High Power RF systems on tokamaks Aditya and SST-1 for Plasma Heating and Pre-ionization experiments in Ion Cyclotron Resonance Frequency Range

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Plan of Talk

- Introduction to RF applications in ICRH Range
- Important results on different tokamaks
- Introduction to Aditya and diagnostics
- ICRH System on tokamak Aditya
- Second harmonic heating experiment on Aditya
- Preionization experiments done on Aditya
- ICRH System on SST-1
- Automatic matching system on SST-1
- Testing done on SST-1
- Conclusions

Why Heating is required?

- **Plasma Formation in tokamak**

The plasma is formed by an electrical breakdown with the help of ohmic transformer and the current is driven inductively in the plasma. With Ohmic heating one can get temperature of the order of 1-2 keV only

- **Plasma Heating**

As the plasma temperature rises the efficiency to heat the plasma by ohmic heating decreases.

At low temperatures the Ohmic heating is quite strong but because the resistance of the plasma varies with temperature as $\mathbf{T_e^{-3/2}}$, it becomes less effective at higher temperatures.

Also radiation losses increase with increase in temperature and finally heating and losses get balanced to make Ohmic heating in-efficient further.

To further raise the temperature of the plasma to fusion grade, one has to use auxiliary heating schemes.

Common Heating Methods

- **Ion Cyclotron Heating and Current drive** in ICRF Range (ICRH) (10-120 MHz)
  - Second Harmonic Heating using Fast Waves
  - Minority Heating
  - Ion Bernstein wave heating: direct and through mode conversion

. **Lower hybrid heating and current drive** (1-10 GHz)

. **ECRH** at fundamental and higher harmonics of electron cyclotron resonance heating(20-200 GHz)

. **NBI**: using high energy neutral beams

. **Adiabatic Compression**

Fast wave heating in ICRF range

Fast magnetosonic waves do not resonate at the cyclotron frequency, but propagate above and below this frequency.

The fast waves are right-circularly polarized and do not couple energy to the ions in a purely single species plasma at fundamental cyclotron frequency due to the fact that E field rotates almost entirely in the opposite direction to that of the ions .

However at a second harmonic resonance in a single species plasma or in presence of second species a significant fraction of the E_{perb} possesses the polarization required to couple to the ions.

- In the presence of a minority species, very efficient heating has been observed at fundamental cyclotron frequency and in case of single species a second harmonic heating seems to be quite efficient.

Heating mechanism

- The wave energy is absorbed either directly by ions through cyclotron absorption, or indirectly via mode conversion in single or multi species plasma.
- Fast waves have also been seen to transfer their wave energy to electrons broadly by two mechanisms.
- The first one is indirect electron heating, where resonating majority or minority ions pick up energy from waves and transfer their energy to electrons via collisional equi-partition. The second mechanism is a direct electron heating where FW is damped on electrons via electron Landau damping (ELD) and transit time magnetic pumping

Important Results on different Tokamaks

- ICRH using fast waves started in mid-seventies

  (**TM1-RF** and **ST** Tokamak with D heating at second harmonic)
- 1979, **TFR** Tokamak, 200 kW, 20ms pulse gave 150 eV ion temperature
- 1980 **upgraded TFR**, 500 kW gave T_i- 200 eV

  At lower densities (10^{13}) gave T_i-500 eV

  However, increase in density, radiation level, impurity, loop voltage was also observed.

. 1984, **PLT** tokamak, 2.6 MW gave T_i-3.6 keV

. 1986, **JET**, 7.2 MW, 10 s gave a T-6 keV

. 1988 **JET**, 18 MW gave T_e-11.5 keV and T_i-8 keV

Recent: **JET**, 32 MW input and coupled power 24 MW, minimum impurity production because of beryllium coating on antenna, H mode achieved

JFT-2M

1.2 T, 150-170 kA, n=2e13/cc, circular limiter plasma, 200 kW at 38 MHz,

Increase in both ion & electron temp.

ΔTi =200eV, ΔTe =100eV

Increase in poloidal beta, Linear increase of Ti & Te with rf power

Electron heating may be due to non-linear electron Landau damping.

DIII-D

1.6T, 300 kA, n=2E13/cc

- RF power: 1MW, 60 MHz,

Direct electron heating observed ΔTe =500eV

- **HT-6M**

1-1.25T, 60-90kA, n=1-3E13/cc
circular limiter plasma, H plasma
RF power: 410 kW, 28 MHz,
ΔTi ~300eV, ΔTe =rise at beginning of rf pulse, then decreases.
Diamagnetic signal shows increment of thermal energy content.
Impurity rise strongly with rf

TFR

4.5 T, 200 kA, n=1e14/cc
RF power : 500-800 kW, 60 MHz
ΔTi =800eV, ΔTe =500eV
Prompt rise in Te

ICRH Heating Expt on Aditya

- Aditya is a medium size tokamak with low density and low temperature circular plasma and ICRH experiments at second harmonic are carried out recently using 200 kW power at 24.8 MHz frequency.
- To the best of our knowledge, direct electron heating in low temperature (<500eV) single species plasma (H2) in a medium size tokamak is not observed elsewhere.

ADITYA Tokamak

- First Tokamak designed by IPR and fabricated in India.
- Commissioned in September 1989

Design Parameters

Major Radius R_0 : 0.75 m
Minor Radius a : 0.25 m
Toroidal Field B_T : 1.50 T
Plasma Current I_p : 250 kA
Pulse Duration : 250 ms
Cross-section: Circular
Configuration : Poloidal Limite
Coils Type (TF & PF) : Copper
Water cooled

Diagnostics on ADITYA

Interferometer: electron density measurements

(nave along chords)

- **Reflectometer**: edge plasma parameters like n(r)
- **Electron Cyclotron Emission**: Electron temperature $T_e(r,t)$ and its radial profile
- **Soft X-Ray Diagnostics**: electron temperature $T_e(t)$
- **Hard X-ray Diagnostics**: Bremstrahlung radiation, no. density and energy of runaway electrons

Spectroscopy UV, VUV and visible

To measure absolute intensities of H and CII, CIII, OII, OIII and therefrom, quantify the fluxes of H, O and C from the SS wall and the Graphite limiters.

- From the visible BL measurement the Z_{eff}
- To detect spectral lines from low ionization states of Oxygen and Carbon
- To detect presence of Fe, Cr, Si from plasma facing components
- To detect H_α for ionization of neutrals
- VUV spectra to detect highly ionized states of Oxygen and Carbon (e.g. OVII and CV).

- **Voltage Loops**: for loop voltage measurement to get
  electric field
- **Rogowski Coils**: Plasma current $I_p(t)$
- **Diamagnetic Loops**: Stored energy and plasma
  pressure
- **Magnetic Probes**: Spectrum of plasma oscillations
  Also for plasma position
- **Mirnov coils**: for MHD activity
- **Langmuir Probes**: Plasma density and temperature
  fluctuations at the edge

RF related diagnostics

- **Rogowskii coil**: antenna current
- **Directional coupler**: forward and reflected power
- **VSWR probes**: 20 in no. to get VSWR to find antenna impedance
- **Dipole probes** : for RF Electric field
- **Magnetic loops**: RF magnetic field measurements
- **Langmuir probes** near antenna : edge density and temperature

RF Power Requirements for Aditya

Minimum power requirement is estimated to get an idea of required output power from the RF generator.

From the consideration of the power balance equation, the expected plasma temperature (Dolan 1982) is,

$$0{\cdot}024n(T_e + T_i)/\boldsymbol{\tau}_E = (P_{\mathrm{in}} - P_r)/V_p.$$

Assuming $P_r \sim 0{\cdot}3P_{\mathrm{in}}$ and $T_i \sim 0{\cdot}4T_e$ we get,

$$T_e = (0{\cdot}7P_{\mathrm{in}}\,\boldsymbol{\tau}_E)/(0{\cdot}034n_{20}V_p).$$

We have calculated energy confinement time using ITER89 P L-mode scaling (Uckan *et al,* 1990)

$$\boldsymbol{\tau}_E = 0{\cdot}048 I^{0\cdot85} n_{20}^{0\cdot1} a^{0\cdot3} R_0^{1\cdot2} A_i^{0\cdot5} P_{in}^{-0\cdot5} \kappa_x^{0\cdot5} B^{0\cdot2},$$

where,

$\boldsymbol{\tau}_E$ = energy confinement time (s),

V_p = plasma volume = $2\pi^2 a^2 R/\kappa$ (m^3),

T_e = electron temperature (keV),

P_{in} = input power = $P_{OH} + P_{\mathrm{aux}}$ (MW),

P_{OH} = ohmic power = $V_{\mathrm{loop}} I_p$ (MW),

P_{aux} = auxiliary power (MW),

P_r = radiative power (MW), and

$\boldsymbol{\tau}_E = 3{\cdot}9$ ms, $T_e = 432$ eV, $T_i = 173$ eV,

where, $P_{\mathrm{aux}} = 0{\cdot}2$MW and $P_{OH} = 0{\cdot}2$MW

Thus, to raise the temperature at least by 0·4 keV and maintain it at that level, we fix the RF power requirement at 200 kW. Hence, the RF generator for ICRH system on Aditya is designed to fulfill the specifications given below,

CW RF power: 200 kW (max)

Radio frequencies: 20 - 40 MHz

RF pulse duration: 100 ms

Computational Aspects

- Indigenously developed codes based upon warm plasma dispersion relation to get 3 roots and the variation of n_{perb}^2 against position shows a very less evanescent layer in fast wave propagation which has helped in fast wave heating.

- Recently we have done computational work using TORAY code which shows that for Aditya parameters 55% electron heating and 45% ion heating should take place.

The codes are used for,

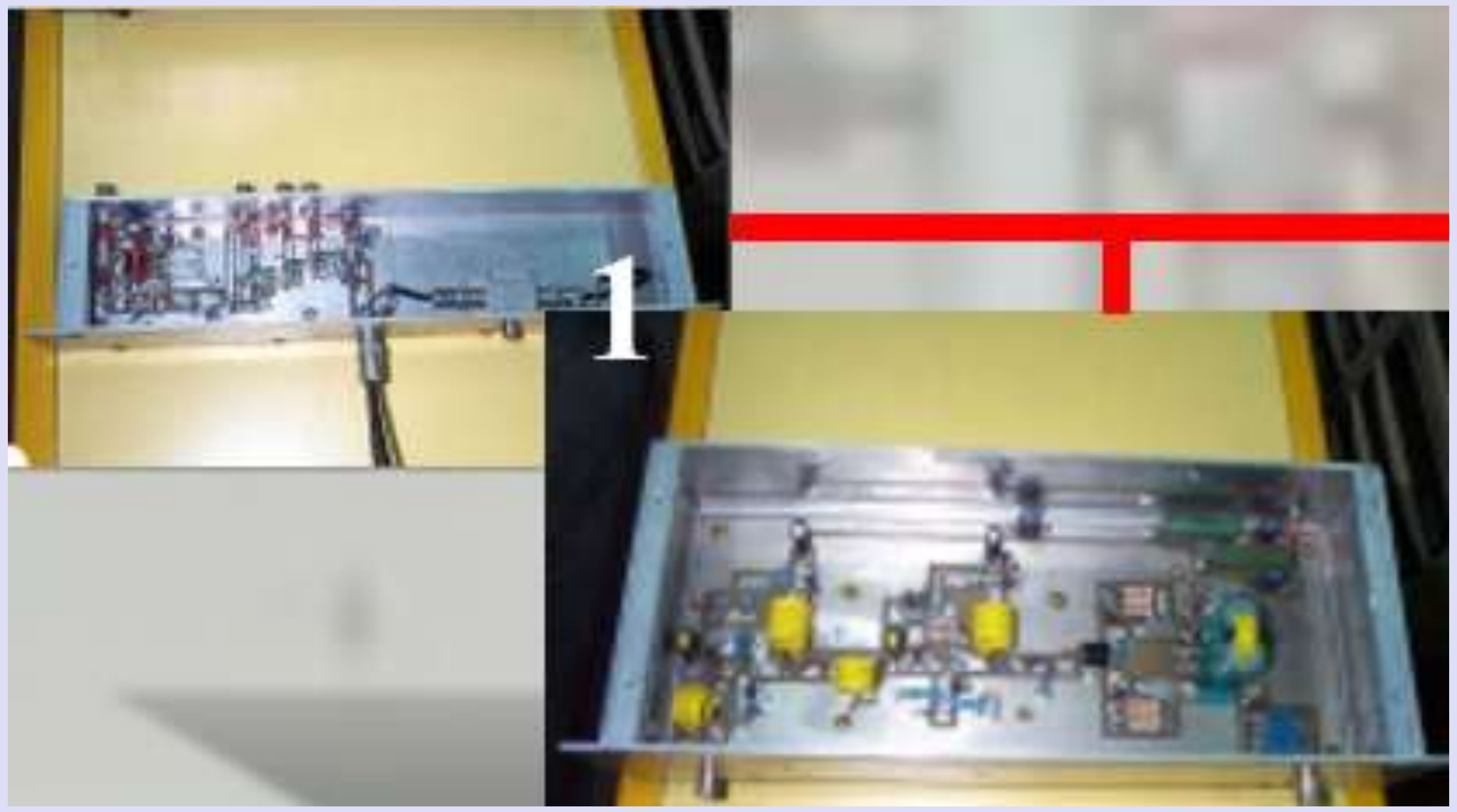
- selecting experimental parameters,
- dimensions of antenna,
- for getting better antenna-plasma coupling,
- for getting the idea of plasma impedance for the design of matching system,
- for understanding the propagation characteristics (less evanescent layer at low field side at 0.75 T)
- For getting the idea of partition of power into different waves
- For deposition of power on the way or at the layer

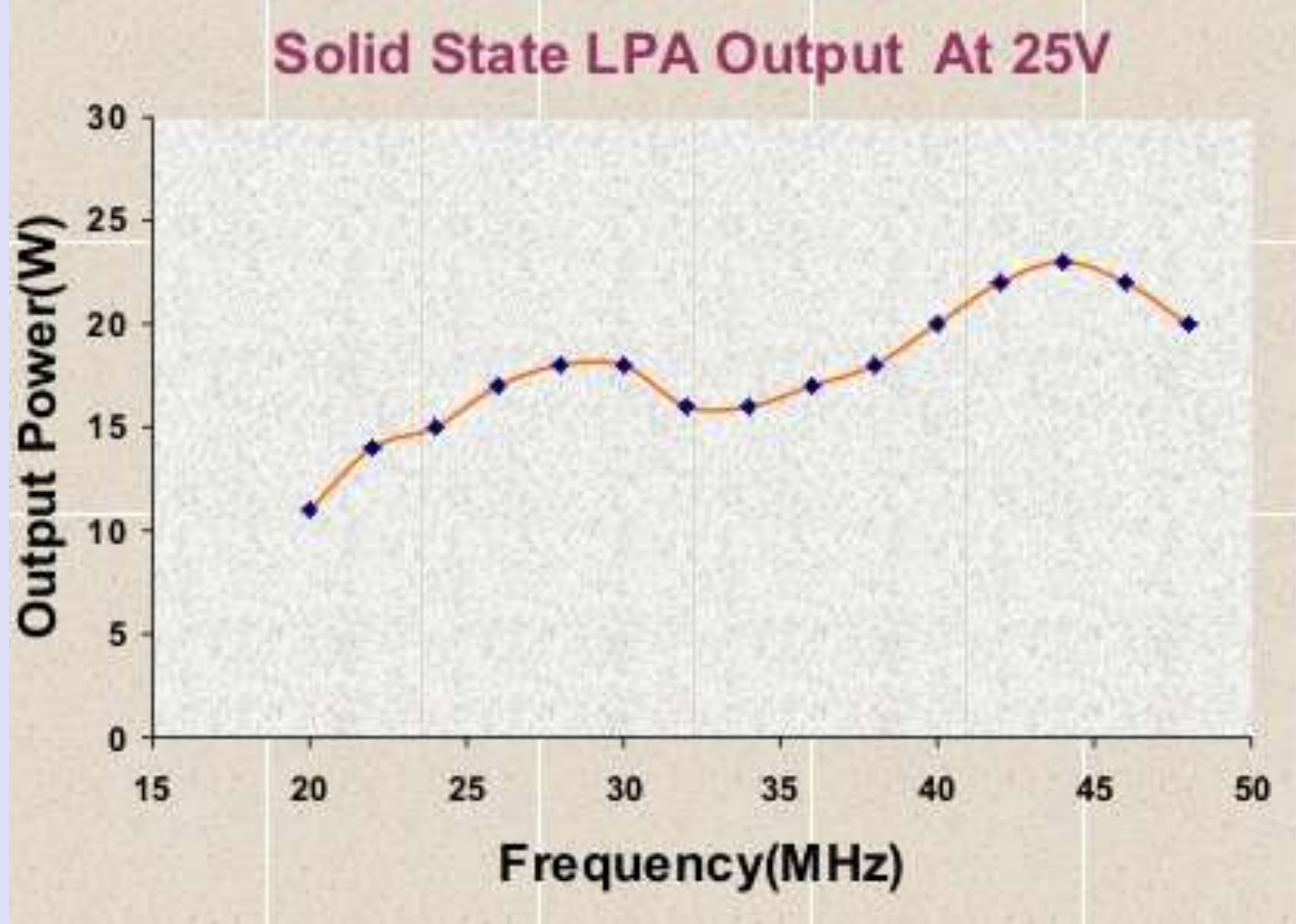
Brief description of Aditya-ICRH system

Schematic of Aditya-ICRH system

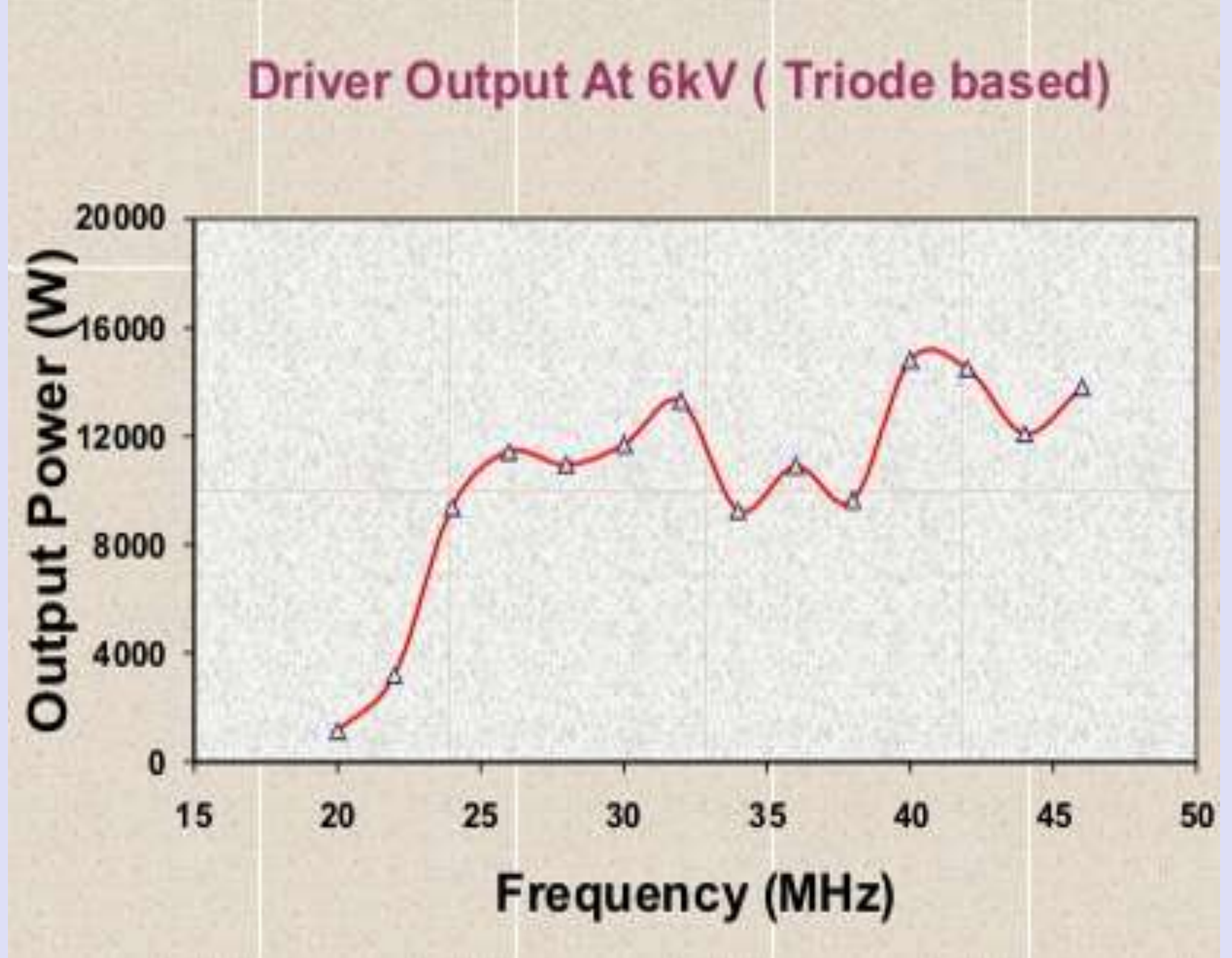
- 20-40 MHz frequency variable,
- 200 kW pulsed operation for ADITYA-icrh
- 50ohm coaxial copper tx lines (6” & 9”) from source to Antenna (~100m)
- Double Stub-PS configuration-Matching network
- Directional Coupler for forward & reflected power monitoring.
- Vacuum Transmission line (VTL) interfaces MN and Antenna with vacuum isolation with Aditya VV

RF Generator Stages (20 MHz – 40 MHz)





Vmax = 4.5 KV Imax = 1 A
Pout = 2 KW Pin = 50W
fout = 20-100 MHz, Air cooled
Zin = 50 Zout = 50
Approx. size : 1m x 1m x 3m
Filament Volt/current : 10V / 16A

