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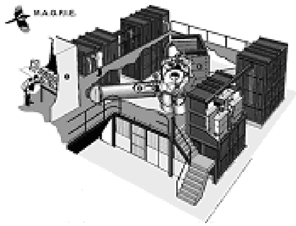

# Pulsed Power Driven Experiments in the Institute of Shock Physics


Simon Bland

*Imperial College London*

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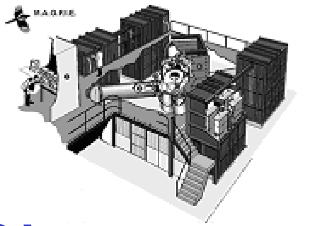

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*Imperial College London*

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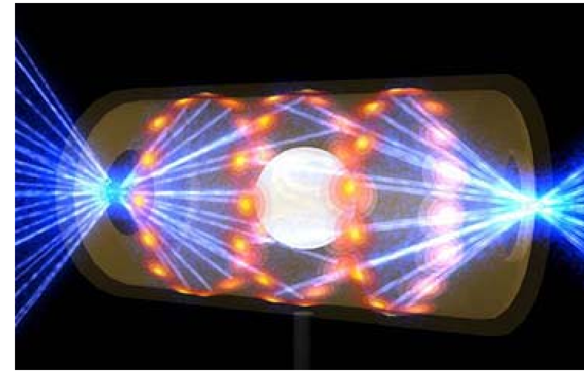
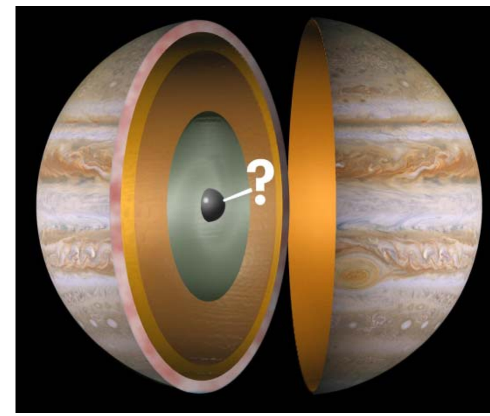
# Outline of talk



Initial (very initial) magnetically driven ramp experiments

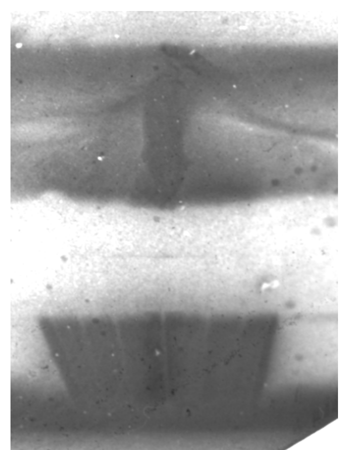
Radiative shock wave and bow shocks in plasmas

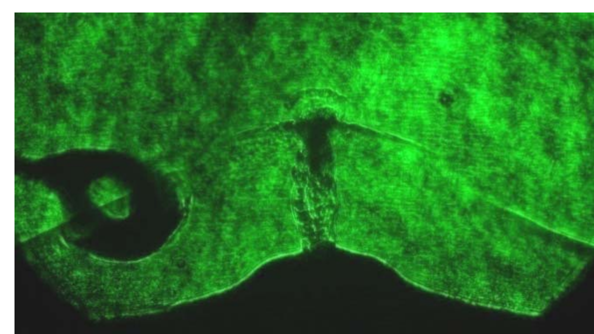


A plasma drive for high pressure experiments

Future program

- MACH
- Diagnostic development
- Advanced concepts





# High Pressure EOS measurements

Diamond anvil cells are used to provide up to Mbar 'static' information

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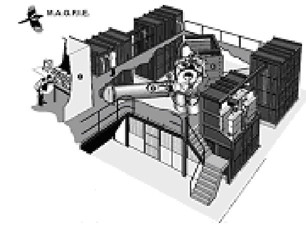
# High Pressure EOS measurements



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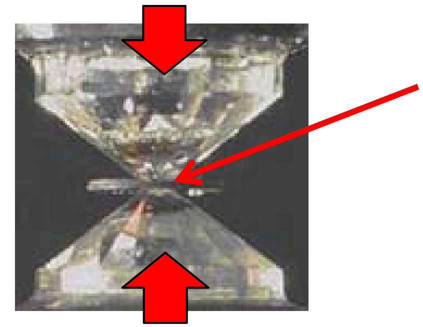
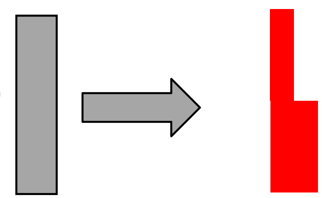



Plate impacts generate shocks to obtain EOS measurements in dynamic systems / at high pressures



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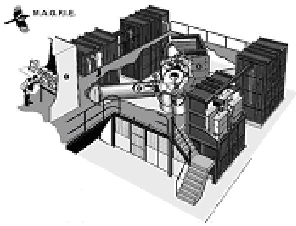
# High Pressure EOS measurements



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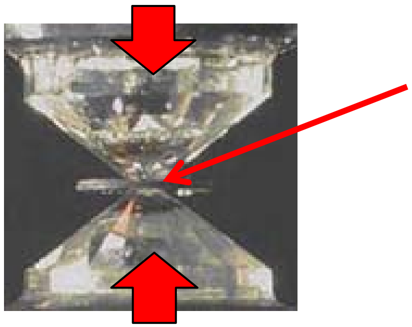


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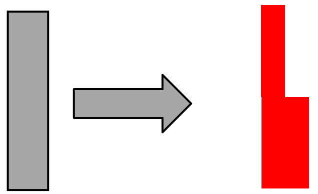
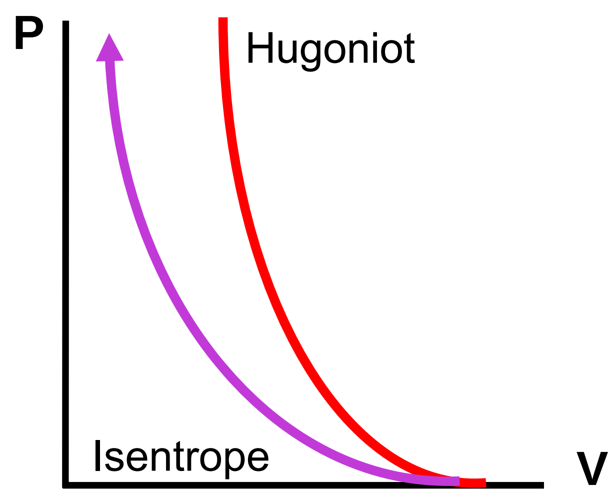


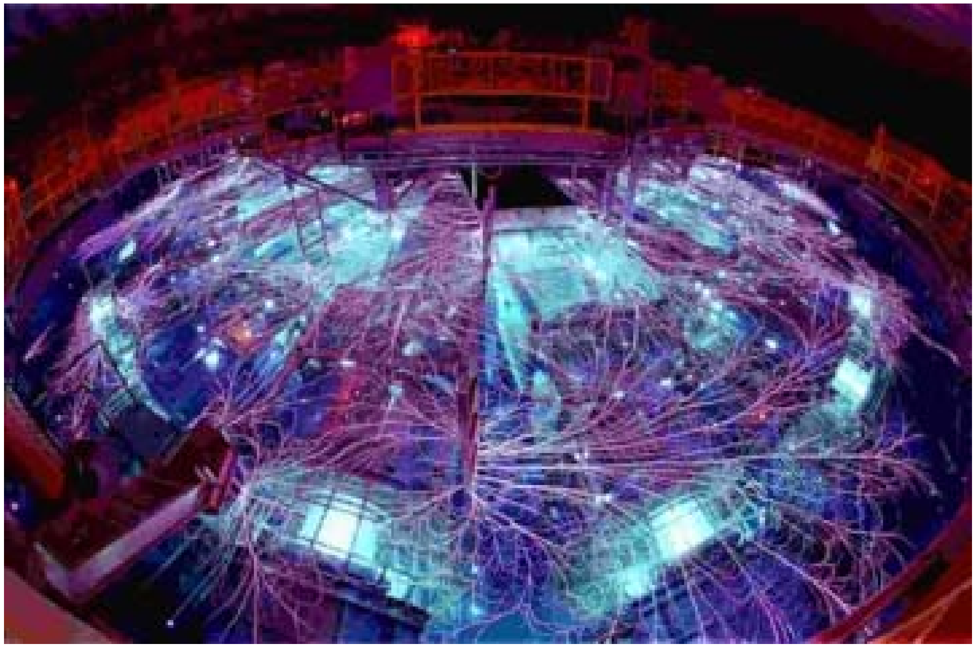

Gas guns generate high precision data up to 2-3 Mbar pressure, but tend to sample along Hugoniot

Magnetic fields (and plasma) generated using pulsed power can drive ramp pressures

- 'quasi isentropic process' sample below Hugoniot to high pressures
- can launch very high speed flyer plates



# Magnetic driven experiments pioneered at Sandia



On Z (26MA, 200ns):

Isentropic pressures up to ~6MBar

Flyer velocities ~10s of $kms^{-1}$

Studies include EOS of Beryllium, diamond, aluminium and special nuclear materials

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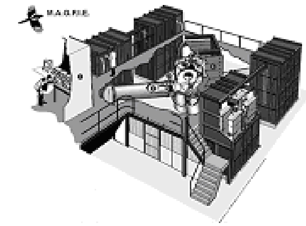
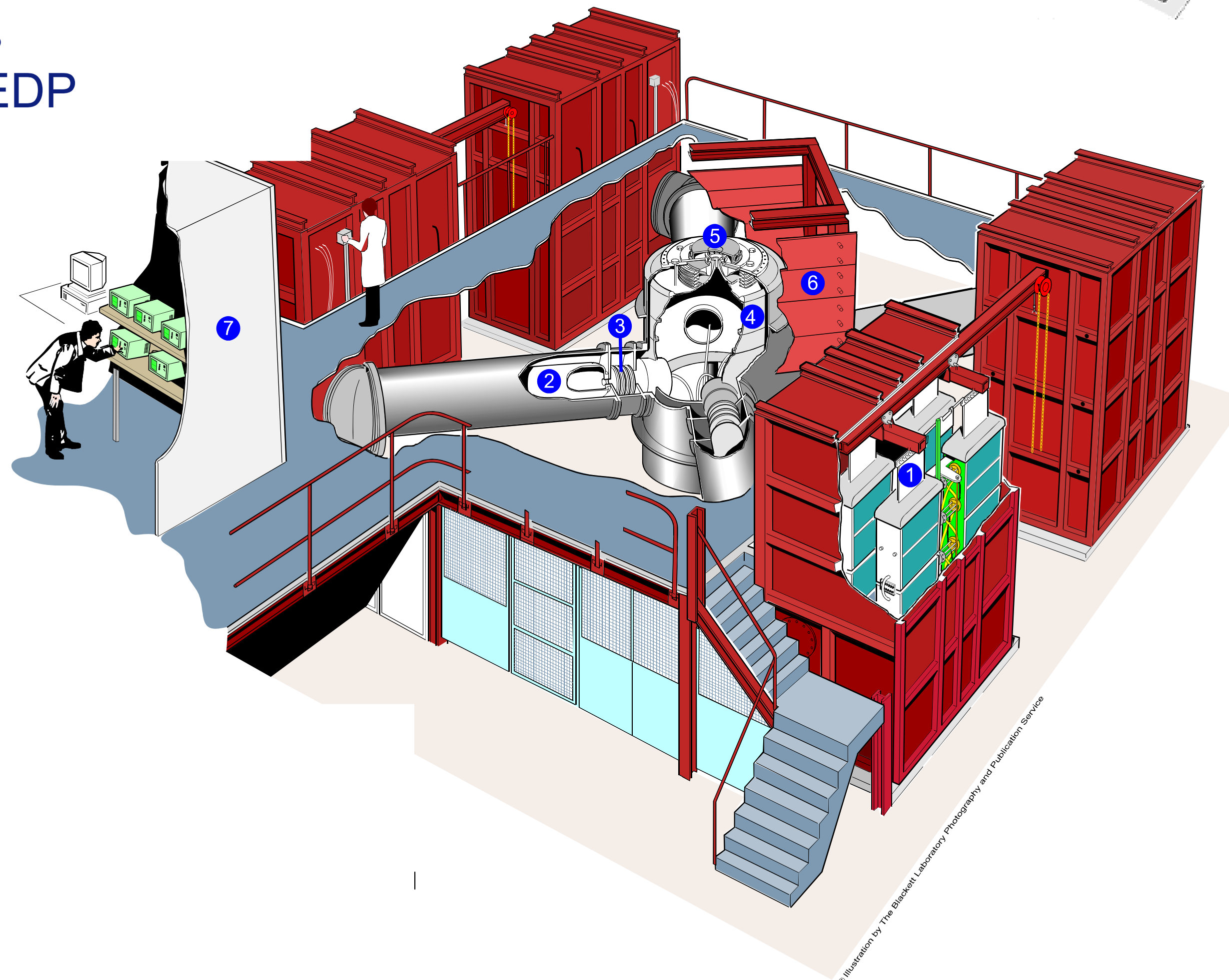
# Imperial College MAGPIE facility



At Imperial the 1.5MA 240 ns MAGPIE generator drives HEDP experiments on a daily basis

**M**ega
**A**mpere
**G**enerator for
**P**lasma
**I**mplosion
**E**xperiments




Get experience in magnetically driven isentropic compression experiments
Can also look at shocks in plasmas - e.g. astro relevant radiative shock waves
And using plasma explore new methods of applying high pressures to targets

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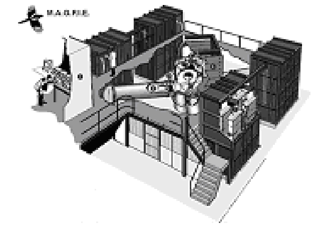
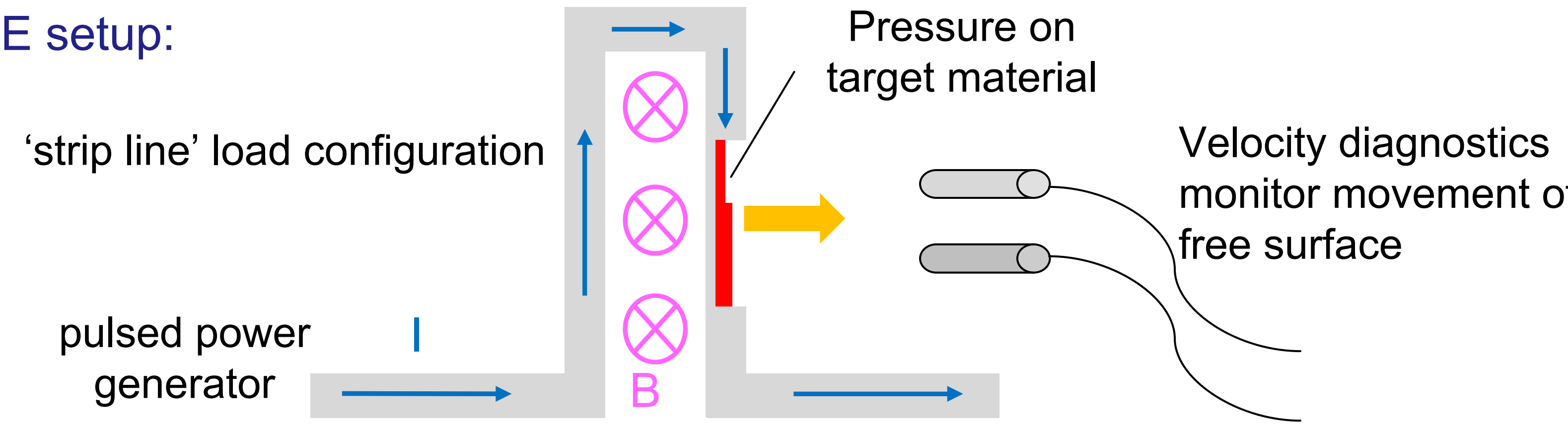


# Magnetically driven EOS experiments

High magnetic field can provides ramp pressure loading

Basic ICE setup:



