# HIGH EFFICIENCY PLASMA FOCUS: FUSION AND APPLICATIONS

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*Information about active 1 MJ PF machines were supplied by:*
*Dr.Marek Sholtz (IPPLM, Warsaw) and Dr. Slava Krauz (Kurchatov Institute, Moscow)*
*The design and optimization of the Plasma Focus PF-50 as well as research program at DIANA Hi-Tech had been carried by: Jan S. Brzosko, Krzysztof Jasowicz, Daniel Gasin, Krzysztof Melzacki, and Charles Powell.*

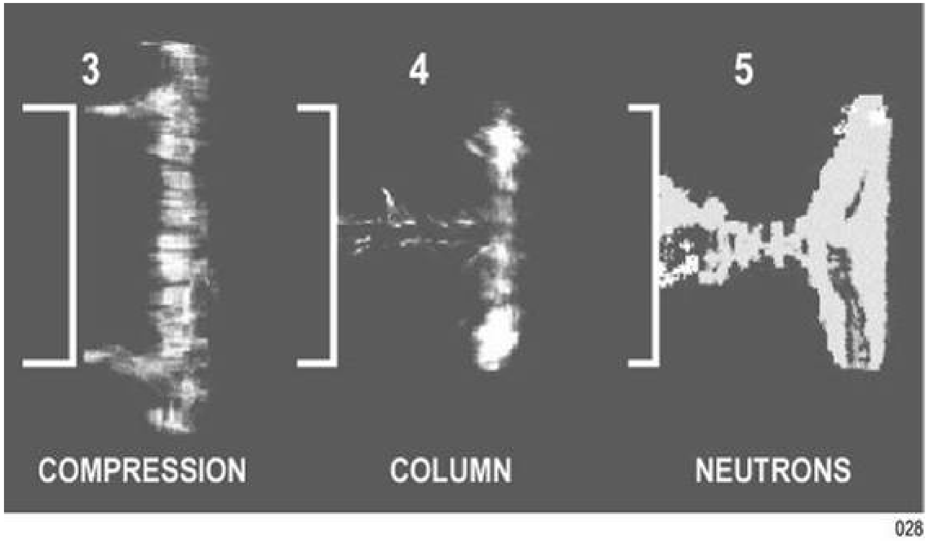
*Opinions and information presented here does not necessary represent opinions of DHS and/or DIANA Hi-Tech and none of these organizations take responsibility for accuracy or reproducibility of presented data.*
*Selection of presented technical information complains with ITAR regulations.*

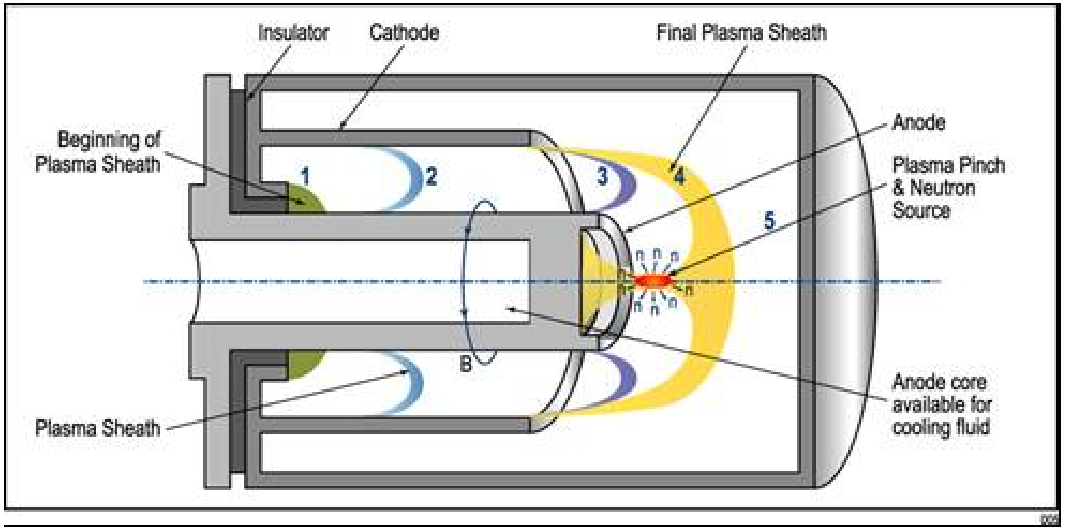
# CONTENT:

1. INTRODUCTION:
   What is Plasma Focus, Troubles in Past and Present, Scaling.

2. BREAKEVEN:
   Is it possible ?, T(d,n)$\alpha$ or $^{3}$He(d,p)$\alpha$ or $^{11}$B(p,2$\alpha$)$\alpha$ ?

3. EXPERIMENTS ON HIGH EFFICIENCY PLASMA FOCUS,
   PF-50, W= 45 kJ.





## DISCHARGE DEVELOPMENT

Sequence of the discharge development in Plasma Focus.

The Schleeren-type pictures helps to visualize sequence of processes leading to neutron emission.

**1**- Discharge initiates along insulator and in 100 ns converts to 2.

**2**- plasma sheath moving $\upsilon \approx 10^5$ m/s toward the anode nozzle, $kT_e \approx$ 5-20 keV

**3**- Plasma rearranges to compressing cylinder.

**4**- Plasma is compressed at the axis, forming dense ($10^{25}$ ions/m$^3$) column (pinch), $kT_e \approx$ 0.5-1 keV, $\upsilon \approx 10^6$ m/s

**5**- The pinch exercises violent instabilities causing ion acceleration to MeV’s energy; these ions are trapped in the dense and hot plasma domains where neutron production occurs.

## Plasma Characteristics at Compression:

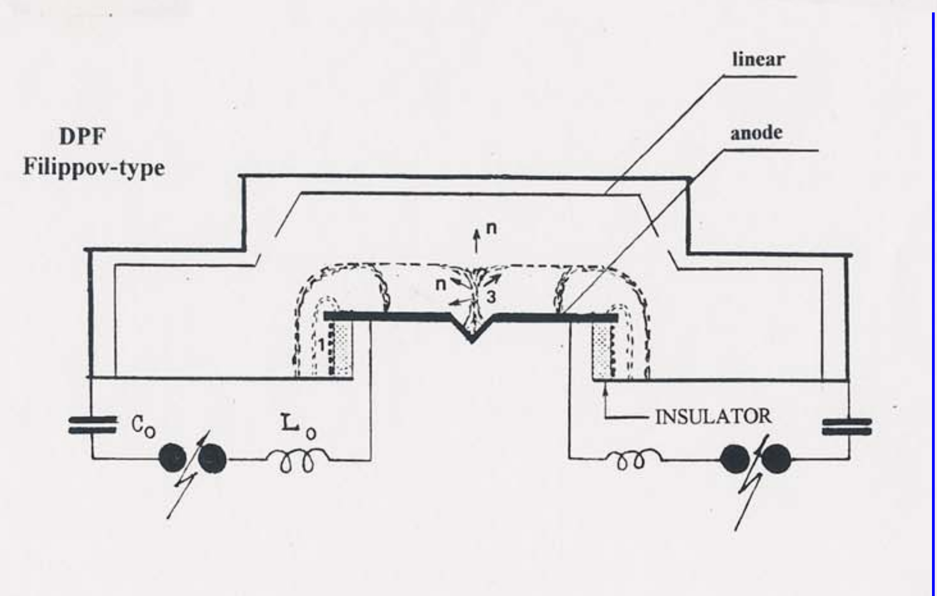
- density: $10^{19}$ ions/cm$^3$
- electron temperature: 0.5-1 keV
- time of compressed phase: 20-500 ns

## Plasma Characteristics at Fusion:

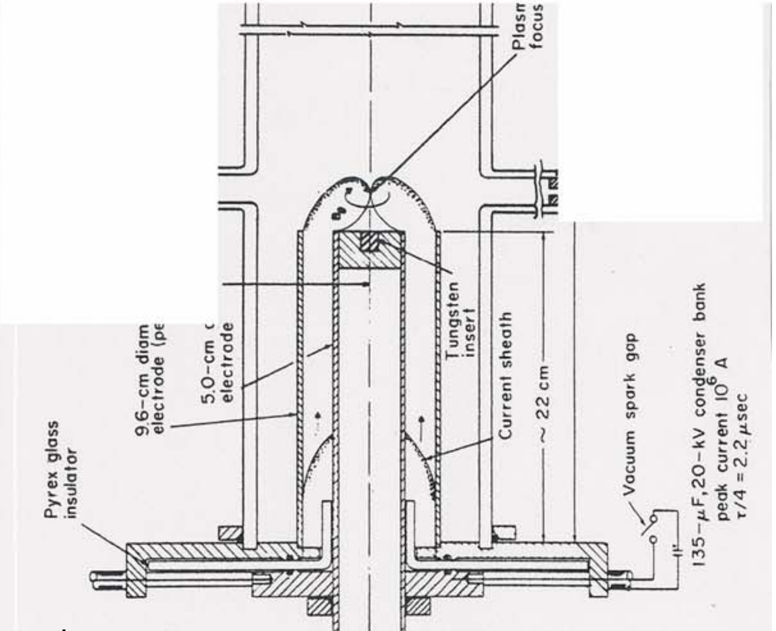
- density: $10^{22-24}$ ions/cm$^3$
- electron temperature: 3-10 keV
- time of ion acceleration: 1-5 ns
- abundant production of MeV ions, and hard X rays

# CLASSIC DESIGN OF PLASMA FOCUS

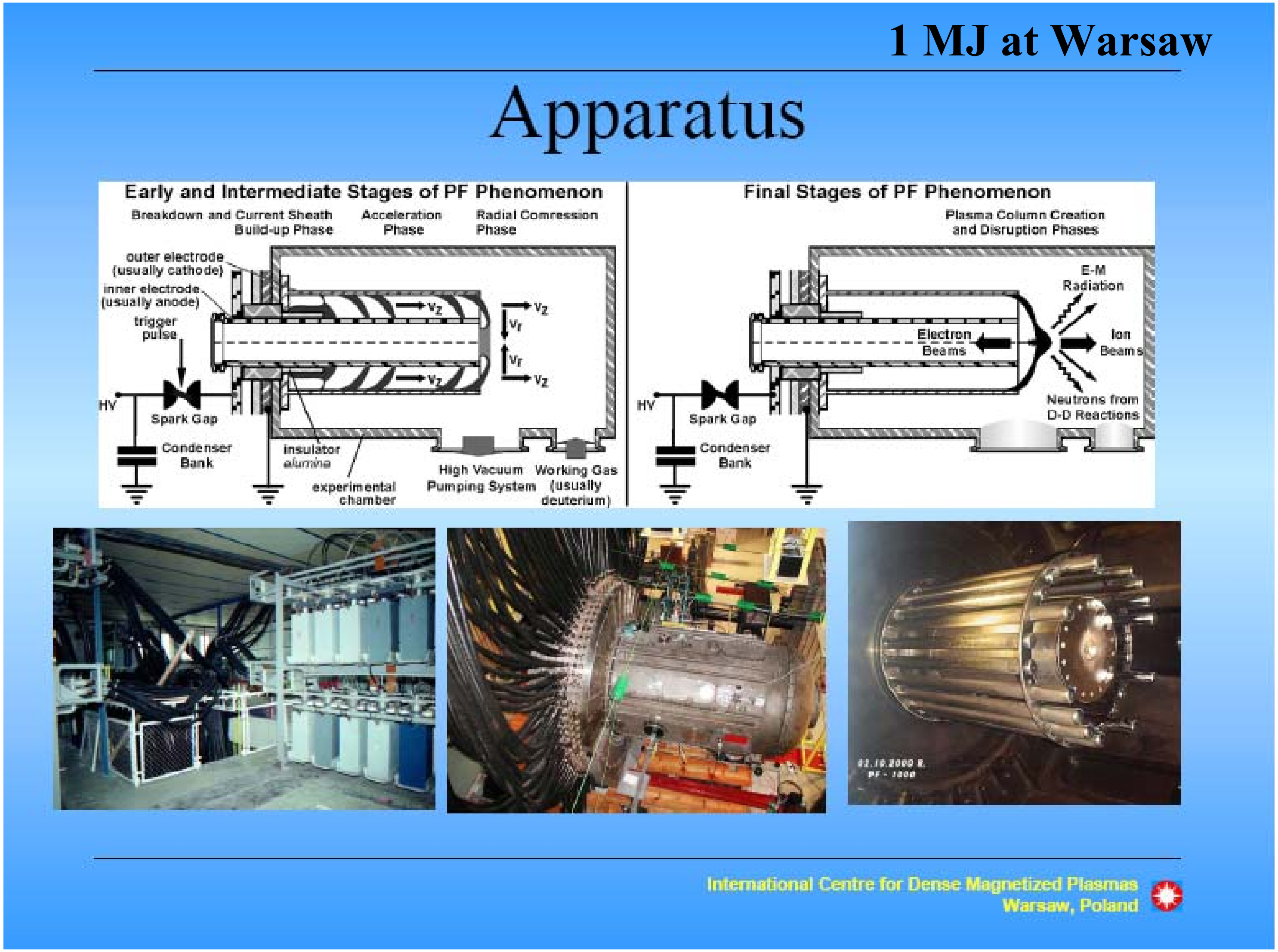
Nicolai and Tatiana **FILIOPPOV** (1961/62)



Joseph **MATHER** (1964)



| | **Fillipov** | | **Mather** | |
|---|---|---|---|---|
| | **50 kJ** | **1 MJ** | **50 kJ** | **1 MJ** |
| Central electrode dia. [m] | 0.5-0.7 | 0.9 | 0.04-0.08 | 0.16-0.25 |
| Central electrode length [m] | 0.12 | 0.26 | 0.2-0.3 | 0.5-0.6 |
| $D_2$ gas Pressure [Torr] | 0.5-2 | 1-3 | 3-8 | 5-10 |
| Voltage [kV] | 15-20 | 15 | 25-40 | 40-50 |
| Neutron yield [per pulse] | $(1\text{-}3)\times10^{10}$ | $10^{12}$ | $10^{10}\text{-}10^{11}$ | $(2\text{-}5)\times10^{12}$ |
| PP Inductance [nH] | 20 | 24 | 50 | 80 |
| Pinch current [MA] | 0.7-0.9 | 2-3 | 0.7-0.9 | 2-3 |



