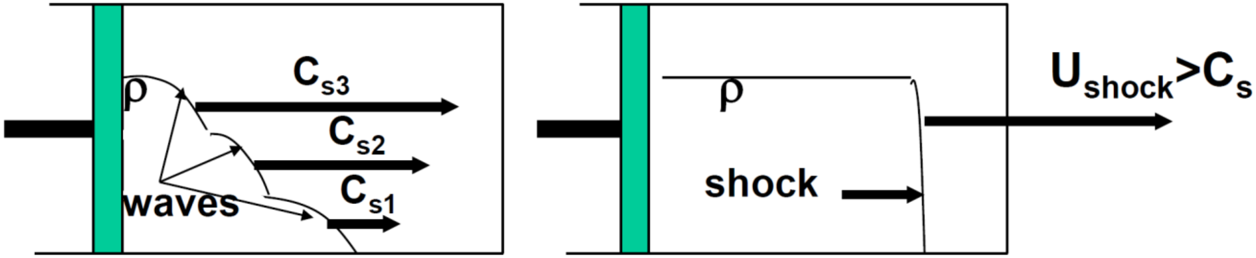
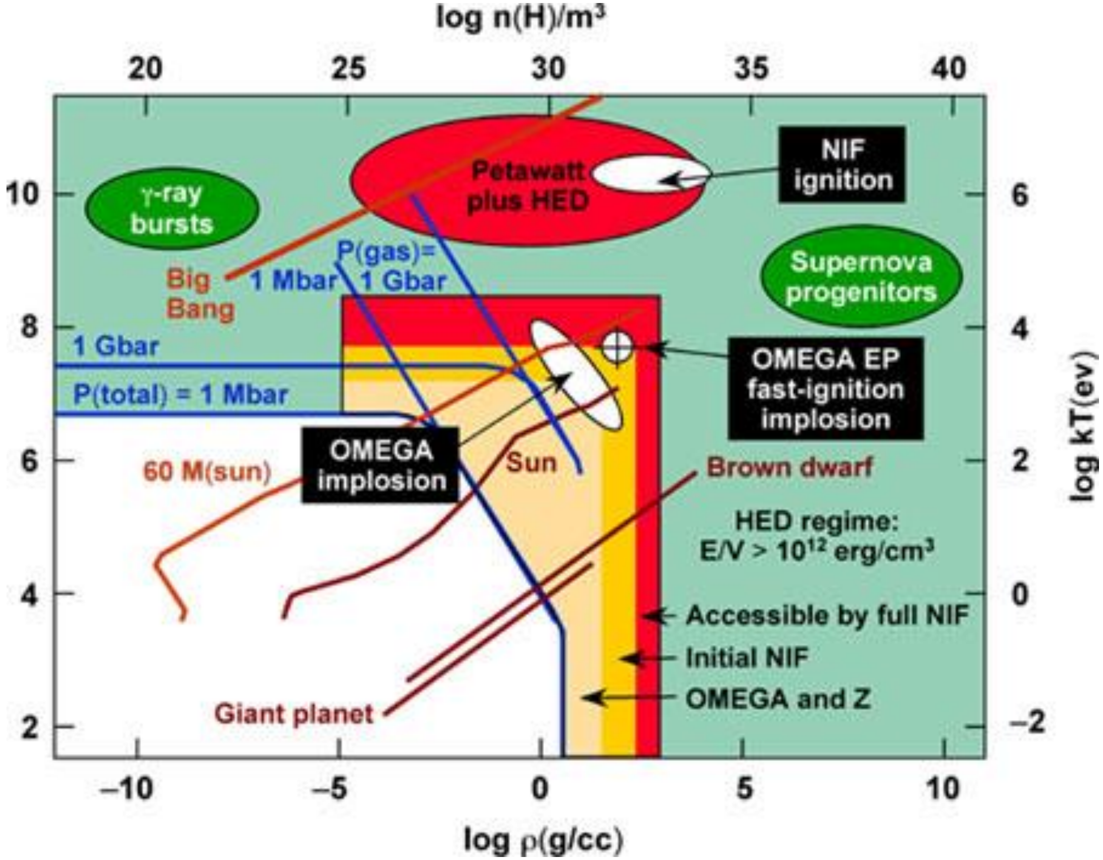
High pressure generation/measurement using shocks



Po-Yu Chang
Inst. Space and Plasma Sciences
National Cheng Kung University

27th November 2023

High energy density plasma (HEDP) is the regime where the pressure is greater than 0.1 T Pa (1 Mbar)



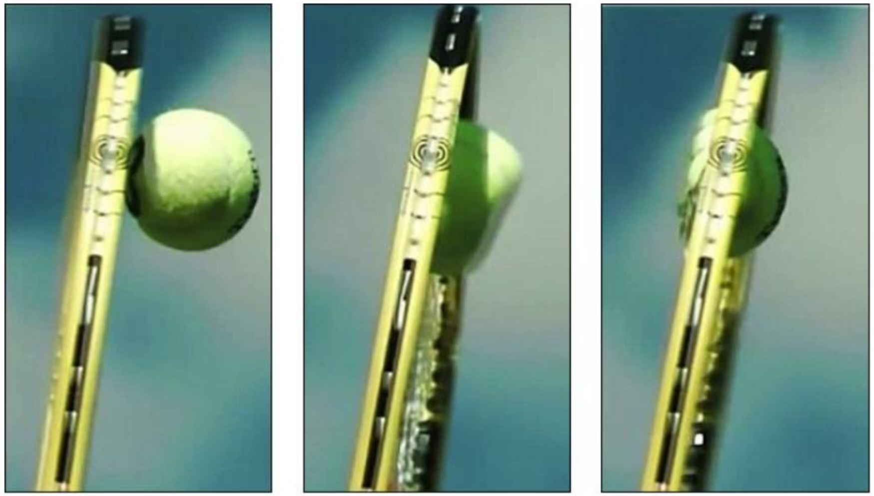
- **The energy density of HEDP regime is higher than 1 kJ of energy per 10 mm^3.**

Frontiers in High Energy Density Physics: The X-Games of Contemporary Science © (2003) by the National Academy of Sciences, courtesy of the National Academies Press, Washington, D.C.

Softer material can be compressed to higher density

- **Compression of a baseball**

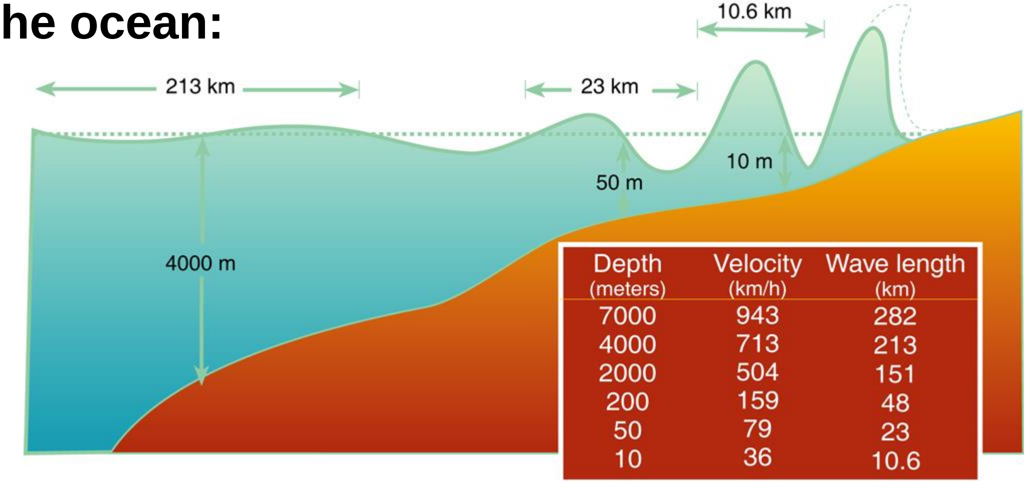
- **Compression of a tennis ball**



https://www.youtube.com/watch?v=uxlIdMoAwbY
https://newsghana.com.gh/wimbledon-slow-motion-video-of-how-a-tennis-ball-turns-to-goo-after-serve/

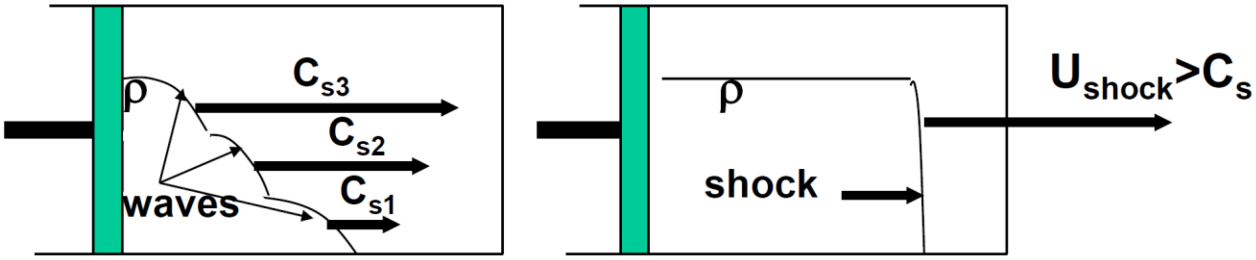
A shock is formed due to the increasing sound speed of a compressed gas/plasma

- **Wave in the ocean:**



Depth (meters)	Velocity (km/h)	Wave length (km)
7000	943	282
4000	713	213
2000	504	151
200	159	48
50	79	23
10	36	10.6

- **Acoustic/compression wave driven by a piston:**



$$c_S \sim \sqrt{\gamma \frac{p}{\rho}} \sim \sqrt{\frac{\alpha\rho^{5/3}}{\rho}} \sim \sqrt{\alpha}\,\rho^{1/3}$$

http://neamtic.ioc-unesco.org/tsunami-info/the-cause-of-tsunamis

*R. Betti, HEDSA HEDP Summer School, 2015

A wave with small amplitude (perturbation) travels with the sound speed

$$\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\,\vec{u})=0$$

$$\rho\left(\frac{\partial\,\vec{u}}{\partial t}+\vec{u}\cdot\nabla\,\vec{u}\right)=-\nabla p+\rho\,\vec{f}$$

$$\frac{\partial}{\partial t}\left(\frac{\rho u^2}{2}+\rho\varepsilon\right)+\nabla\cdot\vec{u}\left[\left(\frac{\rho u^2}{2}+\rho\varepsilon\right)+p\right]=\rho\,\vec{f}\cdot\vec{u}-\nabla\cdot\vec{q}$$

$$\rho=\rho_o+\Delta\rho \qquad p=p_o+\Delta p \qquad \vec{u}=\vec{u}_o+\Delta\,\vec{u}\equiv(u_o+\Delta u)\hat{x}\equiv\Delta u\,\hat{x}$$

$$\frac{\partial\Delta\rho}{\partial t}=-\rho_o\frac{\partial\Delta u}{\partial x} \qquad \rho_o\frac{\partial\Delta u}{\partial t}=-\frac{\partial p}{\partial x}=-\left(\frac{\partial p}{\partial\rho}\right)_S\frac{\partial\Delta\rho}{\partial x}\equiv-{c_s}^2\frac{\partial\Delta\rho}{\partial x}$$

$$\frac{\partial^2\Delta\rho}{\partial t^2}={c_s}^2\frac{\partial^2\Delta\rho}{\partial x^2}$$

$$\Delta\rho=\Delta\rho(x\pm c_S t)$$

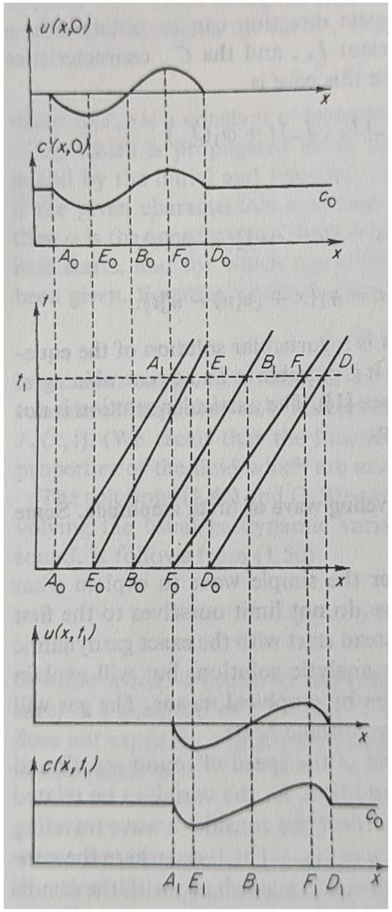
$$\Delta p=\Delta p(x\pm c_S t)$$

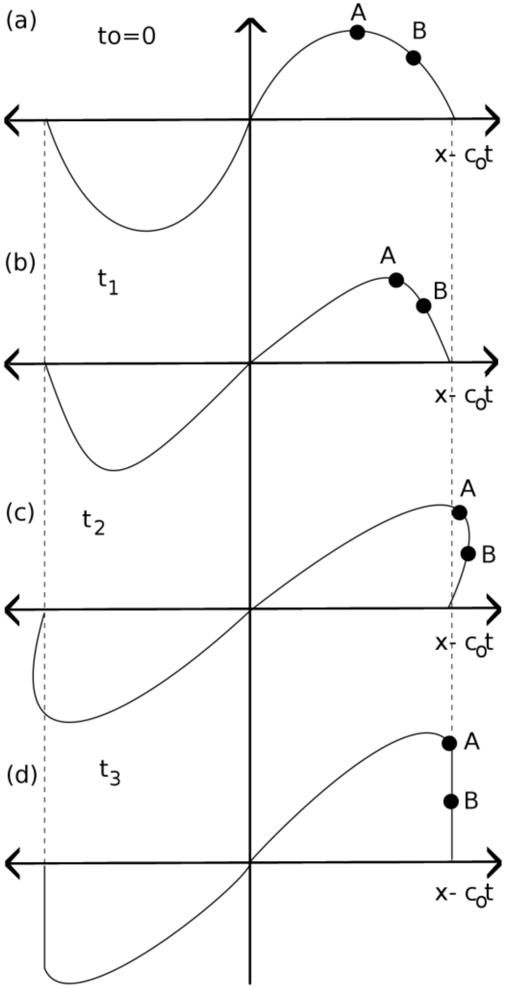
$$\Delta u=\Delta u(x\pm c_S t)$$

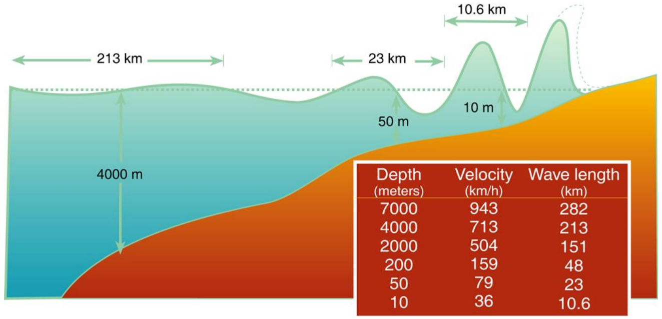
$$c_S\sim\sqrt{\gamma\frac{p}{\rho}}\sim\sqrt{\frac{\alpha\rho^{5/3}}{\rho}}\sim\sqrt{\alpha}\rho^{1/3}$$

Y. B. Zel’dovich & Y. P. Raizer, Physics of shock waves and high-temperature hydrodynamic phenomena
Maria Alejandra Barrios Garcia, PhD Thesis, U of Rochester, 2010

A wave is distorted when the sound speed is not a constant







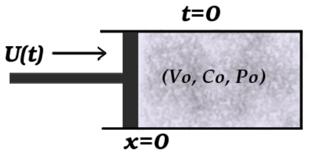
Depth (meters)	Velocity (km/h)	Wave length (km)
7000	943	282
4000	713	213
2000	504	151
200	159	48
50	79	23
10	36	10.6

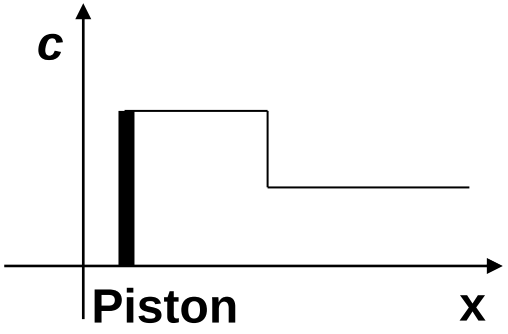
- **A shock wave is formed when a discontinuity is formed.**

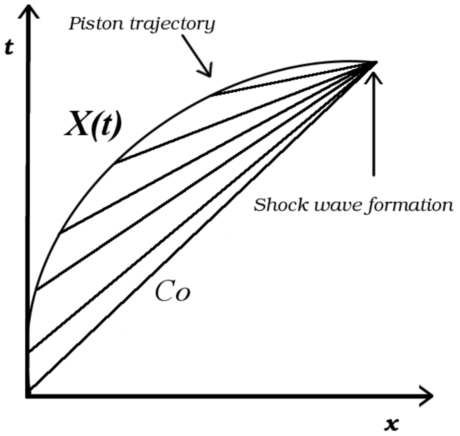
$$c_S \sim \sqrt{\alpha}\rho^{1/3}$$

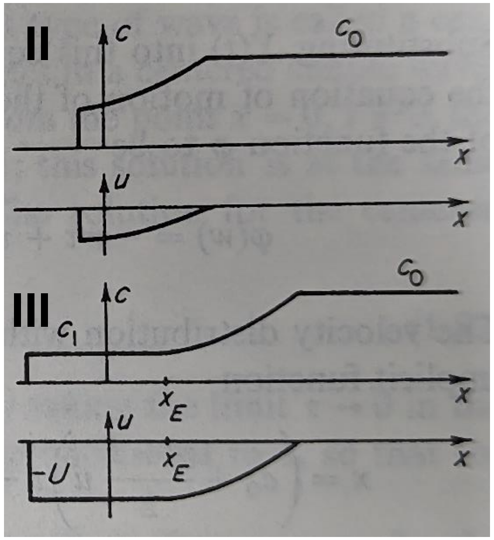
Y. B. Zel’dovich & Y. P. Raizer, Physics of shock waves and high-temperature hydrodynamic phenomena
Maria Alejandra Barrios Garcia, PhD Thesis, U of Rochester, 2010
http://neamtic.ioc-unesco.org/tsunami-info/the-cause-of-tsunamis

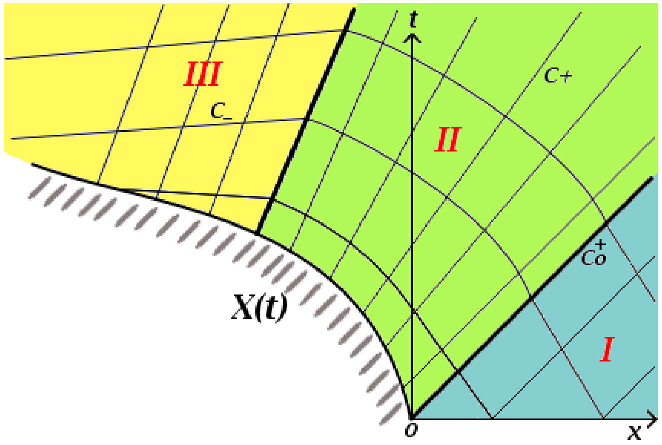
A shock is formed when characteristics merge while a rarefaction wave is formed when characteristics spread out





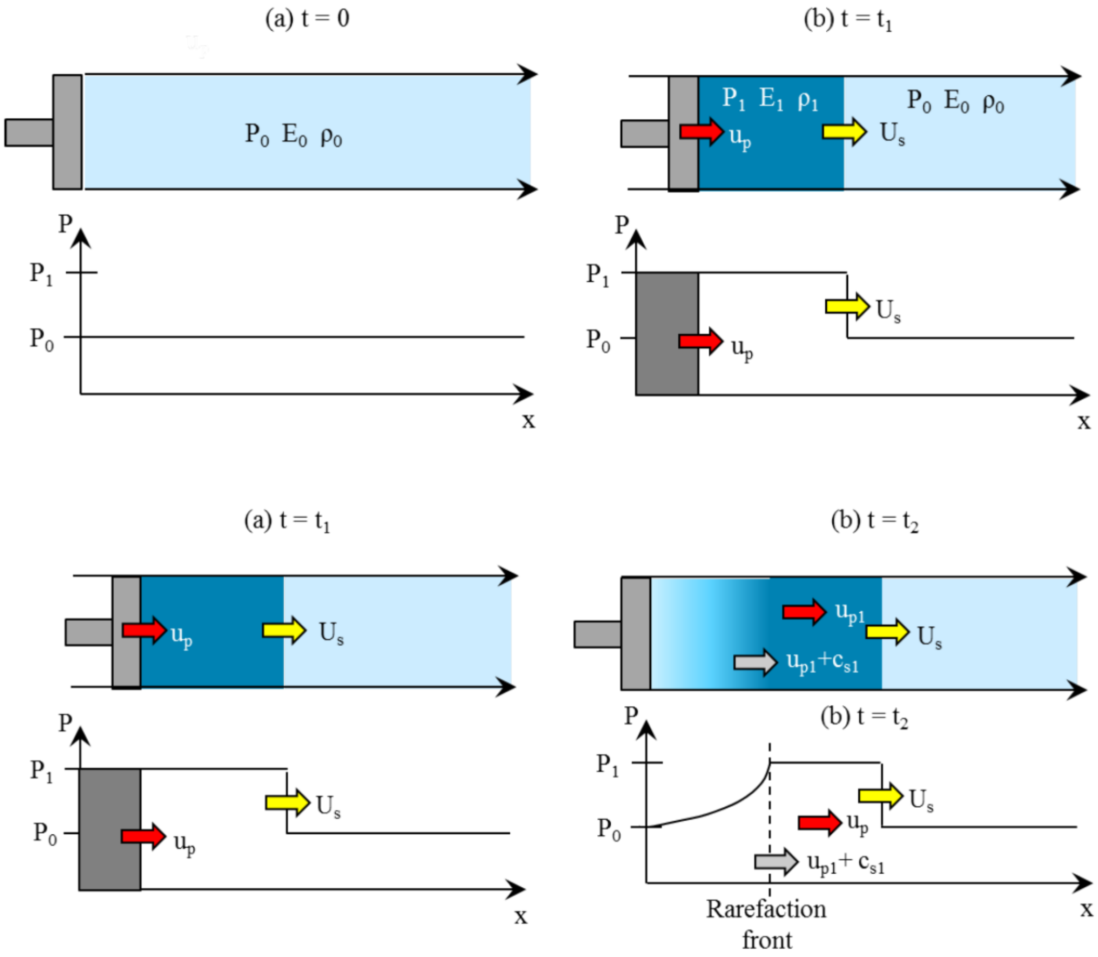






Y. B. Zel’dovich & Y. P. Raizer, Physics of shock waves and high-temperature hydrodynamic phenomena
Maria Alejandra Barrios Garcia, PhD Thesis, U of Rochester, 2010

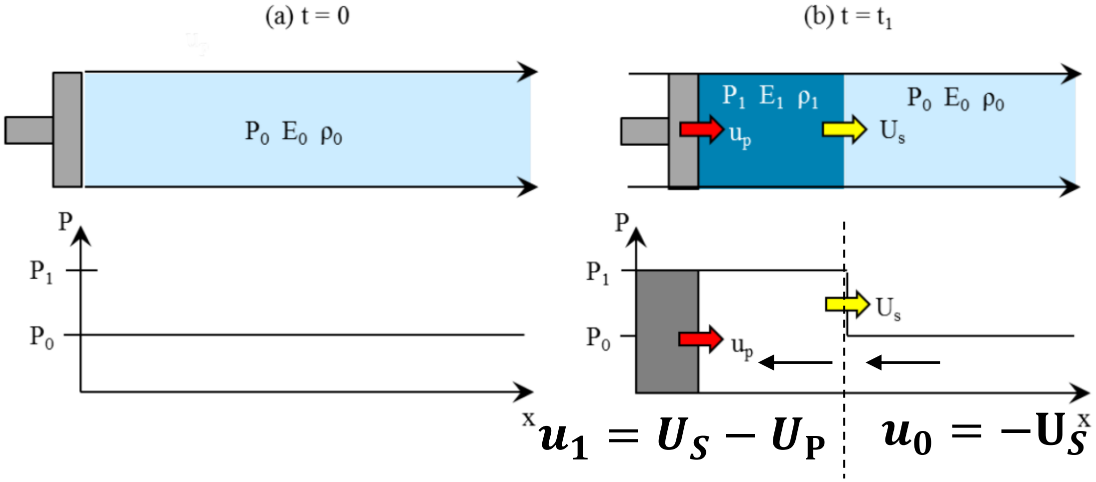
A shock or a rarefaction wave may be formed depending on the driving force from the piston



- **Show simulations.**

Michelle Colleen Gregor, PhD Thesis, U of Rochester, 2017

Mass, momentum, and energy is conserved across the shock front



$$u_1 = U_S - U_P \qquad u_0 = -\mathrm{U}_S$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho\, \vec{u}) = 0$$

$$\rho\left(\frac{\partial\, \vec{u}}{\partial t} + \vec{u} \cdot \nabla\, \vec{u}\right) = -\nabla p + \rho\, \vec{f}$$

$$\frac{\partial}{\partial t}\left(\frac{\rho u^2}{2} + \rho\varepsilon\right) + \nabla \cdot \vec{u}\left[\left(\frac{\rho u^2}{2} + \rho\varepsilon\right) + p\right] = \rho\, \vec{f} \cdot \vec{u} - \nabla \cdot \vec{q}$$

