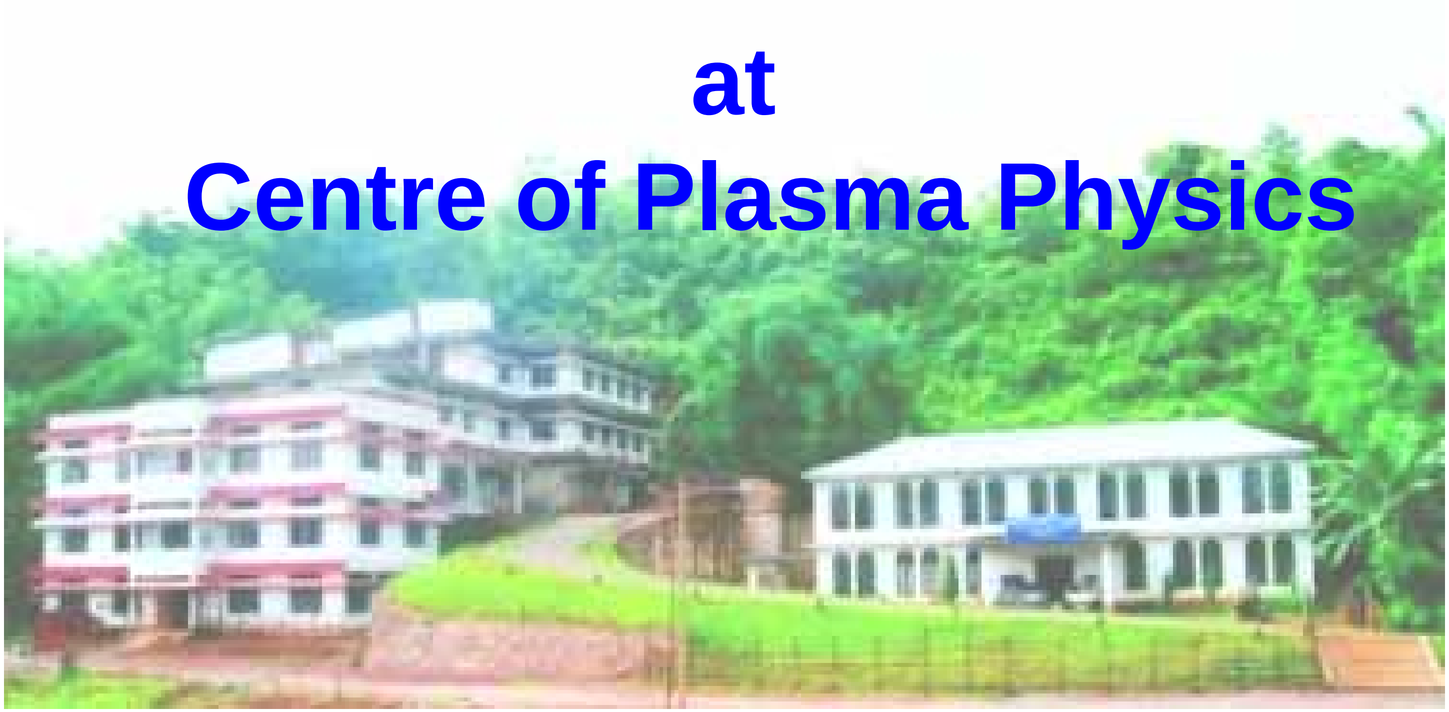
Pinch Plasma Research
at
Centre of Plasma Physics



by

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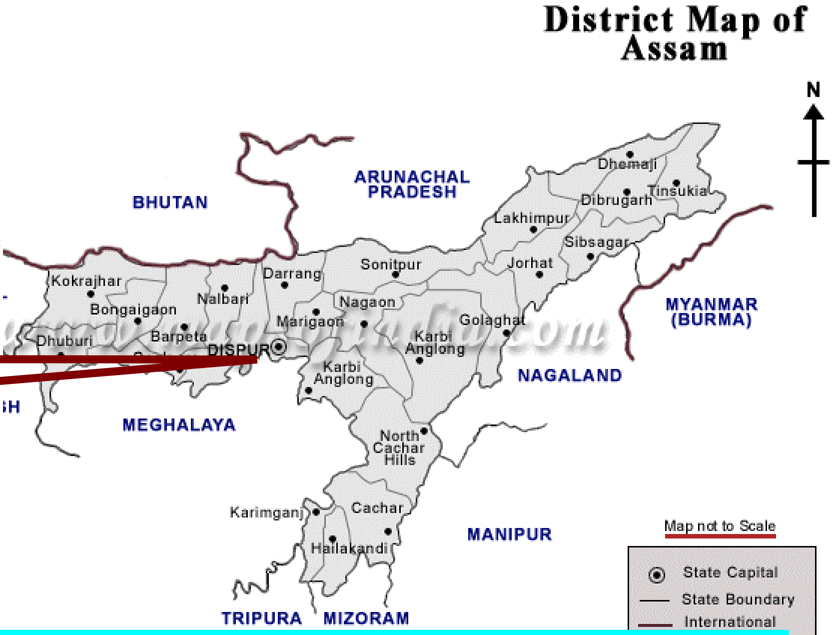
JSPS Fellow

Hotta Lab.,Dept. of Energy Sciences, TITECH

Permanent Address: Centre of Plasma Physics, Assam, India

Brief Introduction of Centre of Plasma Physics (CPP)



Access:

By Air from New Delhi : 2 hours

By Train from New Delhi: 24 hours

CPP - a tiny regional research centre

Administrative & Theoretical Research block

Experimental Research Block

Manpower →

Academic Staff : 8
Support Staff: 15
Research Scholar: 14

Research & Development Activities of CPP

Theory

- Plasma Maser Interaction
- Nonlinear Coherent Structures
- Electron Positron Plasma
- Dusty Plasma
- Plasma Sheath

Experiment

- Dusty Plasma
- Plasma Sheath
- Thermal Plasma
- Low pressure plasma
- Plasma Focus
- Capillary Plasma

Dusty Plasma Experiment

Dusty Plasma Experiment

Objectives

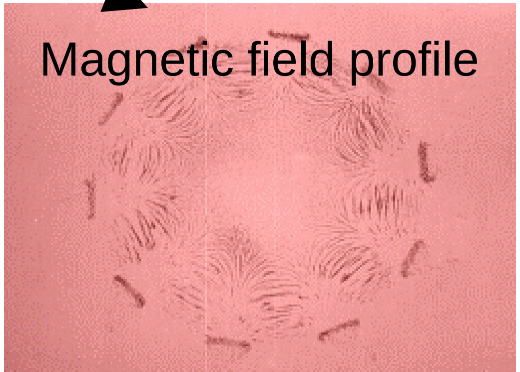
- Measurement of charge on a dust particles embedded in plasma
- Measurement of velocity of the dust grains
- The dust number density
- Dust crystal formation

Detection chamber

Argon plasma is produced by filament discharge

Silver dusts are created by Joule heating

A multi cusp permanent magnet confinement system is used to enhance the plasma density



Magnetic field profile

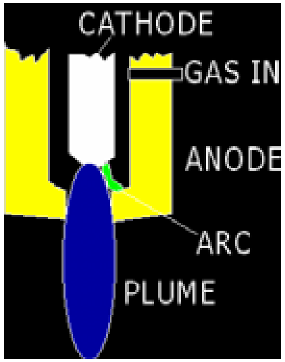
Thermal Plasma Experiment

Full view

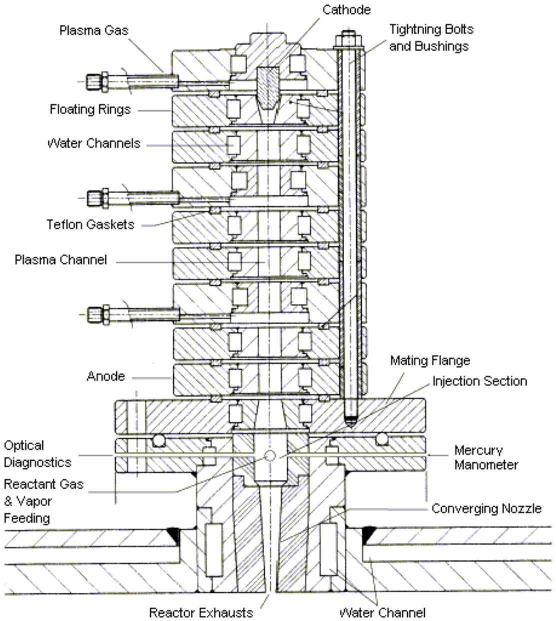
Objectives

- **Set up a thermal plasma based reactor for synthesis of nano-particles of different materials**
- **Study of plasma properties with the help of optical emission spectroscopy and thermocouples**
- **Optimization of the process with respect to particle characteristics**

Chamber containing Torch



Cascade torch and nozzle secton



Low temperature plasma experiment

- DC pulsed low pressure plasma device for nitriding and carburizing of steel specimen
- Characterization of plasma by electrical probe as well as OES
- Nitriding of SS 304 & HCS specimen
- Studying the effect of expt. parameters on nitriding

Plasma Sheath Experiment

Understand the basic sheath physics including physical properties of static and dynamical behavior of plasma sheath under different plasma compositions

Double Plasma Device

Presentation Outline

- Genesis of Plasma Focus Pinch device
- Introduction to Plasma Focus device
- CPP Plasma Focus Device and some basic Diagnostics
- Comparative study of soft X-ray emission
- Measurement of ion yield
- Synthesis of carbonitride coating
- Ion irradiation of American diamond

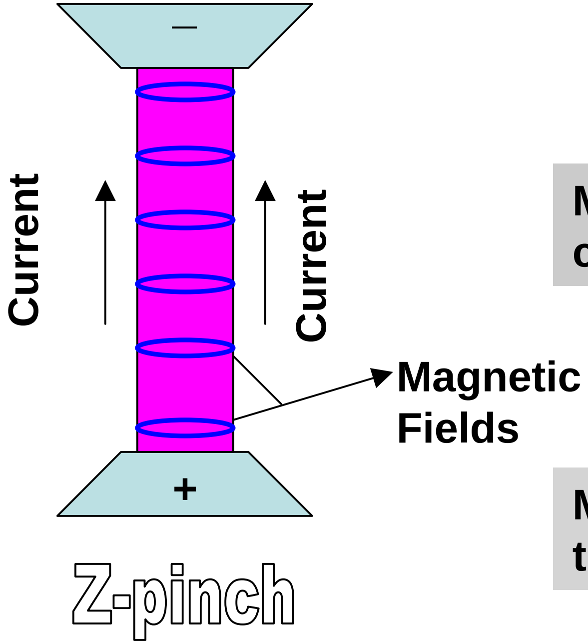
Genesis of Plasma Focus Pinch Device

Plasma Focus device ???

A class of pinch device that is originated from Z-pinch

A Z-pinch is a column of plasma with an axial current that creates azimuthal magnetic field.

One of the earliest and least complicated plasma fusion confinement ideas…



Magnetic pressure from the azimuthal field confines and compresses the column, creating a hot, dense plasma.

Magnetohydrodynamics instabilities usually destroy the pinch within few nanoseconds Limiting its usefulness.

Genesis of Plasma Focus Pinch Device

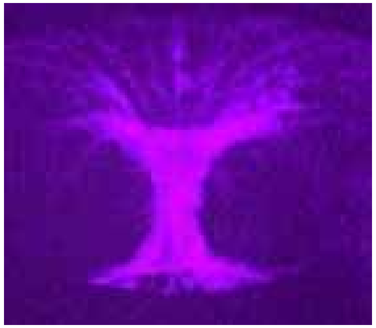
Some of draw backs of classical Z-pinch device

- **Mismatch in between pinching time and maximum of discharge current**
- **Contamination of pinch by insulator material**
- **Stability of pinch column**

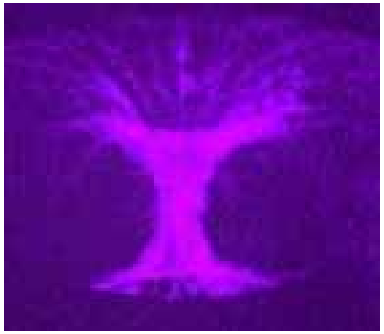
Pinch researcher tried to overcome these demerits of classical Z-pinch

Researcher from LANL and Kurachatov Institute came out with a new electrode geometry Z-pinch device that addressed the above mentioned demerits

Plasma Focus/ Dense Plasma Focus



Plasma Focus (PF)



- A coaxial plasma accelerator that produces high- temperature, high- density short lived plasma

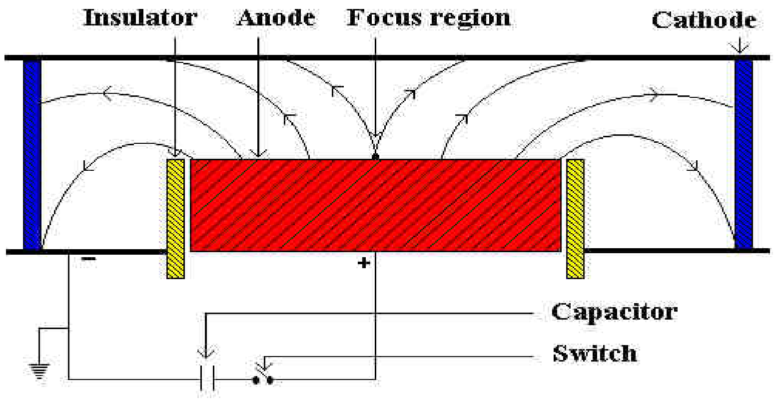
- Temp. ~ 1- 4 keV
  Density ~ $10^{25\text{-}26}$ m $^{-3}$
  Time ~ 100-200 nsec

The **plasma focus** combines feature of both the **EM shock tube** and the **Z-pinch** in such a properly sequenced manner that all the **features** of both devices may be demonstrated in one single **device.**

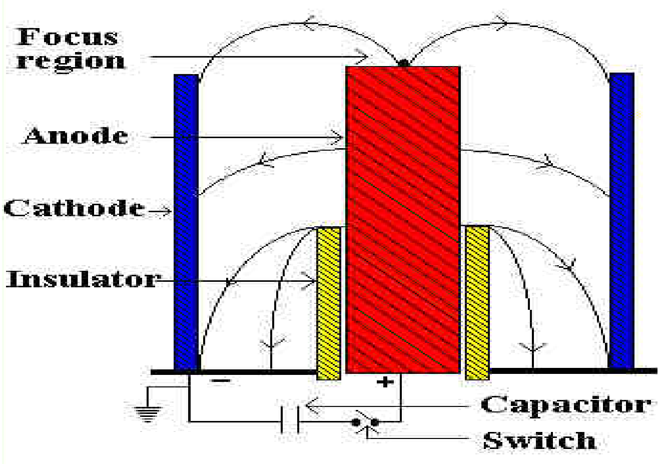
Inventors

N.V. Filippov: 1962, Kurchatov Inst., Russia

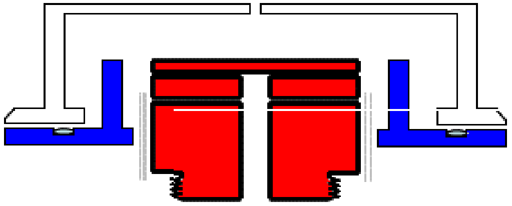
J.W. Mather: 1964, LANL, USA



Filippov type
(Anode Aspect Ratio<< 1)



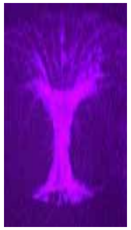
Mather type
(Anode Aspect Ratio>> 1)



HYBRID Type

Anode Aspect ratio~1

Anode Aspect ratio= Anode length / Anode radius



Why ’s it so fascinating ???

- Neutrons
- Particle Beams (ions & electrons)
- EM radiations starting from visible to X-rays, γ-rays

Variety of other interesting phenomena

- Hot spots/plasmoids
- Current filamentations
- Instabilities
- Turbulence

Large range of phenomena observed in easily constructed machine leads to its study in many laboratories.