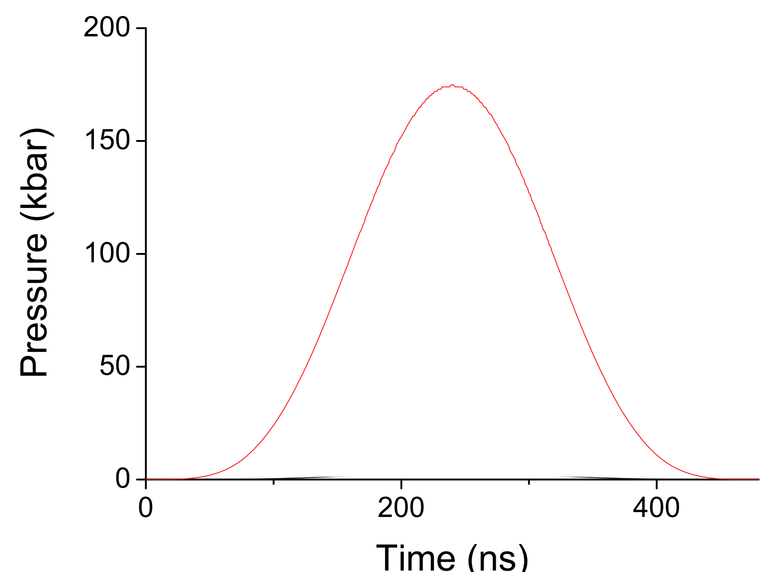

Each side of strip line sees equivalent pressure profile

$$B = \frac{\mu_0 I}{w}$$

(w is width of strip)

$$P = \frac{B^2}{2\mu_0} = \frac{\mu_o I^2}{2w^2}$$

on MAGPIE ~2MA, 250ns rise time, 10mm wide strip line gives ~ 200KBar



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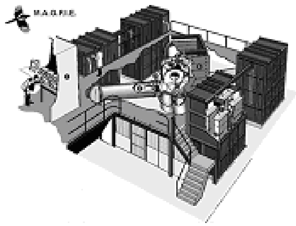
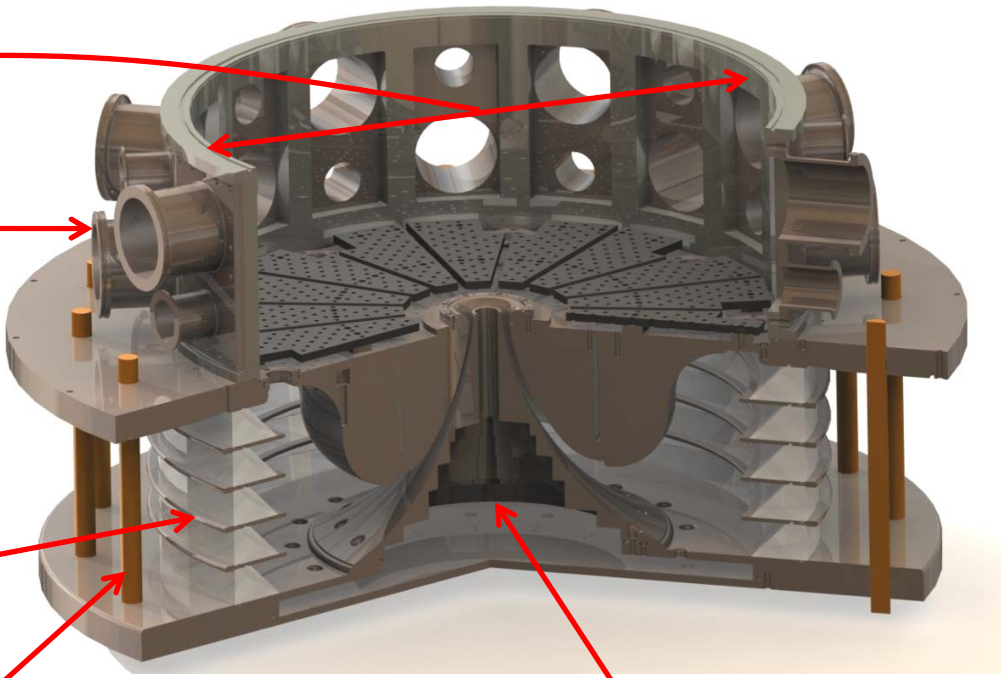


# Prelude to experiments: new power feed and vacuum chamber

Original vacuum chamber was only ~30cm diameter x 15cm tall

Anode and cathode move by 6mm during vacuum

Water ingress meant vacuum time was 3hrs



~70cm internal diameter

Chamber surrounded by 16 port plates with ISO100 and ISO 63

Reinforced steel plates to reduce flex

Rexolite diode rings increase strength reduce water absorption

New Torlon bolts don’t stretch

Vacuum section below MITL removes force on cathode

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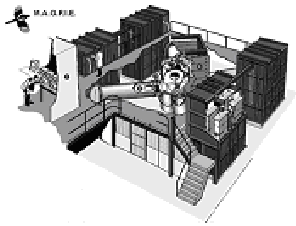

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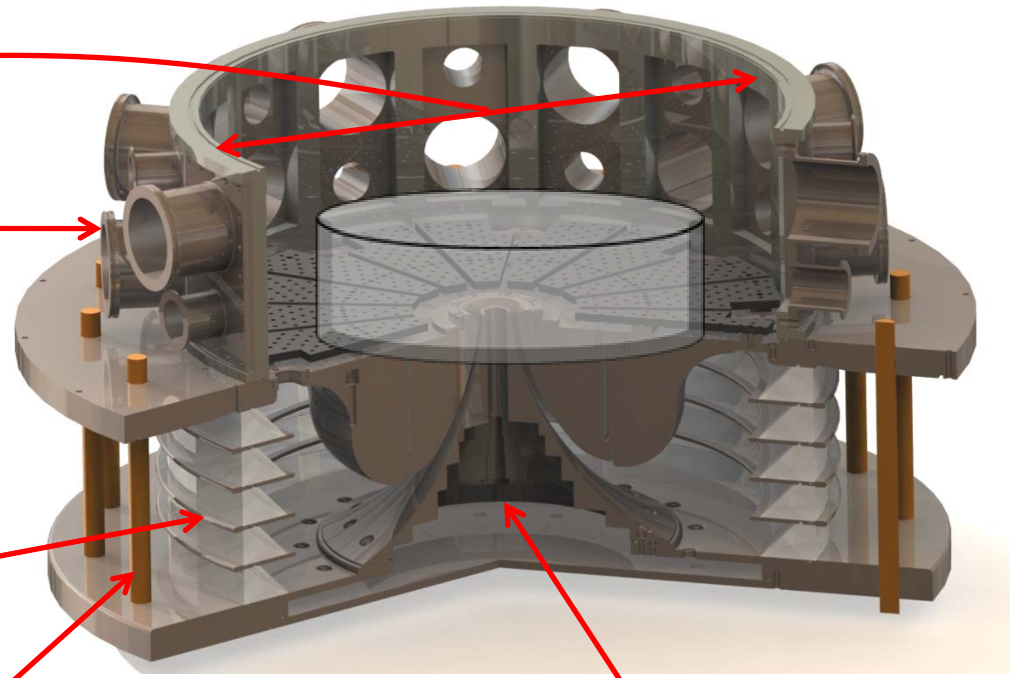

Vacuum section below MITL removes force on cathode

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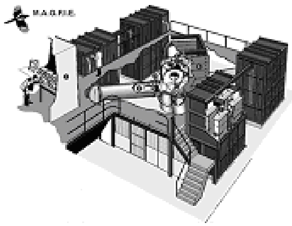

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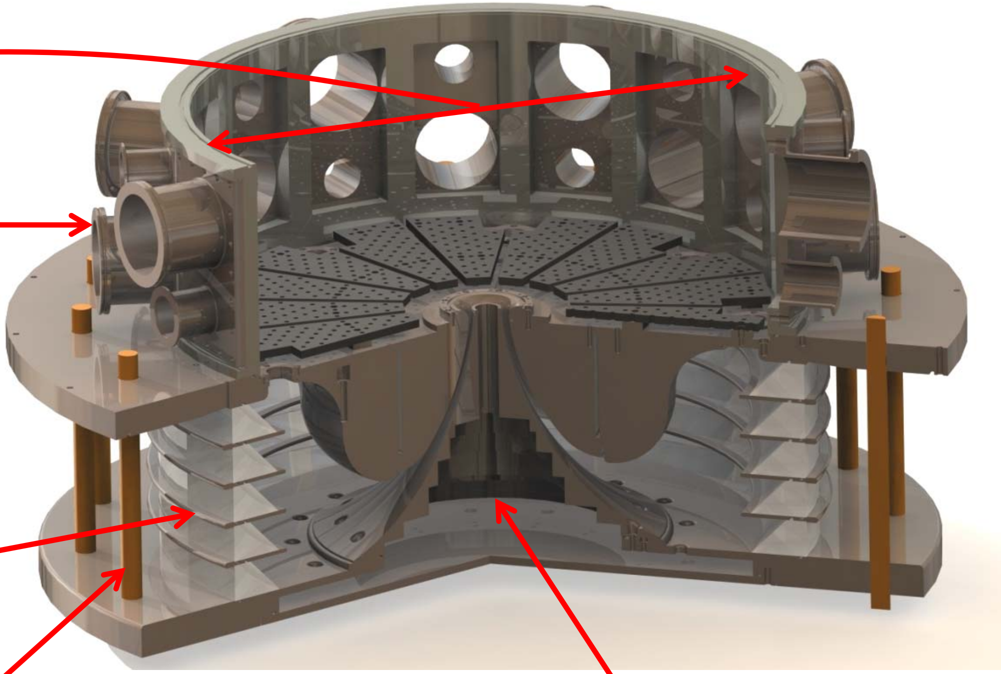

Vacuum section below MITL removes force on cathode

Anode and cathode now move ~25um

Vacuum time <1hr

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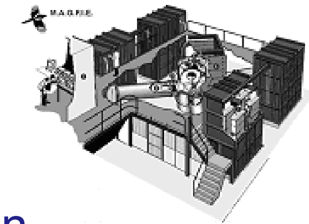


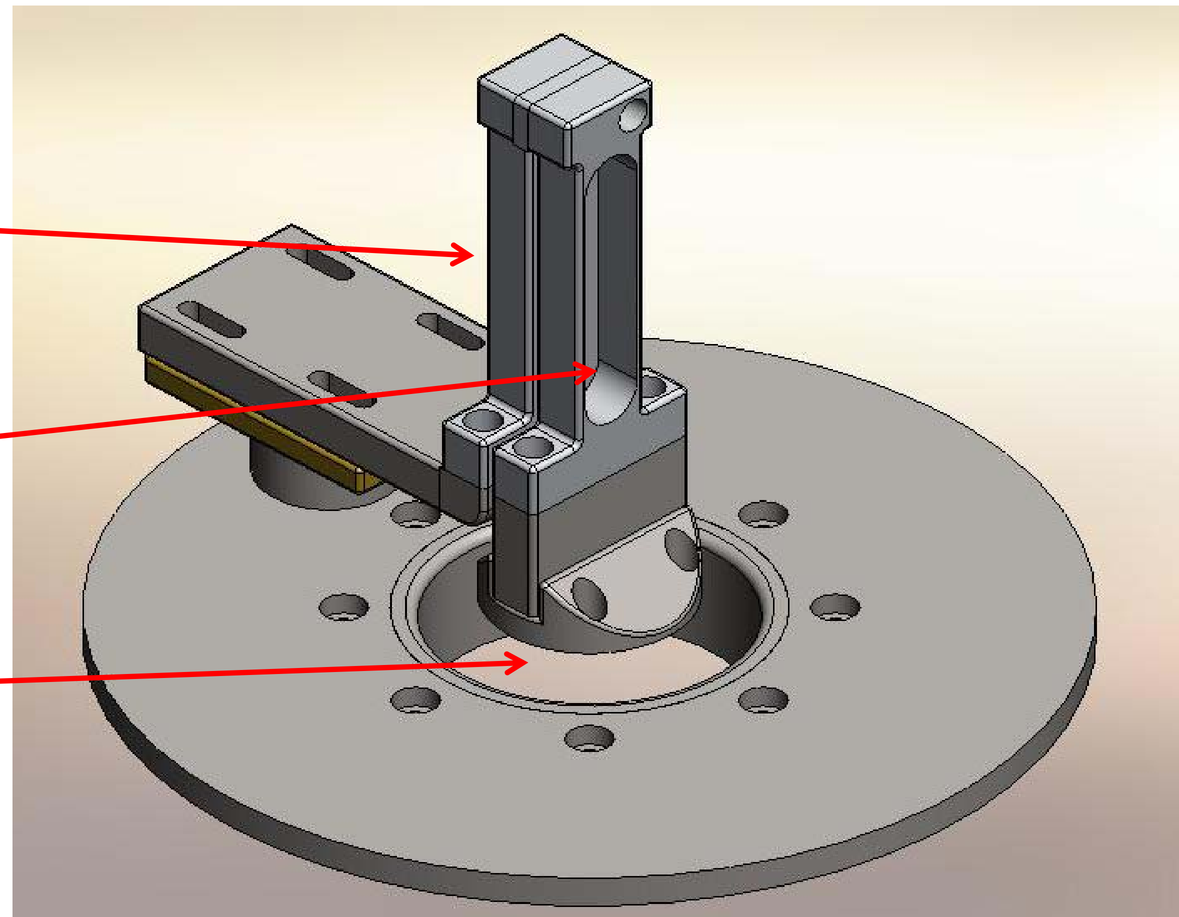
# Initial experiments: Feb 2010

- Stripline design maximises available drive pressure, and simplifies design
- Length of electrodes 40 – 80mm
- Width of electrodes 20 – 10mm → Pressures from ~30-120kBar with 1.5MA drive

15mm width for 60 kBar peak pressure

sample area up to 60x12mm on each side

cathode in throat of MITL



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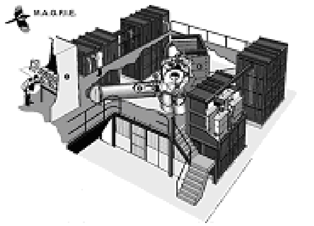


# Initial experiments: Feb 2010

Design and manufacturing issues:

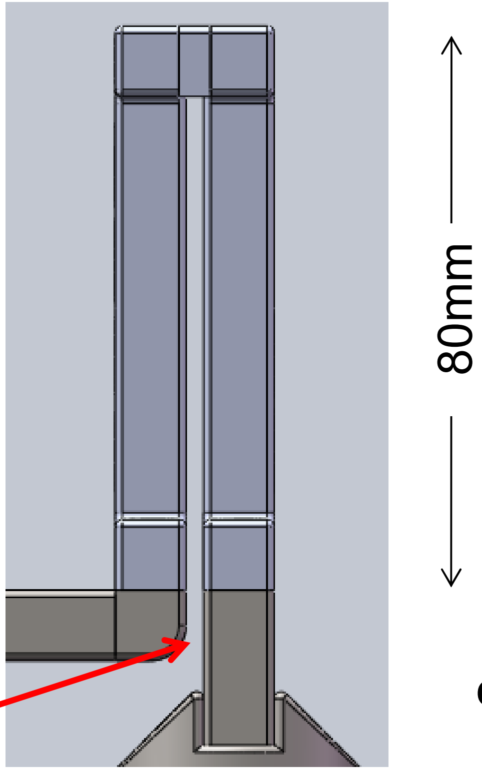
- Will the gap breakdown?
- How uniform is the drive?

EM simulations difficult due to large scale of electrodes c.f. gap in stripline...

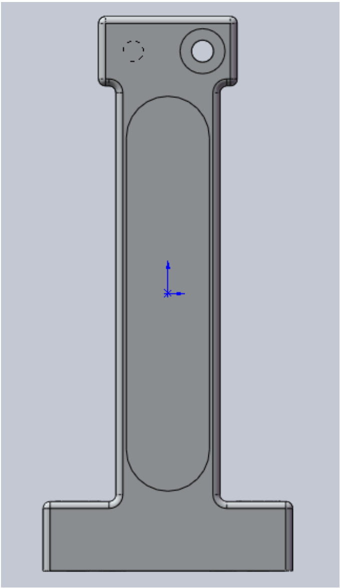
=> electrodes designed from simple assumptions and results will serve as test for code

1 – 2 mm gap in stripline

voltages ~200kV




Side view of stripline



Front view of one electrode with target area outlined

- Need to use a soft material and needs to be easily machined - Copper
- Target thicknesses 1-7mm - shocks expected after ~5mm thickness
- How to support over large areas, polish etc

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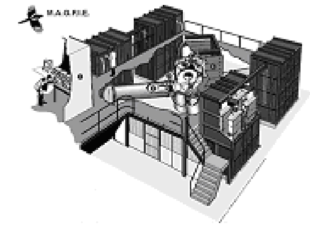
# Initial experiments: Feb 2010



Typically for shock experiments:

flatness ~5um, roughness <um via. diamond machining

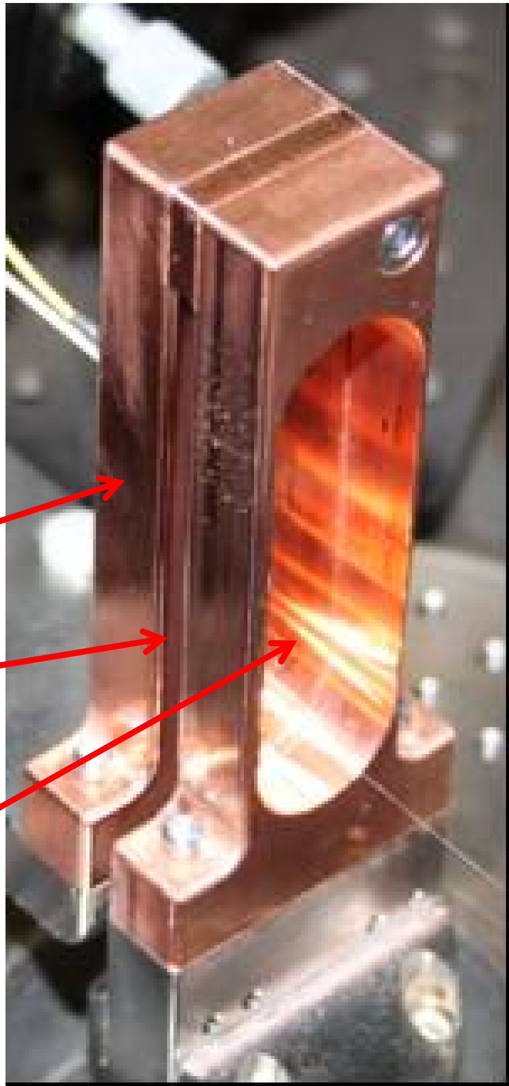
Overkill for initial experiments (and very expensive)

