



UNIVERSITY OF
OXFORD

Laboratorní astrofyzika

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Astrotábor, Vlčková

6. srpna 2010

Obsah přednášky

- Úvod
- Plazma ve vesmíru
- Přehled astrofyzikálních objektů, které jsou simulovatelné v laboratorích na Zemi
- Diagnostické systémy v různých experimentech
- Příklady experimentu
- Z-pinče:
 - fyzikální princip
 - světové experimenty
 - simulace astrofyzikálních výtrisků
- Lasery:
 - fyzikální princip
 - gigantické lasery a fuze
 - stavová rovnice nitra velkých planet a hvězd
 - nekolizní soky v mezihvězdném mediu

Plazma ve vesmíru

Co je to plazma?

Učená definice nám o plazmatu říká: „Plazma je kvazineutrální soubor částic s volnými nosiči nábojů, který vykazuje kolektivní chování“. Pojdme si ji trochu polidštit. To nejdůležitější je, že se v plazmatu nachází volné nosiče náboje. Atomy jsou alespoň částečně ionizované. Stupeň ionizace nemusí být příliš veliký, je-li plazmový útvar dosti rozsáhlý. Právě volné nosiče náboje plazma zcela odlišují od plynů. Plazma je vodivé a silně reaguje na elektrická a magnetická pole. Druhá vlastnost je kvazineutralita. Požadujeme, aby v makroskopických objemech bylo vždy v průměru stejné množství kladných a záporných částic. Navenek se plazma jeví jako nenabitá tekutina (kapalina či plyn). Požadavek kvazineutrality vyčleňuje z definice plazmatu nabitě svazky částic, které mají přece jen poněkud odlišné vlastnosti. Poslední součástí definice plazmatu je jeho kolektivní chování. Tím se rozumí, že plazma je schopné jako celek svými projevy generovat globální elektrická a magnetická pole a na takováto globální pole reagovat. Do plazmatu většinou nezahrnujeme různé svazky nabitých částic (nesplňují kvazineutralitu) a velmi slabě ionizované plyny – například plamen svíčky (nesplňují kolektivní chování). Pojem plazmatu poprvé použil *Irwing Langmuir (1881-1957)*.

- Běžné plazma: elektronové obaly atomů jsou částečně poškozené (vysokou teplotou nebo tlakem). Volné elektrony jsou zodpovědné za plazmatické vlastnosti látky.
- Termonukleární plazma: atomární obaly neexistují, látka je směsicí holých jader a volných elektronů. V tomto stavu je plazma v jádrech hvězd, kde probíhá TJ syntéza.

Plazma v laboratoři

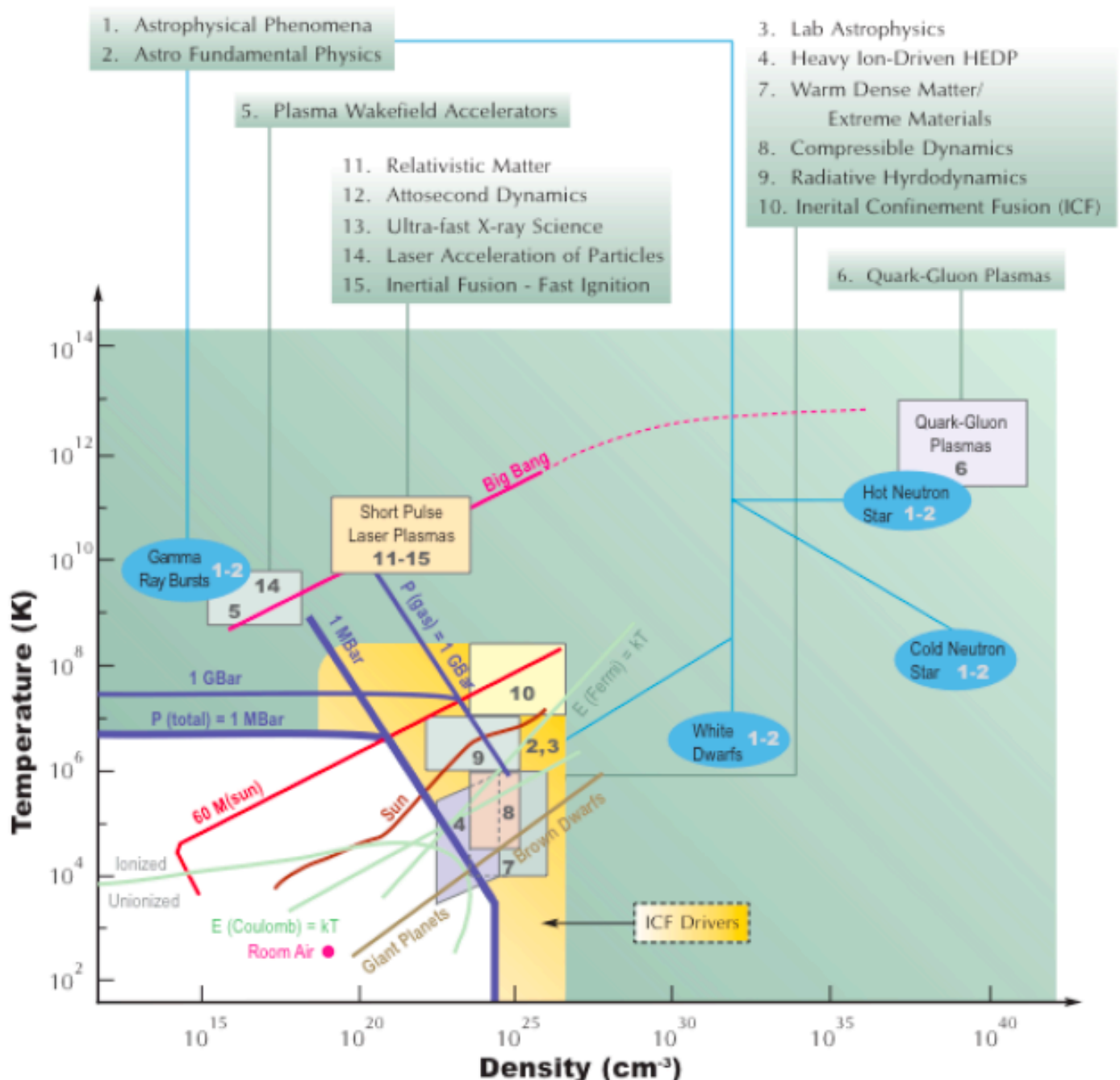
Nejtypičtější příklady jsou:

- laserové plazma – doba života: $10^{-12} \div 10^{-9}$ s
- pulsní plazma – doba života: $10^{-9} \div 10^{-6}$ s
- tokamak – doba života: 1 s
- studené plazma – doba života: hodiny, dny, roky



Fazovy diagram

Map of the HED Universe



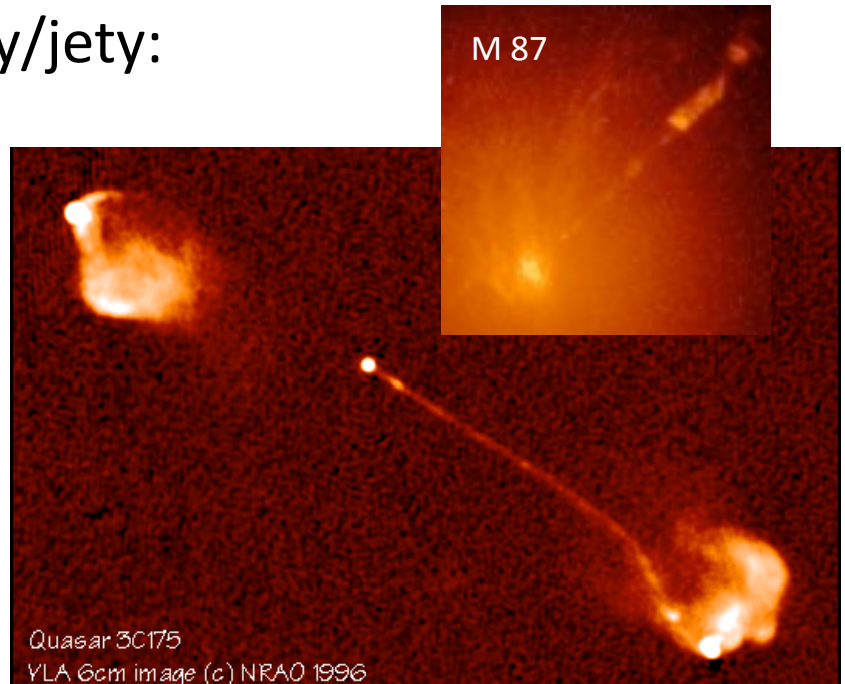
Map of the high energy density physics regime in the density - temperature plane. High energy density as defined in this report corresponds to matter under the extreme conditions in the region above and to the right of the 1 Mbar (heavy blue) curve. The numbered boxes correspond to the 15 science thrust areas identified in this report and show a representative parameter regime for each of these thrust areas.

Astrofyzikalni objekty

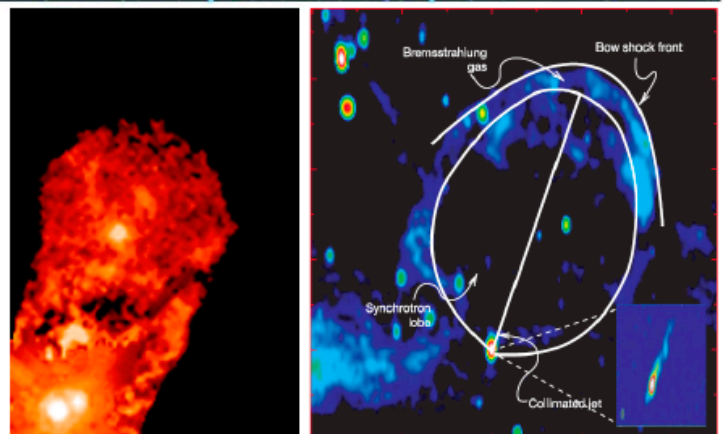
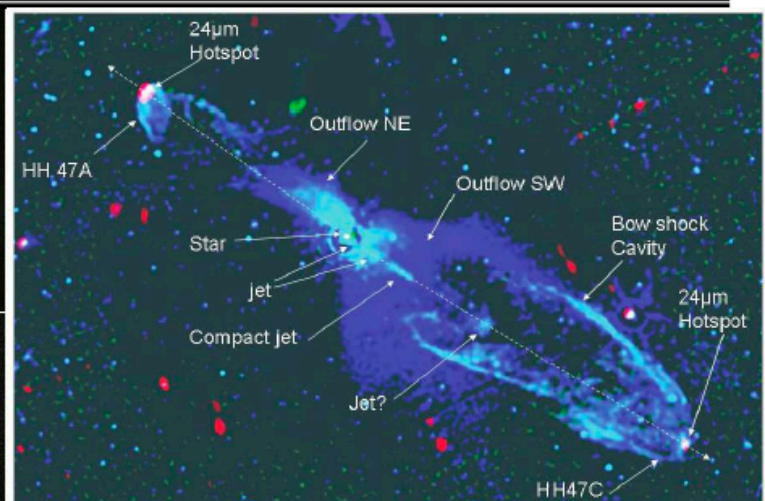
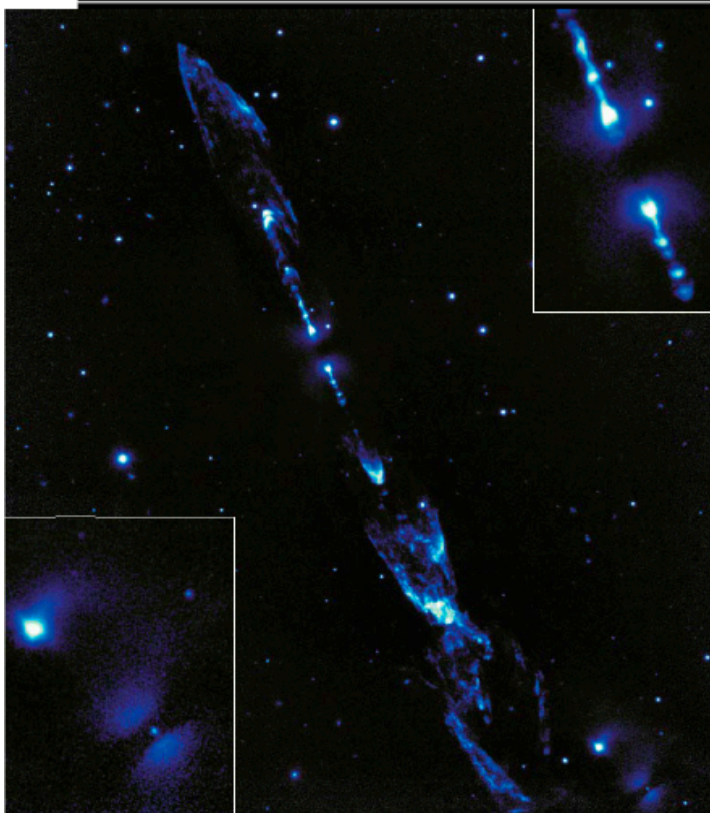
- Astrofyzikalni vytrisky/jety:

Jety se casto objevuji v energetickych procesech jako pad hmoty do cerne diry nebo na povrch neutronove hvezdy – centra akrecnich disku.

Zajimavy fenomen je kolize jetu s mezistelarni hmotou/plazmou.



Jets in the Universe

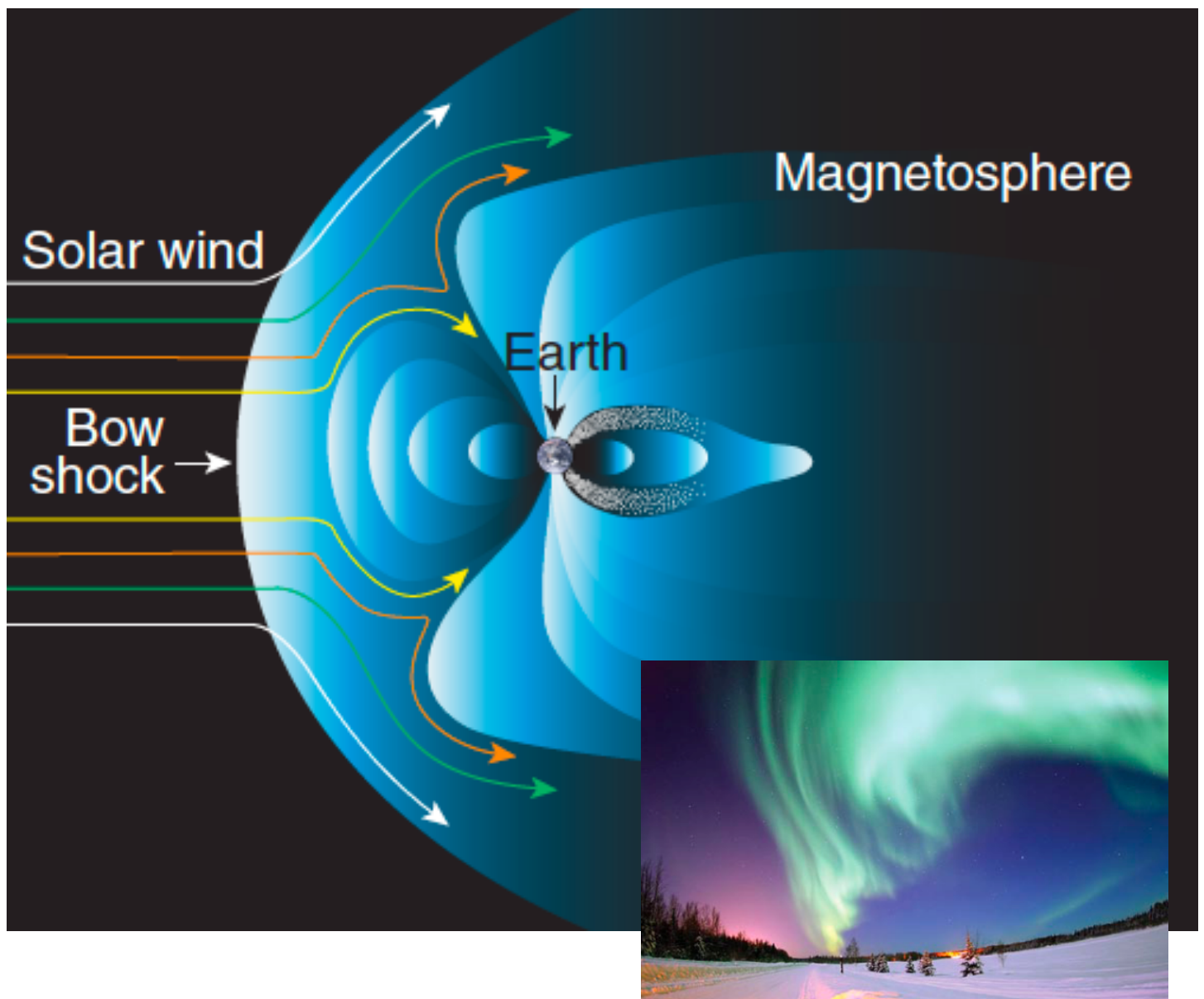


Jets are “fossil” record of activity and give information on inaccessible source regions.

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Astrofyzikalni objekty

- Sokove vlny v mezi-planetarnim mediu:
 - nekolizni soky v meziplanetarnim mediu jsou velkou zahadou, jelikoz v nich castice neinteraguji skrz Coulombovych interakce, ale pomoci plazmovych vln (sirka soku je mensi nez kolizni delka castic)
 - pohyb castic se neda jednoduse predpovedet pomoci teorie, experimentalni investigace je nutna



Astrofyzikalni objekty

• Nitra velkych planet/hnedych trpasliku:

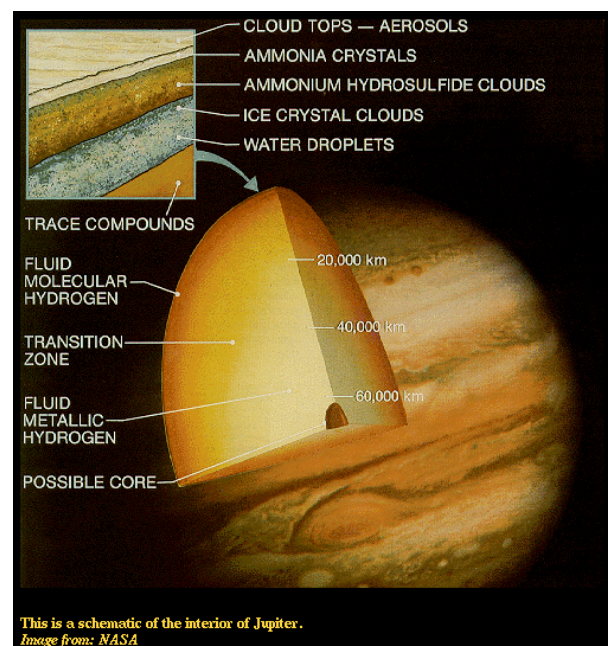
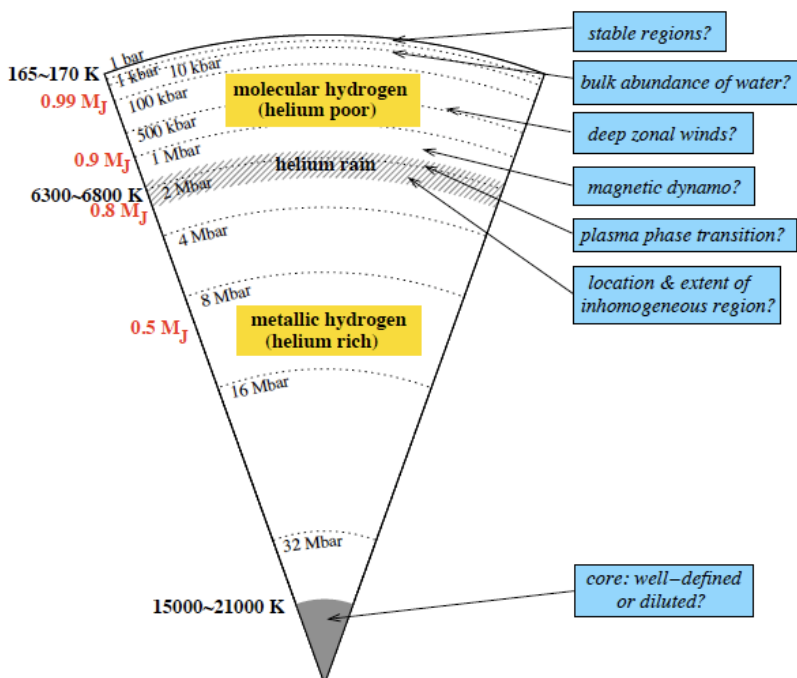
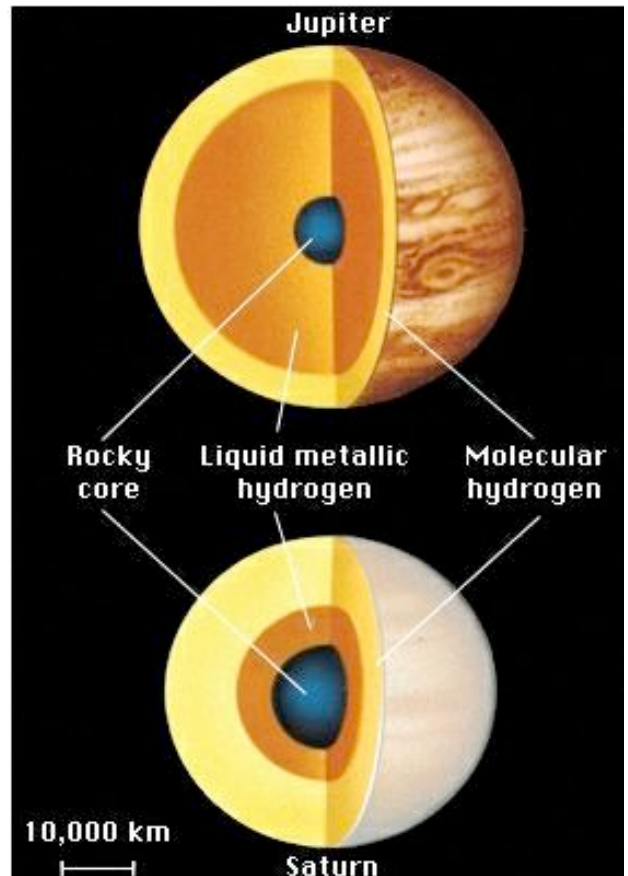
Metalizace vodiku:

- Pod jakym tlakem? teplotou?
- Zmena stavu plynula nebo nahla (first order/plasma phase transition)

Stavove rozdeleni H/He :

- Atmosfericky podil H/He se vyrazne lisi od protoplanetarni mlhoviny
(He schovane hluboko uvnitr?)
- Kondensace He v metalicke obalce vodiku
(He se hur ionizuje nez H)

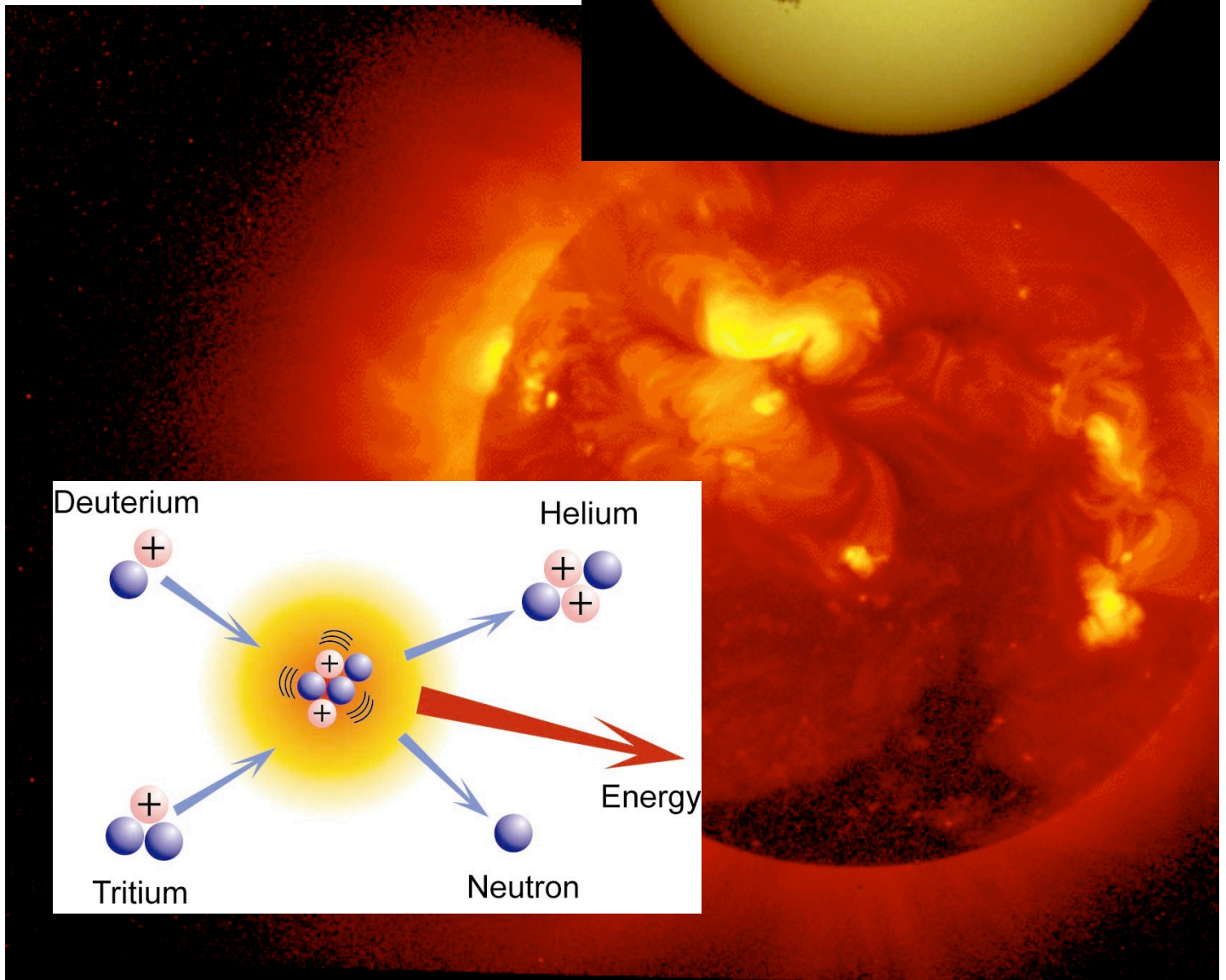
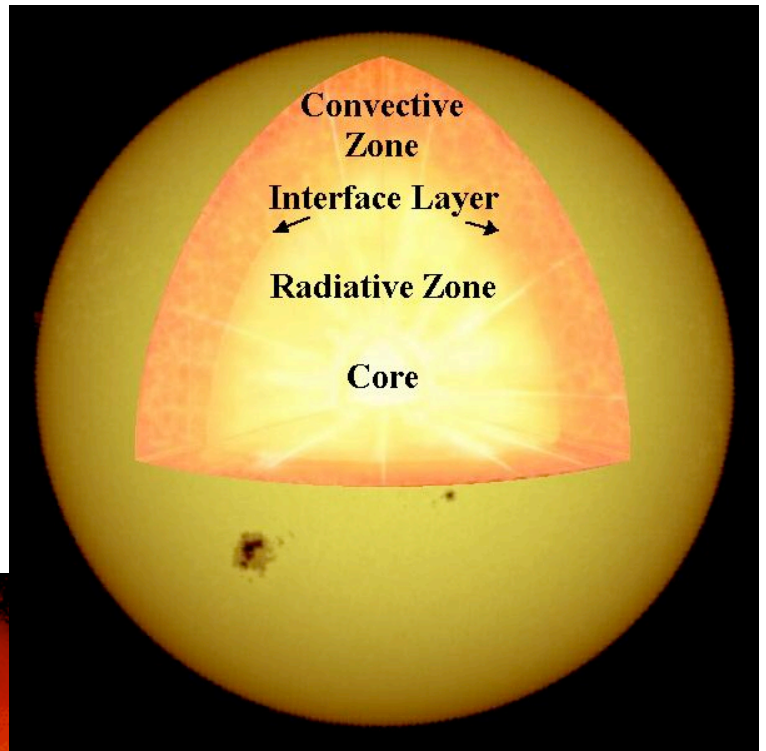
Pevne jadro?



Astrofyzikalni objekty

- Nitra hvezd:

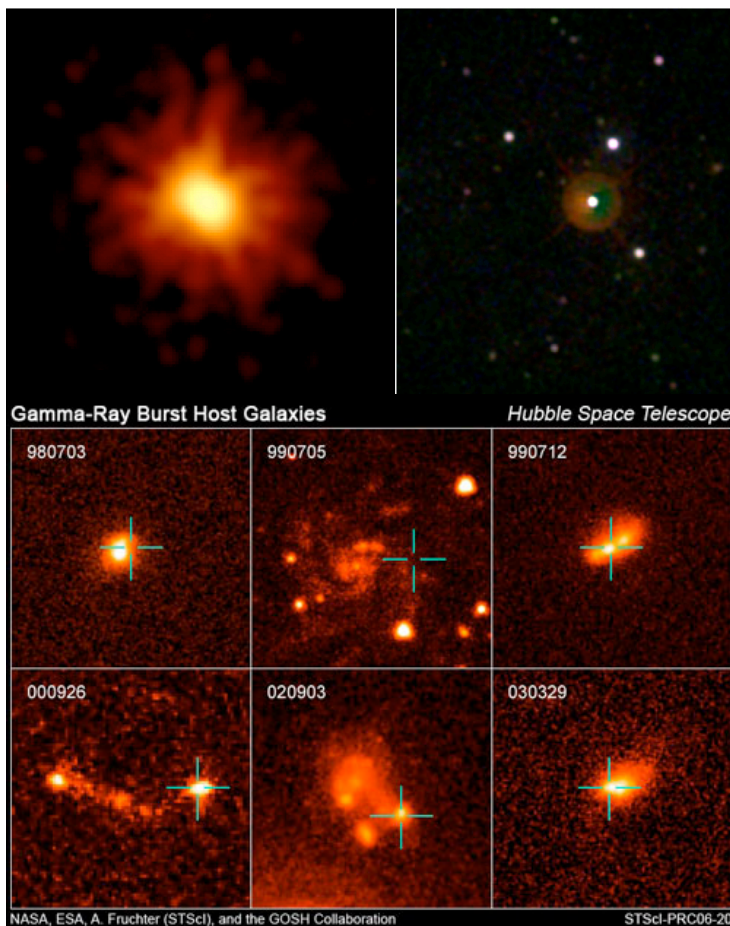
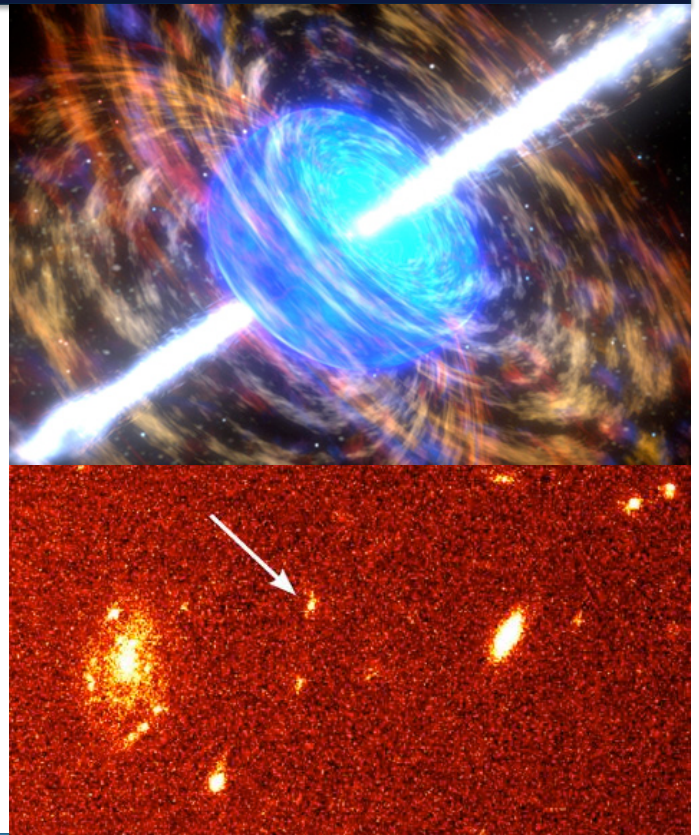
Studium termonuklearnich reakci, které urzuji teplo v “peci” v jadrech vsech hvezd, vctene naseho Slunce muze jednou byt hlavnim cistym zdrojem energie na Zemi – jaderna fuze.



Astrofyzikalni objekty

- Gamma bursts/zablesky:

Silne a nahle vysoko-energeticke zablesky v oboru gama jsou pravdepodobne vysledkem tech nejvetsich explozi ve vesmiru. Nikdo vsak nevi, jak presne tyto zablesky vznikaji. Muze se jednat o nahle vybuchy rotujicich supernov; kolize neutronovych hvezd; nekolizni soky; energeticke procesy, kde vznikaji anticastice (positrony), ktere rychle anihiluji s hmotou, atd.



Gamma-Ray Bursts (GRBs): The Long and Short of It

Long gamma-ray burst (>2 seconds' duration)

A red-giant star collapses onto its core...

...becoming so dense that it expels its outer layers in a supernova explosion.

Jet
Torus
Gamma rays

Short gamma-ray burst (<2 seconds' duration)

Stars* in a compact binary system begin to spiral inward...

...eventually colliding.

The resulting torus has at its center a powerful black hole.

*Possibly neutron stars.

Laboratorni astrofyzika

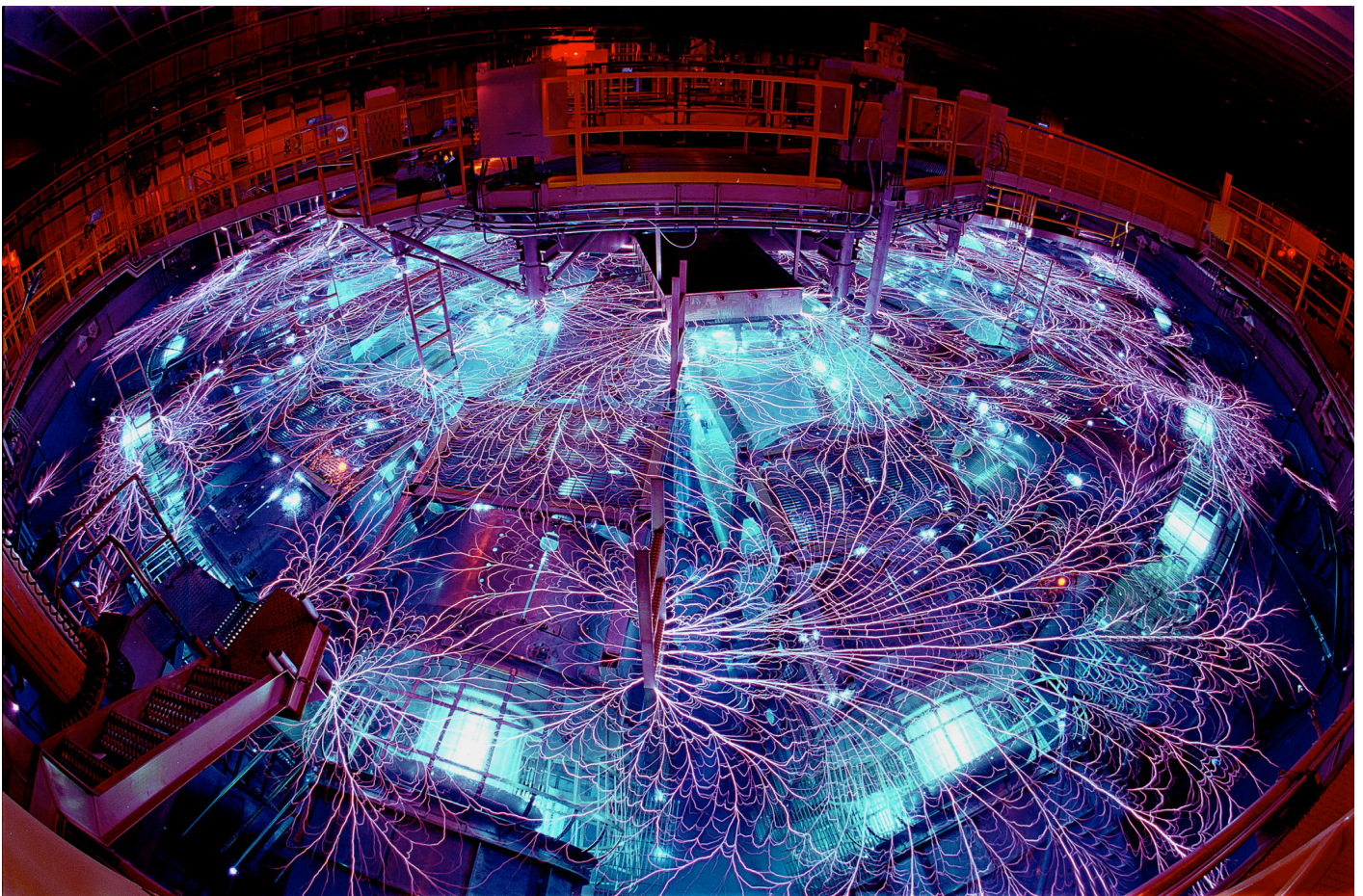
- Studium astrofyzikalnich objektu v laboratorii:
 - bezjednotkovym parametrum (simulace obrovskych objektu v miniaturnich meritkach)
 - vytvoreni identickych podminek (vysoke teploty a tlaky, vysokoenergeticke procesy, magneticka pole)
 - dostupnejsi laboratorni techniky, prime mereni

Name (description)	Formula	Typical value
Sonic Mach number	$M = v_j/c$	$\sim 10 - 50$
Density contrast	$H = \frac{\rho_{jet}}{\rho_{ambient}}$	$\sim 1 - 10$
Cooling parameter	$\chi \equiv \frac{\tau_{cool}}{R_j/v_j}$	$\sim 0.1 - 10$
Plasma beta	$\beta = \frac{P_{thermal}}{P_{magnetic}} = \frac{2nk_B T}{B_{tot}^2/2\mu_0}$	~ 1
Jet aspect ratio	L_j/R_j	$\sim 15 - 1000$
Localization parameter (fluid-like nature of the jet)	$\delta = \frac{\lambda_{mfp}}{R_j}$	$\ll 1$
Reynolds number (viscosity)	$Re = \frac{R_j v_j}{\nu}$	$\gg 1$
Peclet number (heat conduction)	$Pe = \frac{R_j v_j}{\kappa_h}$	> 10

Table 1: Dimensionless parameters of astrophysical jets. Here v_j stands for the characteristic jet velocity, c is speed of sound, ρ is density, τ_{cool} is time for cooling time, k_B is the Boltzmann constant and T is temperature, L_j and R_j are the characteristic radius and length of the jet, λ_{mfp} is the mean free path of the particles perpendicular to the jet flow, ν and κ_h are the viscosity and thermal diffusivity respectively. [12, 8]

Z-pinche

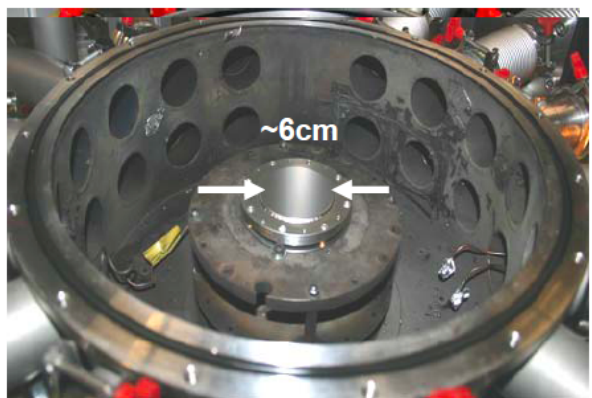
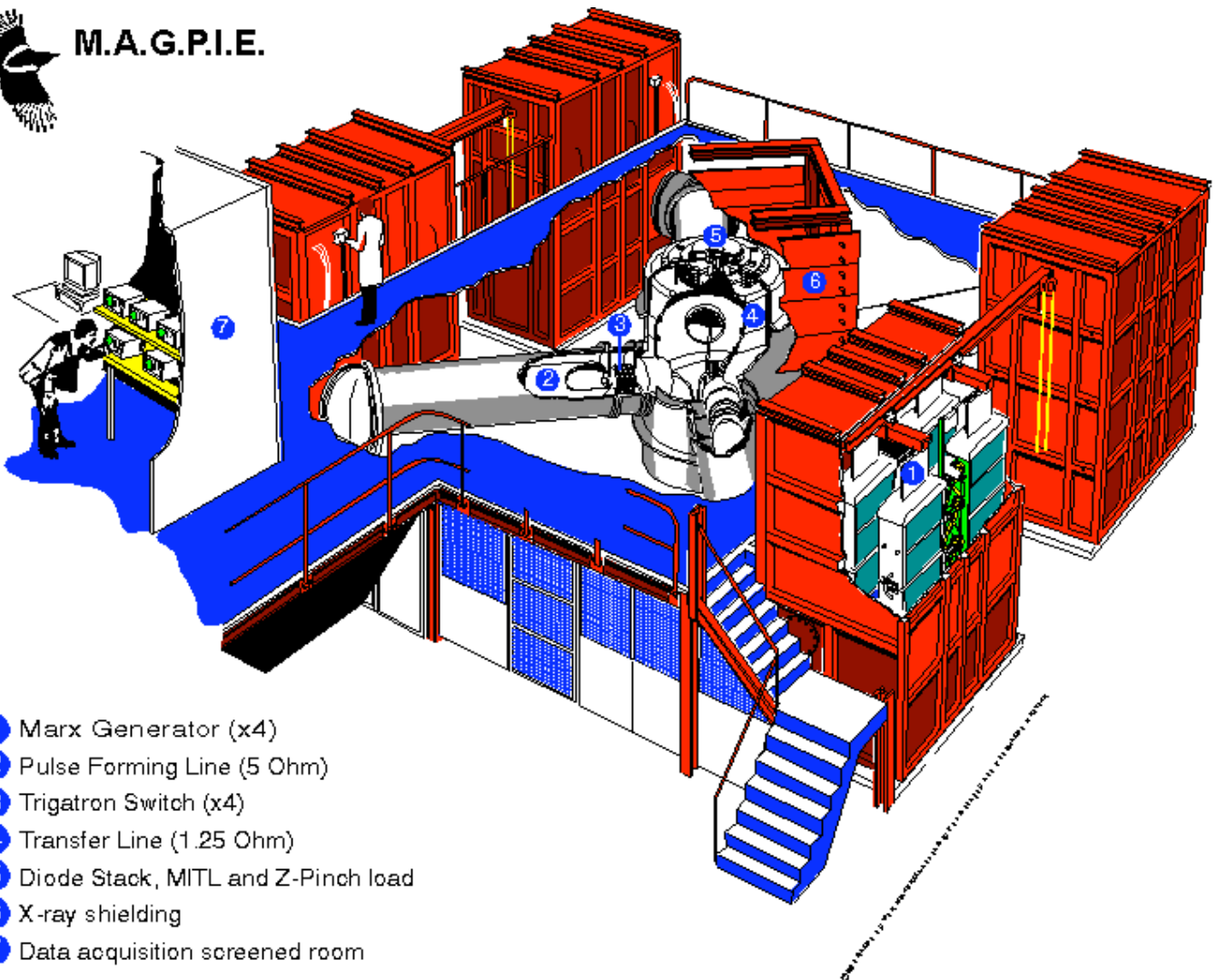
- Z-machine (Sandia National laboratories), New Mexico
- MAGPIE (Imperial College London, UK)
- Cornell University, New York
- CAE, Francie
- Pontificia Universidad Católica de Chile
- FEL, ČVUT, Praha



MAGPIE



M.A.G.P.I.E.