It’s applications

- X-ray lithography
- X-ray microscopy and radiography
- Neutron radiography
- Material modification
- Thin film deposition

➢ **Many companies like AIXUV GmbH , R.E. Beverly III and Associates etc. have already marketed this device for commercial purpose.**

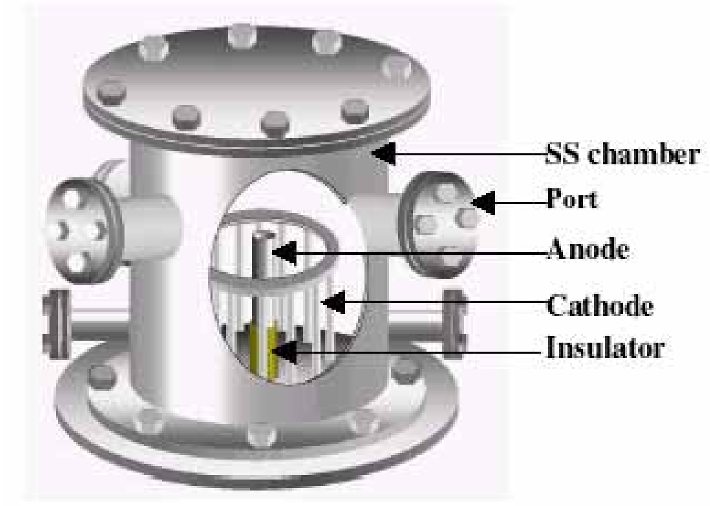
● **CYMER Inc. and SRL in USA are trying to use this device for EUV and X-ray Lithography source**

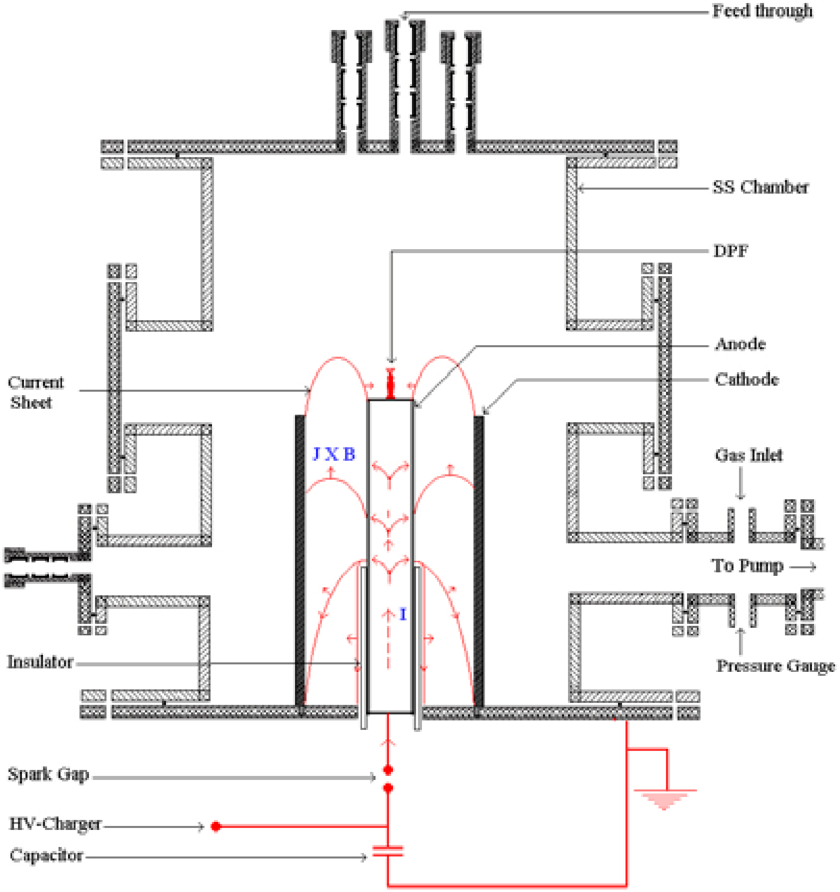
☞ Lawrenceville Plasma Physics group is hoping to use PF for $P^{11}B$ fusion.

www.focusfusion.org

Overview of PF

Comprises of co-axial electrode assembly housed in a vacuum chamber, capacitor bank, high voltage charger, fast switch etc.



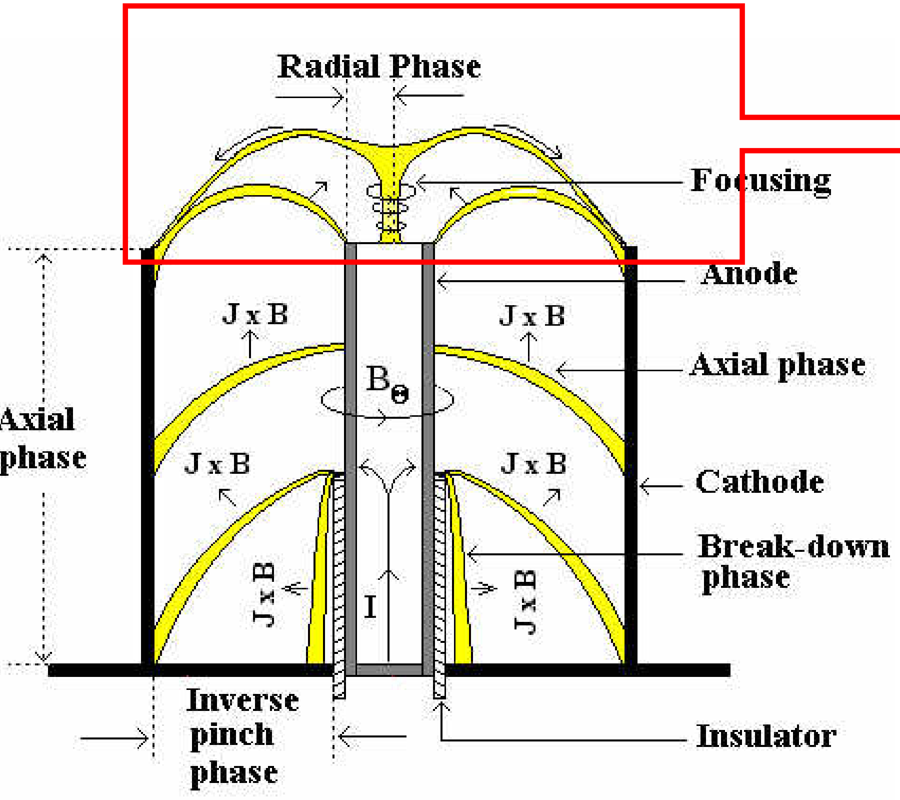


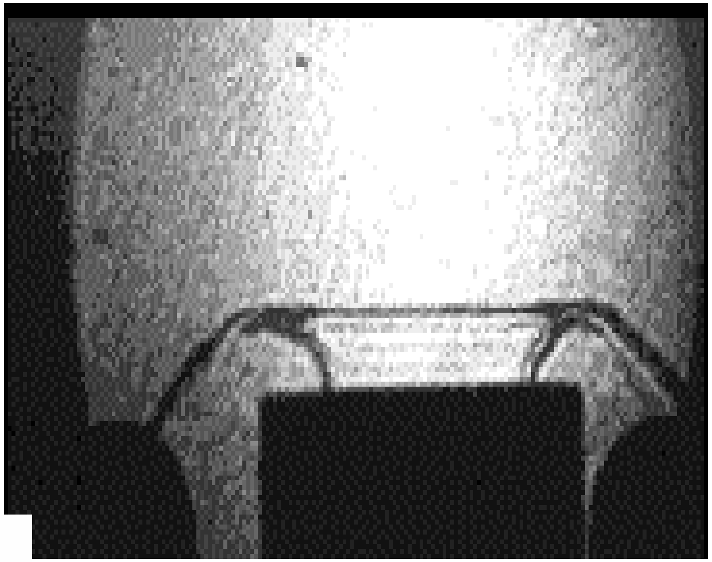
Principle

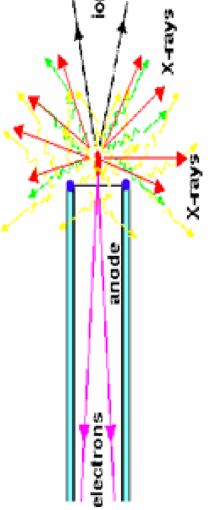
Stored capacitor Energy → **Magnetic Energy** → **Plasma Energy**

Current sheath Dynamics

- Inverse pinch phase
- Axial acceleration/rundown phase
- Radial collapse/ pinch phase

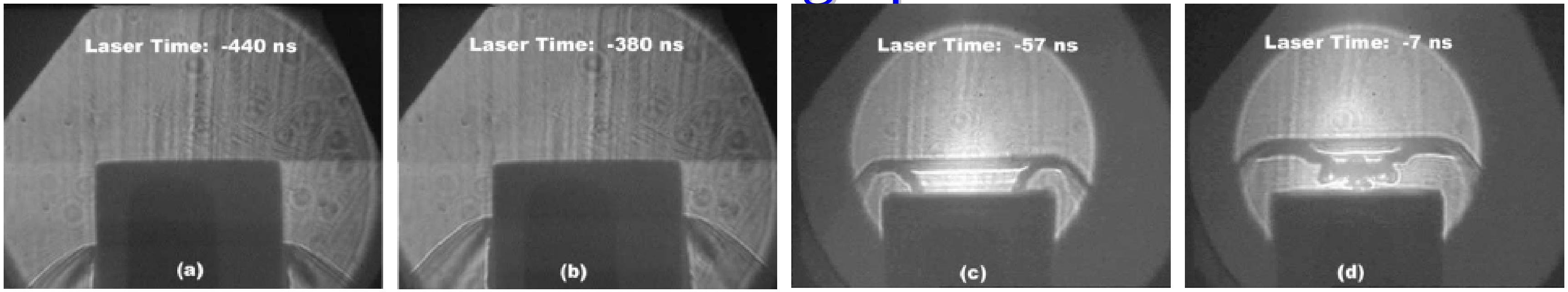




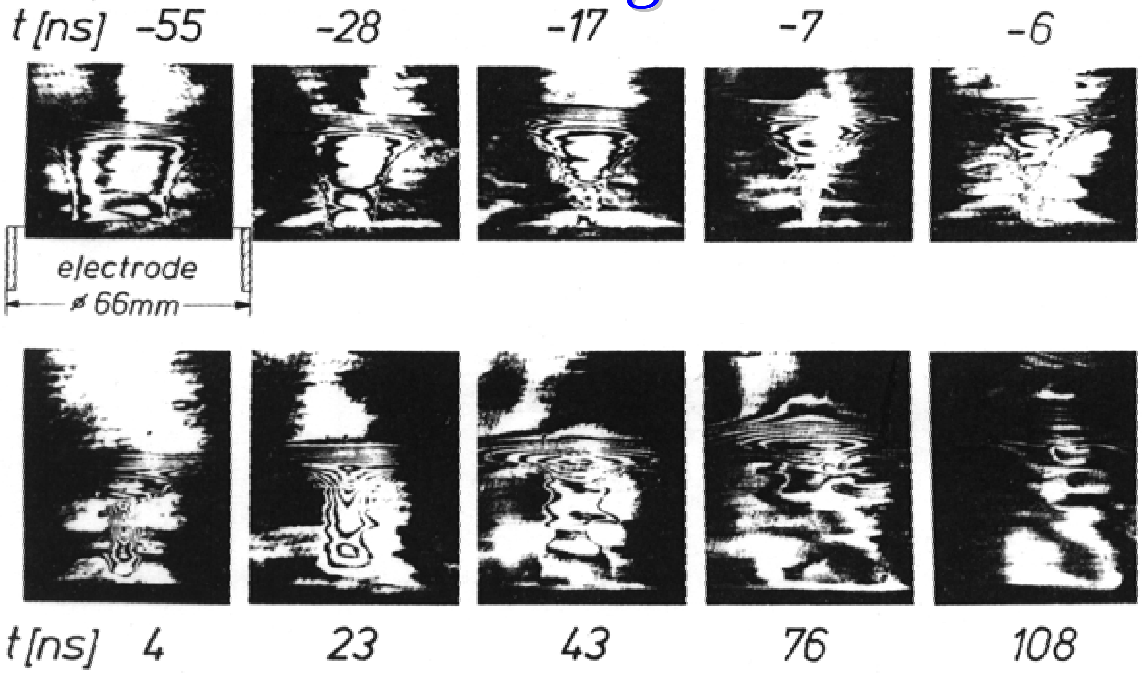


Shadowgraphs & Interferograms Current Sheath

Shadowgraphs



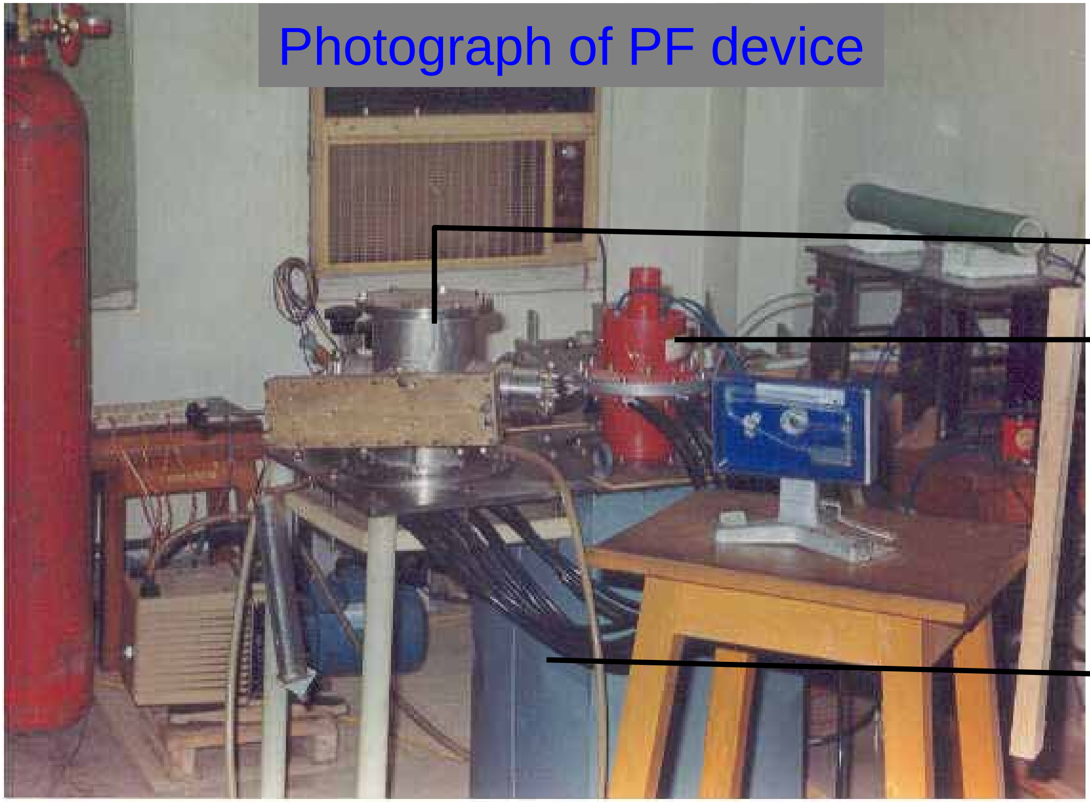
Interferograms



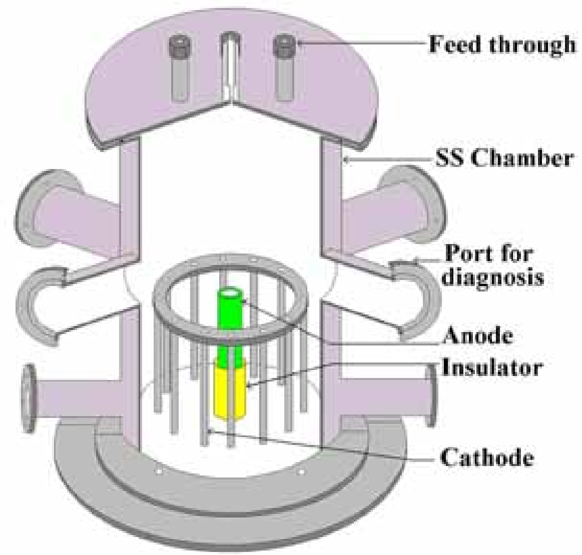
CPP Plasma Focus Device

- CPP started research on Plasma Focus in 1997 after the installation of a low energy Mather type PF device
- Total funding till 2004 is around US $ 70,000

