Laboratory experiments on collisionless shocks

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with input from D. Winske (LANL) & R. Presura (UNR)

- **Historical perspective & early previous experiments**
- **Unresolved Issues**
- **Proposed experiments and opportunities**

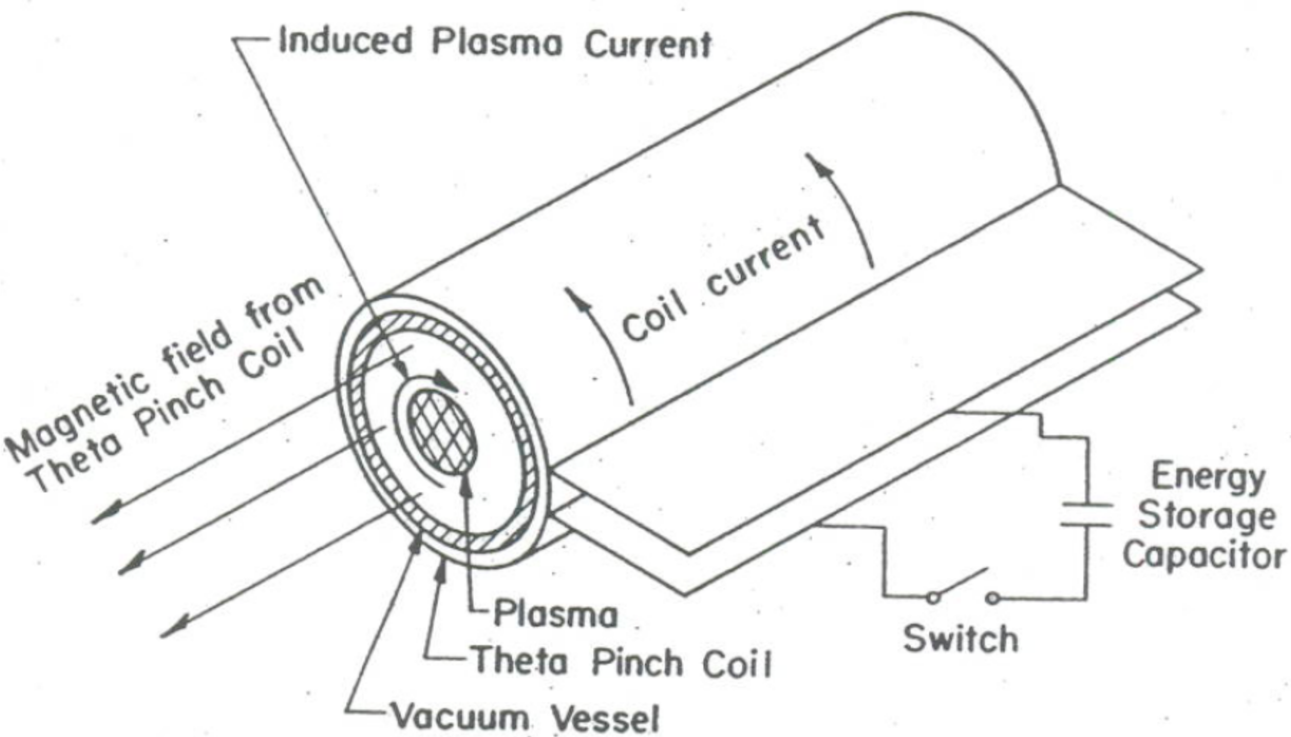
Workshop on Opportunities in Plasma Astrophysics, Princeton, January 18, 2010

Historical perspective

"First Golden Age" (1964-1974)

- Sagdeev proposes collisionless-shock concept
- High altitude nuclear explosions
- Discovery of the bow shock
- **First laboratory experiments**
- Early numerical simulations

Most of the early experiments were based on the θ-pinch concept

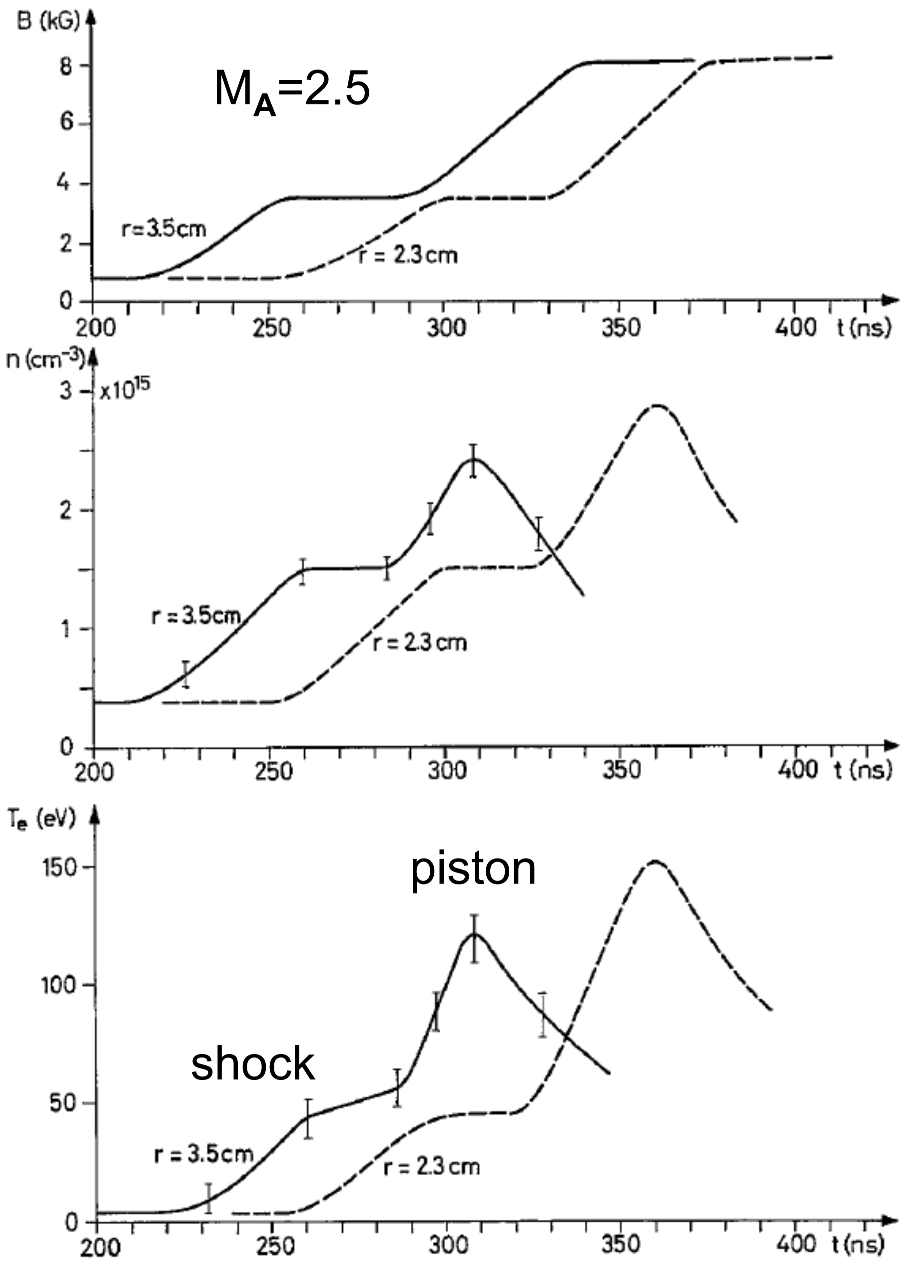


$V_p \sim 10^7$ cm/s
$n \sim 10^{14}$ cm^{-3}
$M_A = 2\text{-}20$
$\Theta_{Bn} = 90^o$

e.g.

