2168-Presentation

Joint ICTP-IAEA Workshop on Dense Magnetized Plasma and Plasma Diagnostics

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Initial Results of Kansas State University Dense Plasma Focus

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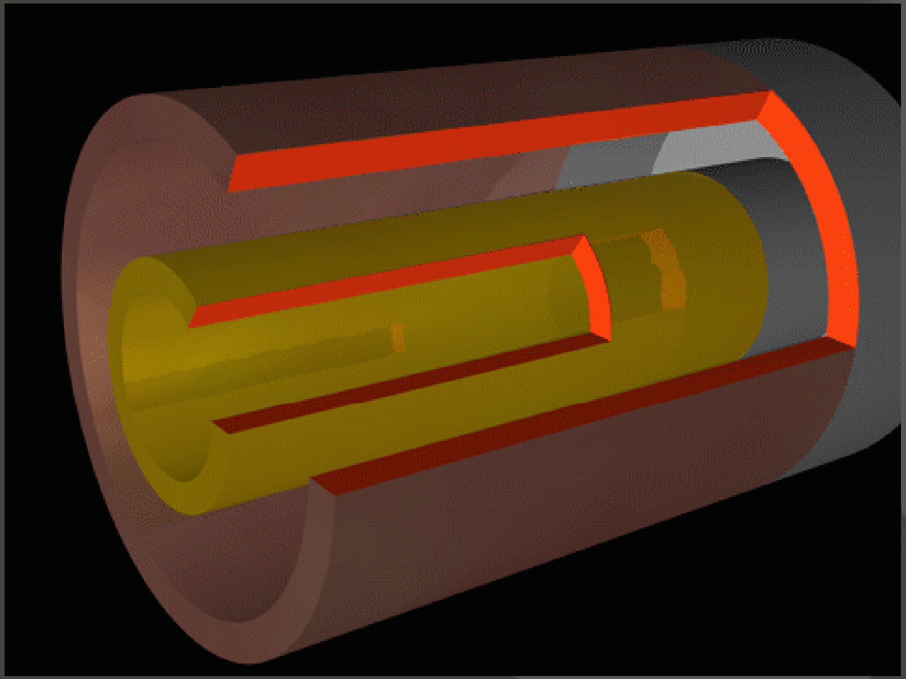
INITIAL RESULTS OF KANSAS STATE UNIVERSITY DENSE PLASMA FOCUS



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Outline

- The Dense Plasma Focus
- Kansas State University Dense Plasma Focus KSU-DPF Device
- Initial Results from KSU-DPF
- Modeling of KSU-DPF Using Lee Model
- Future Work

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What Is Dense Plasma Focus (DPF)?

- A DPF is a pulsed power device capable of producing short-lived (~10s of ns), hot (T_i~kev) and dense ($>10^{19}$ cm^{-3}) plasma during electromagnetic compression (JxB).
- The DPF is capable of producing simultaneously different types of radiation
  - Fusion neutrons (~2.45 Mev from deuterium-deuterium or 14.5 Mev from deuterium-tritium fusion reactions)
  - Hard x-rays ~ 100s kev (electron beam hitting anode base)
  - Ion beams ~ couple of Mev
  - Electron beam ~ 1 Mev
  - Electromagnetic radiation ~ GHz
- The machine was independently invented by J.W. Mather in USA and N.V. Filippov in USSR early in the 1960s.

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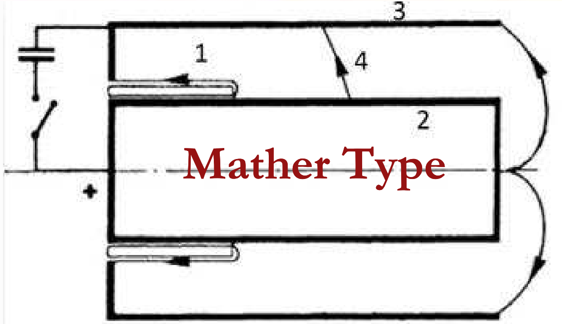
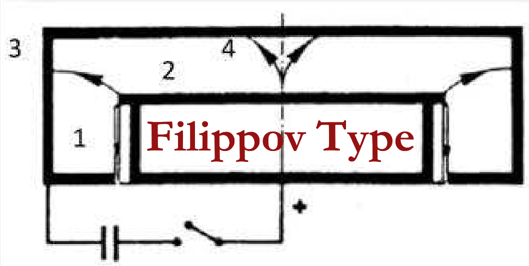
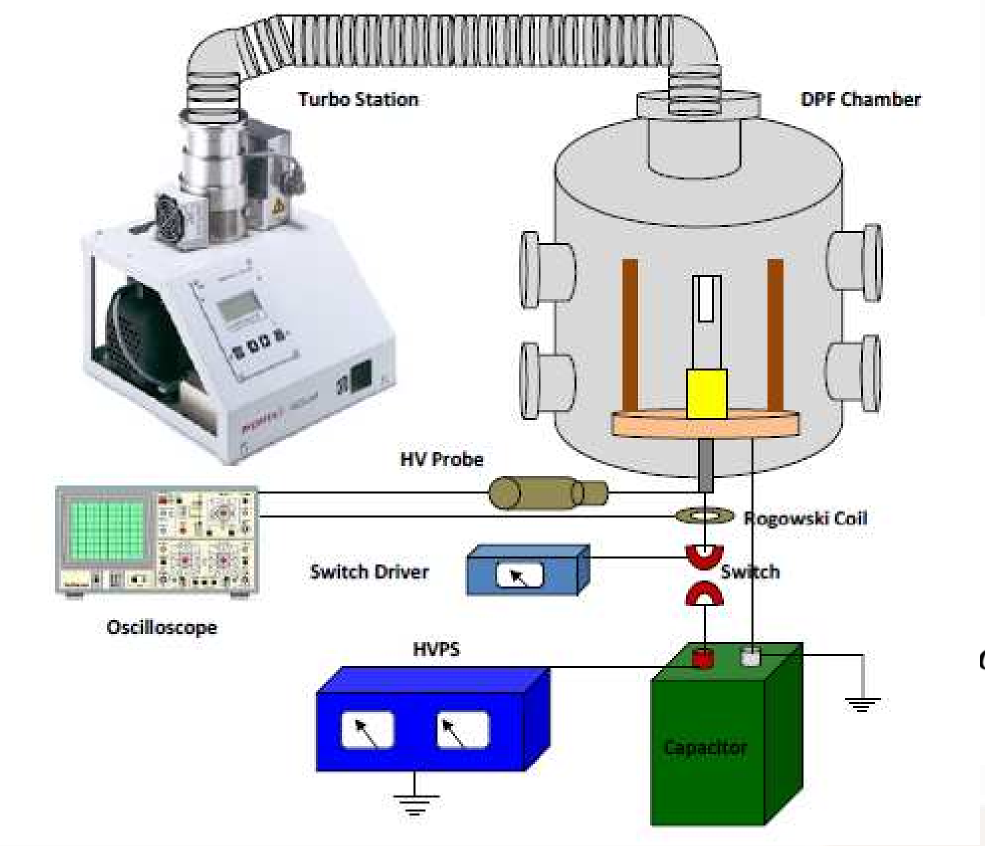
The DPF Comes in Two Different Flavors

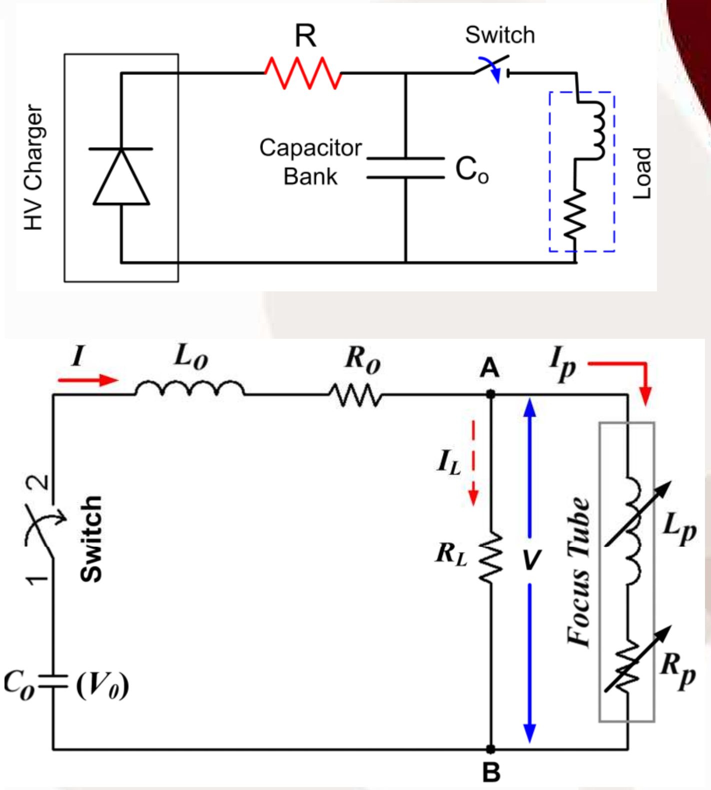




The main difference between Mather- and Filippov-type devices is their Aspect Ratio (AR), defined as the ratio of the height to the diameter of the anode. The Mather-type has a AR>1 while the Filippov has AR < 1.