CPP PF looks like…



Photograph of PF device

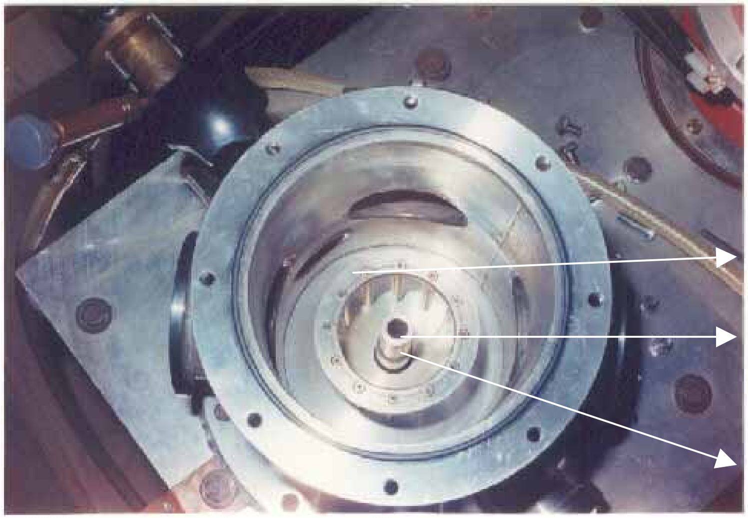


Pressurize Switch

Capacitor

PF is powered by 7.1 µF, 25 kV capacitor

View of PF chamber with electrodes



Most common empirical formula used to design classical plasma focus staring from few kJ to MJ

$$CV^2/pl = K_1$$

$$CV/rpl^2 = K_2$$

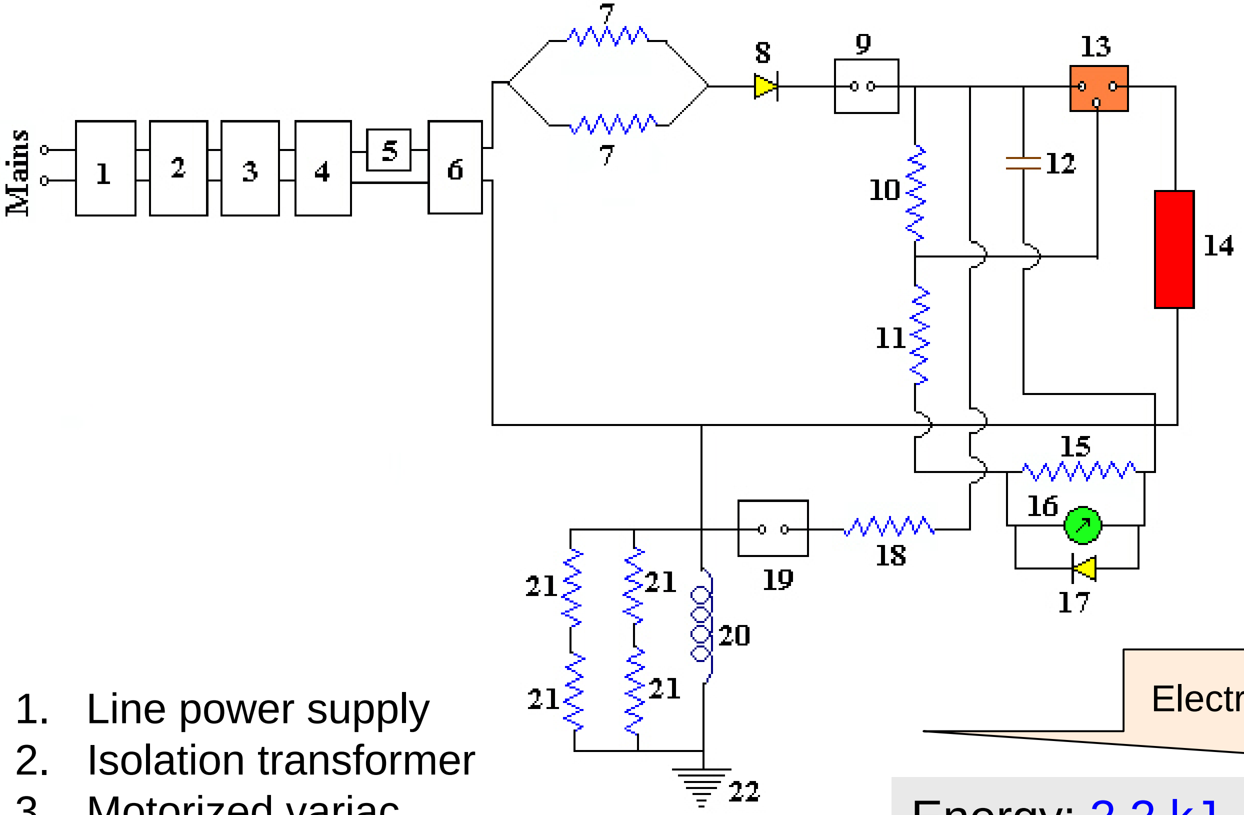
Dimension

Components	Length	Diameter	Material (s)
Anode	115 mm	21 mm (O.D.)	Stainless steel, brass, tungsten, copper and aluminium
Cathode rod	110 mm	90 mm (O.D.)	Stainless steel, brass
Insulator sleeve	45 mm	21 mm (I.D.)	Borosil, Quartz
Vacuum chamber	Volume ~ 6 litres		Stainless steel

Optimum operating filling pressure

Nitrogen → 0.3-0.4 torr
Argon → 0.2-0.3 torr
Hydrogen → 0.8-0.9 torr

Circuit diagram of the PF device

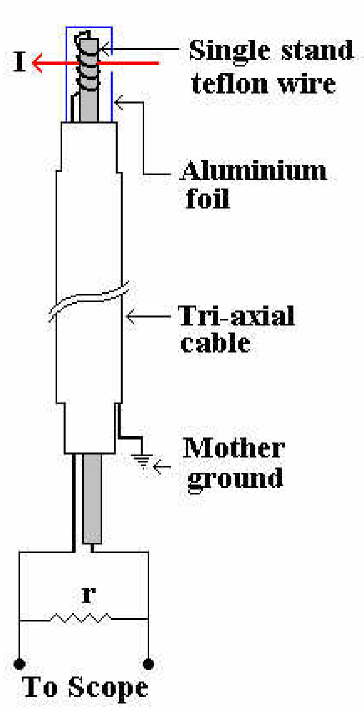


1. Line power supply
2. Isolation transformer
3. Motorized variac
4. Fixed variac
6. HV transformer
9. Connecting/Isolating switch
12. Capcitor
13. Pressurised spark gap
14. PF tube

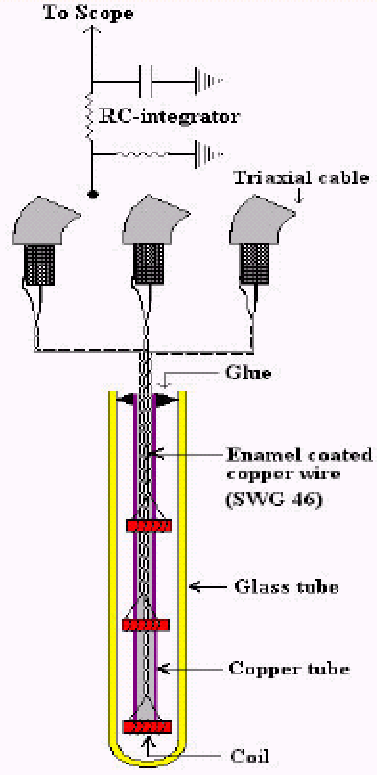
Electrical parameters

Energy: 2.2 kJ
Short circuit inductance: 230 nH
Load current: 135 kA
Quarter period of load current: 2.1 µs

Diagnostics

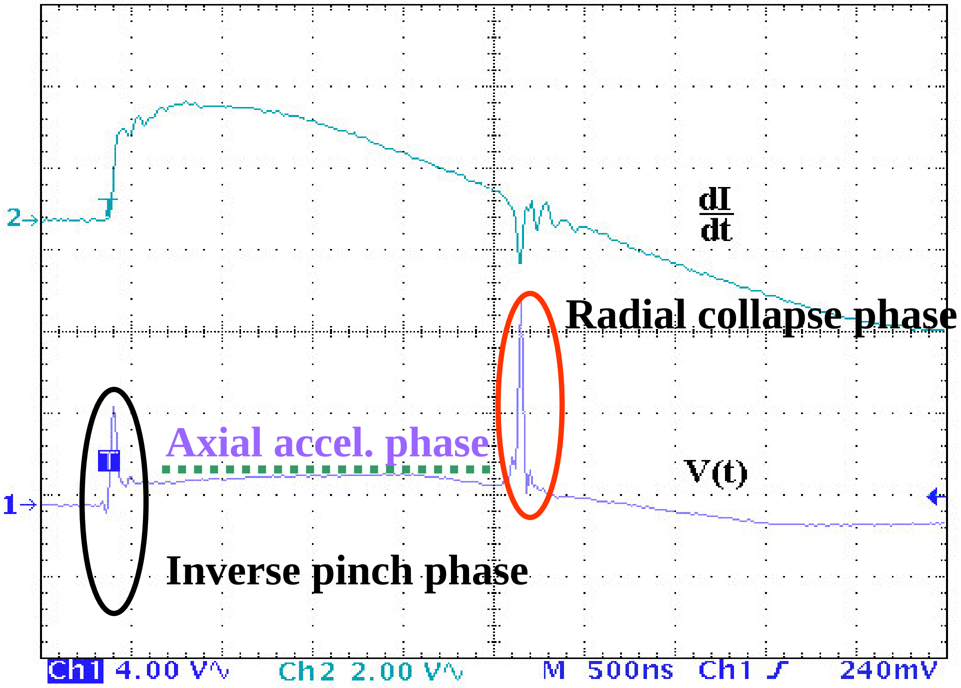


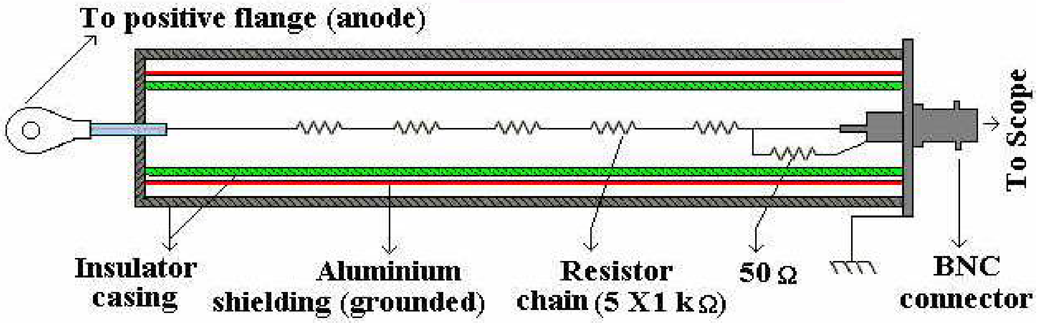
Current probe



Magnetic Probe

Time history of discharge

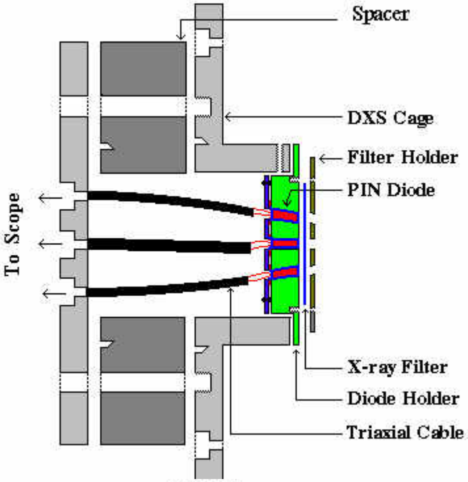




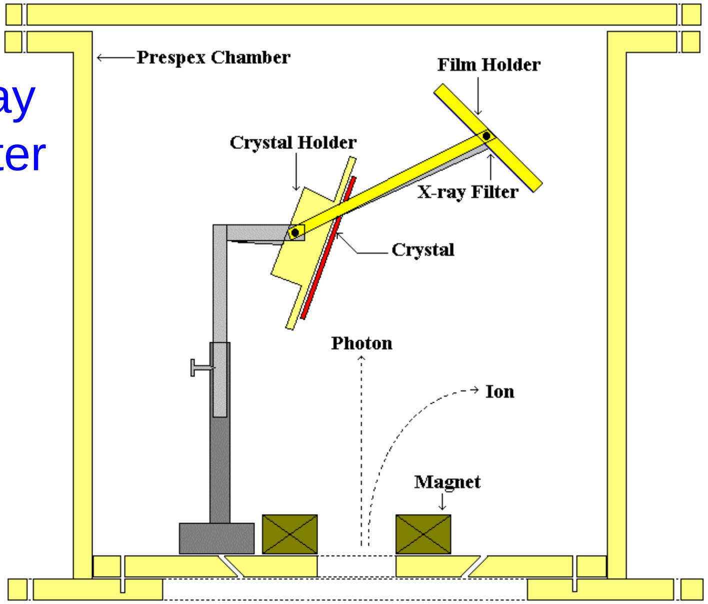
Voltage probe

Diagnostics

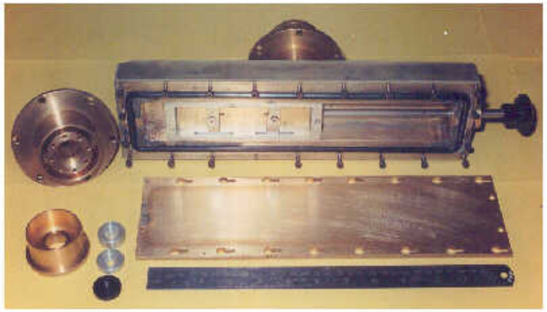
Diode X-ray spectrometer

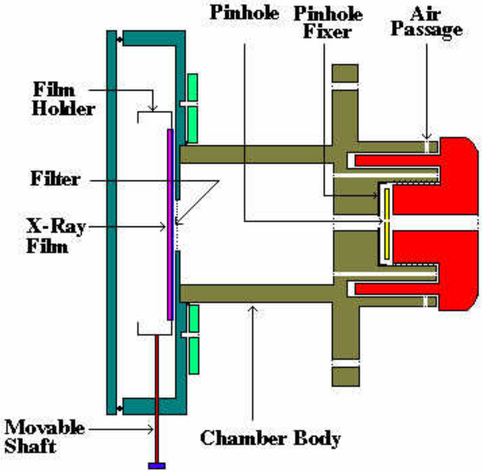


Crystal X-ray Spectrometer

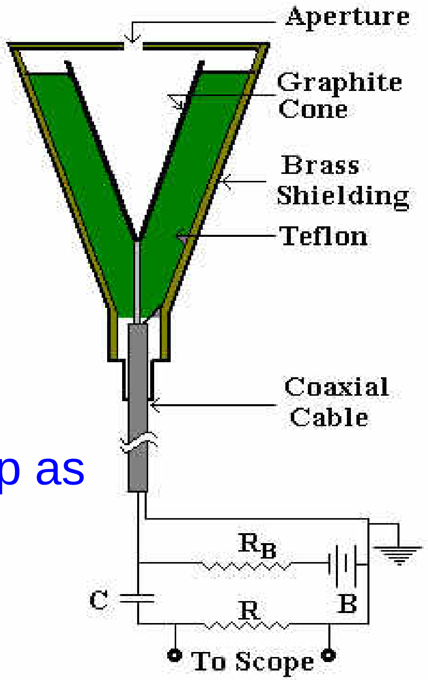


X-ray pinhole camera





Faraday Cup as ion collector



Problems Carried out…..