“Wire array”

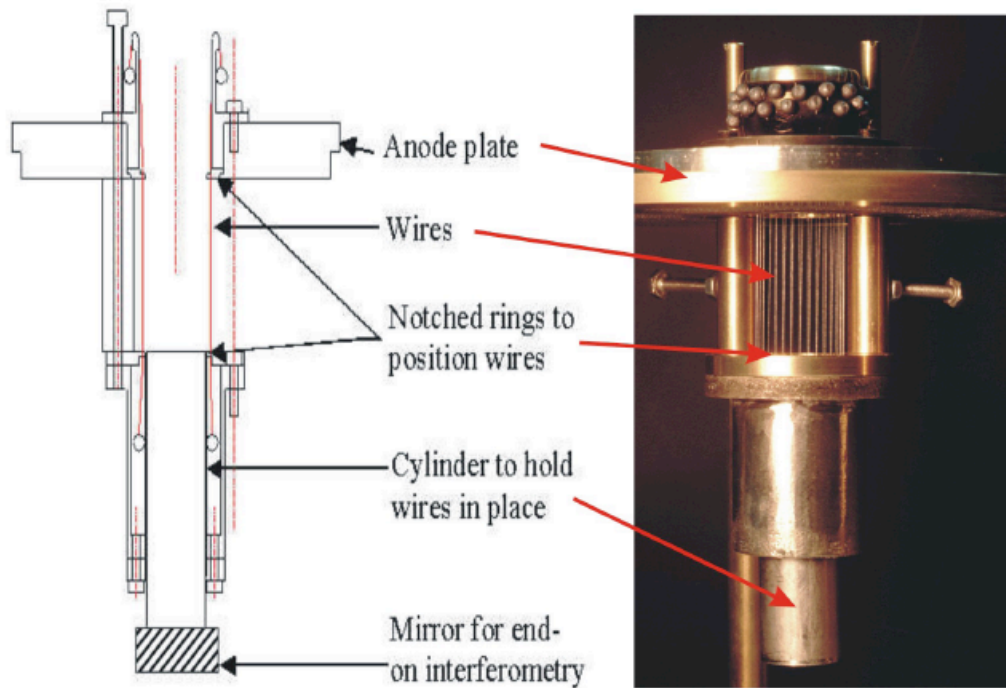
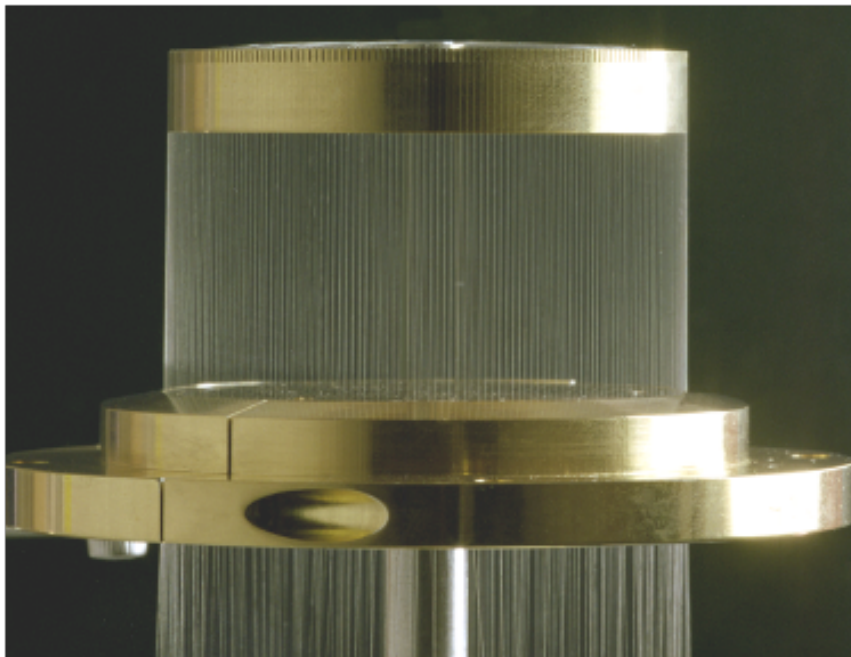


Figure 2: Typical wire array used at the MAGPIE Z-pinch project at Imperial College London. Photo from the MAGPIE Z-pinch project website [14].



Imploze Z-pinche

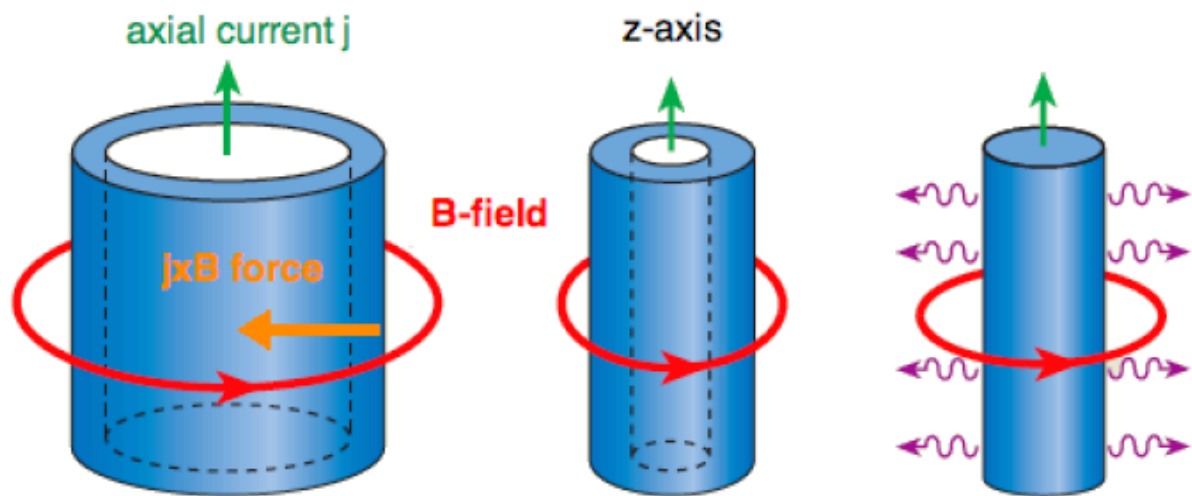
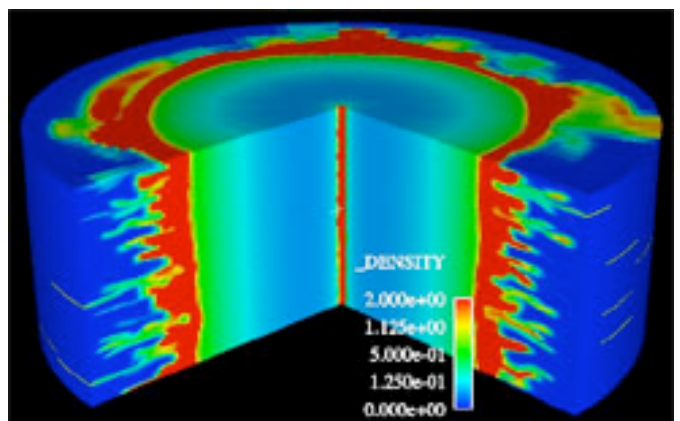
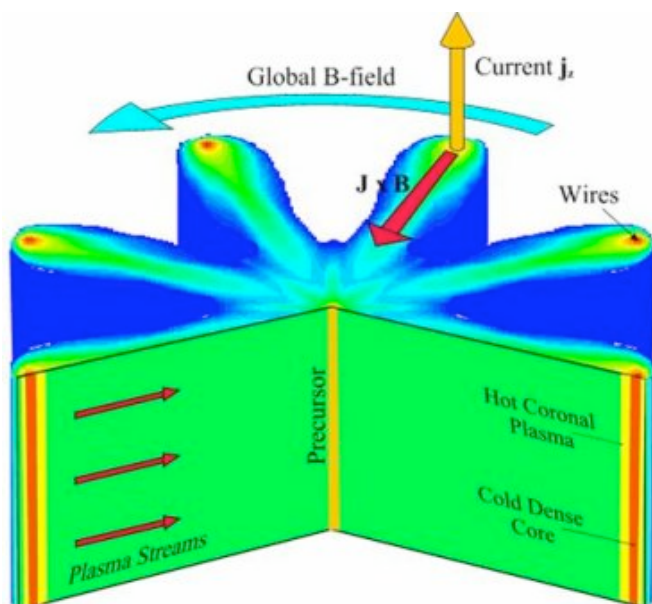
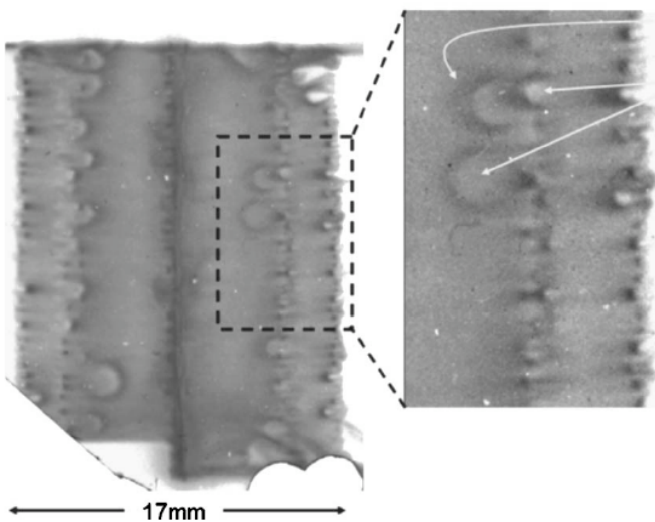
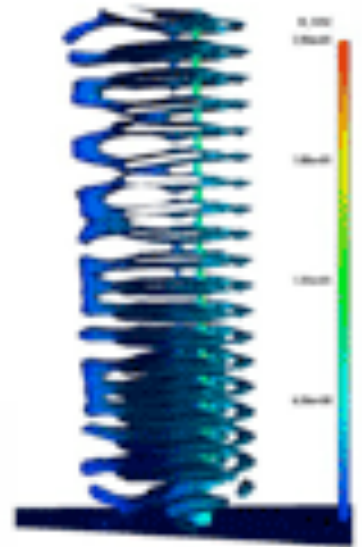
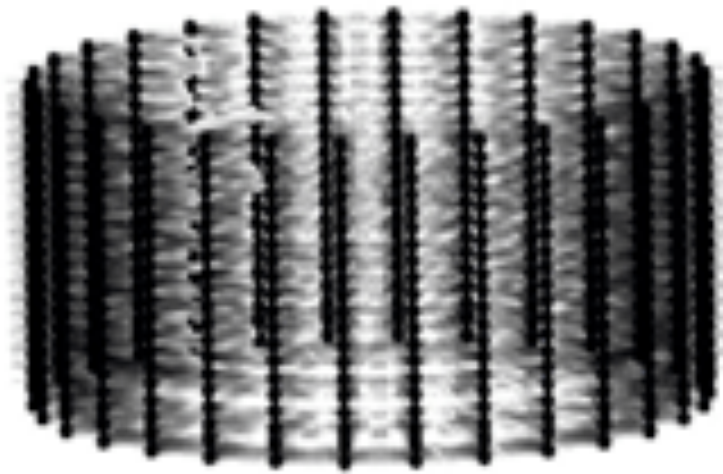
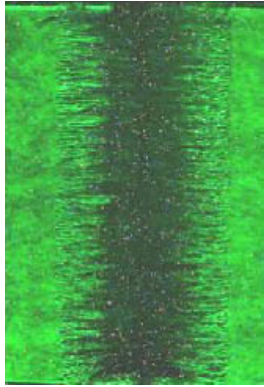


Figure 3: Schematic of a Z-pinch implosion of a cylindrical plasma shell due to axial current j . The radial collapse of the plasma shell is due to the inward $j \times B$ force and the kinetic energy of the plasma is released in form of an X-ray burst when it reaches the z-axis. [4]

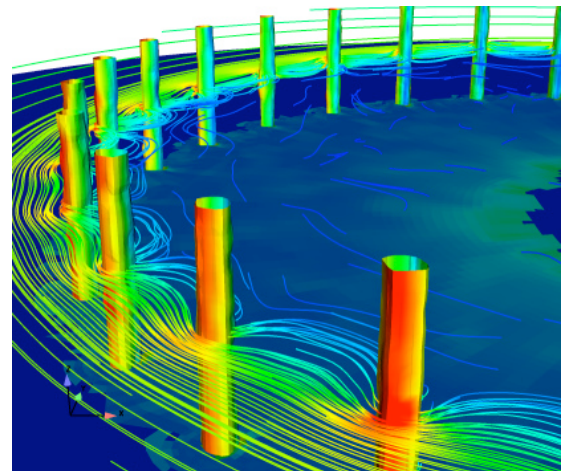
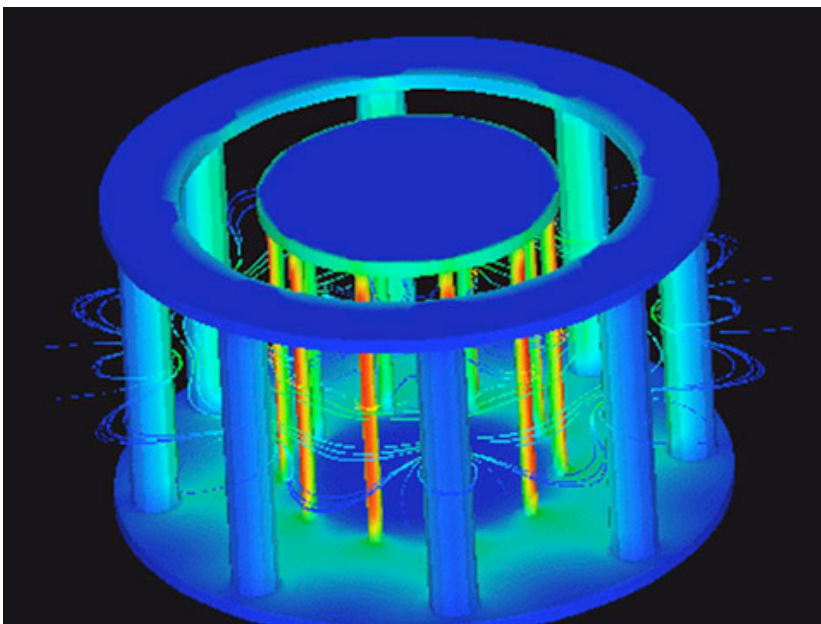
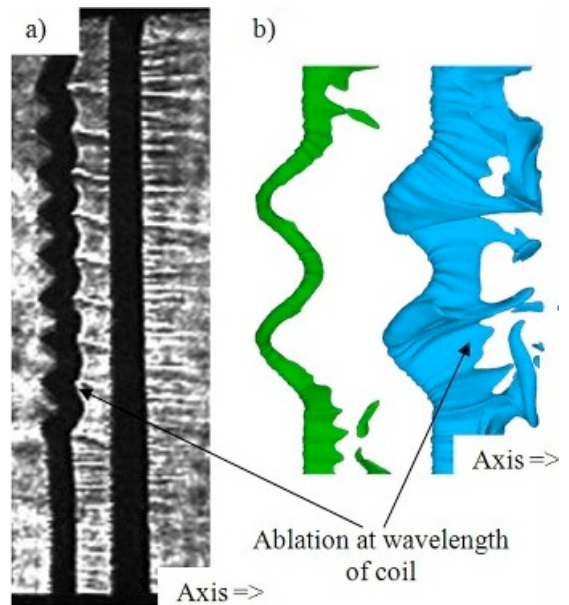
- Magnetická sila: $B_{\theta} = \frac{\mu_0 I}{2\pi r}$
- Energie imploze na osu: $KE \approx \frac{\mu_0 I^2}{4\pi} \ln \left(\frac{r_0}{r_{min}} \right)$



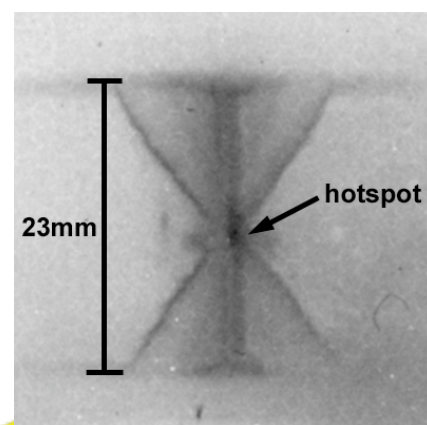
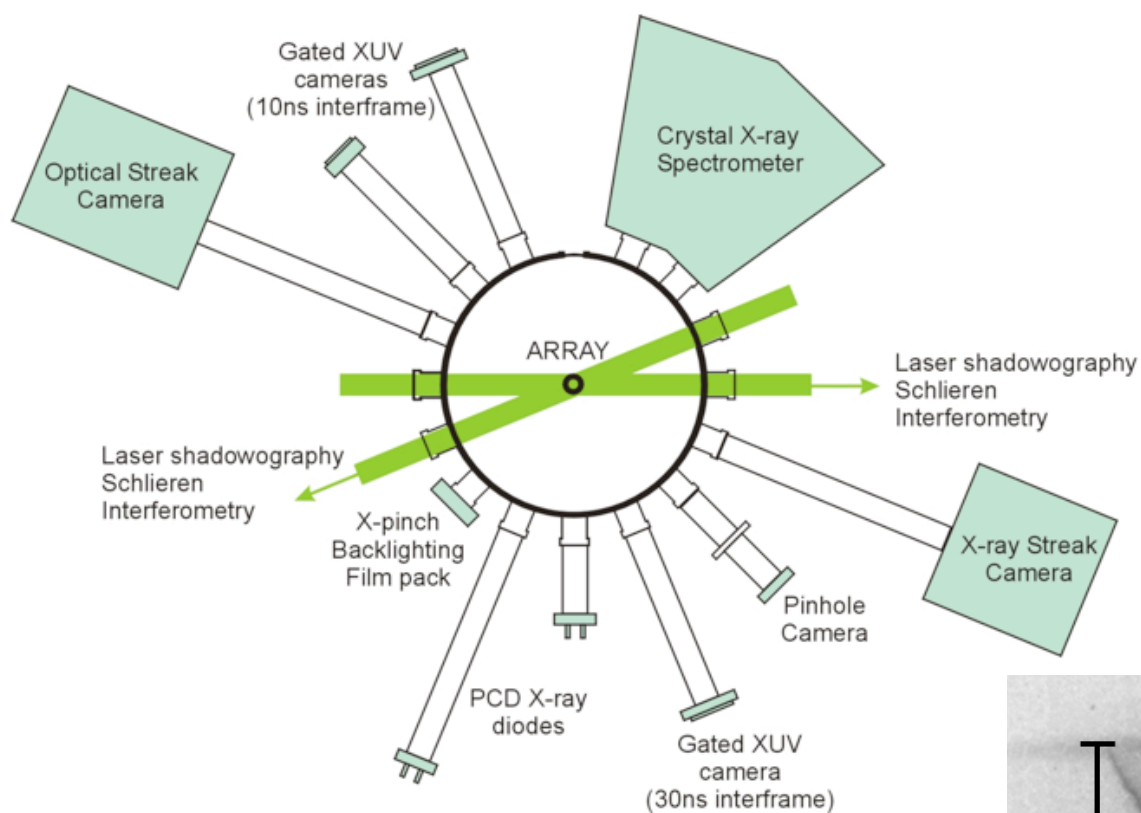
Imploze Z-pinche