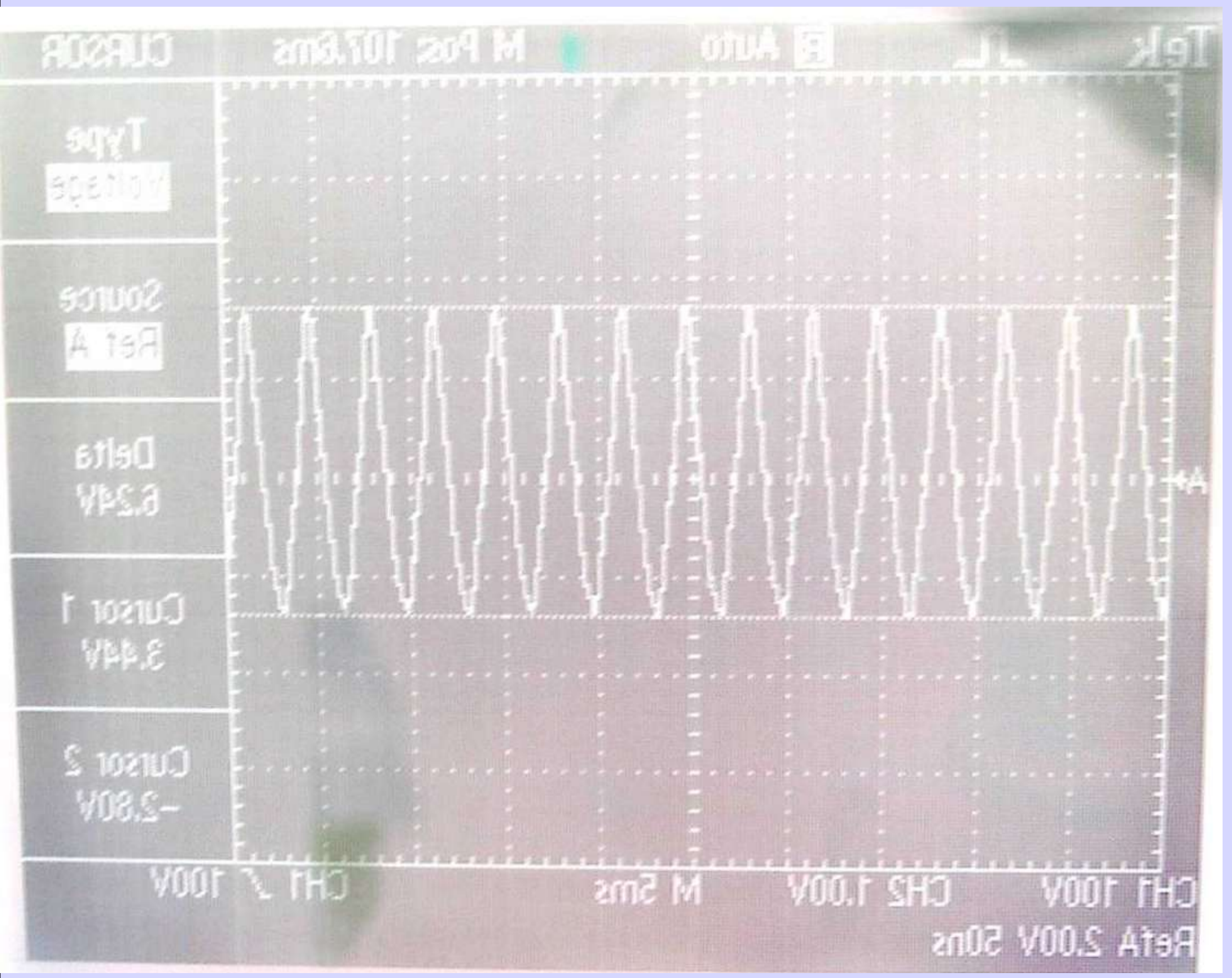


Complete chain

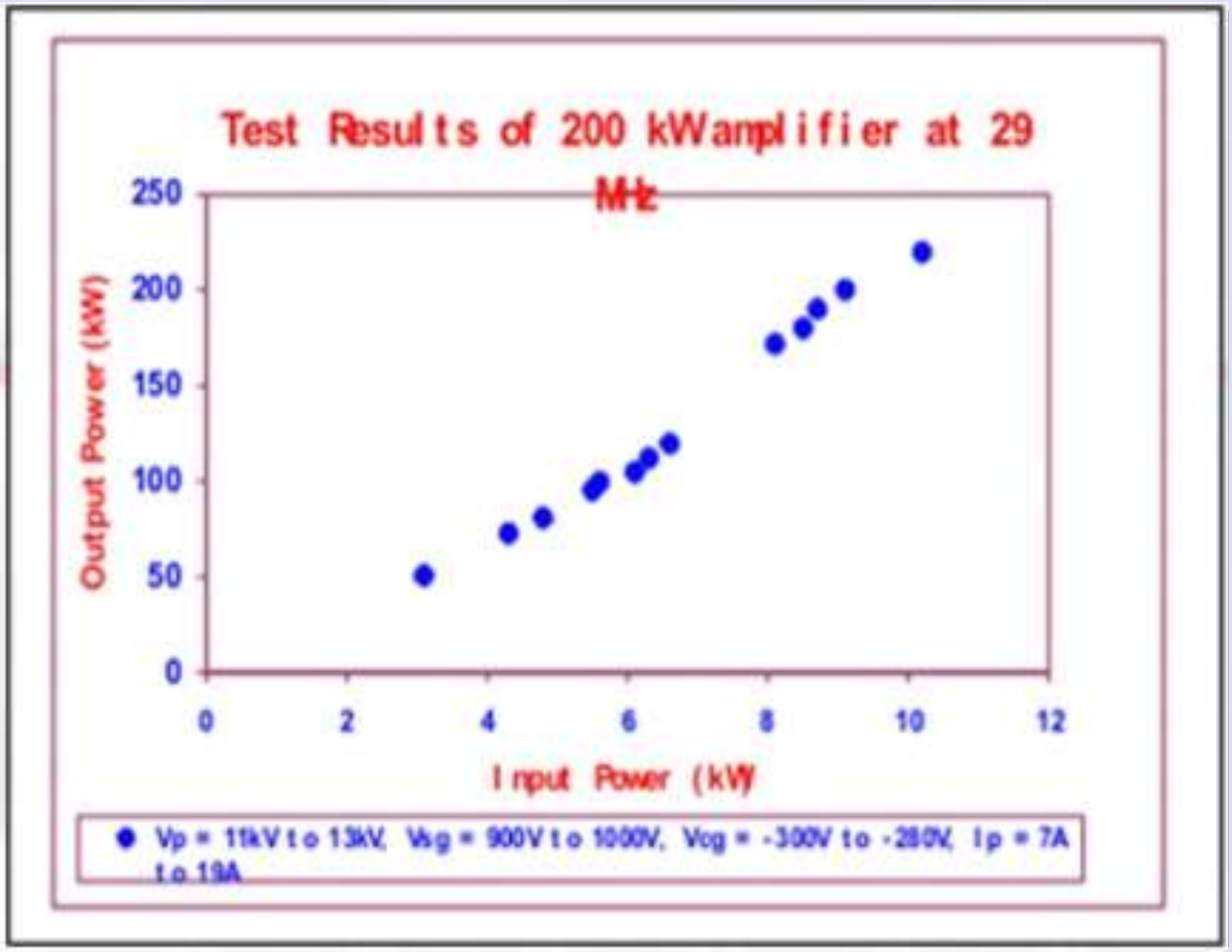
1. **1.5mW oscillator modulator & 30W solid state LPA**
2. **2.2kW Pre-driver stage using 3CW5000A7**
3. **20kW Driver stage using 3CW30000H7**

RF Generator Stages (20 MHz – 40 MHz)

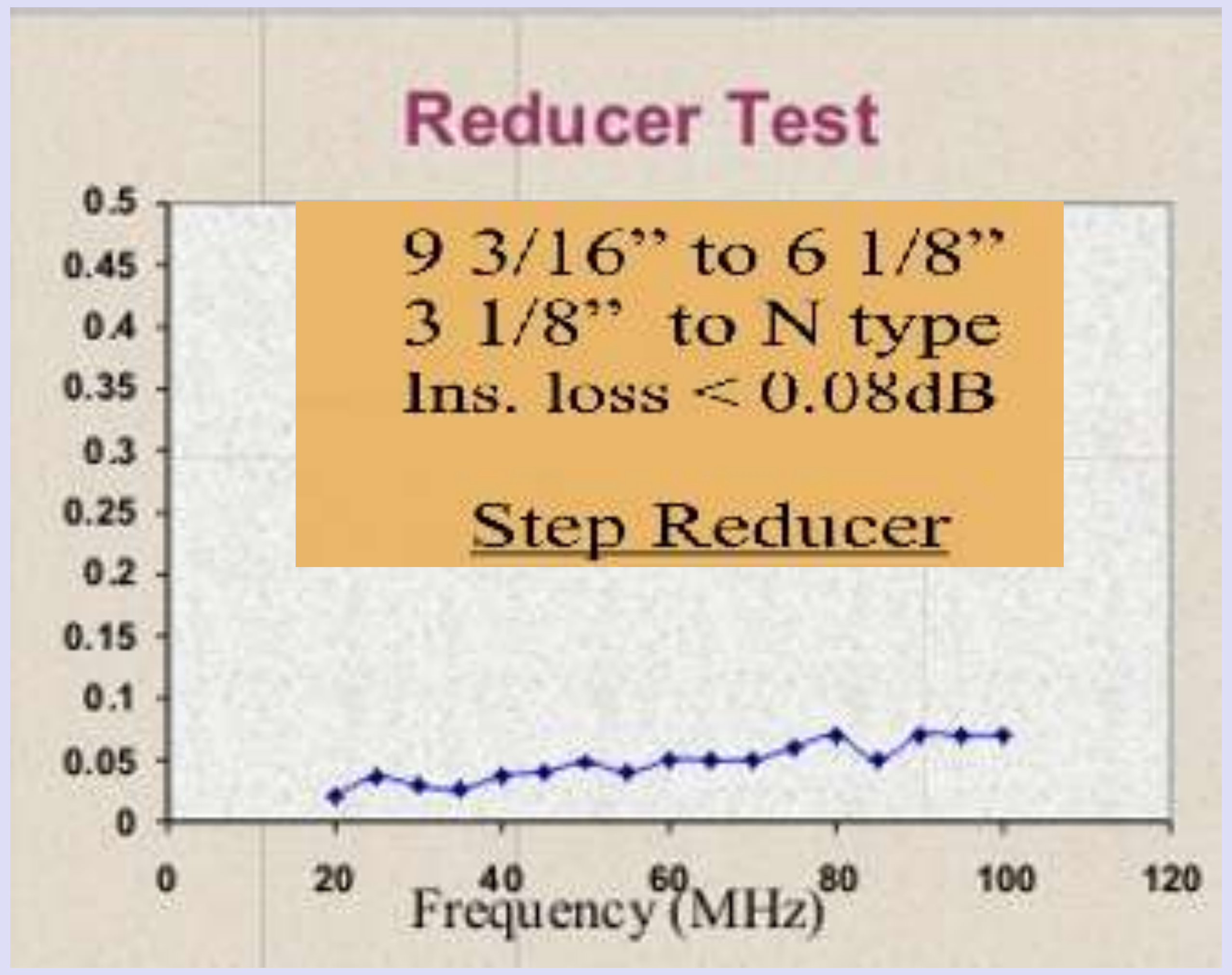
4. **200kW 1st output stage using 4CM300000GA**
5. **1.5MW final stage using 4CM2500KG**