Basic studies

- Current sheath dynamics using multiple magnetic probe { MST, 2003 }
- Comparative study of soft X-ray emission { JAP, 2004 }
- Measurement of ion yield { JJAP, July 2005 }

Applications

- **Nitriding of High Carbon Steel { Surface Engineering, 1999 }**
- **Synthesis of carbonitride coating { Surface Coating &Technology, 2001 }**
- **Ion irradiation of American diamond { Power Beam & Material Processing Conf. Proceedings, 2003}**

Comparative study of soft X-ray emission

Journal of Applied Physics, Vol. 95, p.2975, 2004

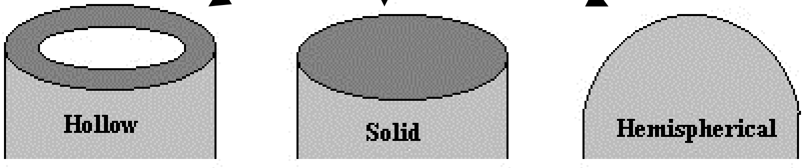
Objective of the work

To enhance X-ray yield by varying experimental parameters and design

Investigated X-ray emission qualitatively and quantitatively

- with various shapes of anode/ central electrode
- with different gases at varying filling pressures

Anode design



Gases

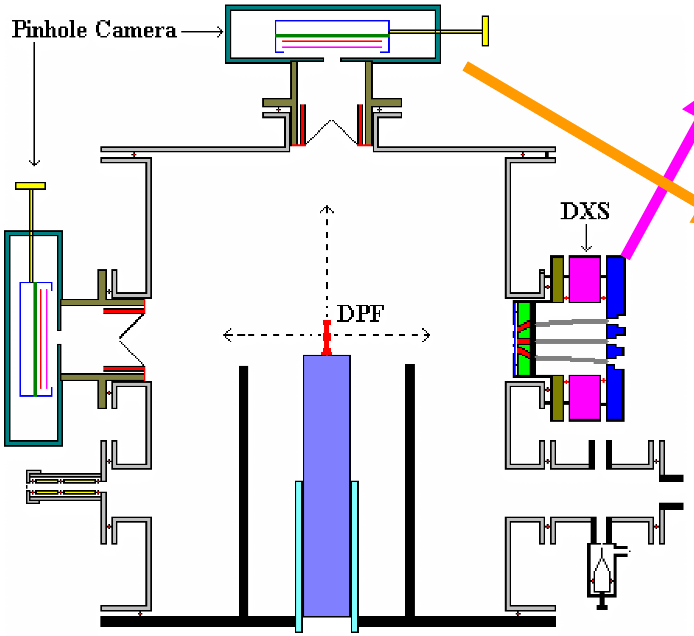
- Hydrogen
- Nitrogen

Diagnostics

- Multi-channel Diode X-ray Spectrometer
- X-ray pinhole camera

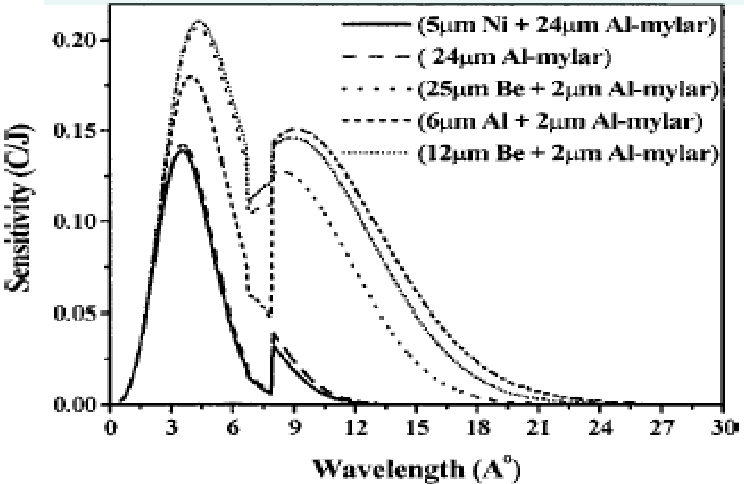
Comparative study of soft X-ray emission

Experimental arrangement

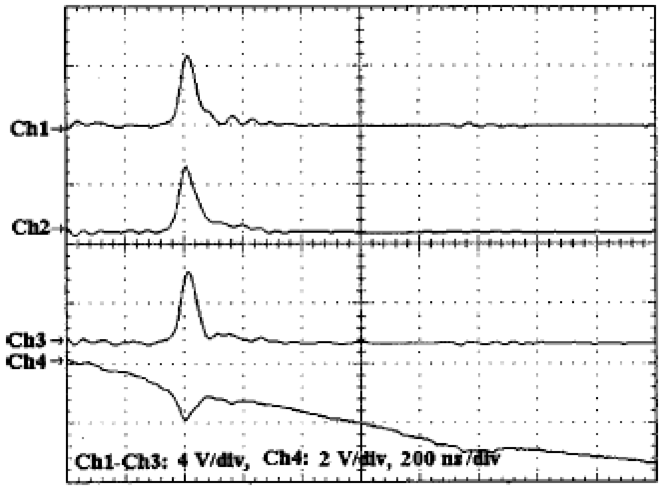


- **DXS looked into the plasma column from side on position**
- **Pinhole camera positioned both at side on and end on position**

Sensitivity of photodiode with filters



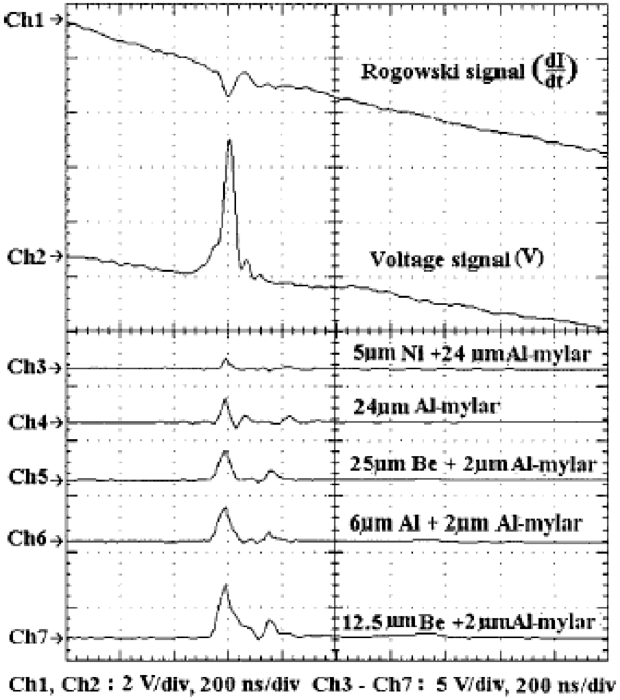
Relative response of diode channel



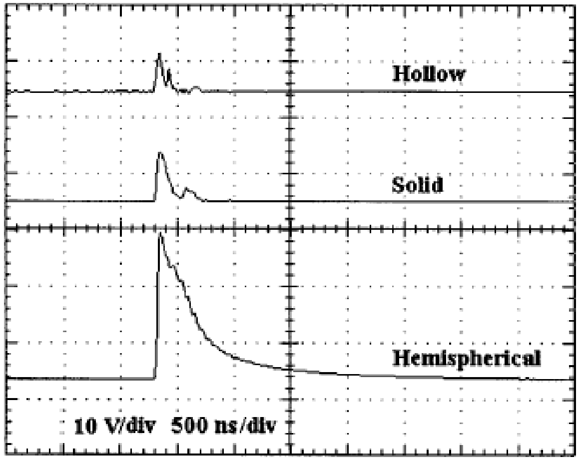
Comparative study of soft X-ray emission

DXS results

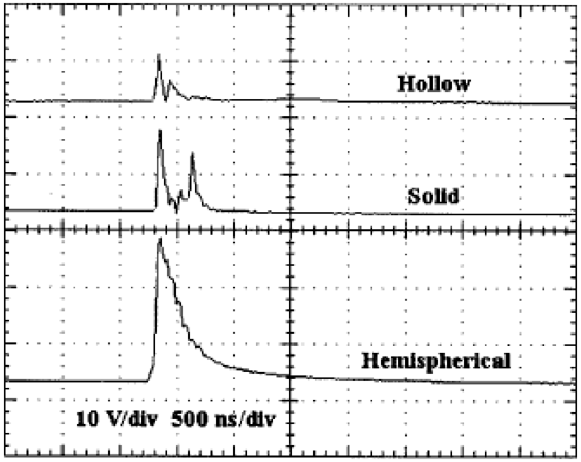
Nitrogen filling pressure at 0.3 torr for hollow anode



Nitrogen



Hydrogen



Multiple X-ray pulses are observed in hollow and solid anode having pulse duration 80-150 nsec

In case of hemispherical a broad X- ray peak is observed

☞ X-ray yield from Plasma Column is strongly influenced by anode geometry and is not so sensitive to filling gas type

Calculation of total X-ray energy in full solid angle

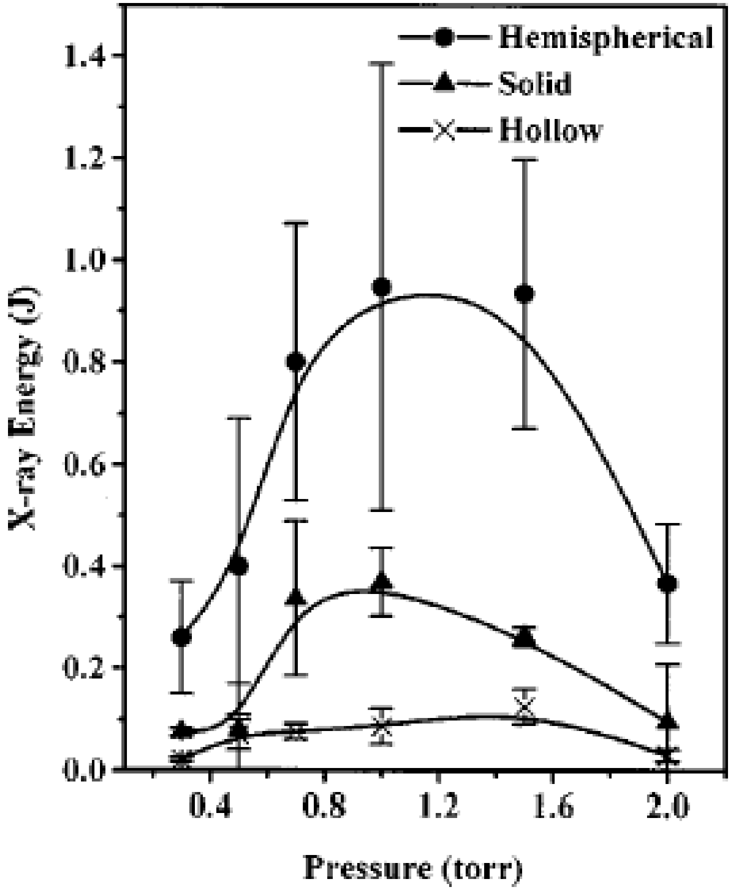
$$E_{4\pi} = \frac{4R^2 \int V\,dt}{R_\Omega\, r^2\, S_D}$$

$\int Vdt$ → Time integral of x-ray signal

R ↔ Distance between detector to X-ray source

r → Radius of detector

S_D → Diode sensitivity



Radiated energy strongly depends upon the filling pressure & anode shapes

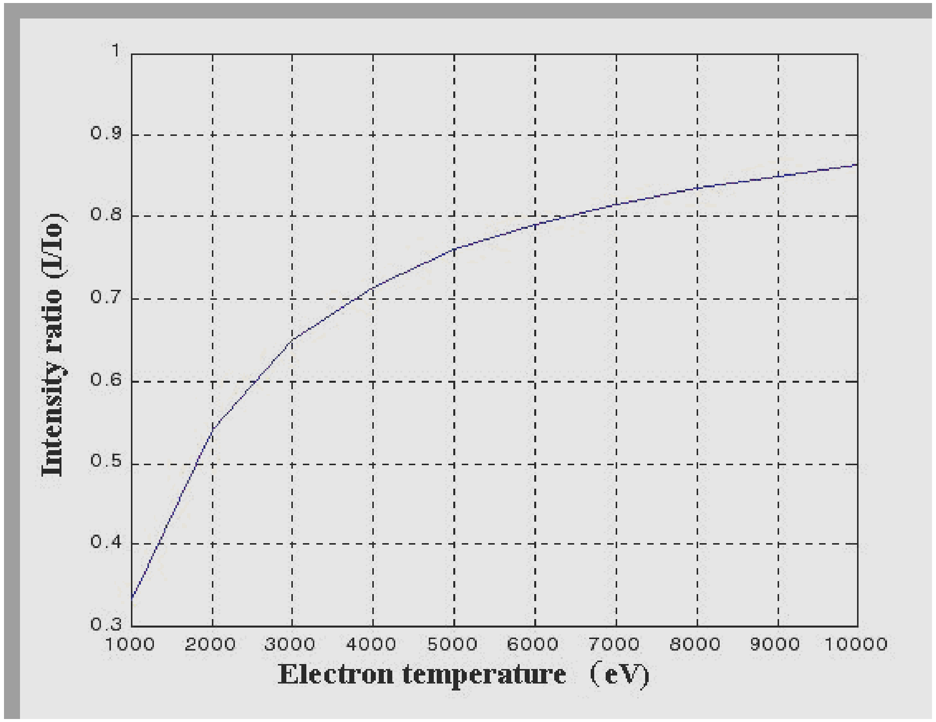
☞Improvement in x-ray yield by more than tenfold was achieved by changing the anode shape from hollow to hemispherical

Evaluation of Electron temperature

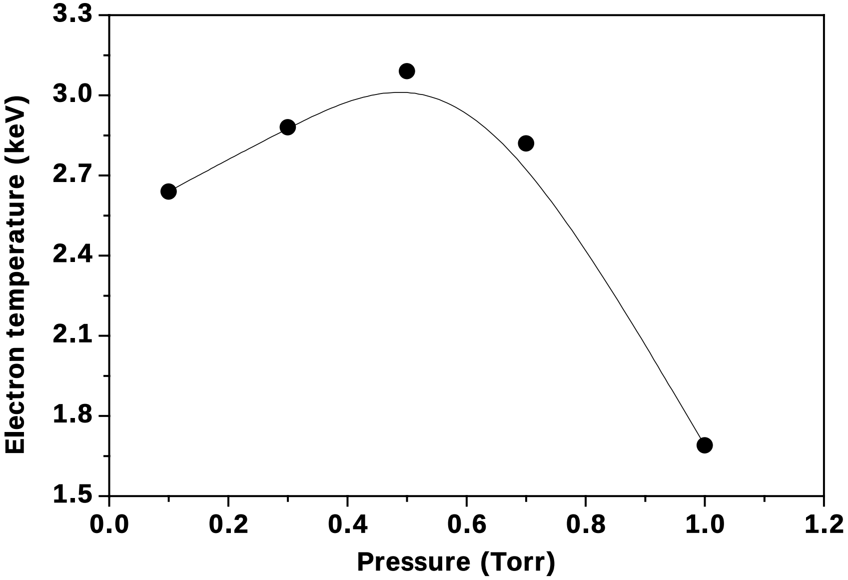
The ratio of X-ray intensity transmitted through two X-ray filters

$$\frac{I_1}{I_2} = \frac{\int_\lambda \frac{1}{\lambda^2} e^{-\frac{hc}{\lambda k T_e} - \mu\rho X_1} d\lambda}{\int_\lambda \frac{1}{\lambda^2} e^{-\frac{hc}{\lambda k T_e} - \mu\rho X_2} d\lambda}$$

