Magnetic field generation in shocks: Experiments and simulations

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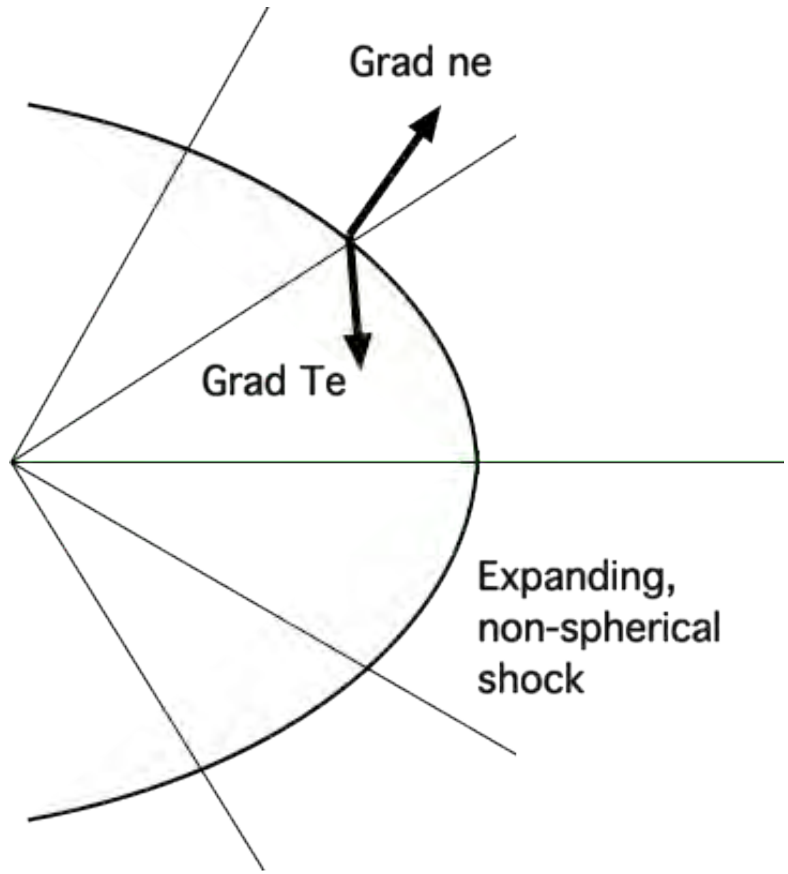
There is now, finally, a lot of experimental activity related to magnetic fields at shocks

- All in relatively early phases
  - Simulations likewise
  - We will take a brief look at several projects
- Large-scale fields
  - Biermann Battery effect
- Small scale fields
  - In magnetized systems
  - In unmagnetized systems
  - In turbulent systems
- We will visit simulations where they exist so far
- If all of this talk is correct in detail it will surprise the hell out of me

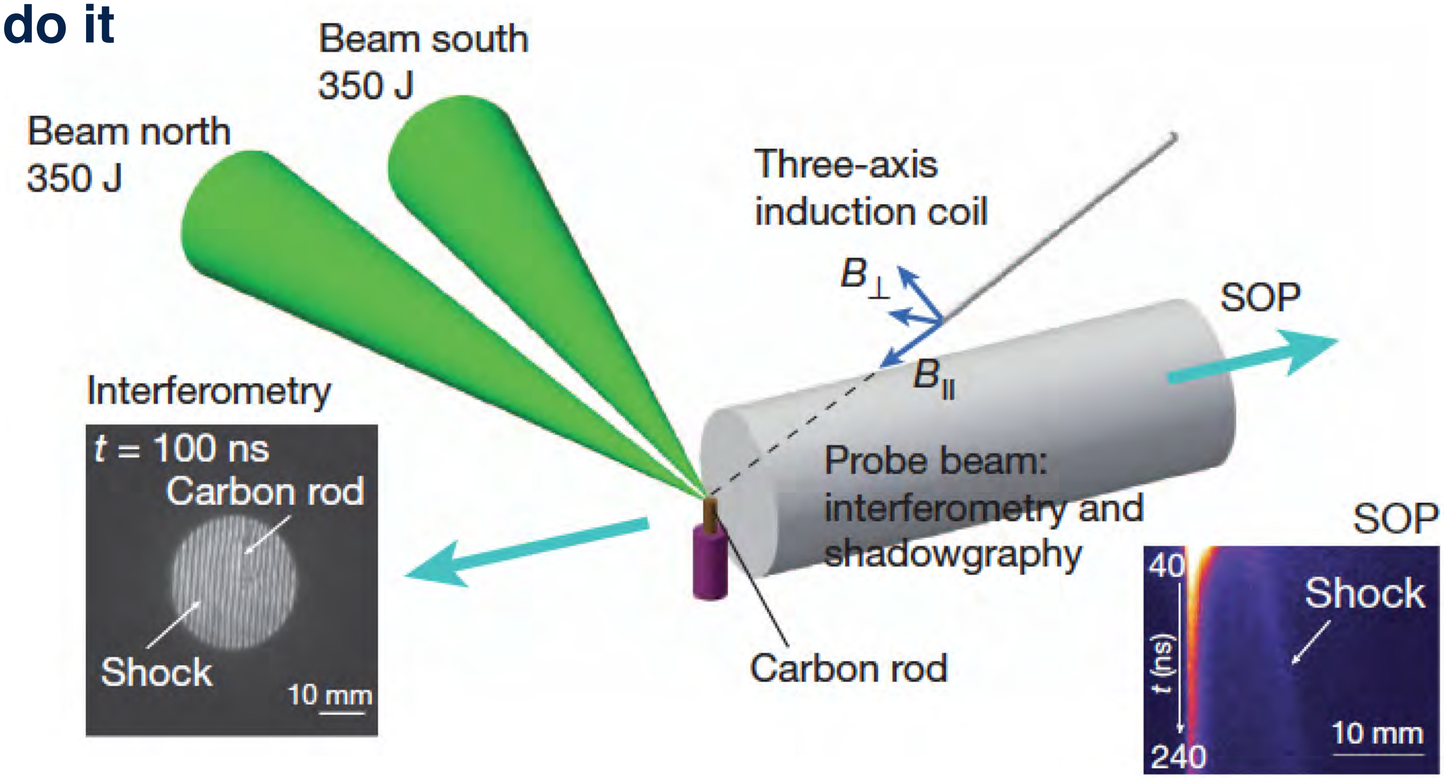
The leading candidate process for the initial magnetization of the universe is the Biermann Battery effect

- **Whenever the gradients of electron density and electron temperature are not parallel, magnetic fields are driven**
- **This occurs at any shock wave lacking 1D symmetry**
- **Example:**



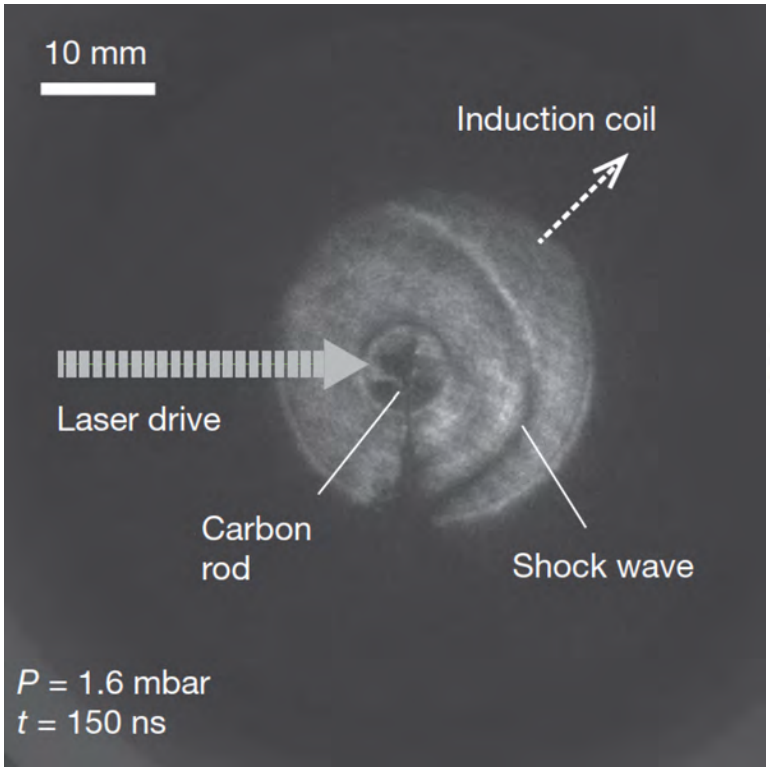
This is pretty easy to do in the lab

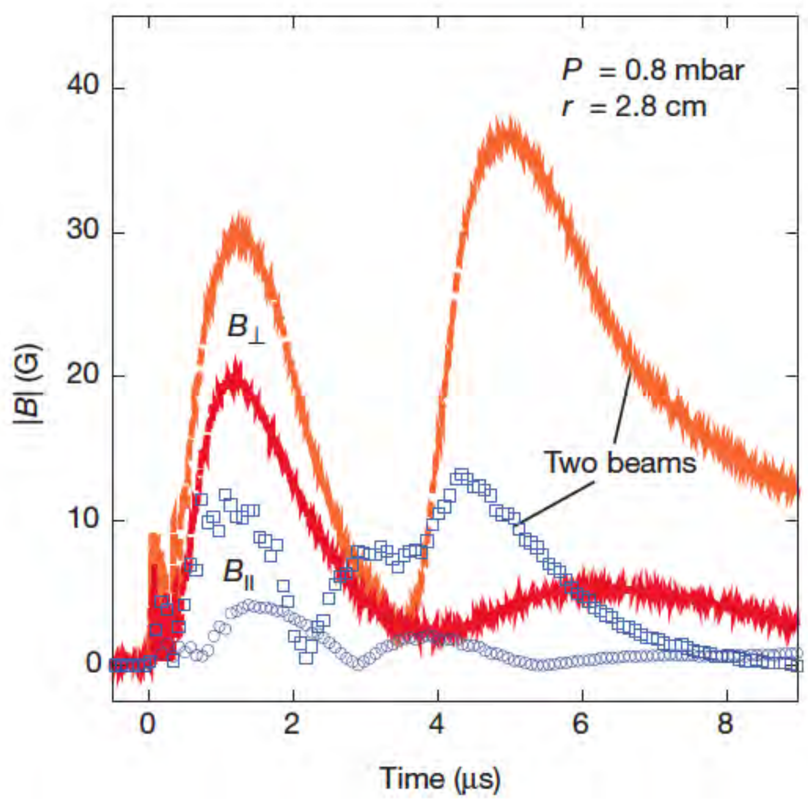
- **Gianluca Gregori of Oxford U. has led this area**
- **If it's so easy why did it take so long?**
  - **Diagnostics**
  - **Sponsor priorities**
- **How to do it**



