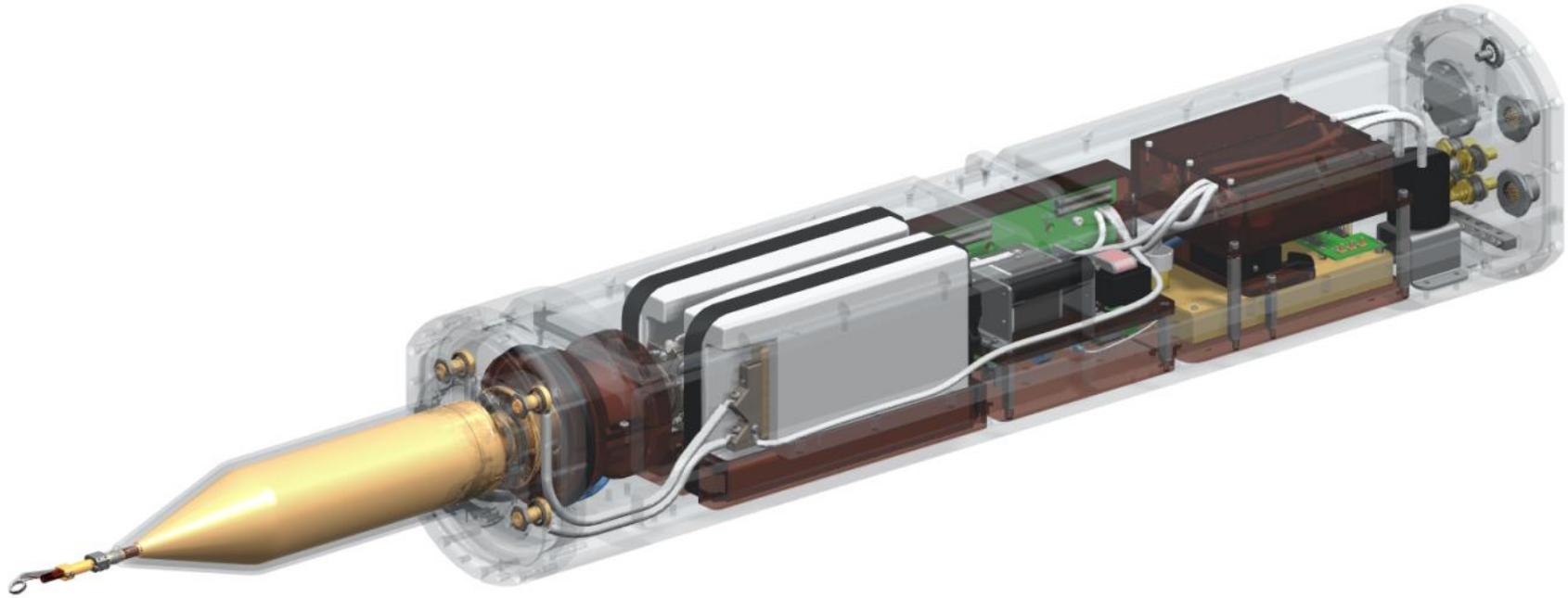
The Case for Magnetized Laser-Plasma Experiments
A White Paper



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Summary

Magnetized laser-plasma experiments provide a versatile laboratory to study basic plasma physics

- The interaction of plasma with magnetic field is a fundamental aspect of plasma physics with many applications
- High-power lasers can produce a very wide range of plasma parameters in the laboratory covering the degenerate, warm-dense and ideal regimes
- The magnetic field generation system MIFEDS on the Omega laser system built with OFES support has led to a wide variety of magnetized plasma experiments being carried out
- To push forward the field frontier will require a new device with external energy storage: concepts to reach 50 T have been developed