DPF Anatomy



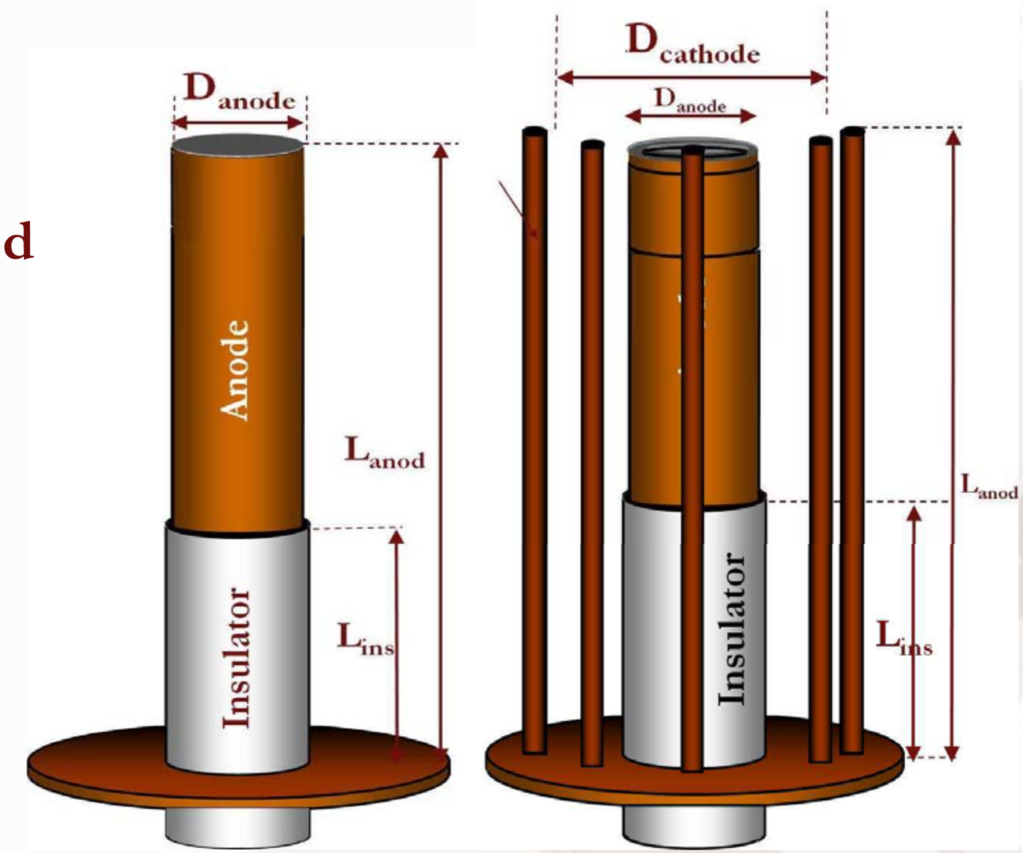


DPF Electric Circuits

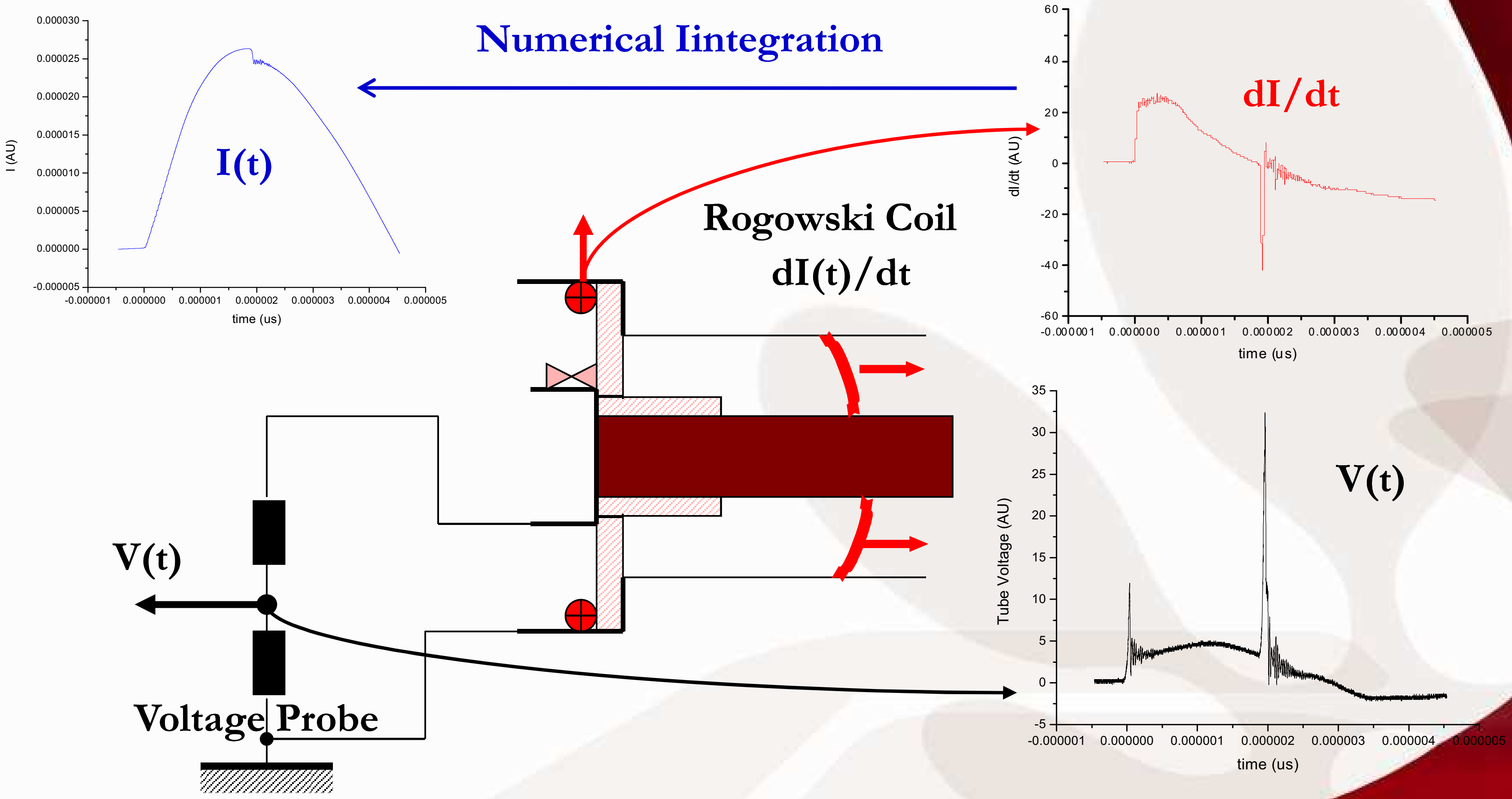
- ❖ A DPF is composed of:
  - ❖ Vacuum system ❖ Charging (driver) system ❖ Switch
  - ❖ Device Head ❖ Data acquisition system ❖ Diagnostics

DPF Device Head

- Anode
  - Straight or Tapered
  - Stainless Steal, Copper, Brass, etc
  - Solid or Hollow
- Cathode
  - Squirrel Cage or Solid Cylinder
  - Copper or Brass
- Insulator
  - Glass or Ceramic