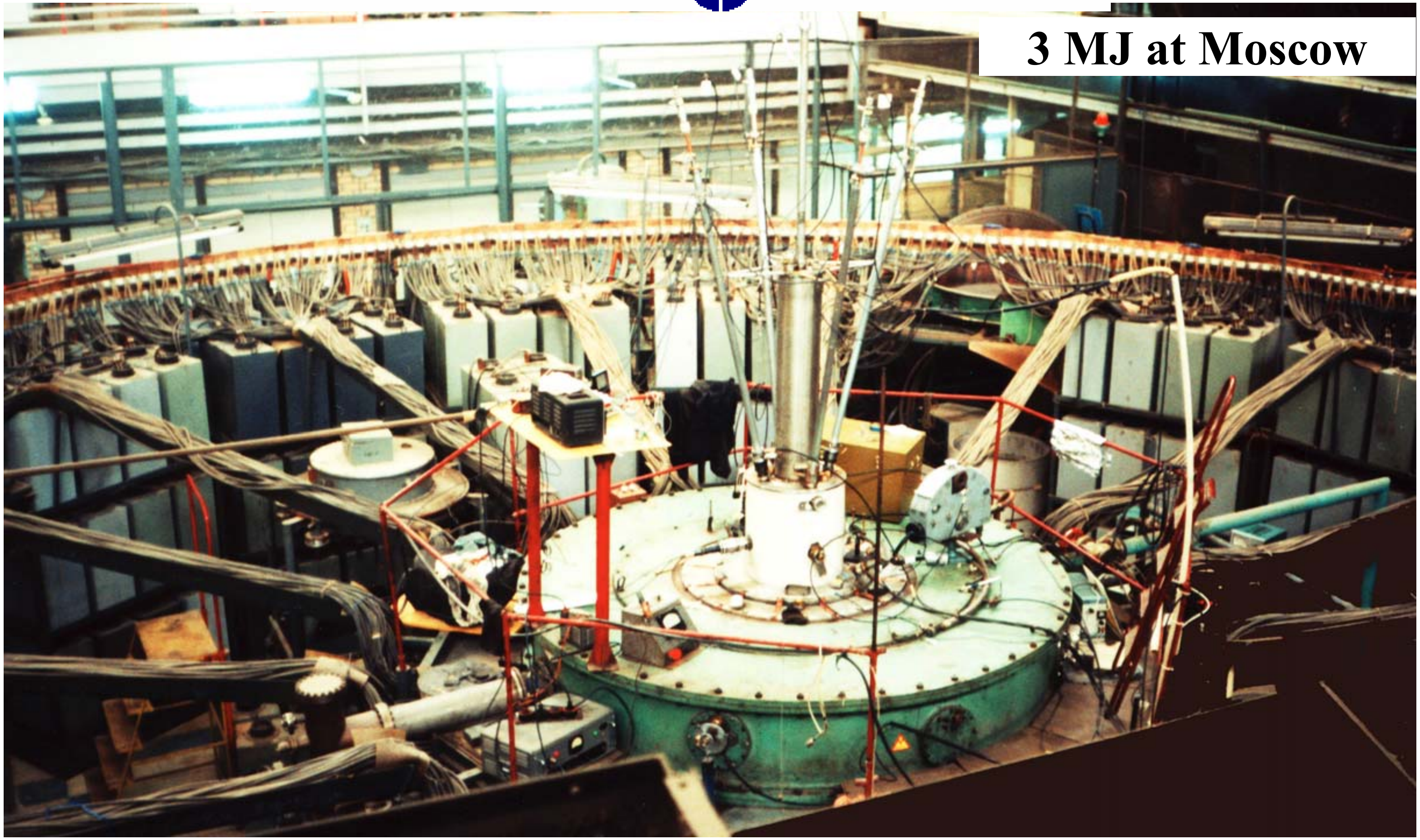
## 1 MJ at Warsaw

# Apparatus

International Centre for Dense Magnetized Plasmas
Warsaw, Poland

# PLASMA FOCUS

RUSSIAN RESEARCH CENTRE KURCHATOV INSTITUTE



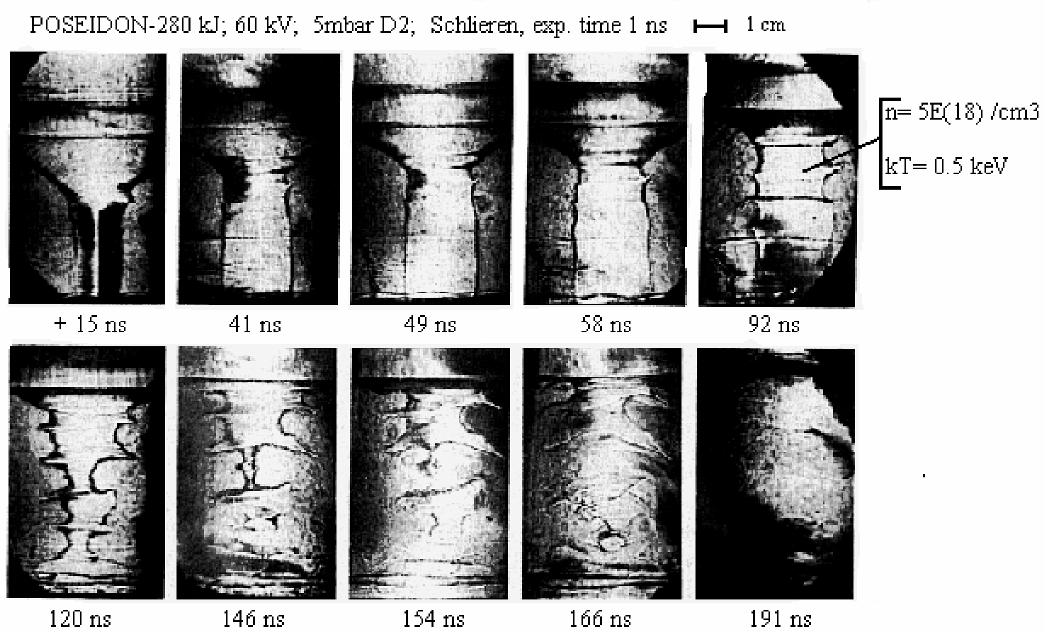
**3 MJ at Moscow**

Presentation at 7-th Symposium **"CURRENT TREND IN INTERNATIONAL FUSION RESEARCH":**
by J.S. Brzosko, 03/07/2007