No harmonic distortion

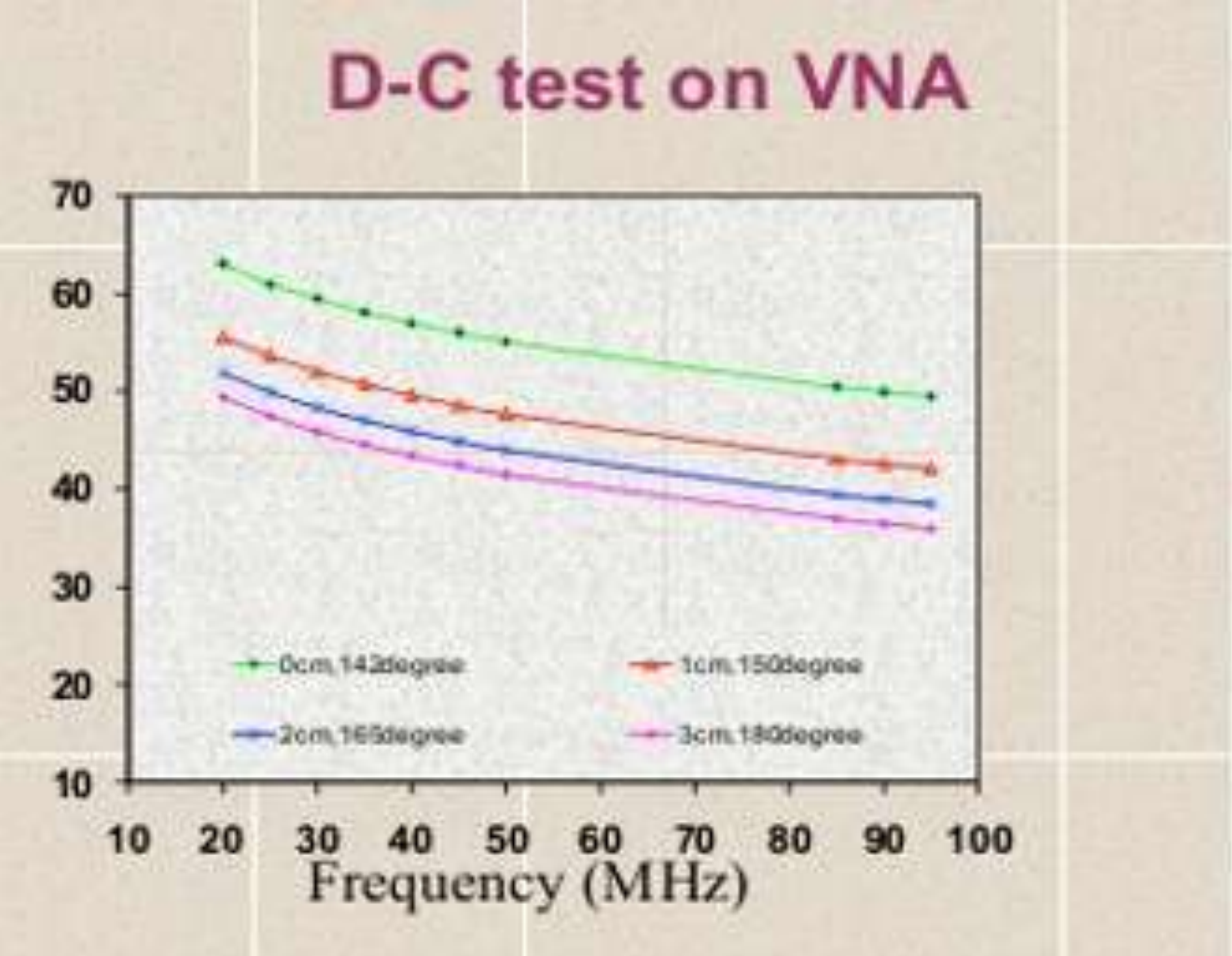


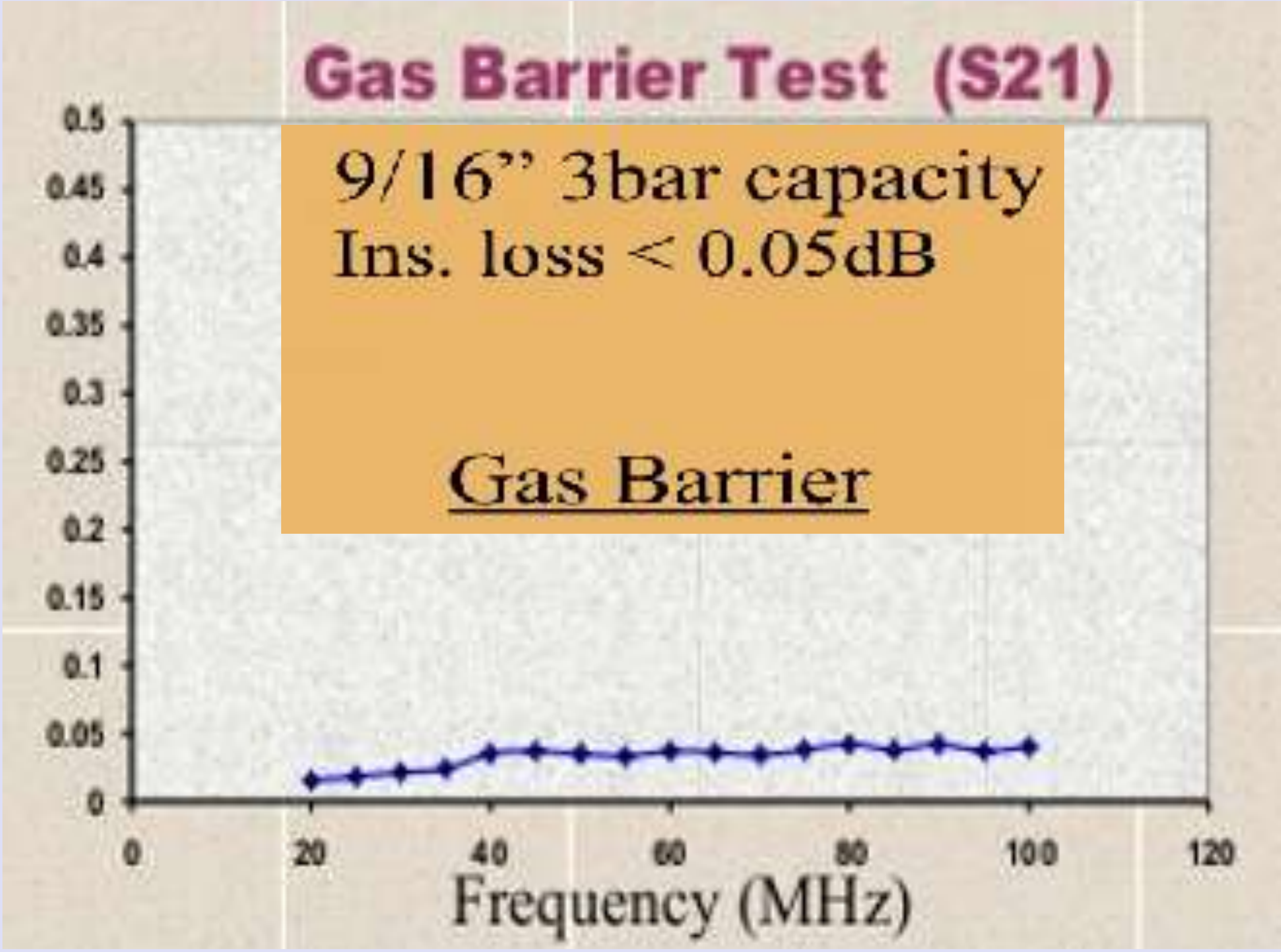
High Power Co-axial Tx-line components



9 3/16" to 6 1/8"
3 1/8" to N type
Ins. loss < 0.08dB

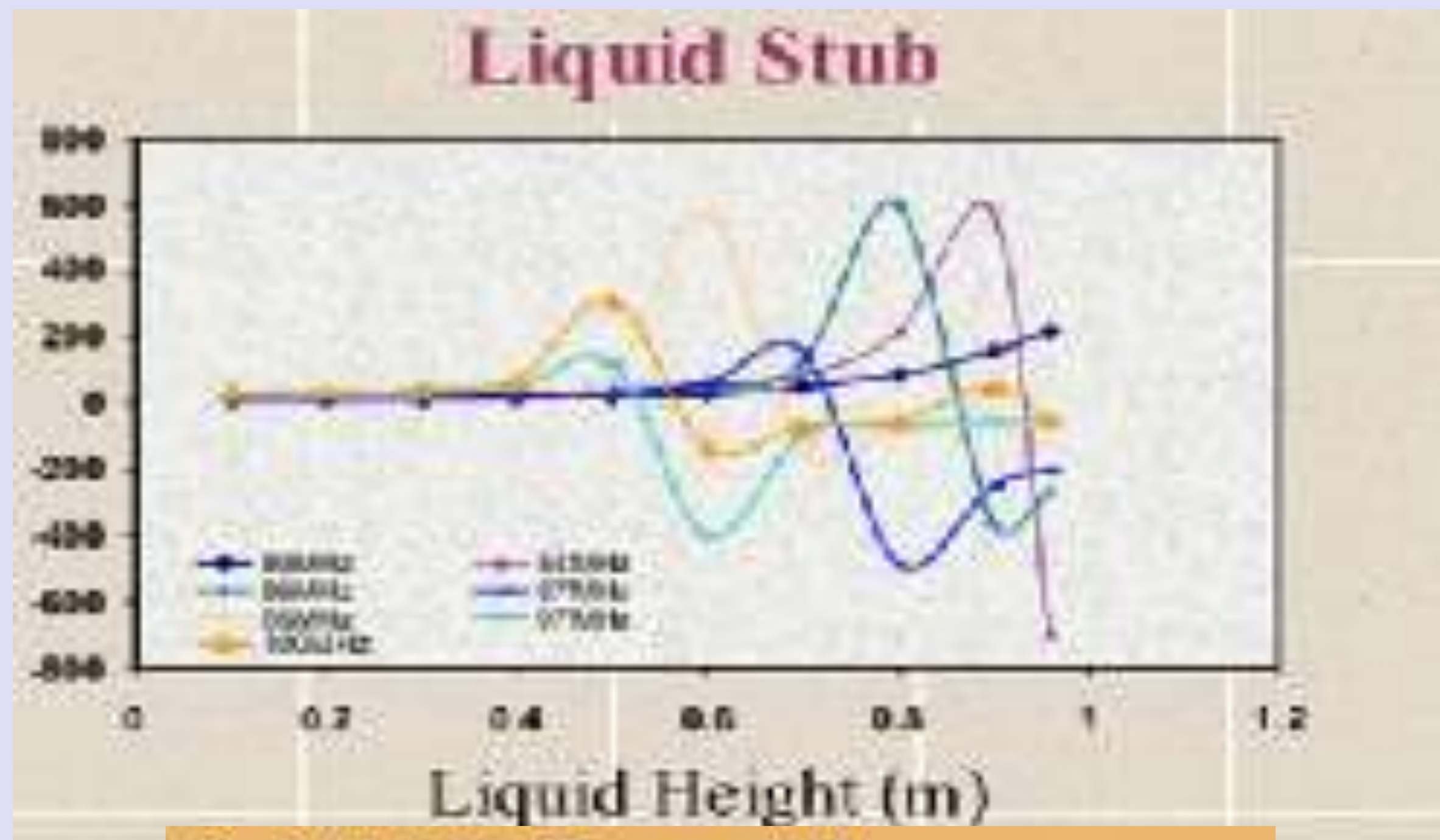
Step Reducer





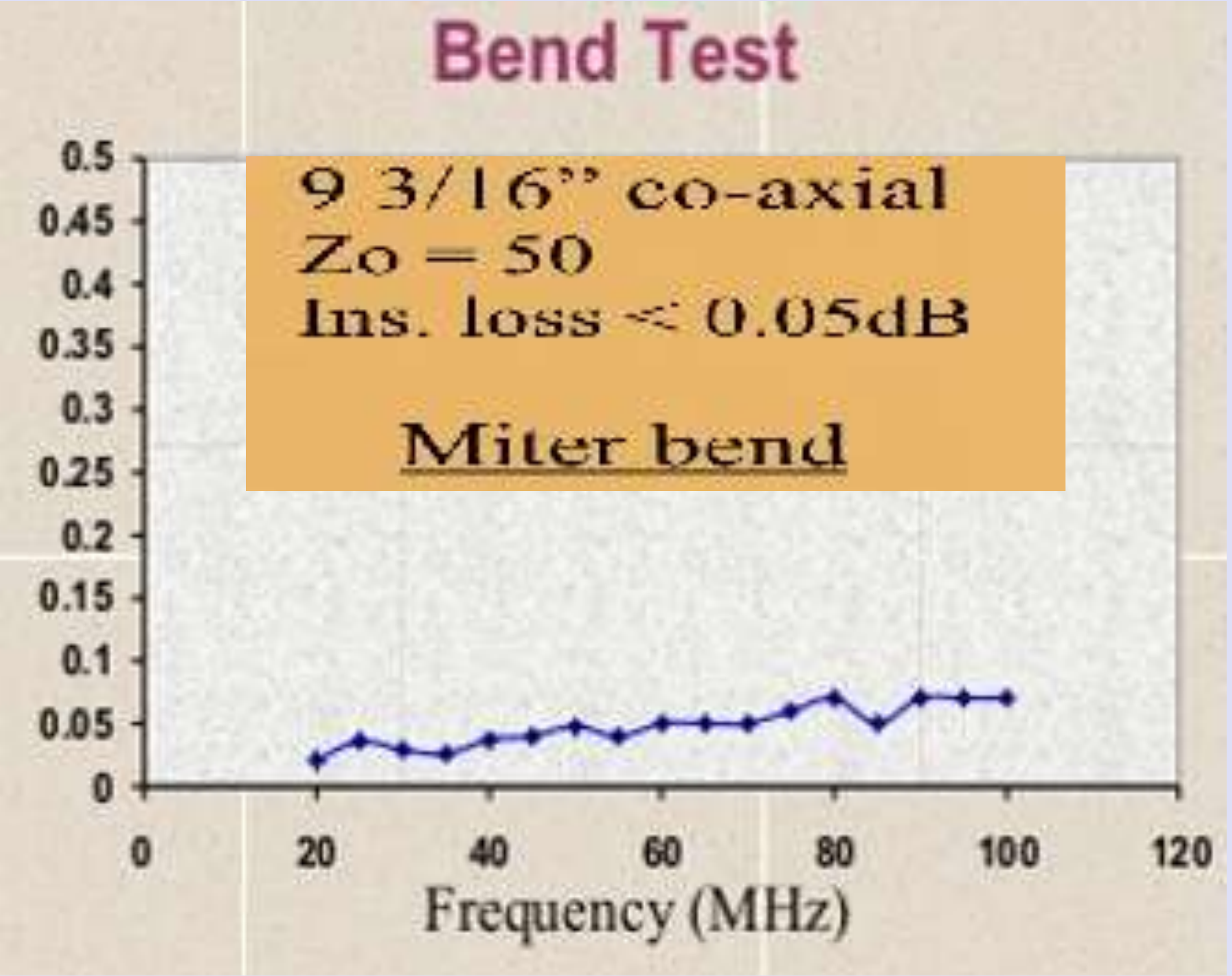
9/16" 3bar capacity
Ins. loss < 0.05dB

Gas Barrier



9 3/16", Zo = 50
Liquids used as dielectrics:
(a)silicon oil
(b)transformer oil

Liquid Stub



9 3/16" co-axial
Zo = 50
Ins. loss < 0.05dB

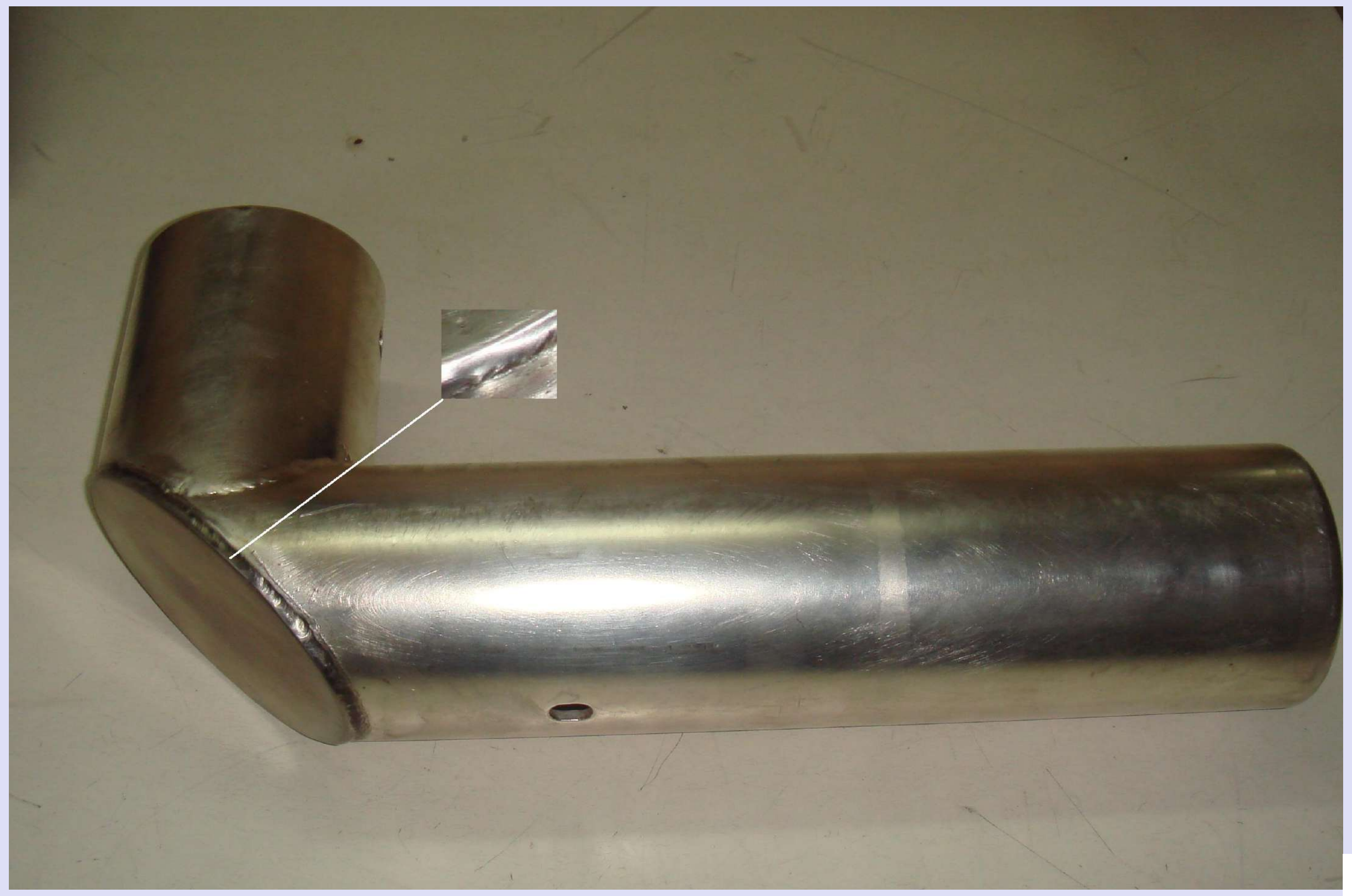
Miter bend

9 3/16" , 6 1/8"
9 3/16" W/C

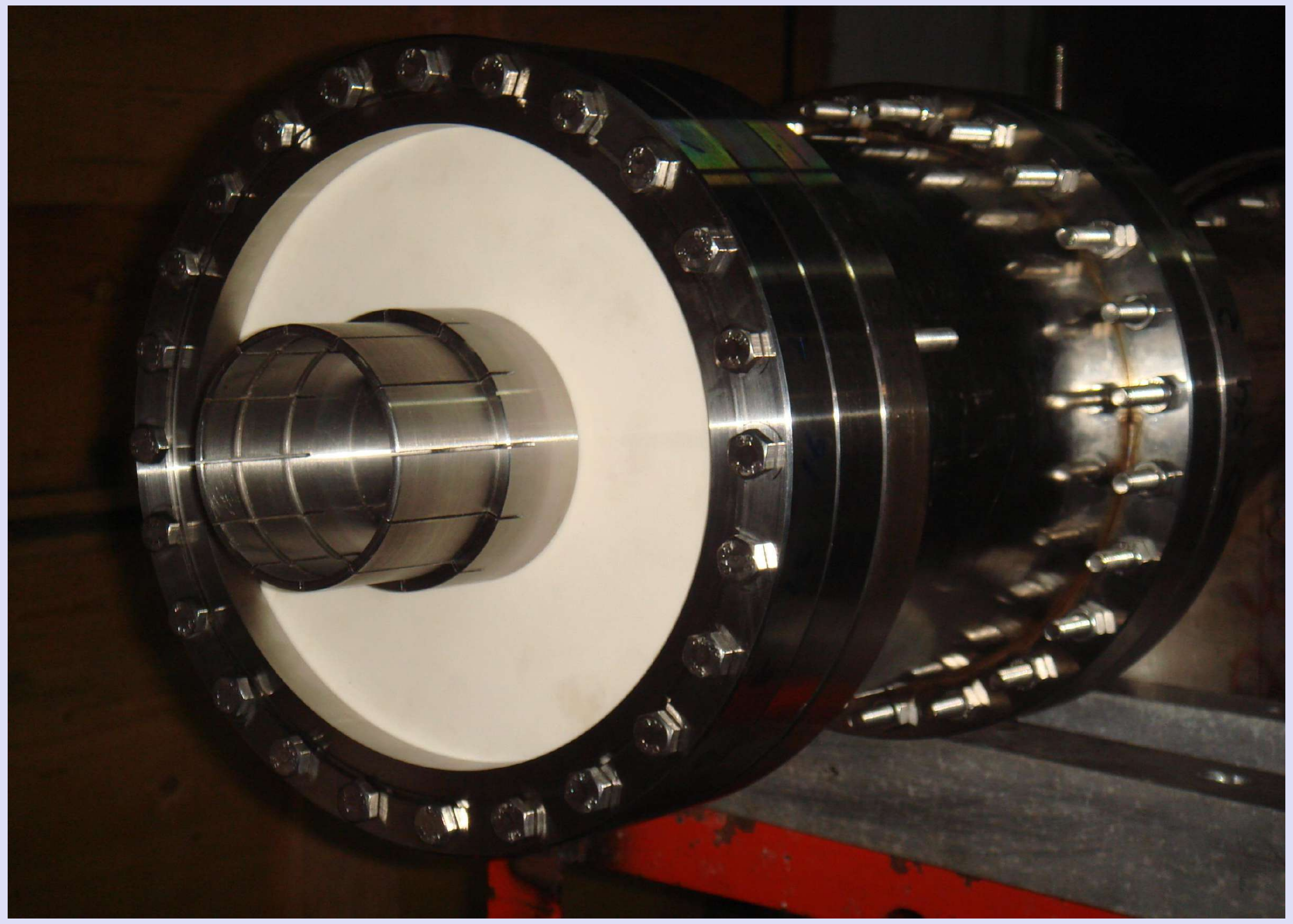
Inner Conductor Joints

Recent Up-gradations on the System

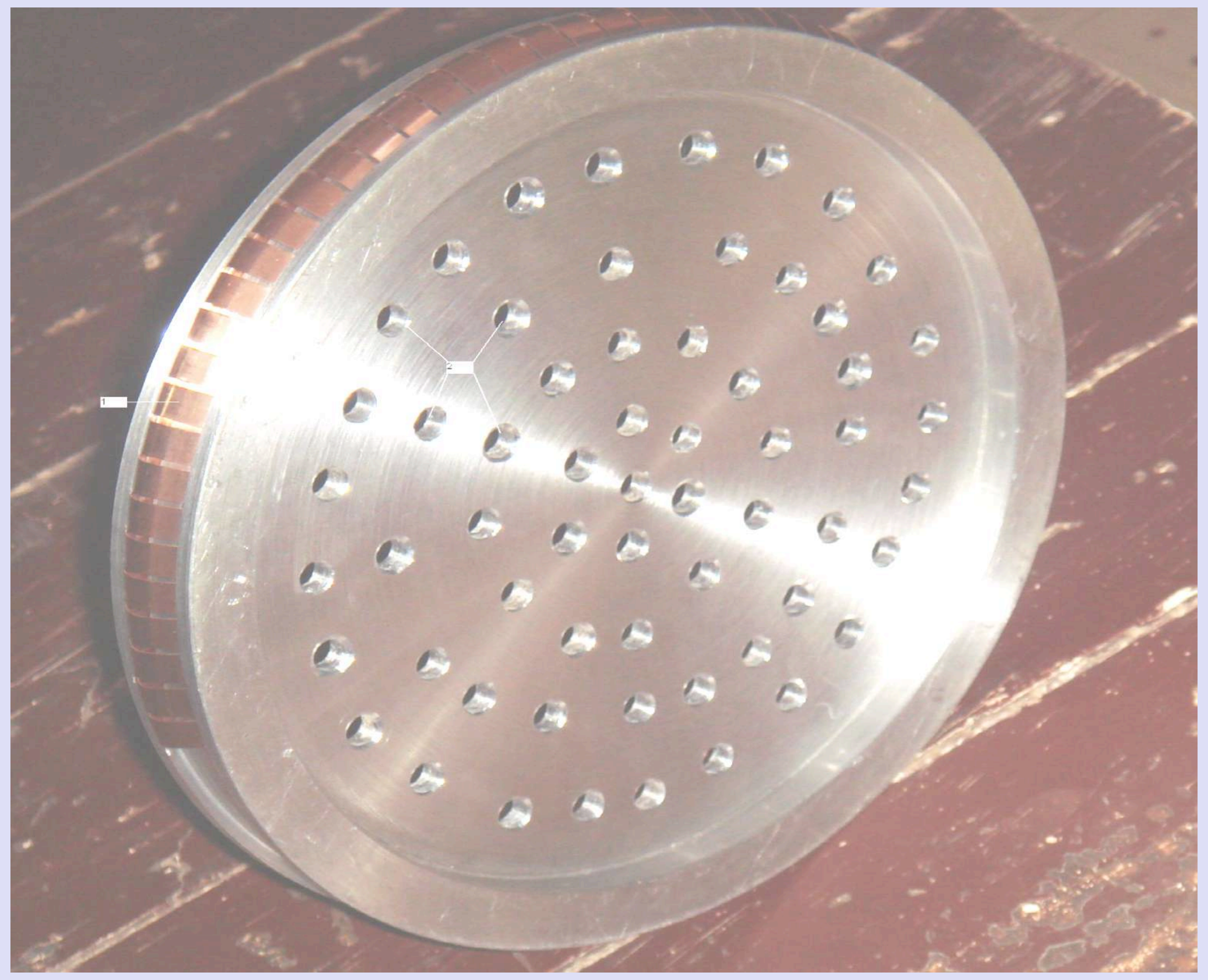
- VTL section recently up-graded with new Coaxial vacuum window, modified feeder and shorting plunger.
- The complete VTL section is tested for high power operation



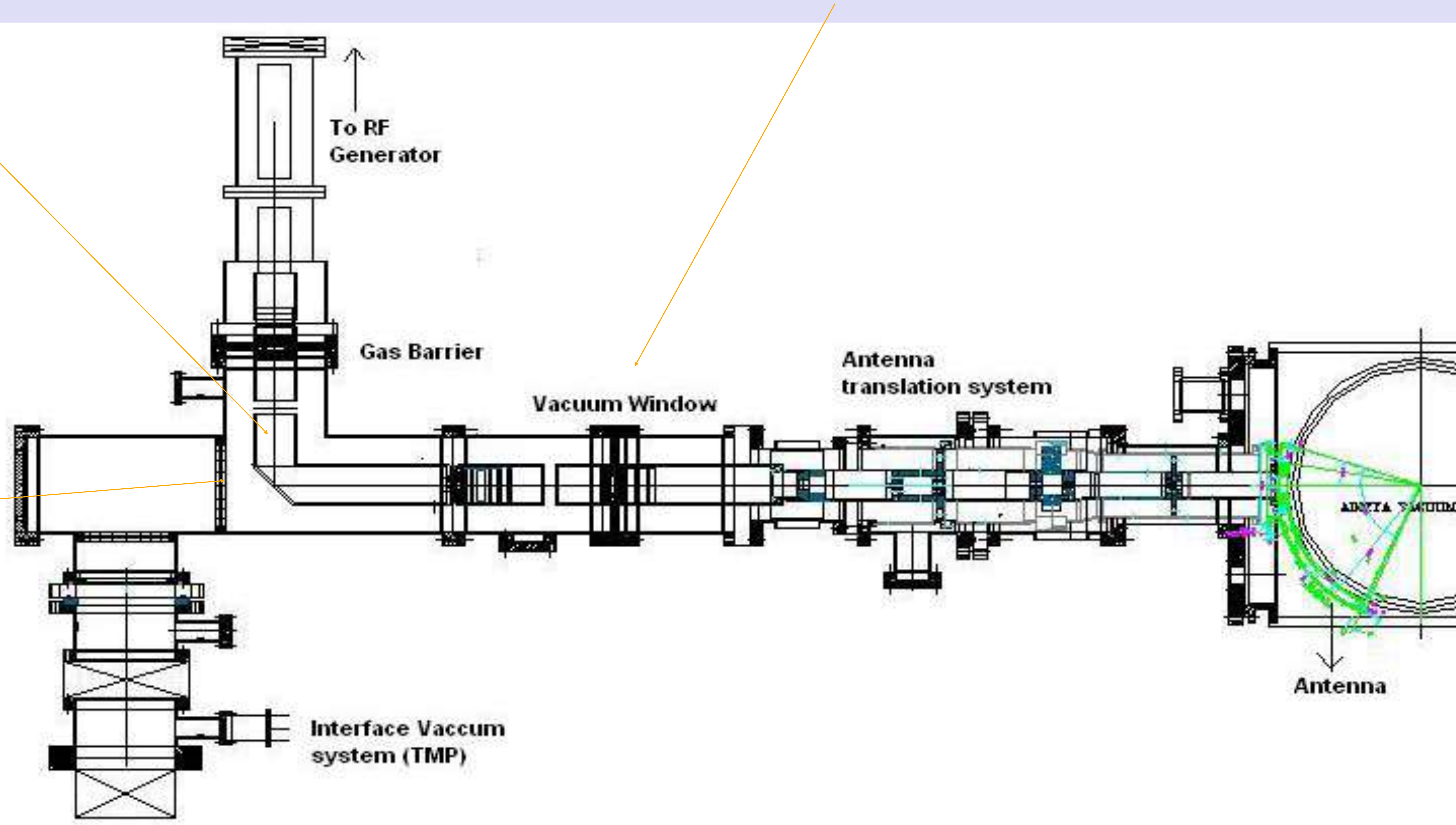
Modified inner conductor



Ceramic vacuum window



Shorting Plunger with finger contact



Recent up-gradations on the system-contd.

- Vacuum window-simple coaxial type

Vacuum isolation by sandwiching a ceramic disk in between inner and outer SS304L flanges.

RF continuity through actual symmetric physical contacts of flanges

Modeled through CST microwave studio

- Transient analysis has been done for different scattering parameters.

Excellent VSWR of less than 1.004 (at 30 MHz)

- Insertion loss less 0.01dB
- Excellent leak tight <1E-9mbar.lit/sec
- 3bar differential pressure handling capability- Gas Barrier

Tested for voltage handling capability at PD facility-24kV pk (sharp edges removed)

Tested for high RF power upto 80kW

Why vacuum window?

