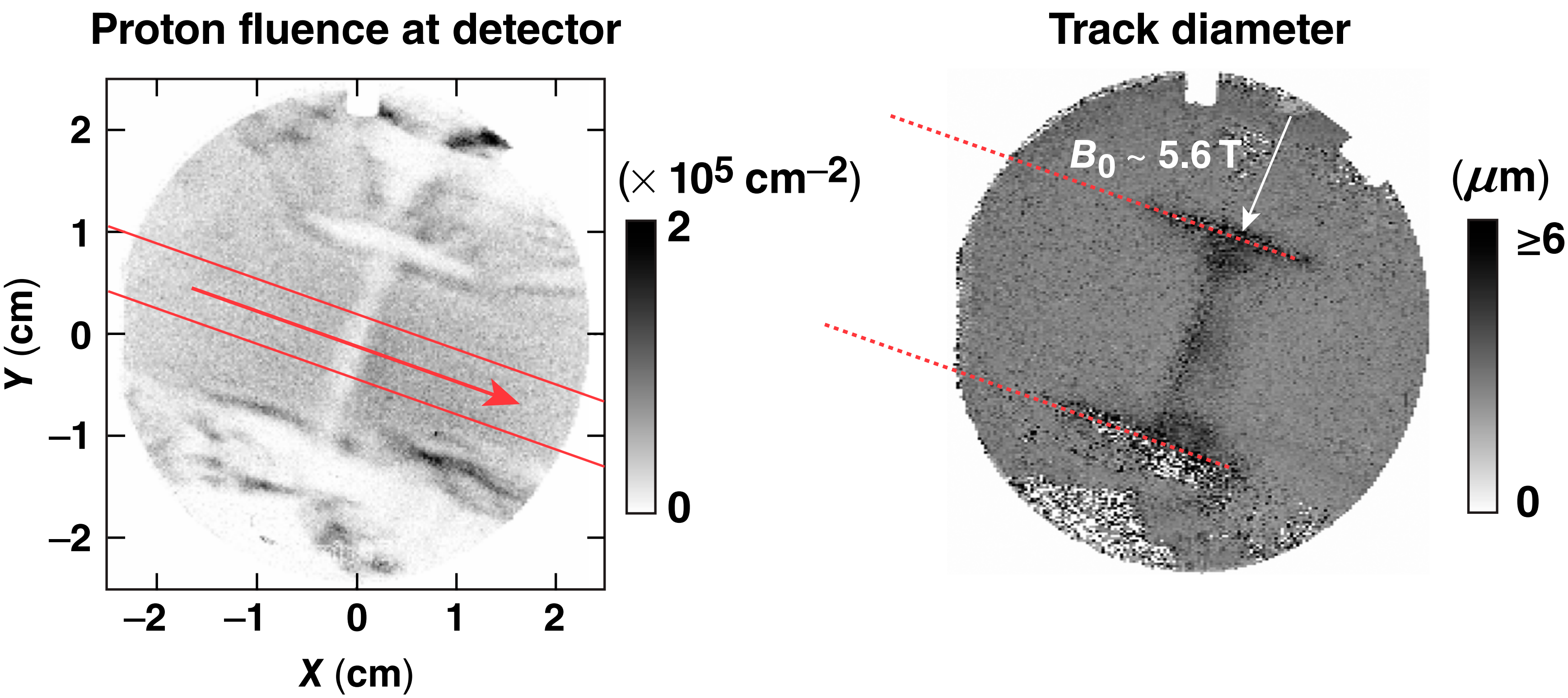
Experimental and simulated proton maps (total and core-traversing)

- 30-MG average core field is the lowest value that can match this deflection
- Matching this deflection with B < 30 MG will exceed the seed flux
  $\theta \sim \langle rB \rangle$, but $\Phi \sim \langle r^2 B \rangle$
- At 60% flux conservation the minimum matching field is 50 MG

E17461a

Proton fluence and track diameter maps for shot 52535 show compressed field deflection

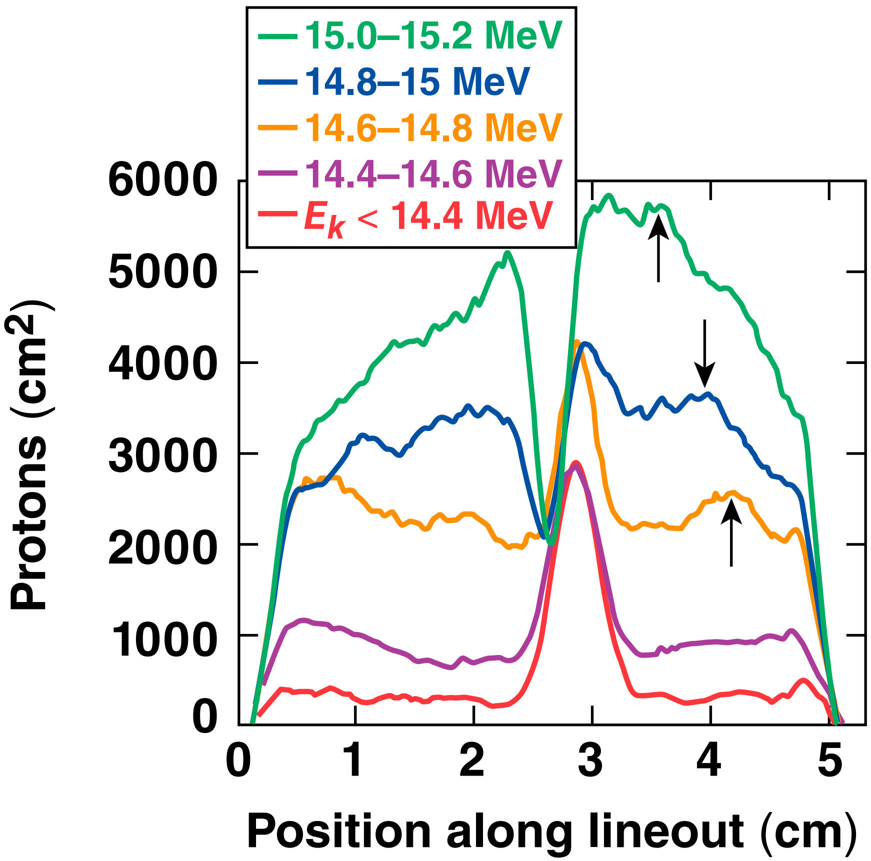
Shot 52535 (deflection toward stalk)
4-h etch



