

Neutron Emission at the Z-pinch Discharges

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Contents

- experimental results at Z-pinches
- today overview of theory and simulations
- future possibilities of Z-pinches
- results at PF-1000
- results at S-300
- results at PF3
- plans for 2007

Today strategy of USA for next 20 years

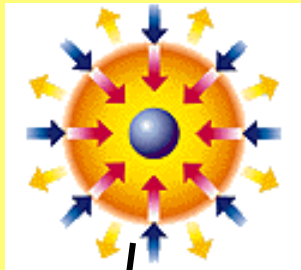
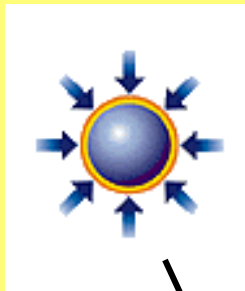
basic research before 2024:

- tokamak ITER (5 milliards \$) ignition after 2020
- ICF NIF, (30 milliards \$), Franc, ignition after 2010
- z-pinch – ZR, ZX, X1 (2 milliards \$) Bajkal, ignition ?

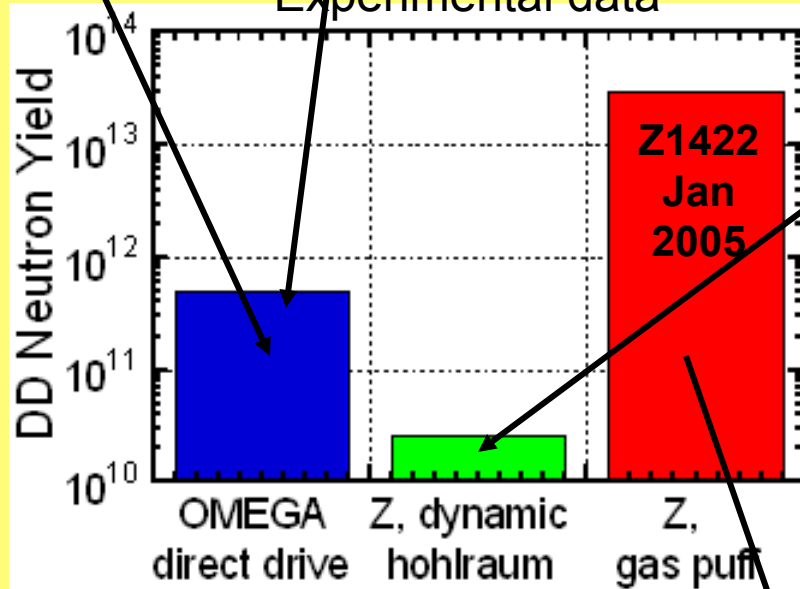
after 2024 development of fusion reactor

Russian strategy – z-pinch external neutron source for fission reactor

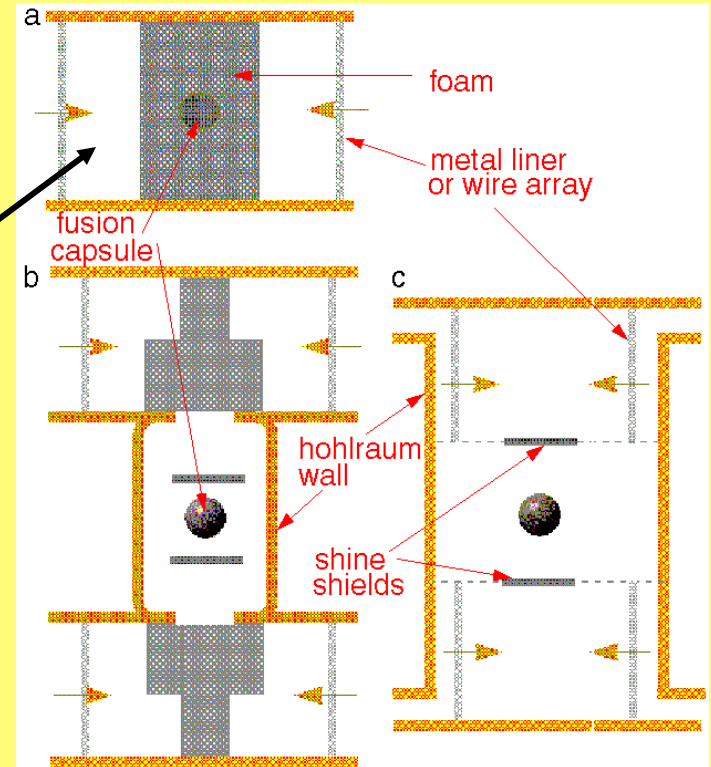
Today's records of ICF (2005)*



Experimental data



New world record for x-ray drive DD*



2004 – 6 shots; 2005 – 3 shots
isotropic distribution of neutron energies

*Cuneo, "Inertial Confinement Fusion with Z-Pinches", ICOPS2005 – Minicourse on the Physics of Z-Pinches, June 18-19, 2005, Monterey, CA

* Velichovitch, DZP Oxford, 2005

Table of neutron yield at the different devices (D-D)

device	record shot	load	plan
JET	10^{14} (10^{16})	gas 10^{20} m^{-3}	
ITER		gas 10^{20} m^{-3}	10^{16} (2021)
W-7		gas 10^{20} m^{-3}	10^{12} (2013)
Z-device D (18 MA)	5×10^{13}	gas-puff	
ZR D (27 MA)		gas-puff	3×10^{15} (2007)
Angara 5 (3 MA)	10^{12}	gas-puff	
PF-1000 (1.5 MA)	$2 \cdot 10^{11}$	gas 10^{24} m^{-3}	
S-300 (1.5 MA)	2×10^9	solid $(\text{CD}_2)_n$ 10^{25} m^{-3}	gas-puff
OMEGA	$5 \cdot 10^{11}$	cryogenic	
NIF		cryogenic	$10^{16} - 10^{17}$ (2010)
ZX (50 MA)		gas-puff	4×10^{16} (2015)

Theory and simulations

1. Velikovich A. et al, *Naval Research report Laboratory, Report 20060425234*

1998 Saturn SNL CD₂ liner 10¹⁰, and 10¹² with gas-puff r- and z- isotropy – thermal?

2005-06 Z 6x10¹³, B-T or thermonuclear ? simulations and theory both

Thermonuclear - * adiabatic compression 10⁶ m/s, Ti 10 keV, Te 1-2 keV, till 10 ns no relaxation

$$Y = \frac{1}{4} n_i^2 \langle \sigma v \rangle \pi R^2 l \tau$$

R₀/R = 10, n_i = 3x10²⁰ cm⁻³, R = 4 mm, l = 2 cm, τ = 4 ns. Y_n = I⁴.

2 problems – isotropic v, time of generation of high-energy tail.

Beam target - path of deuterons before fusion:

For n_i = 3x10²⁰ cm⁻³ a E_d 0,1-1 MeV l = 1900 – 430 μ ⇒ N_{FD} = 10⁴ N_N, I = 100 MA

Influence of B! ⇒ fast deuterons 7-9%, 50-70 kJ, $\frac{1}{\sigma(E) n_i} I^4$. Very promising results!

Nedoseev is pessimist in z-pinch fusion, he believe to system beam-target + dense D target

Vichrev is optimist, he believe into intense high-energy tail of Maxwell distribution

Problems of thermonuclear z-pinch reactor

problems of heating of ions and electrons – relaxation time, fusion ions

Conclusions

Z-pinch – effective source of fusion neutrons

ZR (2007) $\nu_{DD} 3 \times 10^{14}$, $\nu_{DT} 10^{16} - 10^{17} \text{ N}$ - promised for fission reactor and source of 10% of SXR, IONS or HXR 10-20 keV and Z-pinch fusion reactor –

Thermonuclear - ? fusion ions heated mainly electrons, ions only in 20 %
ICF with SXR, HXR, ion beams; more effective than NIF

Today's experiments about origin of neutrons:

temporal evolution of energy distribution of neutrons

mechanism of acceleration of high energy electrons and deuterons

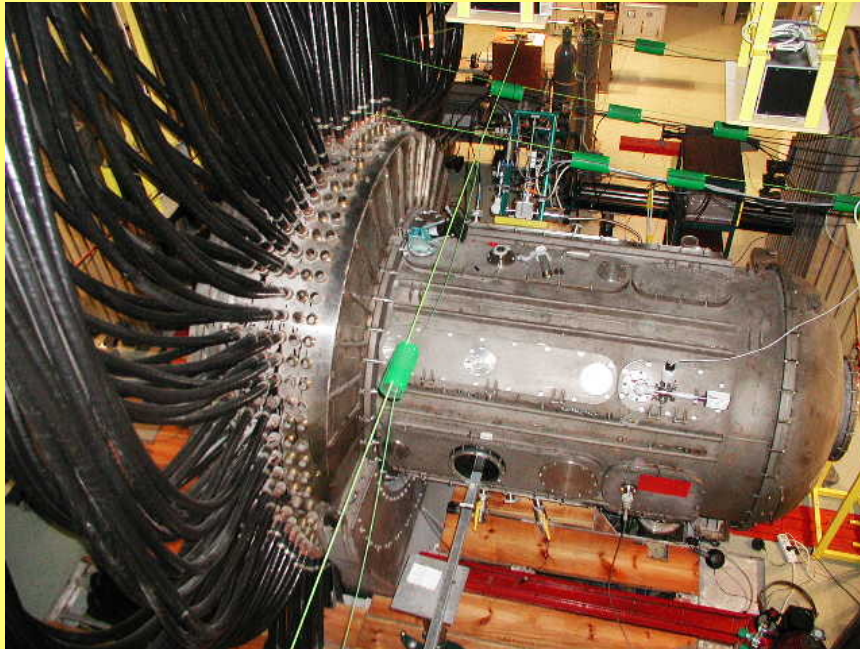
origin of part of thermal neutrons in Z-pinch

