Status and Prospect of MJ Plasma Focus Experiment

by

Marek Scholz

Institute of Plasma Physics and Laser Microfusion

Warsaw, Poland

Outline

1. Introduction
   - Goals of experiment
2. Time evolution of PF discharge for two kinds of electrodes correlated with neutron emission
   - Visualization of the pinch dynamics and structure
3. Neutrons measurements
4. Summary

Neutron yield Y_n

$$P = \frac{N_D n_D}{4} \cdot \langle \sigma v \rangle \cdot \tau$$

$$n_D = \frac{N_D}{\pi a^2} \qquad N_D = \frac{I^2}{4c^2 T} \qquad \tau = \alpha \frac{a}{v}$$

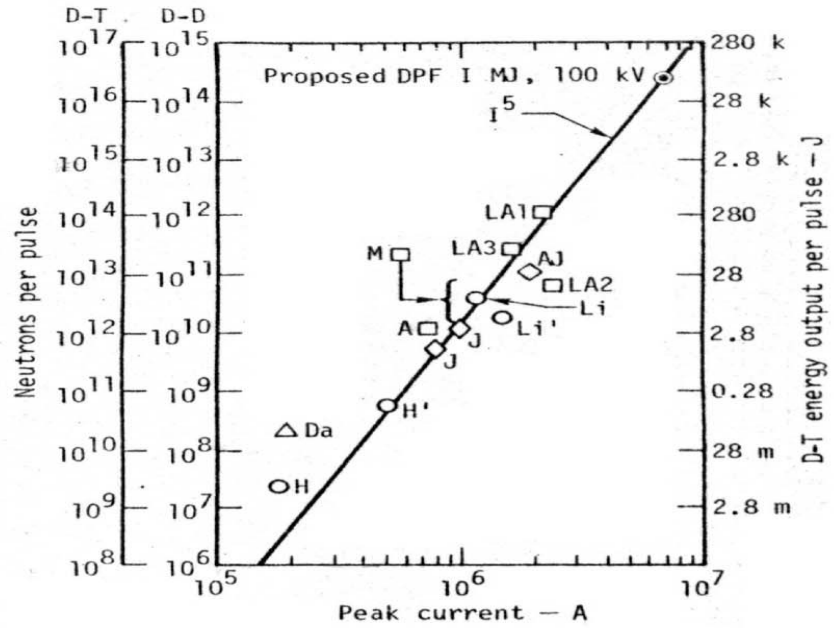
$$Y_n = l \cdot P \propto \alpha \frac{l}{a} I^4 \frac{\langle \sigma v \rangle}{T^{5/2}}$$

for $T = 9\,keV$

$$Y_n = 1{,}6 \cdot 10^7 \alpha \frac{l}{a} I^4$$

Institute of Plasma Physics and Laser Microfusion
Warsaw, Poland

Scaling



Legend

AJ	Aerojet Nucleonics. 250 kJ, 20 kV, 320 μF.
Da	Darmstadt. 0.34 - 1.35 kJ;]0 - 20 kV.
H	Hoboken. Electrode structure is identical to that of Darmstadt group.
H'	Hoboken. About 5 kJ.
A^E	Aerospace Corporation.
J	Julich. 25 kJ; 40 kV.
Li	Limeil. 96 kJ, 40 kV.
Li'	Limeil. Plasma focus driven by expolsive generator.
LA^1	Los Alamos. DPF-6; 420 kJ.
LA^2	Los Alamos. DPF-5; 120 kJ.
LA^3	Los Alamos. DPF-6; 210 kJ.
M	Moscow. Y → 10^{10} to 10^{11} DD neutrons; I = 1 MA.

Institute of Plasma Physics and Laser Microfusion
Warsaw, Poland

Large PF device

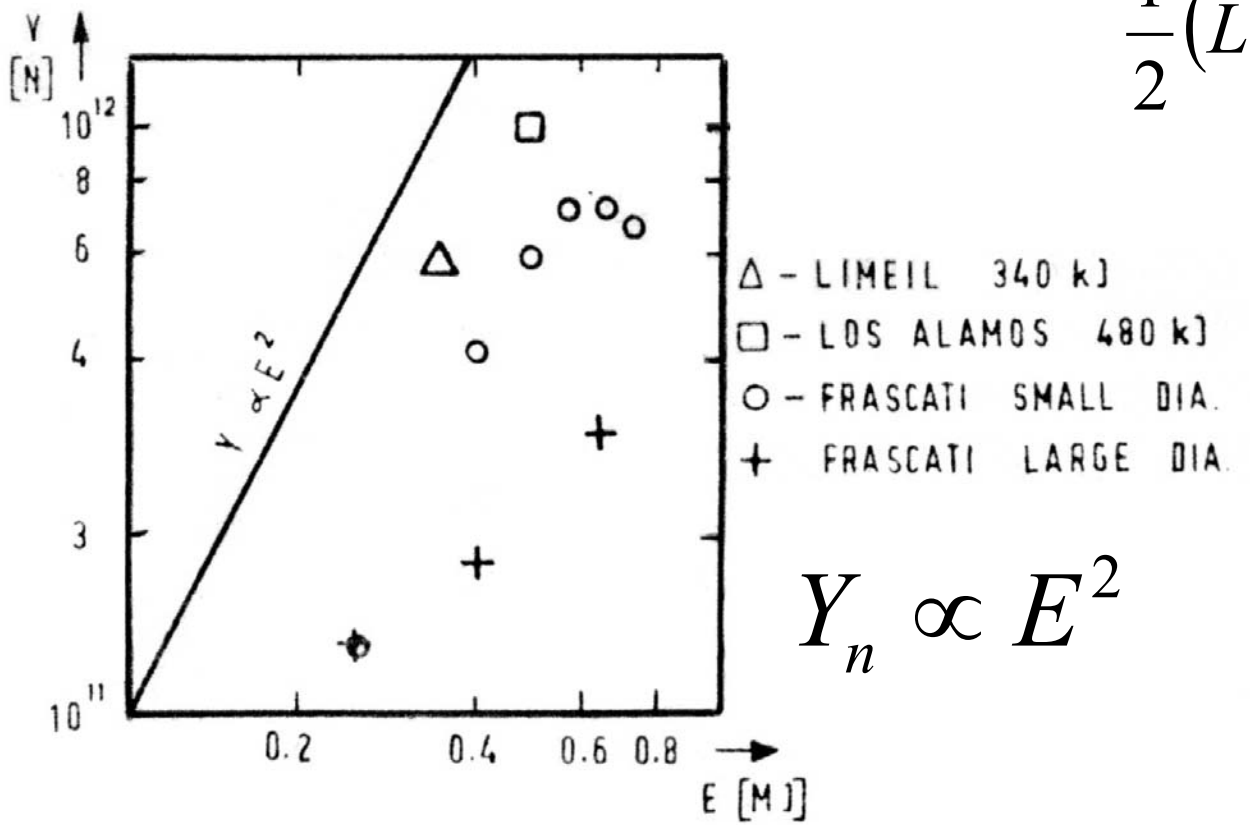
PF – 3 (Moscov), E_b = 3 MJ, U_b= 20 kV;

Frascati (Program Euroatom), E_b = 1 MJ; U_b= 50 kV;

Poseidon (Stutgart), E_b = 750 kJ; U_b= 80 kV;

PF-1000 (Warsaw), E_b = 1 MJ; U_b= 40 kV

Scaling



$$\frac{1}{2}(L + L_0)I^2 \cong \gamma E$$

$$L \cong L_0$$

$$Y_n \propto E^2$$

$$I^2 \propto E$$

Frascati (Program Euroatom), E_b = 1MJ; U_b= 50 kV;

Main Questions

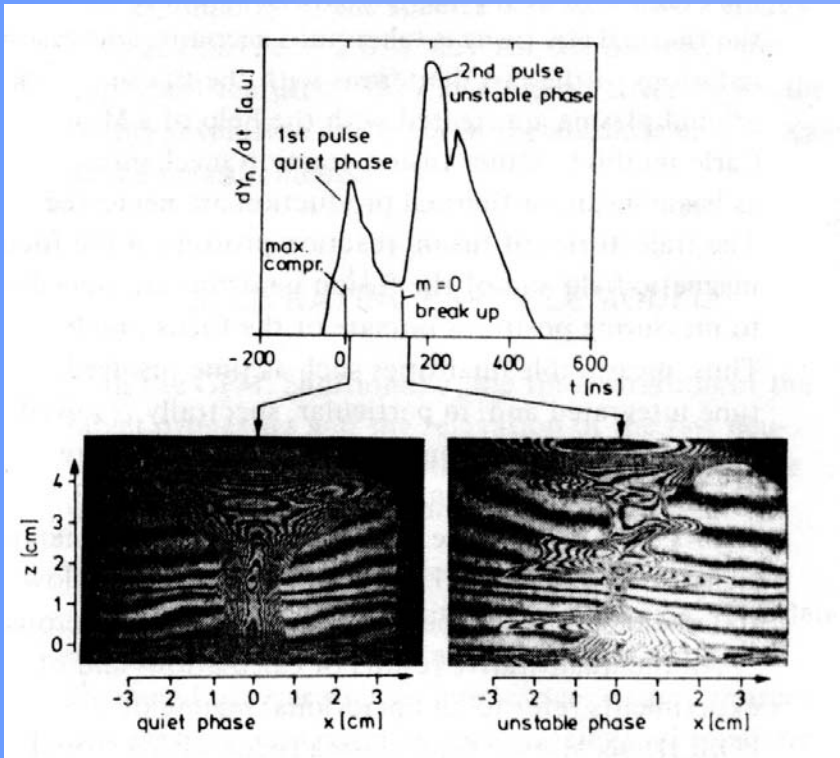
This observed saturation in the Y_n is caused by the incorrect formation of a proper plasma sheath due to many reasons (e.g. impurities, sheath instabilities)

or

There exists a fundamental threshold for saturation in the Y_n

Mechanism of neutron production in large PF facilities

Poseidon (Stuttgart)

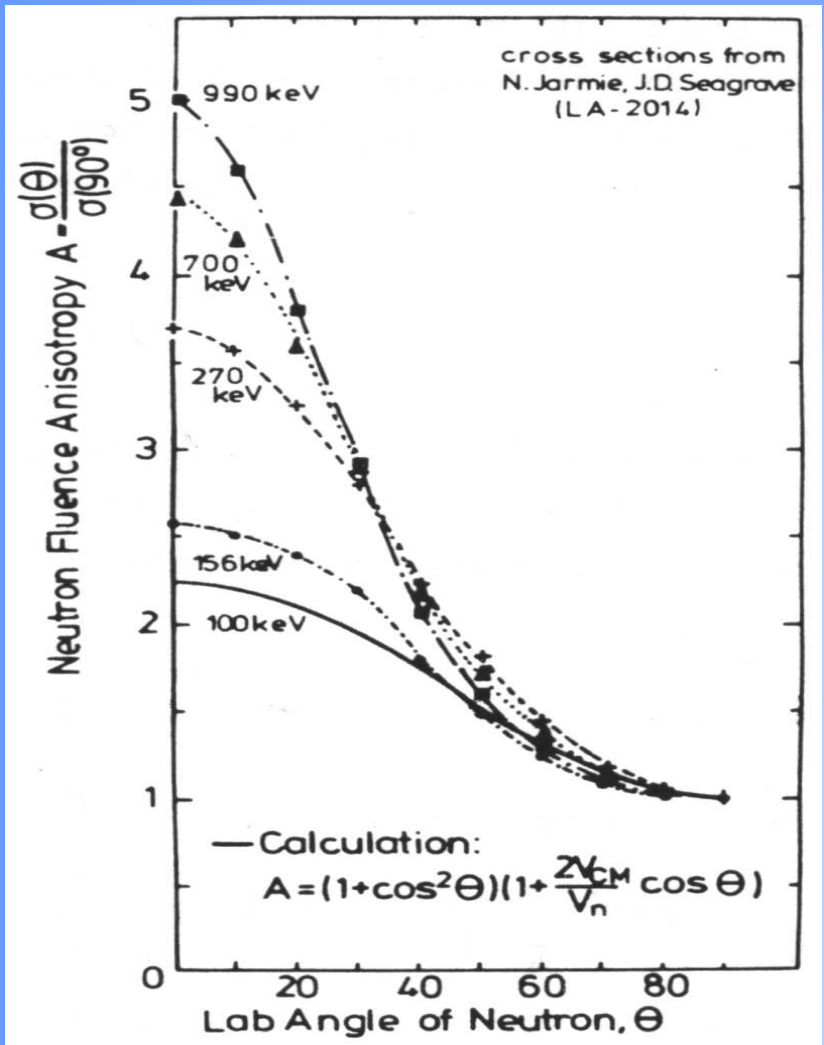


Typical neutron signal on Poseidon

- the compression phase (t<0)
- the quiescent phase (plasma expands to $r \approx 2r_{min}$
- the instability phase (m=0)
- break-up of the plasma column caused by instability

Beam-Target !?

Anisotropy



$$A = \frac{Y(0^0)}{Y(90^0)} > 1$$

$$E_n(0^0) = \frac{3}{4}\left(Q + \frac{E_d}{2}\right)\left(1 + \frac{v}{u}\right)^2;$$

E_D(keV)	20	100	300
$E_n(0^0)$ (MeV)	2.56	2.80	3.06

Institute of Plasma Physics and Laser Microfusion
Warsaw, Poland

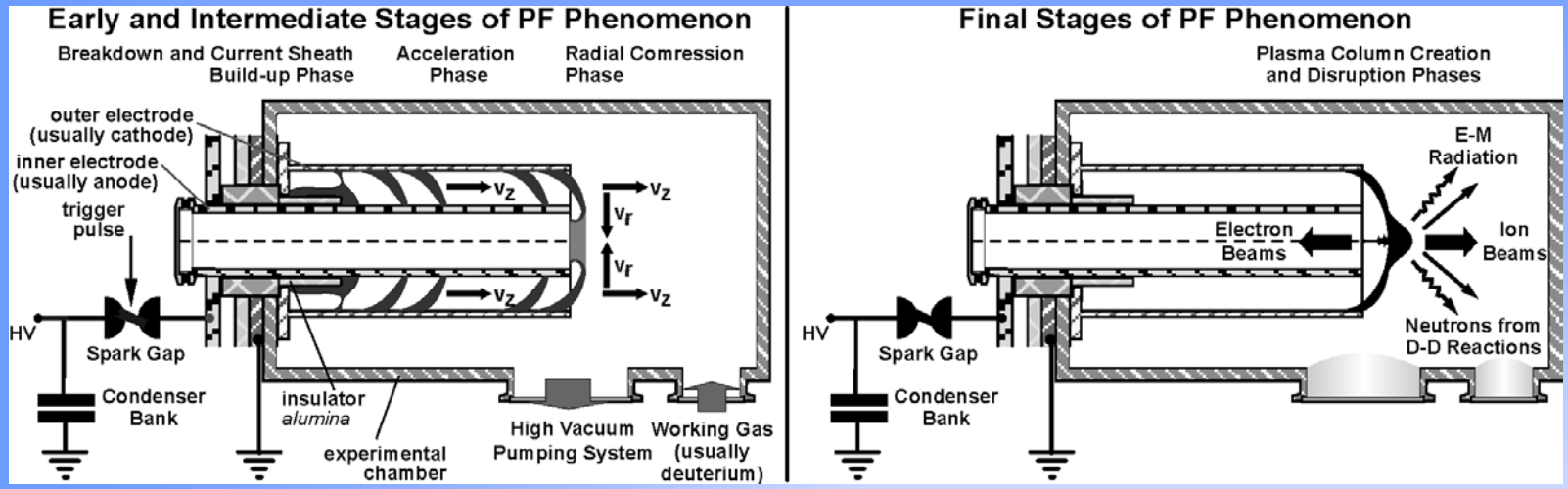
Goals of Experiment

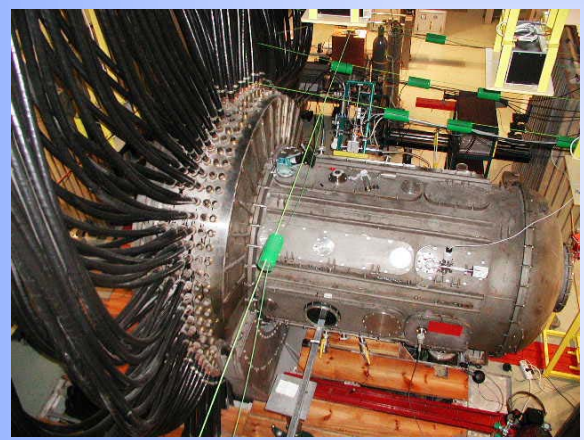
Definition of the neutron emission characteristics (neutron anisotropy and spectra) from large PF facility;