Collaborators

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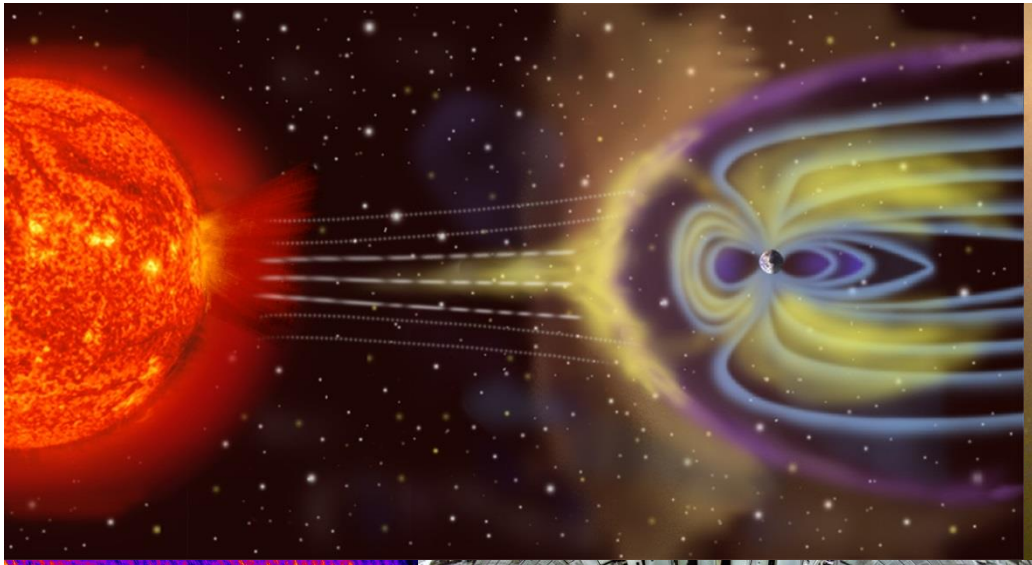
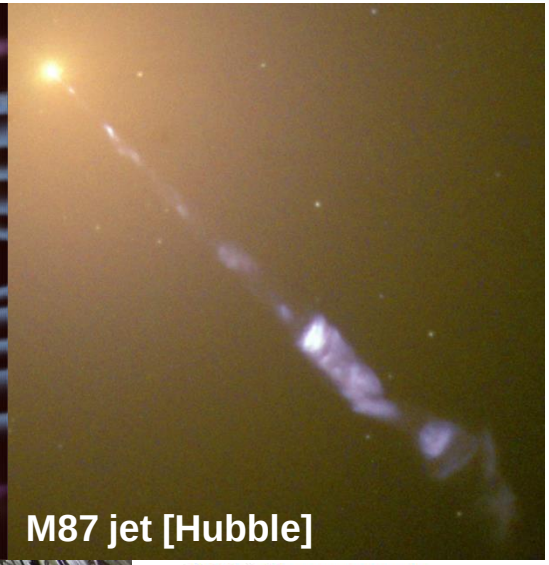
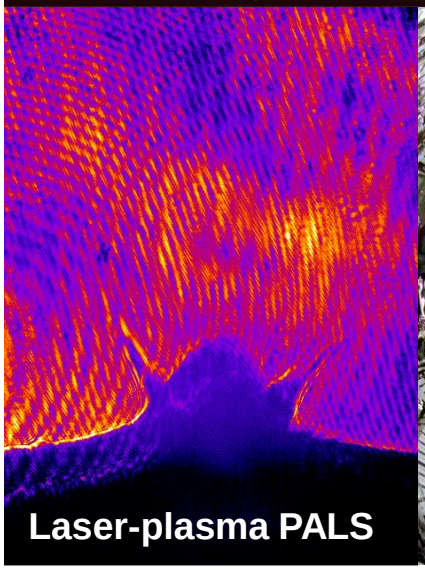
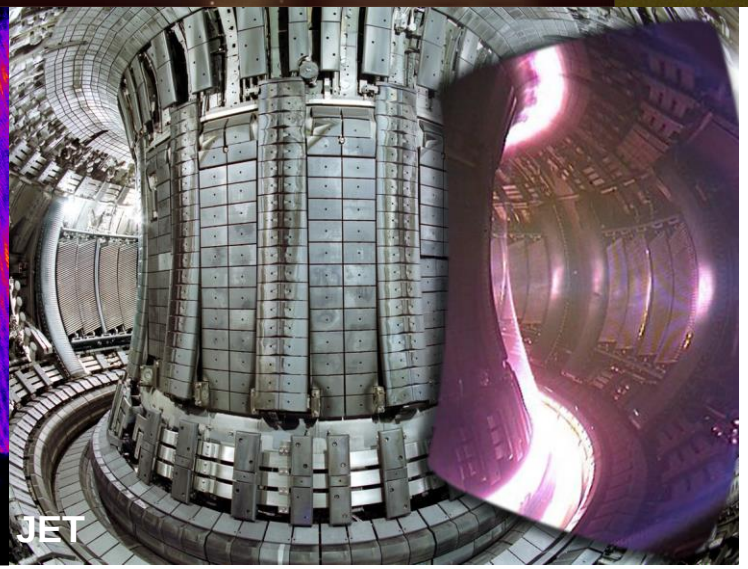
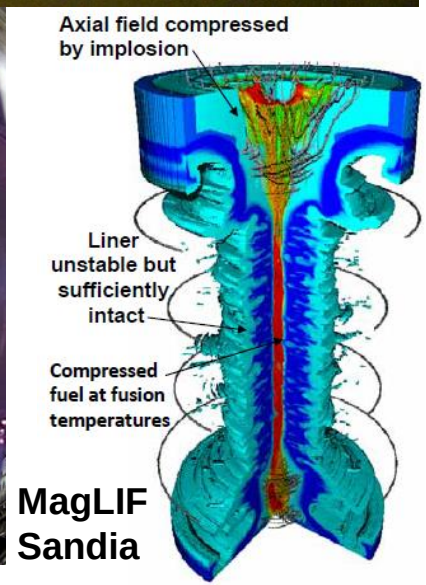
Magnetized plasmas are ubiquitous in the universe and the laboratory