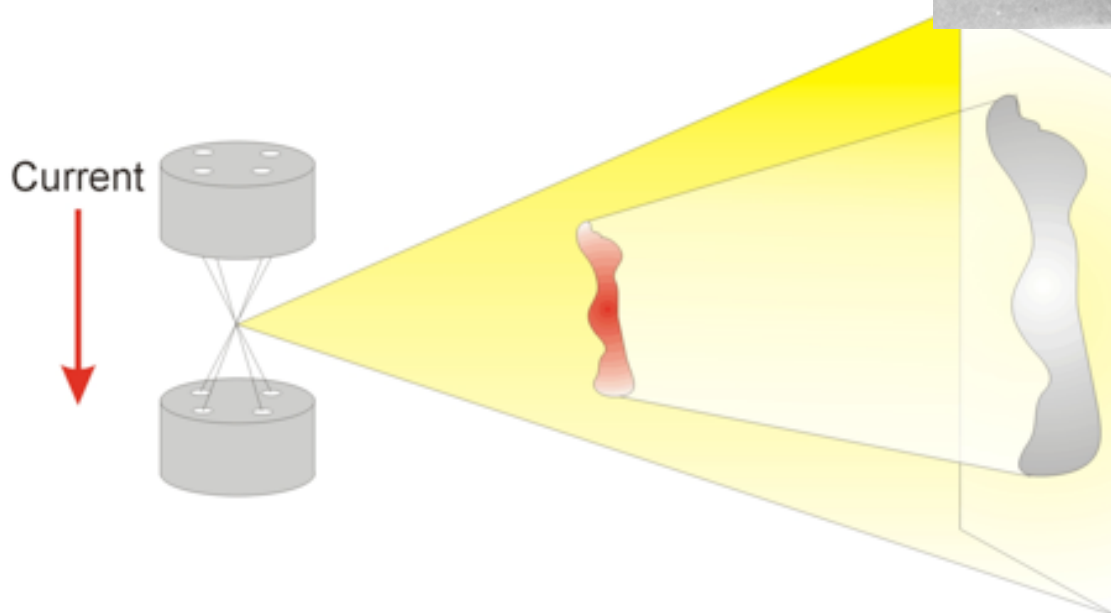
Shock in front
of bubble
J^ΛB 'bubbles'



Diagnosticke pristroje

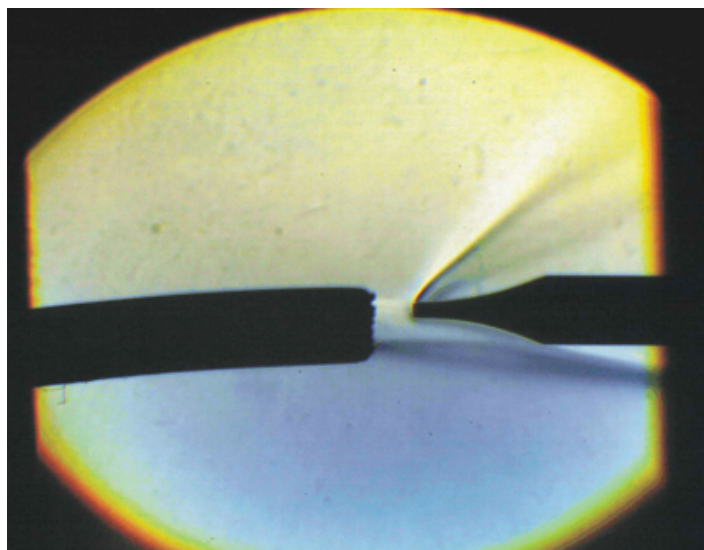
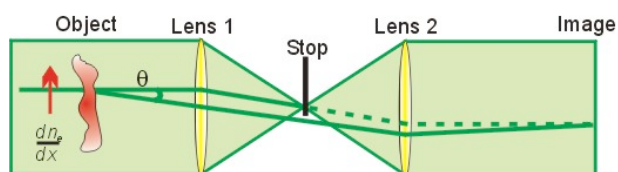


X-pinch backlighting:

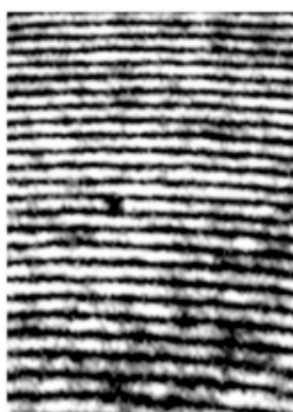
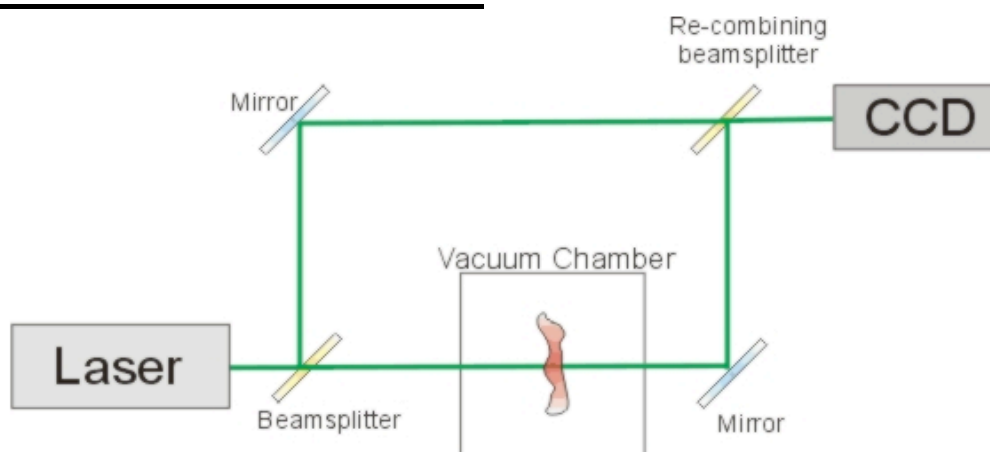


Diagnosticke pristroje

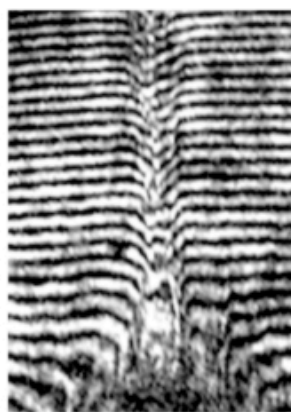
Laserove zobrazovani:



Laserova interferometrie:



No plasma



With plasma

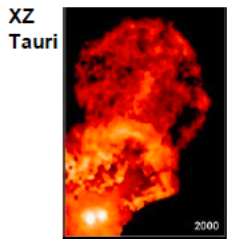
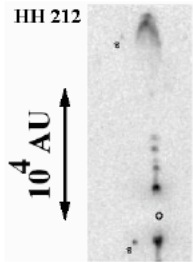
Astrofyzikalni vytrisky na Z-pinchich

Scaling of laboratory jets



Motivation: to produce in laboratory experiments plasma jet with

Space



similar
"shape" &
dimensionless parameters:

Mach number

$$M \sim 10 - 50$$

Density contrast: jet / ambient

$$\eta \sim 1-10$$

Cooling parameter

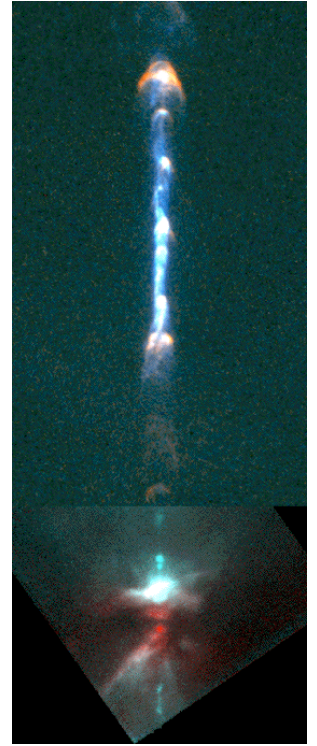
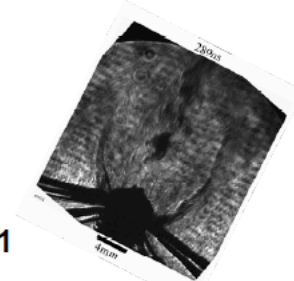
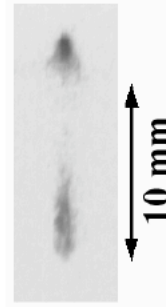
$$\chi \equiv \frac{\tau_{cool}}{R_j / V} \sim 0.1 - 10$$

Magnetic fields:

$$\beta \sim 1$$

$$\lambda/R \ll 1, \text{ Re} \gg 1, \text{ Re}_M \gg 1, \text{ Pe} \gg 1$$

Experiment

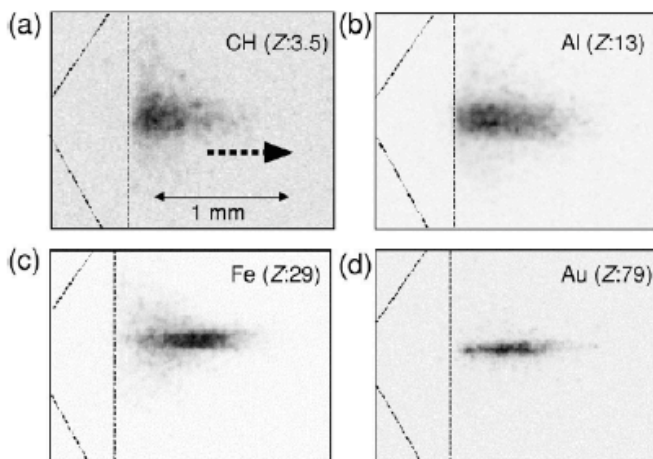


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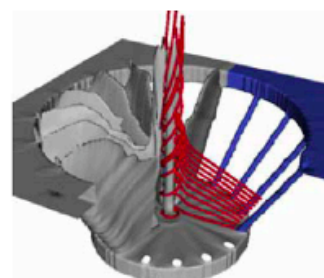
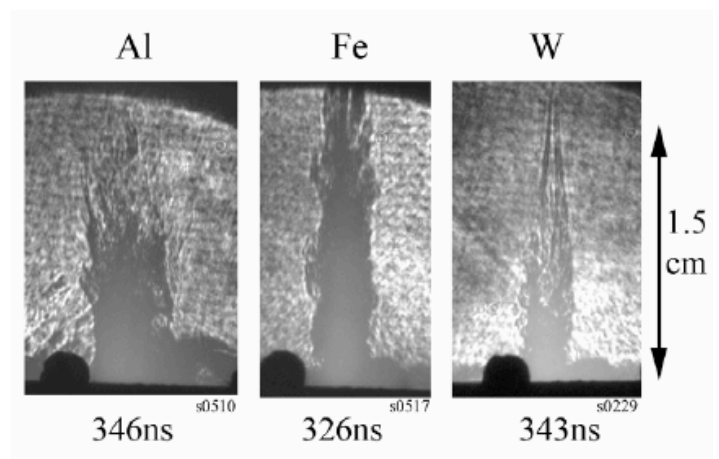
[1] D.D. Ryutov et al., Astrophys. J. 518, 821 (1999) and Astrophys. J., Suppl. 127, 465 (2000)

Radiatively cooled jets:

Gekko-12 laser (Shigemori et al., 2000)



Magpie Z-pinch (Lebedev et al., 2002)

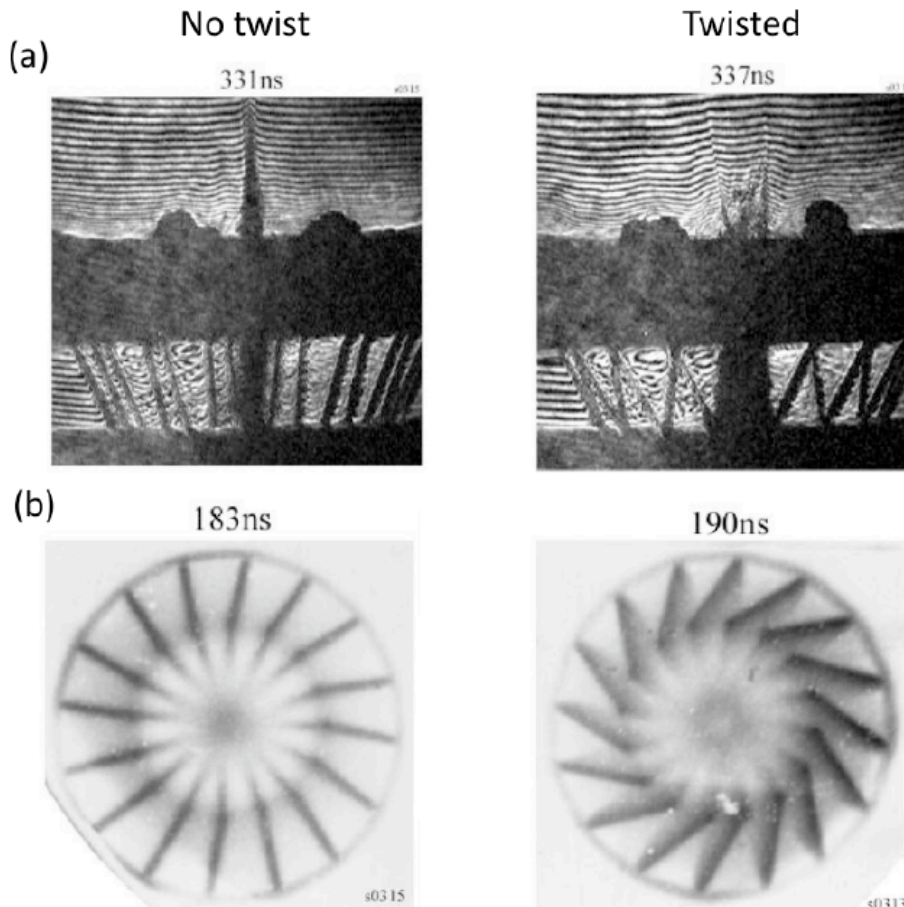
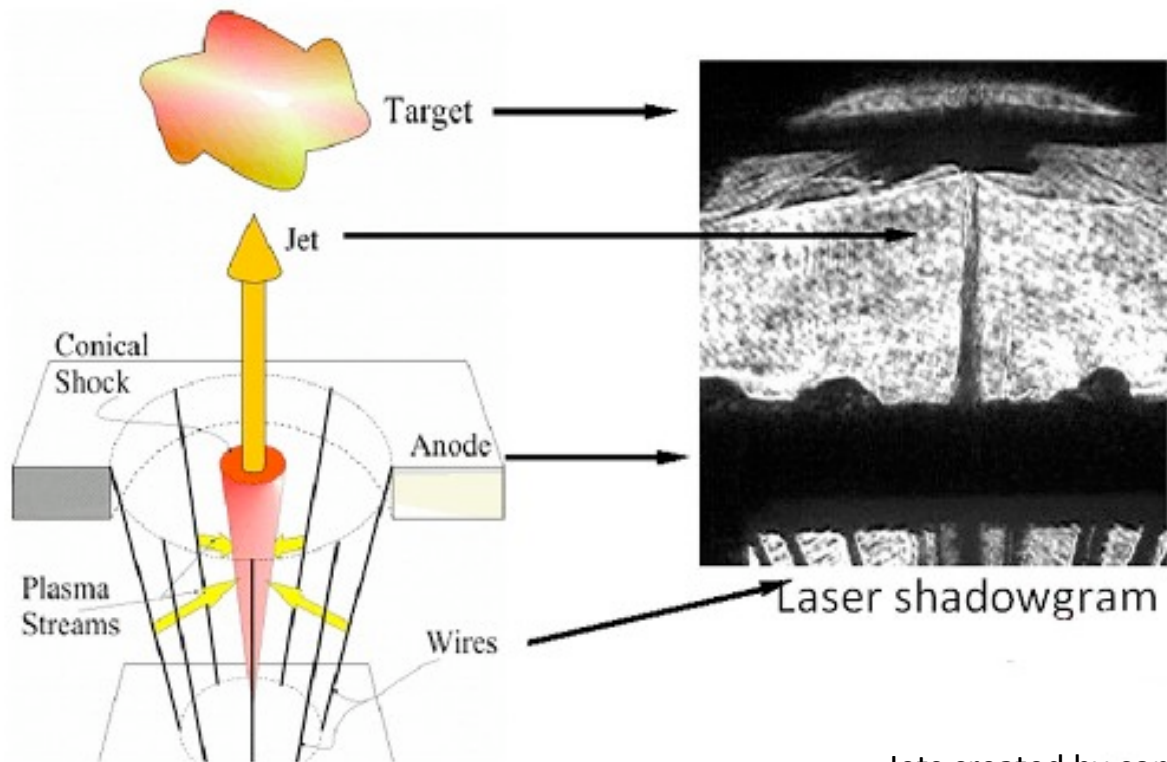


Interaction with ambient plasma
Jets with angular momentum
(Next talk)

High Mach number (~20)

No dynamically significant magnetic field

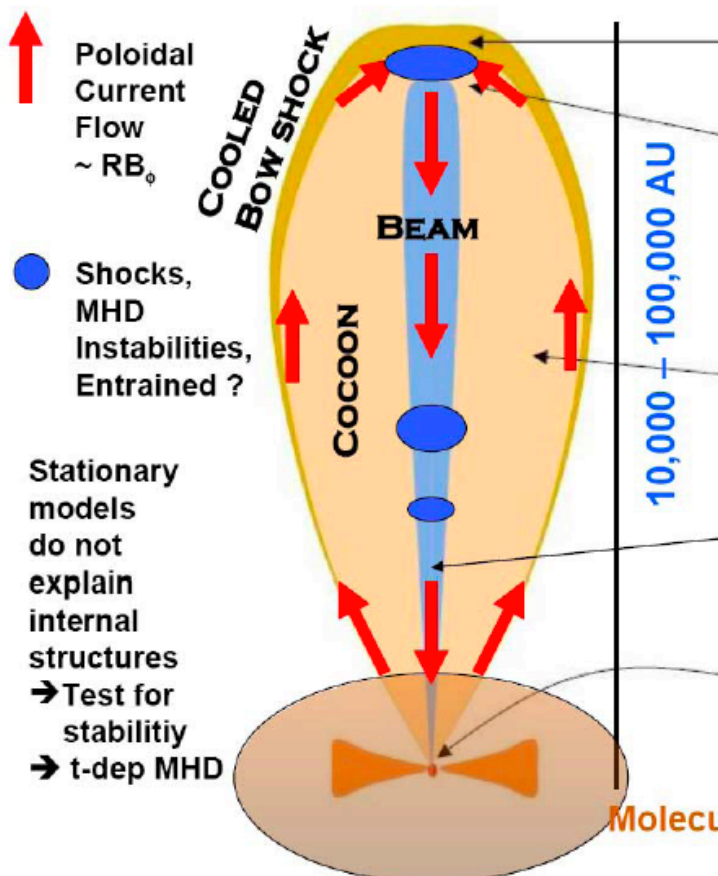
Astrofyzikalni vytrisky na Z-pinchich



Jets created by conical wire arrays with no twist (a) and with wires arranged with $/8$ twist (b). The top two figures are side on laser interferometry images showing the fringe shift due to the vertical jet. The jet from the twisted array is diverging due to the effect of added angular momentum. The bottom two images show XUV self emission imaging at 30 eV from the imploding wires.