ICRH Antenna Details

Antenna specifications

length (cm): 30 cm
number of straps: 1
strap width (cm): 10.0
Distance between plasma and Faraday shield (cm)
(counted from scrape-off edge): approx.1.0 cm from limiter
Distance between plasma and antenna (cm): 3.5 cm from limiter
(counted from scrape-off edge)
Distance between plasma and wall (cm): 5.8 cm from limiter
(counted from scrape-off edge)

Material: SS304L with graphite tiles

length (cm): 30 cm

number of straps: 1

strap width (cm): 10.0

Distance between plasma and Faraday shield (cm): 1.0 cm

Distance between plasma and antenna (cm): 3.5 cm

Distance between plasma and wall (cm): 5.8 cm from limiter

Data Acquisition and Control System (VME)

Interlocks:

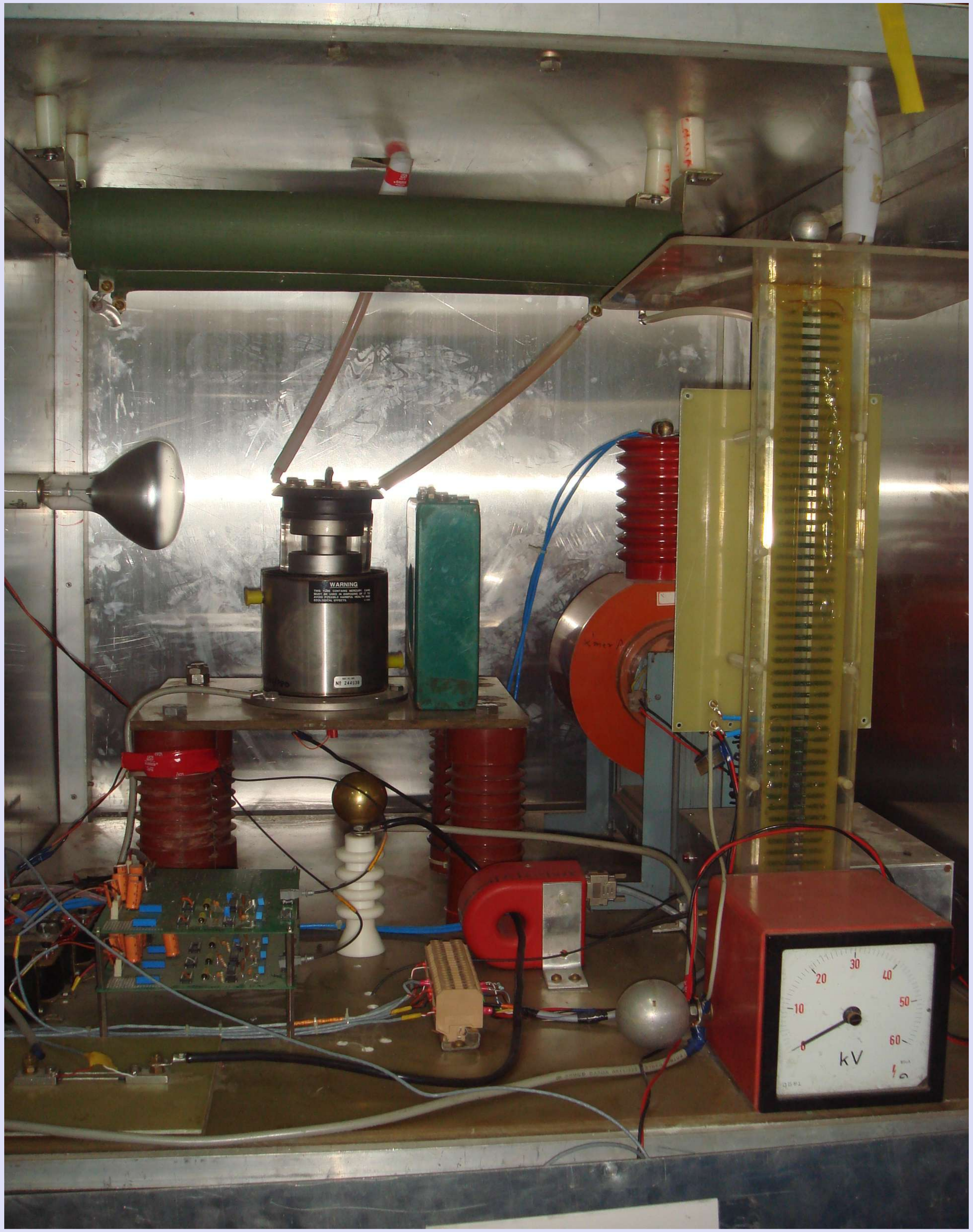
Fast interlocks executed within 10 μs:

- Over voltage, over current, critical dI/dt, Arc, $P_{\mu RF}$ etc

Slow interlocks executed within 50ms range:

- Cooling – pressure and flow, filament power, Over voltage

NL8900 Ignitron Crowbar System



Testing of Individual Sub-systems

- Testing of RF generator with dummy load at high power
- Testing of the generator and transmission line up to vacuum interface
- Testing and conditioning of vacuum interface
- Matching of the antenna impedance with load impedance
- Testing and conditioning of antenna for radiation in vacuum
- Antenna radiating in plasma with minimum reflections

Preliminary Experiments Done

- **ICRH Heating at different RF power levels varying from 5 kW to 85 kW for a duration of 7-10 ms.**
- Bt=0.75 T, gas: H_2, P: 3-5e-5 torr, I_p: 70-90 kA, t: 60-90 ms

  No. of plasma shots: 109

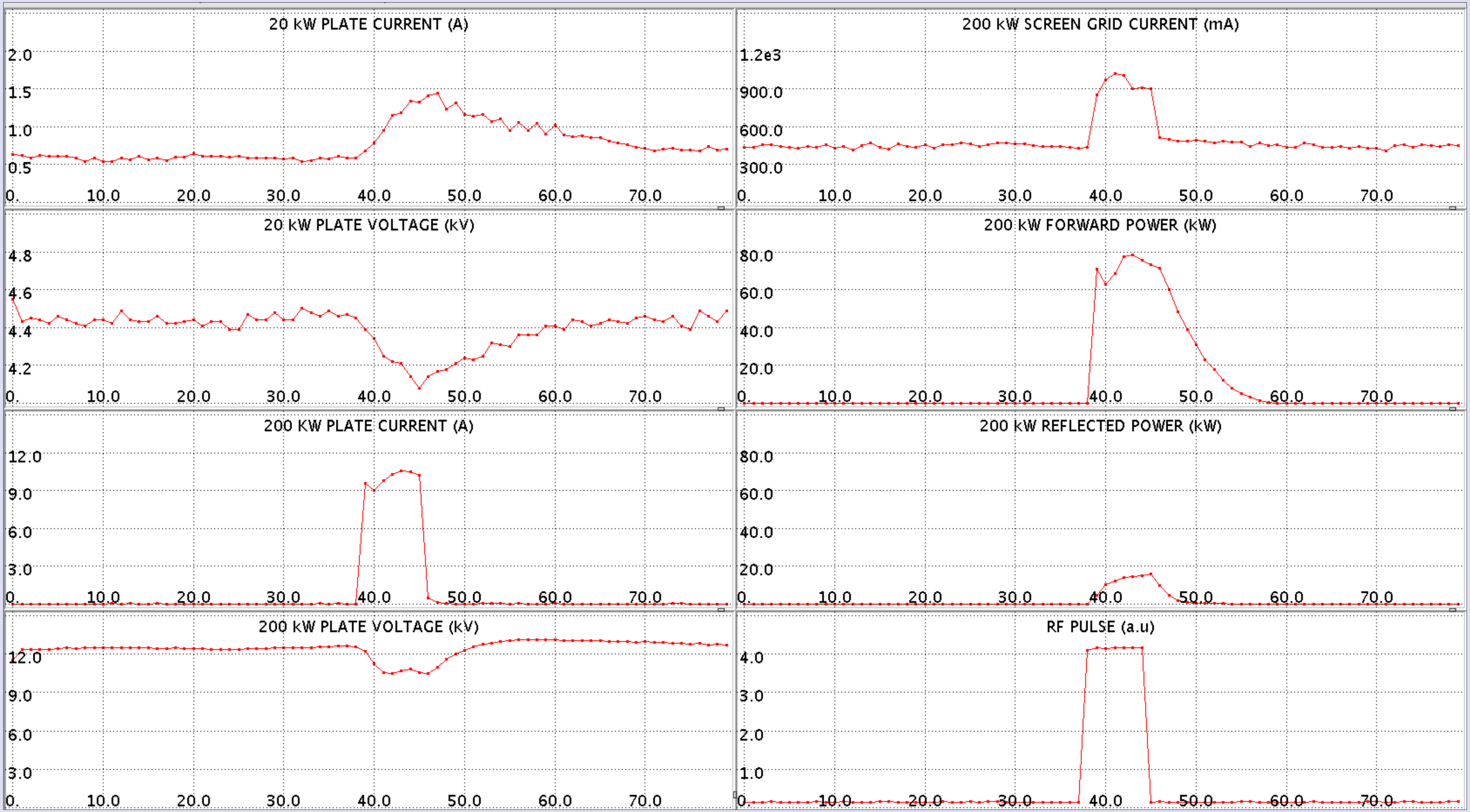
  No. of shots with rf input power: 27

  Heating observed: in almost all shots

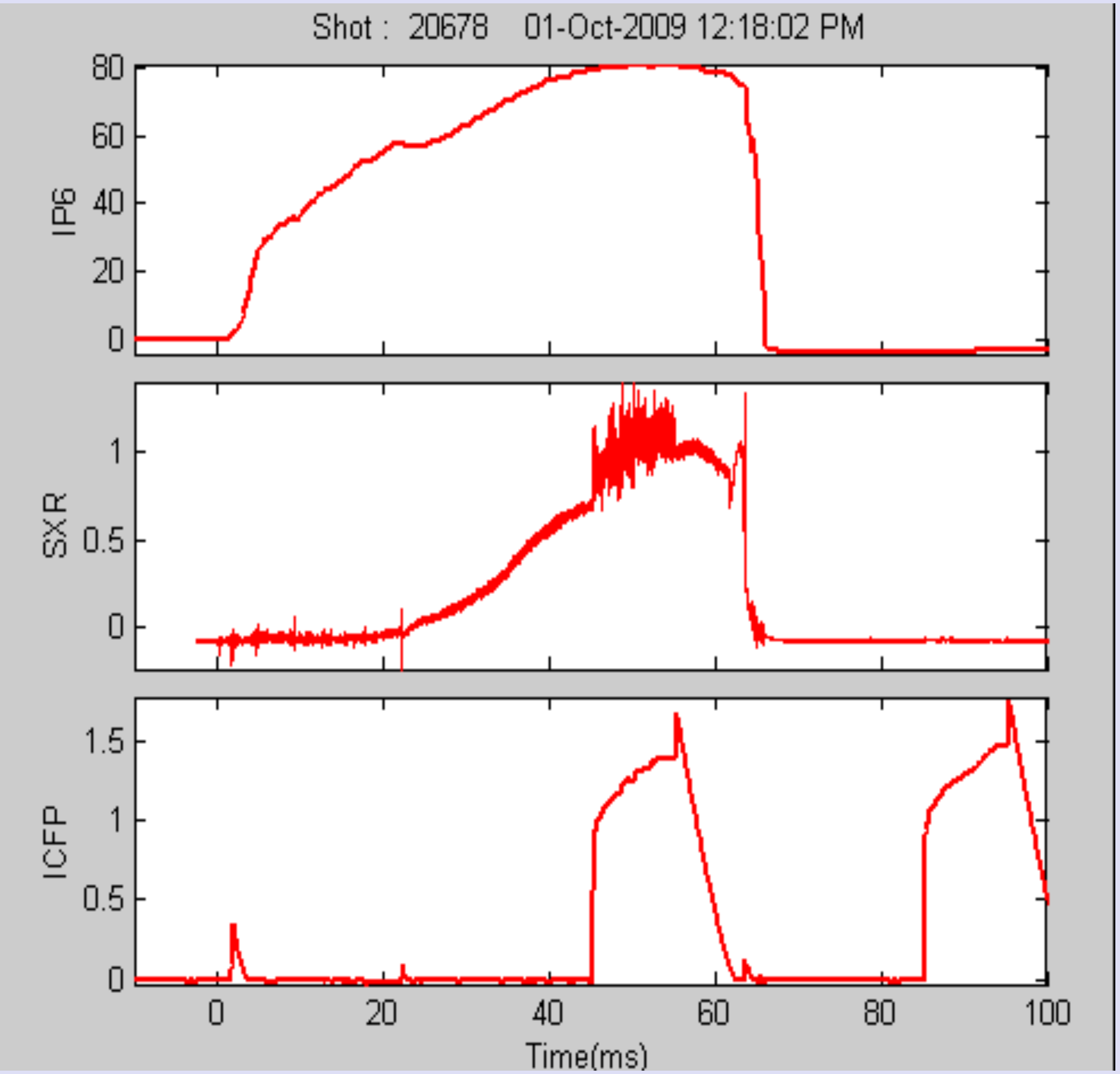
- **Effect of gas puff on antenna-plasma coupling**

  Effect observed : decrease in reflected power .

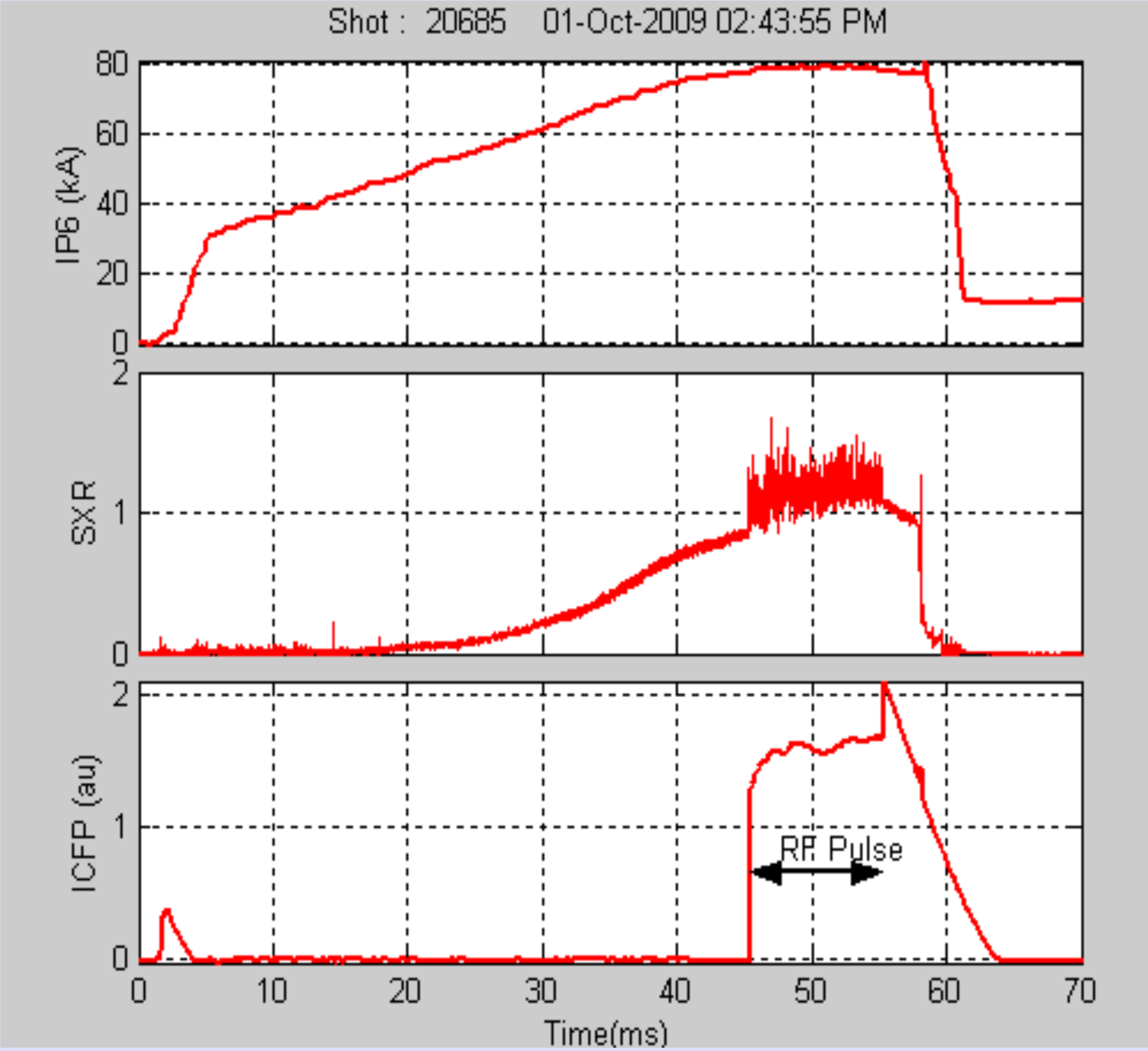
A typical RF pulse and other signals acquired by DAC system at RF Generator



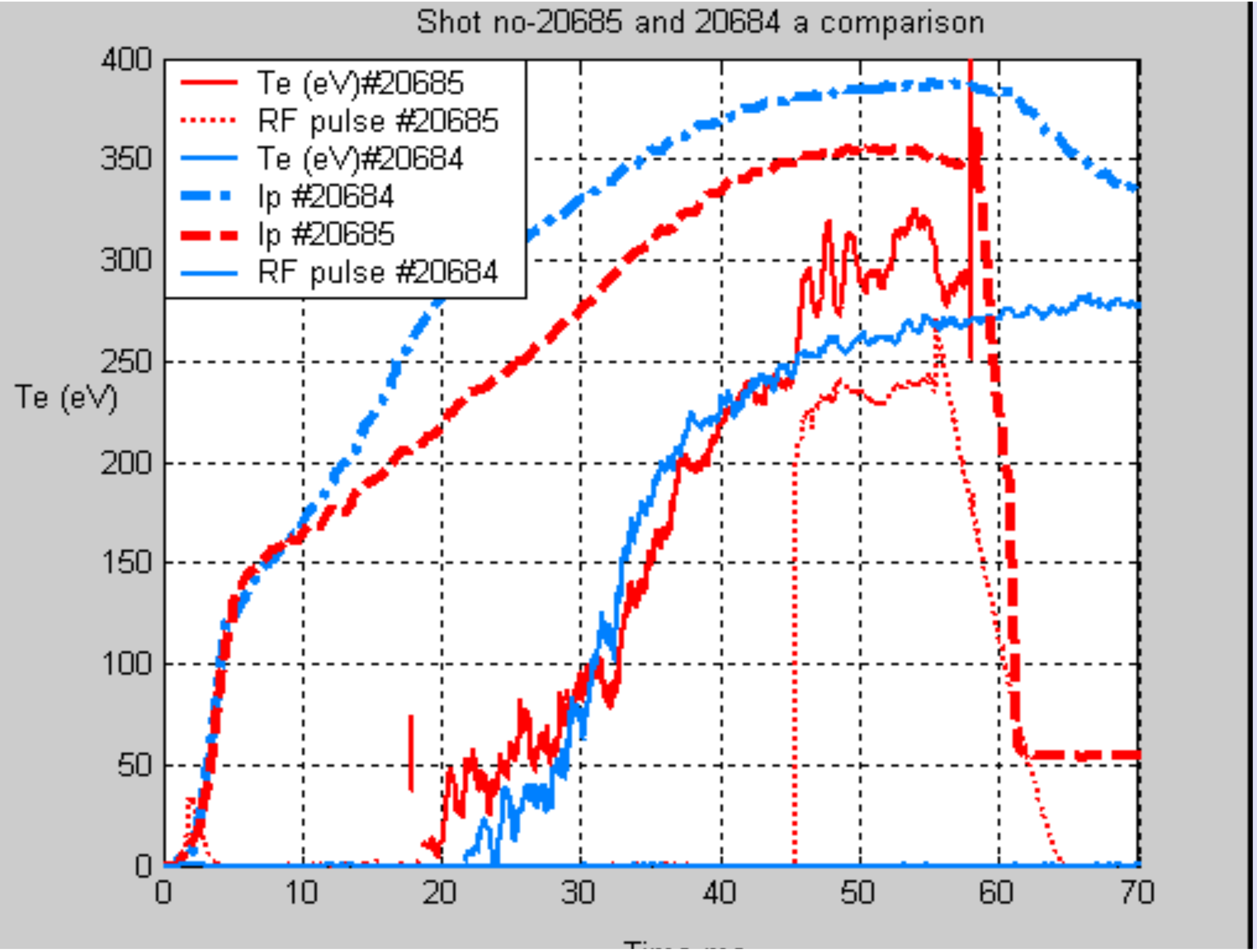
Two RF pulses: No pick-up



Soft X-ray signal with RF



Soft X-ray Signal



The temporal variation of electron temperature for shot no #20685 shows that with RF pulse, the temperature increases from 200eV to 300eV during the duration of RF pulse (45-55ms), whereas a similar shot without RF (#20684) shows no change in temperature during 45-55 ms

Electron Temperature from Soft-X ray Data

figure 2. (a) Measured electron temperature (T_e) time evolution from SXR diagnostics shows immediate rise in temperature with RF power. Chord average electron density measured from interferometer shows very marginal increase in density during RF pulse. The RF pulse duration is from 45ms-55ms time. The plasma discharges obtained are of 60msec duration with and without RF and the disruption at 58msec time is not related to RF. (b) Increase in electron temperature shows a linear relationship with input RF power. Chord average electron density remains constant in all these discharges

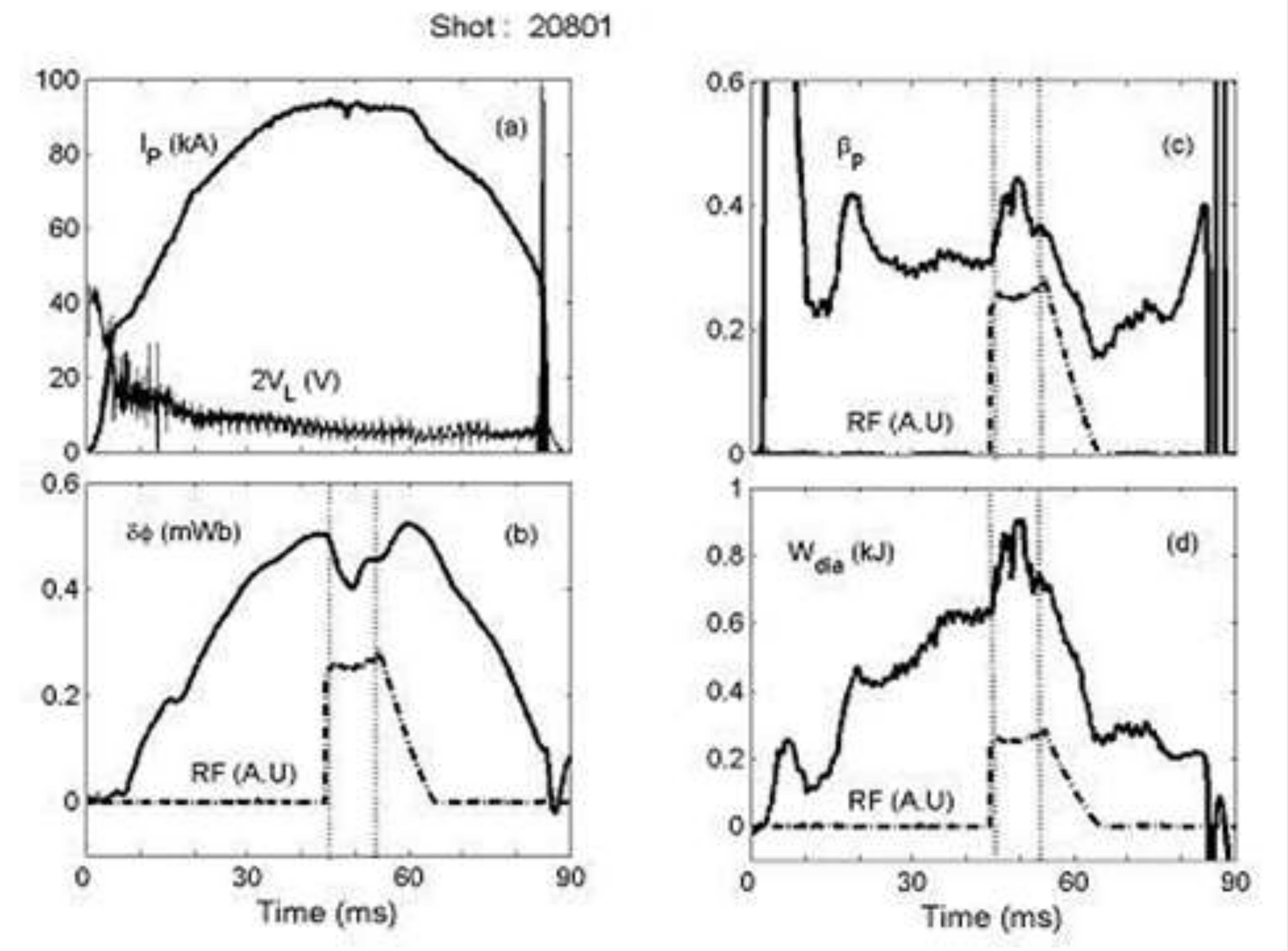


Figure 3. (a) Plasma current and loop voltage in ICRF heated plasma discharge,
(b) diamagnetic flux, (c) poloidal beta, and (d) stored diamagnetic energy