The intensity ratio as function of Te

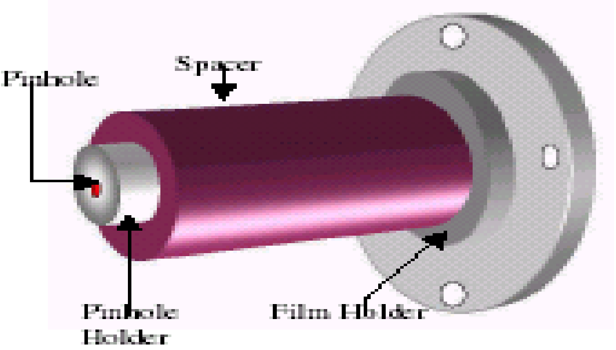


Variation of T_e with nitrogen filling pressure



T_e is found to be in between 1- 3 keV

Results of X-ray pinhole camera

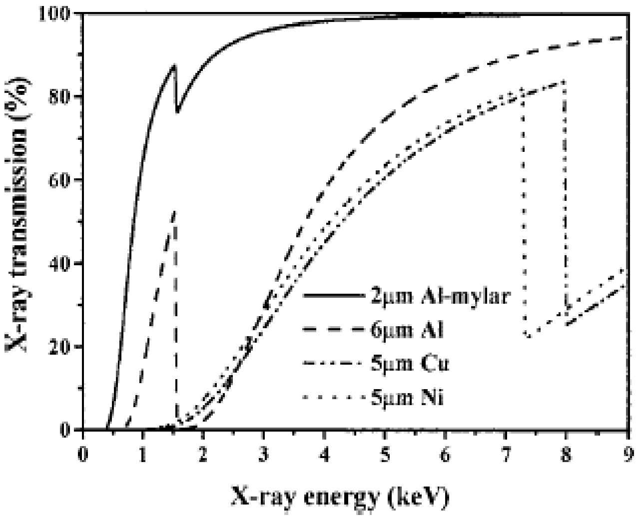


Pin hole: 200 µm

Image recorder: Radiography film

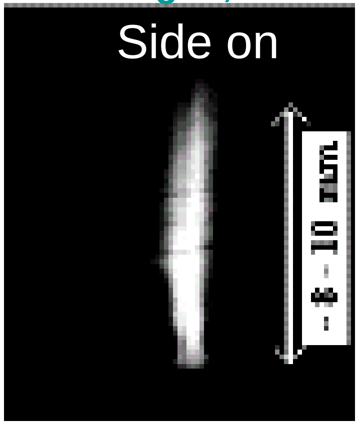
Magnification: ×1

Transmission Curves of filters

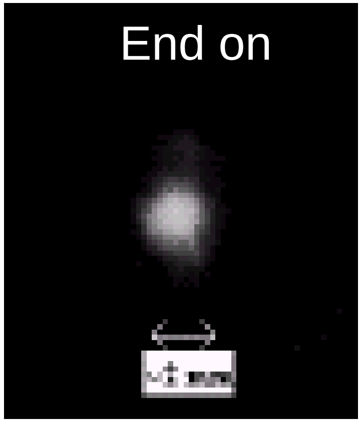


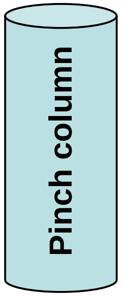
Pin hole covered with 2μm Al mylar
Nitrogen; Hollow anode

Side on



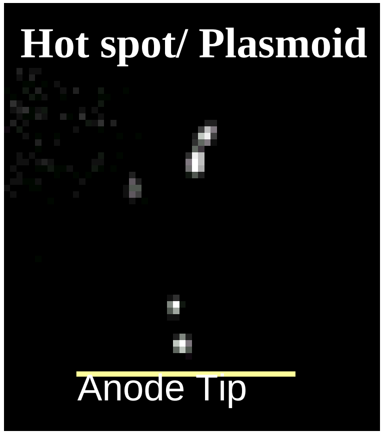
End on

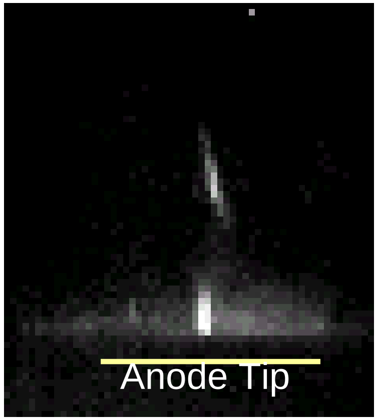




8-10 mm long &
2 mm diameter

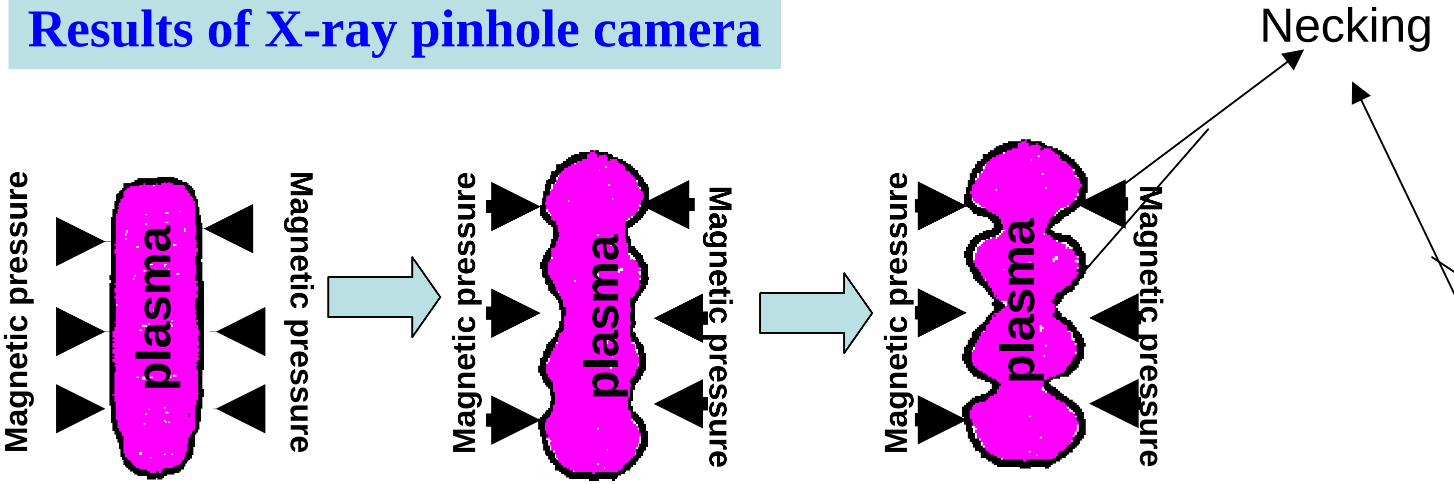
Hot spot/ Plasmoid





Evidence of electron beam heating to solid anode

Results of X-ray pinhole camera



Development of M=0 instabilities

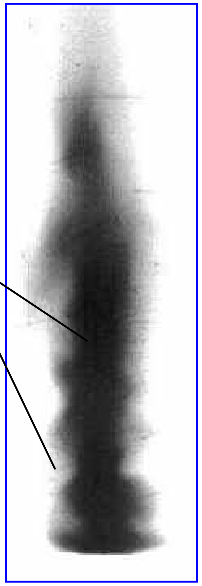
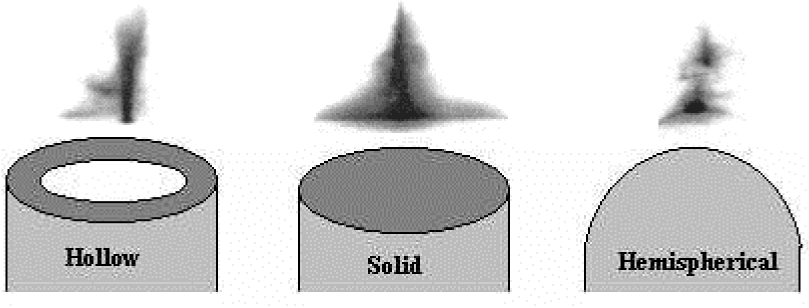


Image of plasma column showing M=0 instabilities



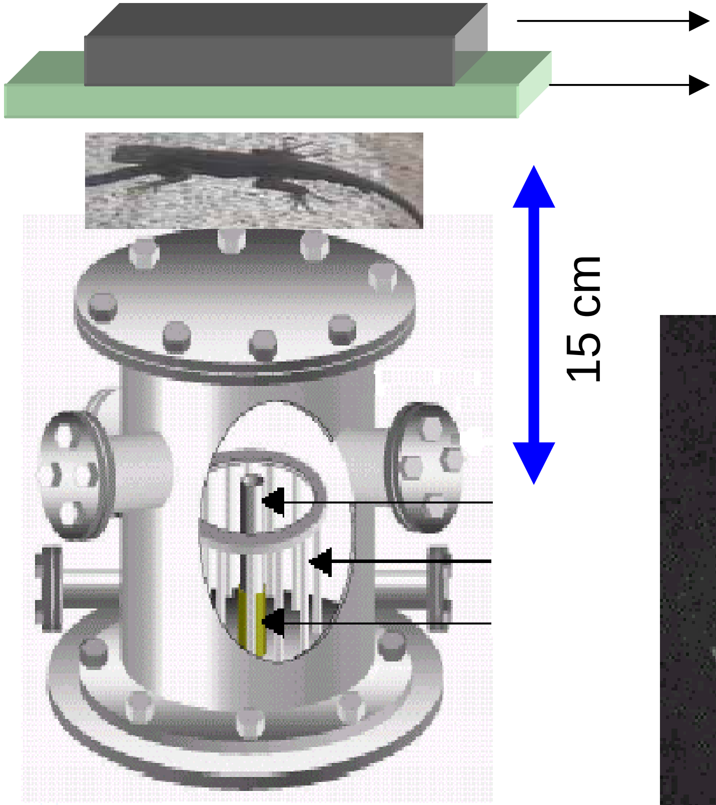
X-ray emitting zone of pinch plasma for different anode geometry

Pinhole image of solid anode is more or less alike with hollow anode except presence of metal vapor

Spot like plasma 500- 800 µm is observed in case of hemispherical anode

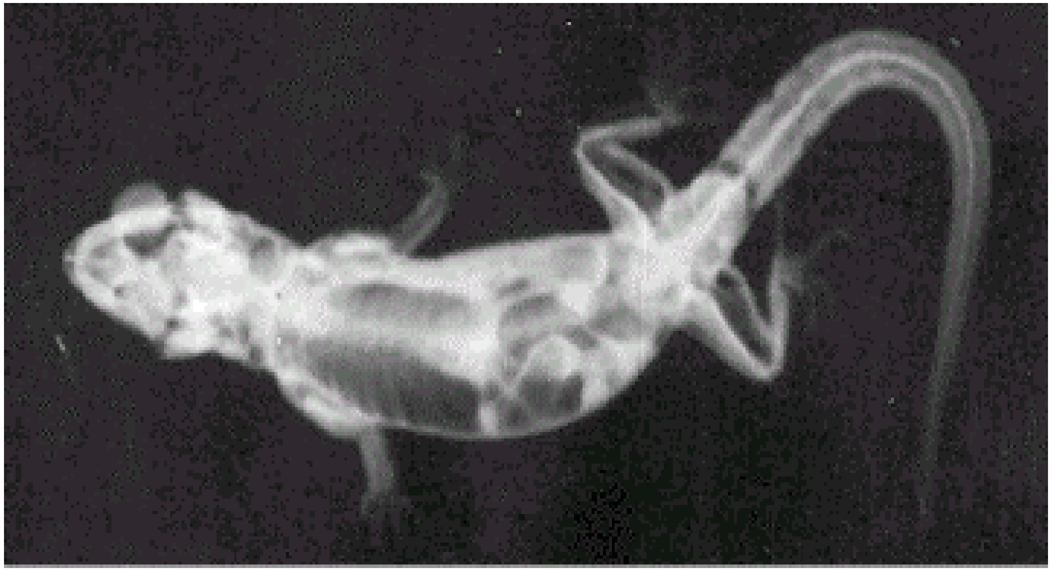
Contact X-ray radiography of a Liz

Contact X-ray radiography of a Lizard



Commercial radiographic film

Aluminized mylar filter



Comparative study of soft X-ray emission

Summary

- Emitted x-rays associated with different shapes (hollow, solid & hemispherical) of anode & in hydrogen/nitrogen gas medium are compared
- Structure of x-ray emitting sites as well as x-ray yields → strongly influenced by the shape of the anode & the filling gas pressure
- X-ray pinhole images of the collapsed plasma with the hemispherical anode indicated spot like structure having 500 – 800 µm in diameter
- An appropriate design of the anode could enhance the x-ray yield by more than ten folds in a conventional low energy dense plasma focus device
- PF device is used for radiography of zoological species

Measurement of ion yield

Development of multi Faraday cup assembly for ion yield measurement

Japanese Journal of Applied Physics, July 2005

Ion beams

- ion implantation
- surface modification
- thin film deposition
- semiconductor doping
- ion-assisted coating

Ion beams of PF

Objective

- Knowledge of ion beam energy, distribution and composition
- Enhance ion intensity by varying experimental parameters

Ion diagnostics

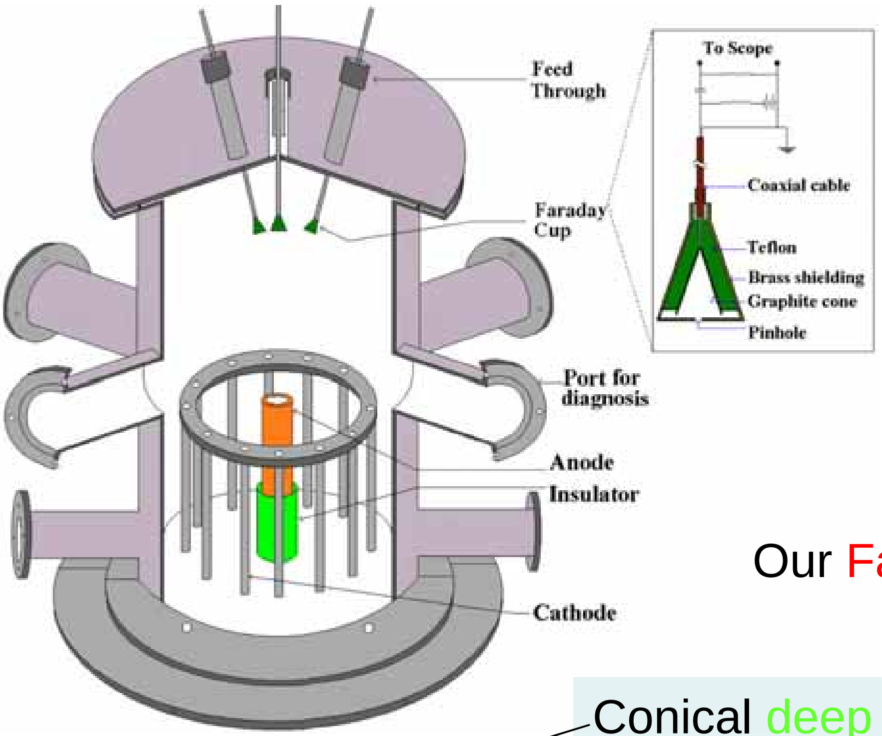
- Nuclear track detector
- Magnetic analyzer
- Thomson spectrometer
- Faraday cup

Faraday cup (FC)

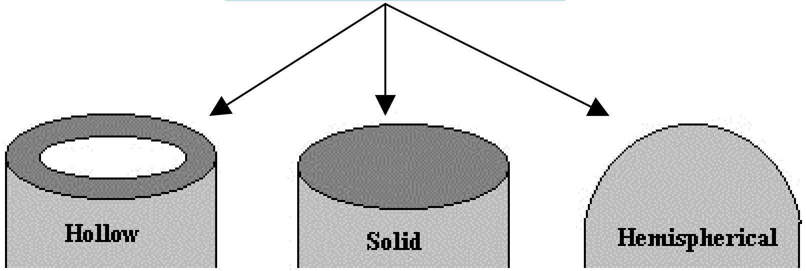
- Low cost and simpler in design
- Fast signal processing time
- Low e-m noise
- Low ion energy detection