The observations were published in Nature

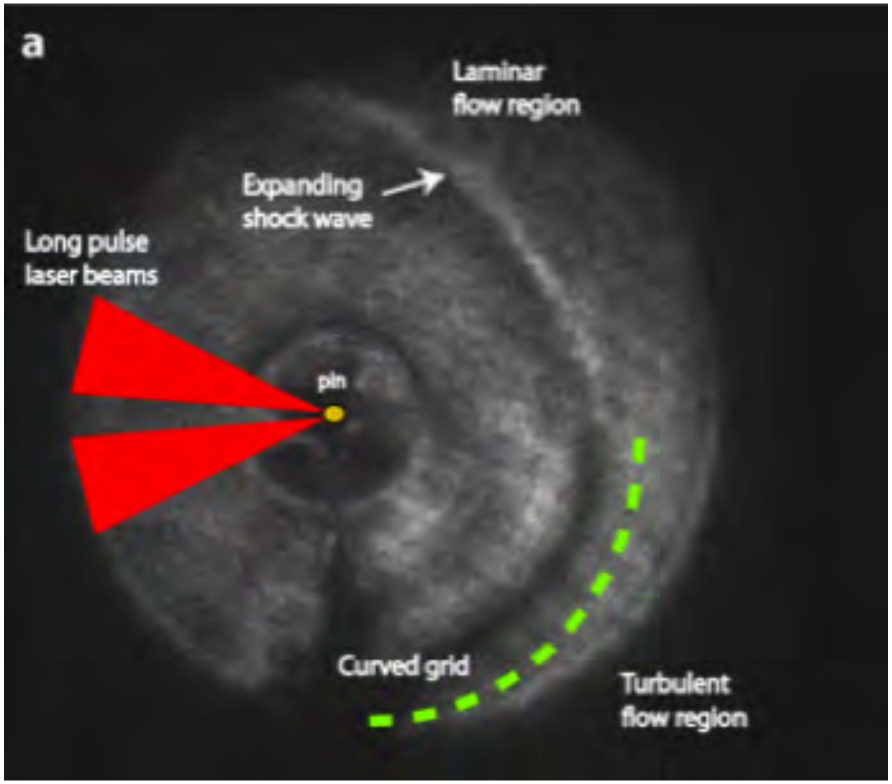
- **Gregori et al., Nature 2012**





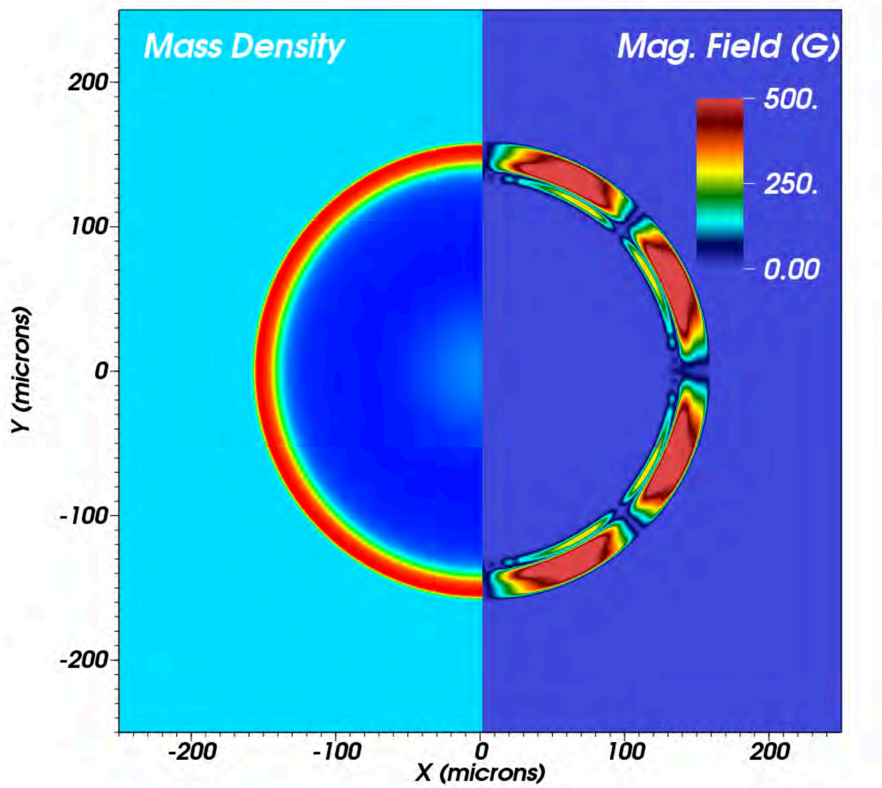
Follow-on work is seeking to create turbulence by various methods

- Blast wave through grid
- Colliding blast waves
- Colliding dense flows
- Gianluca Gregori leads a large collaboration to pursue this



Even this simple case is not so easy to simulate

- **FLASH (Chicago) is an effective code for a wide range of astrophysical and laboratory applications**
- **Simulations on a Cartesian grid create unrealistic field generation (right)**
  - **Structure seen is due to interaction of the grid and source terms**
- **This can be eliminated by turning off the Biermann battery source terms in the shock, but …**



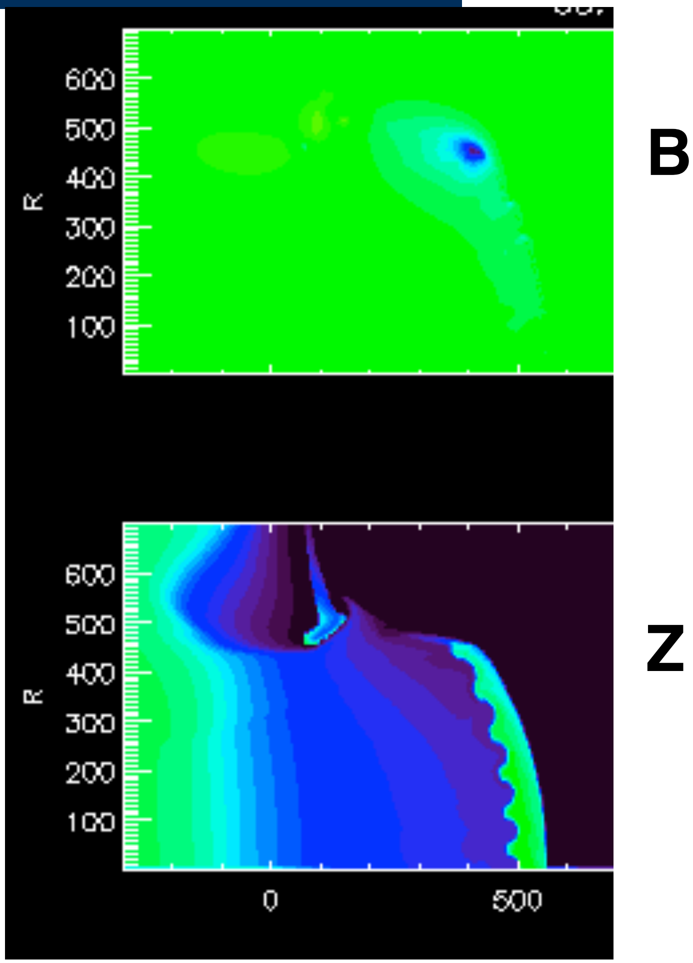
Fatenejad et al, HEDP 2012

Simulations by the UM CRASH code illustrate another challenge in field generation experiments

- Simulation of a blast-wave-driven instability in a shock tube

- The largest field is produced where the shock and tube interact
  - An issue for diagnostics

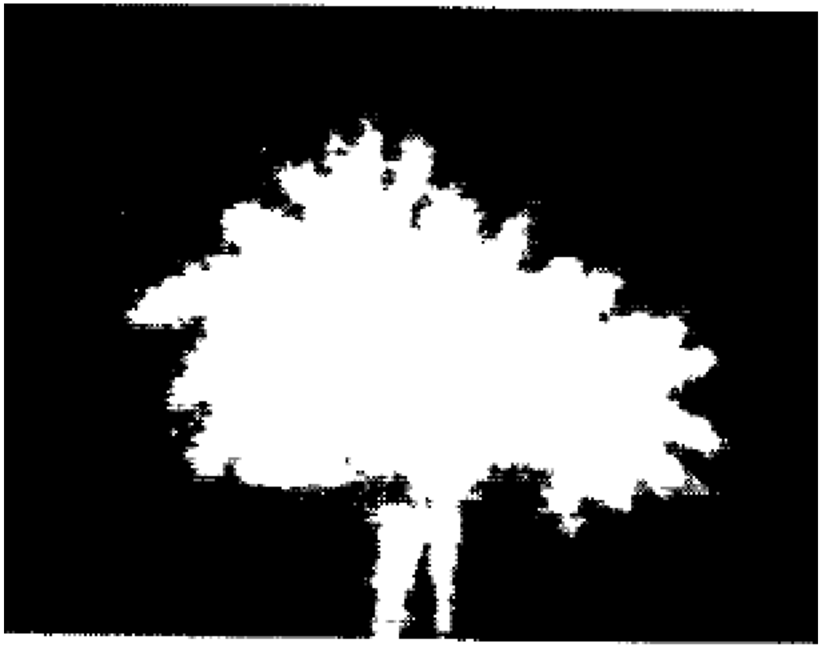
- Simulations with good resolution and realistic resistivity elude us