# PLASMA FOCUS

## PLASMA COLUMN COMPRESSION SEQUENCE

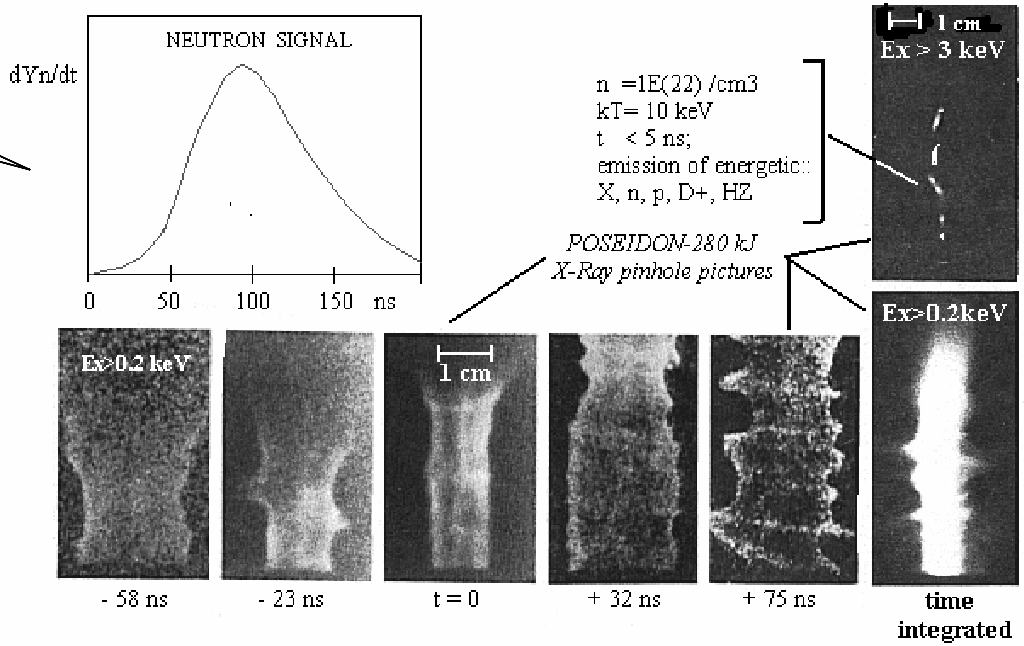
**SCHLIEREN PICTURES**



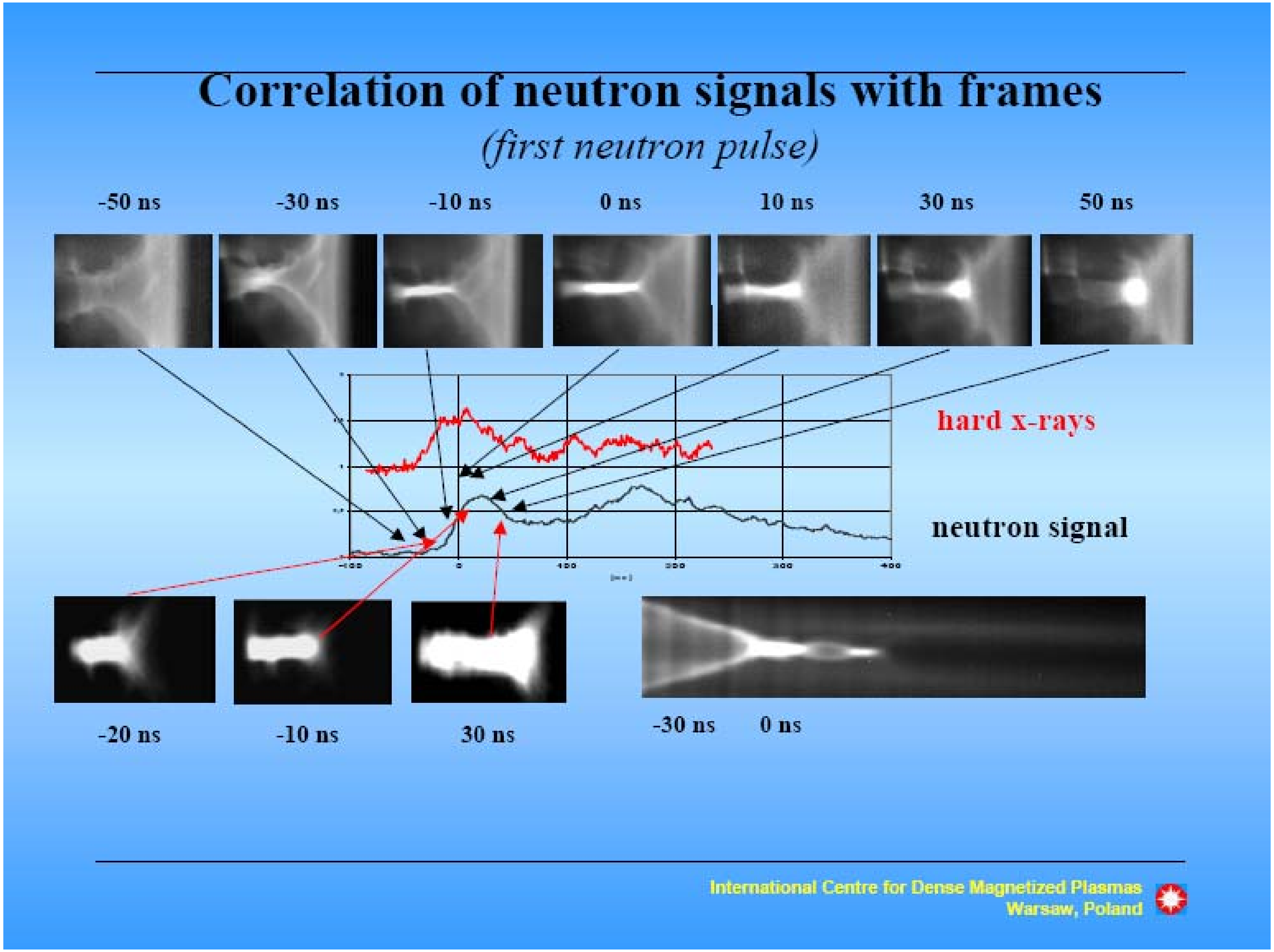
Herold, Schmidt & Stuttgart Univ. Team

**Neutron Signal**

X-ray PINHOLE PICTURES



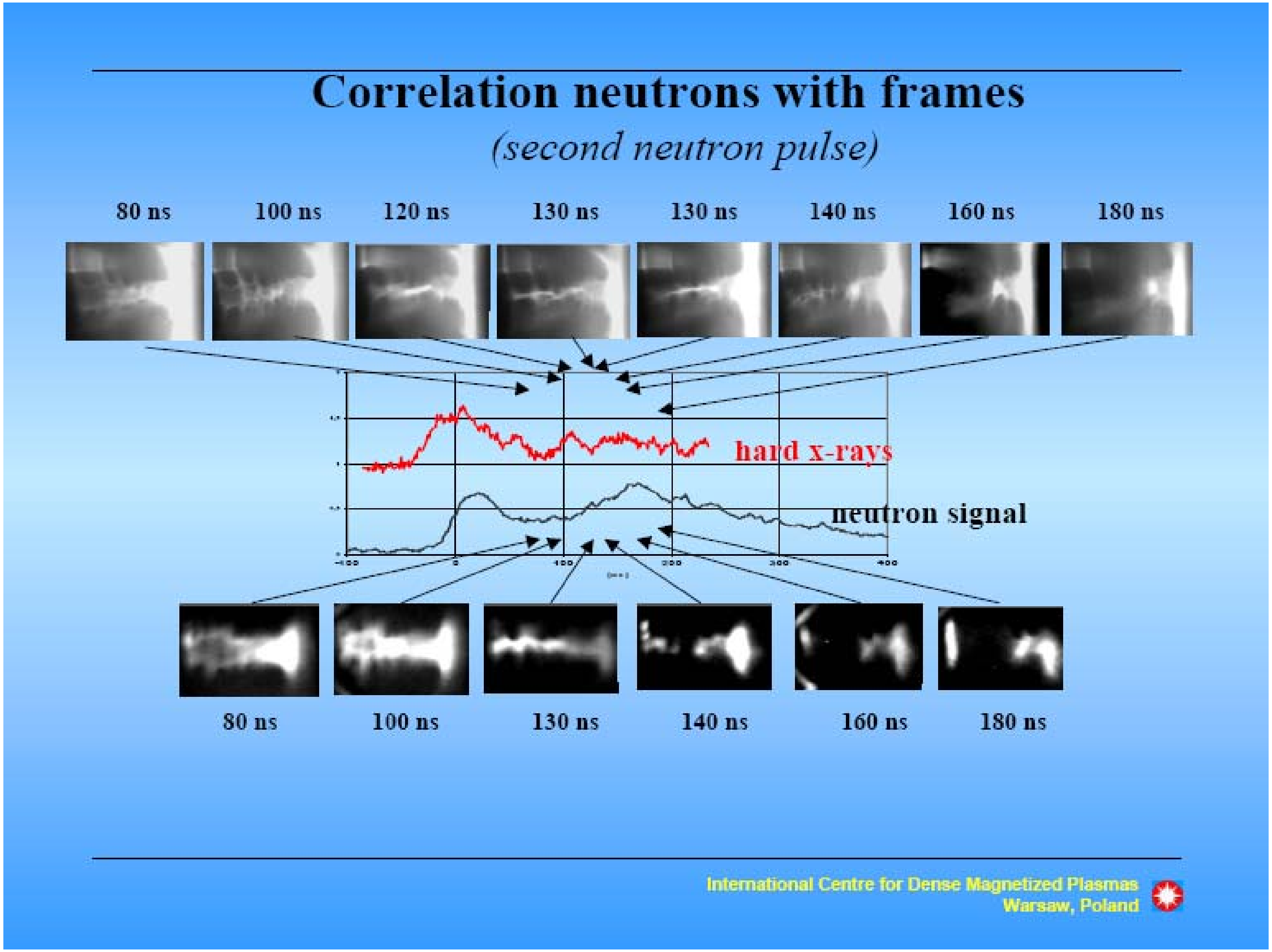
# PLASMA FOCUS



## Correlation of neutron signals with frames

*(first neutron pulse)*

International Centre for Dense Magnetized Plasmas
Warsaw, Poland



# Correlation neutrons with frames

*(second neutron pulse)*

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

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

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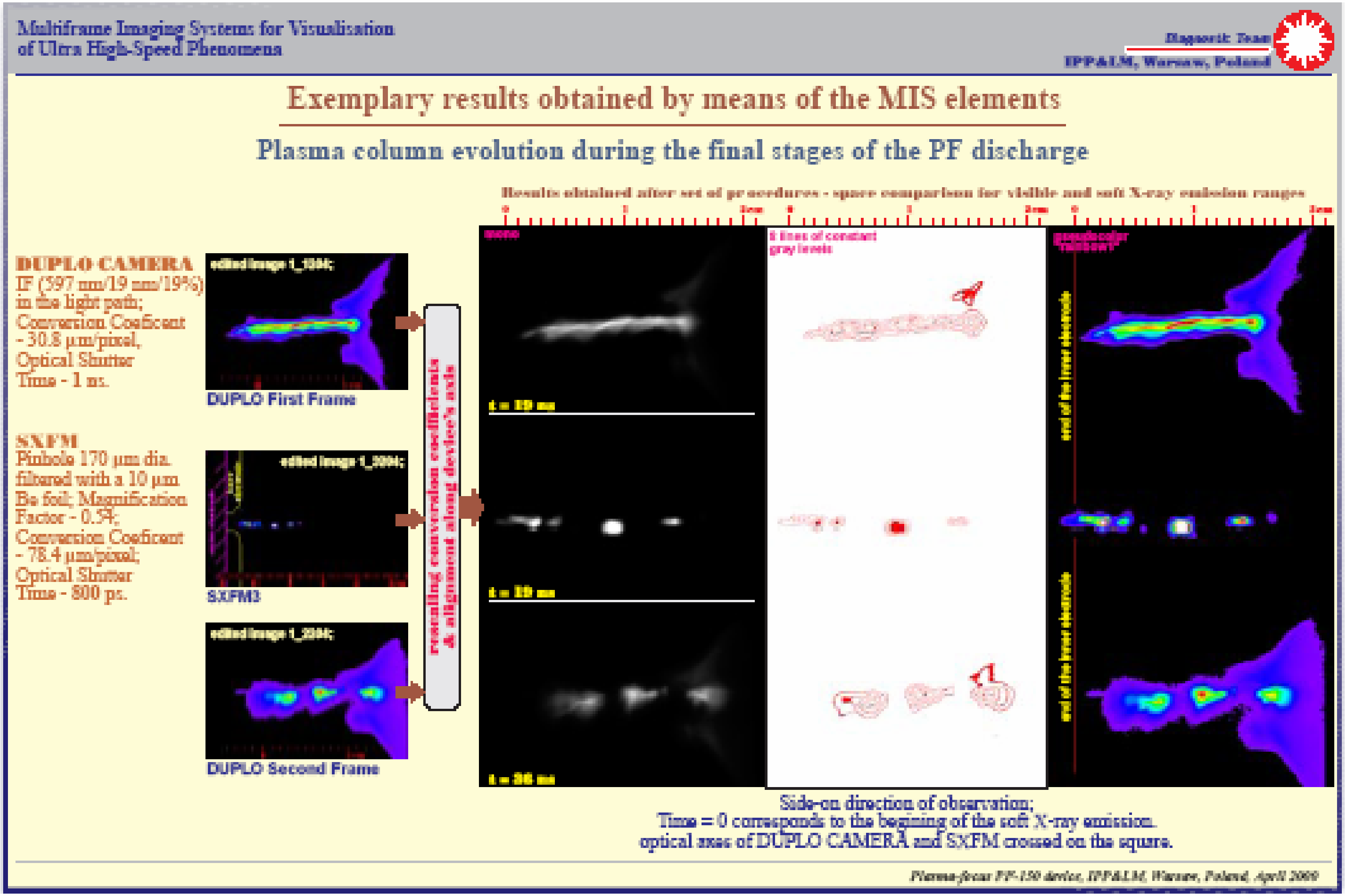
Warsaw, Poland



Multiframe Imaging Systems for Visualisation
of Ultra High-Speed Phenomena

Diagnostic Team
IPPA&LM, Warsaw, Poland

## Exemplary results obtained by means of the MIS elements

### Plasma column evolution during the final stages of the PF discharge

Results obtained after set of procedures - space comparison for visible and soft X-ray emission ranges

**DUPLO CAMERA**
IF (597 nm/19 nm/19%) in the light path;
Conversion Coeficent - 30.8 μm/pixel,
Optical Shutter Time - 1 ns.

DUPLO First Frame

**SXFM**
Pinhole 170 μm dia. filtered with a 10 μm Be foil; Magnification Factor - 0.54;
Conversion Coeficent - 78.4 μm/pixel;
Optical Shutter Time - 800 ps.

SXFM3

DUPLO Second Frame

rescalling conversion coefficients & alignment along device's axis

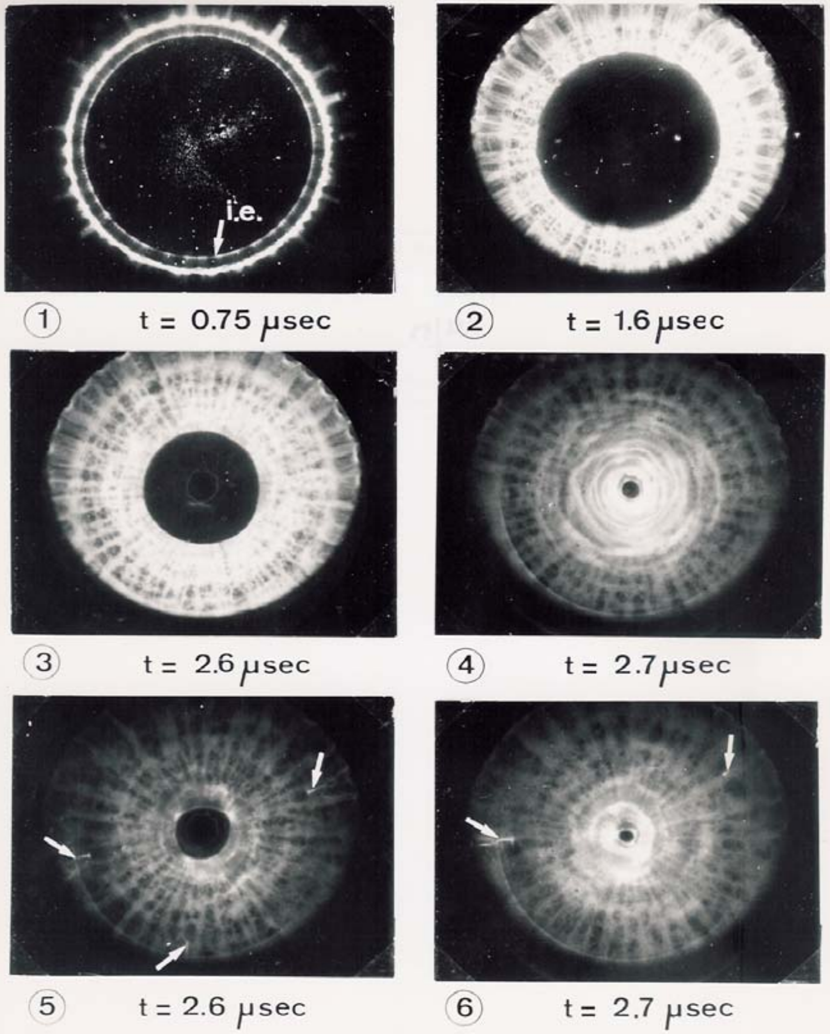
Side-on direction of observation;
Time = 0 corresponds to the begining of the soft X-ray emission.
optical axes of DUPLO CAMERA and SXFM crossed on the square.

*Plasma-focus PF-150 device, IPPA&LM, Warsaw, Poland, April 2000*

## FILAMENT STRUCTURE

FRONT VIEW OF PLASMA SHEET
(camera looks parallel to the axis)
Visible light, image converter camera,
5 ns exposure.

*Filament structure has been observed at Limeil, SIT, Warsaw, Moscow,….*



① t = 0.75 μsec

② t = 1.6 μsec

③ t = 2.6 μsec

④ t = 2.7 μsec

⑤ t = 2.6 μsec

⑥ t = 2.7 μsec

A. Bernard, A. Coudeville, et al, Phys. Fluids, 18, 180 (1975)

## TROUBLES IN PAST:

☞ INSULATOR
☞ Switches
☞ FUSION YIELD FLUCTUATION

## TROUBLES IN PRESENT:

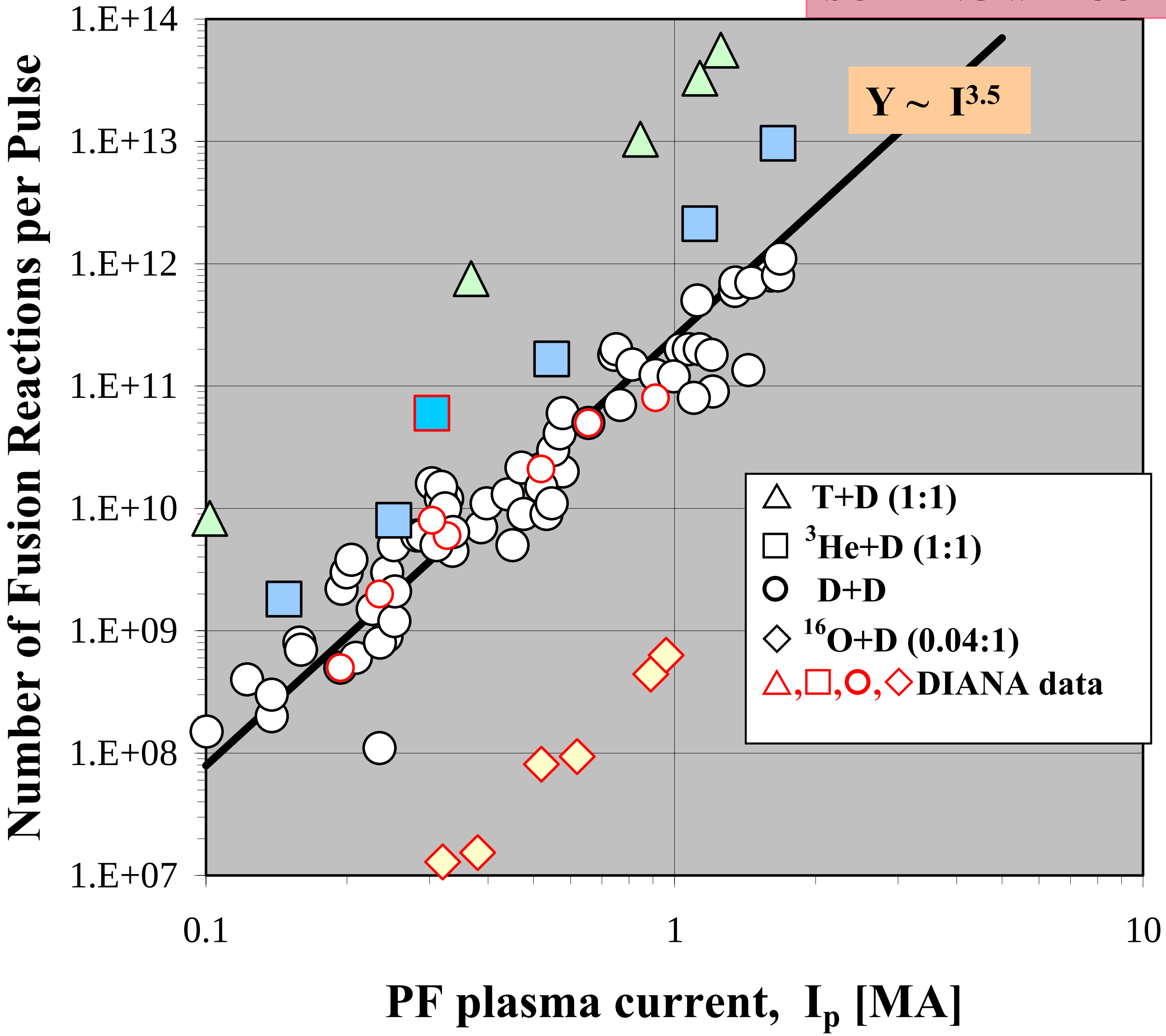
☝ Lack of consistent explanation for: fine structure, ion acceleration mechanism and nuclear reactivity,
☝ Lack of funding for PF fusion development,
☝ Possible neutron yield saturation ?

## POSITIVE SIGNS:

⁂ Large International Collaborations,
⁂ Industrialization of Plasma Focus Machines (small to small/medium sizes).