Culham	J. Paul *et al*., Nature **208**, 133 (1965)
Maryland	J. Stamper *et al*., Phys. Fluids **12**, 1435 (1968)
Garching	M. Keilhacker *et al*., Phys. Rev. Lett. 24, 487 (1971)
Cornell	D. Morse *et al*., Phys. Rev. Lett. **28**, 13 (1972)
Texas	P. Phillips *et al*., Phys. Rev. Lett. **29**, 154 (1972)

USSR, Italy, Columbia, etc …



e.g. M. Keilhacker *et al*., Z. Phys. **223**, 385 (1969)

- **Most experiments showed strong "anomalous" electron heating**
- **Reflected ions were observed only for super-critical shocks (M_A≈3)**
- **Weaker shocks have widths of a few c/w_{pe}**
- **Super-critical shocks show double structure in B & n ("foot" with ~$2c/w_{pi}$ width)**
- **Orbits of reflected ions coincide with "foot"**

“Second Golden Age” (1979-1989)

- Data from extraterrestrial plasmas
  - *ISEE mission*
  - *planetary bow shocks (Voyager)*
  - *cometary bow shocks*
  - *SN remnants*

- Better simulation methods

- Appreciation of electron dynamics at shocks in space ($T_i >> T_e$)

- **However, only few follow-up experiments in 20 years**

More recent experiments with high-power lasers did not answer many questions

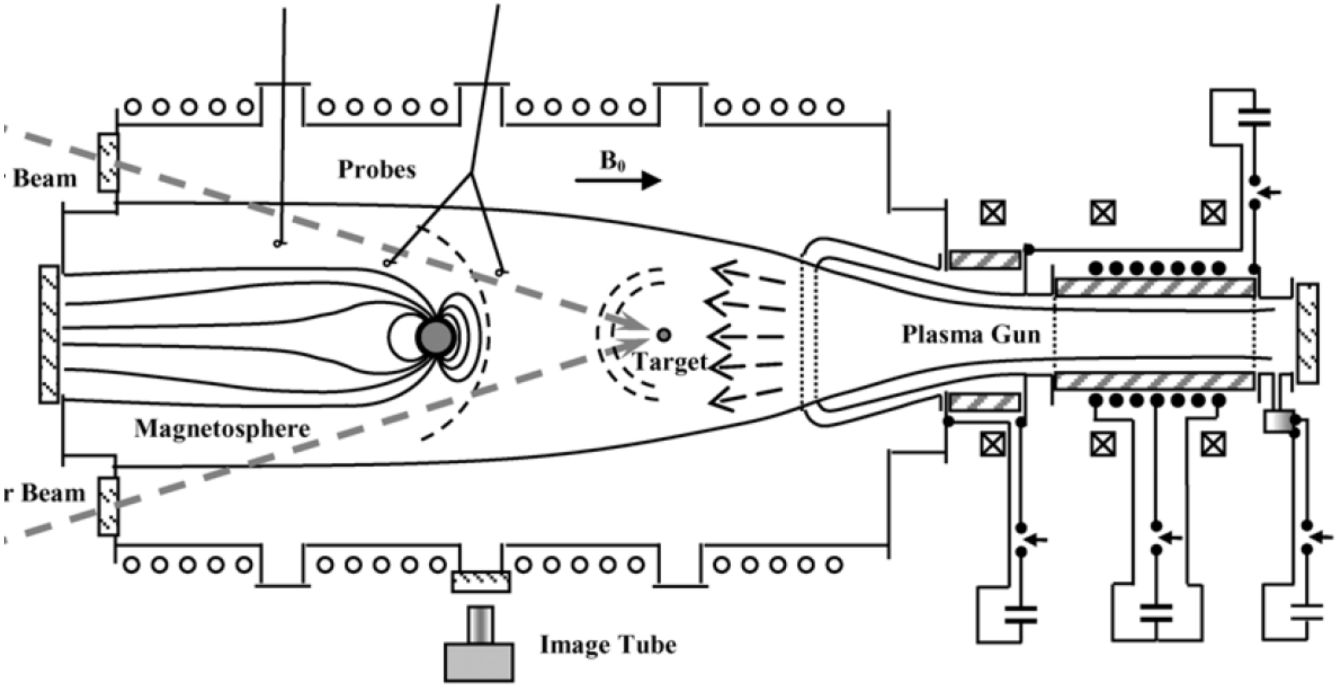
- **exploding plasmas:** $v_{blow\text{-}off} \leq 1000$ *km/s* *for intensities* $10^{12} - 10^{15}$ *W/cm*^{2}
- **oblique & quasi-parallel geometries possible**
- **large spontaneous fields:** *MG – few G further from laser-target*

NRL:	laser-plasma expansion in gas & external B-field	(1980-1990)
LANL:	laser-plasma expansion in gas-filled chamber	(1983)
ILP:	laser-plasma and theta pinch gun	(1970 – now)
RAL:	colliding plasmas in laser-generated B-field	(2000-2003)
LLNL:	exploding plasmas in external B-field	(1990)
LULI:	exploding-plasma interaction with gas-jet	(2007)
etc. ….		