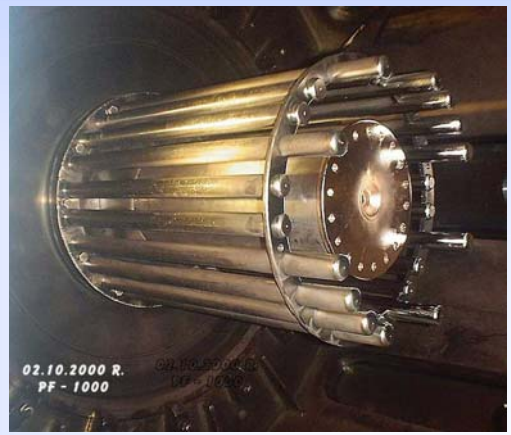
Definition of the relation between the Y_n and plasma sheath dynamics, with particular attention paid to structures appearing within the pinch column;

Definition of correlation between the neutron generation and other types of ionizing radiation produced within PF discharges, i.e. fast electrons, protons from DD reaction, soft and hard X-rays, etc

Apparatus







Institute of Plasma Physics and Laser Microfusion
Warsaw, Poland

Generator PF-1000

the charging voltage - $U_0 = 20 - 40\ kV$,

the bank capacitance - $C_0 = 1.332\ mF$,

the bank energy - $E_0 = 266 - 1064\ kJ$,

the nominal inductance - $L_0 = 15\ nH$,

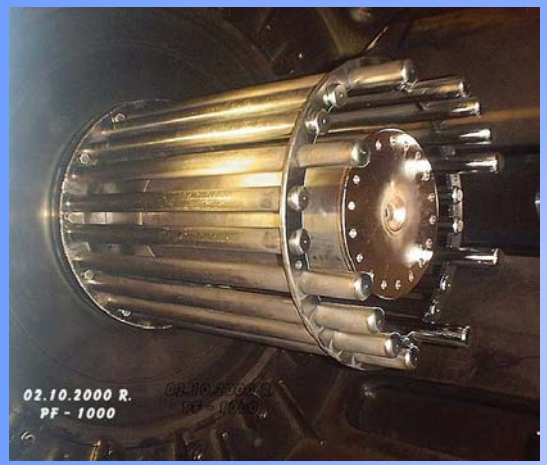
the quarter discharge time - $T_{1/4} = 6\ \mu s$,

the short-circuit current – $I_{SC} = 12\ MA$,

the characteristic resistance - $R_0 = 2.6\ m\Omega$,

Institute of Plasma Physics and Laser Microfusion
Warsaw, Poland

Electrodes



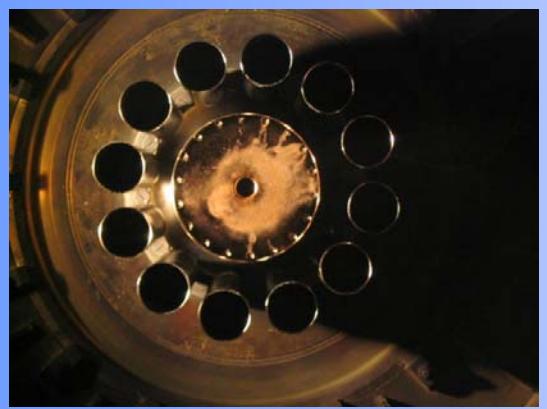
CE diameter - 226 mm

OE diameter - 400 mm

OE consists 24 rods (diam. 32 mm)

length of electrode - 560 mm

length of insulator - 113 mm



CE diameter - 226 mm

OE diameter - 400 mm

OE consists 12 rods (diam. 80 mm)

length of electrode - 560 mm

length of insulator - 113 mm

Diagnostics

$$P = \frac{N_D n_D}{2} \cdot \langle \sigma v \rangle \tau \qquad Y_n = l \cdot P \propto \alpha \frac{l}{a} I^4 \cdot \frac{\langle \sigma v \rangle}{T^{5/2}}$$

Frame cameras;

Streak camera

Silver Activation Counter

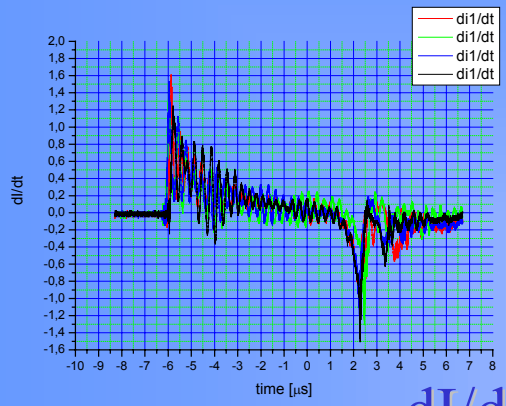
(anizotropy)

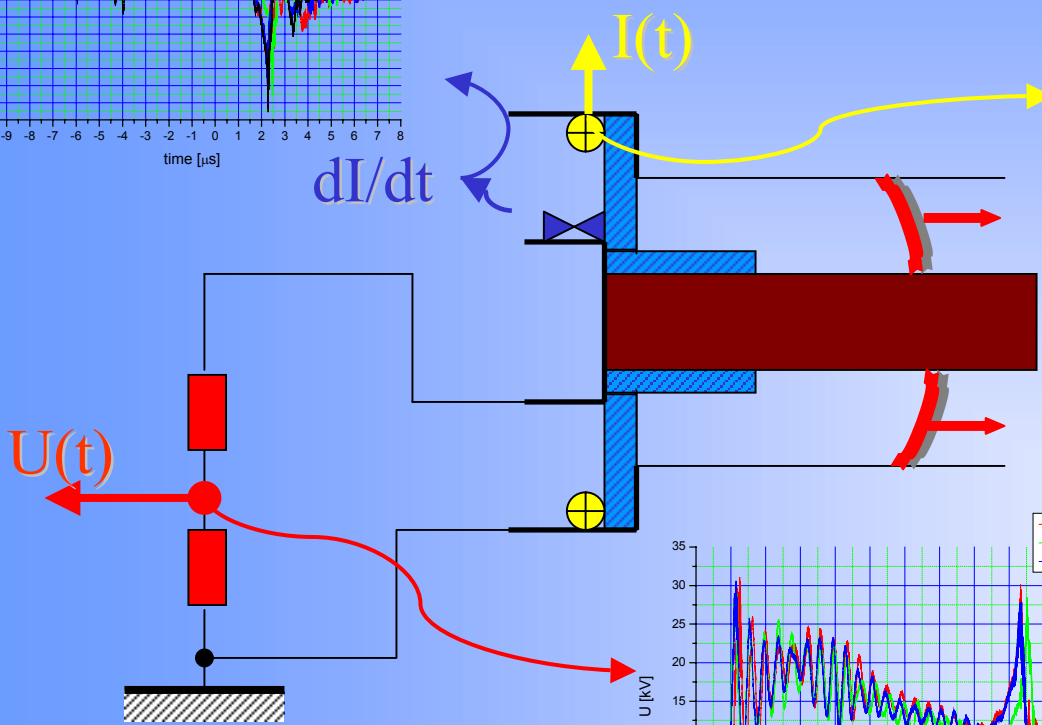
PMT

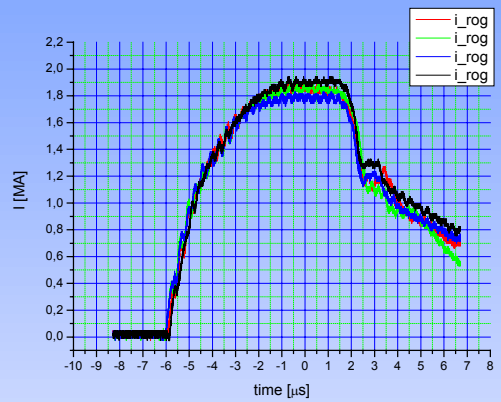
TOF (spectra → T)

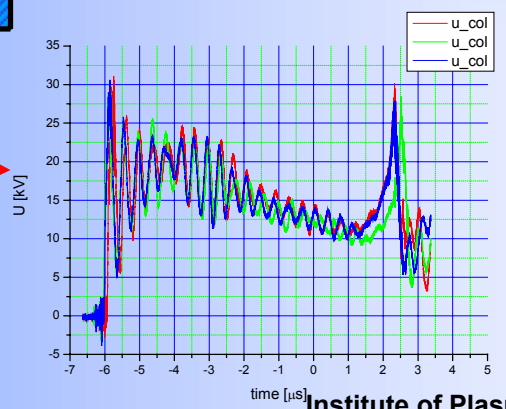
Rogovski coil

Measurements of Current and Voltage









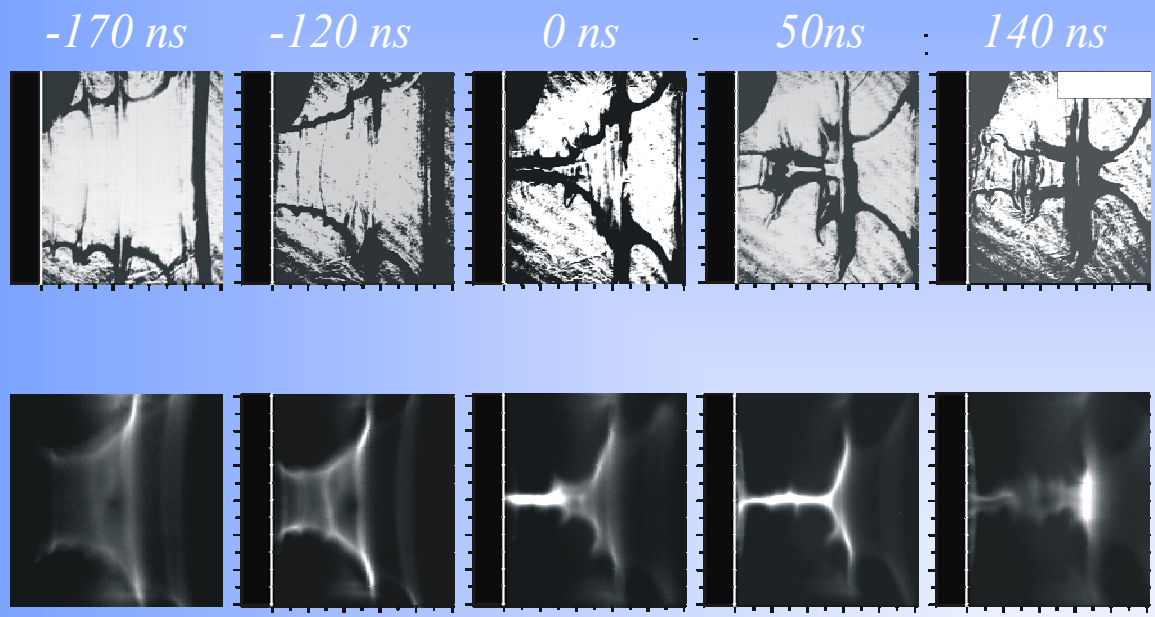
U_b= 27 kV, E_b= 480 kJ,

p = 3,5 Torr

$Y = 5 \cdot 10^{10} - 3 \cdot 10^{11}$

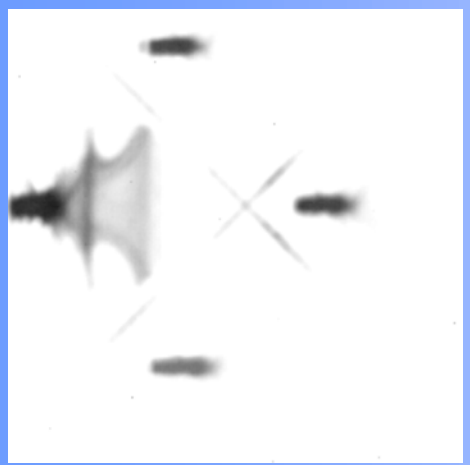
Institute of Plasma Physics and Laser Microfusion
Warsaw, Poland

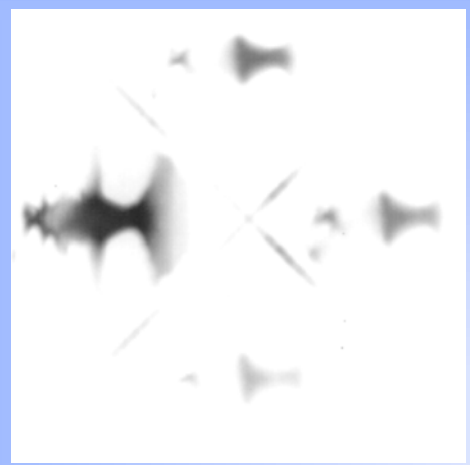
Compression, Pinch & Post-pinch



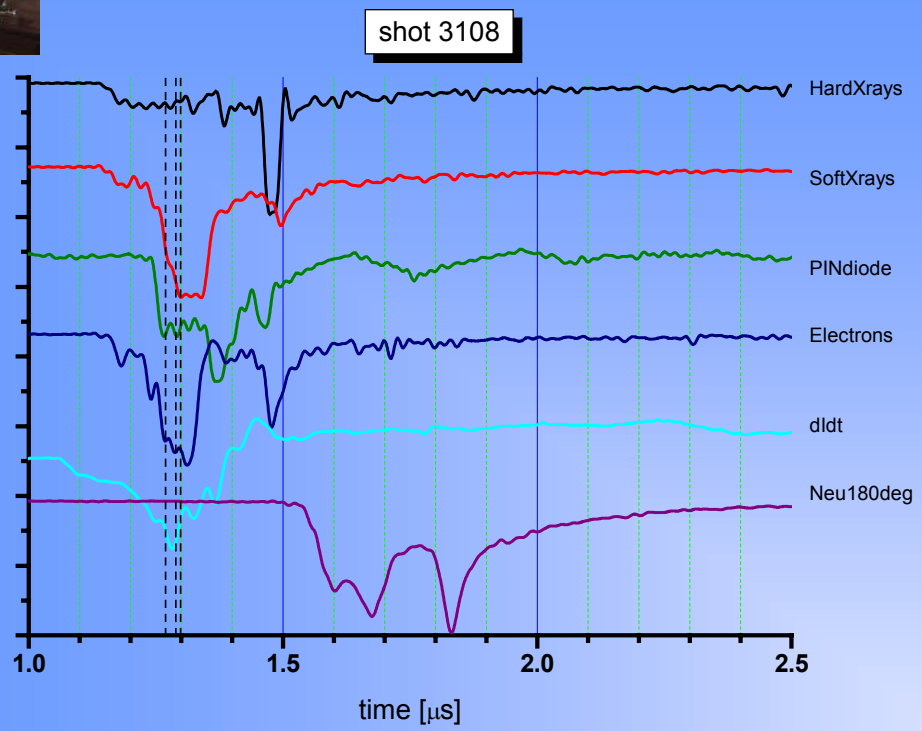
Visible frames - exposure time 1 ns, window 589 nm