Electrical Measurements in DPF



Numerical Iintegration

Rogowski Coil
dI(t)/dt

Voltage Probe

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The KSU-DPF Machine

DPF-KSU Machine Parameters	Value
Max. Stored Energy	~2kJ @ 17kV
Eq. Capacitance	$12.5\mu F$
Eq. Inductance	134nH
Eq. Resistance	23.3mohm
Quarter time period	~2us
Voltage reversal	0.71
Peak current (Ipk) at 17kV/2kJ	~137kA
Operating Voltage Range	8kV - 18kV
Max. Discharge repitition rate	0.2Hz
Max. Neutron Yield @ Ipk ~160KA	~ 10^{8} n/shot (DD) ~ 10^{10} n/shot (DT)
Anode outer radius Anode inner radius Anode length z_o	7.5 mm 5.5 mm 100 mm
Number of cathode rods Cathode length Cathode outer radius b	6 120 mm 27.5 mm
Insulator material Effective insulator length Outer diameter Inner diameter	Glass 15 mm 15 mm 11.8 mm

The KSU-DPF Machine

KSU-DPF Machine (Hardware)

- General Atomics High Voltage Power Supply HVPS 30 kv, 8 kJ/s
- Aerovox capacitor 20 kV, 200 kAmp @ 80% reversal
- Pulsetech 200 kAmp/25 kv Thyrotron switch, 10 ns jitter
- Pulsetech Thyratron heater and trigger unit
- Edwards turbomolecular pumping station
- Gases (Hydrogen, Helium, Deuterium, Neon, Argon or Neutron)
- Gas needle valve
- MKS capacitance manometer (0-100 mbar)
- MKS wide-range gauge (atm-10^{-8}mbar)
- Mechanical gauge (0-50 mbar)
- Two Tektronix 7000 series DPO Oscilloscopes
- Anode (stainless steal or copper, straight or tapered)
- Cathode (copper or brass)
- Faraday cage

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KSU-DPF Machine (Hardware)

Thyratron

GA Power Supply

Capacitor
20 kv, 200KA

Chamber

Anode and Cathode

Edwards Pumping Station

Faraday Cage

Gas

Tektronix 7000 DPO

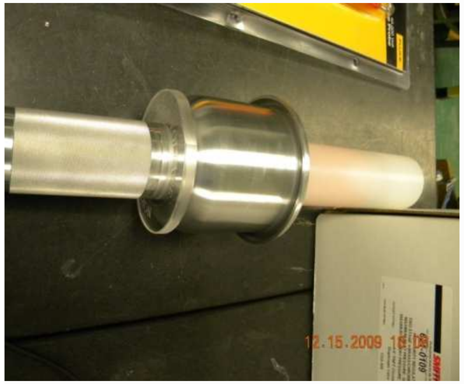
KSU-DPF Machine (Diagnostics)

- Calibrated Rogowski coil for measuring dI/dt
- Northstar high voltage probe HV5 60/100 kv DC/AC 80 MHz
- Neutron detectors
  - BC-418 plastic scintillator, 0.5 ns rise time (for neutron time of flight TOF)
  - LiI scintillator with Bonner spheres
  - He^3 detector with Bonner sphere
  - Fast neutron bubble detector > 100 keV
- X-ray detectors
  - BC-418 plastic scintillator, 0.5 ns rise time
  - Four channels PIN diode BPX65 spectrometer with filters

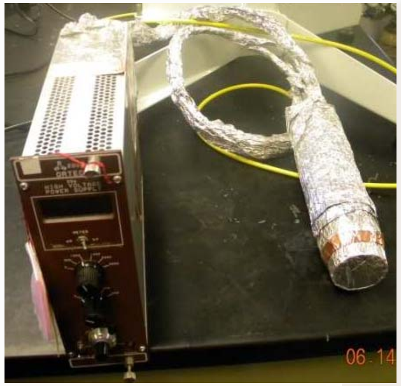
KSU-DPF Machine (Diagnostics)

Bubble Detector

LiI Detector



Voltage Probe



Plastic Scintillator

BPX65 PIN Diode

DC Voltage Probe

Rogowiski Coil

He^3 Detector

He^3 Detector

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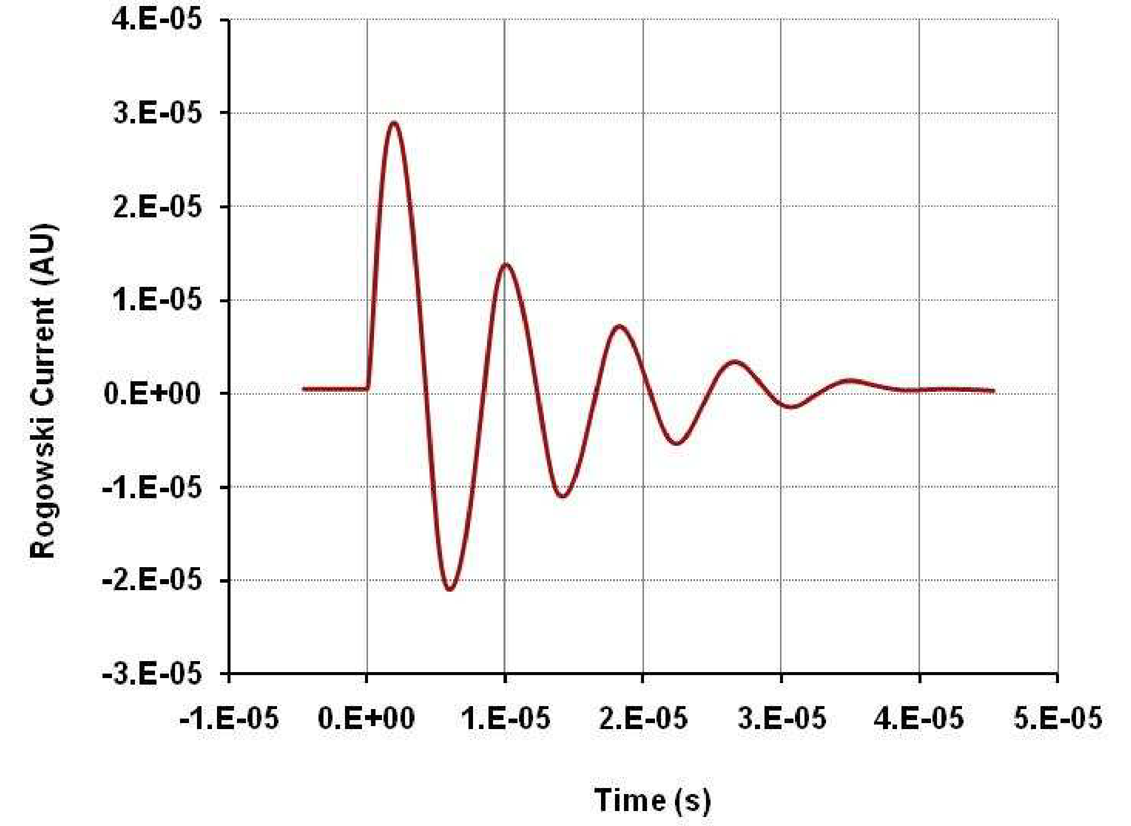
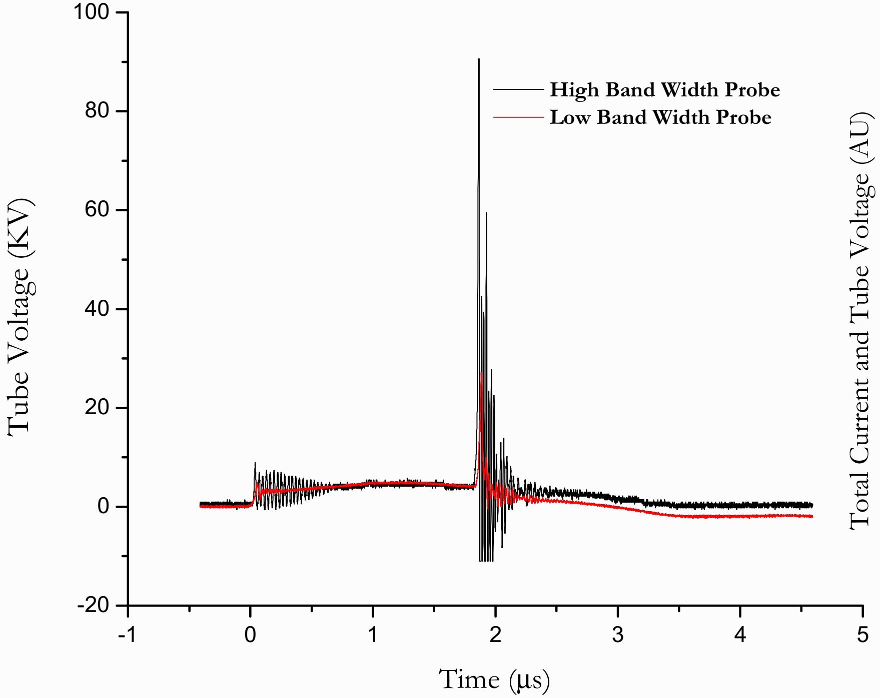
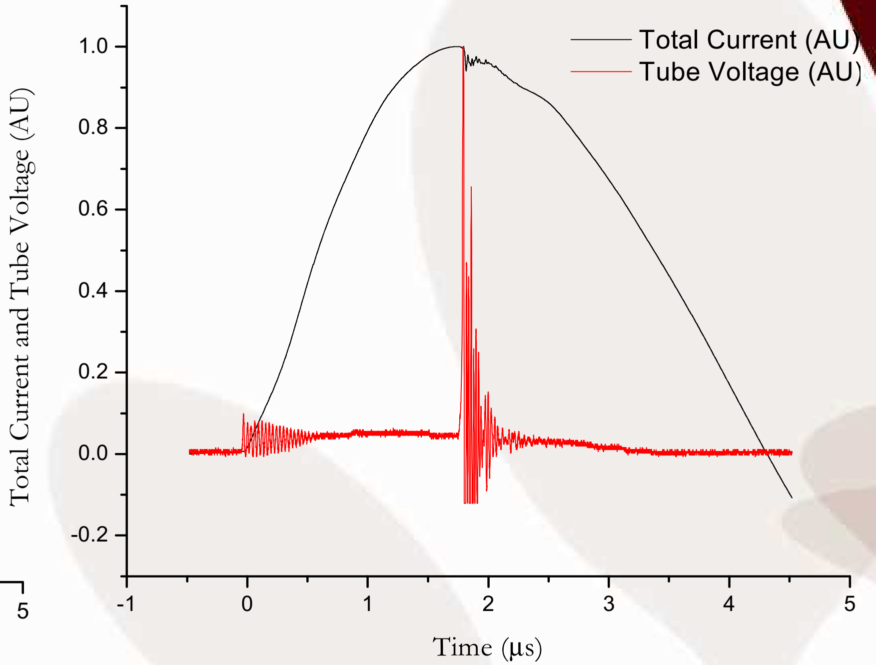
Short Circuit Test at 17 KV