possibility of heating the target with fast deuterons of beam-target origin

PF-1000 IPPLM Warsaw, Poland

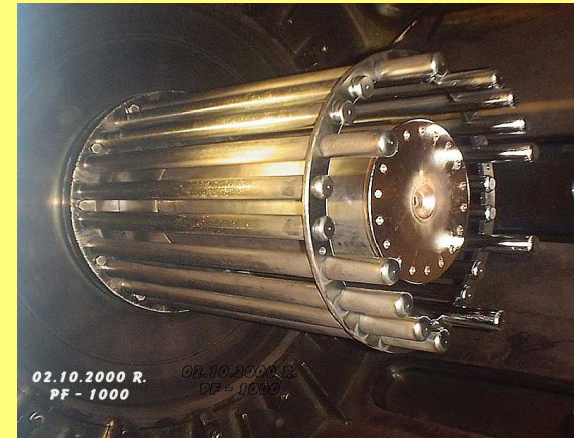
2 MA, 400 kJ, D-D reaction, D₂ gas

facility



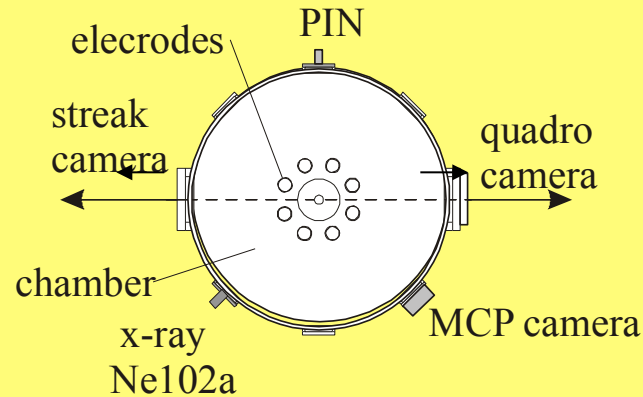
- volume ~ 3.8 m³
- $\varnothing = 1.4$ m
- L = 2.5 m
- energy 300-400 J

electrode system

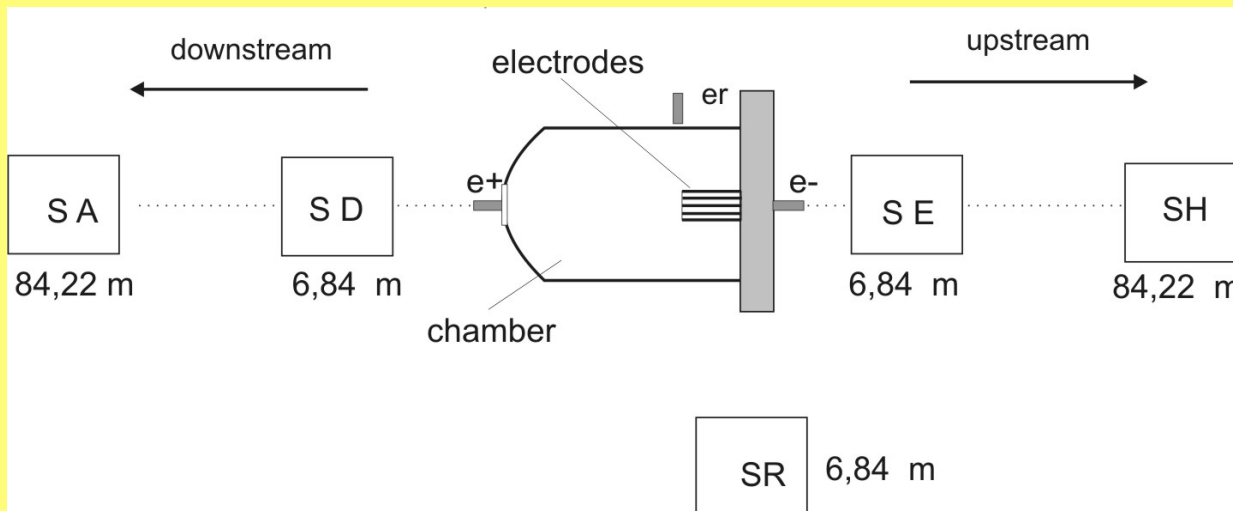


- 8 rods
- $\varnothing a = 230$ mm
- $\varnothing c = 400$ mm
- L = 600 mm
- energy 300-400 J

Scheme of neutron diagnostics with temporal and energy distribution



radial scheme



axial scheme

**10 hard X-ray and neutron scintillation detectors
+ 2 Cerenkov detectors for electrons**

Temporal evolution of neutron energies

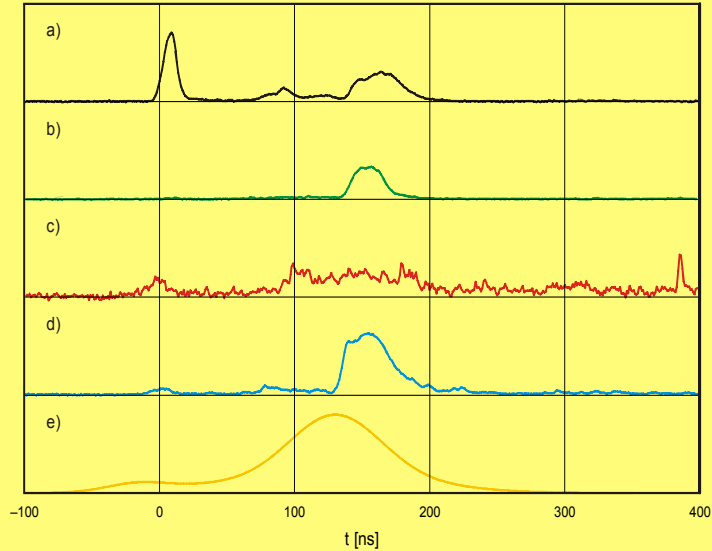
P. Kubes et al, IEEE Transactions on Plasma Science

Vol. 34, No. 5, Part 3, 2349-2355

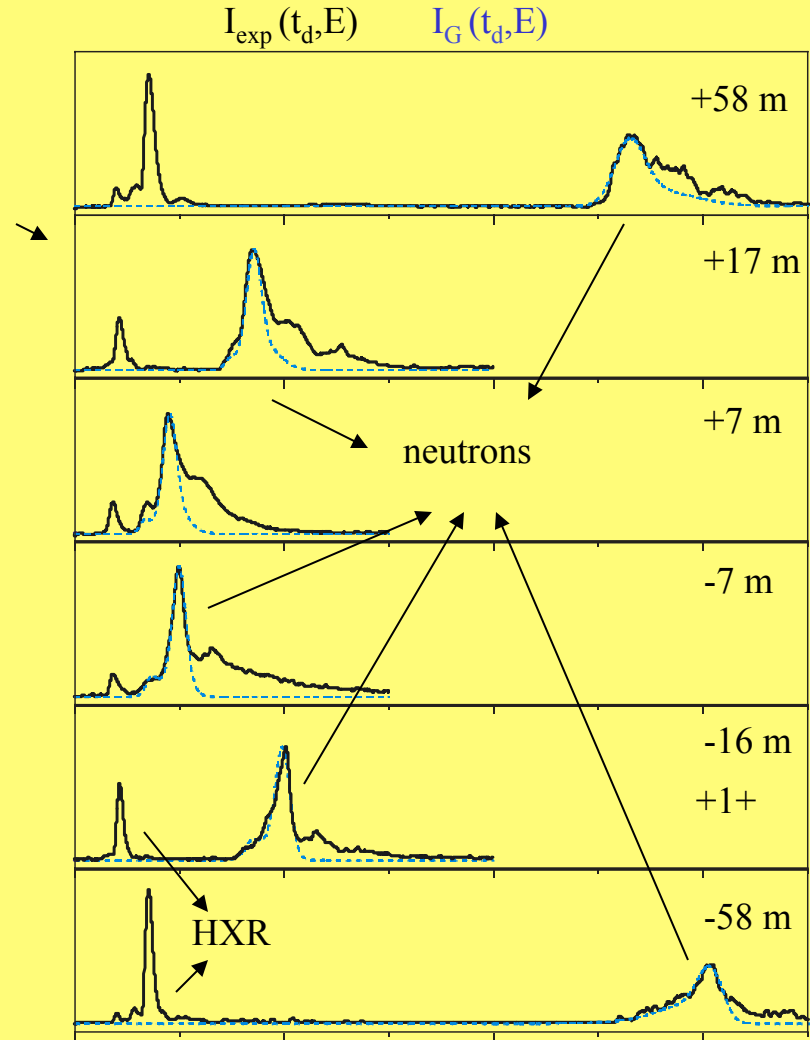
steps:

- 1) time-of-flight and MC simulations $I_{\text{TOF}}(t_0, E)$
- 2) estimations of Gaussian distribution of $I_G(t_{0i}, E_i)$, $i=1, \dots, 4$
- 3) reconstruction $I_G(t_d, E)$ and comparison with $I_{\text{exp}}(t_d, E)$