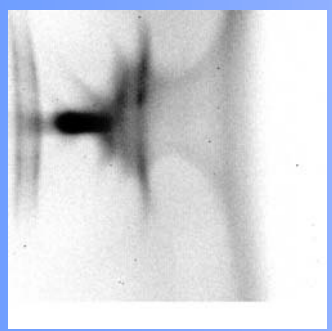
Compression, Pinch & Post-pinch



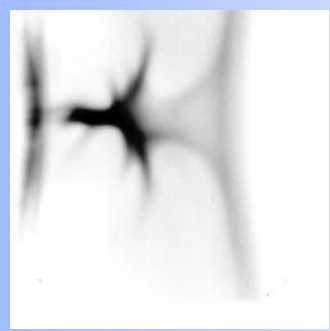


XUV frames - **exposure time 2 ns, window 200-300 eV+above 600 eV**

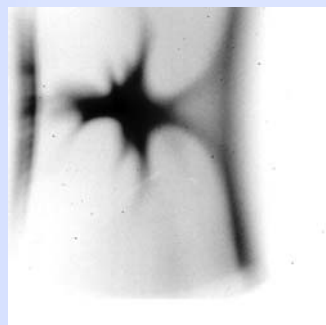




1.269 μs



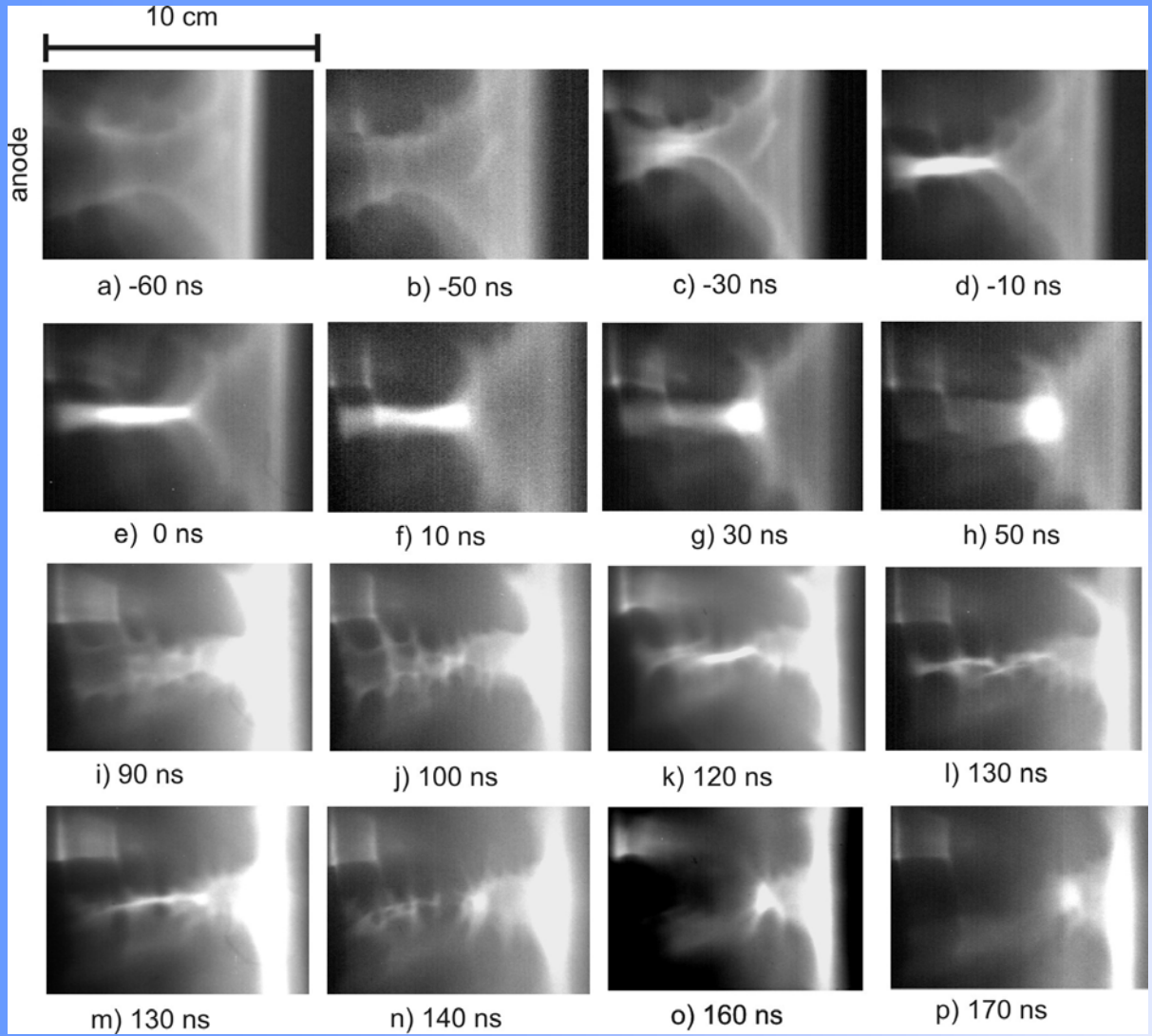
1.289 μs



1.299 μs

Institute of Plasma Physics and Laser Microfusion
Warsaw, Poland

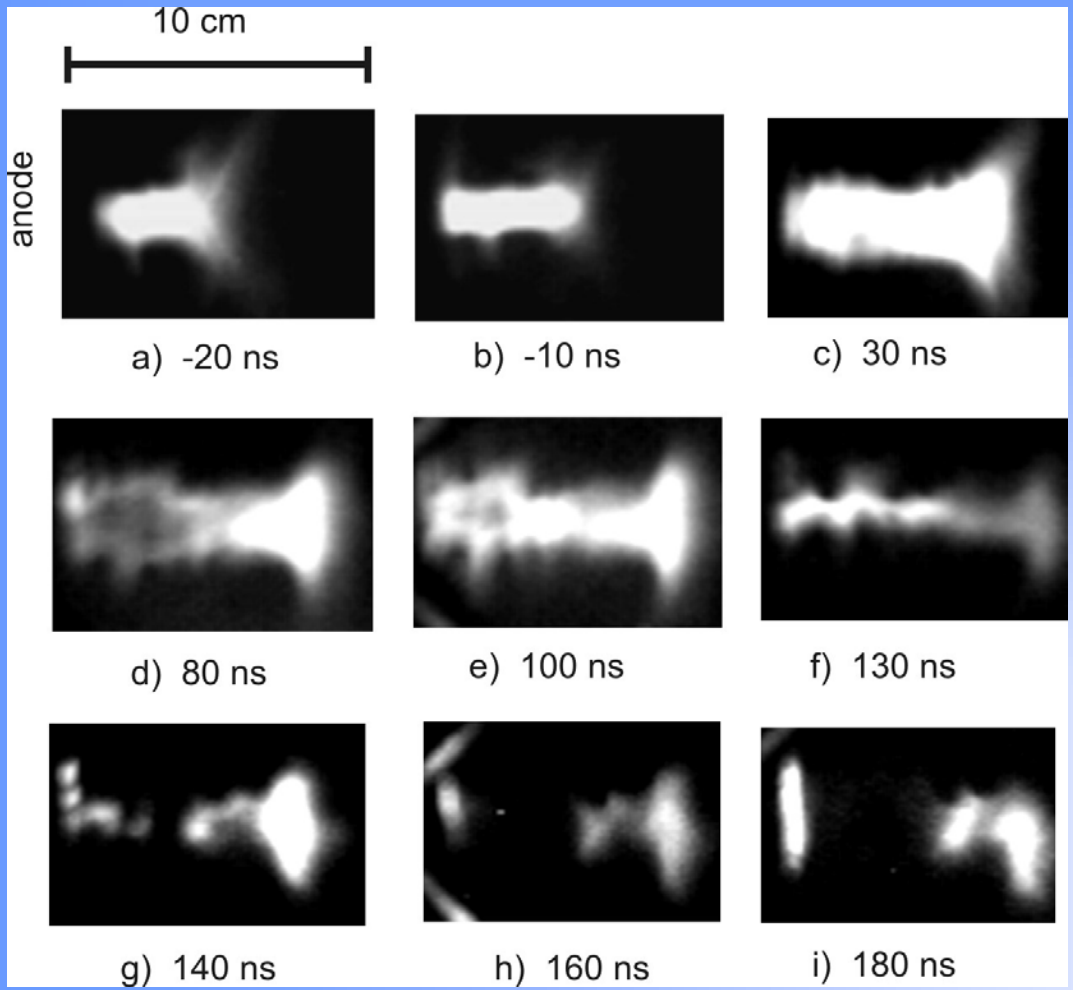
Visible frames - exposure time 1 ns, window 589 nm



a-d implosion $2x10^5$m/s
e minimum radius t=0
c-g intense light - dense plasma, dense spherical structure
g-p instabilities
j-m second pinch
m-n second explosion
m-p second dense structure

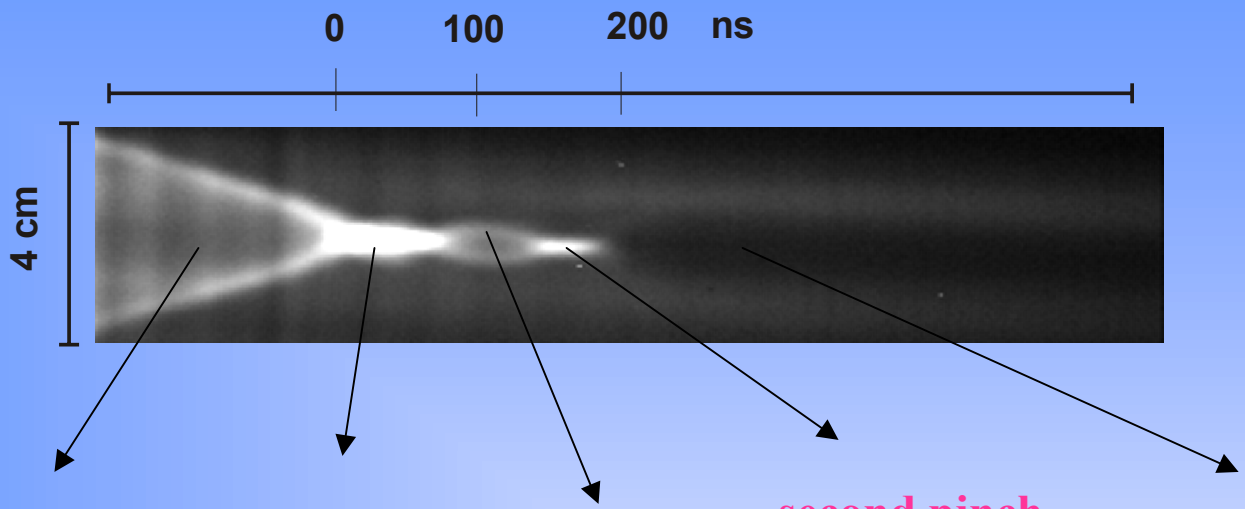
Institute of Plasma Physics and Laser Microfusion
Warsaw, Poland

XUV frames - exposure time 2 ns, window 200-300 eV+above 600 eV



a-c ***pinch ø 1-2 cm;***
d ***– first expansion***
e-f ***- second pinch***
g-i ***explosion, dense structure***
dense spherical structure

Visible streak-camera



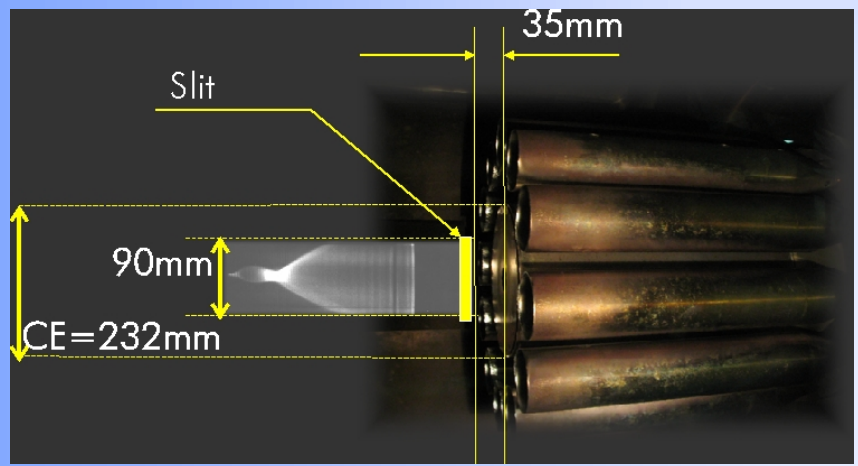
implosion of the current sheath

first pinch

development of instabilities

second pinch

explosion

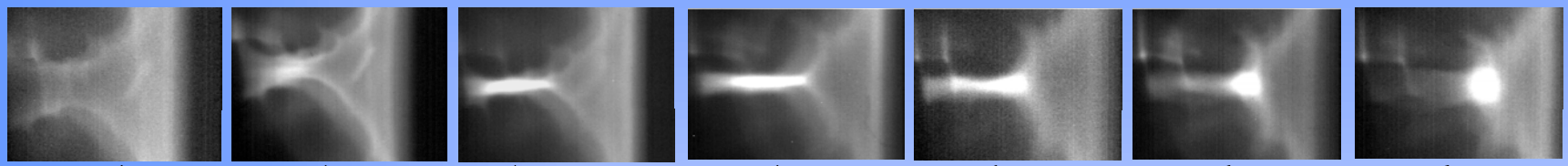


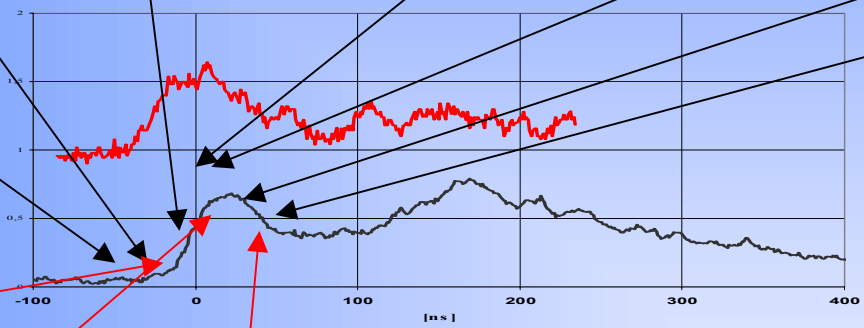
Institute of Plasma Physics and Laser Microfusion
Warsaw, Poland

Correlation of neutron signals with frames

(first neutron pulse)