Tour de Force by Imperial College Instrumentation workshop

2 part ‘glued electrode’ electrode - target area and support

4 axis CNC mill allows fast production of blanks

Precision ground then hand polished – mirror finish ~5um



Return electrode

Gap (2mm)

Target area (60x17mm)

Close up of 20mm wide copper strip line in MAGPIE

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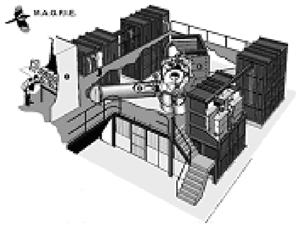
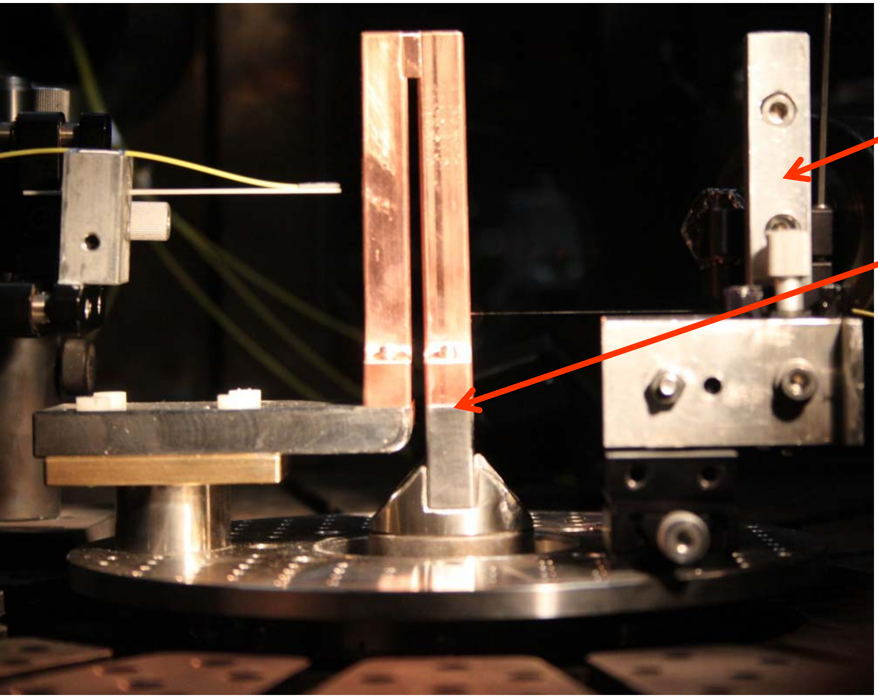
# Initial experiments: Feb 2010



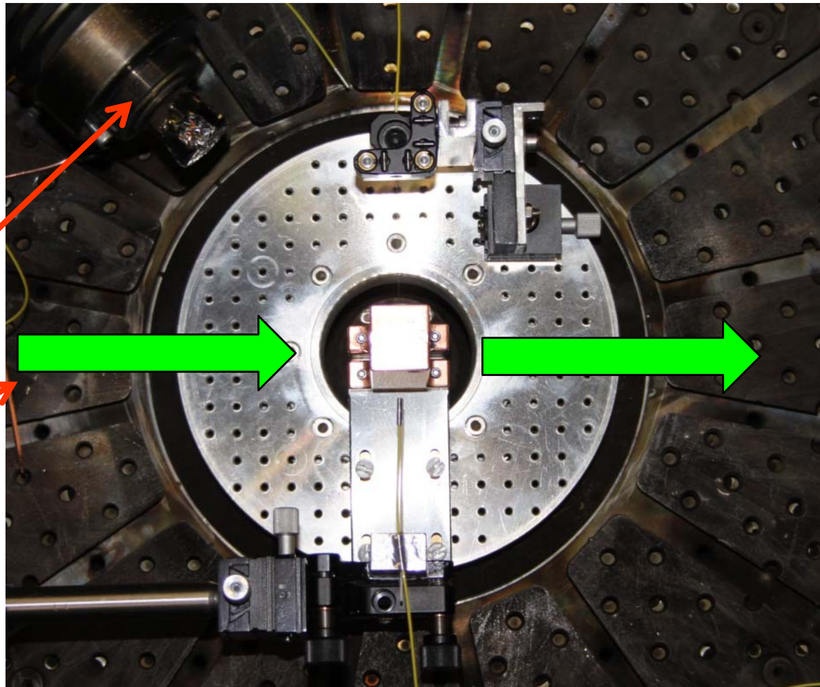


Holder for Het-V probes

Stripline mounted on break away system
to prevent damage to MAGPIE

Side view of strip line

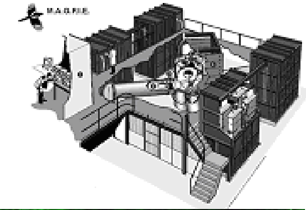
Top down view



Resistive voltage probe

Path of probing laser

½ inch armoured plate top and bottom
to 'catch' stripline (not shown)



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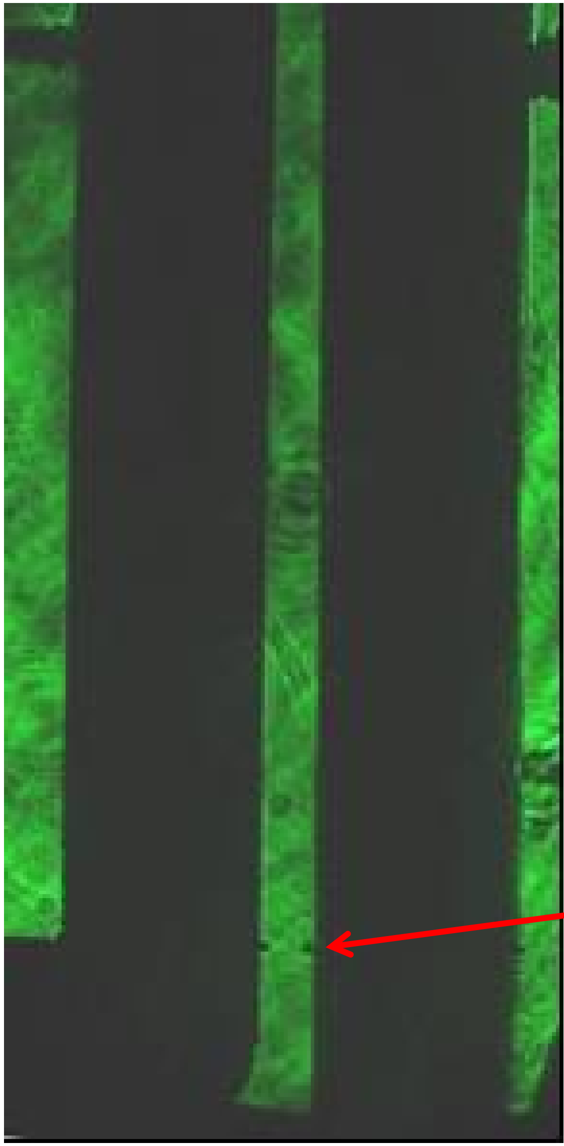


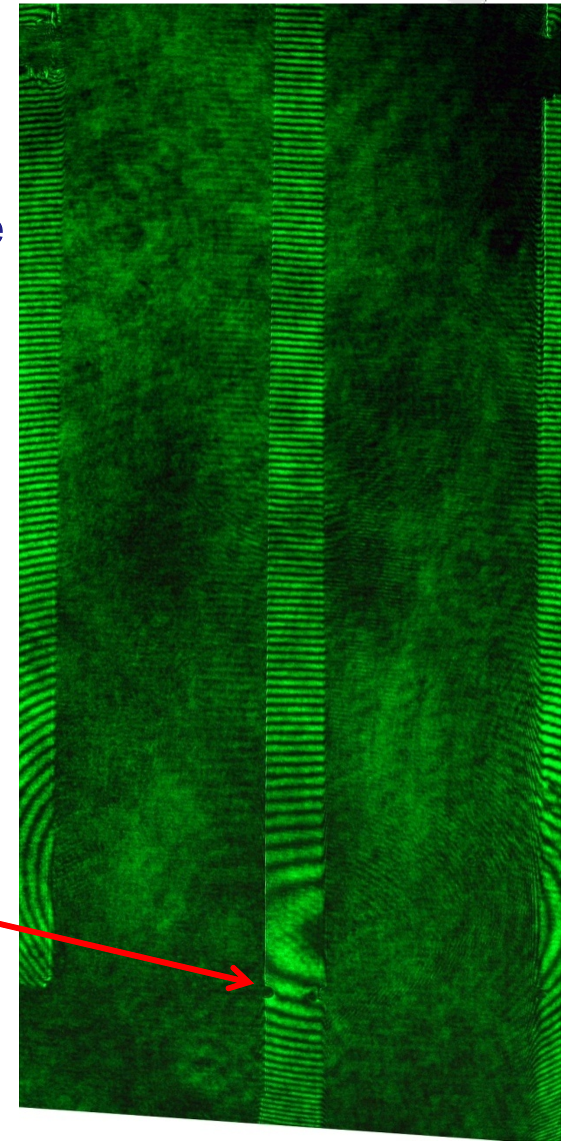
Laser shadow image @200ns

Laser probing of gap in 20mm wide stripline shows little build up of plasma ☺

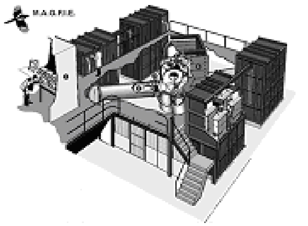
Voltage monitored across stripline also indicates no sudden breakdowns occurring

⇒ Consistent with all current flowing through strip line (should give 20-30kBar)

Only plasma present comes from join to holder – expands ~200um into gap



Laser interferogram @200ns



# Initial experiments: Feb 2010

Post shot target recovery...

80x20mm electrode, with support (left) and target plate (right)

40x20mm target plate

No target plate showed any sign of spall – consistent with isentropic compression

Target plates did prove to be good flyer plates though, vaporising diagnostics and ricocheting off armour plates ☹

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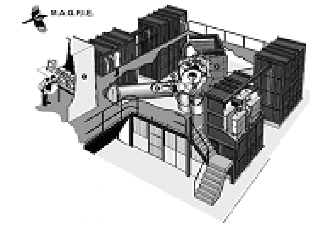
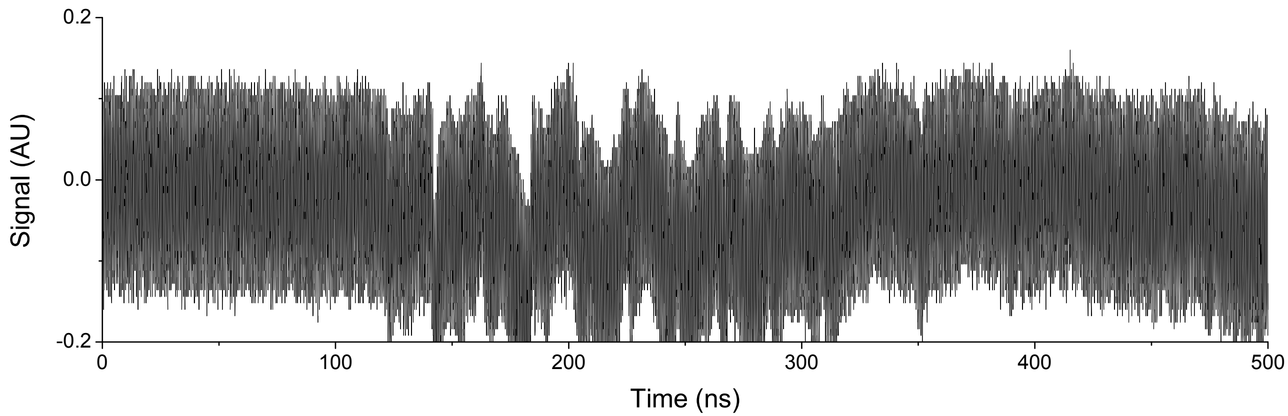


# Initial experiments: Feb 2010

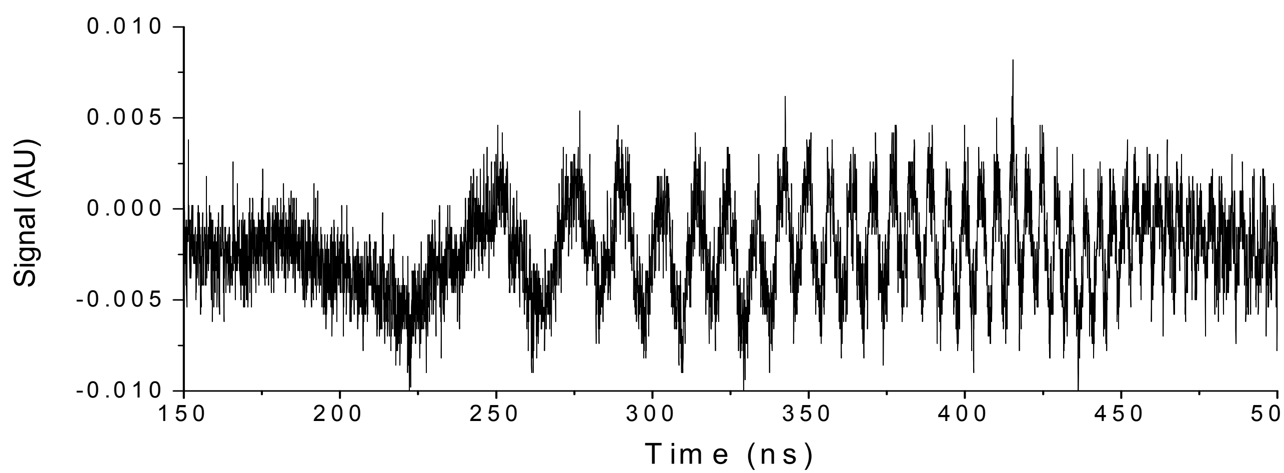
Unfortunately the Het-V probe indicated a laser fault...

... Hence we have no EOS information yet (but only 3 shots)




What we got

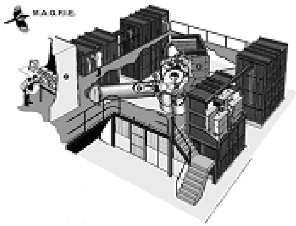
What we wish we had got




Het-V system is now in repair before next shot series

VISAR and line VISAR will be added, in addition to other diagnostics

Meanwhile, we have also examined other ways of driving shock experiments



Pulsed power can also drive large scale, well diagnosed shocks in plasma

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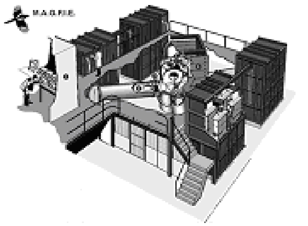


# Pulsed power driven Radiative Shocks

Radiative shock waves occur when strong heating from shocked material affects the shock front

e.g. Supernovae and imploding ICF capsules

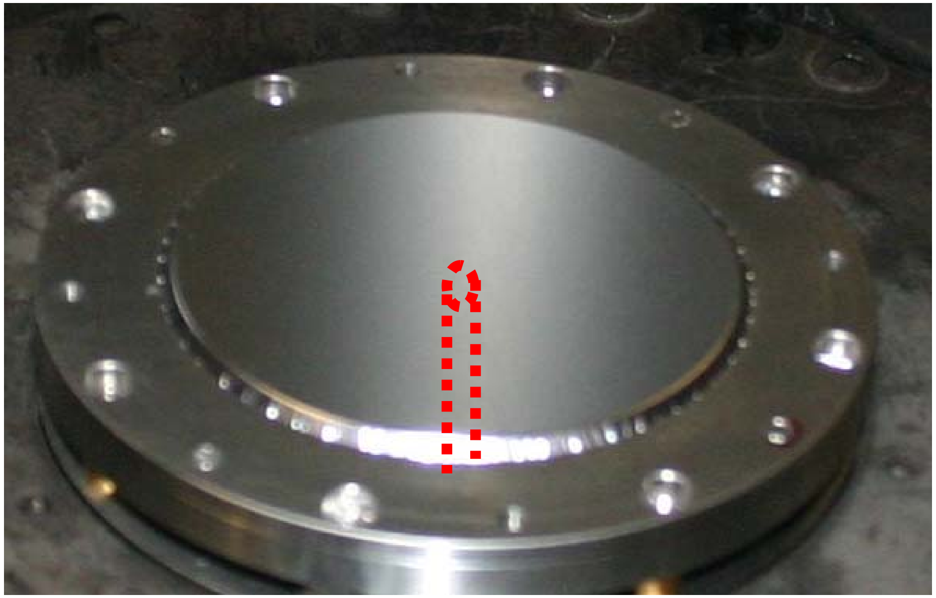
Usually experiments limited to sub mm scale