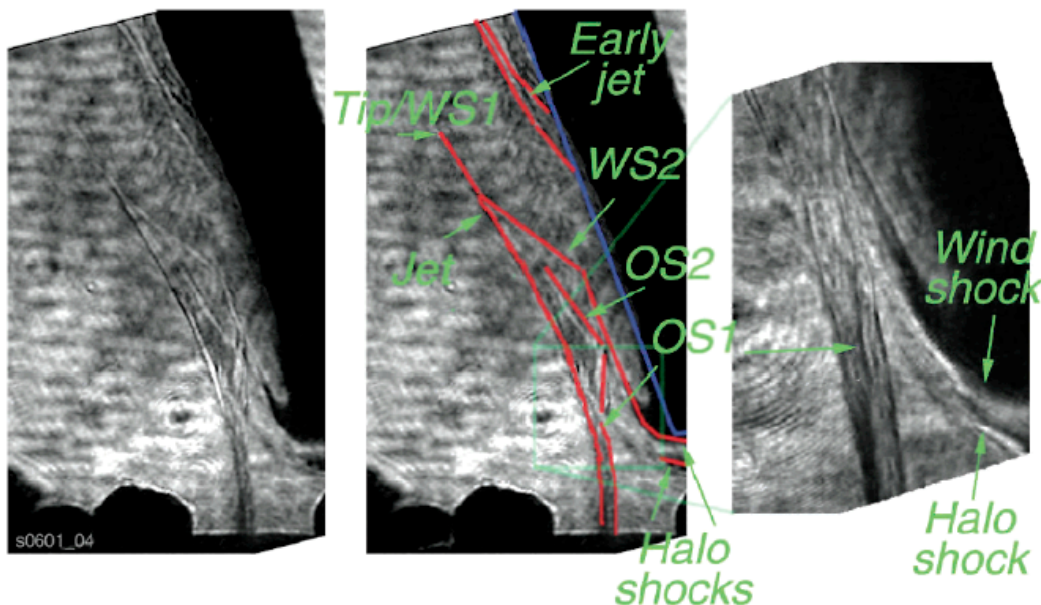
Astrofizikalni vytrisky na Z-pinchich

Magnetized outflows (Camenzind, 2007)



Experiment: plasma outflow driven by toroidal magnetic field + ambient medium

1. Formation of a collimated beam
2. Quasi-periodic generation of the jets
3. Trapping of the toroidal magnetic flux (high Re_M)
4. Efficiency of magnetic to kinetic energy conversion



Side on laser Schlieren images of a jet propagating in a transverse wind produced by ablating a CH foil.

Astrofizikalni vytrisky na Z-pinchich

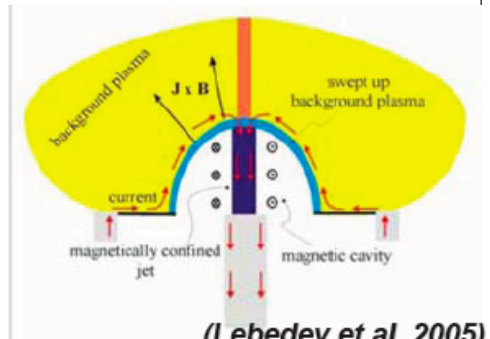
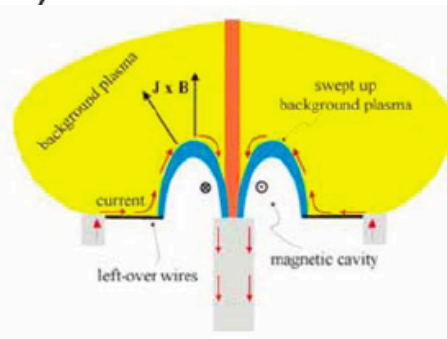
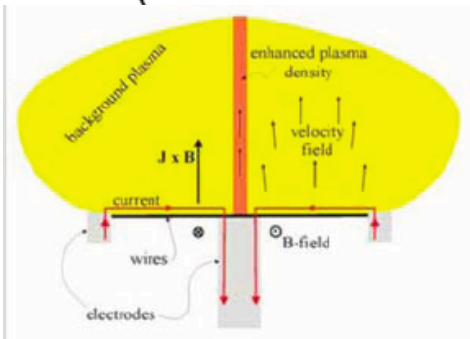
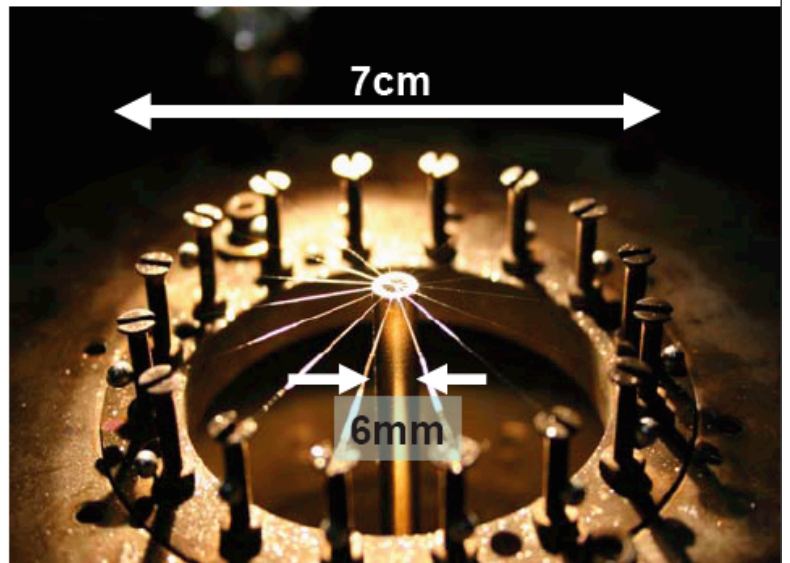
Producing jets in the lab



- **Magnetically driven jet**

- Radial wire array
- Jet driven by predominant toroidal magnetic field

- 16 **metallic wires** (W, Al) (5 - 50 μm diameter)
- Cylindrical **central cathode** (3 – 6mm diameter)



(Lebedev et al, 2005)

→ Current passes through the wires and the cathode

→ **Global toroidal field** from cathode ($B_\phi \propto 1/r$)

→ $J \times B_\phi$ force ablates material from wires forming **background ambient**

→ Denser plasma on axis ("**precursor**" jet)

→ Stronger magnetic field near the cathode

$$dm/dt \propto J \times B_\phi$$

→ **wire breakage**

→ New path of the current

→ Formation of **expanding shock**

("bubble", magnetic cavity)

→ Toroidal field compresses and collimates **jet on axis**

→ **X-ray bursts** (pinch)

→ Current driven MHD **instabilities** disrupt the jet

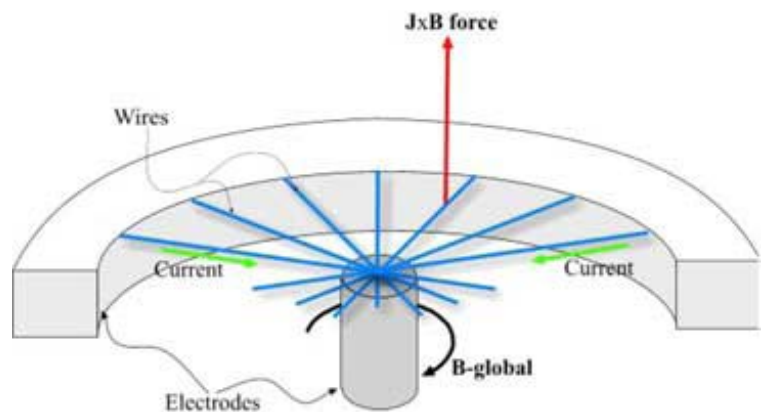
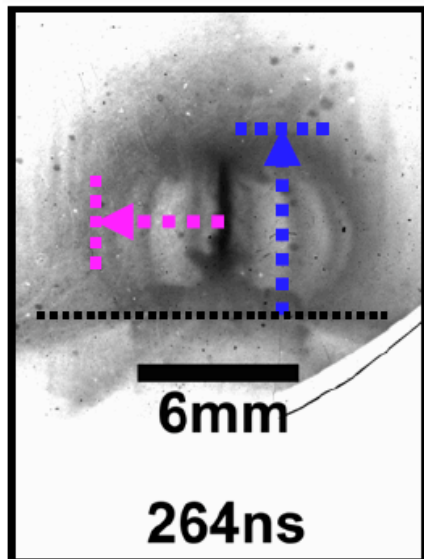
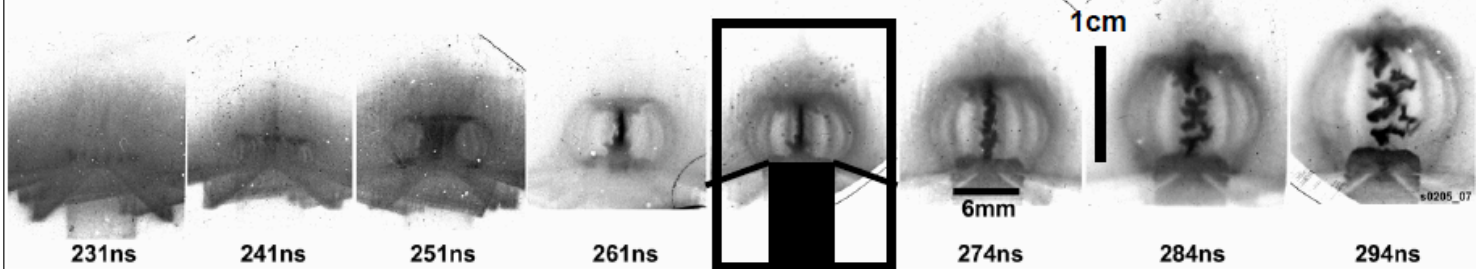
→ Opening of bubble and detachment of column

Astrofizikalni vytrisky na Z-pinchich

Radial wire array: Results

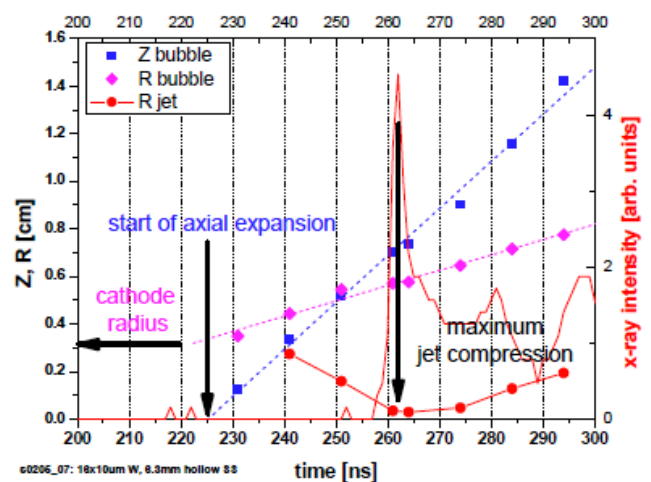


Time resolved XUV emission images ($E > 10\text{eV}$)



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- Measured bubble expansion velocities:
 Axial: $V_z = 198\text{ km/s}$
 Radial: $V_R = 64\text{ km/s}$
- X-ray emission provides timing of "events" in the jet which can be changed by varying cathode and wire diameter



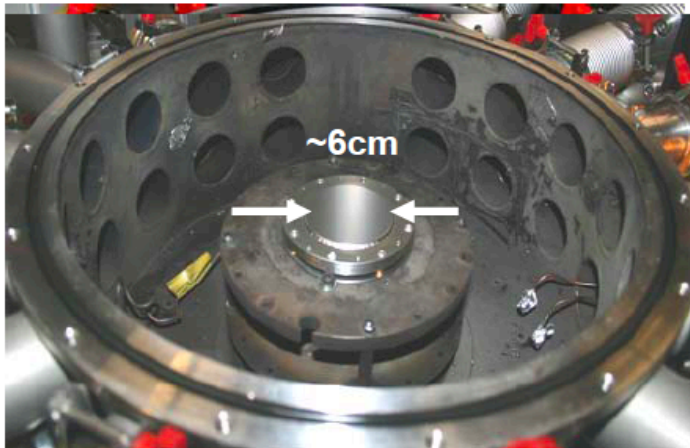
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Astrofizikalni vytrisky na Z-pinchich

Radial foil

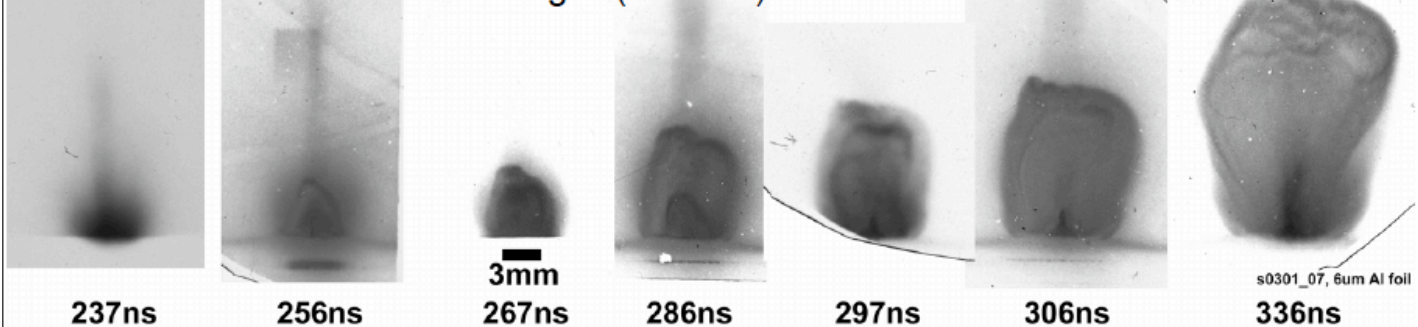


- **Magnetically driven jet using foils**
 - Replacing wires by a **metallic foil** (6 μ m Aluminium)

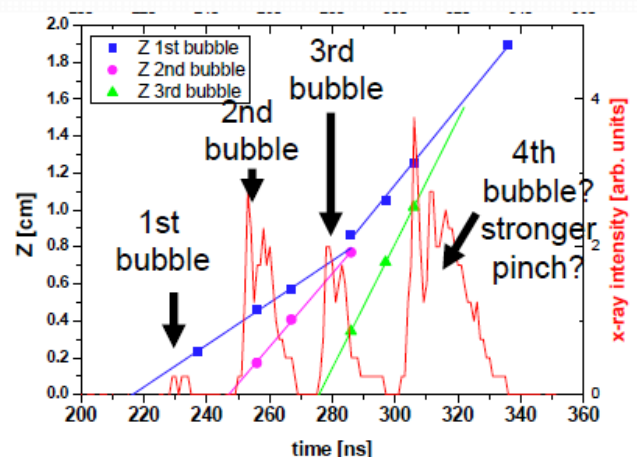


- Easier to build ☺
- Allows to use smaller size cathode
 - B_ϕ is **stronger** at smaller radius
- Mass distribution is different from radial wires
 - Expect different breakage conditions

Time resolved XUV emission images ($E > 10\text{eV}$)

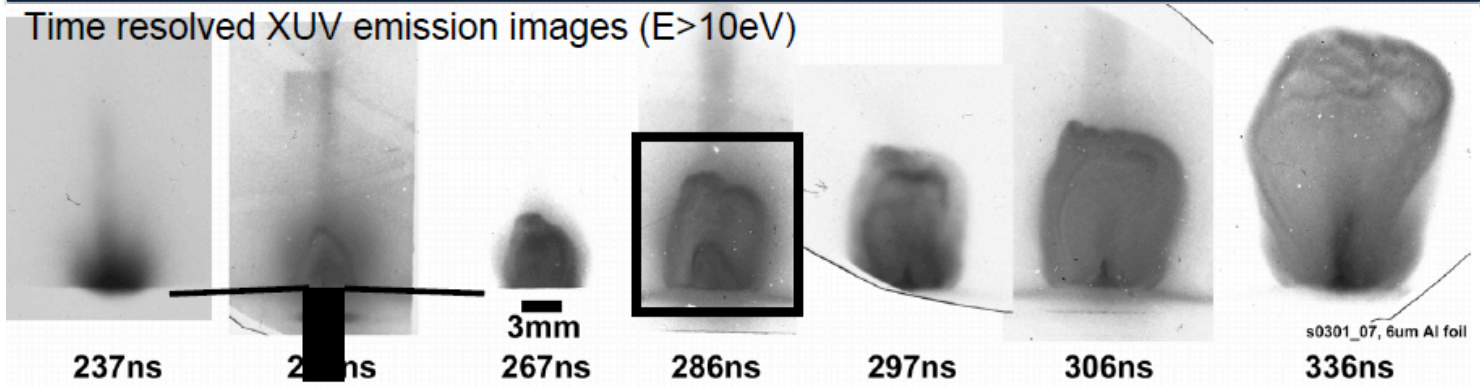


- Formation of “periodic” bubbles with increasing expansion velocities
- Correlated with **x-ray emission**
- Possible **smaller jet** forming on axis for each new bubble

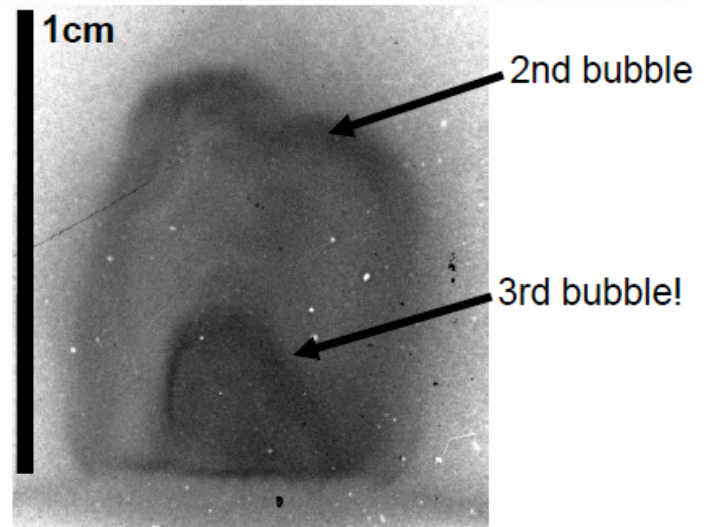


Astrofyzikalni vytrisky na Z-pinchich

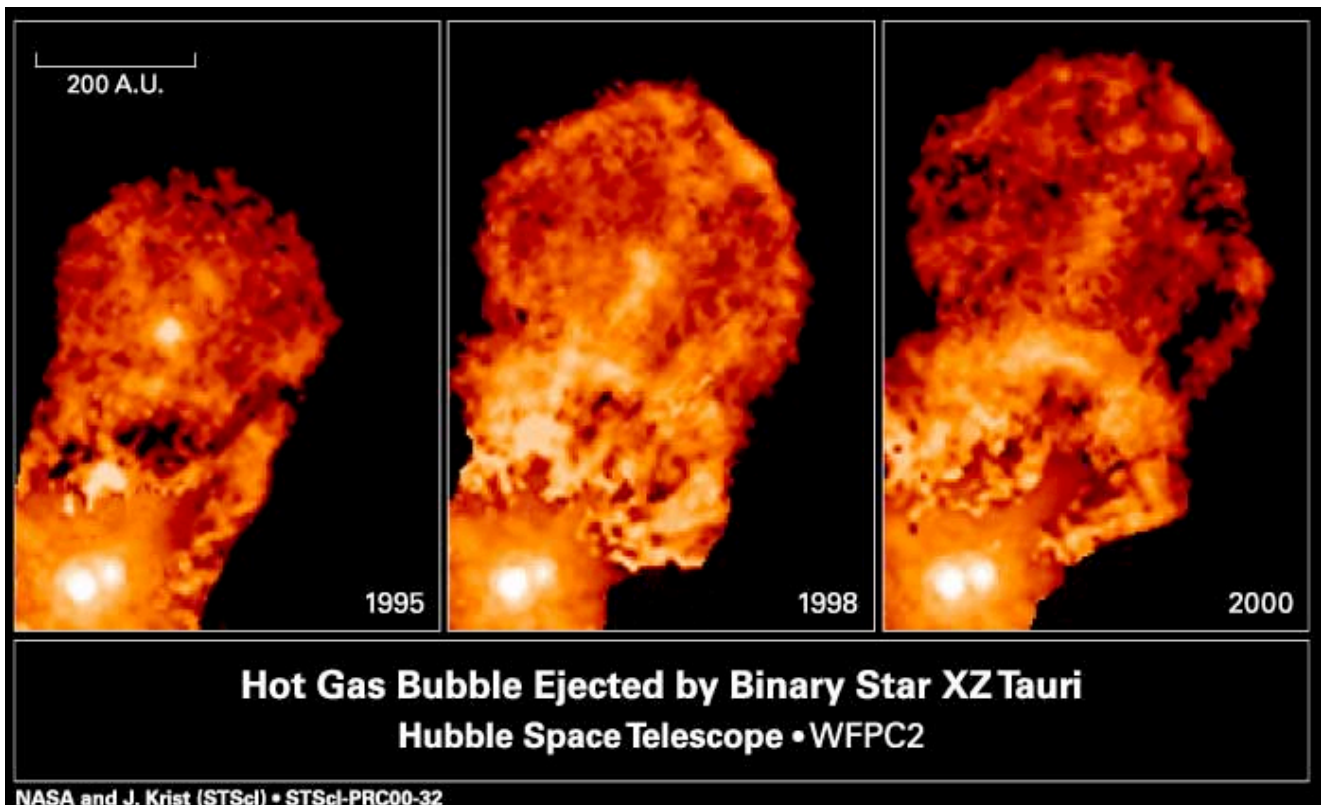
Time resolved XUV emission images ($E > 10\text{eV}$)