Magnetic field leads to complex, anisotropic plasma properties and plasma modifies and generates magnetic fields leading to a complex non-linear system

Two examples:

1) **Electron heat flux for weak temperature gradients in a straight, uniform field:**

$$\vec{q}_e = -\kappa_\parallel \vec{b}\left(\vec{b}\cdot\nabla T_e\right) - \kappa_\perp \vec{b}\times\left(\vec{b}\times\nabla T_e\right) - \kappa_\wedge\left(\vec{b}\times\nabla T\right)$$
$$-\beta_\parallel \vec{b}(\vec{b}\cdot\vec{j}) + \beta_\perp \vec{b}\times(\vec{b}\times\vec{j}) - \beta_\wedge(\vec{b}\times\vec{j}).$$

   – **These transport coefficients have yet to be fully tested experimentally**

2) **Magnetic field evolution in MHD ignoring viscosity:**

$$\frac{\partial\vec{B}}{\partial t} = \nabla\times(\vec{v}_{\rm eff}\times\vec{B}) + \vec{v}_\eta\times(\nabla\times\vec{B}) + \frac{\eta_\perp}{\mu_0}\nabla^2\vec{B} + \frac{\nabla P_e\times\nabla n_e}{n_e^2 e}$$

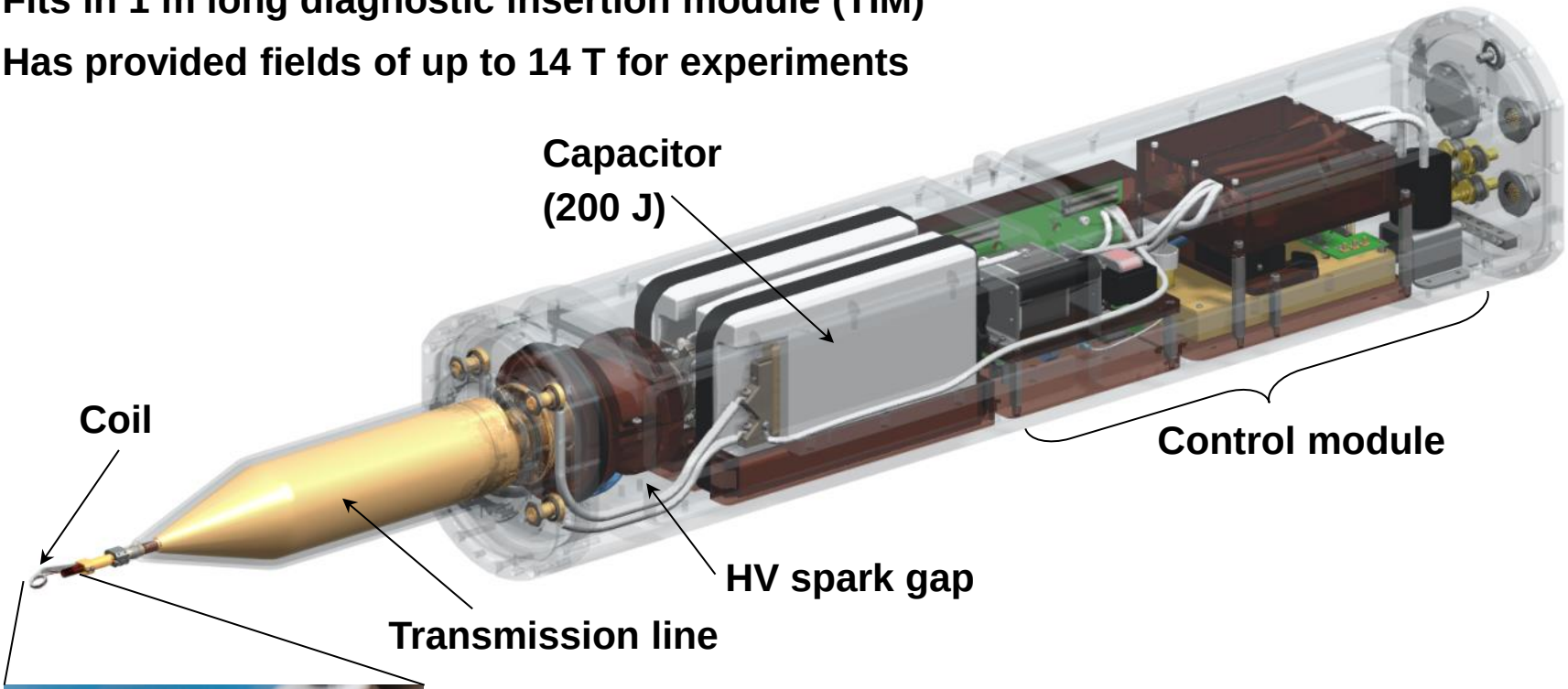
$$\vec{v}_{\rm eff} = \vec{v} - \frac{\vec{j}}{n_e e}\left(1+\frac{n_e e\eta_\wedge}{B}\right) - \frac{\beta_\wedge\nabla kT_e}{eB} - \frac{\beta_\parallel-\beta_\perp}{eB}\vec{b}\times\nabla kT_e, \quad \vec{v}_\eta = -\frac{\nabla\eta_\perp}{\mu_0}$$