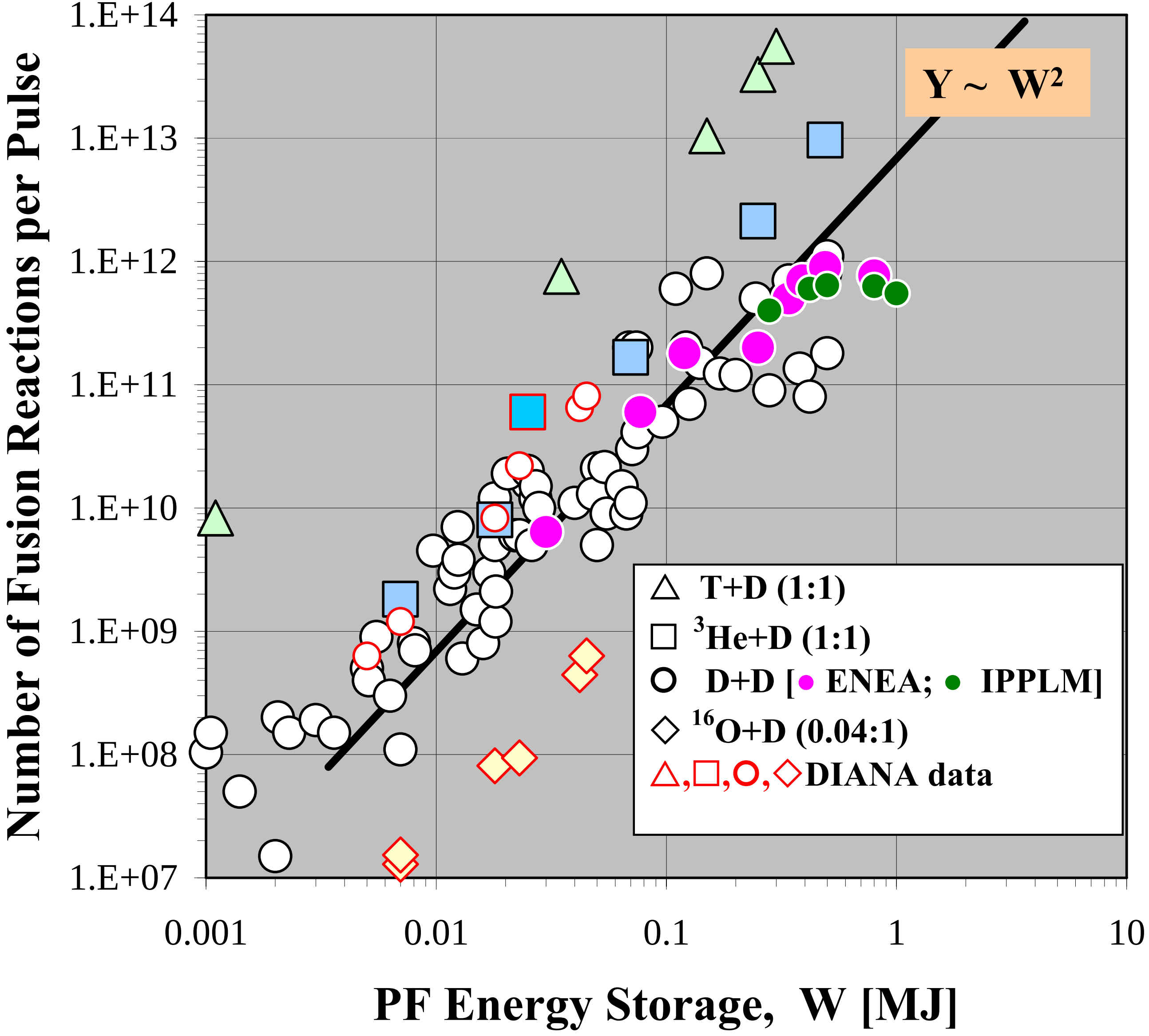
# PLASMA FOCUS

## SCALING with CURRENT



# PLASMA FOCUS

## SCALING with ENERGY



**Strong scattering of has two sources:**

1. **PF design/optimization**
2. **Method of data selection.**

**Above W= 0.5 MJ PF's have yield saturation effect.**

**Is it problem with current remaining on insulator or physics for sheath carrying more than 2 MA ??**

## ESTIMATE of BREAKEVEN

$$\boxed{Y_n = n \times \tau \times \langle \sigma v \rangle \times N_i}$$

**$Y_n$ - is the neutron yield per pulse;**

**n - is the plasma target density, $10^{19}/\text{cm}^3$, W independent;**

**$\tau \sim W^{0.7}$ - is the average confinement time of the $D^+$ and $T^+$ beams;**

**$\langle \sigma v \rangle \sim W^{0.5}$ - is the fusion reactivity;**

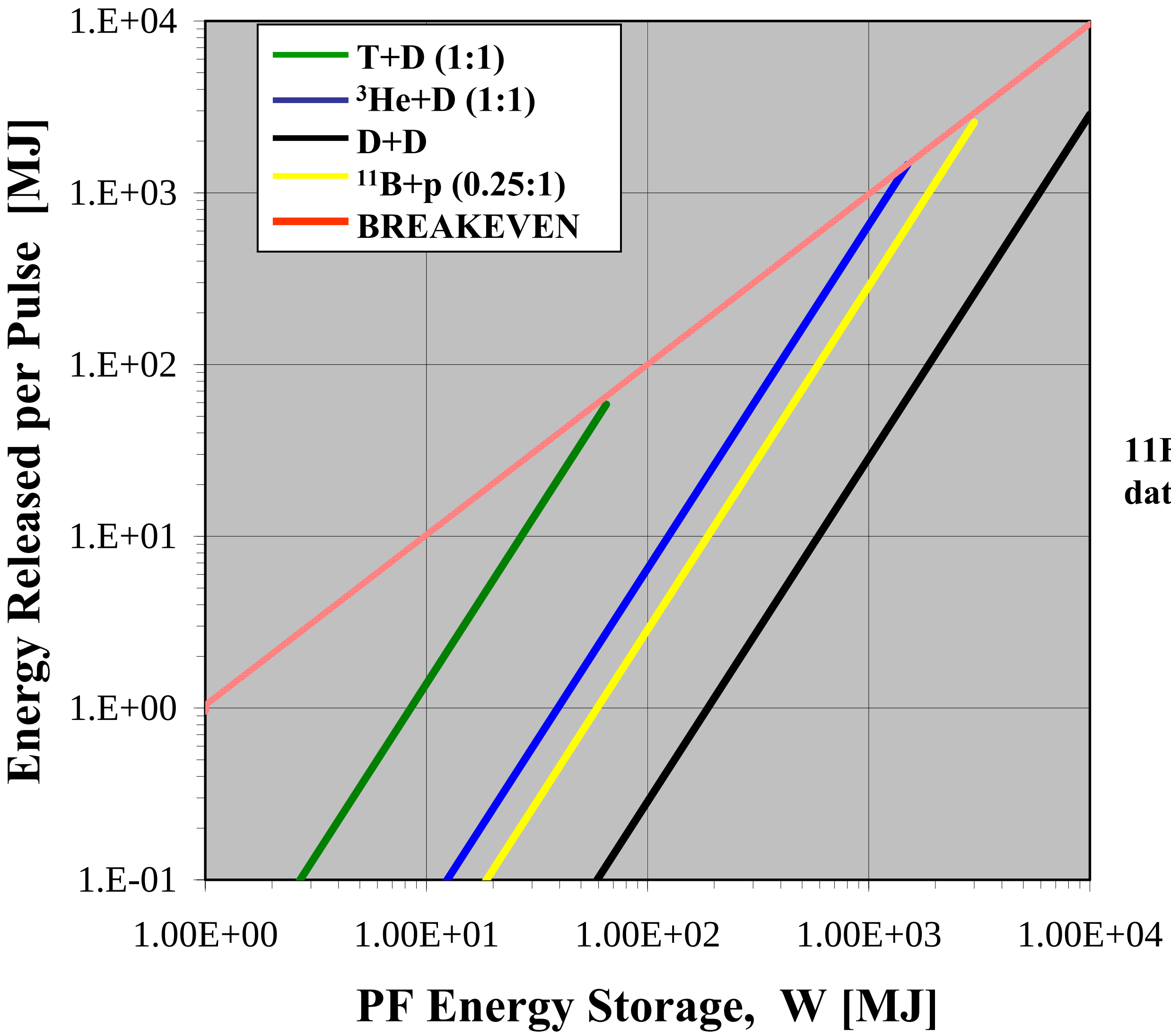
**$N_i = \gamma \times n \times V$**

- **$\gamma = 0.005$ – is the relative abundance of fast ions in plasma target; estimated from experimental data;**
- **$V \sim W^{0.8}$ - is the plasma target volume; very scanty data to substantiate W dependence as proposed.**

**So,**

$$\boxed{Y_n \sim W^{0.7} \times W^{0.5} \times W^{0.8} \sim W^2}$$

## ESTIMATE of BREAKEVEN from experiments W < 0.5 MeV



**11B+p scaling is derived from data on 16O(d,n)**

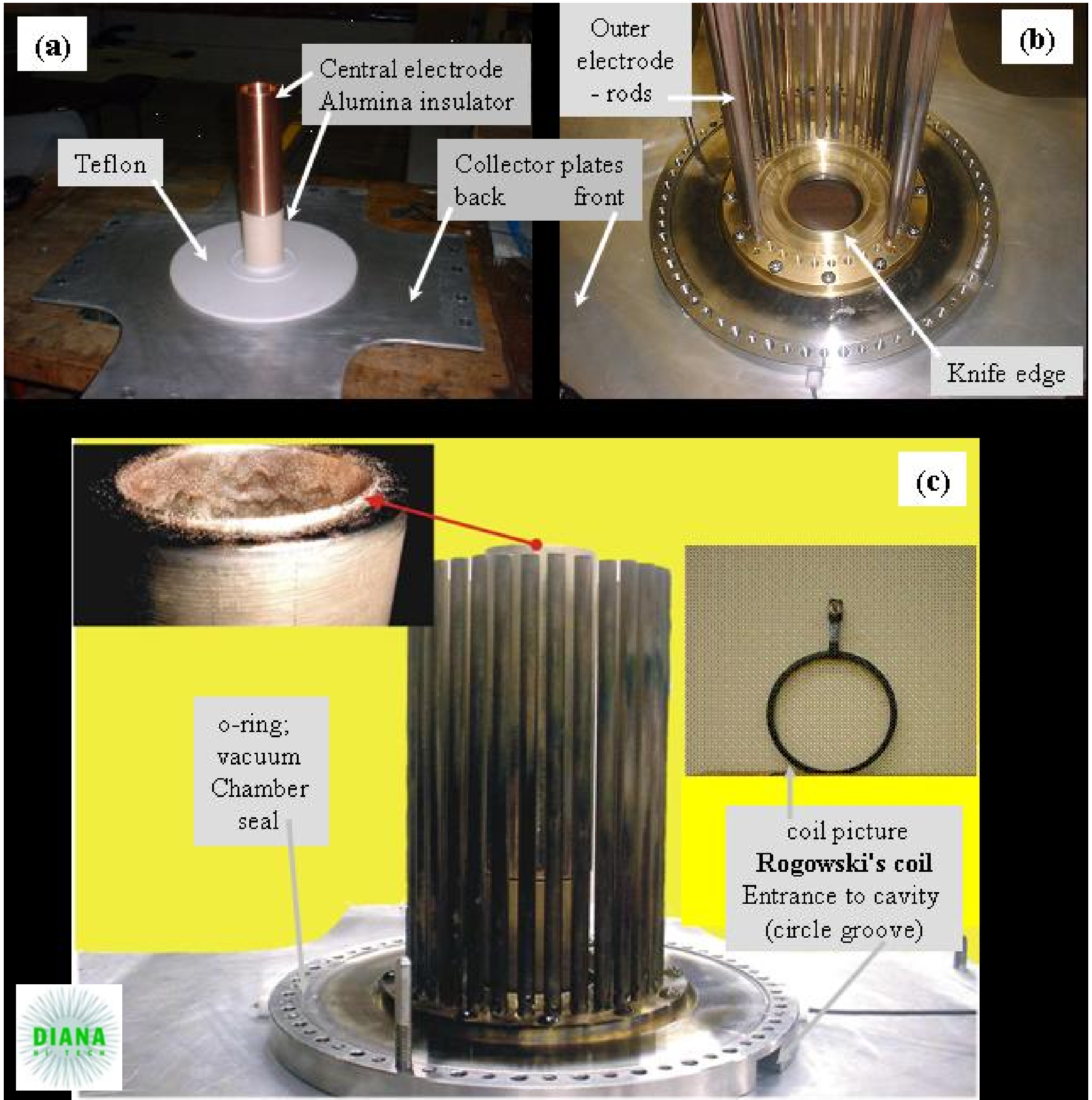
**Recently PF-50 has been built for variety of applications.**

**Target performance parameters:**

**$Y_n = 10^{11}$ 2.5 MeV neutrons/pulse, and/or**
**$Y_n = 10^{13}$ 14.7 MeV neutrons/pulse**
**$Y_R = 10^9$ radioisotopes/pulse; in gaseous form**
**FWHM = 50 ns**

**High reproducibility, clear engineering, potential for 1 Hz operation**

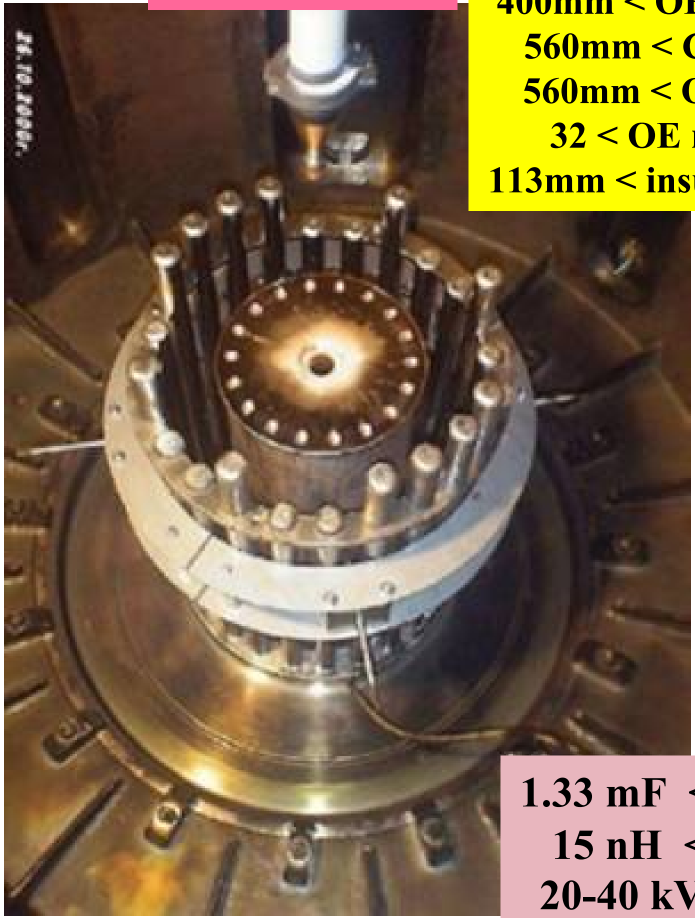
# PLASMA FOCUS



## PF-50 ELECTRODES

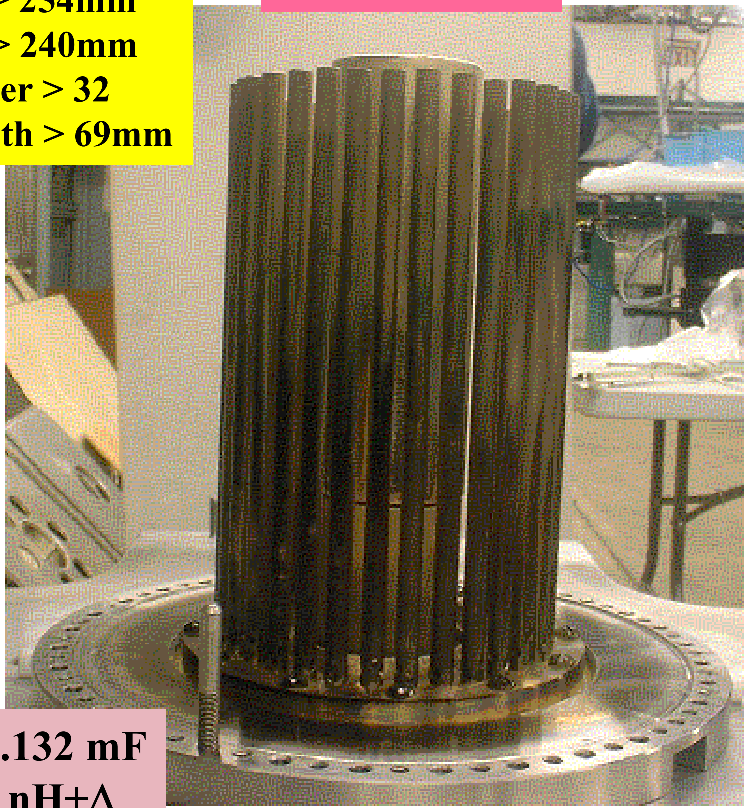
# PLASMA FOCUS

**1 MJ; Warsaw**



**226mm < CE diameter > 65mm**
**400mm < OE diameter > 140 mm**
**560mm < CE length > 254mm**
**560mm < OE length > 240mm**
**32 < OE rods number > 32**
**113mm < insulator length > 69mm**

**50 kJ; DIANA**



**1.33 mF < C > 0.132 mF**
**15 nH < $L_o$ > 25 nH+Δ**
**20-40 kV < V > 20-27 kV**
**6 μs < $T_{1/4}$ > 3.4 μs**
**2.6 mΩ < R > 8 mΩ**

