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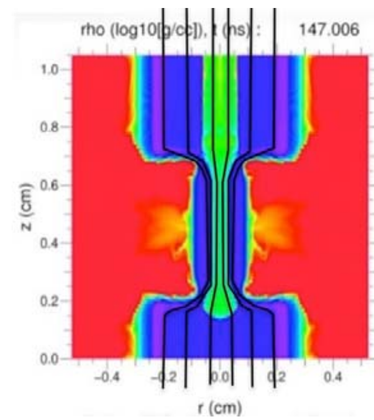
Parallel Discussion Topic B:

Measuring magnetic fields and flux compression, laser preheat issues, general diagnostic discussions, and relevant experiments



M. E. Cuneo et al.
Pulsed Power Sciences Center
Sandia National Laboratories

1st Workshop on Magnetized Liner Inertial Fusion
Albuquerque, NM
Feb. 5-8, 2012

U.S. DEPARTMENT OF ENERGY · NNSA National Nuclear Security Administration

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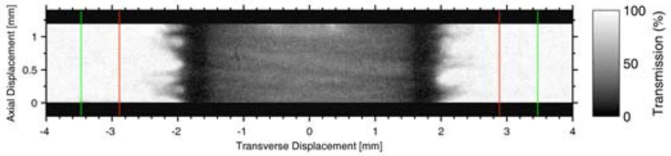
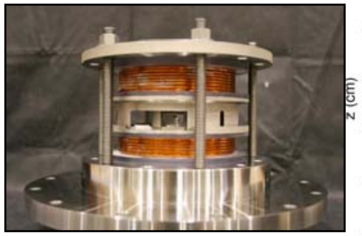
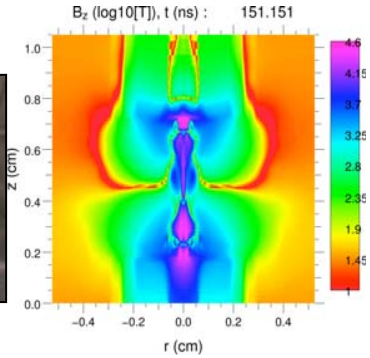
Issues that are preconditions for the MagLIF experiment

- **Liner Implosion Stability**

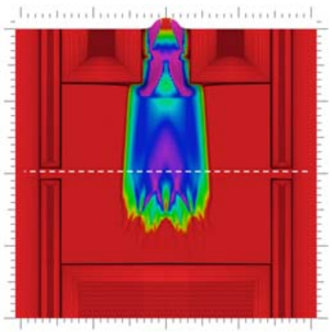


- **Magnetize the hot spot**
  - Require >10 MGauss
  - We can't reach >10 MGauss without flux compression
  - Can we compress flux with plasma?
  - How will we measure it?





- **Can't reach relevant fusion conditions without preheated plasma**
  - How uniform does the plasma need to be?
  - Jets from the cathode end would be bad
  - What about end loss?
  - Are electrodes any better than holes for stopping end loss?
  - How does the magnetic field interact with the preheating?



Validate problems in small, relevant, achievable steps: "as low a risk path as reasonably achievable" (ALARPARA)

- Liner initiation (Peterson et al, Awe et al, Blesener et al)
- Liner implosion stability to small convergence ratio (Sinars et al, Zier et al)
- Liner implosion stability to higher convergence ratio (McBride et al, Lau et al, Miles et al)
- Coupling to target in a power feed compatible with coils (McBride et al)
- Coupling to target with applied-B (McBride, Rovang et al)
- Laser preheat without applied-B (Montgomery, Harding, Sefkow et al)
- Laser preheat with applied-B
- Flux compression efficiency (Gotchev et al, Knauer et al)
- Flux compression efficiency with laser preheat

- Must get these issues right before proceeding

Divide and conquer is necessary, not sufficient: integrated experiments required to uncover all relevant issues

- Integrated experiments (Chang, Fiksel et al)

- What are the real limiting issues?
  - End loss effects?
  - Instability growth?
  - 3D asymmetry in implosion? Flute instability?
  - Mix of fuel and liner (during acceleration, during deceleration)?
  - Convergence ratio attainable?

We had a ***lively*** discussion on measuring magnetic fields, validating flux compression, preheat, and end losses

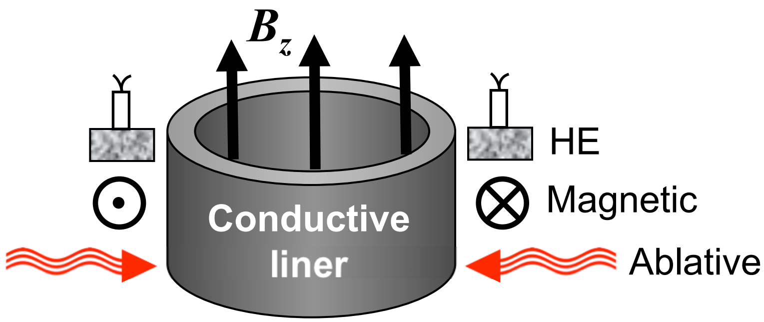
- Sasha Velikovich – The Physics of Magnetic Flux Compression in Plasmas
- John Greenly – Magnetic Probes
- Stephanie Hansen – Zeeman Spectroscopy

- Tom Intrator – Fiber Faraday Rotation, Monochromatic Polarized X-rays
- Roger Smith – Faraday rotation pulsed polarimetry
- Sergey Lebedev – Optical diagnostics in MagLIF conditions
- Vladimir Ivanov – UV and Deep UV Diagnostics for Dense Plasmas

- John Greenly – A horrifying thought…..
- Matt Gomez – Stark Effect and Active Doping
- Patrick Knapp – Absorption Spectroscopy
- Mike Cuneo – Flux Compression Experiments on Z

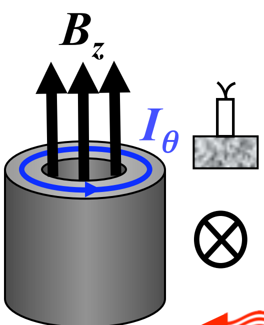
Magnetic flux compression has been shown with high explosives and with laser compression

S. Velikovich



For compression ratio $R_0/R_f = 30$ (stability)
$B_0 = 150$ kG, $B_f = 100$ MG => Rm = 11

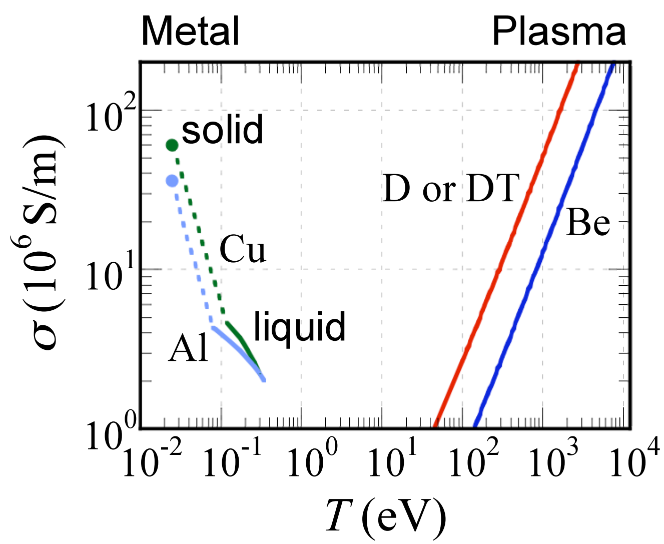
$$Rm_0 = \frac{4\pi}{c^2} R \times V \times \sigma$$



HE	28 MG	Boyko et al
Magnetic	42 MG†	Felber et al
Ablative	>36 MG	U. Rochester

† Inferred, not measured

Conductivity



"The potential is there, but it's so much harder when no one has done it before"

S. Velikovich

- Producing ~100 MG in magnetic flux compression appears to be well within the capabilities of both refurbished Z and NIF
- The results from flux compression experiments on Omega are very encouraging
  - Peak magnetic field of >36 MG measured by proton radiography agrees with 1D simulations and imply Rm ~ 50
- The considerable potential for magnetic flux compression to ~100 MG with pulsed power needs to be demonstrated
  - Peak compressed magnetic fields have never been measured above the level where magnetic probes measurements are possible
  - Data from explosively driven magnetic flux compression does not extend beyond 28 MG
  - RMHD codes used to design experiments and predict their results need both verification and validation

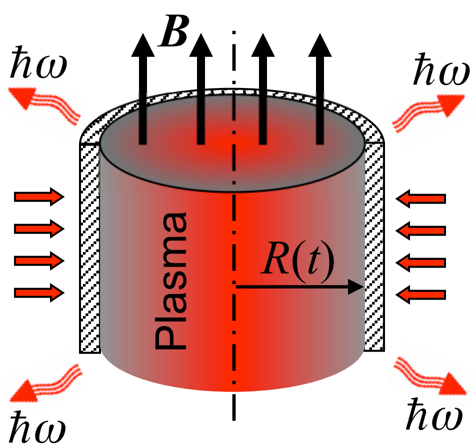
J. Lindl, NIF's chief scientist, quoted in Science **334**, 449 (2011).

O. V. Gotchev *et al*., Phys. Rev. Lett. **103**, 215004 (2009); J. P. Knauer *et al*., Phys. Plasmas **17**, 056318 (2010).

We should be cautious where plasmas are concerned – but not pessimistic

Plasmas are notorious for letting the magnetic field leak

Radiation controlled plasma T

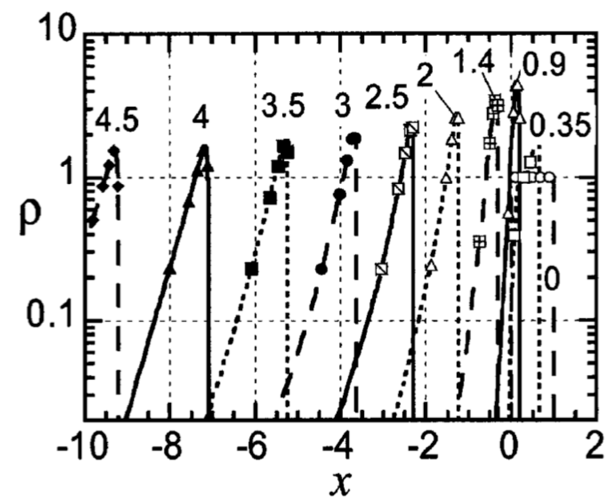


$$\frac{B}{B_0} = \left(\frac{n}{n_0}\right)^{1/2} = \frac{R_0}{R} = \left(\frac{R_0}{R}\right)^{2-1/\mathrm{Rm}}$$

=> $\mathrm{Rm} = 1$

To obtain 100 MG @ Rm=1 one needs to start from 3 MG – not possible.