- **Typically the high-beta laser-plasmas were not sufficiently magnetized,**
- **or the background was not sufficiently ionized**
- **or experiments were too small (mm to cm) and too short**

See reviews by R.P. Drake (2000) and Y. Zakharov (2003)

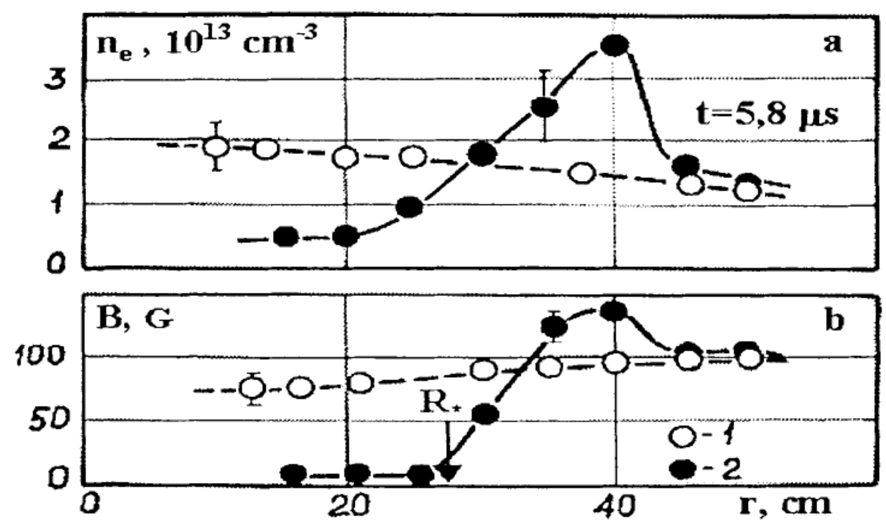
ILP (Novosibirsk): KI 1-facility, 500 J CO_2 laser coupled to Θ-pinch gun



Laser plasma:
$2x10^7$ cm/s
N~ 10^{18}

Θ-pinch gun:
N=$3x10^{13}$ cm^{-3}
~ 1 m^3
R_B ~ 20 cm

$M_A \geq 5$



- collisionless interaction of LPP with homogeneous background
- plasma diamagnetism
- artificial magnetospheres etc.

Y. Zakharov, IEEE TPS **31** (2003)
A. Ponomarenko *et al.*, PPCF **50** (2008)

Unresolved issues

- **Why do laboratory shocks strongly heat electrons, but those in space do not ?**
- **What is the formation time of a shock ?**
- **Can we create Alfvénic shocks in the laboratory ?**
- **Debris and final spatial distribution**

etc.

If we can generate laboratory shocks, what is interesting ?

	Fast: Quasi-perp	Fast: Quasi-par	Fast: Mass-loaded	Slow: Quasi-perp
Shock Formation	L, T	T	T?	T
Shock Structure	L, S, T	S, T	S?, T	S?, T
Shock Heating & Energy Partition	L, S, T (but L, S disagree)	S?, T?	T?	S?, T
Shock stability/steadiness	S?, T	S, T		T?
Debris final spatial distribution	T	T		

L – Laboratory experiments
S – Space observation
T – Theory/simulations

Green – probably doable in the experiment
Yellow – possibly doable
White – probably not doable (space/time scales too long)
Red – well understood; experimental verification not necessary

D. Winske (LANL)

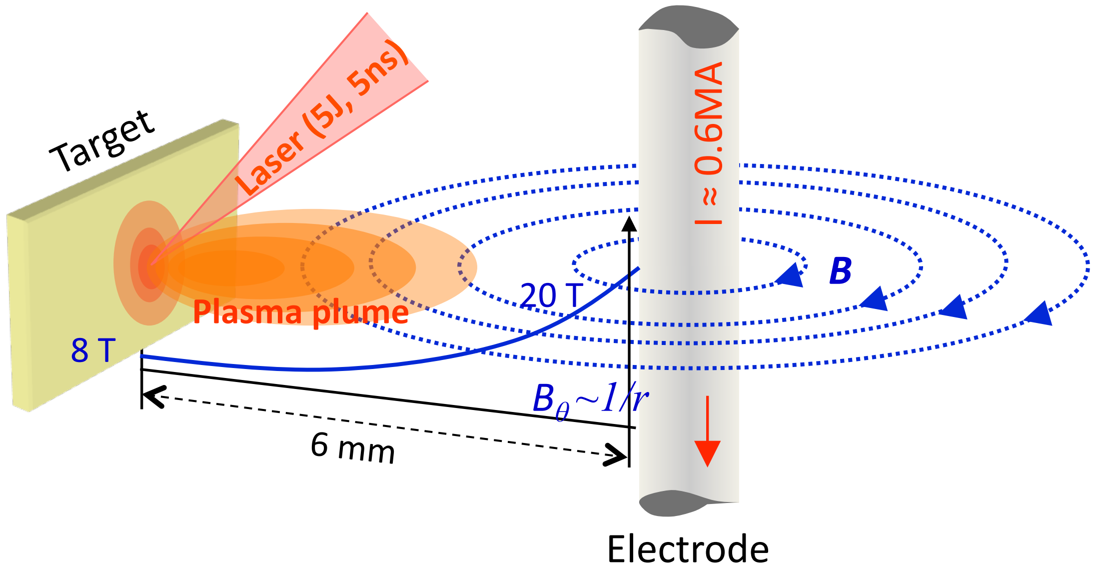
Opportunities for new laboratory experiments

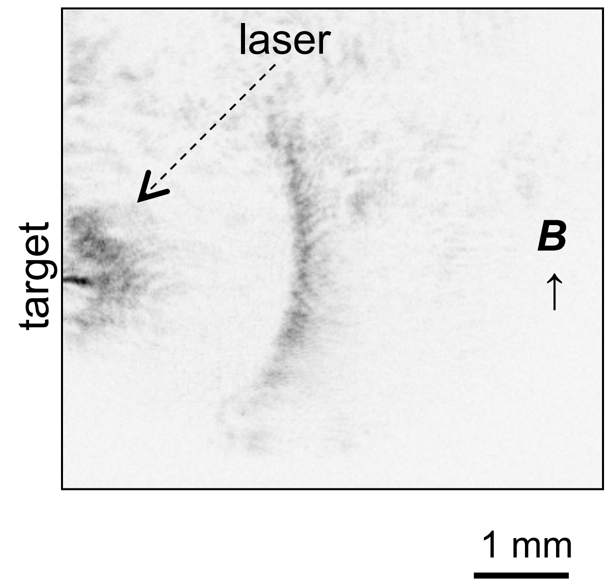
- New facilities
  - *larger lasers,*
  - *lasers & large magnetized plasmas / pinches*
  - *magnetized target fusion experiments*

    …

- Better diagnostics
  - *e.g. proton radiography,*
  - *faster detectors, correlation techniques (turbulence)*
  - *volumetric data sets, etc. …*

Collisionless shock experiment at the Nevada Terawatt Facility





Plasma shell parameters:

velocity: $v_0 \approx 2\times10^7$ **cm/s**

density: $n_e \approx 7\times10^{17}$ **cm^{-3}**

field strength: $B \approx 8 - 10$ **T**

temperature: $T_e \leq 200$ **eV,** $T_i \leq 100$ **eV**

length scale: $L_n \approx 0.2 - 0.3$ **mm**

Plasma regime:

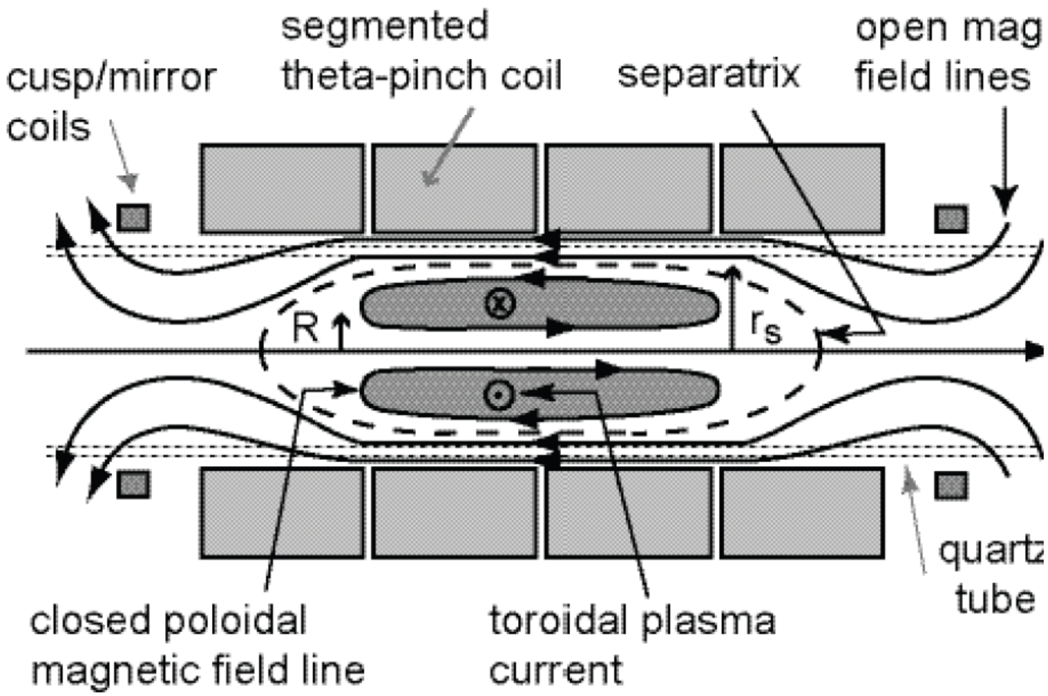
resistive diffusion: $R_M > 30$

Hall term: $(c/\omega_{pi}) \geq L_n$

ion magnetization: $2\pi/\Omega_i \geq t_{exp}$

R. Presura *et al.*, Astrophys. Space Sci. **298**, 299 (2005)
W. Horton *et al.*, Phys. Plasmas **11**, 1645 (2004)

LANL-FRC: Plasma gun method



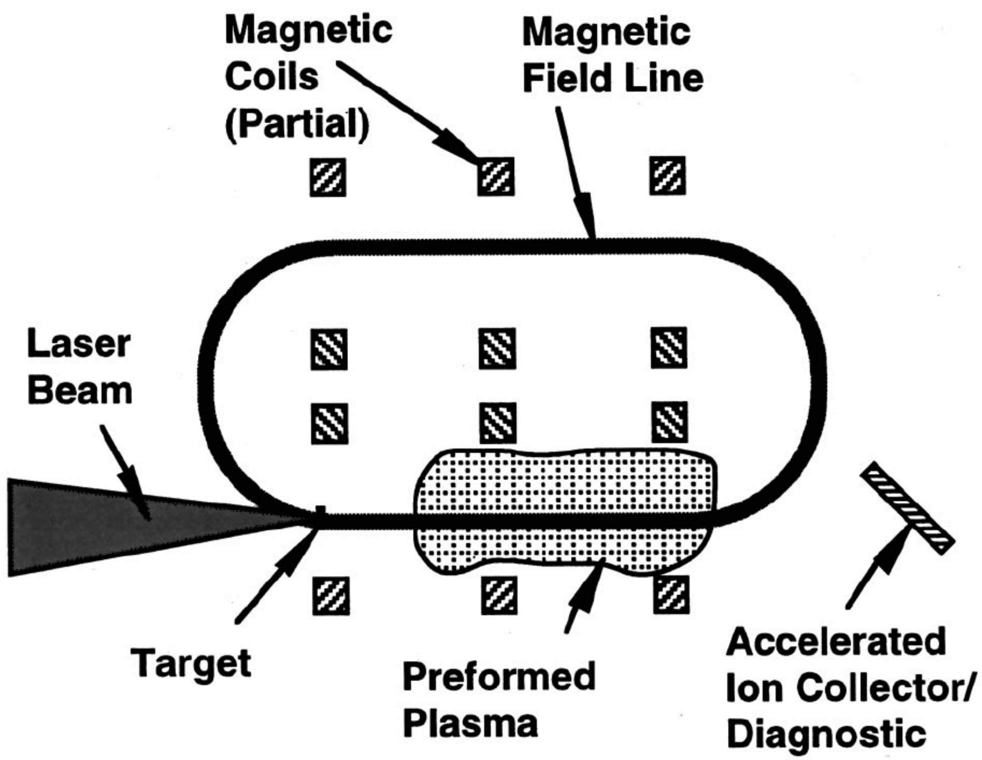
T. Intrator *et al.*,
Phys. Plasmas **11**, 2580 (2004)

Piston magnetized plasma with large v_A crashes into target plasma with small v_A

T_i ≈ 200 eV, n= 4x10^{16} cm^{-3}, B_{target} = 0.3 T, v= 60 km/s ($M_A \approx 3.5$)

size D= 2 cm, shock transit time τ=0.3 μs, r_{Li}= 5 mm,
$\omega_{ci}\tau \approx 5$, D/(c/$w_{pi}$) ≈ 15 , λ_{ii} ≈ size

Proposal by R.P. Drake - Phys. Plasmas 7, 4690 (2000)



