Enhanced Resistance during Neutron Emission in Wire-Array Z-Pinch

D. Klír, J. Kravárik, P. Kubeš, and K. Řezáč
Czech Technical University in Prague
Faculty of Electrical Engineering
Czech Republic
Email: klird1@fel.cvut.cz

S.S. Anan’ev, Yu.L. Bakshaev, A.V. Bartov, P.I. Blinov,
A.S. Chernenko, E.D. Kazakov, V.D. Korolev,
B.R. Meshcherov, V.I. Mizhiritsky, G.I. Ustroev
Russian Research Centre
Kurchatov Institute
Moscow, Russia

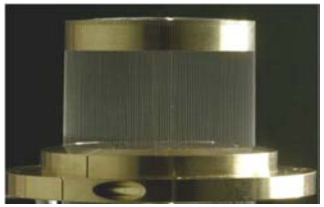
KURCHATOV
S-300
INSTITUTE

ICDMP Workshop
Warsaw, Poland, December 3-4, 2007

Outline

- Introduction – Purpose of our experiment
  Fusion neutron measurement as diagnostic tool
- Experimental set-up and diagnostics
- Experimental results and discussion
  Neutron energy spectrum ⇨ deuteron energy spectrum
  Time of neutron production, temporal correlations
  Plasma resistance
  Acceleration of deuterons
- Summary and conclusion

Introduction
Purpose of our experiment



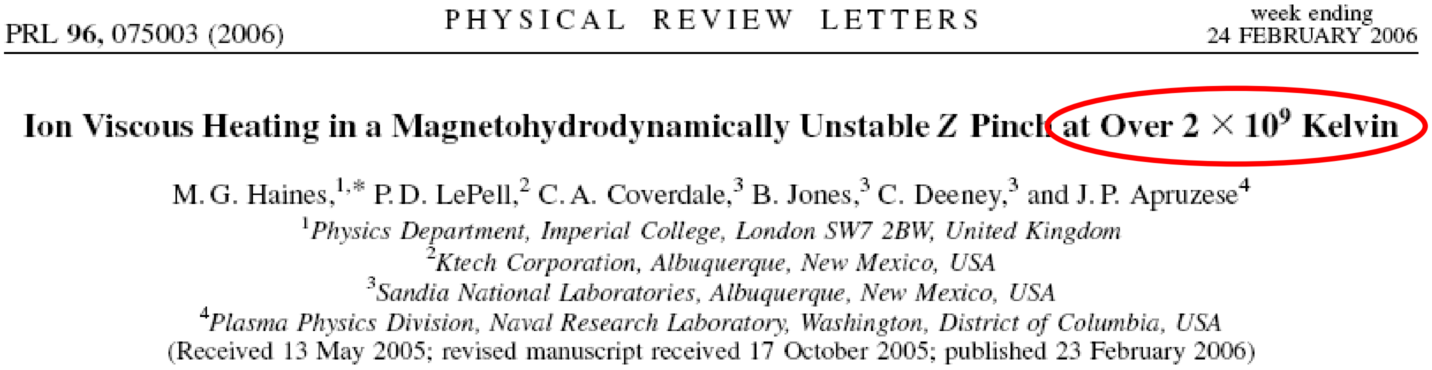
http://zpinch.sandia.gov/

Wire-array Z-pinch

- **Powerful sources of soft X-rays**

  (290 TW, 2 MJ, ICF driver)

  ⇨ detailed studies of EUV, soft and hard X-rays
- **Information about fast ions is rather rare**



PRL 96, 075003 (2006) PHYSICAL REVIEW LETTERS week ending 24 FEBRUARY 2006

Ion Viscous Heating in a Magnetohydrodynamically Unstable Z Pinch at Over 2×10^9 Kelvin

M. G. Haines,[1,*] P. D. LePell,[2] C. A. Coverdale,[3] B. Jones,[3] C. Deeney,[3] and J. P. Apruzese[4]

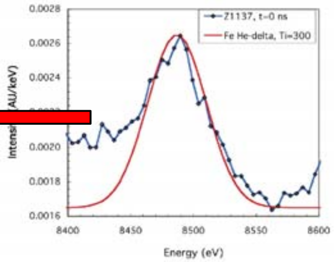
[1]*Physics Department, Imperial College, London SW7 2BW, United Kingdom*

[2]*Ktech Corporation, Albuquerque, New Mexico, USA*

[3]*Sandia National Laboratories, Albuquerque, New Mexico, USA*

[4]*Plasma Physics Division, Naval Research Laboratory, Washington, District of Columbia, USA*

(Received 13 May 2005; revised manuscript received 17 October 2005; published 23 February 2006)



Introduction
Purpose of our experiment

Our primary interest

- **To perform fusion neutron measurement in Z-pinches**

  ⇨ to put a deuterated fibre in the centre of a wire array.

$$\begin{array}{ccccccc} \mathrm{D} & + & \mathrm{D} & \longrightarrow & \mathrm{T}\ (1.01\ \mathrm{MeV}) & + & \mathrm{p}\ (3.02\ \mathrm{MeV}) \\ \mathrm{D} & + & \mathrm{D} & \longrightarrow & {}^{3}_{2}\mathrm{He}\ (0.82\ \mathrm{MeV}) & + & \mathrm{n}\ (2.45\ \mathrm{MeV}) \end{array}$$