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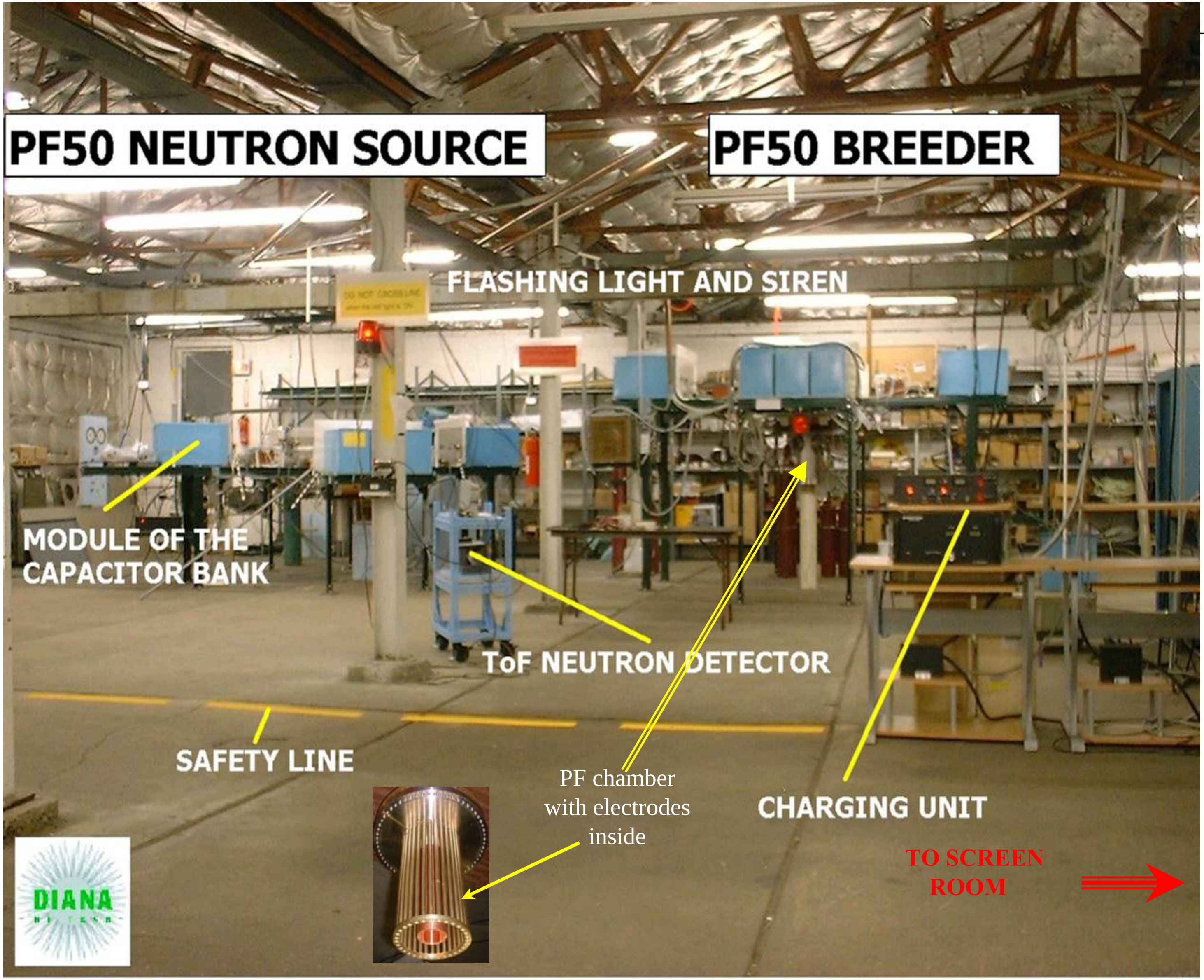
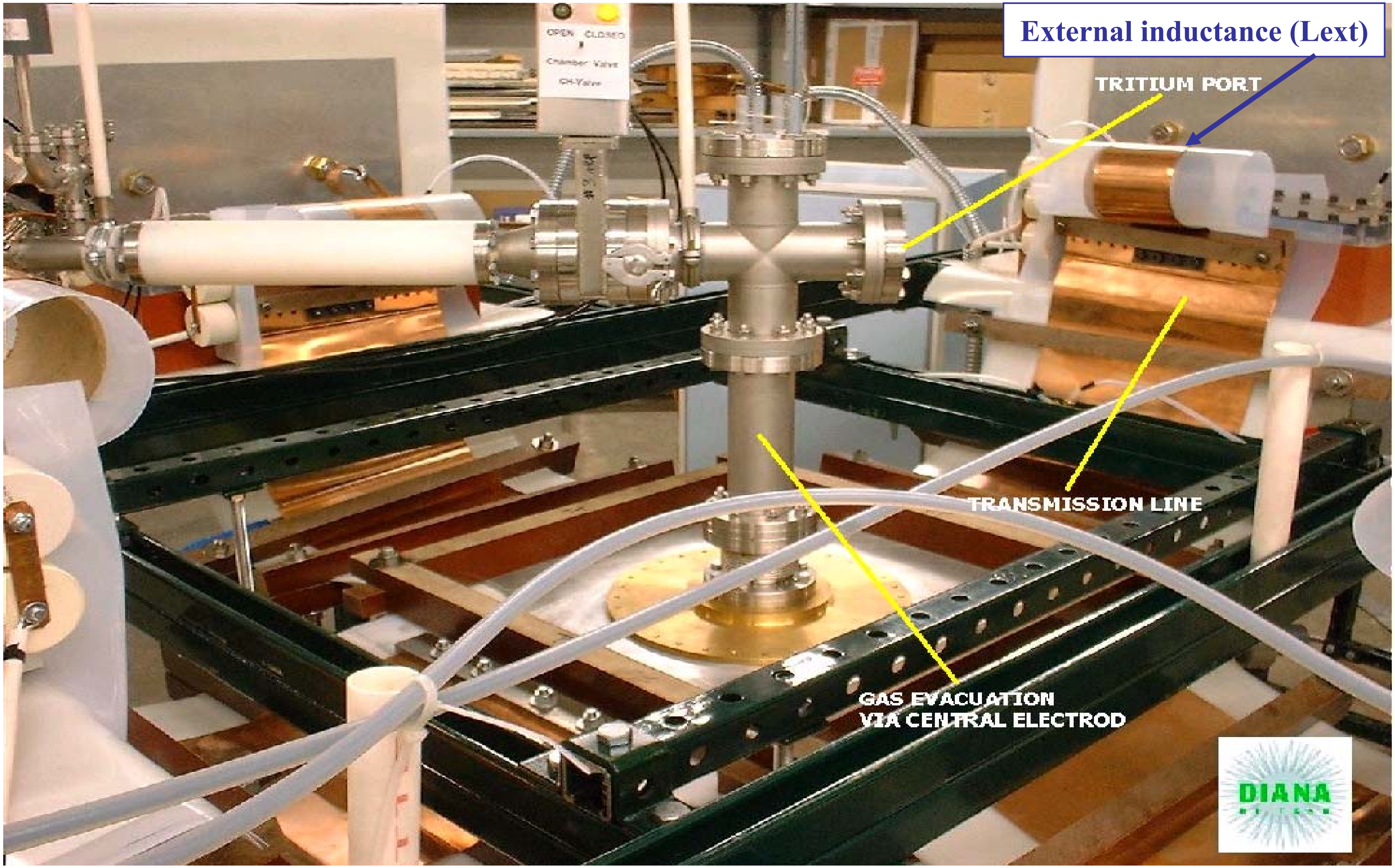
# PLASMA FOCUS



VIEW OF THE EXPERIMENTAL HALL (TWO PF50 ARE SEEN)

# PLASMA FOCUS



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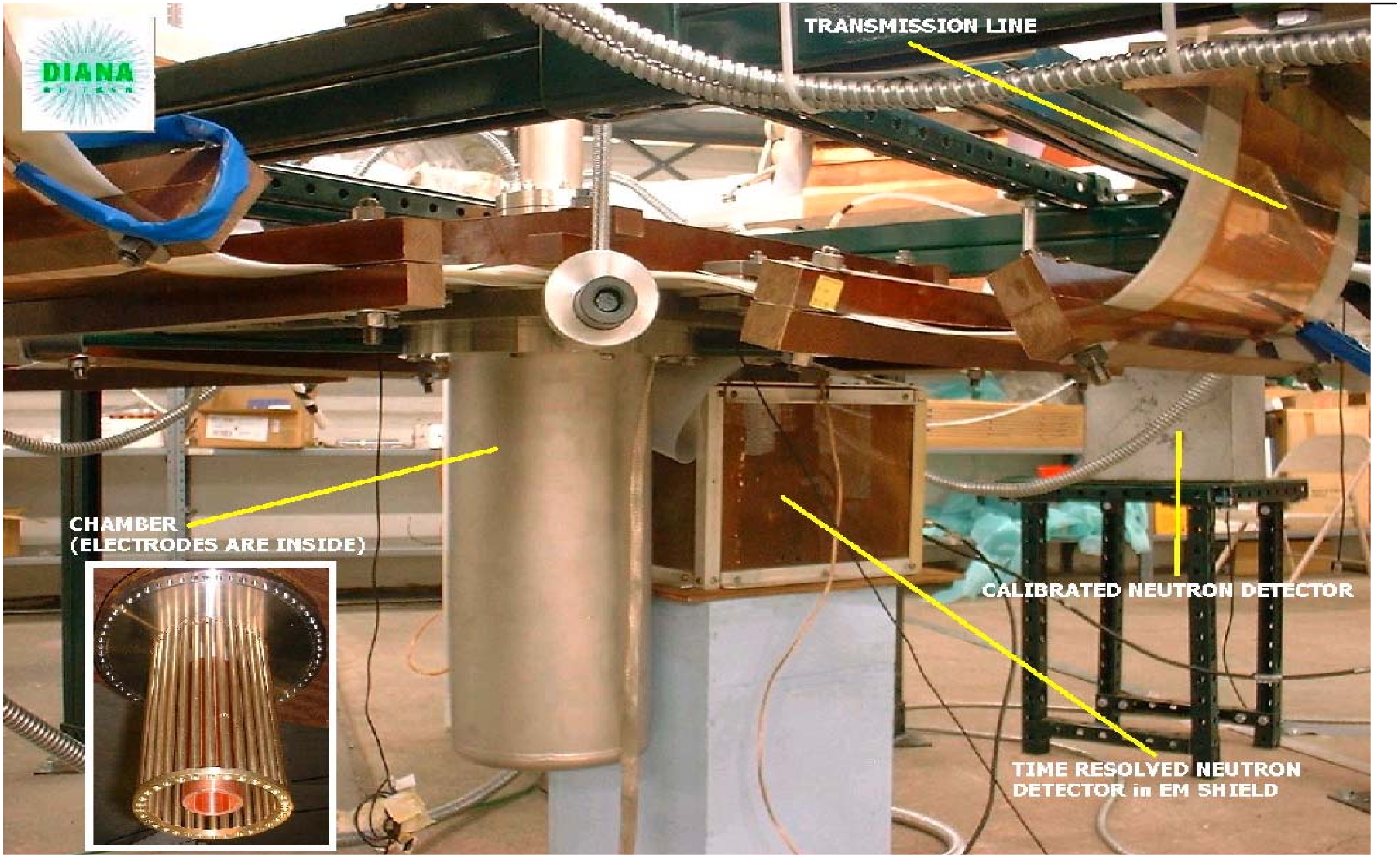

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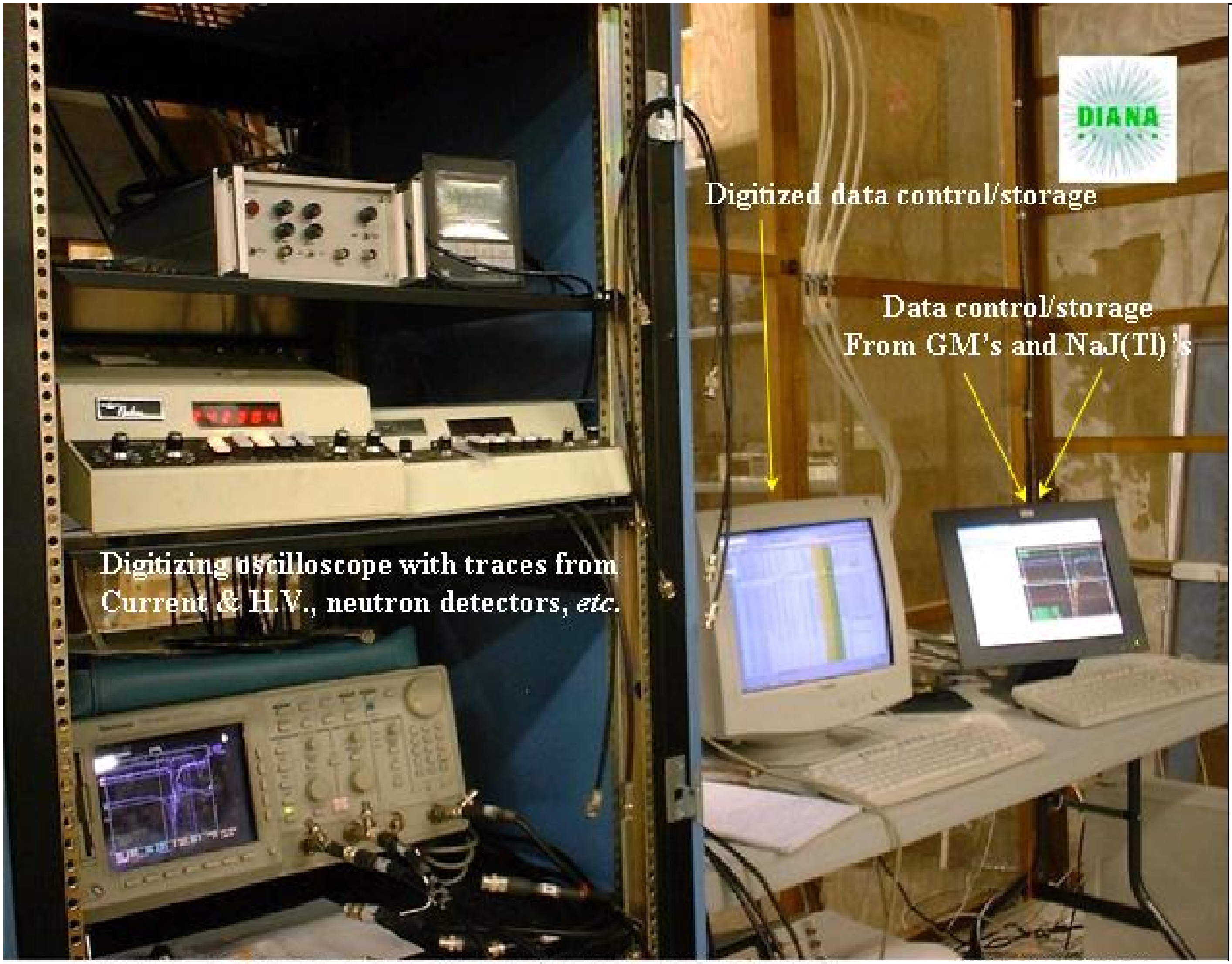

**DATA ACQUSITION ROOM (FARADAY'S CAGE)**

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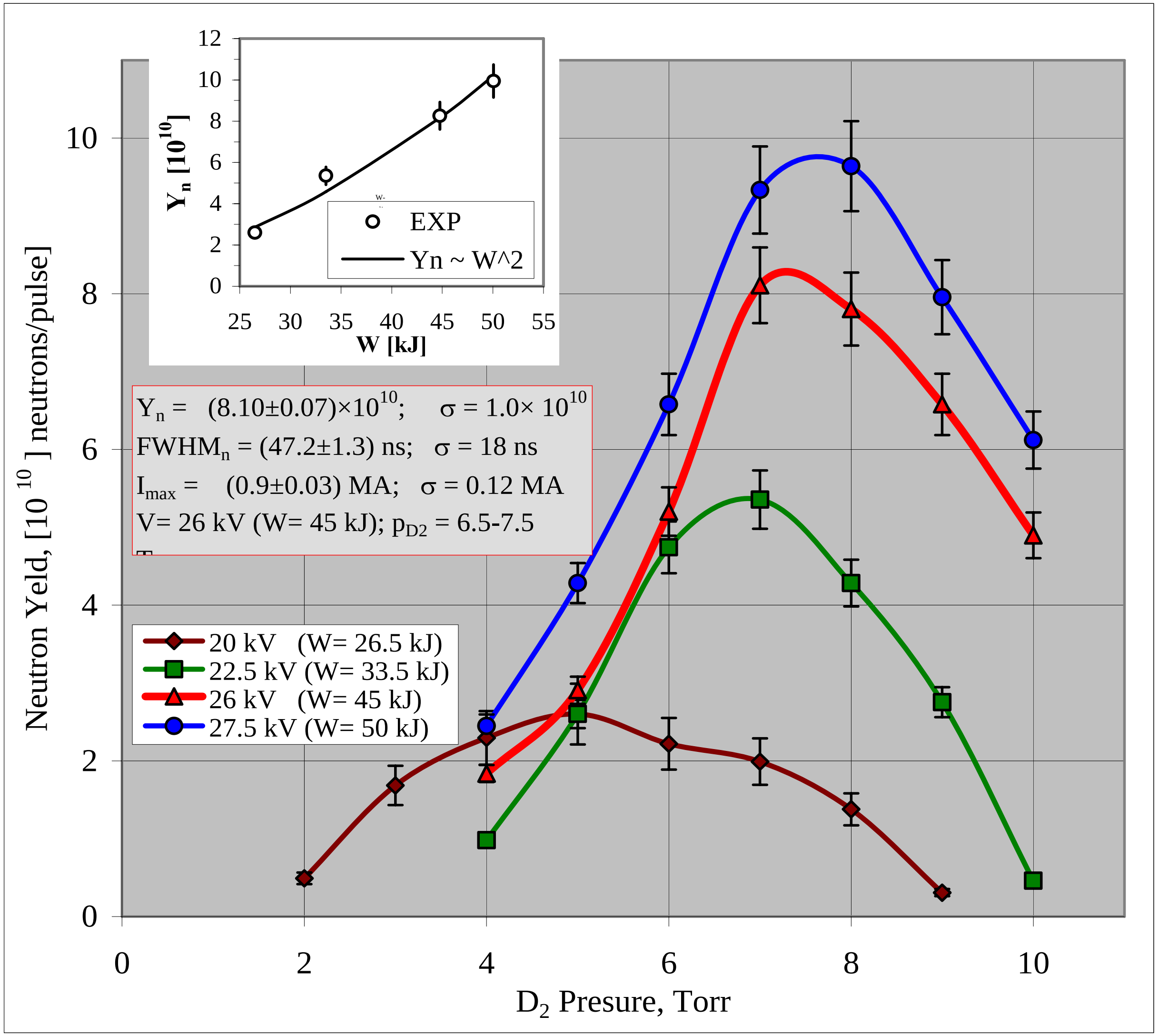
# PLASMA FOCUS