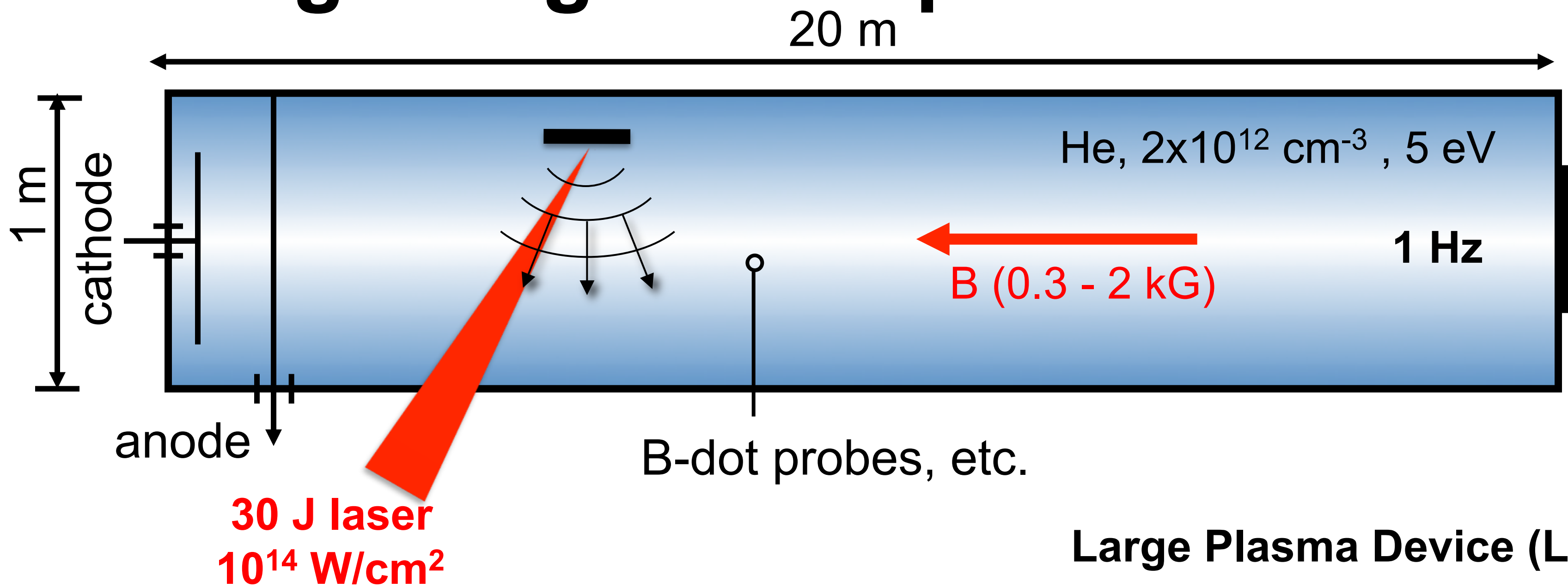
Large preformed plasma
$n=5\times10^{13}$ cm^{-3}, few eV, D=2 m

and kJ-laser to drive piston

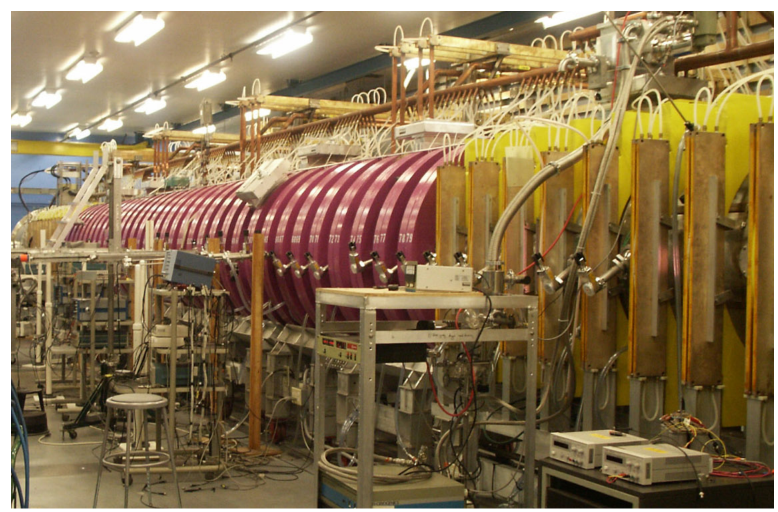
- **Laboratory experiments can create conditions where $M_A > 1$, $D/r_{Li} > 1$, $\beta > 1$ are maintained over an adequate number of growth times for MHD turbulence.**

- **Experiment must be larger than some fraction of a meter**

UCLA: Exploding laser-produced plasma in a large magnetized plasma



Large Plasma Device (LAPD)



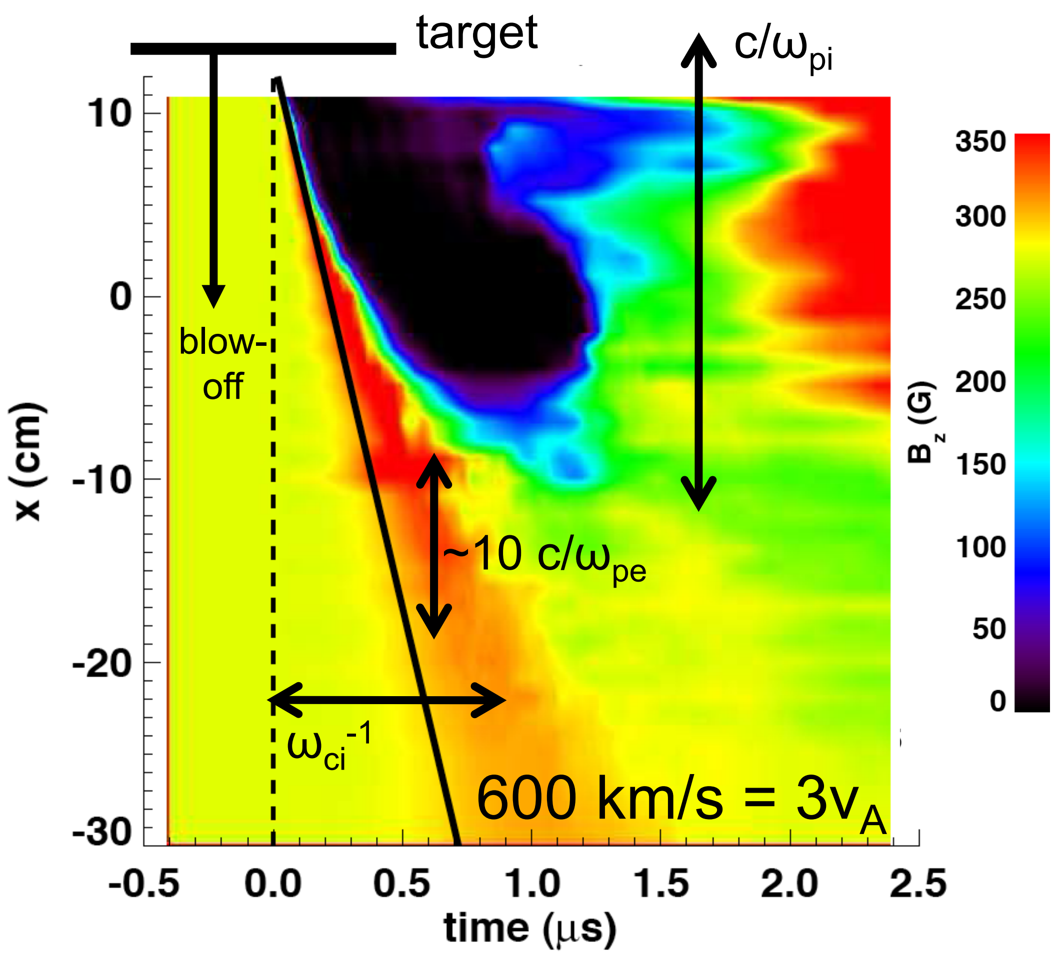
W. Gekelman *et al.*

Perpendicular shocks:

V_s = 500 km/s (M_A≈2.5)
Size D = 50 cm
Shock transit time: τ≈ 1μs
$D/(c/w_{pi}) \approx 1$, $\tau w_{ci} \approx 1$, $\lambda_{ii}/D>500$