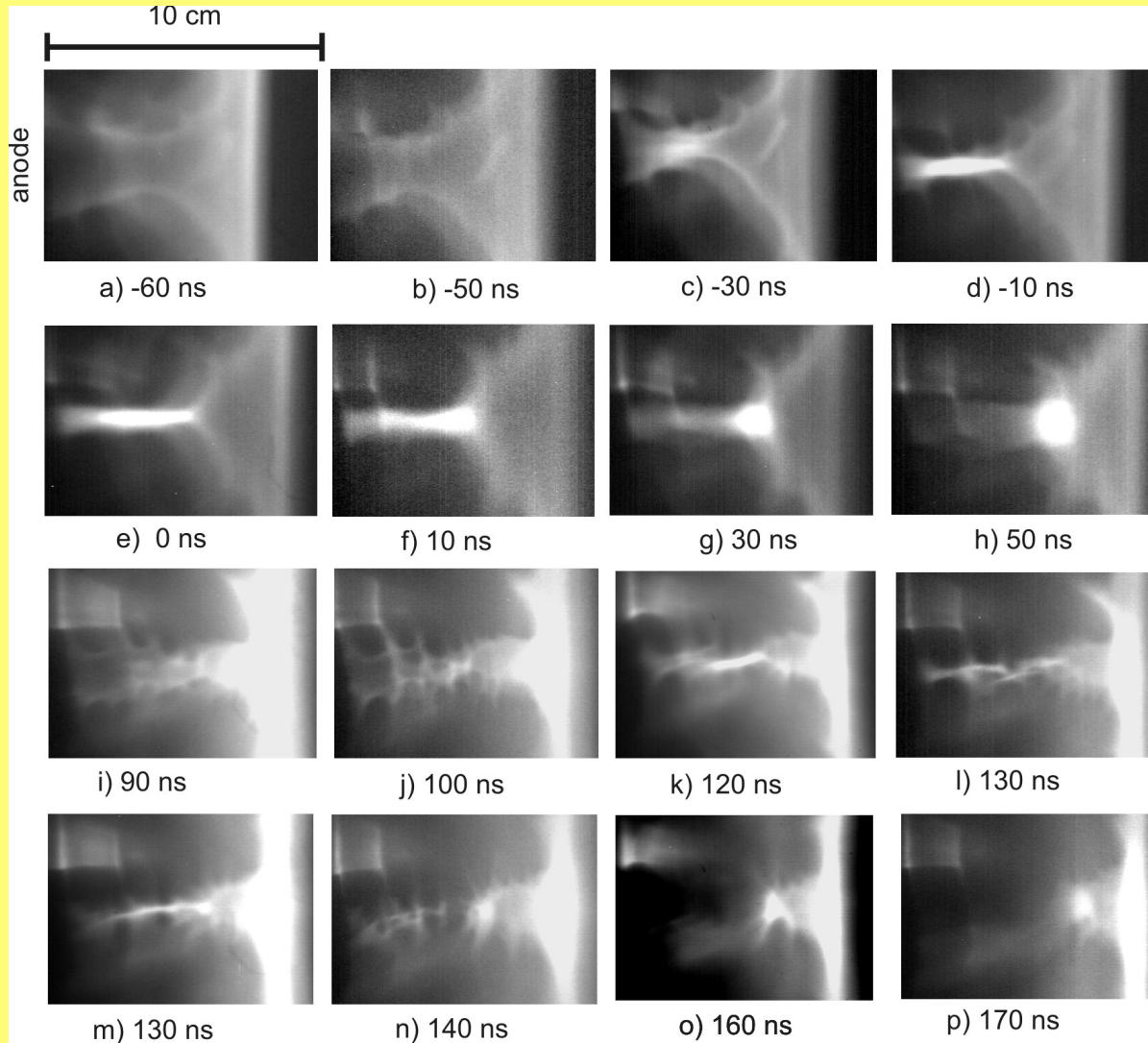
shot 5566



SXR
 e^-
 e^+
HXR
neutrons

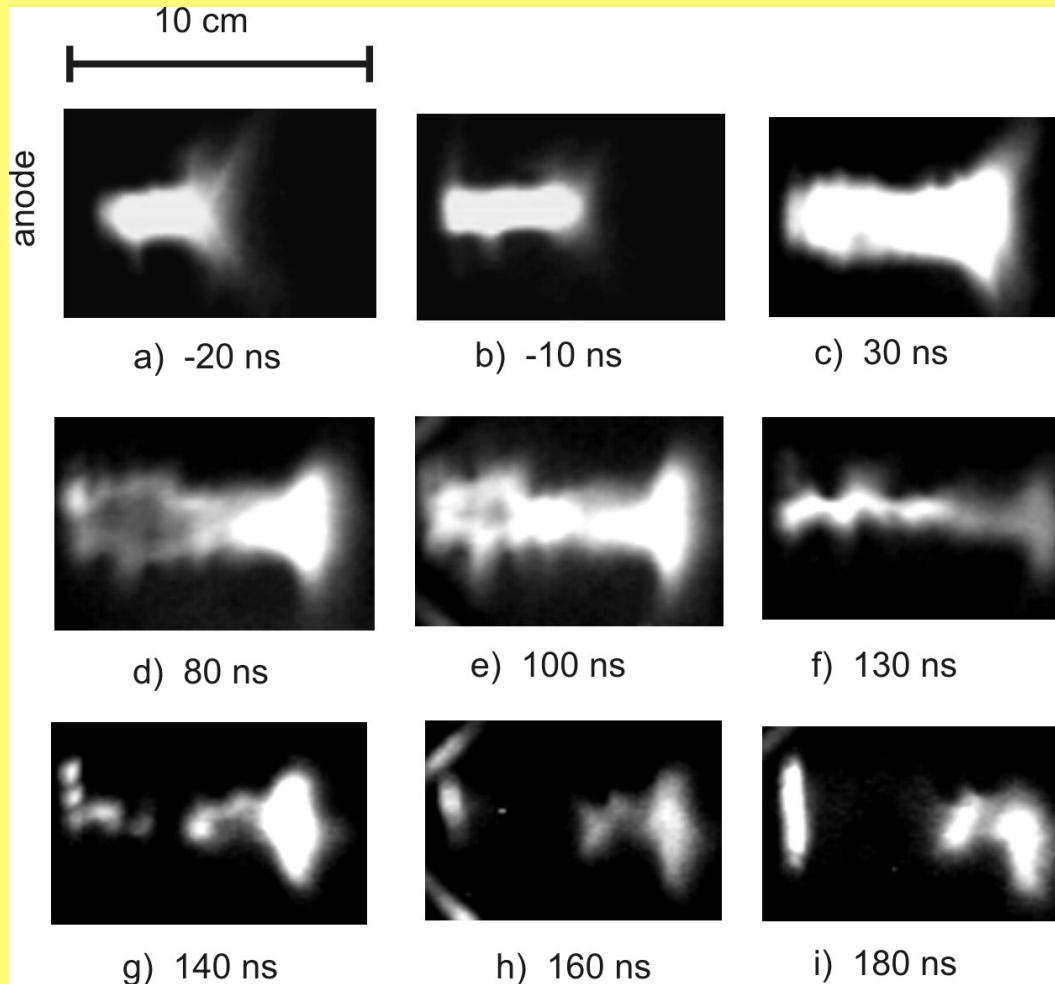


Visible frames - exposure time 1 ns, window 589 nm



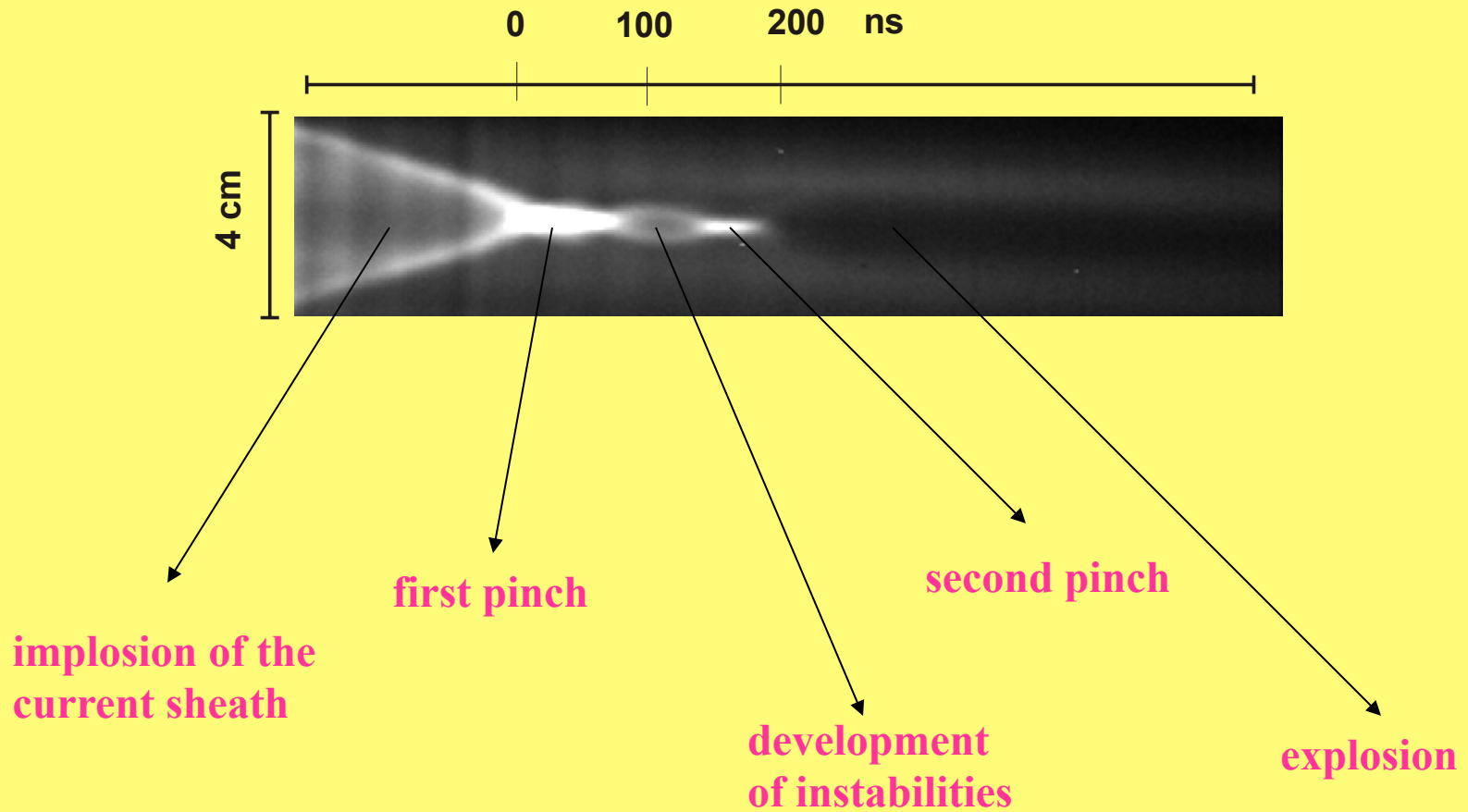
(a-d) imposition $2 \times 10^5 \text{ m/s}$
(e) minimum radius $t=0$
intense light - dense plasma
dense zipper-effect (c-g)
R axial velocity $3 \times 10^6 \text{ m/s}$
L axial velocity $1 \times 10^6 \text{ m/s}$
dense spherical structure
(g-p) instabilities
second pinch (j-m)
second explosion (m-n)
second dense form (m-p)