Credit: Jason Chou

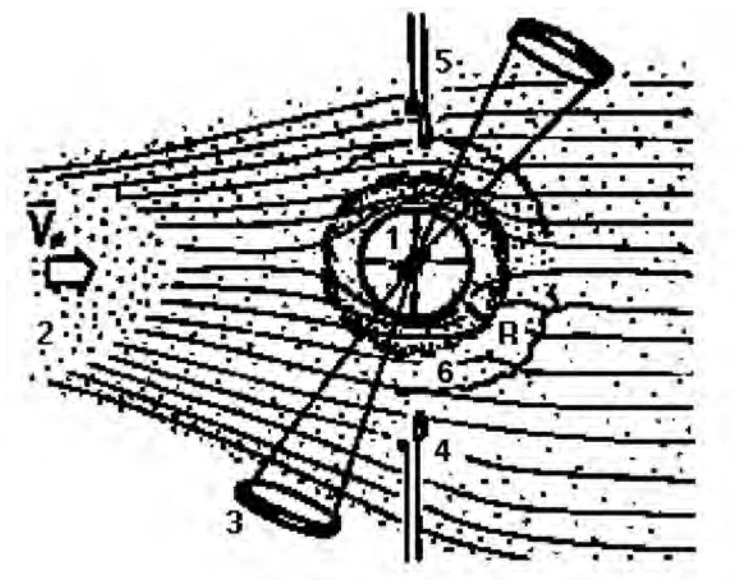
Some previous work examined plasma expansion in a magnetized plasma

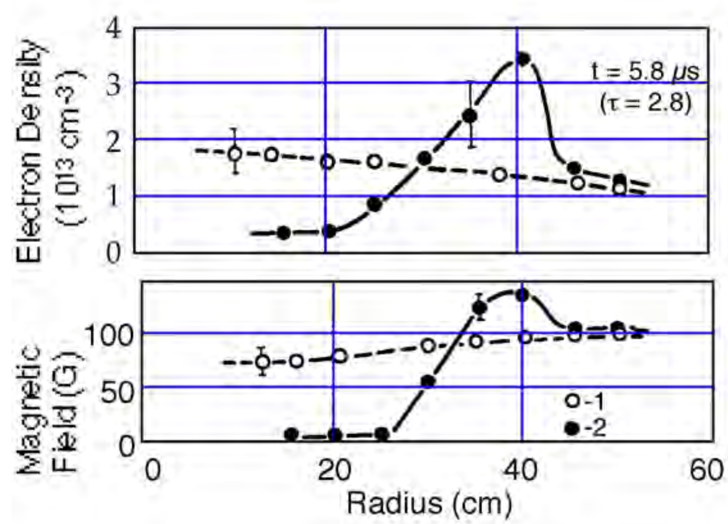
- **Ripin et al. (1993) produced a sub-Alfvenic plasma expansion**
  - **Saw flutelike Large Larmor Radius instabilities**
  - **So not really a shock experiment**



The Russian KI-1 Facility looked at expanding diamagnetic bubbles

- Papers by Zacharov and others
- Theta pinch made plasma
- Guide field let it drift into main chamber
- CO_2 laser exploded small target
- Maybe a shock, maybe not





Much of the interesting physics in astrophysical shocks relates to their collisionless nature

- **Incoming ions are slowed by structured electromagnetic fields**
  - Observed shock transitions are an infinitesimal fraction of typical Coulomb collision length scales
  - Sagdeev was widely disbelieved when he proposed in the 1950's that such shocks could exist
  - Early satellite missions proved him right

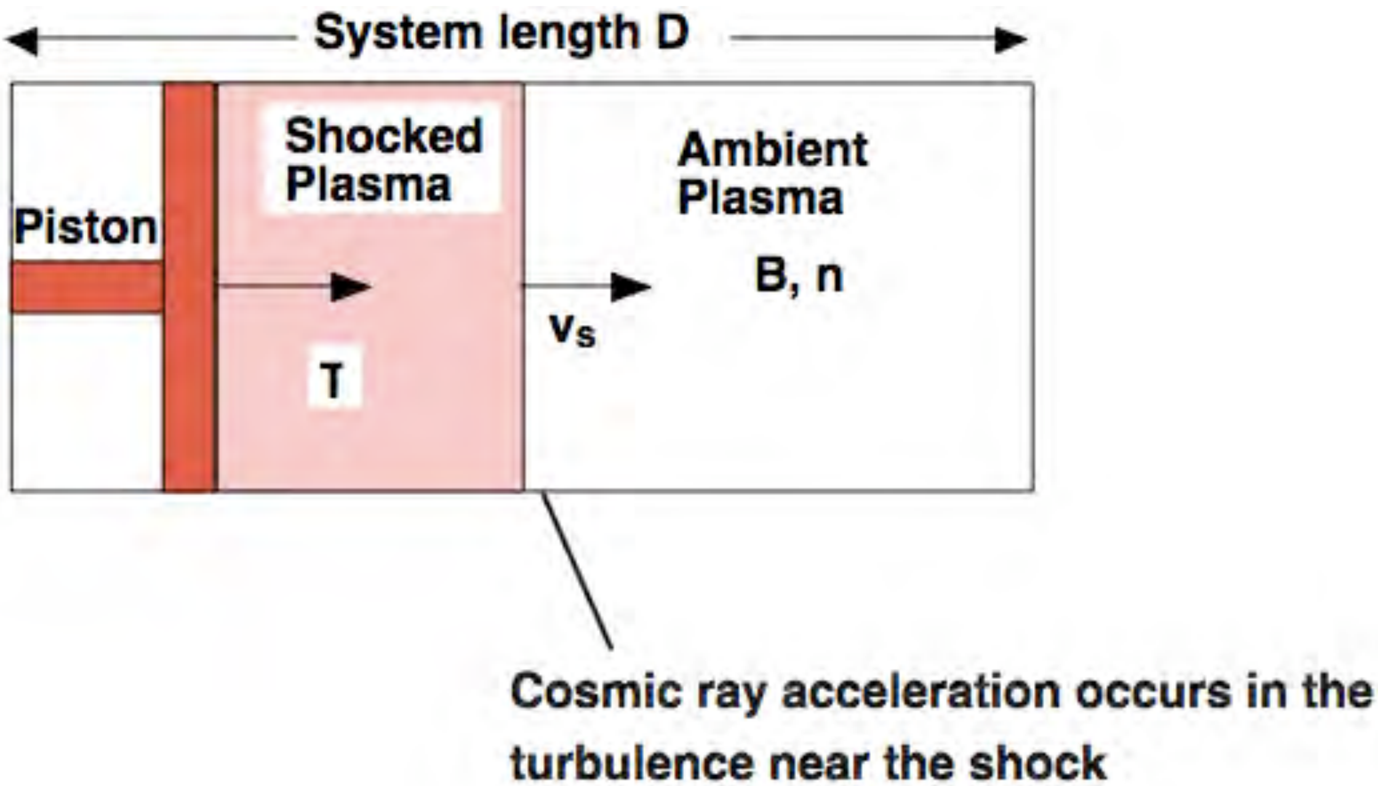
- **Questions abound**
  - How does the structure arise?
  - If necessary, how do the fields arise?
  - What is the long-term fate of these fields

I got interested in this question 15 years ago

- Specifically focused on plasmas having $\beta \sim 1$, typical of many space and astrophysical cases

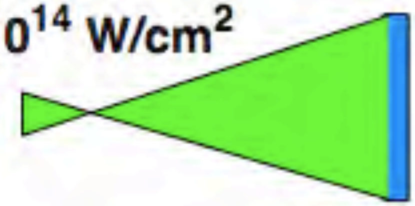
- Experiments desire:
  - Large $D/r_L \propto B$ and large $\beta \propto 1/B^2$
  - The sweet spot seems to be B of order 100 Gauss and densities within small orders of magnitude of 10^{17} cm^{-3}
  - Magnetized plasma despite tendency of plasma creation to exclude field
    - Could ionize a gas (this was my proposal)
    - Could let field diffuse back in (Niemann Trident experiment)
    - Could use plasma guns (Scott Hsu at LANL is trying this)

One can see the key parameters on this sketch



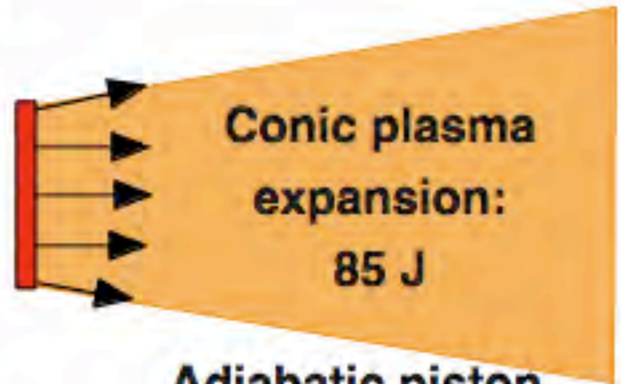
A laser-driven explosion could produce the piston

1 kJ, 1 ns,
0.53 μm
1.3×10^{14} W/cm^2



CH_2
18 μm thick
1 mm dia.

