PROBLEM OF MASSIVE HOMOGENEOUS PLASMA SHELL CREATION IN SELF-IMPLODED MULTITERAWATT DISCHARGES

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TARGETS & APPLICATIONS
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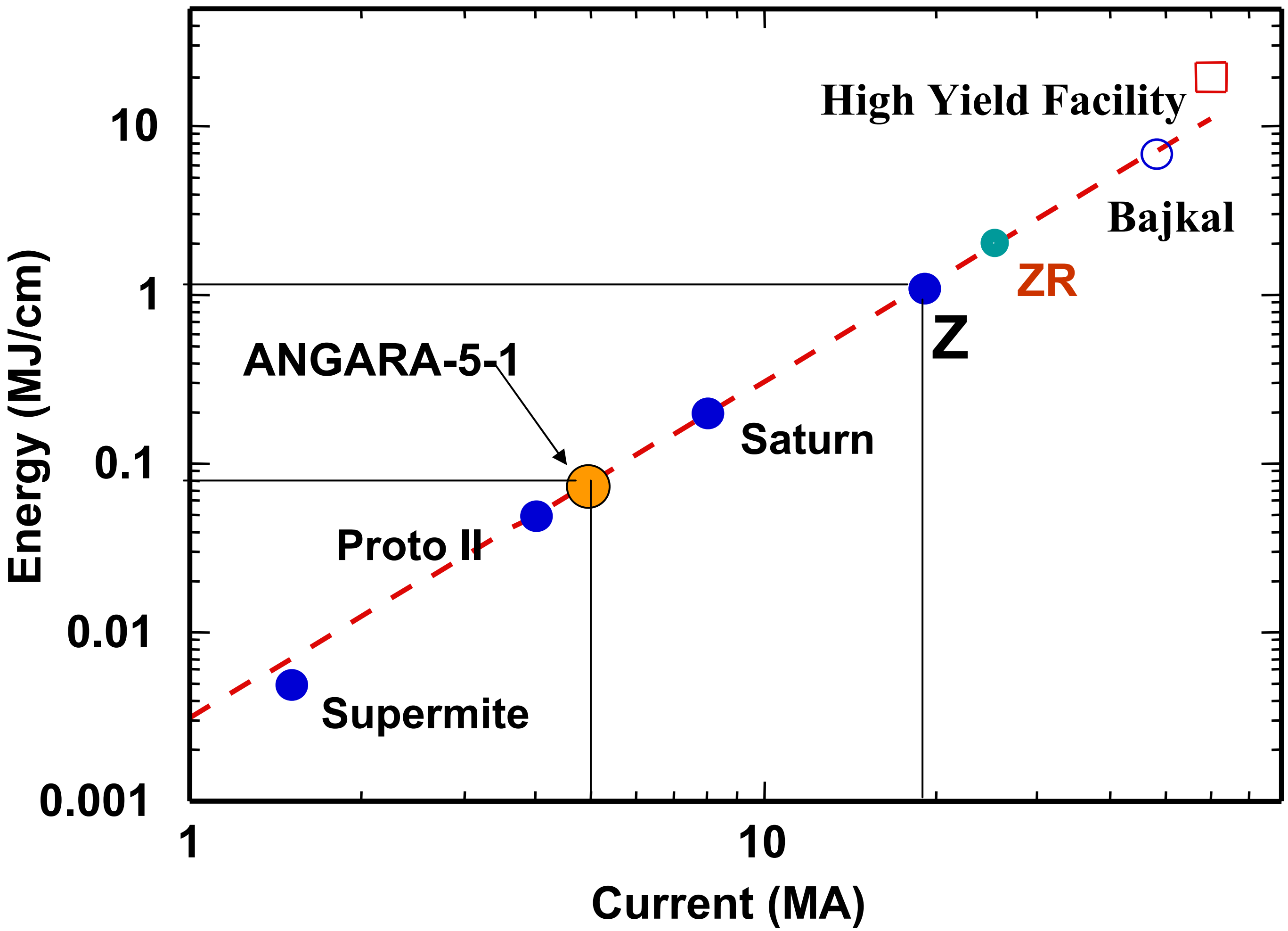
ICF target activation is based on implosion of an integral massive plasma shell generated at the beginning of the process.

The spherical multilayered shell of ICF target is imploded under action of an isotropic flux of laser or x-ray radiation.

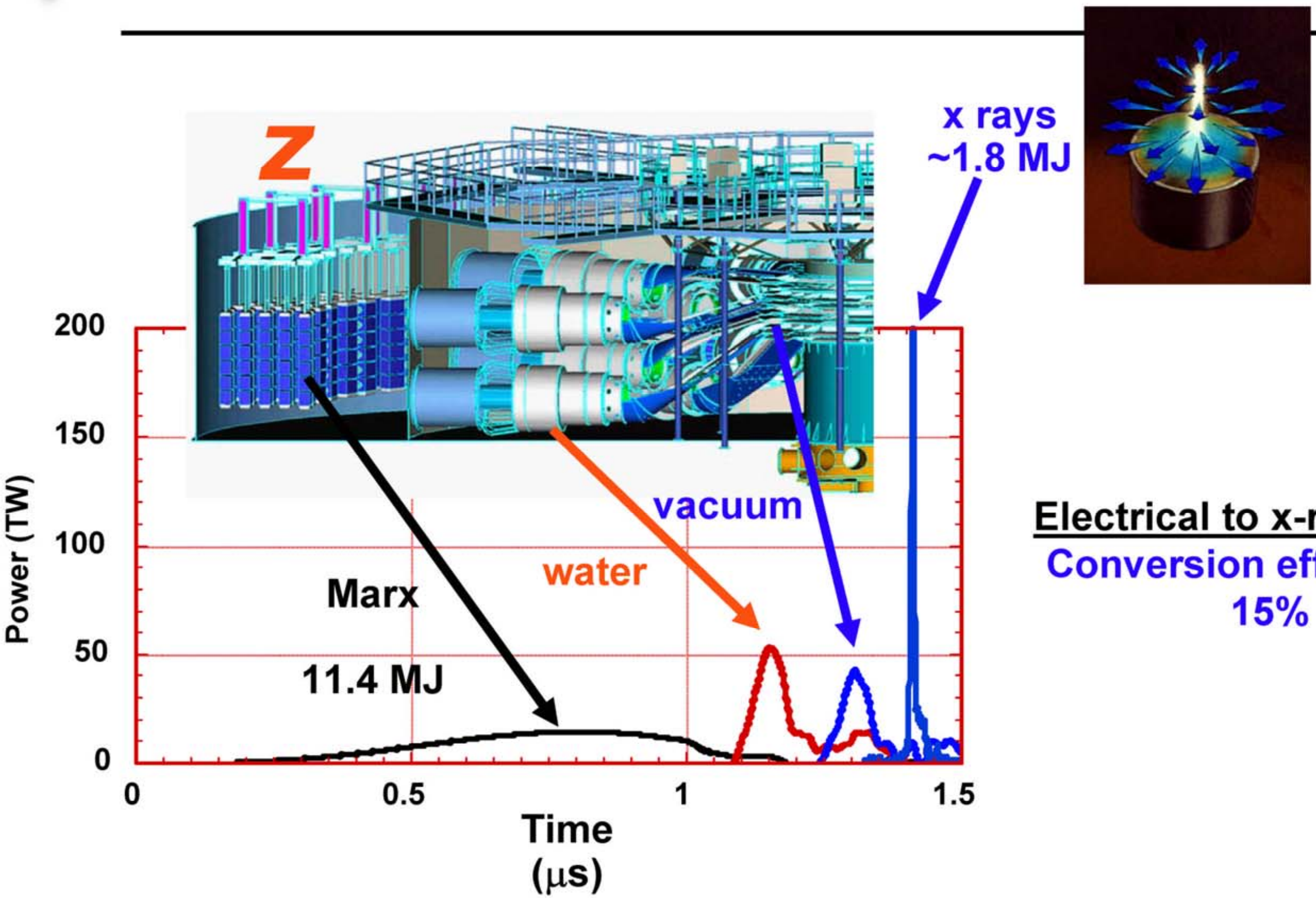
X-ray sources for ICF on Z-pinch basis successfully try to make a competition to the laser ICF driver.

Scientific data of “ANGARA-5-1” team (TRINITI, Russia) and “Z” team (NL SANDIA, USA) will be used in this presentation.

Z-pinch as a source of x-rays for ICF



Z-pinch turned out to be the only candidate on initiating the single thermonuclear micro explosion using the driver based on Pulsed Power technology.