Self-consistent skin depth = twice the density gradient length



$$B \sim \sqrt{n} \sim \exp\left(-\frac{|x - x_p|}{2L(t)}\right)$$

S. Velikovich

Sasha's wish list

- Experimental data for demonstrating the viability of the concept and for code validation
  - Measure the peak magnetic field ~100 MG in plasma (Faraday/Zeeman/other spectroscopic methods?)
  - Measure the peak plasma temperature ~10 keV (dopant line spectroscopy, bremsstrahlung continuum)
  - Measure the degree of mixing between the wall material and compressed D/DT plasma
- Experimental, numerical and theoretical studies for code verification and validation
  - None of the RMHD codes used by the pulsed power community has been validated/verified in the relevant conditions; no experiments have been modeled
  - Effects of major importance in this context, such as Nernst and Ettingshousen effects in plasma, not even included in most codes; verification issues
  - Atomic physics issues for spectroscopic diagnostics (parameter range, dopant materials, spectral lines chosen for diagnostics)
  - Kinetic theory issues: diffusion approach to the transport of fast alpha particles in fusion plasma across the magnetic field still requires clarification

S. Velikovich

Could begin by validating codes against existing experimental flux compression data in plasmas, 1986-2010

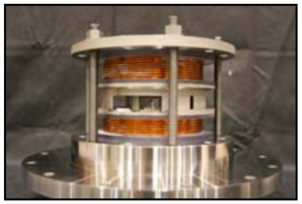
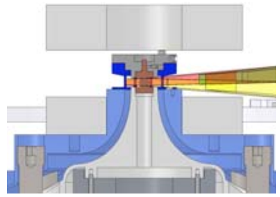
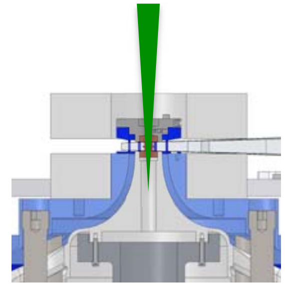
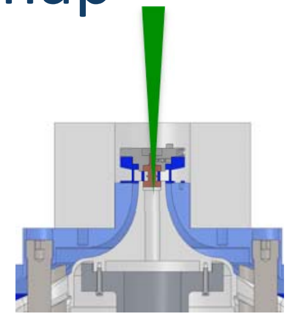
Ref.	Institution	Plasma material	R_0 (mm)	h (mm)	I_m (MA)	B_0 (kG)	B_m (MG)	B_m/B_0
[1]	UC Irvine	H_2, He, CH_4, N_2, CO_2, Ar, Kr, Xe	20	10	0.47	9-18	>1.6	>180
[2]	HCEI	Al	20	10-15	0.13	1-2	>0.065	>55-65
[3]		Ne	7.5	15	1.4	18	2.5	140
[4]		Ar	13.5	24	1.0	18	0.6	33
[5]	Sandia	Ne	12.5	20	7.5	100	42	420
[6]	Imperial College	H_2, He, D_2, Ne, Ar, Kr	15-18	12-15	0.5	3	0.38	126
[7]	TRINITI	W	10	10	3	5	0.3	60
[8]	LLE	D_2	0.225	1.5	N/A	62	36	580

inferred

[1] F. S. Felber *et al*., J. Appl. Phys. **64**, 3831 (1987).
[2] R. B. Baksht *et al*., Sov. Phys. - Tech. Phys. **32**, 145 (1987).
[3] S. A. Sorokin and S. A. Chaikovsky, in *Dense Z-pinches*, AIP Conf. Proc. **195**, 438 (1989).
[4] S. A. Sorokin, IEEE Trans. Plasma Sci. **38**, 1723 (2010).
[5] F. S. Felber *et al*., Phys. Fluids **31**, 2053 (1988).
[6] R. K. Appartaim and A. E. Dangor, J. Appl. Phys. **84**, 4170 (1998).
[7] G. G. Zukakishvili *et al*., Plasma Phys. Reports **31**, 652 (2005).
[8] O. V. Gotchev *et al*., Phys. Rev. Lett. **103**, 215004 (2009).

S. Velikovich

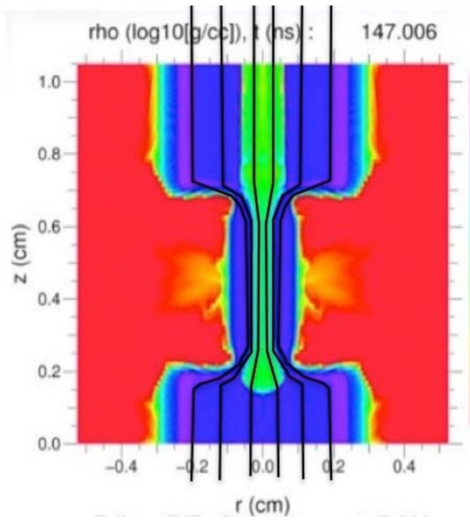
Lets develop a magnetic field diagnostic roadmap

			
2013	2013-2014	2013-2015	2014-2016
No preheat B_{zo} = 0.5–10 T	No preheat B_{zo} =10–15 T	Preheat B_{zo} = 15–20 T	Preheat B_{zo} = 30 T
Radial Access Axial Access	Radial Access Axial Access	Radial Access	No Access (neutrons) Is there a Metric other than yield?
Invasive Non-invasive	Non-invasive	Non-invasive	Integrated

- B_θ (drive)
- B_z (fusion physics, e.g. electron thermal conduction, RT mitigation)

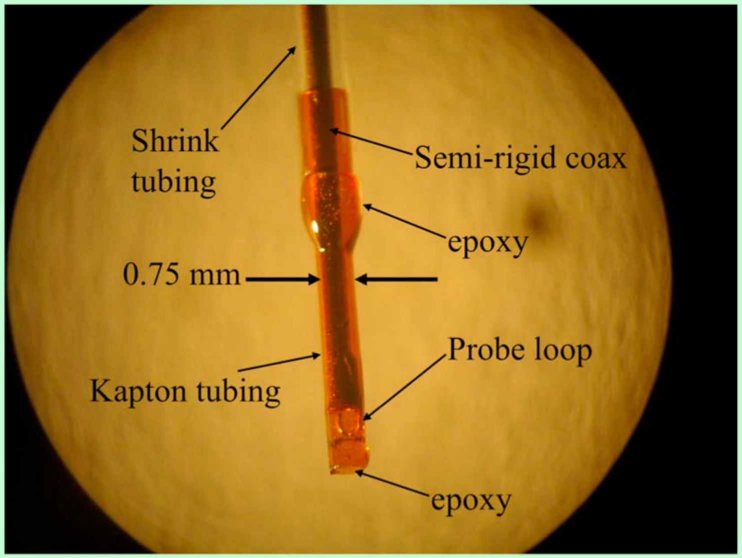
We plan initial experiments on flux compression without laser preheat in 2013

- Compression of flux with liner and no gas present may be efficient
- We expect a high magnetic Reynolds number, R_m, and thus high compression efficiency
- Can we validate this prediction of theory with independent measurements of flux compression and liner convergence ratio?
- Axial and radial access are permitted without laser pre-heat
- Invasive or perturbing probes may permit measurements to a certain convergence ratio
- Would measurements be possible with gas fill heated by the implosion, without laser pre-heat?



Sefkow et al

John Greenly has successfully used micro-B-dot probes in hostile plasma environments from 1 to 10 T/ns



New COBRA Kapton-insulated magnetic probe construction

- 1000 V signal at 10 T/ns with 0.1 mm^2 area
- Up to 80 T measured on COBRA
- Fails with breakdown of insulator
- Failures can be soft, sometimes not obvious
- Signal jumps in direction of plasma potential upon failure
- Can it fail with implosion of the 0.020 inch copper coax of the semi-rigid?
- Measure up to 8:1 convergence ratio
- Suggests experiments with Bo ~ 1.2 Tesla assuming flux conservation, without methods to reduce signal
- Use probes to measure Br inside liners
- Recess in conducting tube could reduce sensitivity further for high fields
- Some ideas on how to configure probes to measure Bz – test on COBRA
- Difficult to ensure probes aligned properly to measure a small field component in the present of a larger one in a different direction

Nano-fabricated B-dots
Borg Nano Probes? Rovang, McBride

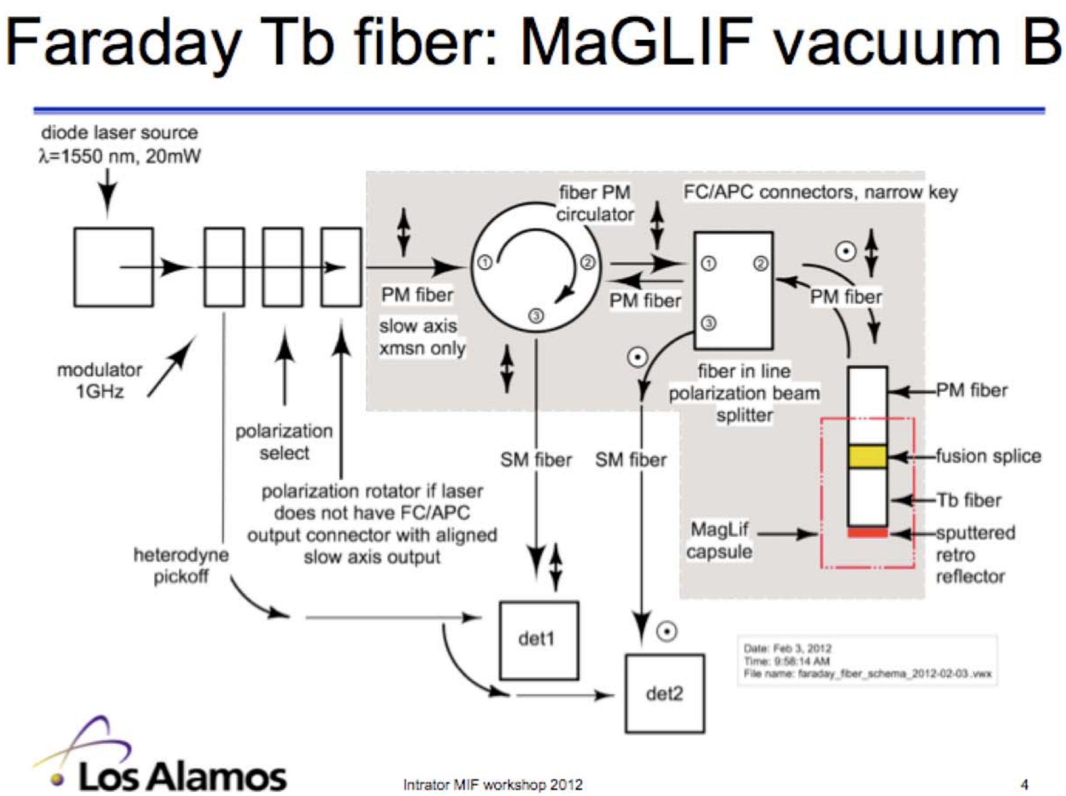
Tom Intrator and his colleagues from MTF offer a challenge

MHED Grand Challenge

Invent and refine techniques to measure the magnetic fields that transform fundamental features of magnetized HED plasmas (possibly ICF capsules too).