- **Neutrons ⇨ favourable diagnostic tool of D-D reaction**

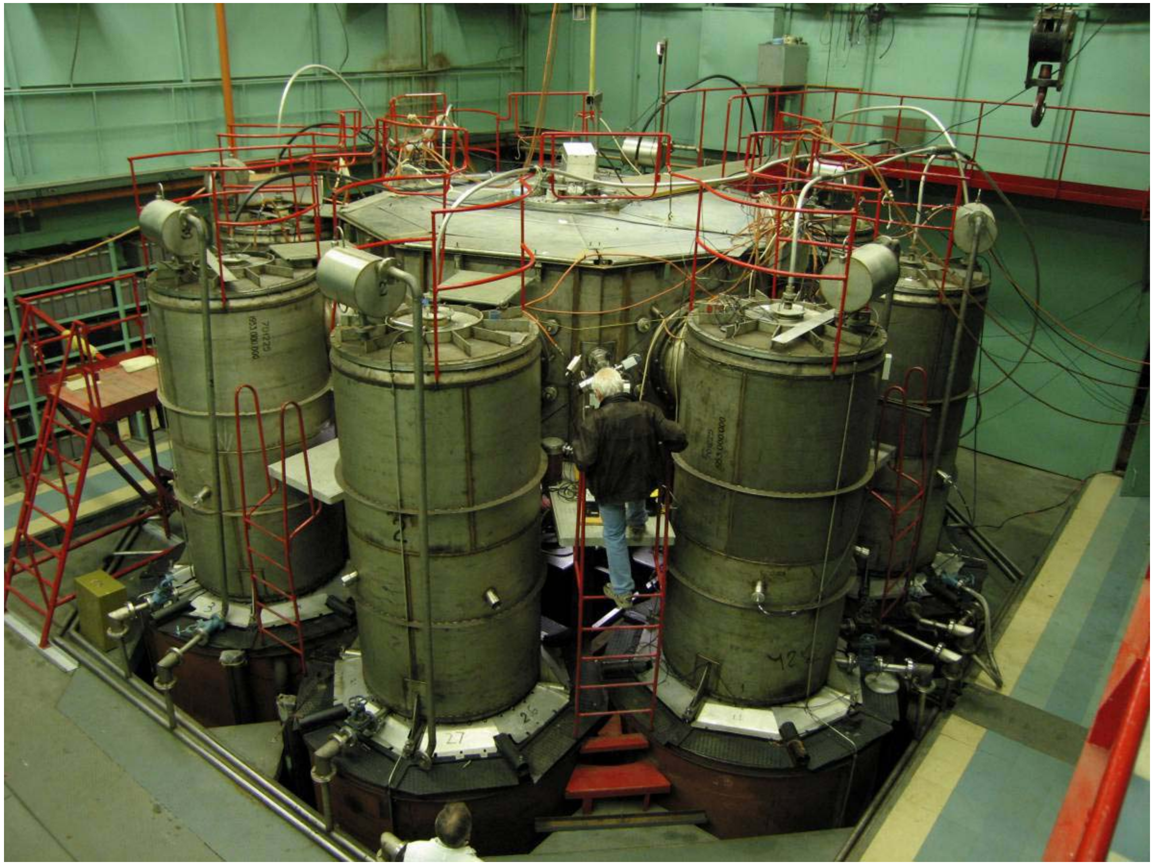
  = are influenced neither by ***E*** nor ***B***

  = weak absorption and scattering in the chamber walls and air

  (TOF analysis for determination of neutron energy spectra, Monte Carlo reconstruction presented by K. Rezac)

EXPERIMENTAL SET-UP AND DIAGNOSTICS

Experimental Set-up

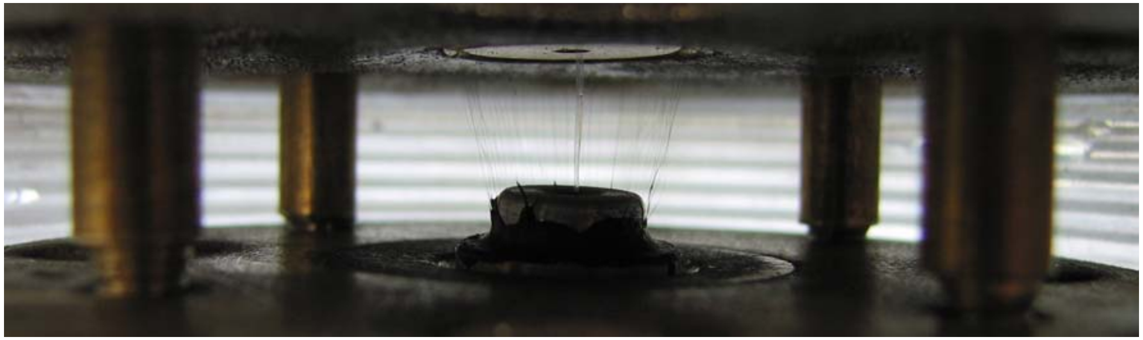


S-300 facility

Marx generator: 8 modules

Electric current: **2.0 MA**
Rise-time: **100 ns**

Experimental Set-up



Mass percentage of ions in Z-pinch load:
Tungsten 73%, carbon 20%, and deuterium 7%.