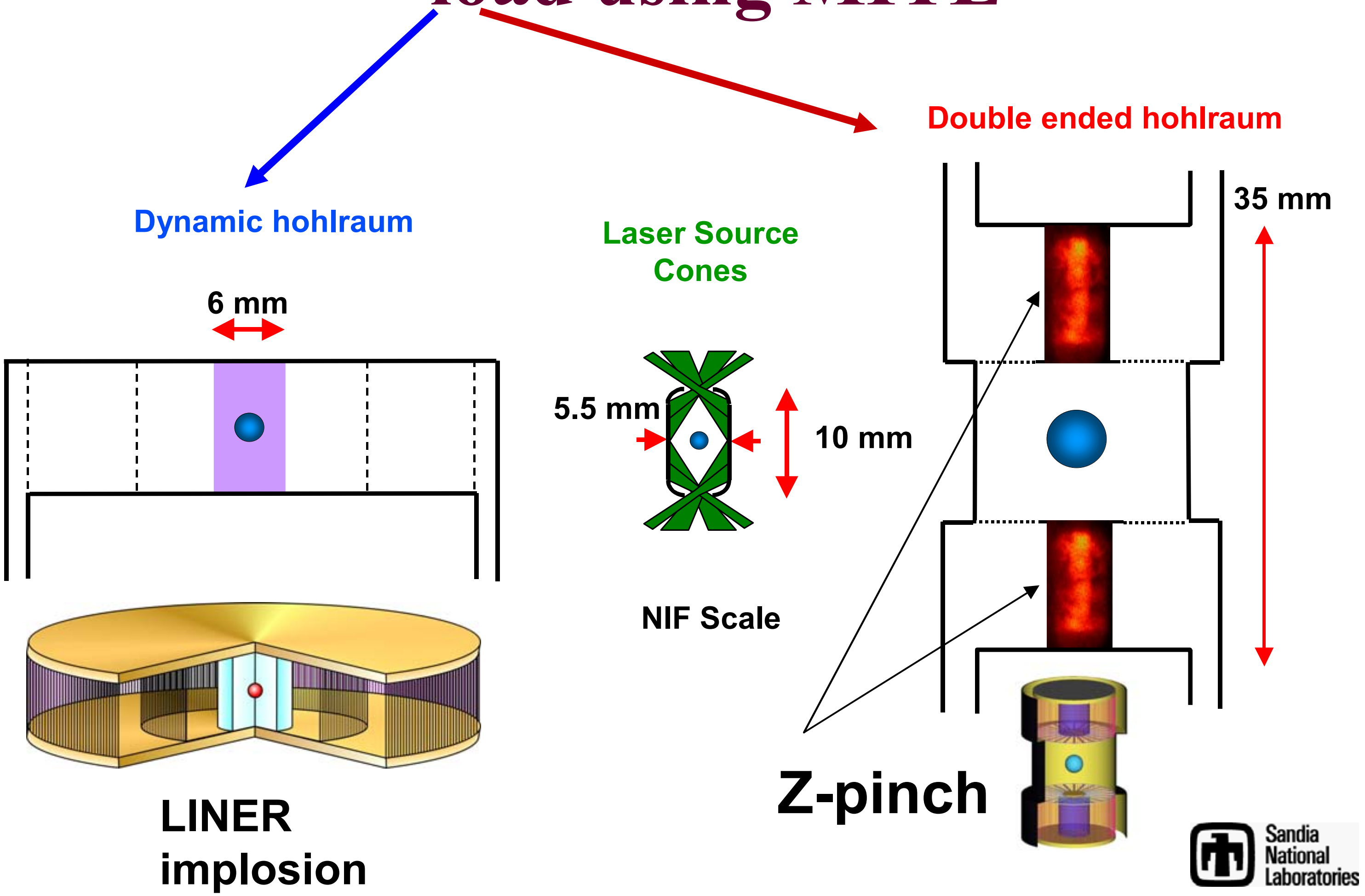


Electrical to x-ray energy

Conversion efficiency > 15%

Sandia National Laboratories

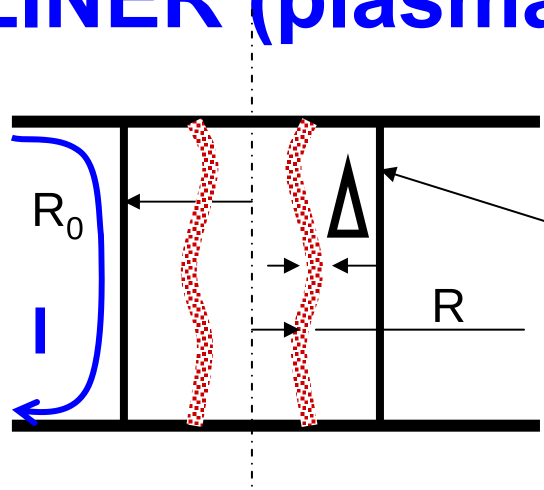
A current pulse of 10-20-50 MA, 1-3-5 MV, ~100 ns is to be delivered from generator to a load using MITL



What is a LINER and Z-PINCH?

- An imploding liner and Z-pinch, both are the different names of the same self-imploding discharge.
- Speaking about the liner, we are interested in kinetic energy of an imploding massive cylindrical plasma shell at its rather small convergence.
- Speaking about Z-pinch, we are interested in parameters of plasma with current stagnated on the discharge axis.This plasma can be strongly inhomogeneous.

LINER (plasma current shell) IMPLOSION



$$\mu \frac{d^2R}{dt^2} = -\frac{I^2}{c^2 R} \qquad E = \mu/2\left(\frac{dR}{dt}\right)^2$$

R-T instability of imploding massive plasma current shell

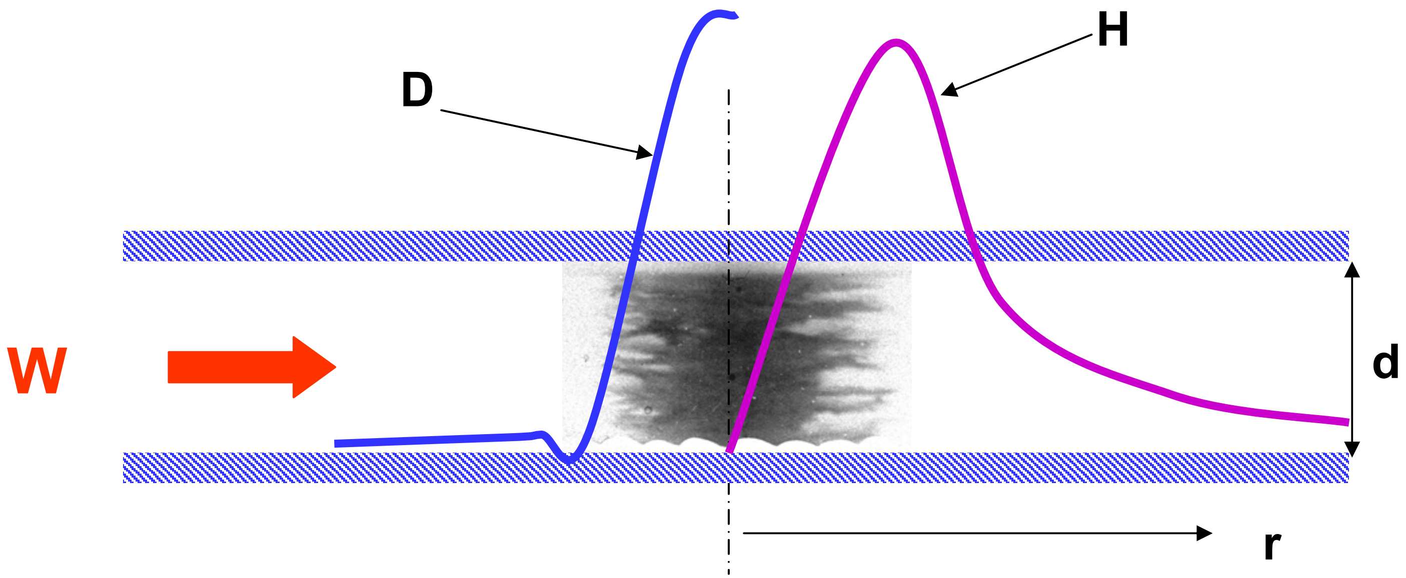
$$E \approx \frac{I_0^2}{c^2}\ln\frac{R_0}{R}$$

$$\Delta \approx (0.1-0.2)R_0 \Rightarrow \frac{R_0}{R} \approx \frac{R_0}{\Delta} \approx (5-15) \longrightarrow E_{MJ/cm} \approx 2.5\cdot 10^{-3} I_{MA}^2$$

$$\boldsymbol{I_{MA} \sim 20E_{MJ/cm}^{1/2}}$$

$W \sim E/t = Ev/\Delta \sim v^3/\Delta$ – **power at collision moment**

Energy flux in Z-pinch

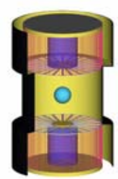
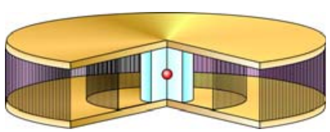
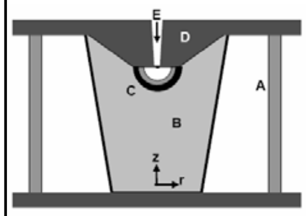
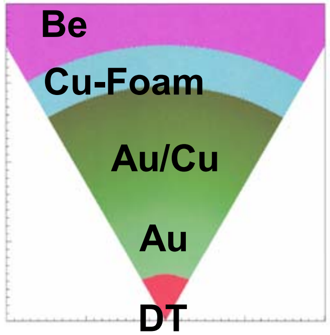
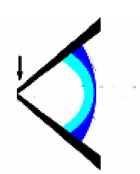
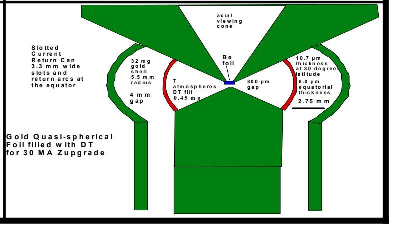


$$W(r) \sim \left(\frac{H^2}{8\pi} + \frac{DV^2}{2}\right)(2\pi r d)V \approx 4.10^{-10} I^3 \frac{d}{r^2\sqrt{4\pi D}}$$

$$W = I^2 Z_{act} \qquad Z_{act}(I, r, D, d) = 4.10^{-10} I \frac{d}{r^2\sqrt{4\pi D}}$$

ICF target options for Z-pinch driver
(by NL SANDIA,USA)

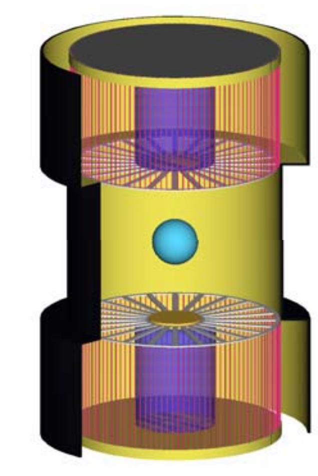
ICF Target

Driver	Cryogenic		Gas fill
	Hot spot ignition	**Fast ignition**	**Double shell**
Vacuum hohlraum Dynamic hohlraum Hybrid Hohlraum	  		
Magnetic field			

Z-pinch indirect drive concepts for high-yield ICF and Z-IFE

Double-Ended Hohlraum

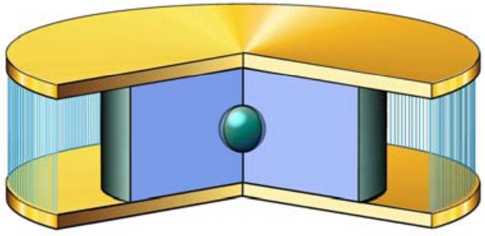
(Z-pinch)



	ICF → IFE
Peak current	2 x (62 – *150?*) MA
Energy delivered to pinches	2 x (19 – *110?*) MJ
Z-pinch x-ray energy output	2 x (9 – 54) MJ
Capsule absorbed energy	1.2 – 8.6 MJ
Capsule yield	400 – 4500 MJ

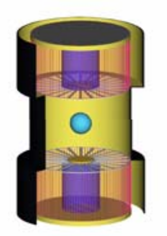
Dynamic Hohlraum

(double liner)