- Formation of “periodic” bubbles

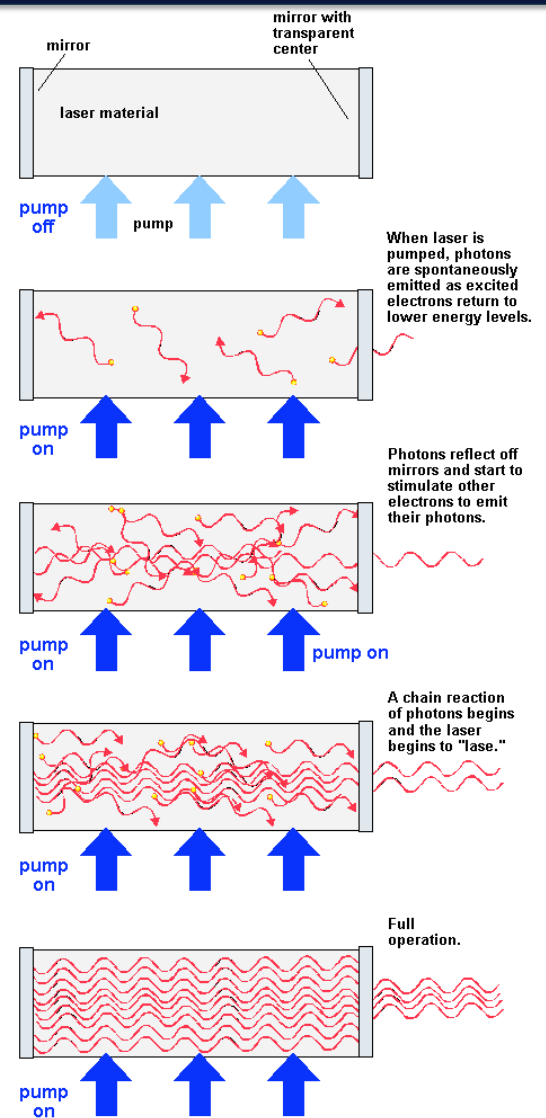
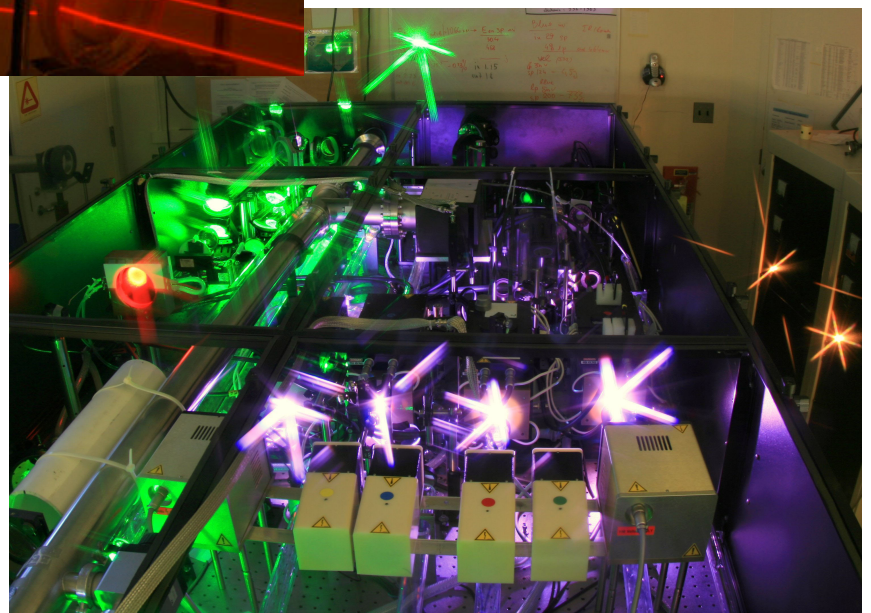
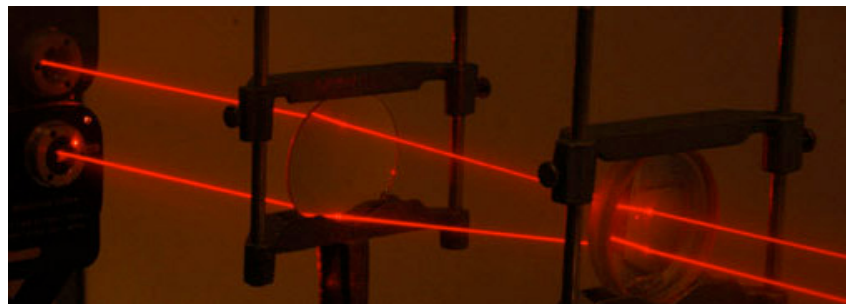
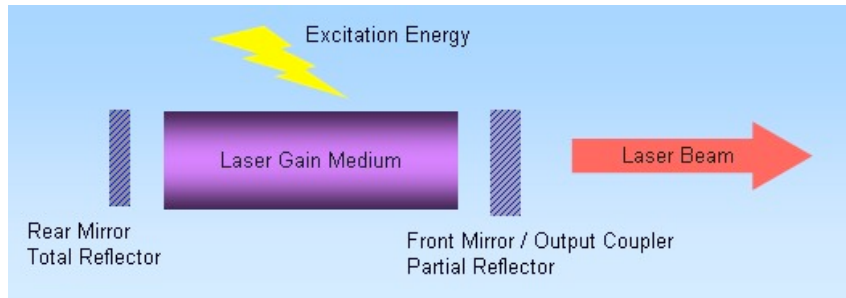


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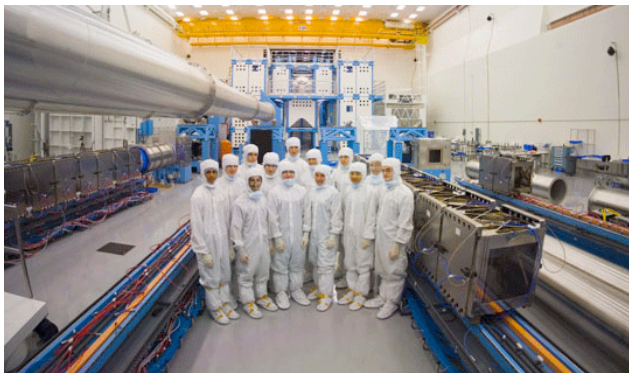
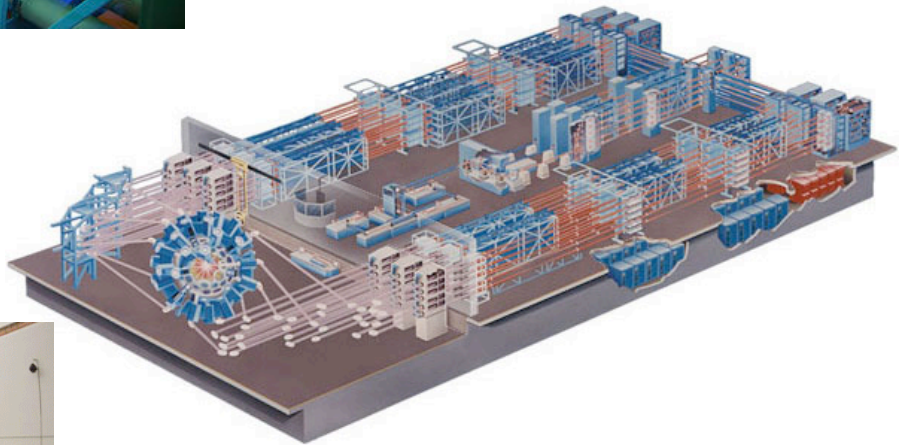
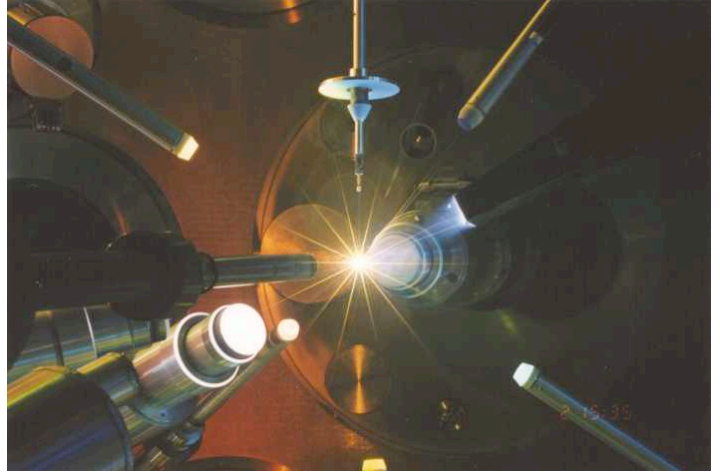
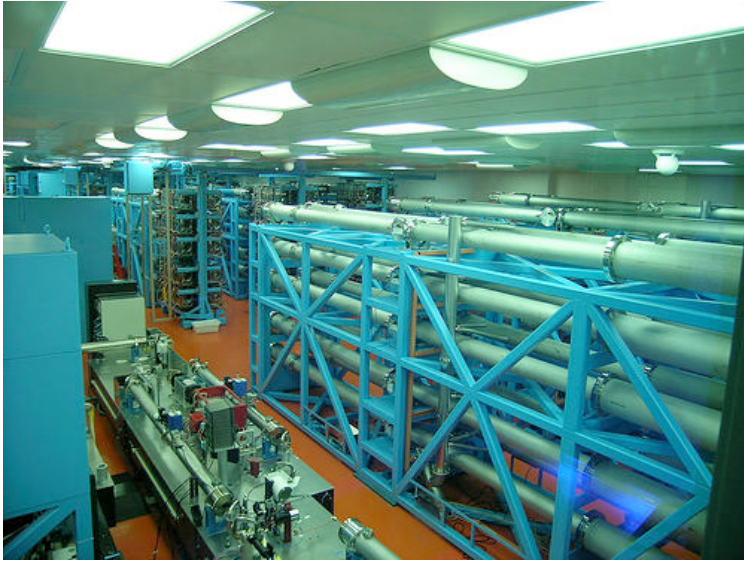


Laserove laboratore

- koherentní (podelne i napric)
- monochromaticke (kvazi-monochromaticke)
- muze mit velmi presnou/kontrolovatelnou polarizaci (pokud zrcadlovy rezonator ma v sobe polarizacni prvek)
- velmi zamereny paprsek s nizkou divergenci
- muze mit vysokou svetelnou intenzitu



Laserove laboratore

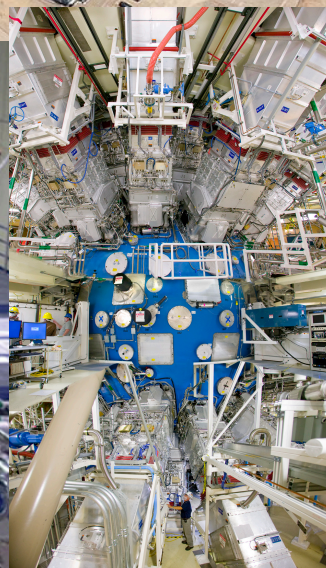
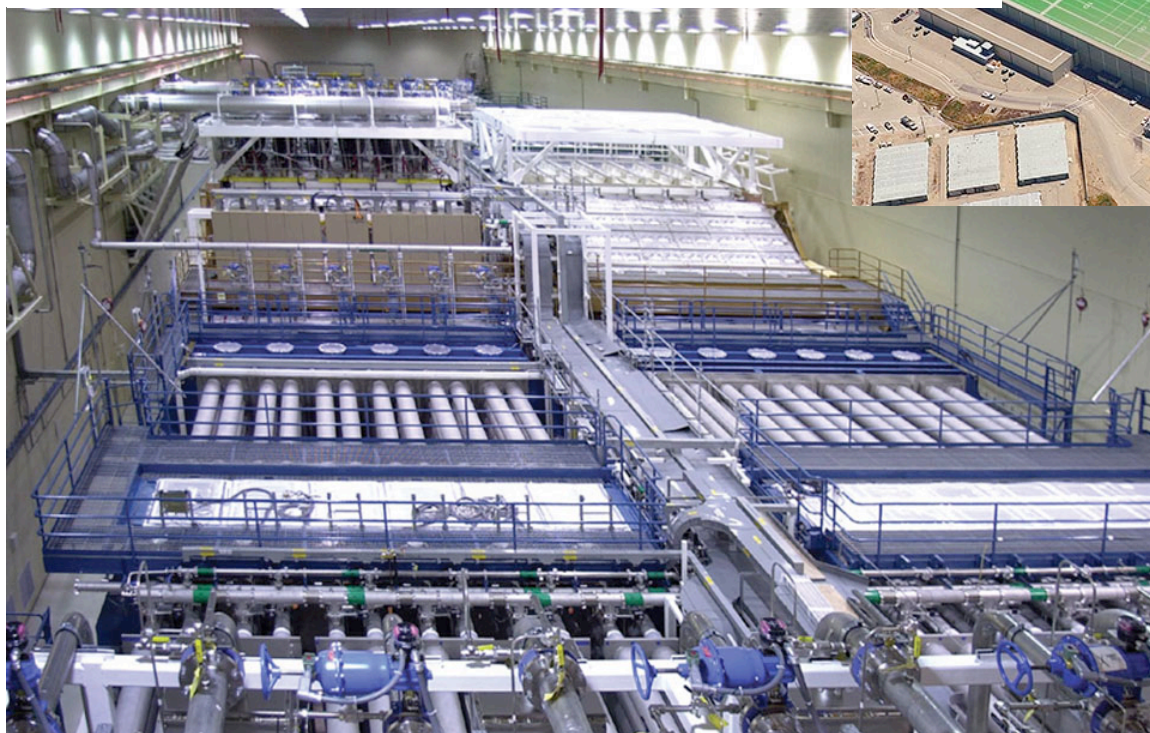
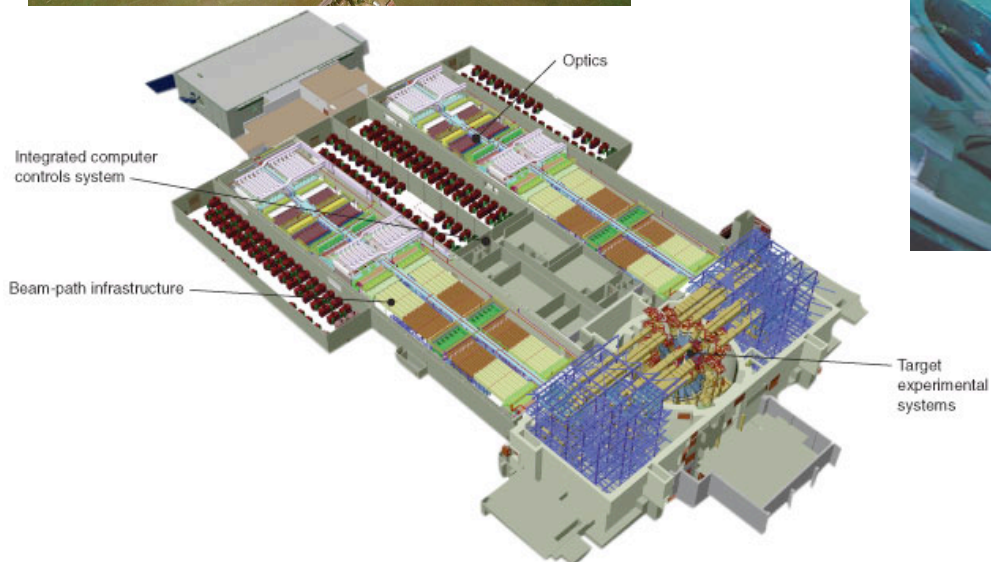
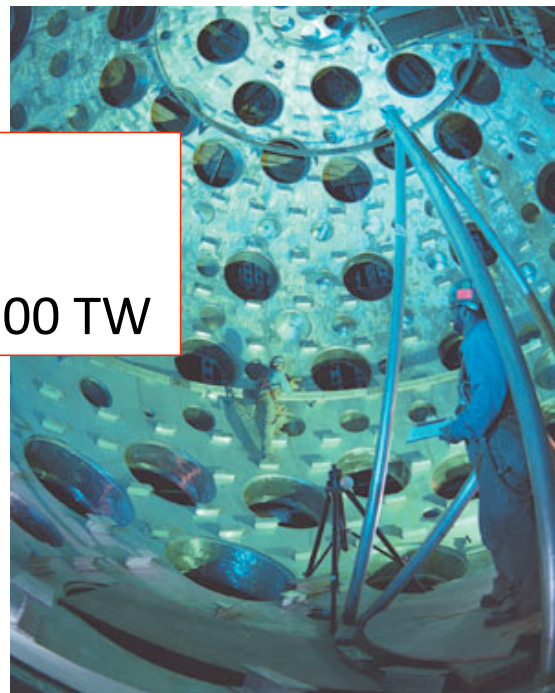


60 paprsku s max. energii
40 000 J, nanosekundove
pulsy & Omega EP – ps
laser - druhý největší laser
na světě!

Laserove laboratore

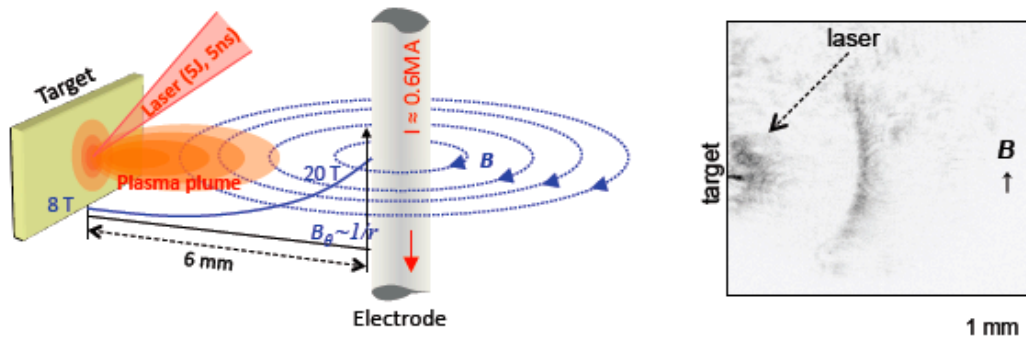


NIF @ LLNL
192 paprsku
celkovy vykon ~ 500 TW



Meziplanetarni soky

Collisionless shock experiment at the Nevada Terawatt Facility



Plasma shell parameters:

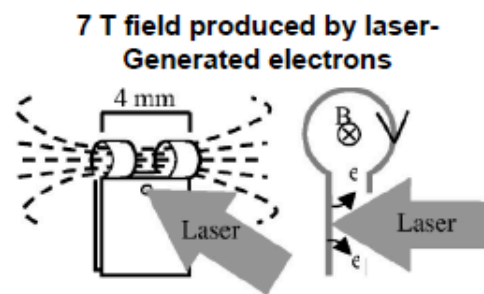
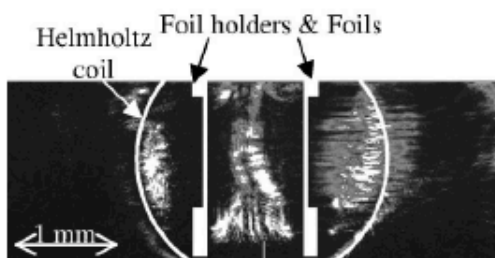
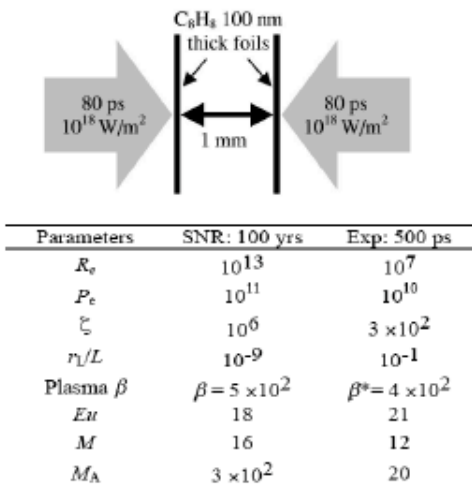
velocity: $v_0 \approx 2 \times 10^7$ cm/s
 density: $n_e \approx 7 \times 10^{17}$ cm⁻³
 field strength: $B \approx 8 - 10$ T
 temperature: $T_e \leq 200$ eV, $T_i \leq 100$ eV
 length scale: $L_n \approx 0.2 - 0.3$ mm

Plasma regime:

resistive diffusion: $R_M > 30$
 Hall term: $(c/\omega_{pi}) \geq L_n$
 ion magnetization: $2\pi/\Omega_i \geq t_{exp}$