‘Radial foil’ z-pinch

6cm diameter 6um Al foil, with 3.1mm cathode underneath

mbar gas fill above foil (He - Xe)

– application of MA currents results in shock launching through gas



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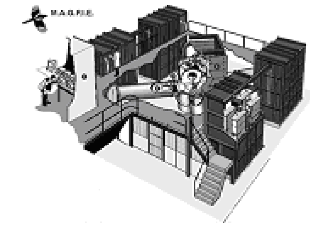
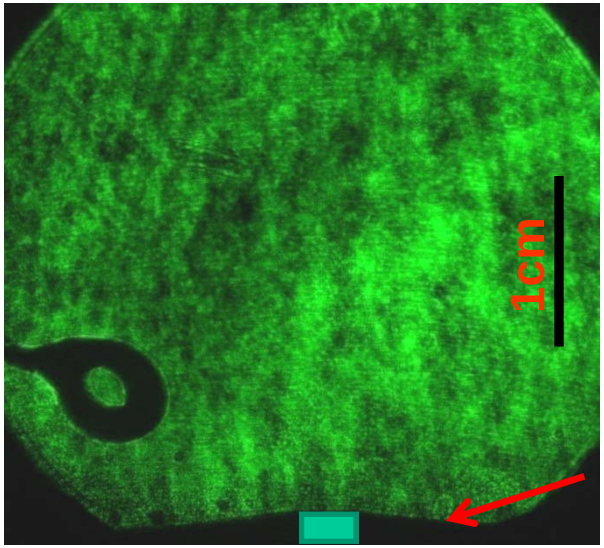
# Pulsed power driven Radiative Shocks



Background image



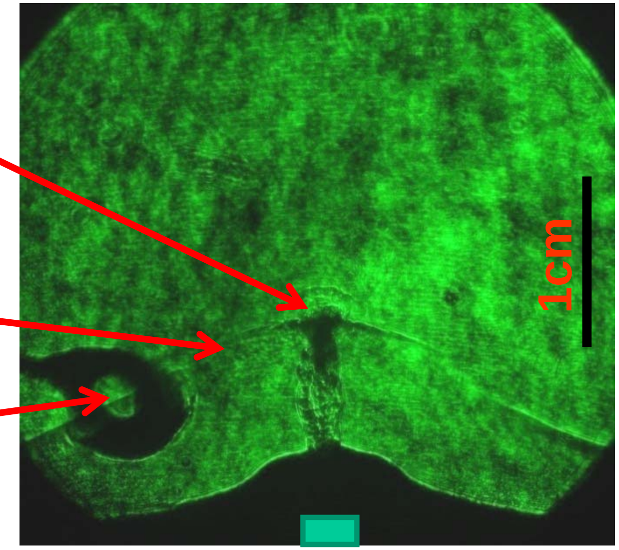

Surface of foil

Collision of plasmas ablating from foil leads to precursor column, mach stem on axis

shock wave

Magnetic probe

Laser shadow@ 263ns




5mbar Argon fill above foil

Radiative shock wave launched from across the surface of the foil and travels at ~60kms$^{-1}$

Dynamics of foil unaffected – later in time implosion occurs as before

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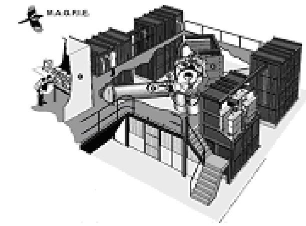
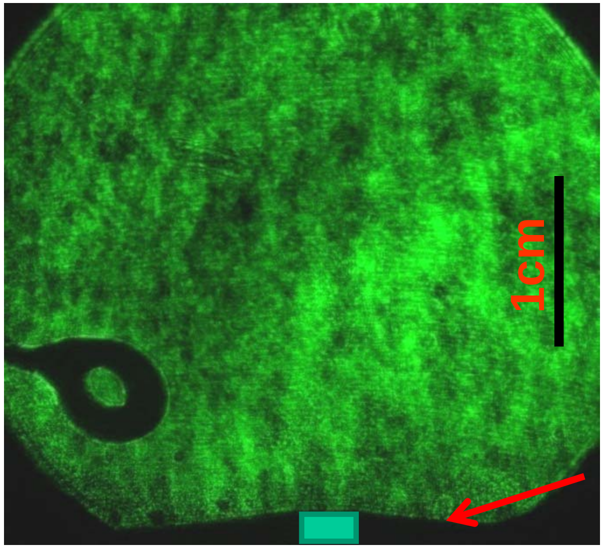


# Pulsed power driven Radiative Shocks

Background image

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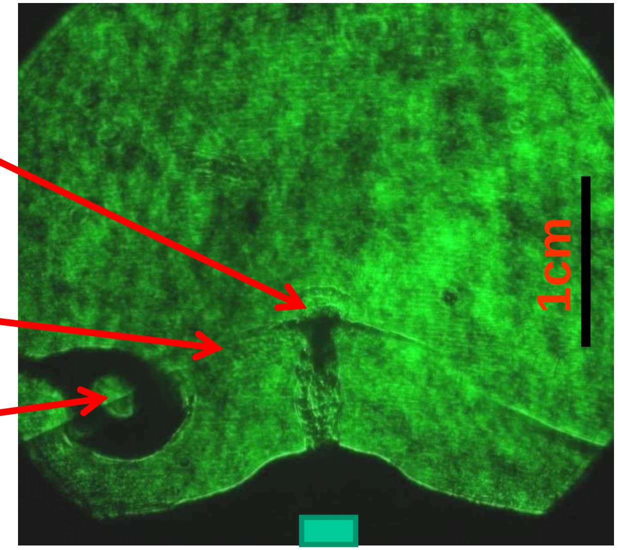


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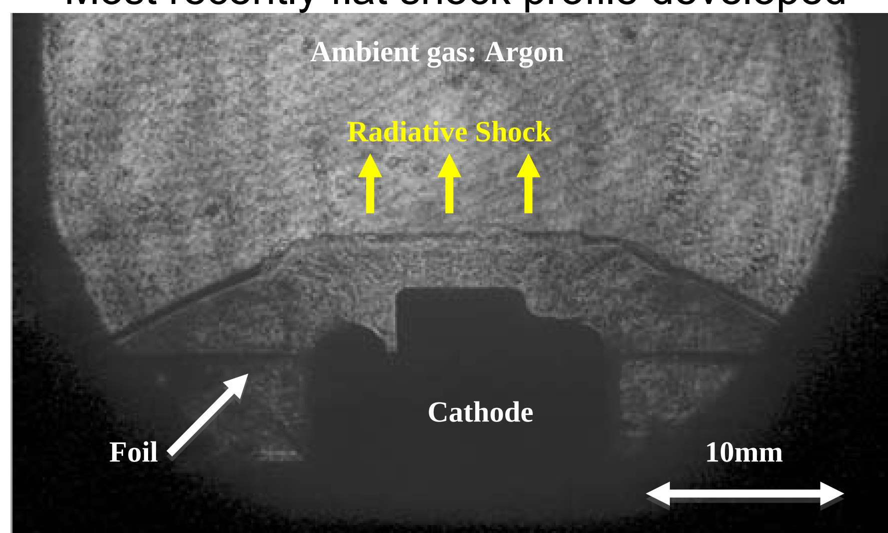
Dynamics of foil unaffected – later in time implosion occurs as before

Most recently flat shock profile developed



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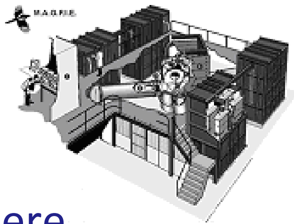
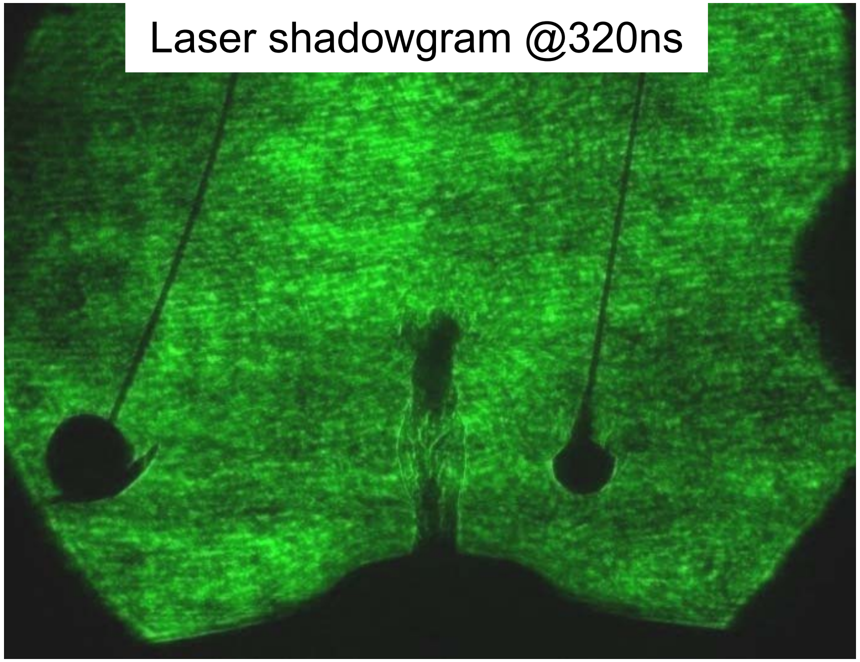
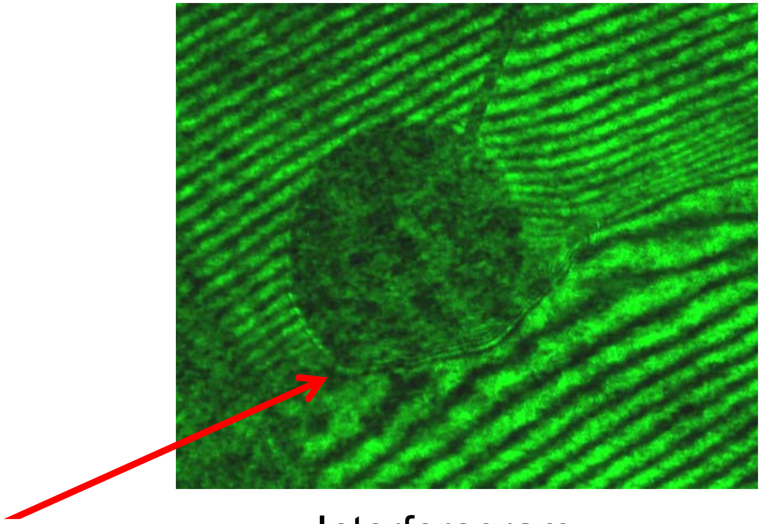
# Pulsed power driven Radiative Shocks



5mbar Argon fill above foil, 2mm stainless steel sphere and 3mm polystyrene sphere



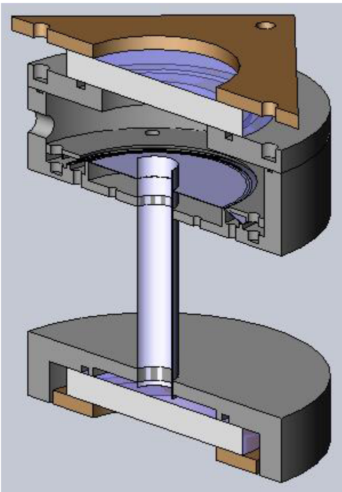



Bow shock

Interferogram

Whatever process is responsible, the large scale shock wave allows extremely well diagnosed interaction experiments.

Now exploring experiments with shock waves that should interact with the targets, and experiments in convergent geometries



Configuration for cylindrical radiative shock experiment

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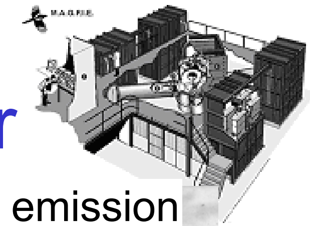
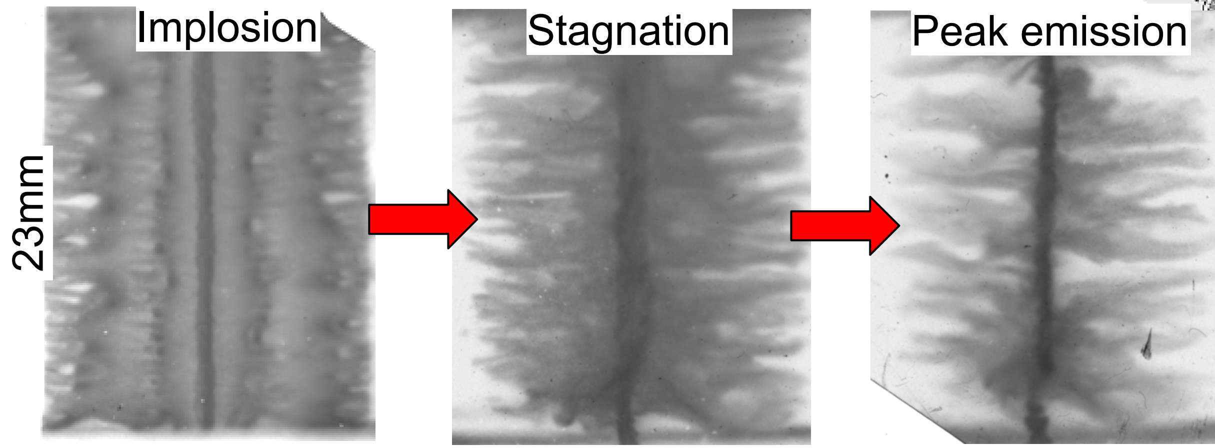
# Using plasma generated by pulsed power





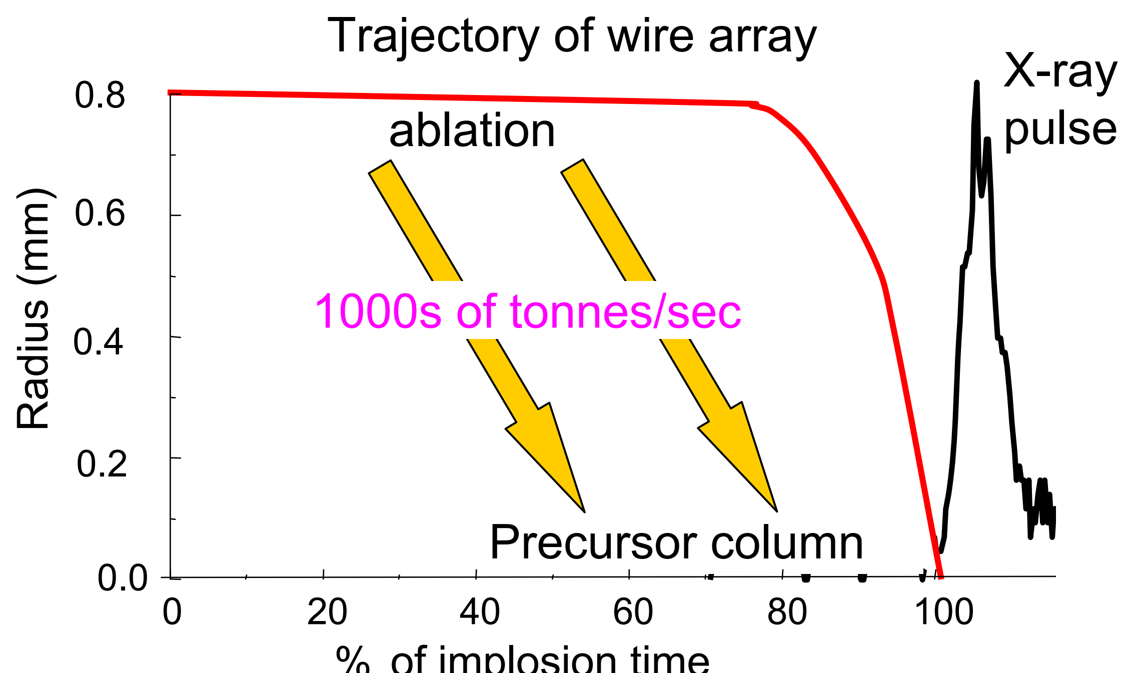

At MAGPIE we pioneered understanding of the implosion of wire array z-pinches

The majority of the evolution of a wire array is dominated by the gradual ablation of the wires into dense, warm plasma