E17771

Lineouts through the proton density map in several energy (track-diameter) bands confirm the strong field

Shot 52535 (deflection toward stalk)



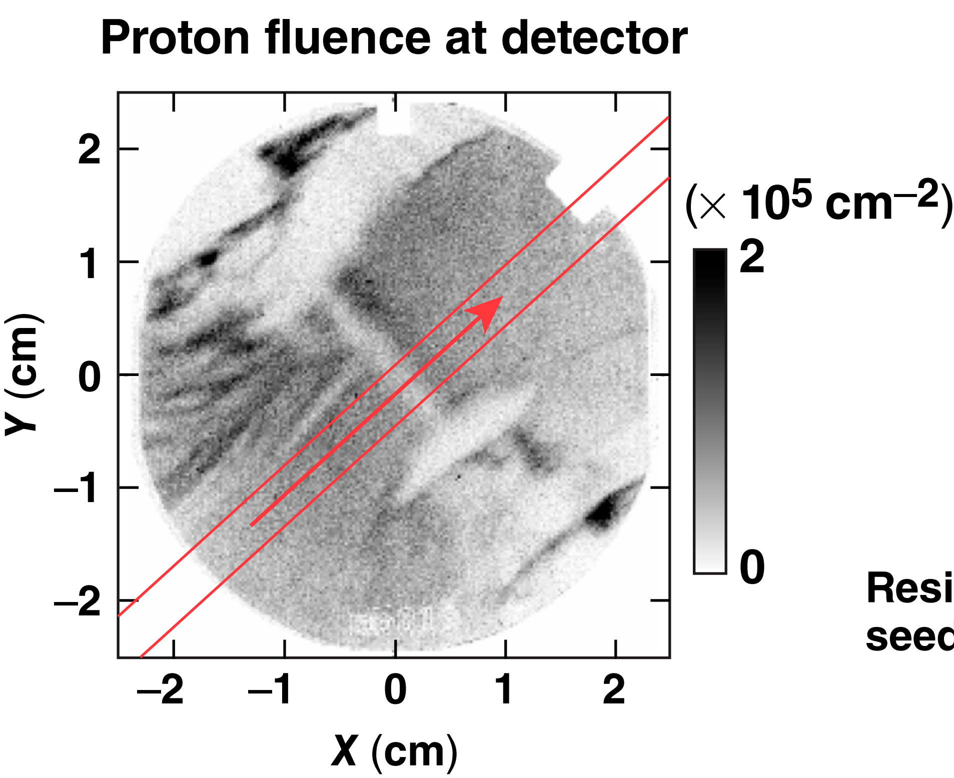
Experimental data at various energy bands (paths through the target)

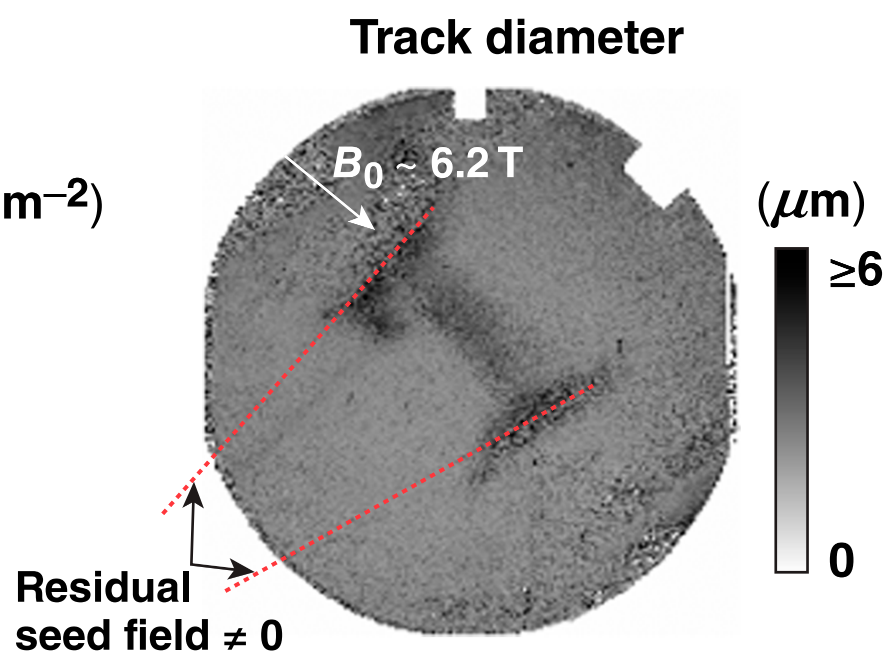
- A realistic core ρR distribution can be recovered by matching the partitioning of particles in the various energy bands.
- The minimum field that matches this deflection is 25 MG (40 MG at 40% flux loss).