-50 ns -30 ns -10 ns 0 ns 10 ns 30 ns 50 ns

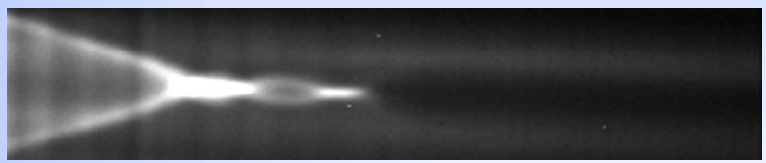




hard x-rays

neutron signal

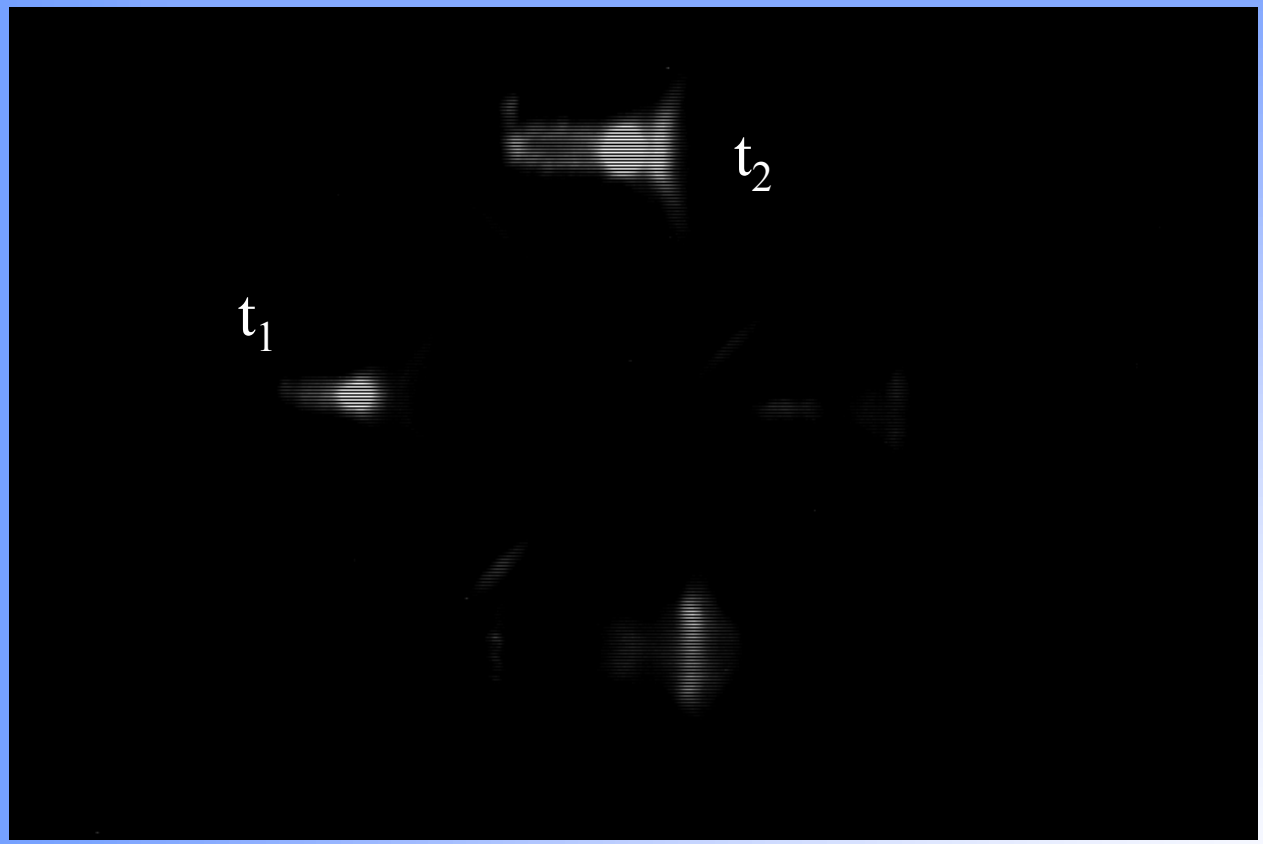
-20 ns -10 ns 30 ns



-30 ns 0 ns

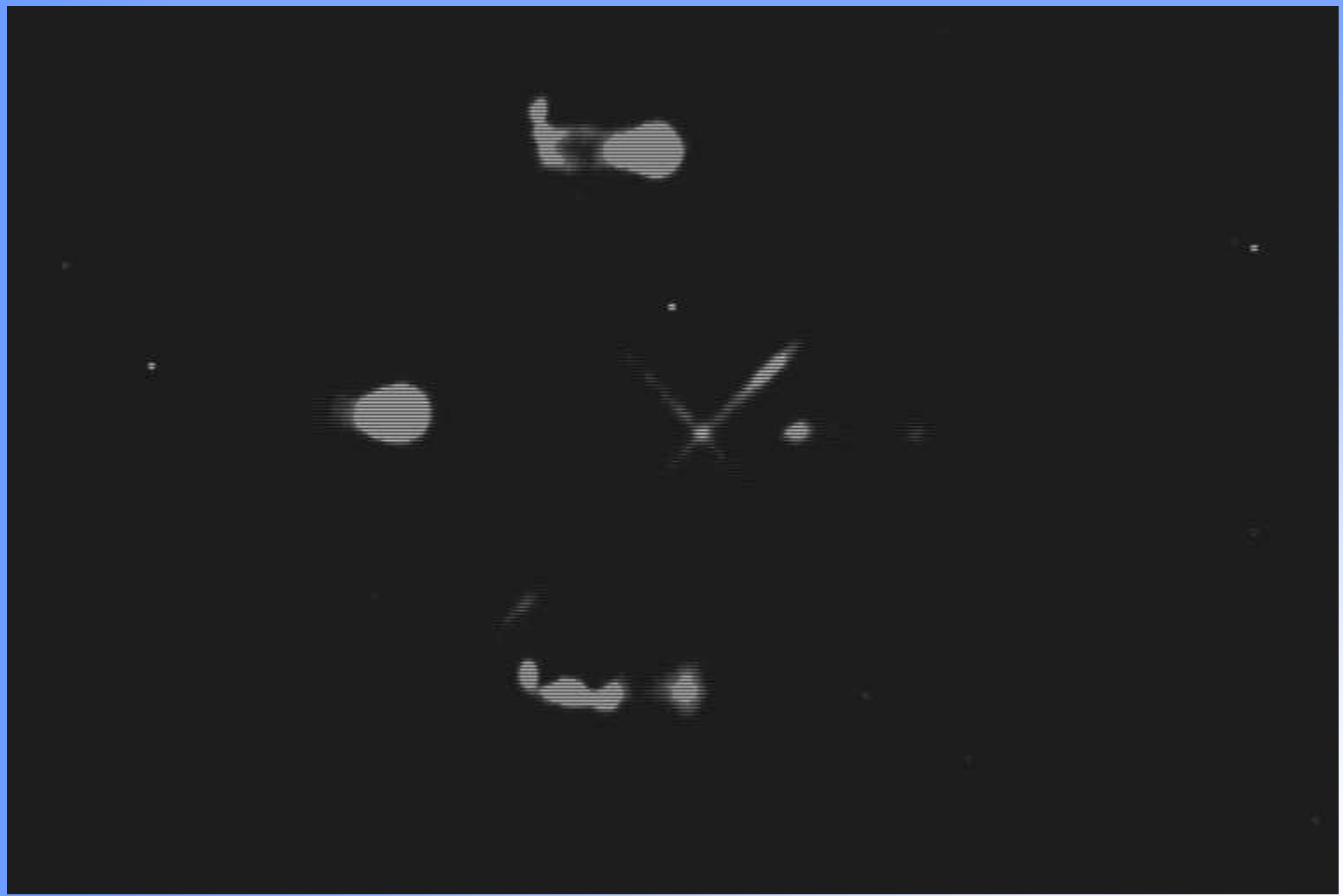
Institute of Plasma Physics and Laser Microfusion
Warsaw, Poland

XUV frames - exposure time 2 ns, window 200-300 eV+above 600 eV



t_2-t_1=10ns

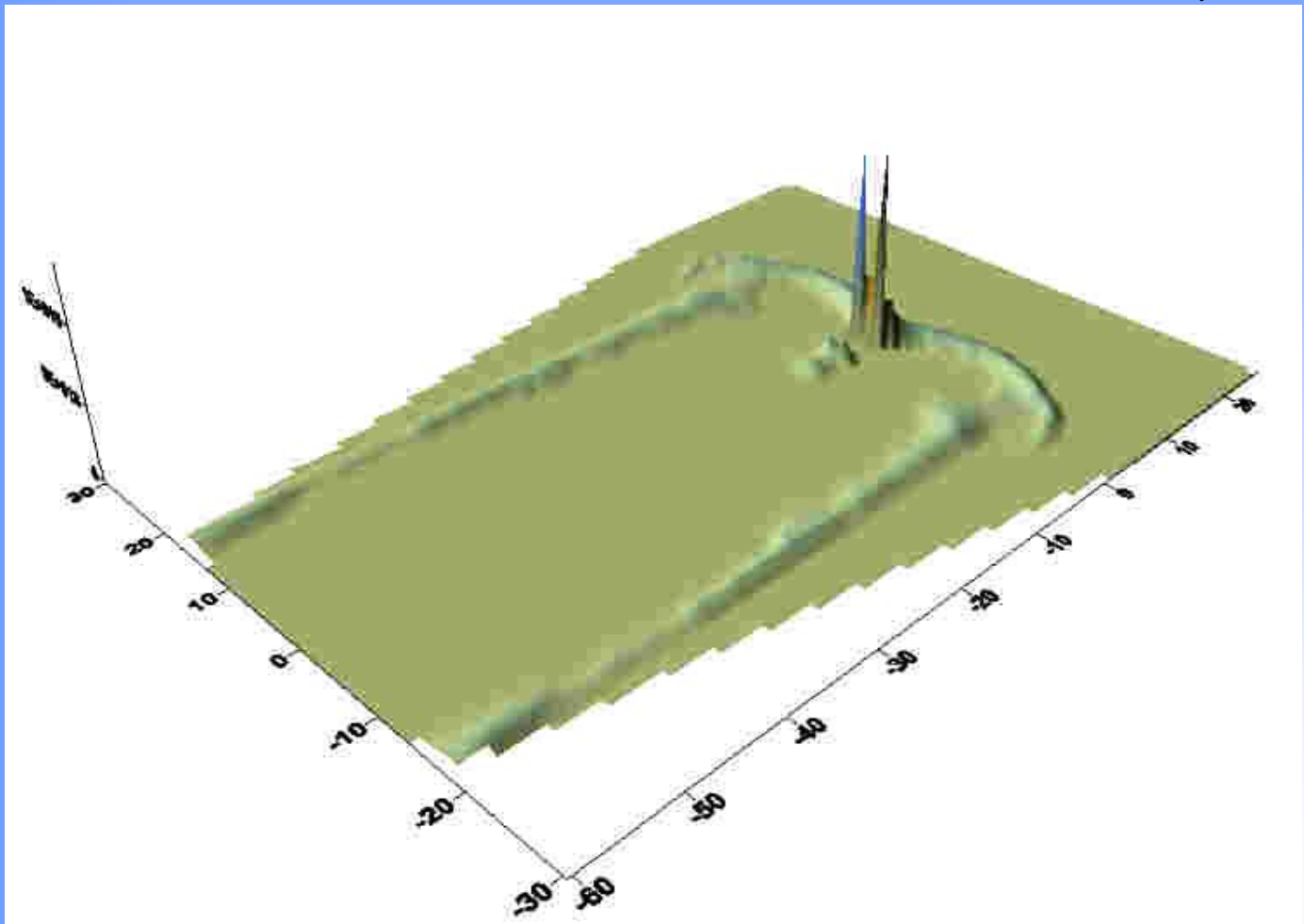
XUV frames - exposure time 2 ns, window 200-300 eV+above 600 eV



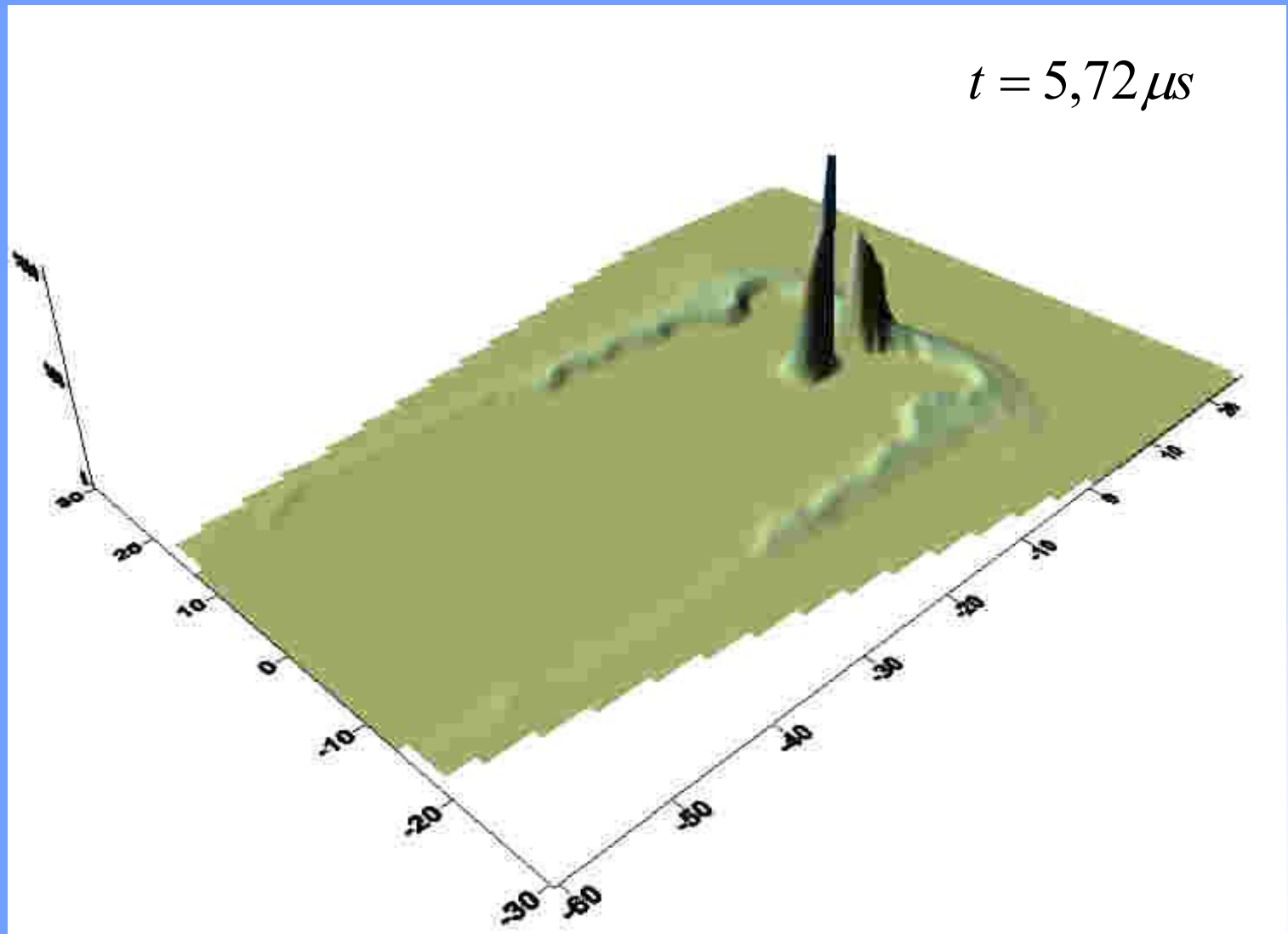
Institute of Plasma Physics and Laser Microfusion
Warsaw, Poland

Calculated density

$t = 5{,}72\,\mu s$

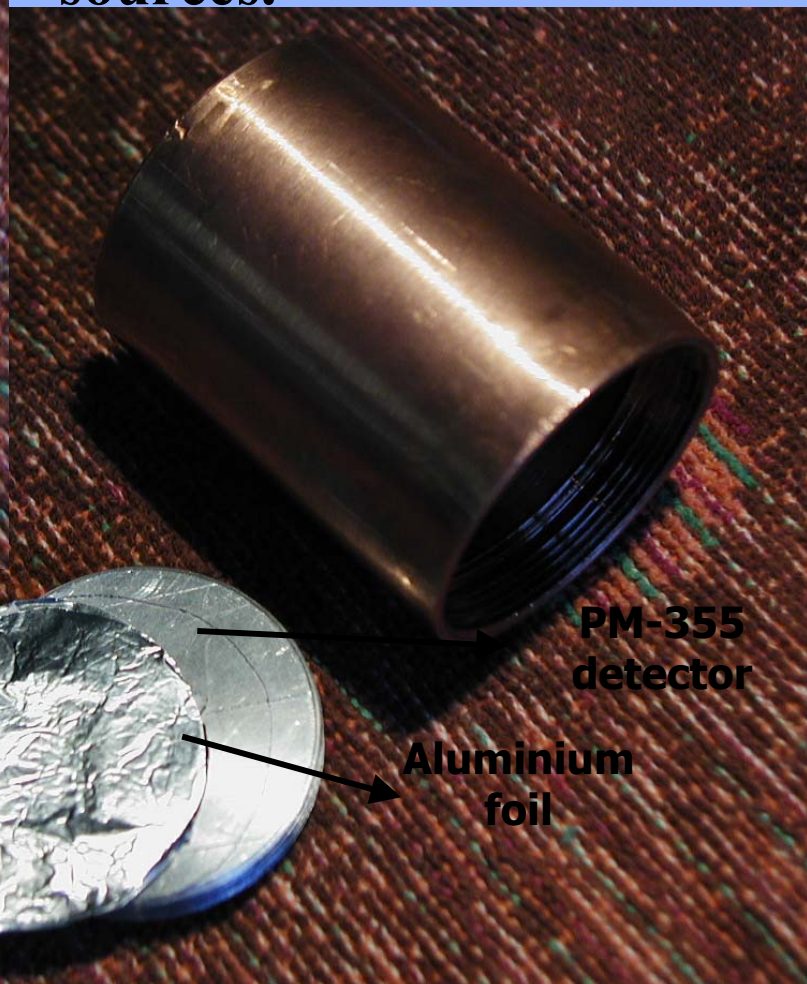


Calculated temperature of ions



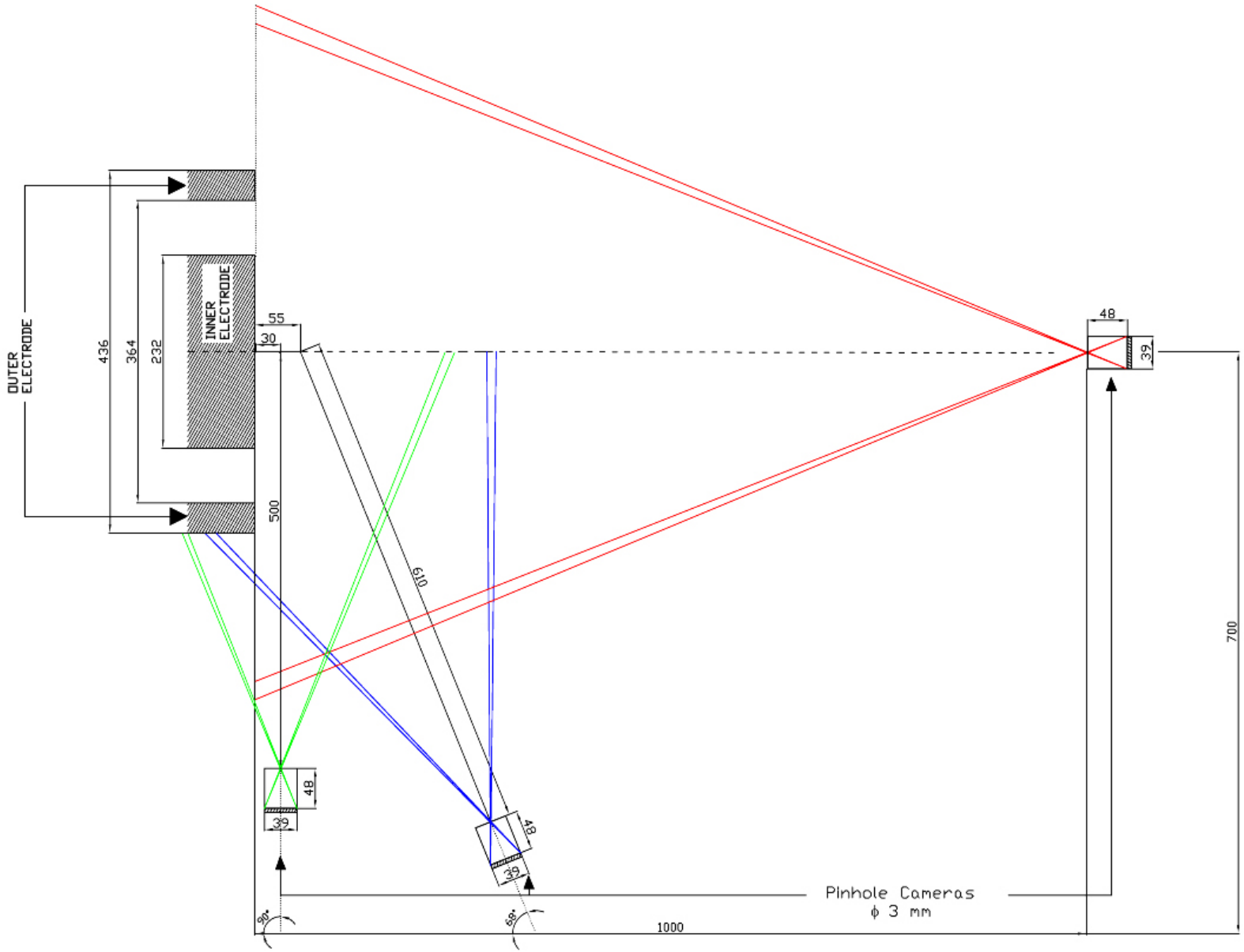
obtained and presentyd by Sadowski, at al