S-300 facility

Marx generator: 8 modules

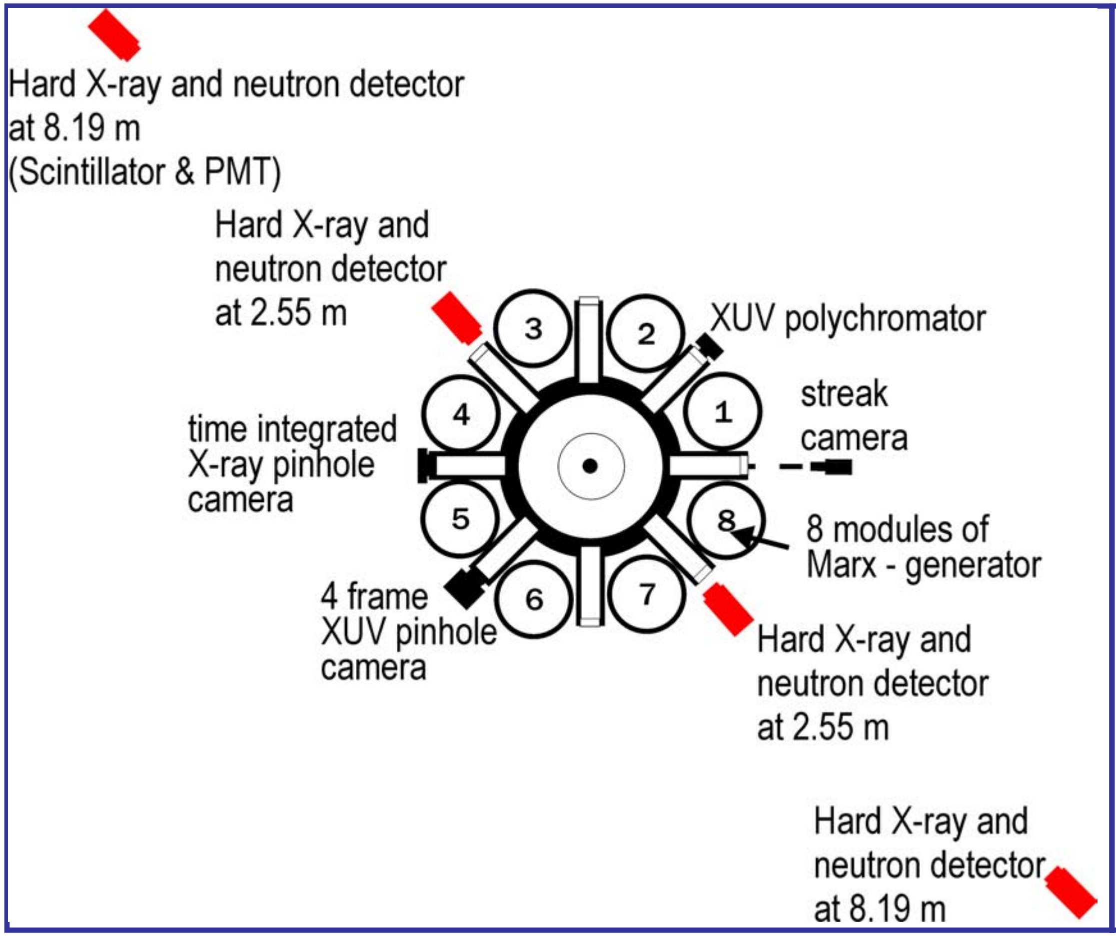
Electric current:	**2.0 MA**
Rise-time:	**100 ns**

30 tungsten wires:
ø = 7 μm, L = 7 mm,
D_{Anode} = 10 mm, D_{C} = 7 mm

$(CD_2)_n$ fibre:
ø = 100 μm, L = 7 mm

Layout of Diagnostics

End-on view



Hard X-ray and neutron detector
at 8.19 m
(Scintillator & PMT)