E17772

The reversal of the seed-field direction for shot 52532 results in a reversed deflection direction

Shot 52532 (deflection away from stalk)
4-h etch

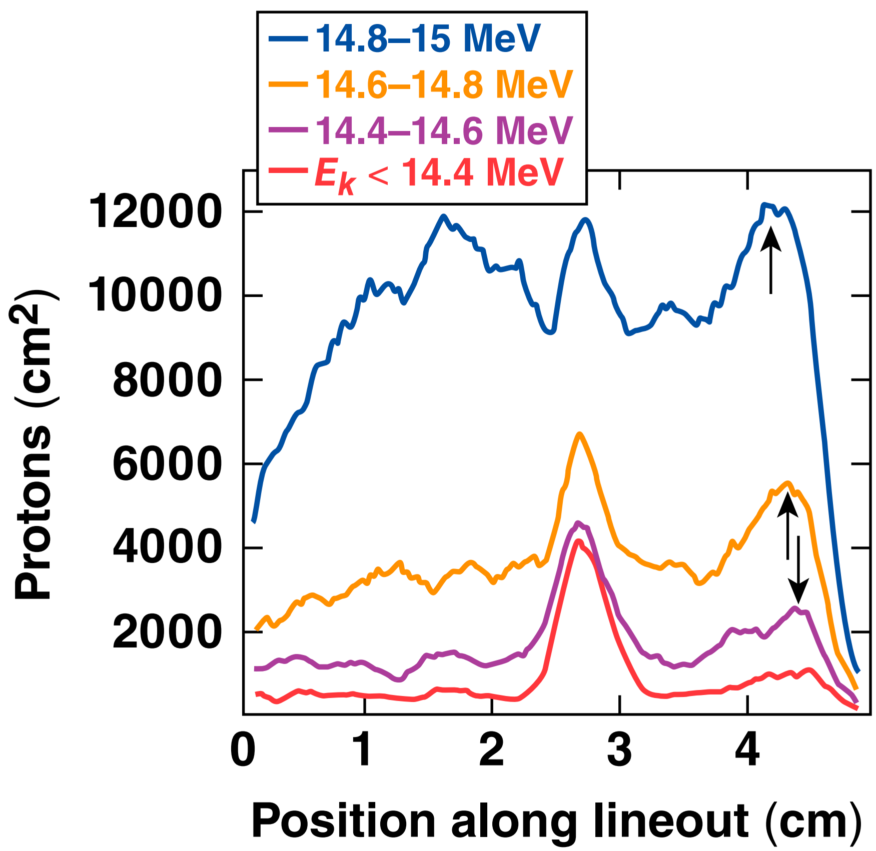




E17773

The reversal of the seed-field direction for shot 52532 results in a reversed deflection direction (lineouts)

Shot 52532 (deflection away from the stalk)



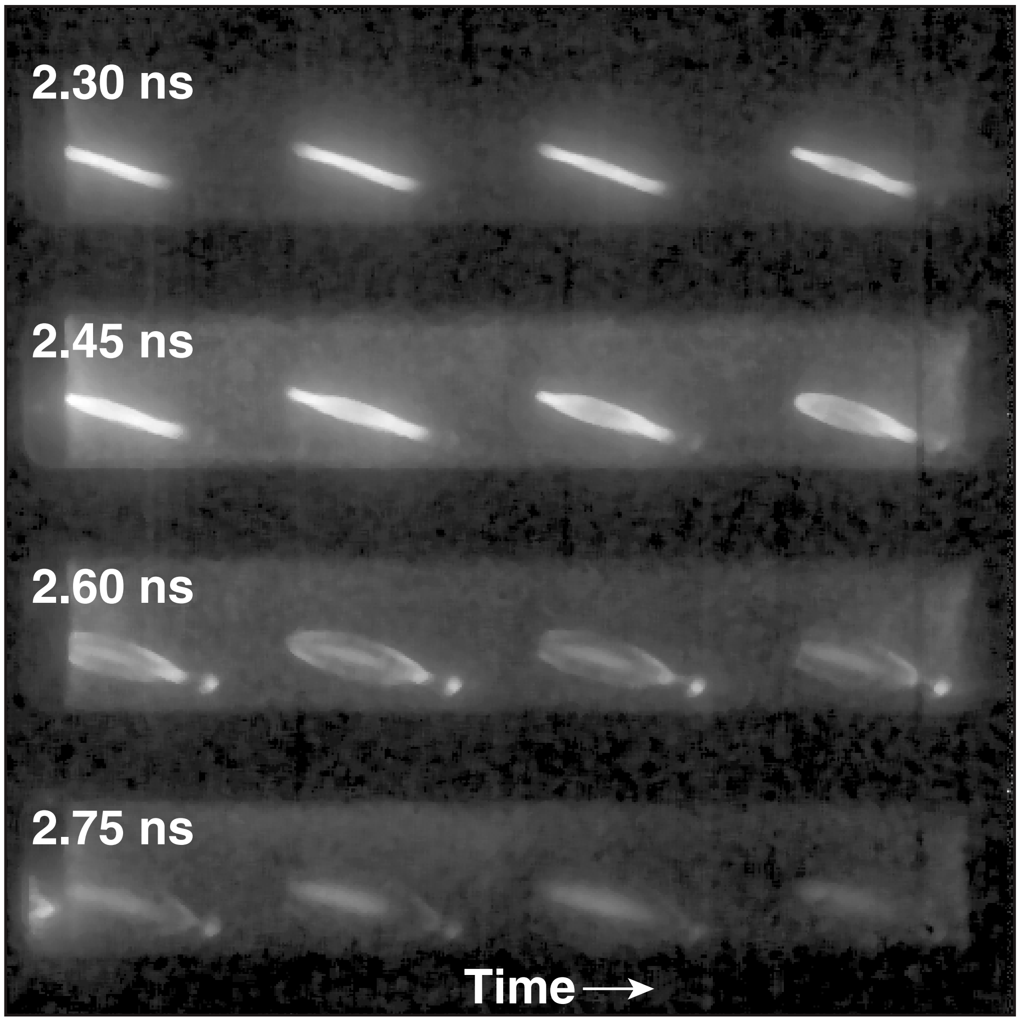
Experimental data at various energy bands (paths through the target)