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



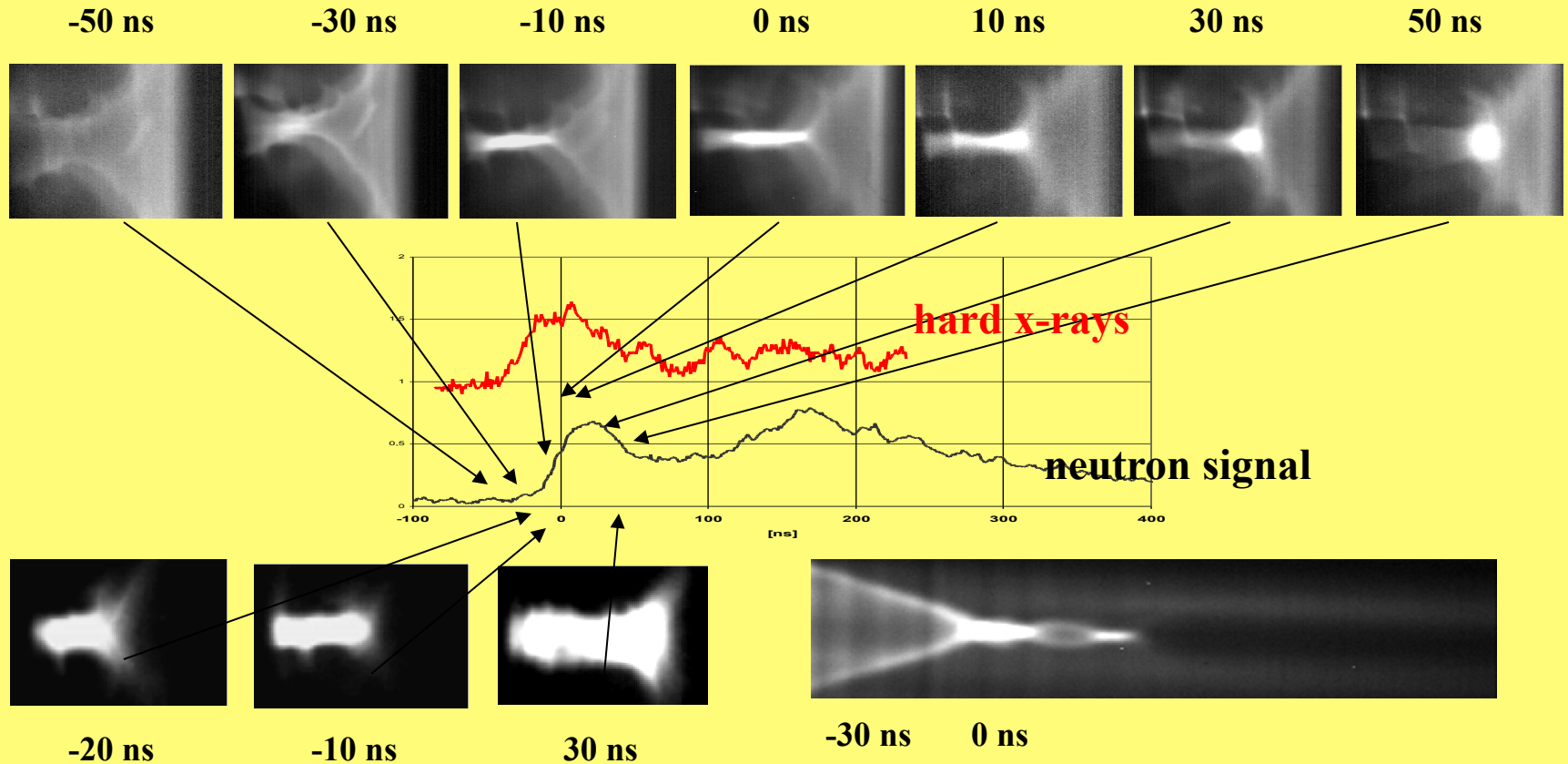
(a-c) pinch Φ 1-2 cm
(d-f) second pinch
(g-i) explosion, dense structure

visible streak-camera



correlation neutrons with frames and laser images

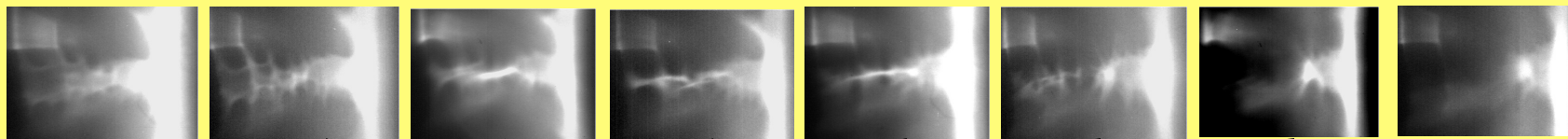
first neutron pulse



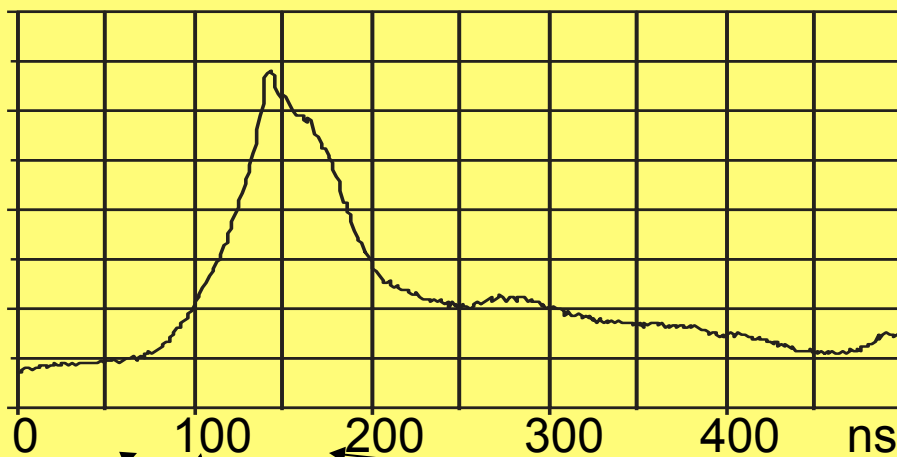
onset of neutron pulse – zipper effect, monoenergetic A-C deuterons
decrease of neutrons – dense structure, isotropic distribution in z-direction

correlation neutrons with frames and laser images

80 ns 100 ns 120 ns 130 ns 130 ns 140 ns 160 ns 180 ns

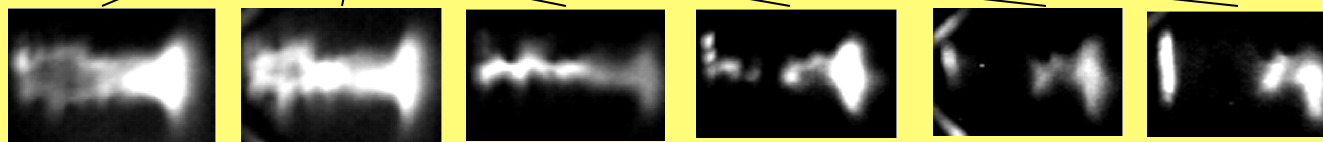


visible



neutron signal

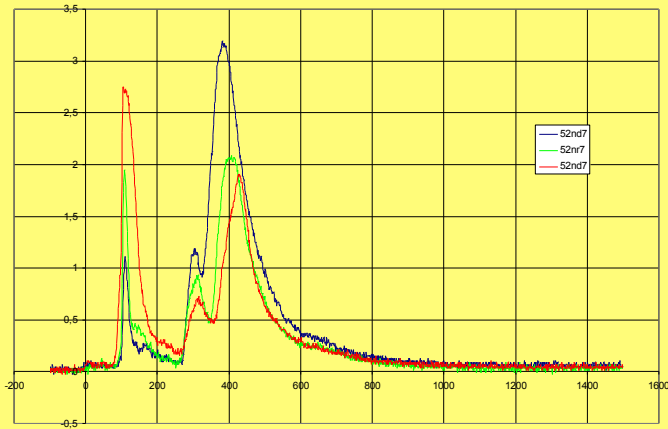
XUV



80 ns 100 ns 130 ns 140 ns 160 ns 180 ns

onset of neutron pulse – instabilities, beam-target + 3.0 MeV
final phase of neutron pulse – isotropic distribution - 2.6 MeV