Hard X-ray and
neutron detector
at 2.55 m

XUV polychromator

streak
camera

time integrated
X-ray pinhole
camera

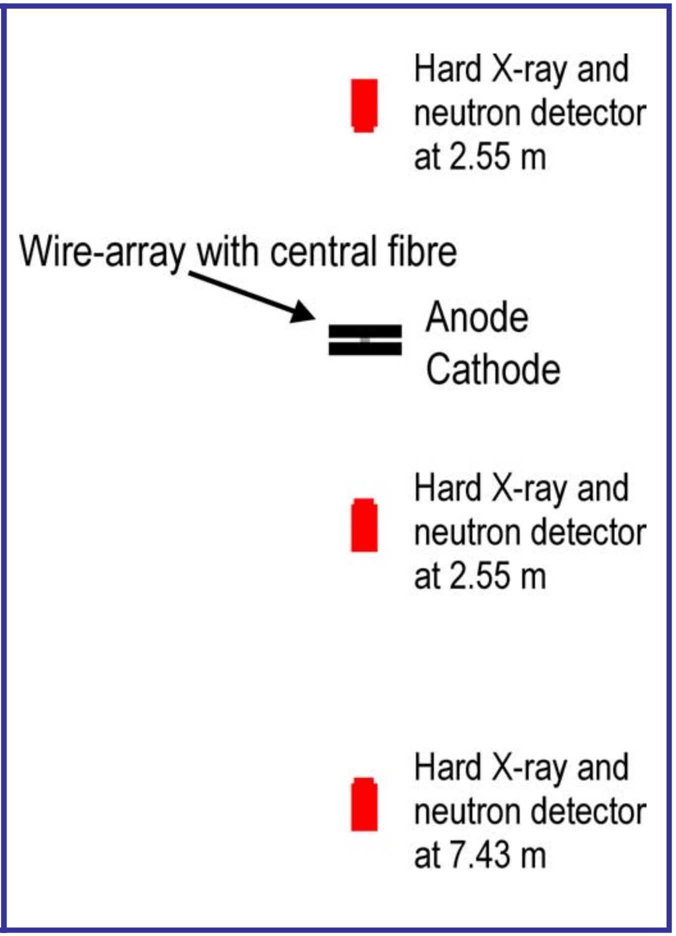
8 modules of
Marx - generator

4 frame
XUV pinhole
camera

Hard X-ray and
neutron detector
at 2.55 m

Hard X-ray and
neutron detector
at 8.19 m

Side-on view



Hard X-ray and
neutron detector
at 2.55 m

Wire-array with central fibre

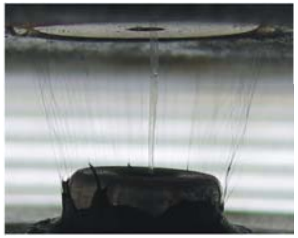
Anode
Cathode

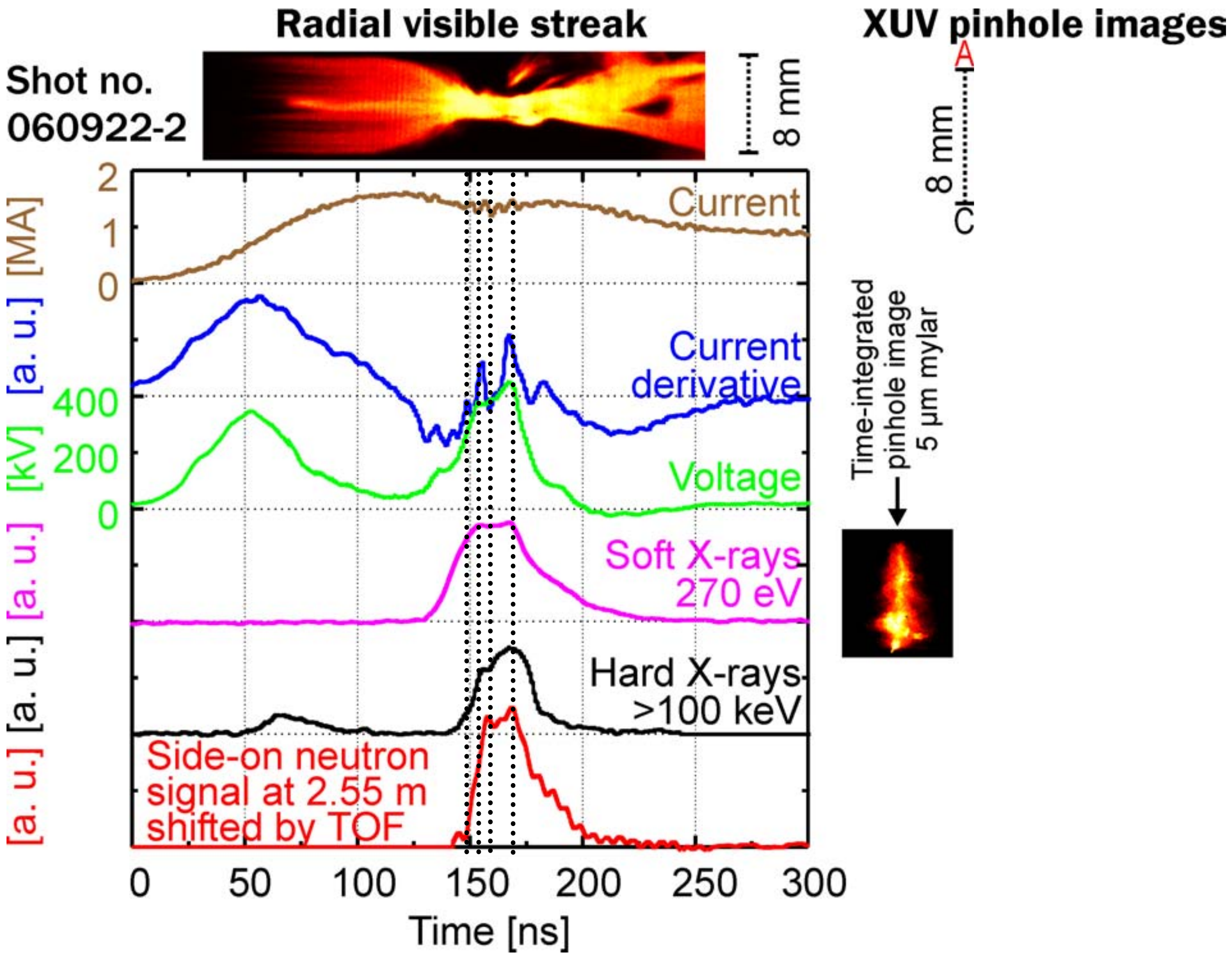
Hard X-ray and
neutron detector
at 2.55 m

