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School and Training Course on Dense Magnetized Plasma as a Source of Ionizing Radiations, their Diagnostics and Applications

8 - 12 October 2012

Introduction to the DPF - Machines, Applications and Properties

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Introduction to the DPF-Machines, Applications and Properties

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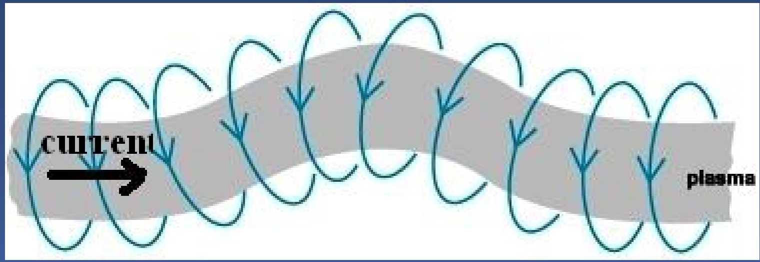
Plan of Talk

- Magnetic compressions- mechanism of the PF and advantages
- PF devices
- Some applications
- General Results of decades of Research
- Modelling and Numerical Experiments
- Scaling Properties of the Plasma Focus

When matter is heated to high temperatures:

- It ionizes and becomes a plasma; emitting radiation
- Generally, the higher the temperature T and density n, the more intense the radiation
- Depending on heating mechanisms, beams of ions and electrons may also be emitted
- In Deuterium, nuclear fusion may take place, if n & T are high enough; neutrons are also emitted.
- Typically T> several million K; & compressed n: above atmospheric density.

One method: electrical discharge through gases.



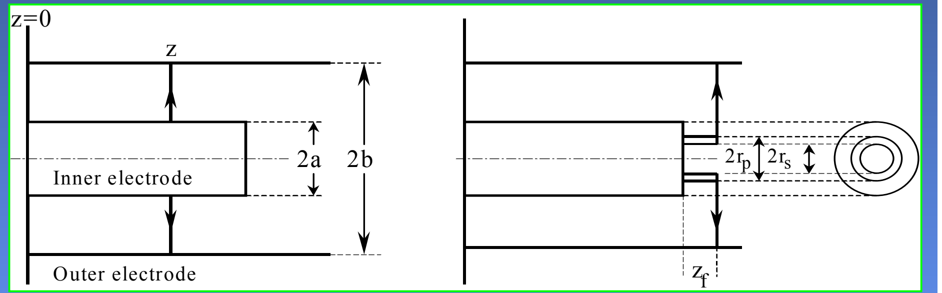
- **Heated gas expands**, lowering the density; making it difficult to heat further.
- **Necessary to compress** whilst heating, to achieve sufficiently intense conditions.
- **Electrical discharge between two electrodes** produces azimuthal magnetic field which interacts with column of current; giving rise to a **self compression** force which tends to constrict (or **pinch**) the column.
- To **'pinch'** a column of gas to atmospheric density at T~ 1 million K, a rather large pressure has to be exerted by the pinching magnetic field.
- Electric current **of hundreds of kA** required, even for column of radius of say 1mm.
- **Dynamic pinching** process requires current to rise very rapidly, typically in under **0.1 microsec** in order to have a sufficiently hot and dense pinch.
- **Super-fast, super-dense pinch; requires special MA fast-rise (nanosec) pulsed-lines**; **Disadvantages**: conversion losses & cost of high technology pulse-shaping line, additional to the capacitor.

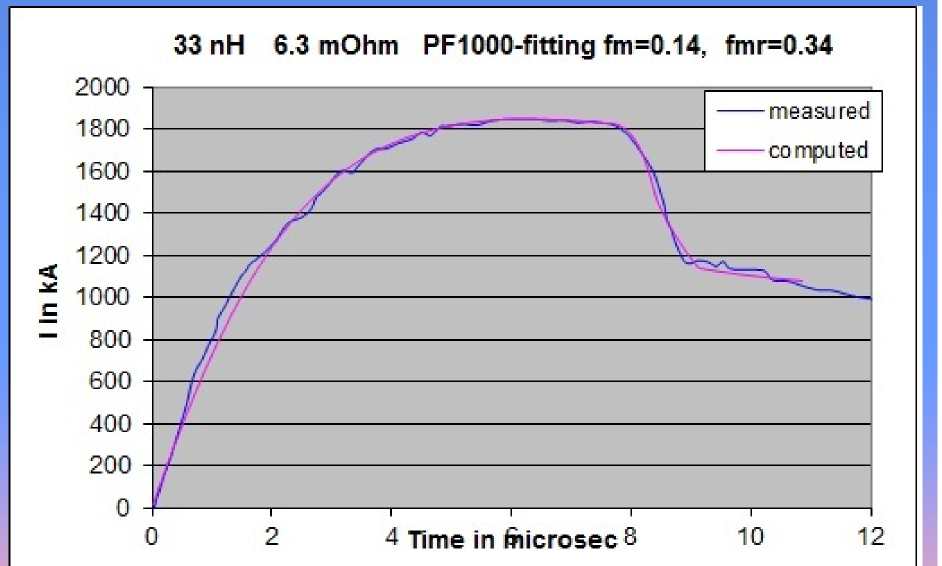
Superior method for super-dense-hot pinch: plasma focus (PF)

- The PF produces superior densities and temperatures.
- 2-Phase mechanism of plasma production does away with the extra layer of technology required by the expensive and inefficient pulse-shaping line.
- A simple capacitor discharge is sufficient to power the plasma focus.

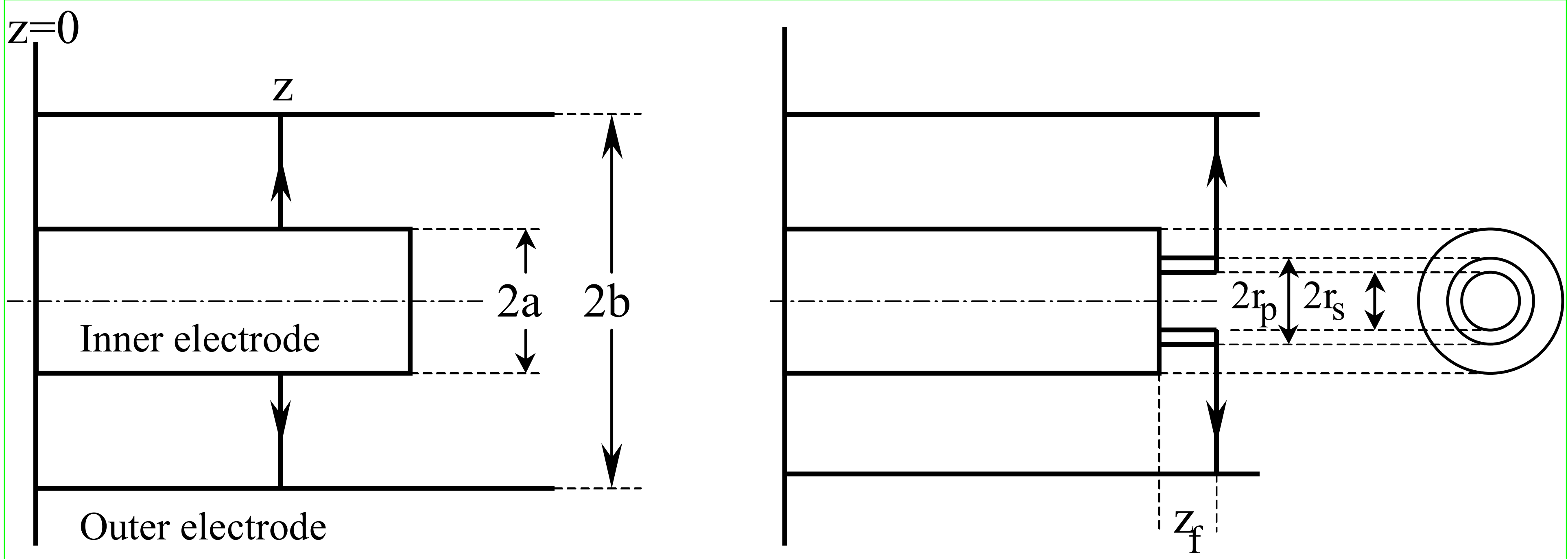
THE PLASMA FOCUS

- The PF is divided into two sections.
- Pre-pinch (axial) section: Delays the pinch until the capacitor discharge approaches maximum current.
- The pinch starts & occurs at top of the current pulse.
- Equivalent to driving the pinch with a super-fast rising current; without necessitating fast line technology.
- The intensity which is achieved is superior to even the super fast pinch.

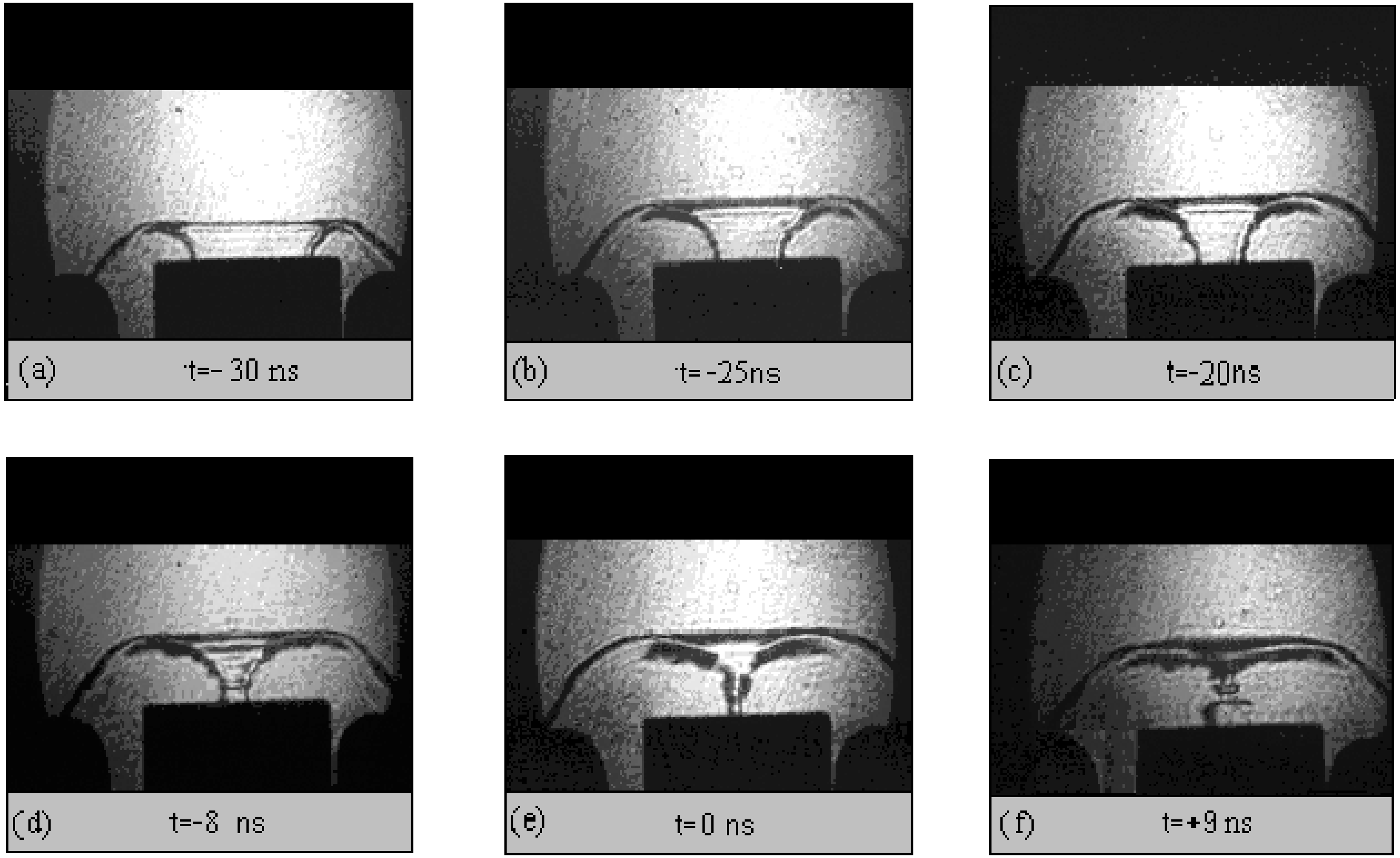




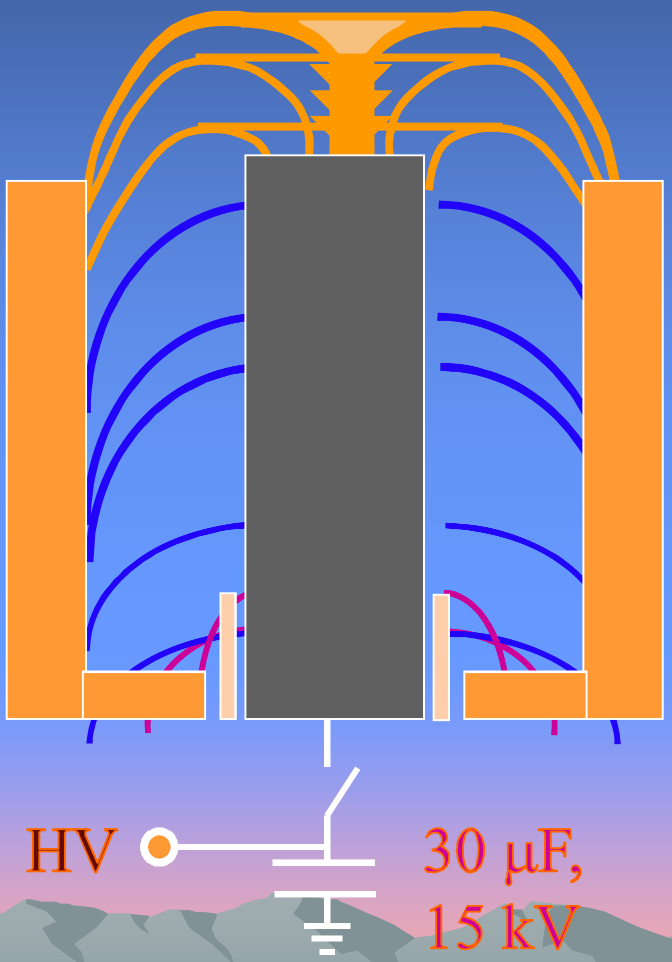
Two Phases of the Plasma Focus



Radial Compression (Pinch) Phase of the Plasma Focus



The Plasma Dynamics in Focus - Rajdeep



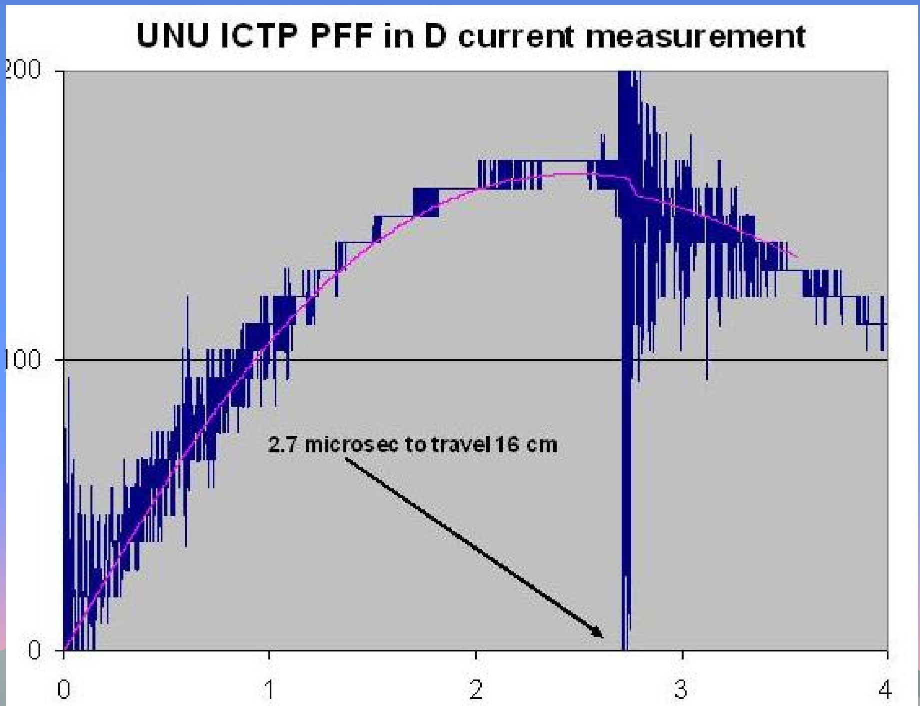
Radial Phase

Axial Acceleration Phase

Inverse Pinch Phase

Basic information from simple measurements

- Speed is easily measured; e.g
- From current waveform



16 cm traversed in 2.7 us

Av speed=6 cm/us

Form factor= 1.6

Peak speed ~ 10 cm/us

At end of axial phase

Estimate Temperature from speeds

- **Speed gives KE.**
- **Shock Waves convert half of KE to Thermal Energy:**
- **$T \sim q^2$; where q is the shock speed ~ speed of current sheet.**

- **For D_2: $T=2.3x10^{-5}q^2$ K q in m/s**

(from strong shock-jump conservation equations)

Compare Temperatures: speeds easily measured; simply from a current waveform; from speeds, temperature may be computed. (e.g. in deuterium)

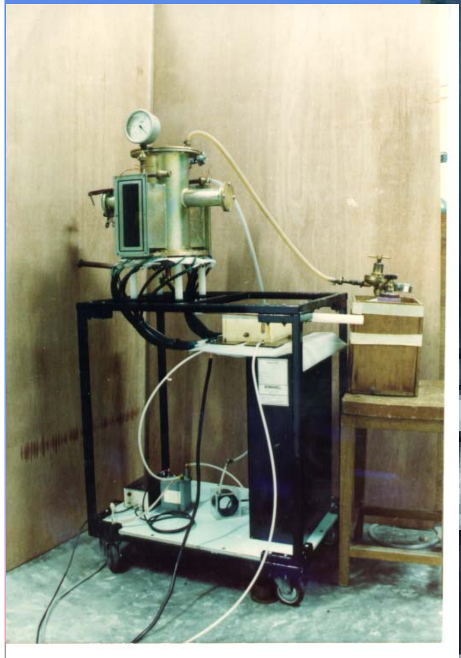
	UNU ICTP PFF	PF1000	
Axial speed	10 [measured]	12	cm/us
Radial speed	25	20	cm/us
Temperature	$1.5x10^6$	$1x10^6$	K
Reflected S	$3x10^6$	$2x10^6$	K

After RS comes pinch phase which may increase T a little more in each case

Temperatures of large PF and small PF: about same; several million K

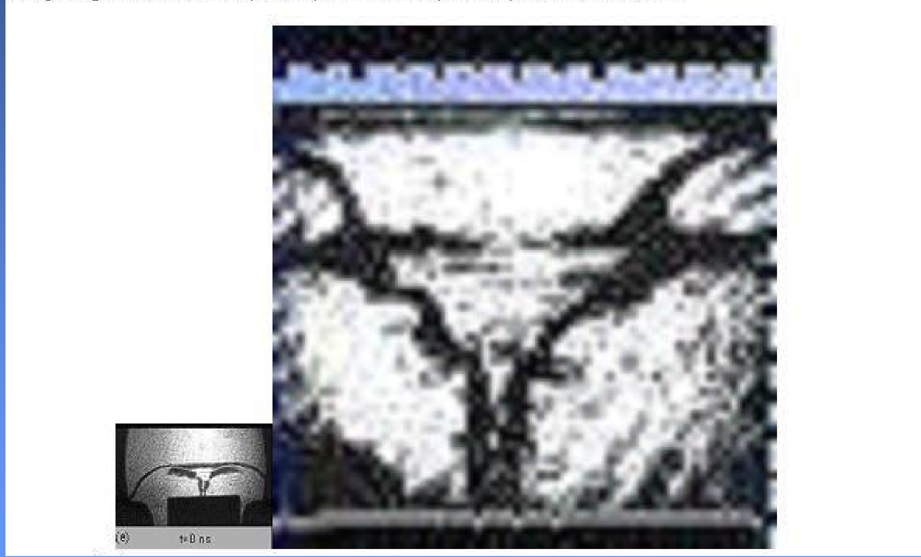
Similar considerations show density also about the same

1997 ICDMP (International Centre for Dense Magnetised Plasmas) Warsaw-now operates one of biggest plasma focus in the world, the PF1000



Comparing large and small PF's- Dimensions and lifetimes- putting shadowgraphs side-by-side, same scale

Comparing UNU ICTP PFF (170 kA) and PF1000 (at 2 MA)- Deuterium 3 Torr



Anode radius	1 cm	11.6 cm
Pinch Radius:	1mm	12mm
Pinch length:	8mm	90mm

Lifetime ~10ns order of ~100 ns

Modern Status

Now PF facilities (small to big) operate in Poland (PF-1000 and PF-6 in IPPLM, PF-360), Argentina, China, Chile, Great Britain, India, Iran, Japan, Mexico, Korea, Malaysia, Pakistan, Romania, Singapore, Thailand, Turkey, USA, Zimbabwe etc.