- Intrator, Weber, Montgomery, Hsu, Smith, McBride, Dolan, Atheron, Struve

Get initial high quality validation data for vacuum B compression with this concept



Intrator

- Low cost
- Measure 0.5 to 1000 Tesla
- Calibrate Verdet constant on the bench with standard
- Could be resilient to fiber darkening (quadrature and heterodyne)
- Use rad hard fiber?
- 100 µm fiber, 200-300 µm sleeve
- Perhaps convergences of 15-30:1
- Use Bo of 1 to 4 Tesla assuming flux conservation
- Axial Faraday probe measured up to 1.6 MGauss before mechanical fracture of sleeve and fibers – see ref. 1, slide 10

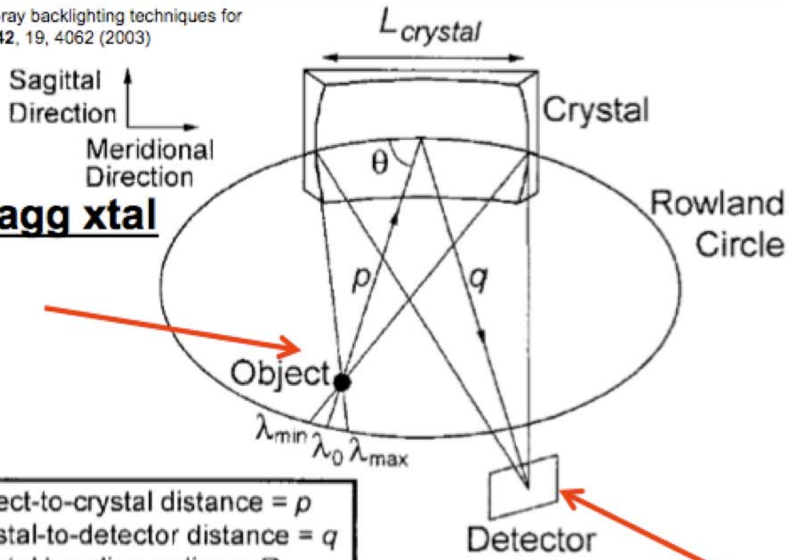
Montgomery, Intrator

Possible Faraday rotation with plasma

Sinars et al, Evaluation of bent crystal x-ray backlighting techniques for the Sandia Z machine, Applied Optics, **42**, 19, 4062 (2003)

Toroidally bent Bragg xtal

- X-ray backlight
- Collimated
- Monochromatic
- Polarized
- X-ray source
- Faraday rotn



Object-to-crystal distance = p
Crystal-to-detector distance = q
Crystal bending radius = R
Rowland Circle radius = $R/2$

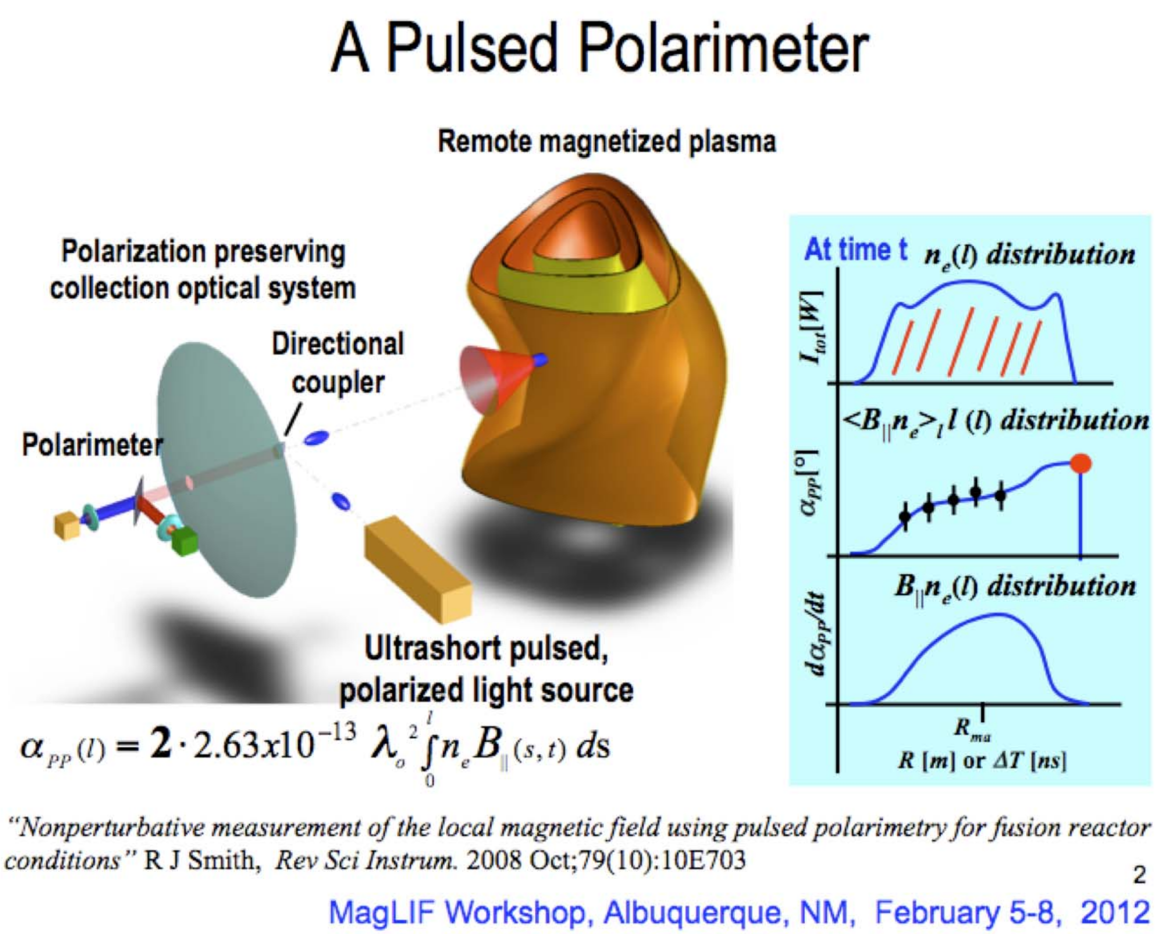
X-rays for Faraday rotn in optically thick plasma

Los Alamos

Intrator MIF workshop 2012 7

- Nascent idea
- 45-degree Bragg reflecting optic as a polarized x-ray source
- 6.1 keV – penetrate the liner
- X-ray polarimeter as a detector
- Measure Br, possibly Bz
- Needs support to develop the idea

R. Smith



- LIDAR Thomson scattering with polarimetry
- Used in MFE
- Powerful – only method for local internal conditions, n, B, T of plasma
- Robust to refraction
- 532 nm measure 20 T in 10^{19} cm^{-3}
- Hard: 50 nm measure 200 T in 10^{21} cm^{-3}
- Could be very useful for characterizing conditions in magnetized pre-heat plasma or initial stages of compression

UV and Deep UV Diagnostics for Dense Plasma (V. Ivanov, UNR)

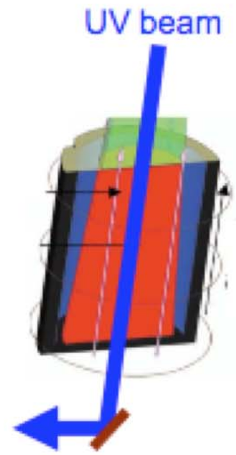
Laser wavelength for UV and deep UV:

λ/4 = 266nm - available for commercial Nd lasers, η = 10-30%

λ/5 = 211nm - available for commercial Nd lasers, η = 5-10%

λ/6 = 176nm - at the experimental stage, crystals exist

λ = 157nm - excimer F2 laser, available (Coherent, 50mJ, 10ns, $200)

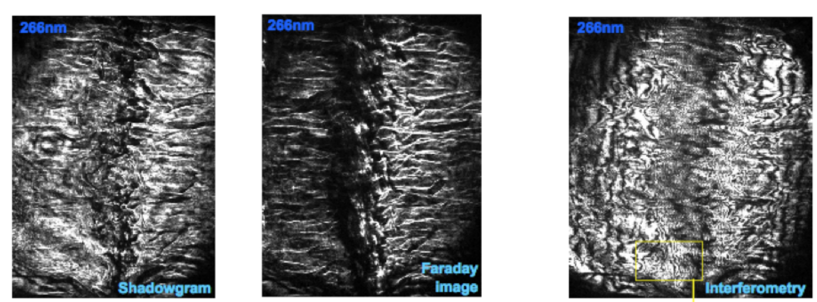


Critical plasma density:

$$n_c = \frac{\varepsilon_0 m_e}{e^2}\omega^2 = 1.12\cdot 10^{13}\cdot\lambda^{-2}\ \text{cm}^{-3}.$$

$n_c = 4\cdot 10^{21}$ cm^{-3} at 532nm, **$n_c = 1.6\cdot 10^{22}$ cm^{-3} at 266nm**, $3.6\cdot 10^{22}$ cm^{-3} at 176nm, and **$4.5\cdot 10^{22}$ cm^{-3} at 157nm**.

- Could probe initial stages of compression (~2:1) up to peak current
- Sufficient transmission of 266 nm beam for a lighter (1/3), shorter load (1/2)
- Fields up to 2-3 MGauss



Refraction on density gradients

Lebedev
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February 2012

D_2, ρ_0 = 1mg/cc (n_{a_0} = $3{\cdot}10^{20}$cm^{-3})

R =3.5mm, L =5mm, B_0 = 20T, T_0 = 200eV

$C_R = R_0/R$ ➔ $n \sim C_R^2$, $B \sim C_R^2$, $T \sim C_R^{4/3}$

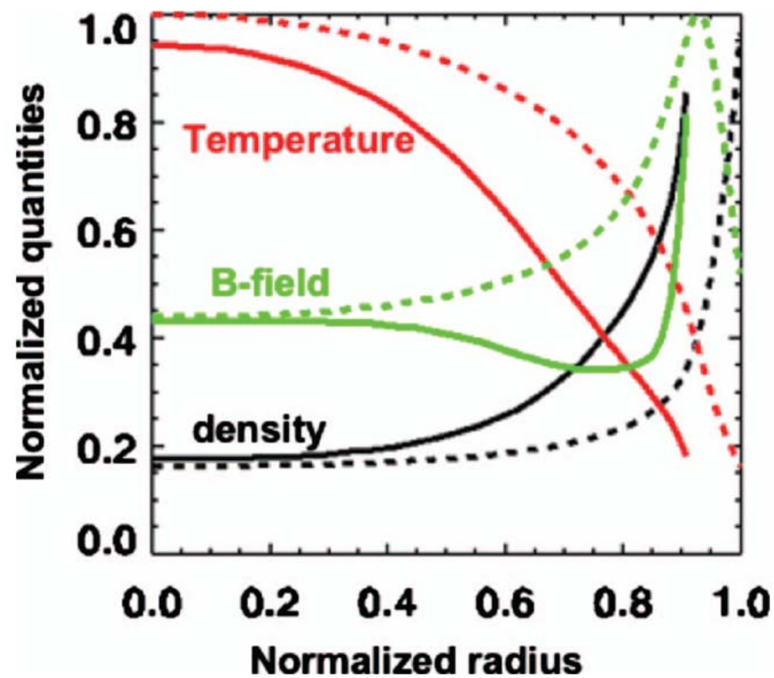
Laser probing:

λ = 0.355μm ($3\omega_0$ Nd) $n_{cr} = 9{\cdot}10^{21}$cm^{-3}

Laser cut-off at $C_R \sim 5.5$

Refraction on density gradients: $\nabla n \sim n/R \sim C_R^3$

$$\theta_{ref} \approx \frac{1}{2n_{cr}} \nabla n_e L \approx 1 \; f\,or C_R = 2.4$$



Refraction could restrict probing possibilities even at early stages of compression

Interferometry and Faraday rotation

Lebedev

s.lebedev@ic.ac.uk
February 2012

Number of interference fringes):

$$F = \frac{\varphi}{2\pi} = 4.46 \cdot 10^{-18} \lambda_{[\mu m]} \cdot \int_{[cm^{-2}]} n_e dl \quad \propto C_R^2$$

Laser λ = 0.355μm (3ω_0 Nd) ➔ F = 10^3 for C_R = 2

Faraday rotation:

$$\theta_{Far[rad]} = 2.26 \cdot 10^{-17} \lambda_{[cm]}^2 \int n_{e[cm^{-3}]} \vec{B}_{[G]} \cdot d\vec{l} \ \propto C_R^4$$

Laser λ = 0.355μm (3ω_0 Nd) ➔ θ_{Far} / 2π = 2 for C_R =2; 11 for C_R =3

Faraday rotation in quartz fibre (ν = 6.6 rad/T/m):

$\theta \sim B \sim C_R^2$ θ / 2π = 0.4 for C_R =2; 10 for C_R =10

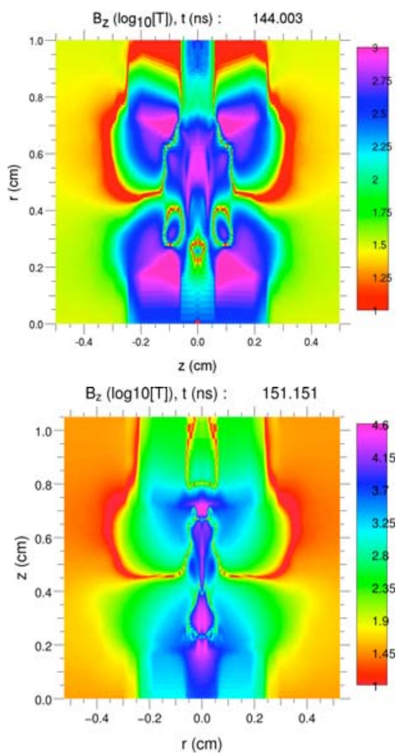
Are there methods to measure the flux compression in integrated experiments with laser pre-heat in 2014?

TANGLED ANISOTROPIC

- Flux loss is potentially large with hot plasma. Would like to validate MHD models of flux compression efficiency under these conditions.

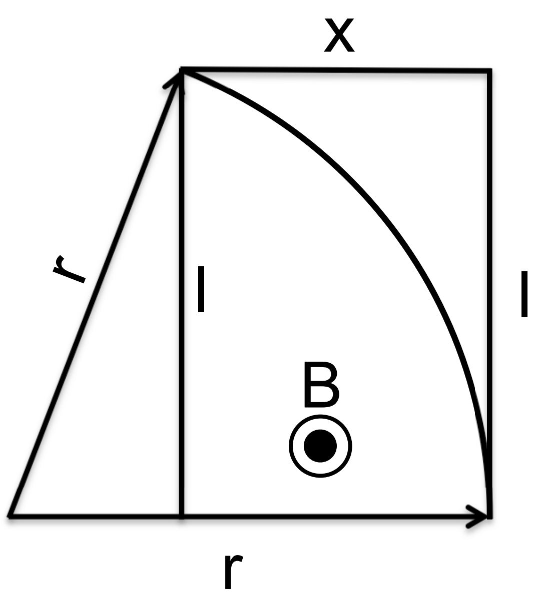
- Diagnostic access is probably radial
  - Limited/No axial probing with laser pre-heat
  - Radial access suggests that the liner opacity could be important
  - Density, temperature, and field gradients will be pervasive
  - B_θ will also be present!
  - Grad n x grad T could be significant

- May have to indirectly infer presence of enhanced magnetic field from integrated results as in Omega experiments



Sefkow et al

Proton radiography is not possible with an integral B•dl of >4000 T-cm to cross



- Assumption: homogeneous B-field
- p+ deflection (mass m, kin. energy E, charge e, mag. field B):

- Measure deflection x over distance l:

→r>l, insert eq. for r and solve for B:

→ or solve for E when B is given:

Few examples:

E=60 MeV, l=1 mm: B must be less than 1.1 kT (11 MGs)

MagLIF: 2 cm gap, 20 MA current, B (in Tesla) = 20*I (in MA)/R(in cm) ~ 200 T : E > 750 MeV

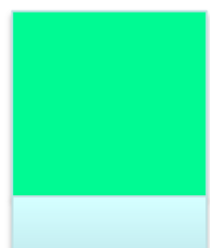
Schollmeier

Spectroscopic techniques may be our only hope to measure 100 MGauss in hot (> keV), dense plasma

- Use Zeeman techniques, but know how they may fail
  - Zeeman should be 3 times larger than all other broadening mechanisms combined (opacities, Doppler, Stark)
  - Side-on and end-on to evaluate mechanisms

- Added atomic physics of splitting to SCRAM

- Try to use spectrometers on hand at Z
  - > 600 eV, 3 – 100 kT
  - 1.5 – 3 eV (optical), 1 – 300 T
  - Top request for a new capability: Time-gated UV – EUV instruments could fill a gap (10 – 500 eV, E/DE ~2000-3000)



S. Hansen

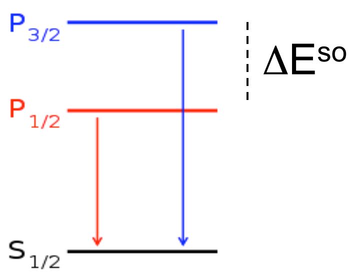
G. Chandler

Zeeman splitting arises from the interaction of bound electrons with an external magnetic field

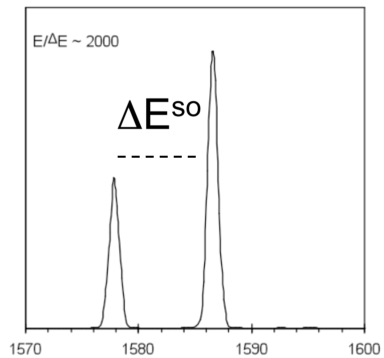
S. Hansen

The orbital motion of electrons in bound states drives an internal magnetic field, which leads to fine structure effects like spin-orbit splitting

e.g.
ns-n'p splitting:

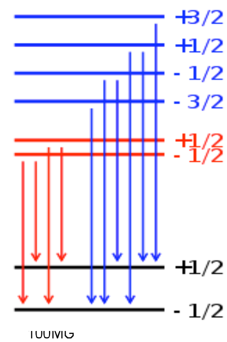


→ a simple doublet:

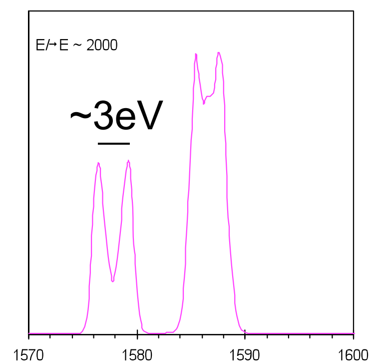


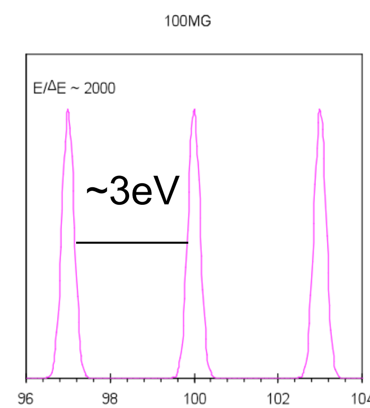
Spectrometers on hand:
> 600 eV (x-ray) & ~1.5 - 3 eV (optical)
(~ 3 – 100 kT) (~1 – 300 T)

Additional magnetic fields break the degeneracy of magnetic sublevels:
$\Delta E^Z \sim \mu_0\, g_J\, m\, B$



ΔE^Z is the same for any photon energy, optical to x-ray!
(~ 3eV for ~10kT)





10 kT is a weak field
($\Delta E^z < \Delta E^{SO}$) for hν~1 keV

but a strong field
for hν~0.1 keV!

Differential splitting may help overcome limitations of instrumental spectral resolution ~ 1000

- Zeeman splitting is larger in the $np_{1/2} – n’s_{1/2}$ line than the more intense $np_{1/2} – n’s_{1/2}$ line

- Since Stark*, thermal, instrumental, and motional broadening are all the same for the two lines, B fields are the only thing that preferentially broaden the smaller line

- Opacity effects would act in the opposite direction

- Fields of ~ 1 – 20 T have been measured at the Weizmann Institute using optical (~2 eV) 4p – 4s lines.