- ❖ Short circuit parameters @ 17 kV are:
  - ❖ Period 8.31 µs ❖ Voltage reversal 0.71
  - ❖ Inductance ~ 130 nH ❖ Resistance ~ 23.3 mΩ

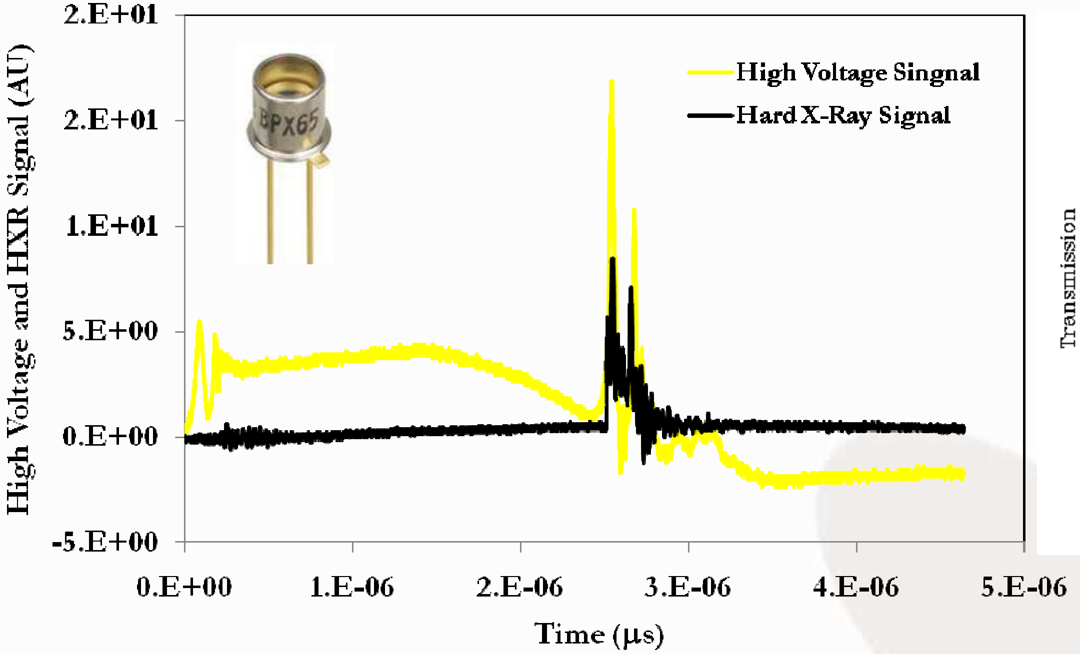
KSU-DPF Tube Voltage Signal

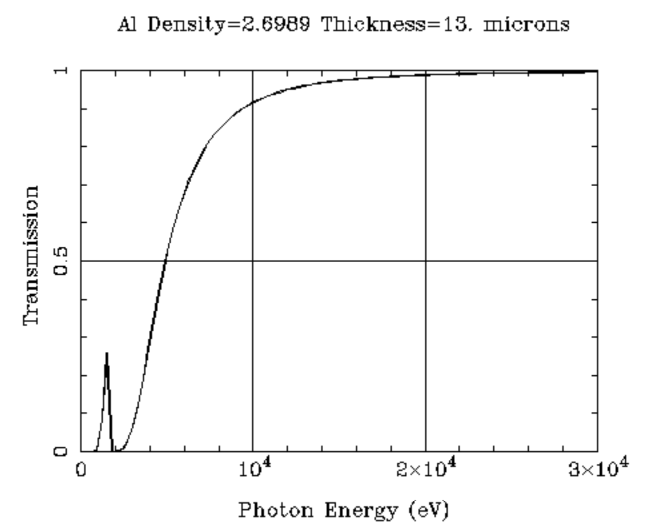




- **Operating conditions: 17 kV, 5 mbar, Deuterium, ~137 Amp, SS tapered anode**
- **The high band width probe (Northstar HV5 60/100 KV DC/AC 80 MHz) signal shows tube voltage exceeding 100 KV during pinch time.**

KSU-DPF Hard X-Ray Signal





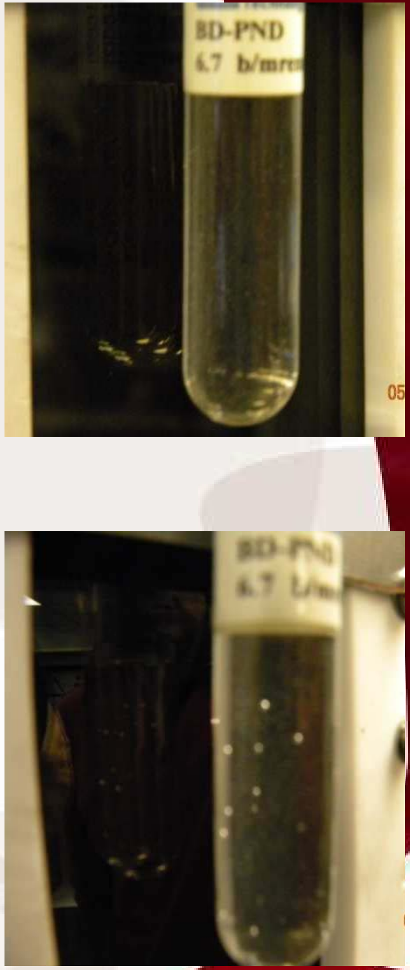
- Operating conditions: 17 kV, 5 mbar, Neon, ~137 Amp, Copper anode
- The hard x-ray (> 10 keV)was measured using 4 channels x-ray spectrometer. Each channel has a BPX65 PIN diode and Al filter in front of it. The hard X-ray signal coincides with the tube voltage signal.