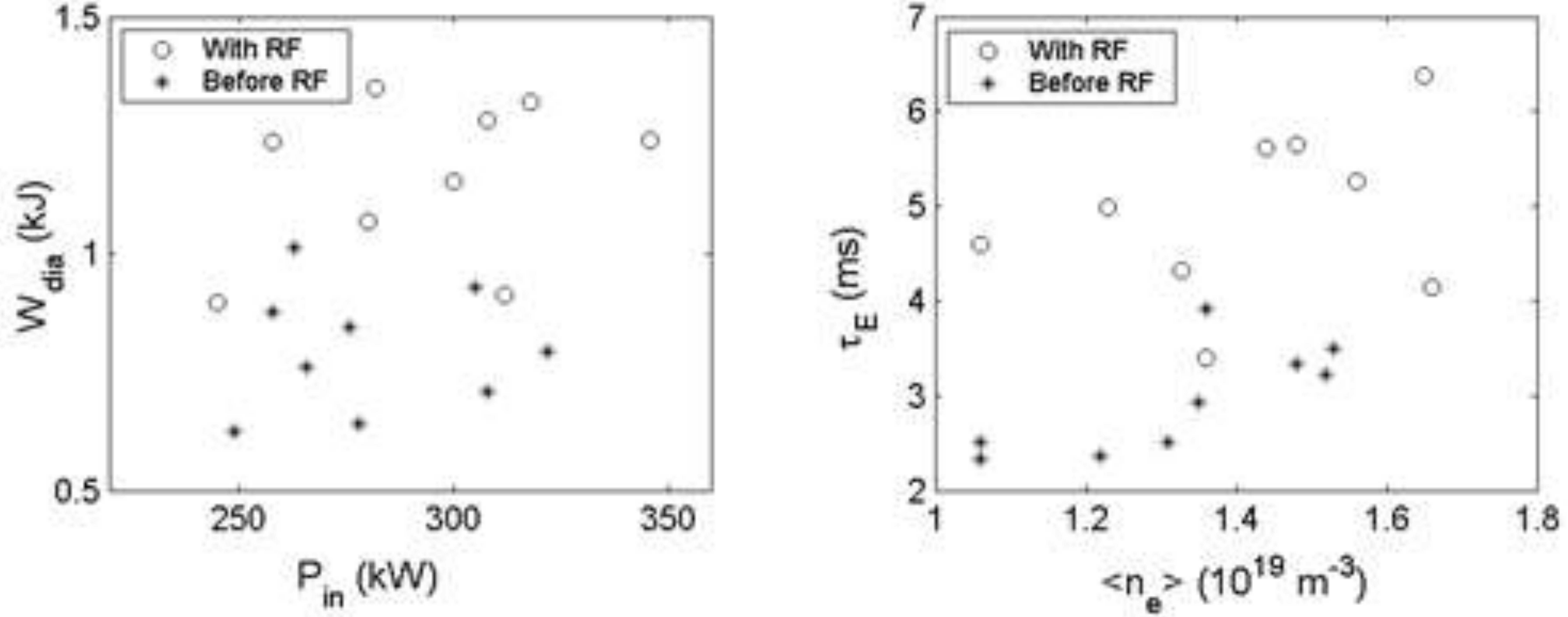
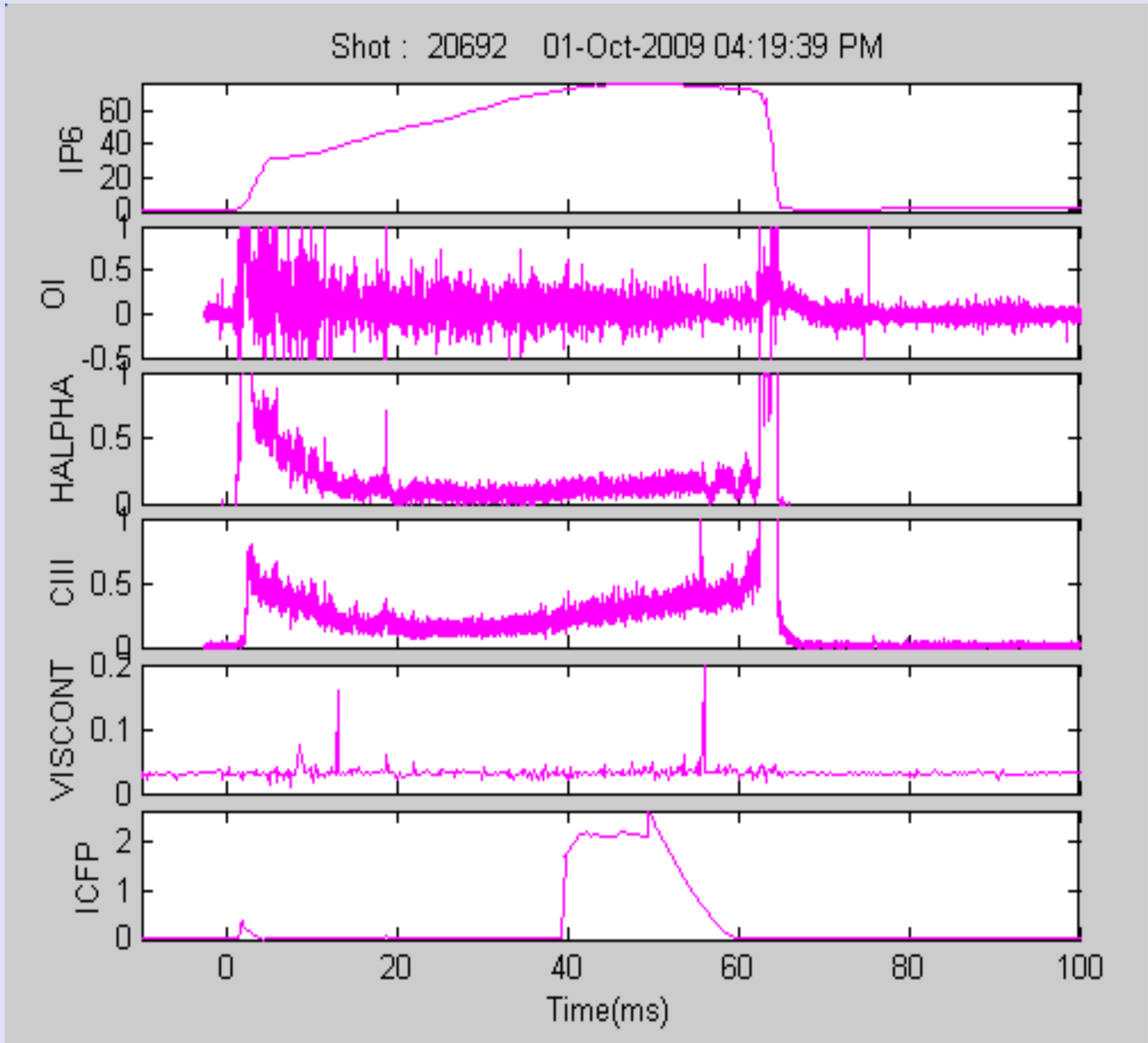


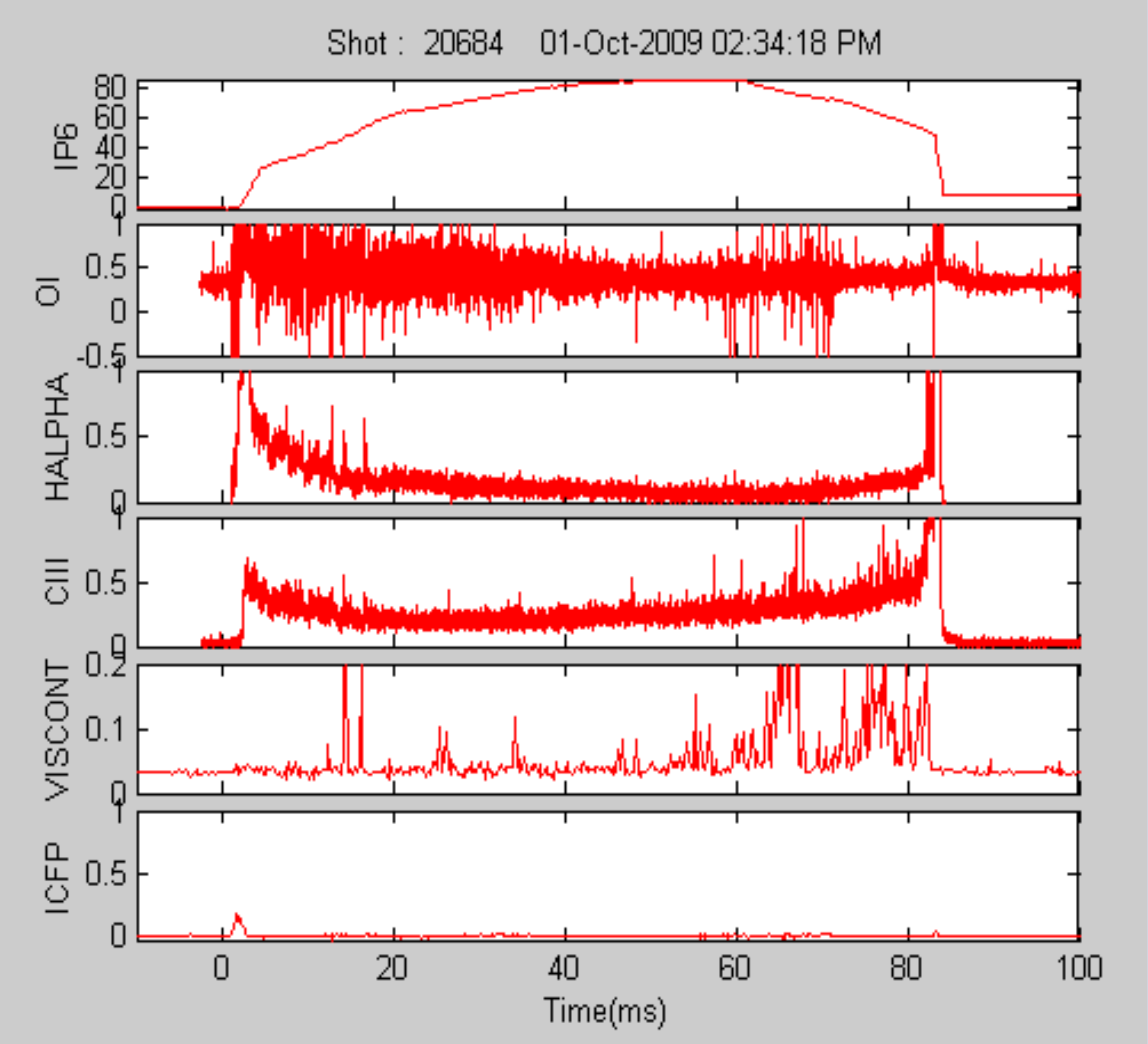
Figure a) Stored energy measured with diamagnetic loop, , as a function of absorbed power ,

(b) The energy confinement time as a function of chord-averaged plasma density , measured by microwave interferometer.

Impurity Signals Detected by Spectroscopy Diagnostics

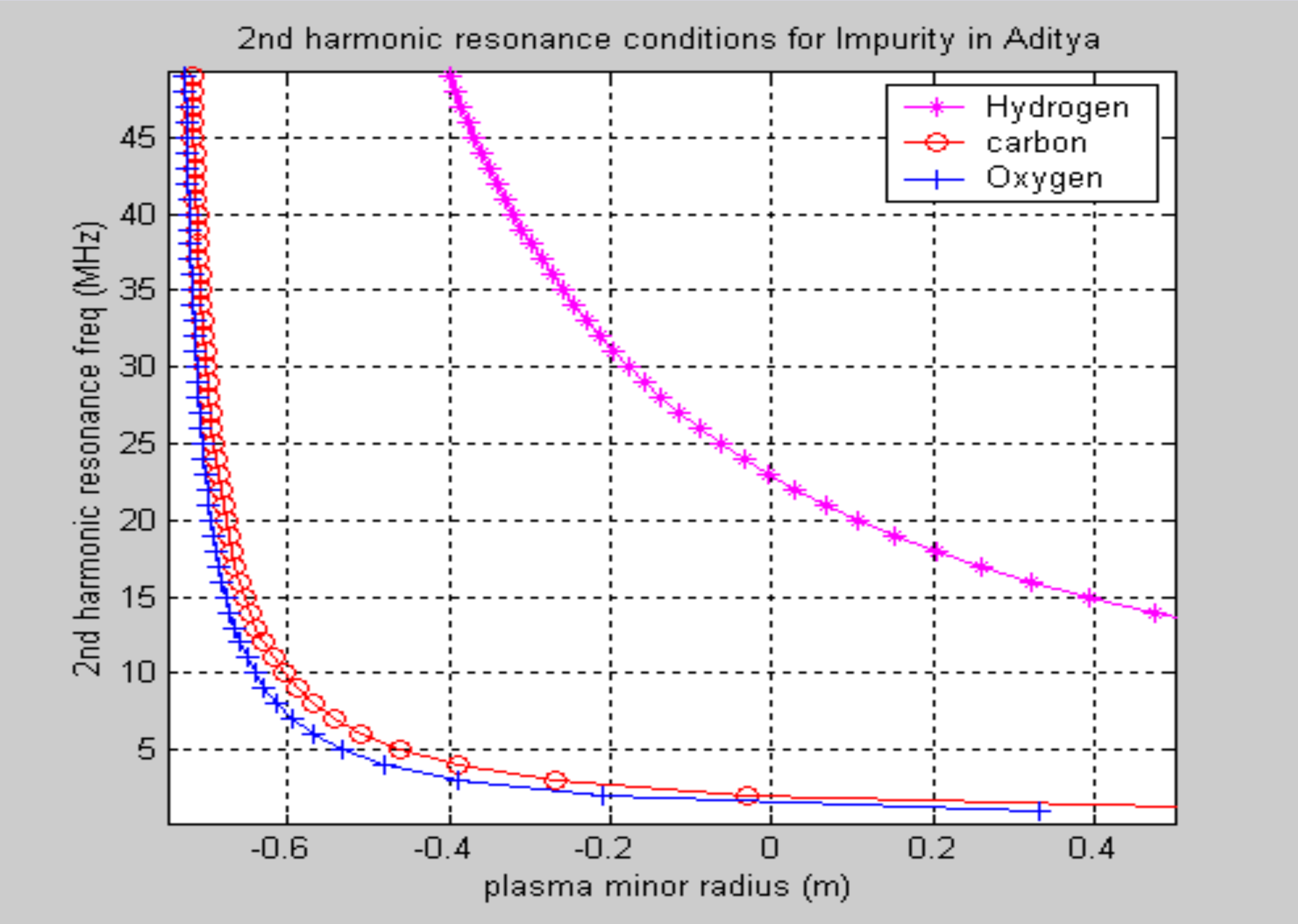


With rf power



Without rf power

Is there a direct impurity heating?



There is no resonance layer for c and o

Type of Heating ?

Possibilities:

Only electron heating
Only ion heating
First electron heating and then ion heating
First ion heating and then electron heating

(A) First ion heating and then electron heating

Electron heating from energy transfer from energetic ions through collisional process.

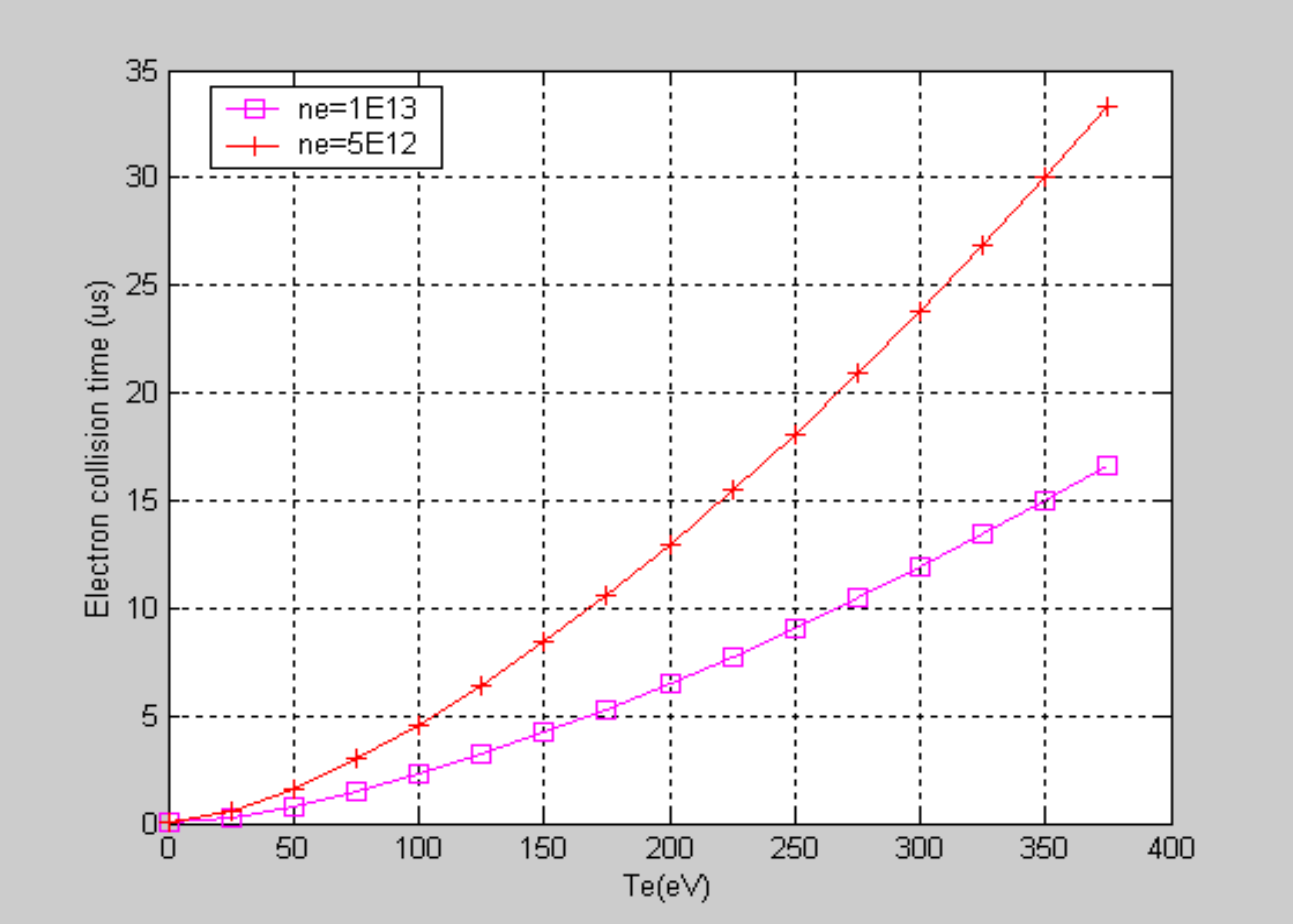
- Typical time scale of fast ion slowing down on electrons (~18msec for present experiment).
- Probably not happening

B. Direct Electron Heating:

- Typical time scale is electron electron collision time.
- Direct electron heating is possible through NLD and TTMP
- A linear dependence of electron temperature with RF power (similar to that observed on JET).
- This should also give rise to ion heating

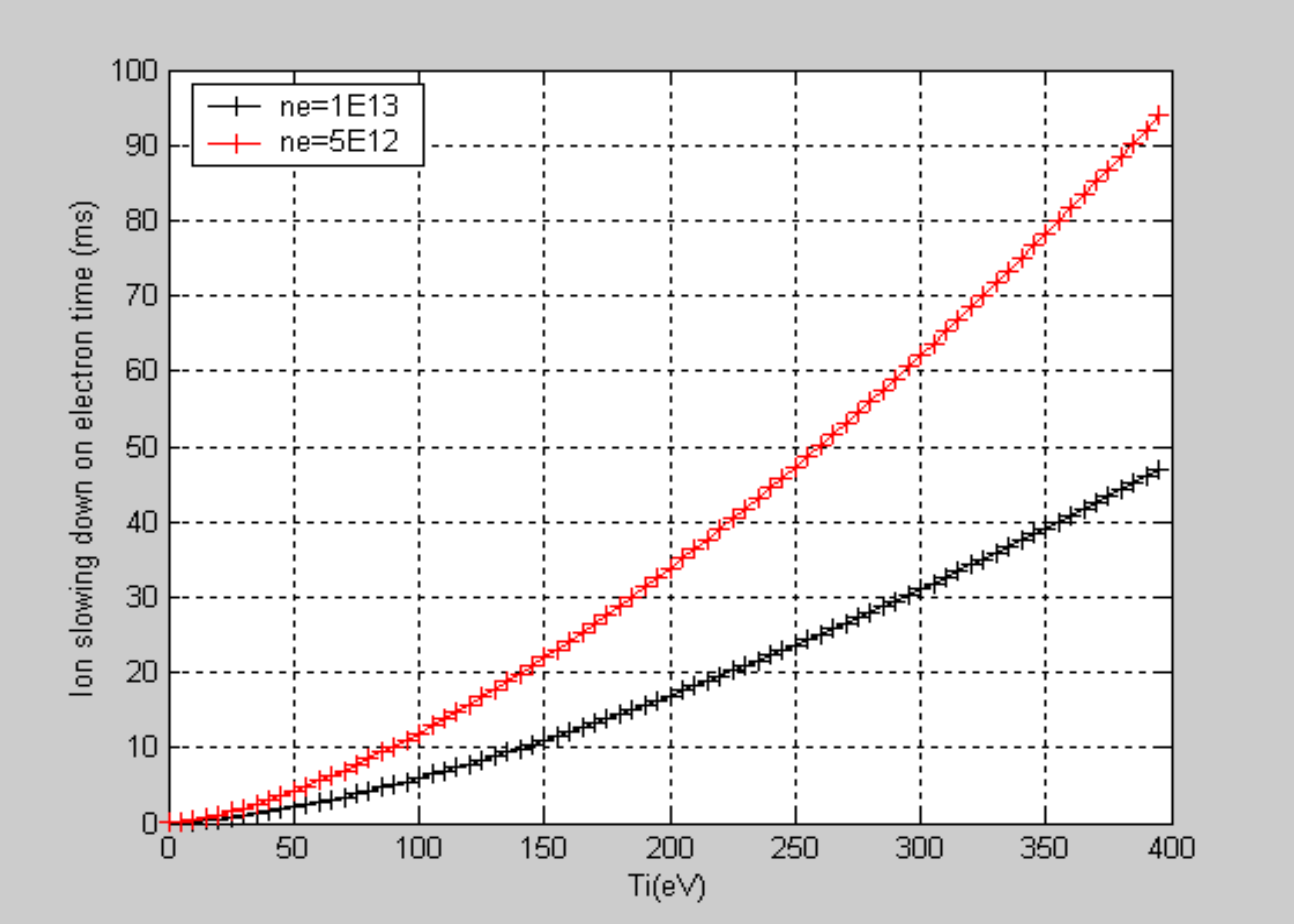
A combination of both heating method is also seen in earlier experiments. (Eriksson et al. NF V-29, p875 (1989))

In current experiment, a combination of ion heating through cyclotron resonance and direct electron heating might be happening.



Electron collision frequency

$$\nu_e = 2.91 \times 10^{-6} n_e \ln \Lambda T_e^{-3/2} \sec^{-1}$$



Ion slowing down time on electron

$$\tau_i = \frac{3\sqrt{m_i}(kT_i)^{3/2}}{4\sqrt{\pi}n\,\lambda e^4} = 2.09\times 10^7\frac{T_i{}^{3/2}}{n\lambda}\mu^{1/2}\ \mathrm{sec.}$$

Summary of preliminary experiments

- The two RF pulses given during and after the plasma shot shows that there is no RF pick-up in most of the diagnostics signals

- Soft X-ray diagnostics shows that there is an immediate increase of 80-100 eV temperature rise during RF pulse of 70-80 kW power and shows that electron heating is taking place.