Measurement of ion yield

Experimental arrangement



Anode design



Filling gas → Nitrogen

Our Faraday Cup ☞ BIC mode

Conical deep graphite cup having coaxial geometry

For reduction of surface heat density

For trapping secondary electron

Low secondary electron emission effect

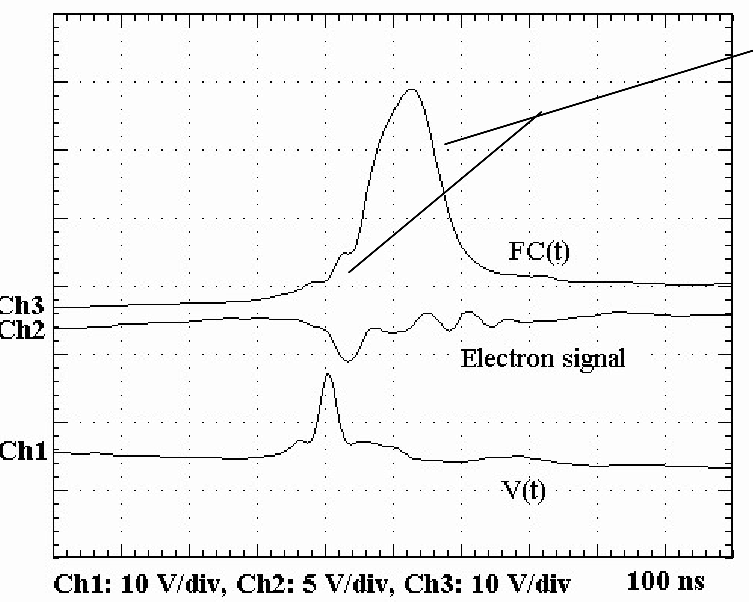
Impedance matching

☞ FCs are placed at axis (O°) as well as off- axis (5°, 10°)

Measurement of ion yield

Results

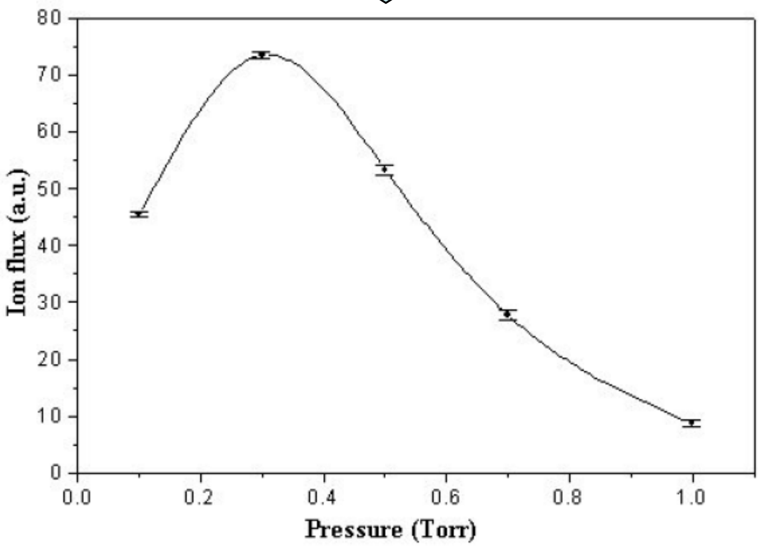
Ion signal with voltage and electron signals



Two peaks → 1st one: small ~30-40 ns
2nd one large ~150-170ns

☞1st Peak is not due to ion; may be due to X-ray

Ion flux as a function of filling gas pressure

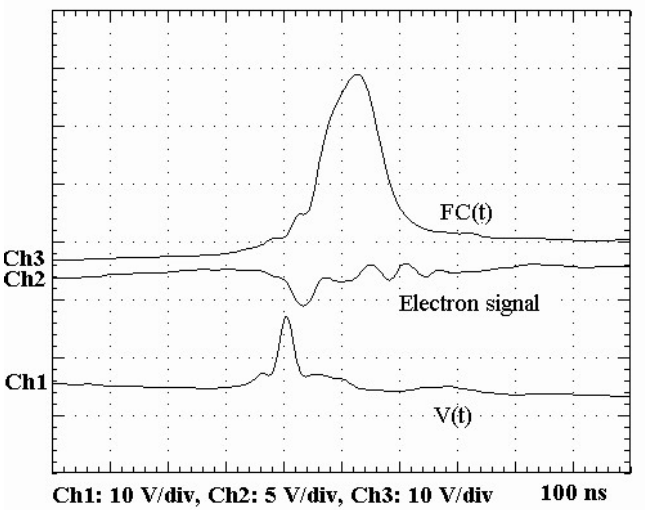


The best operating pressure is at 3 Torr

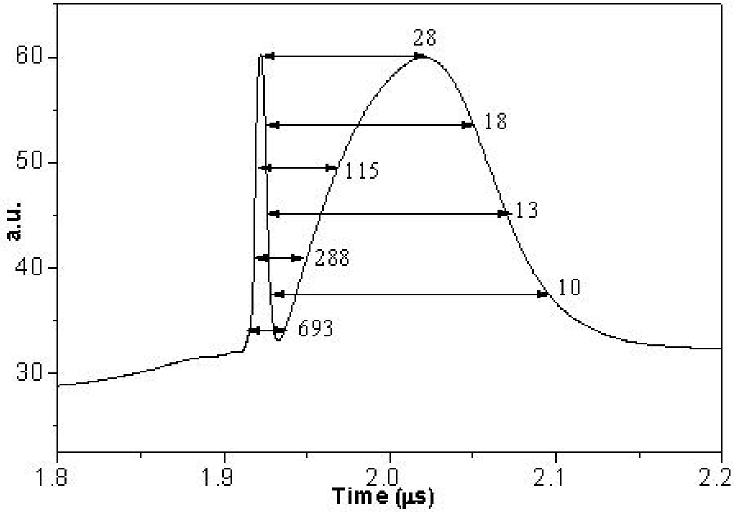
Measurement of ion yield

Ion energy measurement by TOF

FC signal

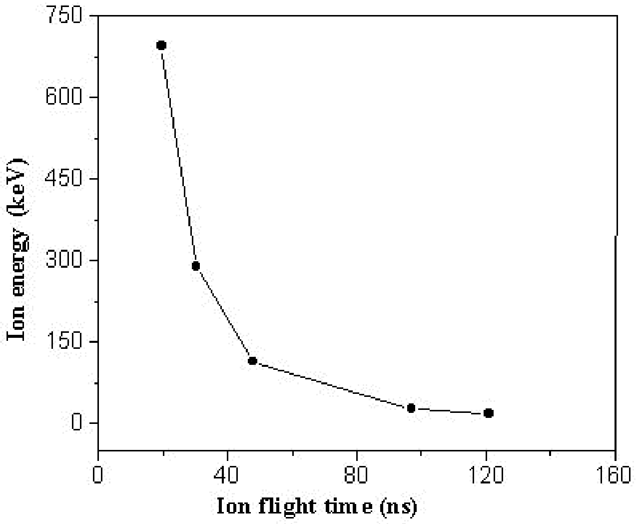


Normalized X-ray signal with FC signal



Kinetic energy ranging from 700 keV to 10 keV
Kinetic energy of lower value ~5 keV observed

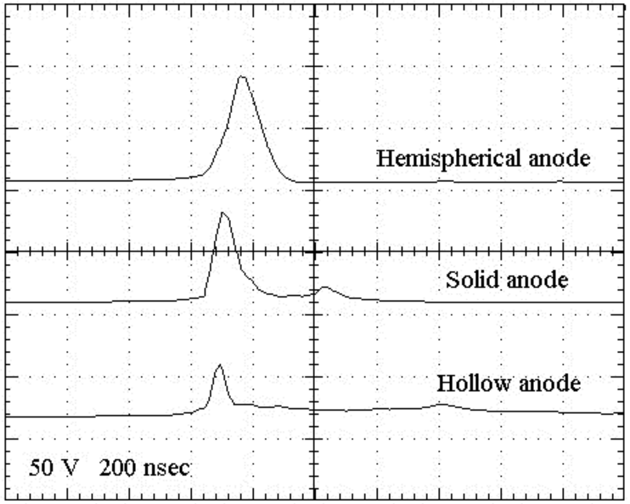
Variation of ion energy with ion flight time



Higher energy ions > 300 keV reaches the detector within 30ns

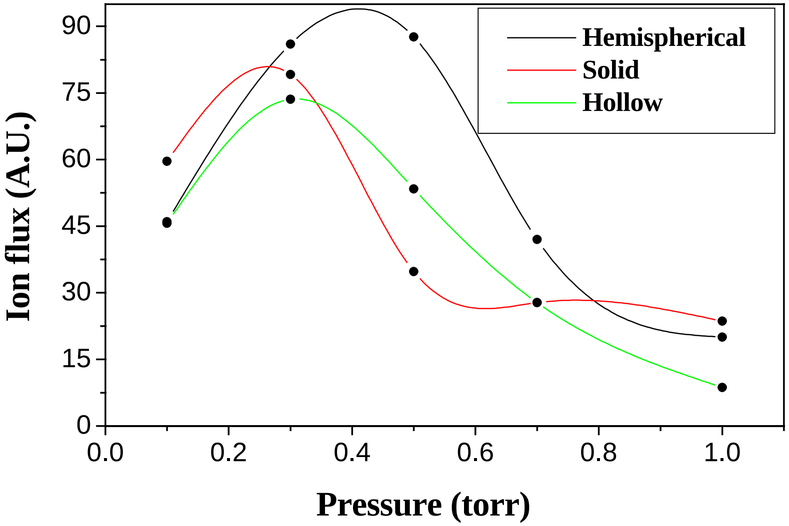
Measurement of ion yield

FC signal for different anode design



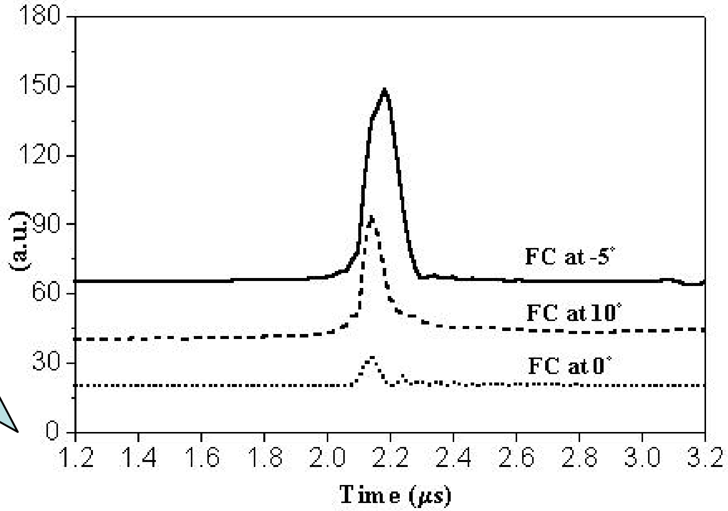
☞Maximum ion intensity in case of the hemispherical anode and minimum in case of the hollow anode

Comparison of ion flux for different anode design



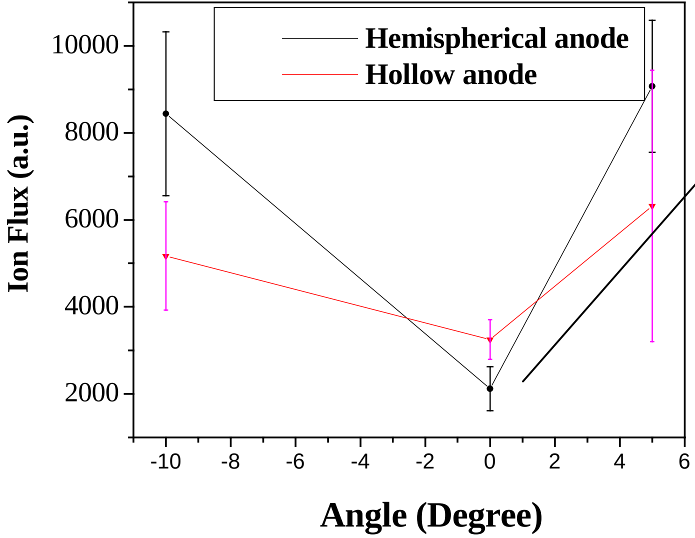
FC signal for different angular position

Ion flux maximum in 5^0 and minimum at axis irrespective of anode design



Measurement of ion yield

Angular distribution of ion



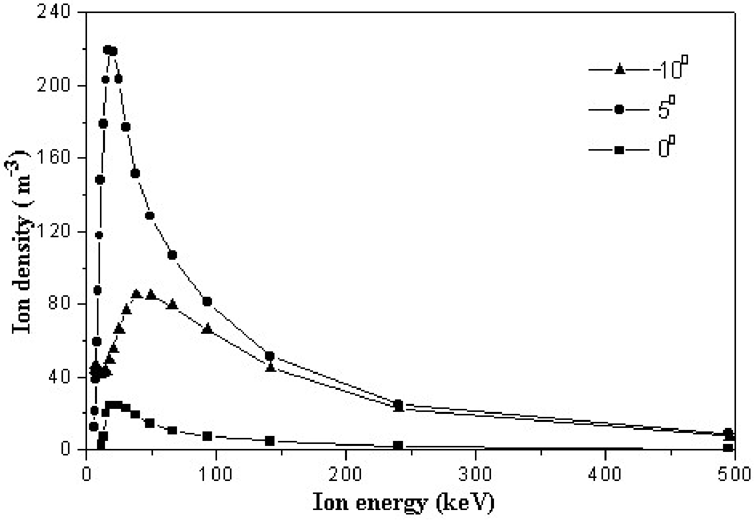
The ion angular distribution shows a distinct emission dip at 0

The anisotropic emanation

the fast ions are generated in different micro-sources formed inside plasma column And those sources may not be in pinch axis

- The dip might correspond to the lack of accelerated ions within a hole of an ion Larmor diameter

Energy spectrum of ion



No. density of the order of $10^{17}m^{-3}$
Most probable ion energy is nearly > 50keV

Measurement of ion yield

Summary

- A fast response charge collector has been successfully deployed for measuring the ion energy spectrum of our PF device
- The design feature that makes our FC unique is that it can register ion energy of higher kinetic value (~MeV) as well as lower kinetic value (~ keV)
- Ion flux and ion energy are found maximum in case of the hemispherical anode whereas minimum in case of the hollow anode.
- The energy spectrum shows that at the most favorable operational condition the maximum ion energy is ~ MeV and the most probable ion energy is >50 keV
- Our ion emission using hemispherical anode is of importance for developing an ion source of high fluence

Synthesis of Carbonitride (C_3N_4) coating on graphite substrate

{Surface Coating & Technology, vol 145 (2001) 8}

C_3N_4

Carbonitride is a high elastic modulus and high hardness compound whose structure is analogous to Si_3N_4

Silicon nitride (**Si_3N_4**) is found with two structures both of them hexagonal

Cohen and Liu made theoretical calculations to predict such compound in 1989

{A.Y. Liu, M.L. Cohen, Science, vol 245 (1989) 841}

Experimental methods

- **Ion beam sputtering**
- **Laser beam processing**
- **PCVD**
- **Magnetron sputtering**