This direction is also traditional for Russia: Kurchatov Institute (PFE, 180 kJ and biggest in the world facility PF-3, 2.8 MJ), Lebedev Institute ("Tulip", PF-4), MEPhI, Sarov, ITEF (PF-10)-

- This slide adapted from V.I. Krauz

INTI UC Centre for Plasma Research -Plasma Focus & Pulse Power Laboratory

23 June 2009 - First test shot of INTI-PF

10 kV
2 Torr Neon

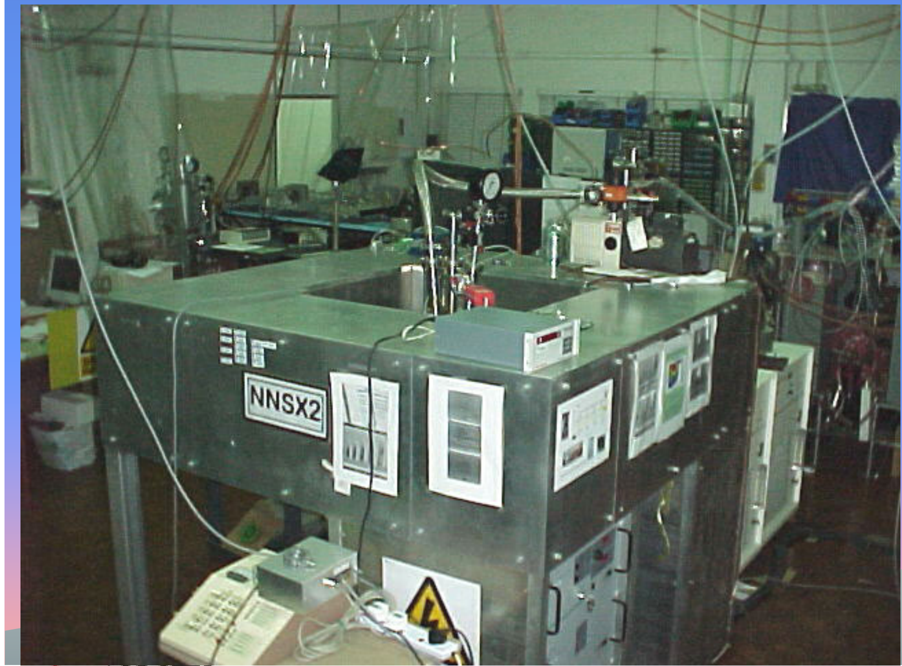
Current: 120 kA

Temperature:
2 million °C

Soft x-ray burst:
100 Megawatt-
10 ns

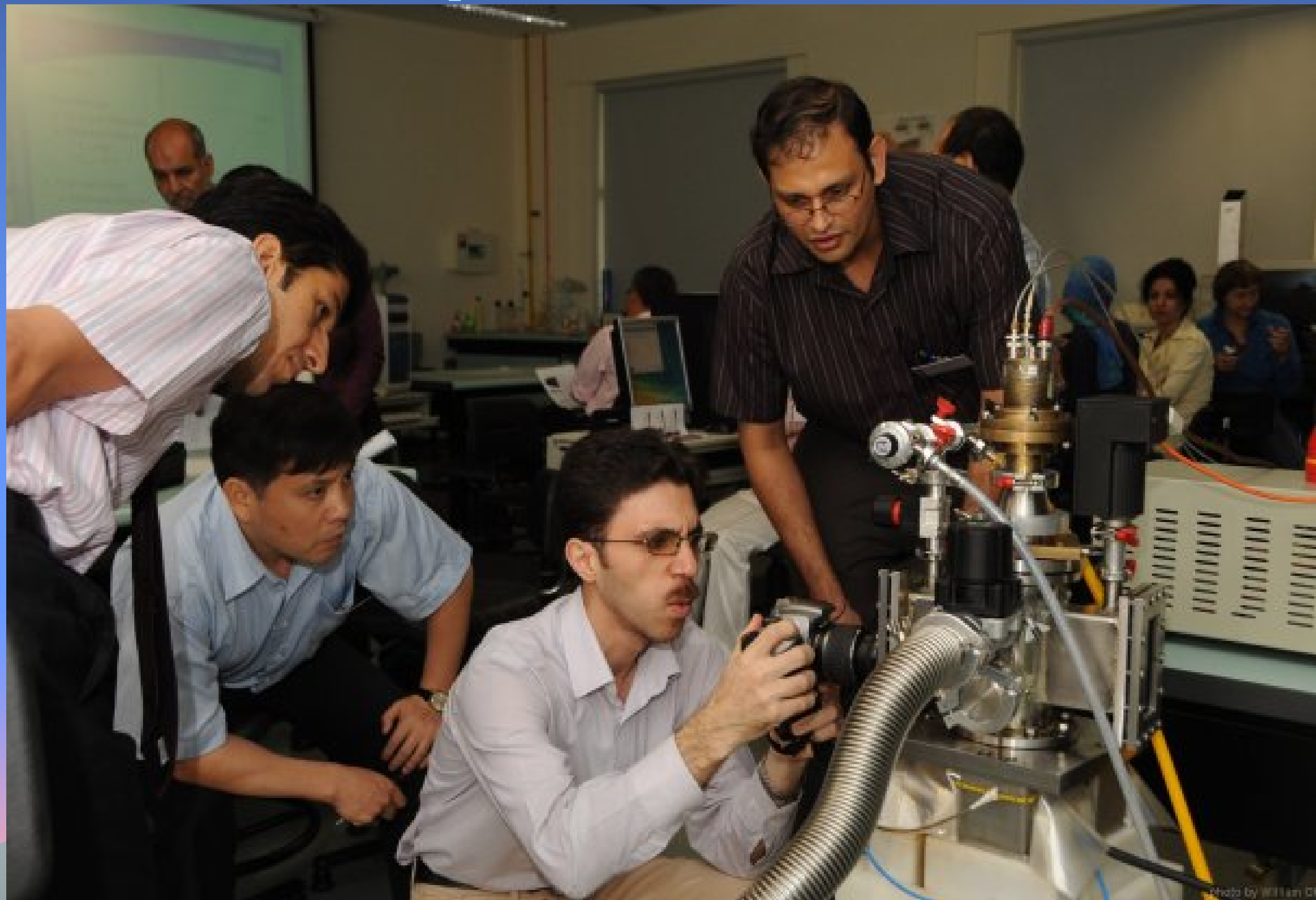
NX2-Plasma SXR Source-Hi Rep, Singapore

- 11.5kV, 2 kJ
- **16 shots /sec**; 400 kA
- 20J SXR/shot (neon), upgraded to >50J per shot
- 10^9 neutrons/shot

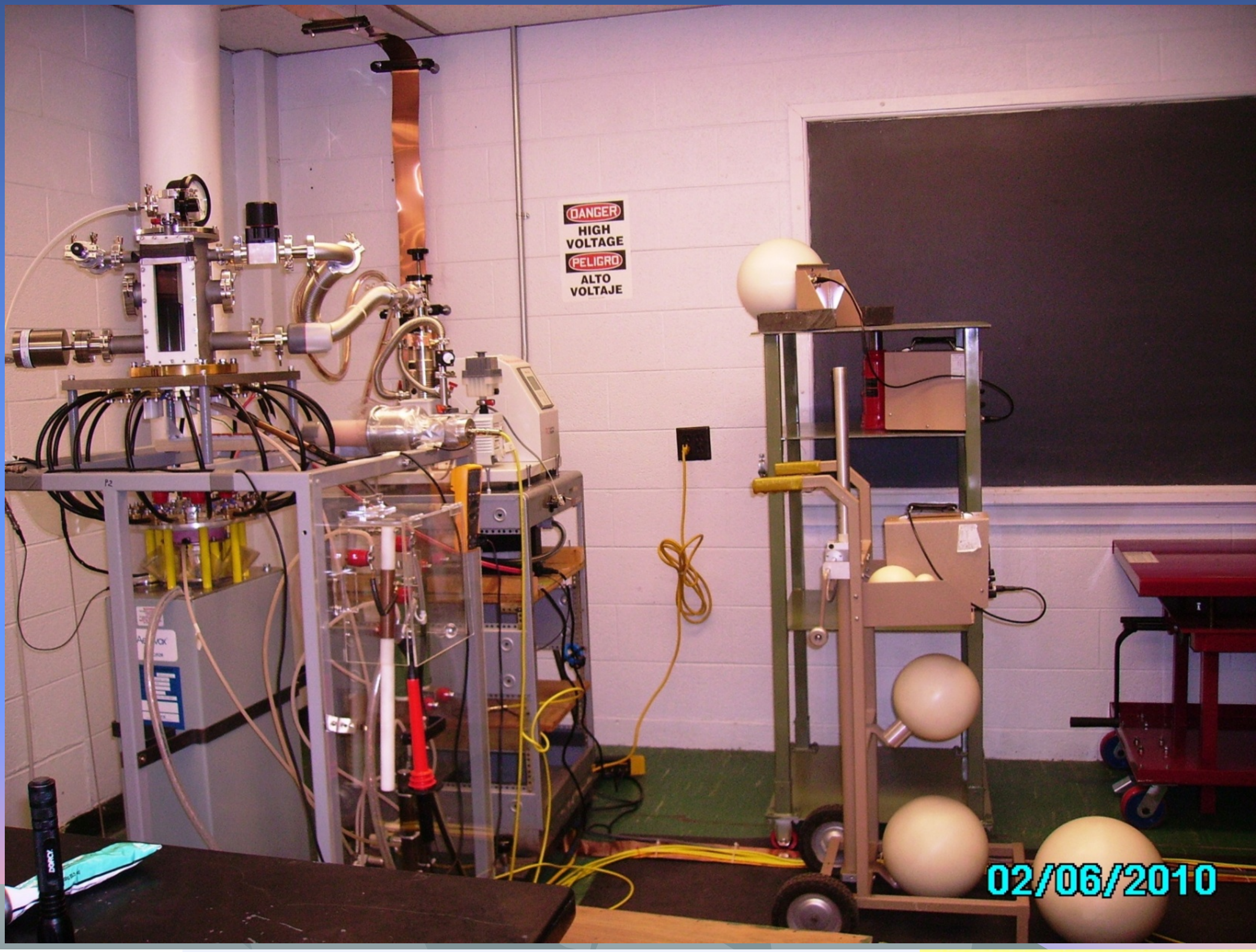


300J PF: Miniature (Singapore)

(2.4 µF, *T*/4 ~ 400 ns, 15 kV, 270 J, total mass ~25 kg)
neutron yield: 10^6 neutrons/shot at ~80 kA peak current;
compact, portable, quasi-continuous pulsed neutron fusion source, a 'fast miniature plasma focus device'



KSU Plasma Focus- Kansas State University



Alameda Applied Science Corporation- M Krishnan has developed a number of high-rep plasma focus- the most exciting of which is the voltage step-down current-muiltiplied system, 100J storage capable of 100 Hz operation.

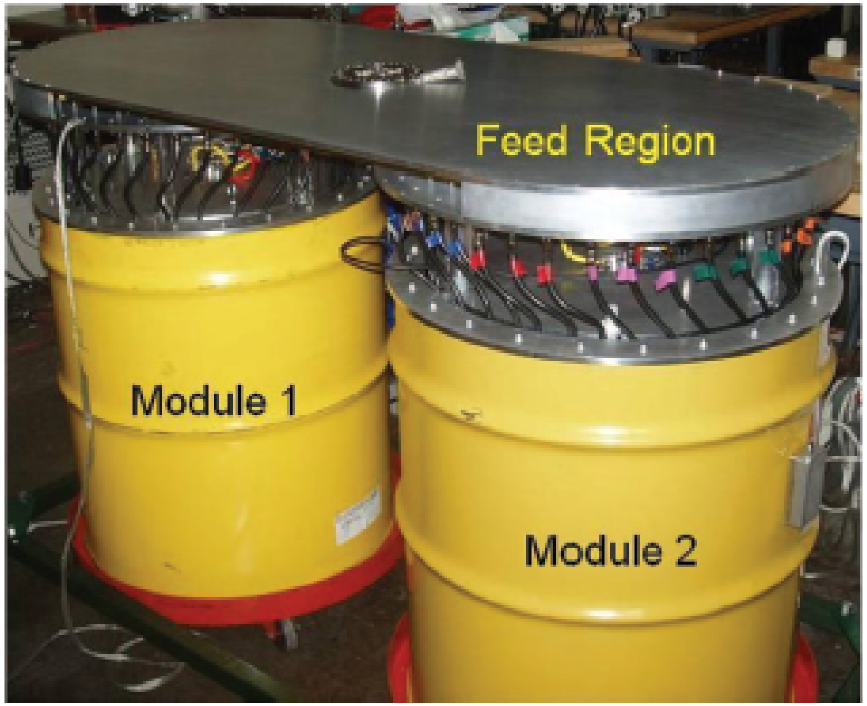


FIG. 4. (Color online) Two transformer modules combined using a bi-plate feed.

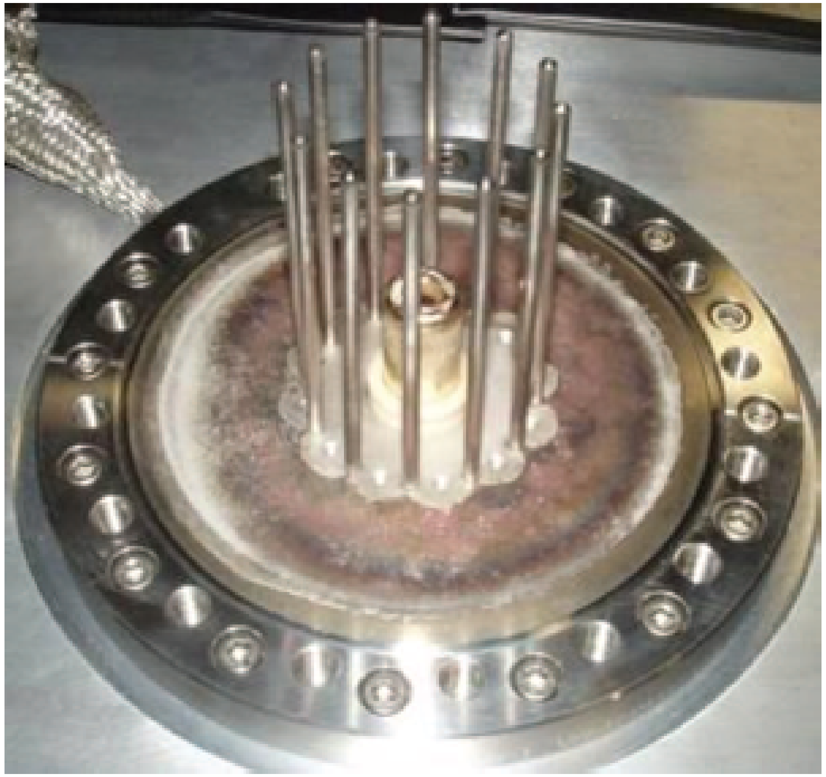
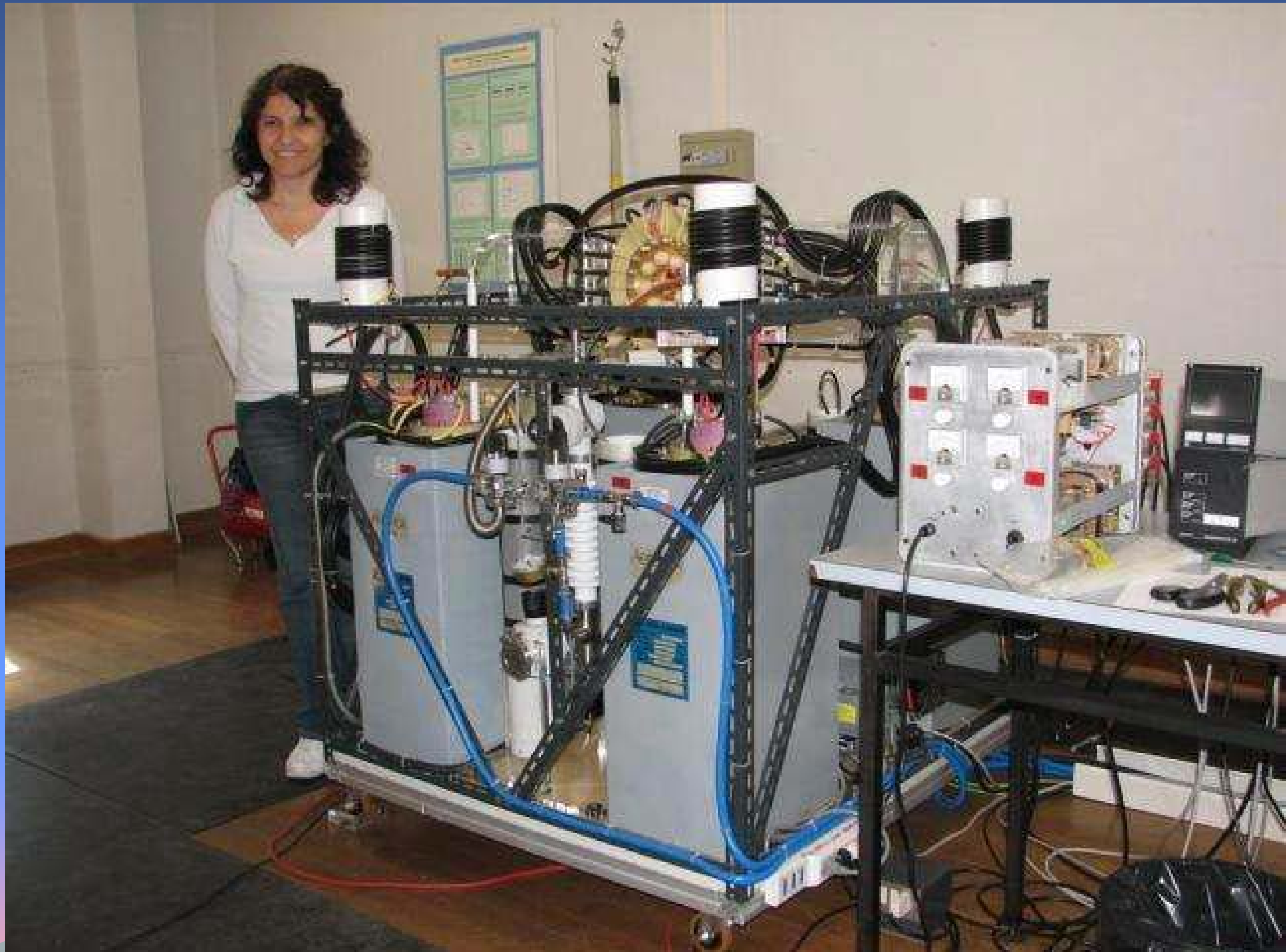
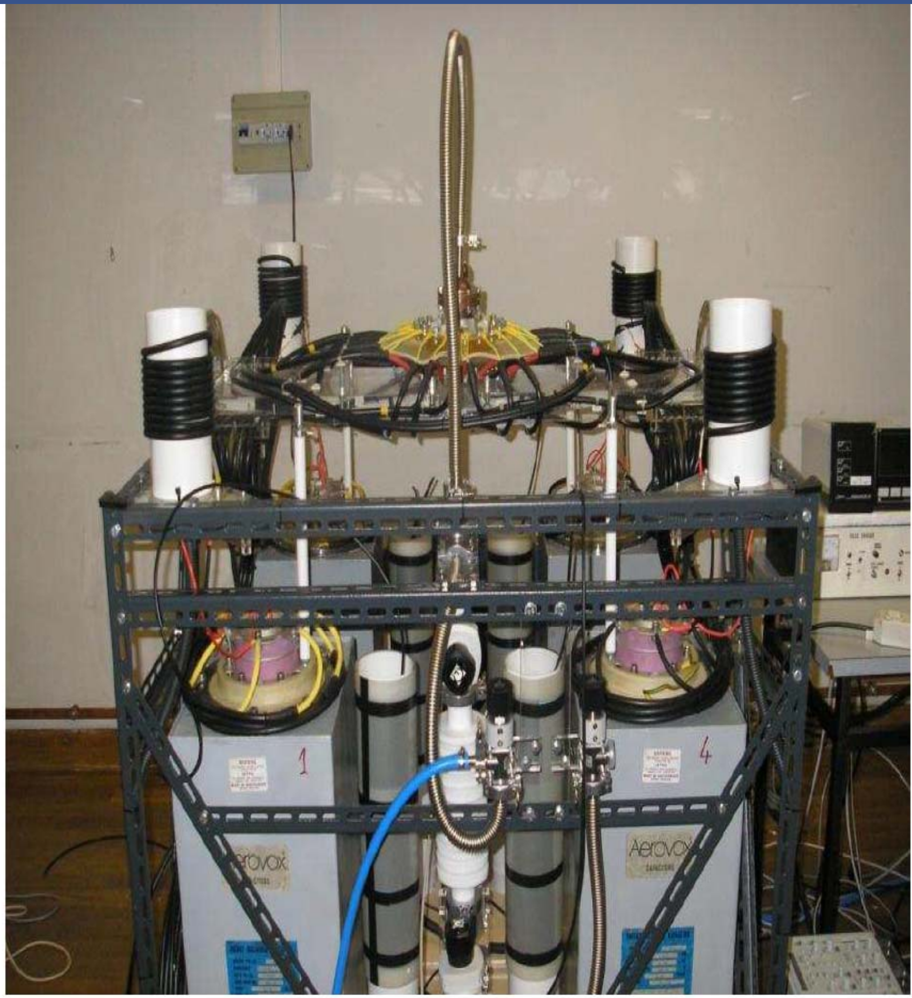