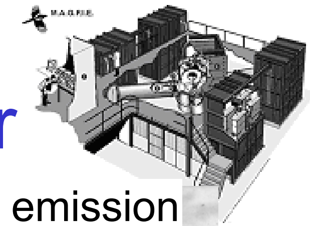
$n_i \sim 10^{16} - 10^{17}\ cm^{-3}$

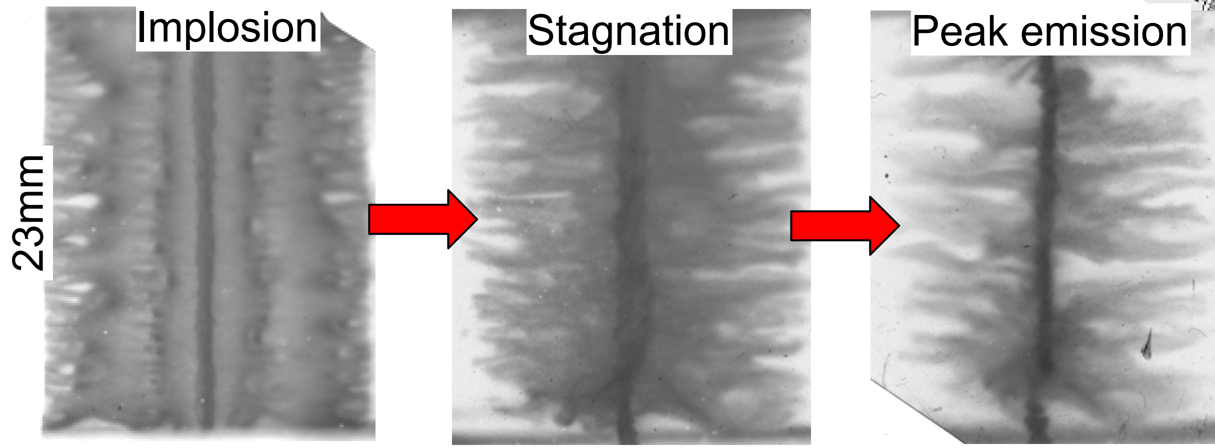
$T_i \sim 30eV$

velocity $\sim 150 kms^{-1}$



# Using plasma generated by pulsed power



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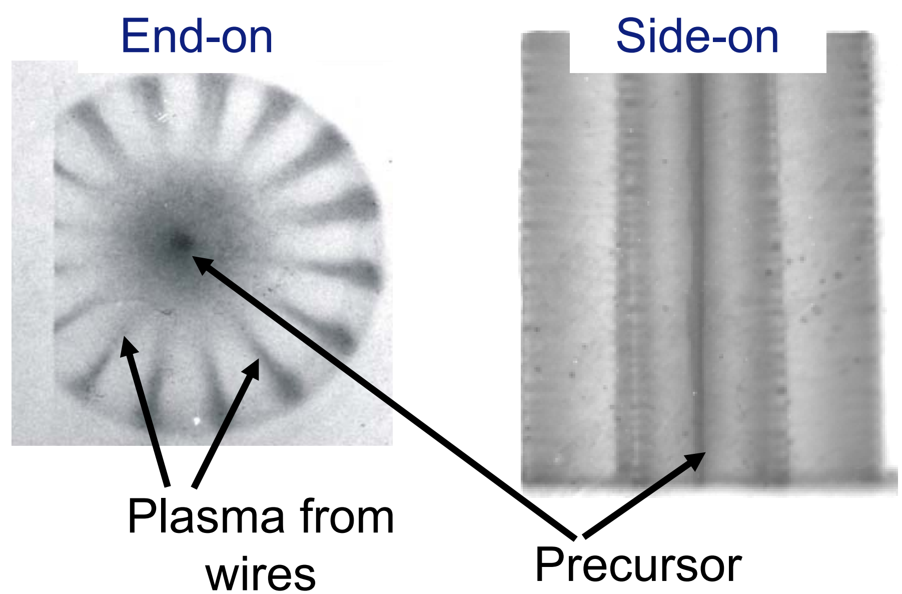
$T_i$ ~30eV

velocity ~ $150 kms^{-1}$



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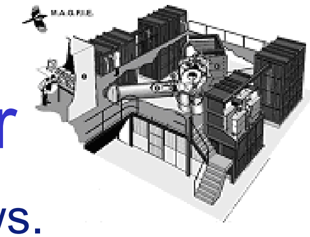
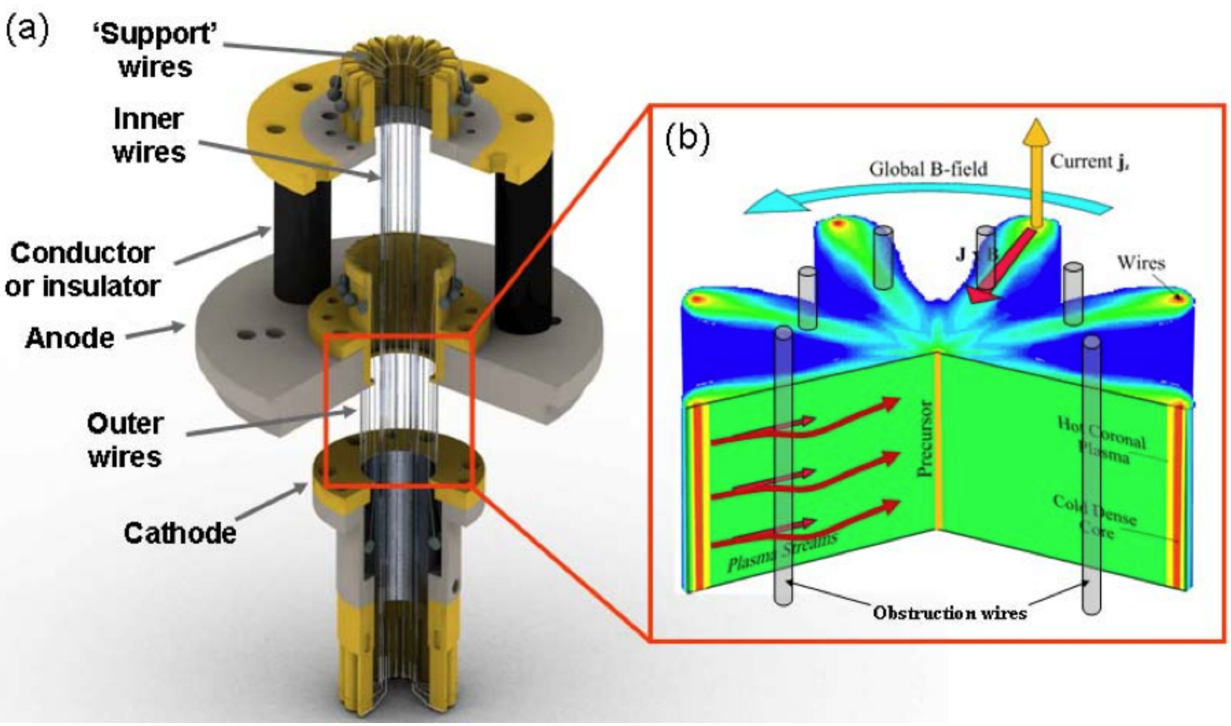
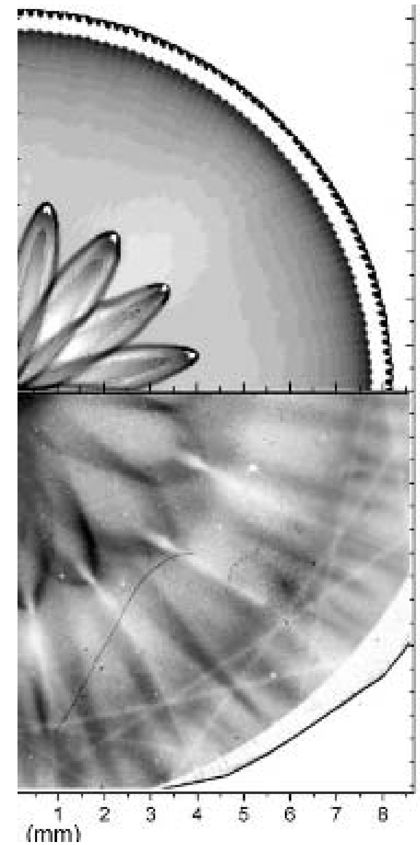



# Using plasma generated by pulsed power

We can place targets in the flow to examine bow shocks in high Mach flows.




Experimental set up




End on emission images(bottom) and simulations (top)

In experiments later this year we will make a planar flow of plasma that projects into open space – vastly simplifying experimental set up and diagnostic access

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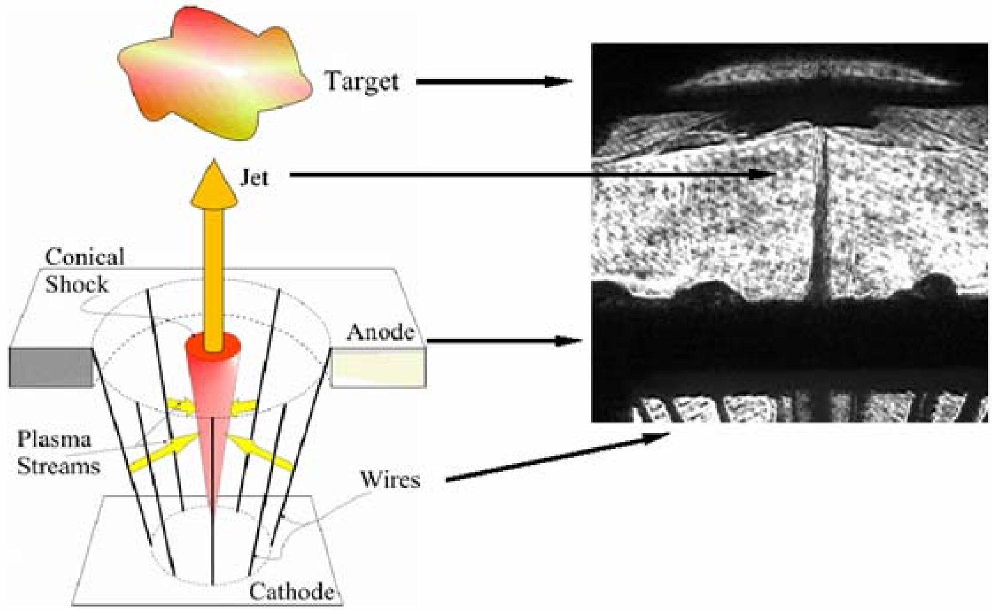
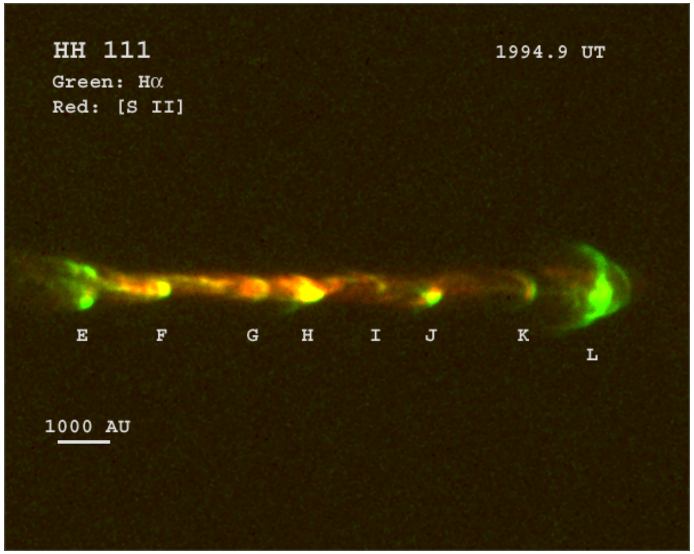
# Using a plasma jet to apply high pressures




Using a conical array results in ablated plasma being redirected out of the array as a high mach number plasma jet

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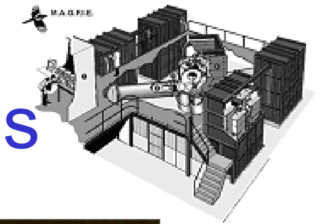
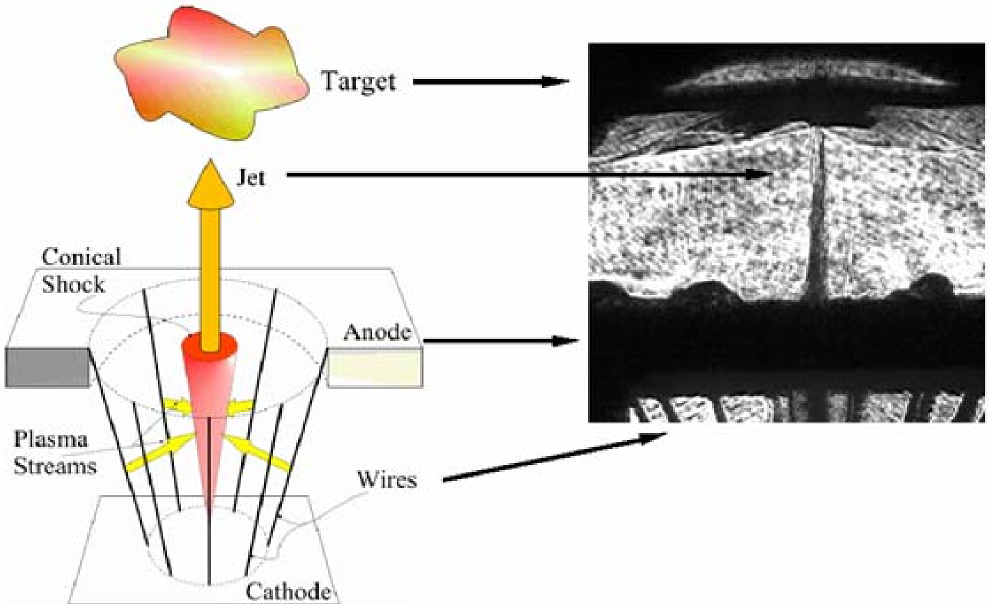
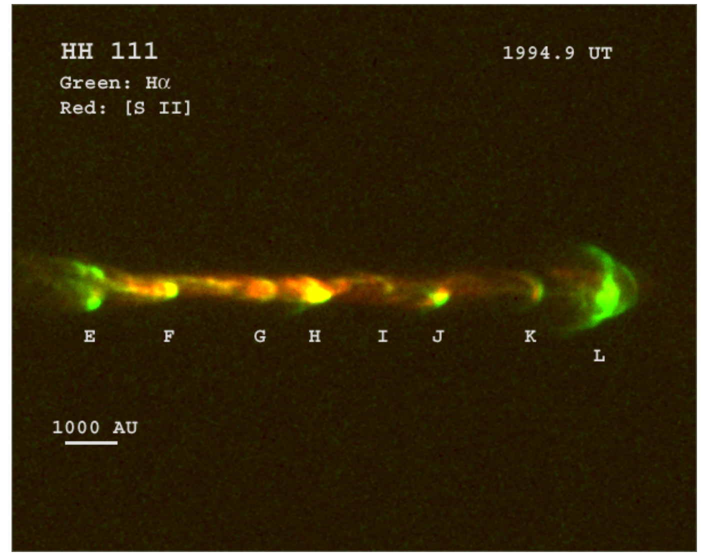
# Using a plasma jet to apply high pressures





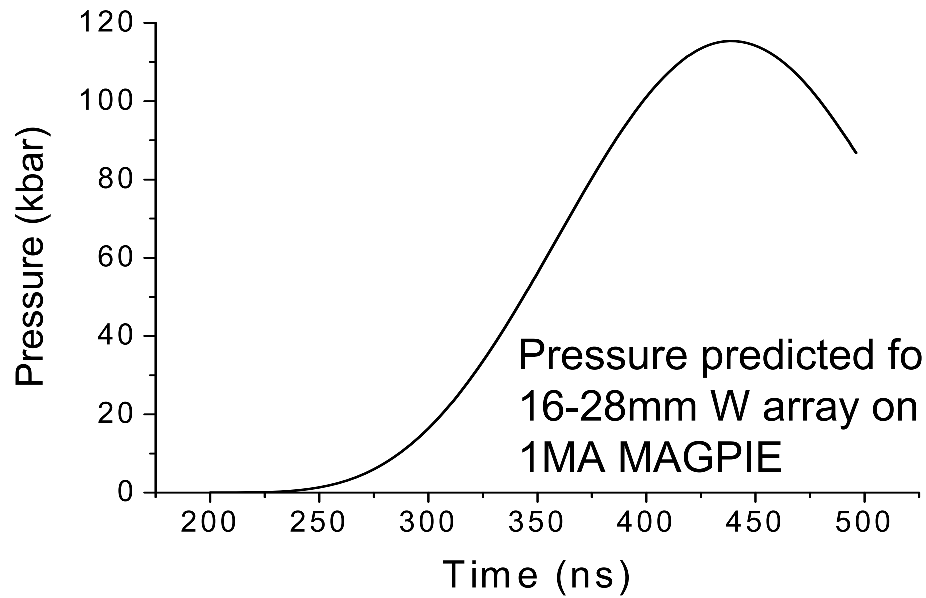

Using a conical array results in ablated plasma being redirected out of the array as a high mach number plasma jet

Ablation as rocket model

$$\frac{dm}{dt} = \frac{1}{v_{abl}} (I \wedge B) = \frac{\mu_o I^2}{4\pi . R v_{abl}}$$