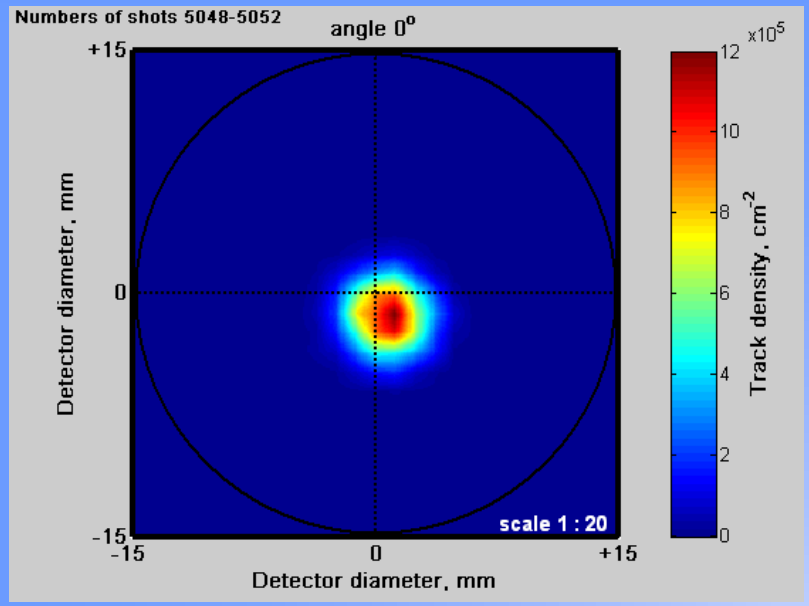
Small ion pinhole cameras equipped with PM-355 detectors were used to determine fusion-reaction proton emission sources.

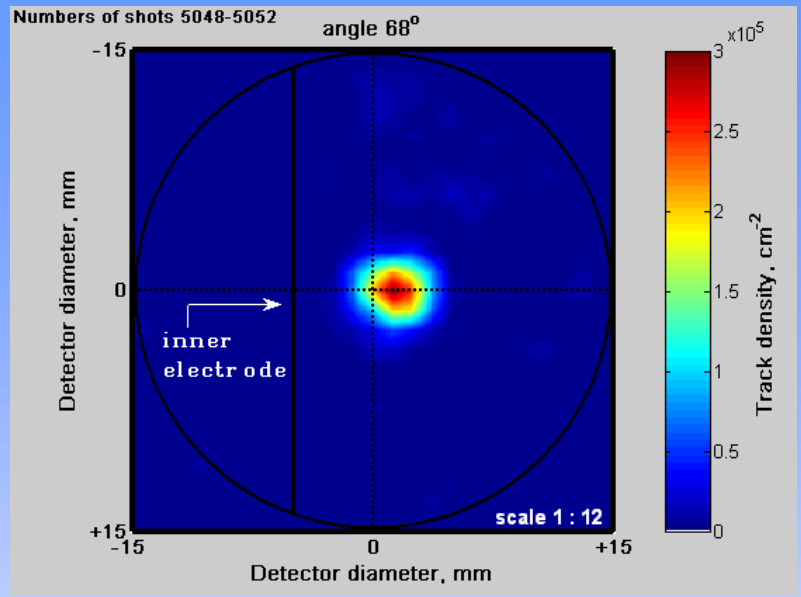


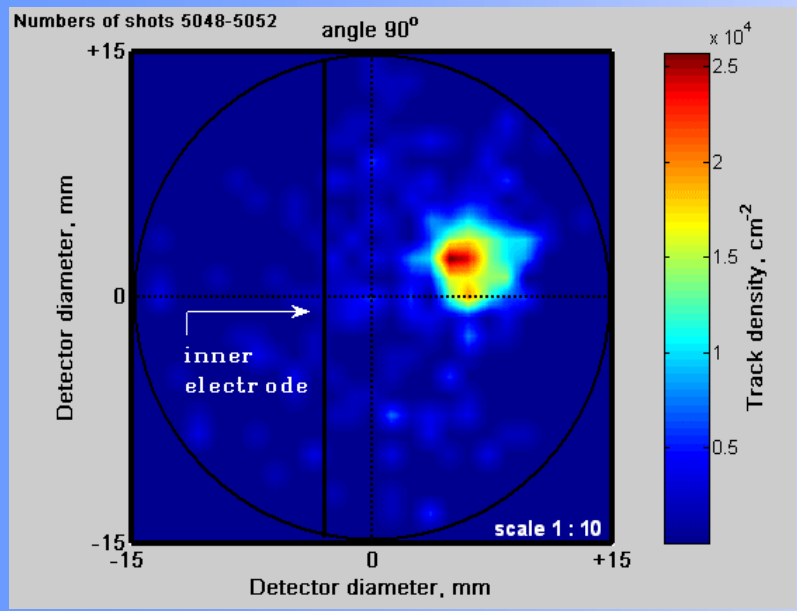
To eliminate fast primary deuterons the detector samples used in the cameras were covered with 80 μm thick Al-foils

Positioning of ion-pinhole cameras within the PF-1000 facility during measurements of fusion-produced protons.



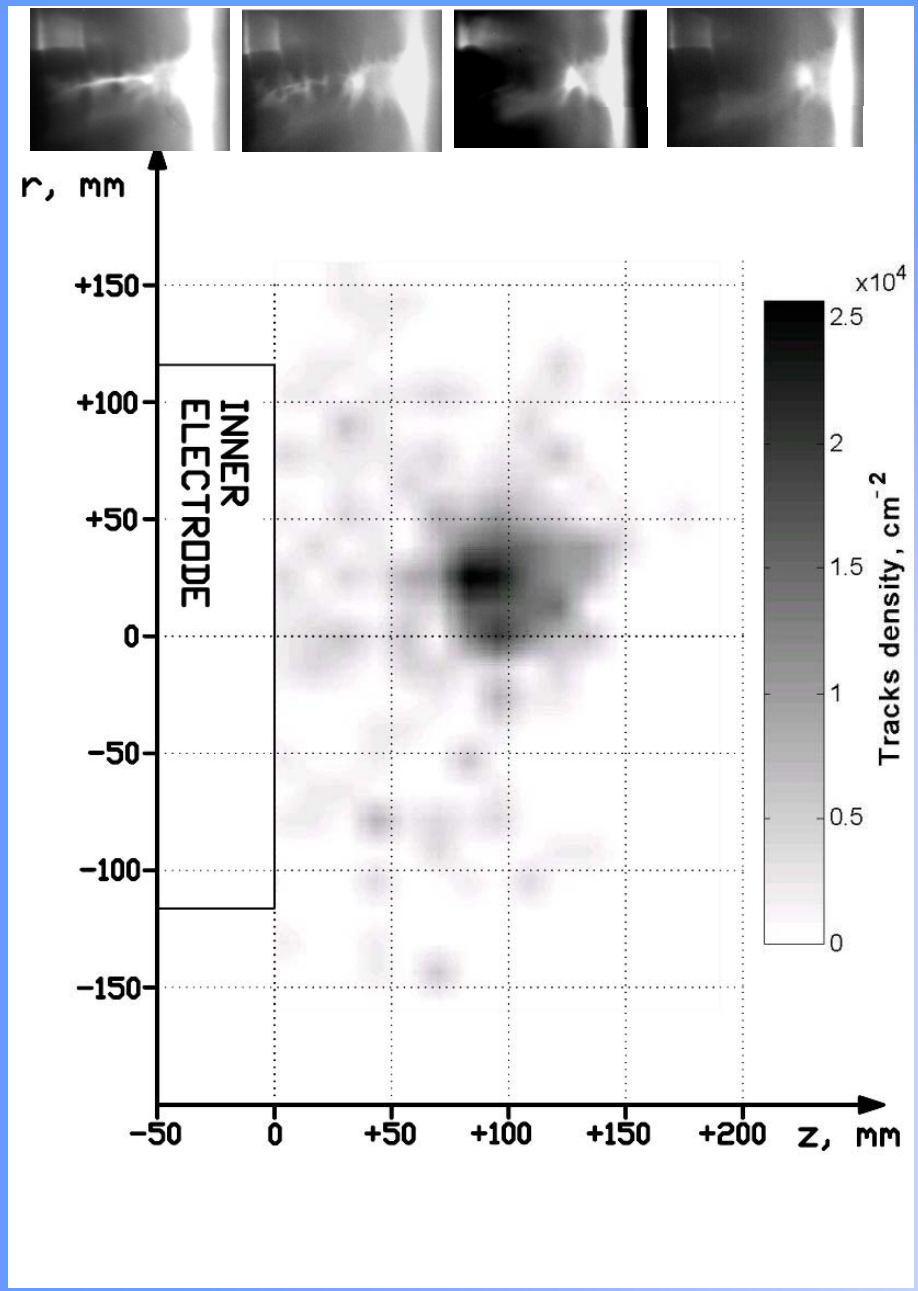


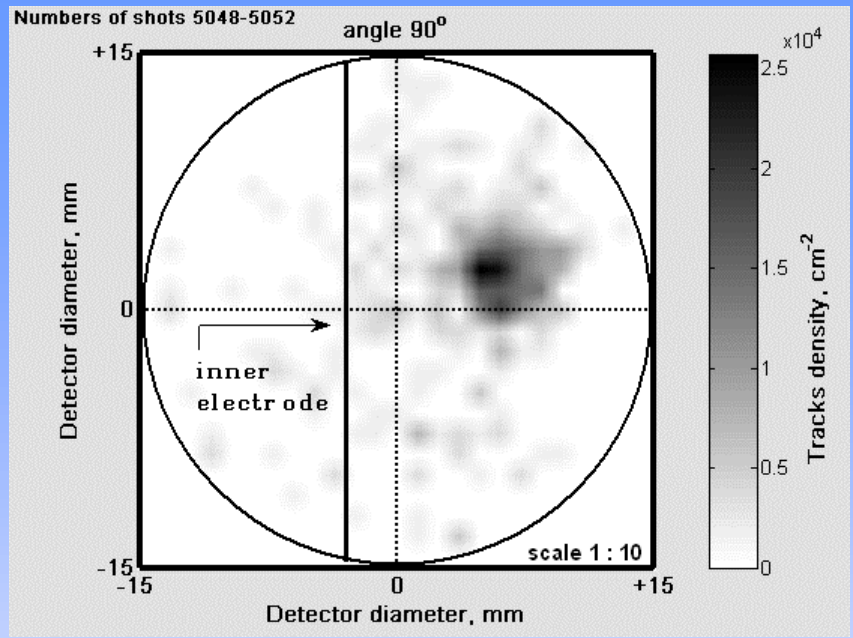




Images of fusion-proton emitting areas, as obtained after etching of the PM-355 detectors irradiated during five successive discharges within the PF-1000 facility (operated at p_0 = 4 Torr D_2, U_0 = 31 kV).

Institute of Plasma Physics and Laser Microfusion
Warsaw, Poland



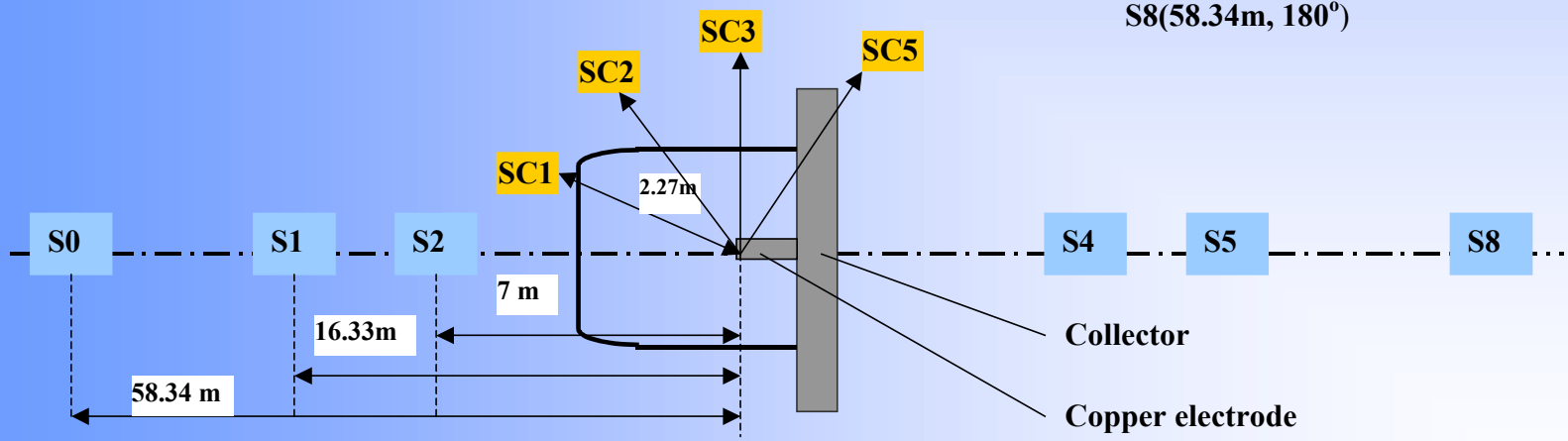


Example of the image of the fusion-produced protons, as recorded upon the detector placed at 90^0 to the z-axis in the PF-1000 facility.