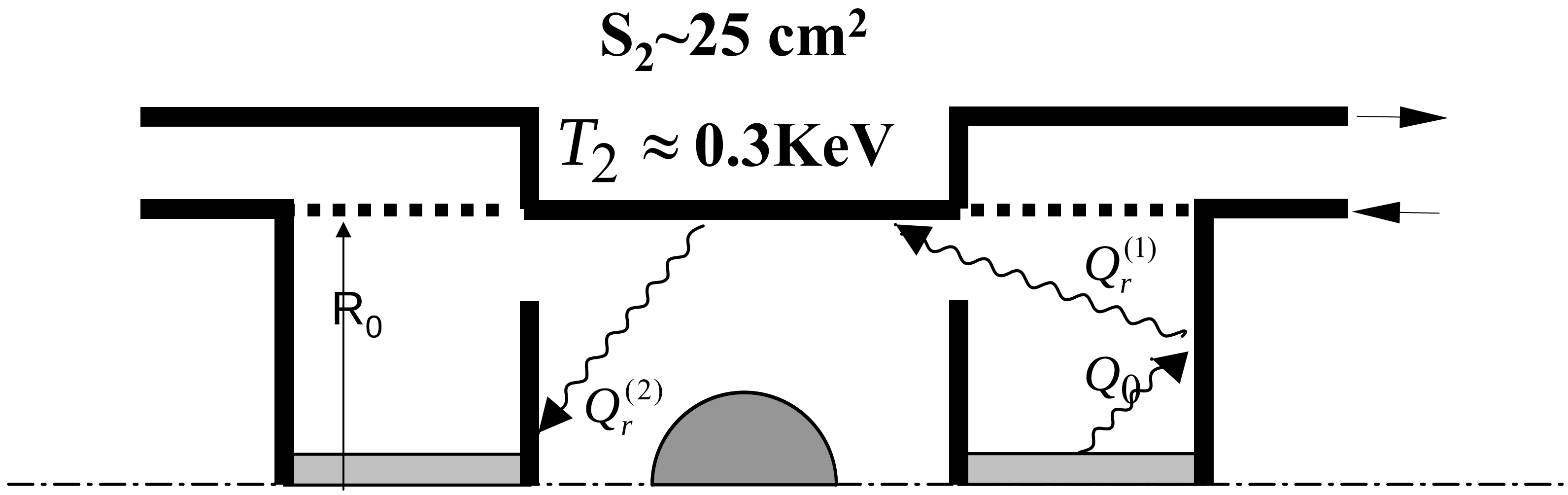
Peak current	56 – 95 MA
Energy delivered to pinch	14 – 42 MJ
Capsule absorbed energy	2.4 – 7.2 MJ
Capsule yield	530 – 4600 MJ

J. Hammer, M. Tabak *J. Lash, S. Slutz, R. Vesey*



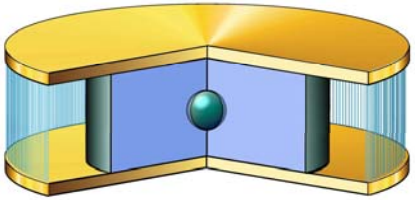
Double-Ended Hohlraum

by L.Mchitarjan,VNIIEF,
Sarov,Russia



$E_0 = 14$MJ $\quad$ I_0=90MA $\quad$ T~130 ns

u=550km/sec $\Rightarrow \mu = 160$ mg/cm



DL and DH concepts

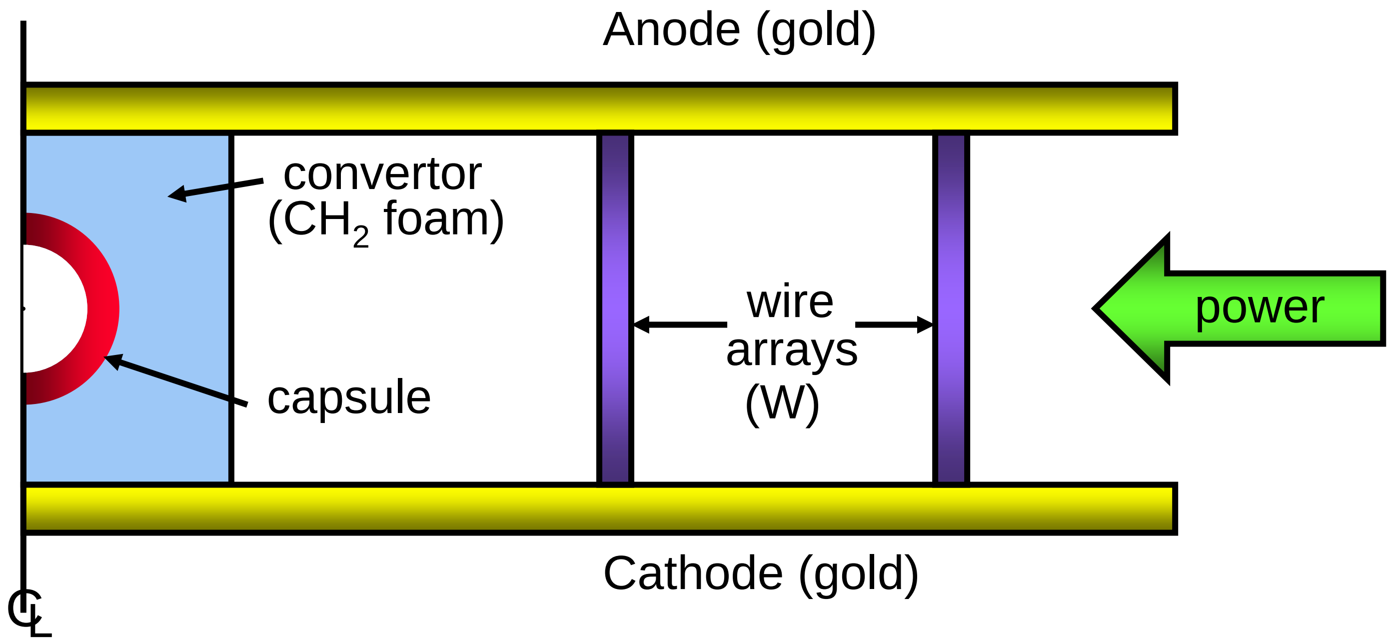
In the «double liner» (DL) concepts (V.P.Smirnov, S.V.Zacharov, 1988, “Angara-5-1”), radiation in an internal liner cavity is a result of collision of the external cylindrical plasma liner with the internal one.

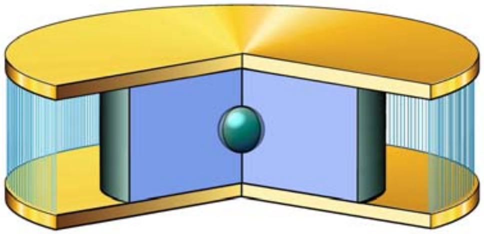
At high rate of compact liners collision ($V > 4\cdot10^7$ cm/s) the radiation is a consequence of transformation of kinetic energy of the external liner in a radiating shock wave in the internal liner substance. Radiation is partially locked inside of the internal liner, where the target is positioned.

Now such a scheme is called as «dynamic hohlraum» (DH)

The dynamic hohlraum achieves high radiation temperatures through close coupling

- Z-pinch driven wire arrays impact a convertor
- A high temperature shock wave generates radiation
- High-Z wire array material traps the radiation (RT => nonuniformities)
- Cylindrical shock and absorbing electrodes result in radiation asymmetries





Dynamic Hohlraum ICF status on "Z"

- Demonstrated >200 eV x-ray drive temperatures in dynamic hohlraums on Z
- Imploded thin shell surrogate capsules absorbing 40+ kJ of thermal x-rays (NIF-sized capsules)
- Measured T_e~1 keV, n_e~$1\text{x}10^{23}$ from Ar K-shell spectra from imploded capsules
- Measured $2.6\pm1.3\text{x}10^{10}$ thermonuclear D-D neutrons from ICF capsules absorbing >20 kJ, $8\text{x}10^{10}$ from capsules absorbing 40 kJ
- Symmetry measurements of capsule core x-rays made through 'thin walled' dynamic hohlraums (a/b~0.6, CR~6)
- Capsule x-ray emission history (PCDs) in good agreement with simulations
- Capsule implosion time reproducible to 160 ps

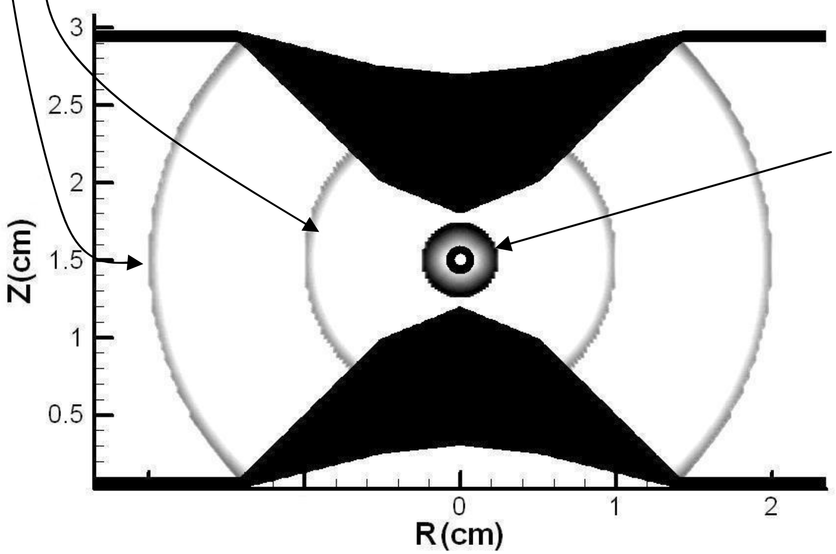
Increase in radiation intensity in quasi-spherical system « double liner » / «dynamic-hohlraum»

V.P Smirnov, S.V.Zacharov, E.V.Grabovsky

External spherical shell R_{01}=2 cm, linear mass at a level of equator M_1=5.65 mg/cm

Internal spherical shell R_{02}=1cm with M_2=2.85 mg/sm.