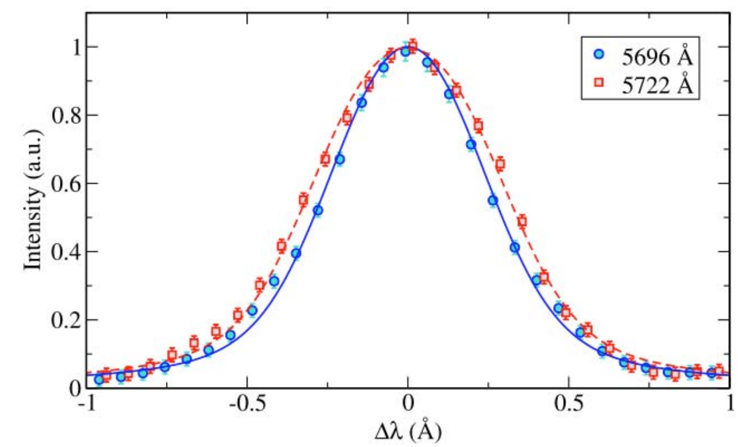
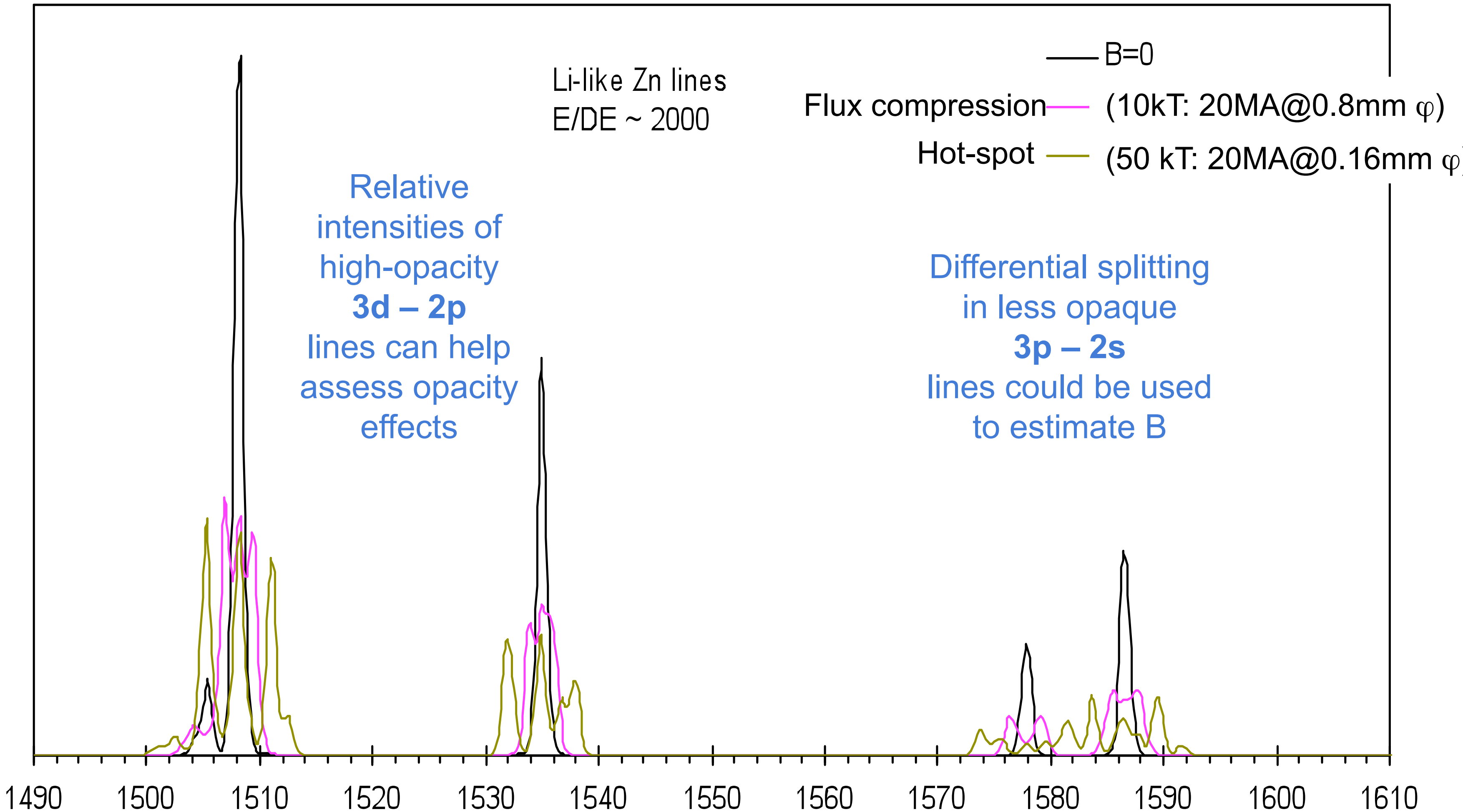


FIG. 5 (color online). The AlIII $4p$-$4s$ (5696 & 5722 Å) doublet. The line shapes of the two components are peak-normalized and shifted to a common spectral center. The smooth lines represent best-fit calculations for $B = 0.9$ T, $N_e = 2 \times 10^{16}$ cm^{-3}, and $T_e = 10$ eV.

Stambulchik, Tsigutken, and Maron, *Phys. Rev. Lett*. **98**, 225001 (2007).

*As long as total broadening $\Delta E_z < \Delta E^{SO}$ (line separation)

For higher fields, x-ray Li-like lines in transition metals might give B at moderate spectral resolution



S. Hansen

Practical Zeeman spectroscopy on Z will have to balance multiple considerations

- **Optical:** S. Hansen
  - Zeeman effect will be large
  - Lines may be optically thick (even continuum κ gets large for $h\nu$ < 100 eV)
  - For diagnosing flux compression in MagLiF side-on, they will not escape liner
  - Stark broadening may be very large at the densities we care most about
  - Photons from hot emission regions might overwhelm the transitions of interest
  - Most useful for measurements in initial stages of compression

- **X-rays:**
  - May be the only way to asses fields in hot plasmas
  - Zeeman splitting may be near instrument resolution
  - Differential splitting may help us overcome resolution requirements (E/DE ~ 5000 for direct measurements)
  - Li-like 3p – 2s transitions are promising candidates:
    - Emitted from plasma regions with T ~ 0.3 – 3 keV from transition metals up to Kr
    - Nearby 3d – 2p transitions can help asses opacity effects
    - relatively large ΔE^{so} (~10x larger than ΔE^{so} of Lyα at similar energies) – so we could use Weizman differential splitting analysis
  - X-rays may escape Be liner, so we are not restricted to end-on lines of sight

Tom Awe prepared a diagnostic data sheet to describe proposed methods

—MAGNETIC FIELD MEASUREMENT TECHNIQUE DATA SHEET—

TECHNIQUE: ____
ADVOCATE(S): ____

DESCRIPTION OF METHOD
Measures: [ ] B_z [ ] B_θ [ ] Both
COMMENTS: ____
[ ] Direct or [ ] Indirect
COMMENTS: ____
[ ] Invasive or [ ] Non-invasive
COMMENTS: ____
[ ] Passive or [ ] Active
COMMENTS: ____
[ ] Radial or [ ] Axial
COMMENTS: ____

IMPLEMENATION:
Diagnostic access requirements: ____
Instrumentation needed: ____
Will any hardware be in vacuum chamber? [ ] Yes or [ ] No
COMMENTS: ____

Estimated cost: ____
Lead time: ____
Incompatibilities or limitations (e.g. integration with pulse power, integration with laser preheat, other): ____

Technical issues to be resolved for the Z environment (e.g. radiation, neutrons, shocks, acceleration, other): ____

Engineering requirements/challenges: ____

PERFORMANCE:
Maximum inferred field or currents: ____
Minimum inferred field or currents: ____
Accuracy: ____
Precision: ____
Time resolution: ____
Spatial resolution: ____

ANALYSIS:
Calibration technique: ____

Method for unfolds, or interpretation. Is it qualitative or quantitative? ____

Are any special codes or models necessary? ____

ADDITIONAL COMMENTS: ____

—Suggested MagLIF Experimental Measurement—

PARAMETER TO BE MEASURED/PHYSICS OBJECTIVE: ____

TECHNIQUE: ____
ADVOCATE(S): ____

DESCRIPTION OF METHOD
[ ] Direct or [ ] Indirect
COMMENTS: ____
[ ] Invasive or [ ] Non-invasive
COMMENTS: ____
[ ] Passive or [ ] Active
COMMENTS: ____

IMPLEMENATION:
Diagnostic access requirements: ____
Will any hardware be in vacuum chamber? [ ] Yes or [ ] No
COMMENTS: ____
Instrumentation needed: ____

Estimated cost: ____
Lead time: ____
Incompatibilities or limitations (e.g. integration with pulse power, integration with laser preheat, other): ____

Technical issues to be resolved for the Z environment (e.g. radiation, neutrons, shocks, acceleration, other): ____

Engineering requirements/challenges: ____

PERFORMANCE:
Maximum measured/inferred value: ____
Minimum measured/inferred value: ____
Accuracy: ____
Precision: ____
Time resolution: ____
Spatial resolution: ____

ANALYSIS:
Calibration technique: ____

Method for unfolds, or interpretation. Is it qualitative or quantitative? ____

Are any special codes or models necessary? ____

ADDITIONAL COMMENTS: ____

Diagnostic data sheets were submitted

—MAGNETIC FIELD MEASUREMENT TECHNIQUE DATA SHEET—

TECHNIQUE: Bdot probes
ADVOCATE(S): John Greenly

DESCRIPTION OF METHOD
Measures: [ ] B_z [ ] B_θ [X] Both
COMMENTS: ______
[X] Direct or [ ] Indirect
COMMENTS: ______
[X] Invasive or [ ] Non-invasive
COMMENTS: inserted axially, 0.7 mm diameter
[X] Passive or [ ] Active
COMMENTS: I assume this means no power supplies or other drivers needed?
[ ] Radial or [X] Axial
COMMENTS: This means axial insertion

IMPLEMENATION:
Diagnostic access requirements: insulated coax about 0.060 OD, inserted through the end cap- this has been worked out for R. McBride's hardware.
Instrumentation needed: signal acquisition channel and cabling, signal levels <1000 V.
Will any hardware be in vacuum chamber? [X] Yes or [ ] No
COMMENTS: signal cables must get into the vacuum chamber, and the probes themselves will be inside, consisting of SMA connector, copper and steel semirigid coax and polyimide (Kapton) insulation.

Estimated cost: ~$30 materials per probe.
Lead time: 1 day to fabricate and calibrate.
Incompatibilities or limitations (e.g. integration with pulse power, integration with laser preheat, other): Integration with load hardware has been worked out by R. McBride. Probes are inserted through the anode end cap at nominal ground potential. If the laser damages the insulation severely, probes may not survive the preheat phase.
Technical issues to be resolved for the Z environment (e.g. radiation, neutrons, shocks, acceleration, other): The probes will fail at some time in the pulse because of erosion/ablation/breakdown of insulation. They do survive up through implosion in wire arrays, immersed in the wire ablation plasma, and fail when the X-ray pulse is generated.
Engineering requirements/challenges: ______

PERFORMANCE:
Maximum inferred field or currents: Fields have been measured >60 T, rates of change to 10T/ns
Minimum inferred field or currents: 0.01T or less if desired (loop area can be increased).
Accuracy: 5% calibration, and accuracy of orienting the loop, ~10 degrees. Overall <10%.
Precision: Calibration is reproducible to <3%, orientation reproducible within 10 degrees.
Time resolution: 3 ns or better (with adequate cabling and signal acquisition).
Spatial resolution: a probe samples an area of ~0.1 mm^2. Accuracy of location can be <0.5 mm.

ANALYSIS:
Calibration technique: individually calibrated in a fast pulsed magnetic field.

- Micro-Bdots (Greenly)
- Borg nano-probes (Rovang)

Diagnostic data sheets were submitted

—MAGNETIC FIELD MEASUREMENT TECHNIQUE DATA SHEET—

TECHNIQUE: faraday active fiber magnetic field measurement for vacuum MAGLIF shots

ADVOCATE(S): T. Intrator , T. E. Weber, S.C. Hsu (LANL), R. McBride, D. Dolan, R. Atherton (Sandia)

DESCRIPTION OF METHOD

Measures: [x] B_z [ ] B_θ [ ] Both

COMMENTS: axial (z direction) PM fiber fusion spliced to a Terbium doped short (3mm) length of 125um fiber. This will give us 10 degrees of Faraday rotation per mm of Tb fiber at Bz=10 Tesla. Estimated precision of measurement is about 1 degee of rotation, so we could resolve a fraction of a Tesla. At 1000 Tesla resolution will be determined by dynamic range ang bit depth of digitizers, and possible fringe counting software. We could field 2 fibers as is done with VISAR to un confuse the fringe counts at high field.