FIG. 6. (Color online) Electrodes for the experiments. Anode is in the center of the coaxial electrodes with a 15 mm diameter and 20 mm length. The

Bora Dense Plasma Focus-ICTP M-Lab



DPF Bora with chamber for hard X-rays



b)

Fig. 70 DPF "Bora" fully assembled with a chamber for hard X-Ray radiation

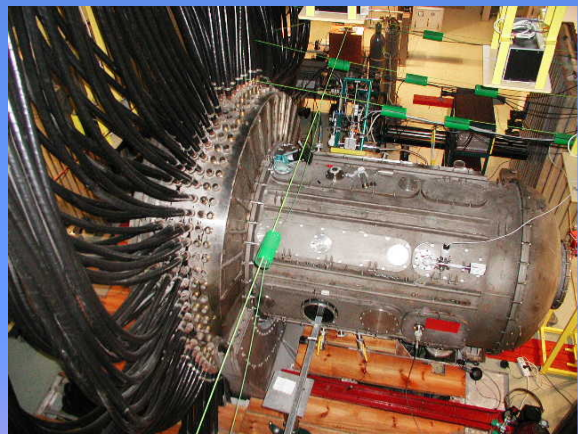
1997 ICDMP (International Centre for Dense Magnetised Plasmas) Warsaw-now operates one of biggest plasma focus in the world, the PF1000

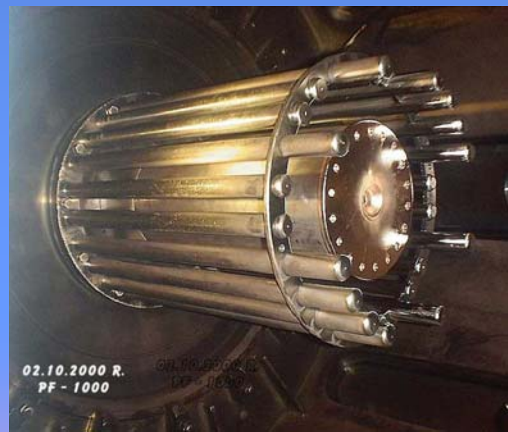
PF1000 40kV 1332uF 9nH 1.1MJ Io= 15MA

PF-1000, IPPLM, Warsaw-courtesy M Scholz

Charging voltage - $U_0 = 20 - 40\ kV$,
Bank capacitance - $C_0 = 1.332\ mF$,
Bank energy - $E_0 = 266 - 1064\ kJ$,
Nominal inductance - $L_0 = 15\ nH$,
Quarter discharge time - $T/4 = 6\ \mu s$,
Short-circuit current – $I_{SC} = 12\ MA$,
Characteristic resistance - $R_0 = 2.6\ m\Omega$,

Vacuum chamber ~ 3.8 m^3
∅= 1.4 m, L = 2.5 m
Anode diameter is 226 mm
Cathode diameter is 400 mm
Cathode consists of 24 rods (32 mm in diameter)
Anode length is 560 mm
Insulator length is 113 mm

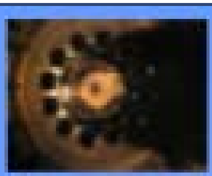


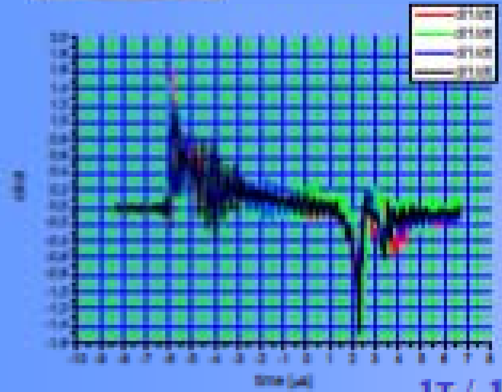


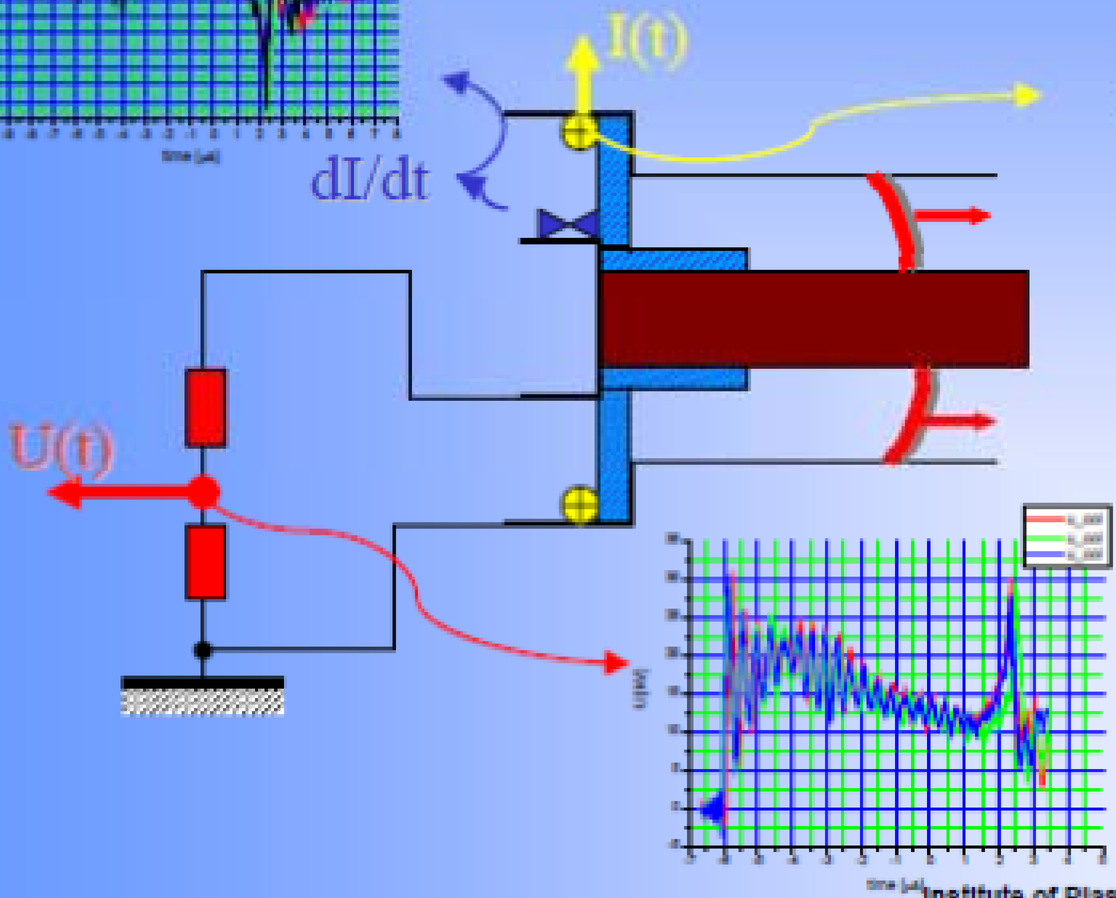
Main goal – studies on neutron production at high energy input

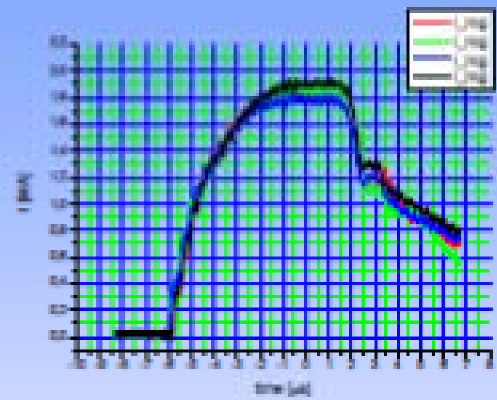
Presented by M.Scholz, IPPLM

Measurements of Current and Voltage









$U_b = 27$ kV, $E_b = 480$ kJ,

$p = 3{,}5$ Torr

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

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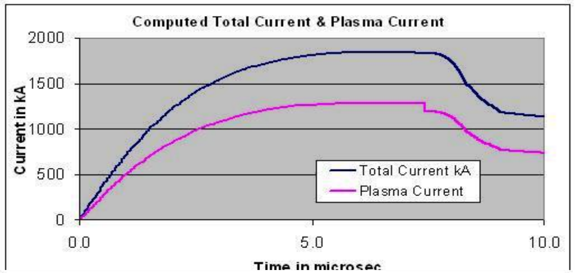
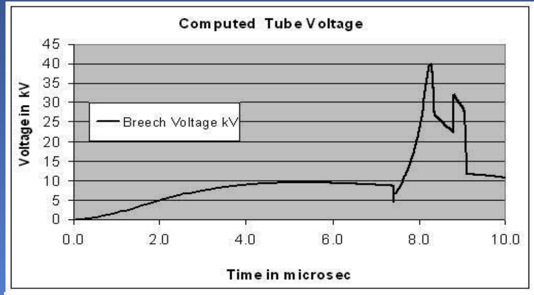
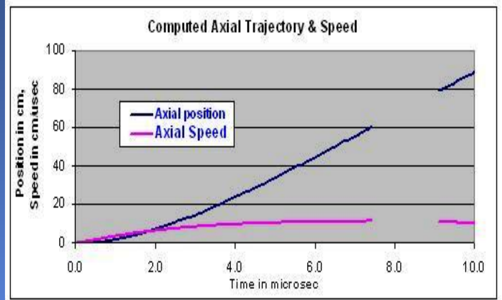
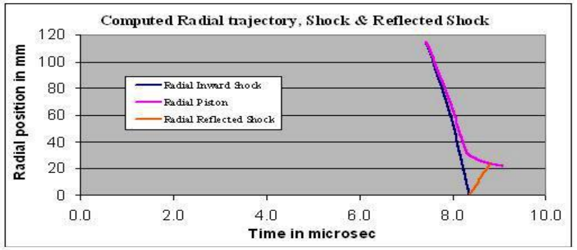
Warsaw, Poland

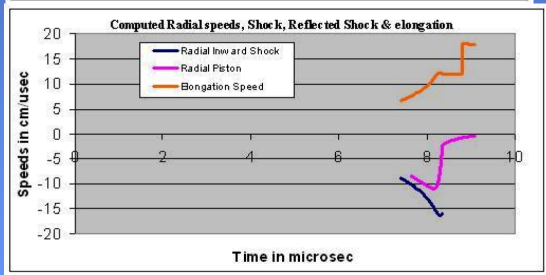
Computed Properties of the PF1000: Currents, tube voltage, trajectories, speeds, energy distributions, temperatures, densities, SXR power and neutron yield