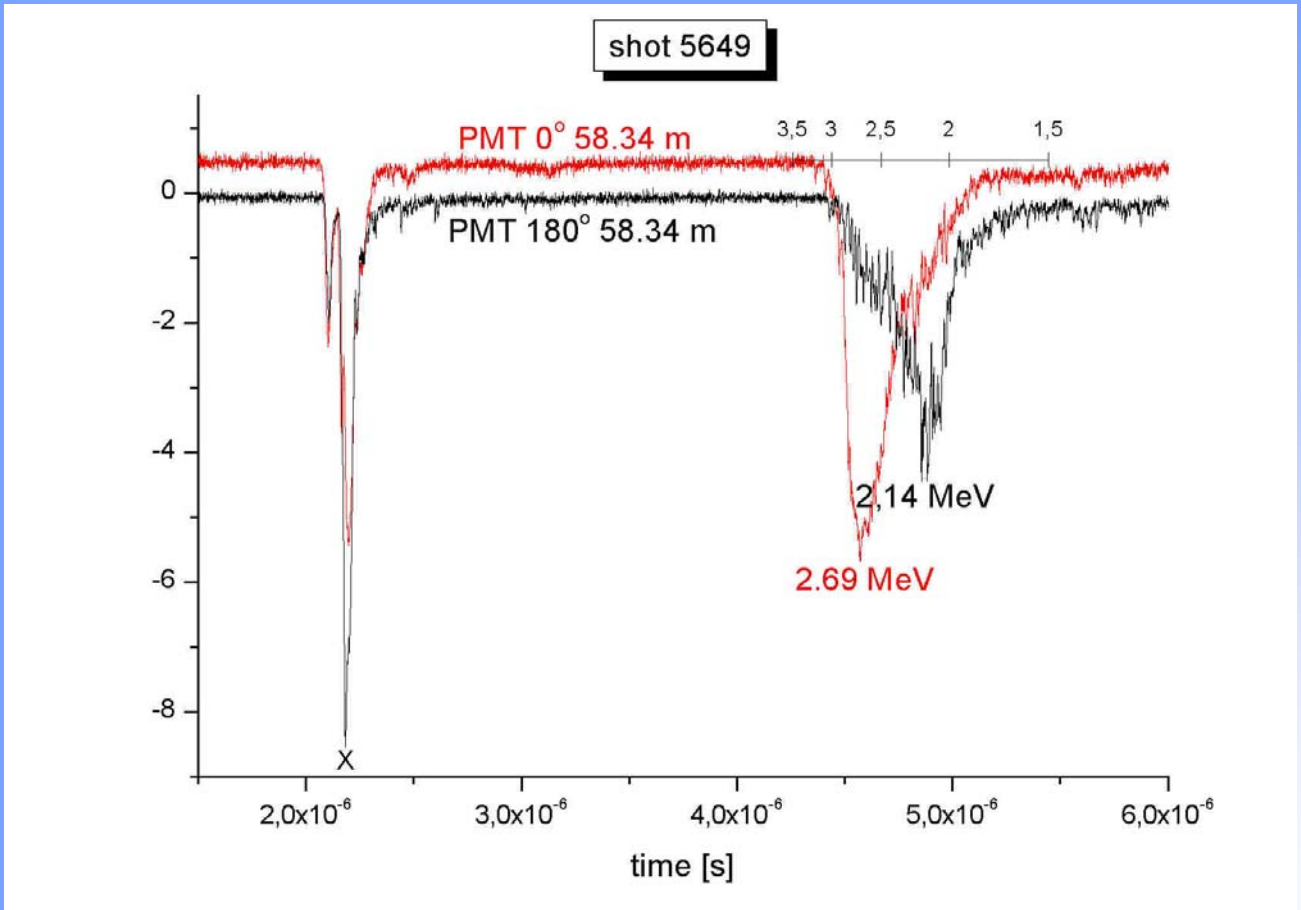
Institute of Plasma Physics and Laser Microfusion
Warsaw, Poland

Activation silver counters:
SC1(30°), SC2(60°),
SC3(90°), SC5(150°)

Scintillator PMT detectors:
S0(58.34m, 0°), S1(16.33m, 0°),
S2(7m, 0°), S4(7m, 180°), S5(17m, 180°),
S8(58.34m, 180°)

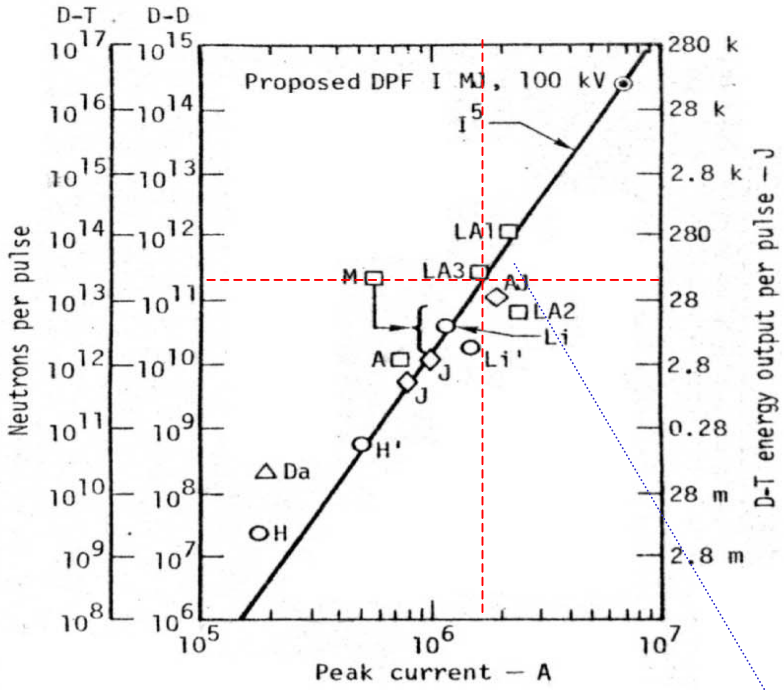


TOF Measurement



Results of TOF measurements

Shot number	Y_n $L_1(90^o)$	t_n (0^O) [μs]	t_n (180^O) [μs]	$\Delta t = t_n$ (180^O) - t_n (0^O) [μs]	E_b [keV]
5544	$2.03.10^{11}$	4.734	5.055	0.321	70.0
5566	$1.49.10^{11}$	4.615	5.035	0.420	120
5569	$1.76.10^{11}$	4.643	4.965	0.322	70.4
5575	$1.92.10^{11}$	4.509	4.789	0.280	53.2
5592	$1.34.10^{11}$	4.623	4.911	0.288	56.3
5605	$2.28.10^{11}$	4.770	5.158	0.388	102
5620	$1.14.10^{11}$	4.860	5.147	0.287	55.9
5649	$1.55.10^{11}$	4.573	4.874	0.301	61.5



Legend

AJ	Aerojet Nucleonics. 250 kJ, 20 kV, 320 μF.
Da	Darmstadt. 0.34 - 1.35 kJ;]0 - 20 kV.
H	Hoboken. Electrode structure is identical to that of Darmstadt group.
H'	Hoboken. About 5 kJ.
A^E	Aerospace Corporation.
J	Julich. 25 kJ; 40 kV.
Li	Limeil. 96 kJ, 40 kV.
Li'	Limeil. Plasma focus driven by expolsive generator.
LA^1	Los Alamos. DPF-6; 420 kJ.
LA^2	Los Alamos. DPF-5; 120 kJ.
LA^3	Los Alamos. DPF-6; 210 kJ.
M	Moscow. Y → 10^{10} to 10^{11} DD neutrons; I = 1 MA.

A "historical" experimental scaling law for neutron yield as a function of the total dischargecurrent (assembled in 1975).

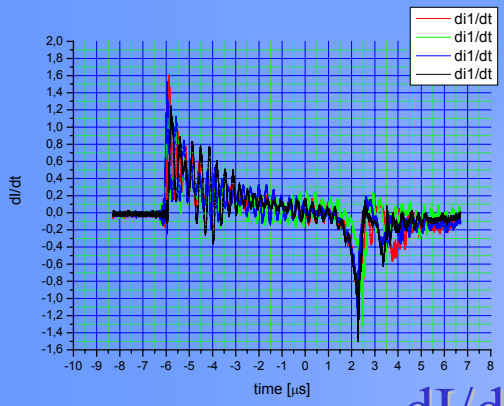
PF-1000, 1,8 MA,

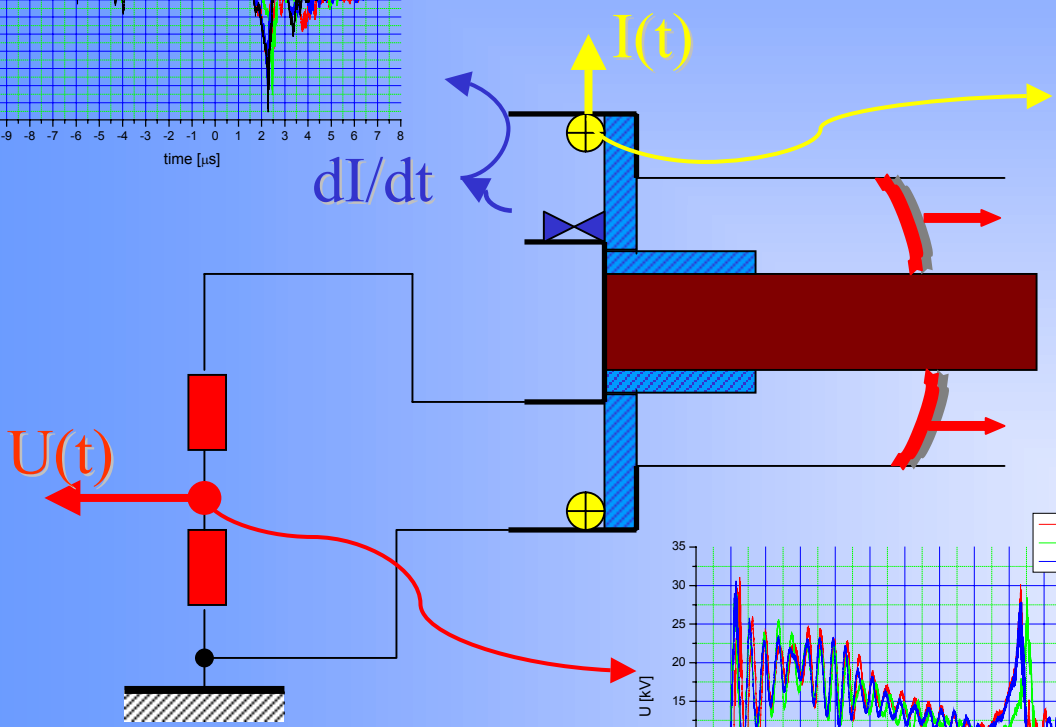
Y≅ 3·10¹¹ n/shot,

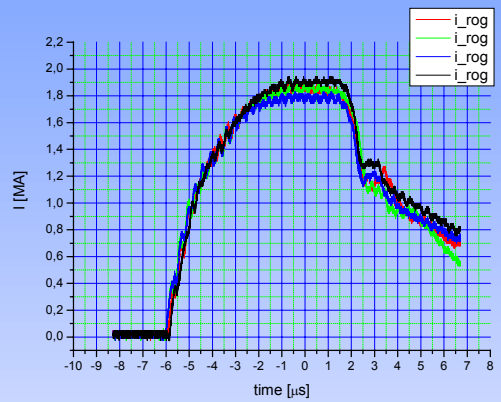
E=480 kJ

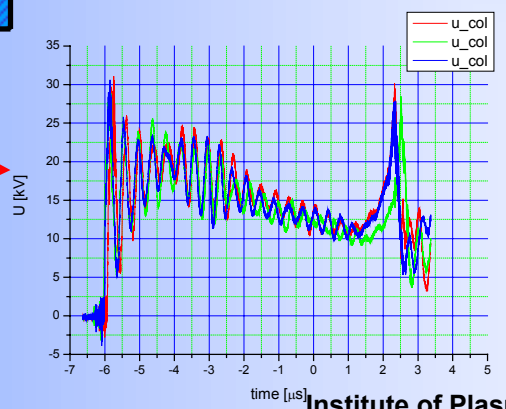
Institute of Plasma Physics and Laser Microfusion
Warsaw, Poland

Measurements of Current and Voltage









U_b= 27 kV, E_b= 480 kJ,

p = 3,5 Torr

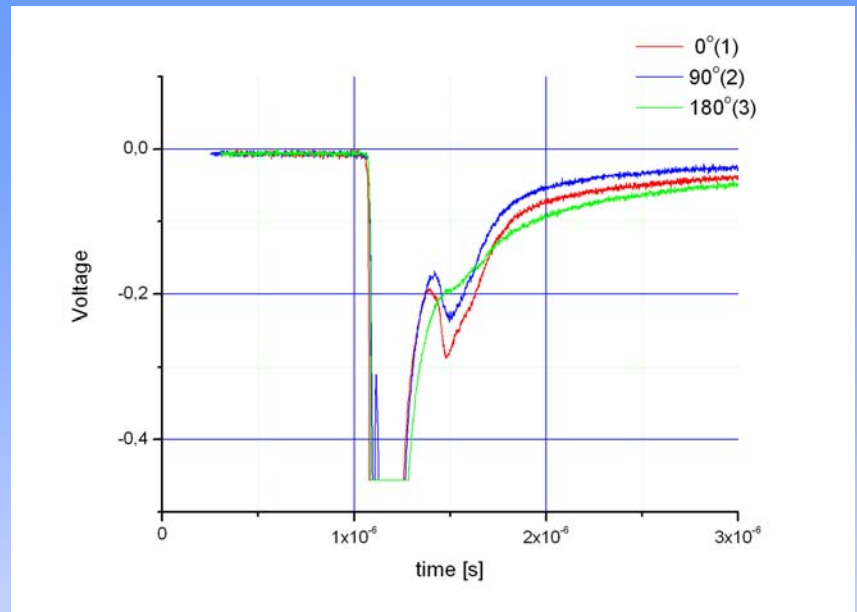
$Y = 5 \cdot 10^{10} - 3 \cdot 10^{11}$

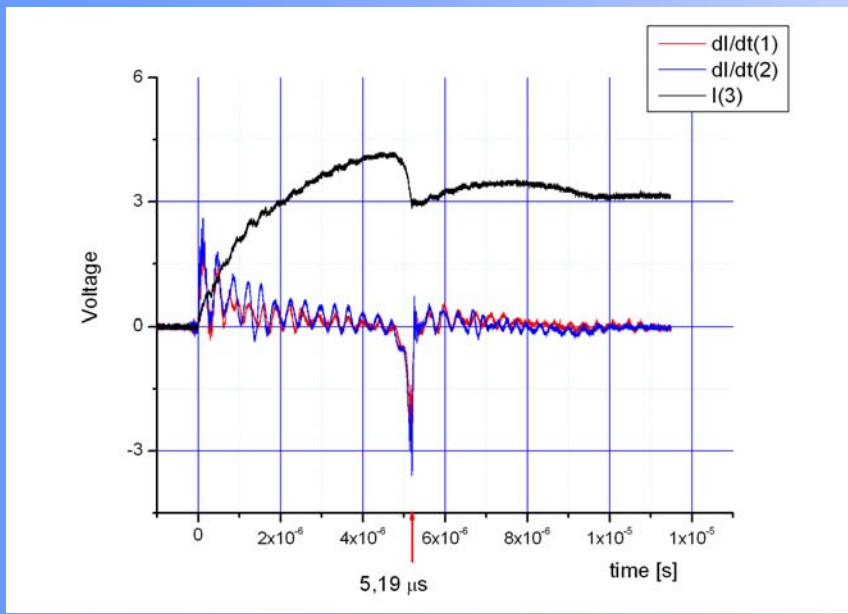
Institute of Plasma Physics and Laser Microfusion
Warsaw, Poland

SHOT 6814

2,5 Tr 29 kV

L1	124 286	3,057x10^6
L2	89152	3,036x10^6
L3	72593	4,192x10^6
L4	67608	4,777x10^6
L5	46426	6,583x10^6

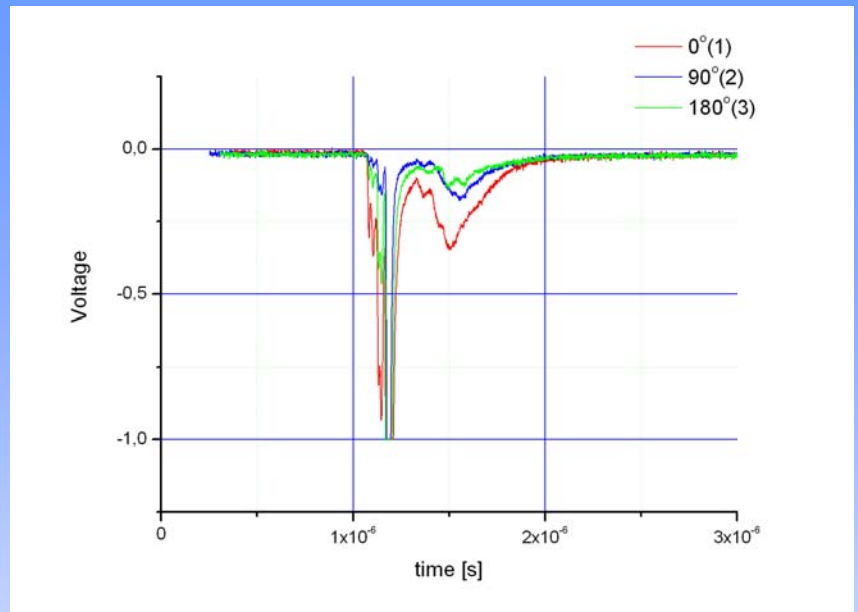


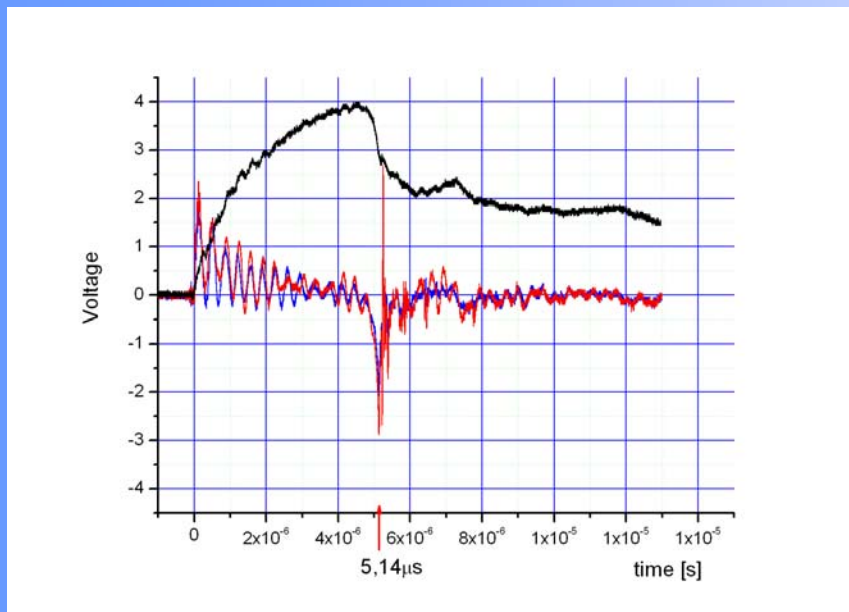


Institute of Plasma Physics and Laser Microfusion
Warsaw, Poland

SHOT 6817 2 Tr 29 kV

L1	102078	3,057x10^6
L2	74183	3,036x10^6
L3	57928	4,192x10^6
L4	47904	4,777x10^6
L5	35016	6,583x10^6