– 12 Mbar shock at 40 km/s
– post shock acceleration to 120 km/s
– post shock c_s = 22 km/s



Adiabatic piston velocity ≥ 200 km/s

> The 200 km/s piston would drive a 270 km/s forward shock, producing 140 eV shocked ambient ions. One would adjust the target thickness to get the desired shock velocity

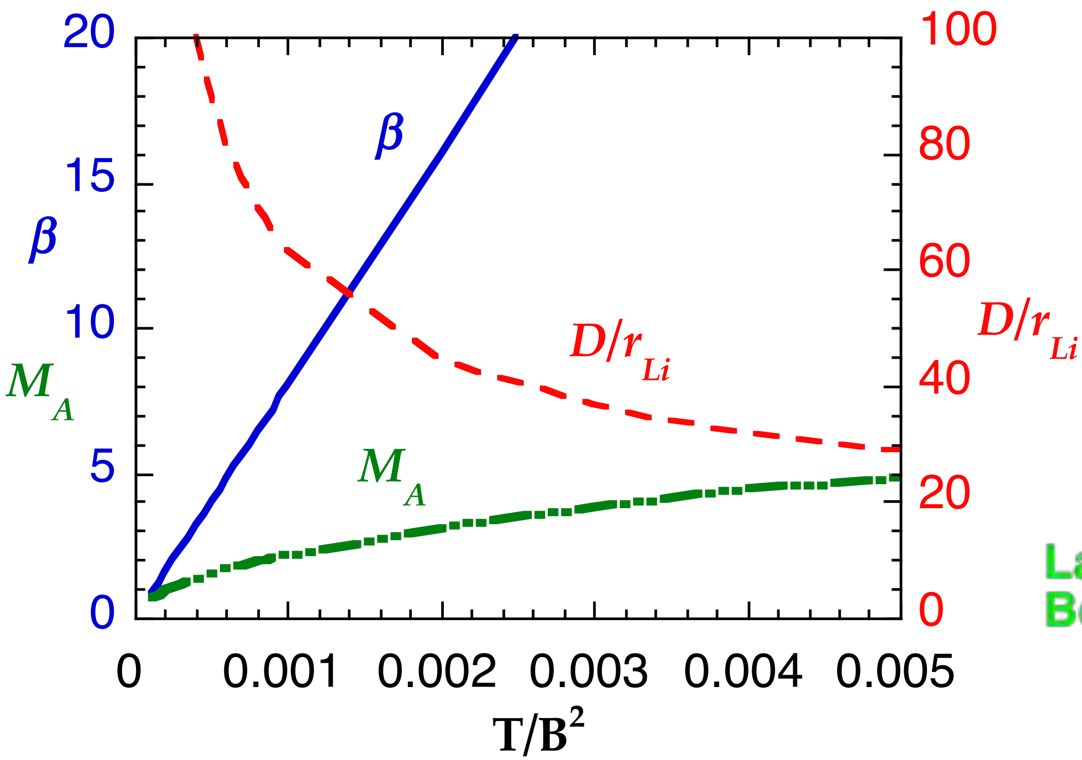
> Remarks:

At "low" density (below 10^{20} /cc) the hydrogen will pull out in front and accelerate further

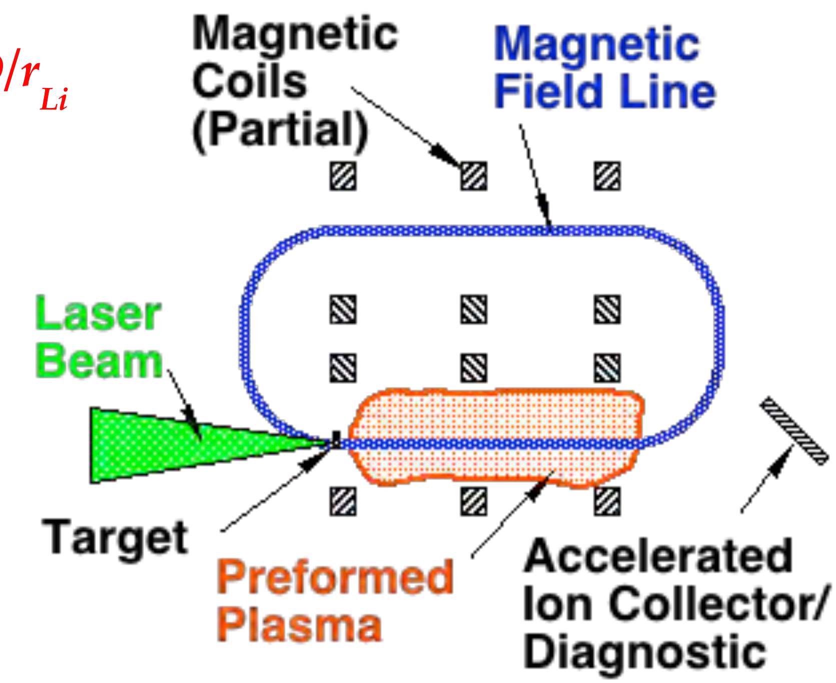
In consequence the actual initial piston velocity is underestimated

This approach builds upon work at the Russian KI-1 facility

One way to accomplish diffusive particle acceleration at collisionless shocks



From R.P. Drake,
Physics of Plasmas, Nov. (2000)



Plot is for achievable $nD^2 = 1.4 \times 10^{18}$ cm^{-1}
Parameters will increase with larger nD^2

The payoff:
particle acceleration

- Each (non-relativistic) diffusive cycle increases velocity by ~ $3v_s/4$
- The diffusive cycle time is (Lagage and Cesarsky) $T_{cyc} = \left(\frac{\lambda_1}{u_1} + \frac{\lambda_2}{u_2}\right)$
- Here λ is the mean free path ~ the shock reflected ion gyroradius; u is fluid velocity in the shock frame; 1 & 2 are upstream & downstream
- Parallel shocks: $T_{cyc} \approx \frac{5}{\omega_{ci}}$ so $\frac{\tau_{expt}}{T_{cyc}} = \frac{D}{v_s T_{cyc}} \approx \frac{1}{5}\frac{v_{th}}{v_s}\frac{D}{r_{Li}} = \frac{1}{12}\frac{D}{r_{Li}}$ ~ 5 to 10
- Limiting energy is gyroradius ~ experiment size ⇒ energy ~ 10 keV
- One should see a highly evolved ion distribution function!
- Caveat for experts: this assumes adequate injection, which is likely

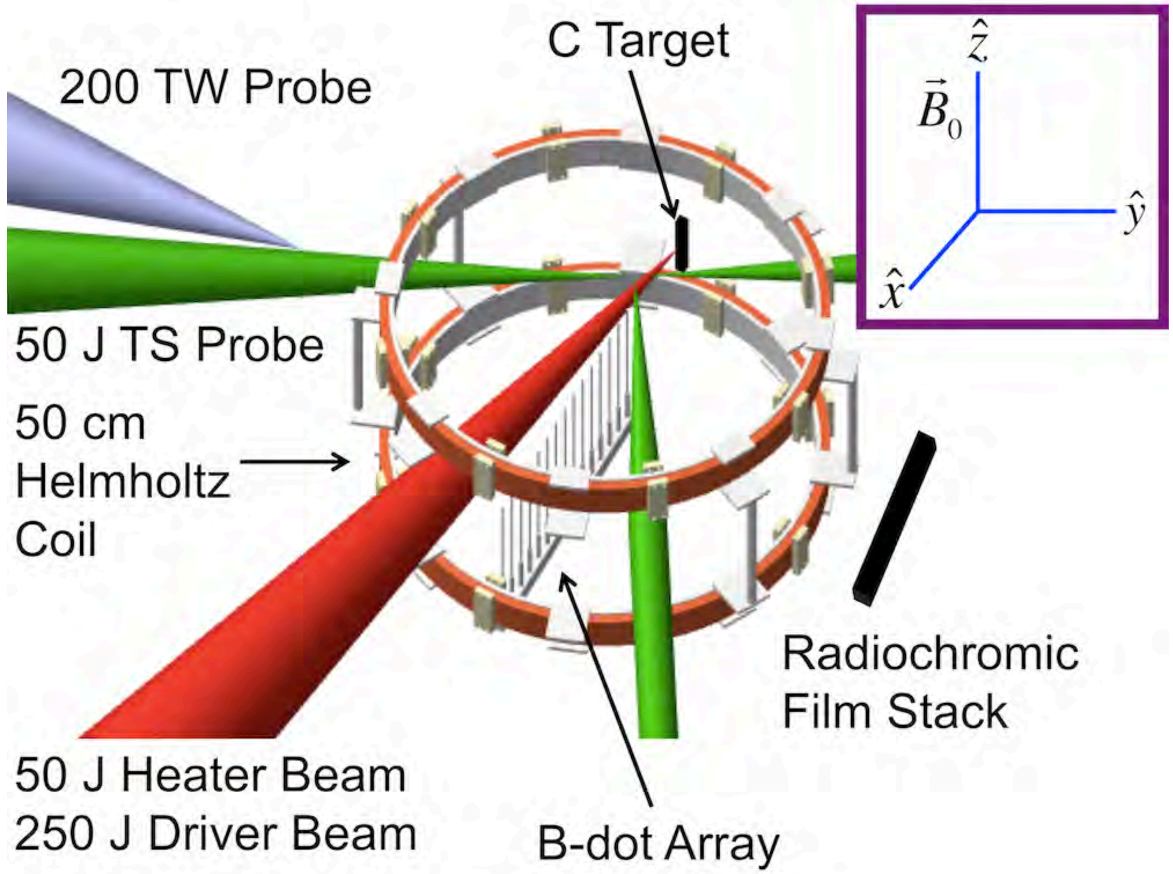
There has been progress toward such experiments

- I tried around 2000 to sell a facility that could do them but gave up after a few years

- Walter Gekelman at UCLA has led work in this direction
  - But mostly experiments on LAPD with laser explosions in a strongly magnetized plasma
  - Not clear there is any shock as distinct from a diamagnetic bubble
- Scott Hsu at LANL is pursuing a plasma-gun-based approach
- Christoph Niemann of UCLA led the first experiments to make serious progress, at the Trident laser at LANL