Neutron Yield Measurements

Neutrons are generated as a result of two different mechanisms

Mechanisms

- Fusion $${}^{2}_{1}D + {}^{2}_{1}D \rightarrow {}^{1}_{0}n + {}^{3}_{2}He$$
- Beam- target interaction



10- 20% in the maximum compression period of plasma column

90- 80% in the decaying period

Marek Scholz, "Status and Prospect of MJ Plasma Focus Experiment", Workshop and Expert Meeting on Dense Magnetized Plasmas, *ICDMP, Warsaw, December 3 -4, 2007*

In KSU-DPF @ 17 kV and 5 mbar the total current I~140 KA, the plasma current Ip~112KA and neutron yield Y~ 10^8 neutrons (using bubble detectors)

Neutron Yield Scaling Laws

- **Neutron yield Y_n versus I_{pinch}**

  Consistent with experimental and numerical experiments:

  Over all range of Mather-type Plasma Focus:

$$Y_n \,\alpha\, I_{Pinch}^{4.5}$$

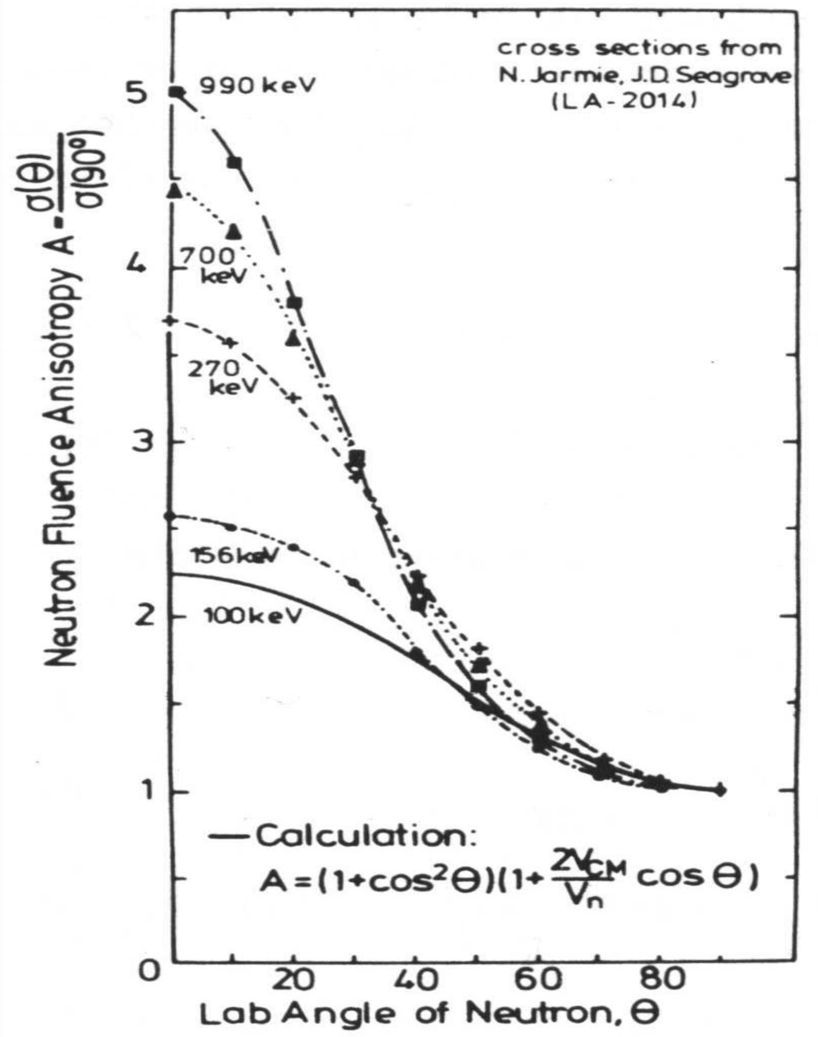
- **Y_n versus storage energy E_0 *(Global Picture combining numerical experiments and measured data)***

$$Y_n \,\alpha\, E_o^{2}$$

for E_0 energy range sub kJ to around 100kJ

As energy goes higher, the Y_n scaling deteriorates, index drops below 2, index dropping to 0.8 by at energy level of 25MJ, according to numerical calculation

Neutron Yield is Anisotropic in Nature



$$A = \frac{Y\left(0^0\right)}{Y\left(90^0\right)} > 1$$

$$E_n\left(0^0\right) = \frac{3}{4}\left(Q + \frac{E_d}{2}\right)\left(1 + \frac{v}{u}\right)^2;$$

E_D(keV)	20	100	300
$E_n(0^0)$ (MeV)	2.56	2.80	3.06

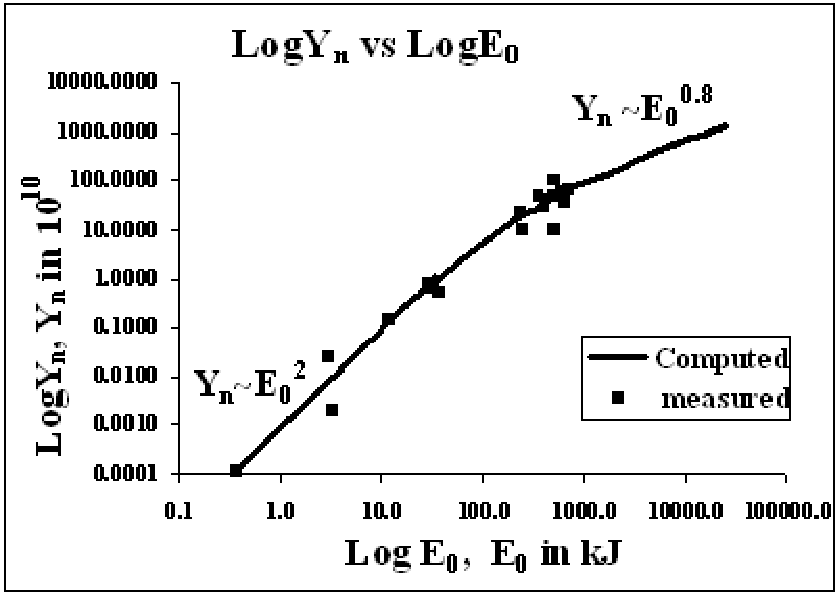
Marek Scholz, "Status and Prospect of MJ Plasma Focus Experiment", Workshop and Expert Meeting on Dense Magnetized Plasmas, *ICDMP, Warsaw, December 3 -4, 2007*

Neutron Yield Saturation Phenomena

❖Global Y_n scaling law, combining experimental & numerical data- numerical experiments computing Y_n from 0.4 kJ to 25 MJ (solid line), compared to Y_n measurements (squares) from 0.4 kJ to 1 MJ.

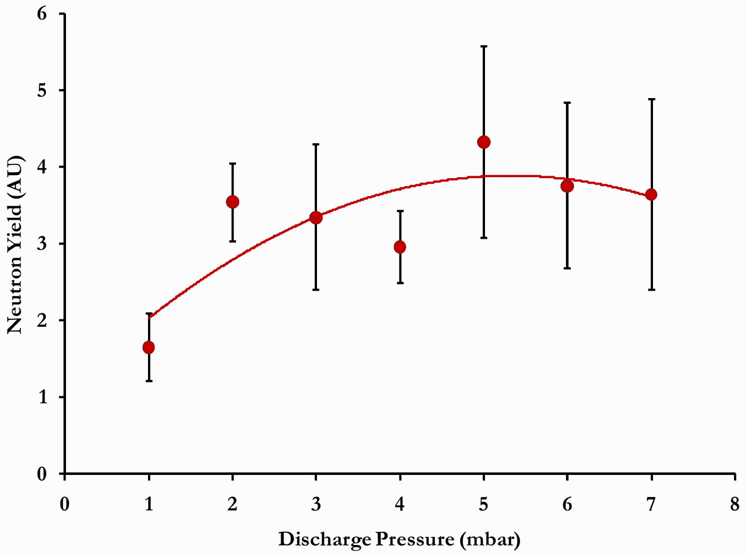
❖Neutron yield shows saturation phenomena above ~ 0.8 MJ.