Hard X-ray and
neutron detector
at 7.43 m

EXPERIMENTAL RESULTS

Implosion of Conical Wire-Array onto Deuterated Fibre





Optical streak camera

$V_{IMP} = 2\times10^{7}$ cm/s

Soft X-ray emission

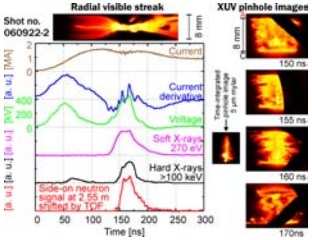
5 kJ energy, 100 GW power

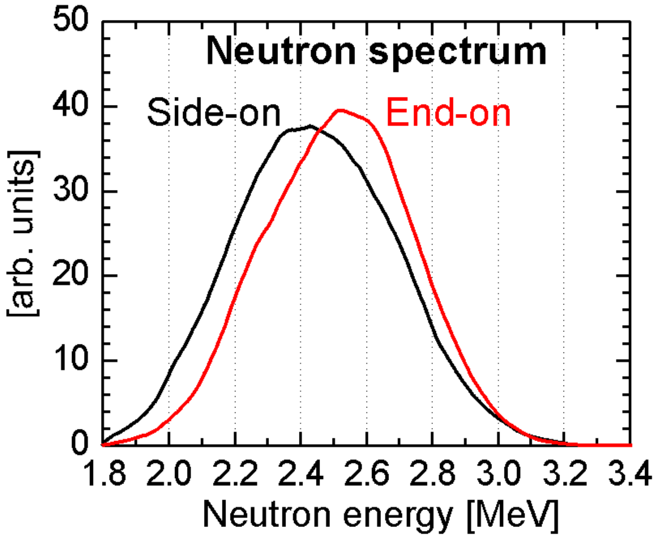
Max. spect. power density at 120 eV ⇨ T_{BB}=40 eV

Neutron emission

10^9 neutrons during :
(i) Plasma stagnation
(ii) Dips in *dI/dt*
(iii) Voltage peak
(iv) X-ray peak

Neutron Energy Spectra, shot 22-2





Side-on direction (perpendicularly to Z-pinch axis):

mean energy of neutrons about 2.4 MeV,
broader energy spectra radially than downstream

Downstream (axial direction behind cathode):

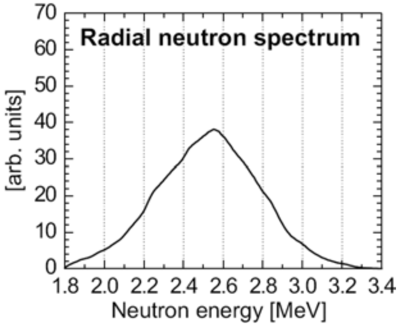
mean energy of neutrons shifted to 2.55 MeV

Neutron Energy Spectra, 15 shots

Side-on direction

peak neutron energy: 2.48±0.05 MeV

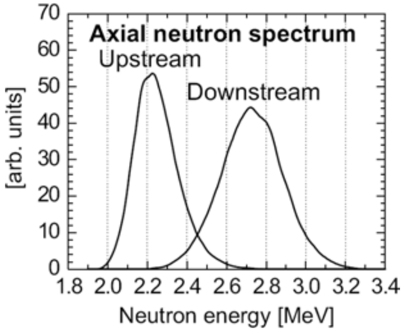
FWHM of energy spectrum: 450±100 keV



End-on direction (downstream)

peak neutron energy: 2.65±0.10 MeV

FWHM of energy spectrum: 350±100 keV

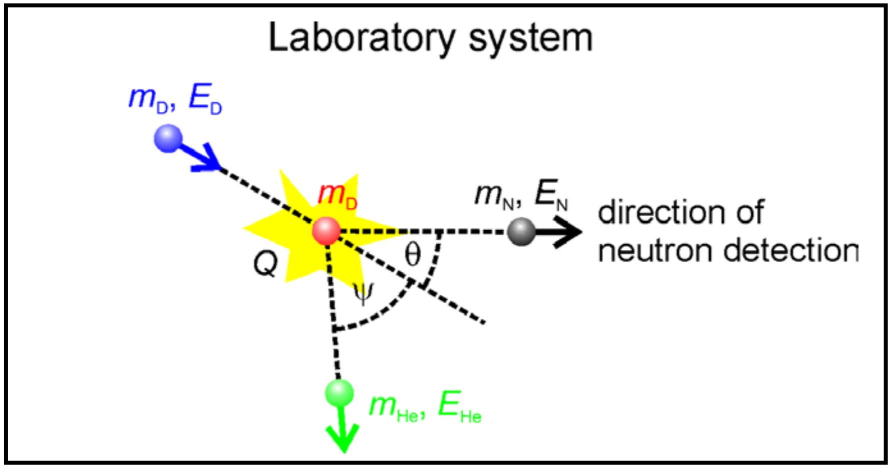


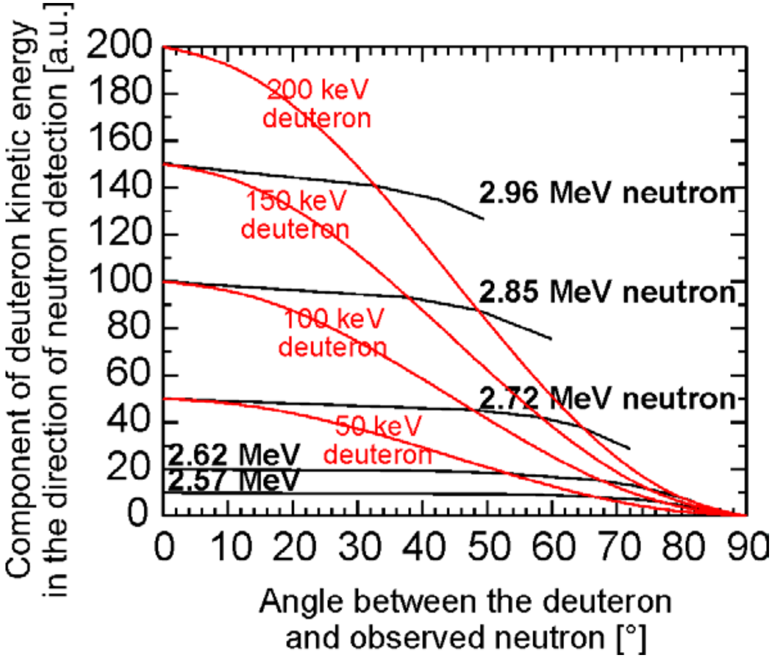
Similar values were observed in other Z-pinch configurations