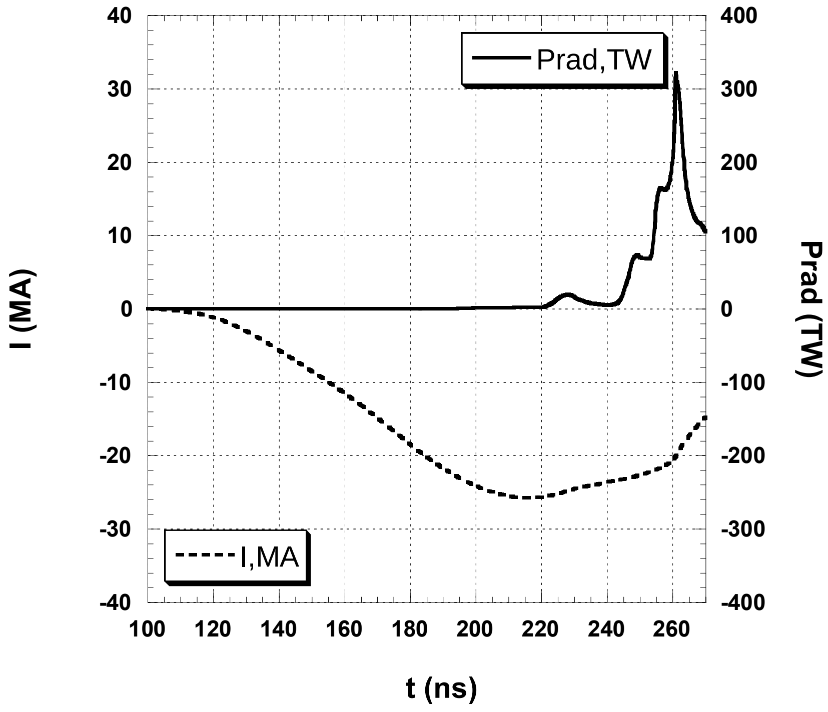
Angular distribution of shells mass $m(\theta) \propto \sin^{-2}\theta$

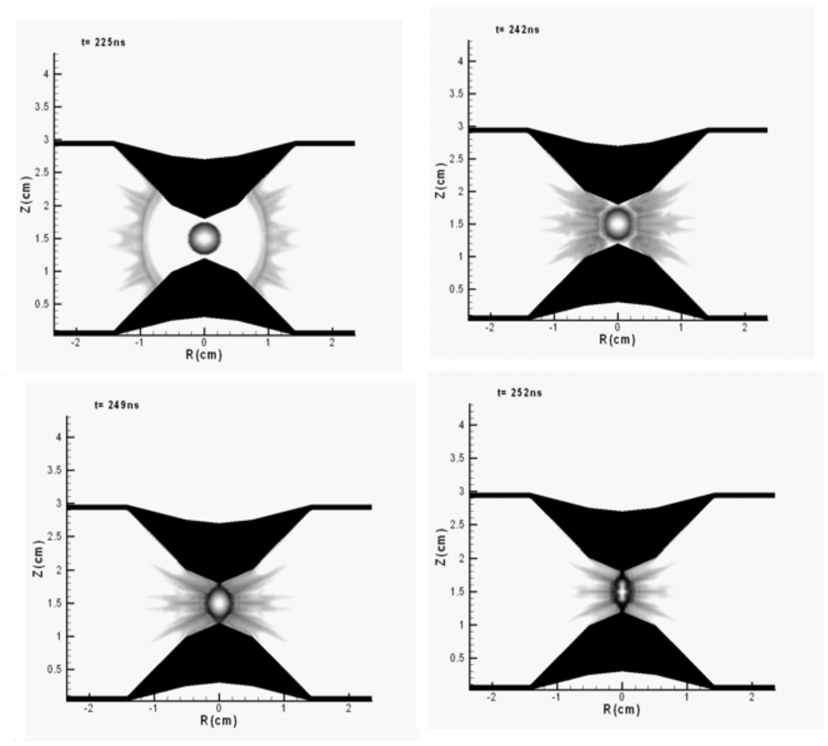


The internal spherical liner with radius R=2.4 mm and thickness 0.3 mm, with M=10.6 mg/cm at equator.

Material - low density plastic with the additive of 5-10 % of W

Despite of instability of liners implosion, transition to quasi-spherical geometry allows to increase considerably an intensity of radiation inside of the double liner in comparison with a cylindrical case at the same power of the pulse generator.

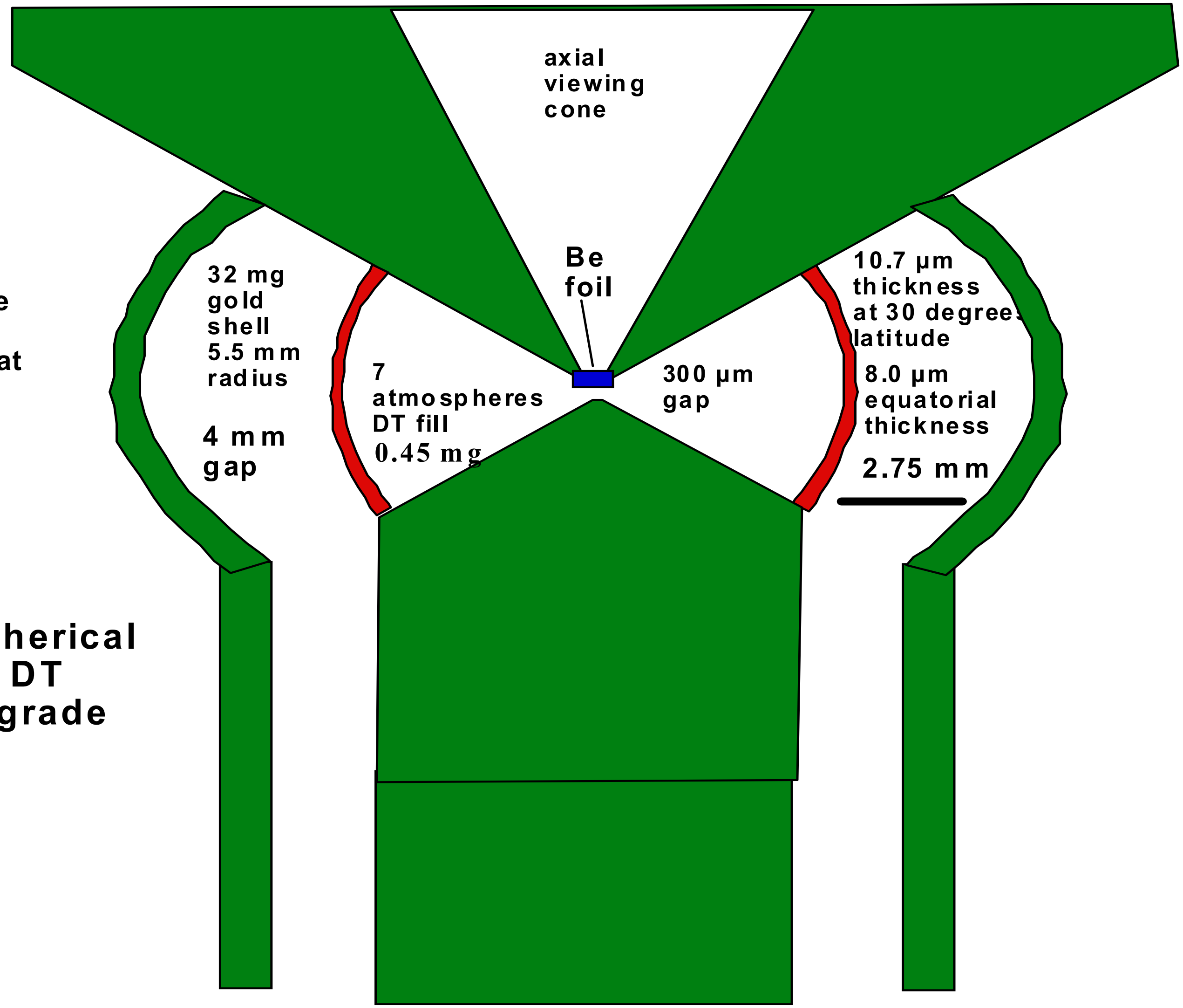




Quasi-spherical Shell Implosions on “Z”

T. J. Nash

Slotted Current Return Can 3.3 mm wide slots and return arcs at the equator



Gold Quasi-spherical Foil filled with DT for 30 MA Zupgrade

The magnetic implosion of a high-Z quasi-spherical shell filled with DT fuel by the 20-MA Z accelerator can heat the fuel to near-ignition temperature.

The implosion velocity on Z for an 8 mm diameter quasi-spherical shell, 13-cm/μs, is fast enough that thermal losses from the fuel to the shell are small.

The fuel is initially heated by an ion acoustic wave to 200-eV after a convergence of 4.

The implosion is adiabatic and the temperature increases as the square of the convergence.

To reach the ignition temperature of 5-keV an additional convergence of 5 is required.

The convergence required to reach ignition temperature decreases with machine current.

$$C > 186 / I(MA)^{2/3}$$

For I = 20 MA, C > 25

For I = 30 MA, C > 19

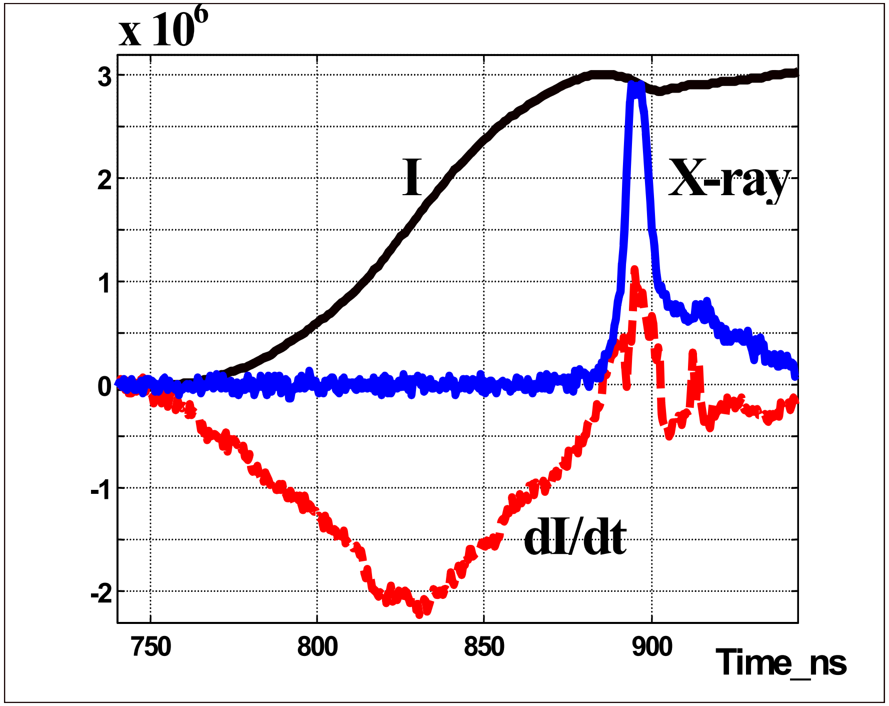
For I = 60 MA, C > 12

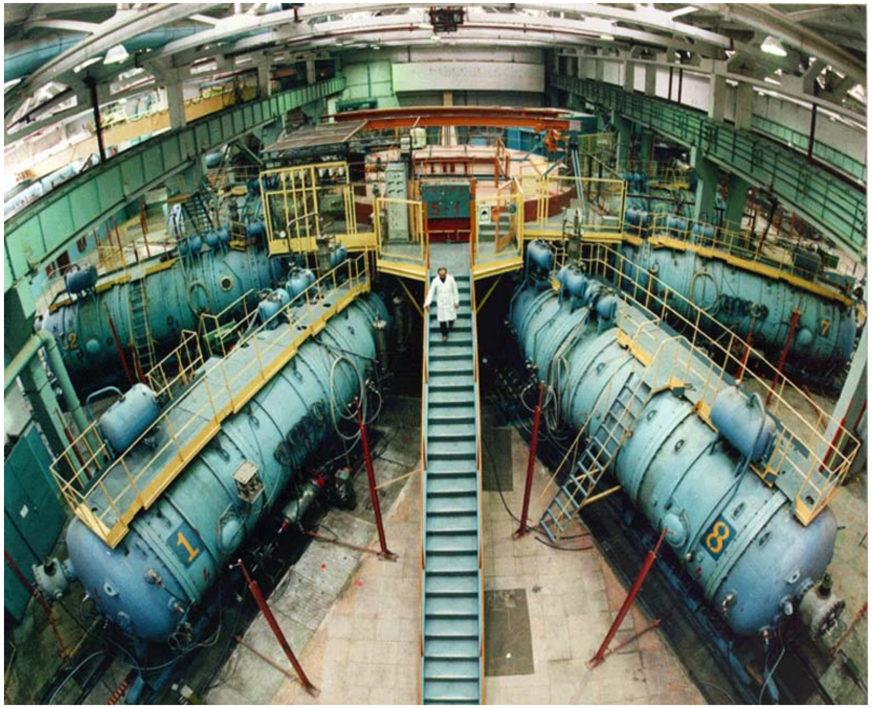
2D simulations of quasi-spherical implosions show that shell surface mass flow from the poles to the equator limits the convergence to less than 25. This flow also gives axial velocity shear which is stabilizing to RT.