C. Constantin *et al.*, Astrophys. Space Sci. **322**, 155 (2009)

Measurements show super-Alfvénic pulse (M_A=2-3) propagating away from piston



- fast B-field diffusion
- large amplitude shear-waves
- 2D hybrid simulations predict that $c/w_{pi} \geq 10$ is required for shock to form

Facility improvements will significantly increase the design space for CSW experiments at UCLA

LaB_6 cathode: 5×10^{13} cm^{-3}, >10 eV (H_2 or He^{2+} ?) & better duty cycle

$M_A \approx 3\text{-}4$, $c/(w_{pi}) \approx 3$ cm, $1/w_{ci} = 0.2$ μs

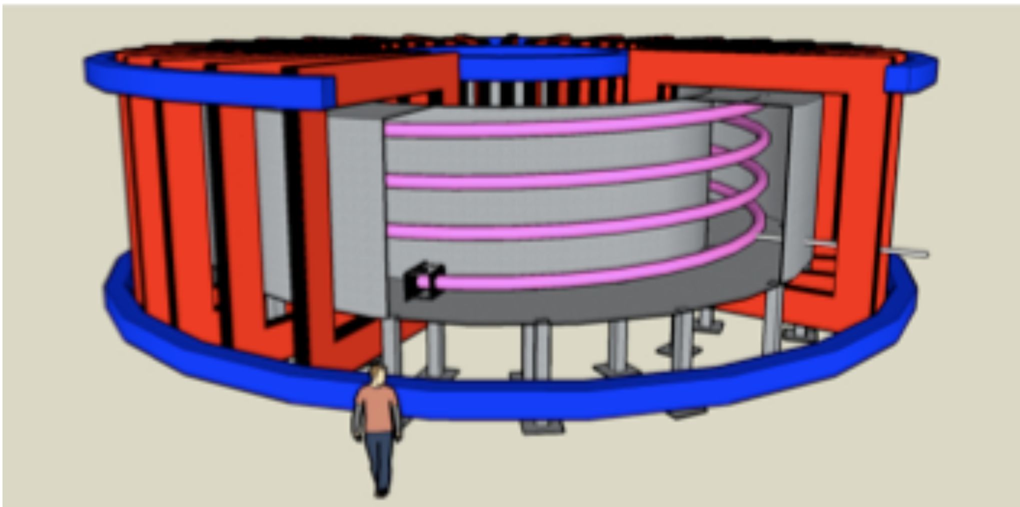
Laser upgrade: >500 J (20 ns to several 100 ns) & 15 J @ 2w probe beam for TS

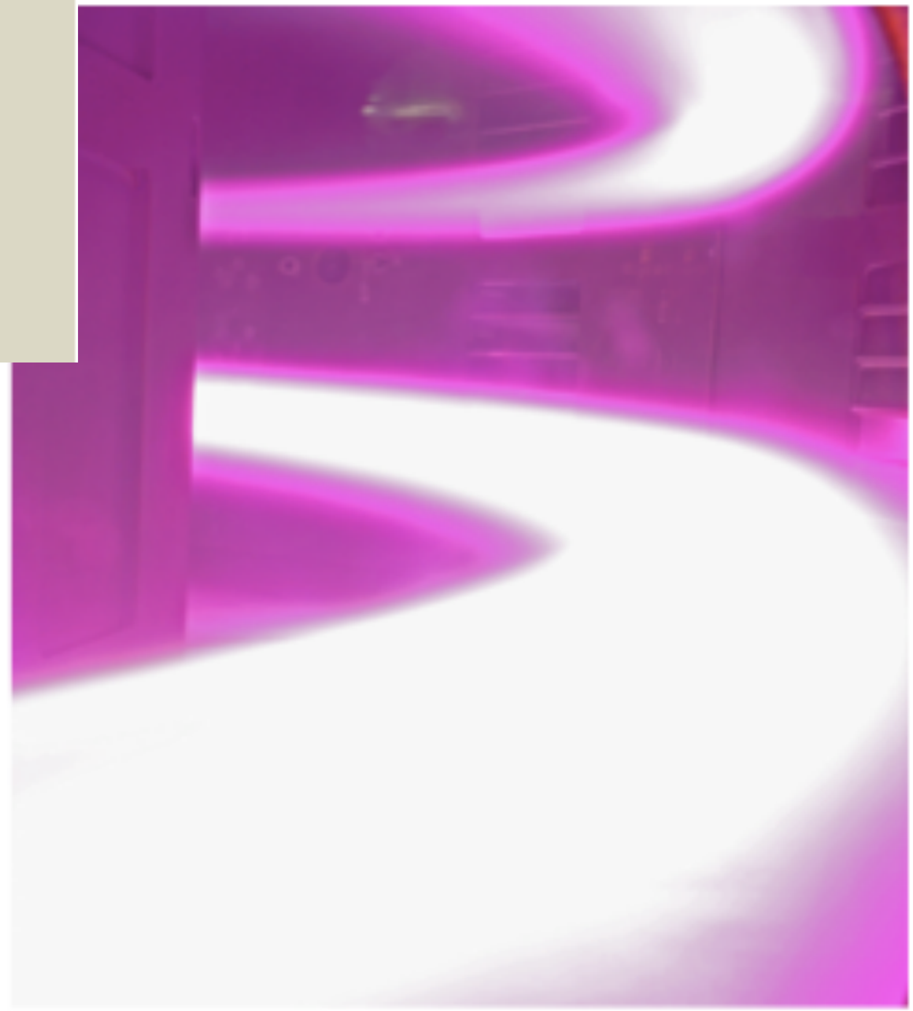
- enough energy to shock entire ambient @ $M_A \approx 1$
- faster blow-off speed

Perpendicular (50 cm): $M_A=4$, $D/(c/w_{pi}) \leq 15$, $\tau w_{ci} \leq 5$, $\lambda_{ii}/D \approx 20$

Parallel (20 m): $M_A=1$, $D/(c/w_{pi}) \leq 300$, $\tau w_{ci} \leq 300$ 1, $\lambda_{ii}/D \approx 0.6$

UCLA’s Enormous Toroidal Plasma Device (ETPD) could be a much better laser target for CSW experiments