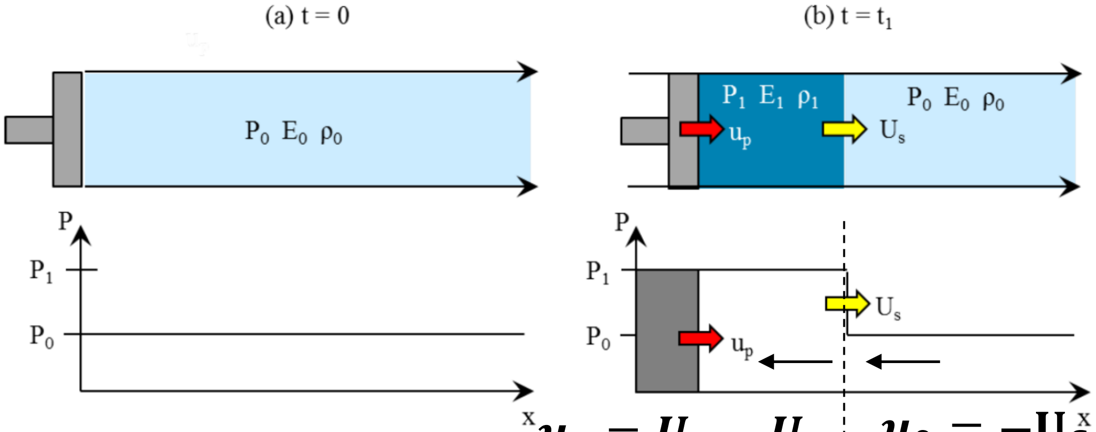
$$\rho_1 u_1 = \rho_0 u_0$$

$$p_1 + \rho_1 {u_1}^2 = p_0 + \rho_0 {u_0}^2$$

$$\epsilon_1 + \frac{p_1}{\rho_1} + \frac{{u_1}^2}{2} = \epsilon_0 + \frac{p_0}{\rho_0} + \frac{{u_0}^2}{2}$$

Michelle Colleen Gregor, PhD Thesis, U of Rochester, 2017

The Hugoniot equations relate the pre- and post-shock conditions via the particle velocity(U_p) and shock velocity (U_s)



$u_1 = U_S - U_P$ $u_0 = -U_S$

$$\rho_1 u_1 = \rho_0 u_0$$

$$p_1 + \rho_1 {u_1}^2 = p_0 + \rho_0 {u_0}^2$$

$$\epsilon_1 + \frac{p_1}{\rho_1} + \frac{{u_1}^2}{2} = \epsilon_0 + \frac{p_0}{\rho_0} + \frac{{u_0}^2}{2}$$

$$\rho_0 U_S = \rho_1 (U_S - U_p)$$

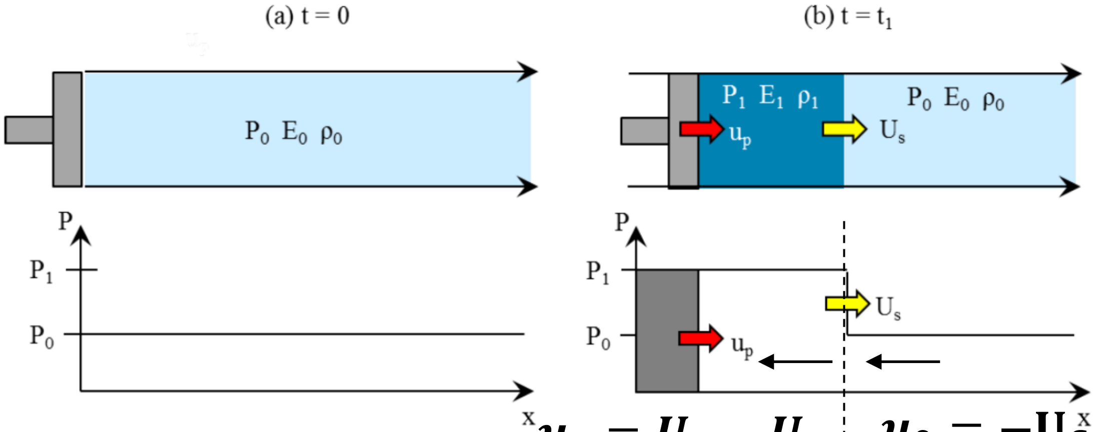
$$p_1 - p_0 = \rho_o U_S U_p$$

$$u_0 \left[\frac{\rho_0 {u_0}^2}{2} + \rho_0 \epsilon_0 + p_0\right] = u_1 \left[\frac{\rho_1 {u_1}^2}{2} + \rho_1 \epsilon_1 + p_1\right]$$

$$p_0 u_0 - p_1 u_1 = \rho_1 u_1 \left(\epsilon_1 + \frac{{u_1}^2}{2}\right) - \rho_0 u_0 \left(\epsilon_0 + \frac{{u_0}^2}{2}\right) = \rho_0 u_0 \left[\left(\epsilon_1 + \frac{{u_1}^2}{2}\right) - \left(\epsilon_0 + \frac{{u_0}^2}{2}\right)\right]$$

Michelle Colleen Gregor, PhD Thesis, U of Rochester, 2017

The Hugoniot equations relate the pre- and post-shock conditions via the particle velocity(U_p) and shock velocity (U_s) – cont.



$u_1 = U_S - U_P$ $\quad$ $u_0 = -U_S$

$$\rho_0 U_S = \rho_1 (U_S - U_p)$$

$$u_0\left[\frac{\rho_0 {u_0}^2}{2} + \rho_0\epsilon_0 + p_0\right] = u_1\left[\frac{\rho_1 {u_1}^2}{2} + \rho_1\epsilon_1 + p_1\right]$$

$$p_1 - p_0 = \rho_o U_S U_p$$

$$p_0 u_0 - p_1 u_1 = \rho_1 u_1\left(\epsilon_1 + \frac{{u_1}^2}{2}\right) - \rho_0 u_0\left(\epsilon_0 + \frac{{u_0}^2}{2}\right) = \rho_0 u_0\left[\left(\epsilon_1 + \frac{{u_1}^2}{2}\right) - \left(\epsilon_0 + \frac{{u_0}^2}{2}\right)\right]$$

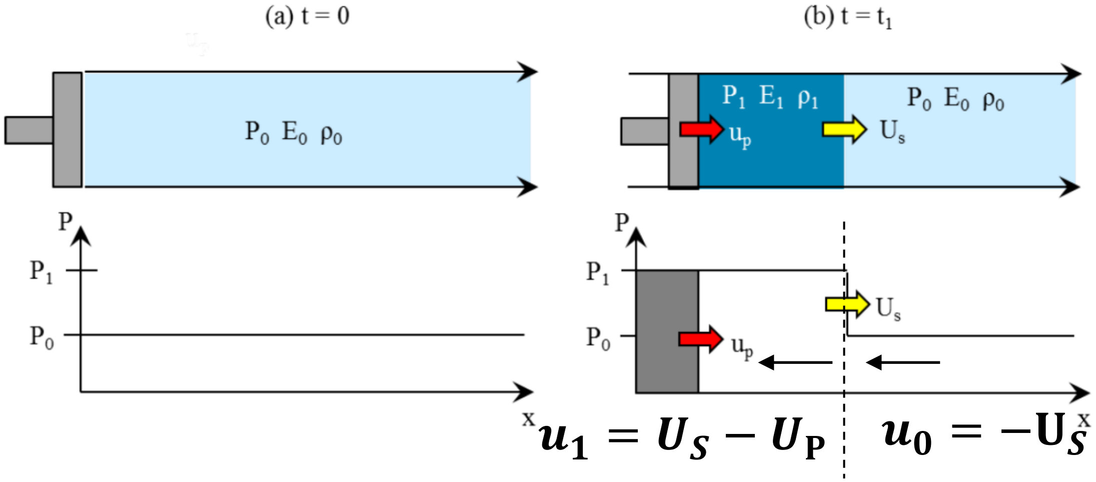
$$\text{Let } V_{1,2} \equiv \frac{1}{\rho_{1,2}}$$

$$ {u_0}^2 = {V_0}^2 \frac{p_1 - p_0}{V_0 - V_1} \qquad {u_1}^2 = {V_1}^2 \frac{p_1 - p_0}{V_0 - V_1}$$

$$\epsilon_1 - \epsilon_0 = \frac{1}{2}(p_0 + p_1)(V_0 - V_1)$$

Michelle Colleen Gregor, PhD Thesis, U of Rochester, 2017

The density is only compressed by a limited amount even in a strong shock



$$u_1 = U_S - U_P \qquad u_0 = -U_S$$

$$V_{0,1} \equiv \frac{1}{\rho_{0,1}} \quad u_0{}^2 = V_0{}^2\frac{p_1 - p_0}{V_0 - V_1} \quad u_1{}^2 = V_1{}^2\frac{p_1 - p_0}{V_0 - V_1} \quad \epsilon_1 - \epsilon_0 = \frac{1}{2}(p_0 + p_1)(V_0 - V_1)$$

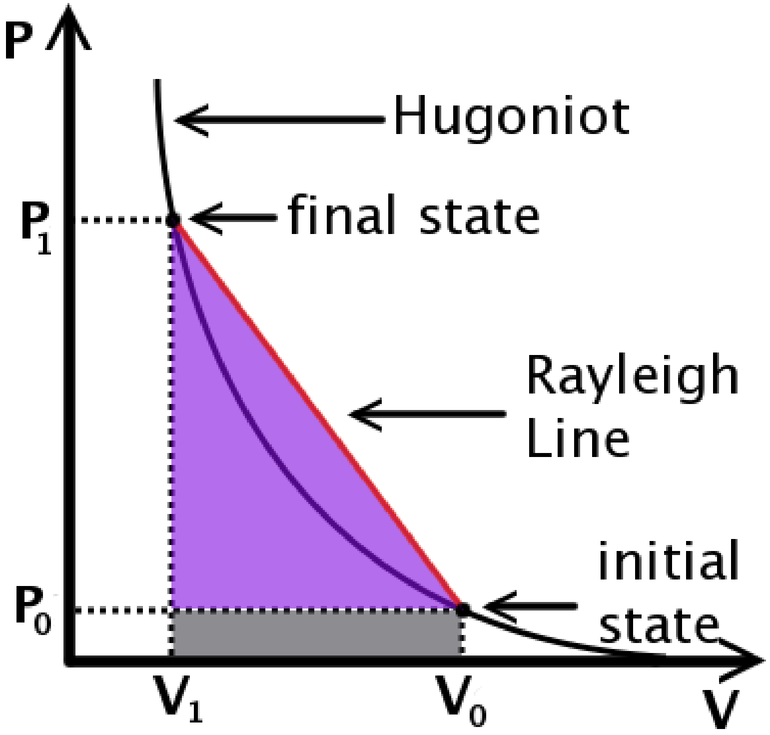
$$\frac{\rho_1}{\rho_0} = \frac{V_0}{V_1} = \frac{p_1(\gamma+1) + p_0(\gamma-1)}{p_1(\gamma-1) + p_0(\gamma+1)} \sim \frac{\gamma+1}{\gamma-1}\left(\text{for } \frac{p_1}{p_0} \gg 1\right) \sim 4\left(\text{for } \gamma = \frac{5}{3}\right)$$

$$u_0{}^2 = \frac{V_0}{2}[(\gamma-1)p_0 + (\gamma+1)p_1] = \frac{p_0}{\rho_0}\frac{(\gamma+1)\,p_1/p_0 + (\gamma-1)}{2}$$

$$u_1{}^2 = \frac{V_0}{2}\frac{[(\gamma+1)p_0 + (\gamma-1)p_1]^2}{(\gamma-1)p_0 + (\gamma+1)p_1}$$

Michelle Colleen Gregor, PhD Thesis, U of Rochester, 2017

The Hugoniot curve is a curve on the *p*, *V* diagram passing through the initial state p_0, V_0

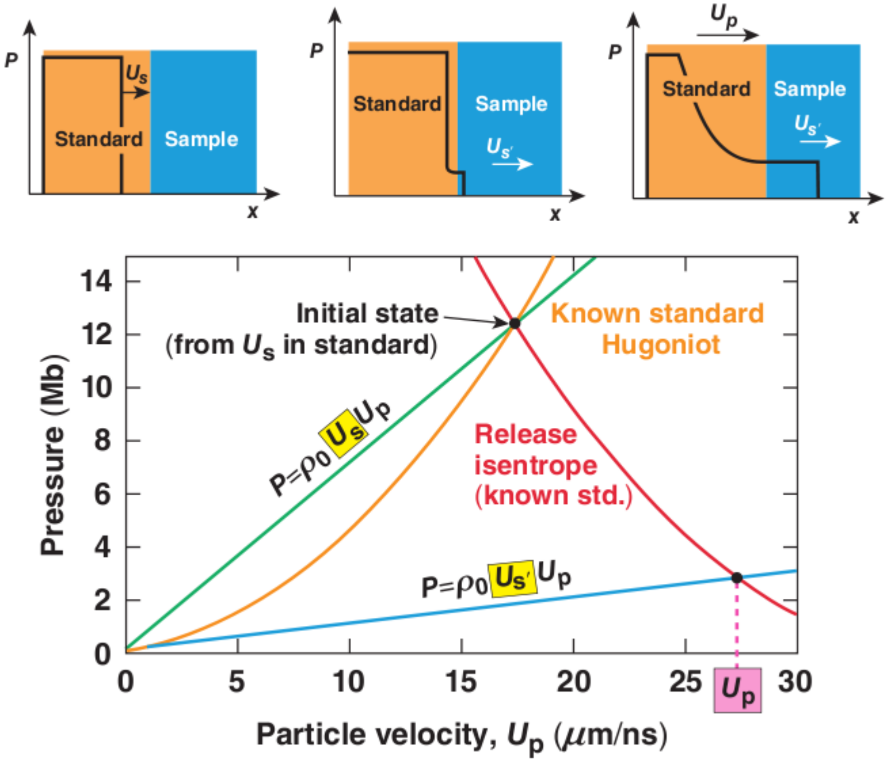


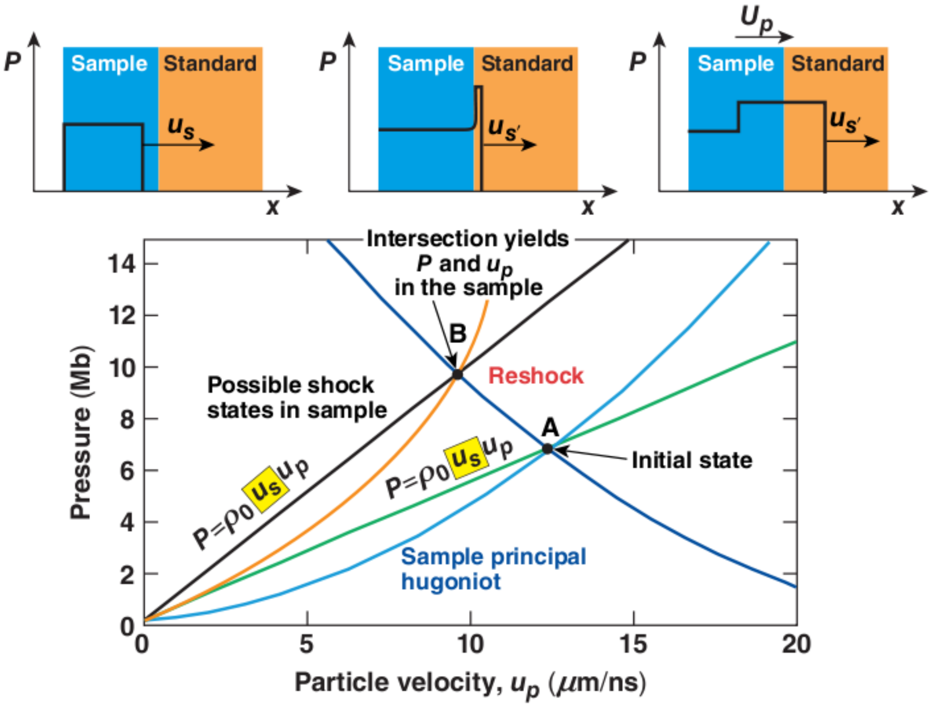
$$\frac{V_0}{V_1} = \frac{p_1(\gamma+1)+p_0(\gamma-1)}{p_1(\gamma-1)+p_0(\gamma+1)}$$

$$V_{0,1} \equiv \frac{1}{\rho_{0,1}}$$

Maria Alejandra Barrios Garcia, PhD Thesis, U of Rochester, 2010

Pressure can be referred by measuring the shock speed with a sample with known Hugoniot curve

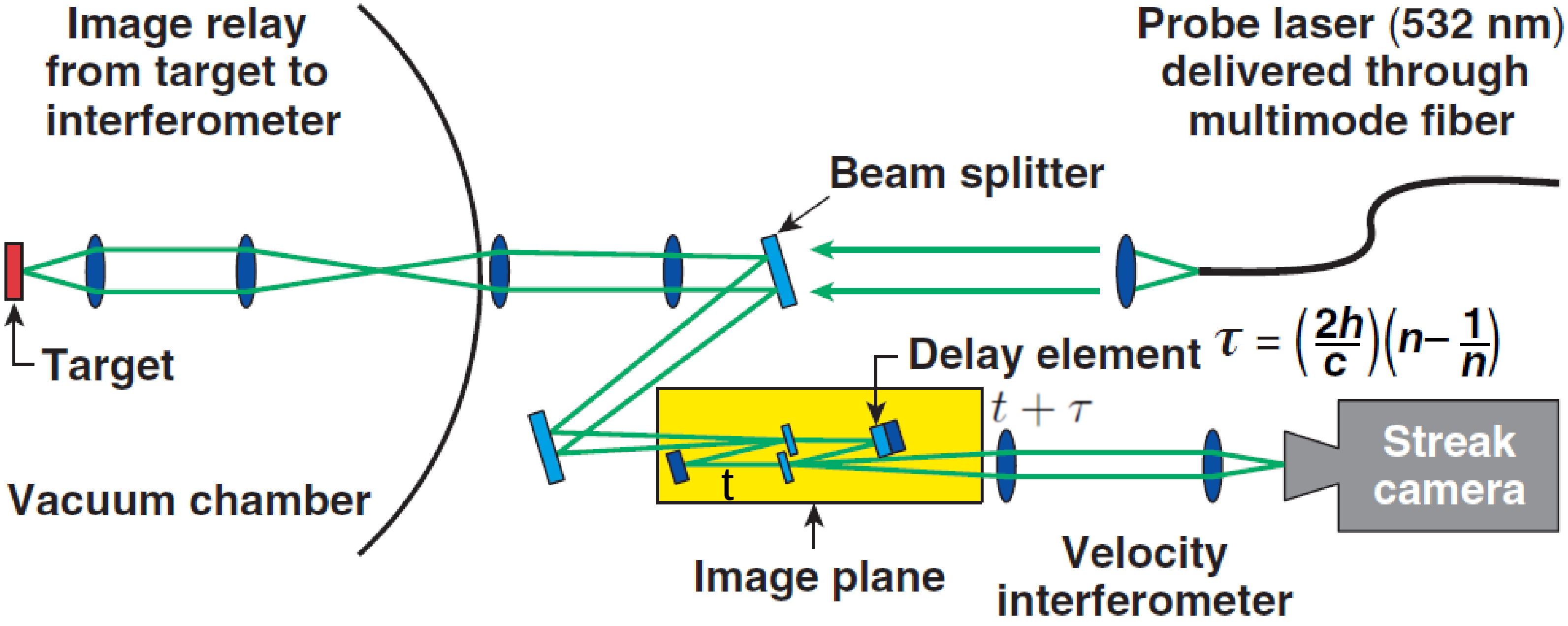


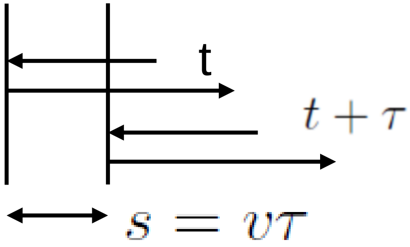


$$p_1 - p_0 = \rho_o U_S U_p$$

Maria Alejandra Barrios Garcia, PhD Thesis, U of Rochester, 2010

Shock velocities are measured using time-resolved Velocity Interferometer System for Any Reflector (VISAR)





$$\Delta\phi = \frac{v\tau}{\lambda} \propto v$$

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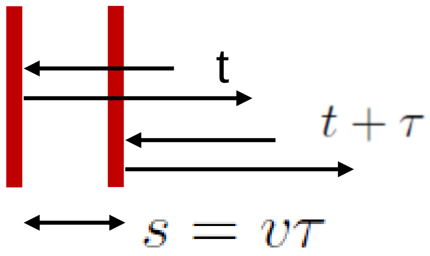
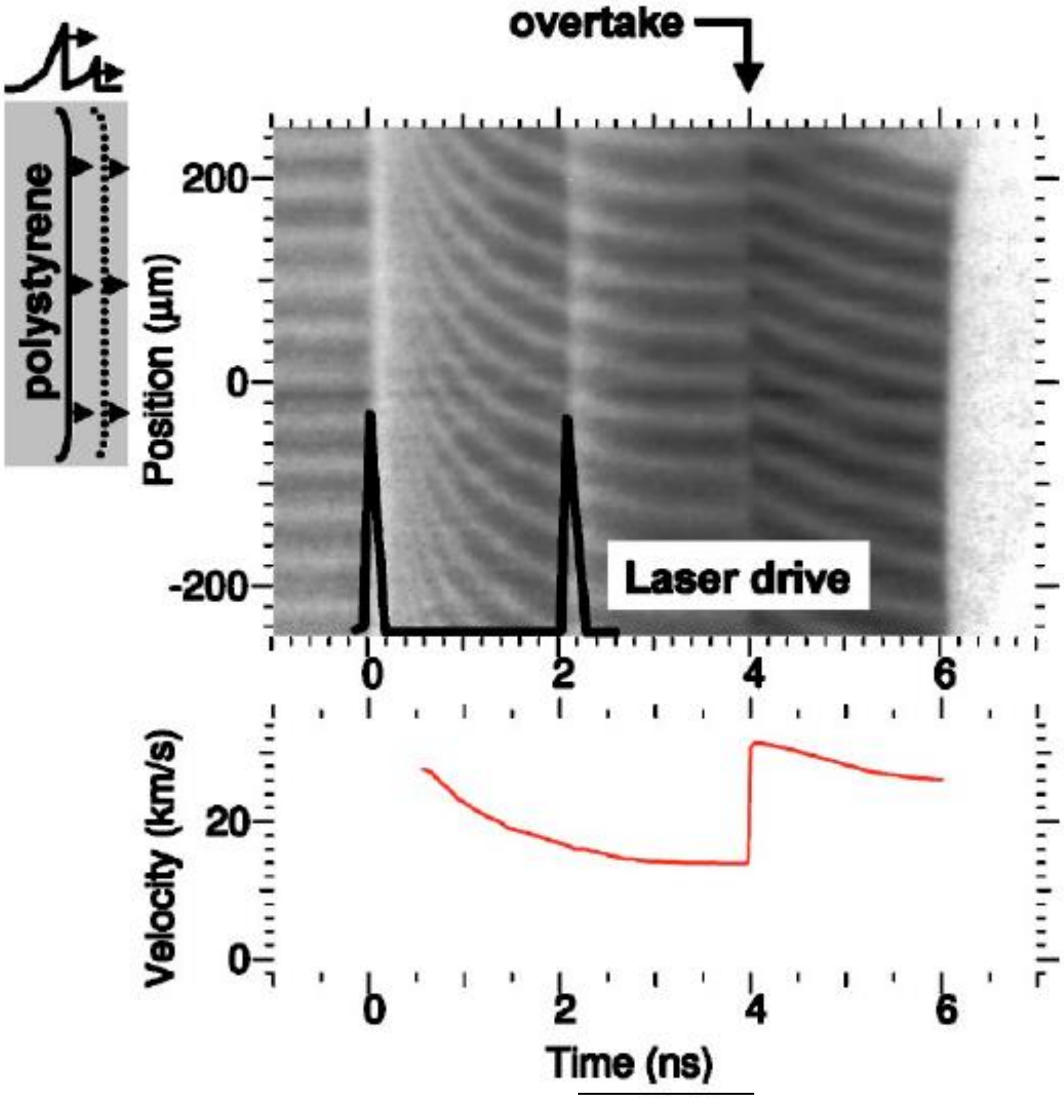
http://hedpschool.lle.rochester.edu/1000_proc2013.php