   – **Magnetic field evolution due to electron heat flux (Nernst advection and the cross field heat flux dynamo) and resistivity gradients have yet to be studied in controlled experiments**

MIFEDS was built in 2006* with a grant from the OFES Joint HEDLP program and replaced with a completely new design in 2012**

Fits in 1 m long diagnostic insertion module (TIM)

Has provided fields of up to 14 T for experiments



Coils wound on 3D printed plastic mounts allow for a wide range of field topologies eg single coils, solenoids, Helmholtz coils and magnetic mirrors

*O. V. Gotchev *et al*, Rev. Sci. Instrum. **80**, 043504 (2009)
G. Fiksel *et al*, Rev. Sci. Instrum. **86, 016105 (2015)

The Omega laser system provides up to 62 laser beams in a flexible configuration and a vast suite of diagnostics

- **60-beam OMEGA**
  - **Up to 500 J per beam in 0.1 to 4 ns long, shaped pulses**
- **4-beam OMEGA-EP**
  - **Up to 6.5 kJ in 1 to 10 ns long pulses**
  - **CPA capability on 2 beams giving up to 2.6 kJ in 1 to 10 ps pulses**
  - **The CPA beams can be sent into the OMEGA target chamber**
  - **The CPA beams are regularly used for proton probing on both systems**
- **Planned: EP-OPAL an OPCPA beam line for EP delivering 1.5 kJ in 20 fs giving 75 PW with intensities up to 10^{24} W cm^{-2}**
- **Diagnostic capabilities cover neutron emission, charged particle emission, x-ray emission, x-ray backlighting, streaked optical pyrometry, VISAR, proton probing to measure magnetic and electric fields, UV and x-ray Thomson scattering, and a UV probe beam with Faraday rotation**