Pressures gradually rising >>100 Kbar

Can use jet to apply high pressures



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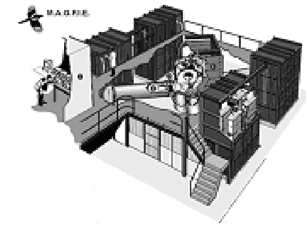
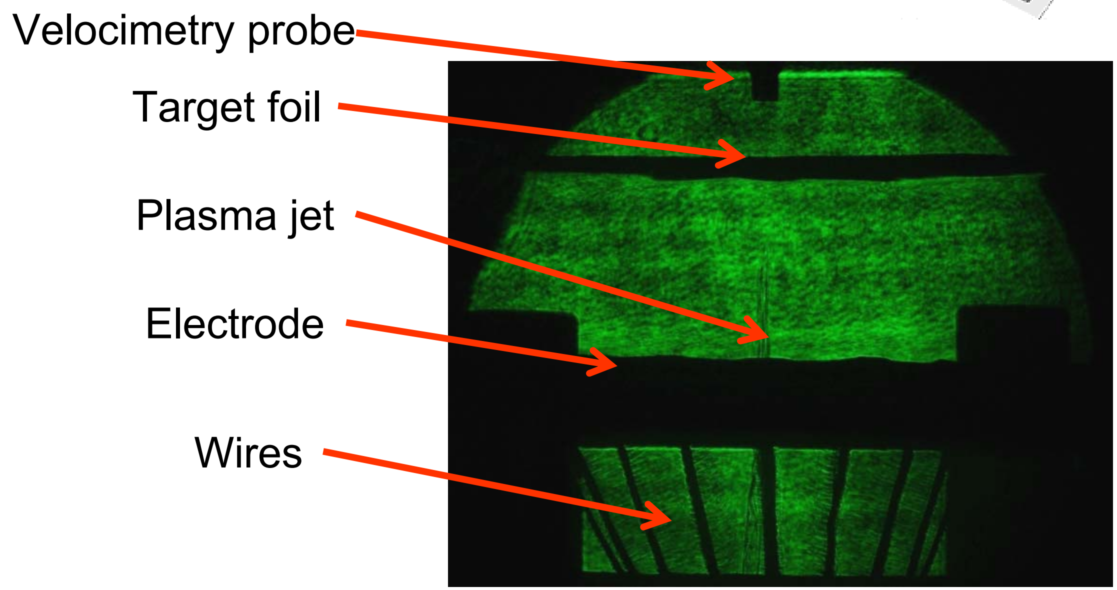
# Initial plasma drive experiments

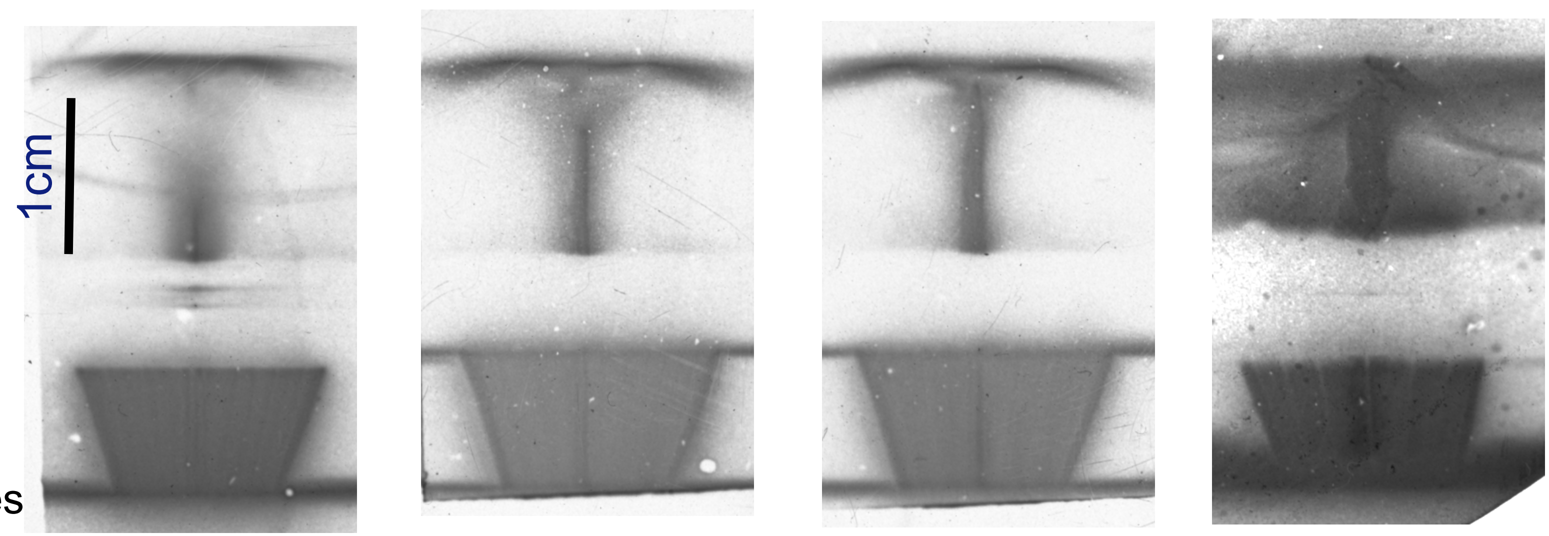


- It takes time for the ablating plasma to form a jet
- Before arrival of jet ablated plasma gathers on foil
- Once formed jet speed 200kms$^{-1}$
- Arrival of jet launches shocks




Laser probing image @ 264ns

XUV images




165ns 195ns 215ns 334ns

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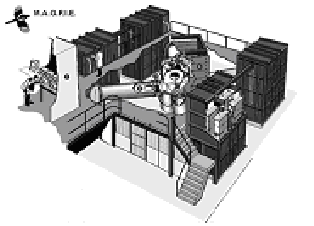
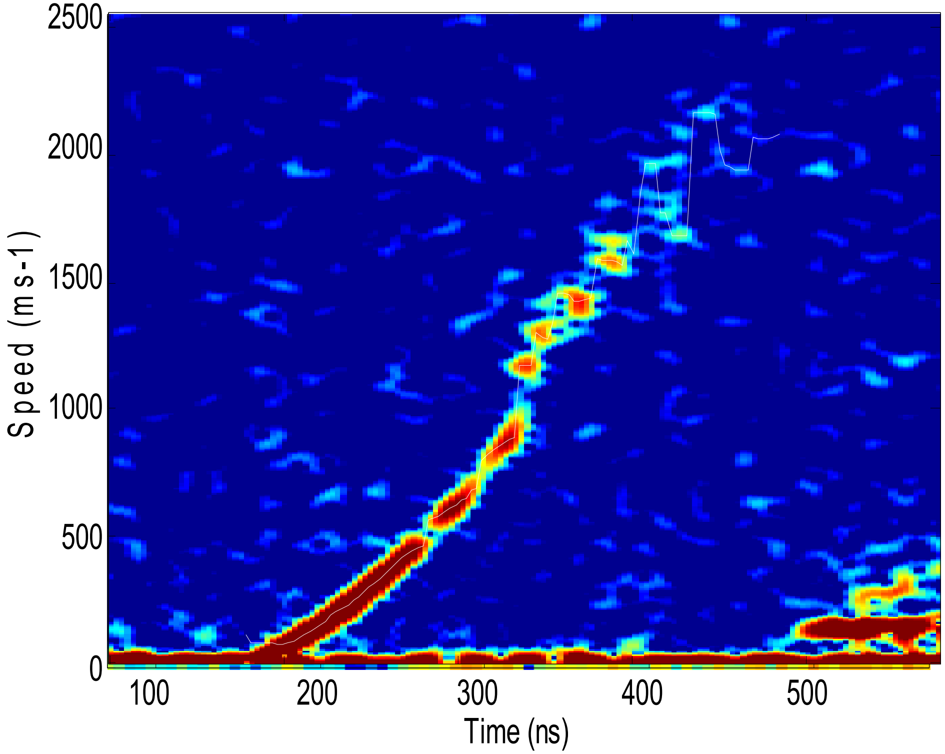
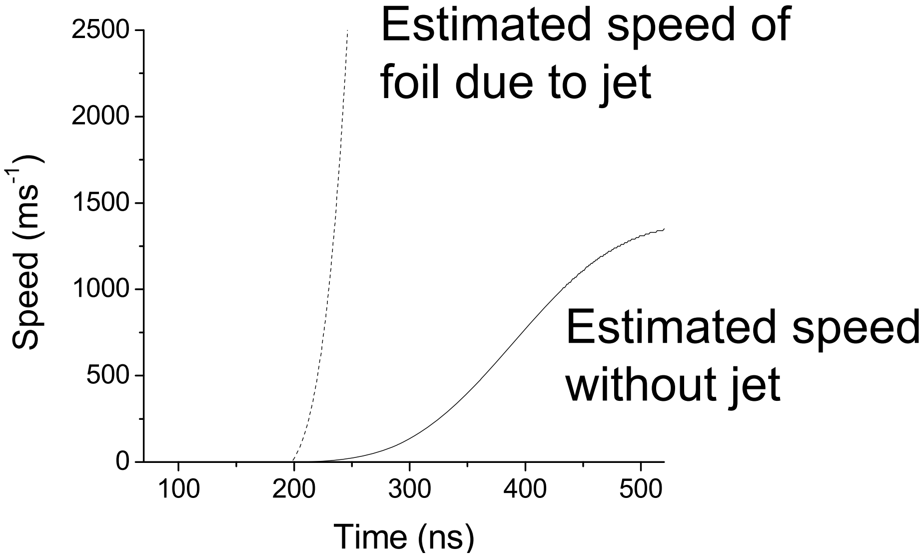
# Initial plasma drive experiments






Initial acceleration is ~6x10$^{9}$ ms$^{-2}$ and remains constant until ~280-300ns

Corresponds to ~2KBar pressure

After 280ns, small 'discrete' readings of higher velocities

Initial acceleration is due to plasma ablating from array reaching target foil before jet forms

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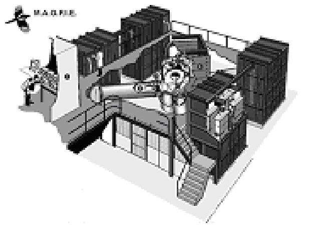
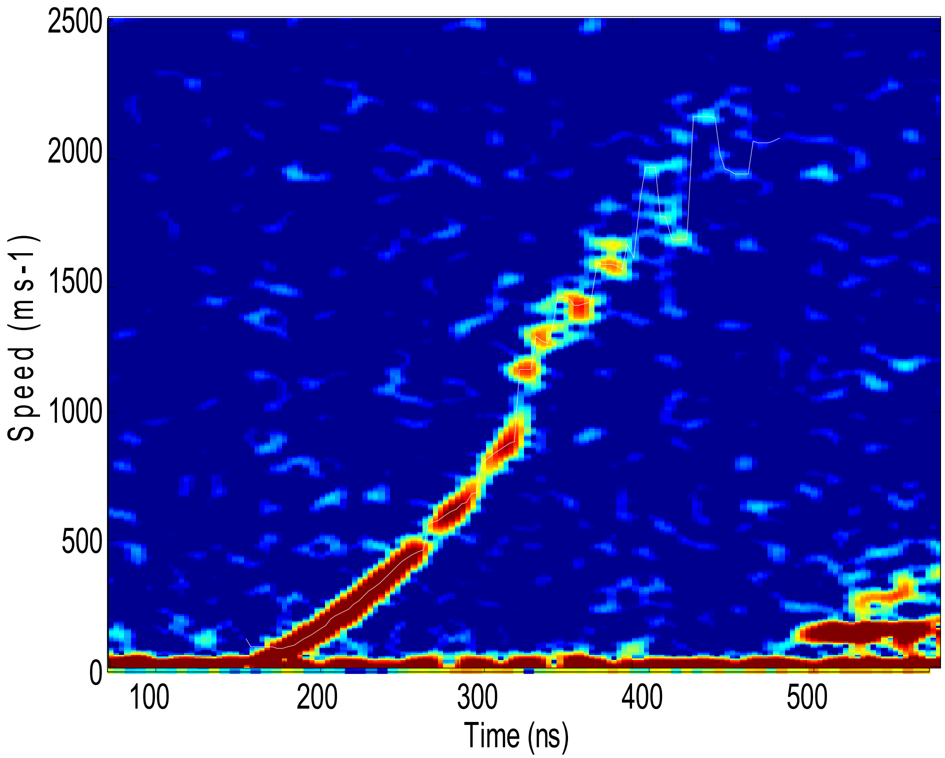
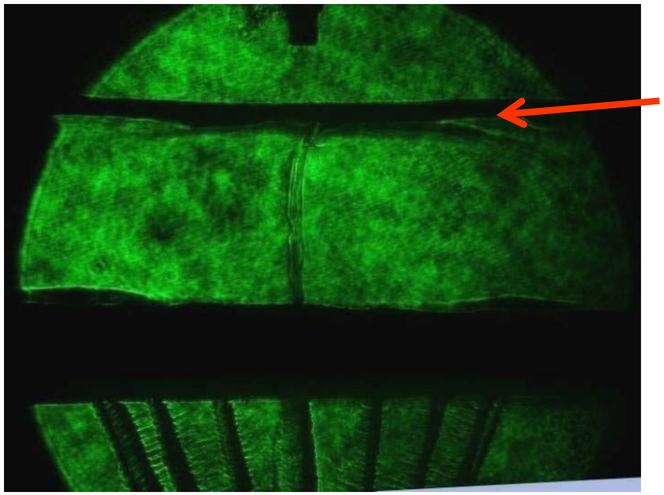
# Initial plasma drive experiments






287ns after start of current

Initial acceleration is ~6x10$^9$ ms$^{-2}$ and remains constant until ~280-300ns

Corresponds to ~2KBar pressure

After 280ns, small 'discrete' readings of higher velocities

Initial acceleration is due to plasma ablating from array reaching target foil before jet forms

Arrival of jet launches shock through foil destroying back surface

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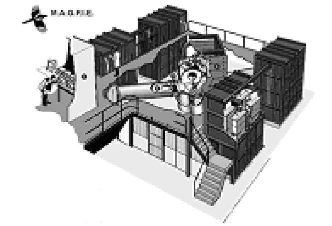
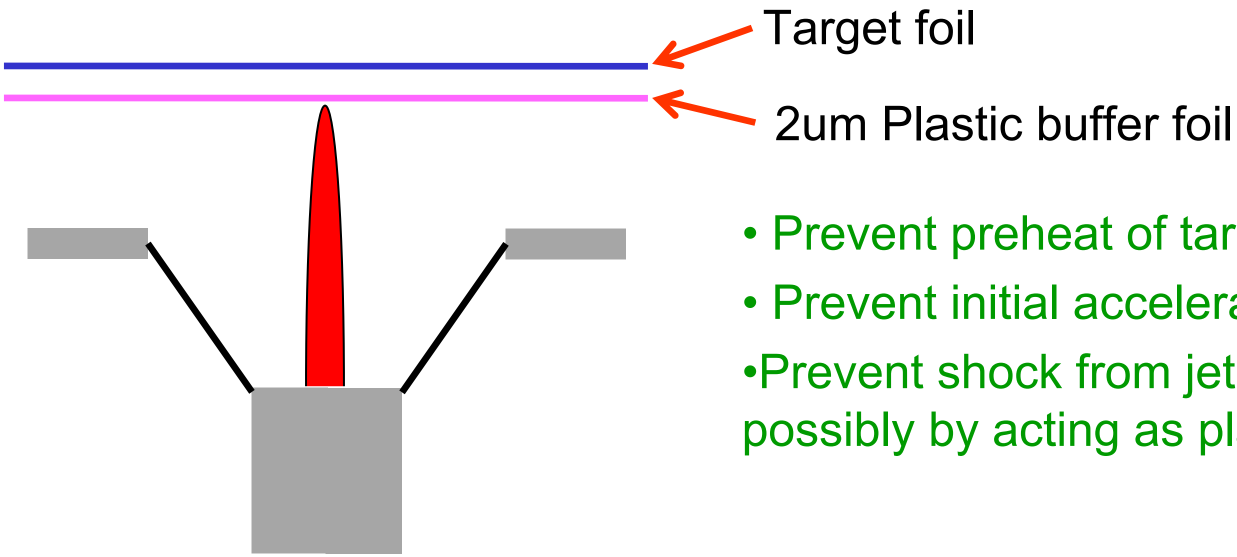


# Initial plasma drive experiments




- Prevent preheat of target foil
- Prevent initial acceleration of foil
- Prevent shock from jet destroying target, possibly by acting as plasma reservoir