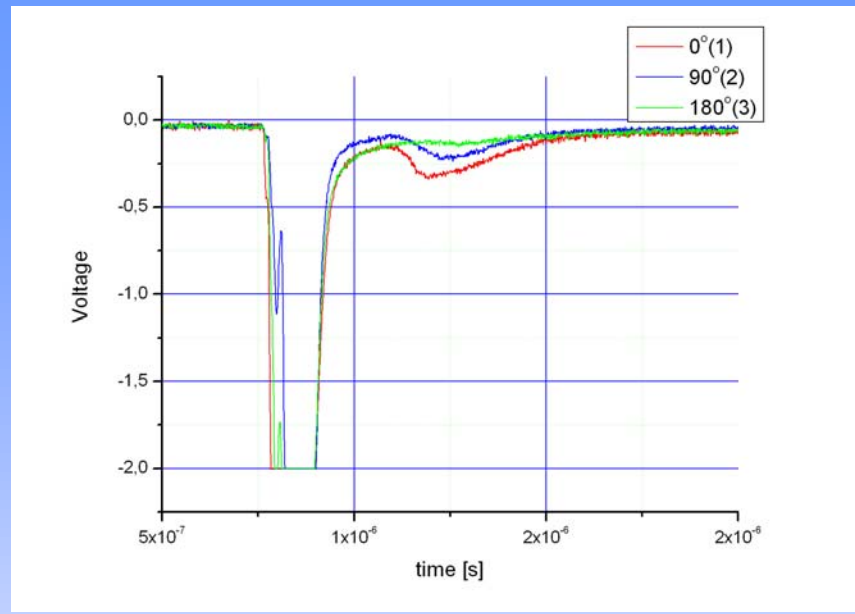


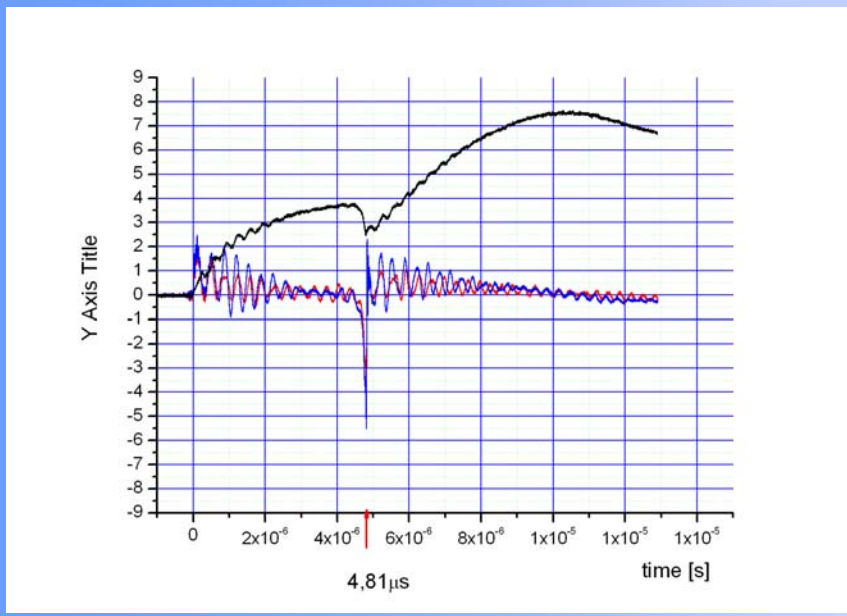


Institute of Plasma Physics and Laser Microfusion
Warsaw, Poland

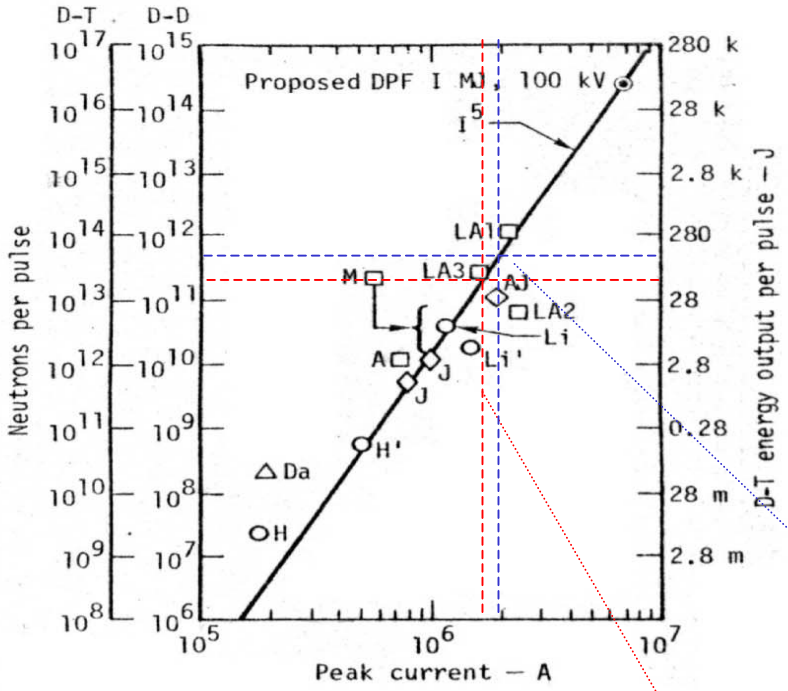
SHOT 6820 2,75 Tr 29 kV

L1	163160	3,057x10^6
L2	106836	3,036x10^6
L3	96329	4,192x10^6
L4	93122	4,777x10^6
L5	57110	6,583x10^6





Institute of Plasma Physics and Laser Microfusion
Warsaw, Poland



Legend

AJ	Aerojet Nucleonics. 250 kJ, 20 kV, 320 μF.
Da	Darmstadt. 0.34 - 1.35 kJ;]0 - 20 kV.
H	Hoboken. Electrode structure is identical to that of Darmstadt group.
H'	Hoboken. About 5 kJ.
A^E	Aerospace Corporation.
J	Julich. 25 kJ; 40 kV.
Li	Limeil. 96 kJ, 40 kV.
Li'	Limeil. Plasma focus driven by expolsive generator.
LA^1	Los Alamos. DPF-6; 420 kJ.
LA^2	Los Alamos. DPF-5; 120 kJ.
LA^3	Los Alamos. DPF-6; 210 kJ.
M	Moscow. Y → 10^{10} to 10^{11} DD neutrons; I = 1 MA.

A "historical" experimental scaling law for neutron yield as a function of the total dischargecurrent (assembled in 1975).

PF-1000, 1,95 MA,

Y≅ 6·10¹¹ n/shot,

E=550 kJ

PF-1000, 1,8 MA,

Y≅ 3·10¹¹ n/shot,

E=480 kJ

Institute of Plasma Physics and Laser Microfusion
Warsaw, Poland

Question for future

- Determination of parameters of the dense plasma structure in the head of the pinch
- role of outflow
- role of disipation procesess of magnetic field energy into a pinch plasma
- nature of neutron generation

Correct neutron measurements

Measurements of a current flowing in a pinch

Diagnostics

$$P = \frac{N_D n_D}{4} \cdot \langle \sigma v \rangle \tau$$

$$Y_n = l \cdot P \propto \alpha \frac{l}{a} I^4 \cdot \frac{\langle \sigma v \rangle}{T^{5/2}}$$

Interferometry !!;

Streak camera

Activation Measurements

(anizotropy !!)

Method of calibration!

PMT

TOF (spectra)

Current probes

Soft X-ray Measurements

(D+Ar or D+Kr)

Interferometry for PF-1000

Mach-Zenhder

Laser output specyfication

Max. Pulse energy, mJ

At 1053 nm	1000
At 527 nm	450
At 351 nm	320
At 263 nm	160

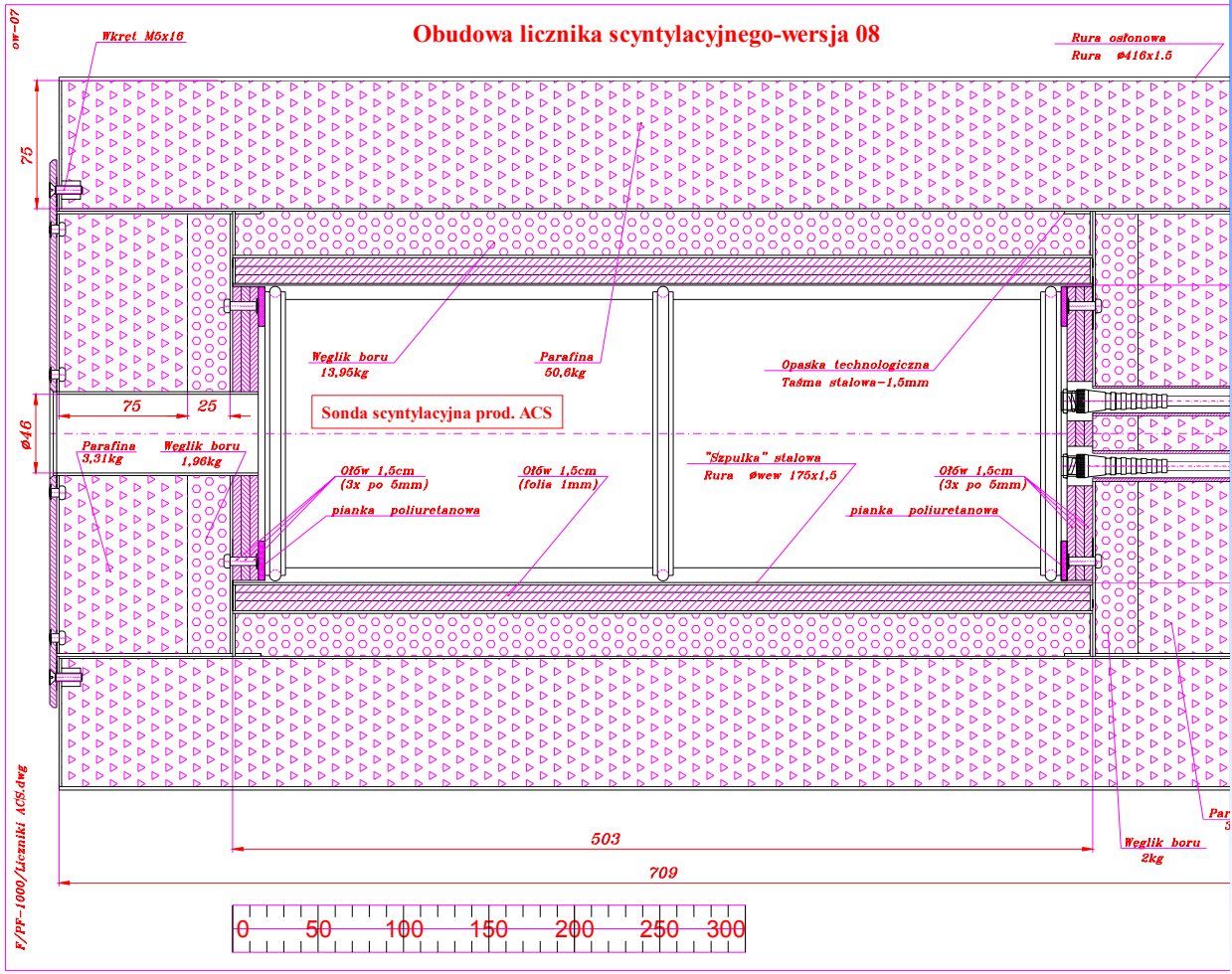
Pulse duration at 1053 nm (FWHM) < 1 ns

Optical pulse jitter +/-1 ns

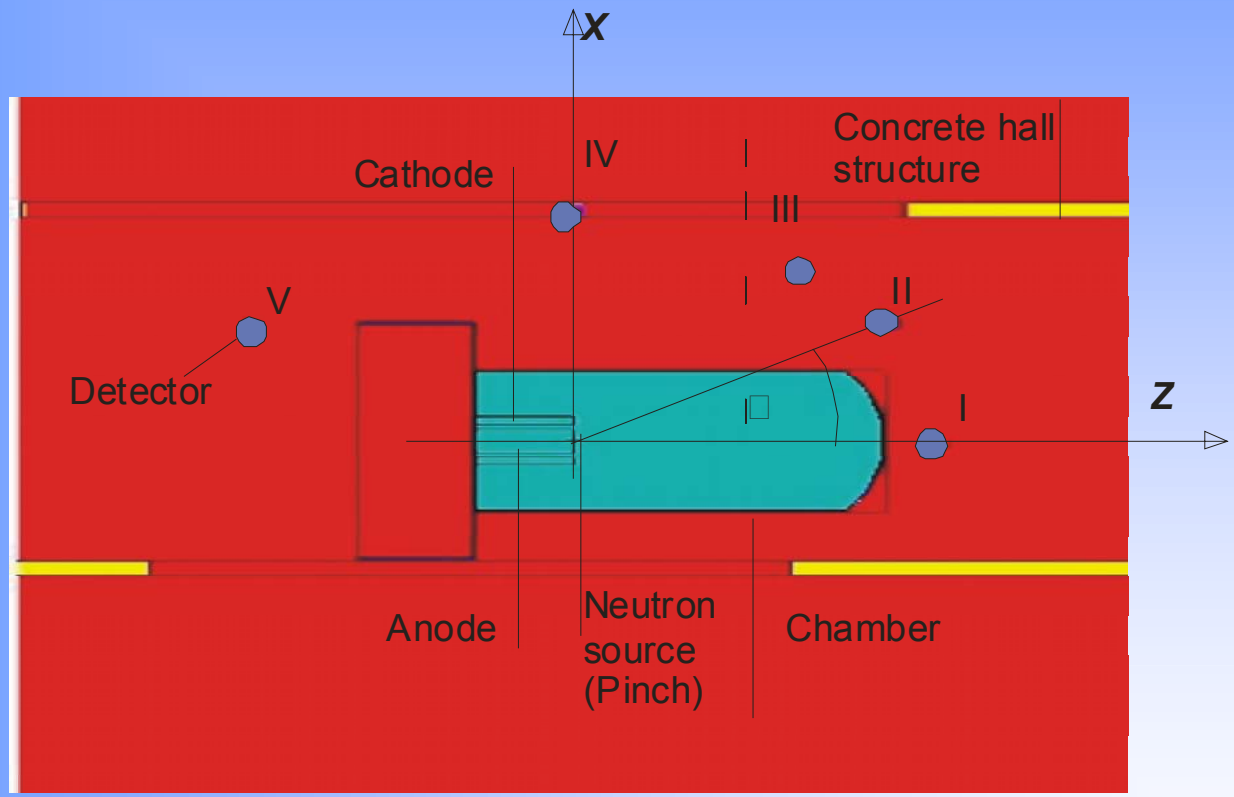
Beam divergence at 1053 nm (ful angle @ 1/e2) < 0.25 mrad