[x] Direct or [ ] Indirect

COMMENTS: ______

[x] Invasive or [ ] Non-invasive

COMMENTS: ______

[ ] Passive or [x] Active

COMMENTS: ______

[ ] Radial or [x] Axial

COMMENTS: ______

IMPLEMENATION:

Diagnostic access requirements: retroreflector on faraday fiber allows single ended access to MAGLIF capsule,

Instrumentation needed: laser, GHz modulator, PM fiber, 5 channels digitizers >1GHz

Will any hardware be in vacuum chamber? [x] Yes or [ ] No

COMMENTS: fiber leading out to a safe place (could be 30-50 meters away)

Estimated cost: $10 for hardware, + $90k for Intrator effort

Lead time: 4 months after March

Incompatibilities or limitations (e.g. integration with pulse power, integration with laser preheat, other): this diagnostic is designed for use with vacuum shots, ie no laser plasma. But full magnetics and implosions are anticipated

Technical issues to be resolved for the Z environment (e.g. radiation, neutrons, shocks, acceleration, other): possible fiber darkening if neutrons are generated. Ken Struve has a VNIEFF collaboration to look into this. Fiber will get smashed at the convergence of implosion so the fiber packages are consumable.

Engineering requirements/challenges: engineering does not look very complicated, indeed straightforward

PERFORMANCE:

Maximum inferred field or currents: 10-1000 Tesla

Minimum inferred field or currents: 10 Tesla

Accuracy: We anticpate 10 degrees of Faraday rotation per mm of Tb fiber at Bz=10 Tesla, so 30 degress per 3mm Tb section at 10 Tesla. Estimated precision of measurement is about 1 degee of rotation, so we could resolve a fraction of a Tesla. At 1000

- Fiber Faraday (Intrator)

Diagnostic data sheets were submitted

- UV Faraday (Ivanov)

—MAGNETIC FIELD MEASUREMENT TECHNIQUE DATA SHEET—

TECHNIQUE: Deep UV laser probing (Faraday rotation diagnostic)
ADVOCATE(S): V.V. Ivanov, UNR

DESCRIPTION OF METHOD
Measures: [X] B_z [ ] B_Θ [ ] Both
COMMENTS:
[X] Direct or [ ] Indirect
COMMENTS: Faraday rotation of the polarization plane
[ ] Invasive or [X] Non-invasive
COMMENTS: Laser probing
[ ] Passive or [X] Active
COMMENTS:
[ ] Radial or [X] Axial
COMMENTS:

IMPLEMENATION:
Diagnostic access requirements:
Instrumentation needed: A laser source of deep UV radiation
Will any hardware be in vacuum chamber? [X] Yes or [ ] No
COMMENTS: Mirrors and lenses

Estimated cost: $0 for 266nm experiments on Zebra. Z: $300K if excimer laser is using. The cost of the long-pulse oscillator and crystals for conversion if Beamlet is using
Lead time: 1 y
Incompatibilities or limitations (e.g. integration with pulse power, integration with laser preheat, other): triggering of the laser

Technical issues to be resolved for the Z environment (e.g. radiation, neutrons, shocks, acceleration, other): Optics should be installed on the top and bottom of the liner

Engineering requirements/challenges: Optical elements should be at >1-2m from the liner

PERFORMANCE:
Maximum inferred field or currents: Depends on the plasma density, > 3 MG
Minimum inferred field or currents: Depends on the plasma density, <0.2MG
Accuracy:
Precision:
Time resolution:
Spatial resolution:

ANALYSIS:
Calibration technique: Preliminary experiments can be performed on Zebra at UNR

Method for unfolds, or interpretation. Is it qualitative or quantitative? quantitative
Are any special codes or models necessary? no

ADDITIONAL COMMENTS:

Diagnostic data sheets were submitted

- Zeeman (Hansen)

—MAGNETIC FIELD MEASUREMENT TECHNIQUE DATA SHEET—

TECHNIQUE: Zeeman spectroscopy
ADVOCATE(S): S. Hansen, M. Cuneo, G. Rochau, M. Gomez

DESCRIPTION OF METHOD
Measures: [ ] B_z [ ] B_θ [x] Both
COMMENTS: visible & x-ray for Bz; x-ray for Bθ (or visible on axial LOS)
[ ] Direct or [x] Indirect
COMMENTS: measure B-field effect on atomic structure through emission lines
[ ] Invasive or [x] Non-invasive
COMMENTS: Requires external spectrometers with lines of sight to target
[x] Passive or [ ] Active
COMMENTS: Record plasma self-emission
[x] Radial or [x] Axial
COMMENTS: Both are possible

IMPLEMENATION:
Diagnostic access requirements: unobstructed LOS
Instrumentation needed: existing spectrometers (possibly new crystals/ substrate)
Will any hardware be in vacuum chamber? [x] Yes or [ ] No
COMMENTS: SVS fibers

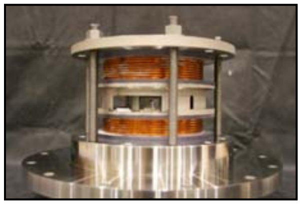
Estimated cost: $3 – 20k for new crystals (may not be required)
Lead time: ~3 months
Incompatibilities or limitations (e.g. integration with pulse power, integration with laser preheat, other): x-ray option may prevent spectroscopic diagnostics in other spectral ranges; SVS may require holes in current return can; axial diagnostics must work with laser
Technical issues to be resolved for the Z environment (e.g. radiation, neutrons, shocks, acceleration, other):
Engineering requirements/challenges: Adequate spatial, spectral, and temporal resolution

PERFORMANCE:
Maximum inferred field or currents: 3 – 100 kT (x-ray)
Minimum inferred field or currents: 1 T – 300 T (visible)
Accuracy: ~factor of 2-3
Precision: ~30%
Time resolution: ~ns
Spatial resolution: ~100 um

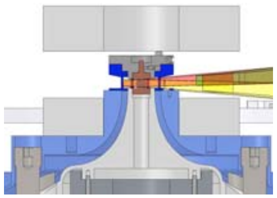
ANALYSIS:
Calibration technique: existing wavelength & intensity calibrations are probably adequate
Method for unfolds, or interpretation. Is it qualitative or quantitative? quantitative (within limitations of theory and given likely gradients & uncertainties in data)
Are any special codes or models necessary? existing NLTE and lineshape models may be adequate and can be refined

ADDITIONAL COMMENTS: Selection of lines that will be emitted and sensitive to local fields will be the most challenging aspect of the diagnostic

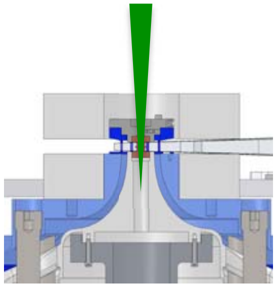
We handed out homework to develop a magnetic field diagnostic roadmap



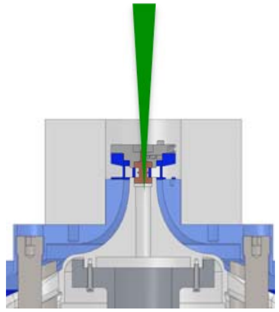
2013
No preheat
B_{zo} = 1–10 T
Radial Access
Axial Access
Invasive
Non-invasive



2013-2014
No preheat
B_{zo} =10–15 T
Radial Access
Axial Access
Non-invasive



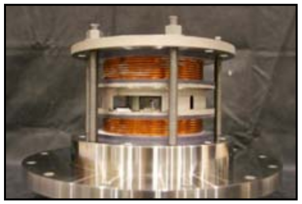
2013-2015
Preheat
B_{zo} = 15–20 T
Radial Access
Non-invasive



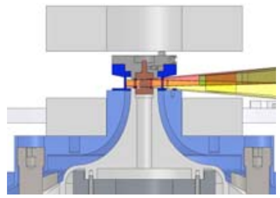
2014-2016
Preheat
B_{zo} = 30 T
No Access
(neutrons)
Integrated

- B_θ (drive)
- B_z (fusion physics, e.g. electron thermal conduction, RT mitigation)

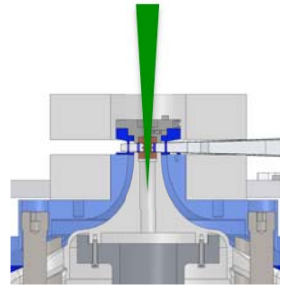
We handed out homework to develop a magnetic field diagnostic roadmap



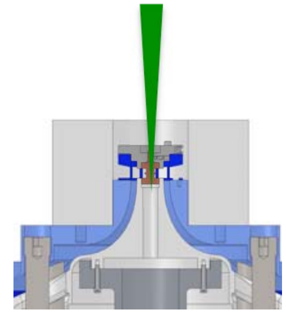
2013
No preheat
B_{zo} = 1–10 T
Radial Access
Axial Access
Invasive
Non-invasive



2013-2014
No preheat
B_{zo} =10–15 T
Radial Access
Axial Access
Non-invasive



2013-2015
Preheat
B_{zo} = 15–20 T
Radial Access
Non-invasive



2014-2016
Preheat
B_{zo} = 30 T
No Access
(neutrons)
Integrated

Faraday fiber (Bz)

B-dot (Br)

Pulsed LIDAR
Polarimetry (Bz)

Needs support
to develop for
MagLIF conditions

Bragg crystal
X-ray source
for Faraday rotation
Br, maybe Bz
6.1 keV penetrates radially
through the liner