- Diamagnetic loop signal shows that there is an increase in internal energy (0.6-1kJ to 1-1.3 kJ) of the plasma during rf pulses indicating that due to heating the stored energy of plasma increases after thermalization.

- The estimated energy confinement time 2-4 ms in Ohmic phase and 3-6 ms during rf heating phase.

Although we have not measured ion temperature, the literature and simulation supports the idea of partial electron and ion heating. (to be established)

- The spectroscopy diagnostics show that the impurity level keeps on increasing with time and do not show extra increase in impurities during RF pulse, indicates that the possibility of impurity heating is less.

- Microwave interferometer signal shows that there is slight increase in the plasma density during RF pulse which is reported on many tokamaks.

- Microwave interferometer signal also shows enhancement in amplitude of MHD activities during RF pulse

Pre-ionization and current ramp-up experiments on Aditya

PI on different tokamaks

- TEXTOR
- ICRF plasma production and its assisted low voltage ohmic start up have been demonstrated in TEXTOR-94 for the first time. In this experiment conventional double loop antenna is used to produce Helium plasma with line averaged density up to ~3×10^{12}cm^{-3} in presence of toroidal magnetic field of B_T =0.36 – 2.24T only.
- RF plasma density is found to be proportional to base gas pressure and RF power.
- The electron temperature deduced from spectroscopic and probe measurements is in the range of 10-40eV.

- In this experiment, reproducible low voltage ohmic discharges are obtained in a narrow window of pressure.
- Interestingly without ICRF assistance no start up is achieved on application of low loop voltage.
- The plasma production through ICRF is believed to be mainly because of absorption of RF wave energy by electrons in presence of toroidal magnetic field.
- The RF electric field parallel to magnetic field may be responsible for this neutral gas breakdown and initial plasma build up. The parallel electric field may be generated between antenna central strap and sidewall of the antenna.

JFT-2M

- A 12-strap combline ICRF antenna is used to study pre-ionization on JFT-2M. The minimum power at which plasma is produced is ~15kW at B_T=2.2T and fill pressure ~ 7.5x10^{-6} torr. The plasma produced by ICRF antenna is found to be localized around the antenna and at outside lower quadrant. Successful start up and current ramp up is also achieved when this ICRF plasma is applied to low loop voltage.

TORE SUPRA

In TORE SUPRA, two ICRF antennas are used to produce plasma and study its wall conditioning efficiency in presence of permanent toroidal magnetic field of 3.8T.

ICRF power is applied in the range of 20-340kW and electron density obtained is in the range of 1-5 x 10^{11} cm^{-3}.

ICRF Preionization on different Tokamaks

JET:

ICRF 130-245kW @34MHz (0.5-4 sec pulse)

He4 fill pressure= ~5E-5 torr

Bt =1.85-2.25T

Gas breakdown time ~50-60ms

Breakdown time is independent of machine size (for power & freq constant)

ASDEX:

He P ~7E-5 to 6E-4 torr

Prf = 3-120kW @30MHz

Bt =1-2T

Pulse 0.3- 4sec

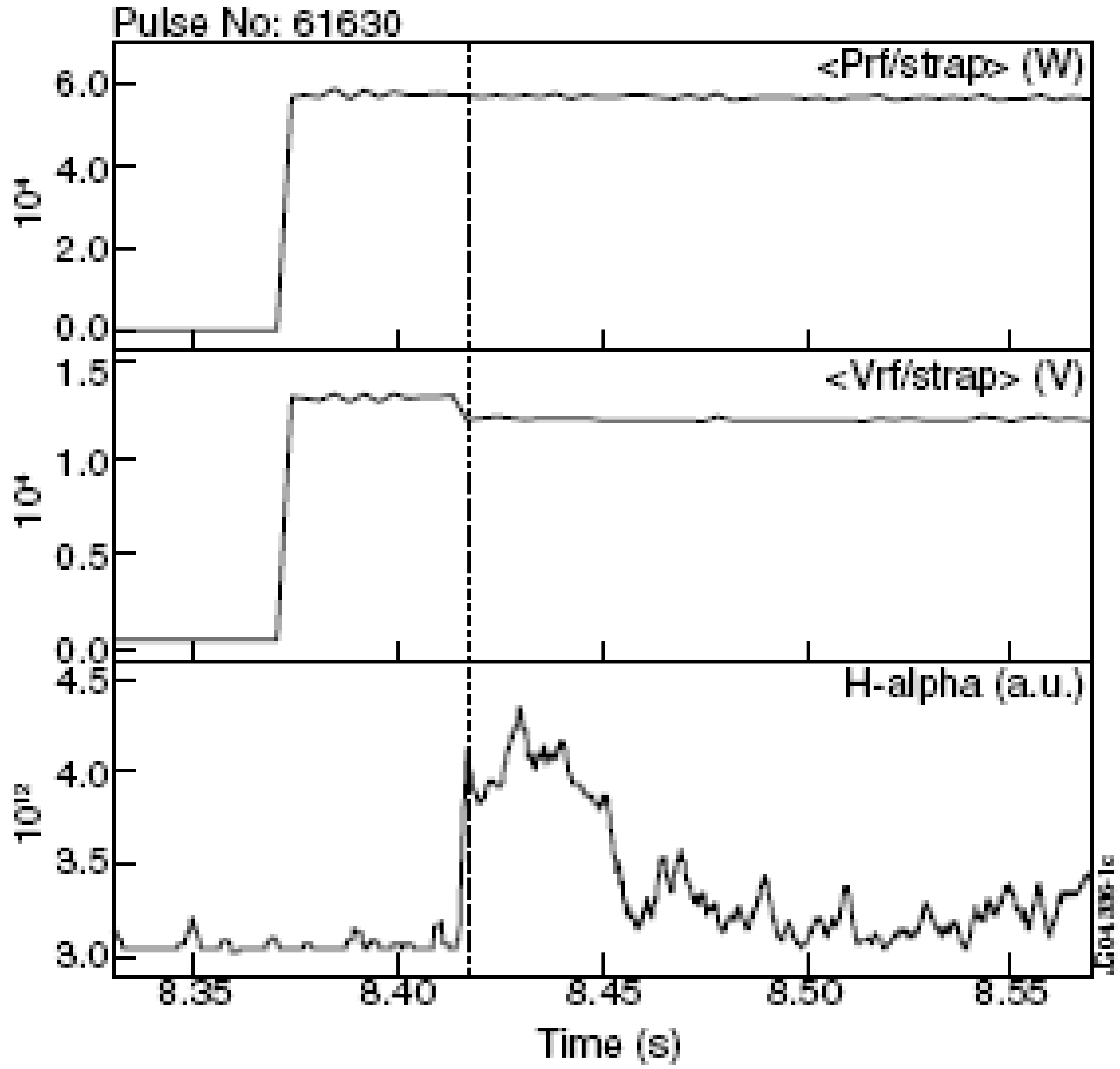


Figure 1: The transition from the neutral gas breakdown phase to the ICRF discharge phase in JET.

Expts. on Antenna Test Facility

- Antenna test facility was upgraded in terms of magnetic field coils, magnet power supply, pressure gauges, flow meter, cooling system, compressor for gate valve, probes, RF power etc.
- **First Pre-ionization experiment is** carried out using ion Bernstein wave antenna to prove that pre-ionization in Aditya is possible
- Pressure-10**-3 to 10**-5 mBar
- RF power - 1 to 15 kW, Frequency: 36.5 MHz
- This gave us a confidence to do pre-ionization experiment on Aditya

Pre-ionization Experiments on Aditya

- RF Power : 19 kW to140 kW at 24.8 MHz
- B Toroidal : 0.075 T- 0.825 T
- Antenna : Fast wave, Poloidal type
- Pressure : 10**-3 to 10**-5 torr
- Current Ramp up: up to 90 kA, 90 ms

Experiments done on Aditya

- In **first phase** only RF breakdown plasma is produced at 24.8 MHz using a fast wave antenna without toroidal magnetic field and loop voltage.
- In this phase it was observed that the breakdown is produced in antenna box in a wide range of pressures between 10^{-3} mBarr to 5×10^{-5} mBarr.
- However the position of breakdown changes with pressure.

In **second phase**, RF plasma is produced at 24.8 MHz using a fast wave antenna, toroidal magnetic field and the developed RF system of 200 kW.

Parameters varied

B Toroidal; 0.075 T to 0.825 T

Pressure: 8x10-4 to 3x10-5 Torr

RF Power: 19 kW to 120 kW

Minimum TF required : 900 Gauss

Minimum RF power required for PI: 19 kW

Figure 1. Time series of (*a*) H_{α} (a.u) (b) Pressure (value x calibration factor 4) (c) ICRF power d) Reflectometry (e) Dia-magnetic loop signal

- In **third phase**, the experiments are carried out with RF power and the full loop voltage of 22 volts. The duration of pre-ionization pulse is from -150 ms with reference to Ohmic loop voltage starting at 0 ms. In this experiment, the over-lapping time of RF power with loop voltage is varied and also the RF power is varied. The adjustment of the vertical field as well as the magnitude, duration and the frequency of the gas puff is varied to have current build up.

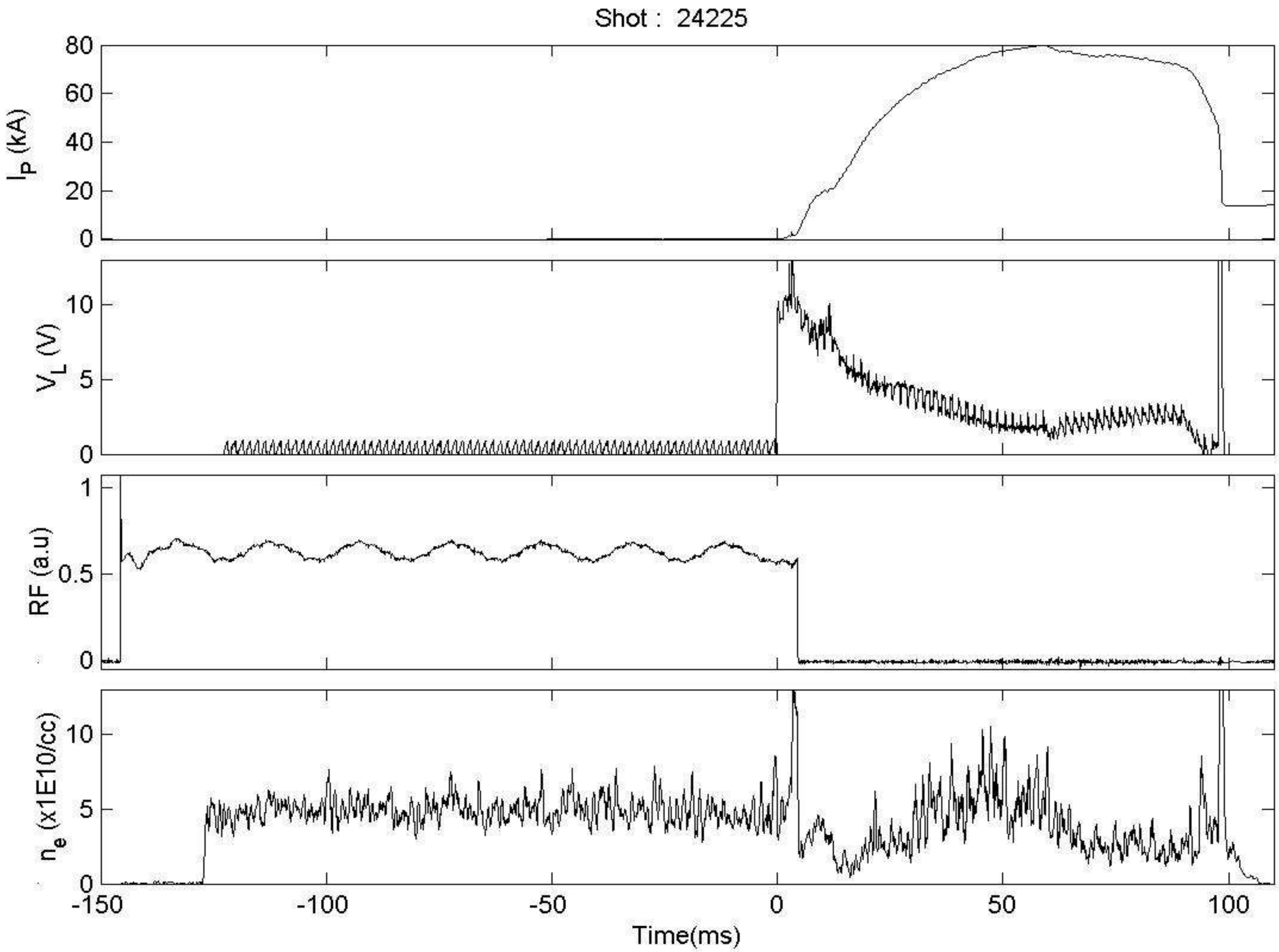
- In **fourth phase** the loop voltage of Ohmic transformer is decreased by decreasing the current through the transformer due to which the available volts-sec also decrease.

- In **fifth phase** the resistors in the ohmic transformer are changed to keep available volt-seconds constant and the current ramp-up experiments are carried out at 22V to 8 volts loop voltage.

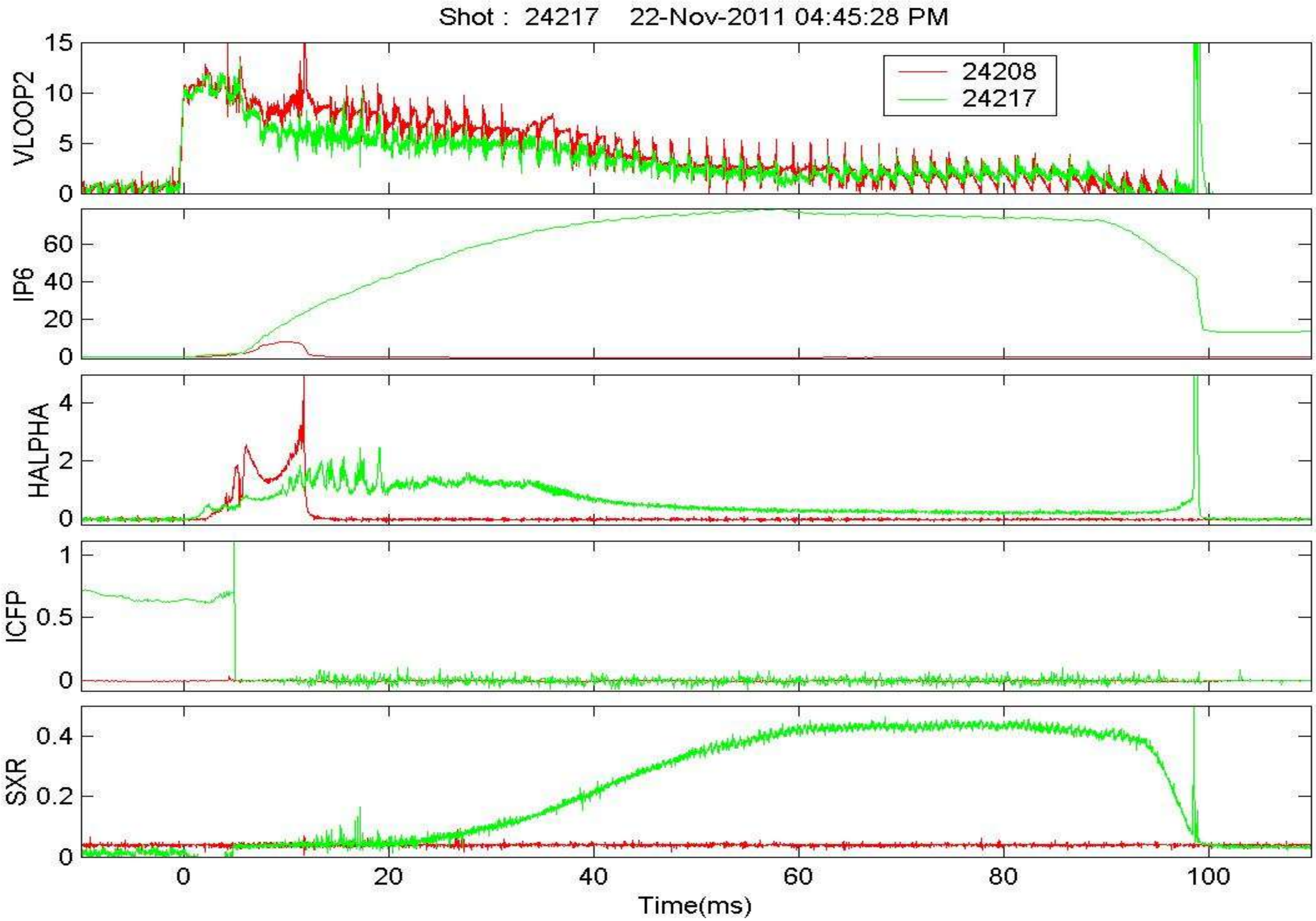
-

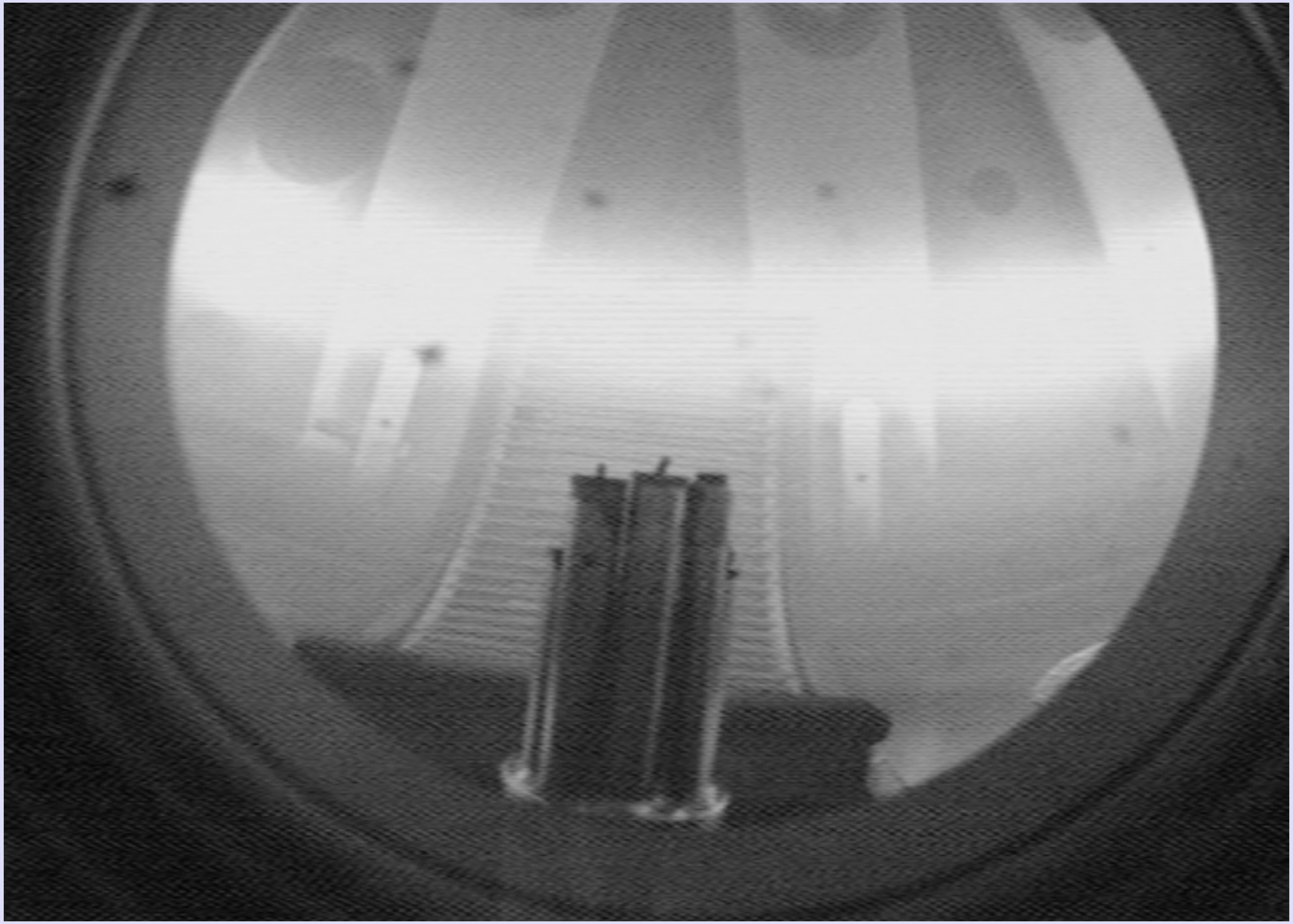
- In **sixth phase** the current build up experiments are carried out at fixed low loop voltage (8volts) at fixed RF power and gas pressure but with a slow rise time.