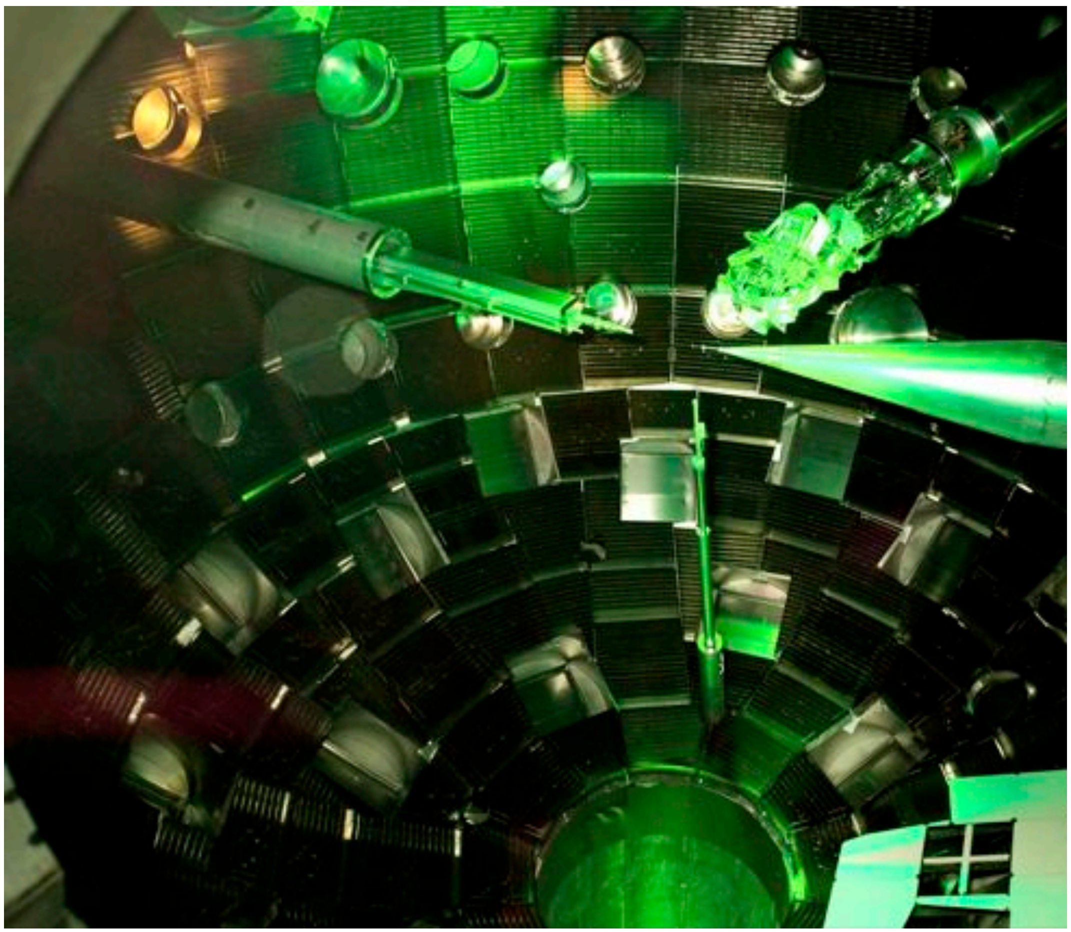
200 m long @ 5×10^{13} cm^{-3} and 20 eV

- hotter plasmas
- less effected by material walls
- LARGER: (D_{perp} = 1-2 m, $D_{||}$= 200 m)

M_A=4, $D/(c/w_{pi}) \leq 100$, $\tau w_{ci} \approx 15$

Experiments at the National Ignition Facility could be designed that create CSW at M_A>10

- **MJ in 20 ns and 192 beams into 10 m chamber**
- **NIF is now operational and transitioning into a user facility**



- photoionized gas
- magnetized flows
- colliding plasmas
- multiple shocks …

With adequate magnetization:
(10^{13}-10^{14} cm^{-3}, few 100 G)

M_A>10
$D/(c/w_{pi}) > 100$
$\tau w_{ci} > 100$
$\lambda_{ii}/D > 10$

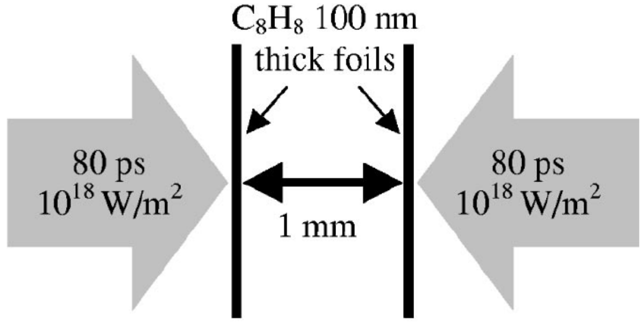
Summary

- Laboratory experiments from the past 50 years have contributed to our understanding of CSW

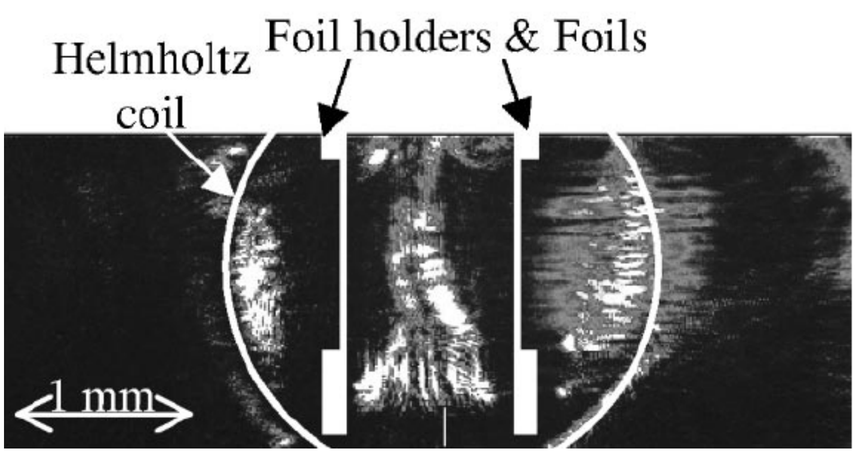
- Unresolved questions remain (e.g. energy partition, formation time …)

- … and can be addressed with new facilities
  (i.e. $D/(c/w_{pi})>10$, $\tau w_{ci} > 10$, $M_A>10$, $B_\Theta=0^o$)

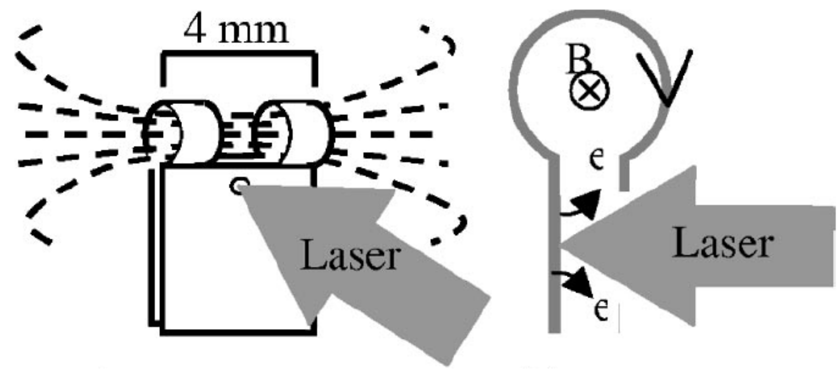
Vulcan: Colliding laser-produced plasmas in magnetic field