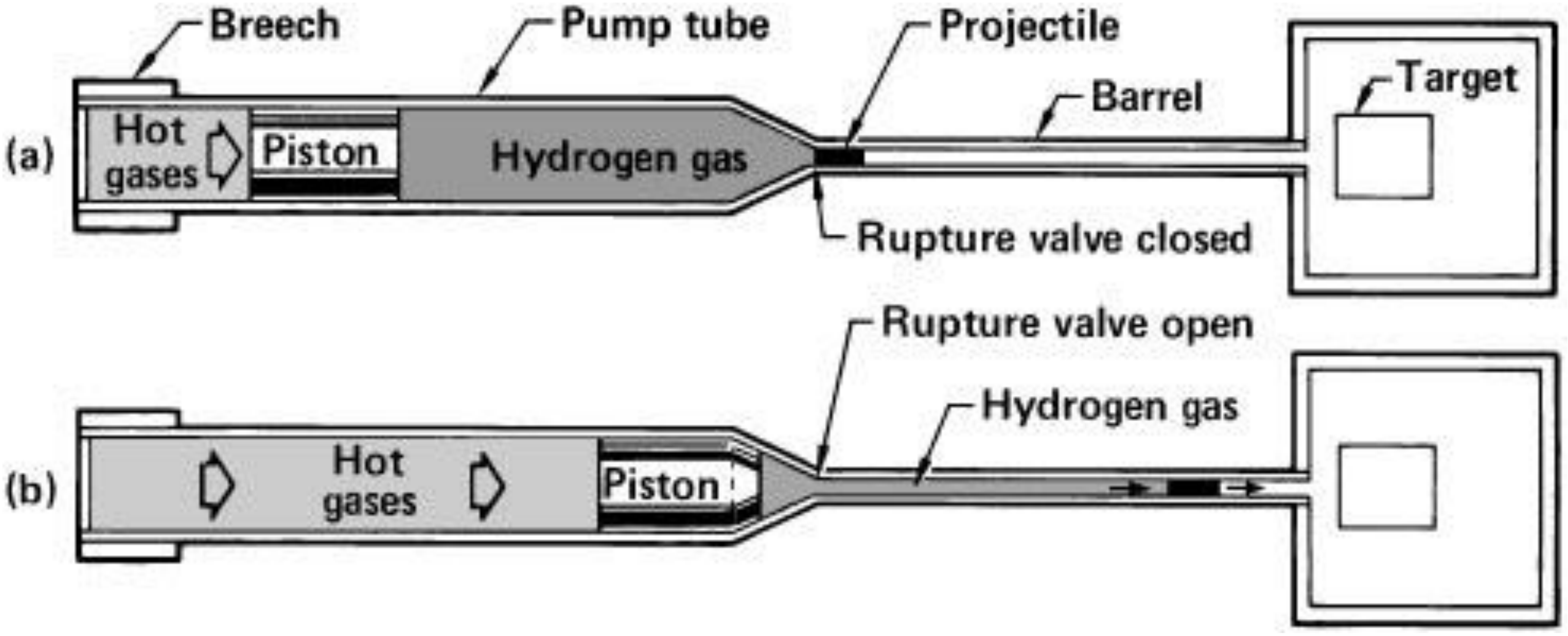
Shock velocities are measured using time-resolved Velocity Interferometer System for Any Reflector (VISAR)





P. M. Celliers *et al.*, Rev. Sci. Insytum. **75**, 4916 (2004)

A piston can be driven by a gas gun



J. Freim, etc., J. Materials Research 11, 112 (1996)

Rochester is known as “The World's Image Center”

There are many famous optical companies at Rochester

Kodak

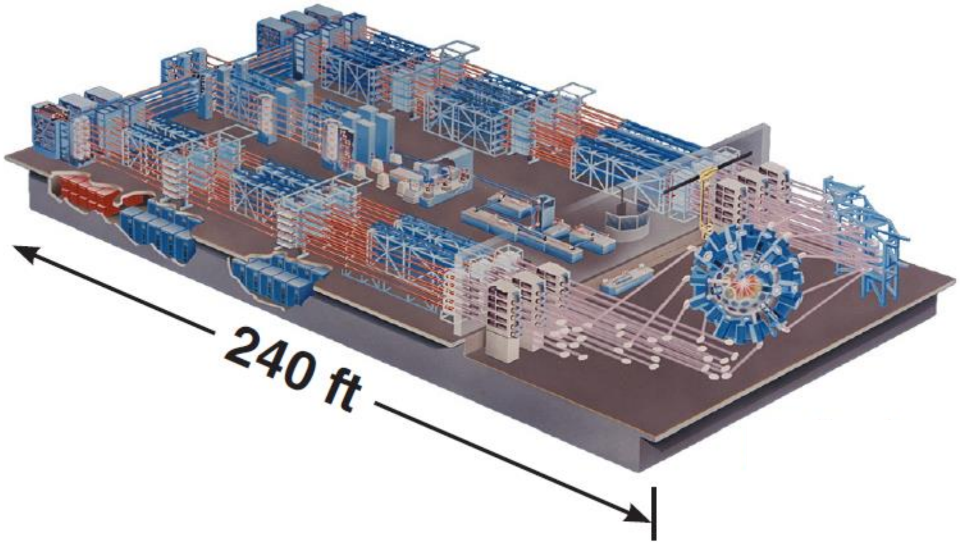
xerox ®

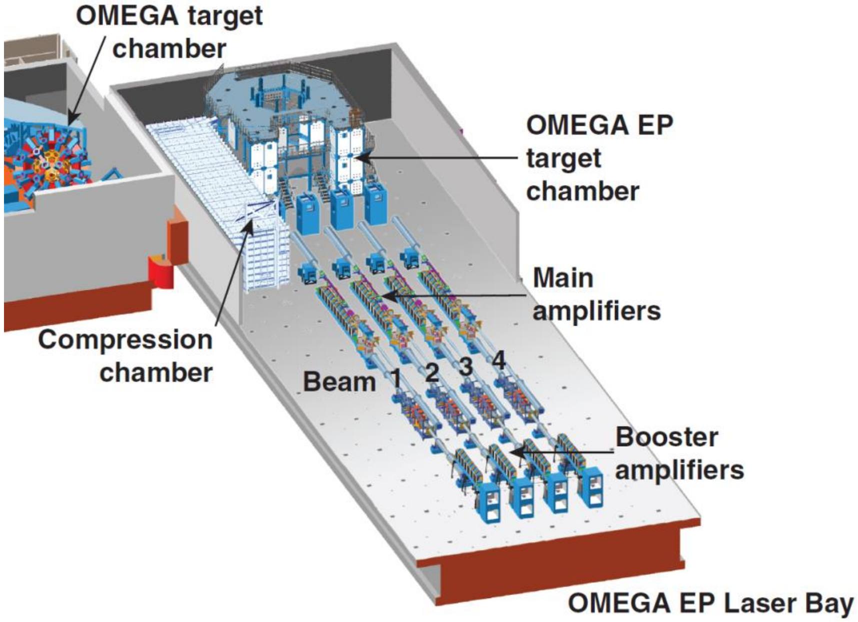
Eastman school of music

BAUSCH + LOMB

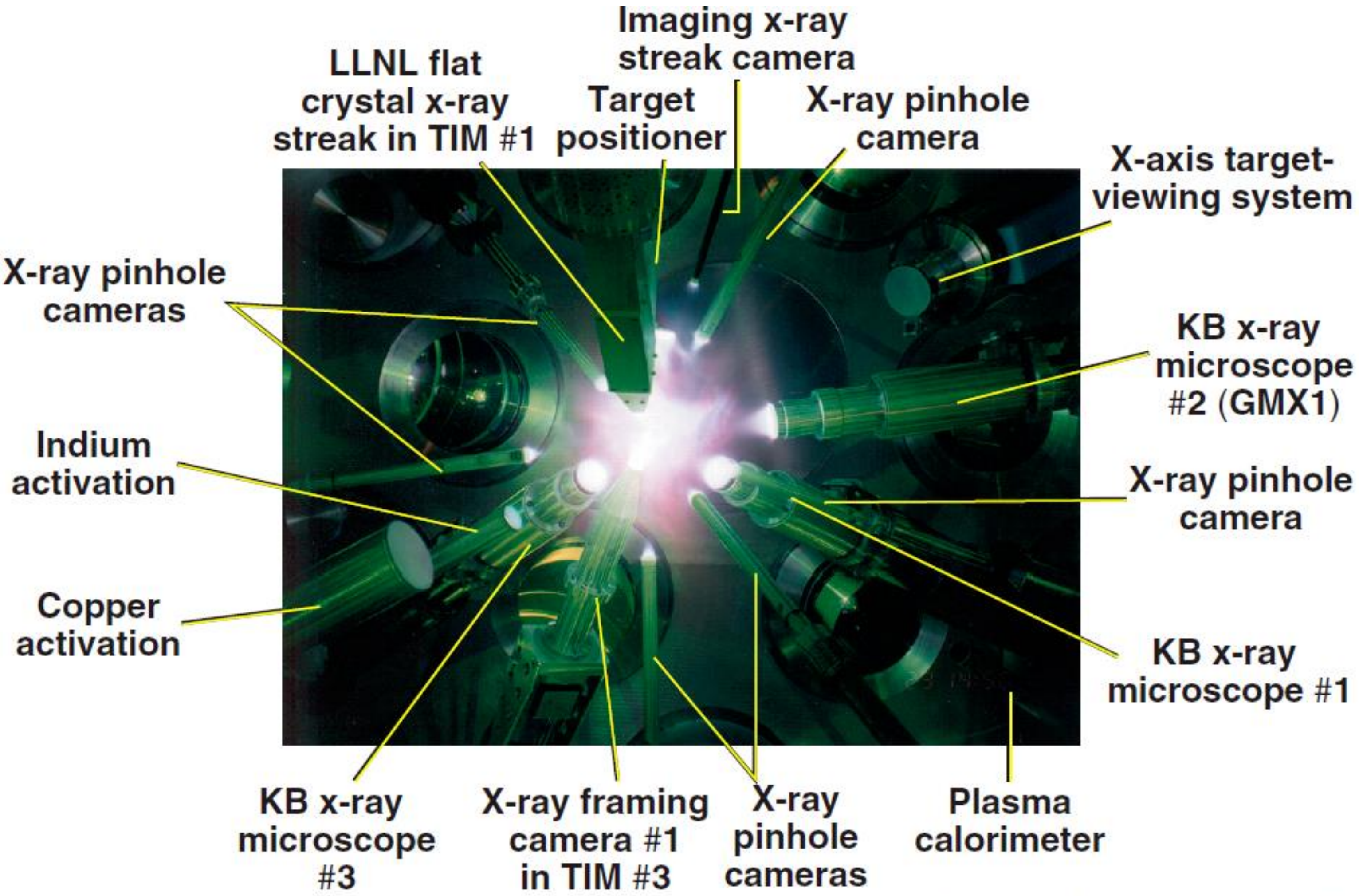
Laboratory for Laser Energetics, University of Rochester is a pioneer in laser fusion

- **OMEGA Laser System**
  - **60 beams**
  - **>30 kJ UV on target**
  - **1%~2% irradiation nonuniformity**
  - **Flexible pulse shaping**
- **OMEGA EP Laser System**
  - **4 beams; 6.5 kJ UV (10ns)**
  - **Two beams can be high-energy petawatt**
    - **2.6 kJ IR in 10 ps**
    - **Can propagate to the OMEGA or OMEGA EP target chamber**





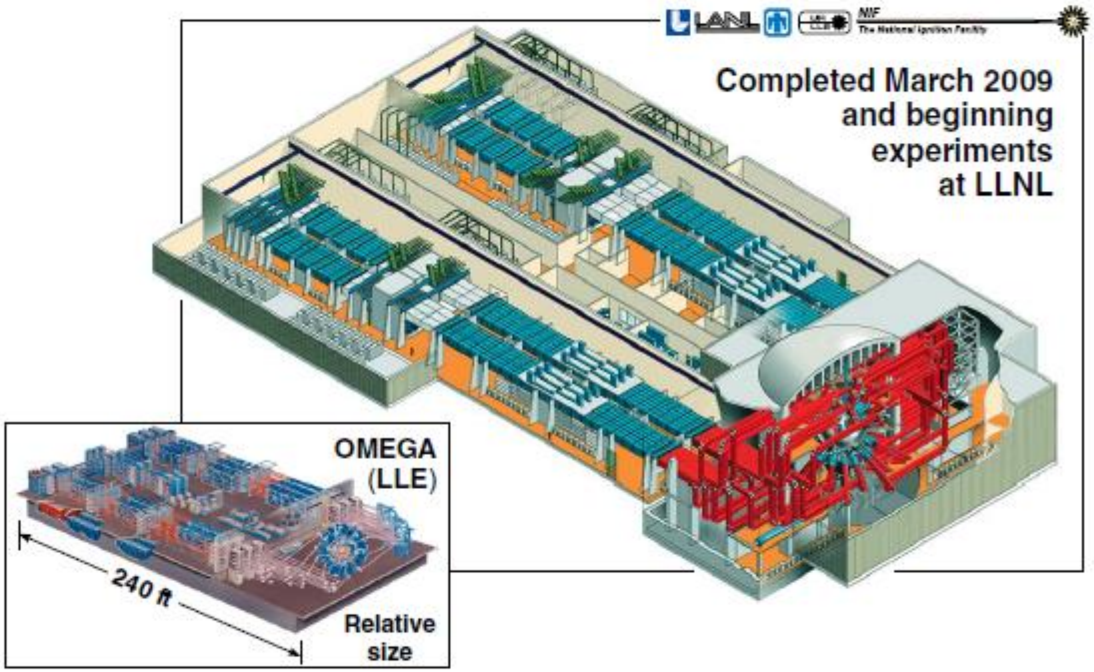
The OMEGA Facility is carrying out ICF experiments using a full suite of target diagnostics



E8012b

Photo taken from port H11B

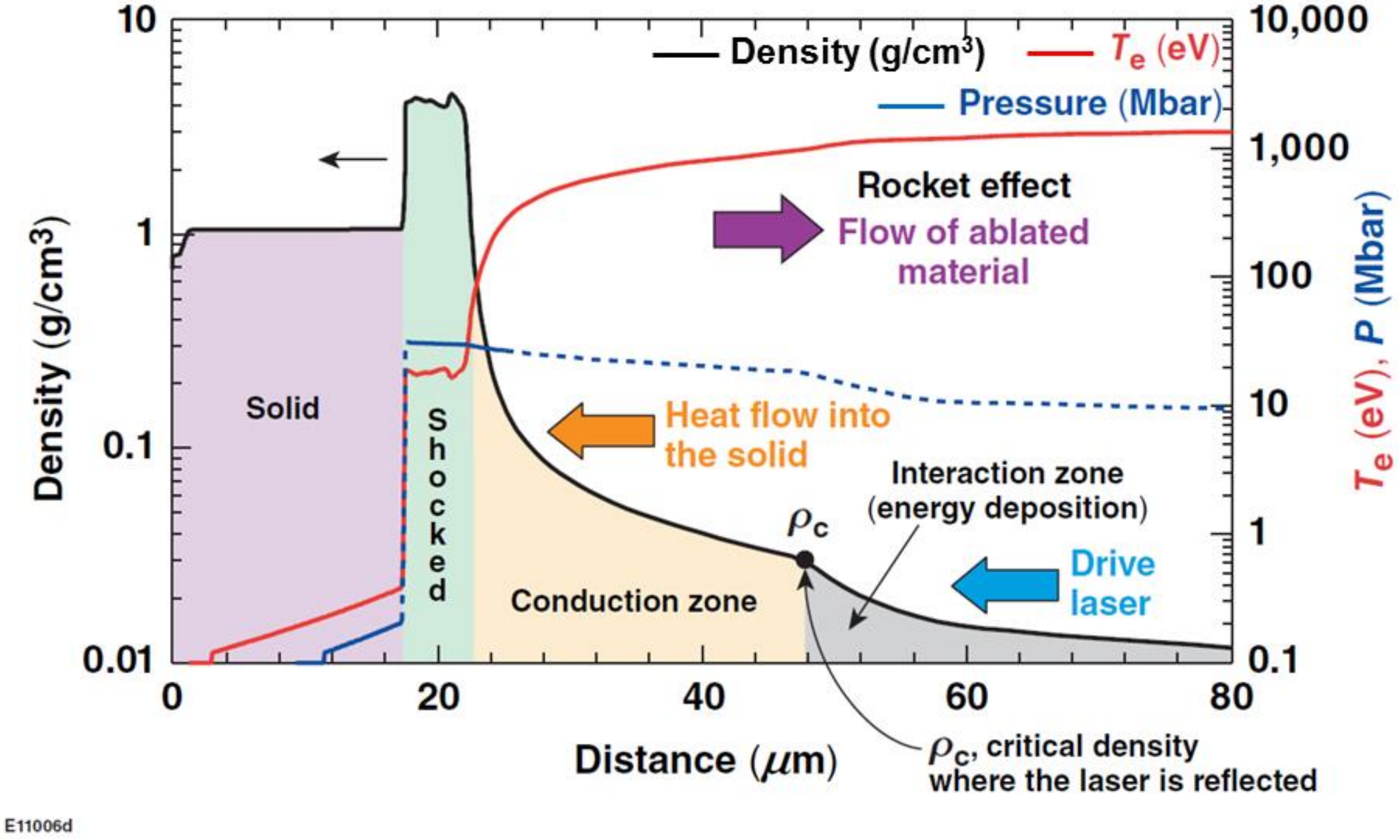
The 1.8-MJ National Ignition Facility (NIF) will demonstrate ICF ignition and modest energy gain



Completed March 2009 and beginning experiments at LLNL

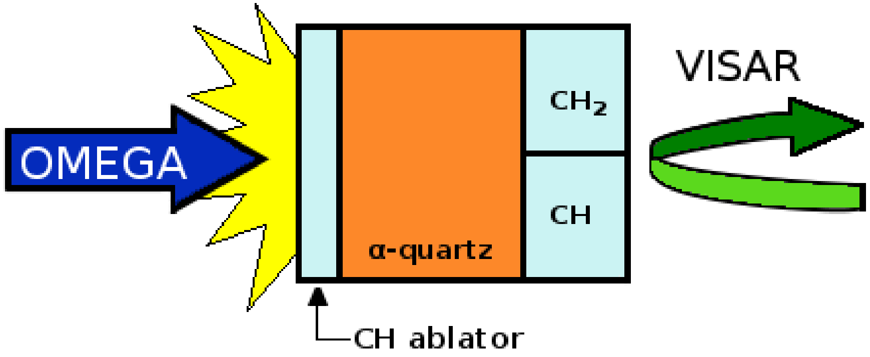
OMEGA experiments are integral to an ignition demonstration on the NIF.

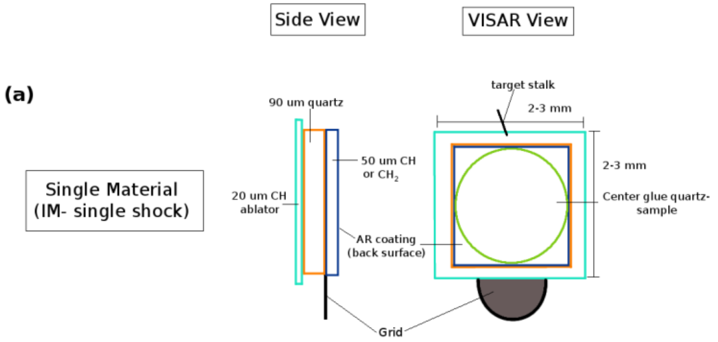
A strong shock can be generated using a high power laser

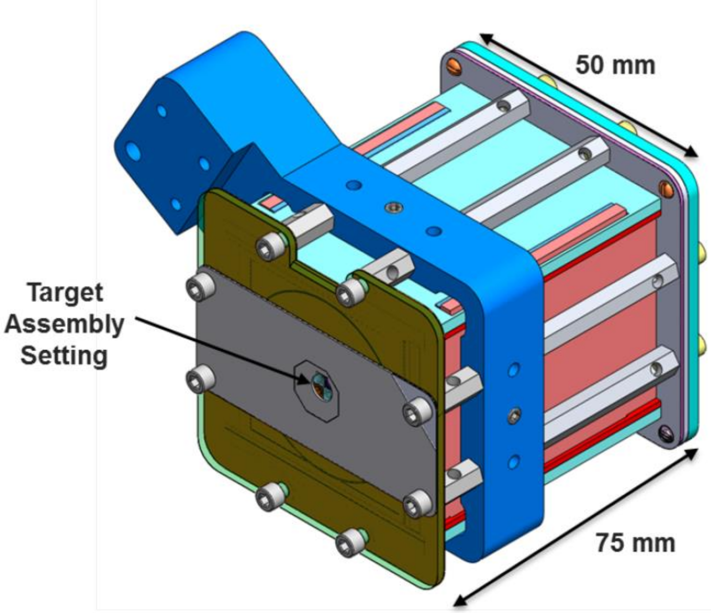


LLE viewgraph database
Danae Nicole Polsin, PhD Thesis, U of Rochester, 2018

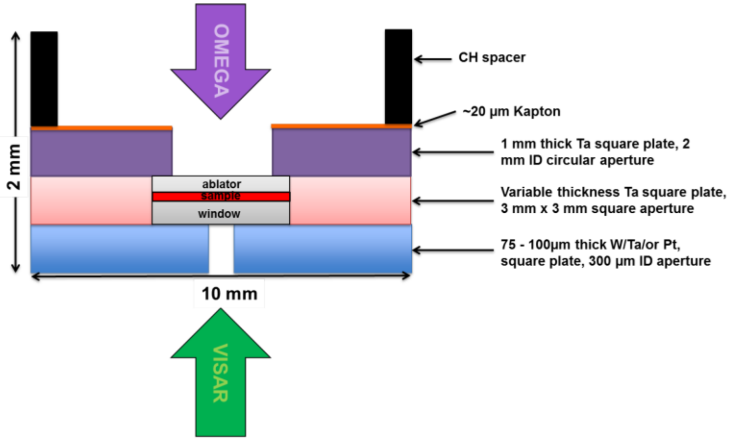
The powder x-ray diffraction image plate (PXRDIP) package for studying the shock phenomena





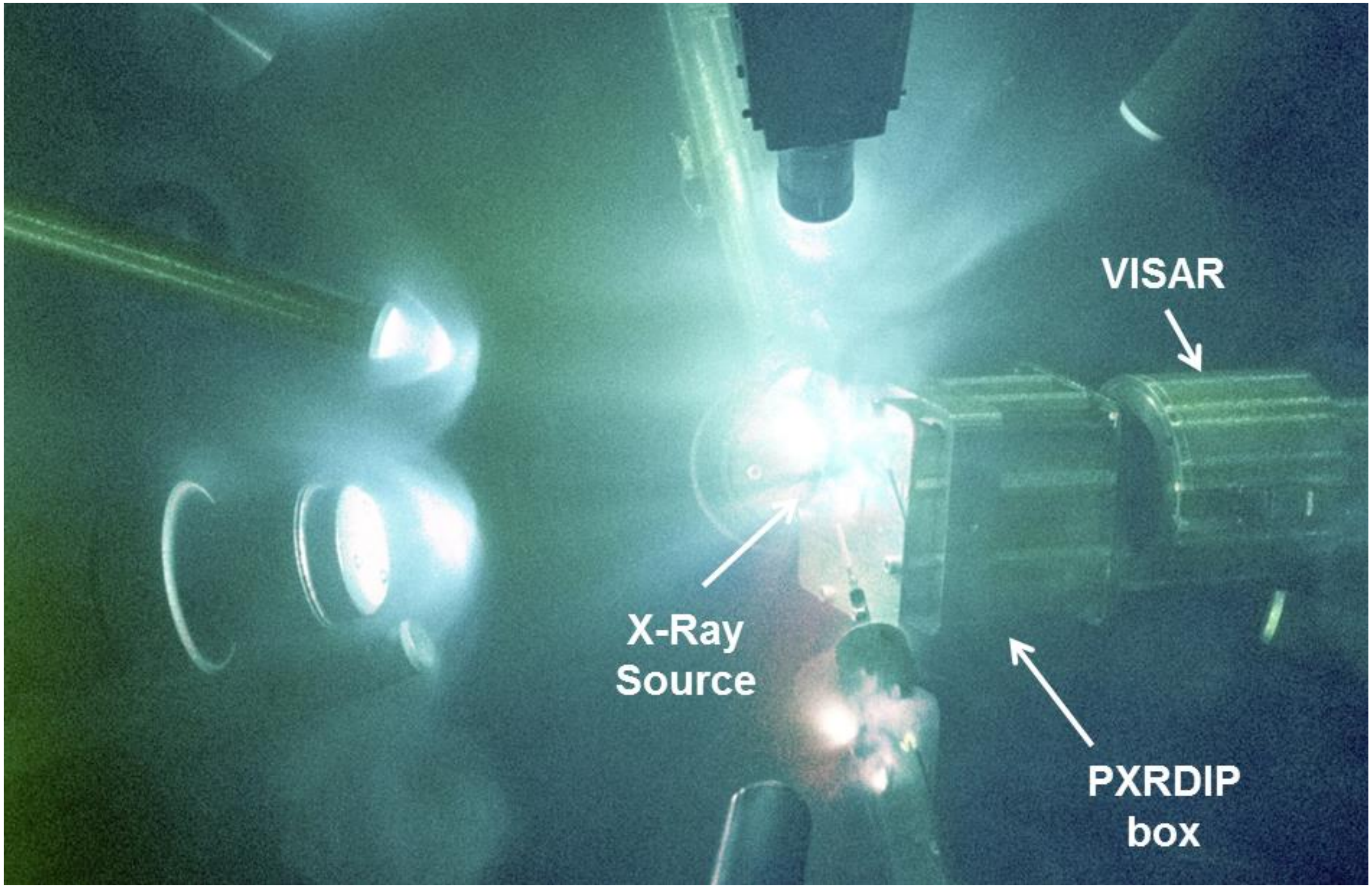


16 Omega beams



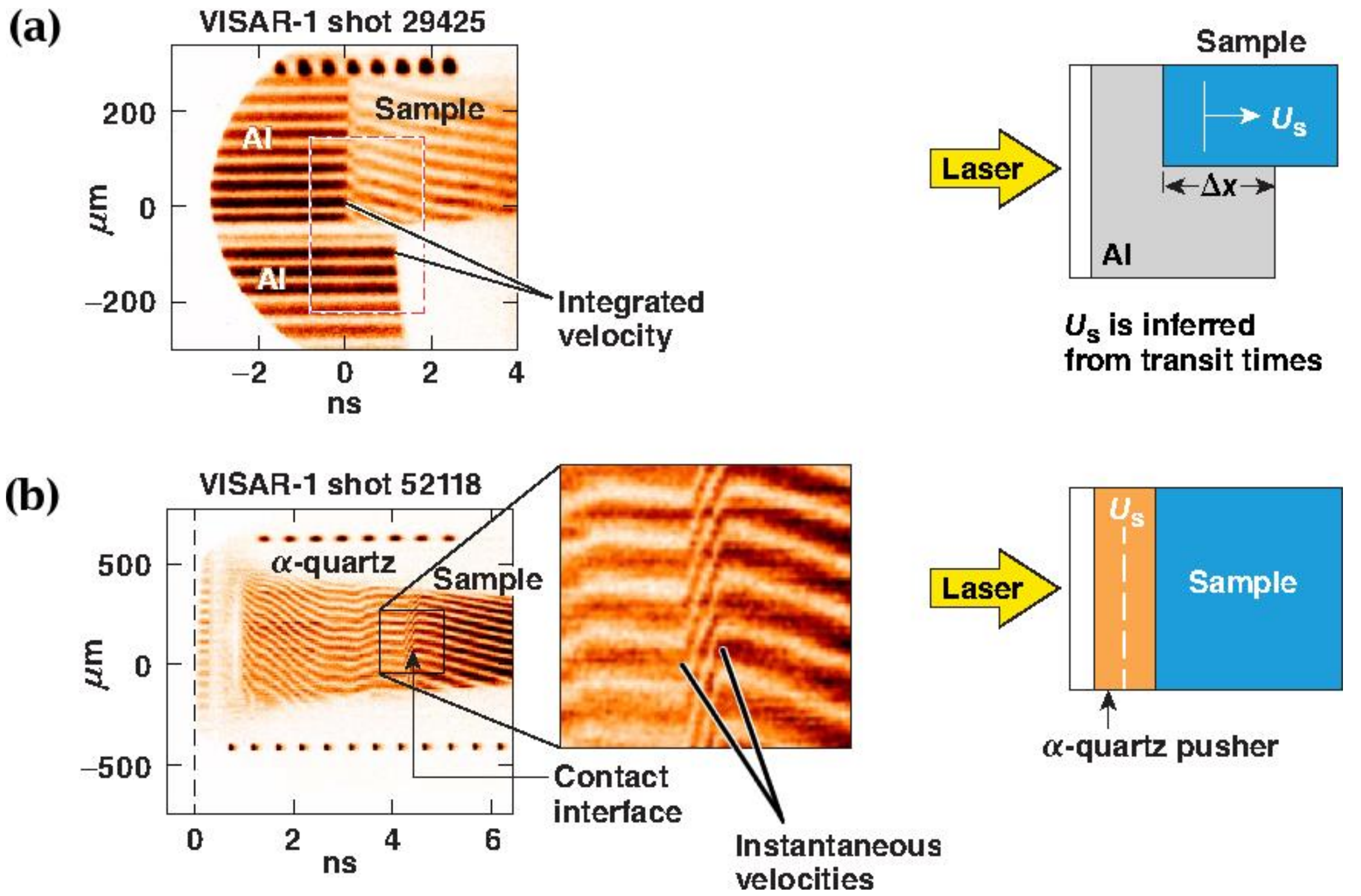
Maria Alejandra Barrios Garcia, PhD Thesis, U of Rochester, 2010
Danae Nicole Polsin, PhD Thesis, U of Rochester, 2018
J. R. Rygg, etc., Rev. Sci. Instrum. 83, 113904 (2012)