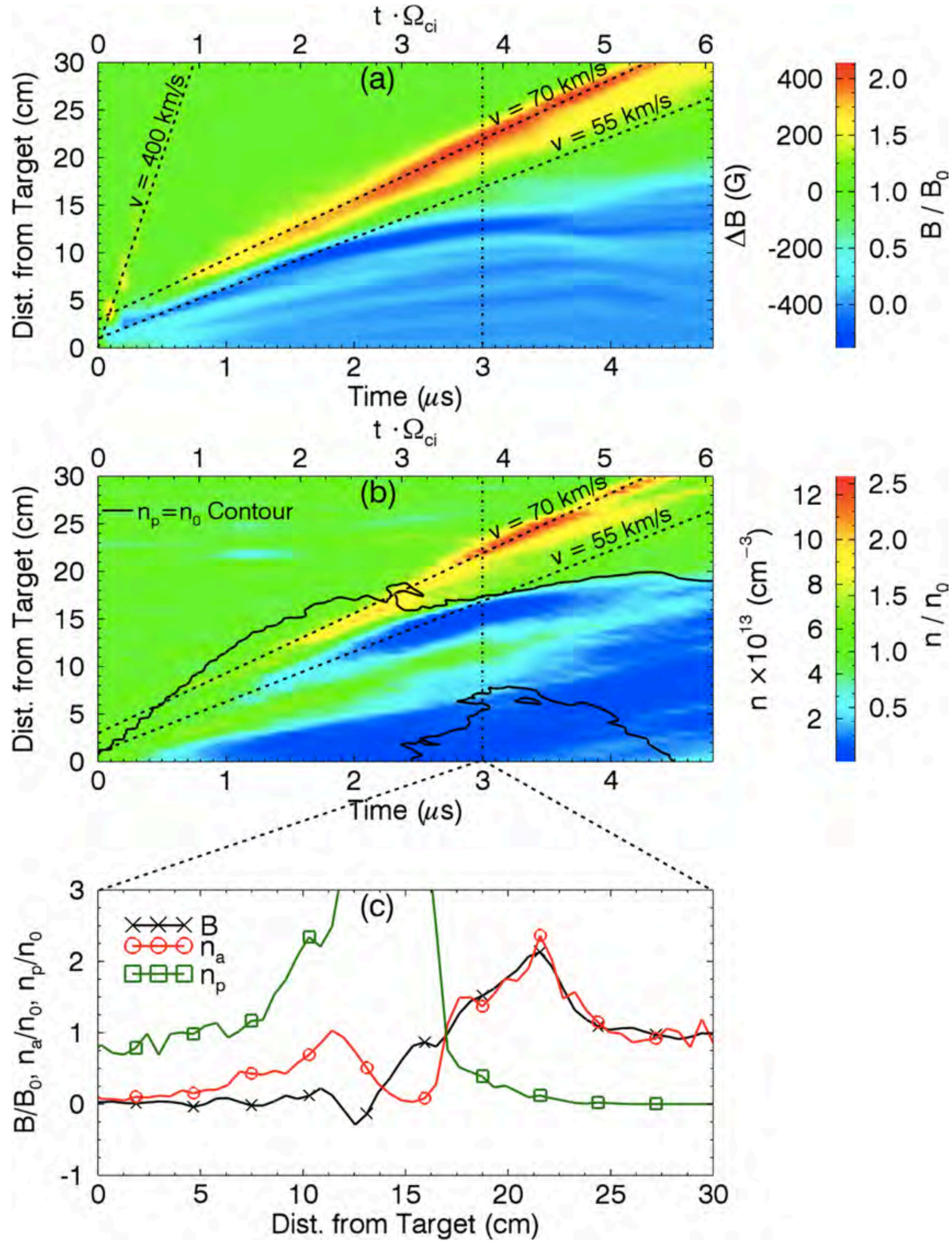
The Niemann experiment used four laser beams

- **Two to make plasma and two to probe**
- **Key innovation**
  - **Create a plasma and then allow time for the field to diffuse back in**
- **Geometry is a perpendicular shock**
- **Shaeffer et al., PoP 2012**



Simulations indicate formation of a shock

- **Hybrid, fluid electron kinetic ion simulations**
  - **Concur well with magnetic field data**
- **The “driver pulse” launched a plasma that excluded the field, driving a field and density feature ahead**



Now we turn to the initially unmagnetized case

- Initiated by counterstreaming plasmas – "two-stream, Weibel, filamentation"
- The electrostatic two-stream instability
    - (Forslund, later Silva)
  - Easily initiated and fast growing
  - Believed to saturate at low level
  - Has upper limit Mach number
  - Observation claimed in several experiments from Japan
- Weibel-driven shocks (Historically many, Medvedev for GRBs) -- being pursued by ACSEL collaboration
  - Supersonic flows from two laser-irradiated targets collide
  - The collision process must be a collisionless interaction
  - Simulations suggest 300 ion skin depths are needed.

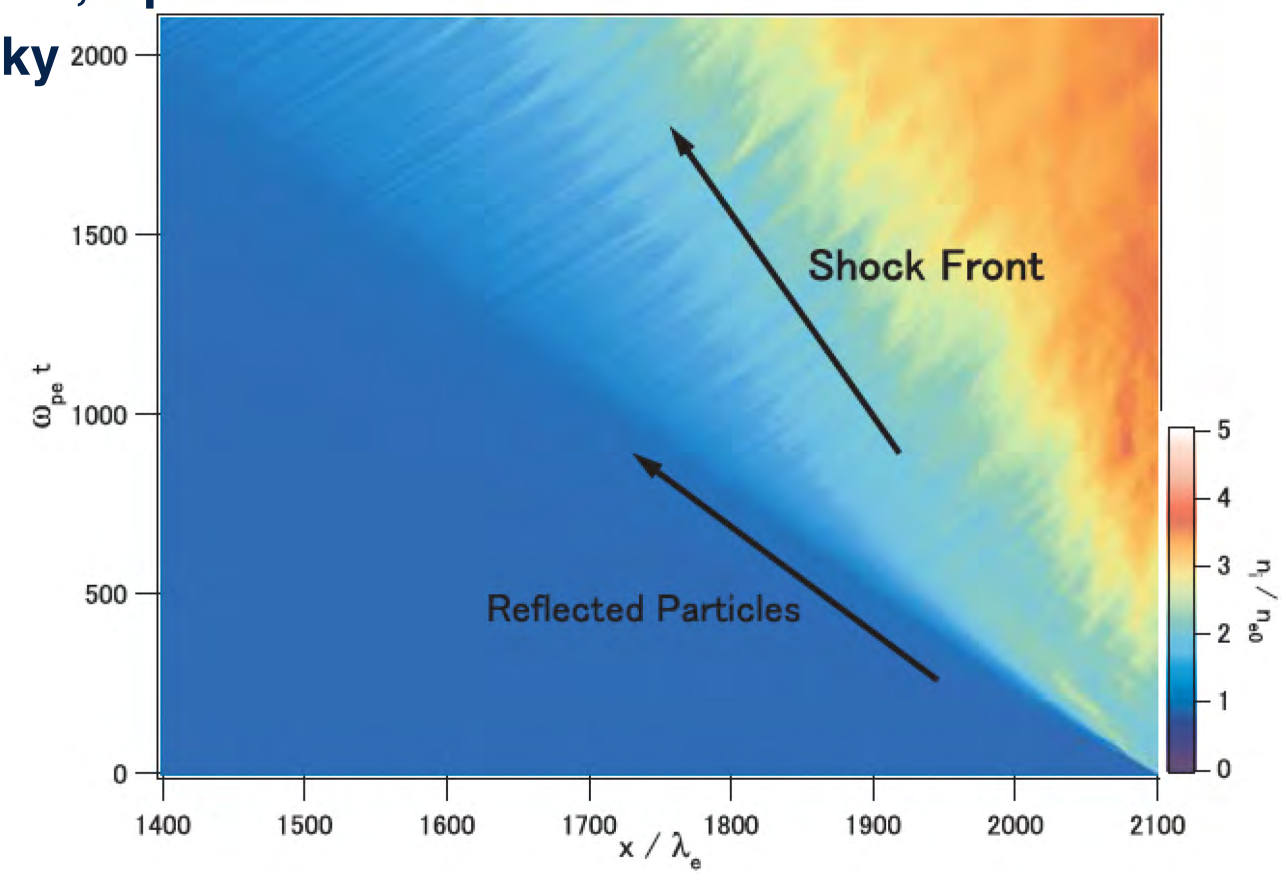
This research direction was initiated by simulations

- Opposed plasma streams in uniform plasmas at 0.45c
- Kato and Takabe, ApJL 2008
- Also Spitkovsky

- Conclusion:

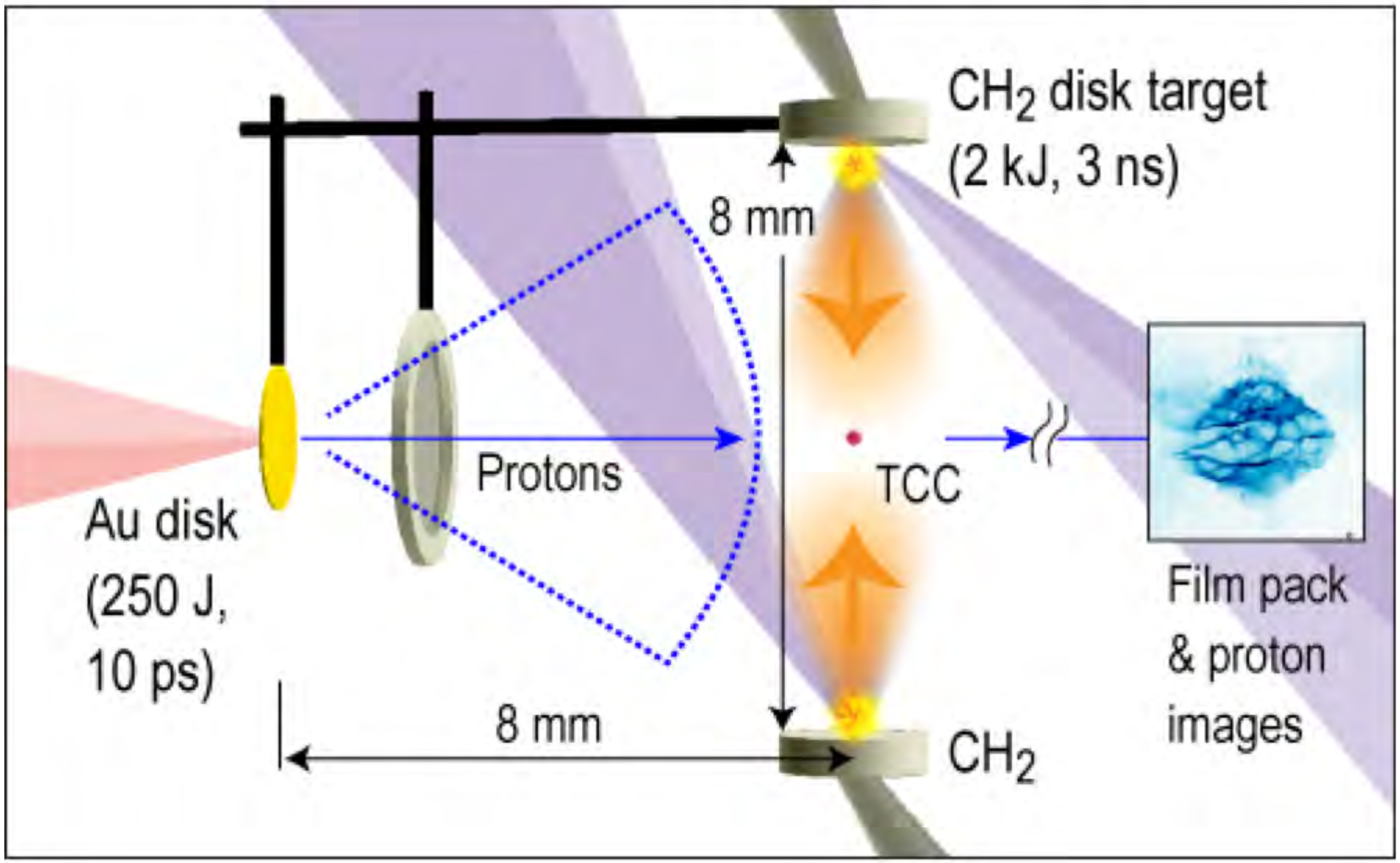
Need interaction distance of

300 c/ω_{pi}



These experiments typically involve interacting flows

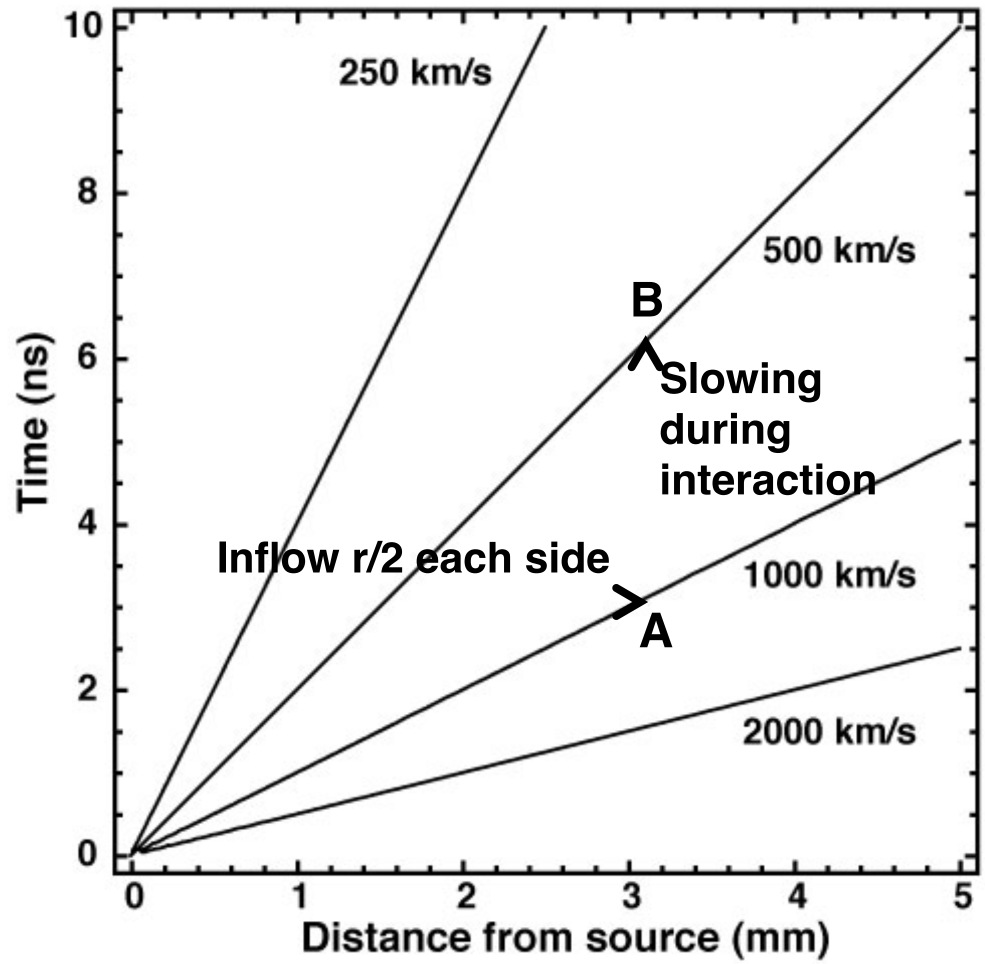
- **Kugland et al., Nature Physics 2012**



Because the expanding flows are homologous, these experiments are at mm and ns scales

- Free flows have approximately u = r/t
- At point A must have r ~ 300 c/ω_{pi}
  - Density beyond A falls exponentially or more rapidly
- At point B must still be collisionless
  - Well developed shock is at point B
- Discussion of the next few slides: Drake & Gregori, ApJ 2012

Flow velocity = half collision velocity



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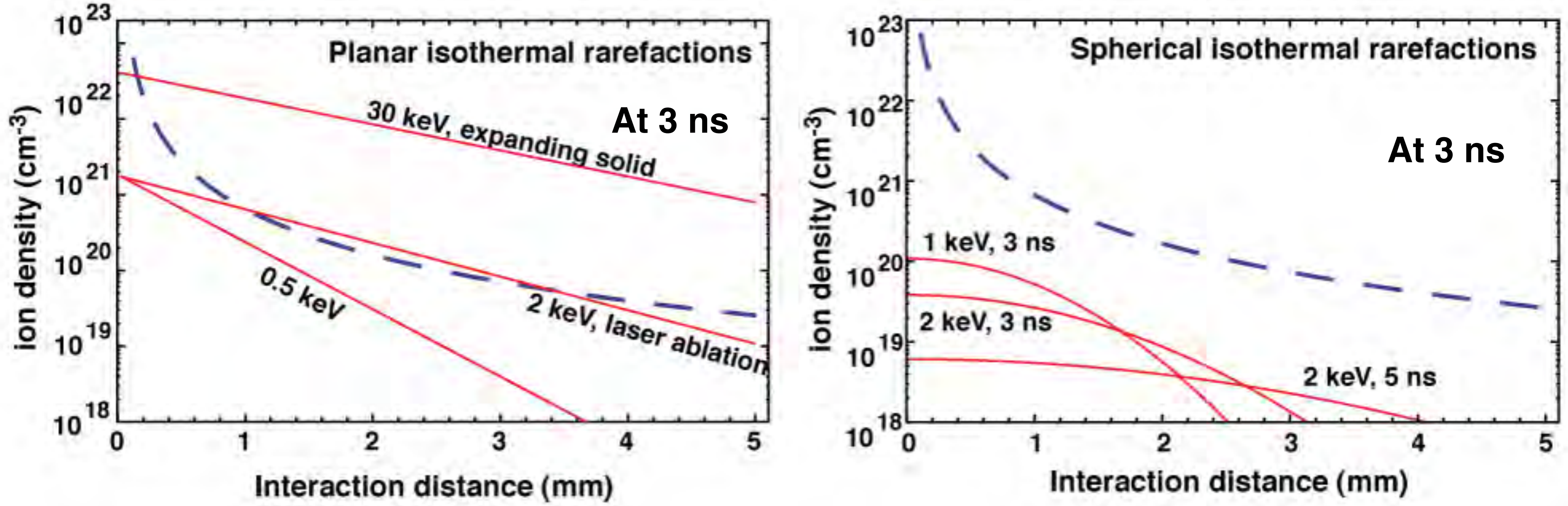
CRASH

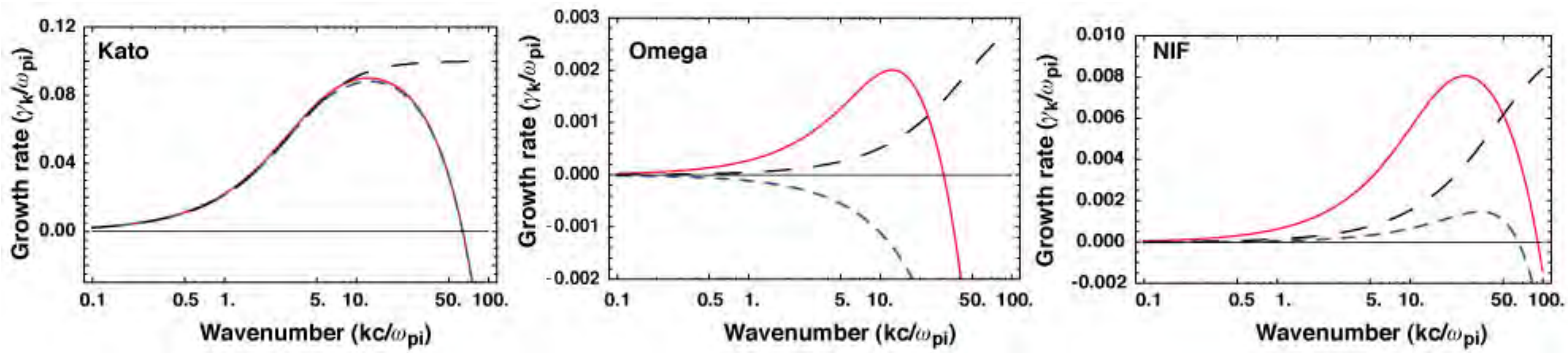
Isothermal rarefactions



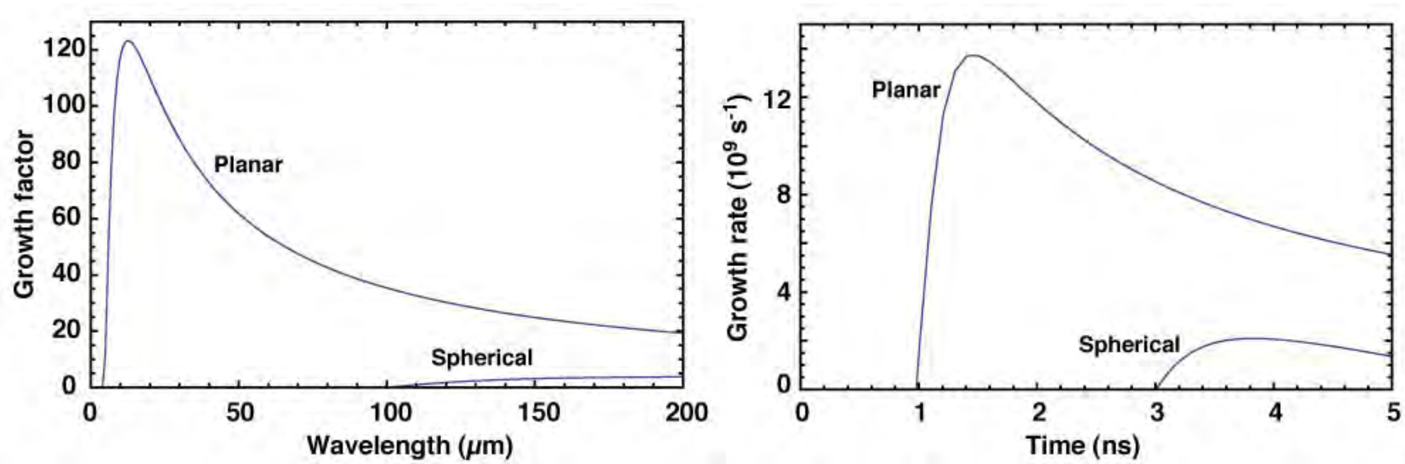
- Blue curve shows r = 300 c/w_{pi}; Red shows isothermal rarefactions
- Planar isothermal rarefaction is overestimate (plasma diverges)
- Spherical isothermal rarefaction should be underestimate