THE BASIC PROBLEM OF REALIZATION OF THE PROPOSED SCHEMES

- **Usually, in calculations assume, that from the very beginning, there is massive, spatially continuous plasma shell with electric conductivity, sufficient for skin-effect of an increasing current.**
- **Then set some initial inhomogeneity of the shell parameters, which are necessary for the consent of calculations with results of measurements.**
- **By itself, receive the consent of calculations with experimental results.**
- **But always the “cold start” of the discharge is used in experiments. It means that a main current pulse is applied to plasma producing substance for the initial plasma shell production.**
- **At the «cold start» the homogeneous plasma current shell is absent.**

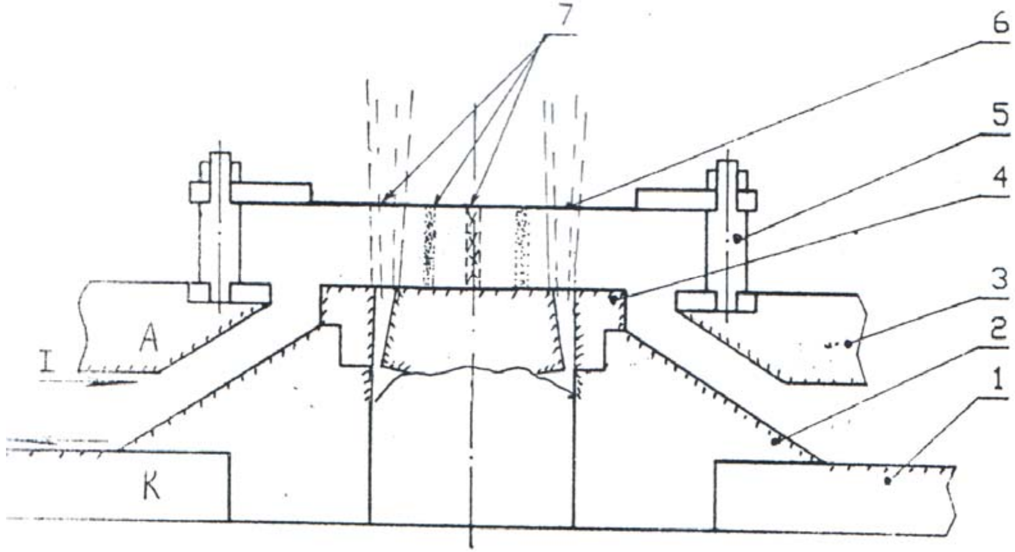
PROPERTIES OF THE SELF-IMPLODED RADIATING DISCHARGE WITH "COLD START"





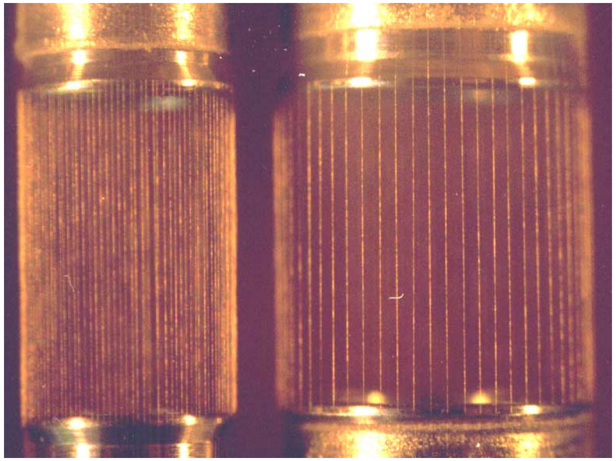
GAS-PUFF, FOAM LINER, WIRE-ARRAY AND THEIR COMPOSITIONS WERE INVESTIGATED AT COLD START REGIME ON "ANGARA-5-1"

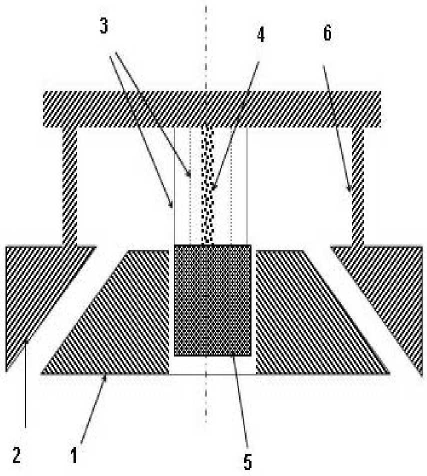
Load unit scheme on “Angara-5-1”



DOUBLE LINER EXPERIMENT

Gas-puff and foam liners





WIRE-ARRAY EXPERIMENT

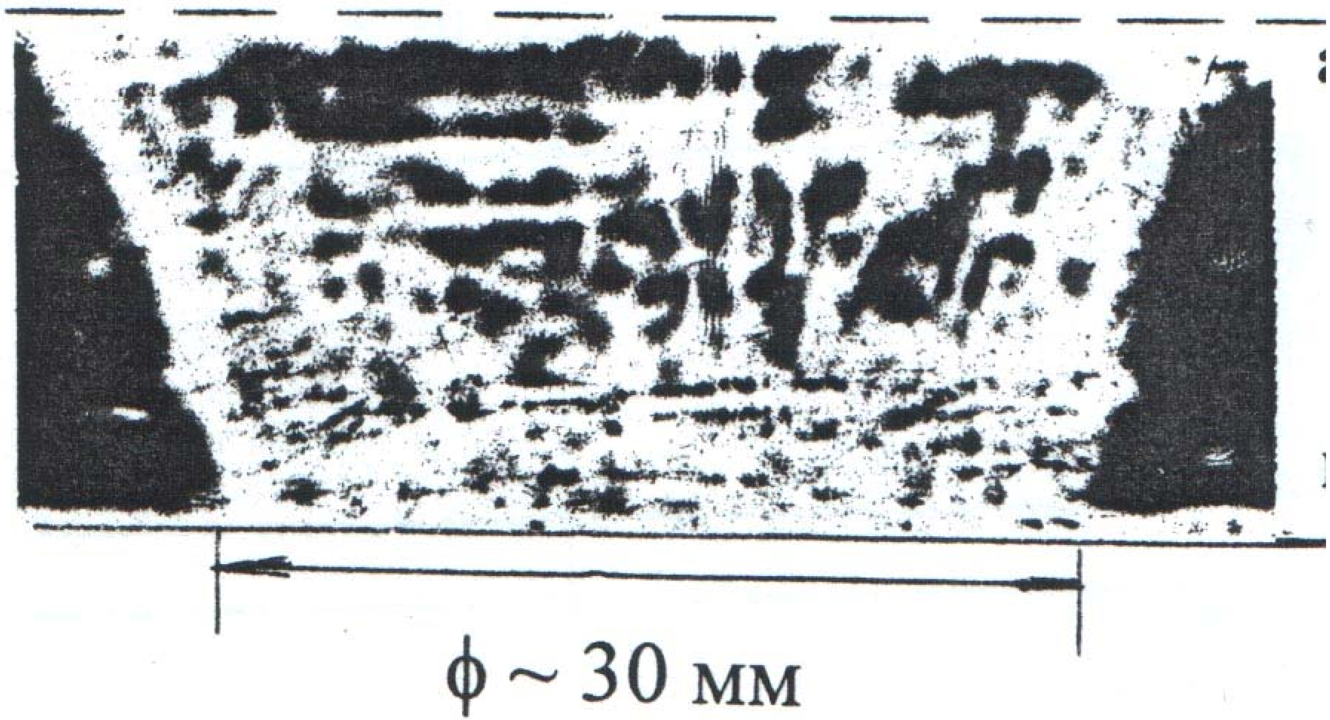
Cold start of Z-pinch

- All Z-pinches with high **dI/dt**, investigated by the present time, have the COLD START.
- The main consequence of cold start is a prolonged plasma production.
- In all the cases the prolonged plasma production is spatially non-uniform.

The inhomogeneities of prolonged plasma production and subsequent plasma implosion are so large that any integral imploding plasma shell is out of the question.