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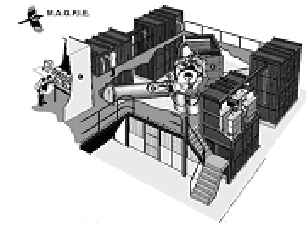
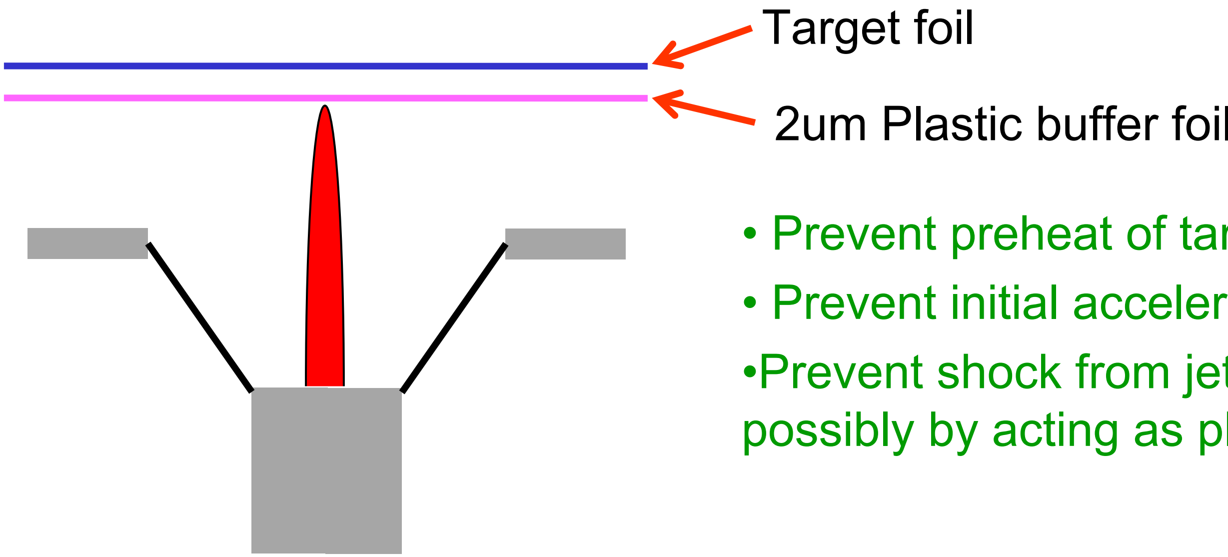


# Initial plasma drive experiments

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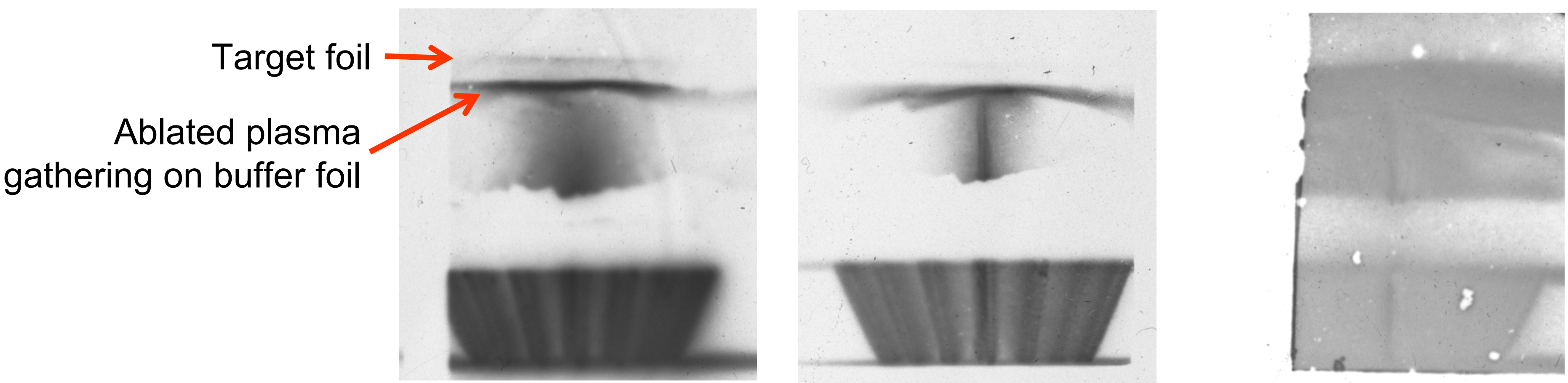

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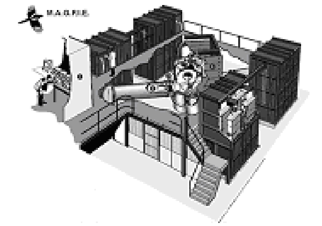
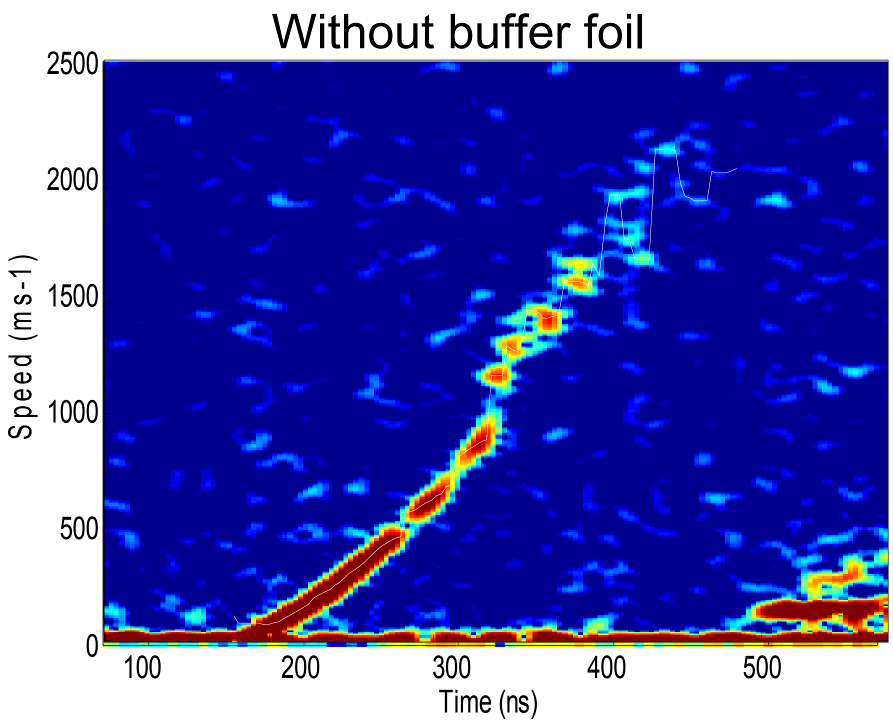
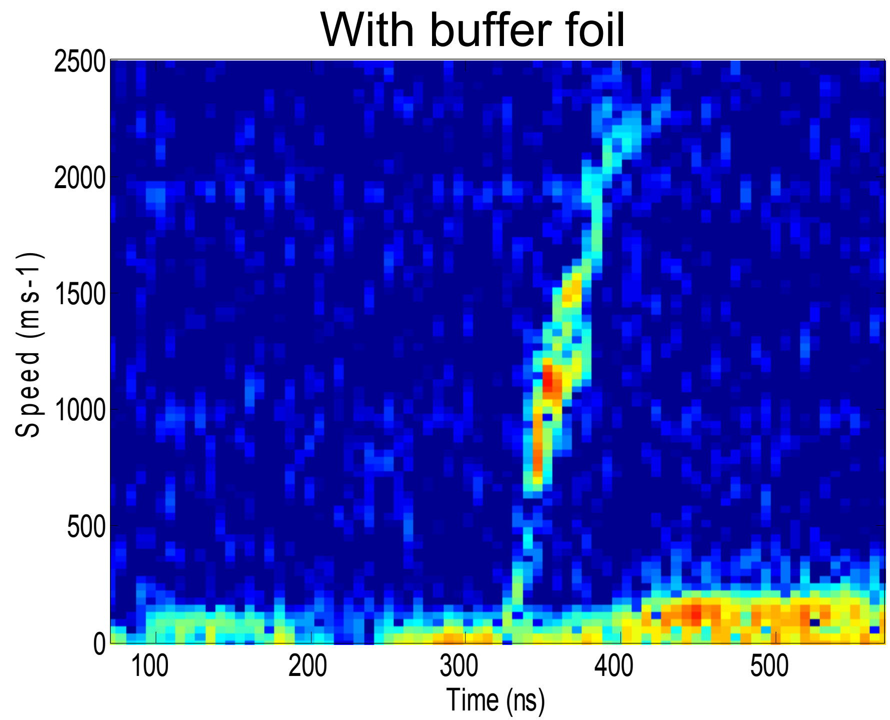
# Initial plasma drive experiments





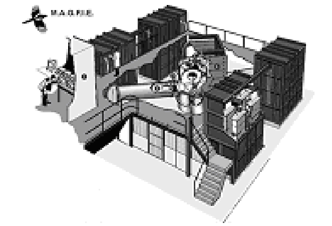

With buffer foil, no acceleration due to ablated plasma is observed

Rapid acceleration observed once jet arrived at foil

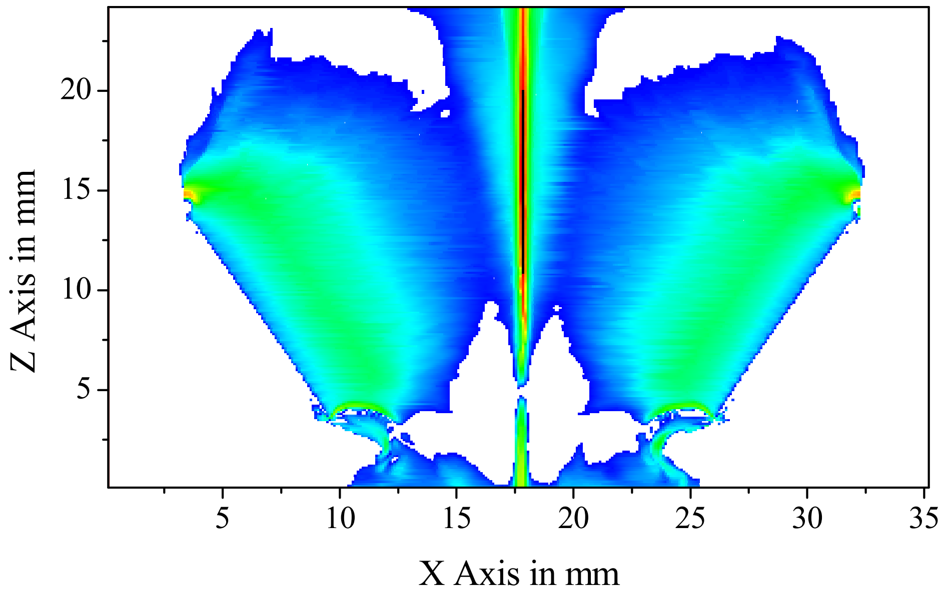
Acceleration ~ $40 \times 10^9$ $ms^{-2}$ corresponds to 14KBar

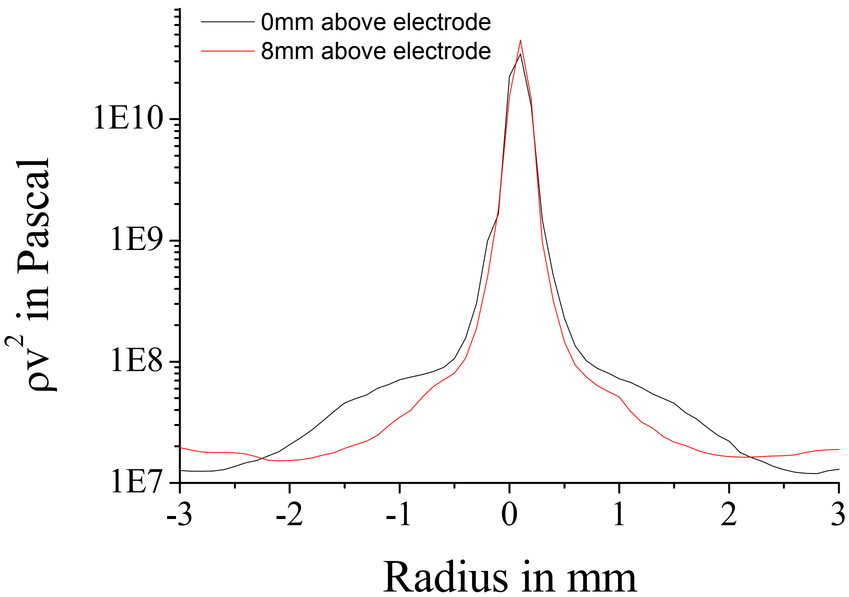
Still somewhat lower than expected? Why?

# Initial plasma drive experiments



2D MHD GORGON simulations




Jet is too narrow

1mm outside jet, pressure reduced by 2 orders

Buffer foil could also reduce pressure

Future experiments will use line and 2D imaging VISAR to examine profile of jet

Then we will examine ways to launch plasma projectile to drive shocks in targets

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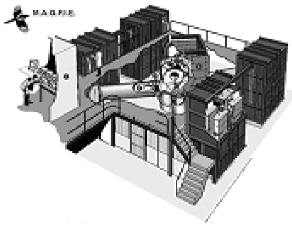

# Development of pulsed power driven shock physics experiments in next 3 years

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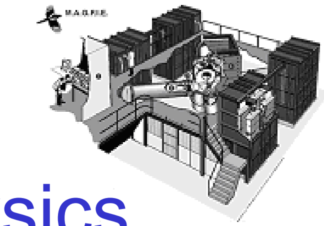


# The MACH generator – A new pulsed power source for shock physics

MAGPIE is very busy

need for small, fast turn around machine for dedicated to shock physics experiments, especially when developing new ideas

**M**ega

**A**mpere

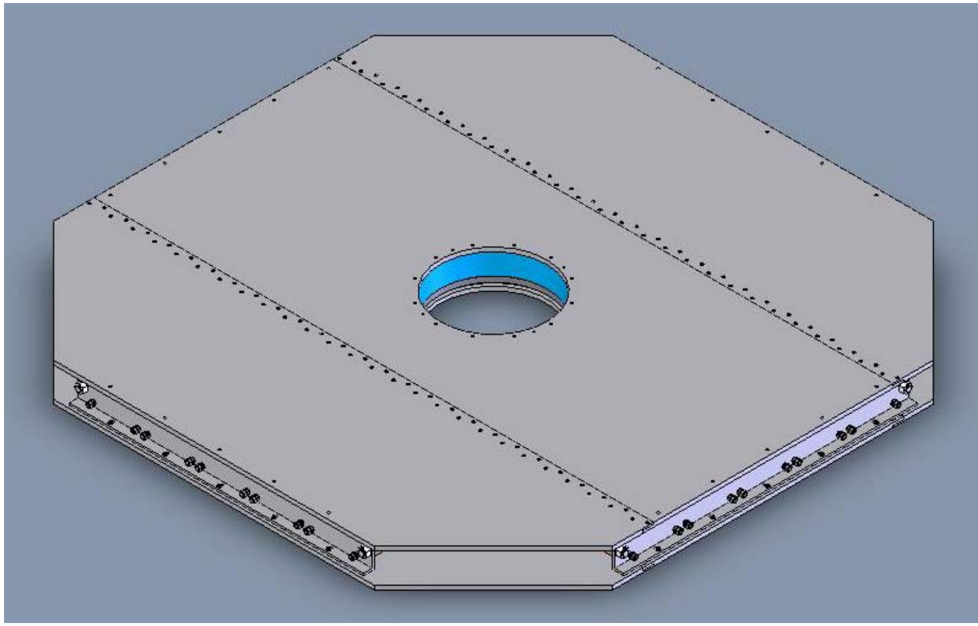
**C**ompression **&**

**H**ydrodynamics

In house facility being developed by Rick Spielman of Ktech for the ISP

•Low maintenance – no oil, no water, no SF6 gas (light, almost portable – maybe put at end of beam lines)

• Pressure drive can be shaped



2.5m LTD cavity being built by Ktech

Ktech CORP.