Current ramp-up at 10 volts using 60 kW RF power

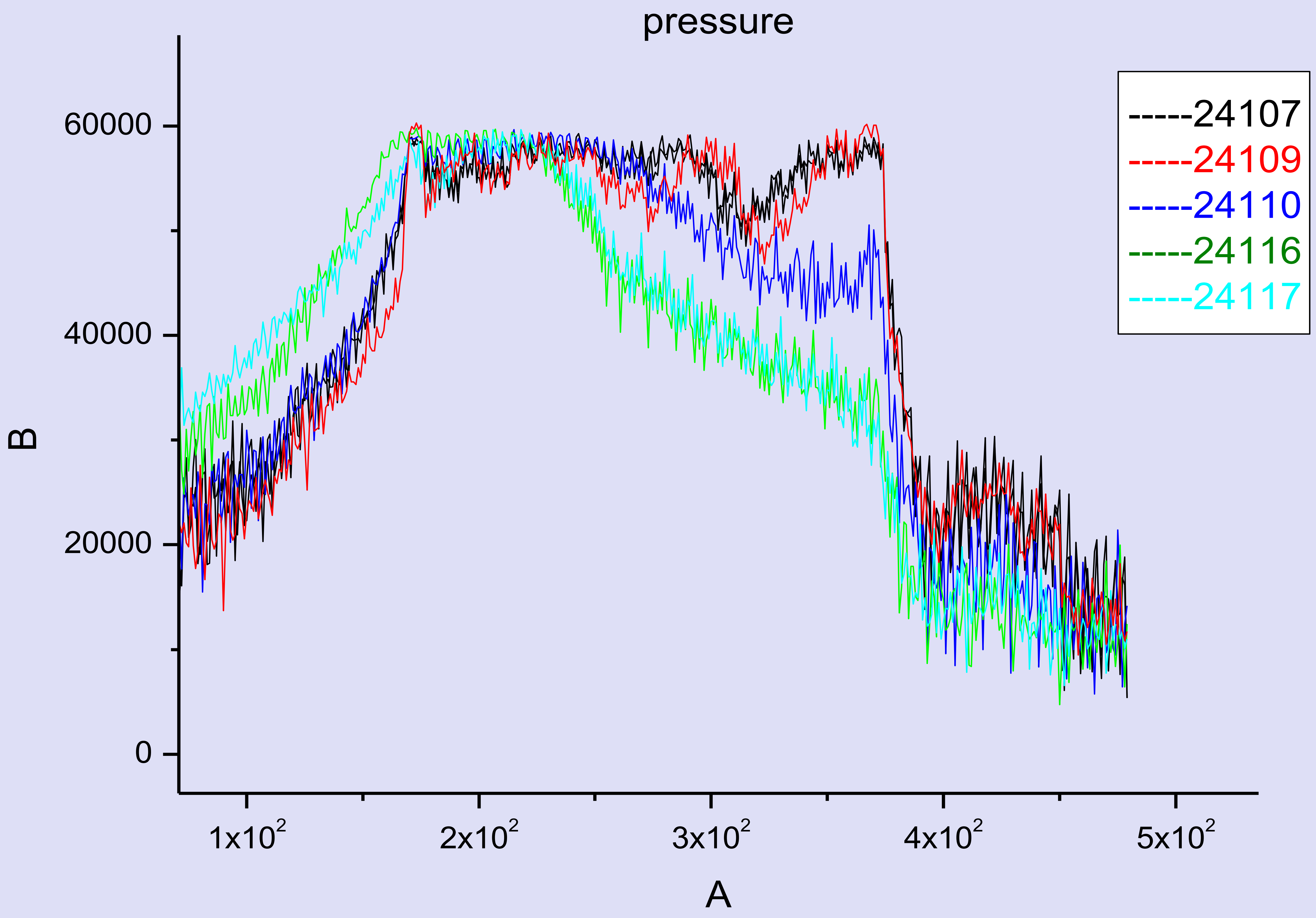


Current ramp-up at 10 volts using 60 kW RF power

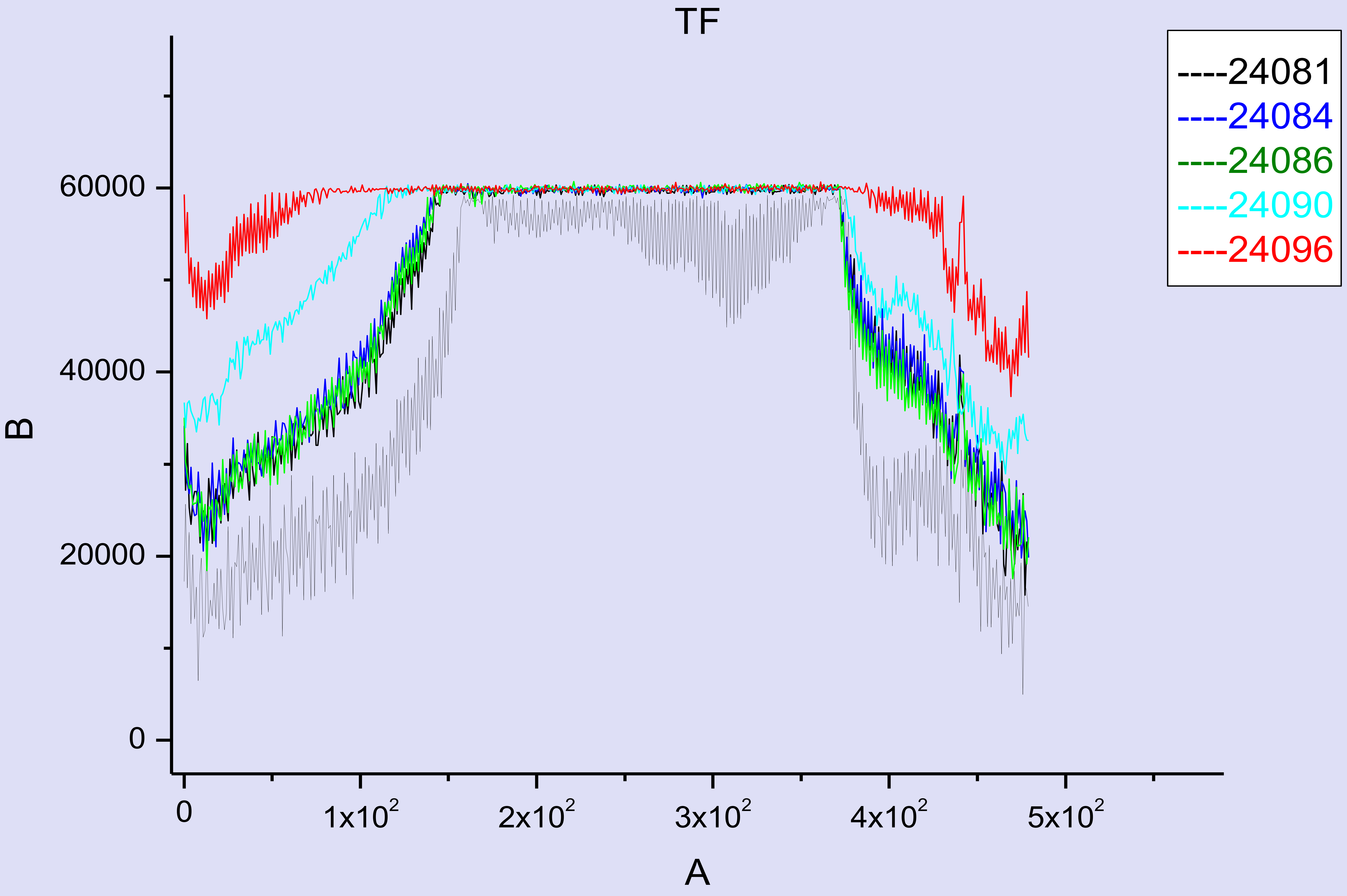




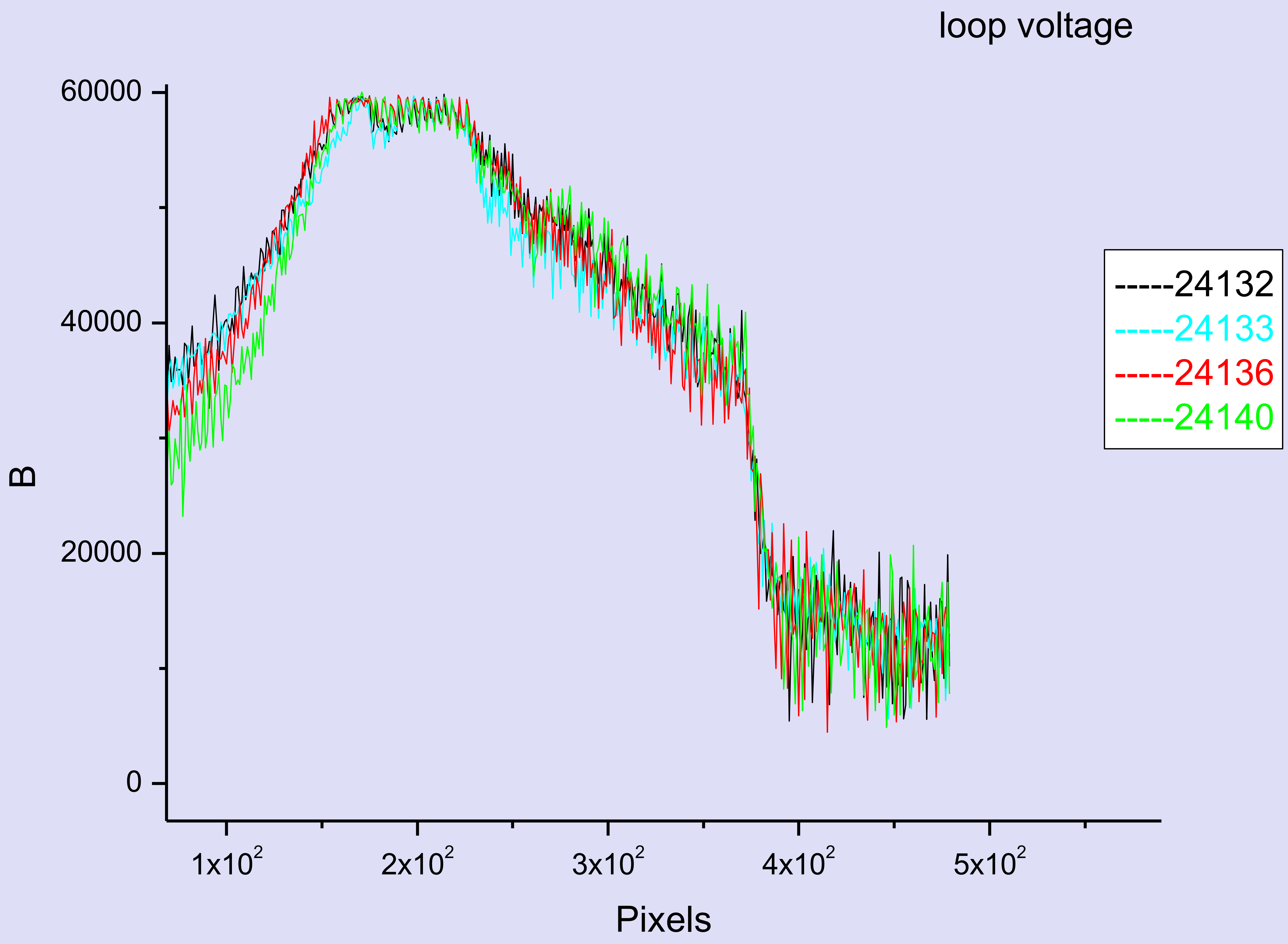
Shot no. 24411 - 4
Vloop - 8 volts, Ip - 66 kA, 85 ms



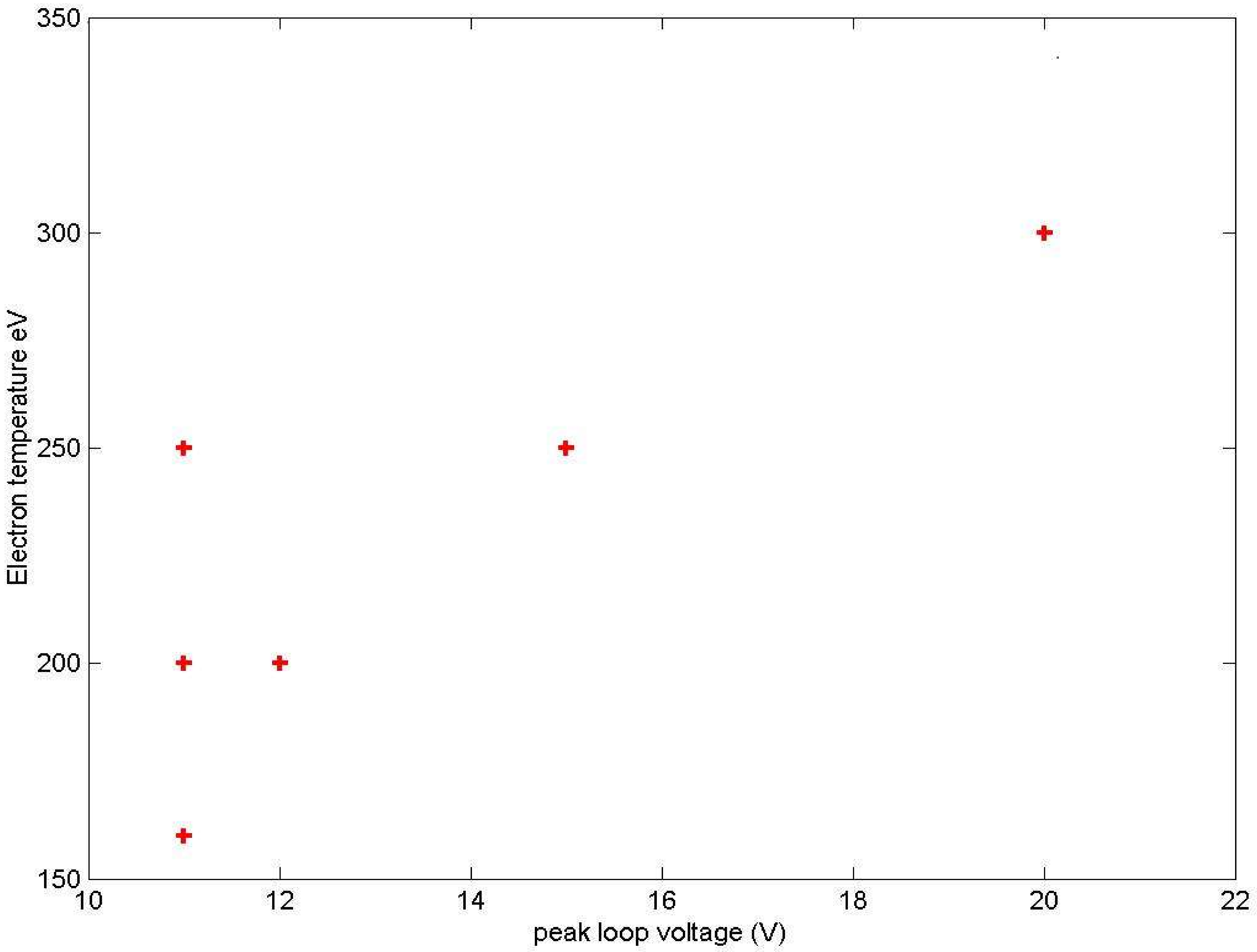
Variation of relative intensity with radial position at different pressures (p: 1.0e-4 – 1.0e-5 mBarr)



Variation of relative intensity with radial position at different magnetic fields
(red: 0.75 T and black: 0.075)



Variation of relative intensity with radial position at different loop voltages (22 V - 8 V)



RF - 80 kW, Variation of Te with loop voltage

Figure : shows the estimated density using reflectometer as a function of toroidal magnetic field (a) and as a function of loop voltage (b)

Figure: (a) The variation of H$_{\alpha}$ signal and delay with magnetic field, (b) variation of H$_{\alpha}$ signal and delay with pressure (b) (c), and the variation of delay and H$_{\alpha}$ signal with RF power (-9.6 dB$_m$ =50 kW and -8 dB$_m$ = 80 kW).

Conclusions of PI Experiment

The pre-ionization experiments are carried out in tokamak Aditya at different loop voltages, different magnetic fields to vary the position of the resonance layer and also in the wide range of pressure range for the tokamak operation in ion cyclotron frequency range.

It is observed that in presence of resonance layer the pre-ionization plasma mainly forms between antenna and the resonance layer and with proper vertical field and gas puff the current ramp up is possible even at lower loop voltages.

Although we have produced pre-ionization plasma under non-resonant conditions we are yet to produce current ramp-up which is in progress

It is expected that these results will be useful for the steady state operation of the tokamak SST-1 where the available loop voltage is less due to penetration depth of the cryostat.

There is no plasma below 0.09 T and also below 20 kW RF power

ICRH System on SST-1

Physics Experiments planned for First Phase

- Second Harmonic Heating
- using single transmission line with two antennas
- using two transmission lines with four antennas
- 0,0 phasing
- 0, 180 phasing
- Pre-ionization Experiment
- Glow Discharge Cleaning/wall conditioning
- successful on TEXTOR, ASDEX, Tore Supra, HT7 and JET

RF Power Requirements for SST-1

- **ICRH**
- 1 MW, 45.6 MHz (1.5 T Operation)
- 1 MW, 91.2 MHz (3.0 T operation)
- 1 MW, 20-30 MHz (minority heating at 3.0 T)

Antenna Details

- Antenna is designed using standard codes
- Optimised parameters
- Length –40 cm
- Width 8 cm
- Thickness- 0.7 cm
- Strip separation- 17 cm
- Resistance-1-4 Ohm
- Reactance-10-50 Ohm

SST-1 Antenna

Made up of SS304L. One antenna box contains two antennae. Each antenna is shorted strip-line. Each antenna will carry RF power of 250kW.

Antenna is shielded from the plasma by 30 no. of Faraday shields in a single column.

Graphite tiles has to be fixed on all four sides of the box from inside

Cooling connections are done during assembly

Block diagram & brief details of ICRH system on SST-1

RF GEN VME

Pre-Trigger

Osc 45.6 MHz

LPA

2kW

20 kW

80 kW

1.5 MW

DC Break

SST-1 RF- VME

SST-1 Central Control room

Dummy Load

Hybrid Coupler

SPDT Switch

Dummy Load

Opto-isolator

RF ground

Course Tuner

VVC

PS

STUB

Voltage probes, FP, RP

Voltage probes, FP, RP

PS

STUB

VVC

Diagnostics electronics

TMP

Automatic Matching Network

Vacuum Window

Bellow: Antenna Movement

Prematching Stub

TMP

DC break
Ground isolation

ANT I, II

ANT III, IV

RF edge diagnostics for antenna

Interface (8 inch Tx line in Vacuum)

9 inch Tx line

Electronic signal

Transmission Line and Matching System

- Complete transmission line from 1.5 MW stage up to SST-1 is installed.
- It consists of two phase shifters, two stubs and vacuum variable capacitors, probe sections etc. and is installed.
- It is tested up to 40 kW level
- It is designed for 1.5 MW level with forced air cooling as well as pressurization
- Tx line with forced air at 3 barr-testing is in progress
- However our calculations show that cooling is not required up to 700 kW power for 3 seconds. Hence when power and vacuum vessel are available, then it will be tested for cooling and pressurization in presence of RF.

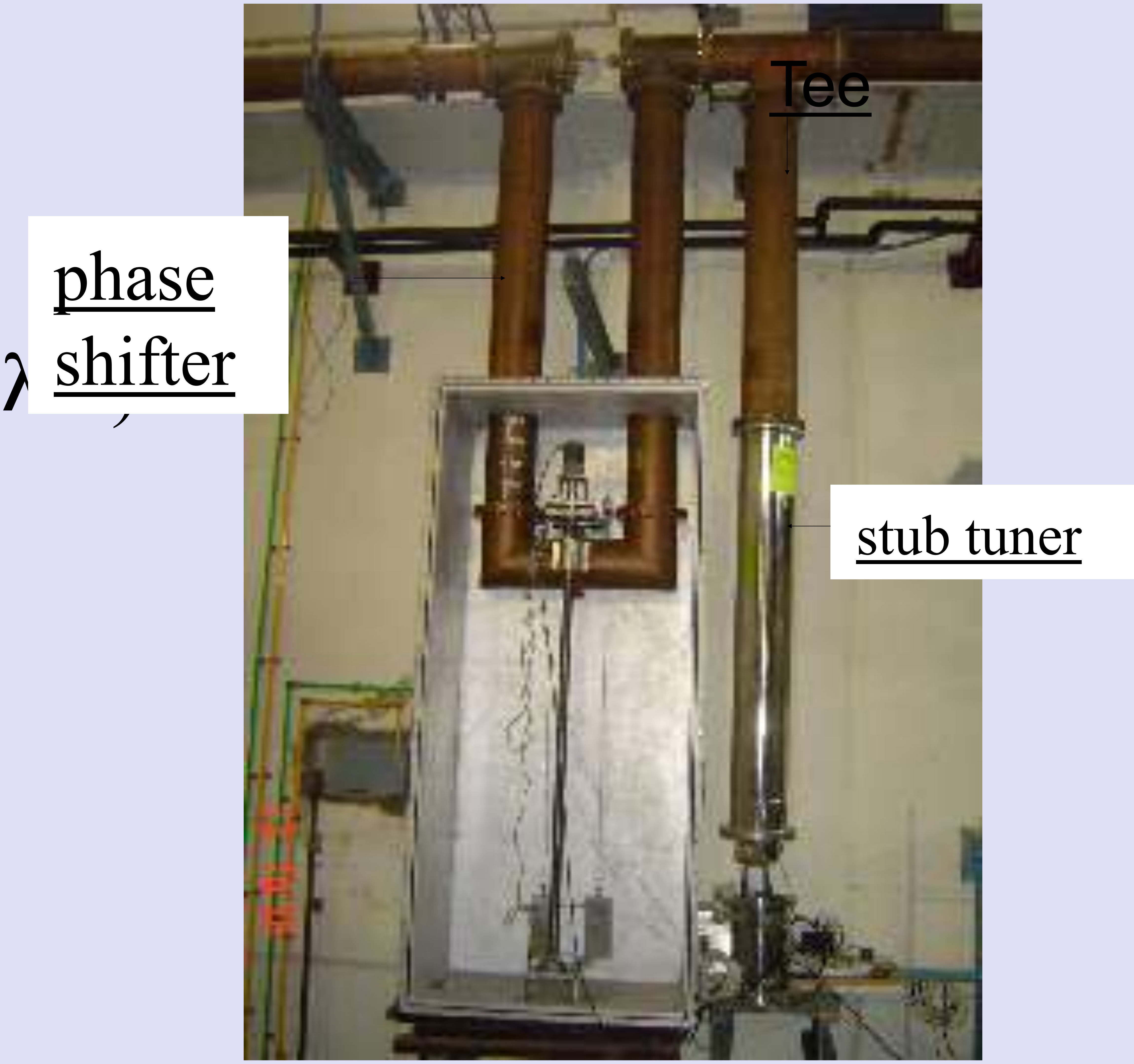
Matching Systems

Matching of antenna impedance to the generator impedance is important for delivery of maximum power

_Three levels of matching:

(I)Course tuner:

- Single phase shifter (λ/2) and stub tuner (λ)
- Connected in shunt using Tee
- Involves mechanical movement of inner conductor inside the outer conductor
- Hence more response time ≈ few sec



II) Automatic matching system

- Double stub configuration
- Two VVCs (vacuum variable capacitors connected in parallel with two stubs.
- Capacitor is moved by servo drive motor
- Response time ≈ 40-50 msec.

Automatic Matching System

RF source 1.5 MW

Tx. Line

Hybrid Coupler

Dummy Load

Probe section

Direction coupler

Automatic Matching Network

Coarse Matching Network

Interface

Antenna Port6

Probe section

Direction coupler

Automatic Matching Network

Coarse Matching Network

Interface

Antenna Port14


MotorB
MotorA
VVC2
VVC1
Load
STATIC STUB2
STATIC STUB1
MOTOR CONTROLER
V2
Vr
Vf
V1
Hybrid Coupler
RF Generator
Load
MotorB
MotorA
VVC2
VVC1
Load
V2
Vr
Vf
V1
STATIC STUB2
STATIC STUB1
VME PROCESSOR
MOTOR CONTROLER

Automatic matching system is tested with randomly variable dummy load and is found that it can match plasma impedance in 20 ms if the variation is small and takes 120 ms for extreme plasma load impedance.