Parameters	SNR: 100 yrs	Exp: 500 ps
R_e	10^{13}	10^7
P_e	10^{11}	10^{10}
ζ	10^6	3×10^2
r_L/L	10^{-9}	10^{-1}
Plasma β	$\beta = 5 \times 10^2$	$\beta^* = 4 \times 10^2$
Eu	18	21
M	16	12
M_A	3×10^2	20



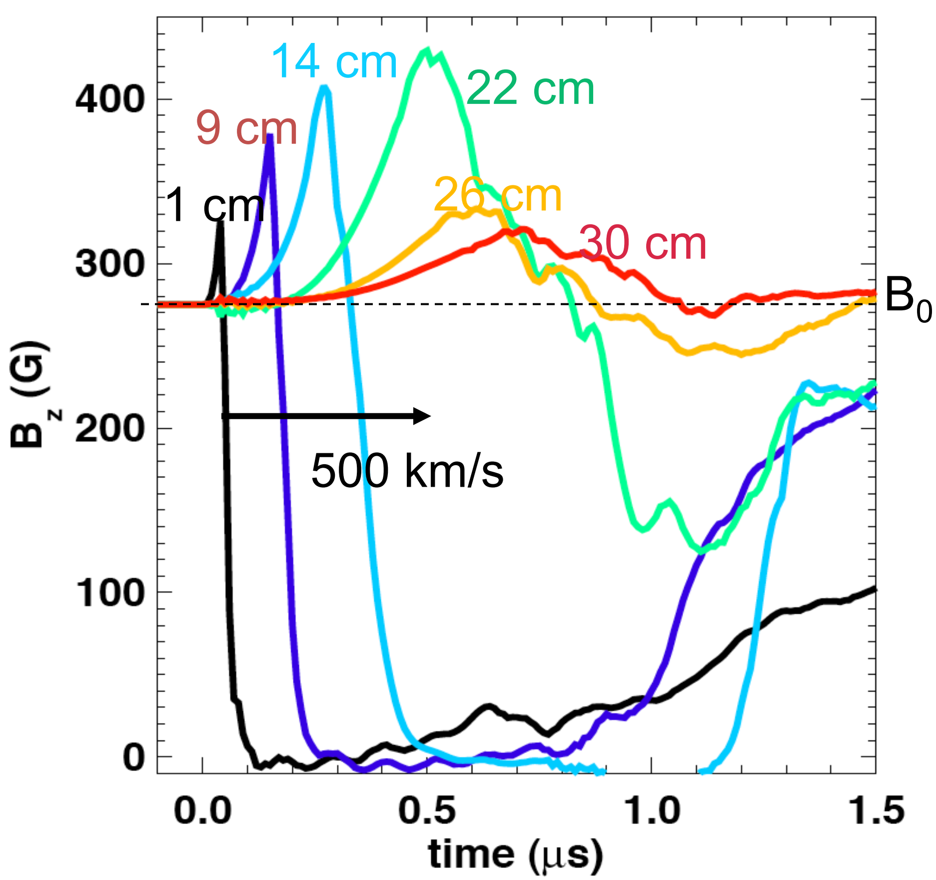
7 T field produced by laser-Generated electrons

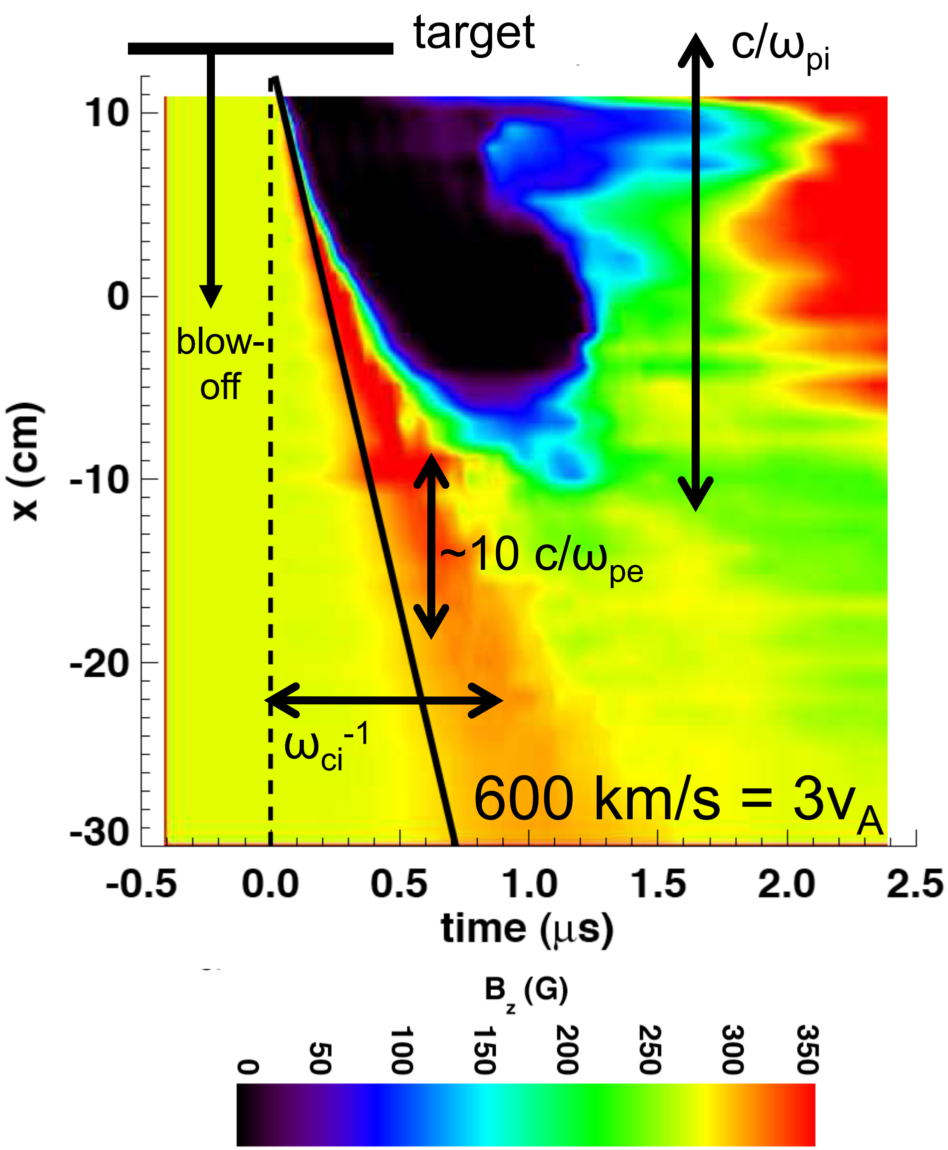


- observed features smaller than λ_{ii}
- no evidence of collisionless shock
- plasma not enough magnetized

N. Woolsey *et al*., Phys. Plasmas **8**, 2439 (2001)

Measurements show super-Alfvénic pulse (M_A=2-3) propagating away from piston





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