The PXRDIP box in the chamber



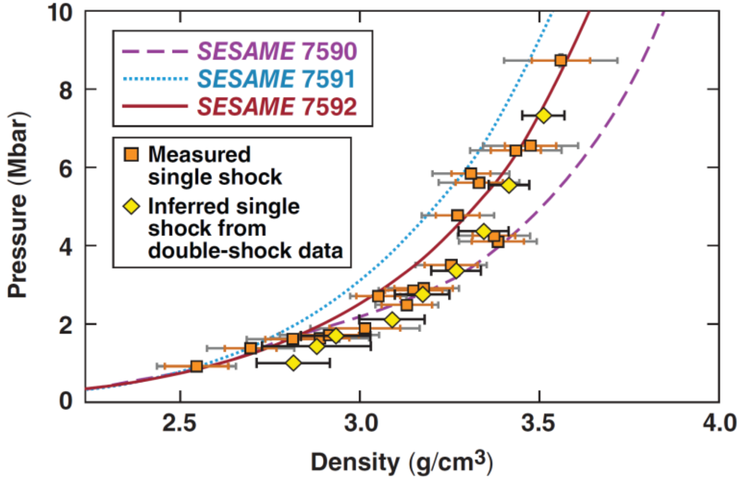
Danae Nicole Polsin, PhD Thesis, U of Rochester, 2018

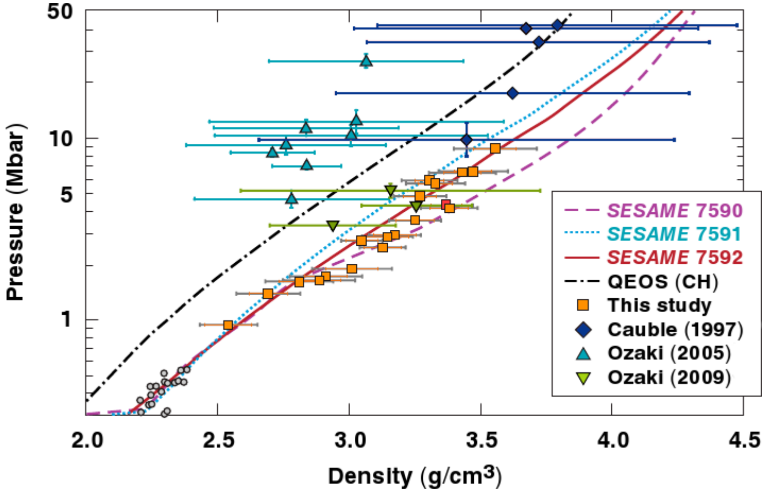
Interference pattern shifts when a shock breakouts

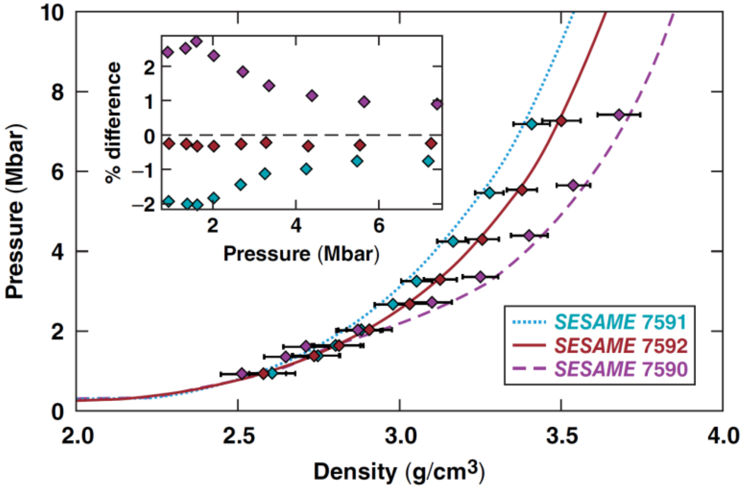


Maria Alejandra Barrios Garcia, PhD Thesis, U of Rochester, 2010

The pressure studied using high-power laser is in the range of 1 TPa (10 Mbar)

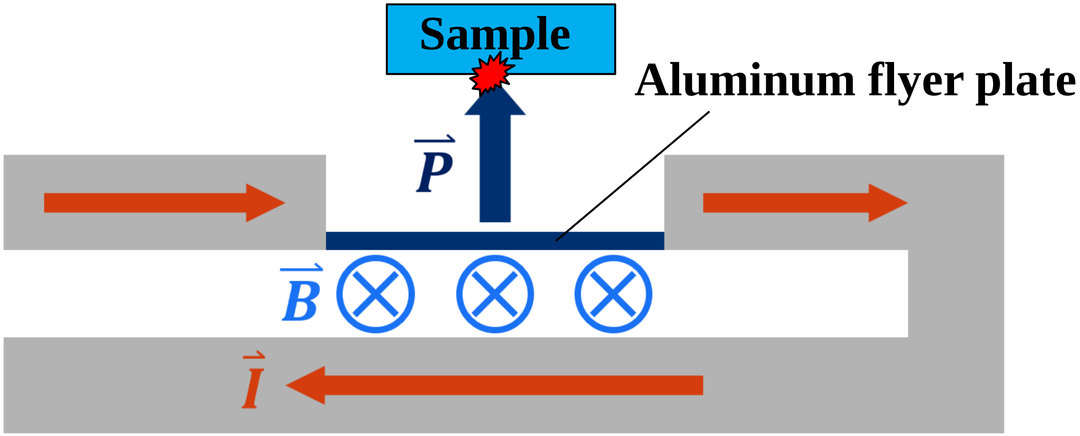


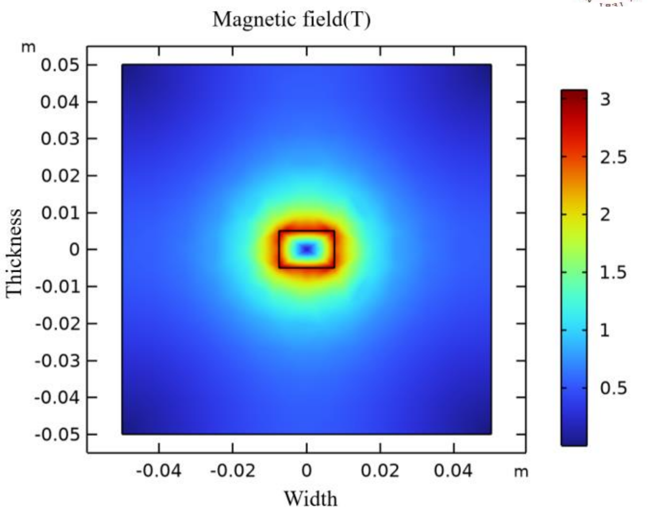


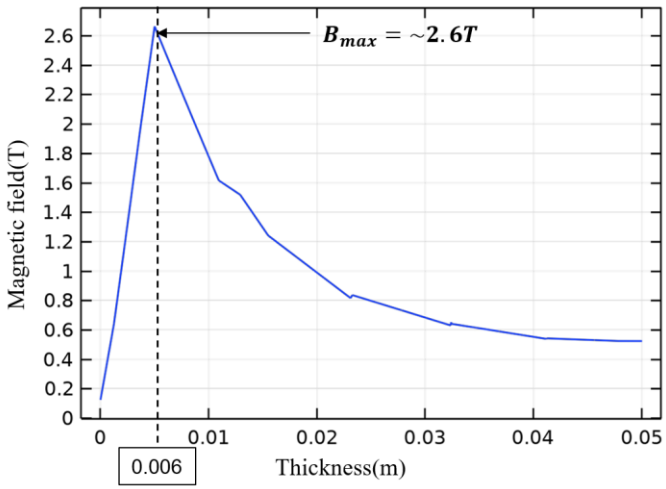


Maria Alejandra Barrios Garcia, PhD Thesis, U of Rochester, 2010

A flyer plate can be used to as the “piston” to generate the shock in a sample

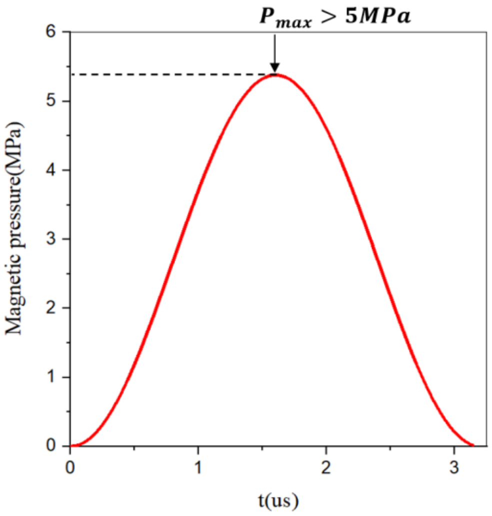




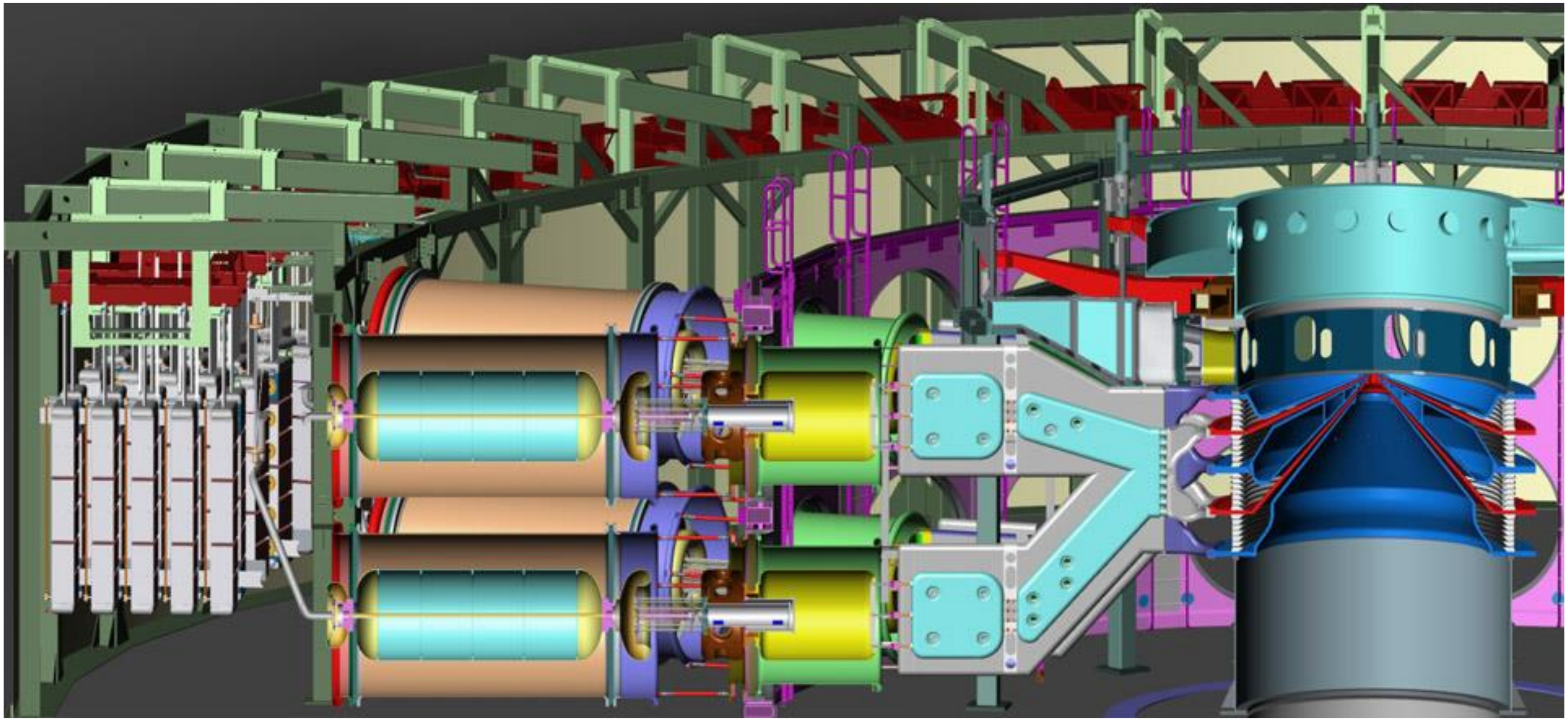


$$B = \frac{\mu_0 I}{w}$$

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



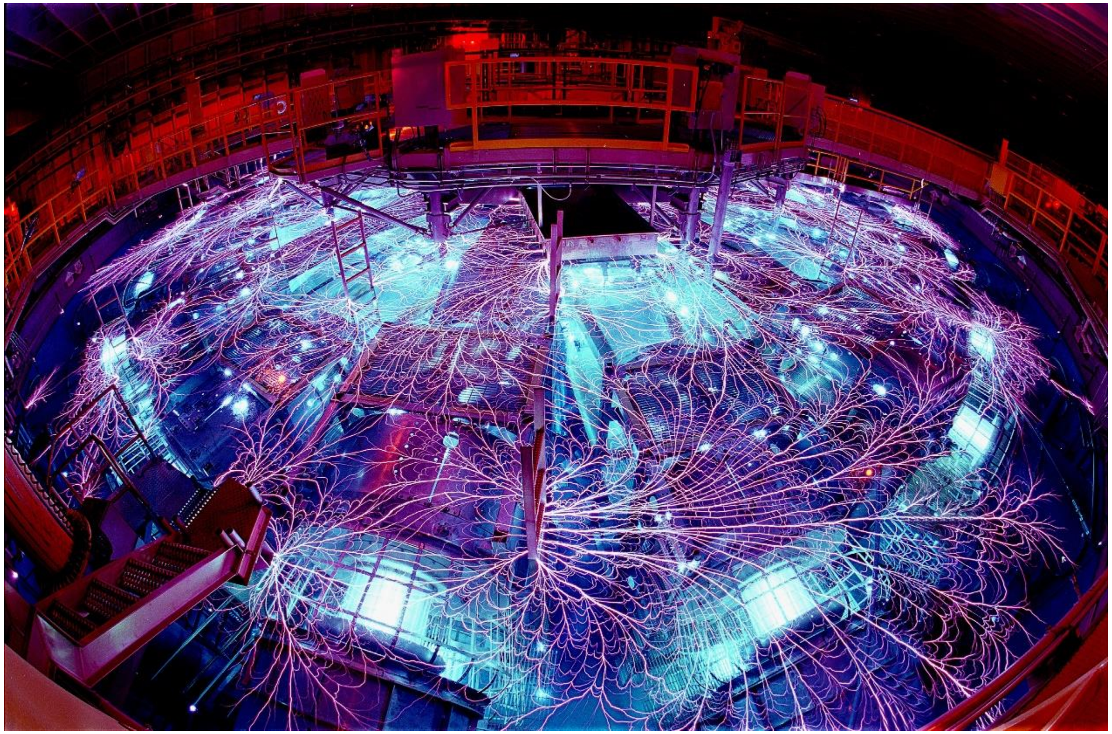
Sandia’s Z machine is the world's most powerful and efficient laboratory radiation source



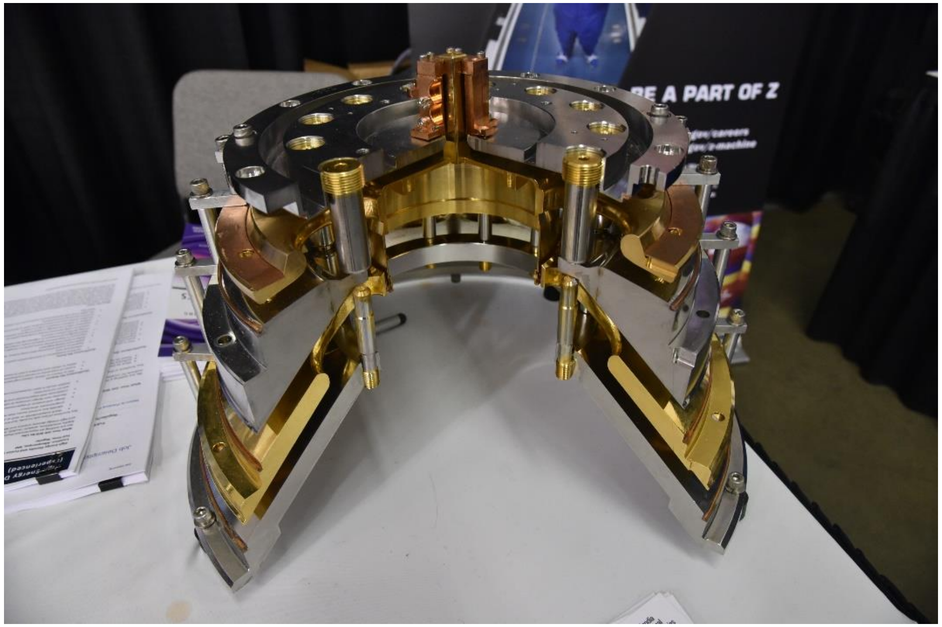
- Stored energy: 20 MJ
- Marx charge voltage: 85 kV
- Peak electrical power: 85 TW

- Peak current: 26 MA
- Rise time: 100 ns
- Peak X-ray emissions: 350 TW
- Peak X-ray output: 2.7 MJ

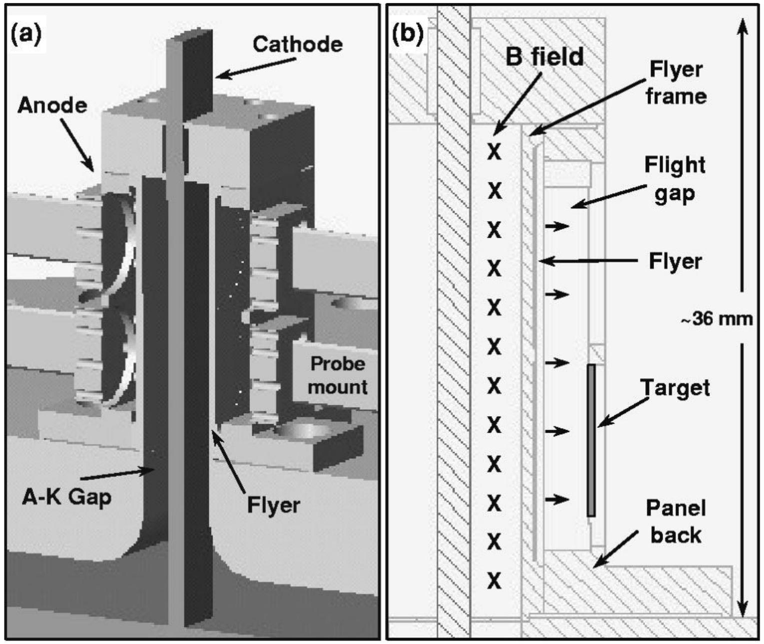
Z machine discharge



Z machine



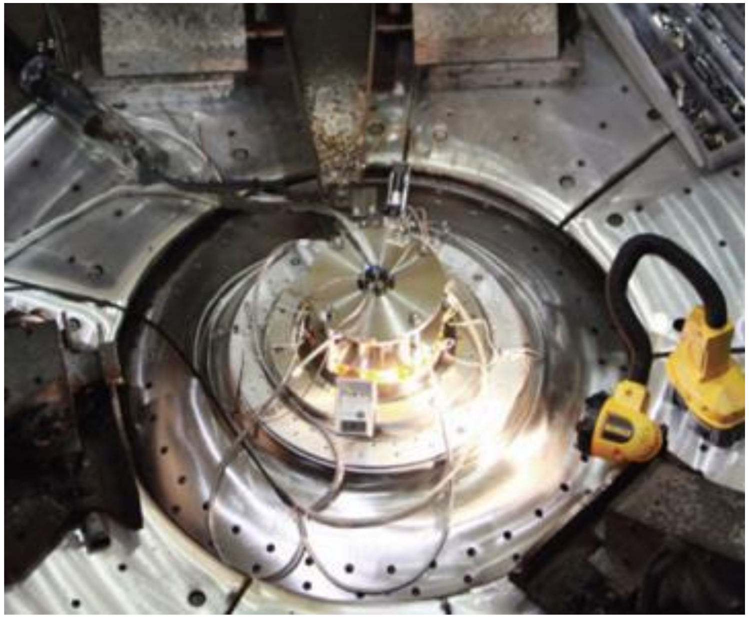
The flyer plate used in the Z machine



M. D. Knudson, etc., J. Applied Physics 94, 4420 (2003)
https://newsreleases.sandia.gov/releases/2005/nuclear-power/z-saturn.html
Pulsed Power Driven Experiments in the Institute of Shock Physics, by Simon Bland