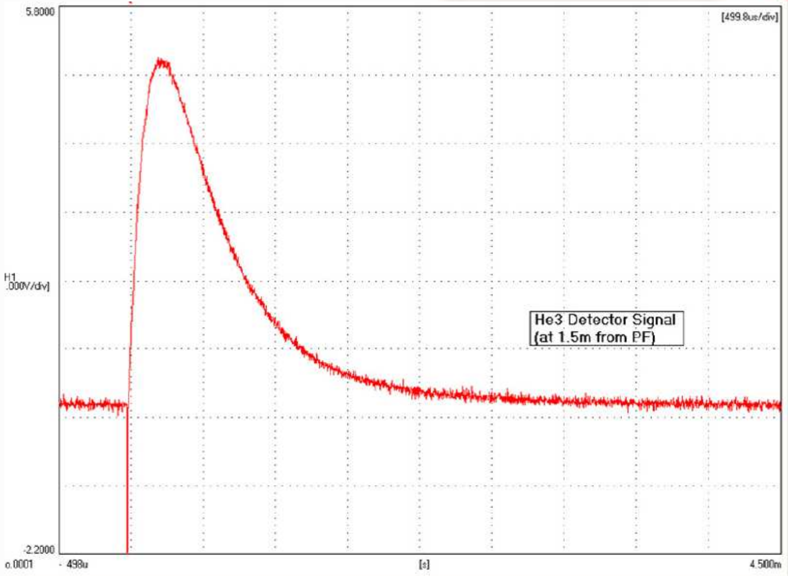
❖The phenomena can be explained by Lee model and it is attributed to the dynamic resistance (1/2 dL/dt)



S. Lee "Neutron yield saturation in plasma focus: A fundamental cause", APL, 95, 2009

Pressure Scan for Neutron Yield

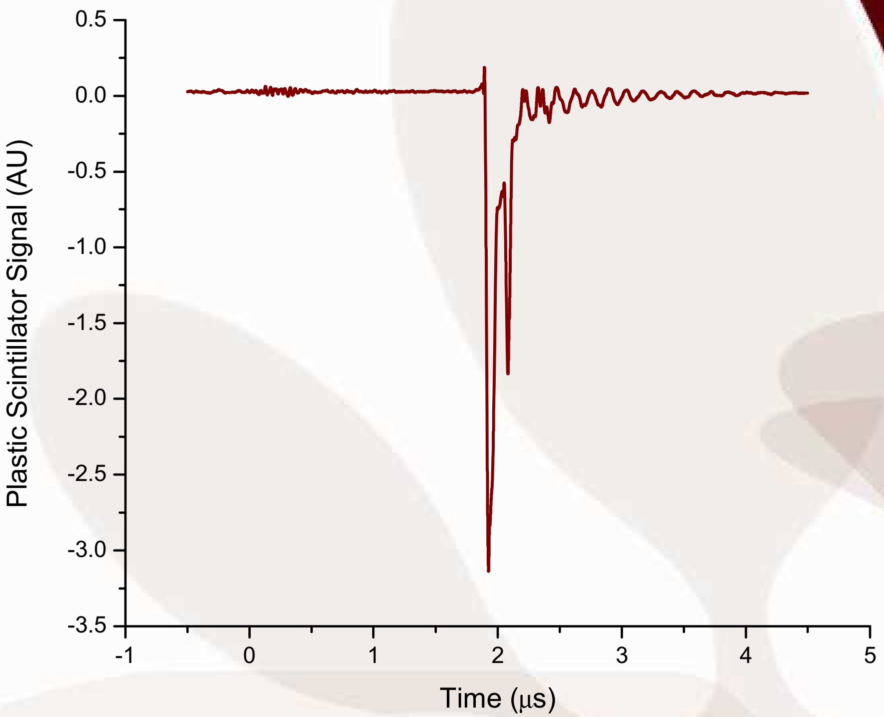




- Operating conditions: 17 kV, Deuterium, ~137 KAmp, SS tapered anode
- The neutron yield pressure scan shows a maximum at 5 mbar
- The neutron yield is measured using the He^3 neutron detector

Neutron Time of Flight Measurement

- ❖Two Saint Gobain BC-418 plastic scintillators are used to measure the neutron energy using neutron Time OF Flight technique.
- ❖The detector was mounted at 3 m away from the anode top at 90 degrees
- ❖At 3m, neutron TOF ~ 140 ns for 2.45 MeV



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DPF Modeling

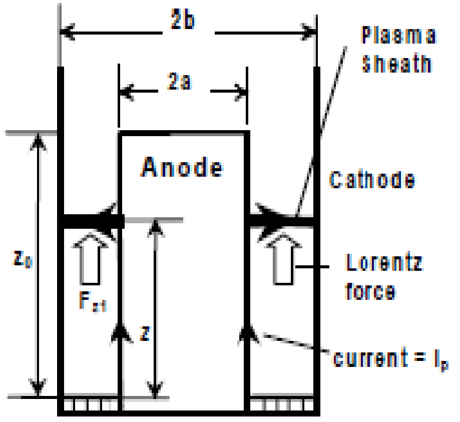
1- Lee Model (Six Different Phases)

a.Axial Phase (circuit equation and equation of motion)
b.Radial Inward Shock Phase
c.Radial Reflected Shock (RS) Phase
d.Slow Compression (Quiescent) or Pinch Phase
e.Anomalous resistive instable phase
f.Expanded Column Phase

2- MHD Model

3- Particle-In-Cell PIC simulation

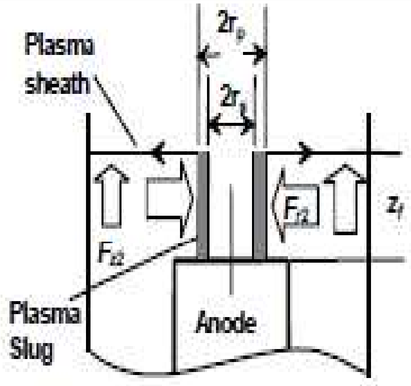
DPF Lee Model Phases



(a) Axial Phase

(a) Axial Phase:

- Plasma sheath is formed and moves axially upward, conduct discharge current and collect gas:
- Start at: $z = 0$; End at: $z = z_0$
- Sheath Position: z

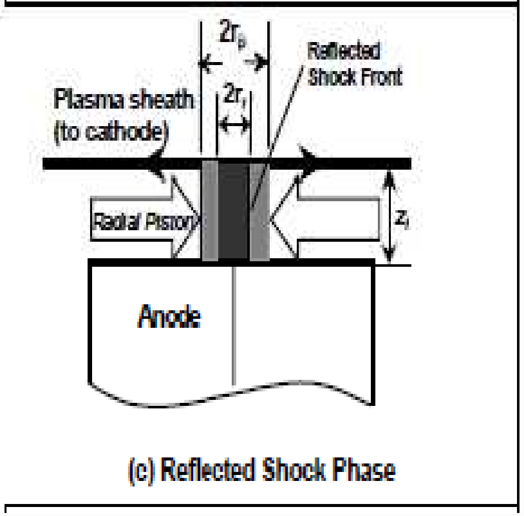


(b) Radial Inward Shock Phase

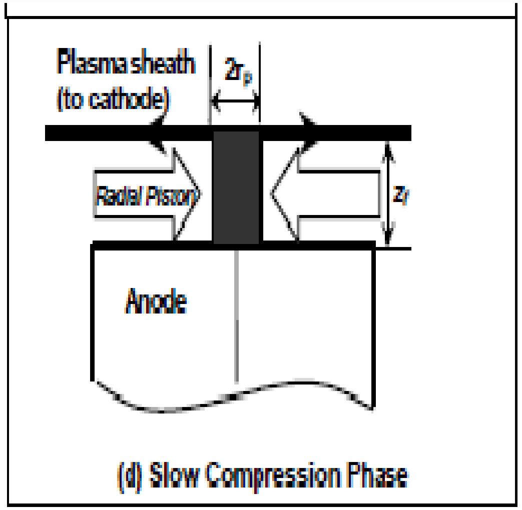
(b) Radial Inward Shock Phase:

- Plasma Slug is formed and compresses radially inward until the shock front meet at center:
- Start at: $r_p = r_s = a$, $z_f = 0$; End at: $r_s = 0$
- Plasma Slug Height z_f Outer radius r_p (Magnetic Piston) Inner radius r_s (Shock front)