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

Vulcan: Colliding laser-produced plasmas in magnetic field

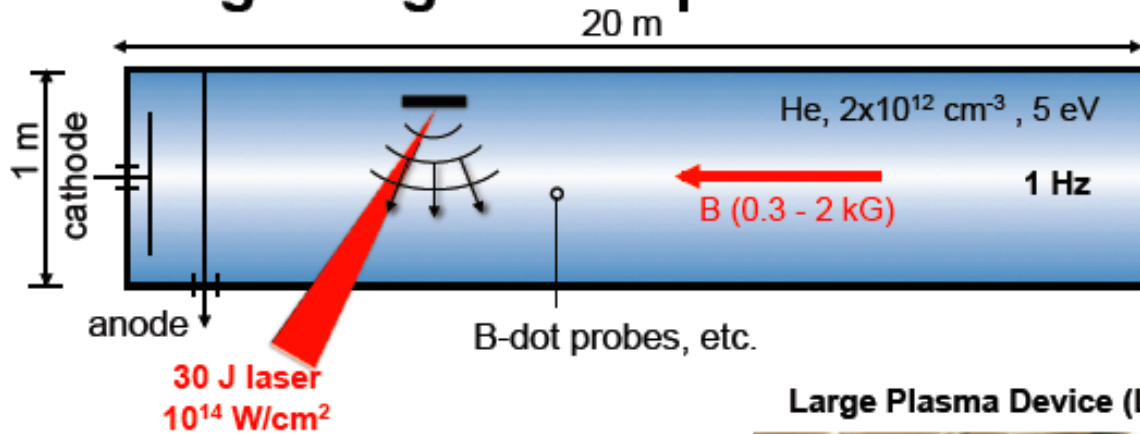


- observed features smaller than λ_{ii}
- no evidence of collisionless shock
- plasma not enough magnetized

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

Meziplanetarni soky

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



Large Plasma Device (LAPD)



W. Gekelman *et al.*

Perpendicular shocks:

$$V_s = 500 \text{ km/s } (M_A \approx 2.5)$$

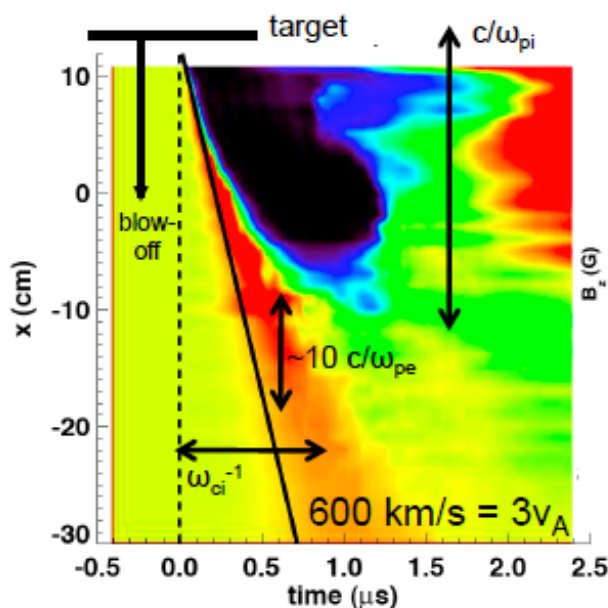
$$\text{Size } D = 50 \text{ cm}$$

$$\text{Shock transit time: } \tau \approx 1 \mu\text{s}$$

$$D/(c/w_{pi}) \approx 1, \tau w_{ci} \approx 1, \lambda_{ii}/D > 500$$

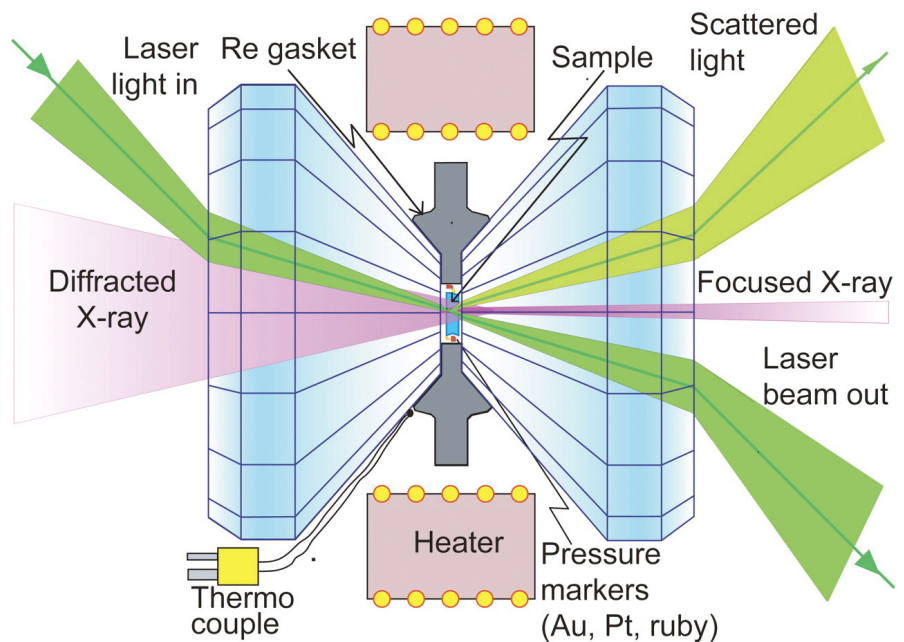
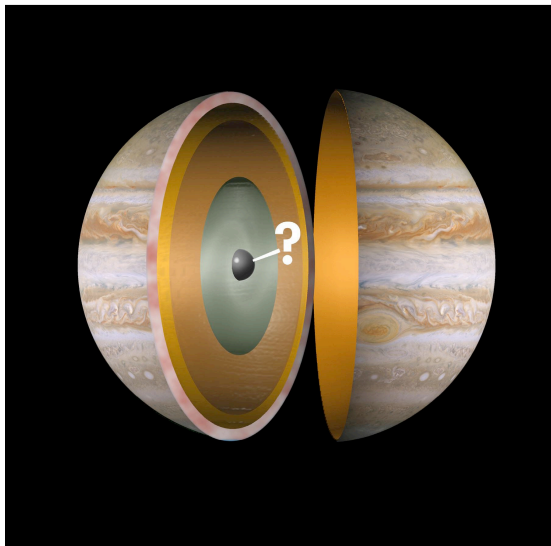
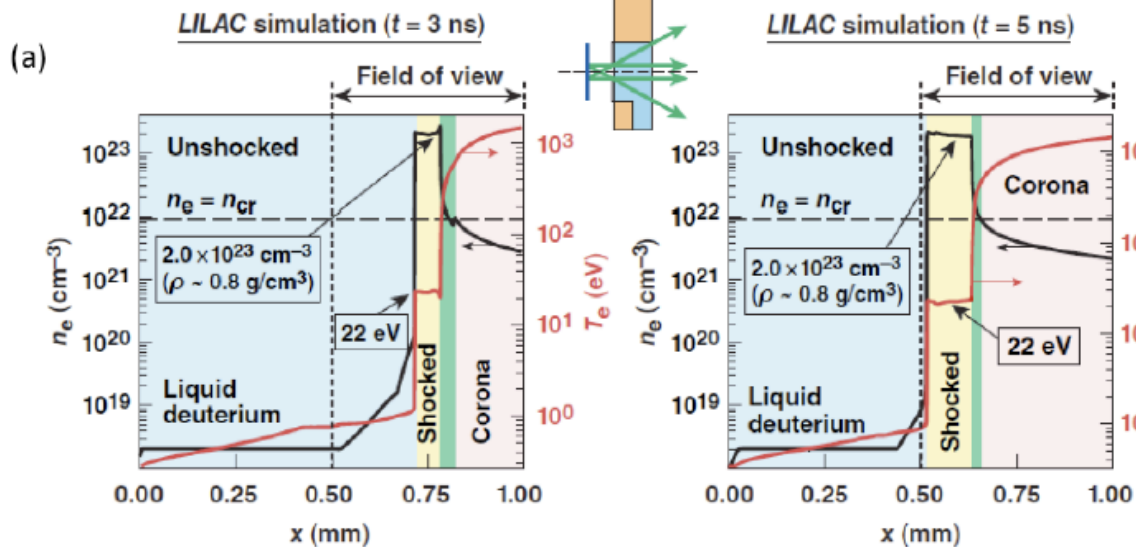
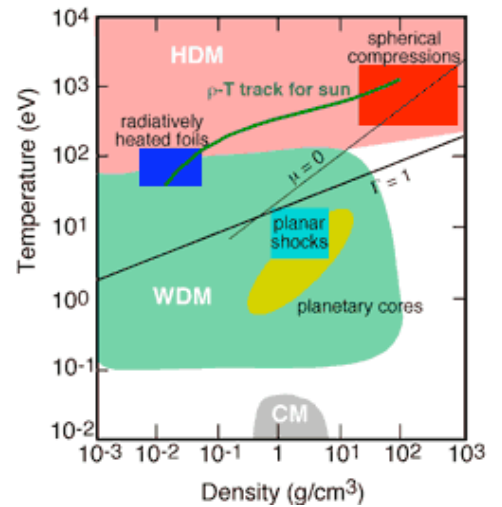
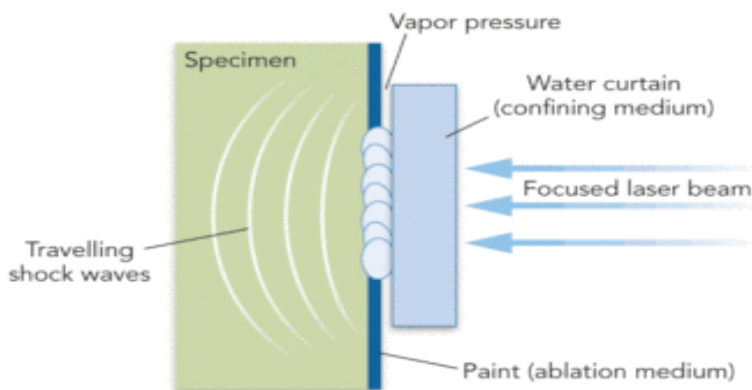
C. Constantin *et al.*, *Astrophys. Space Sci.* 322, 155 (2009)

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



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

Nitra velkých planet



Nitra velkých planet

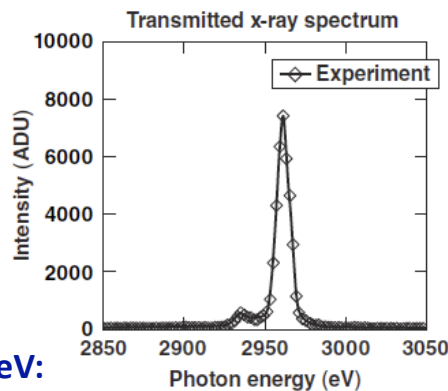
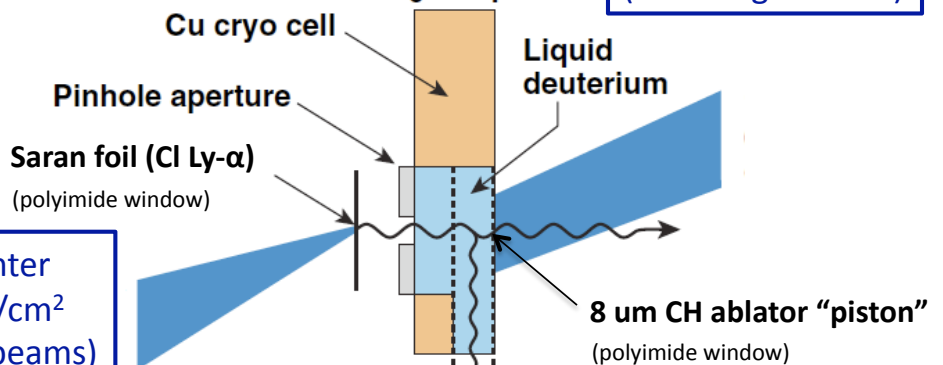
Planar cryogenic target



Non-collective 90° X-ray scattering geometry:

6 ns drive pulse
with 10^{14} W/cm²
(12 Omega beams)

1 ns backlighter
with 10^{16} W/cm²
(16 Omega beams)



X-ray probe: Cl Ly- α @ 2.96 keV:

VISAR set up"

Stacked 6 ns drive
with 10^{13} W/cm²
(12 Omega beams)

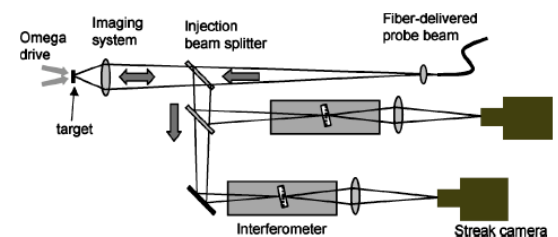
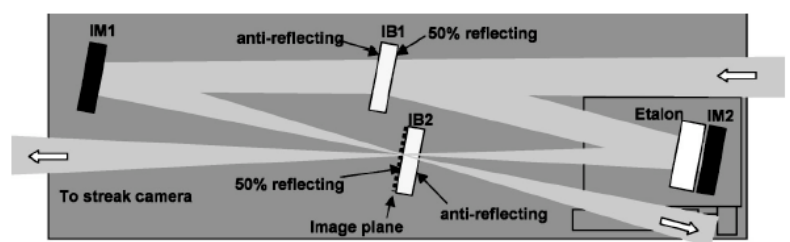
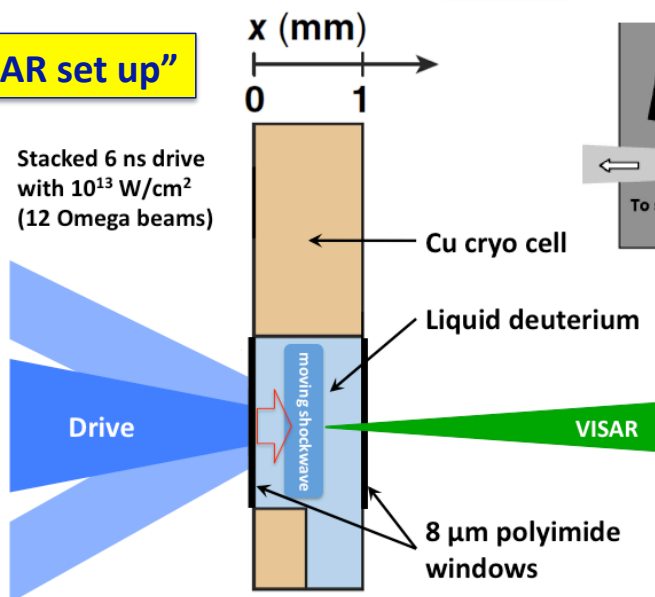
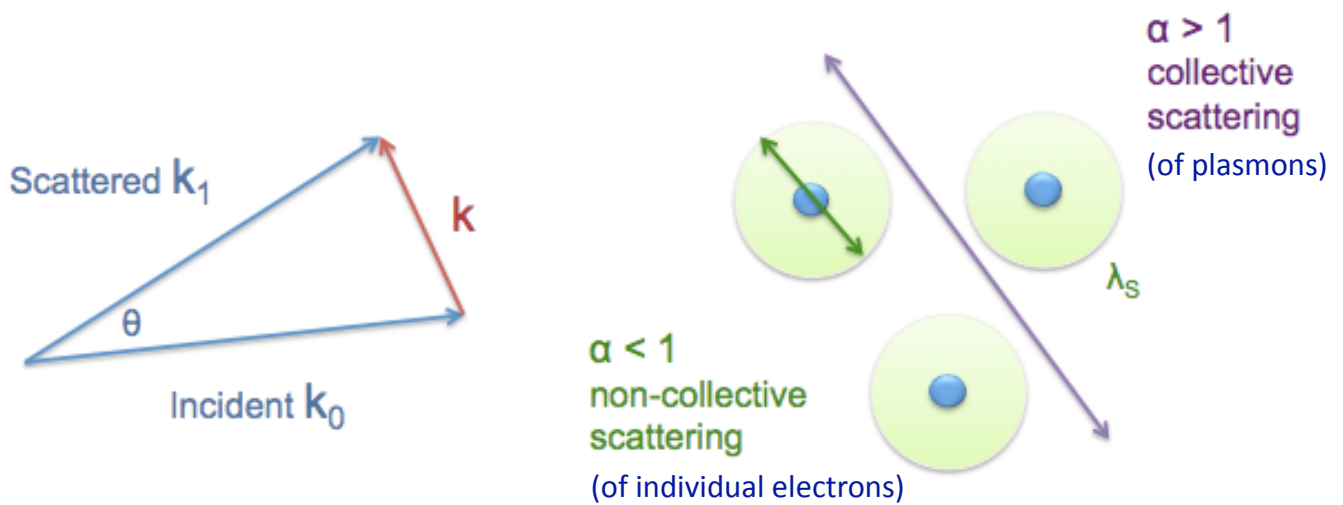


FIG. 1. Conceptual layout of the OMEGA line-imaging shock breakout diagnostic. An image of the target is relayed to the streak cameras through a pair of velocity interferometers.

Thomsonuv rozptyl

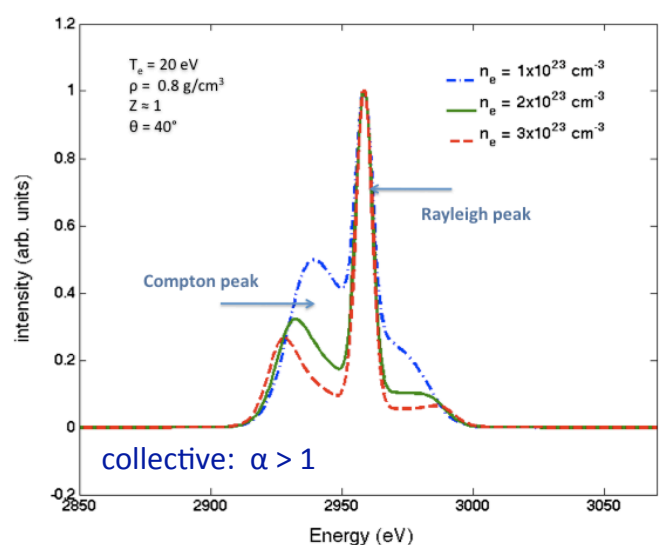
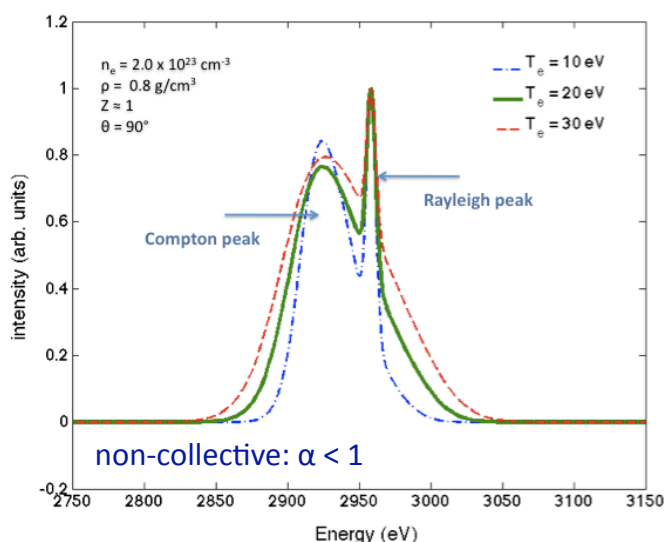


Scattering vector: $k = (4\pi / \lambda_0) \sin(\theta/2)$

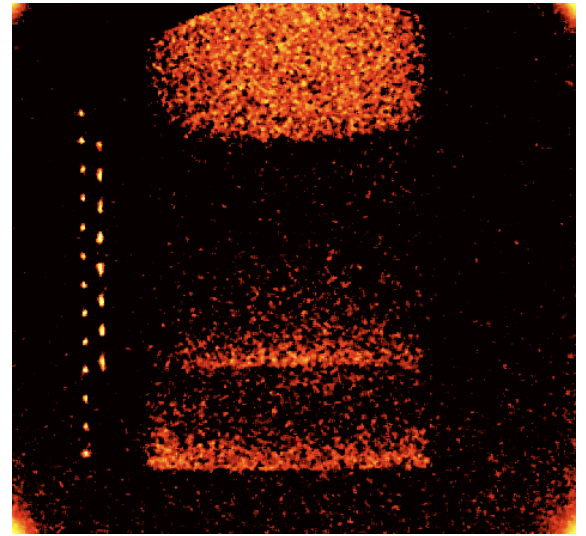
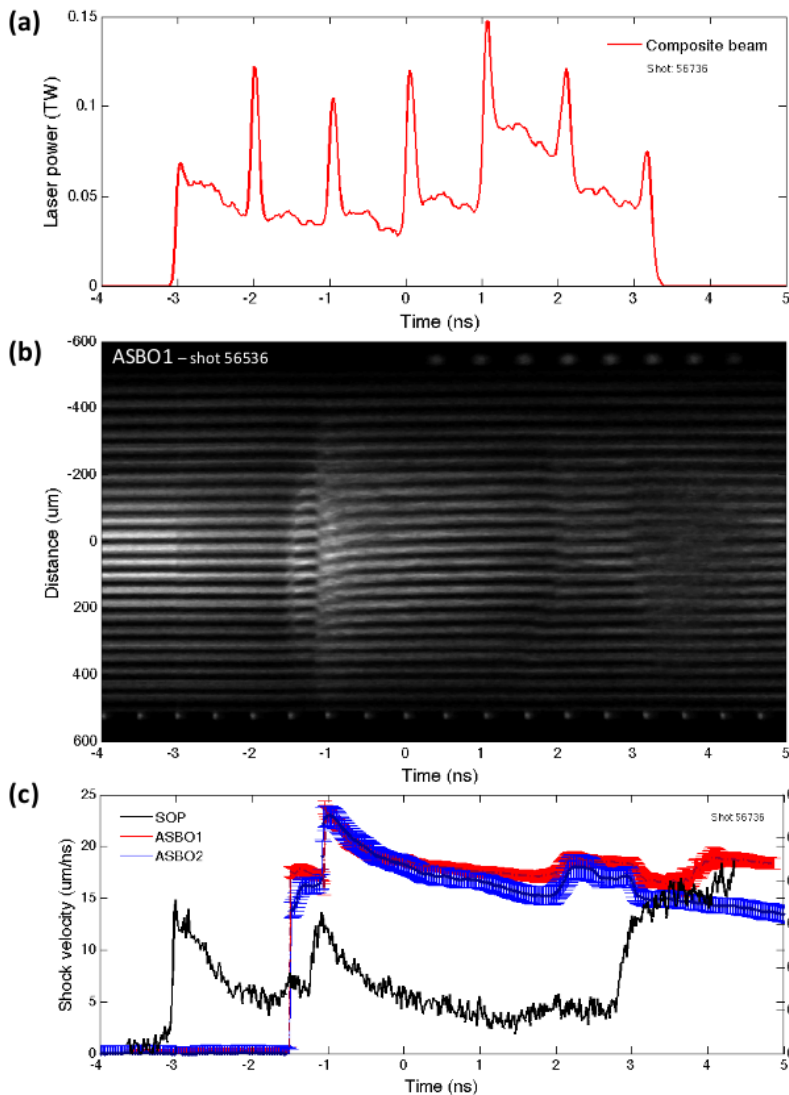
Dynamic structure factor: $S_{ee}^{tot}(k, \omega) = |f_I(k) + g(k)|^2 S_{ii}(k, \omega) + Z S_{ee}^0(k, \omega)$