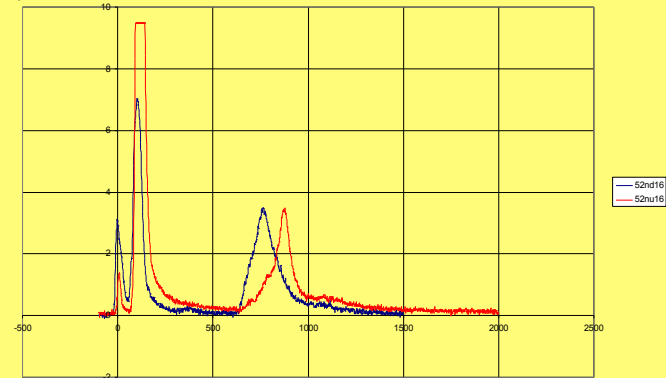
results 2006



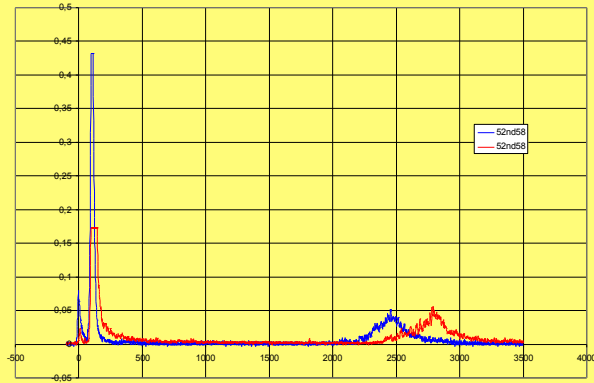
7 m

decrease of energy b-t neutrons in

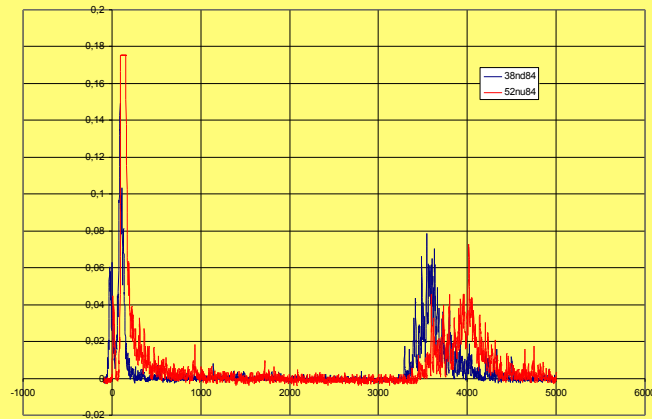
+



16 m



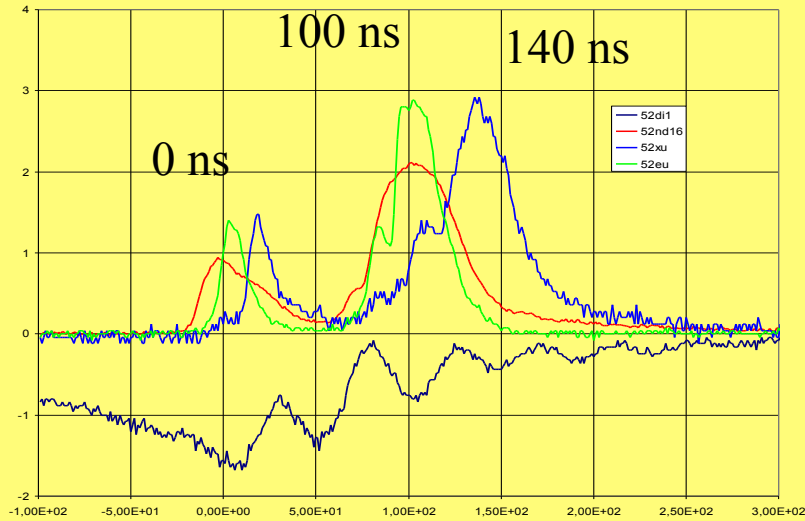
58 m



84 m

First neutron pulse – first -, later bt, last isotropic (thermal) neutrons

Shot 6552 - signals



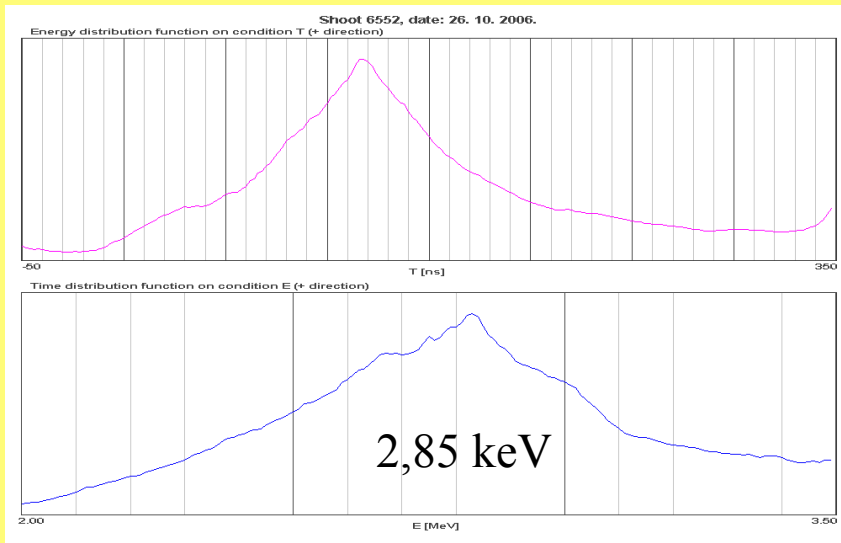
e-

HXR

XR 7keV

dI/dt

118 ns

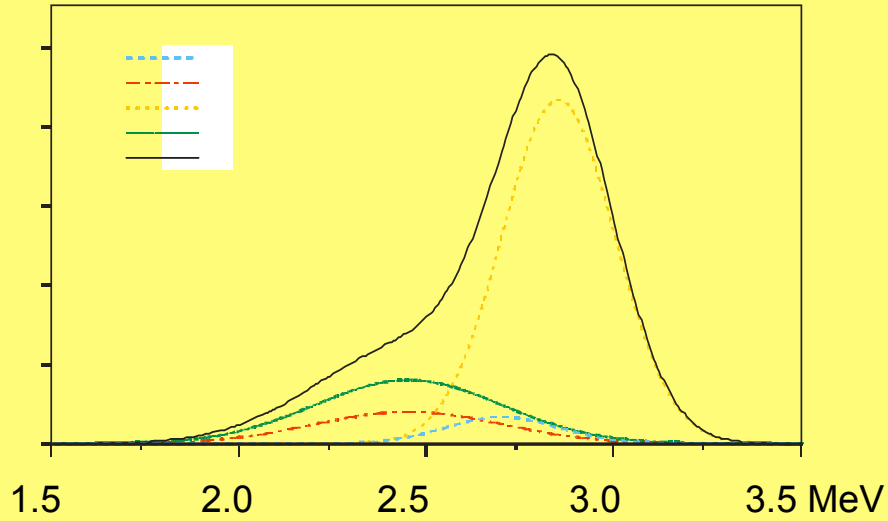


t neutrons

E neutrons +

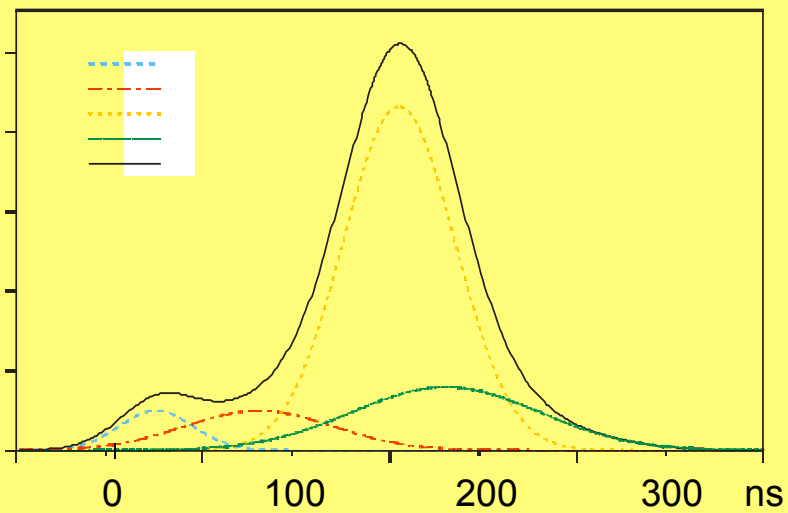
neutron source function

optimization $I_G(t_0, E)$



$I(E)$ energy distribution (+)

shot 5566



$I(t)$ temporal distribution

Conclusions for PF-1000

neutrons and fast electrons are produced after the pinch phase during development of instability (second pinch and forming of dense structures)

the initial anisotropy of neutrons 70% → A – C deuterons 100-200 keV

final isotropy distribution of energies 30%

time delay between hard X-rays and neutrons to 20-30 ns:

neutrons after hard X-rays – 70%

neutrons and hard X-rays – together 25%

neutrons before hard X-rays – 5%

profile of neutron pulse may be quite different from the profile of the hard X-rays