Compressional Z-pinches: Andrianov 1958, Anderson 1958, Mather 1958…

Plasma foci: Bernstein 1972, Bernard 1975, …

Deuteron Kinetic Energy

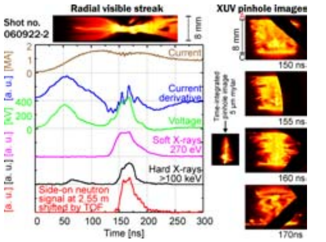


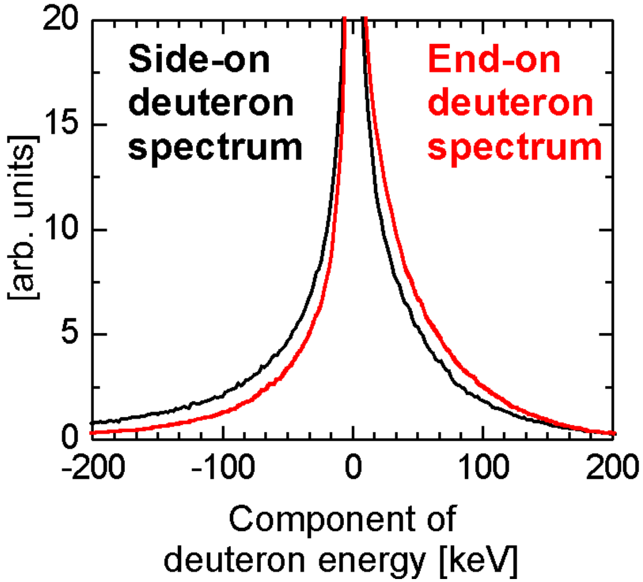


$$E_N(E_D,\theta) = E_D \frac{m_N}{2(m_N+m_{He})} \cdot \left(\cos\theta + \sqrt{\frac{m_{He}}{m_N}\left(1+\frac{2Q}{E_D}\right) - \sin^2\theta} \right)^2 \approx 2.5\ \text{MeV} + f(E_D\cos^2\theta)$$

Neutron energy is given mainly by the component of deuteron kinetic energy in the direction of neutron detection.

Energy Distribution Function of Reacting Deuterons, shot 22-2





Axial direction: mean energy component $\langle |E_{\parallel}| \rangle = 60\ \mathrm{keV}$

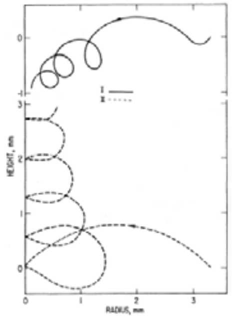
Side-on direction: mean energy component $\langle |E_{\perp}| \rangle = 40\ \mathrm{keV}$

Fusion neutrons were produced mainly by deuterons with the average kinetic energy $\langle E_{\mathrm{d}} \rangle = \langle E_{\parallel} \rangle + 2 \langle |E_{\perp}| \rangle \doteq 150\ \mathrm{keV}$

Anisotropy of neutron flux: below 1.2

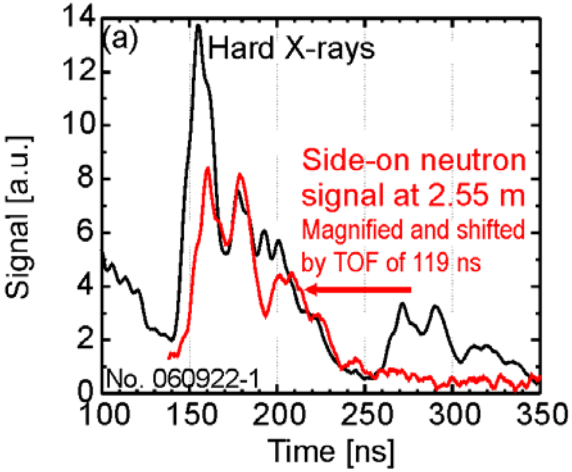
Trajectories of Fast Deuterons

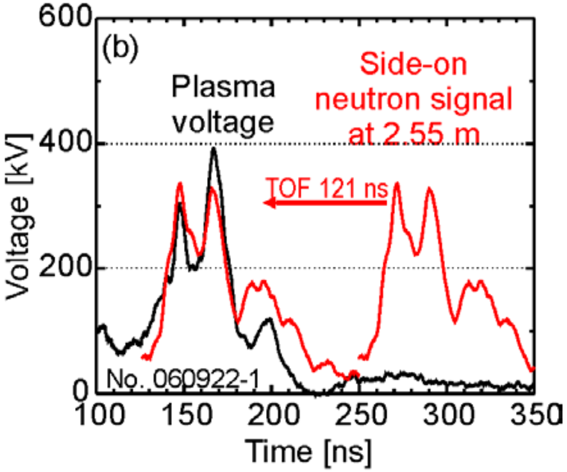
- Neutron emission anisotropy (2.7 MeV neutrons downstream)
  implies the role of beam-target model
- Broad neutron energy spectrum in the radial direction
  100 keV deuterons in the radial direction
  indicate that the linear beam-target model did not occur
- Generalized beam target model
  Trajectories of fast deuterons could be complex
  E.g. trajectories described by Bernstein 1972
  It could explain:
    observed neutron spectra
    neutron flux anisotropy (<1.5)
  Problem: how are these deuterons accelerated?
    emission during expansion phase
    relatively long duration