Shot days executed using MIFEDS and the topics covered broken down by user group

Collisionless shocks

Magnetic reconnection

Field compression

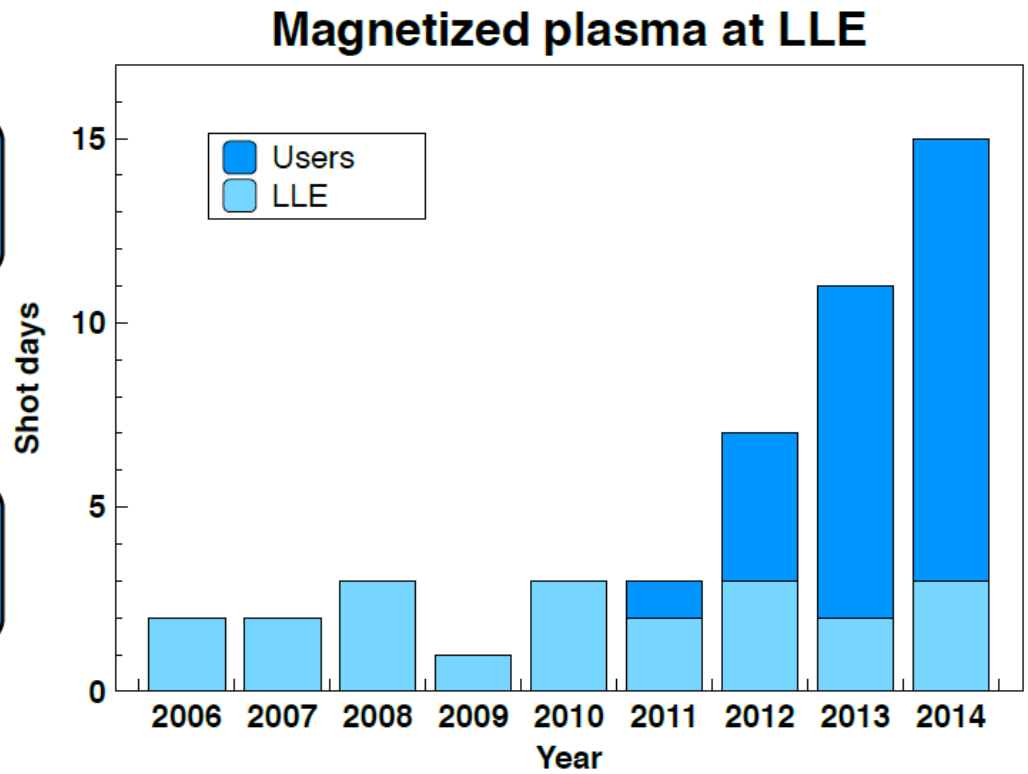
Magnetized jets

Positron focusing

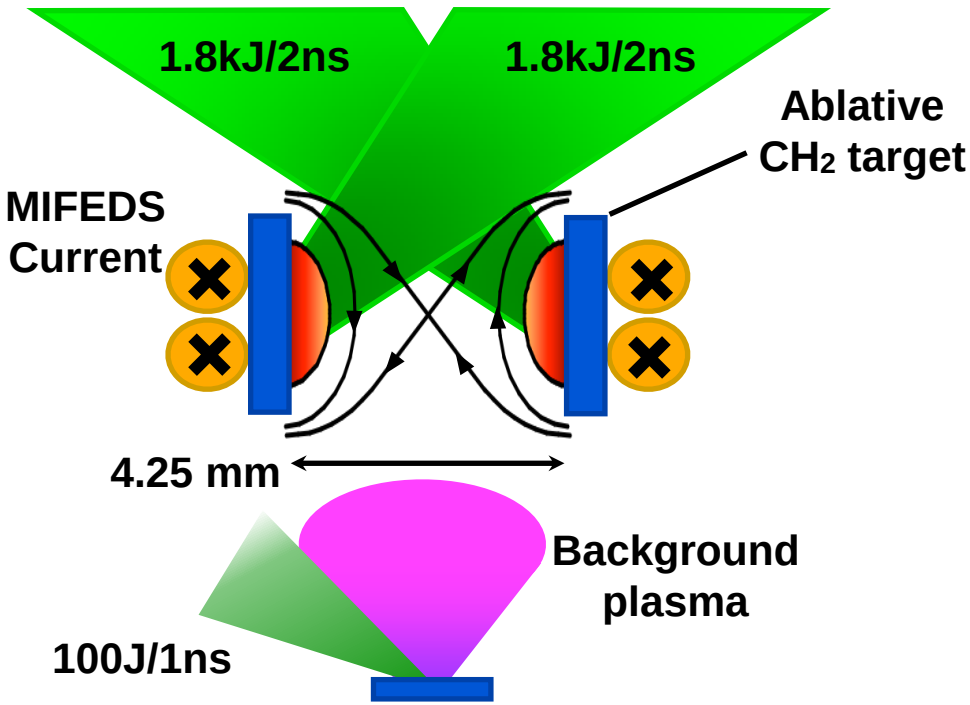
Magnetized liner