Plasma screening length: $\lambda_S \sim \lambda_{TF} = \sqrt{\frac{2\epsilon_0 E_F}{3n_e e^2}}$ (Thomas-Fermi scale length)

Scattering parameter: $\alpha = 1/k\lambda_S$

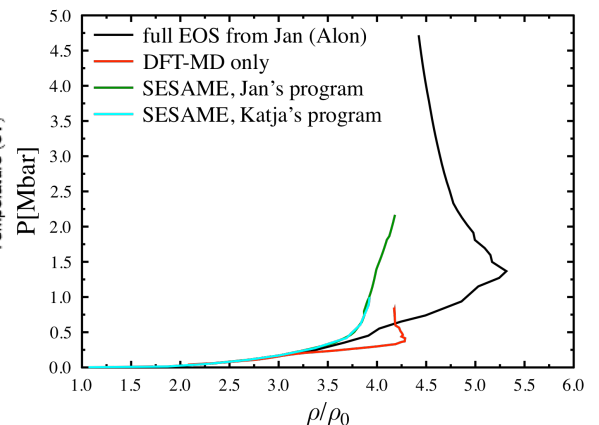


Diagnosticke pristroje – VISAR, SOP



VISAR = Velocity Interferometry of Any Reflector

SOP = Streakwd Optical Pyrometry



- Velocity (first shock):
 17 ± 0.9 km/s

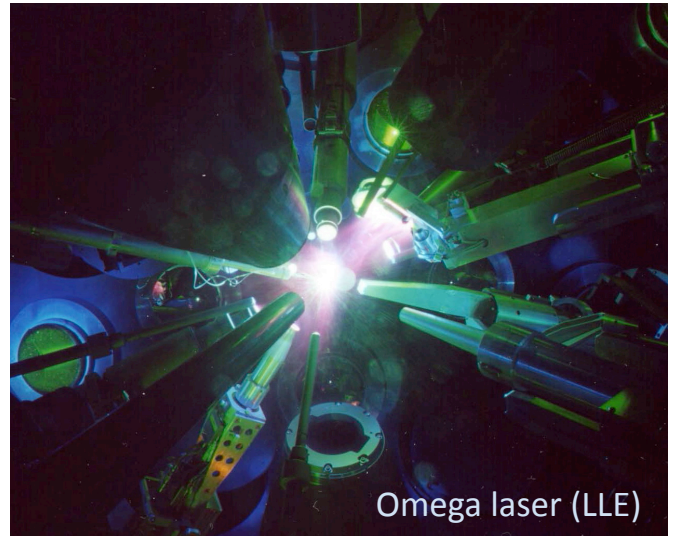
- Velocity (2nd shock):
 23 ± 1.0 km/s

ρ	0.65 g/cc
P	0.45 Mbar
T	0.45 eV

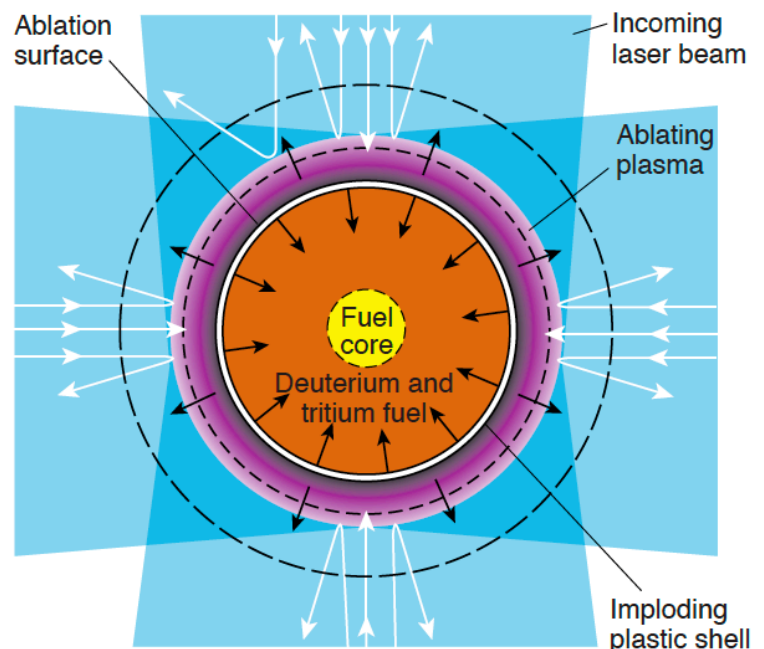
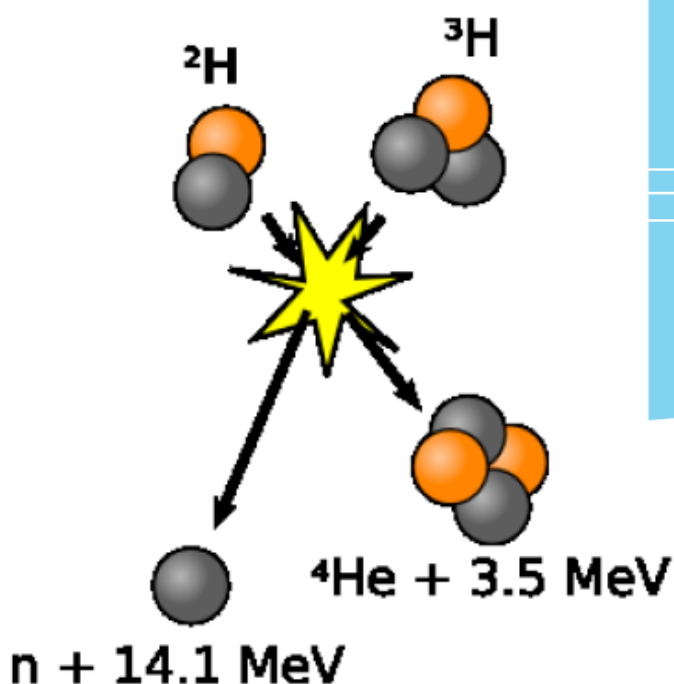
ρ	0.68 g/cc
P	0.76 Mbar
T	0.75 eV

Inercialni fuze

- Tyto laserove systemy maji desitky az stovky jednotlivych paprsku, které se vsechny soustredi do jednoho bodu => rovnomerne ozareni fuzni kulicky
- Vysko-energeticke lasery (kazdy paprsek ma 200 – 1000 J)
- Pomerne dlouhe pulsy nekolik nanosekund => vykon: 10^{12} W = TW !!!
- Tyto parametry jsou velmi dulezite pro vyzkum inercialni fuze a laboratorni astrofyziky
- Lasery jsou schopne vytvorit podminky panujici v nitrech velkych planet a hvezd

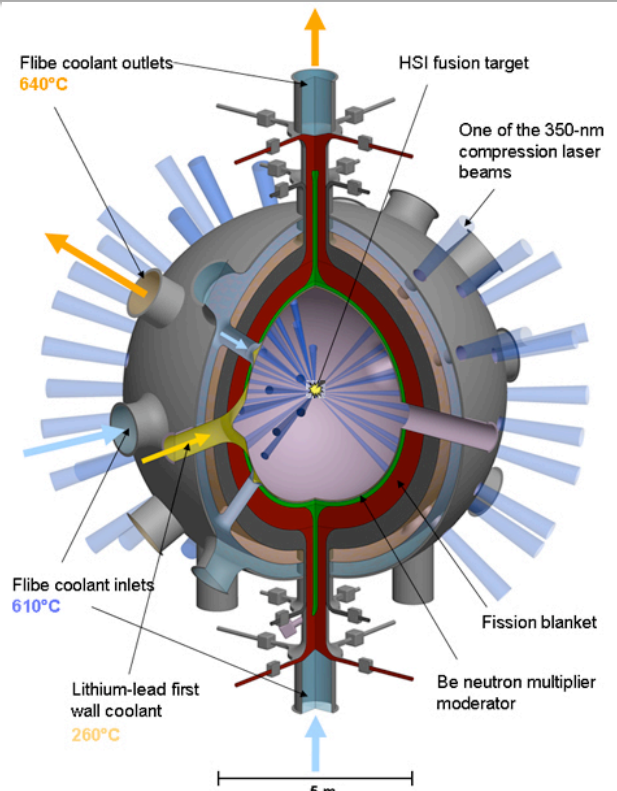


Omega laser (LLE)



Inercialni fuze

Vedle velmi zname magneticke fuze, kterou si fyzikove procvicuji na tokamacich JET a brzo snad i v ITERu, existuje nemala skupinka vedcu, kteri se pokouseji o “zazech” na nejvetsich laserovych systemech sveta jako NIF, Omega nebo Gekko.



- Direct drive:

Lasery uniforme ozari povrch zmrazene kulicky deuteria tritia (D-T). Hmota z povrchu se rychle zahreje a zacne expandovat jako raketa. Silne sokova vlna pak padi smarem do centra, pricemz stlacuje a zahriva vodik uvnitr, ve kterem se nakonec zazehne termonuklearni reakce.

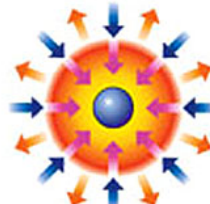
→ Radiation

→ Blowoff

→ Inward transported thermal energy



Laser beams or laser-produced x rays rapidly heat the surface of the fusion target, forming a surrounding plasma envelope.



Fuel is compressed by the rocketlike blowoff of the hot surface material.



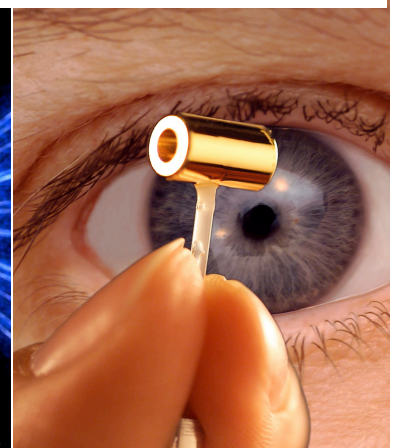
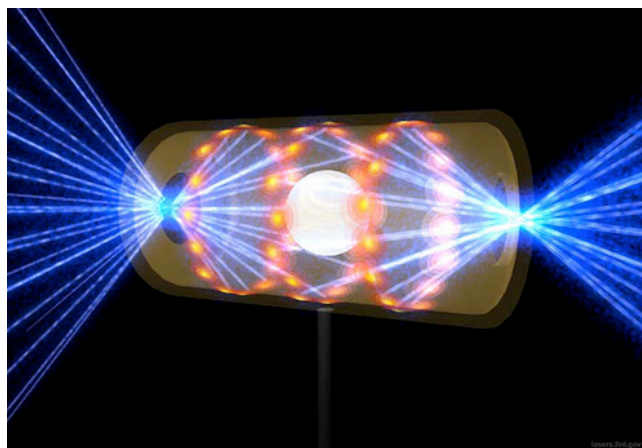
During the final part of the capsule implosion, the fuel core reaches 20 times the density of lead and ignites at 100,000,000°C.



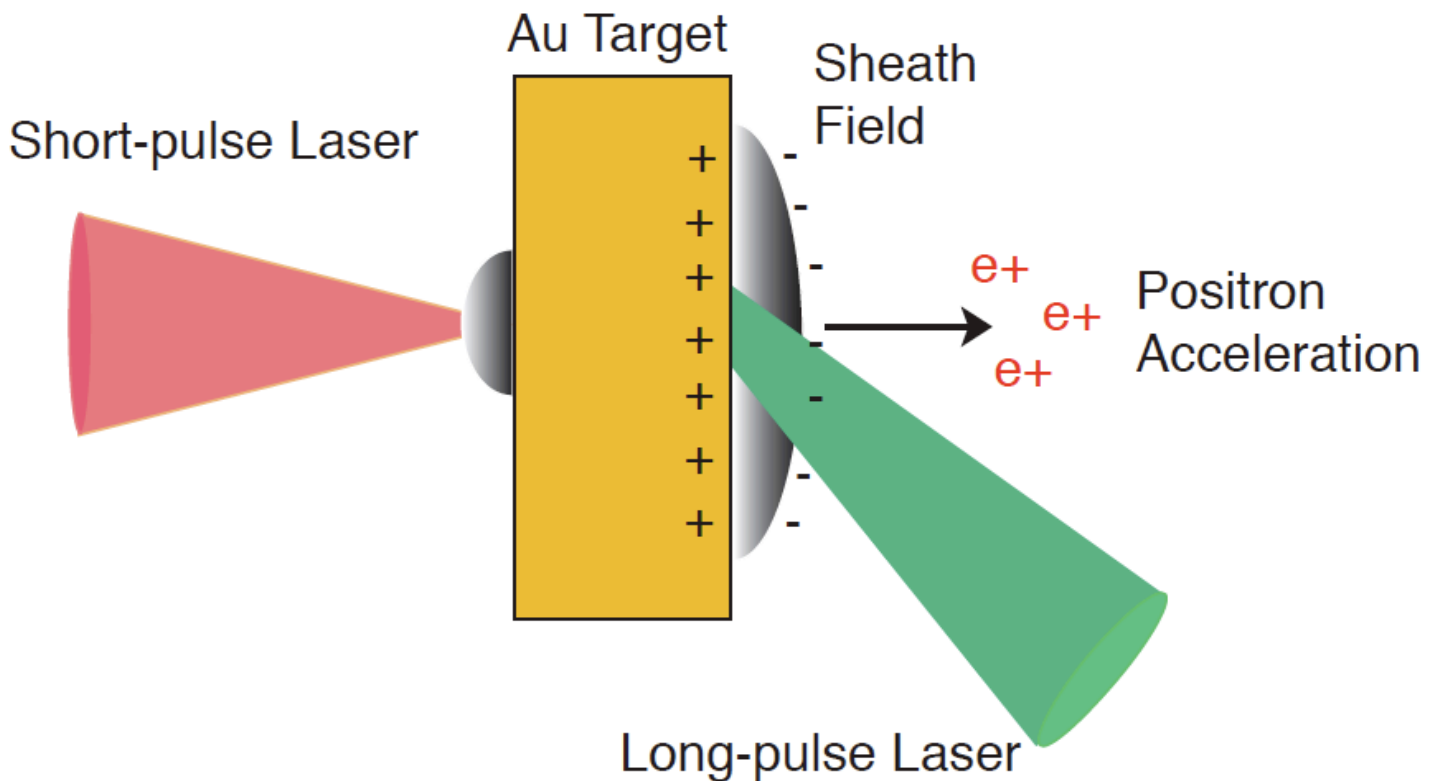
Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the input energy.

- Indirect drive:

Lasery zari na vnitřni povrchu zlateho hohlraumu, který vyzařuje silné a rovnoměrné Rentgenové záření, které pohání sokovou vlnu v D-T.



Lasery umi vyrabet i positrony!



- Two Possible Mechanisms:

- Direct process:



- Trident process

- Indirect process (via Bremsstrahlung):

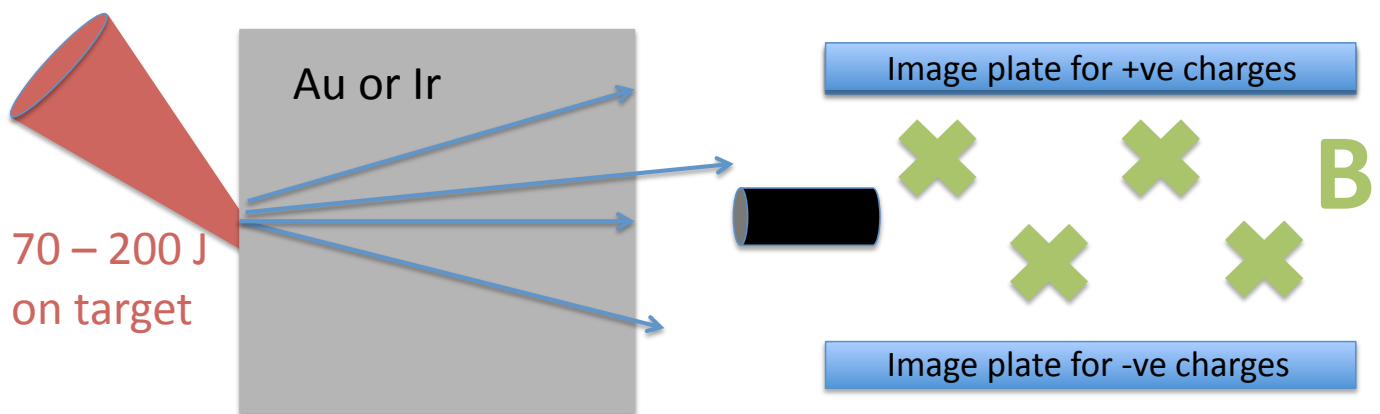


- Bethe-Heitler (BH) Process

- Since electrons have a shorter stopping distance thick targets favour BH

Obsah přednášky

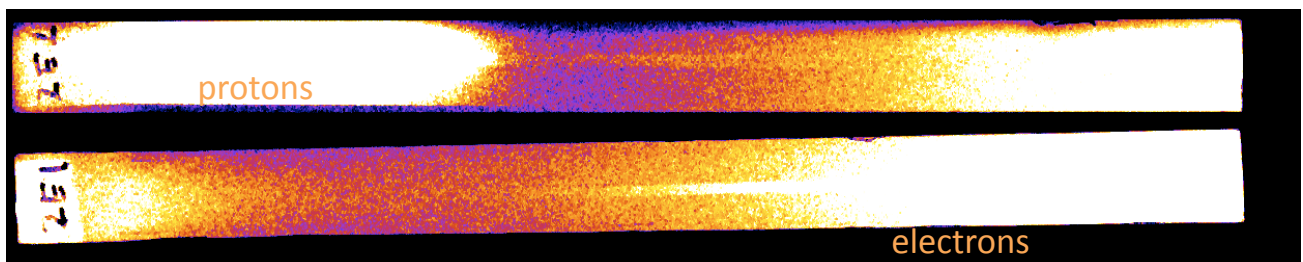
- Laser vyrábí celou řadu nabitých částic a fotonů, ze zadní strany jsou urychleny elektrony, pozitrony, protony a ionty



← Increasing Energy (or mass)



POSITRONS!!!



Dalsi priklady & zaver

- Dalsi priklady astrofyzikalnich objektu, které se simulují v laboratorích při podobných experimentech:
 - výbuchy supernov (Z-pinche, lasery)
 - dynamika Slunce/hvezd & korona (lasery)
 - akreční disky & MHD nestability (lasery)
 - mlhoviny/molekulová mrakna (lasery, Z-pinche)
 - kosmické záření (SLAC)
 - černé díry (urychlovace)
 - Velký třesk (LHC ???)
 - ... atd ...
- Laboratorní astrofyzika se v posledních letech stala důležitou součástí výzkumu vesmírných objektů
- S novými energetičtějšími lasery, Z-pinči, urychlovacími a dalšími výkonnými zařízeními jsou dnešní vědci schopni vytvářet i ty nejextremnější podmínky panující ve vesmíru
- Hlavní výhodou těchto experimentů je široká škála diagnostických technik, které přímo a současně mohou studovat fyzikální procesy – astronomové mají k dispozici jen omezené množství diagnostik (spektroskopie - teleskopy, magnetometry + chemická analýza – kosmické sondy)