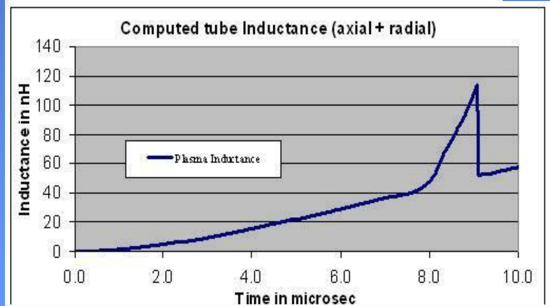


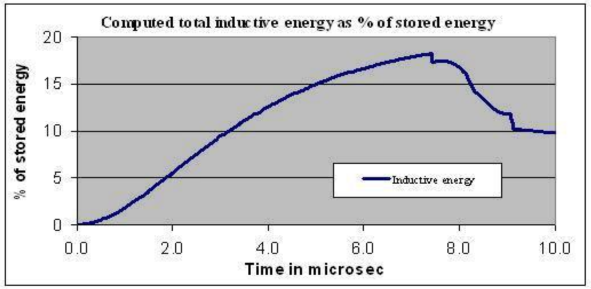


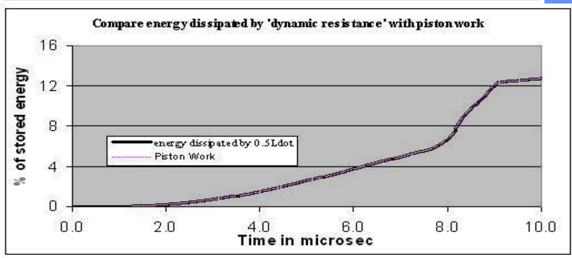


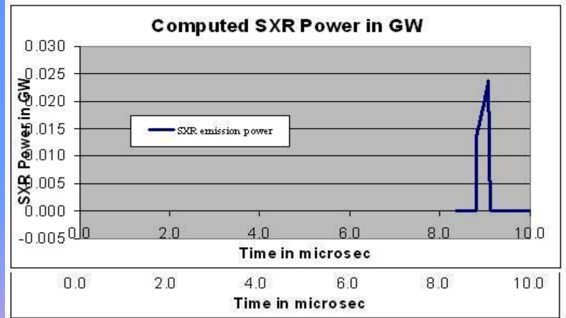


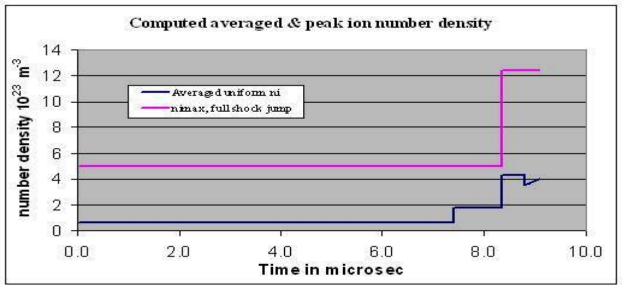


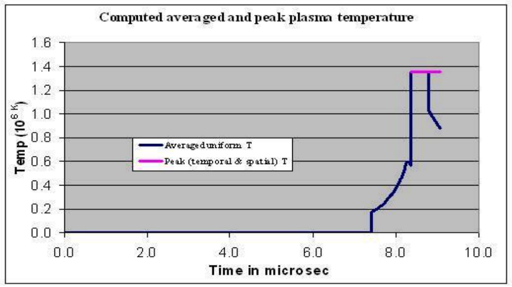


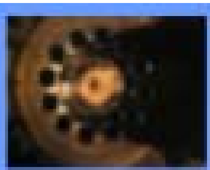






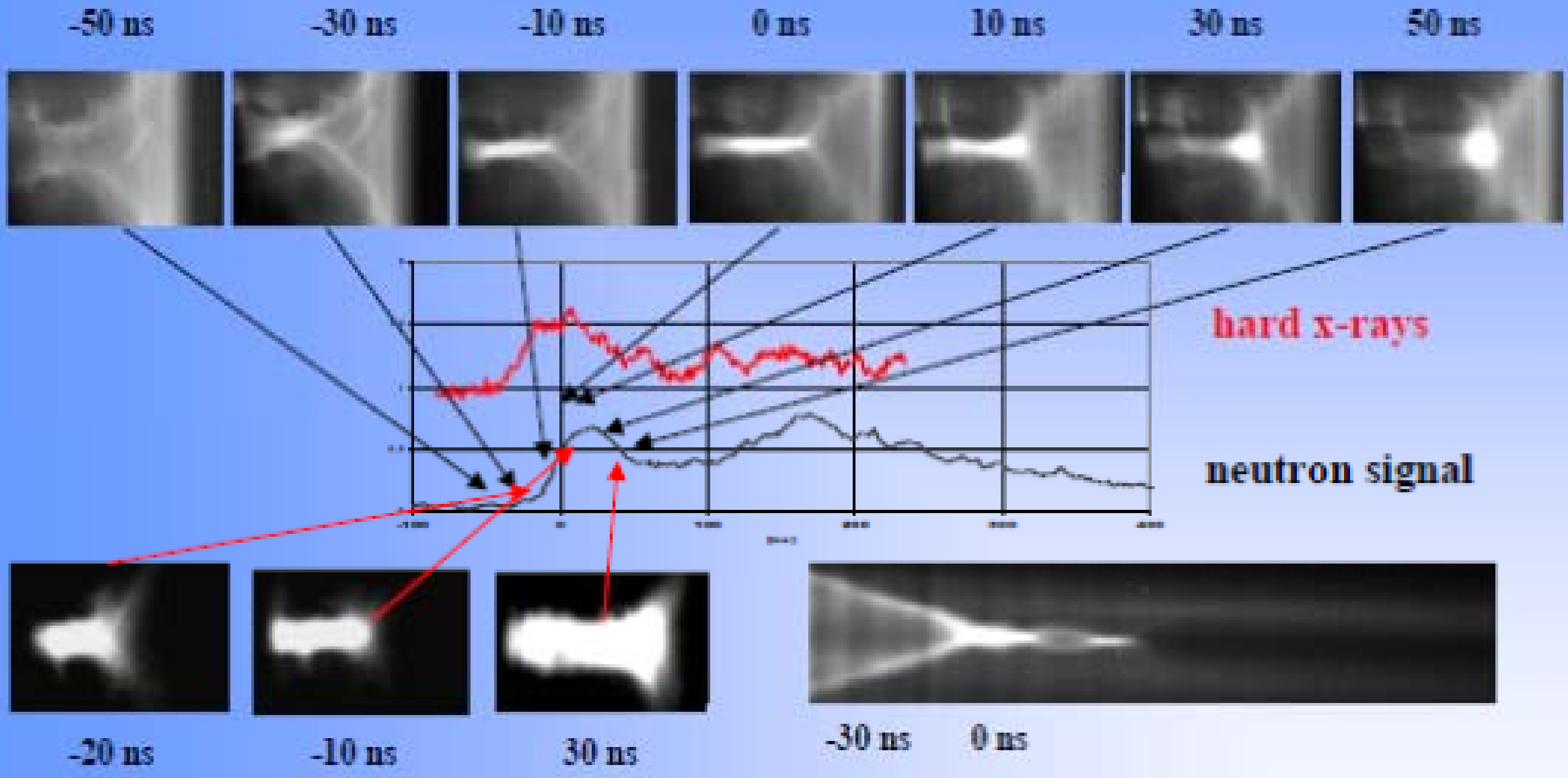






Correlation of neutron signals with frames

(first neutron pulse)



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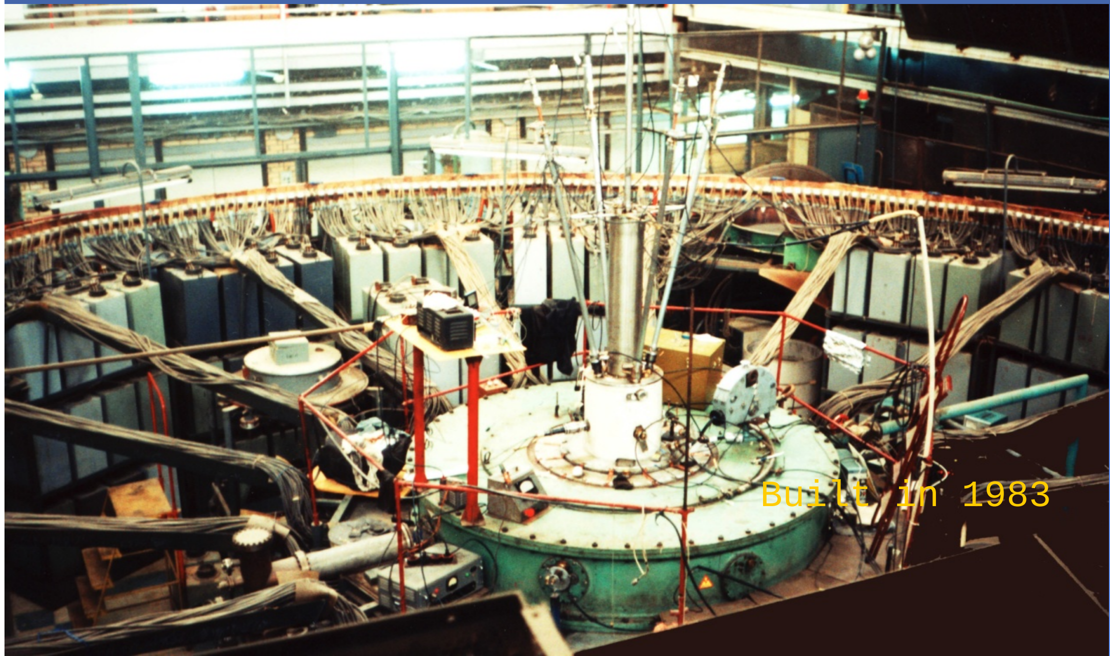
Plasma Focus PF-3- courtesy V I Krauz (5 slides)



- Filippov's-type
- Anode Diameter = 1 m
- Chamber Diameter=2,5 m
- Cathode - 48 rods; diameter = 115 cm
Distance between anode and upper = 10 cm
- Height of the insulator = 14 cm
- Maximal energy (C_{max}=9,2 mF, V_{max}=25 kV) is 2,8 MJ
- Short-circuit current =19 MA
- Current on the load - up to 4 MA at 1MJ

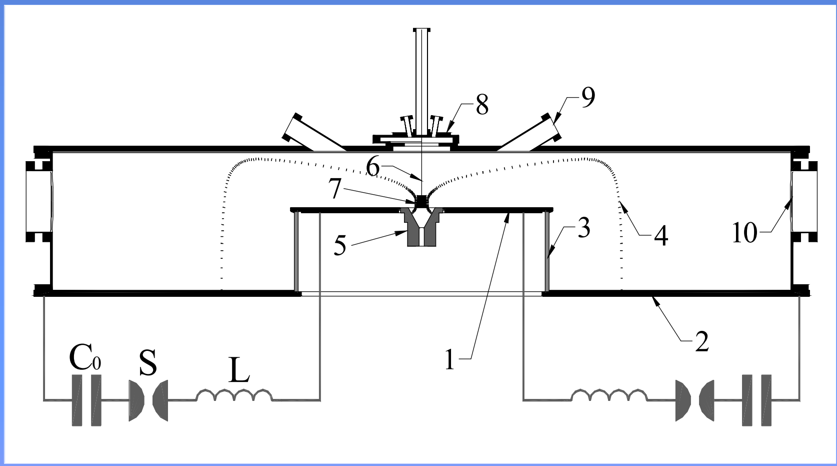
Main direction of activity - Search of new ways of PF performance and applications.

E.g. use PF as a driver for magnetic compression of liners

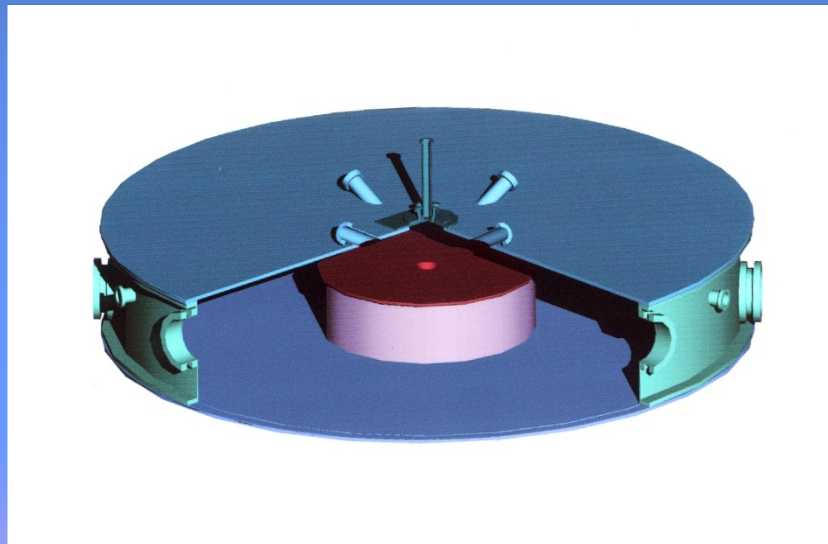
PF-3 Experimental Setup- with plasma producing substances

Experiments with various plasma-producing substances & various filling gases were recently the main content of activities at the PF-3 facility

Vacuum lock developed for delivery of liners to compression zone.



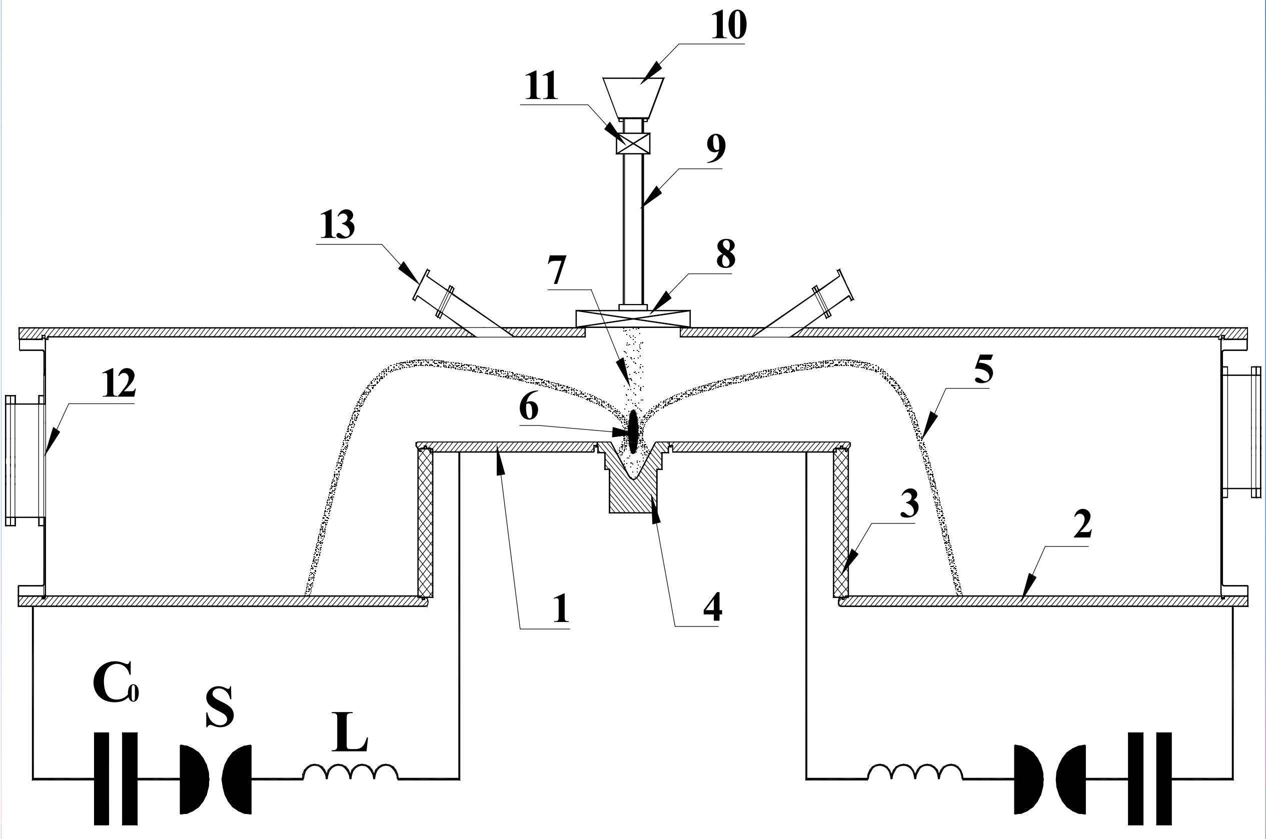
***1** – anode; 2 – cathode; 3 – insulator; 4 – plasma current sheath; 5 – anode insertion; 6 – suspension ware; 7 – liner; 8 – loading unit with a vacuum lock; 9, 10 – diagnostics ports;*



PF discharge chamber

Experimental set-up – Dust Target

Dust target produced at system axis as a freely-falling flow of fine-dispersed (2 - 50 μm) powder of Al_2O_3

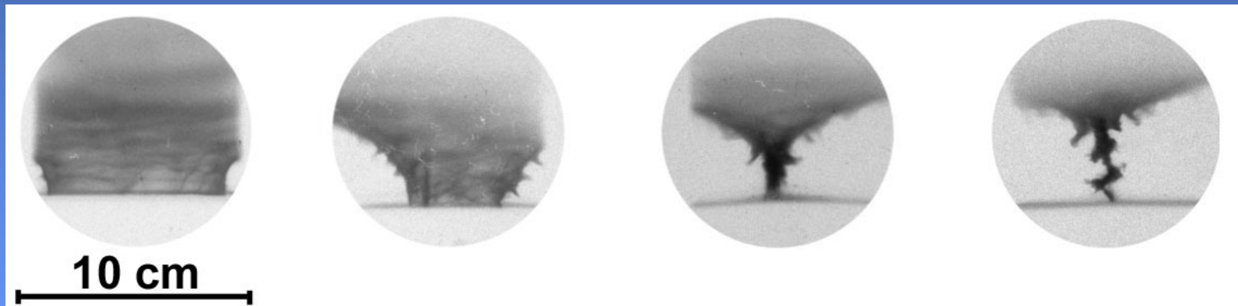


1 – anode; 2 – cathode; 3 – insulator; 4 – central anode insert; 5 – plasma-current sheath; 6 – pinch; 7 – dust column; 8 – vacuum lock; 9 – shaping drifting tube; 10 – tank with powder; 11 – electromagnet; 12, 13 – diagnostic ports

Frame Camera Pictures of Pinch Formation

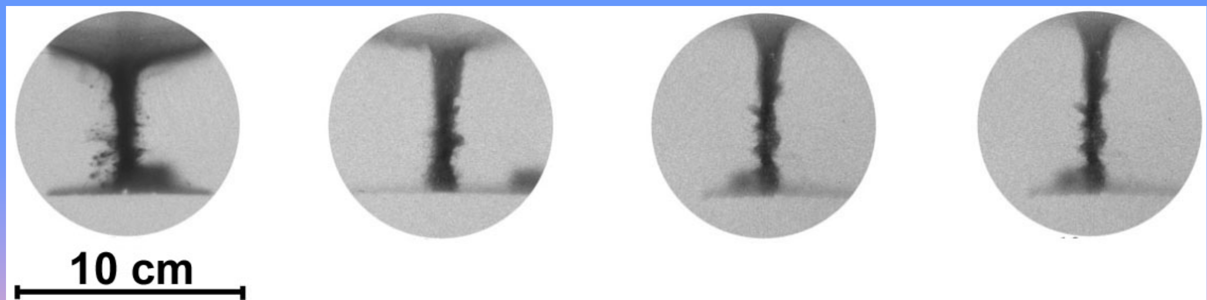
Frame exposure – 12 ns, time delay between frames – 150 ns

Discharge in neon without dust



-300 ns | -150ns | 0 ns | 150 ns

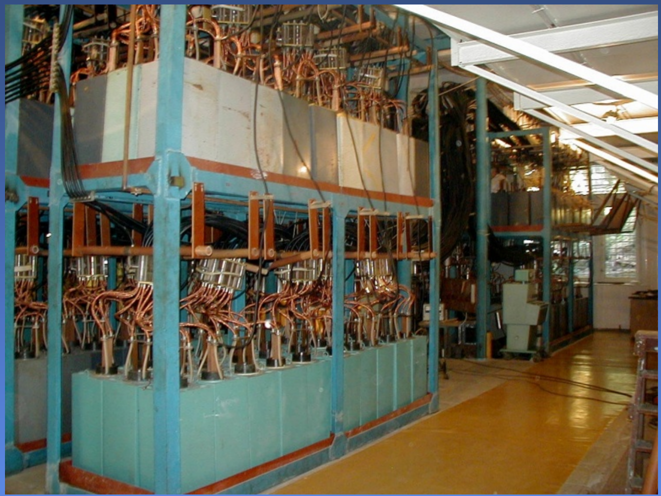
Discharge in neon with dust



500 ns | 650 ns | 800 ns | 950 ns

KPF-4 ("PHOENIX"), SPhTI, Sukhum

Yu .V.Matveev



Capacitive storage (left) & chamber with current collector (right)

W_{max}= 1.8 MJ, V_{max}=50 kV, Mather-type

outer electrode – 300 mm in diameter (36 cooper rods, 10 mm in diameter)

inner electrode (anode) – 182 mm in diameter, 326 mm in length

insulator – alumina, 128 mm in diameter, 50-100 mm in length

Discharge dynamics studied up to 700 kJ and discharge currents 3-3.5 MA

Main goal – development of powerful neutron and X-ray source for applications.

(E.A.Andreeshchev, D.A.Voitenko, V.I.Krauz, A.I.Markolia, Yu.V.Matveev, N.G.Reshetnyak, E.Yu.Khautiev, 33 Zvenigorod Conf. on Plasma Phys. and Nuclear Fus., February 13-17, 2006, Zvenigorod, Russia)

Plasma Focus for medical application programme (PFMA_1)

This program is developed in Italy in cooperation of Ferrara and Bologna Universities

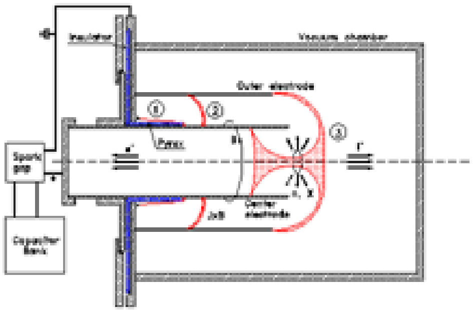
Today's status is:

- **Preliminary campaign with a relatively small Plasma Focus device (7 kJ, 17 kV, 600 kA maximum) confirmed the feasibility of short-live radioisotopes: ~ 1 mCi/shot of ^{13}N, ^{15}O, ^{17}F is achieved.**
  (E. Angeli, A. Tartari, M. Frignani, D. Mostacci, F. Rocchi, M. Sumini, Applied Radiation and Isotopes 63 (2005) 545–551)

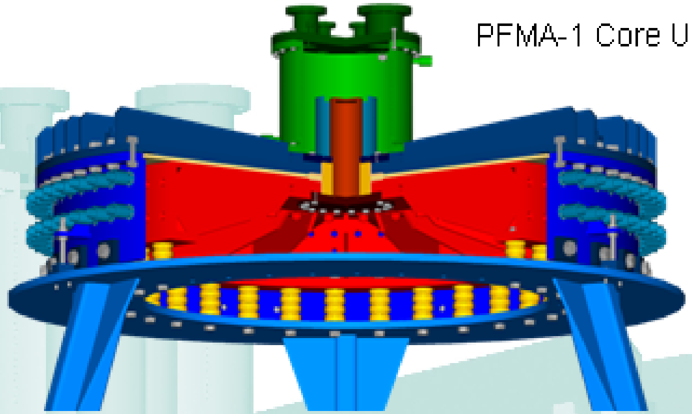
- **150 kJ machine (350 mF, 30 kV, 3 MA) is just completely assembled and a preliminary test campaign will be starting soon**

Courtesy A.Tartari, University of Ferrara

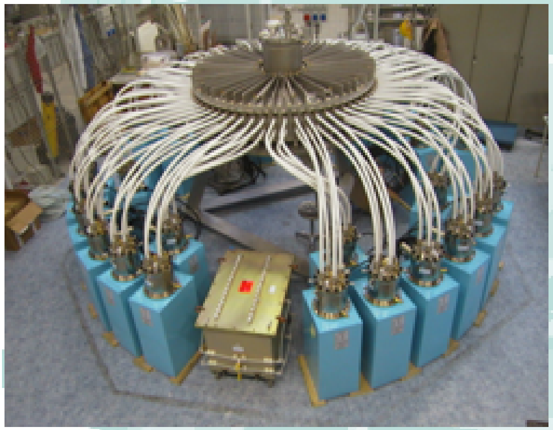
Plasma Focus Technology: PFMA-1, Plasma Focus for Medical Applications, the first prototype of a PF device for 18-F production, a 150 kJ (350 µF @ 30 kV) Mather-type Plasma Focus operated at 1 Hz repetition frequency that could breed ~ 1 Ci of F^{18} in 2 hours.