Objective

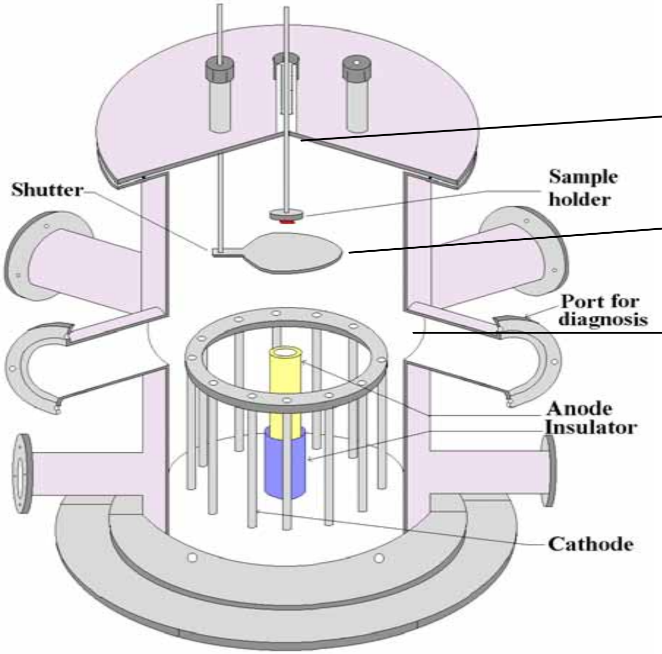
To synthesis carbonitride coating on graphite by an ingenious method

Using the energetic nitrogen ions emerging from plasma focus

Synthesis of carbonitride coating

Experimental

Samples → Polished electrode grade graphite circular disc with 2.5cm diameter and 1cm thickness



Samples are placed at 6 cm from the top of anode

Shutter was used during conditioning

Nitrogen was working gas

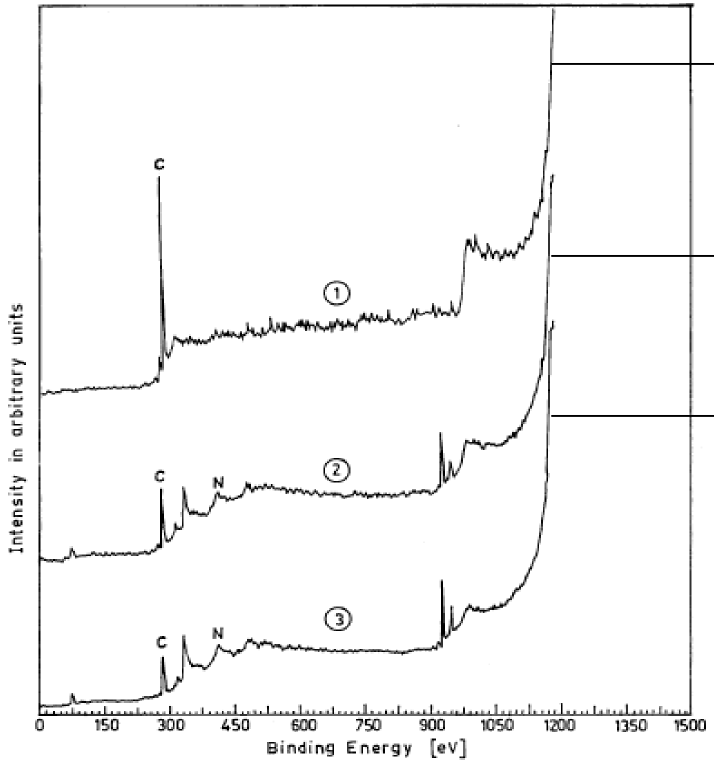
Samples were exposed to 20-30 shots

Exposed & Unexposed samples

- **X-ray photoelectron spectroscopy**
- **X-ray diffraction**
- **Scanning electron microscopy**
- **IR spectroscopy**
- **Microhardness test**

Synthesis of carbonitride coating

X-ray photoelectron spectroscopy result



Unexposed

20 PF shots

30 PF shots

C1s spectra in all samples

N1s spectra at around 400eV

N/C ratio : 0.233 for 20 PF shots
0.518 for 30 PF shots

BE of resultant bands after curve fitting

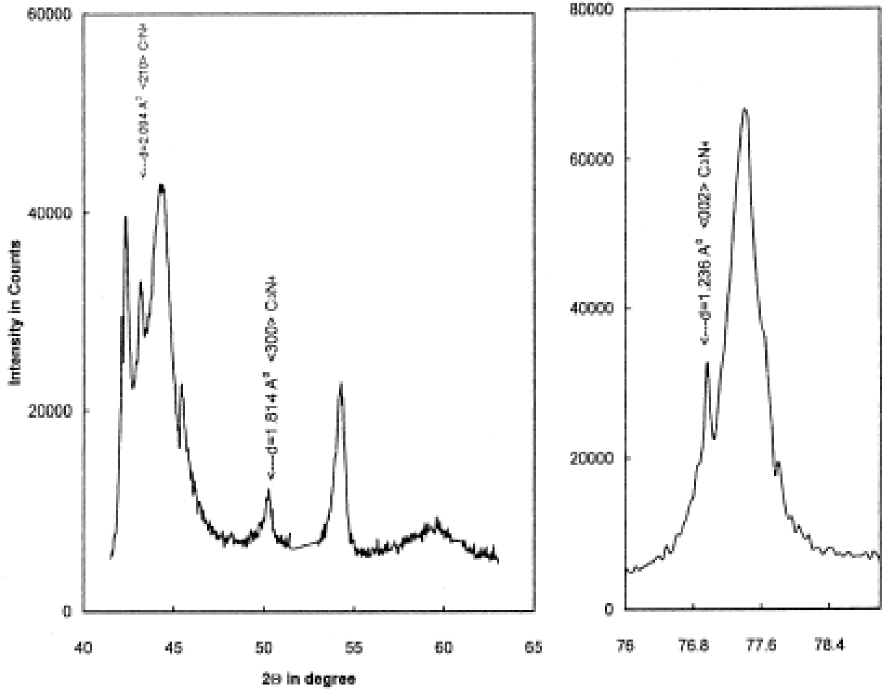
Sample	C1s (eV)	N1s (eV)
Unexposed	286.34; 289.42	Not observed
20 PF shots	286.44; 288.23	401.18; 403.56
30 PF shots	285.54; 286.98	399.76

C=N sp^2 hybridization

C-N sp^3 hybridization

Synthesis of carbonitride coating

X-ray diffraction result



No standard Diffraction data file

L.C. Chen et al. Appl. Phys. Lett. 72 26 1998 3449

J. Wang et al. Phys. Rev. B58 1998 11890

Strong reflections from < 210 > & < 002 >

Weak reflections from < 111 > & < 300 >

Unexposed

d (Å)	(I/I_0)	hkl
3.38	100	002
2.13	43	100
2.04	47	101
1.68	16	004
1.56	3	–
1.23	64	110
1.16	32	112

20 PF Shots

d (Å)	(I/I_0)	hkl (C_3N_4)
3.38	100	
2.14	42	
2.09	26	210
2.04	37	
2.00	15	111
1.81	4	300
1.69	70	
1.54	40	
1.24	20	002
1.23	64	
1.16	35	

30 PF Shots

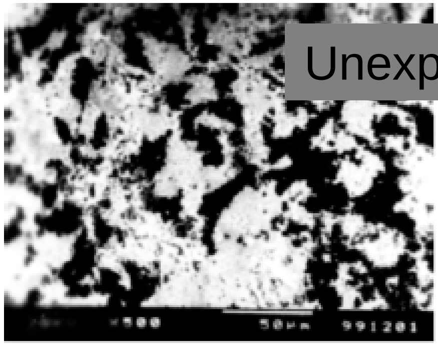
d (Å)	(I/I_0)	hkl (C_3N_4)
3.38	100	
2.14	21	
2.09	34	210
2.04	42	
1.81	4	300
1.69	8	
1.56	4	
1.24	20	200
1.23	59	
1.16	26	

Underlined values are due to C3N4

Synthesis of carbonitride coating

Scanning electron microscopy (SEM) result

Unexposed

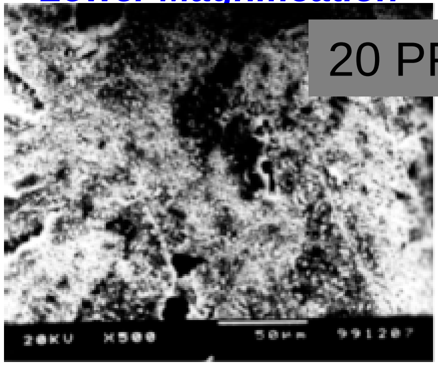


Lower Magnification

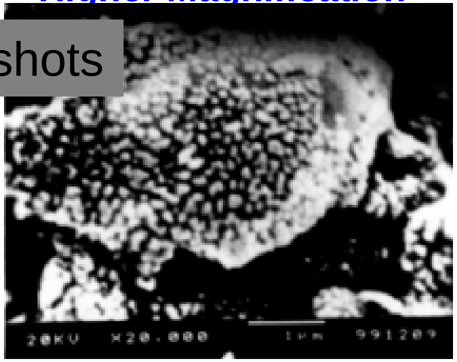
Higher Magnification

Layer structure

20 PF shots

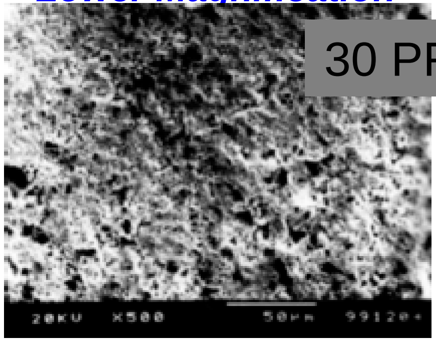


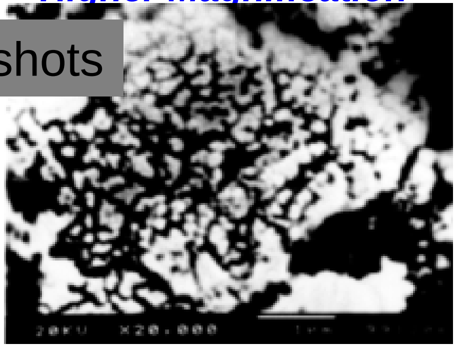
Lower Magnification



Higher Magnification

30 PF shots





Rounded island like grains

Grain size 0.3-0.5 µm

Thickness of nitride layer 50-60 µm

Lower Magnification =× 500

Higher Magnification =× 20,000

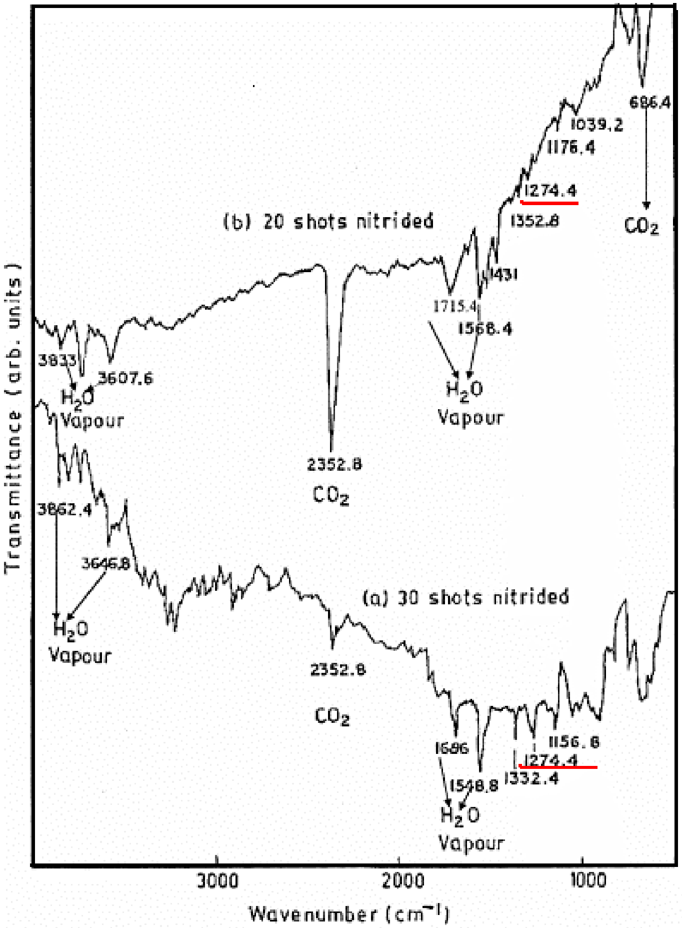
Synthesis of carbonitride coating

IR spectroscopy results

Absorption peaks at 1274.4 cm^{-1}

↓

C_3N_4 phase



Microhardness results

	Sample	VHN (50 g load)[a]
I	Unnitrided graphite	163–195
II	Nitrided graphite (20 shots)	370–490
III	Nitrided graphite (30 shots)	560–720

[a] Five readings were recorded in the central region of each circular disc specimen.

3 to 4 fold increase in hardness value

Synthesis of carbonitride coating

Summary

- PF devices can be successfully utilized to produce nitrided carbon coating layers on graphite surface
- XPS establishes that nitrogen bonding takes place with carbon
- Lattice spacings nitrided coatings determined from XRD compares well with the predicted values for hexagonal $C_3 N_4$
- Surface morphohology of the nitrided layers exhibits 0.3 to 0.5-µm size rounded and island structures
- Hardness of nitrided layer improved by 3 to 4 times
- PF proves to be a successful process which can nitride not only metals, but also non-metals like graphite with appreciable reduction in nitriding time and free domfrom toxic gas or liquid handling

Ion Irradiation of American Diamond in a Plasma Focus Device

{ Best poster award in Power Beams & Material Processing-2003 }
[Communicated to NIMB]

Background Of The Work

•Ion implantation	*J N Feugeas et al. Rad Eff Def Solids, 128 (1994) 267* *T K Borthakur et al. Surface Engg, 15 (1999) 55*
•Surface Modification	*R S Rawat et al. Mater Res Bull, 35 (2000) 47* *B Liu et al. Thin Solid Films, 390 (2001) 149*
•Thin film deposition	*C R kant et al. Phys. Lett A 239 (1998) 109* *H X Zhang et al. Thin Solid Films 349 (1999) 162*
•Semiconductor doping	*M P Srivastava et al. Phys Lett A 215 (1996) 63*

Ion irradiation of American diamond

AIM

To investigate whether ion irradiation could be used as a material processing technique to induced physio-chemical changes in ~~natural diamond~~

American Diamond is high purity cubic zirconia (ZrO2), man-made gemstone that closely resembles to diamond

Importance of Zriconia

- **Oxygen Sensor**
- **Fuel Cell Membranes**
- **High Temperature Applications**
- **Catalyst**
- **Gem Stone**

Specimens

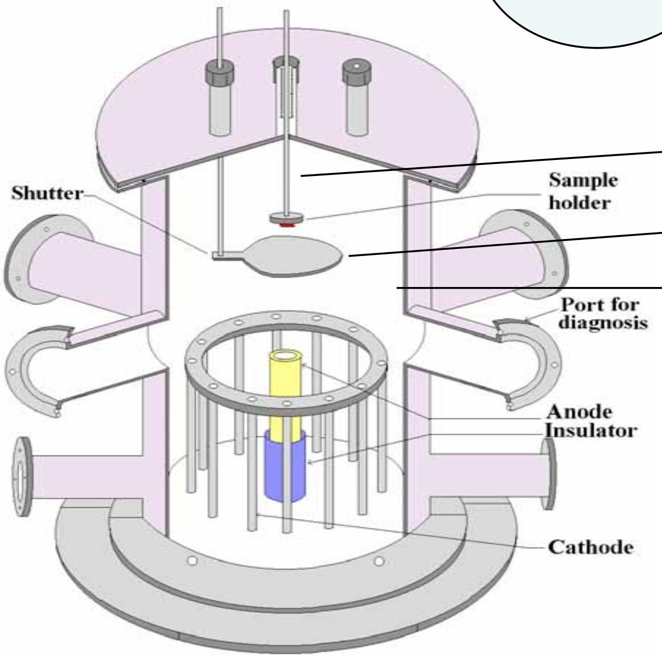
Commercially available American Diamond
Colored as well as colorless

Cubic Zirconia → **Monoclinic Zirconia**

Ion irradiation of American diamond

Experimental

Samples → Polished flat rectangular American Diamond specimen of thickness 2 mm and area 25 mm^2