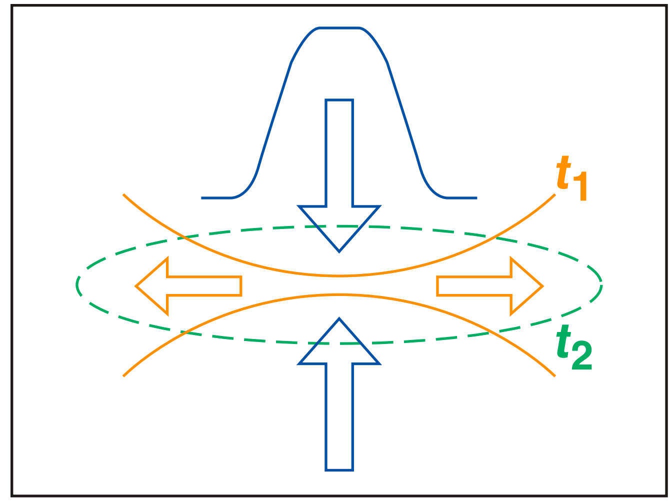
- The compressed field is larger than in shot 52535, in part due to the higher seed field and, in part, due to a more homogeneous hot spot.
- The minimum estimate matching this deflection is 50 MG (80 MG at 40% flux loss).

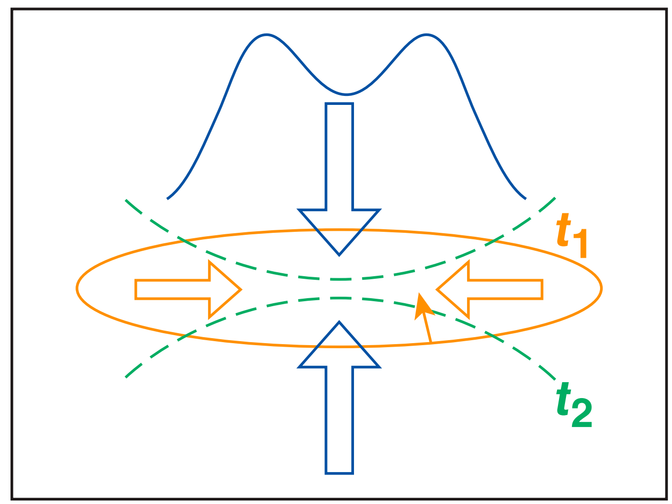
E17774

Centrally peaked intensity profile drives the middle of the cylinder harder, creating an axially diverging plasma flow

Log plot of XRFC2 data, shot 52527







E17775

Yield-performance variation is due, in part, to target positioning and orientation

52527
4T seed field
$Y_n = 2.2 \times 10^8$

52538
no seed field
$Y_n = 1.54 \times 10^8$

52537
4.9T seed field
$Y_n = 2 \times 10^7$

52536
5.6T seed field
Y_n undetectable

- Target build quality, gas retention, alignment, and illumination varied ...

LILAC-yield predictions are invalid because, in the cylindrical implosions, the ions are in the kinetic regime; the higher the field, the more collisionless the ions

- $n_{e\ hs} = 8 \times 10^{22}$ cm^{-3}, $\ln\Lambda_{ie} \approx 5$, $\ln\Lambda_{ii} = 8.7$
- The Gamow peak energy[1] is $E_{GP} = 6.27\ T_{e\ hs}^{2/3} = 8.2$ keV

	R_{hs} μm	T_{hs} keV	n_{ehs} 10^{23} cm^{-3}	ν_{ie} ns^{-1}	ν_{ii} ns^{-1}	ω_{ci}/ν_{ii}	mfp$_{ie}$ μm	mfp$_{ii}$ μm	r_1 μm
Cylindrical	20	1.5	0.8	5.45	56	2.6	151	5.6	5.7
Spherical	18	3.9	30	40	2150	0.07	27.3	0.51	7.7