Mather type PF scheme



PFMA-1 Core Unit



PFMA-1

UNIVERSITY OF BOLOGNA

ABO PROJECT 2010

azienda Ulss 12 veneziana

UNIVERSITY OF FERRARA

A.Tartari, University of Ferrara

Other Plasma Focus Devices

- A range of fast plasma focus devices from **sub-Joules** to hundreds of kJ at the Chilean Nuclear Energy Commission- **Nano Focus**, PF-50J, PF-400J, SPEED 4 and SPEED 2
- Several small and medium energy machines in India, Pakistan, Iran, Eqypt, Syria, Turkey, Thailand, Zimbabwe, Belgrade
- MAJA PF at Andrzej Soltan Institute for Nuclear Studies in Poland
- FoFu 1- at New Jersey; Eric Lerner's efforts towards aneutronic fusion

High Power Radiation from PF

- powerful bursts of x-rays, ion beams, REB's, & EM radiation (>10 gigaW)
- Intense radiation burst, extremely high powers
- E.g. SXR emission peaks at 10^9 W over ns
- In deuterium, fusion neutrons also emitted

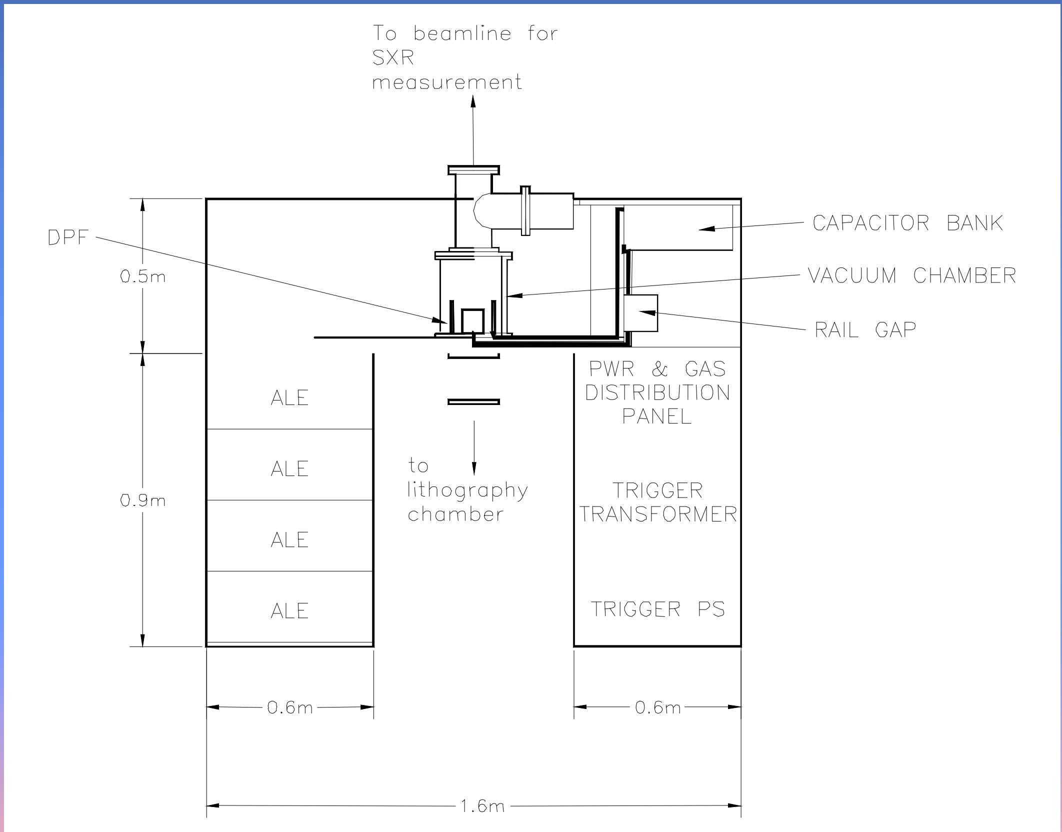
Applications

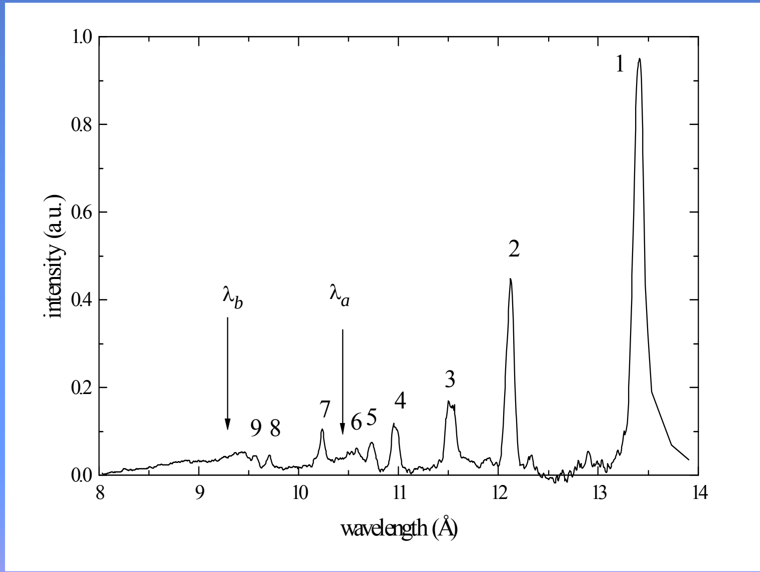
SXR Lithography

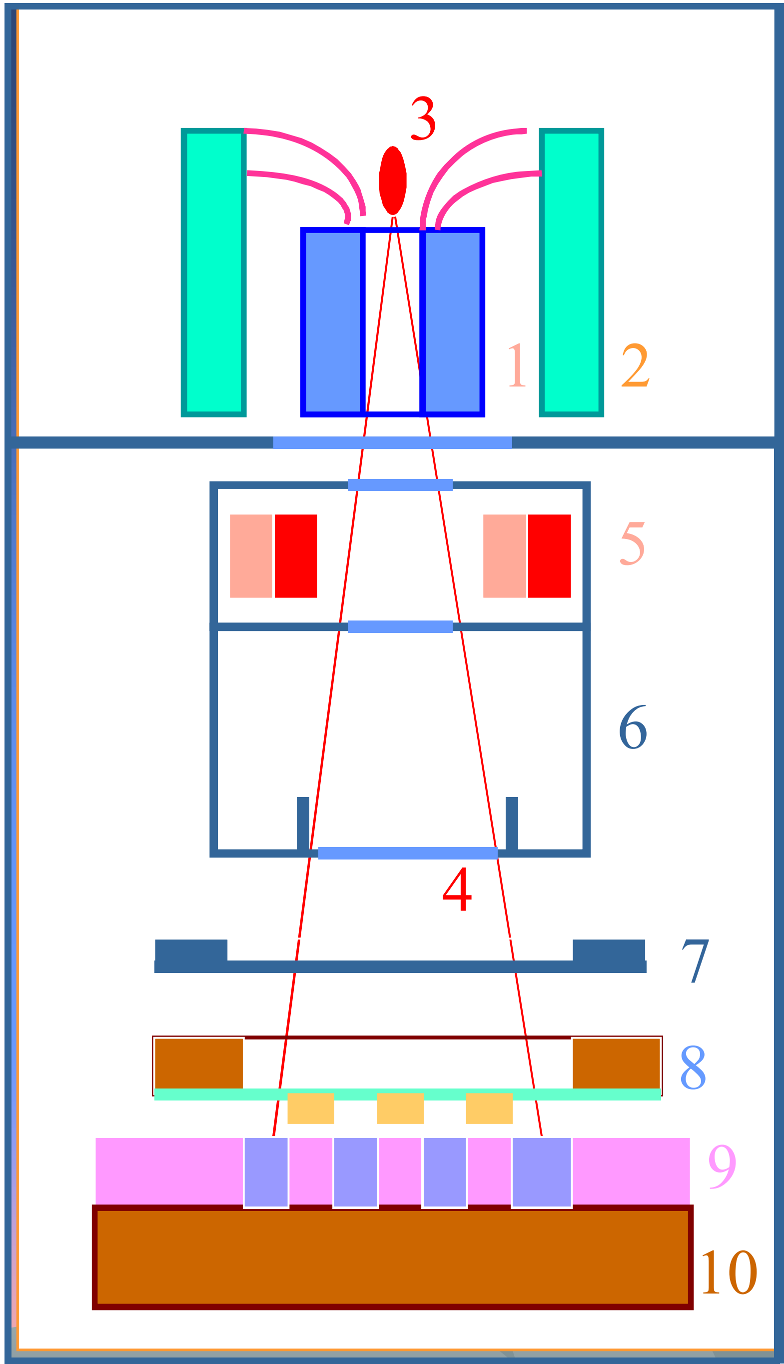
- **As linewidths in microelectronics reduces towards 0.1 microns, SXR Lithography is one possibility to replace optical lithography.**

- **Baseline requirements, point SXR source**
  - **less than 1 mm source diameter**
  - **wavelength range of 0.8-1.4 nm**
  - **from industrial throughput considerations, output powers in excess of 1 kW (into 4pi)**

SXR lithography using NX2



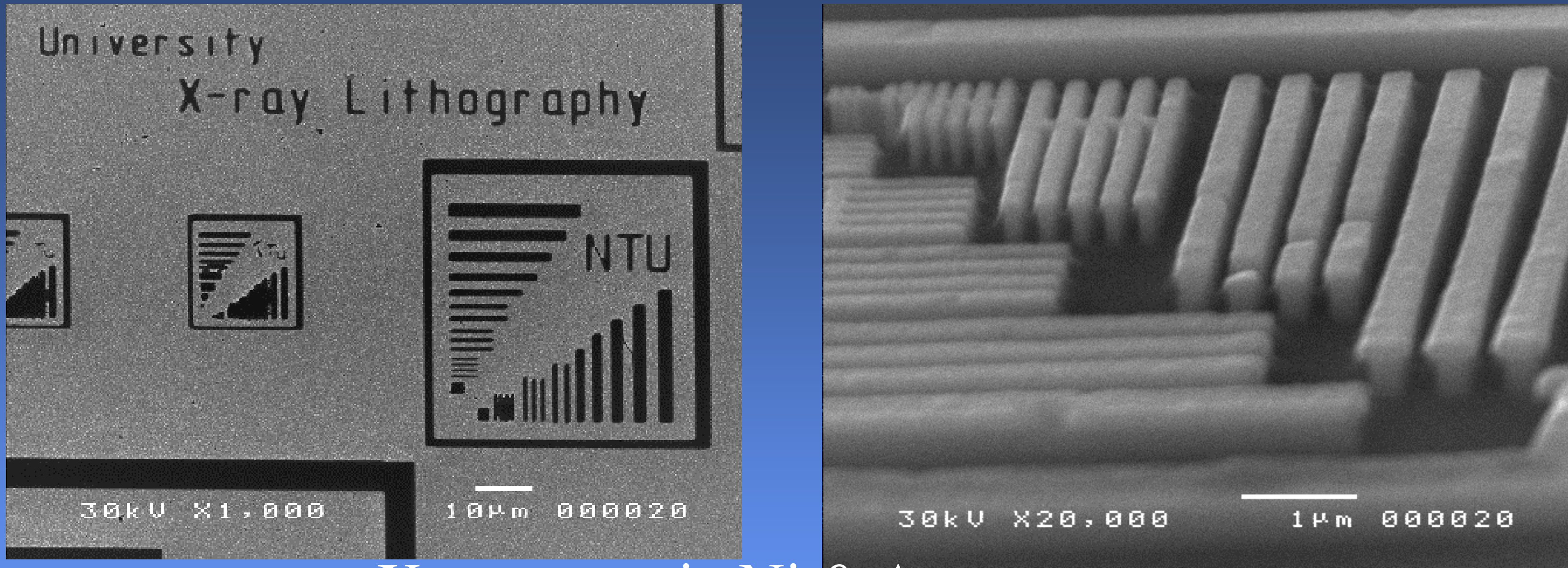




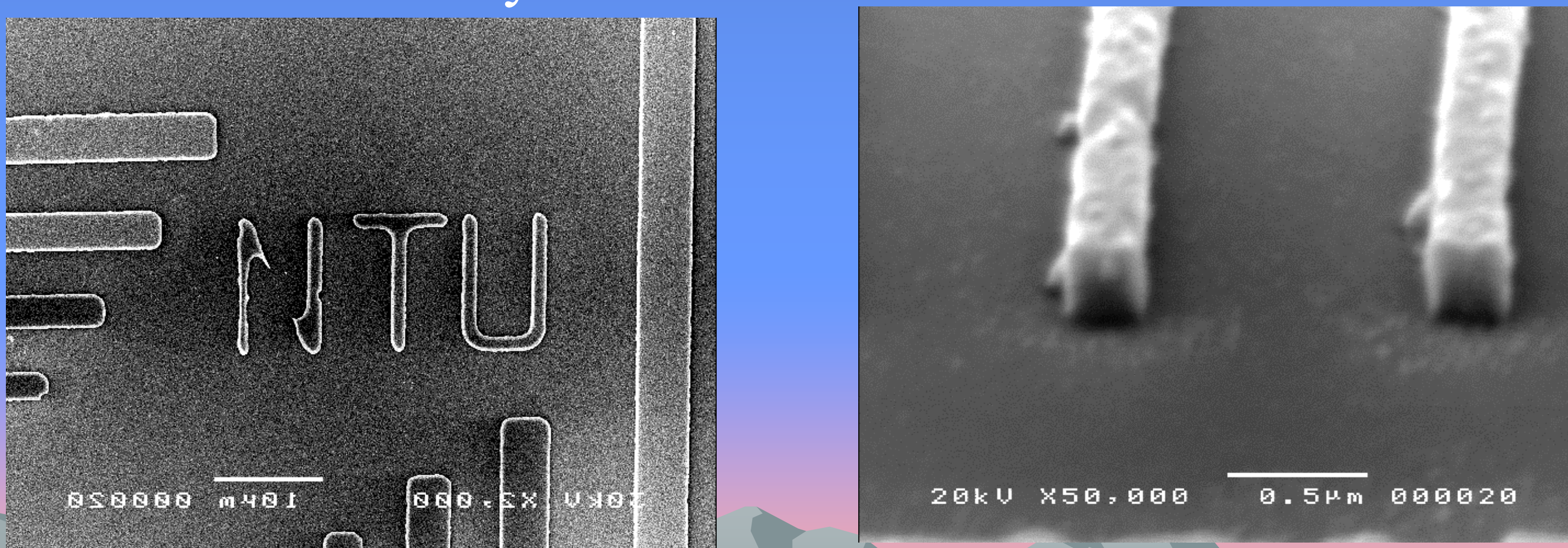
PF SXR Schematic for Microlithography

- 1 - anode
- 2 - cathode
- 3 - SXR point source
- 4 - x-rays
- 5 - electron beam
- deflection magnets
- 6 - shock wave shield
- 7 - Be window
- 8 - x-ray mask
- 9 - x-ray resist
- 10 - substrate

Lines transferred using NX2 SXR

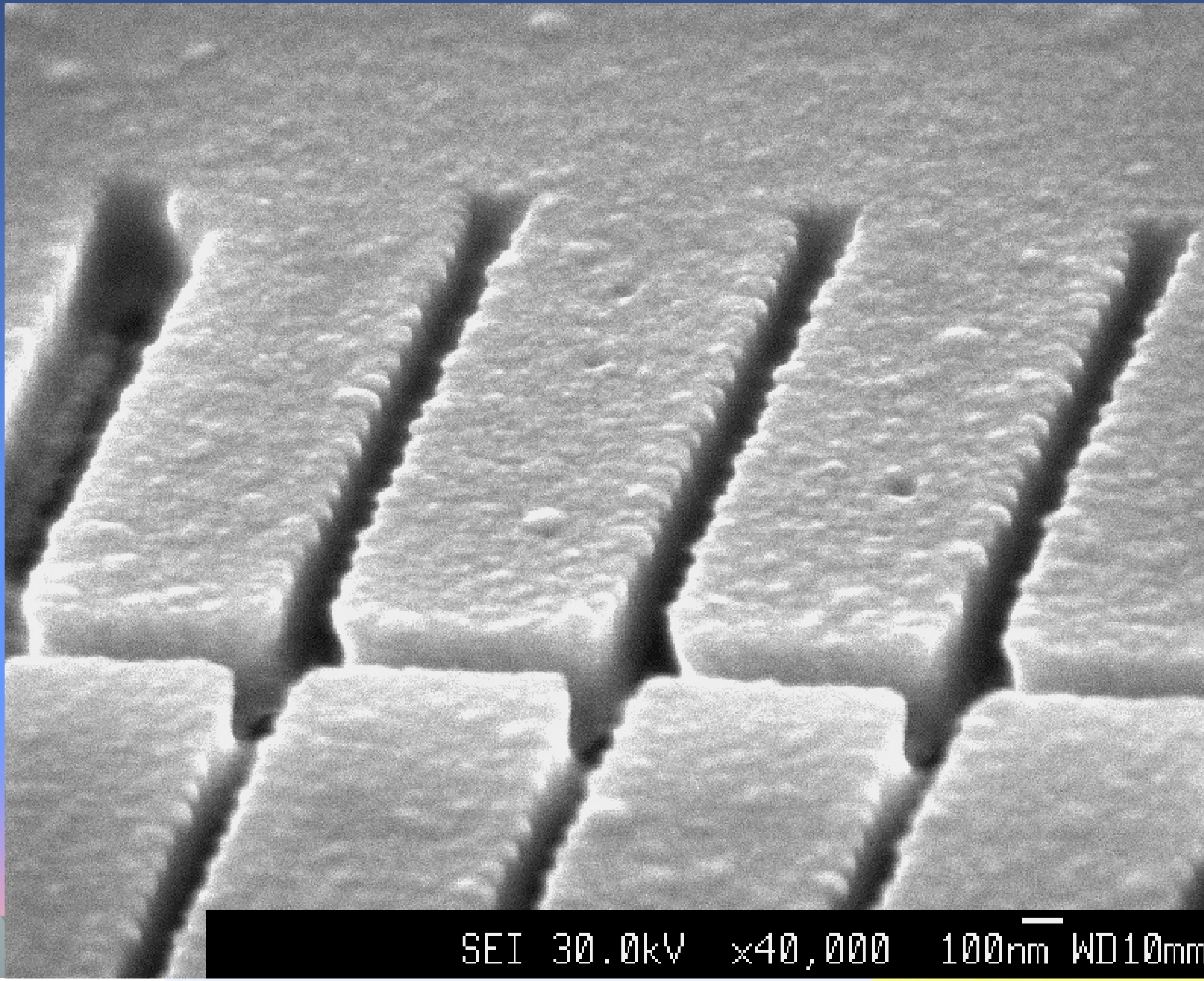


X-ray masks in Ni & Au



SEM Pictures of transfers in AZPN114 using NX2 SXR

X-ray Micromachining



Other Applications –non fusion

Materials modification using Plasma Focus Ion Beam

For plasma processing *of thin film materials on different substrates with different phase changes.*