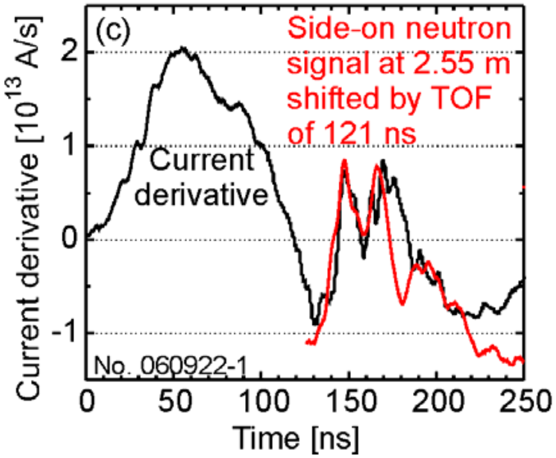


Temporal correlations

!!! Side-on neutron detector as close to the neutron source as possible !!!







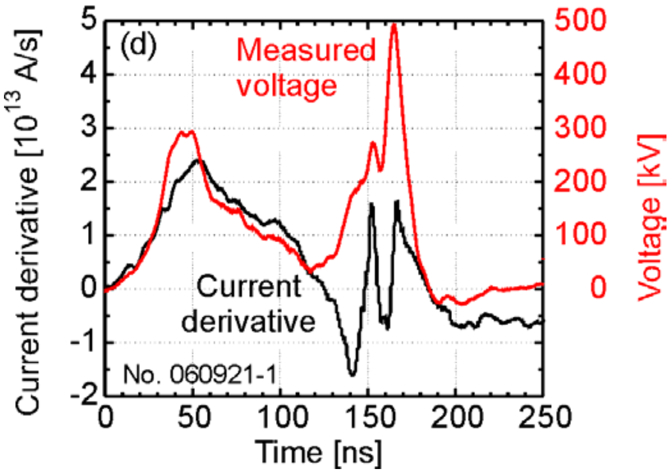
Evident correlation between side-on neutron signal and HXR, voltage, and *dI/dt* waveforms.

$$V = \frac{\mathrm{d}}{\mathrm{d}t}\left((L_\mathrm{P} + L_0)I\right) + R_\mathrm{P} I = (L_\mathrm{P} + L_0)\frac{\mathrm{d}I}{\mathrm{d}t} + \left(\frac{\mathrm{d}L_\mathrm{P}}{\mathrm{d}t} + R_\mathrm{P}\right) I$$

Induced voltage *LdI/dt* contributed to voltage peak

118 ns: time-of-flight of 2.45 MeV neutrons to detector located at 2.55 m

Plasma Resistance and Inductance



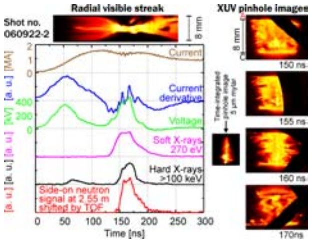
!!! Measurement of voltage *V*, current derivative *dI/dt* and current *I* enabled the estimation of the $R_P + dL_P/dt$ term from

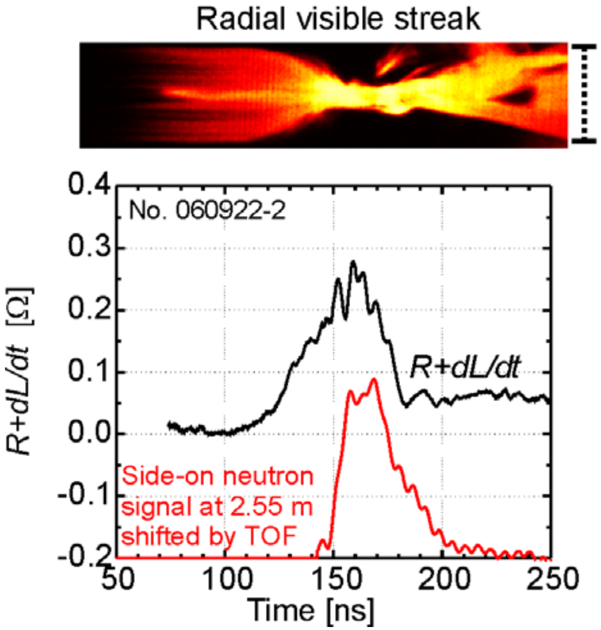
$$R_\mathrm{P} + \dot{L}_\mathrm{P} = \frac{V - L\dot{I}}{I}$$