Need investment in this
transformational technology

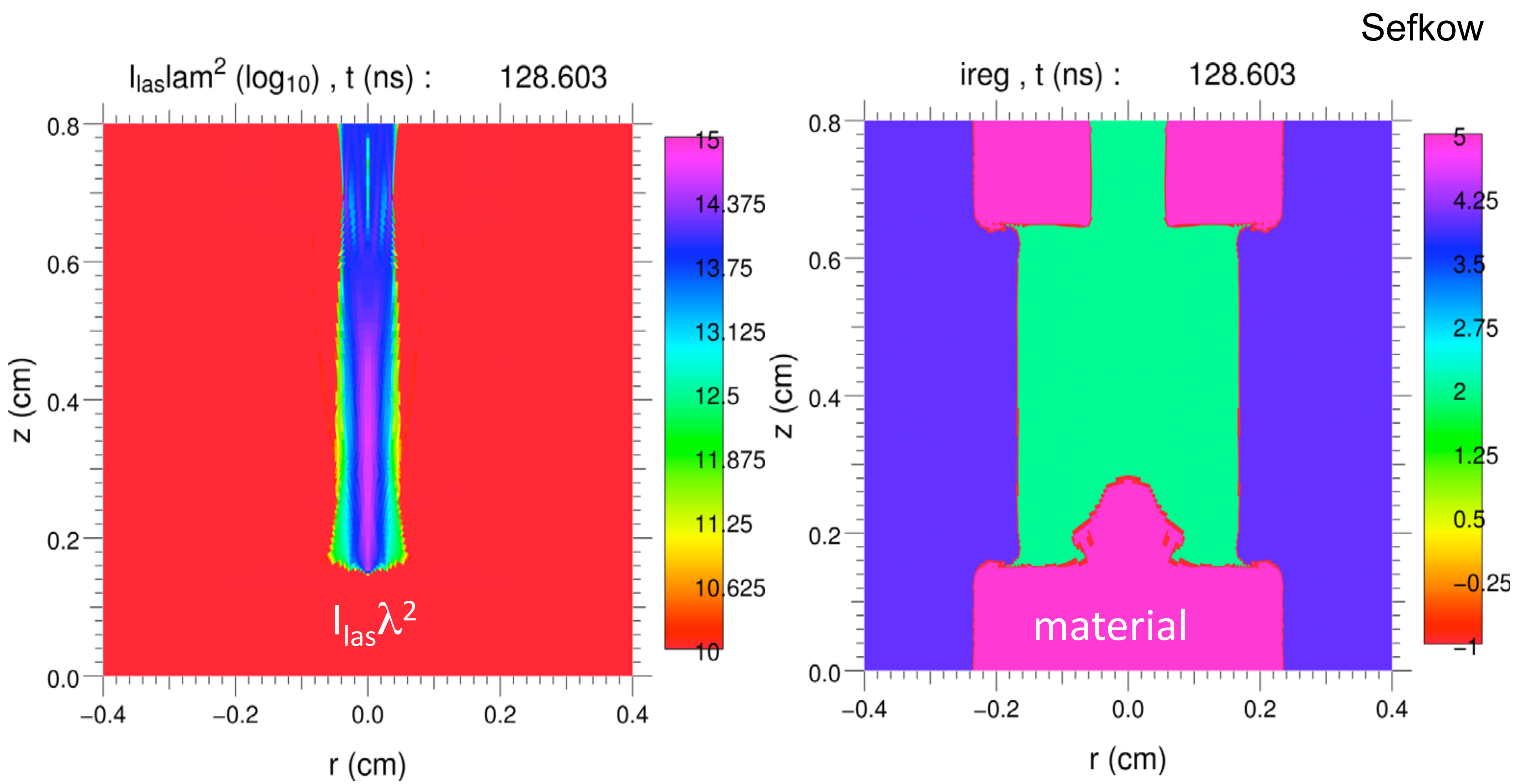
Intrator

- B_θ (drive)
- B_z (fusion physics, e.g. electron thermal conduction, RT mitigation)

Questions about preheat and end-loss

- How uniform does the preheated plasma have to be? What are the requirements?
- Is it really OK to just heat the central part of the liner?
- Why have any electrodes at all?
- Are experiments at other facilities pertinent?
- What about the uniformity in the azimuthal direction? Simulations? Experiments? (Weber, Grabowski)
- The language of MFE was prominent: what is the energy and particle confinement time and how does this compare to plasma formation time?, implosion time?, burn time?
- Could mirror fields at either end be used to improve confinement?
- How should the cathode ablation be mitigated?

Laser deposition can ablate cathode material into the fuel region, and so must be avoided or mitigated



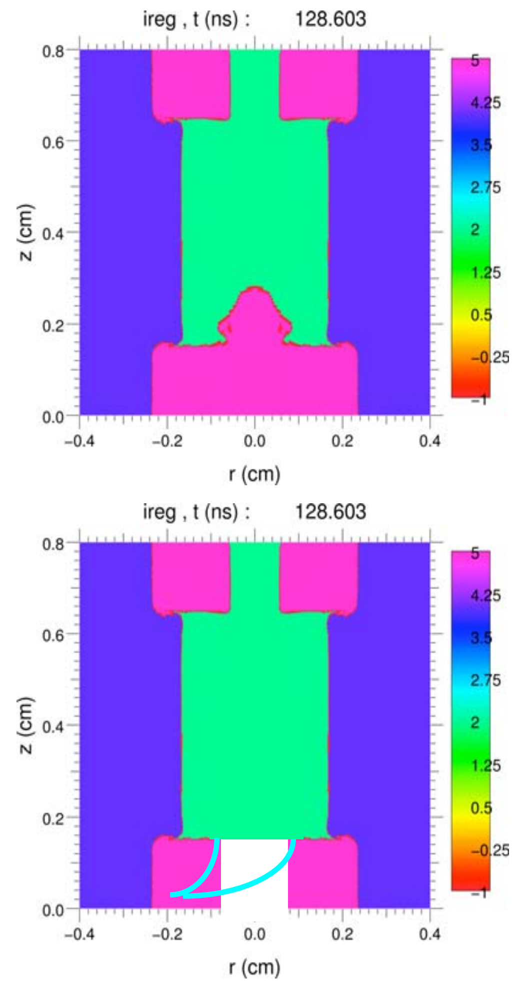
Mitigation of laser produced jetting of cathode

- Increase laser absorption in the gas
  - Clusters
  - Nanoparticles of LiDT

- Coat the cathode end with cryogenic deuterium and use the absorption

- Recess in cathode
  - Does this only increase end loss?

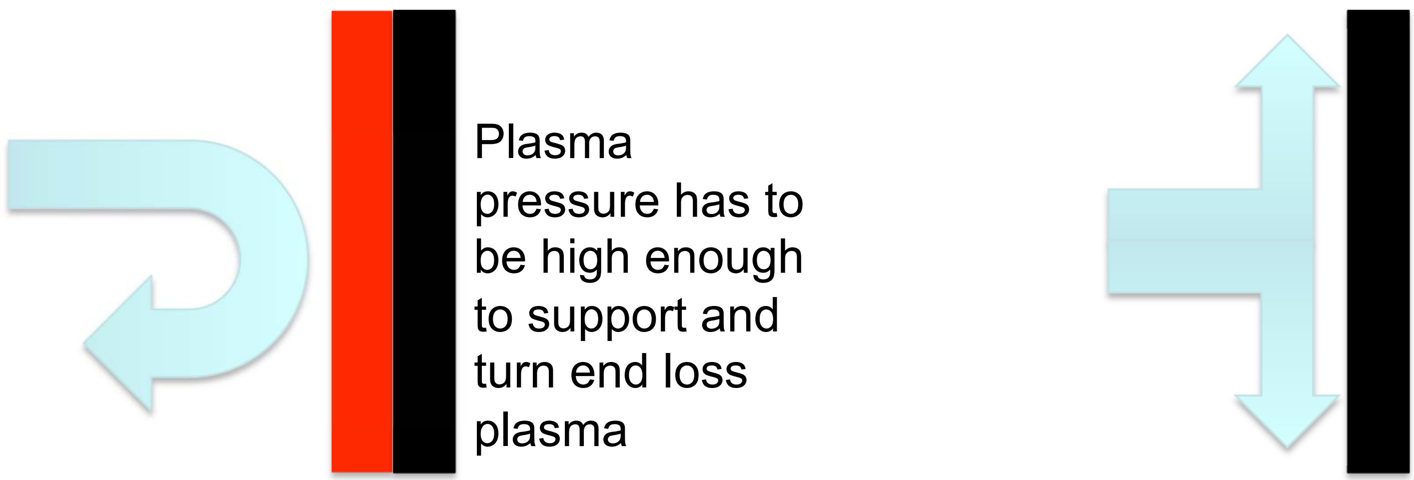
- Angled mirror surface or Rayleigh cone



Sefkow

Dick Siemon asks “are electrodes any better than holes for stopping end loss”?

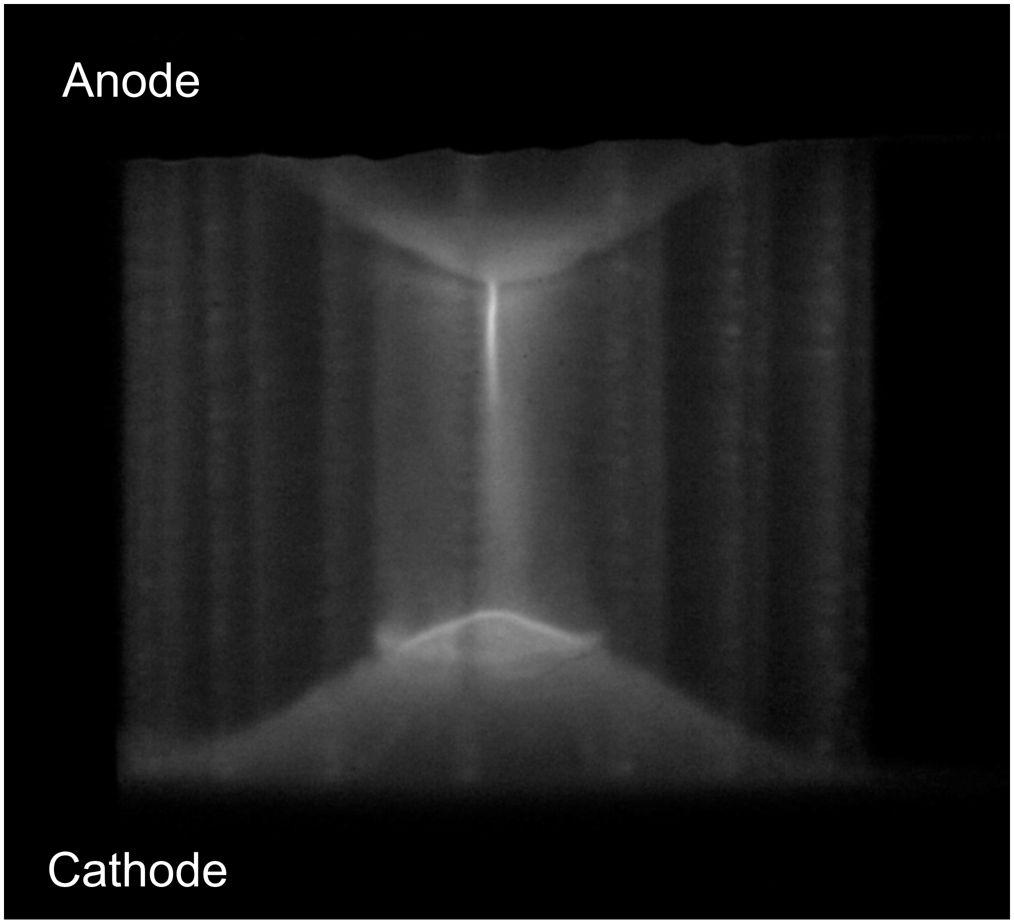
- How does MHD does treat real electrodes?
- Model electrodes as perfectly absorbing, perfectly reflecting (change the Z of the electrodes in the simulations)
- Wall’s may act as a cryo-pump and “absorb” or divert the plasma reaching them
- Treatment of electrodes with lithium increased particle confinement in a theta-pinch



Prevailing opinion is that laser preheat is matched to university scale (and may be the only part of problem that is)

- Universal agreement that need to have a laser preheat test bed with a magnetic field
- Of the 3 problems (liner stability, flux compression, and laser preheat), laser preheat may be the easiest problem to treat. Still need to validate.
- Scale gas cell size to university lasers and facilities
- Trident?
- Gennady Fiksel suggests NLUF experiments with smaller target, MIFEDS, x-ray imaging, spectroscopy, Thomson scattering, get 1 day of data (20 shots)
- Proposals for NLUF may be due soon