PF-nanoparticles synthesis project-

R S Rawat et al Procs IWPCA 2008 pg 23- Ed SH Saw-ISSN 165-0284

- Synthesize nano-phase (nano-particles,nano-clusters and nano-composites) magneticmaterials energeticDensePlasmaFocus(DPF)Device
- To understand the mechanism of nano-phase material synthesis
- To investigate the effect of various deposition parameters on themorphology and size distribution of deposited nano-phase material
- To reduce the phase transition temperatures

Applications

- **DataStorage**
- Size of data bits fallen to 300nm x15nm in 2002
- Currentstorage media:CoCrPtX Superparamagnetism:10nm
- FePt:3nm (Tb/inch2)

- **Medical Imaging**
- Nanomagnets can be used to enhance signal from MRI
- Iron- oxide NPs, depending on their size and chemical coating ,travel to different organs of the body. By selecting particles of particular sizes, researchers then study specific parts of the body

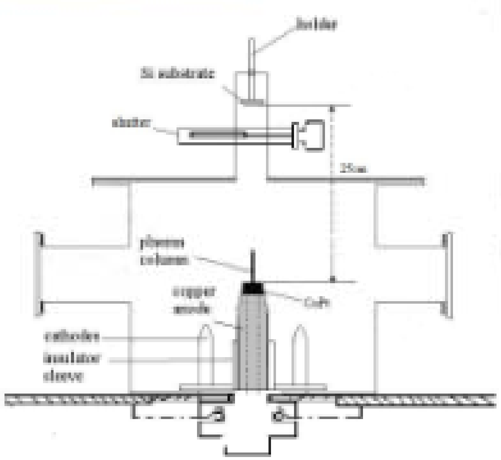
- **Drug Delivery**
- NPs are first laced with drug molecules and then steered by external magnetic-field gradients they reach the desired parts of the human body.

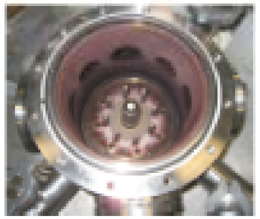
- **Cancel Therapy**
- Cancer cells are more susceptible to high temperatures. By increasing tissue temperature >42°C, cells could be selectively destroyed
- Magnetic NPs could be injected into malignant tissue. With strong field of optimum frequency, the NPs absorb energy and heat surrounding tissue, affecting only infected cells.
- Applications

2. Hi- Rep NX2, using FeCo or CoPt anodes, bombarded by electron beams to produce the relevant plasma plumes for direct deposition onto silicon substrates

CoPt nanoparticles synthesis-I

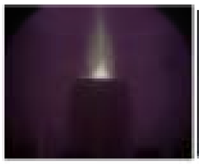
NX2 DPF device --- as a repetitive deposition facility





Capacitance (C_0)	27.6 μF (0.6 μF × 46)
Inductance of circuit (L_0)	26 nH
Impedance (Z_0)	30.1 mΩ
Circuit resistance (R_0)	7.2 m Ω
Charging voltage	8 kV
Anode radius (a)	Starting at 1.55 cm and then tapered down to 1.15 cm for last 2.5 cm
Cathode rod separation ($2b$)	9.4 cm
Repetition rate	1 Hz
Operating current (at 8 kV)	266 kA
Storage energy	880 J
Operating Gases	H_2

➢ **Optimized focus mode:**



H_2 gas pressure: 6 mbar
Axial deposition distance: 25 cm
No. of deposition shots: 25~200

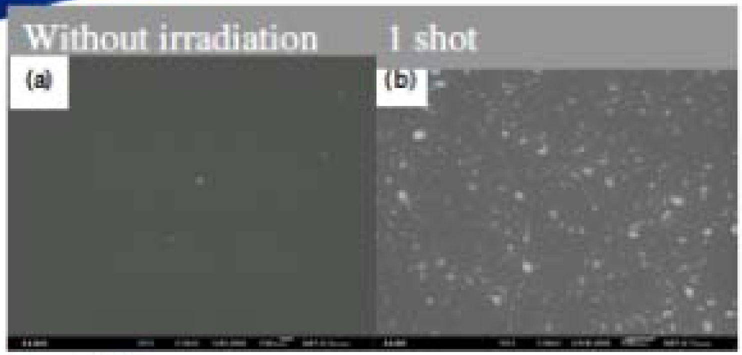
➢ **Non-optimized focus mode:**

H_2 gas pressure: 0.5 mbar
Axial deposition distance: 10 cm
No. of deposition shots: 25

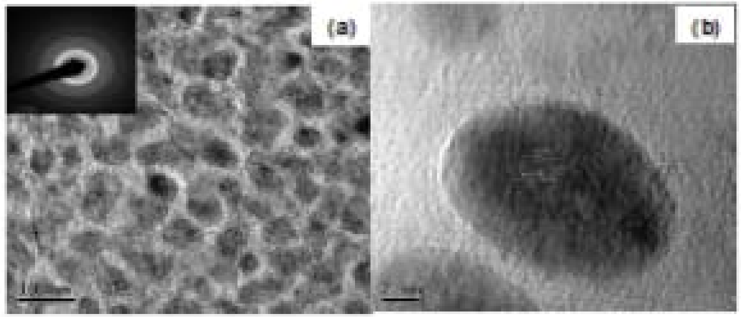
NANYANG TECHNOLOGICAL UNIVERSITY **International Workshop on Plasma Diagnostics and Applications, Singapore** **July 2 – 3, 2009** NIE

FePt nanoparticles synthesis-II

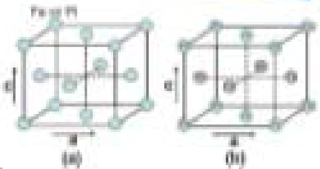
Morphology:

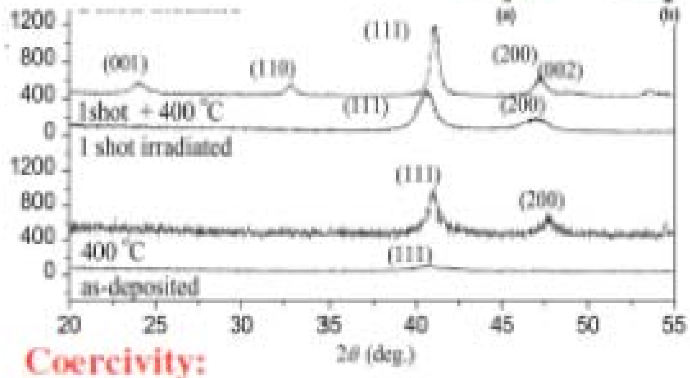


Crystallites:

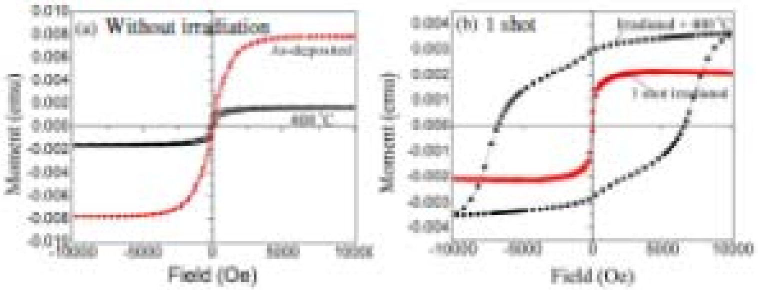


Structure: *fcc* → *fct*



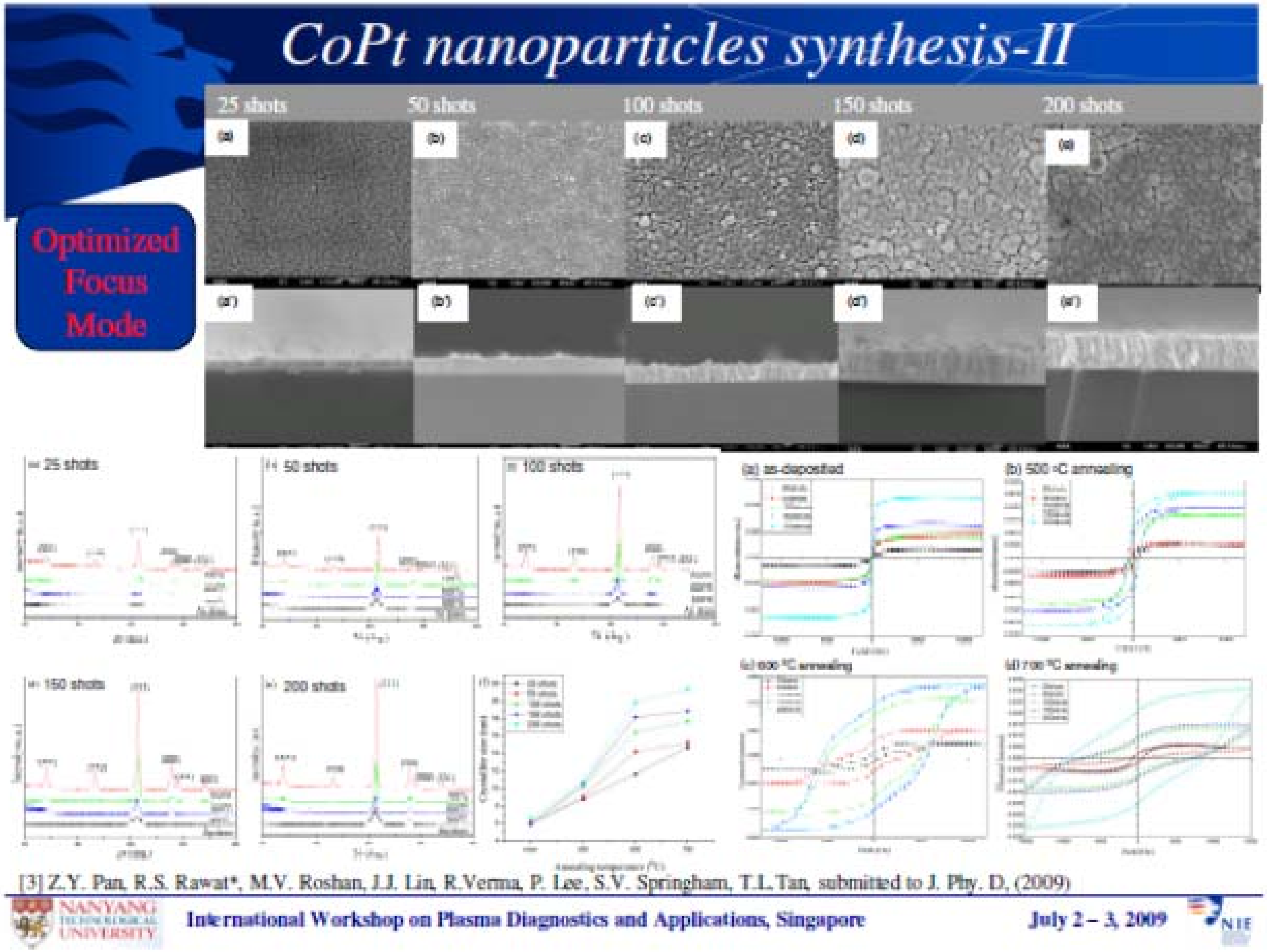


Coercivity:



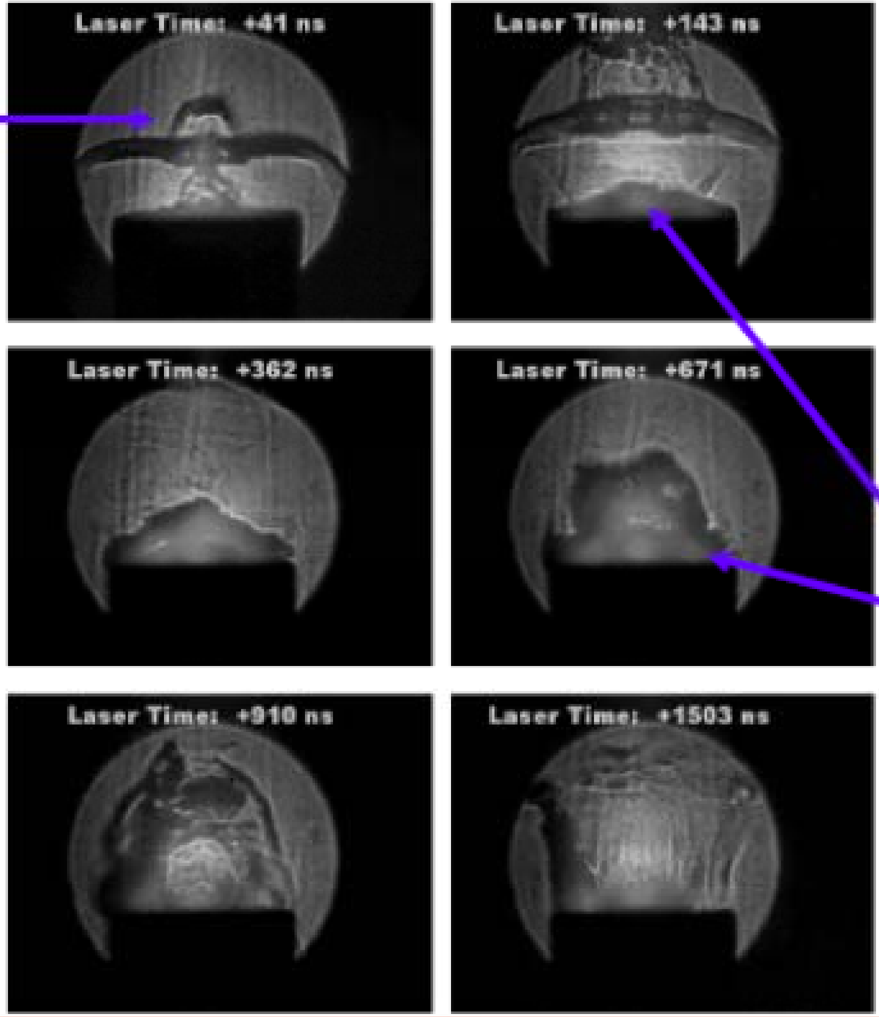
[1] Z.Y. Pan, J.J. Lin, T. Zhang, S. Karamat, T.L. Tan, P. Lee, S.V. Springham, R.V. Ramanujan, R.S. Rawat, Thin Solid Films 517 (2009) 2753.

[2] Z.Y. Pan, R.S. Rawat, J.J. Lin, T. Zhang, P. Lee, T.L. Tan, S.V. Springham, Applied Physics a-Materials Science & Processing (2009). (Available on line)


CoPt nanoparticles synthesis-II
Optimized Focus Mode
25 shots
50 shots
100 shots
150 shots
200 shots
(a)
(b)
(c)
(d)
(e)
(a')
(b')
(c')
(d')
(e')
25 shots
50 shots
100 shots
(a) as-deposited
(b) 500 °C annealing
150 shots
200 shots
(c) 600 °C annealing
(d) 700 °C annealing
[3] Z.Y. Pan, R.S. Rawat*, M.V. Roshan, J.J. Lin, R.Verma, P. Lee, S.V. Springham, T.L.Tan, submitted to J. Phy. D, (2009)
NANYANG TECHNOLOGICAL UNIVERSITY
International Workshop on Plasma Diagnostics and Applications, Singapore
July 2 – 3, 2009
NIE

Thin Film Deposition Mechanism Study using Laser Shadowgraphy

High energy plasma



Shadowgraphs taken at late times. Plasma observed at times long after the focus to understand plasma conditions for deposition applications.

High density, low temperature plasma from ablated material (C)

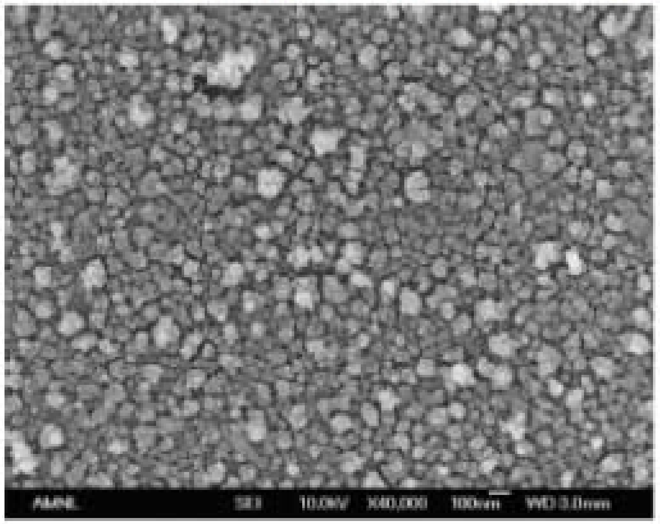
L.Y. Soh, P. Lee, X. Shuyan, S. Lee, and R.S. Rawat, *Shadowgraphic Studies of DLC film deposition process in Dense Plasma Focus Device*, IEEE Trans. Plasma Sci. 32(2) 448 (2004).