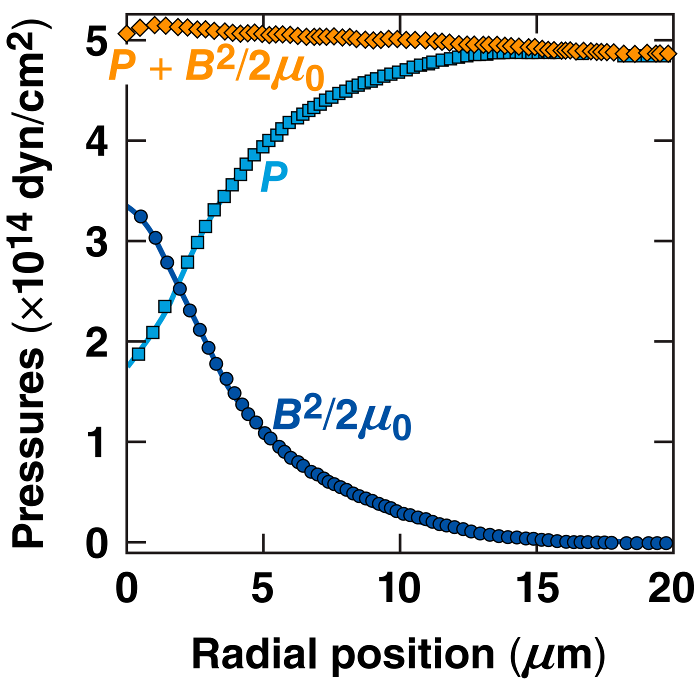
- Based on this, the 8-keV ions will escape the hot spot with only a few collisions
- With thermal equilibration time ~100 ps, the increase in $T_{e\ hs}$ will not couple effectively into $T_{i\ hs}$

E17777

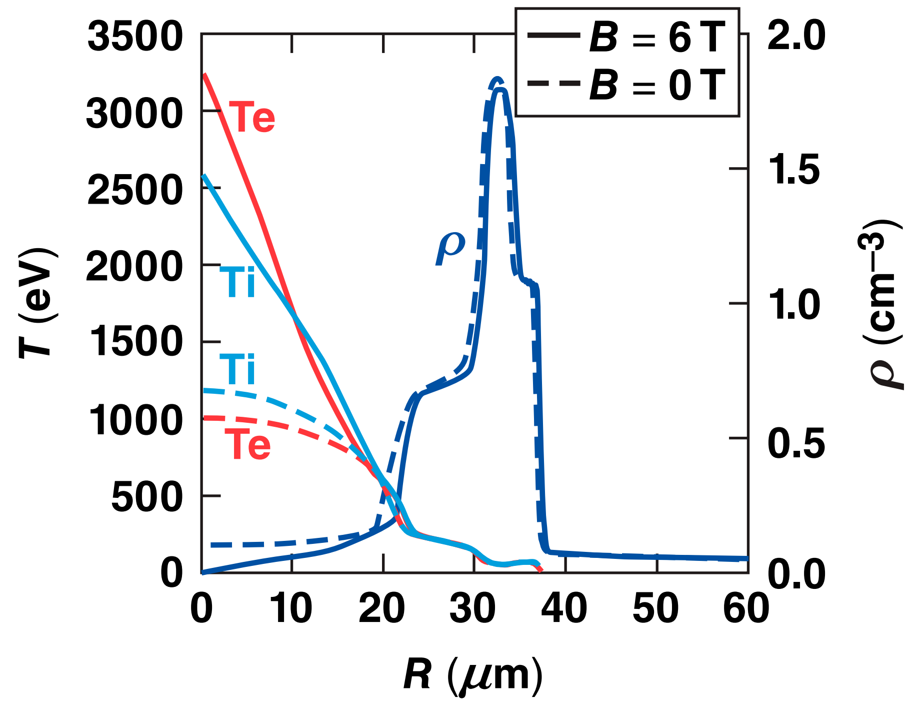
[1] S. Atzeni and J. Meyer-ter-Vehn, The Physics of Inertial Fusion: Beam Plasma Interaction, Hydrodynamics, Hot Dense Matter, (Clarendon Press, Oxford 2004).

The magnetic field pushes the hot-spot plasma out of the center, reducing the density and hydro pressure

There is a balance between $B^2/2\mu_0$ and the hot-spot pressure that sets the pressure profile (plotted for B_{seed} = 80 kG)



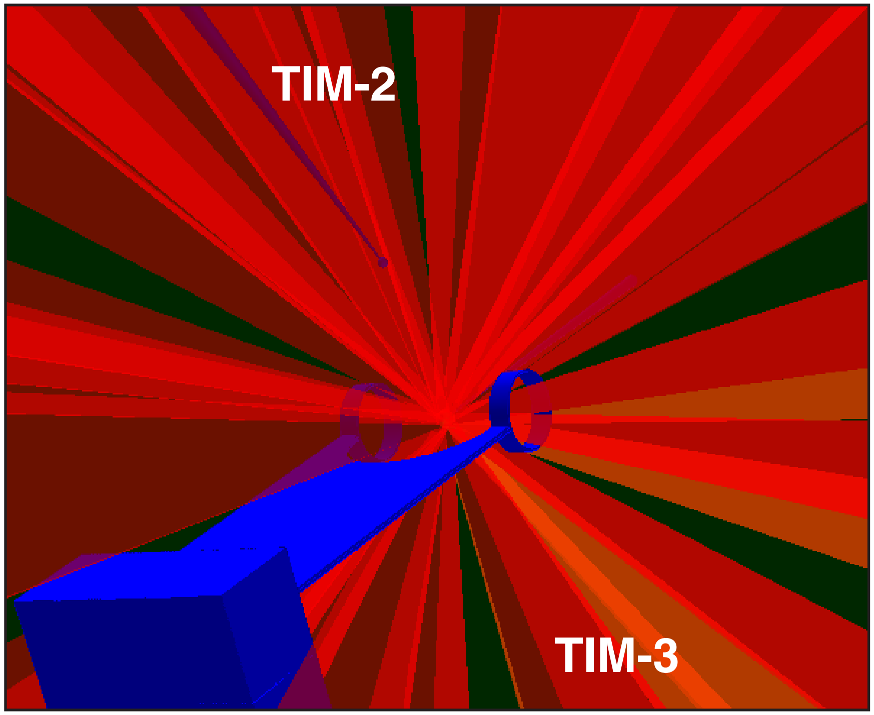
LILAC–MHD simulations show a density drop due to the magnetic field