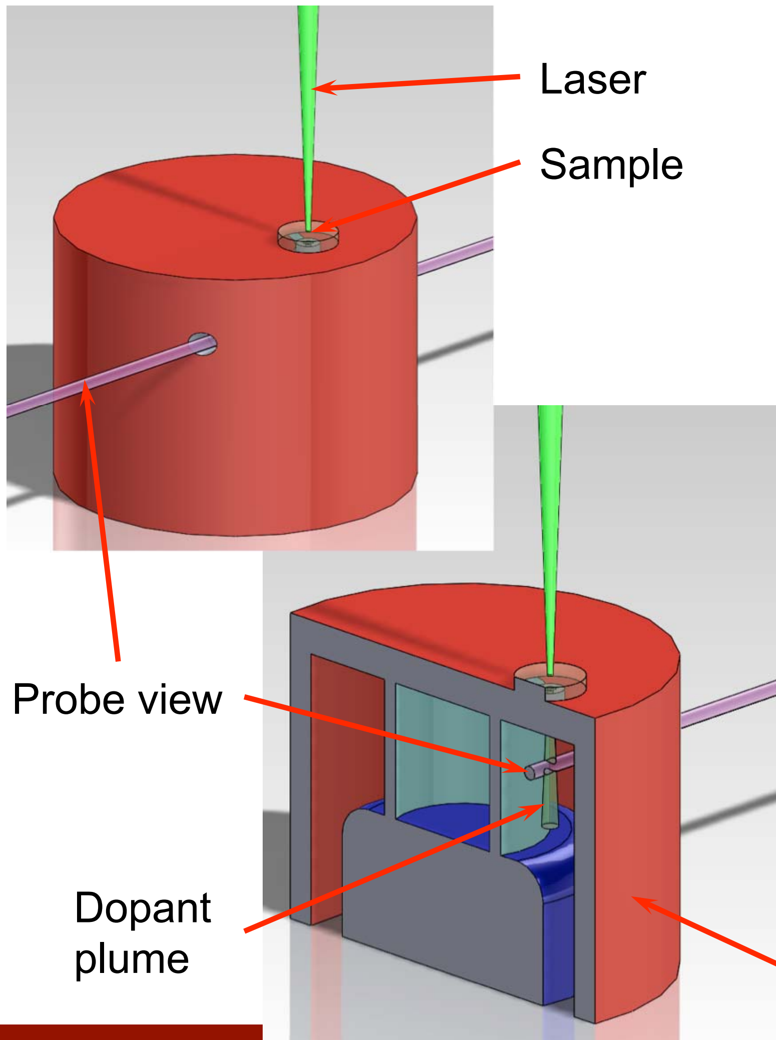
As we discuss end loss, John Greenly has a horrifying thought before the 3:00 PM break……

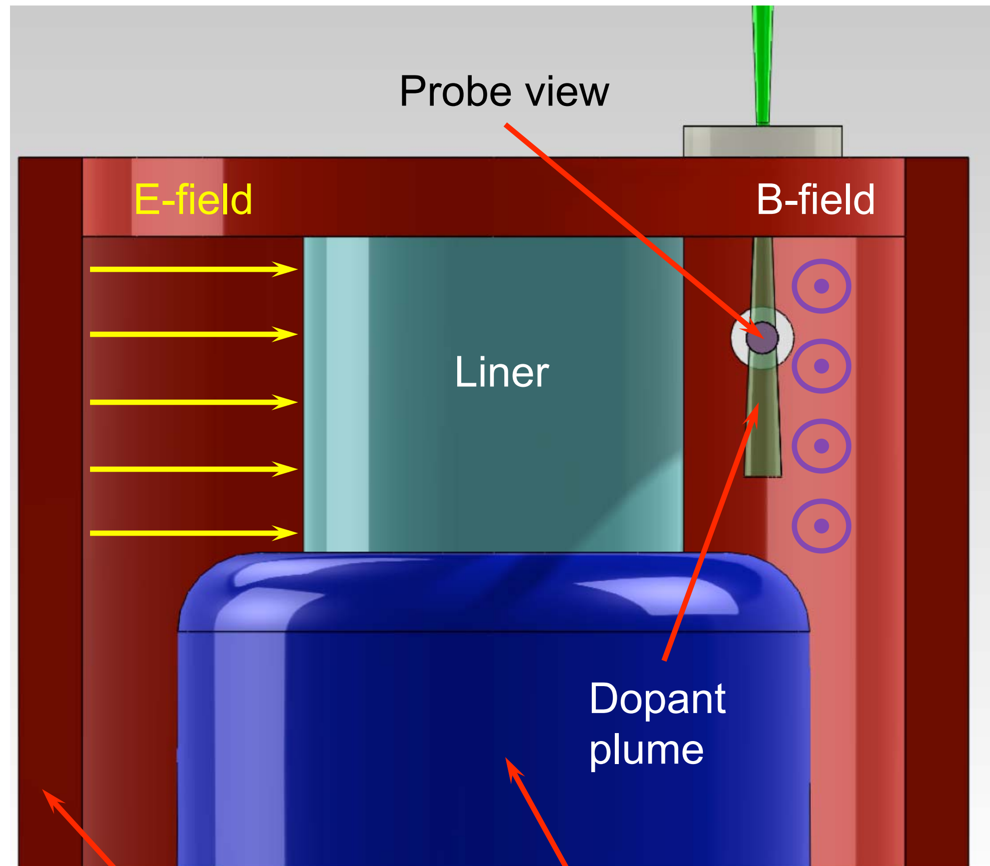


- MHD does not know about polarity – this tungsten precursor plasma does
- Is this a Hall effect?
- 20 T in 100 ns
- Could the dB/dt from flux compression generate an electric field that impacts plasma flow inside the liner – enhance end loss?
- Other terms in generalized Ohms law could also be at work.
- Post process the results from MHD codes on the grid to evaluate the possible size of the Hall term
- Evaluate impact with EMHD (Martin, Seyler).

Active dopant techniques and optical spectroscopy could be used to diagnose the E- and B-fields in MagLIF relevant plasmas when and where you want to

M. Gomez

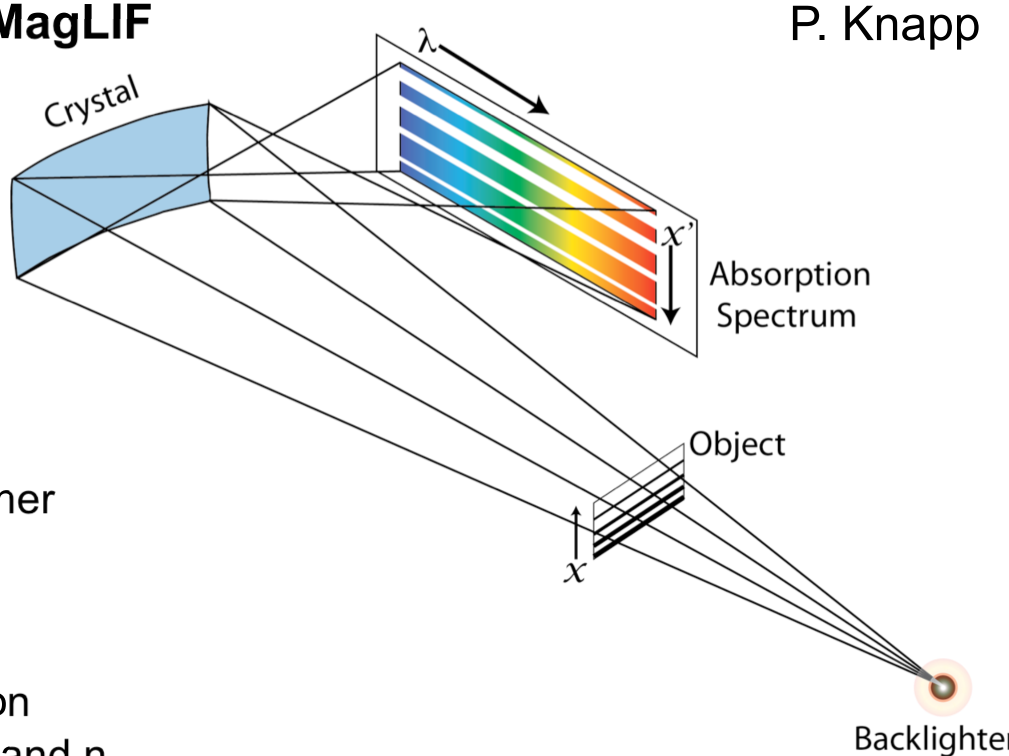




Absorption Spectroscopy Directly Measures the Line Integrated Ionization State of a Plasma

This information is well-suited to address questions in several key areas for MagLIF

P. Knapp



- Trailing Mass
•Density and temperature
•Conductivity, Ohmic heating
•How do instabilities effect Drive

- Liner Conditions
•Shape of K-edge can tell us state of the liner
•Density from Stark Broadening
•Surface ablation

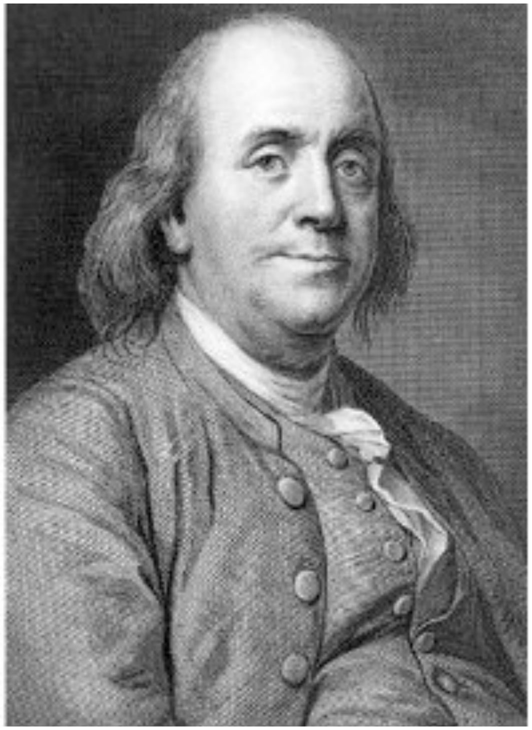
- Preheated Fuel Conditions and evolution
•Inverse Brems. Absorption depends on Z and n_e
•Bleaching wave propagation in r and z
•Ionization equilibration dynamics

Concluding discussion

- What is the "as low a risk path as reasonably achievable" (ALARPARA) in executing these experiments, to maximize learning, and chance of success?
- What do you worry about the most? Or what would keep you up at night about MagLIF?
- What would history say we are not getting right?
- Where are we fooling ourselves? What critical issue are we missing?
- What have we not priced in? Is this a bubble or an efficient market?
- Question asked most often: where do we go from here?

Sergey proposes a test problem: What is it?

We are all immigrants to magnetized targets from inertial or magnetic fusion - some arrived earlier than others



"We must all hang together, or assuredly we shall all hang separately."

At the signing of the Declaration of Independence