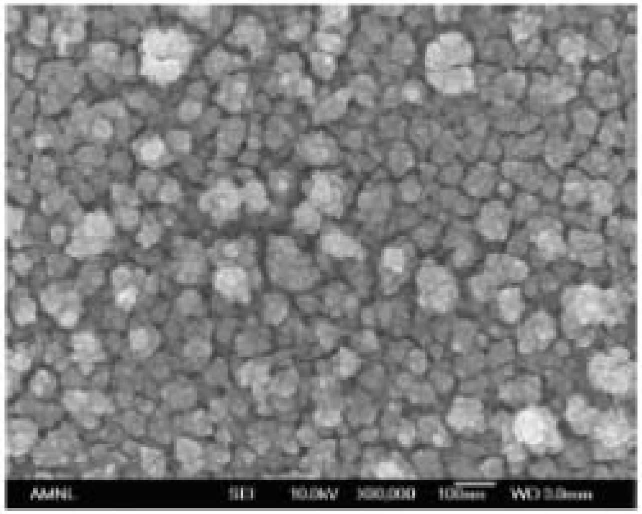
International Workshop on Plasma Computations and Applications 14 July 2008

Synthesis of FeCo using FeCo anode

Repetitive PF: SEM results

25 repetitive shots at 12 mbar hydrogen at 12 kV



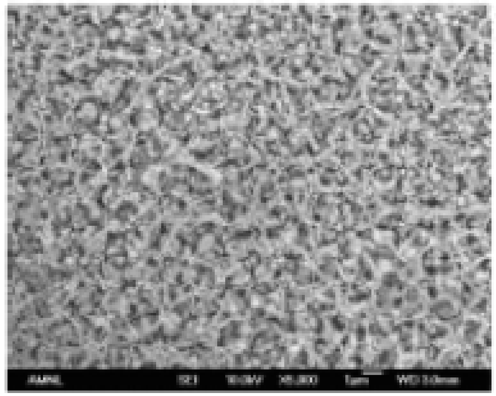


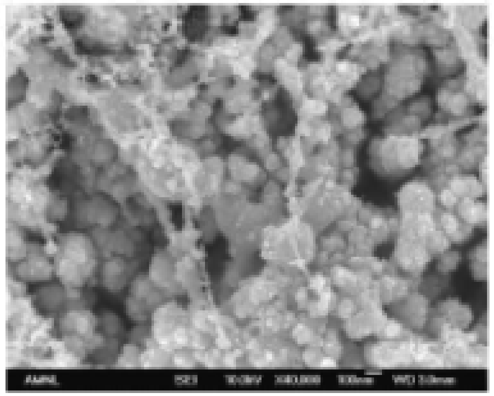
100 nm Agglomerates composed of particles size 20-30 nm

International Workshop on Plasma Computations and Applications 14 July 2008

Repetitive PF: SEM results

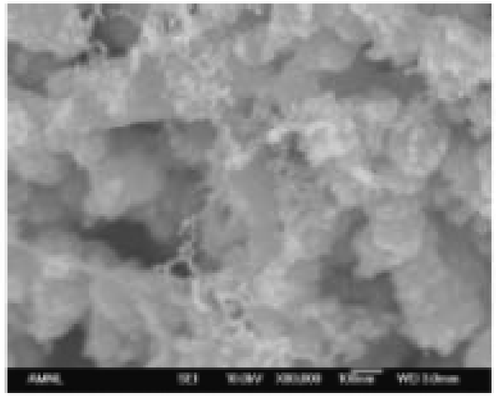
100 repetitive shots at 12 mbar hydrogen at 12 kV

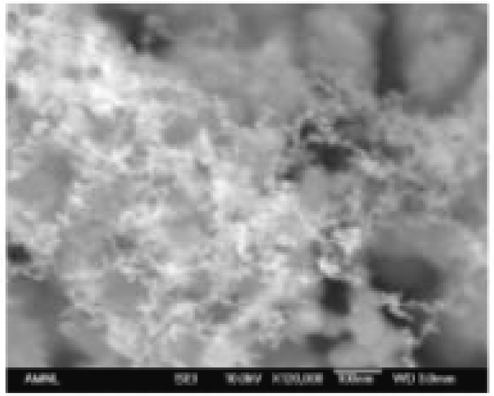




Network structure

like beads arranged on the string

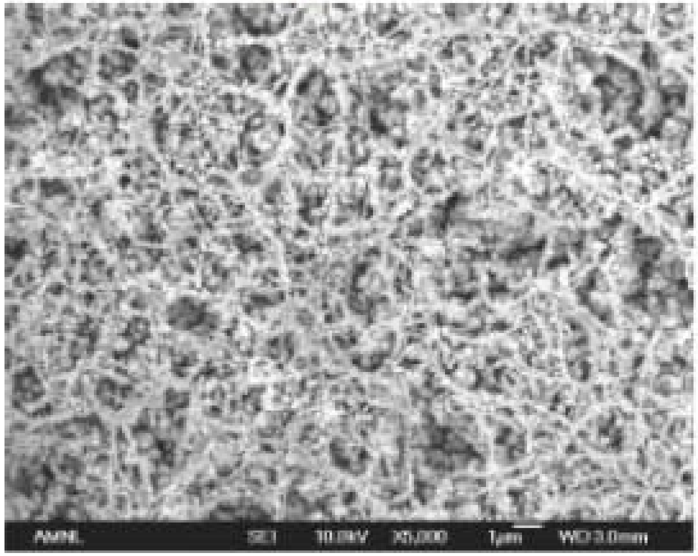


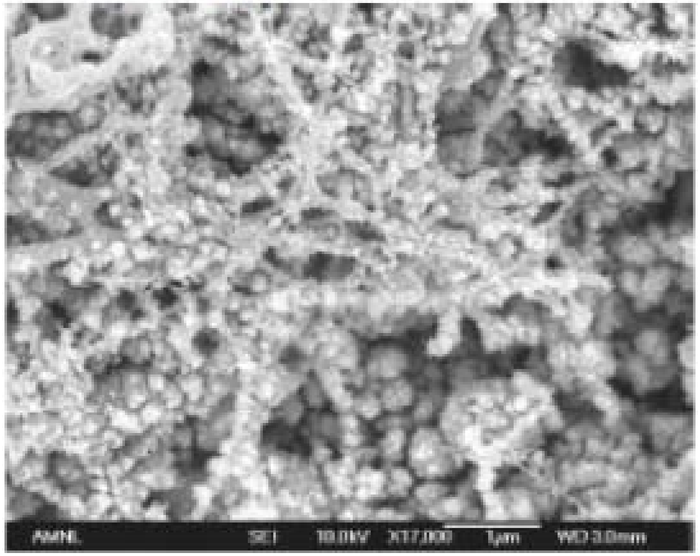


Small size nanoparticles less than 10nm

Repetitive PF: SEM results

250 repetitive shots at 12 mbar hydrogen at 12 kV

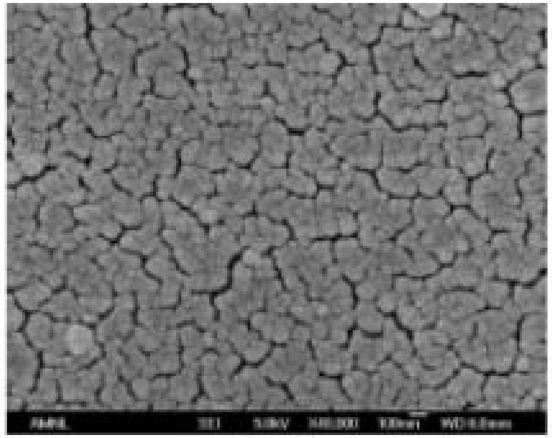




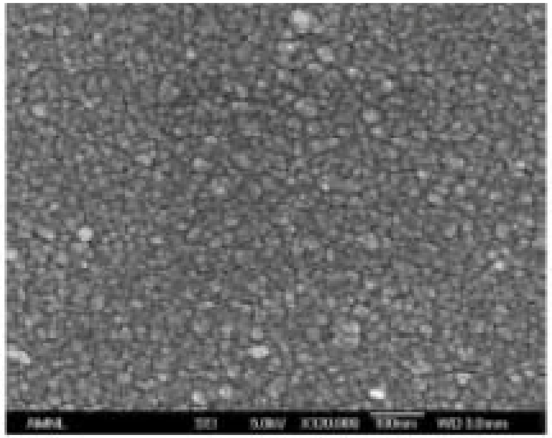
More dense network

More uniform beads-on-string structure

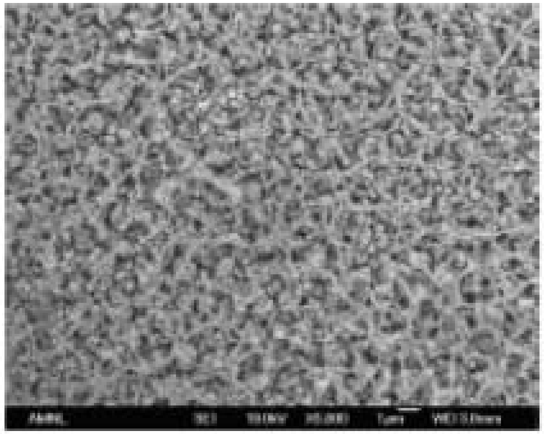
Effect of Gas Pressure – 100Shots, 12 kV



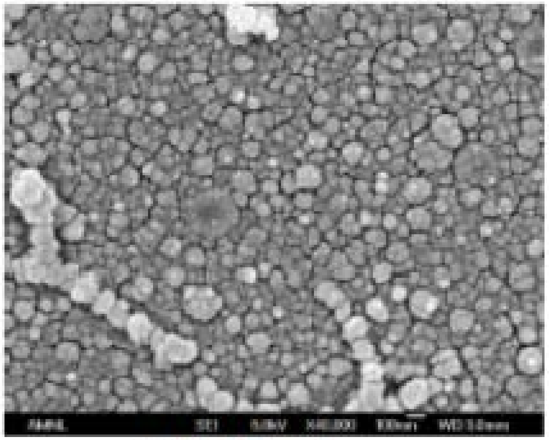
(a) 4 mbar



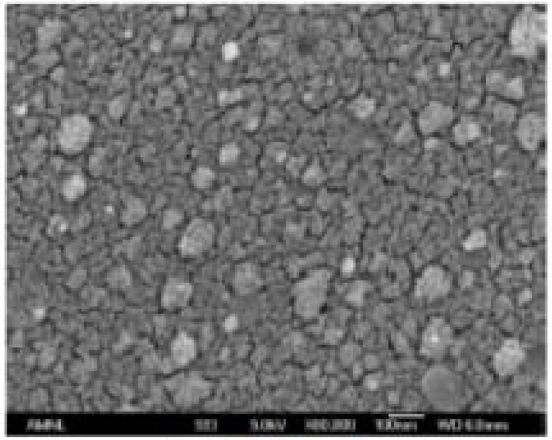
(b) 8 mbar



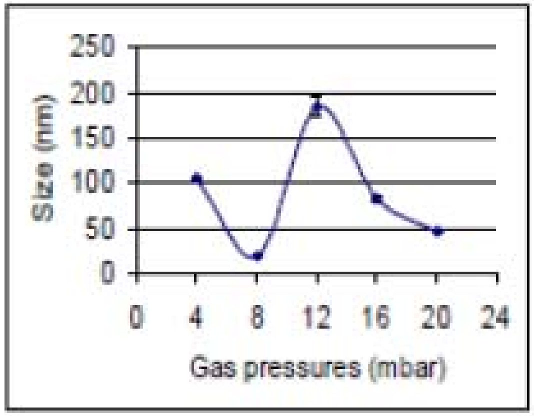
(c) 12 mbar



(d) 16 mbar



(e) 20 mbar



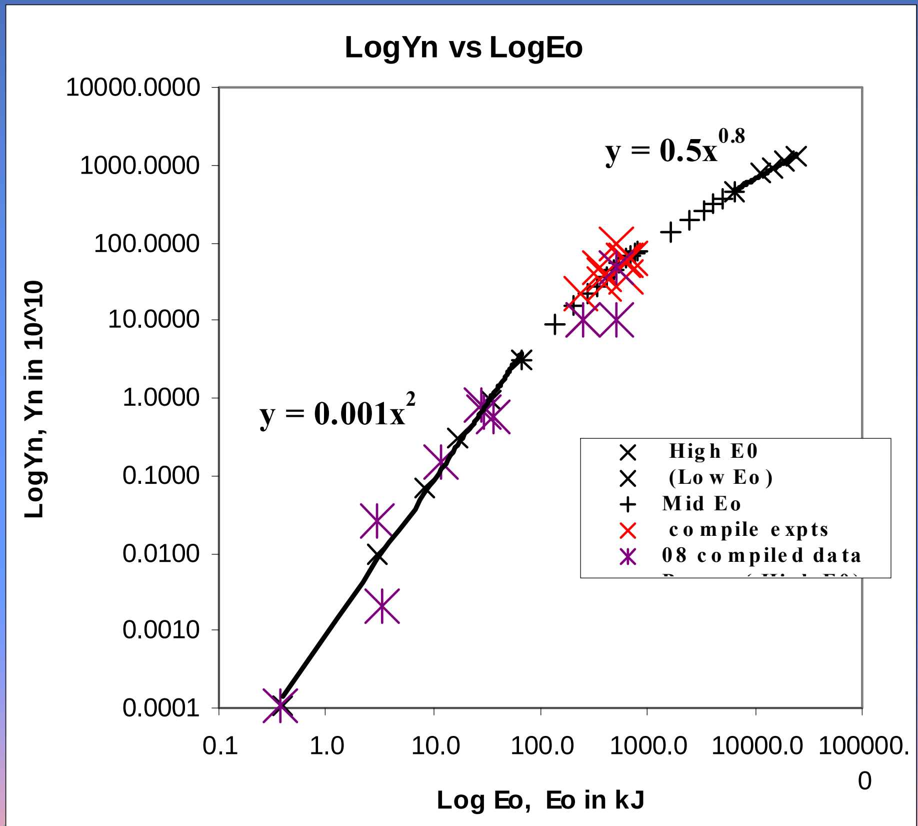
Other Applications

- Studies on Radiation safety & pulsed neutron activation
- Baggage inspection using pulsed neutrons
- Plasma propulsion
- Pulsed neutron source for on-site e.g. oil well inspection
- High speed imaging using combined x-rays & neutrons
- **Broad-spectrum, improved contrast x-ray tomography**
- **Simulation of radiation from nuclear explosion**
- **Testing of materials for suitability for use as plasma facing wall materials in future fusion devices.**

Global Scaling Law

Insights 2

Scaling deterioration observed in numerical experiments (small black crosses) compared to measurements on various machines (larger coloured crosses) Neutron 'saturation' is more aptly portrayed as a scaling deterioration-Conclusion of IPFS-INTI UC research



- **S Lee & S H Saw**, J Fusion Energy, 27 292-295 (2008)
- **S Lee**, Plasma Phys. Control. Fusion, **50** (2008) 105005
- **S H Saw** & **S Lee**.. Nuclear & Renewable Energy Sources Ankara, Turkey, 28 & 29 Sepr 2009.
- S Lee Appl Phys Lett **95**, 151503 (2009)

Cause: Due to constant dynamic resistance relative to decreasing generator impedance

Scaling for large Plasma Focus

Scaling 1

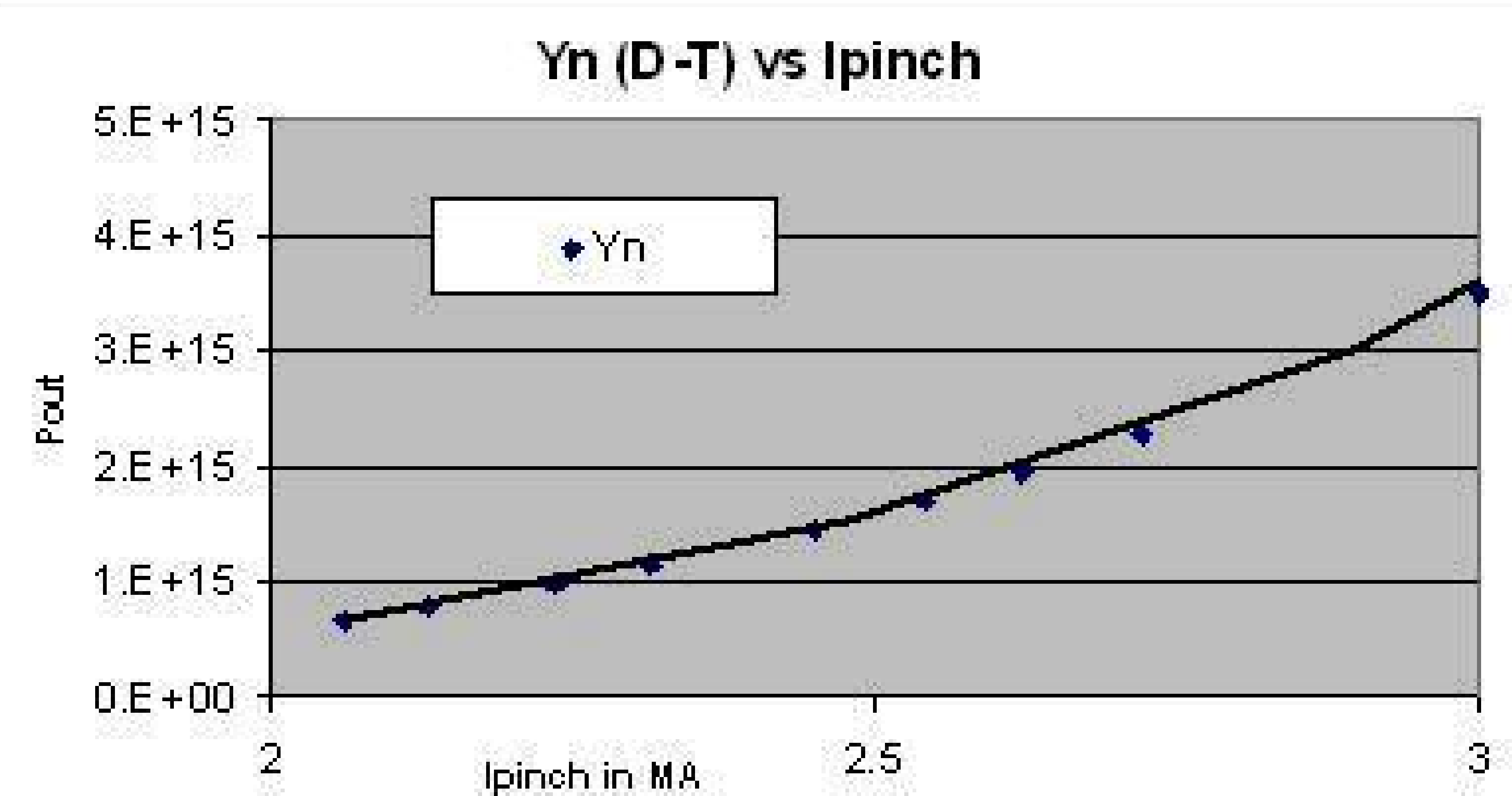
Targets:

1. IFMIF (International fusion materials irradiation facility)-level fusion wall materials testing

(a major test facility for the international programme to build a fusion reactor)- essentially an ion accelerator