One must have lots of linear Weibel growth

- **One must evaluate the full kinetic theory with electrons**



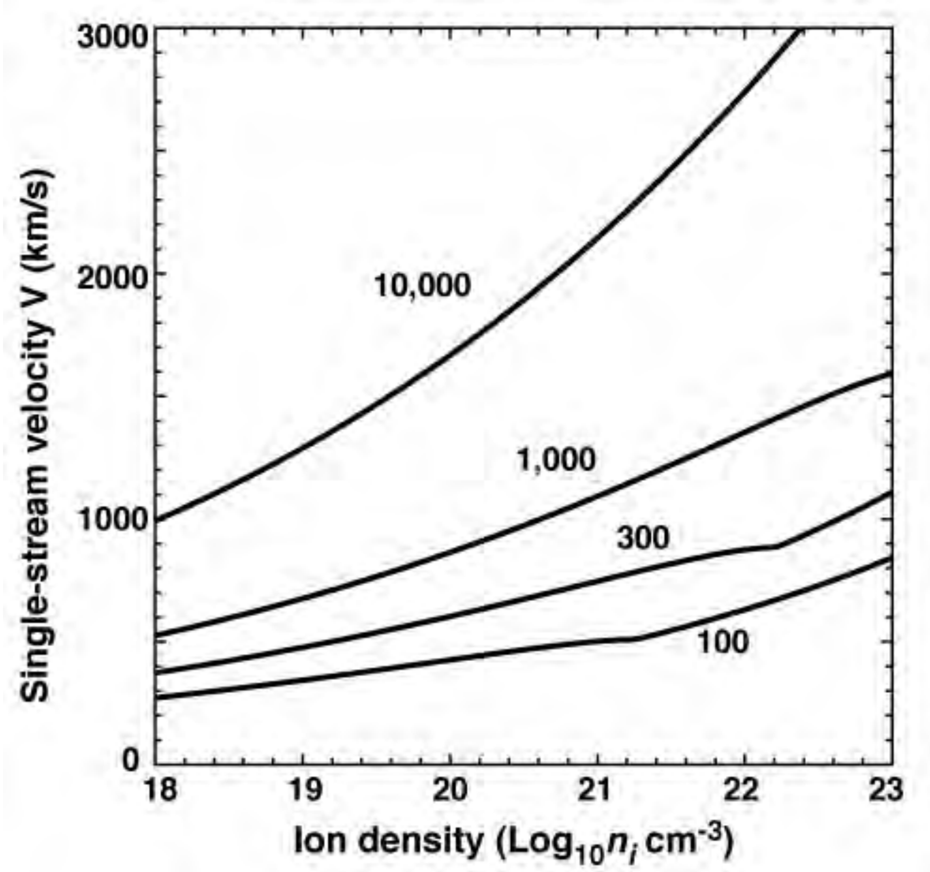
- **Getting enough growth to develop a shock at Omega seems unlikely**



The counterstreaming ions must be fast enough to create negligible density increase from collisional effects

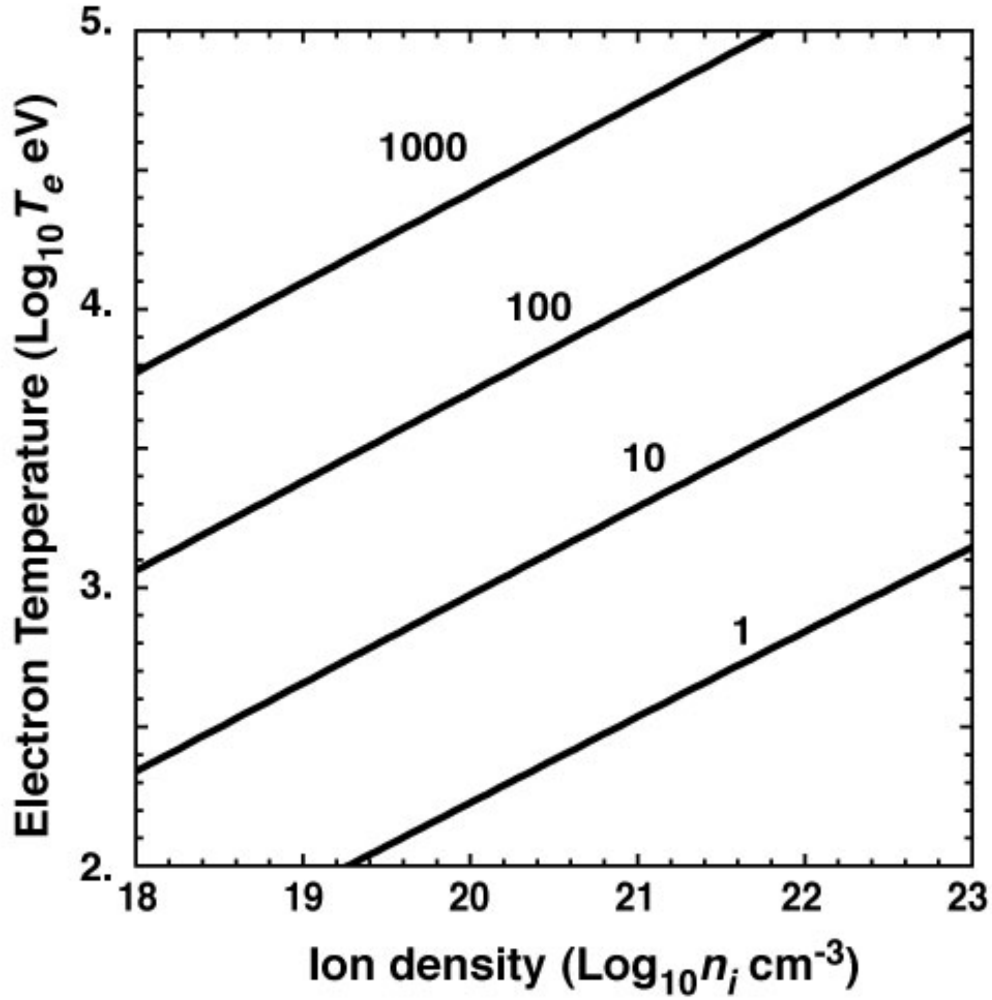
- **Contours of ion skin depths per mean free path for transverse scattering of counterstreaming ions: want this to be >> 300**
- **Not very sensitive to details**
  - **Except relative velocity v_d**
- **Implication**
  - **At 10^{18} to 10^{19} per cc want v_d near or > 1,000 km/s**

$$\chi_{ctr} = 9.2 \times 10^{-20} \frac{A^{3/2} v_d^4}{\sqrt{n_{ip}} Z Z_p^2 \ln \Lambda_{ctr}}.$$



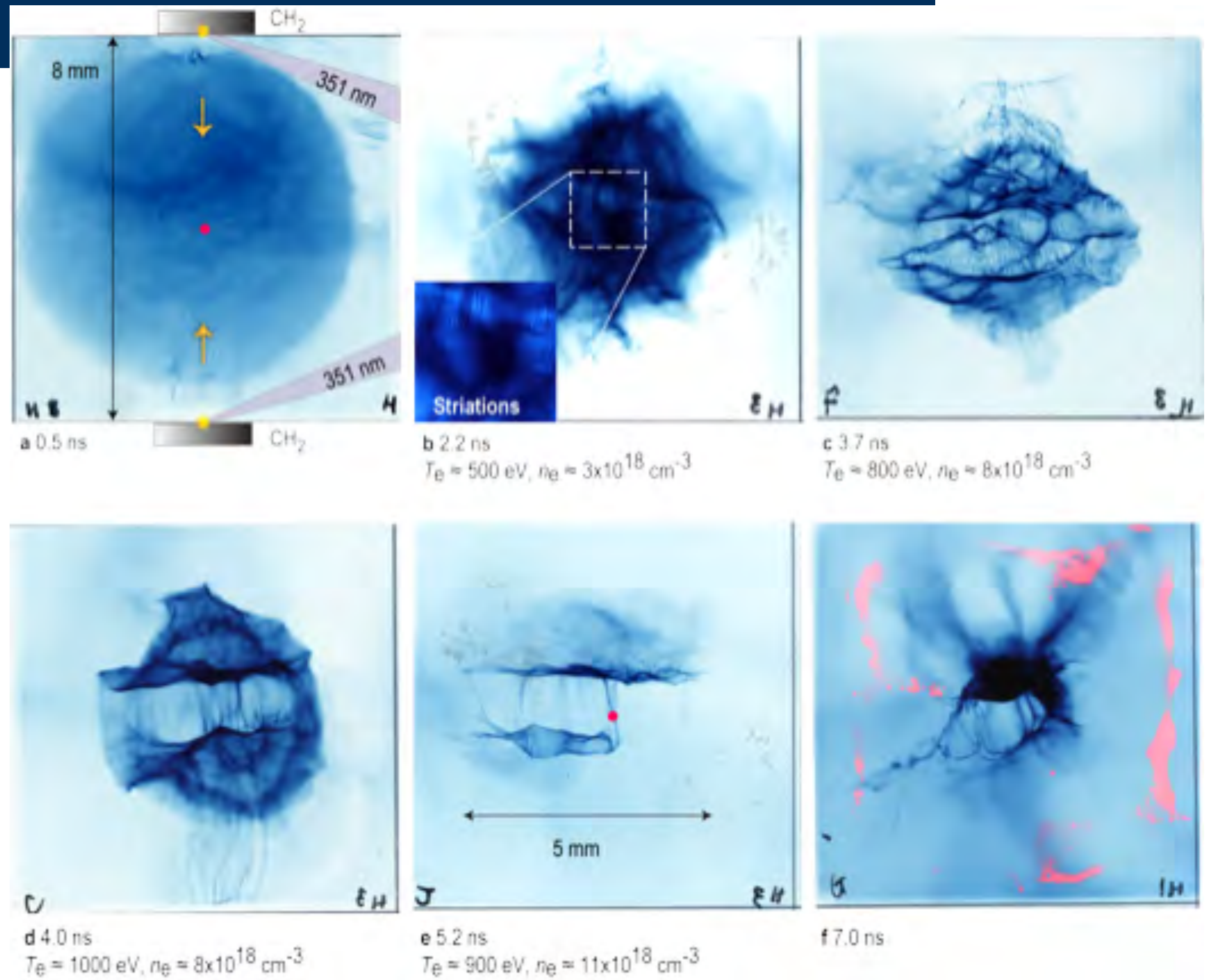
The ratio of Weibel growth rate to magnetic diffusion rate must be large