*** acceleration of fast electrons and deuterons – ? 2 independent mechanisms of release of pinch energy**

correlation of the neutron pulse with development of $m=0$ instability (second pinch and formation of dense structure in a heel of the current sheath)

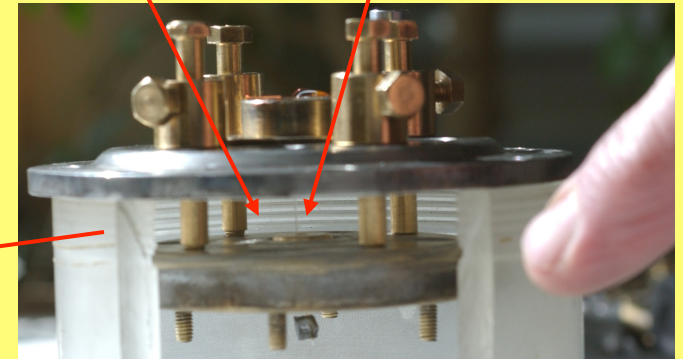
high neutron anisotropy, high deuteron energies, non-equilibrium X-ray emission → **beam-target origin of neutrons**

Origin of neutron with isotropic distribution – thermal or \pm , or isotropic beam-target ?

S-300 Kurchatow Institute Moscow, Russia

2 MA, 400 kJ, D-D reaction, CD₂ fiber + W wire array liner

conical W wire array (1x1 cm, 40 wires Φ 6 μ m)
+ CD₂ fibre Φ 80-120 μ m



D – 10% of mass, 60% of particles

Axial and radial scheme of diagnostics

hard-X and neutron
scintillator 2.55 m

fast electrons

anode

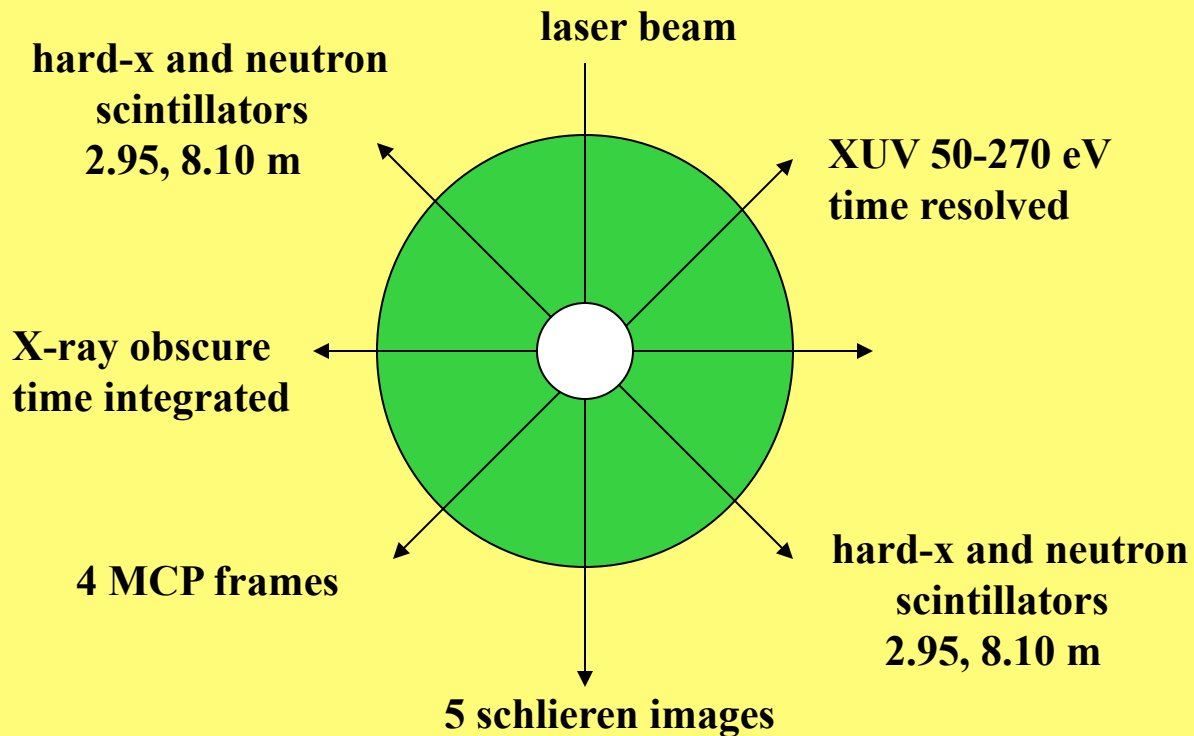


cathode



hard-X and neutron
scintillators
2.55 m, 4.42 m

7 HXR and neutron scintillators



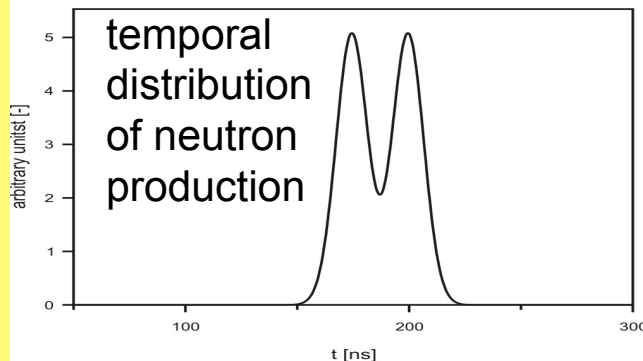
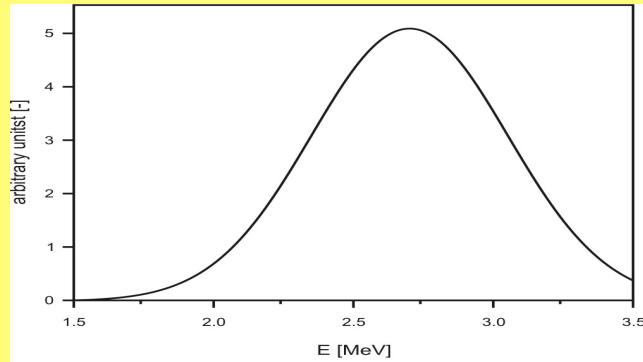
neutron yield – absolute calibrated scintillator

Time-of-flight and MC methods and reconstruction of neutron source function

Shot 0506152

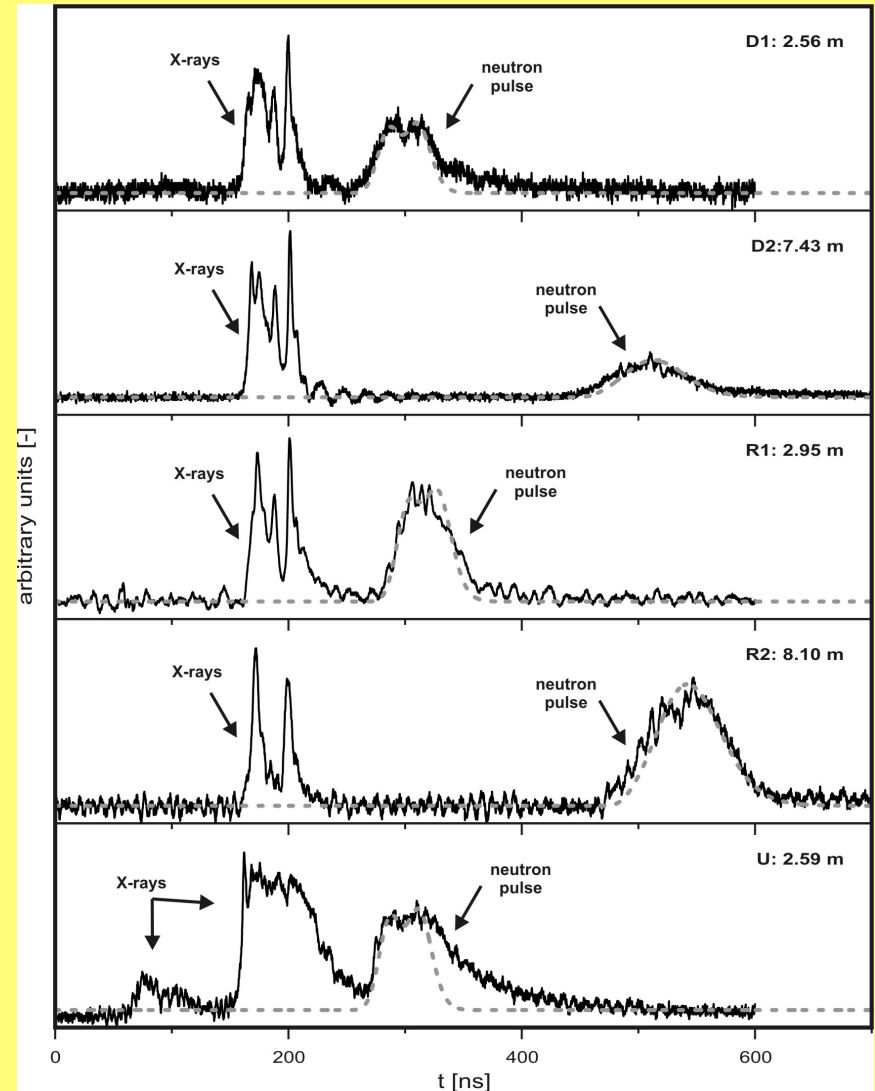
Gaussian independent distribution of energies and time of production

neutron energies



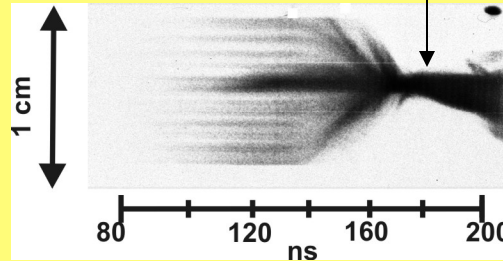
neutron energy peak 2.75 MeV is considerably above 2.45 MeV in all directions!