Samples are placed at 6 cm from the top of anode

Shutter was used during conditioning

Nitrogen/Argon/Hydrogen as working gas

Samples were exposed to single shot

Colored specimens (red, green, yellow) → Colorless

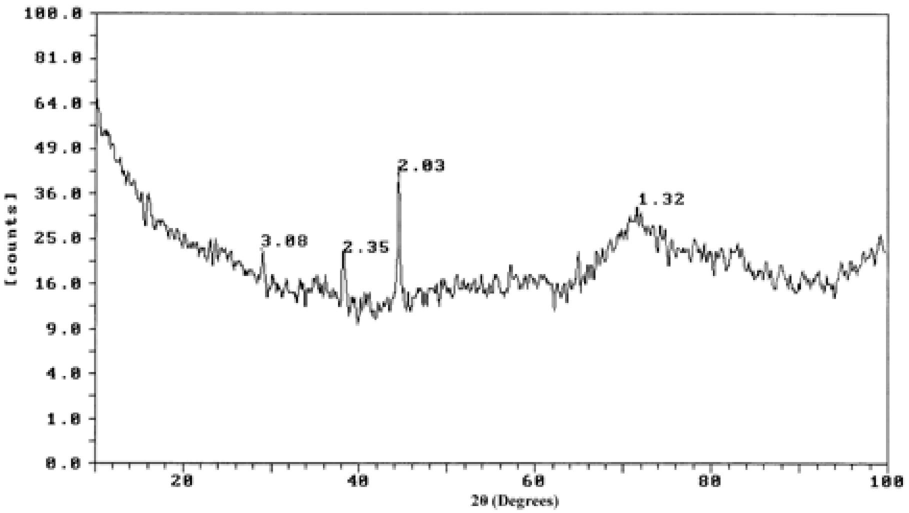
White colored specimens → Light Pink color

Exposed & Unexposed samples →

- **X-ray diffraction**
- **Scanning electron microscopy**
- **Micro-hardness test**
- **UV- Visible spectroscopy**
- **Energy Dispersive X-ray analysis**

Ion irradiation of American diamond

XRD pattern of unexposed Zirconia

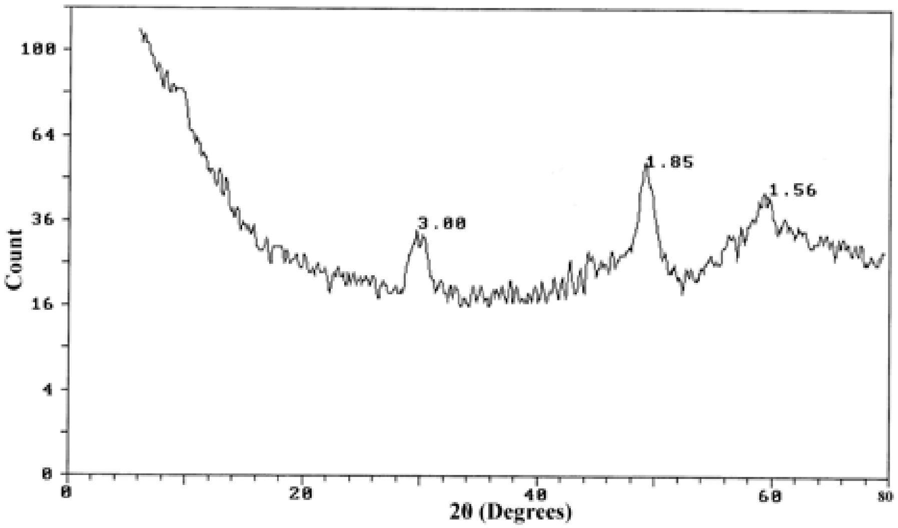


Peaks at 2θ 29^0 (-111) 38.5^0 (120) 45^0 (211) & 71^0(400)

Inter planar spacing 3.08 2.36 2.03 & 1.32 A^0

Monoclinic & Cubic

XRD pattern of exposed Zirconia



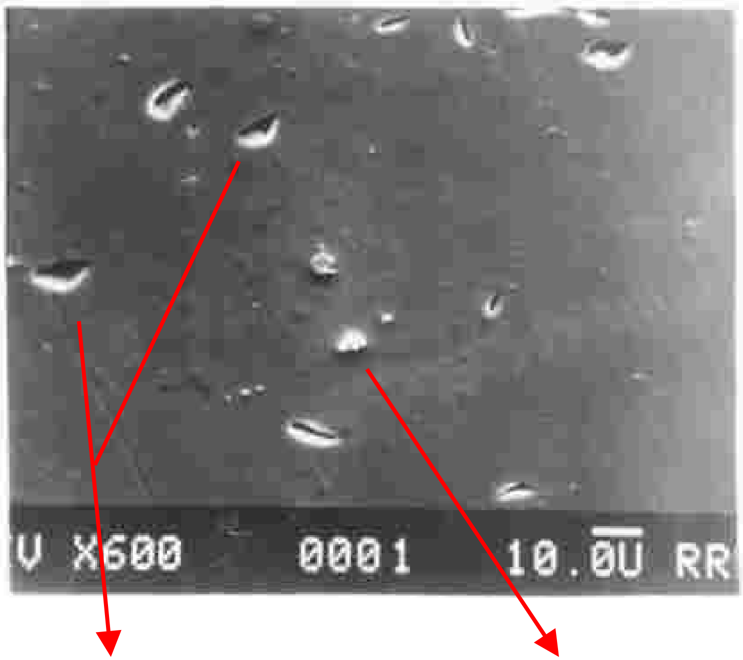
Peaks at 2θ 30^0 (003) 49^0 (104) 59^0 (113)

Inter planar spacing 3.00 1.85 1.56

Hexagonal

Ion irradiation of American diamond

SEM Micrographs of Unexposed Zirconia

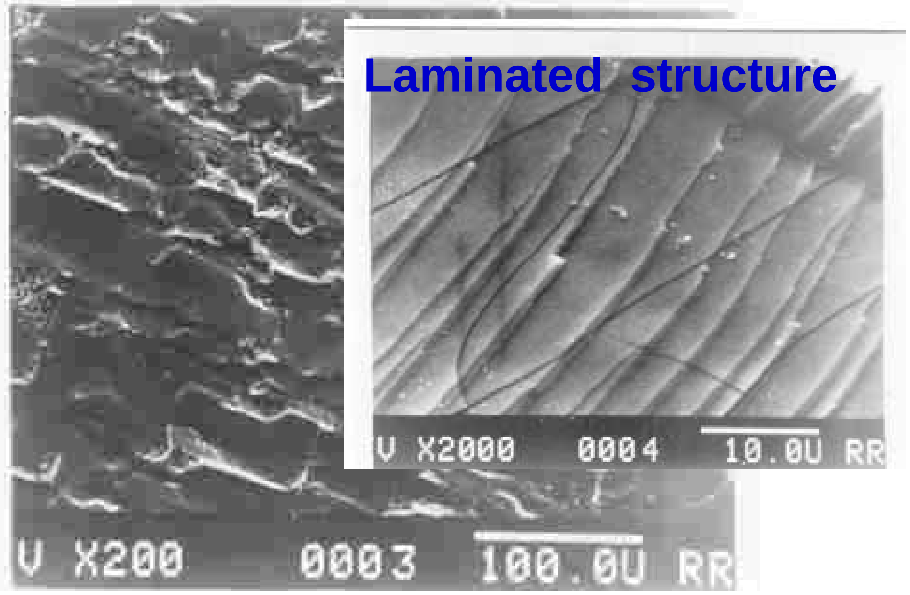


Pit holes

Dirt

Reasonably smooth without any cracks but filled with few Pits

SEM Micrographs Of Exposed Zirconia



Laminated structure

Removal of surface material due to ion bombardment

Ion irradiation of American diamond

Micro hardness test

Specimen	Hardness, HV 0.05
Unexposed	1883, 2180, 2121, 2242, 2306
Exposed	1706, 1813, 1813,1746, 1768

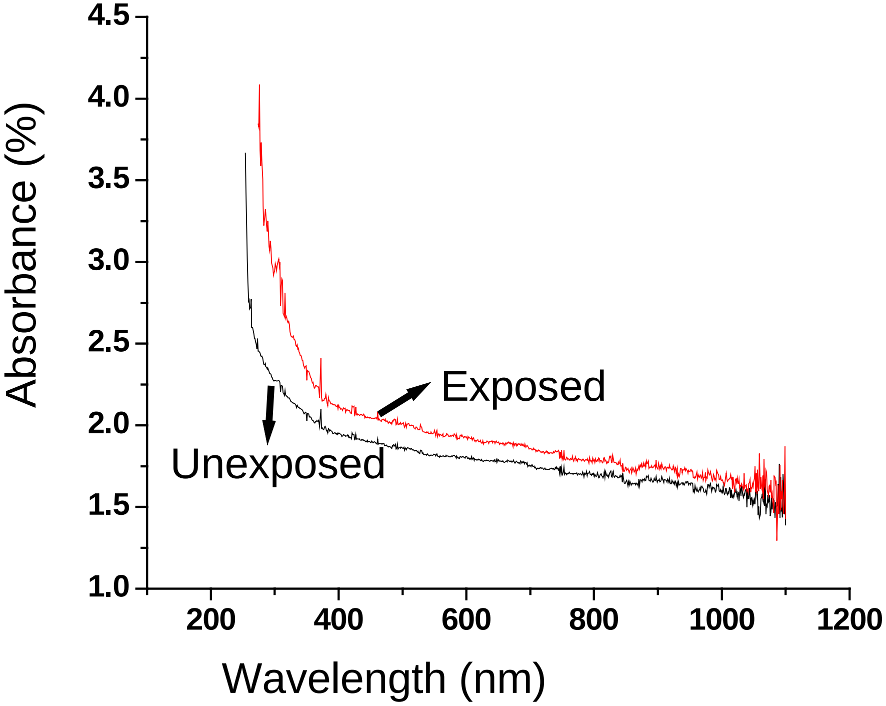
Hardness decreases because of the formation of defects and color centers created by ionizing radiation

Color center

Defect in the regular spacing of atoms within a solid that absorbs visible light of a particular color or IR or UV

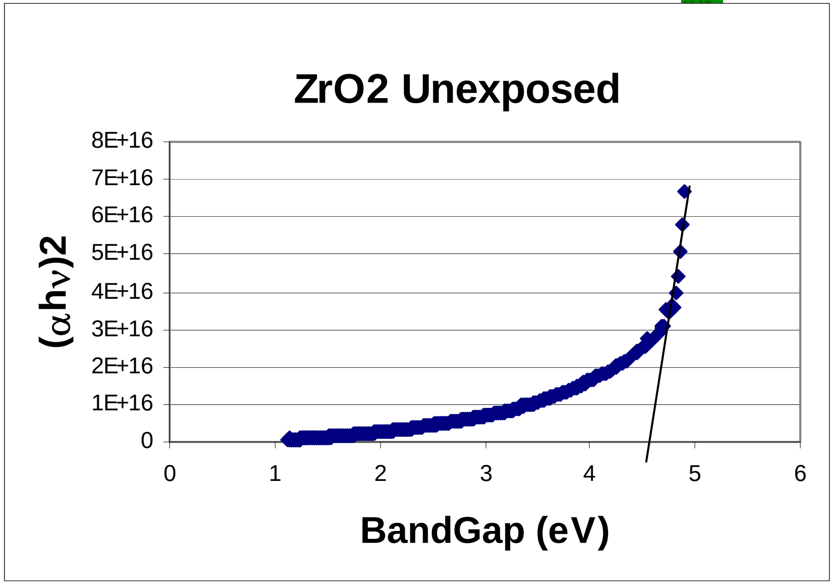
Ion irradiation of American diamond

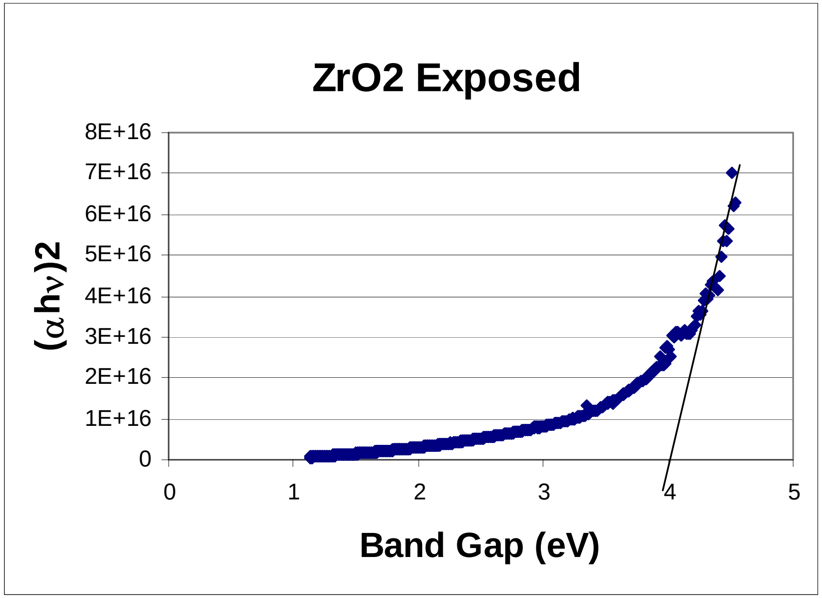
UV-Visible Spectroscopy



Ion irradiation decreases the transmission slightly and absorption edge slightly shifts towards higher wavelength side.

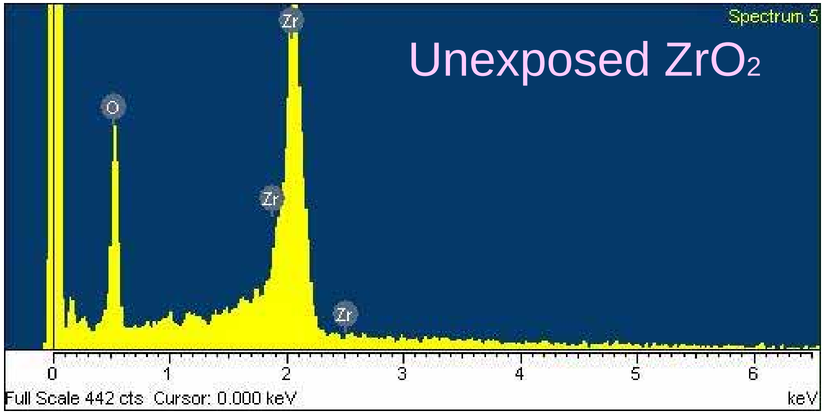
Band Gap energy reduces from 4.6 eV to 4 eV which could be associated with lattice deffects



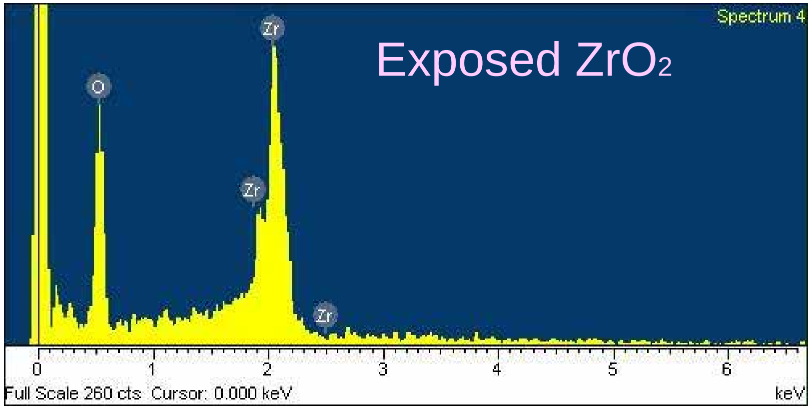


Ion irradiation of American diamond

EDX Analyses


Unexposed ZrO_2

Element	Atomic %
O K	75.75
Zr L	24.25


Exposed ZrO_2

Element	Atomic %
O K	81.43
Zr L	18.57

Summary

Pulsed energetic ion beams of PF device successfully processed ZrO2 specimens exhibiting change in color, surface morphology and structure.

Welcome to

To spend some time at CPP so that you can enjoy RESEARCH as well as nature…..

Thank you...