**PF-50 has operation range**
**W= 25- 50 kJ**



$Y_n$ = (8.10±0.07)×$10^{10}$; σ = 1.0× $10^{10}$
$FWHM_n$ = (47.2±1.3) ns; σ = 18 ns
$I_{max}$ = (0.9±0.03) MA; σ = 0.12 MA
V= 26 kV (W= 45 kJ); $p_{D2}$ = 6.5-7.5 T

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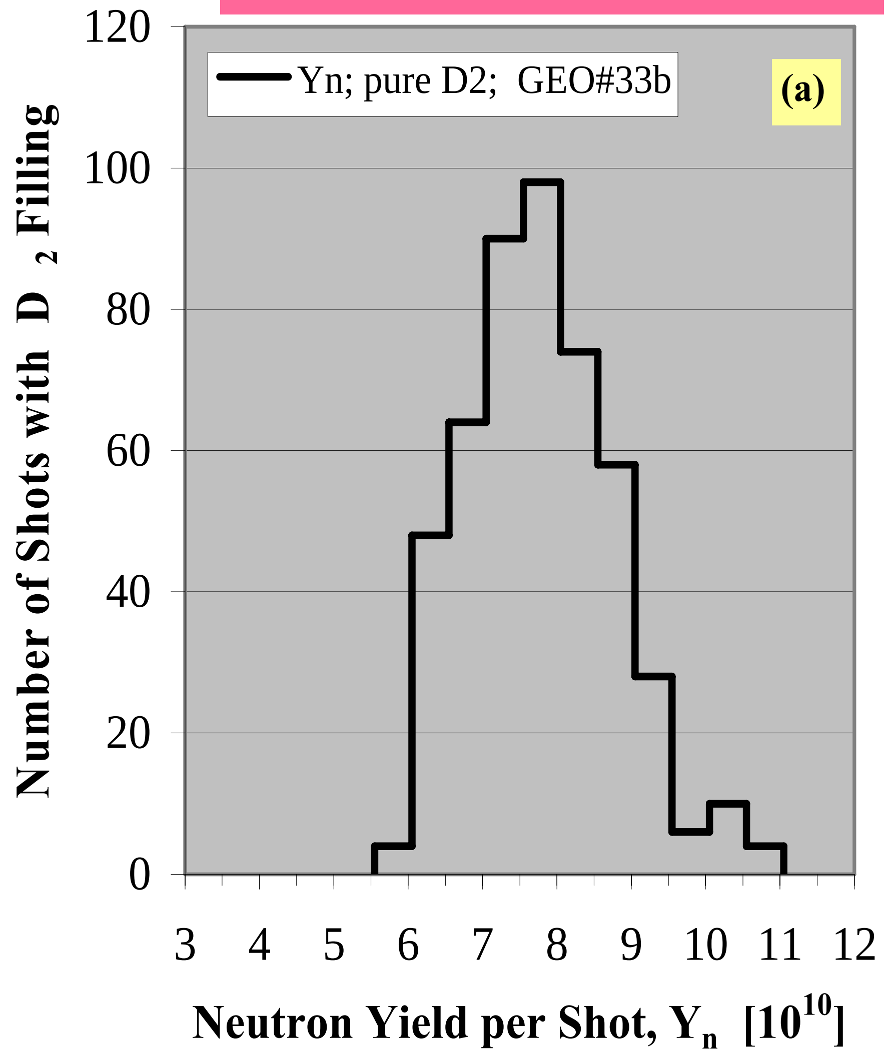
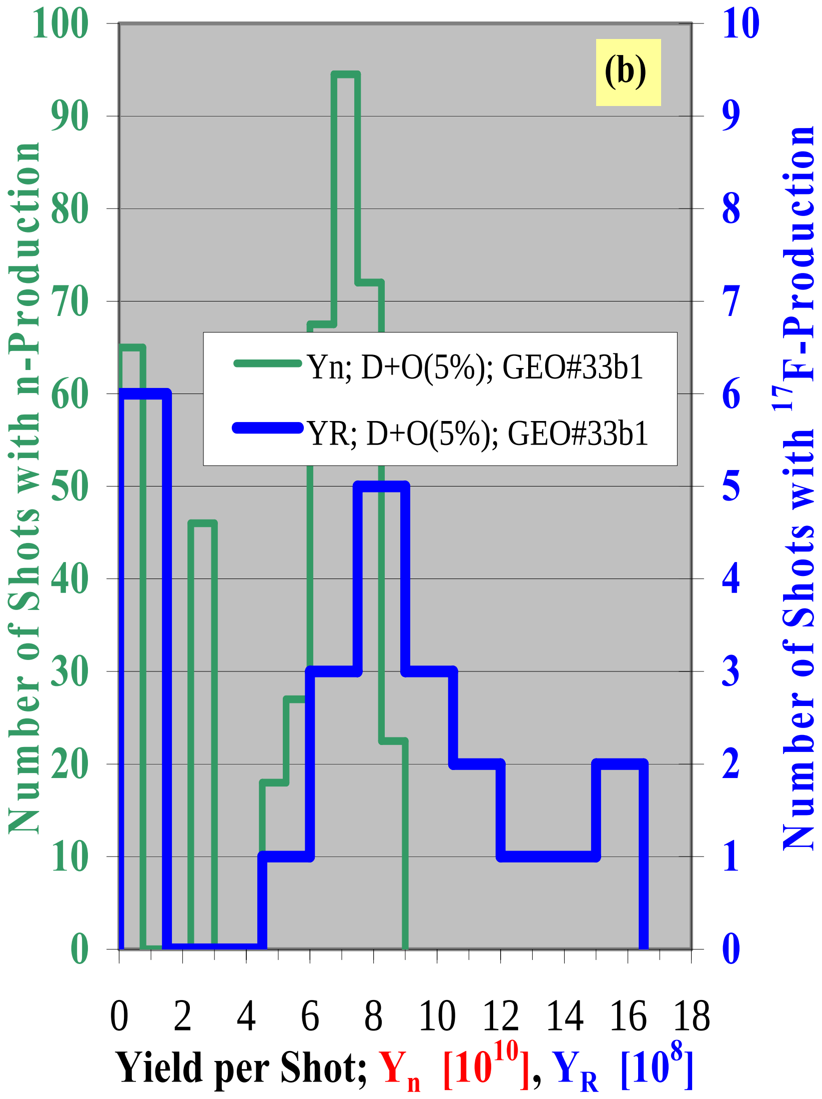
# PLASMA FOCUS

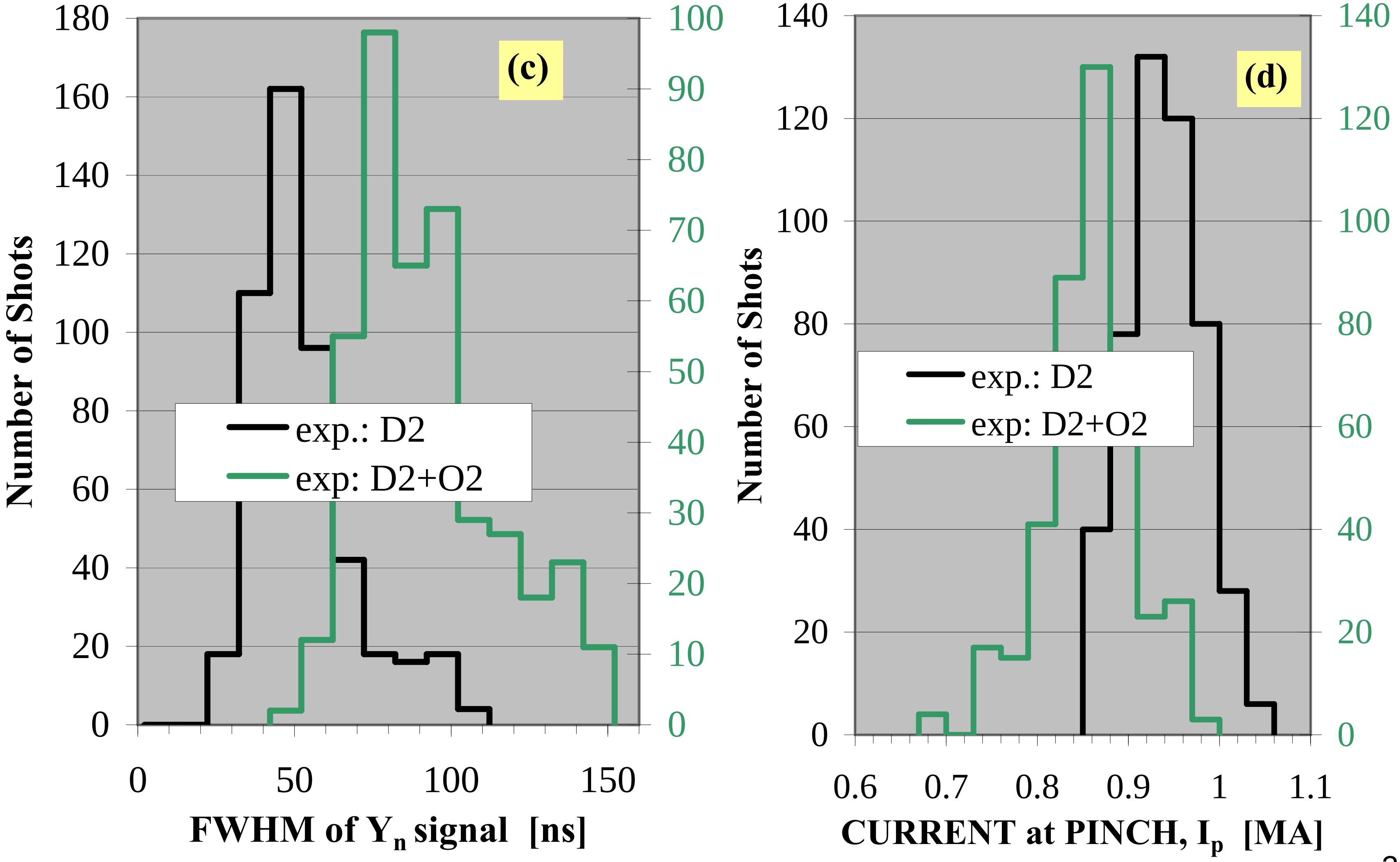
## STATISTICAL CHARACTERISTICS





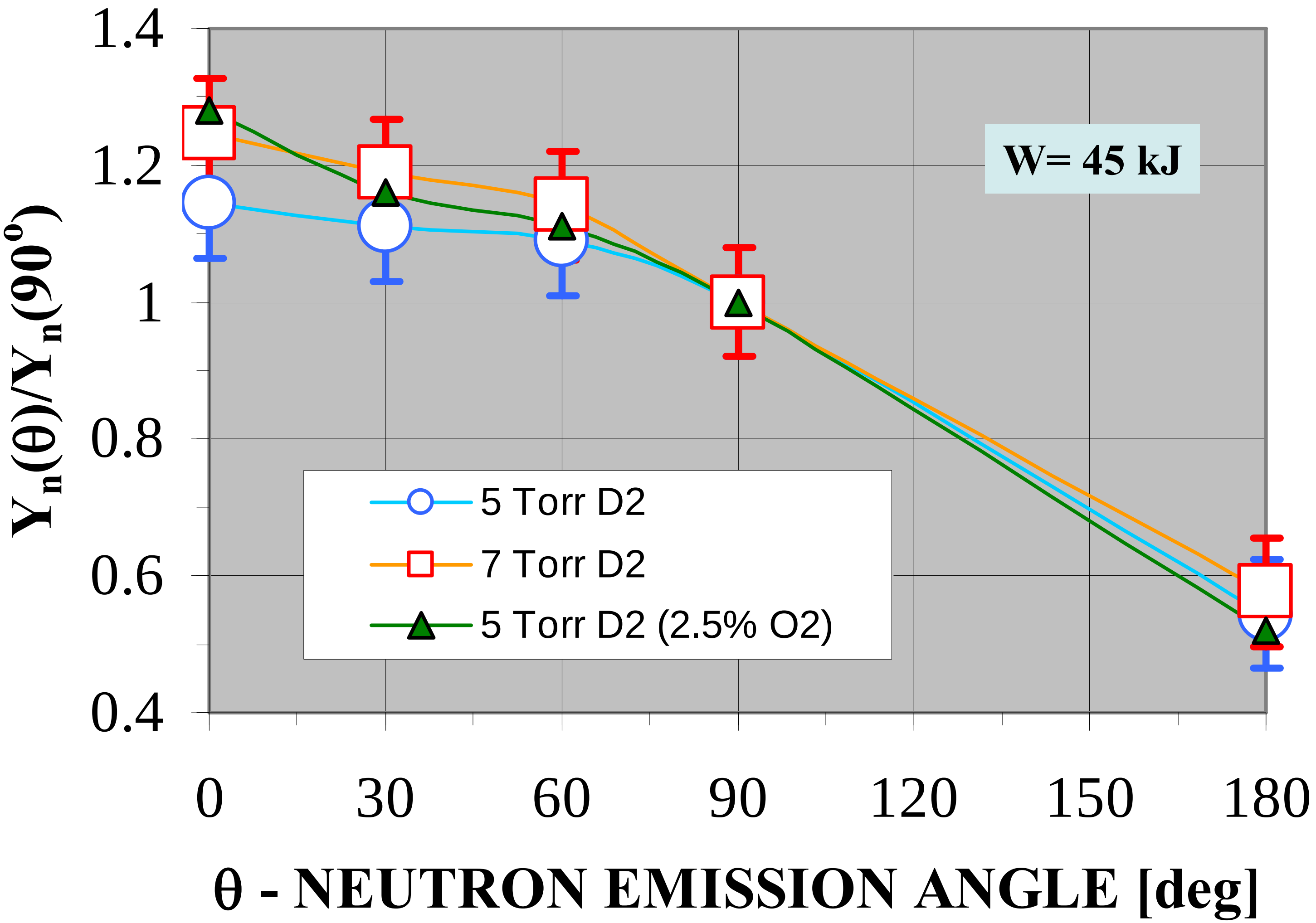
# PLASMA FOCUS

## STATISTICAL CHARACTERISTICS



# PLASMA FOCUS

## ANGULAR DISTRIBUTION OF NEUTRONS



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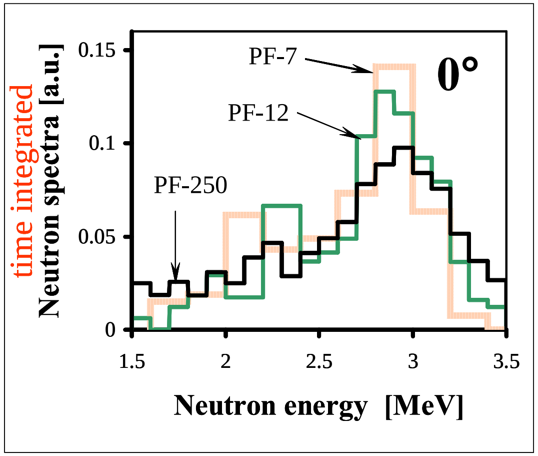
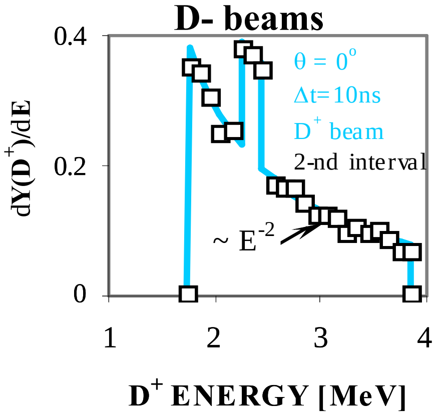
# PLASMA FOCUS