In these conditions, it would be improper to use the formalism of Rayleigh-Tailor instability as well, as the classical " snow plough " model, do describe the dynamics of the multiwire array Z-pinch

GAS-PUFF. INHOMOGENEOUS PLASMA PRODUCTION AT COLD START



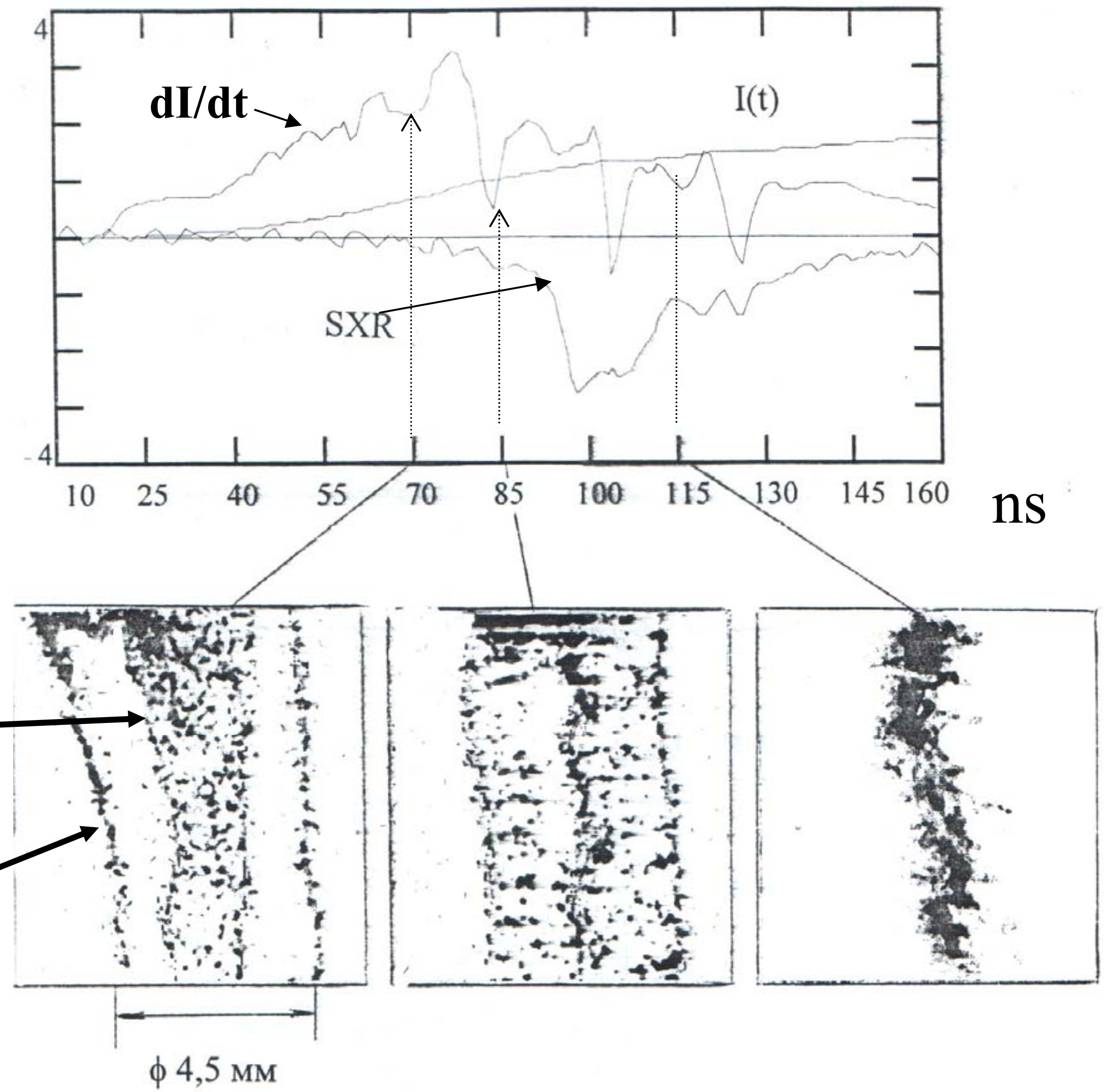
Laser shadow picture. The white is plasma. I=1.5 MA