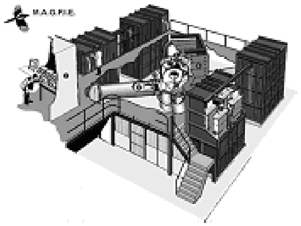
Before and after shots

- **Before shots**



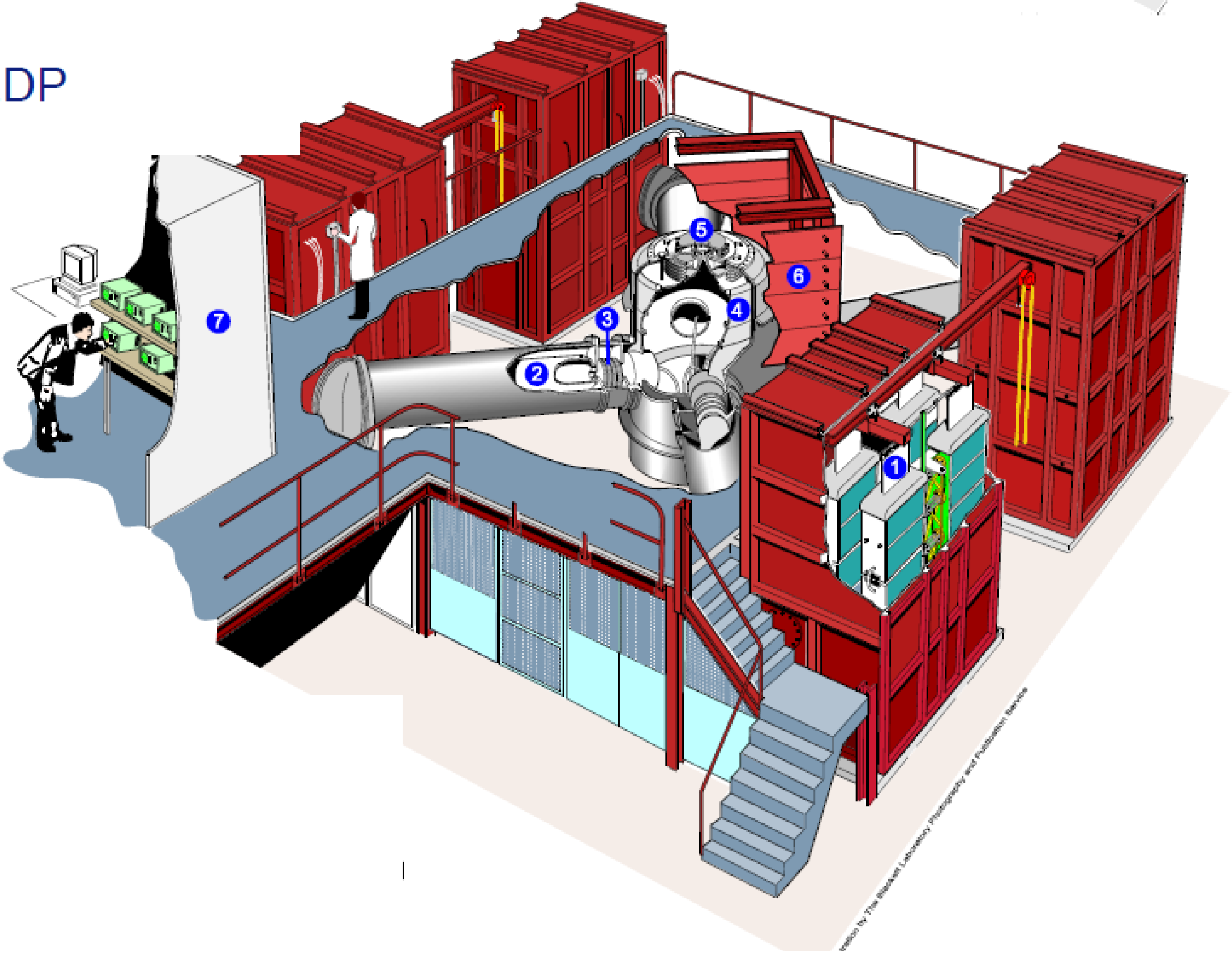
- **After shots**

SAND2017-0900PE_The sandia z machine - an overview of the world's most powerful pulsed power facility.pdf



Imperial College MAGPIE facility

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



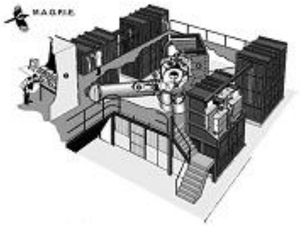
ation by The Blackett Laboratory Photography and Publication Service

Mega
Ampere
Generator for
Plasma
Implosion
Experiments

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

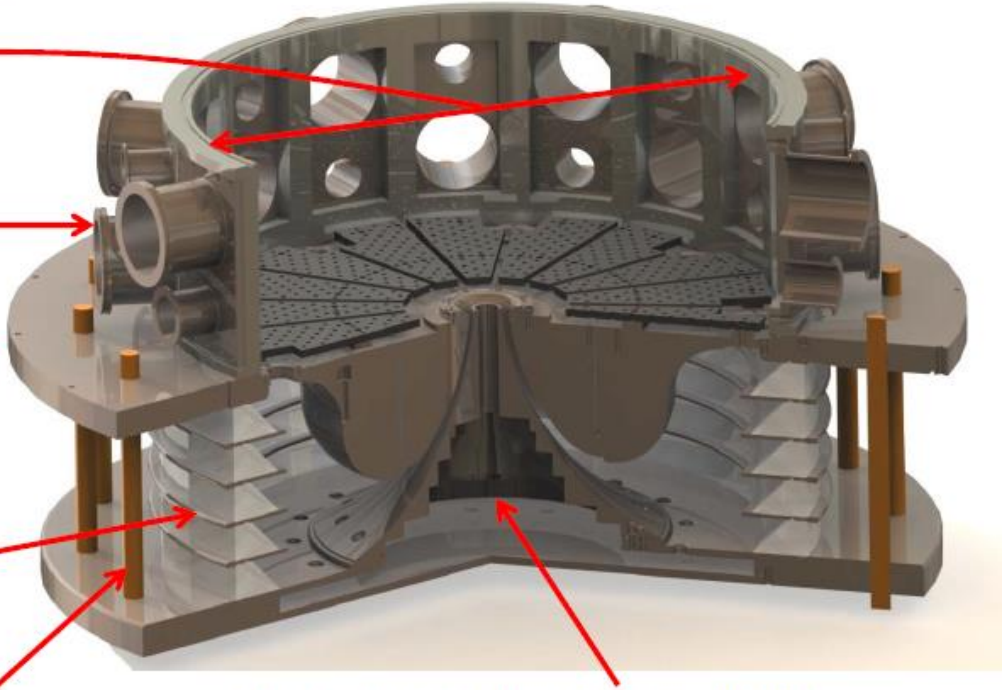


Prelude to experiments: new power feed and vacuum chamber

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

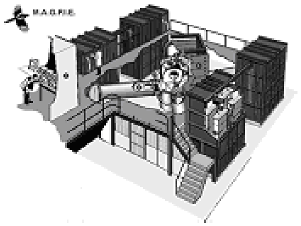
Rexolite diode rings
increase strength reduce
water absorption

New Torlon bolts don't stretch

Vacuum section below MITL
removes force on cathode

Anode and cathode now move ~25um

Vacuum time <1hr



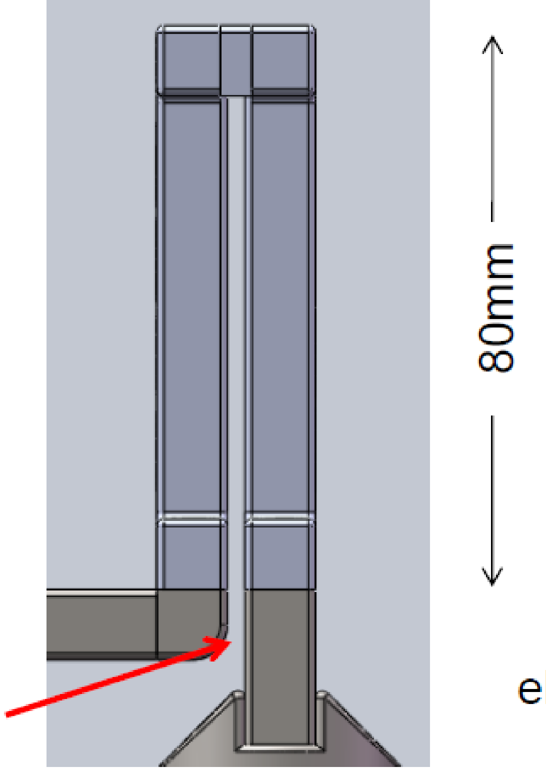
Initial experiments: Feb 2010

Design and manufacturing issues:

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

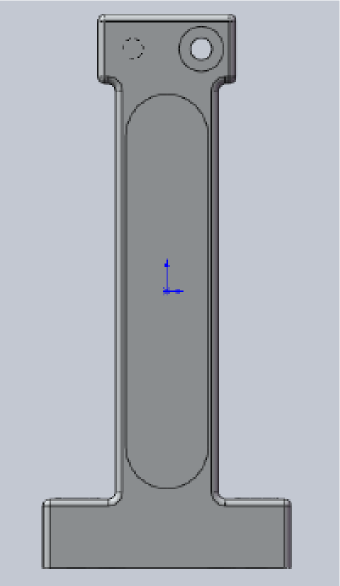
EM simulations difficult due to large scale of electrodes c.f. gap in stripline...

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



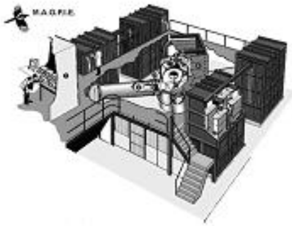
1 – 2 mm gap in stripline
voltages ~200kV

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



Initial experiments: Feb 2010

Typically for shock experiments:

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

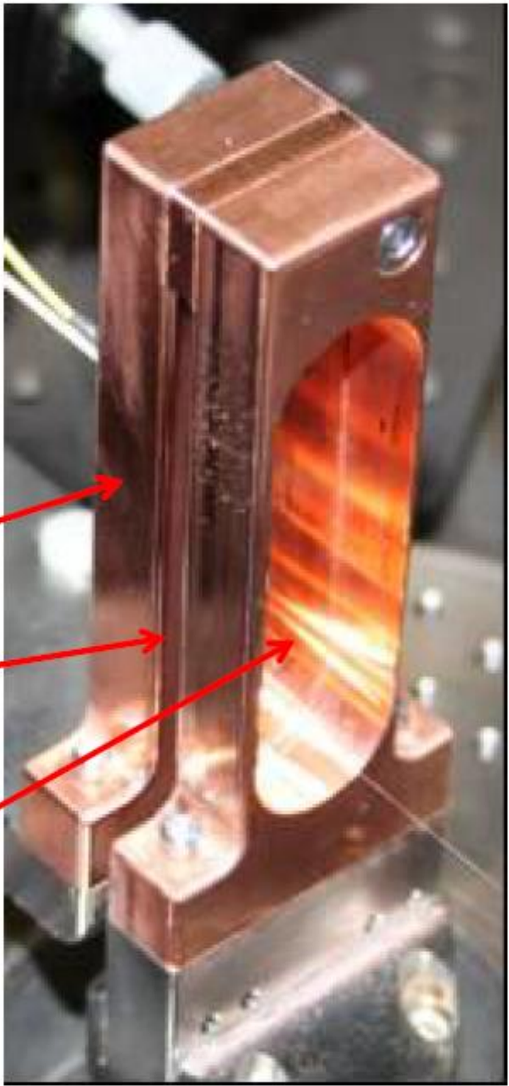
Overkill for initial experiments (and very expensive)

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



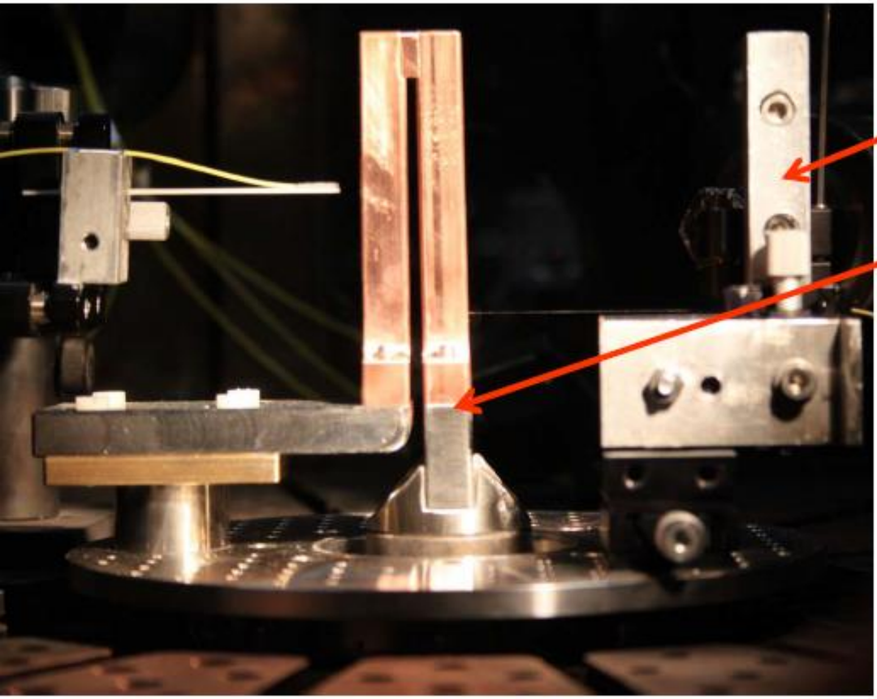
Return electrode

Gap (2mm)

Target area
(60x17mm)

Close up of 20mm wide copper
strip line in MAGPIE

Initial experiments: Feb 2010

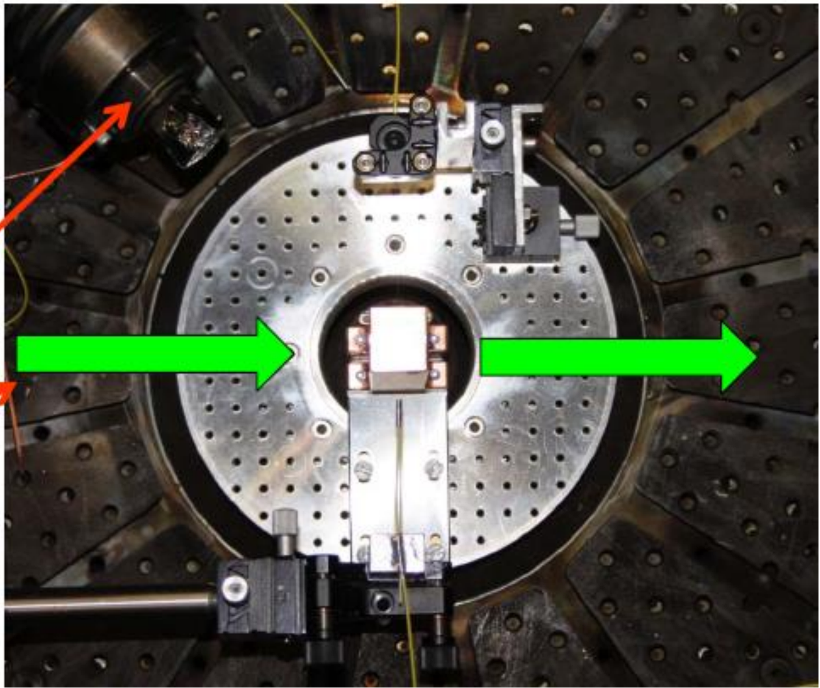


Holder for Het-V probes

Stripline mounted on break away system to prevent damage to MAGPIE

Side view of strip line

Top down view

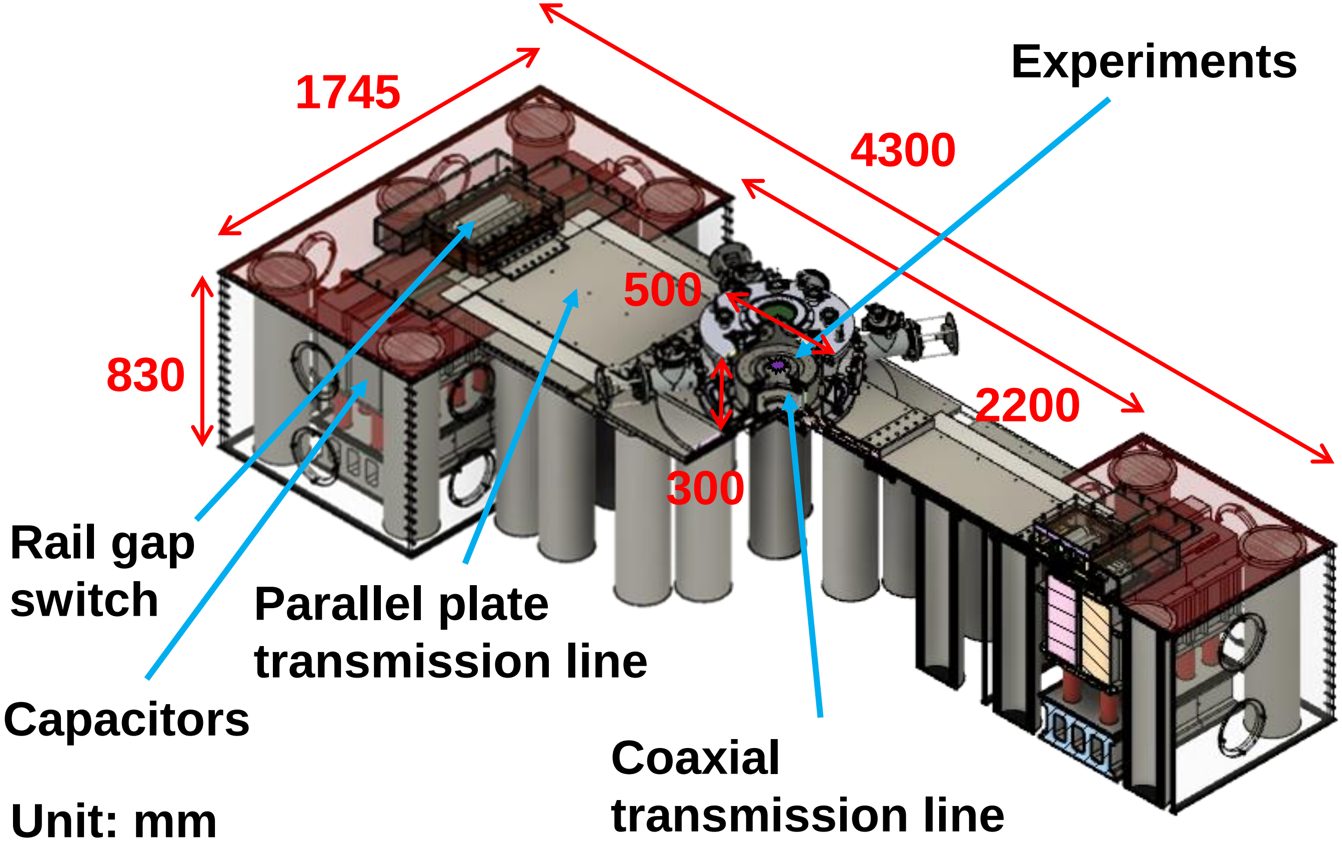


Resistive voltage probe

Path of probing laser

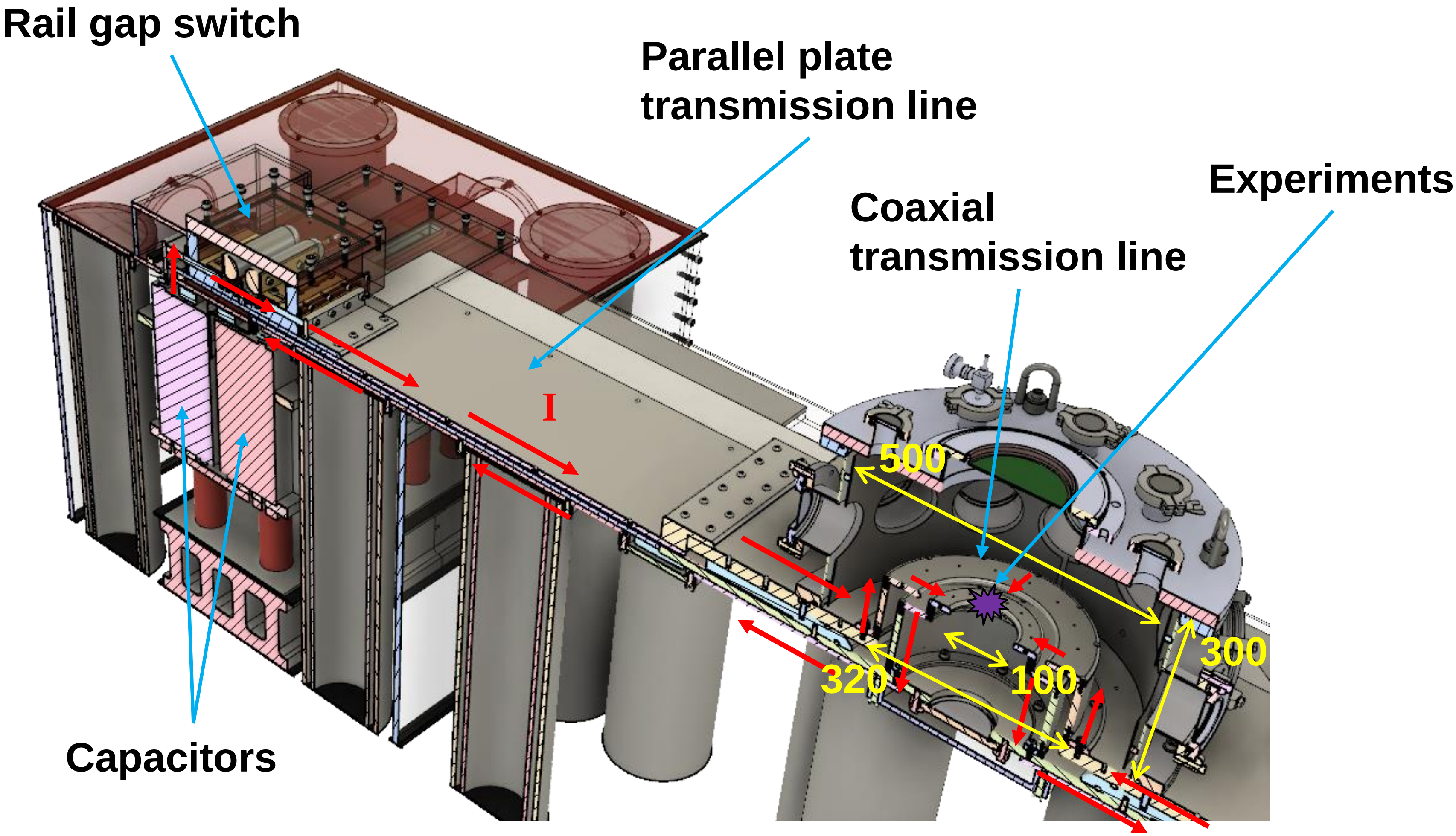
½ inch armoured plate top and bottom to 'catch' stripline (not shown)

The pulsed-power system was built by only students



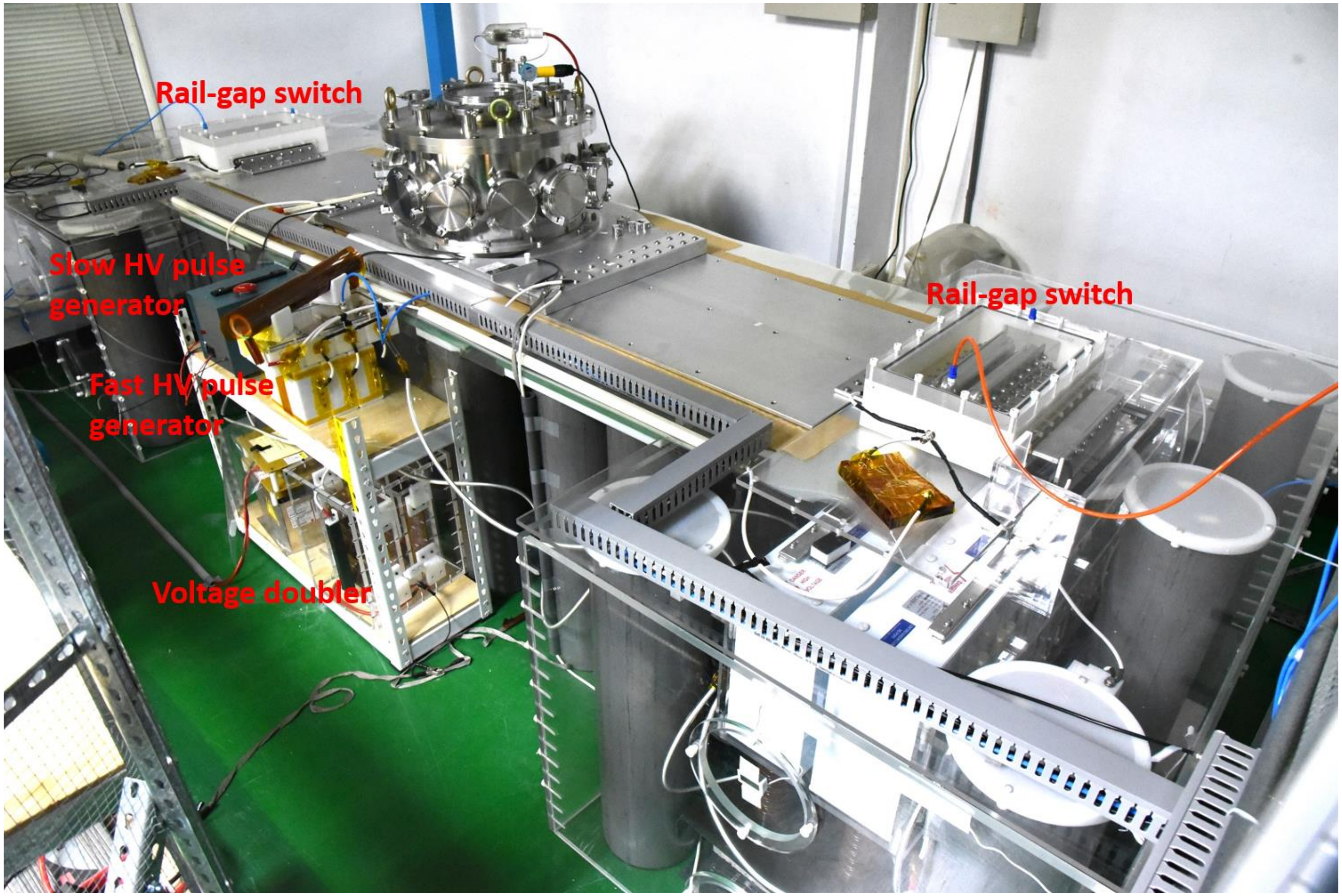
- **A 1 kJ pulsed-power system at ISAPS, NCKU started being operated since September, 2019.**