DPF Lee Model Phases



(c) Reflected Shock Phase



(d) Slow Compression Phase

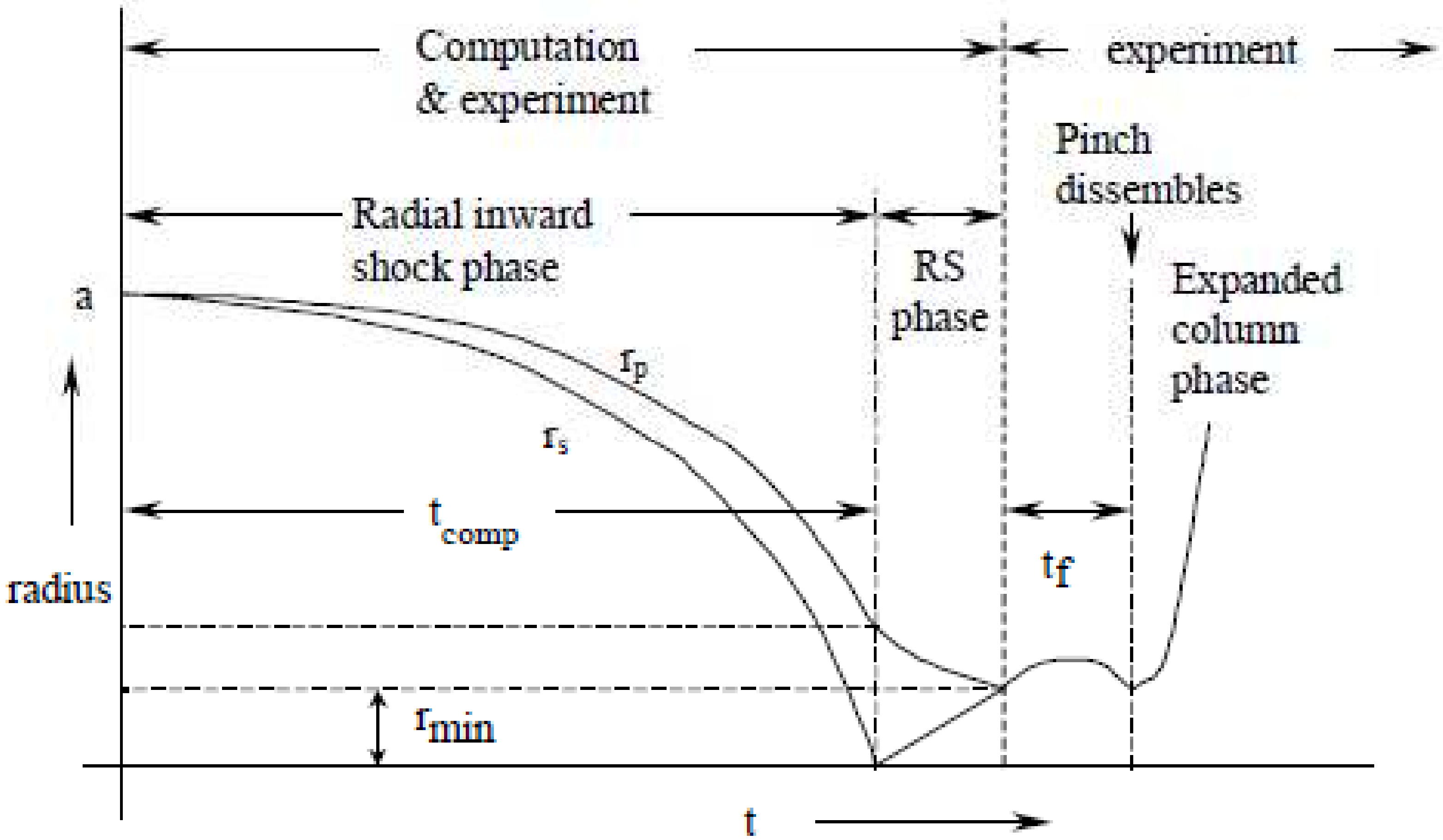
(c) Radial Reflected Shock Phase:

- ❖Plasma Column continues compressing to a narrow column region and result in hot & dense plasma :
- ❖Start at: $r_r = 0$; End at: $r_r = r_p$
- ❖Dense region radius r_r (Reflect shock front) Piston position r_p

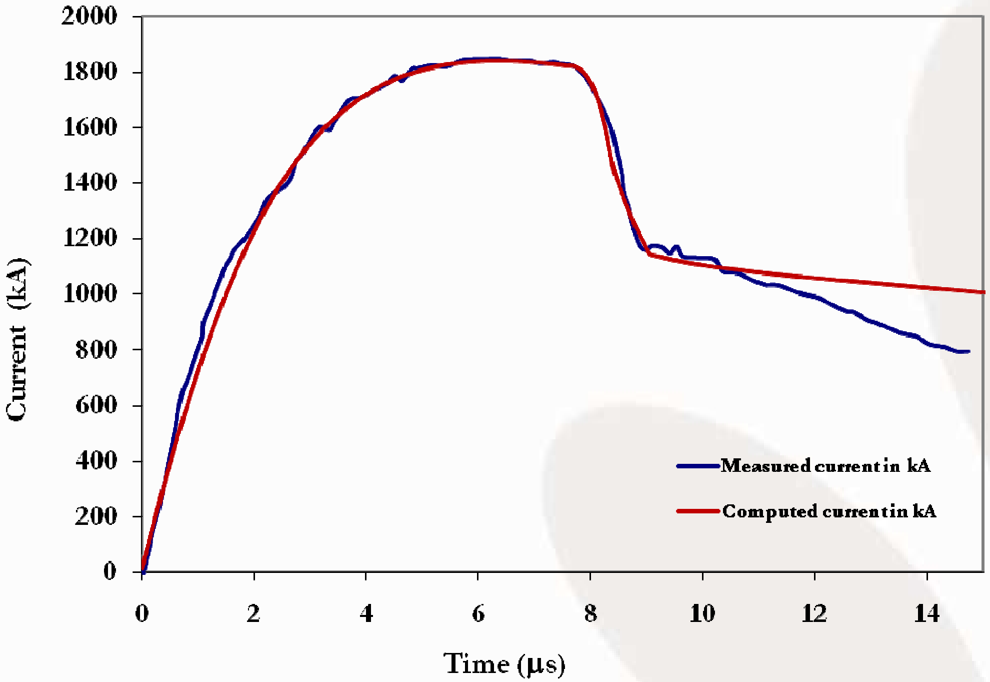
(d) Slow Compression Phase:

- ❖Quasi-stable Plasma Column slow compressed by radial piston:
  - ❖Plasma Column Height z_f
  - ❖Plasma Column radius r_p

Lee Model, Radial Phases

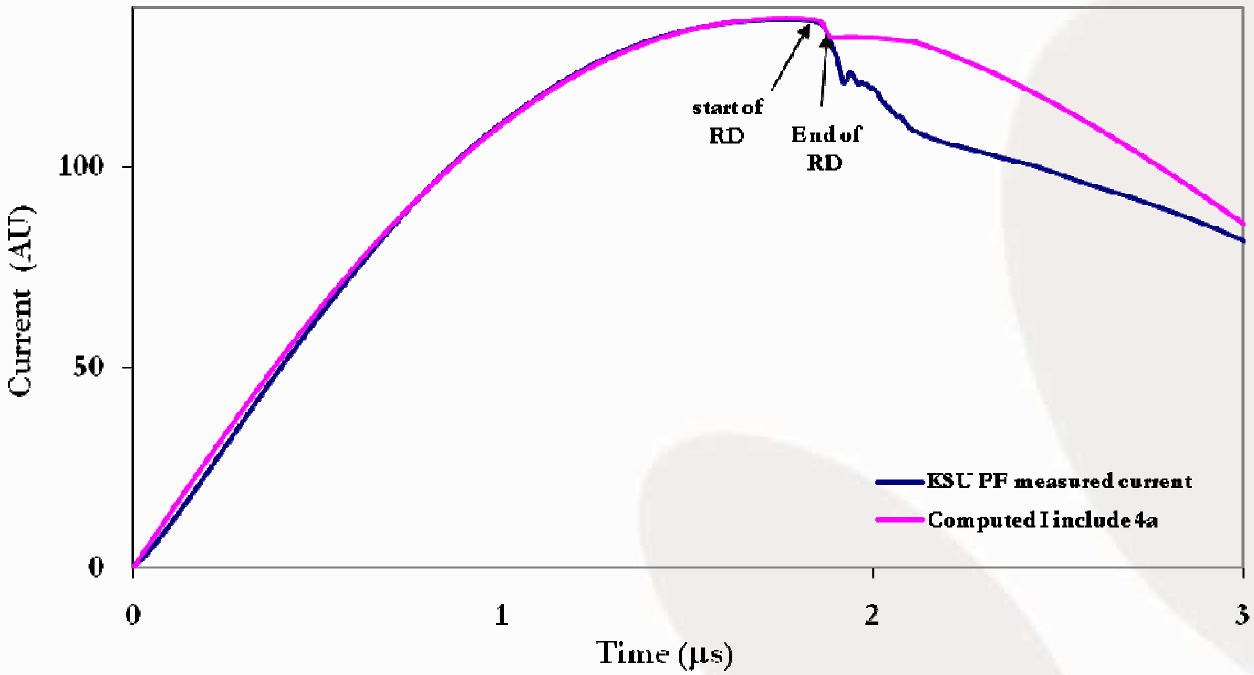


Fitting Computed I_{total} to Measured One



The earlier 5-phase Lee model is found adequate for fitting all plasma focus with low static inductance L_0 (below 80nH) which we class as Type- 1, for example the PF1000 see figure, where the vertical scale is "Total current in MA"