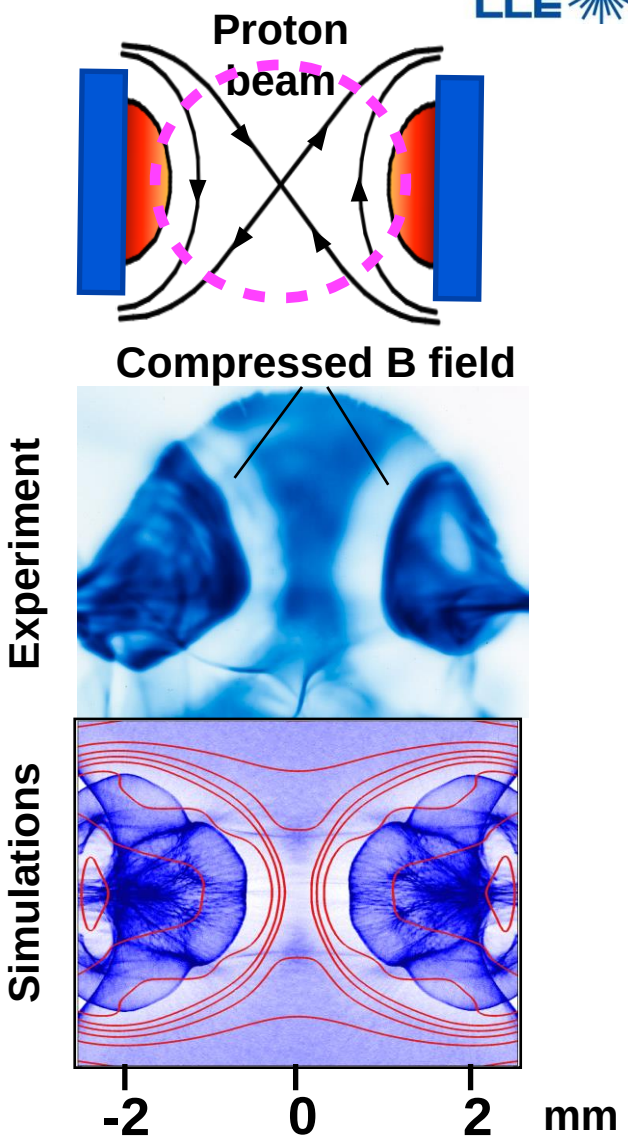
LPI in hohlraums

Astro-shocks



A sample set-up: magnetic reconnection on OMEGA-EP



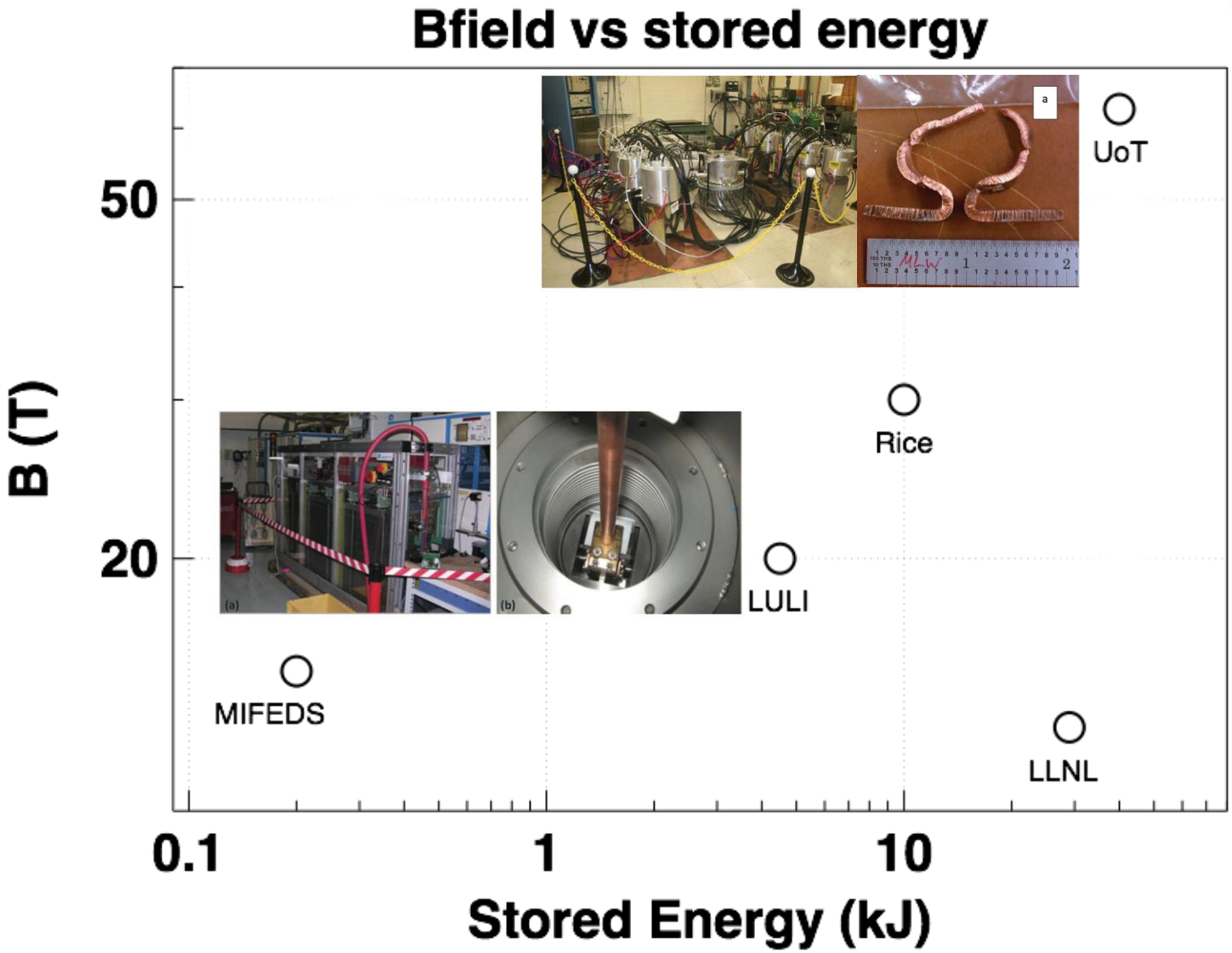


4th beam accelerates protons from a thin foil to probe the magnetic field

UV probe beam used to give information on density and magnetic field