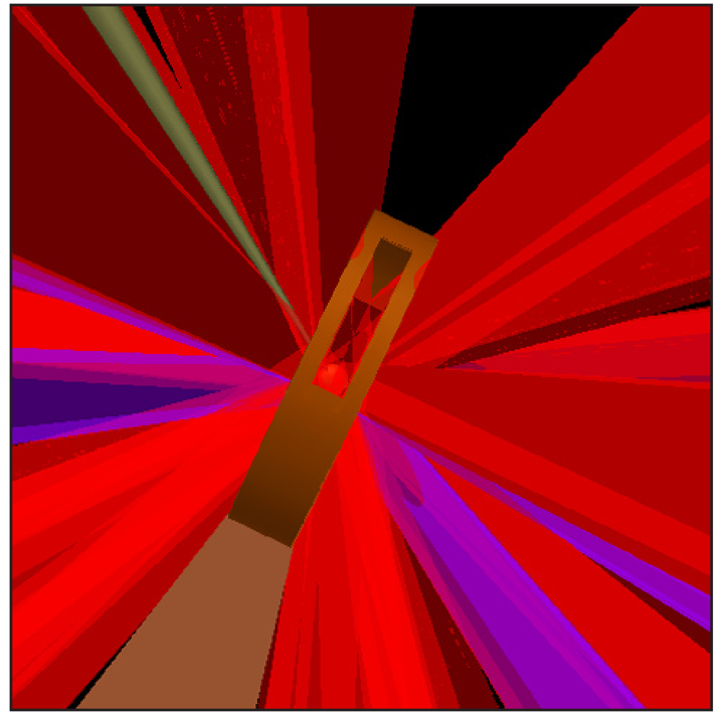
- The mass-averaged hot-spot temperature (20-μm radius) is 1100 eV for the magnetized case versus 974 eV for the B = 0 case.

E17778

Spherical implosions in the axial field can shed light on possible heat-transport inhibition in the ablation region



Helmholtz-like coil setup requires 1-cm separation of the coils with field in the target 0.9 T