Foam liner implosion

X-ray pinhole-camera instant pictures

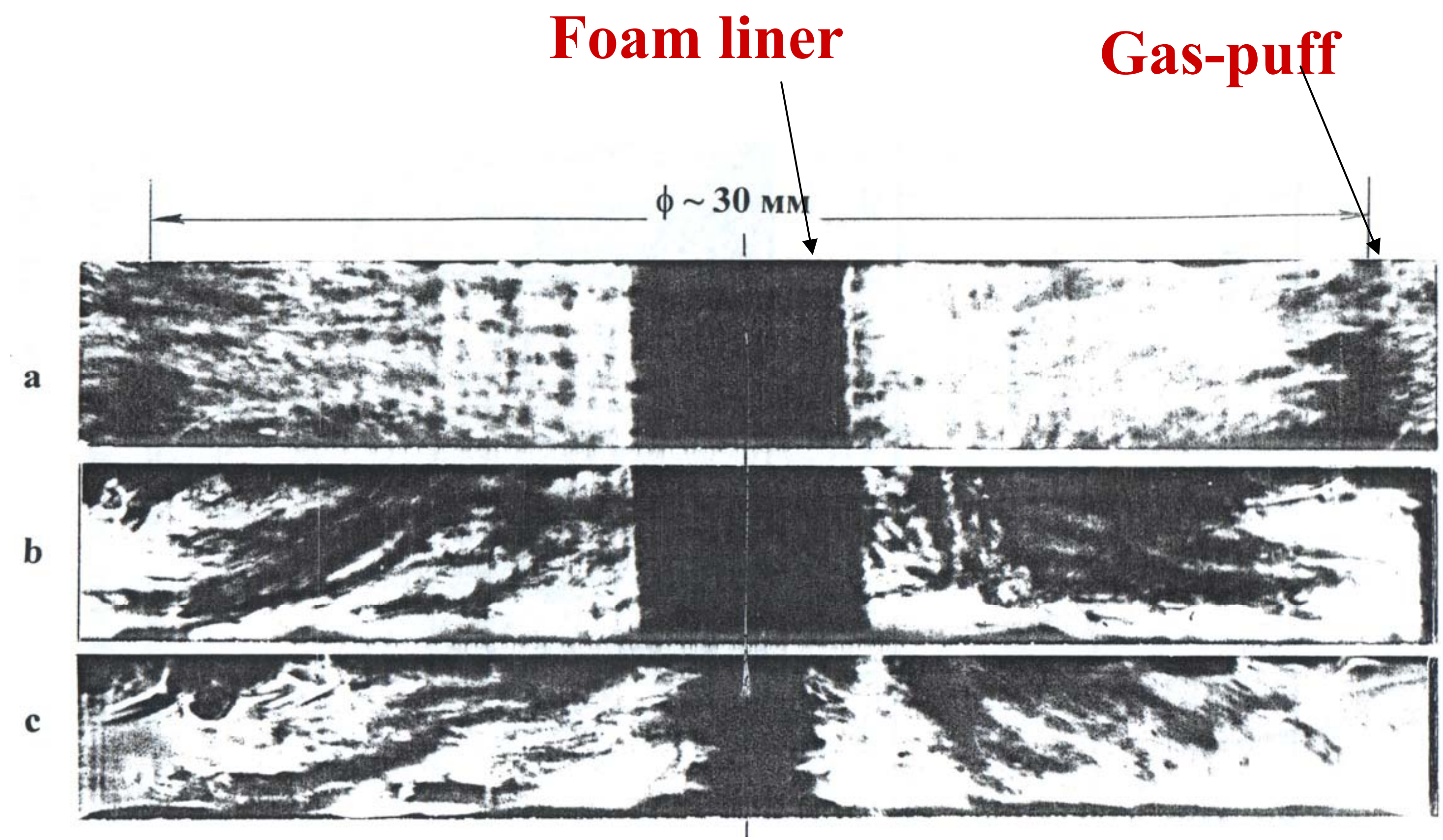
Foam plasma precursor

Initial foam position

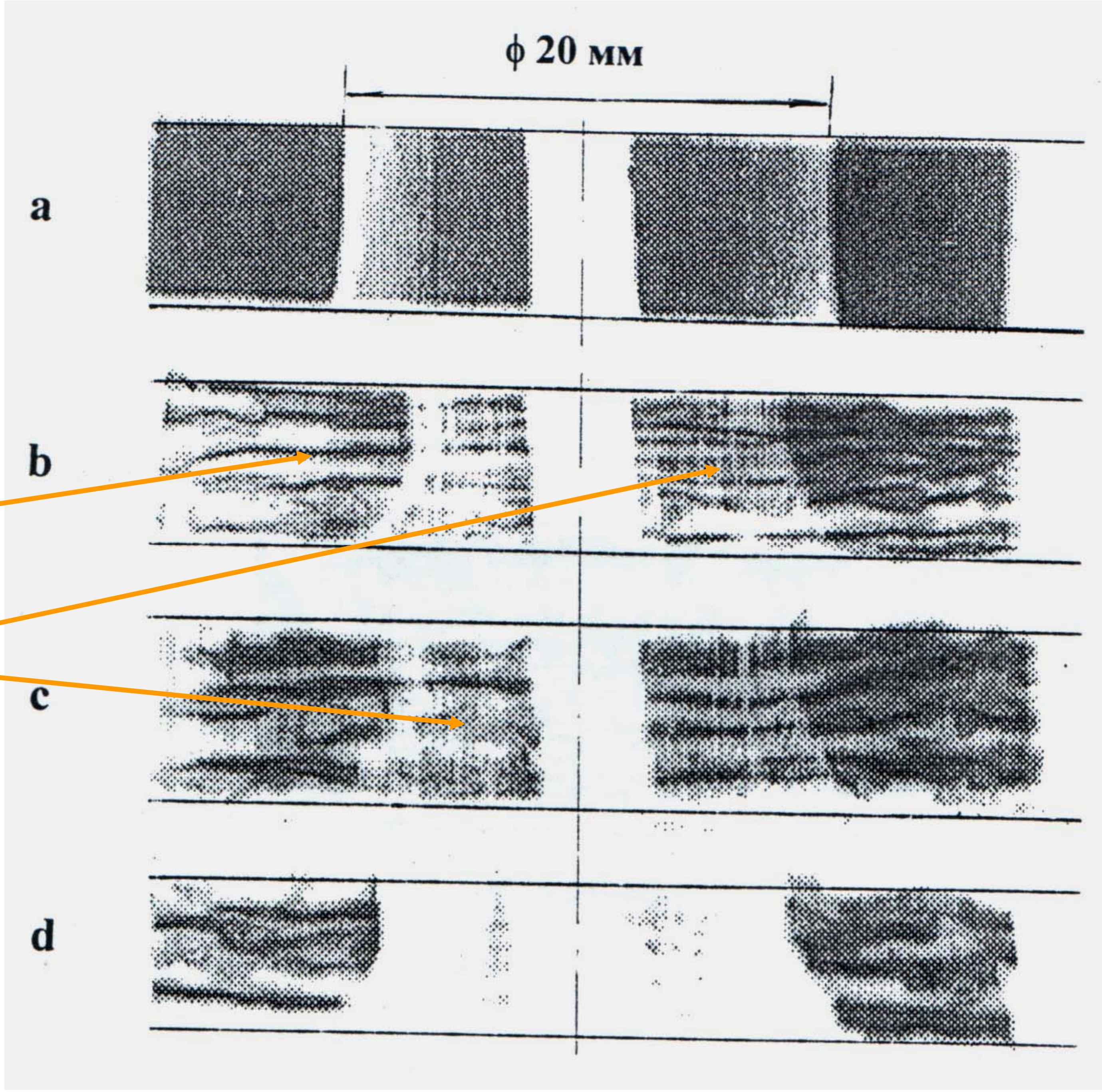


DOUBLE LINER IMPLOSION

magnetic flux break in cathode zone, no radial implosion of the external liner



Gas –puff, foam, foam composition

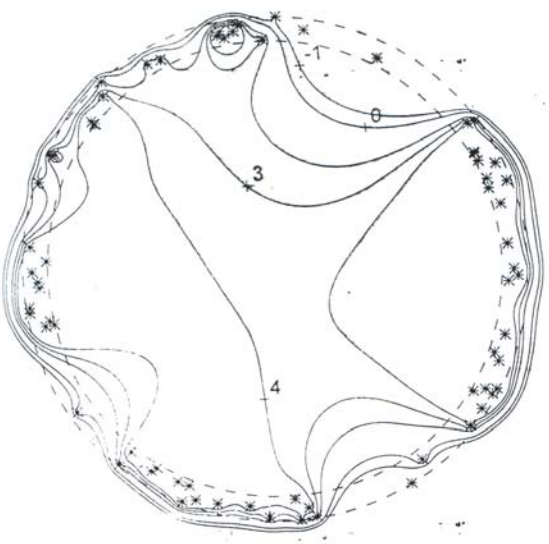


Gas-puff liner break

Current filaments on external foam liner

Laser shadow picture

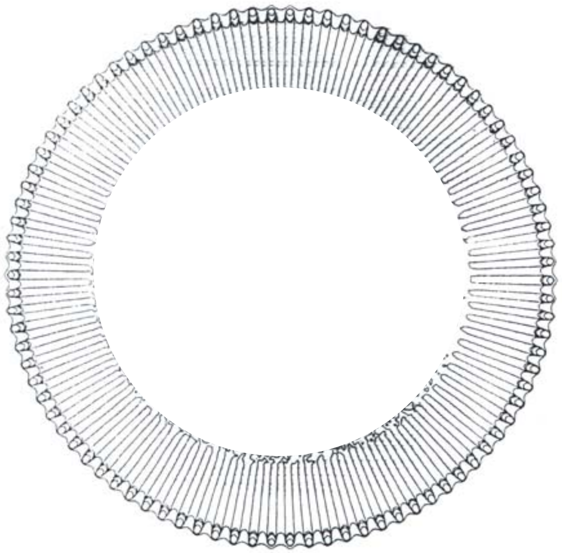
Force lines of a magnetic field of 90 current filaments, with their random distribution in substance of the liner at identical values of the filament current.



Some filaments are incorporated in groups, and in a number of places the magnetic stream crosses substance of the liner

The picture of a total field of random located filaments shows, that hopes for azimuthal uniformity of compression of such liner are ill-founded

The same structure for 90 uniformly distributed identical current channels.

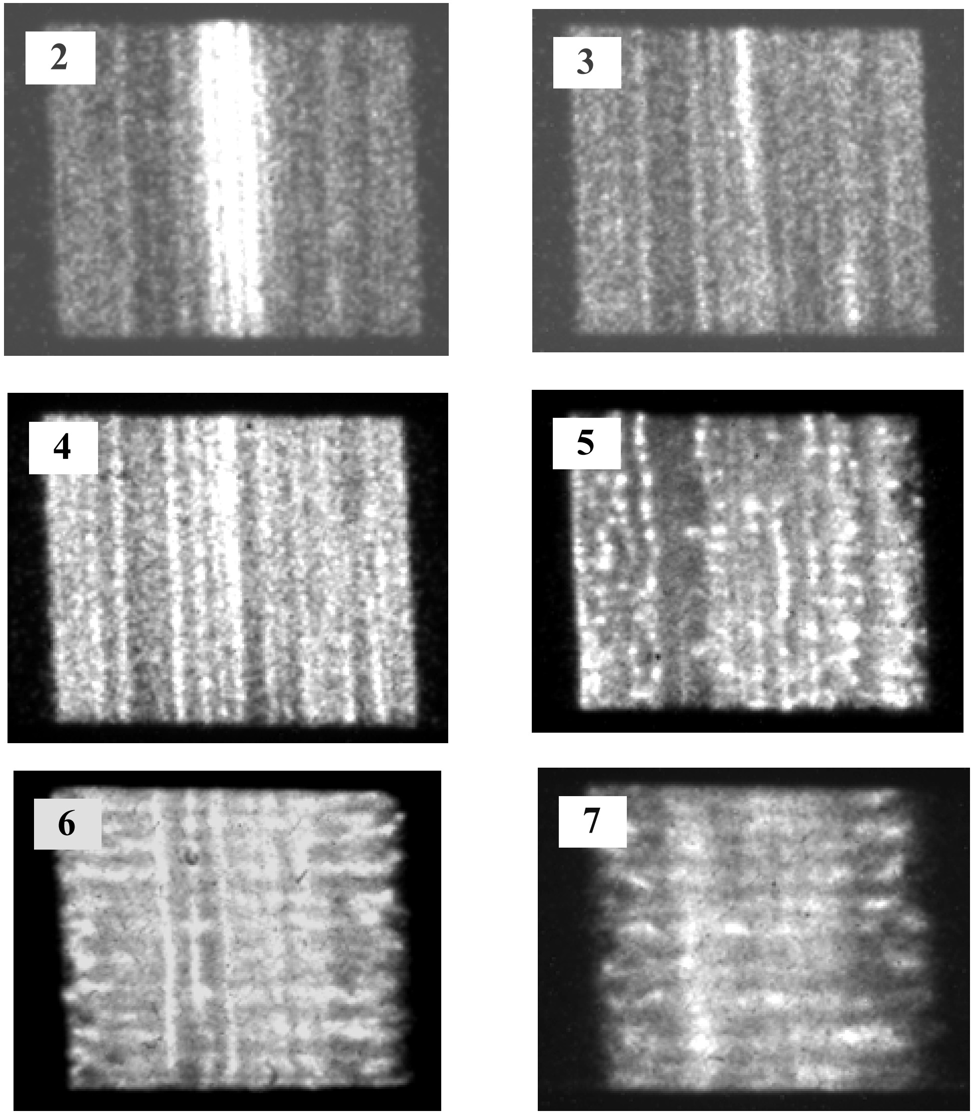


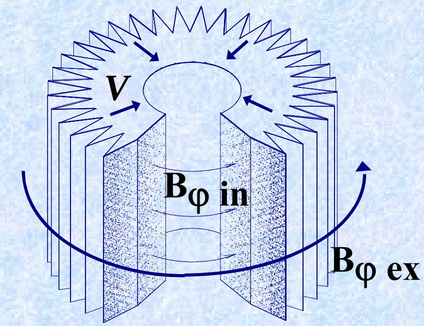
This structure can be realized in a wire-array. It looks better.

Now the wire-array implosion is under intensive investigation.

Prolonged plasma production is a specific feature of the wire-array implosion at cold start

INSTANT X-RAY FRAMES OF PROLONGED PLASMA PRODUCTION

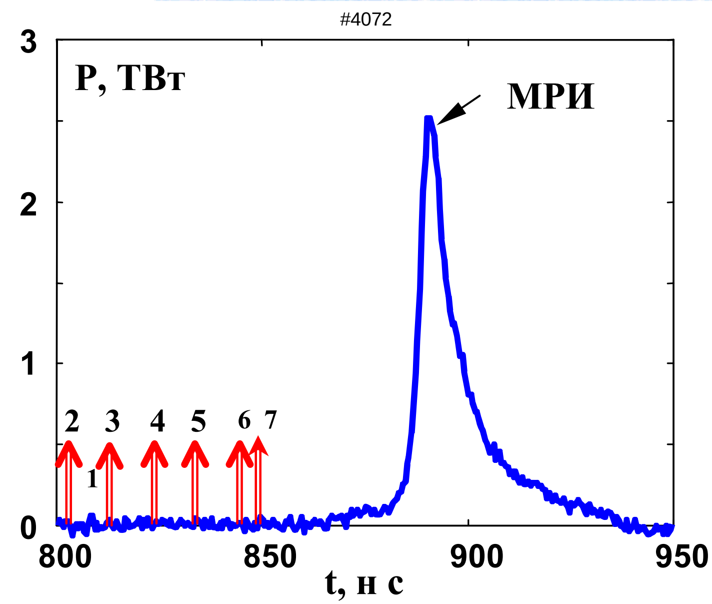




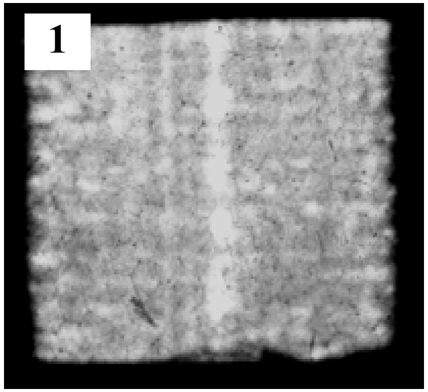
$$H^2/8\pi >> nT$$

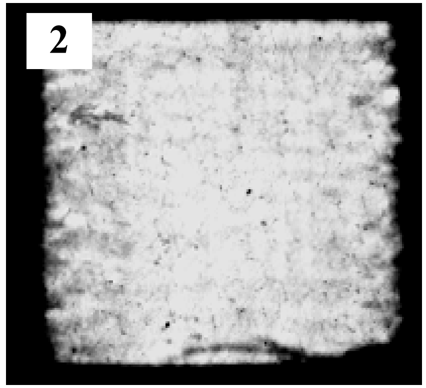
$$m' = m'(t, I, \Delta \ldots)$$

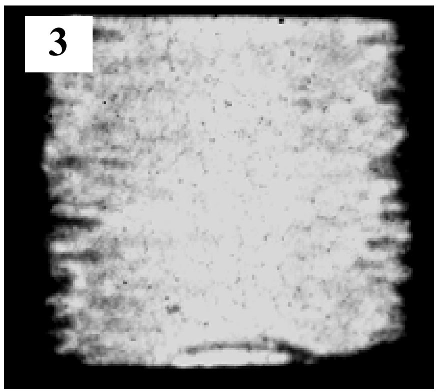
$$\dot{m} = 0.2\left(\frac{I_{\mathrm{MA}}}{R_{\mathrm{cm}}}\right)^{1.8} \frac{\mu\mathrm{g}}{\mathrm{cm}^2\mathrm{ns}}$$