W. Fox *et al, Phys. Rev. Lett.*, **111**, 225002 (2013)
G. Fiksel *et al*, *Phys. Rev. Lett.*, **113**, 105003 (2014)

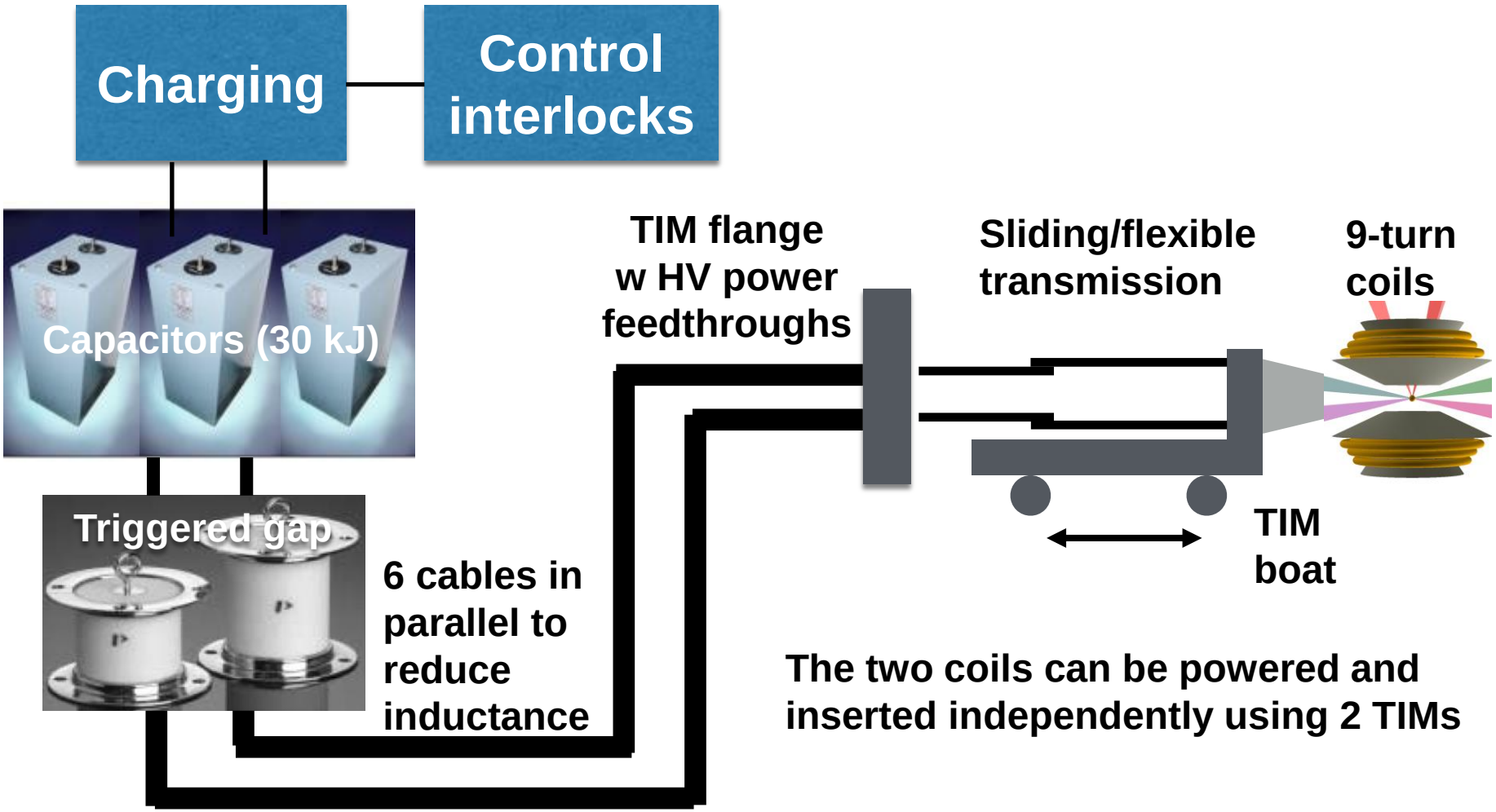
Magnetic field generation systems have been added to smaller laser systems and one is planned for the NIF