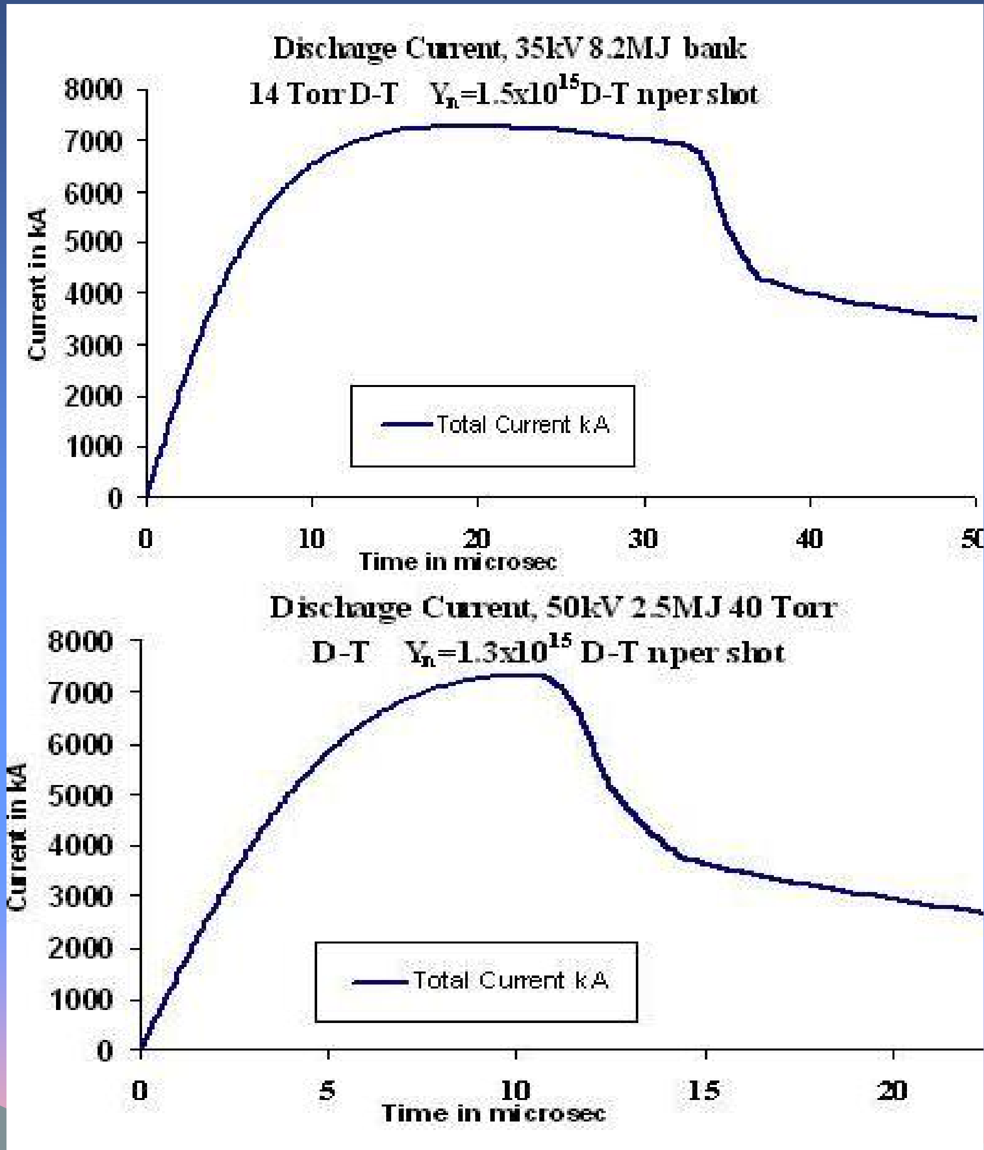
Fusion Wall materials testing at the mid-level of IFMIF: 10^{15} D-T neutrons per shot, 1 Hz, 1 year for 0.1-1 dpa- Gribkov

Scaling 1



Ongoing IPFS numerical experiments of Multi-MJ Plasma Focus

Scaling 1

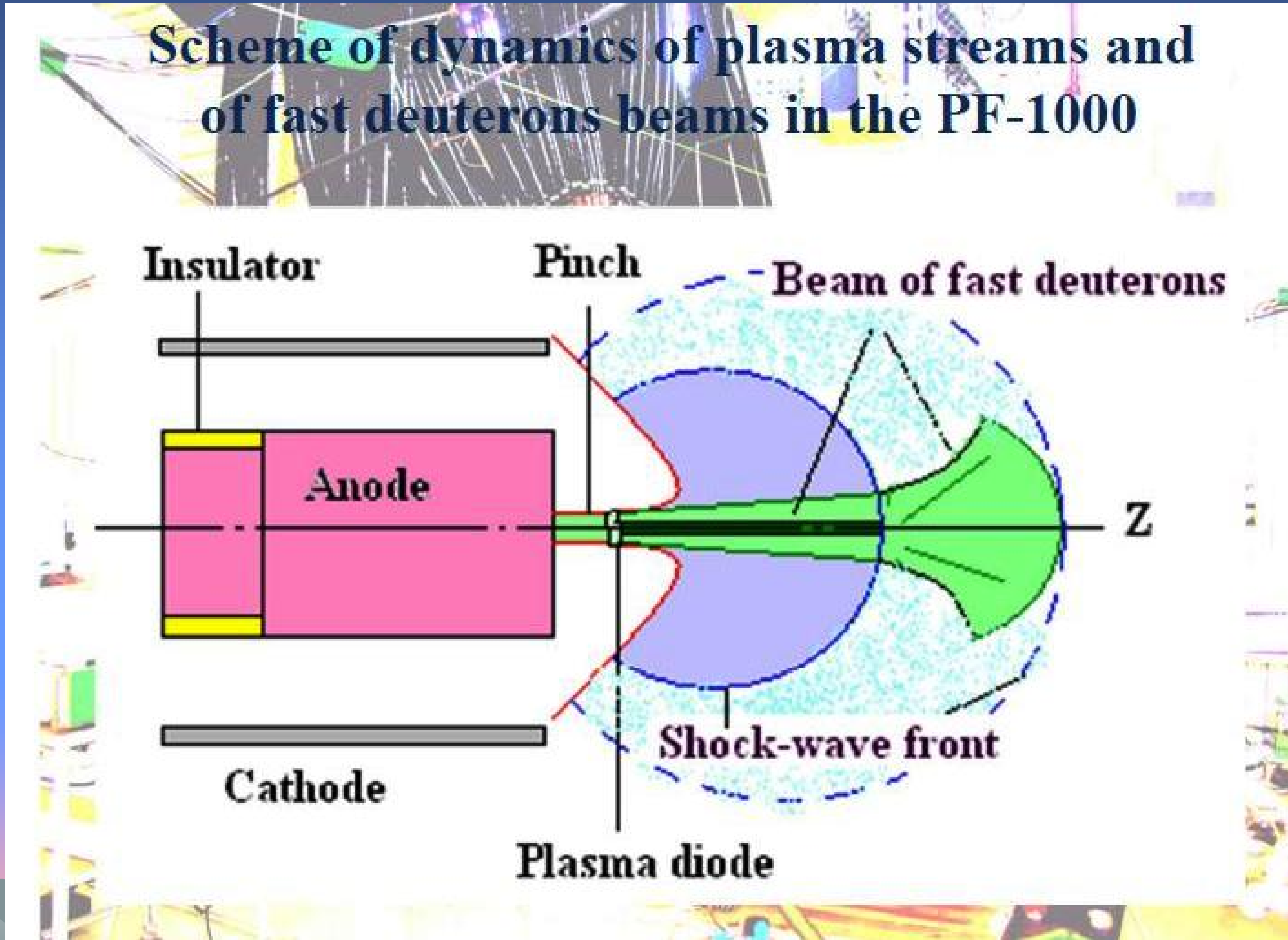


IFMIF-scale device

Scaling 1

- Numerical Experiments suggests the possibility of scaling the PF up to IFMIF mid-scale with a PF1000-like device at 50kV and 2.5 MJ at pinch current of 2.8MA
- **Such a system would cost only a few % of the planned IFMIF**

Extracted from V A Gribkov presentation: IAEA Dec 2012



Post-Pinch Plasma Streams

- 1. Testing of fusion-related wall materials

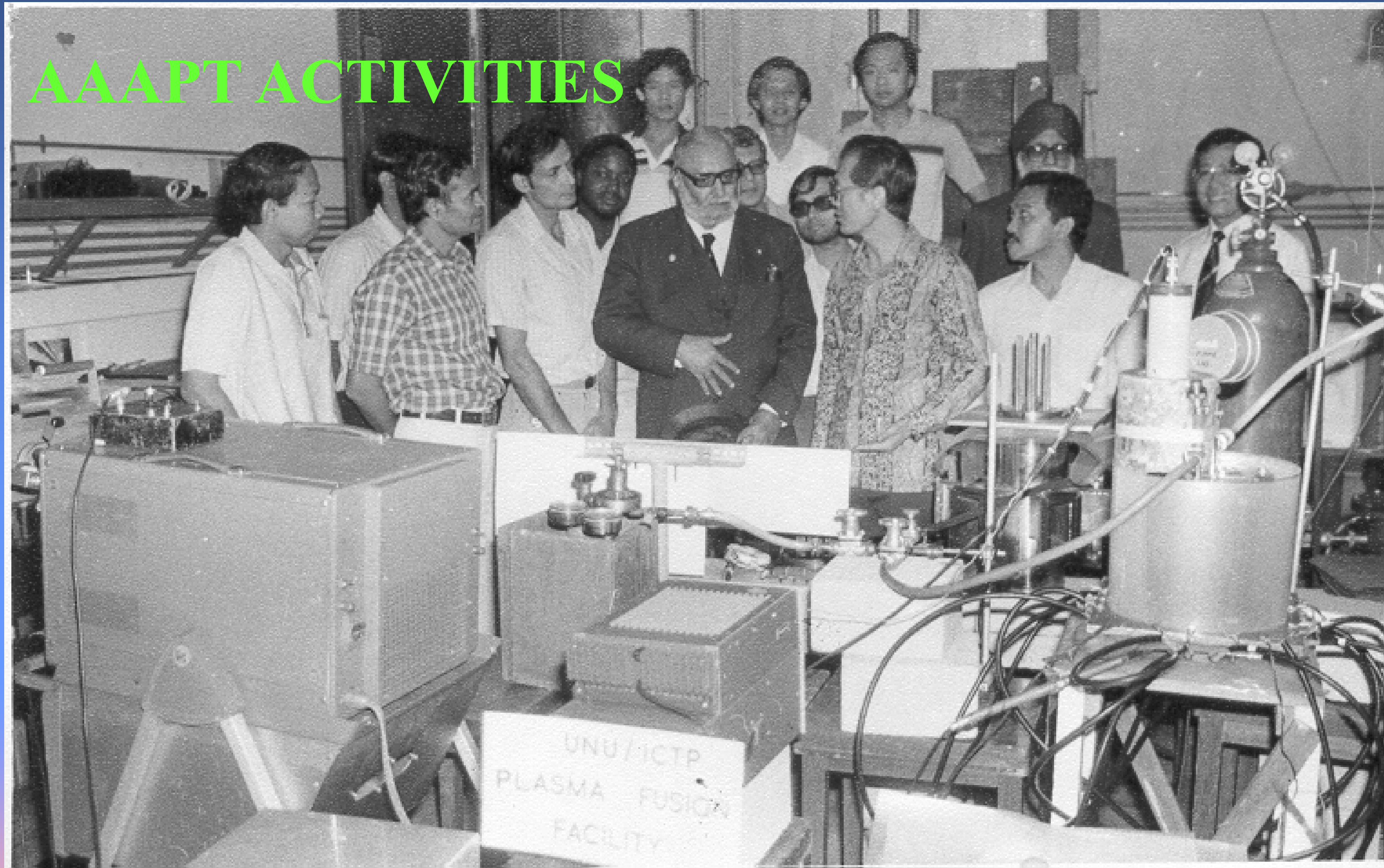
- 2. Radiative shocks phenomena for astrophysical studies e.g. radiative precursors- current interest in laser-driven shocks (1/3 atmospheres 5cm/us in Kr or Xe) with radiative precursors. Similar densities and higher speeds are achieved in post-focus pinch high speed plasma streams

International Collaboration

- Plasma Focus
  - is a very cost effective experimental set-up
  - Multitude of physical phenomena
  - Many applications

- PF is used as facilities for scientific collaboration
  - Asian African Association for Plasma Training
  - International Centre for Dense Magnetised Plasmas

UNU/ICTP Training Programmes



Abdus Salam with UNU Plasma Focus Trainees, Kuala Lumpur, 1986

IAEA Co-ordinated Research Programme

IAEA Co-ordinated Research Project "Investigations of Materials under High Repetition and Intense Fusion-Relevant Pulses"- collaboration of institutions from 13 countries: Bulgaria, Chile, Czech Republic, Estonia, Germany, Italy, Kazakhstan Malaysia, Poland, Russia, Singapore, Ukraine.

The main directions of applications developed are:

-Damage processes of plasma facing materials of fusion devices;

-Classification of main factors affecting performance of these materials

-Establishment of data base of erosion behaviour of selected materials

-Validation of available codes against experimental results within CRP

-Development and standardization of specific relevant diagnostics

-Investigation of damage and activation processes by DPF and fissile reactor neutrons

(extracted from: Summary of 1st Research Coordination Meeting of CRP F1.30.13, 6-9 December 2011, Vienna, Austria.)

Important general results from Decades of research

measuring all aspects of the plasma focus:

-imaging for dynamics

-interferometry for densities

-spectroscopy for temperatures

-neutrons, radiation yields, MeV particles, ion beams

Result: commonly accepted picture today of important mechanisms within the focus pinch :

- micro- & MHD instabilities

-acceleration by turbulence

- 'anomalous' plasma resistance

Result: --**neutron yields are non-thermonuclear in origin**

- scaling properties and scaling laws

- ion beams, much data awaiting correlation, benchmarking, scaling laws

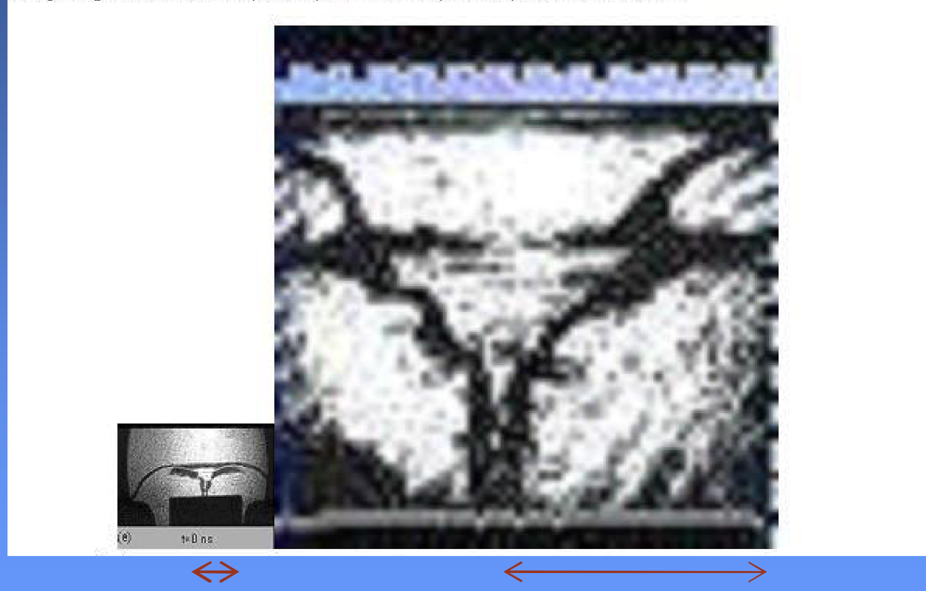
Plasma Focus Scaling Properties

3 kJ machine

1000 kJ machine

Comparing large and small PF's- Dimensions and lifetimes- putting shadowgraphs side-by-side, almost same scale

Comparing UNU ICTP PFF (170 kA) and PF1000 (at 2 MA)- Deuterium 3 Torr



Anode radius 1 cm	11.6 cm
Pinch Radius: 1mm	12mm
Pinch length: 8mm	90mm

Lifetime ~10ns **order of ~100 ns**

Comparing small (sub kJ) and large (thousand kJ) Plasma Focus, the following results are recorded from numerical experiments

Scaling Properties: size (energy) , current, speed and yield

Table 1.

	E_0	a	z_0	V_0	P_0	I_{peak}	v_a	ID	SF	Y_n
	kJ	cm	cm	kV	Torr	kA	cm/μs	kA/cm	(kA/cm) torr$^{0.5}$	10^8
PF1000	486	11.6	60	27	4	1850	11	160	85	1100
UNU ICTP	2.7	1.0	15.5	14	3	164	9	173	100	0.20
PF-400J	0.4	0.6	1.7	28	7	126	9	210	82	0.01

Scaling of anode radius, current and Y_n with energy E_0

Peak current I_{peak} increases with E_0.

- Anode radius 'a' increases with E_0.
- Current per cm of anode radius (ID) I_{peak} /a : narrow range 160 to 210 kA/cm
- SF (speed factor) $(I_{peak}/a)/P^{0.5}$:

  narrow range 82 to 100 (kA/cm) per Torr $^{0.5}$ D

  Observed Peak axial speed v_a : 9 to 11 cm/us.

- **Fusion neutron yield Y_n :**

10^6 for PF400-J to 10^{11} for PF1000.

Variation of ID SF and Y_n

- ID and Speed Factor are practically constant at around 180 kA/cm and 90 (kA/cm) per torr$^{0.5}$ deuterium gas throughout the range of small to big devices

- Y_n changes over 5 orders of magnitude.

Comparing small (sub kJ) & large (thousand kJ) Plasma Focus, results recorded from numerical experiments

Scaling Properties: size (‘a’) , T, pinch dimensions & duration

Table 2.

	c= b/a	a	T_{pinch}	v_p	r_{min}	z_{max}	Pinch duration	r_{min}/a	z_{max}/a	Pinch duration/a
		cm	10^6K	cm/μs	cm	cm	ns			ns/cm
PF1000	1.4	11.6	2	13	2.2	19	165	0.17	1.6	14
UNU ICTP PFF	3.4	1.0	8	26	0.13	1.4	7.3	0.14	1.4	8
PF400J	2.6	0.6	6	23	0.09	0.8	5.2	0.14	1.4	9

Focus Pinch T, dimensions & lifetime with anode radius 'a'

- Dimensions and lifetime scales as the anode radius 'a'.
- r_{min}/a (almost constant at 0.14-0.19)
- z_{max}/a (almost constant at 1.5)
- **Pinch duration** narrow range 8-14 ns/cm of 'a'

- T_{pinch} **is measure of energy per unit mass**.

Quite remarkable that this **energy density varies so little** (factor of 5) over such a large range of device energy (factor of 1000).

Scaling Properties

Table 3.

		Deuterium	Neon (for SXR)
minimum radius	r_{min}	0.15a	0.05a
max length (hollow anode)	z	1.5a	1.6a
radial shock transit	t_{comp}	$5x10^{-6}a$	$4x10^{-6}a$
pinch lifetime	t_p	$10^{-6}a$	$10^{-6}a$
Speed factor	SF	90	

Rule-of-thumb scaling properties, (subject to minor variations caused primarily by the variation in c=b/a) over whole range of optimised device

Axial phase energy density (per unit mass)	constant
Radial phase energy density (per unit mass)	constant
Pinch radius ratio	constant
Pinch length ratio	constant
Pinch duration per unit anode radius	constant

Conclusion: In this lecture we have covered the following:

- Magnetic compressions- mechanism of the PF and advantages
- PF devices
- Some applications
- General Results of decades of Research
- Scaling Properties of the Plasma Focus

Thank You

School and Training Course on Dense Magnetized Plasma as a Source of Ionizing Radiations, their Diagnostics and Applications
8-12 October 2012, ICTP, Trieste, Italy.

Introduction to the DPF-
Machines, Applications and Properties

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