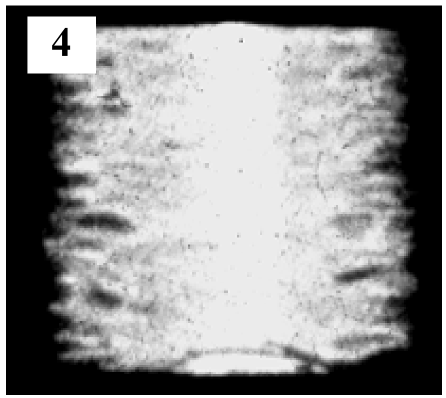


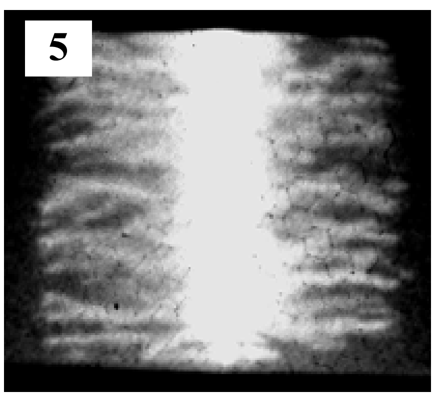
INSTANT X-RAY FRAMES OF PLASMA RAINSTORM

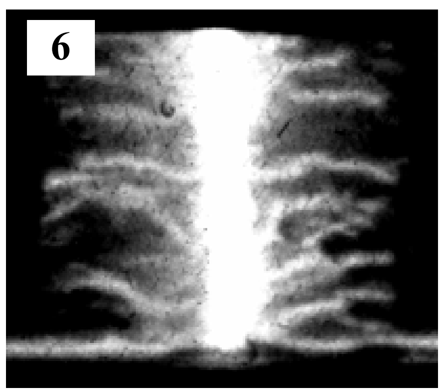


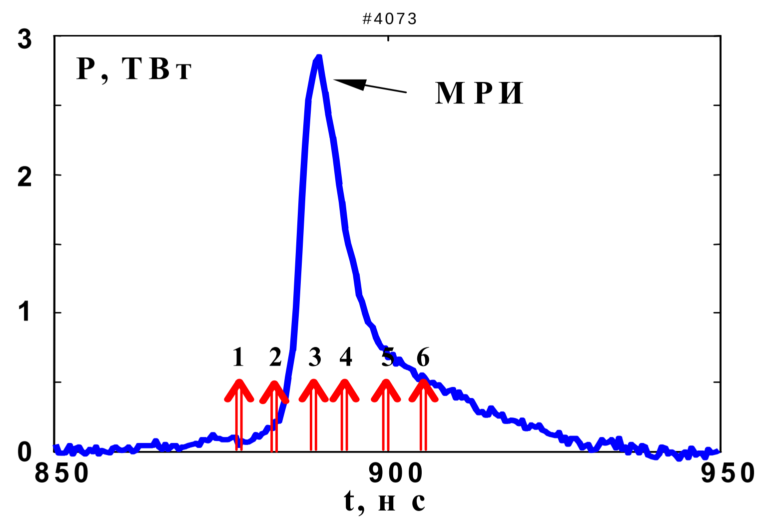




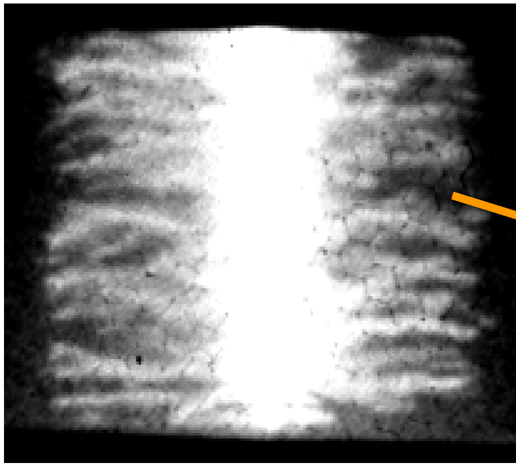


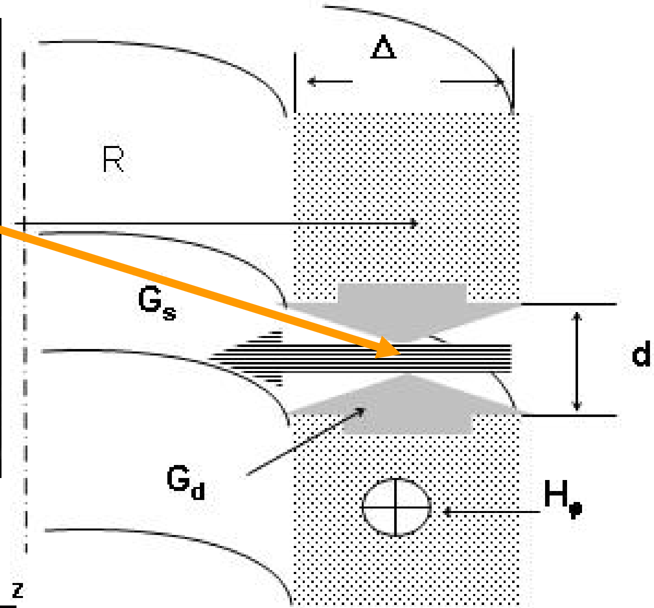


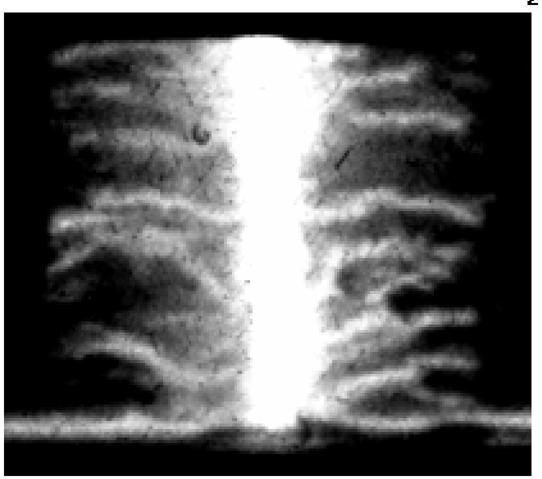




BREAKE OF AZIMUTHAL MAGNETIC FLUX PRODUCES “PLASMA RAINSTORM”



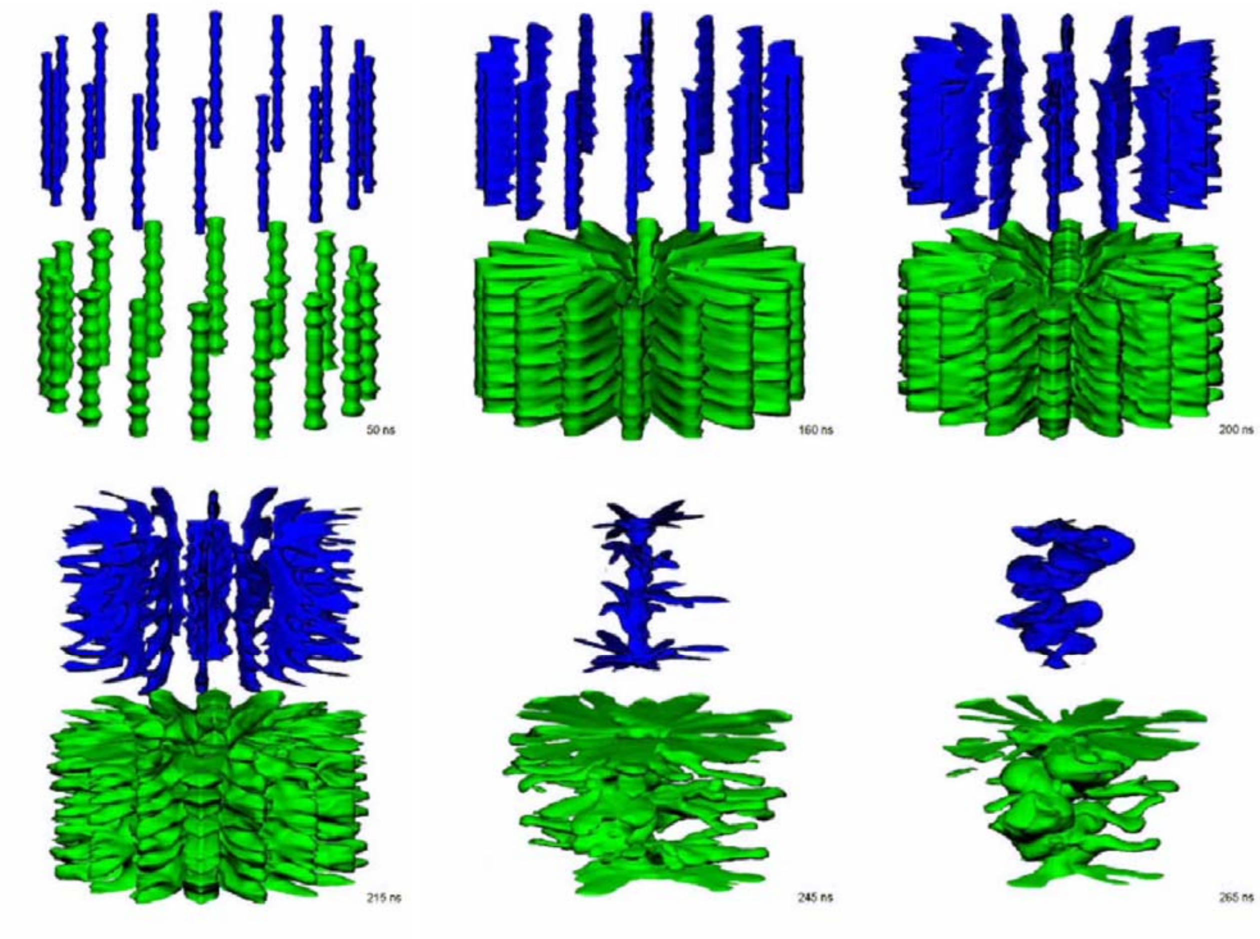




D ~10^{-4} g/cm^3,
σ~10^{14} CGSE,
Δ~d~0,1 cm,
R~1cm,
I_{cr} ~3 MA.

$$I_{cr[A]} \sim 3.10^{21} \frac{\sqrt{D}}{\sigma} \frac{R\Delta}{d^2}$$

RESULTS OF Dr.CHITTENDEN CALCULATIONS.
IMPERIAL COLLEGE, LONDON, 2003.



Effects of Z-pinch cold start

- Prolonged inhomogeneous plasma production
- Break of a magnetic flux through destroyed plasma producing zone
- Plasma rainstorm
- MHD-turbulent heating and radiative cooling of compressed plasma
- Effective transformation of stored magnetic energy in Z-pinch heating

- **POWERFUL, NON-CURRENT PREIONISATION OF PLASMA PRODUCING SUBSTANCES IS NON-REALIZED ALTERNATIVE TO COLD START.**
- **IT IS A NECESSARY CONDITION TO SOLVE THE PROBLEM OF MASSIVE HOMOGENEOUS PLASMA SHELL CREATION IN SELF-IMPLODED MULTITERAWATT DISCHARGES**

Having filled this shell,

we shall fly in the blue sky…

THANK YOU!

S.L.Nedoseev