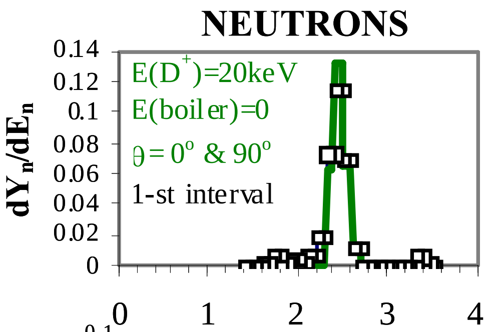
## MOVING BOILER

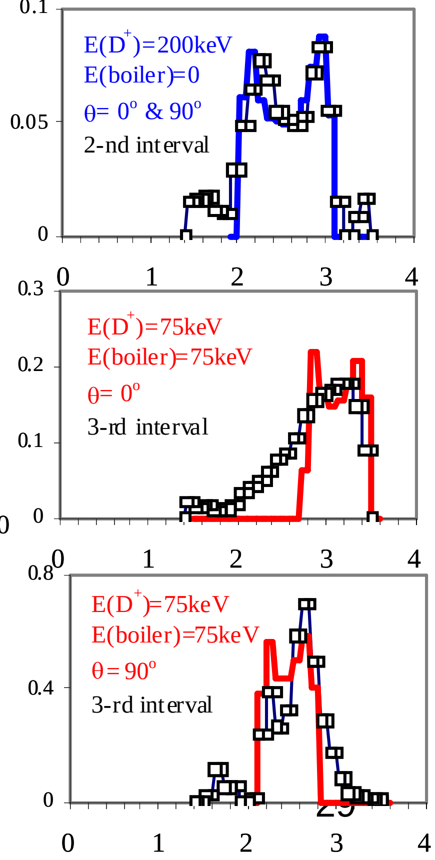


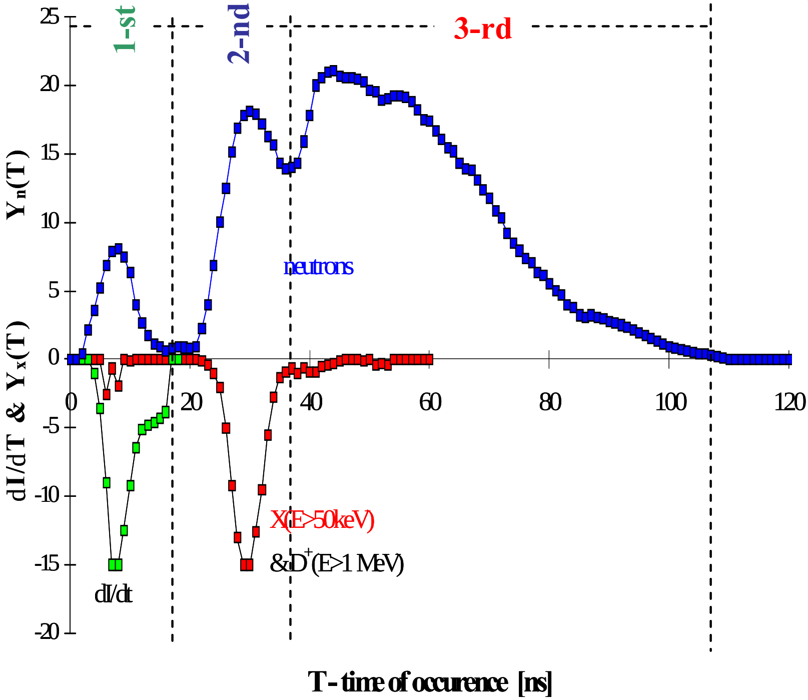
Time integrated neutron spectra: Measured at 0 deg. have maximum at $E_n \approx 3$ MeV; Measured at 90 deg. have symmetric maximum at $E_n \approx 2.45$ MeV; and FWHM ≈0.3-1 MeV; Measured at 180 deg. have maximum at $E_n \approx 2.1$ MeV.

*Conclusion*: neutrons emitting plasma moves axially with speed equivalent to 30-40 keV/nucleon

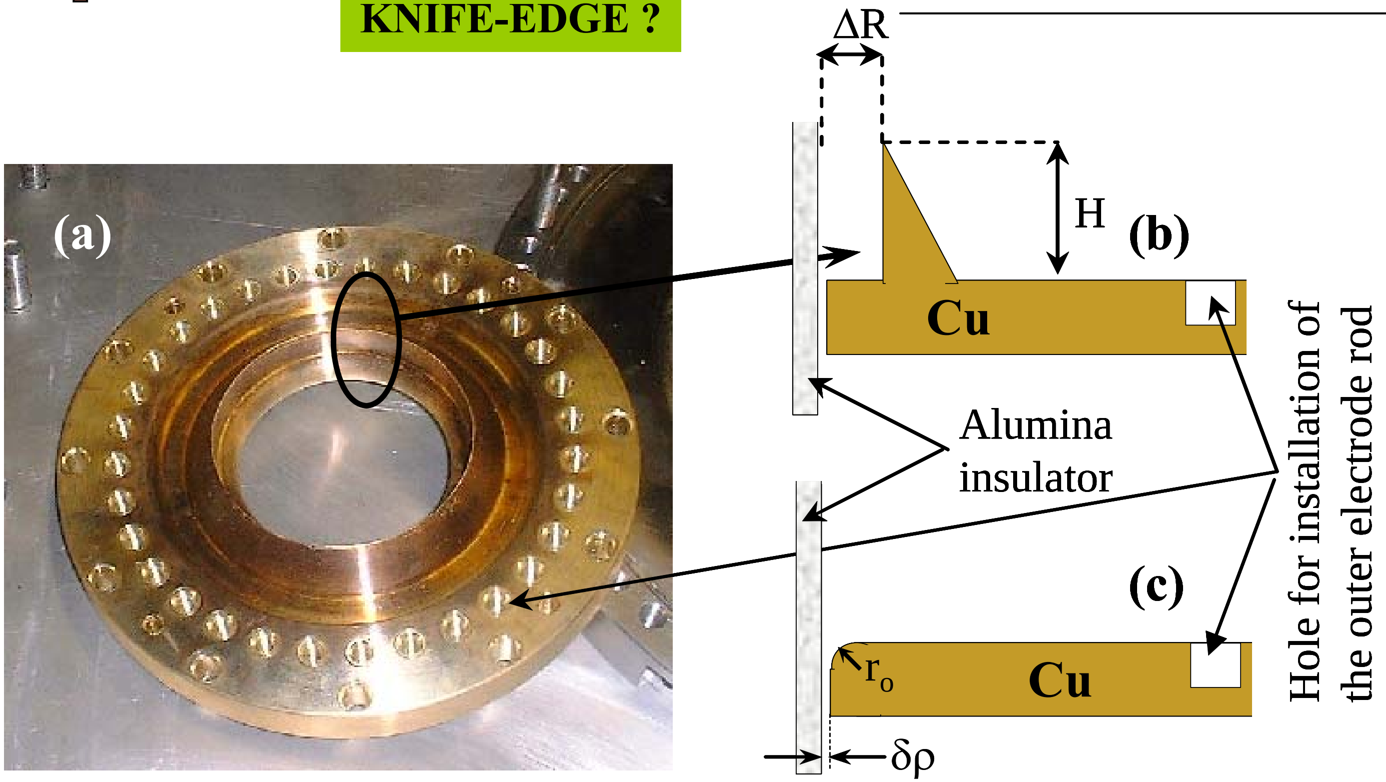






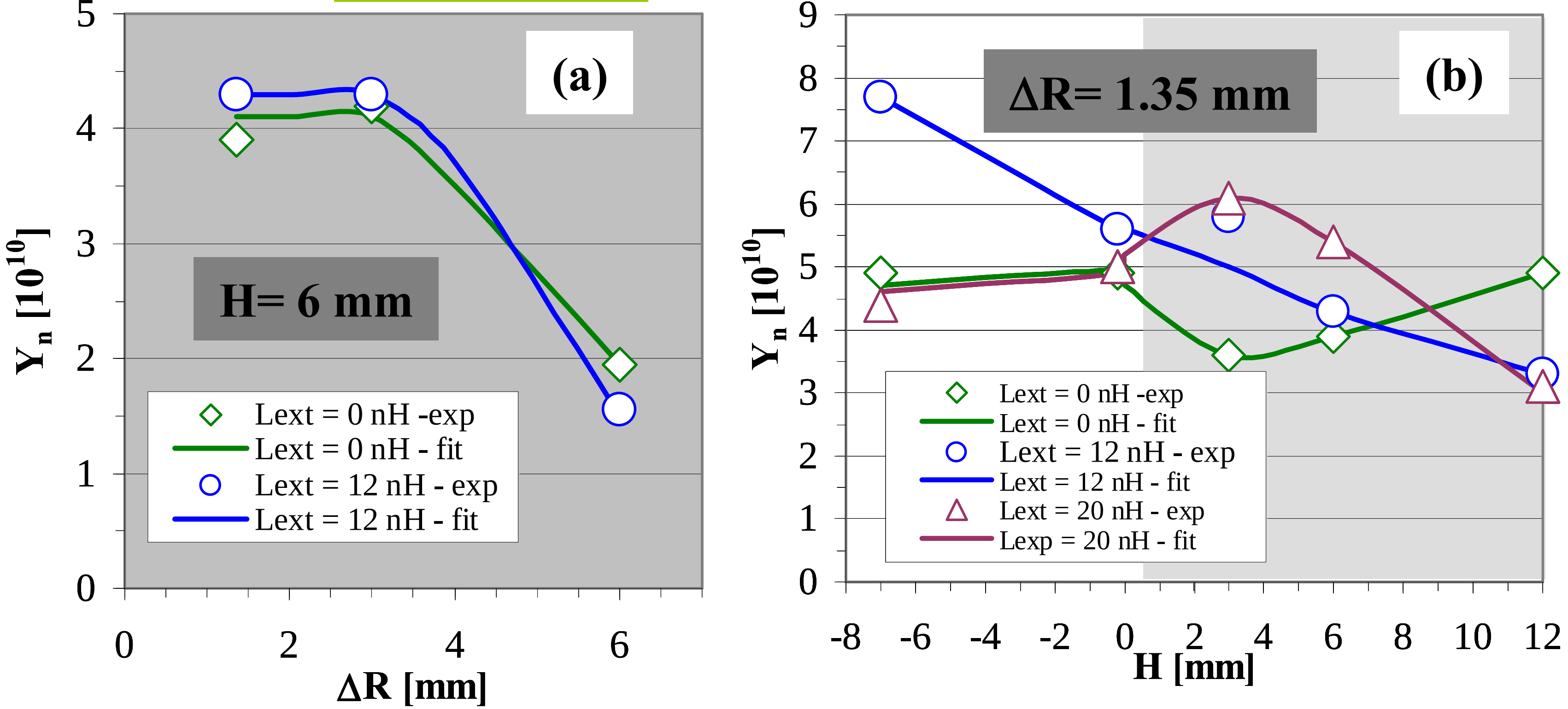


## KNIFE-EDGE ?



Details of *knife-edge*. Design of a knife-edge is shown in (b). (c) Shows case when front plate has rounded edge with radius $r_0$; usually $r_0$ = 0.01-5 mm. Spacing between insulator and front plate is about 0.1 mm. Length of insulator is counted from upper surface of the front plate.

# KNIFE-EDGE ?



Some trends in neutron yield vs. design parameters of a knife edge. (a) shows $Y_n(\Delta R)$ – ΔR is the distance between insulator and the knife edge; (b) shows $Y_n(H)$ – H is the height of the knife edge. In (b) are included results for the “negative knife-edge”; $r_0$ instead of H is used. Experimental data show average $Y_n$ values as measured for optimum of filling gas pressure. Smooth curves connect points of the same series.

**Best operation at 45 kJ requires installation of a negative knife-edge !!**

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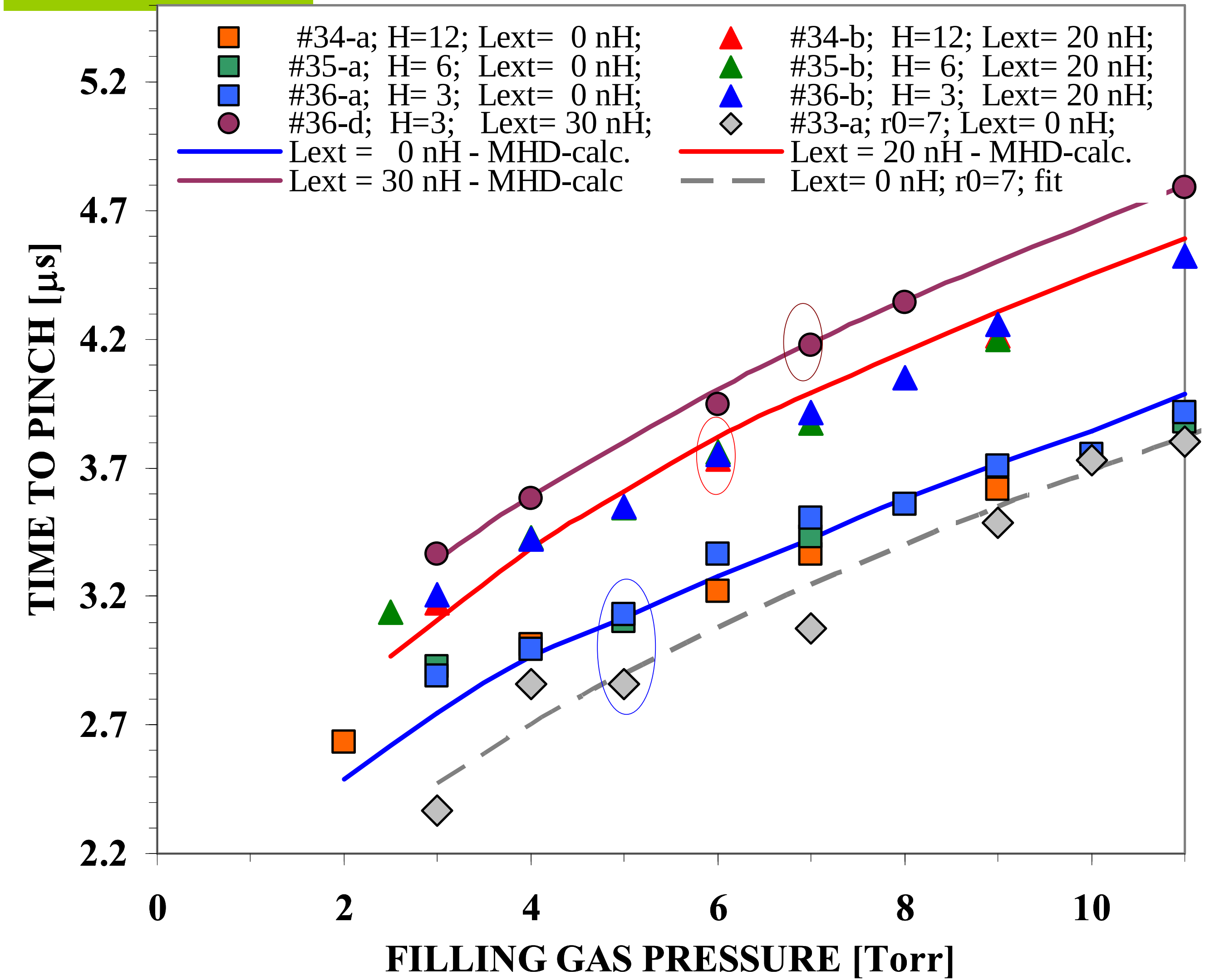
# PLASMA FOCUS