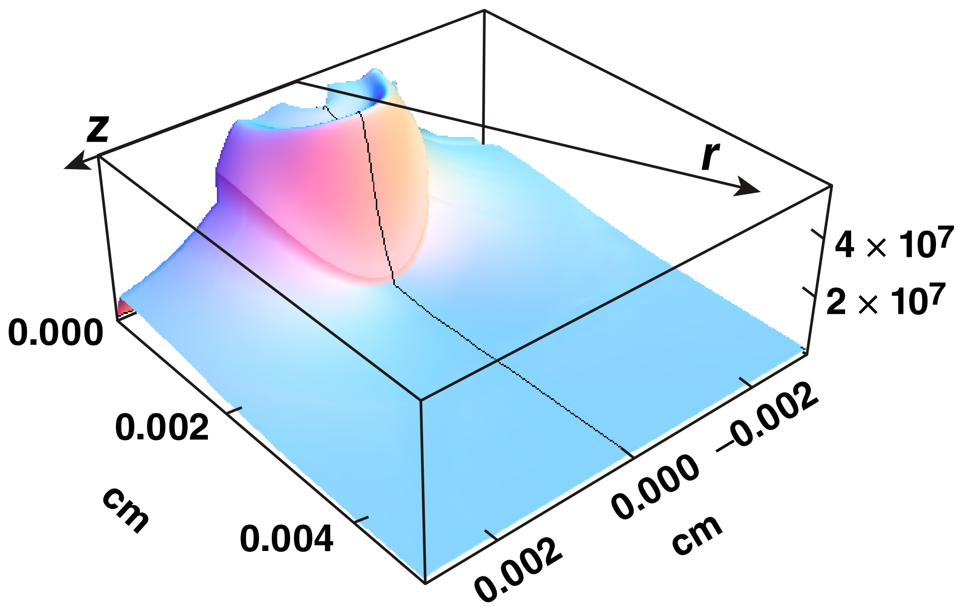


A single coil setup keeps the field at 8 T

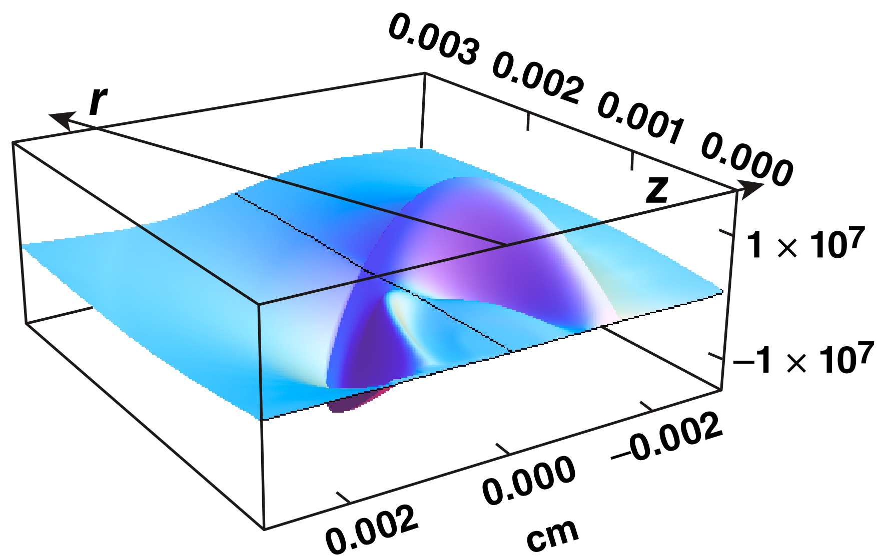
- These implosions will have higher ρ_{hs} leading to more collisional ions
- Shot-to-shot variation is expected to be under better control for spherical targets

E17779

DRACO-MHD simulations of spherical implosions show significant compression of the axial field



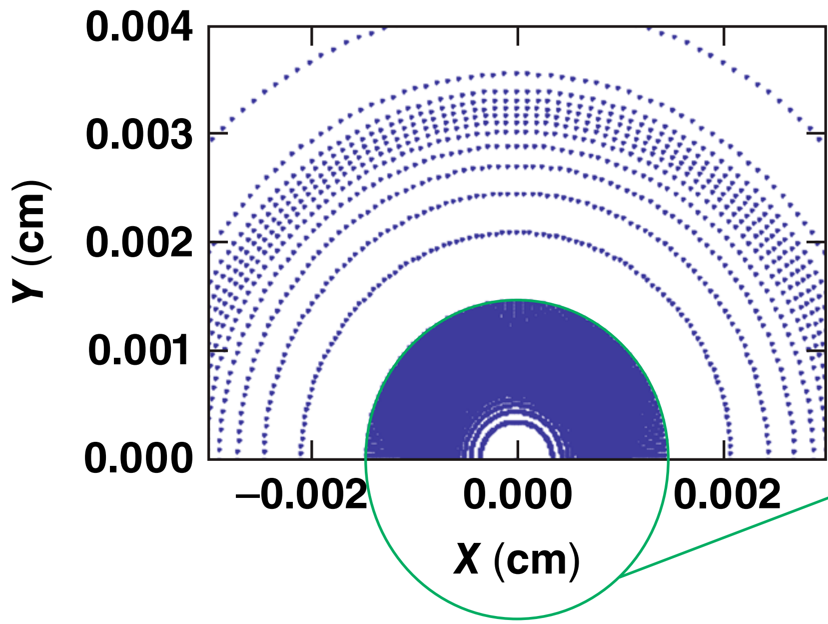
$B_{z\ max}$ = 56 MG

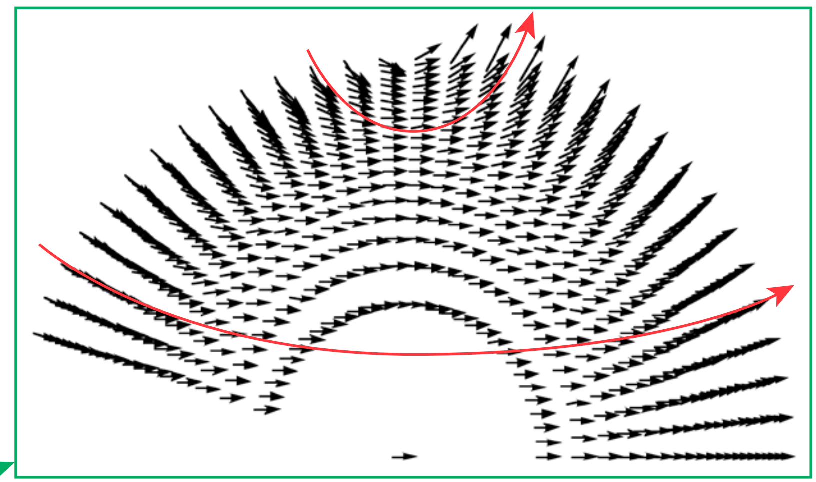


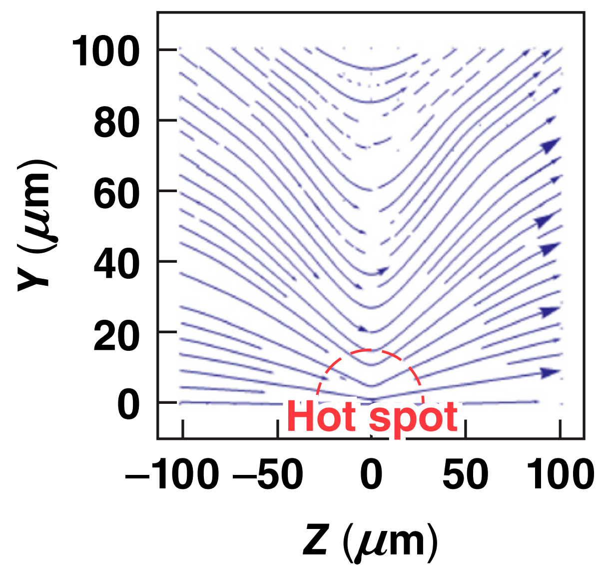
$B_{y\ max}$ = 16 MG

- A significant transverse (nonaxial) field component has grown from the compression.