recorded and calculated neutron signals

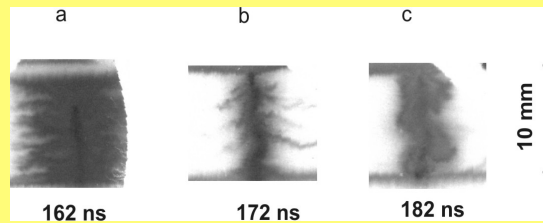


Shot 050615-2

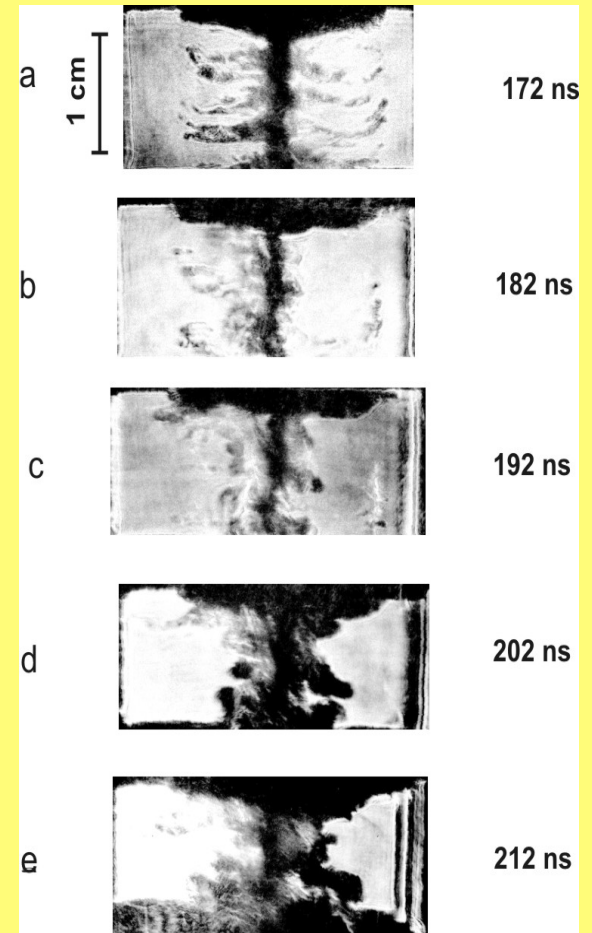
$v = 10^5$ m/s



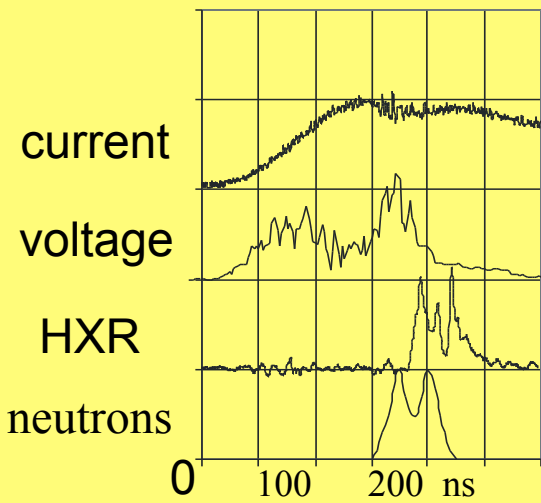
streak camera



XUV frames



laser shadows

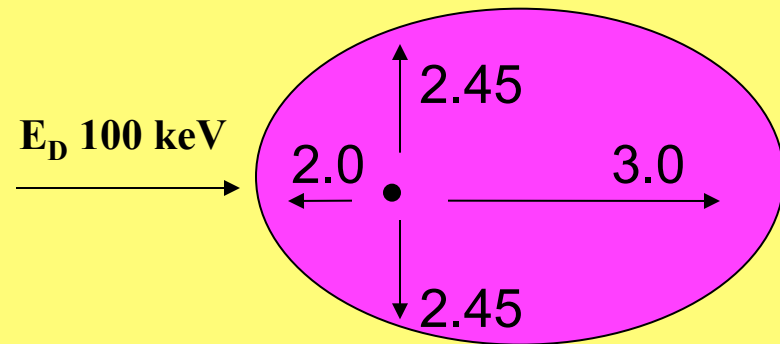


oscillogram

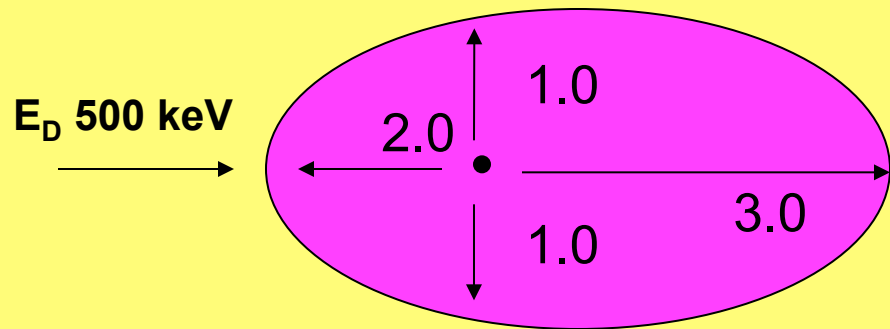
neutron production 170 – 220 ns

Angular dependance of the neutron production

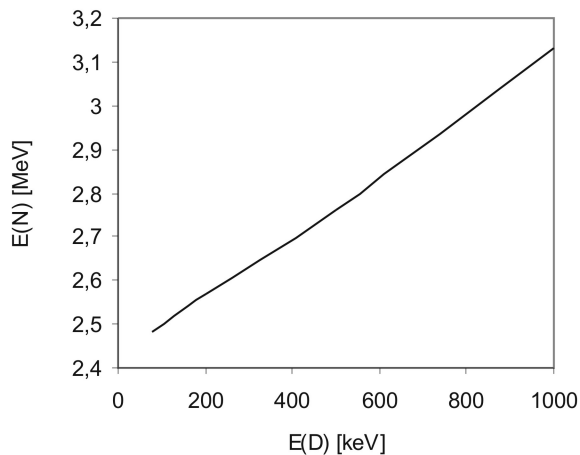
2 reason for neutron energy above 2.45 MeV



angular anisotropy of neutron energy



angular anisotropy of cross section at DD reaction

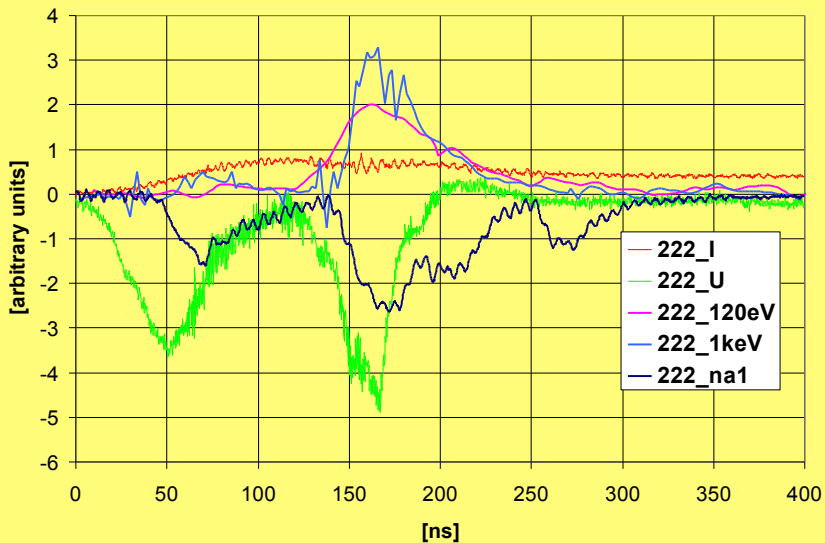


Dependence of the mean value of the neutron energy on the energy of deuterons with isotropic distribution

Results 2006

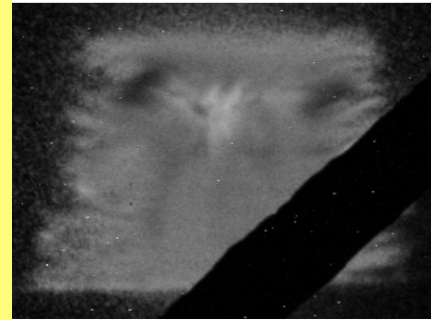
conical liner Φ 8, 12 mm
60 tungsten wires $6\ \mu\text{m}$
 CD_2 fiber $100\ \mu\text{m}$