Fast ferrite tuner for SST-1 tokamak

- Specifications:

Frequency range: 20 MHz – 91 MHz

Input power = 1.0 MW

Return loss > -25 dB

Insertion loss <- 0.1 dB

Mismatch region ρ = 0.65 with all phases.

Response time: 6 ms

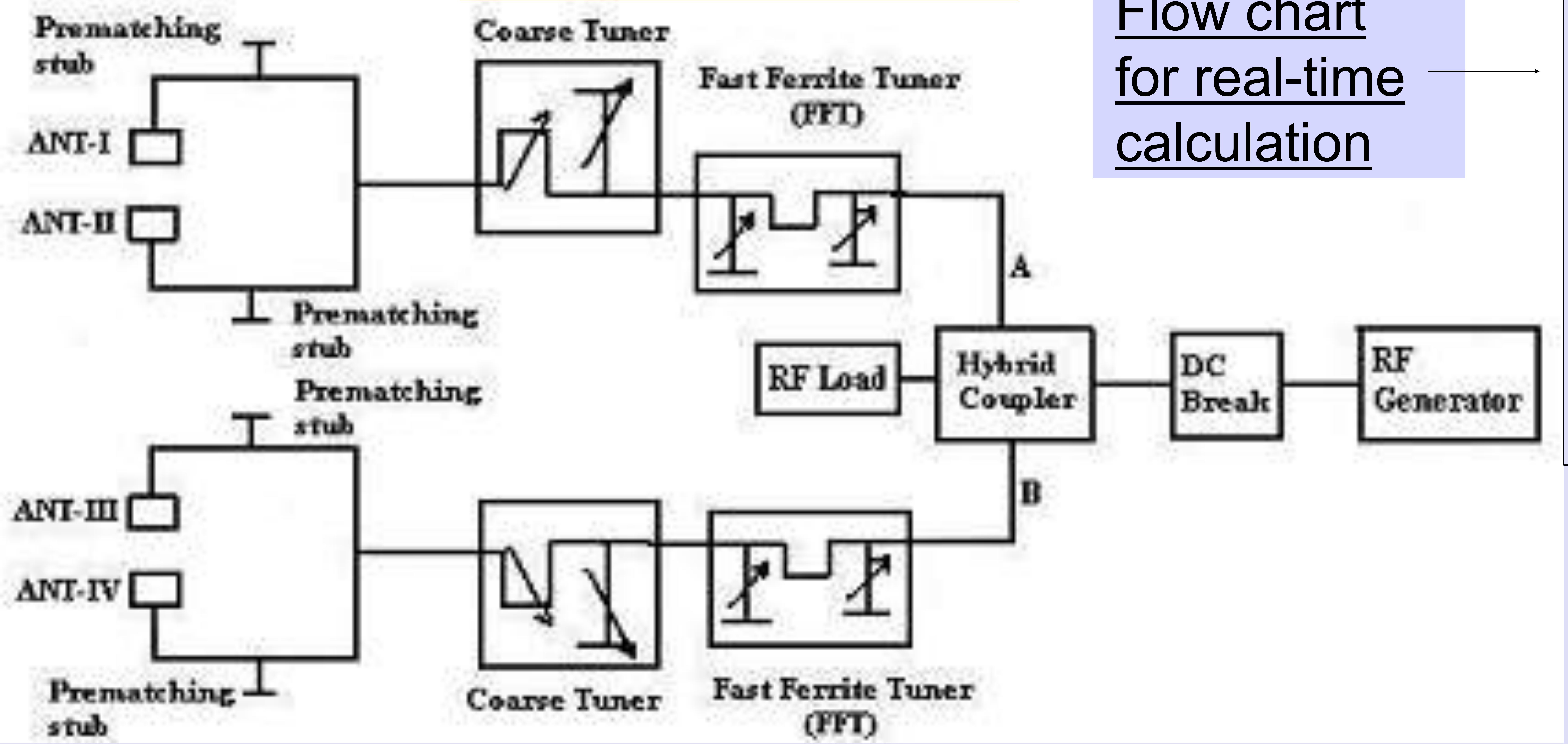
Tested with VNA and then with 1 kW rf generator with random load

Developed 500 kW FFT for SST-1

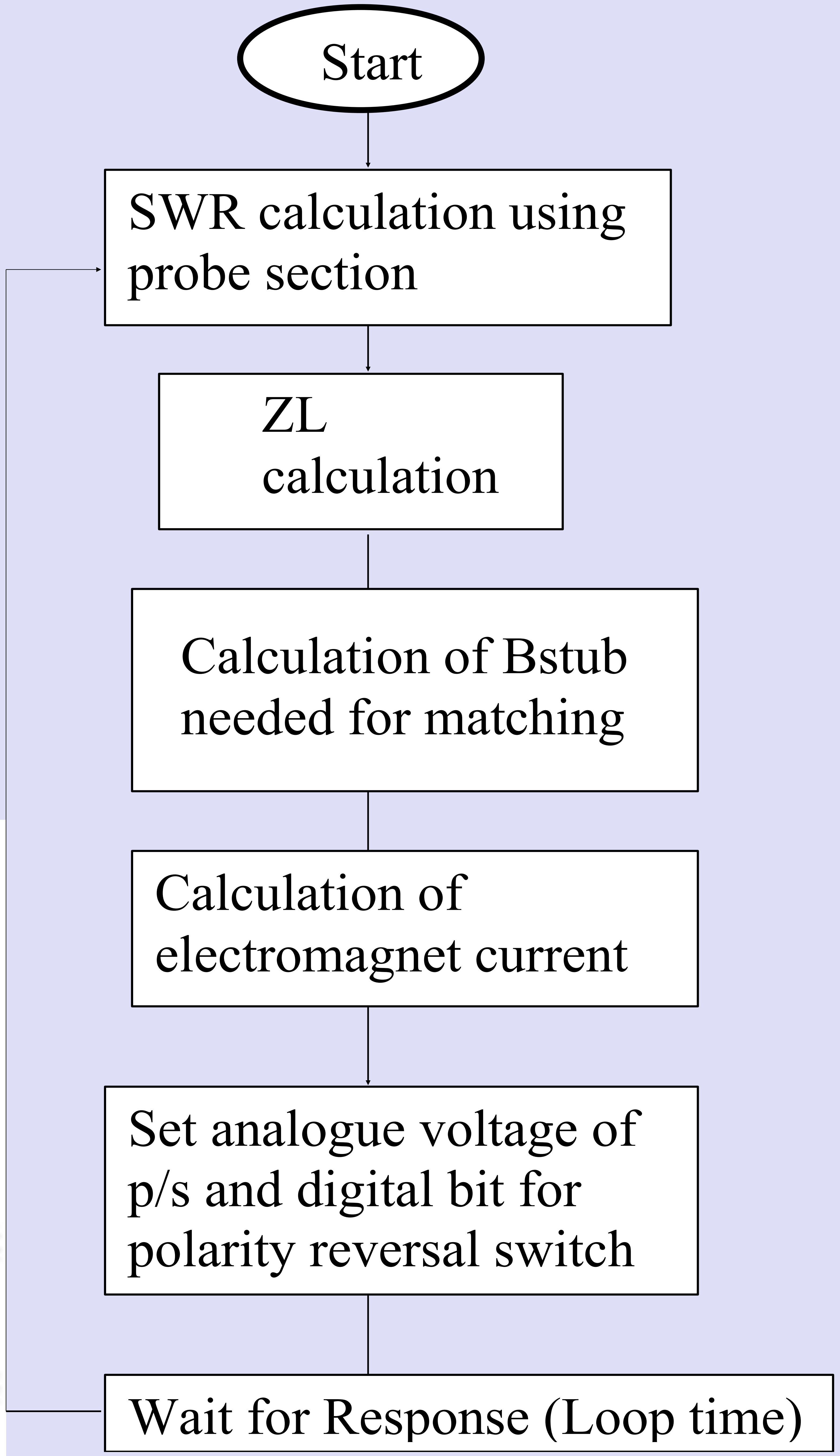
VME system for Automatic Feed-back and power-supply control

1. Real time Acquisition, Monitoring and Control of FFT Signals
2. SWR calculation using probe signals and RF-Detector.
3. Online matching of plasma load to generator by generating control signals based on Real time calculation
4. Control signals will be fed to power-supply which will change electromagnet current and hence μ_r of ferrites to achieve matching

FFT on SST-1



Flow chart for real-time calculation →


Start

SWR calculation using probe section

ZL calculation

Calculation of Bstub needed for matching

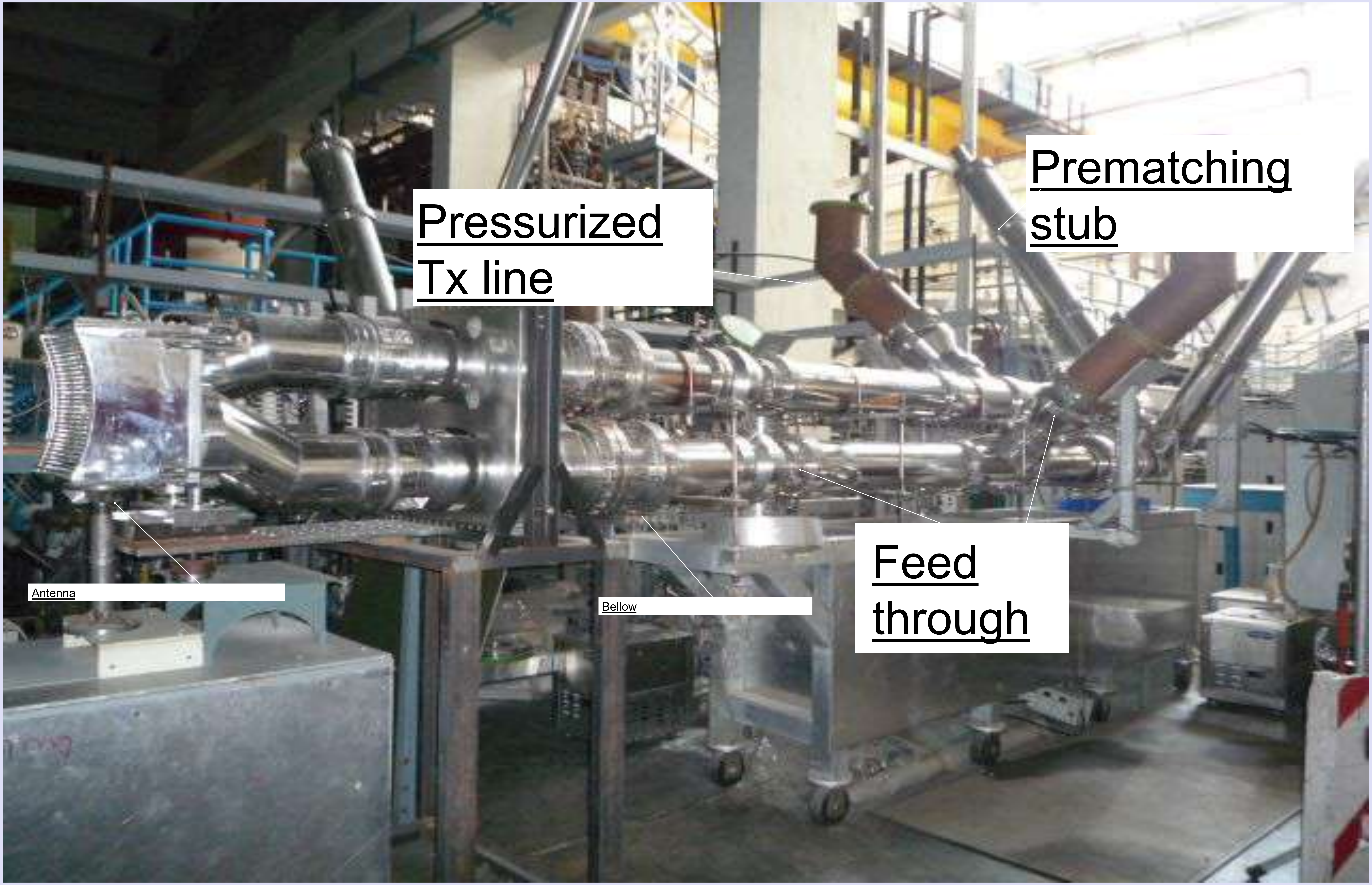
Calculation of electromagnet current

Set analogue voltage of p/s and digital bit for polarity reversal switch

Wait for Response (Loop time)

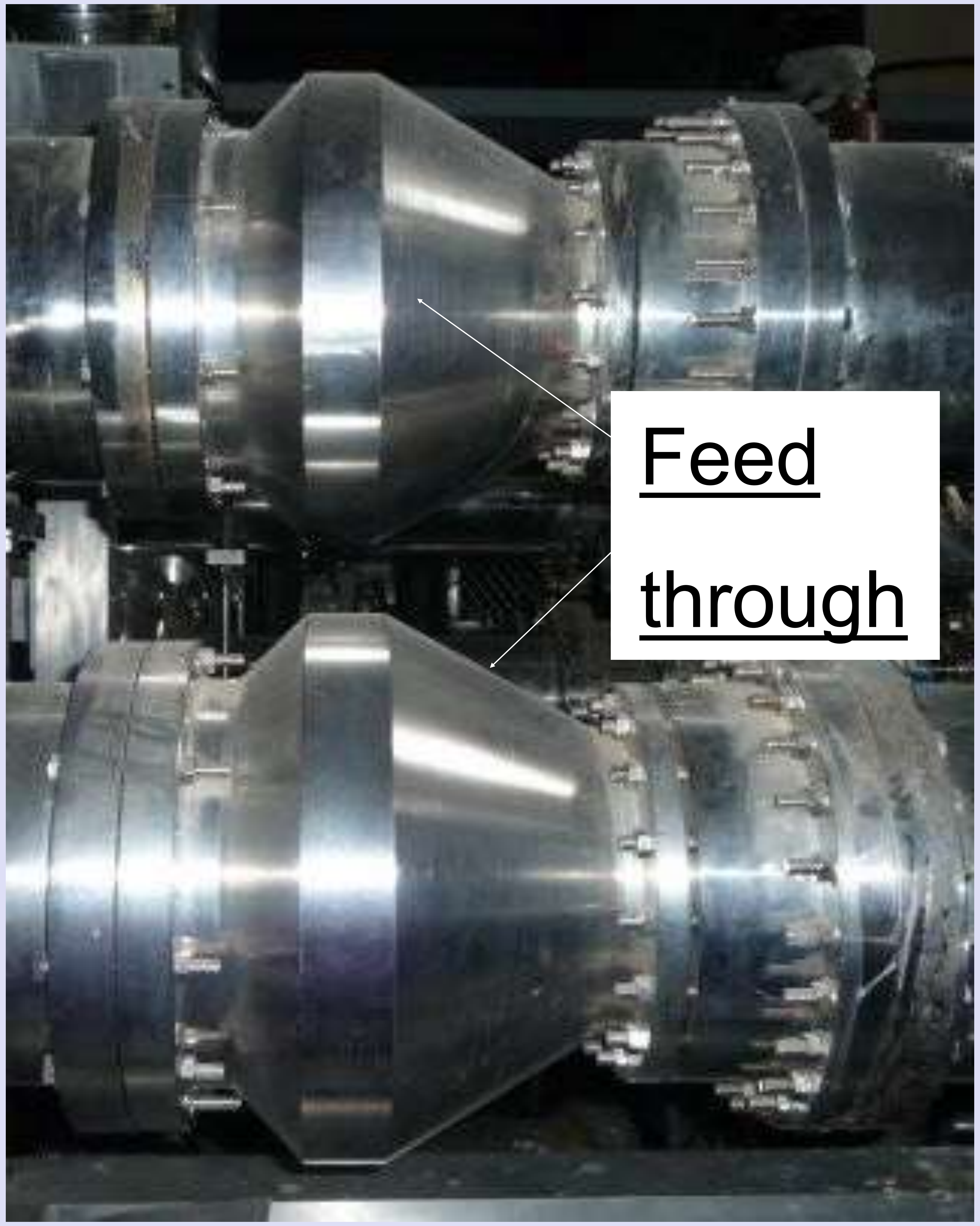
Interface Section

Connects antenna to the transmission line, made up of SS304L



Purpose of Vacuum interface

- 1. To provide separation between ultrahigh vacuum of torus and pressurized transmission line by using two rf vacuum feed-through.



- ➢ceramic cylinders fitted in space between inner and outer conductor.
- ➢Withstand electric stress and potential difference.
- ➢ORNL Design
- ➢It has its own vacuum system (TMP)

2. Torque ring inside the interface section takes up the mechanical stress generated on antenna during disruption

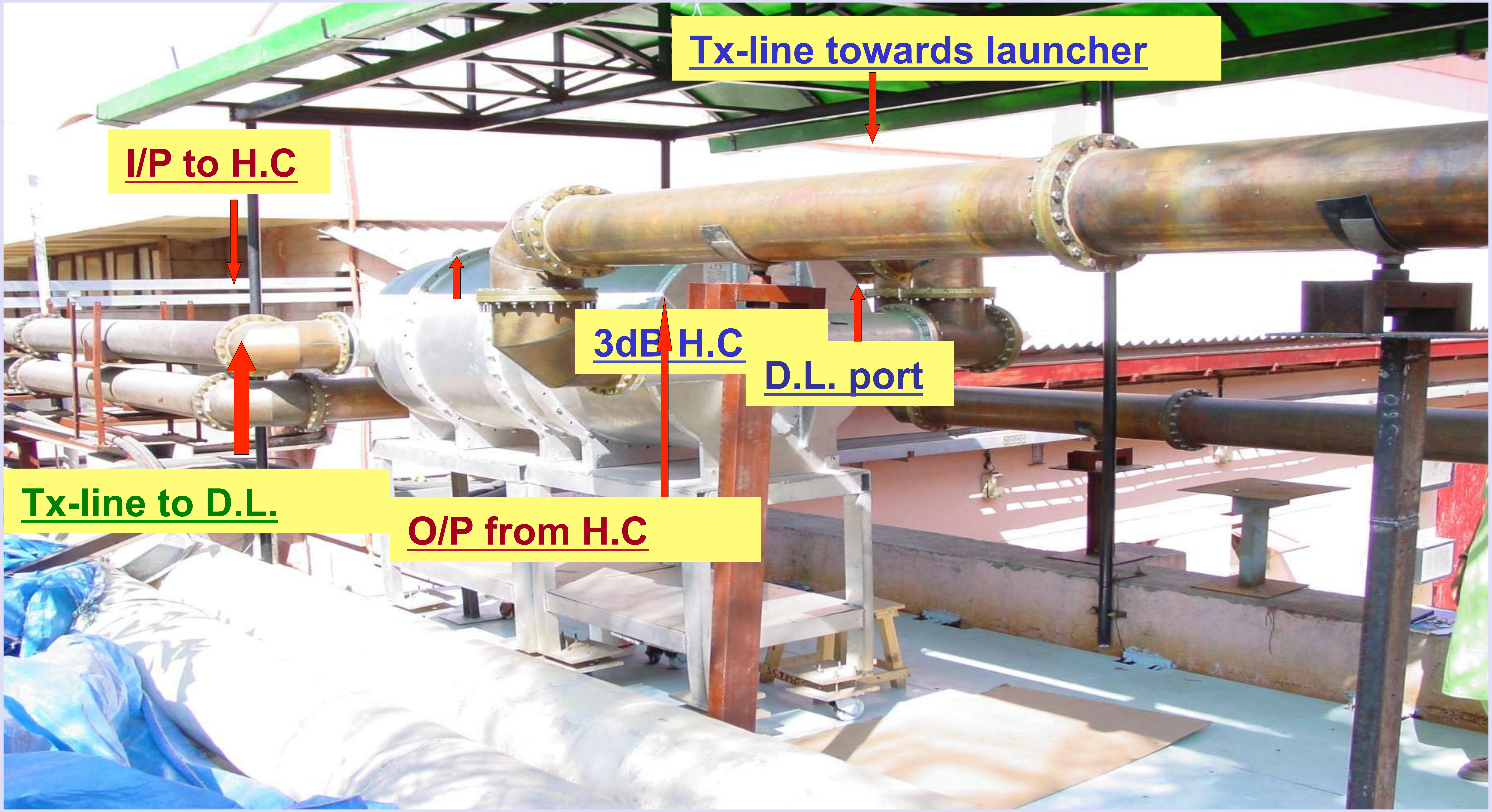
3. To Provide 100 mm antenna movement inside the machine.

4. To reduce the high VSWR to a reasonable number with the help of pre-matching stub

Specification of Hybrid Coupler: To divide power equally in two arms

3 dB Hybrid Coupler

- 4 port device, Modular setup, F: 22 MHz – 25 MHz, 45.6 MHz & 91.2 MHz
- Power handling capability: 1.5 MW CW, Type: Coaxial line, EIA 9 3/16” 50 Ohm
- Coupling: 3 dB ± 0.07dB, VSWR: > 26 dB, IL: 0.09 dB (Max.), Isolation >35 dB



Diagnostics for ICRH-SST1

A. Antenna Edge Plasma Diagnostics:

To measure Plasma edge parameters like

- » Electron density (ne)
- » Electron Temperature (Te)
- » Electric Field (E_θ & E_φ)

A probe hat consists of
Langmuir probe,
Electric dipole,
magnetic loop,

near of RF launchers, as coupling of RF waves is greatly dependent on the plasma edge conditions. The probe hats have linear movement mechanism (~5 cm)

B. RF Diagnostics:

To measure RF parameters

Antenna current : Rogowski coil

VSWR : VSWR probe section

Forward & reflected power : Directional coupler

Antenna tiles temperature : thermocouple

C. **Interface Diagnostics:**

Interface Pressure : ionization gauges

Interface Arc : Arc detectors

Interface cooling & interlock : flow meters & switch

Interface temperature : calorimetric

Data Acquisition and Control System

- The DAC is based upon two real time VME systems.
- First VME is dedicated for RF generator
- Second VME communicates with SST-1 central control system and is for automatic matching system
- Complete software and front end electronics is designed, developed and is working well

Status of ICRH system on SST-1

- One arm of transmission line, interface and antenna is commissioned on SST-1
- The ultimate vacuum in achieved in interface after sufficient baking.
- The transmission line, interface and antenna is conditioned with short RF pulses starting from low power to high power up to 140 kW.
- With 1.2 kGauss toroidal magnetic field and right pressure of H2 gas, the breakdown is produced and it is observed that it spreads toroidally in the vacuum vessel.
- Second antenna and interface is commissioned on SST-1 and testing will start soon.

Acknowledgements

- The contributions from all RF group members (Present and Past) are highly acknowledged.

- Special thanks to Aditya Operation Team and the members of various Diagnostics Groups for bringing preliminary success to the experiment.

- Thanks to Prof. Kaw and Prof. Bora for constant support and encouragement.

Thank You