- This ratio is related to magnetic Reynolds number
  - Credit D.D. Ryutov
- Plot shows contours of constant ratio for ionized Be plasma with v_d = 2,000 km/s
- Implication
  – Keep heating plasma; want Te > 1000 eV



Experiments to develop plasmas and diagnostics have seen remarkable self-organization

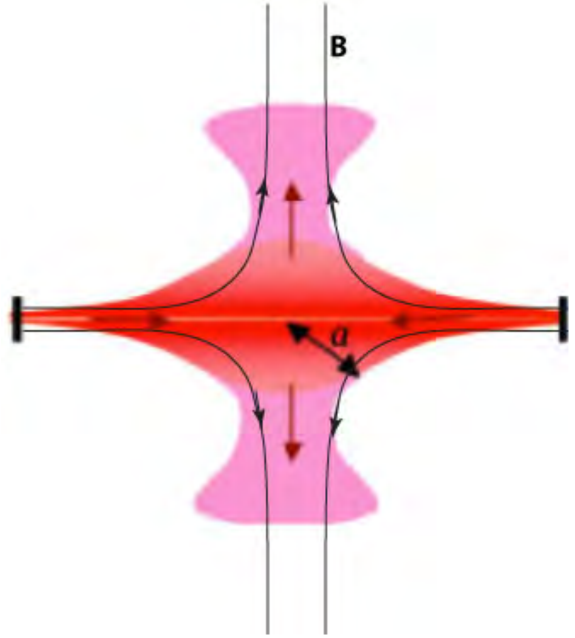
- **Kugland et al., Nature Physics 2012**
- **Images of protons that have probed the plasma**
- **Caustics reveal regular structure**



Accretion disks may provide a route to studies of turbulent dynamo effects (there are others)

- **Dmitri Ryutov proposed flow-driven accretion disks as a vehicle to do this.**
  - **The disk is driven by shocking of incoming jets**
  - **Generally should be turbulent, at least per Rayleigh criterion**

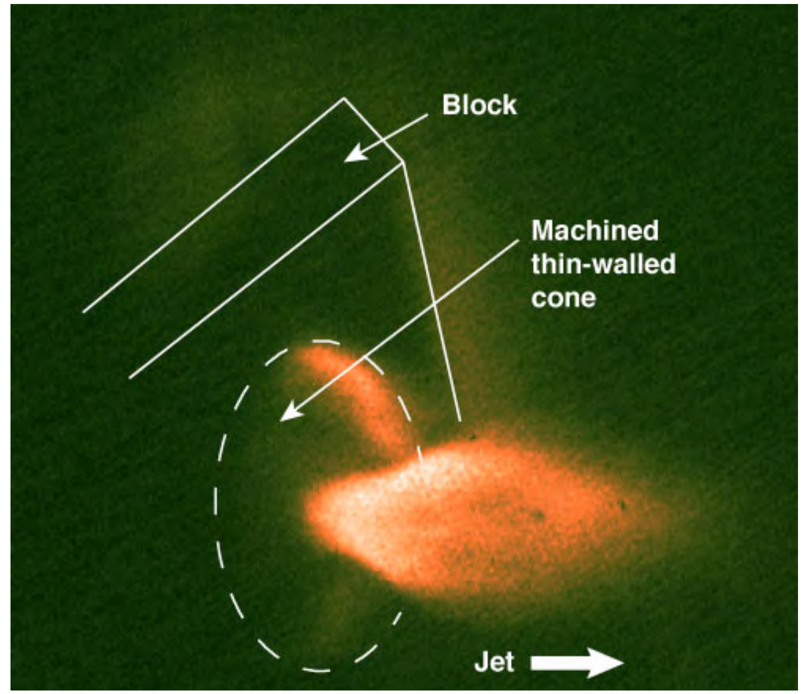
Top view

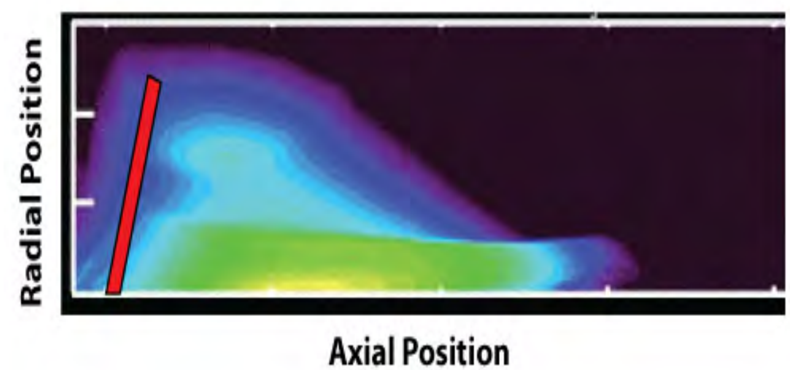


Side view

Our work to date has been toward producing the required plasma jets

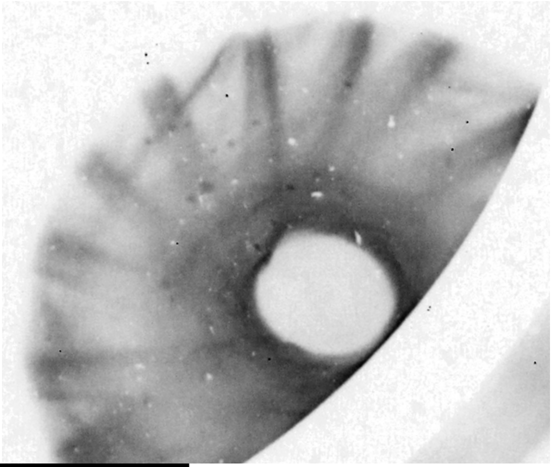
- Rear surface irradiated cones on the Omega laser
- Use converging rarefaction to create the jet
- Diagnose with emission and scattering
- Optical image (top) and simulated density (bottom)
- Credit Carolyn Kuranz, Rachel Young, Ryan Sweeney





Both laser and pulsed power systems can produce interesting parameters

- **Flow-driven accretion disk from MagPie pulsed power device at imperial College**
  - **Credit Sergey Lebedev and Francisco Villalobos**
- **Anticipated parameters**



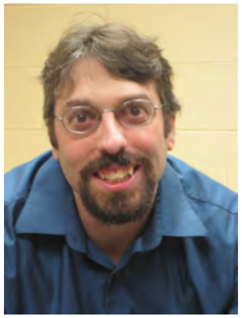
Parameter	Symbol	Omega	MAGPIE
Ionization	Z	4	6
Electron density	n_e (cm^{-3})	10^{21}	10^{19}
Disk diameter	D_{disk} (mm)	1	4
Inflow velocity	U (km/s)	180	130
Electron temperature	T_e (eV)	100	100
Reynolds number	Re	$7\text{x}10^5$	10^5
Magnetic Reynolds number	R_m	10	10

There is now, finally, a lot of experimental activity related to magnetic fields at shocks

- **All in relatively early phases**
- **Large-scale fields**
  - **Biermann Battery effect**
- **Small scale fields**
  - **In magnetized systems**
  - **In unmagnetized systems**
  - **In turbulent systems**
- **Simulations play various roles but remain far from complete or ubiquitous**
- **This talk drew on work by many colleagues at UM and across the community – tried to give credit on slides**

The Michigan team with whom I have the pleasure to work

- CLEAR Experimental Program
  - Grad students:
    - Visco, Huntington, Krauland, Di Stefano
    - Gamboa, Young, Wan, MacDonald
  - Many undergrads
  - Staff:
    - Grosskopf, Klein, Lowenstern,
    - Gillespie, Susalla



Dr. Paul Keiter

Dr. Carolyn Kuranz

- Center for Radiative Shock Hydrodynamics (CRASH)
  - Staff: Fryxell, Myra, Toth, Sokolov, van der Holst, Andronova, Torralva, Rutter
  - Grad students: Patterson, Chou, and many others
  - UM Professors: Powell, Holloway, Stout, Martin, Larsen, Roe, van Leer, Fidkowsky, Thornton, Nair, Karni, Gombosi, Johnsen
  - TAMU: Adams, Morel, McClarren, Mallick, Amato, Raushberger, Hawkins
  - Simon Frazer: Bingham

We value our scientific and financial collaborators

CLEAR Team members:

Florida State – *Plewa*

Texas – *Wheeler*

Arizona – *Arnett*

Scientific collaborators:

LLE/Rochester – *Knauer, Boehly, Fiksel*

LLNL – *Park, Remington, Glenzer, Fournier, Doeppner, Robey, Miles, Froula, Ryutov, others*

LANL – *Montgomery, Lanier, Benage, Workman, others*

France – *Bouquet, Koenig, Michaut, Loupias, Falize, others*

Britain – *Lebedev, Gregori*

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