5-Phase Lee Model Failed to Fit KSU-DPF

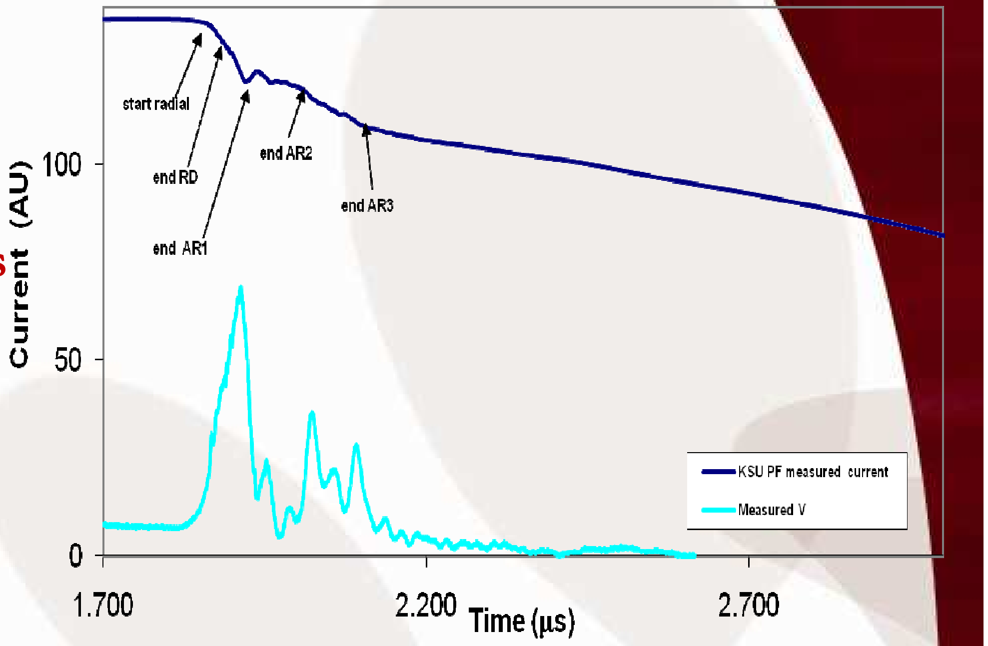


The KSU PF with L_0=130nH is classed as Type 2, which requires an extension of the Lee model code in order to fit the observed extended dip (ED) beyond the regular dip (RD) computed by the 5-phase model.

where R_0 is of the order of 1Ω; t_1 is representative of the rise time of the anomalous resistance and likewise t_2 is characteristic of the fall time.

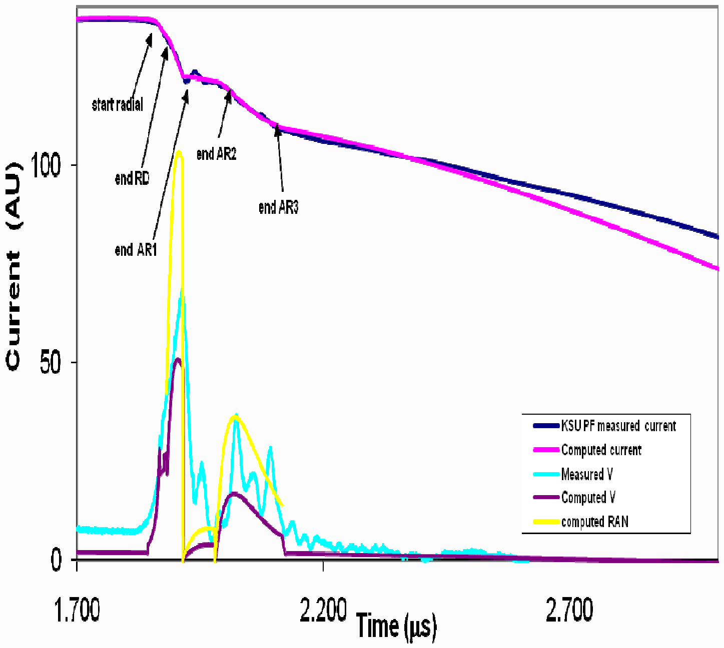
❖For this particular shot, 3 anomalous resistance terms are applied, one after another in sequence in order to fit regions AR1, AR2 and AR3 of the ED.

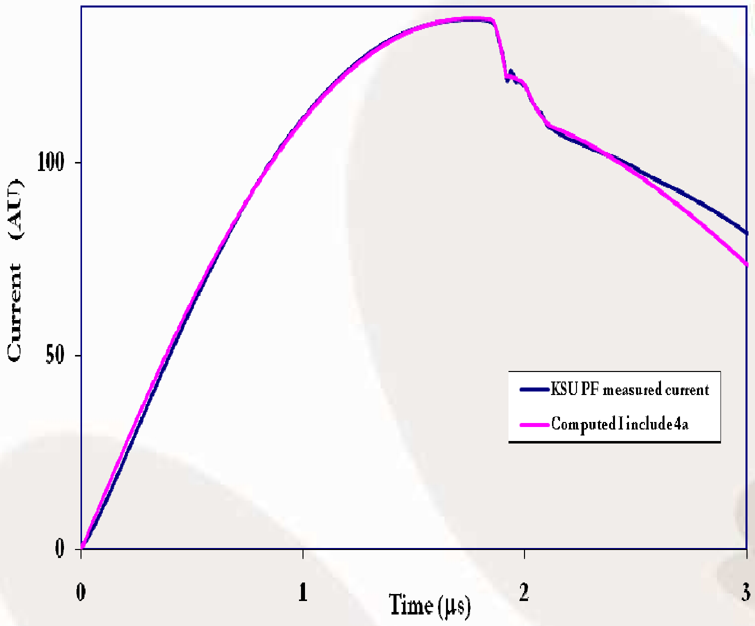
❖The fitting of the current dip in the shown slide is expanded, not showing the current rise, only showing the current dip. The introduction of this instability phase (termed phase 4a) extends to a 6-phase Lee model. Thus the KSU PF is fitted.



$$R \;\alpha\; R_o\left(e^{-\frac{t}{t_2}} - e^{-\frac{t}{t_1}}\right)$$

Modeling the KSU-DPF Requires Additional Phase with Anomalous Resistance





$$R \; \alpha \, R_o \left(e^{-\frac{t}{t_2}} - e^{-\frac{t}{t_1}} \right)$$

Characterizing Plasma Focus Devices- Role of the Static Inductance- Instability Phase Fitted by Anomalous Resistances, submitted to Appl Phys Letts-S Lee, S H Saw, A E Abdou & H Torreblanca

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KSU-DPF Future Research

- Characterization
  - Pressure scan (neutron, x-ray, electrical, etc)
- Neutron yield measurement
- X-ray yield measurement
- Ion beam energy distribution and anisotropy
- Electron beam energy distribution and anisotropy
- Breakdown mechanisms and its correlation to the neutron yield
- Current filamentation and its correlation to neutron yield

Potential Applications of DPF

- Nuclear Fusion energy source (not yet)!
- Space propulsion
- Fast Neutron Activation Analysis
- Neutron Radiography
- X-ray radiography (hard x-ray)
- Lithography
- Short lived radioisotopes production
- Material Science (deposition, modification, implantation)
- Nanotechnology

Thank You for Your Attention