## KNIFE-EDGE ?



Marked points represent conditions (gas pressure) for best neutron production

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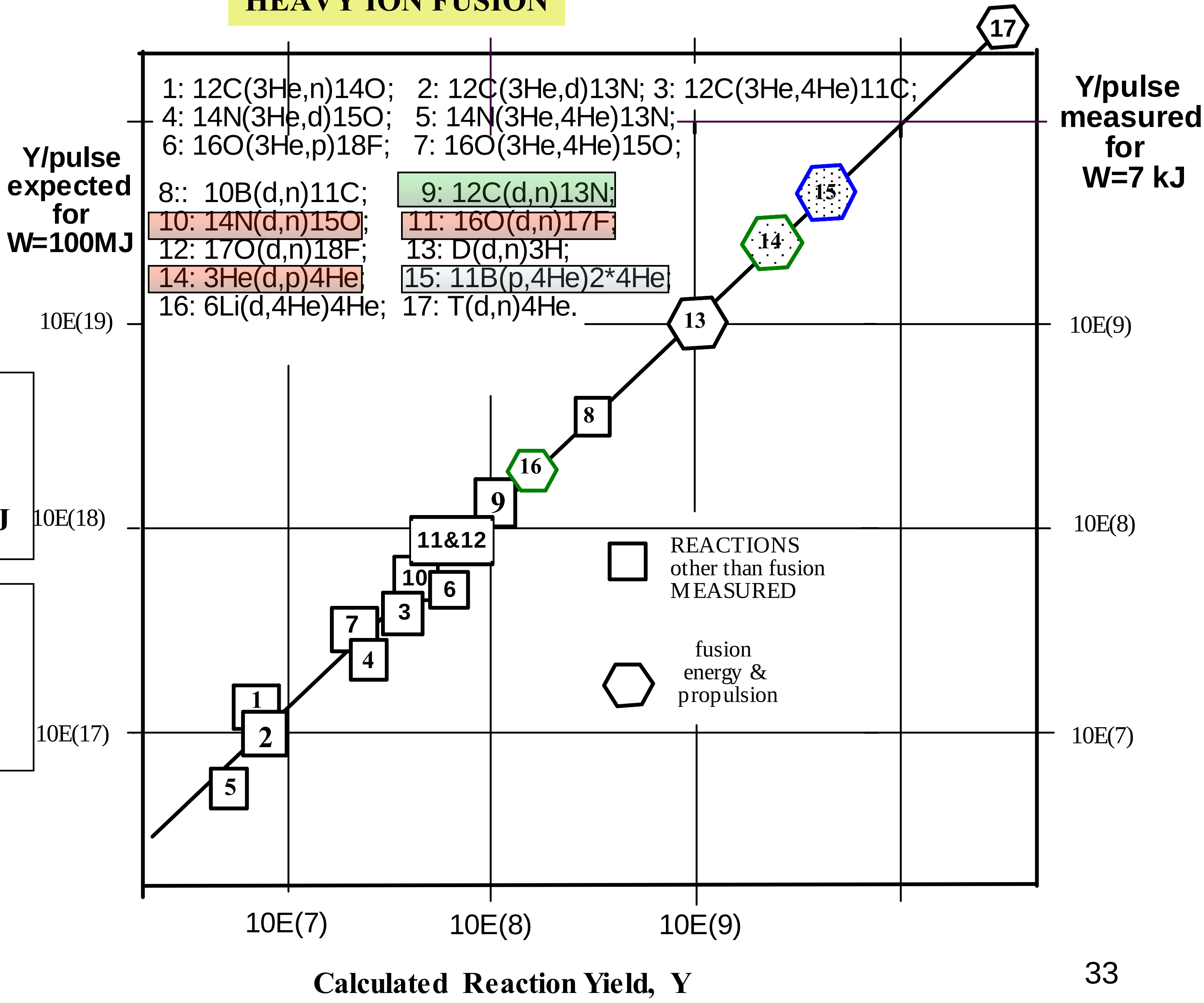
# PLASMA FOCUS

## HEAVY ION FUSION



1: 12C(3He,n)14O; 2: 12C(3He,d)13N; 3: 12C(3He,4He)11C;
4: 14N(3He,d)15O; 5: 14N(3He,4He)13N;
6: 16O(3He,p)18F; 7: 16O(3He,4He)15O;
8:: 10B(d,n)11C; 9: 12C(d,n)13N;
10: 14N(d,n)15O; 11: 16O(d,n)17F;
12: 17O(d,n)18F; 13: D(d,n)3H;
14: 3He(d,p)4He; 15: 11B(p,4He)2*4He;
16: 6Li(d,4He)4He; 17: T(d,n)4He.

*W= 7 kJ; 50% HZ & 50% LZ; Y ~ W^2*

🟥 **Reactions additionally confirmed for W= 18, 45 kJ**

🟩 **Reaction additionally confirmed for W= 18 kJ**

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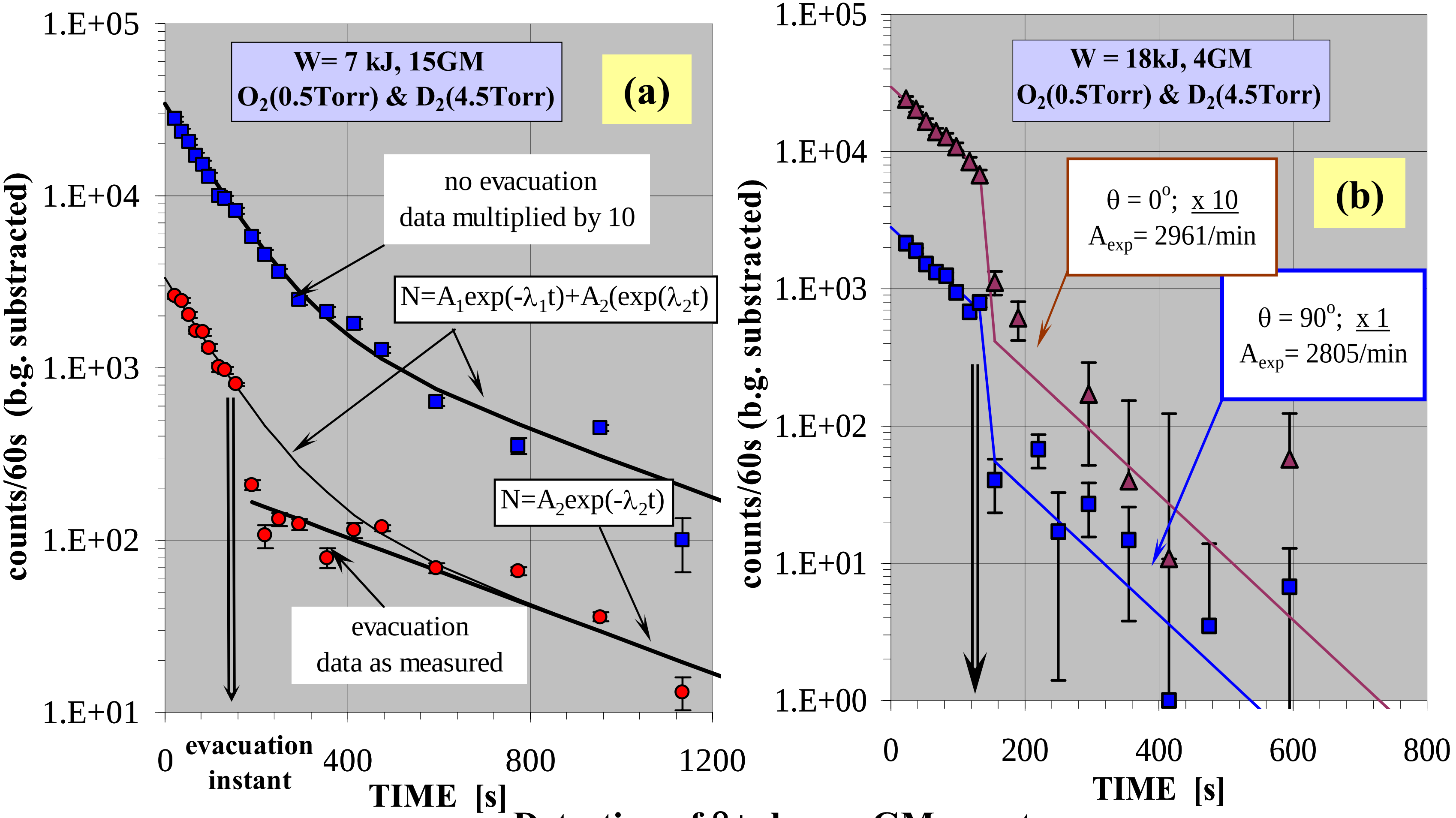
# PLASMA FOCUS

## HEAVY ION FUSION



**Detection of β+ decay; GM counters**

**10 folds decrease of radioactivity after evacuation proves plasma origin the radioisotopes production**

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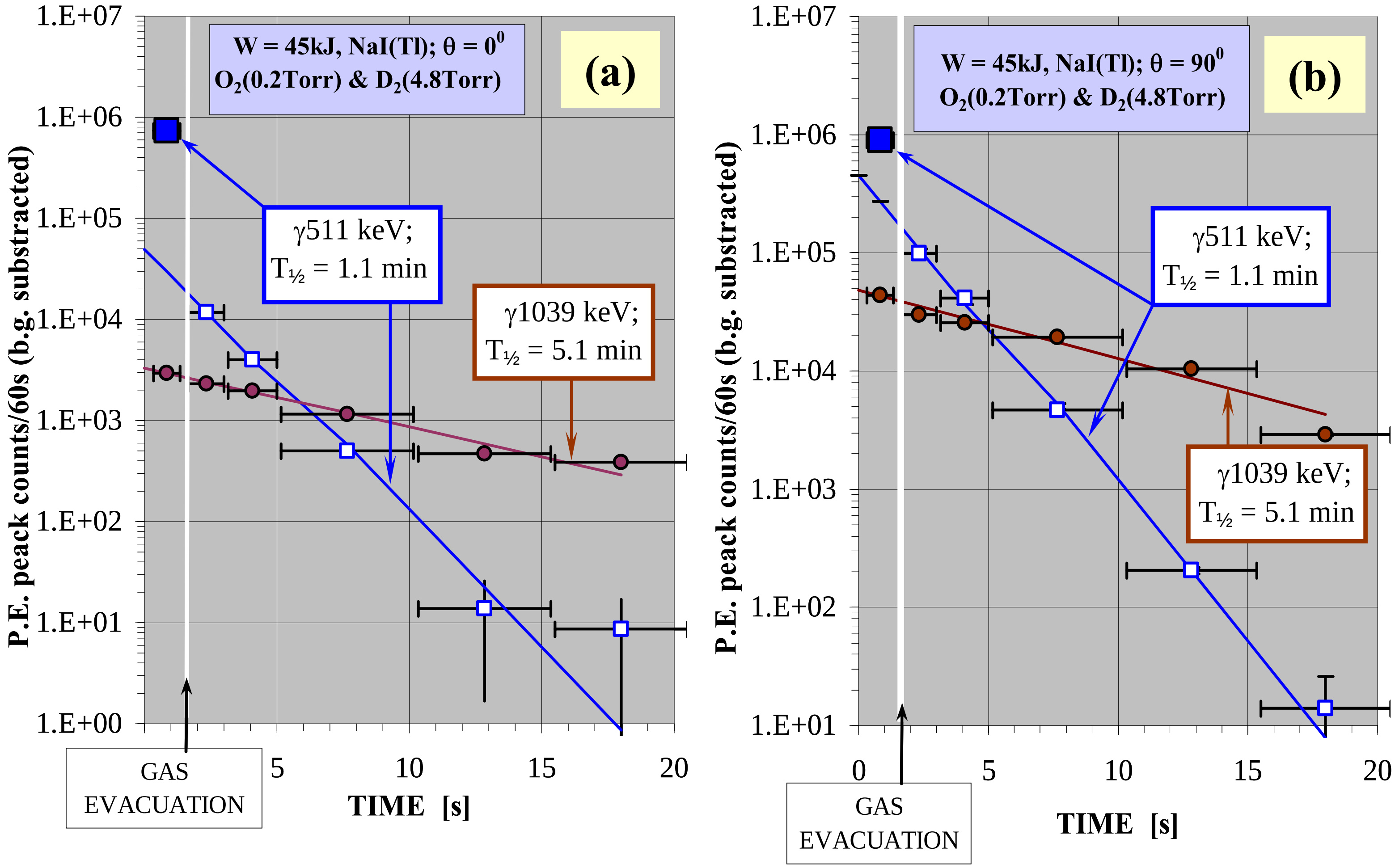
## HEAVY ION FUSION



**γ detection with NaI(Tl)**

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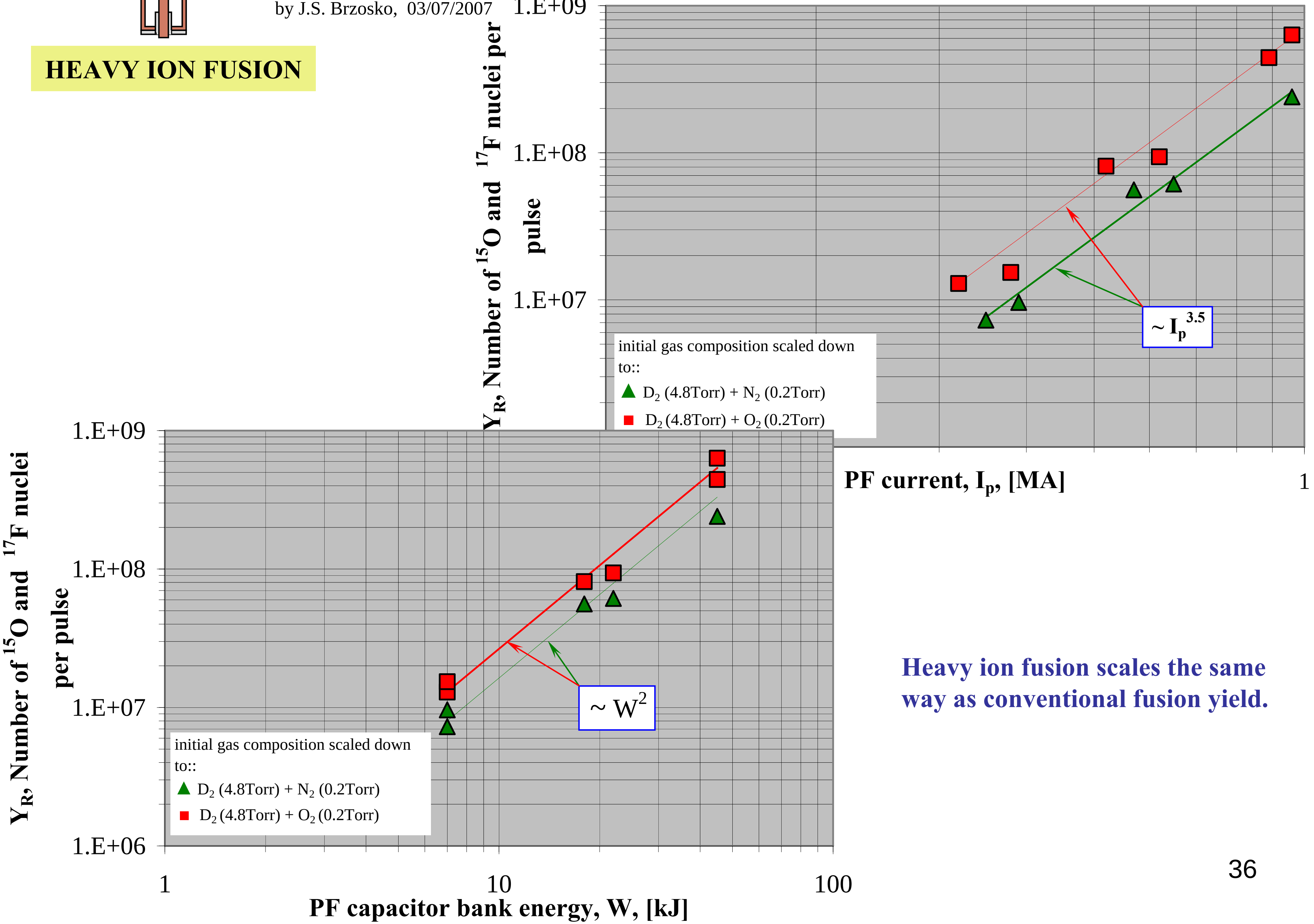
# PLASMA FOCUS

## HEAVY ION FUSION



**Heavy ion fusion scales the same way as conventional fusion yield.**

## CONCLUSIONS FROM PF-50 PROGRAM:

- **Pulsed Power:: PF-50kJ can be build to work without failure for $10^7$ shots at 1 Hz; limiting factors: energy and life time.**
- **Reproducibility of pulses (yield, duration): very good.**
- **Electrode erosion:: not limiting factor;**
- **Deuterium or Tritium circulation:: not limiting factor;**
- **Cooling:: not limiting factor;**
- **Tritium/deuterium leak:: requirement for certain temperature window (for chamber).**
- **System ready for engineering version.**