Experiments will be taken placed at the center of the vacuum chamber

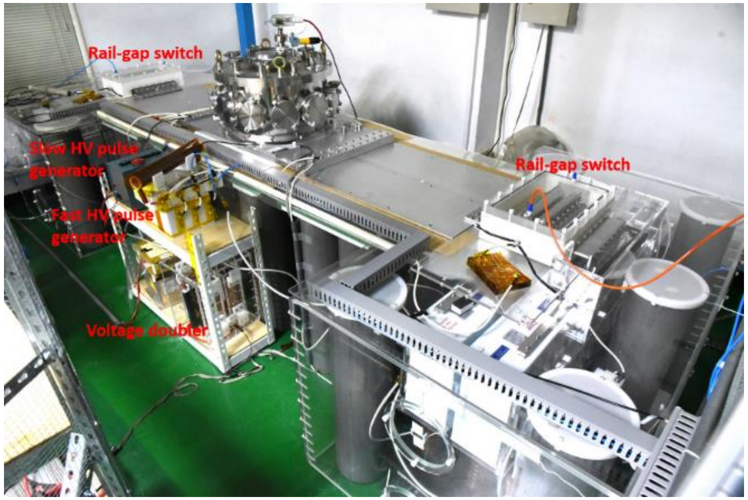


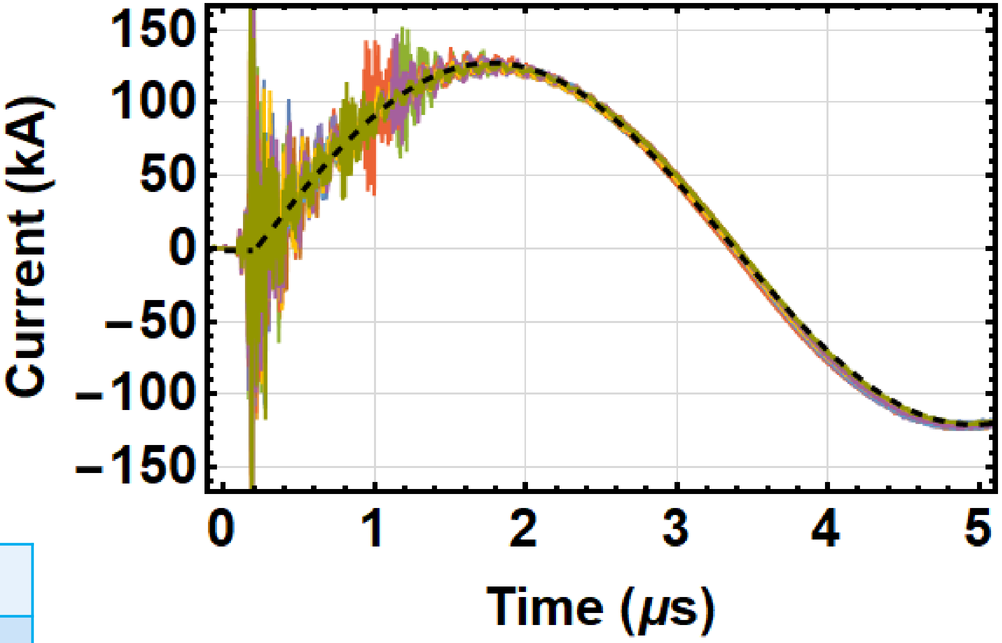
Unit: mm

The 1-kJ pulsed-power system



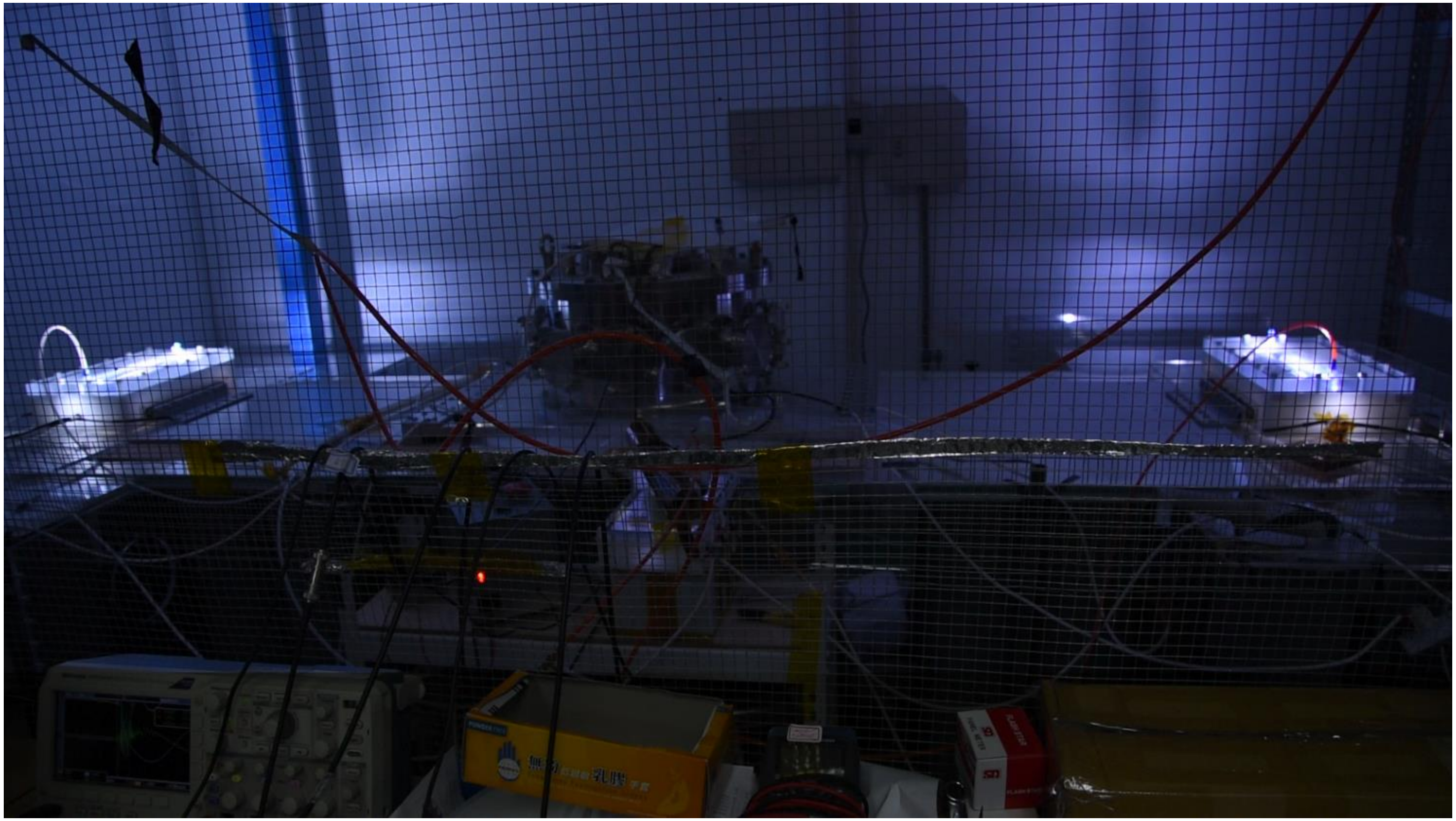
A peak current of ~135 kA with a rise time of ~1.6 us is provided by the pulsed-power system



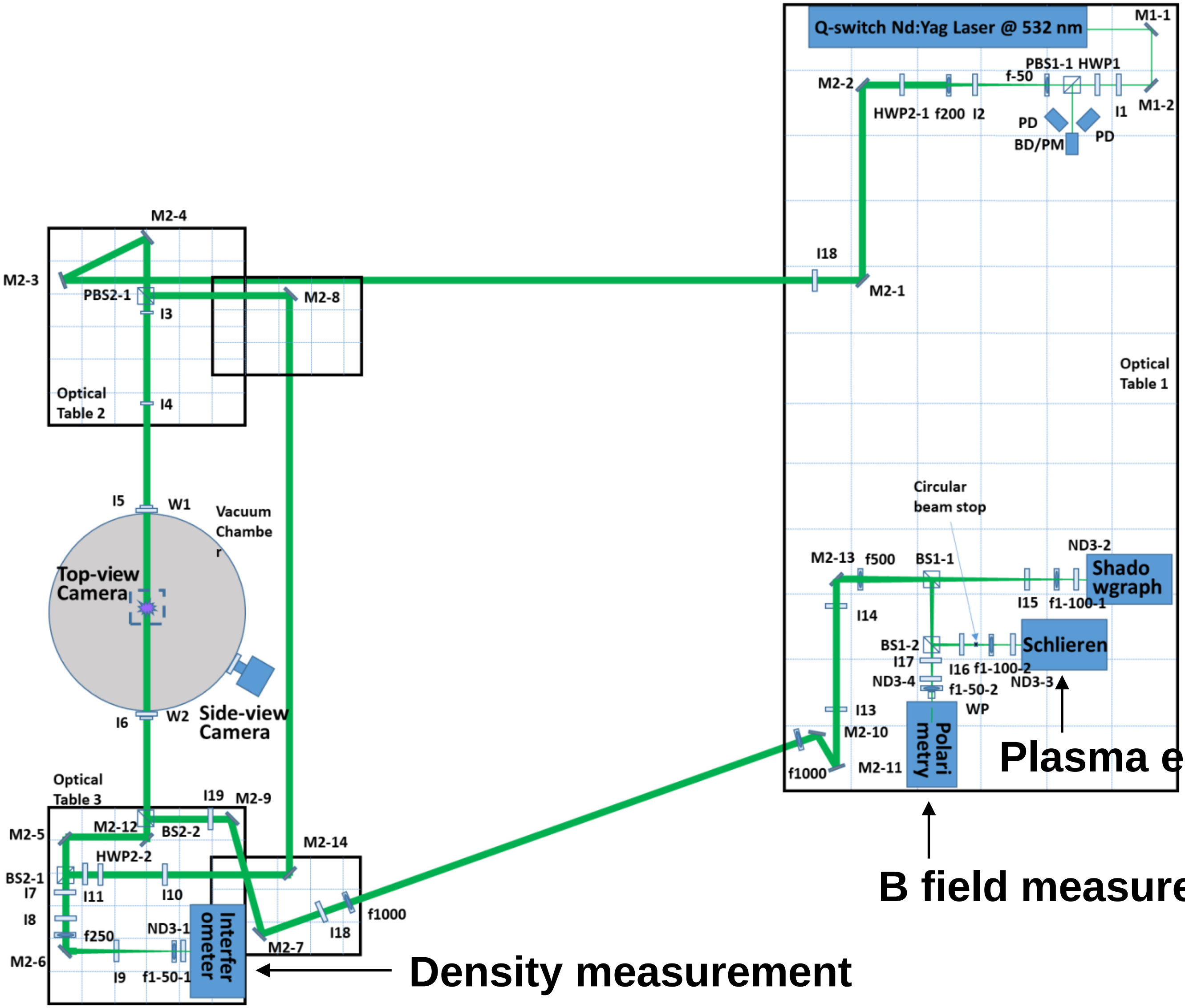


Capacitance (μF)	5
V_{charge} (kV)	20
Energy (kJ)	1
Inductance (nH)	204 ± 4
Rise time (quarter period, ns)	1592 ± 3
I_{peak} (kA)	135 ± 1

First shot with two synchronized rail-gap switches



Time-resolved imaging system with temporal resolution in the order of nanoseconds was implemented

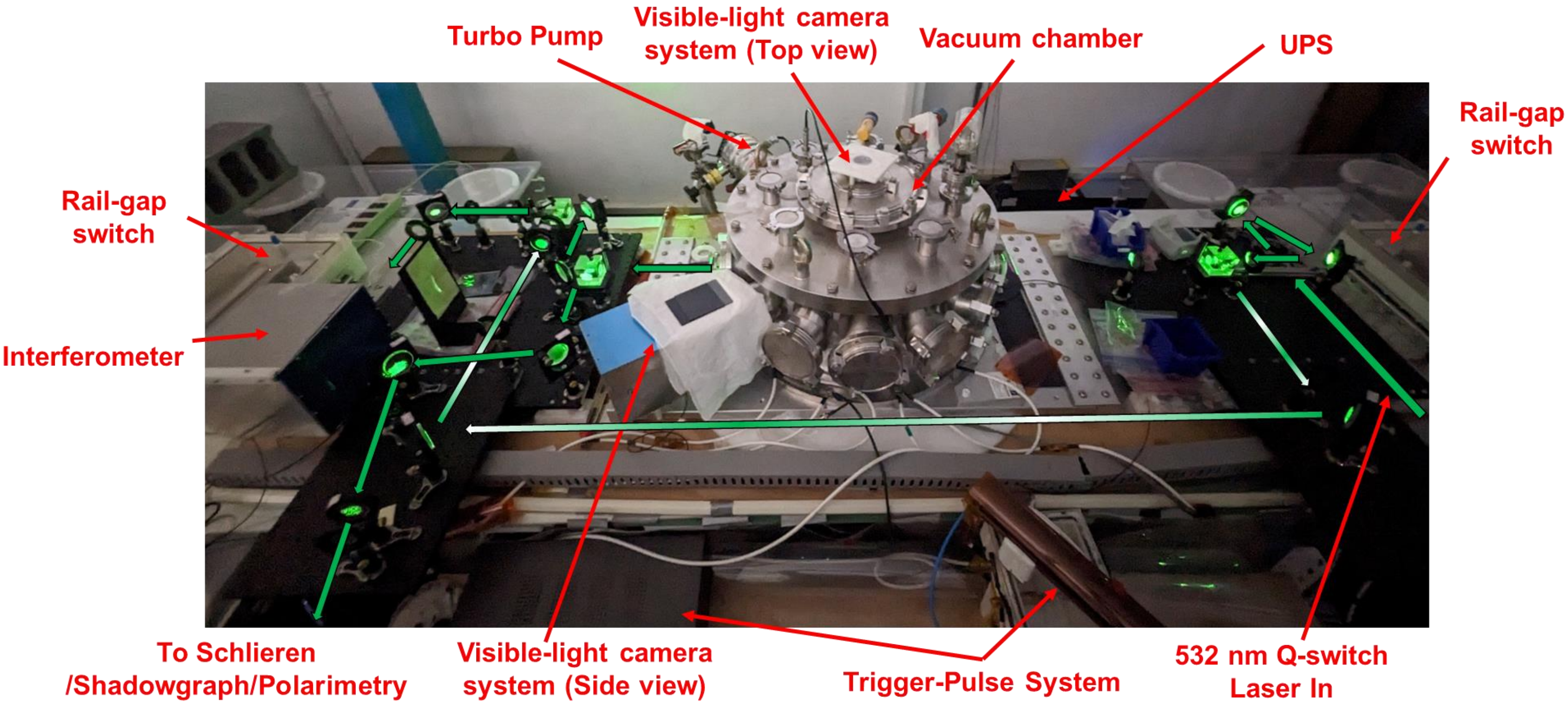


Plasma edge detection

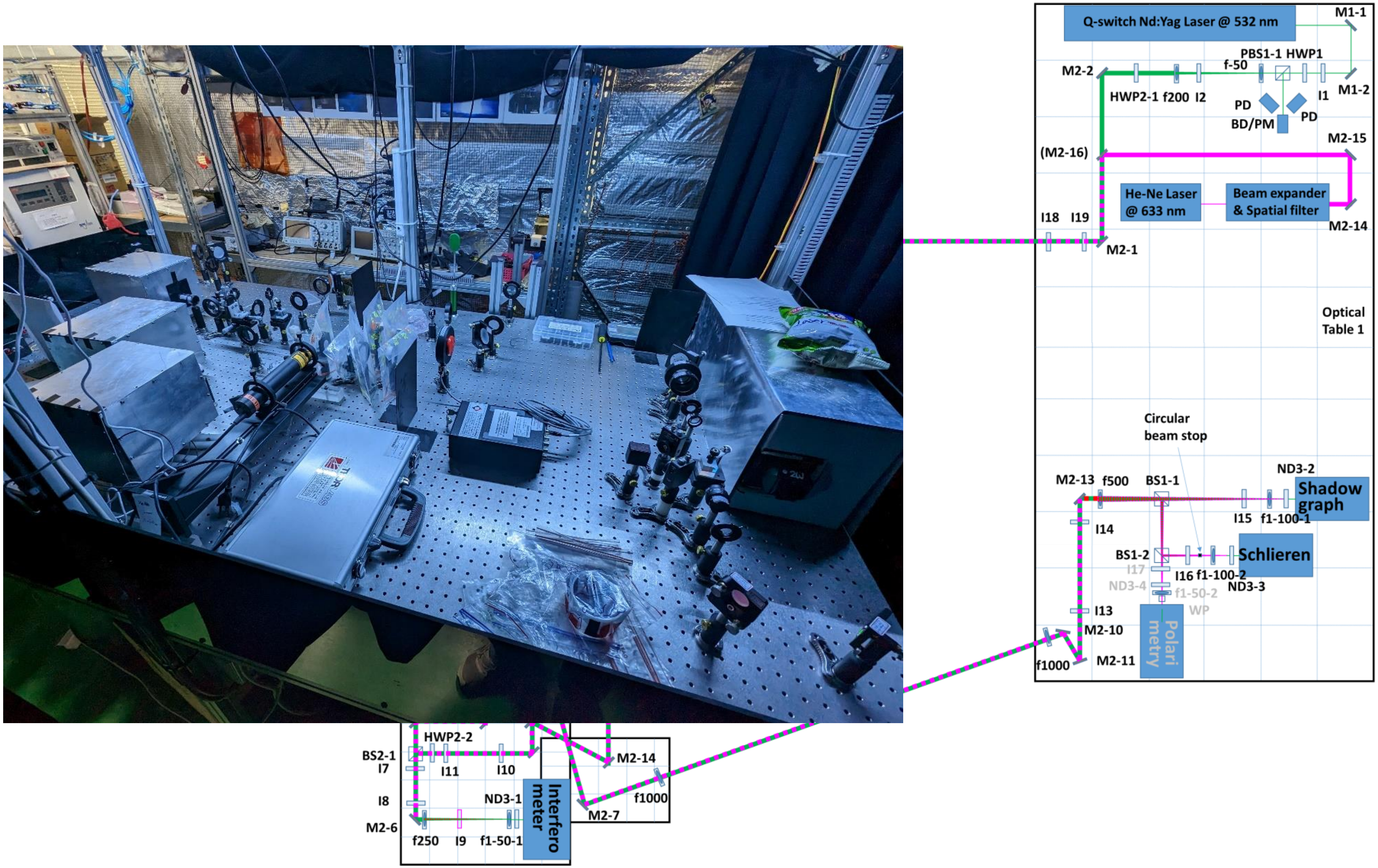
B field measurement

Density measurement

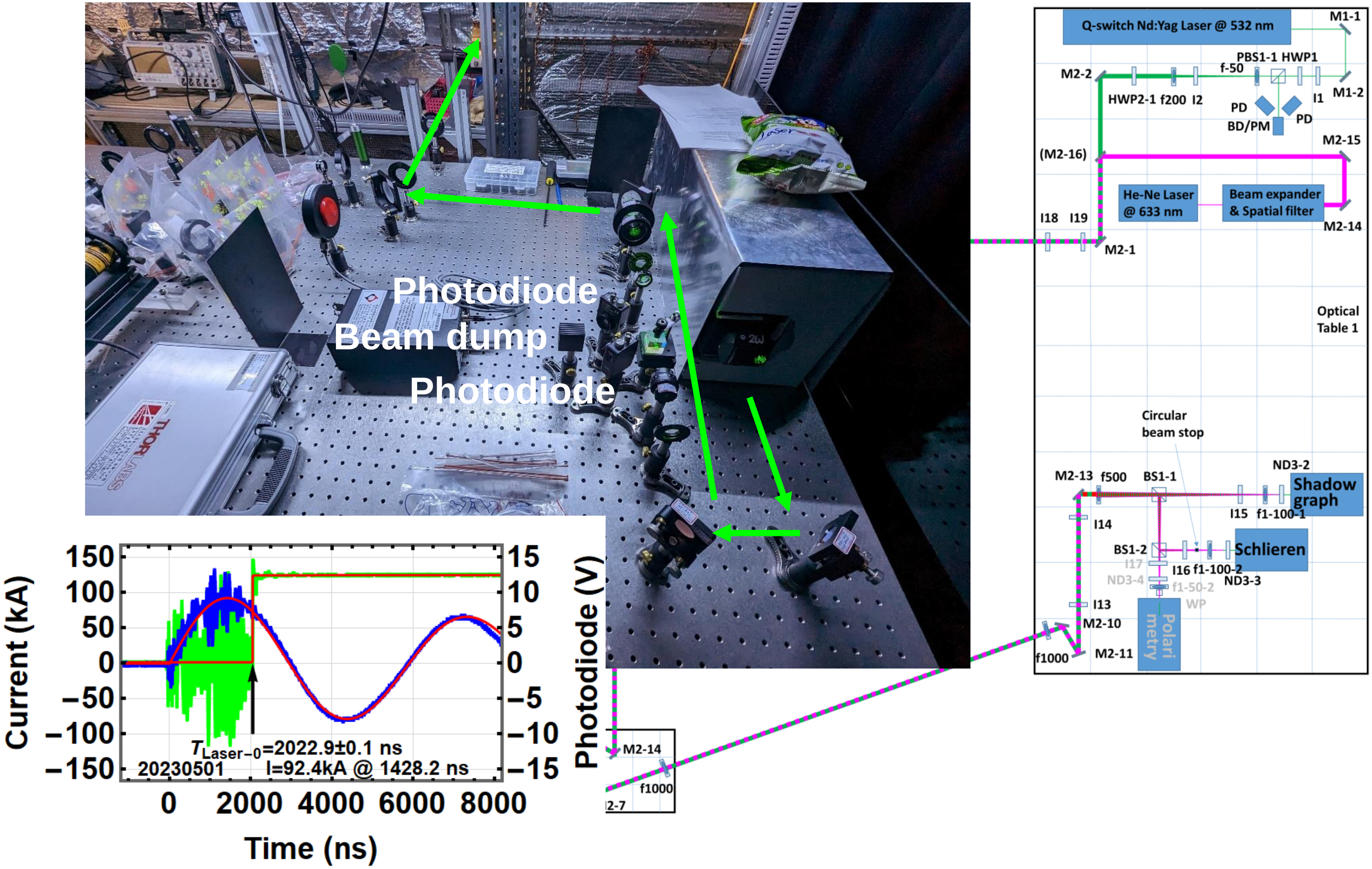
Varies diagnostics were integrated to the system



Beam path


Q-switch Nd:Yag Laser @ 532 nm
M1-1
PBS1-1
HWP1
f-50
M2-2
M1-2
HWP2-1
f200
I2
I1
PD
PD
BD/PM
M2-15
(M2-16)
He-Ne Laser @ 633 nm
Beam expander & Spatial filter
I18
I19
M2-14
M2-1
Optical Table 1
Circular beam stop
ND3-2
M2-13
f500
BS1-1
Shadow graph
I14
I15
f1-100-1
BS1-2
Schlieren
I17
I16
f1-100-2
ND3-4
f1-50-2
ND3-3
WP
I13
M2-10
Polari metry
f1000
M2-11
HWP2-2
BS2-1
I7
I11
I10
M2-14
I8
ND3-1
Interfero meter
f1000
M2-6
M2-7
f250
I9
f1-50-1