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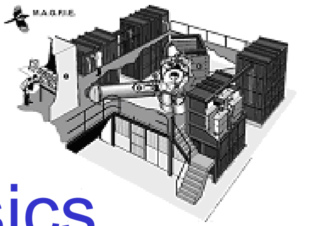
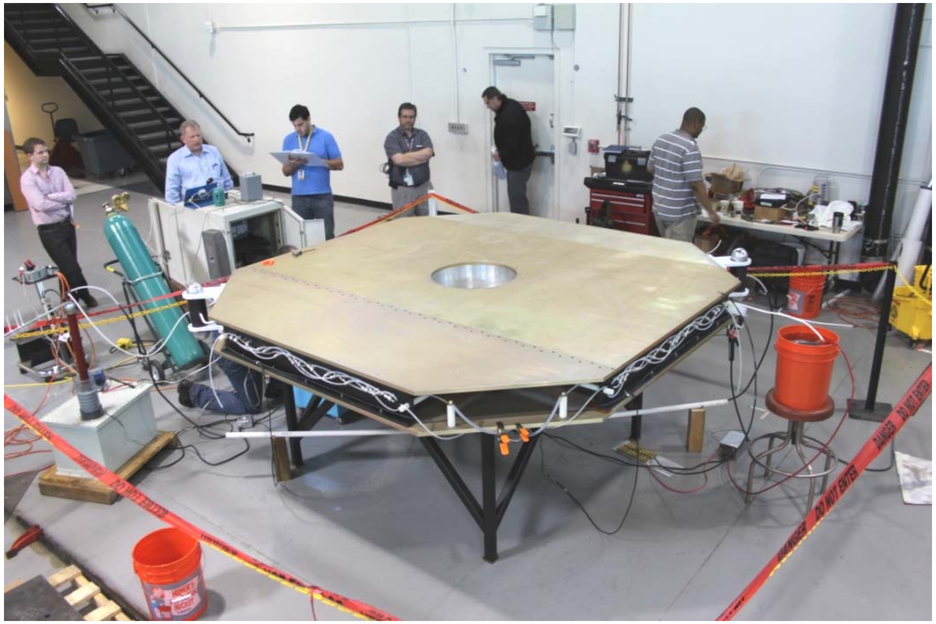
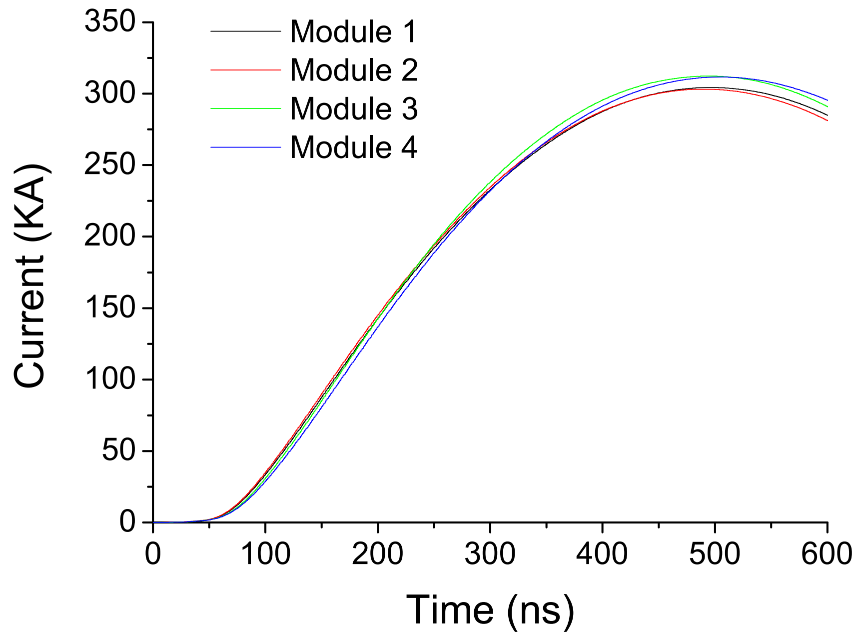


# The MACH generator – A new pulsed power source for shock physics






70kV charge demonstrates 1.2MA, 260ns pulse into resistive test load

With 100kV, and inductive load this will give 2MA ~200ns risetime expected

MACH is complete and shipping to Imperial College

Generator can be stacked: Add in series for more voltage (bigger targets)

Add in parallel for more current (pressure)

In future more generators – 2 series, 2 parallel = 4MA current, ~ Mbar isentropic drives

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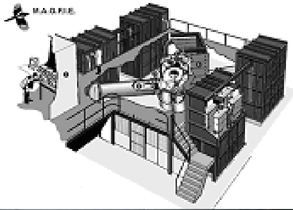
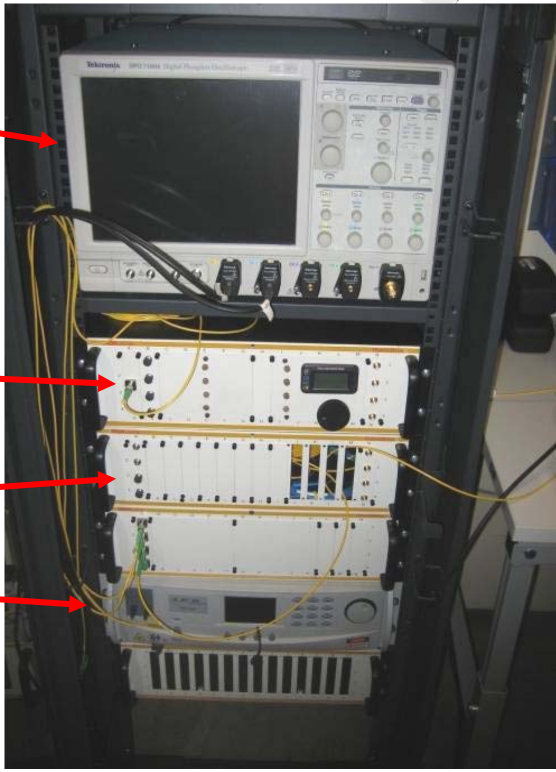


# Diagnostics Development

**Fibre based diagnostic systems**

- 4 channel Heterodyne Velocimetry system has been developed with help from AWE
- A fibre based interferometer is also being developed to monitor formation of plasma around electrodes of stripline
- A 4 channel fibre based point VISAR is being planned to accompany the laser



16Ghz scope

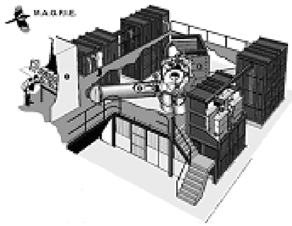
Het-V system

Interferometer

2W Fiber laser

The Het-V and interferometry system is all fiber based and mounted on a wheeled 19inch rack for portability.

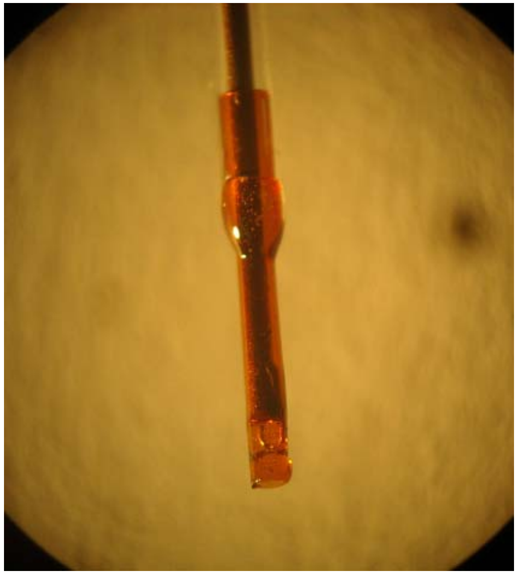
# Diagnostics Development



Line VISAR system is in development

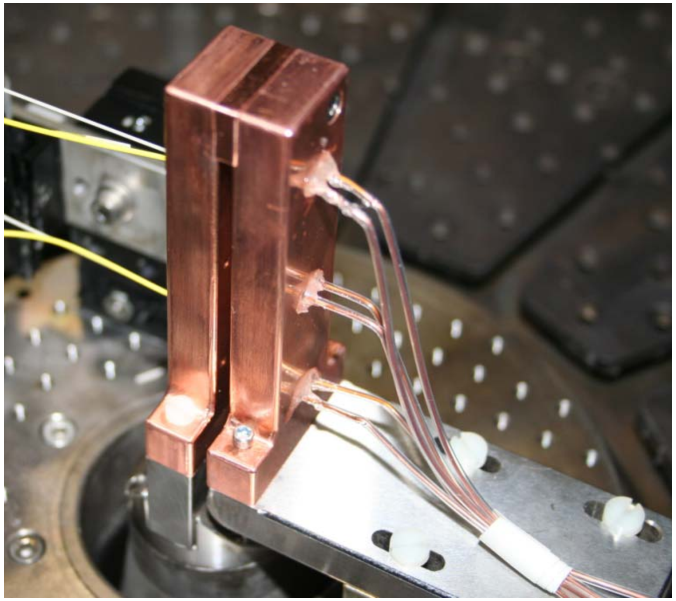
- In house built 1J 532nm laser with stable pulse 50ns – 10s of us
- 2 independent VISAR channels sampling 100um wide and up to 25mm long
- Speeds ~ 200$ms^{-1}$ per fringe to 25$kms^{-1}$
- Output will be to 2 Hadland streak cameras kindly loaned by AWE
- SOP will also be fielded to a 3rd channel

Miniature magnetic probes



Magnetic probes only 0.75mm diameter are fielded at different depths fielded in targets

– directly monitor current over surface of stripline and diffusion through target material



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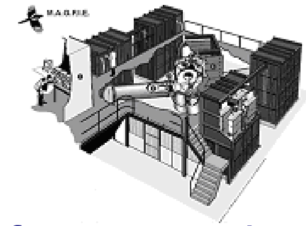
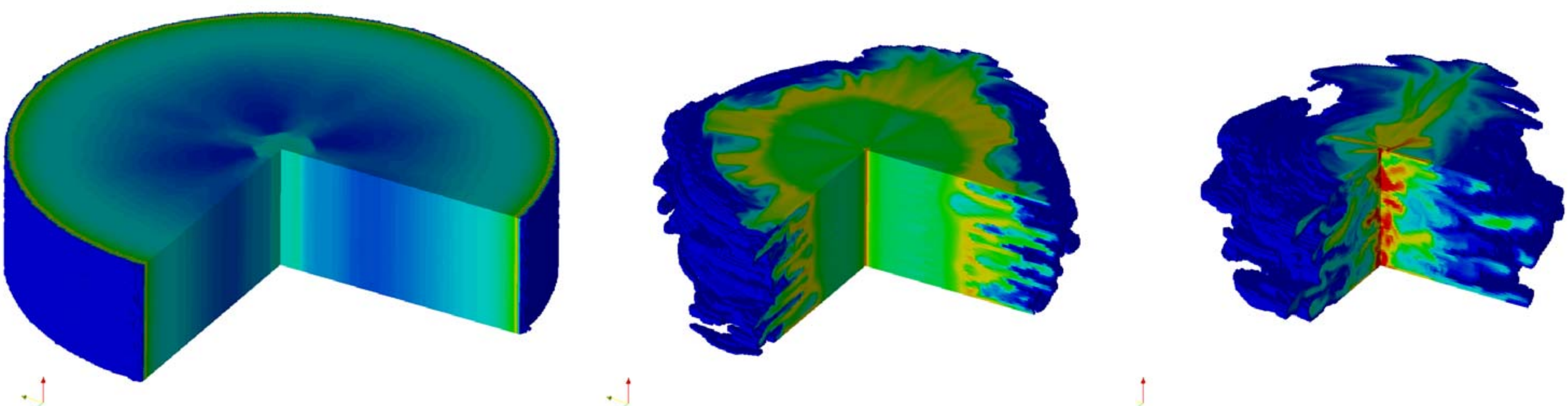


# Code Development

- Over summer 2010 develop simple 1D Lagrangian code for estimates of compression and development of shocks in targets
- Explore using COMSOL to look magnetic field around electrodes and couple to simple 1 and 2D compression effects
- Long term aim to add condensed matter EOS to GORGON code
  - in house developed 3D resistive MHD code, used for z-pinch and HEDP research
  - massively parallel code, able to handle large scale 3D structures
  - everything from electron emission at electrodes, through to ablated plasma at surface of strip lines to compressed material in electrodes



3D MHD code results showing implosion of 80mmx20mm wire array z-pinch

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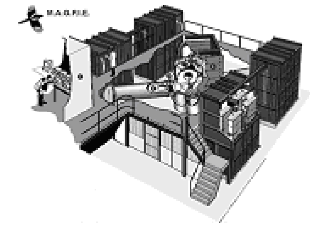
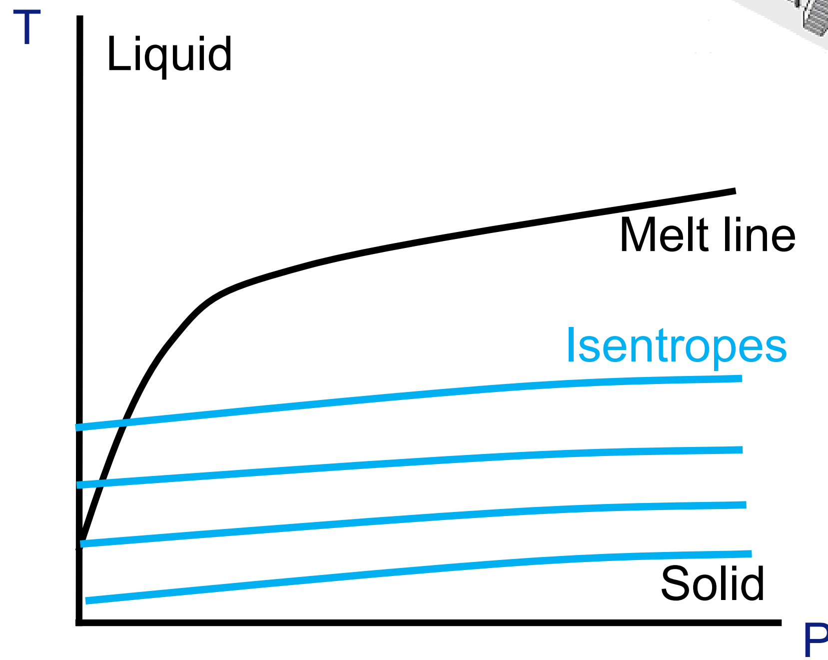


# Advanced Target Systems




Methods to change initial conditions

•Heating systems allow exploration of EOS near phase boundaries

Iron found in earths core

EOS of tin near around melting point

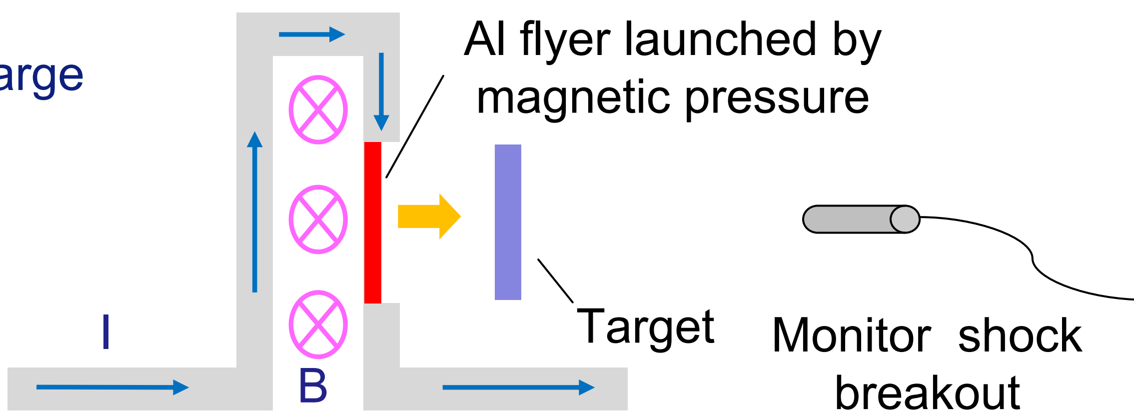
•Cryogenics systems to use of gases in liquid/solid state

e.g. $H_2$, He mix in Jupiter

Explore launching of Al flyer plates

Isentropic pressure drive launches large area, solid fronted flyer plate to high velocities

•Mbar pressures (shocked)



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# Advanced Target Systems

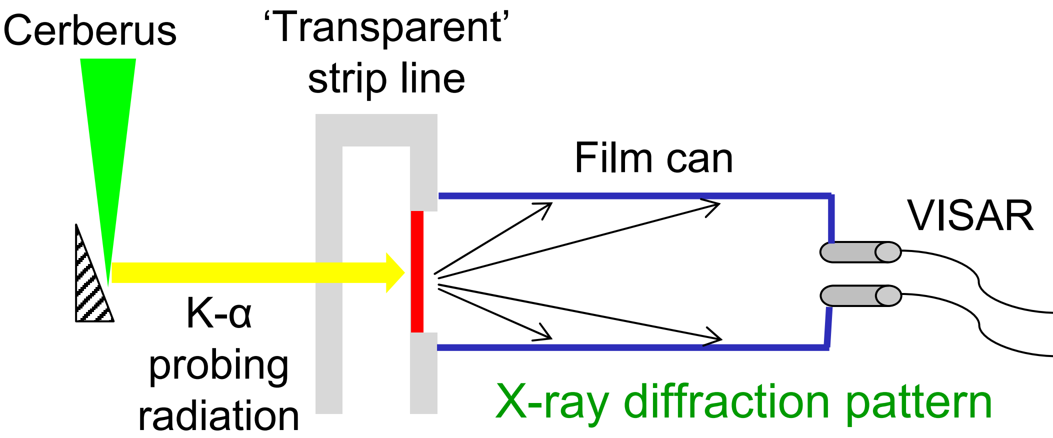
**Cerberus Laser**

Plasma Physics – Laser consortium project

50J long pulse and short pulse beams (150fs)

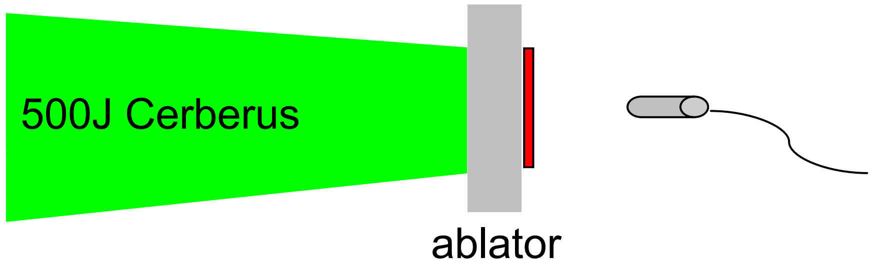
- Thomson Scattering for plasma temperature
- Proton probing for field measurement in HEDP experiments

**Cerberus EOS studies**




- Probe **microscopic scale** (e.g. changes in lattice structure) in relation to **macroscopic properties** (e.g. strength)

- With energy upgrade (parts from AWE Helen laser) could directly drive shock experiments



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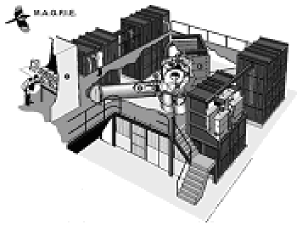

# The End...