Beam diametr 12 mm

16 frames, 60 ns between frames

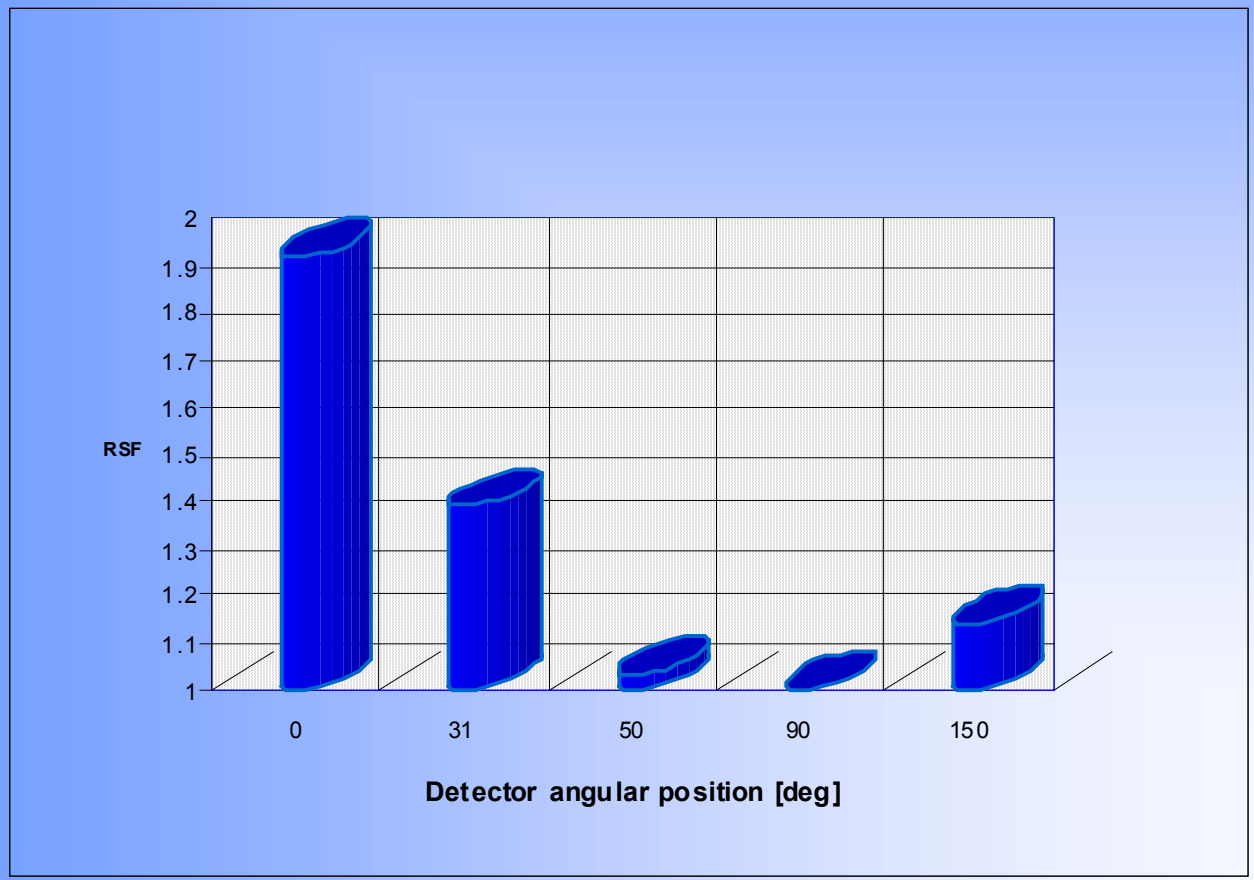

Obudowa licznika scyntylacyjnego-wersja 08
ow-07
Wkręt M6x16
Rura osłonowa
Rura ø416x1.5
75
Węglik boru
13,95kg
Parafina
50,6kg
Opaska technologiczna
Taśma stalowa-1,5mm
75
25
Sonda scyntylacyjna prod. ACS
ø46
Parafina
3,31kg
Węglik boru
1,96kg
Ołów 1,5cm
(3x po 5mm)
Ołów 1,5cm
(folia 1mm)
"Szpulka" stalowa
Rura øwew 175x1,5
Ołów 1,5cm
(3x po 5mm)
pianka poliuretanowa
pianka poliuretanowa
503
Węglik boru
2kg
709
0
50
100
150
200
250
300
F/PP-1000/Liczniki ACS.dwg

Cut view of MCNP geometry of PF-1000 facility.



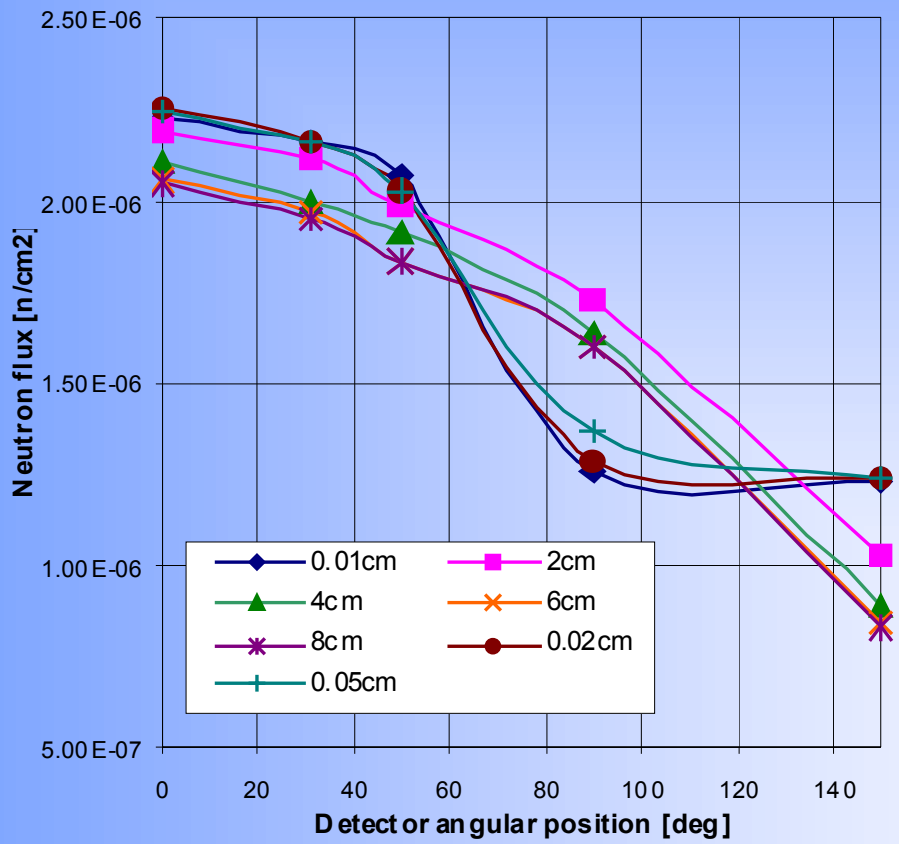
RSF (Response Scaling Factor) as a function of detector angular position.

RSF =Response(2.5 MeV source) / Response(Am-Be source).



Institute of Plasma Physics and Laser Microfusion
Warsaw, Poland

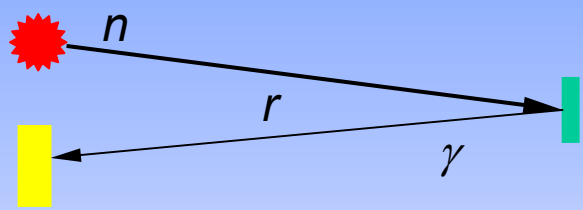
Thermal neutron flux as a function of detector position calculated for point 2.5 MeV neutron source located on ‘Z’ axis and distanced 0.1, 0.2, 0.5, 2, 4, 6 and 8 cm from the anode



Institute of Plasma Physics and Laser Microfusion
Warsaw, Poland

Idea of the method

Fast neutron interactions



(n,n'γ) $t_{ch} \sim 10^{-12}$ s

$$F = \frac{MN_A}{A} \cdot \langle \sigma\Phi \rangle \cdot (a\psi)$$

$$Y = \frac{MN_A}{A} \cdot \langle \sigma\Phi \rangle$$

(n,γ), (n,n'), (n,2n)

(n,p), (n,α), (n,β)

$T_{1/2}$ s

$$A_0 = \frac{MN_A}{A} \cdot \langle \sigma\Phi \rangle \cdot (a\psi)\eta\left(1 - e^{-\lambda T}\right)$$

$$\langle \sigma\Phi \rangle = \int \sigma(E)\Phi(E)dE$$

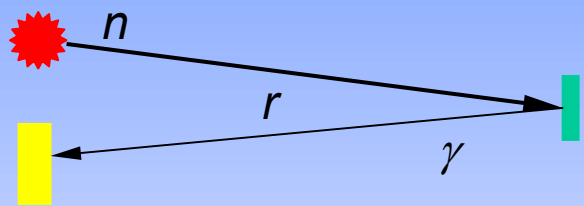
Institute of Plasma Physics and Laser Microfusion
Warsaw, Poland

Procedure of calibration

1. $\langle \sigma\Phi \rangle = \dfrac{A_0}{(a\psi)M(N_A/A)\eta(1-e^{-\lambda T})}$

Calibration source with defined S

$$S = \frac{\langle \sigma(E)\Phi(E) \rangle_{\exp}}{K_{\exp}}, \left[\frac{n}{s}\right]$$



2. MCNP modelling including:

defined calibration source;

all masses surrounding the source;

defined samples

$$S = \frac{\langle \sigma(E)\Phi(E) \rangle_{cal}}{K_{cal}}, \left[\frac{n}{s}\right]$$

3. MCNP modelling including:

DD neutron source (plasma) Y_n;

all masses surrounding the source;

defined samples

$$Y_n = \frac{\langle \sigma(E)\Phi(E) \rangle_{DD}}{K_{DD}}, \left[\frac{n}{s}\right]$$

Neutron Activation Diagnostic

New Foil Project

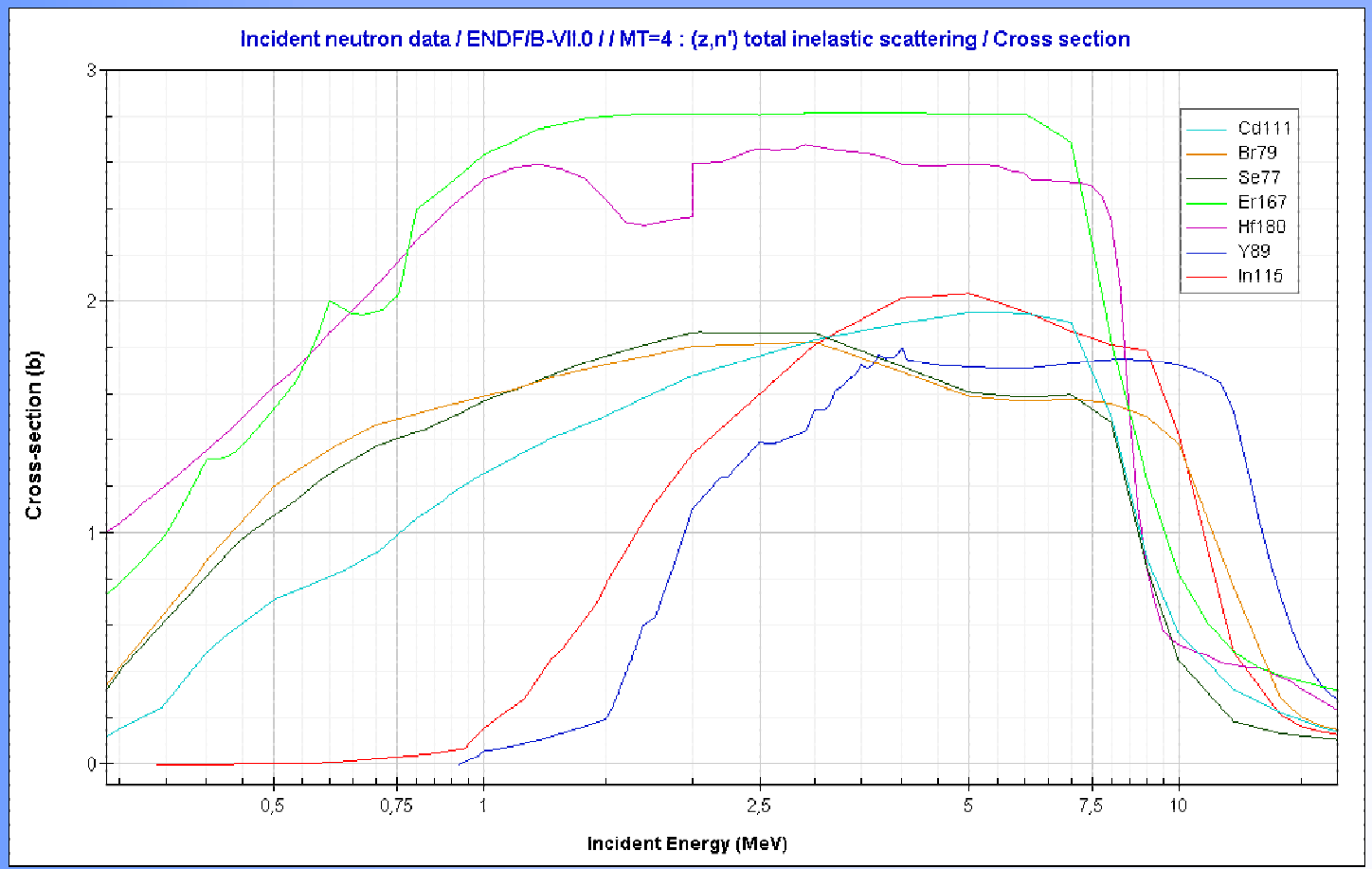
***1**.Selection of an appropriate set of neutron activation foils, depending on the anticipated measurement conditions.*

Reaction	Eγ [keV]	Max γline En. Effic (C19 cal)	Daughter $T_{1/2}$	$\sigma_{2.45}$ [barn]	Parent abundance ratio (Θ)	Sensitive for thermal neutrons (S_{th})	Relative mass ratios				
^{27}Al (n,γ) ^{28}Al	**1779(1)**	**0.6 •10^{-3}**	**2.2 m**	**0.4**	**1**	**Yes**	**20%**	**37%**	**18%**	**22%**	**27%**
^{27}Al (n,p) ^{27}Mg	844(0.718), 1014	1.6 •10^{-3}	9.5 m	1.5E-5	1	No					
^{180}Hf (n,n') ^{180m}Hf	**215, 332(0.941), 443, 501**	**4.4 •10^{-3}**	**5.5 h**	**2.7**	**0.3508**	**No**	**20%**	**0%**	**18%**	**0%**	**26%**
^{180}Hf (n,γ) ^{181}Hf	133, 346, 482(0.805)	2.9 •10^{-3}	42.4 d	0.03	0.3508	Yes					
^{111}Cd (n,n') ^{111m}Cd	**151, 245(0.94)**	**6.2 •10^{-3}**	**48.5 m**	**1.76**	**0.128**	**No**					
^{116}Cd (n,γ) ^{117}Cd	273(0.279), 344, 1303	5.5 •10^{-3}	2.5 h	*0.01*	0.0749	Yes	**36%**	**0%**	**33%**	**40%**	**48%**
	1066, 1997(0.262)	0.6 •10^{-3}	3.4 h	*0.01*		Yes					
^{89}Y (n,n') ^{89m}Y	**909(0.9916)**	**1.4 •10^{-3}**	**15.7 s**	**1.12**	**1**	**No**	**24%**	**43%**	**21%**	**26%**	**0%**
^{77}Se (n,n') ^{77m}Se	**162(0.53)**	**9.5 •10^{-3}**	**17.36 s**	**1.87**	**0.763**	**No**	**0%**	**8%**	**4%**	**5%**	**0%**
^{79}Br (n,n') ^{79m}Br	**207.2(0.76)**	**7.4 •10^{-3}**	**4.86 s**	**1.82**	**0.5069**	**No**	**0%**	**12%**	**6%**	**7%**	**0%**

Institute of Plasma Physics and Laser Microfusion
Warsaw, Poland

Neutron Activation Diagnostic

New Foil Project



Institute of Plasma Physics and Laser Microfusion
Warsaw, Poland

Neutron Activation Diagnostic

New Foil Project

2.*New germanium detector provides the increasing high energy resolution and high efficiency measurement of the full energy peaks for multi-elements sample.*

To use IPPLM's HPGe detector (35% 'effectivnes', coaxial, pre-calibrated)

3.*Fast neutron spectrum unfolding method using activation measurements. The method is based on the procedure of minimize following functional:*

$$J_x[\varphi(E)] = \int_0^\infty [\varphi(E) - \varphi_0(E)]^2 \cdot \sigma_x^{\,2}(E) \cdot dE$$

for given reaction type – x, where $\varphi_0(E)$ is a first step approximation of the spectrum, which was obtained from another procedure (e.g. MCNP modelling, TOF)