The most common user request is a higher field and some experiments require higher fields

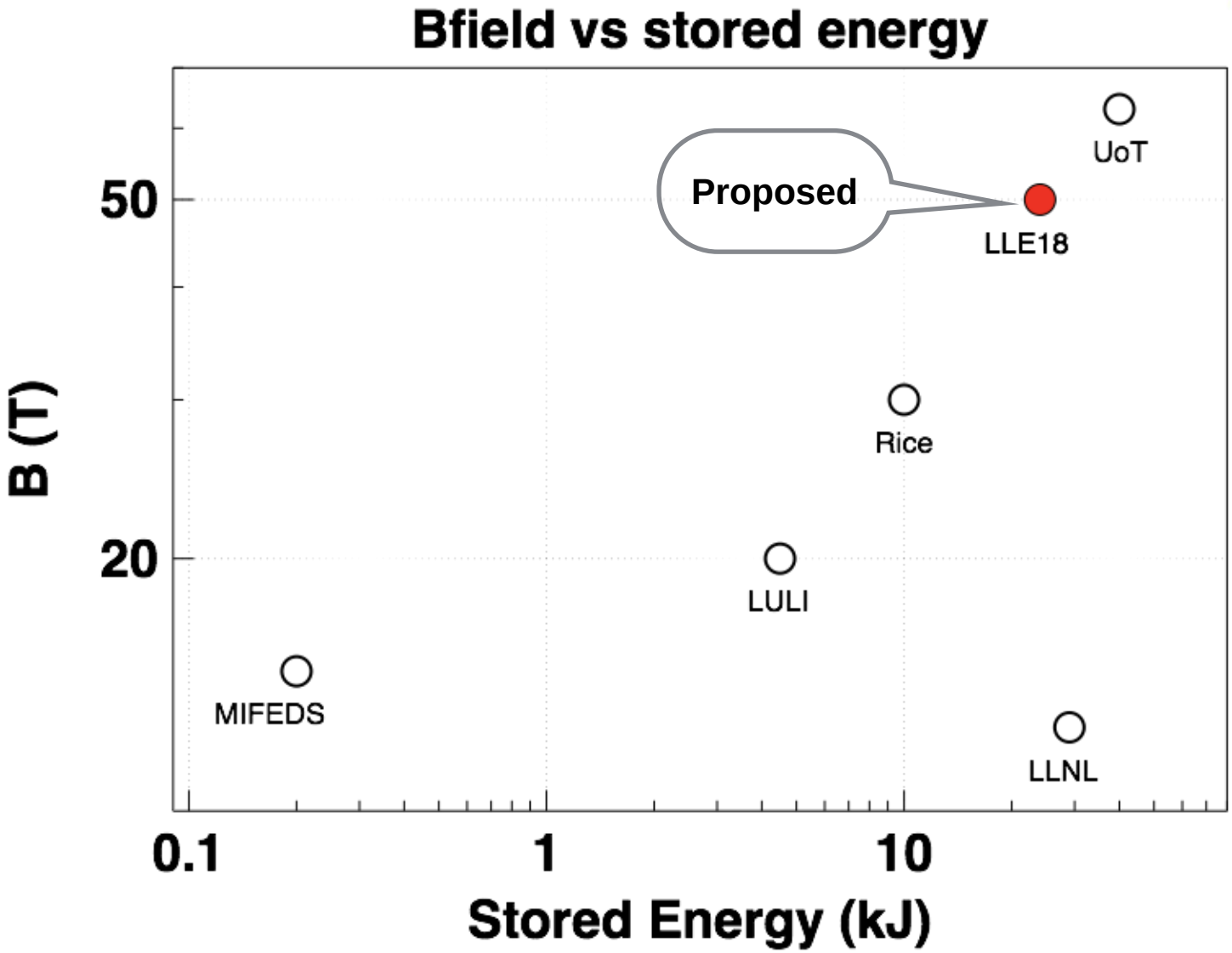
- The field is currently insufficient for the collisionless shock and plasma jet campaigns
- The magnetic field MIFEDS can provide is energy limited
  - With only 200 J it is difficult to match the thermal energy in plasmas produced by kJ lasers
- It is not possible to increase the field significantly without external energy storage
- Two concepts are being discussed:
  - A 10-MA range pulse power facility connected to EP, which could be used to provide a magnetized target chamber for EP experiments: long-term project
  - A system with a mobile external capacitor bank: 2 – 3 year project

A feasibility study for a system with a mobile external capacitor bank storing 30 kJ that could reach 50 T has been carried out



The two coils can be powered and inserted independently using 2 TIMs

This would be comparable to the highest field currently available with better laser and diagnostic access



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