Beam path


Photodiode
Beam dump
Photodiode
Current (kA)
Photodiode (V)
Time (ns)
150
100
50
0
−50
−100
−150
15
10
5
0
−5
−10
−15
0
2000
4000
6000
8000
$T_{Laser-0}$=2022.9±0.1 ns
20230501
I=92.4kA @ 1428.2 ns
Q-switch Nd:Yag Laser @ 532 nm
M1-1
PBS1-1 HWP1
M2-2
f-50
HWP2-1 f200 I2
I1
M1-2
PD
PD
BD/PM
M2-15
(M2-16)
He-Ne Laser @ 633 nm
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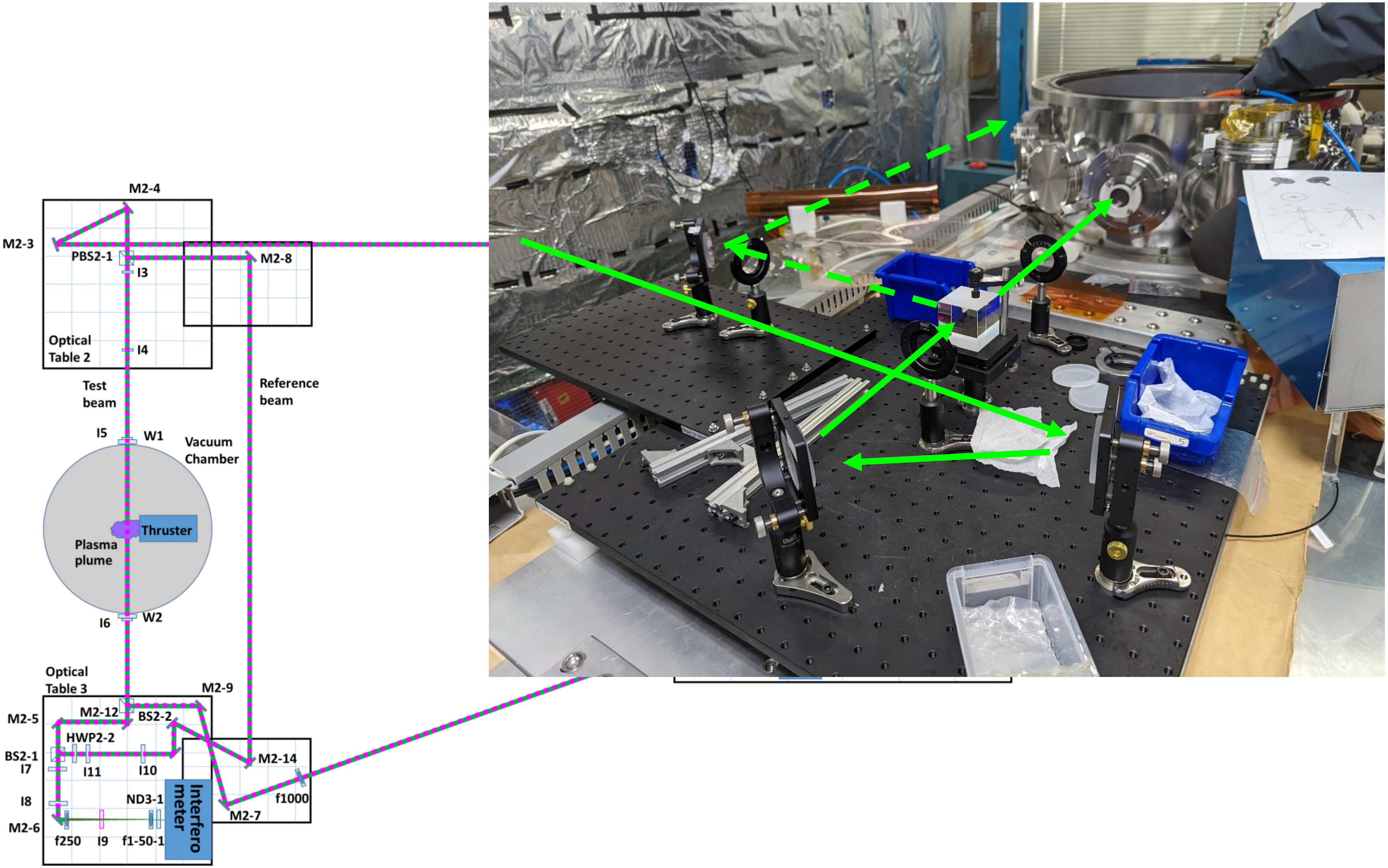
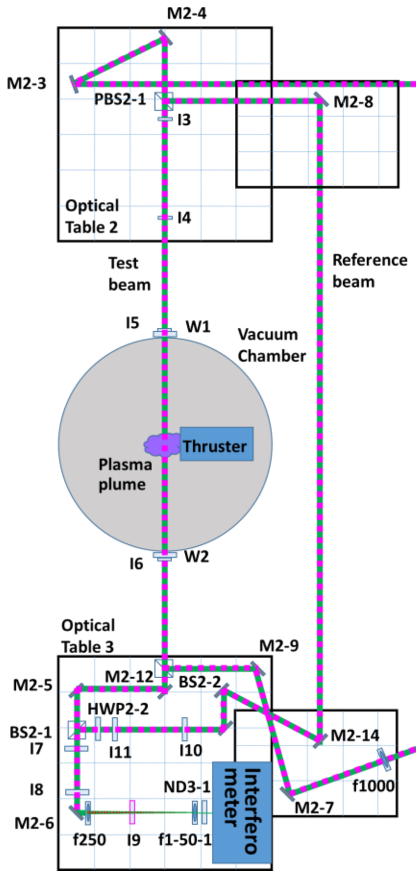
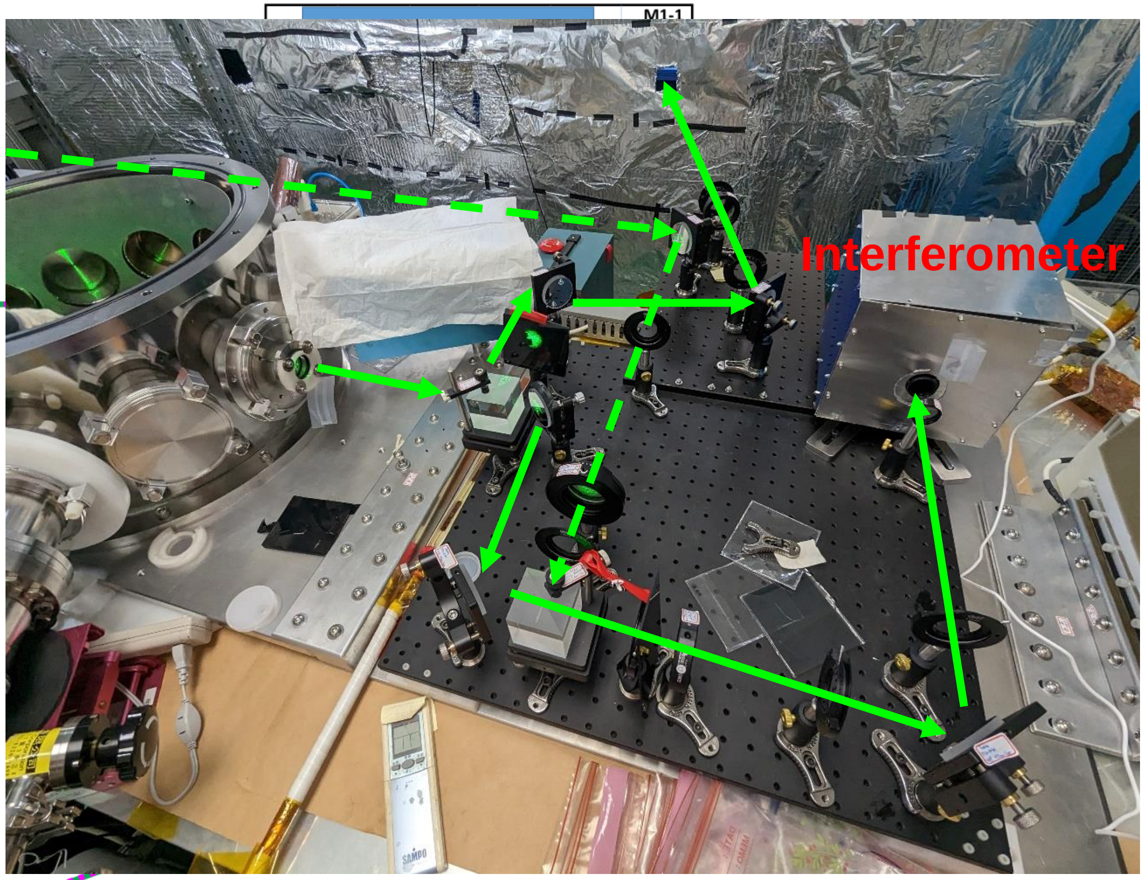
BS1-2
Schlieren
I17
I16 f1-100-2
ND3-4
f1-50-2
ND3-3
WP
I13
M2-10
Polari metry
f1000
M2-11
M2-14
f1000
2-7

Beam path

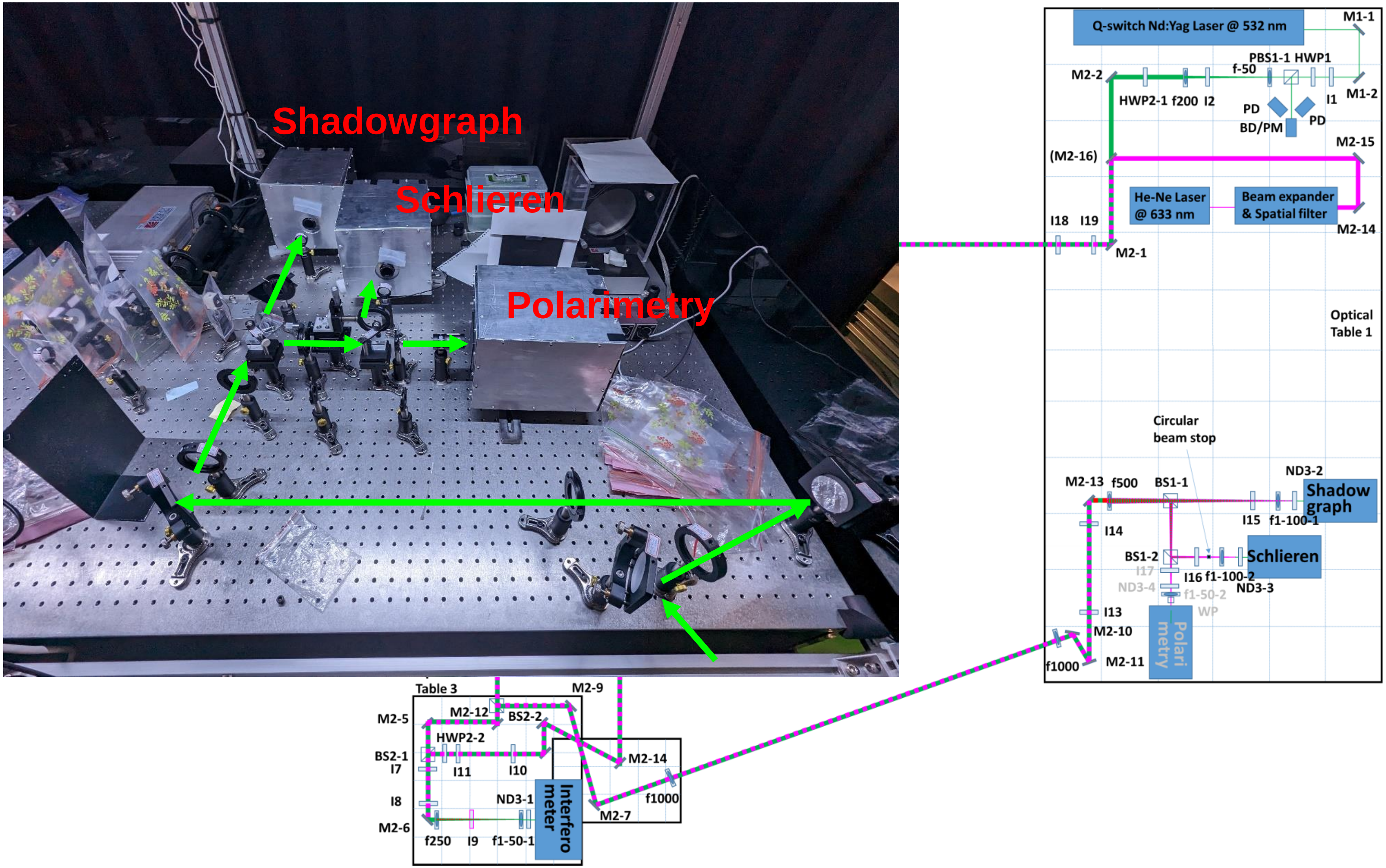

M2-4
M2-3
PBS2-1
I3
M2-8
Optical Table 2
I4
Test beam
Reference beam
I5
W1
Vacuum Chamber
Thruster
Plasma plume
I6
W2
Optical Table 3
M2-9
M2-5
M2-12
BS2-2
HWP2-2
BS2-1
I7
I11
I10
M2-14
f1000
I8
ND3-1
Interfero meter
M2-7
M2-6
f250
I9
f1-50-1

Beam path


M2-4
M2-3
PBS2-1
I3
M2-8
Optical Table 2
I4
Test beam
Reference beam
I5
W1
Vacuum Chamber
Thruster
Plasma plume
I6
W2
Optical Table 3
M2-9
M2-5
M2-12
BS2-2
HWP2-2
BS2-1
I7
I11
I10
M2-14
I8
ND3-1
Interfero meter
f1000
M2-7
M2-6
f250
I9
f1-50-1


M1-1
Interferometer

Beam path


Shadowgraph
Schlieren
Polarimetry
Q-switch Nd:Yag Laser @ 532 nm
M1-1
PBS1-1 HWP1
f-50
M2-2
HWP2-1 f200 I2
I1
M1-2
PD
PD
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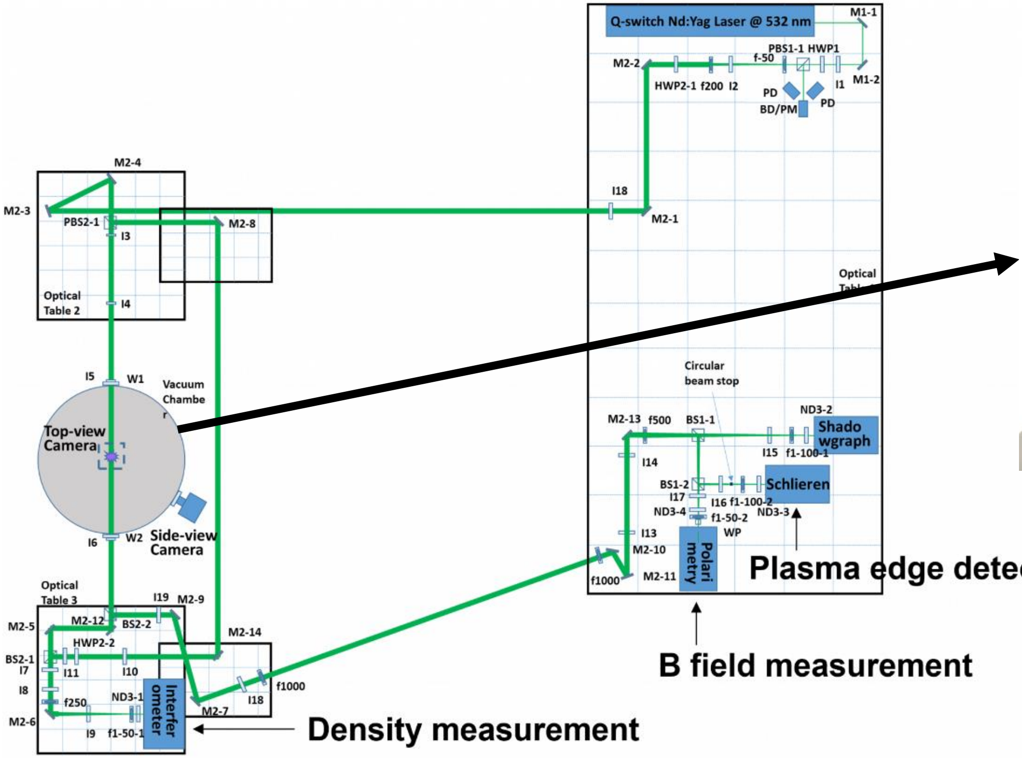
Schlieren
I17
I16 f1-100-2
ND3-4
ND3-3
f1-50-2
WP
I13
M2-10
Polari metry
f1000
M2-11
Table 3
M2-9
M2-5
M2-12
BS2-2
HWP2-2
BS2-1
I7
I11
I10
M2-14
I8
ND3-1
Interfero meter
f1000
M2-7
M2-6
f250 I9 f1-50-1

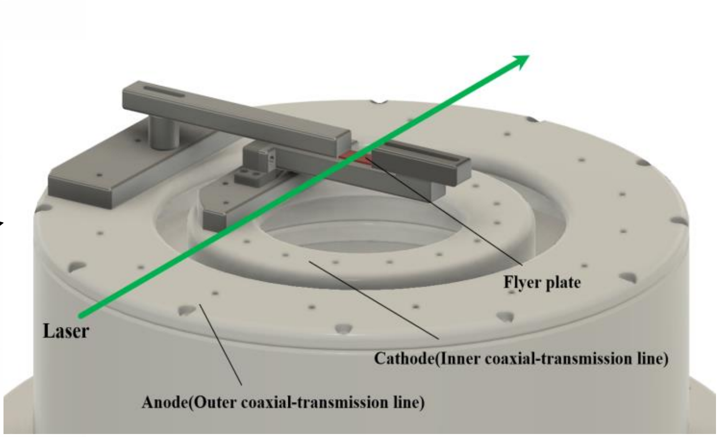
The design of our flyer-plate launcher

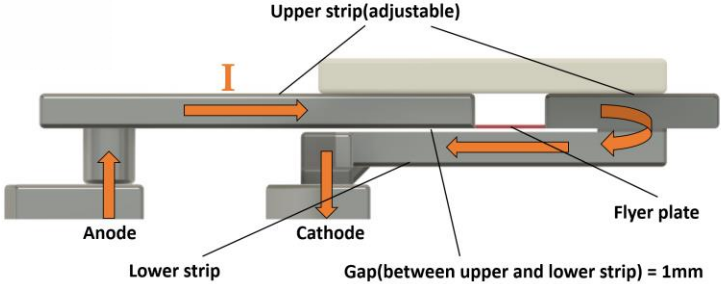


Plasma edge detection

B field measurement

Density measurement

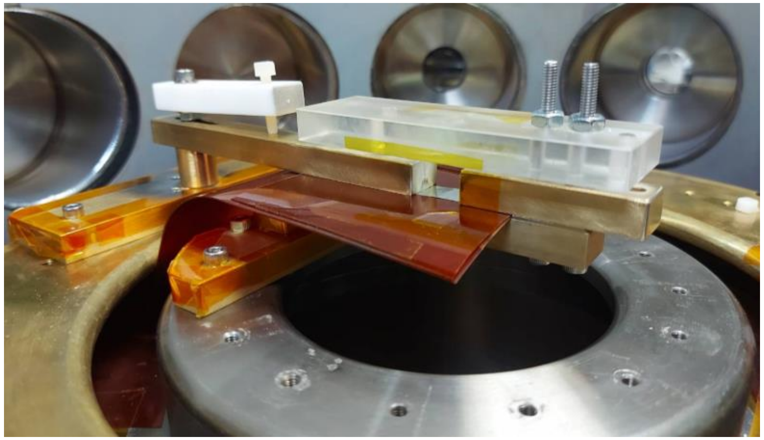




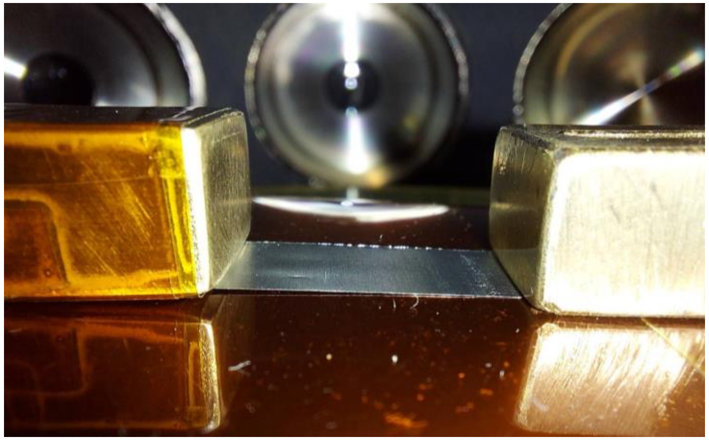
Y.-Z. Pan, Science day, College of Science, NCKU 2023
Y.-Z. Pan, Progress report, Pulsed-Plasma Laboratory 2023

Photos of our flyer-plate launcher

- **Assembly with target**

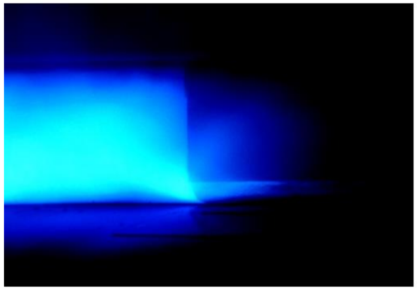


- **Assembly w/o target**



- **Self emission w/o a target**

- **Self emission w/ a target**

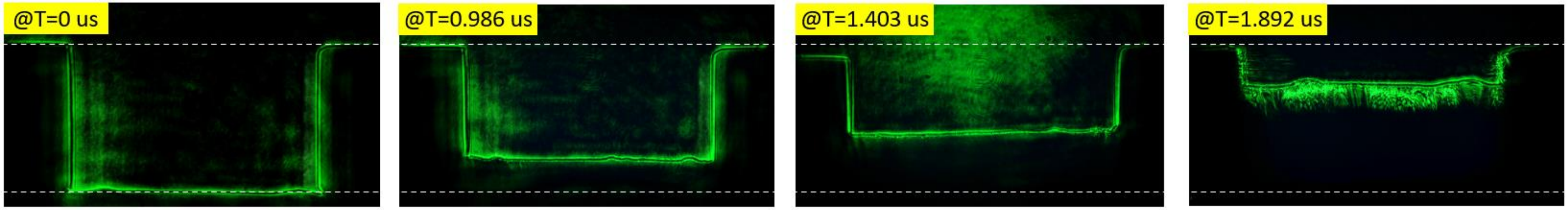


- **After shot**

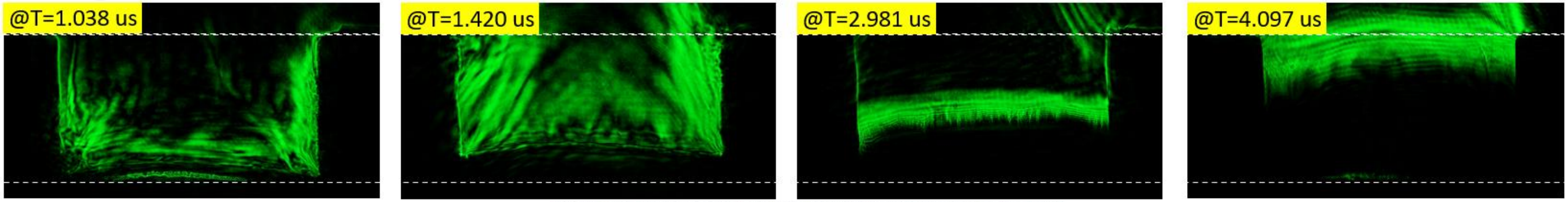
Y.-Z. Pan, Science day, College of Science, NCKU 2023
Y.-Z. Pan, Progress report, Pulsed-Plasma Laboratory 2023

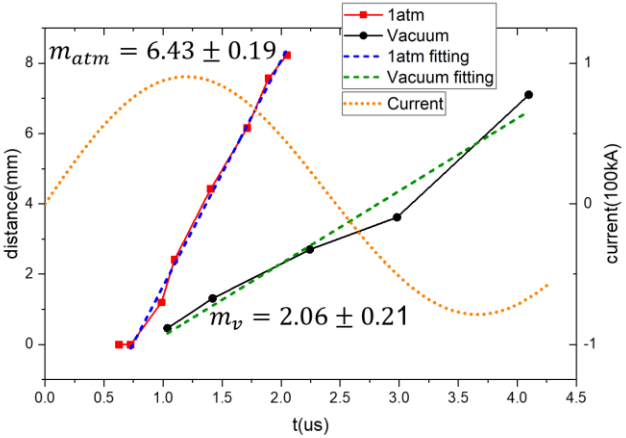
Velocities of the flyer plate were different when experiments were conducted in 1 atm and in vacuum