8 scintillation detectors –
3 axial and 5 in radial directions

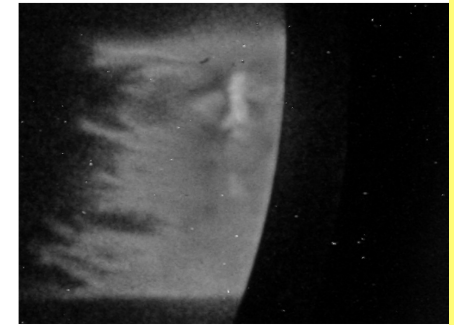


S-300 shot 0609222

C

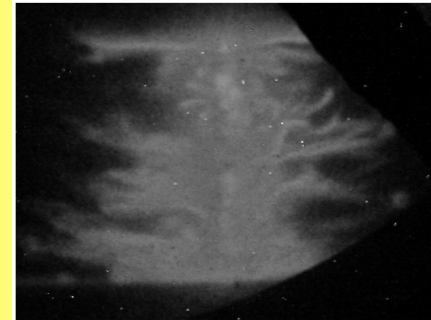


152 ns



157 ns

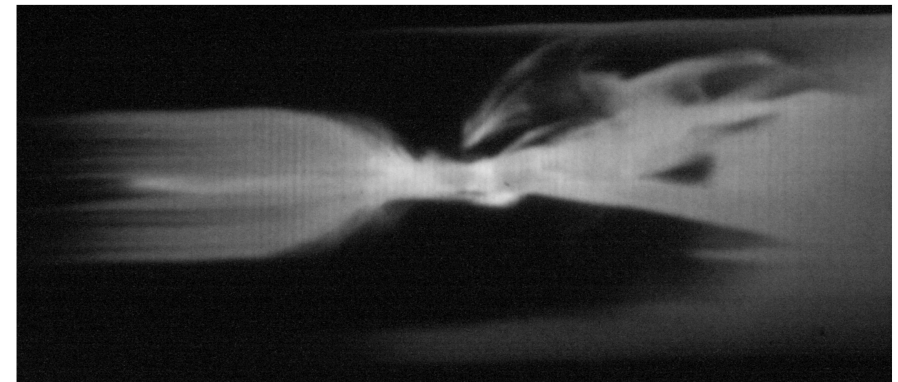
A



162 ns



172 ns



mcp is filtered with mylar $3\ \mu\text{m}$

Conclusions for S-300

temporal evolution of energy distribution of neutrons

supposing Gaussian distribution $t, E \rightarrow$

energy PF – initial dominant regimes a-c direction 1.9-3.3 MeV,

- final isotropic 2.45 MeV,

Z-pinch - more directions 2.6-2.8 MeV

conical wire array – expressive axial anisotropy, weaker radial anisotropy

time of neutron generation - after pinch phase, at the evolution of instabilities probably in localities with dense plasma

time delay between hard X-rays and neutrons:

neutrons after hard X-rays – 70%

neutrons and hard X-rays – together 25%

neutrons before hard X-rays – 5%

profile of neutron pulse may be different from the profile of the hard X-rays

* **acceleration of fast electrons and deuterons** - 2 independent mechanisms of release of pinch energy due to reconnection of internal magnetic fields

high neutron anisotropy, high deuteron energies, non-equilibrium X-ray emission

→ **origin of neutrons is non-thermal, beam-target**

Russian Research Center, Kurchatov Institute Moscow

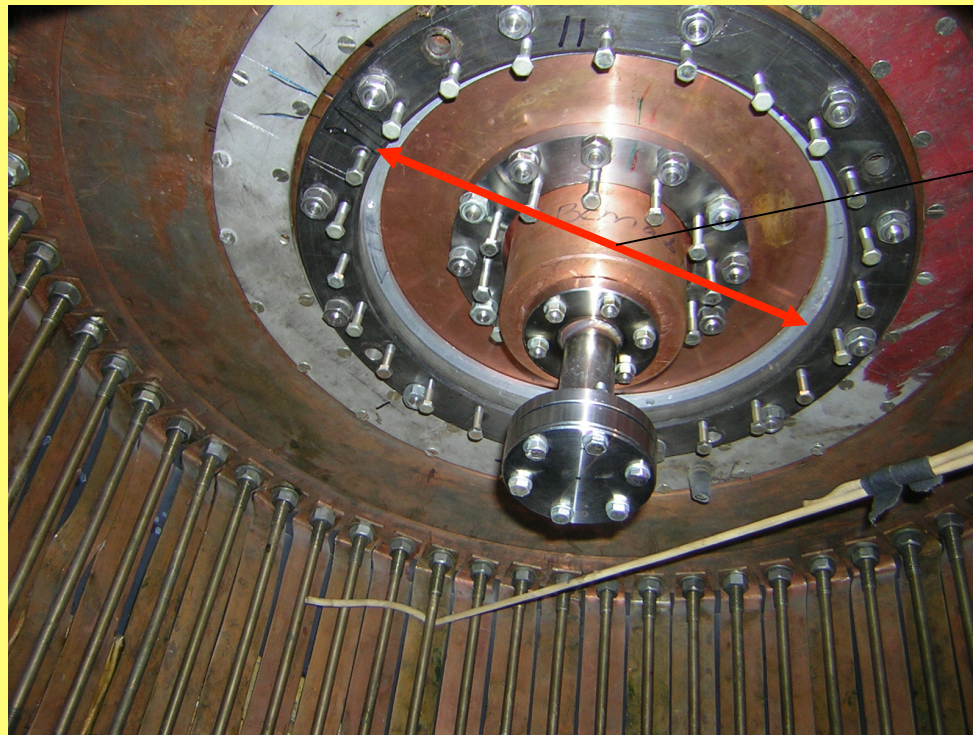
PF-3, 3 MA, 15 μ s

M.A.Karakin, E.Yu.Khautiev, V.I.Krauz, A.N.Mokeev, V.V.Myalton, V.V.Vinogradov

RRC "Kurchatov Institute", Nuclear Fusion Institute, 123182 Moscow, Russia

V.Ya.Nikulin, A.V.Oginov, I.V.Volobuev

Lebedev Physical Institute RAS, Moscow, Russia

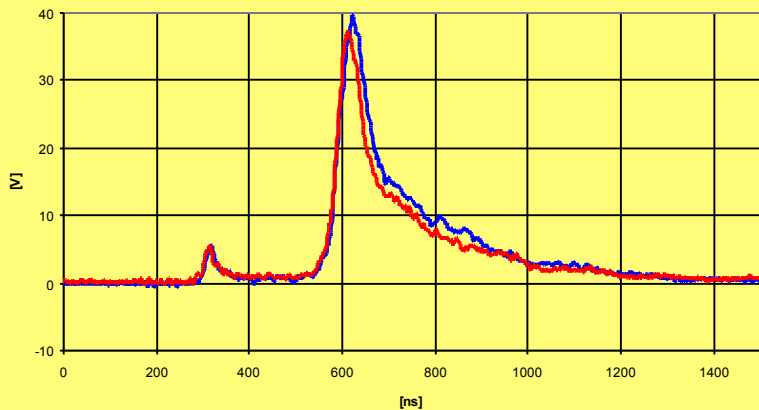


Anode units

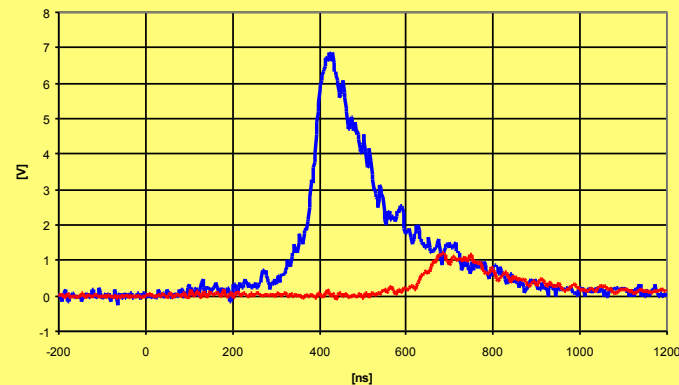
PF-3, 3 MA, December 2005

CD₂ fibre Φ 100 μ m, 7 cm length, Ne, A current-sheath 400 Pa

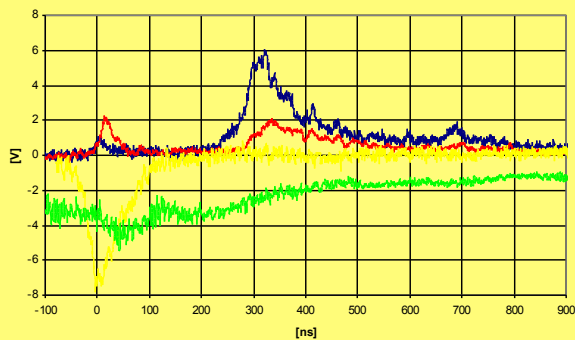
Shot 05112905



comparisson of both detectors



Signals of two radial detectors
blu 620 cm, red 1290 cm



radial neutrons
axial neutrons
pin signal
current derivative

Shot 05120634

Results at PF-3

- 5 shots in Ne current-sheath – without neutron yield, intensive x-rays
- 5 shots in A current-sheath – in 2 shots neutron yield 6.5×10^6 without x-rays
- In D neutron yield $(0.2 - 1.5) \times 10^{10}$ with FWHM of 70-150 ns

Plans for future study

More detail study of neutron production – detection, time-of-flight analysis, determination of the neutron source function, space anisotropy.

Clarify theory and simulations of the acceleration of fast deuterons

Study of interaction of fast deuterons with target

Heating of the target with the deuteron beams

Relaxation time and heating of electrons

Estimation of structures of magnetic field

Influence of polarity of the current on the orientation of the fast particles

Study of mechanism of acceleration of fast electrons and deuterons –

- 1) diode mechanism and anomalous resistivity due to turbulence**
- 2) penetration, dissipation and reconnections of internal magnetic fields**

Study of influence of gas-puff load on the production of high energy particles

Diagnostics of the plasma structures with new laser