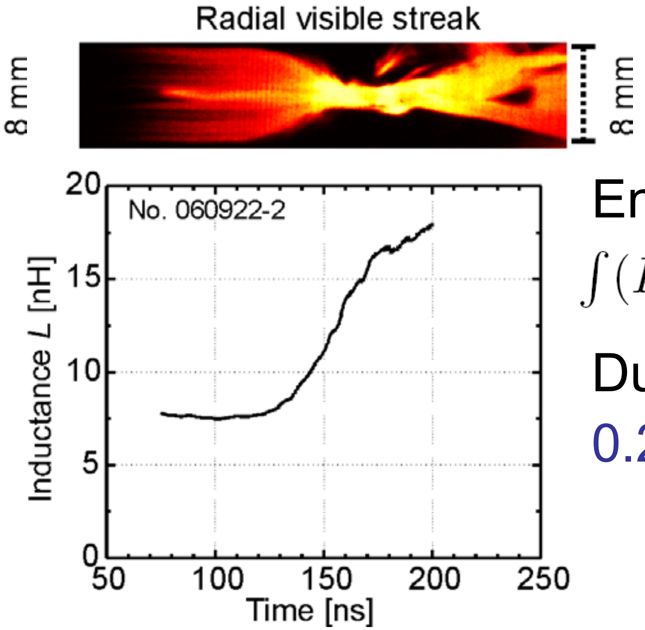
$L = L_P + L_0$ is the inductance including the external inductance of transmission line L_0

We assumed that the inductance *L*(t) of about 9 nH was approximately constant during the implosion.

Plasma Resistance and Inductance







Energy input

$$\int (R_P + \dot{L}_P) I^2 \mathrm{d}t = 20\ \mathrm{kJ}$$

During implosion:

0.2 Ω could be ascribed to dL_P/dt

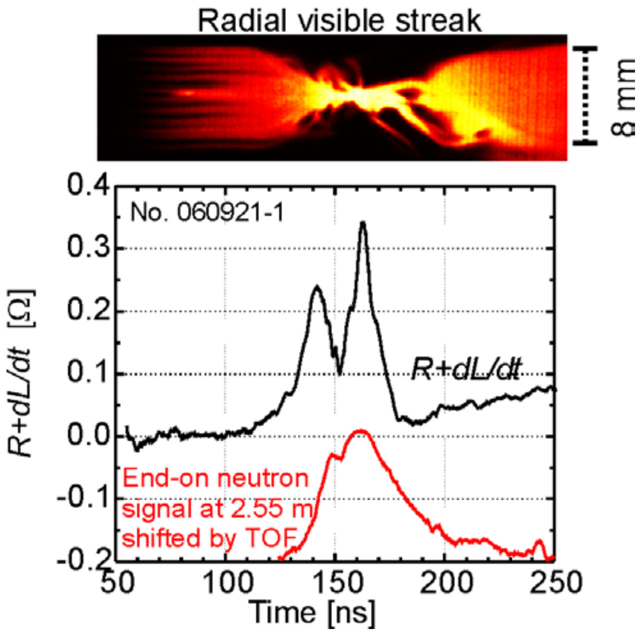
$$|\dot{L}_P| = \frac{\mu l v_{\mathrm{imp}}}{2\pi R}$$

If plasma resistance is neglected:

1. No evidence of the plasma expansion
2. Increase of inductance to 18 nH: collapse to 10 μm diameter OR increase of effective plasma length
3. Magnetic energy $\frac{1}{2}\triangle L_P I^2 \doteq 10\ \mathrm{kJ}$ stored after the plasma radiation

Plasma Resistance and Inductance

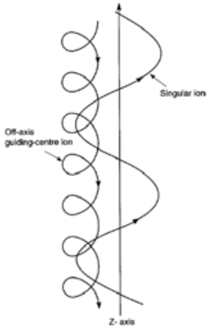
In post-stagnation phase: significant role of enhanced resistance (Spitzer is not sufficient)



The value of 0.2÷0.4 Ω also measured by Bernard 1978 and Decker 1983

Energy conservation – debated issue in Z-Pinches (Whitney04, Haines06)

Acceleration of Deuterons



Experimental results best fit to generalized beam-target model.

However, it is not clear how the beam of fast deuterons was created?

- Diode action: Because of the correlation between neutron emission and 400 kV voltage peaks, deuterons could be accelerated to 150 keV energies by diode action in peripheral plasma. Axially accelerated deuterons have to be bent by magnetic fields.
  Problem: the origin of plasma voltage during post-stagnation phase
- Microturbulences: High plasma voltage during the post-stagnation phase could be a result of microturbulences in plasma (Haines 2001). Microturbulences could not only induce high electric fields but also form a high energy tail of the ion distribution function (Ryutov 2000).
  Advantages: 1. radial velocities of deuterons, neutron flux anisotropy
  2. neutron emission during the stagnation and expansion
  3. measured enhancement of plasma resistance

Summary

Implosion of tungsten wire-array onto deuterated fibre:

- Neutron yield of 10^9 during plasma stagnation at fibre
- Reconstruction of neutron energy spectra
- Estimation of kinetic energies of deuterons producing fusion reactions
- Measurement of voltage and plasma resistance and time-varying inductance
- Discussion of acceleration mechanisms

Suggestions for PF-1000

- To have one neutron detector as close to the neutron source as possible in order to measure neutron emission time.
- To measure side-on neutron emission in order to estimate radial velocity distribution of deuterons.
- To measure plasma voltage in order to evaluate the energy input and plasma resistance.

Acknowledgements

This research has been supported by the research program MSMT No. 1P04LA235, No. 1P05ME761, No. LC528 and by GACR grant No. 202-03-H162.