- @ ~1 atm

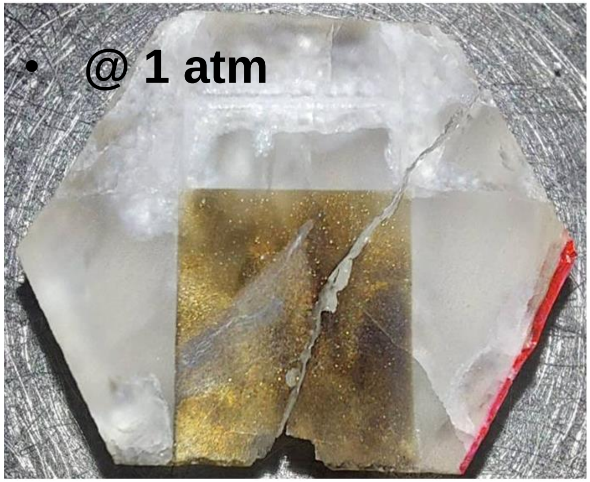


- @ ~10^{-5} torr

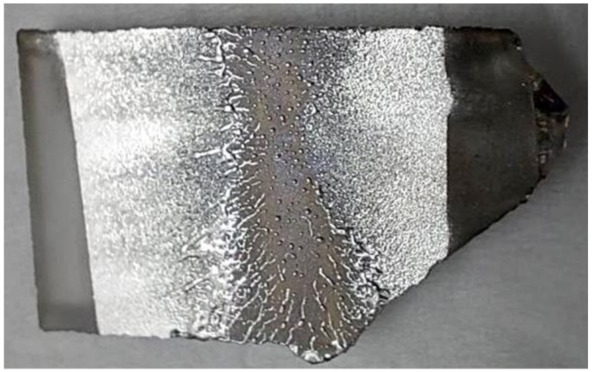




- **@ 1 atm**

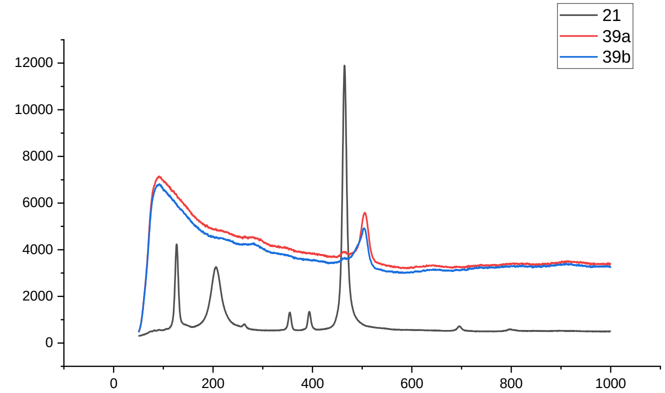


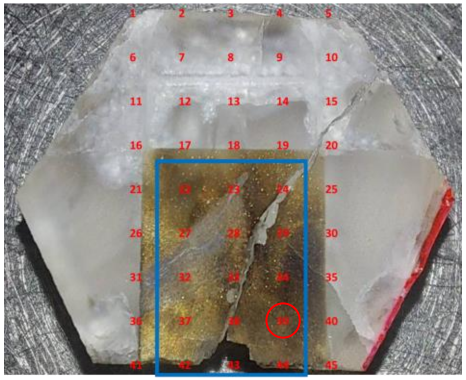
- **@ ~10^{-5} torr**

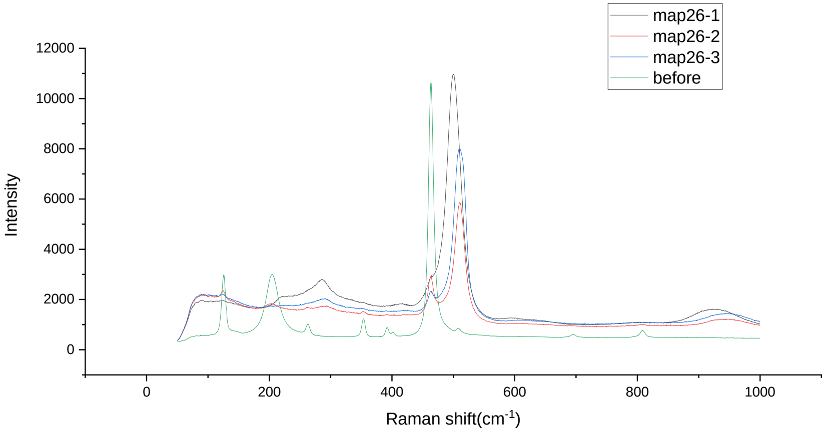


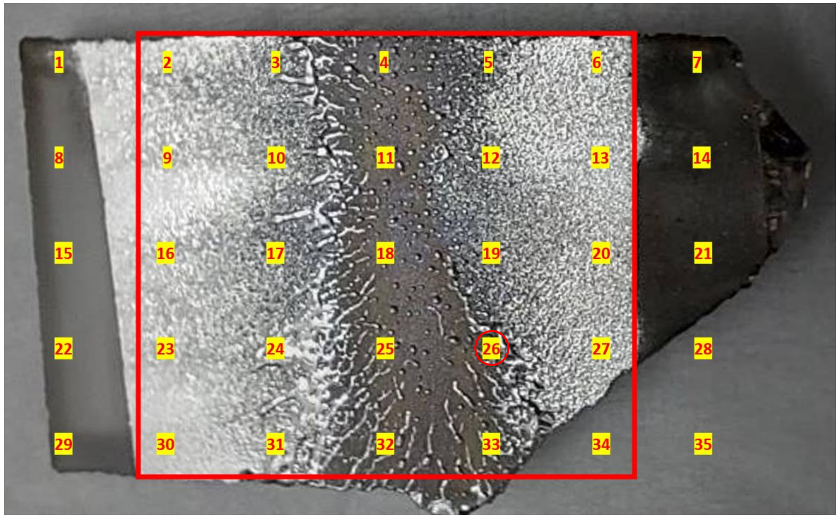
Y.-Z. Pan, Science day, College of Science, NCKU 2023

Raman shift of the SiO2 sample behaved differently after being shocked

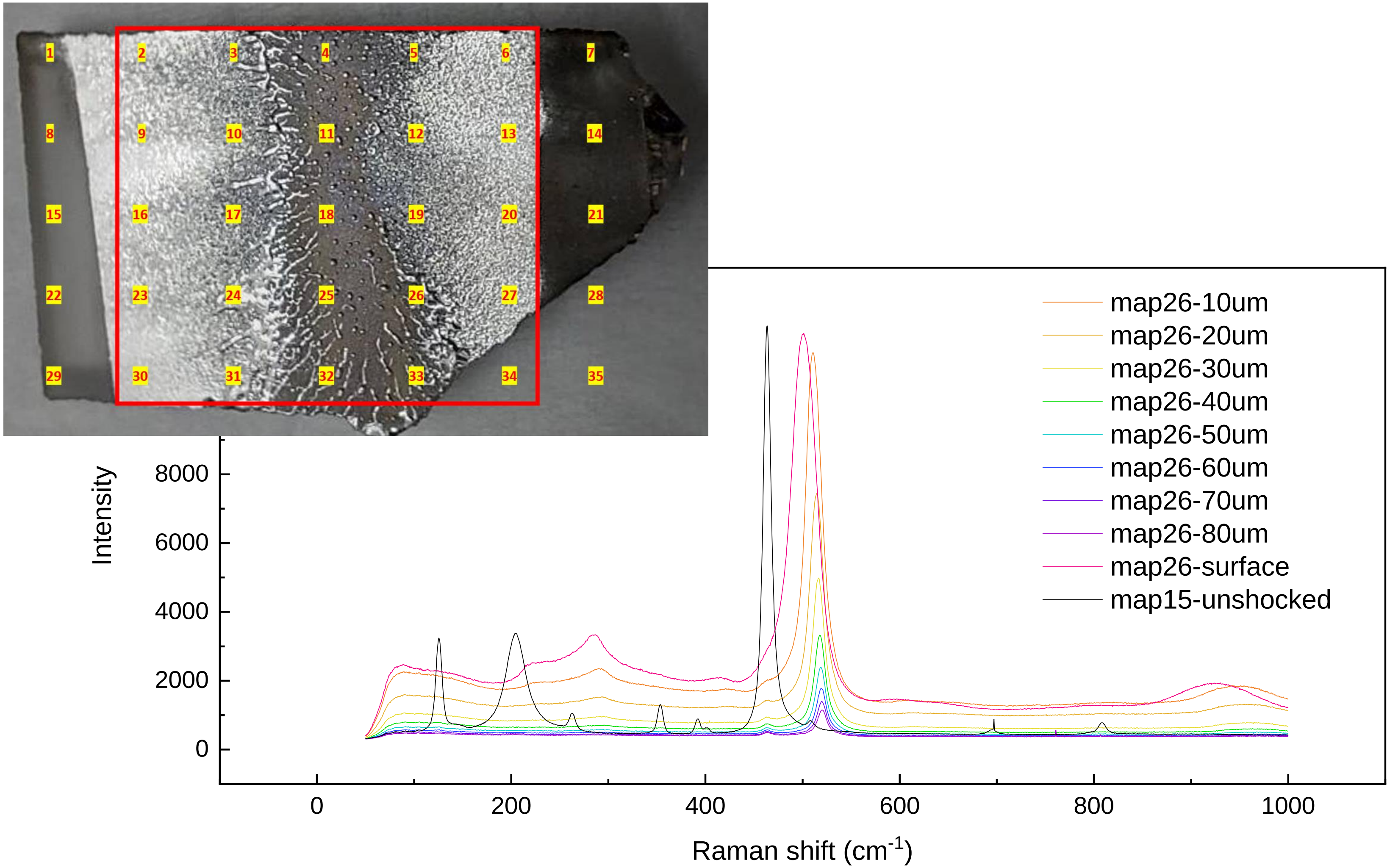




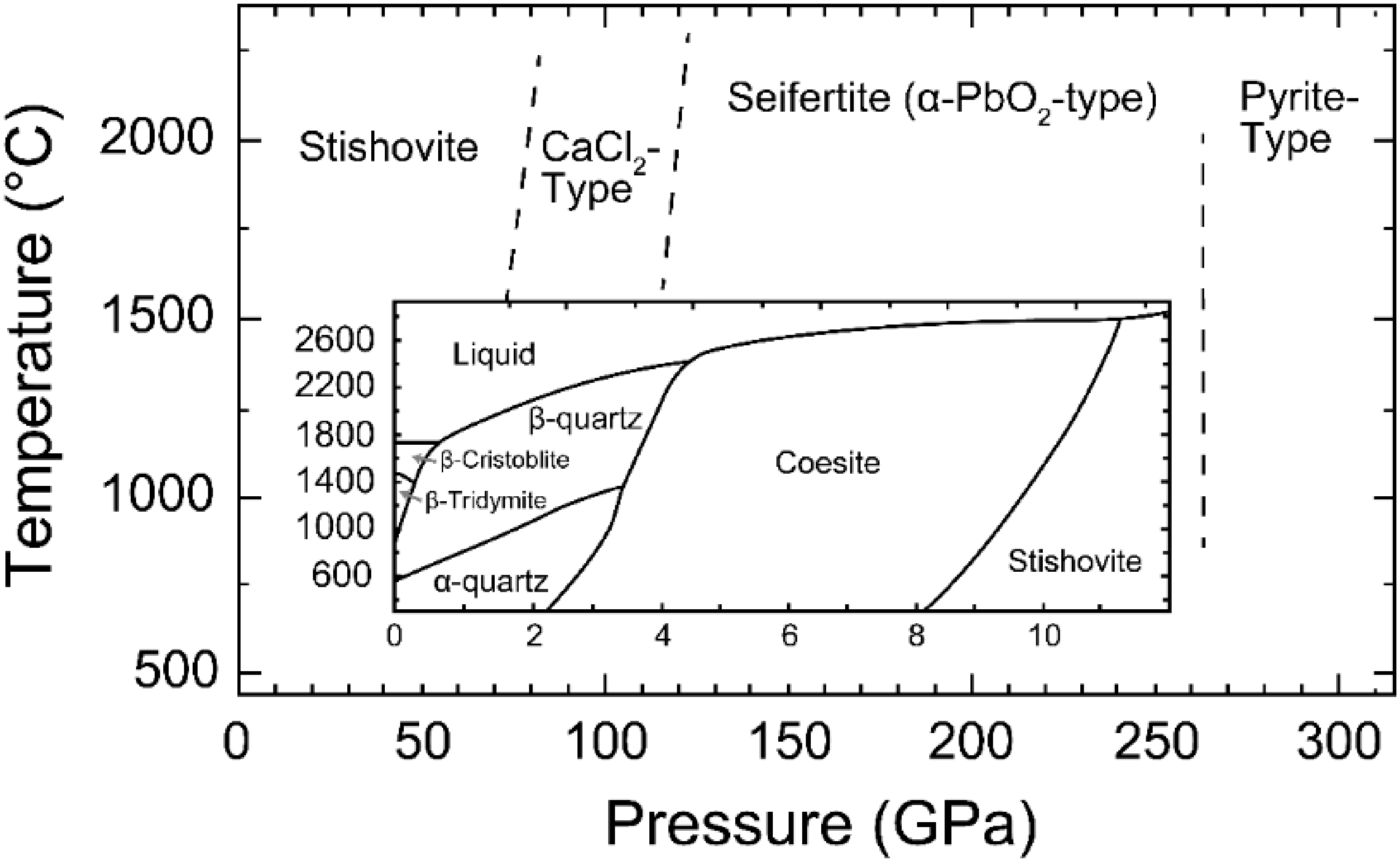




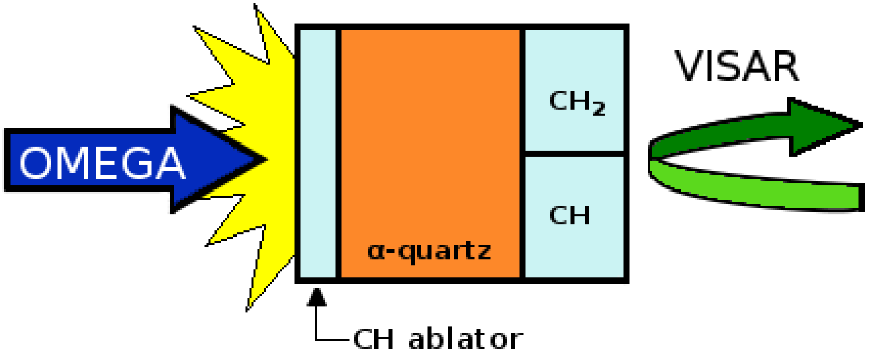
Raman shift of 520 cm-1 was observed suggesting that Coesite was formed

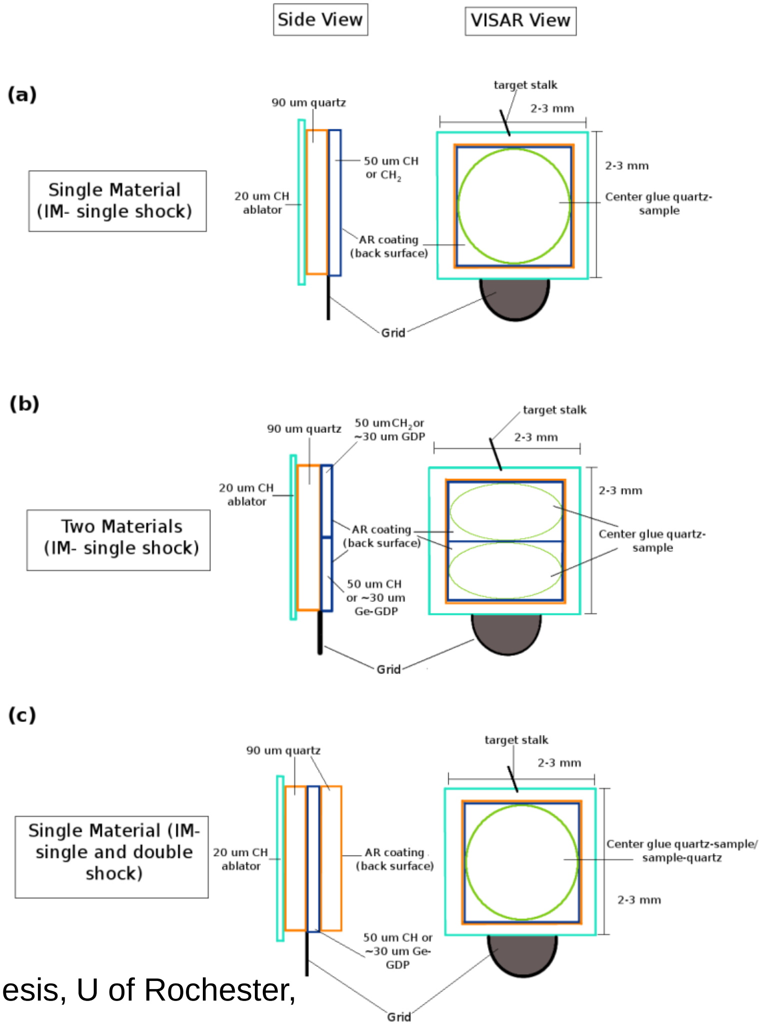


The raman shift indicated that a pressure more than 2 Gpa was generated

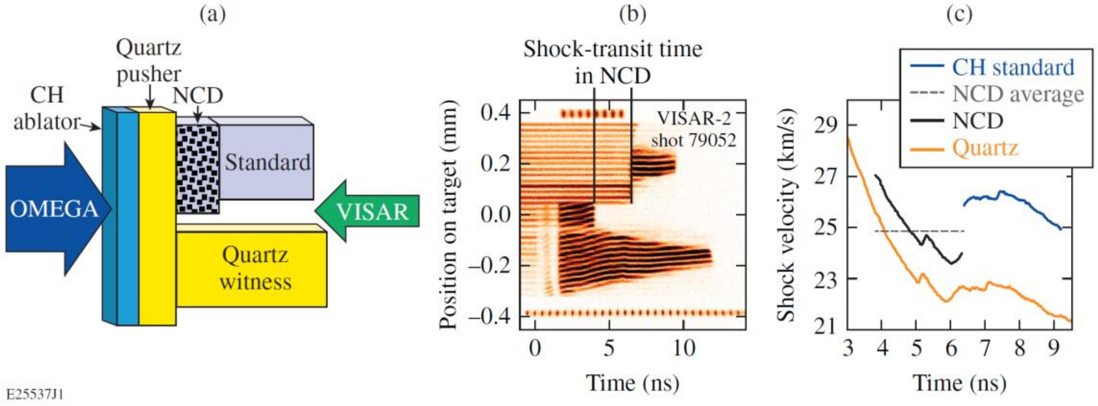


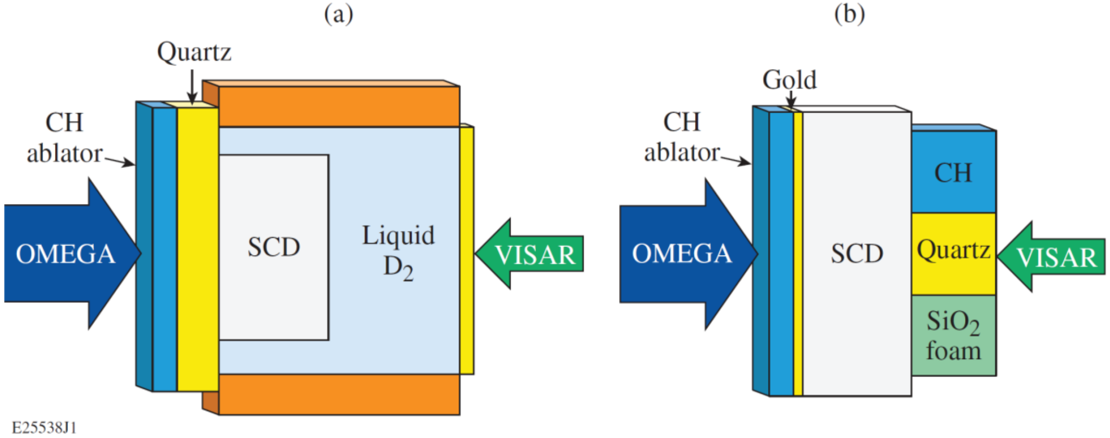
M. Kayama, etc., Minerals 8, 267 (2018)



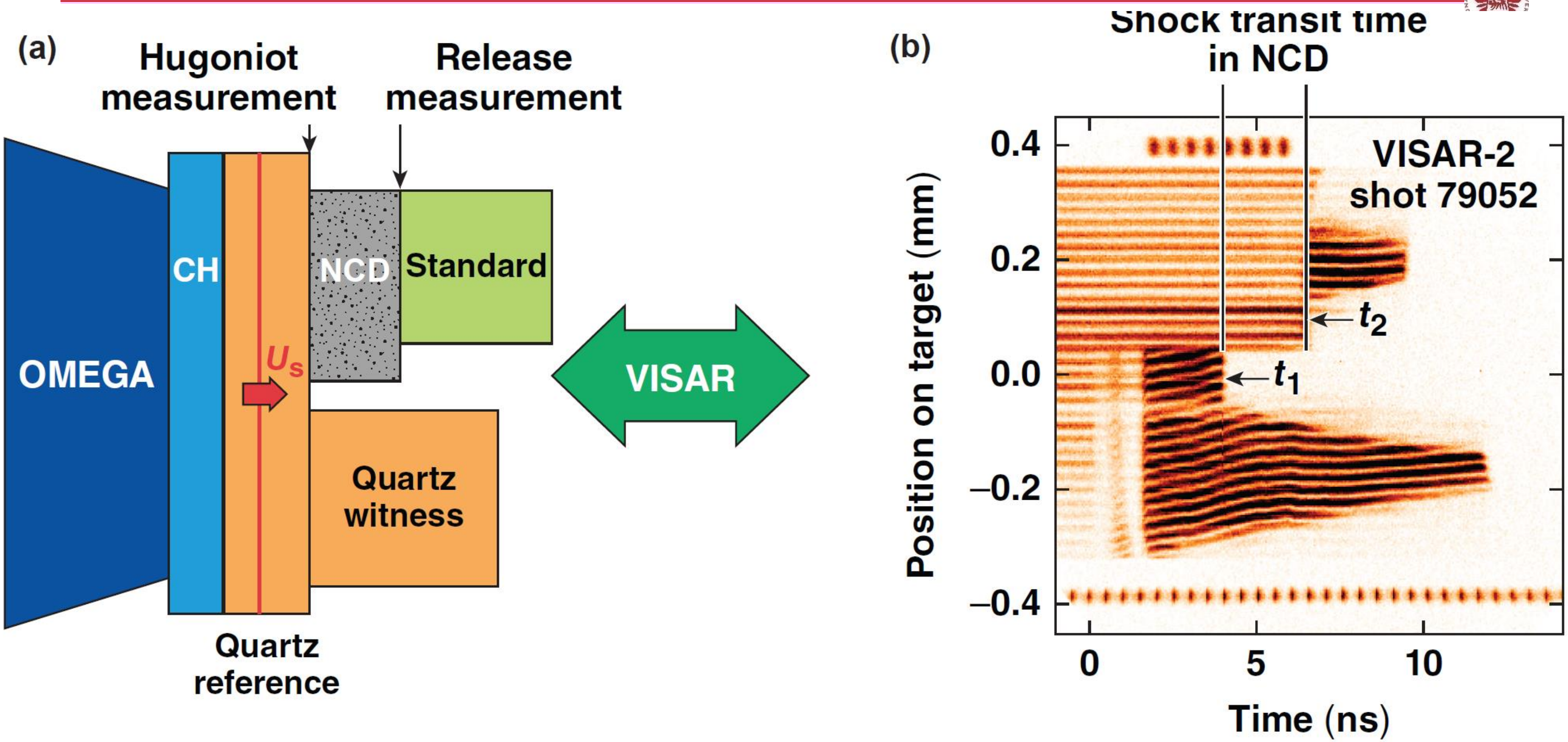


Maria Alejandra Barrios Garcia, PhD Thesis, U of Rochester, 2010

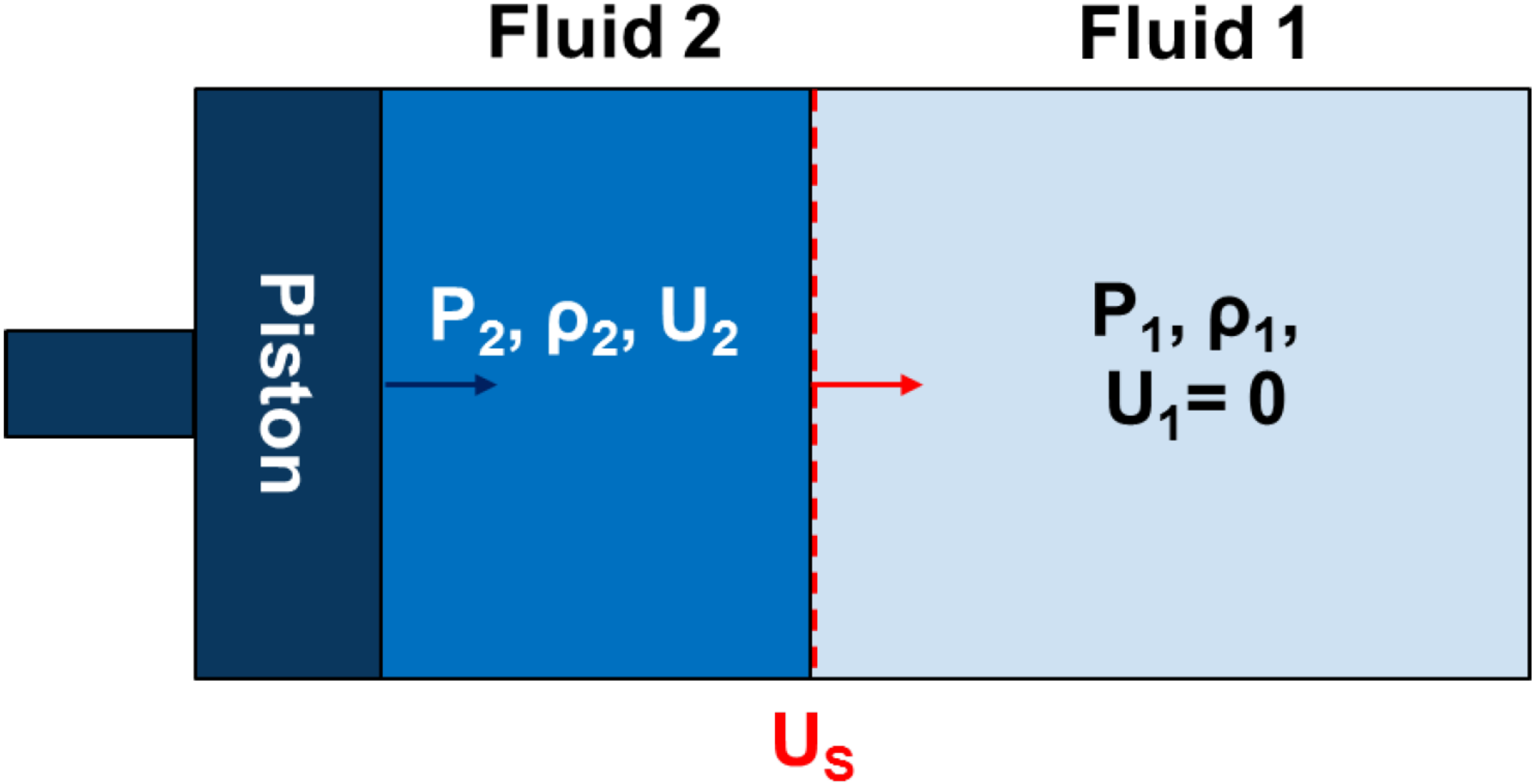




Michelle Colleen Gregor, PhD Thesis, U of Rochester, 2017



Michelle Colleen Gregor, PhD Thesis, U of Rochester, 2017



Danae Nicole Polsin, PhD Thesis, U of Rochester, 2018