DRACO-MHD simulations show that, near peak compression, the field within the hot spot remains mostly axial

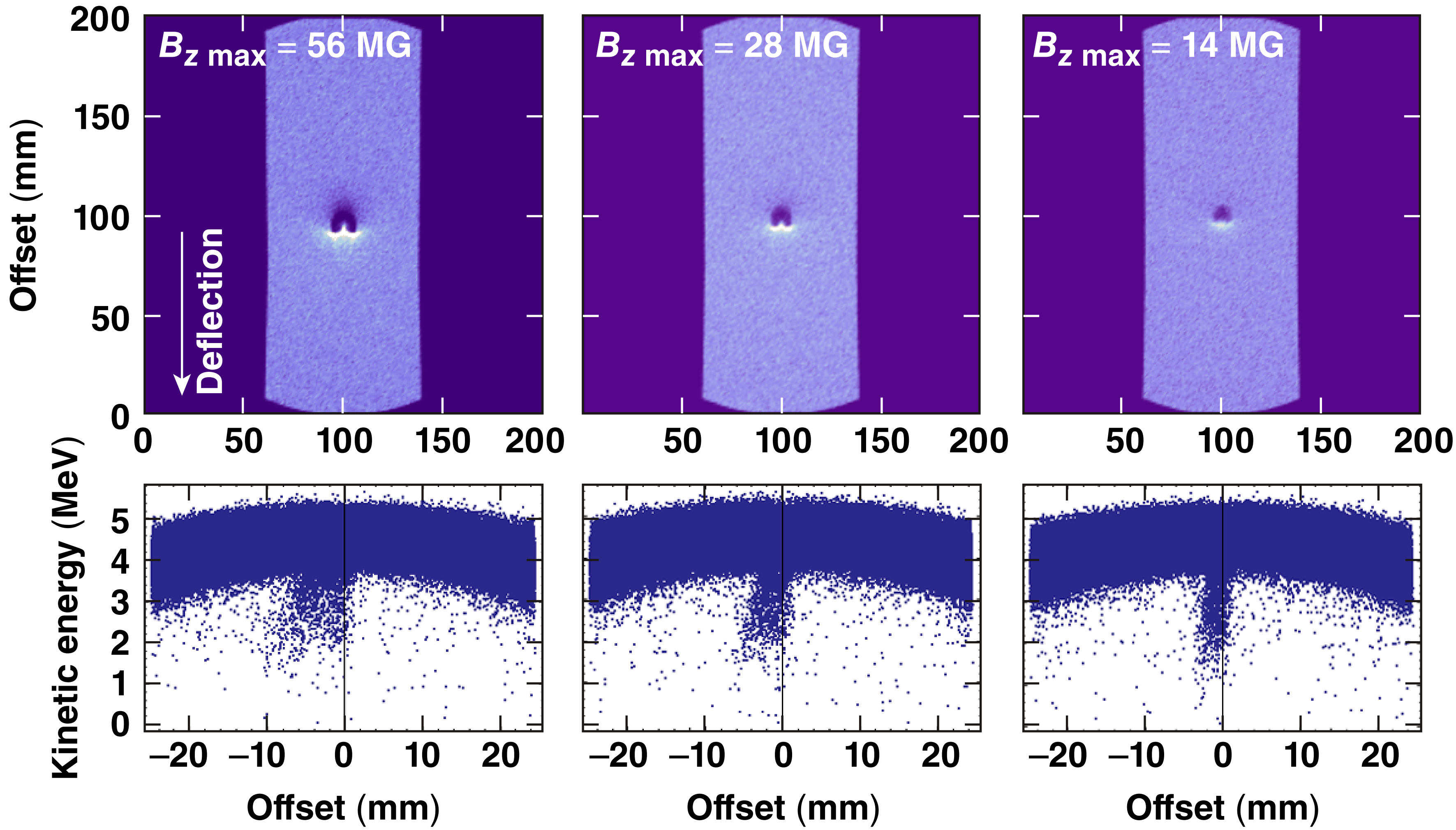






- The irregular Lagrangian mesh {$Bz(r,\varphi)$, $By(r,\varphi)$} is interpolated inline in GEANT4. Advantage of the azimuthal symmetry is taken.

Monte Carlo simulations show that the strength of the compressed field can be determined via deflectometry



- Monte Carlo simulation with the full-, half-, and quarter-compressed fields (from *DRACO*-MHD)

E17782

Summary/Conclusions

The first experiments on magnetized ICF show that multi-MG fields can be attained in the hot spot

- Magnetized cylindrical targets were imploded on OMEGA to compress a pre-seeded magnetic flux to high values
- An ~100-kG seed magnetic field was generated with a double coil driven by a portable capacitive discharge system (MIFEDS)
- Proton deflectometry along with data interpretation tools were developed and used to detect the compressed magnetic fields
- The data consistently show fields of many tens of MG in the hot spot
- Spherical implosions in the axial field are planned to study flux compression and heat transport in the conduction zone in the presence of the axial seed field