Advances in LHCD system for SST1 tokamak

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Plan of the talk

- Introduction
- LHCD system description.
  - Physics
  - Technology
  - Long pulse operation issues
- Conclusions and
- Future plans

Introduction

- Steadystate Superconducting Tokamak (SST1) aims to sustain/maintain plasma for long pulse (1000 seconds) CW operation.

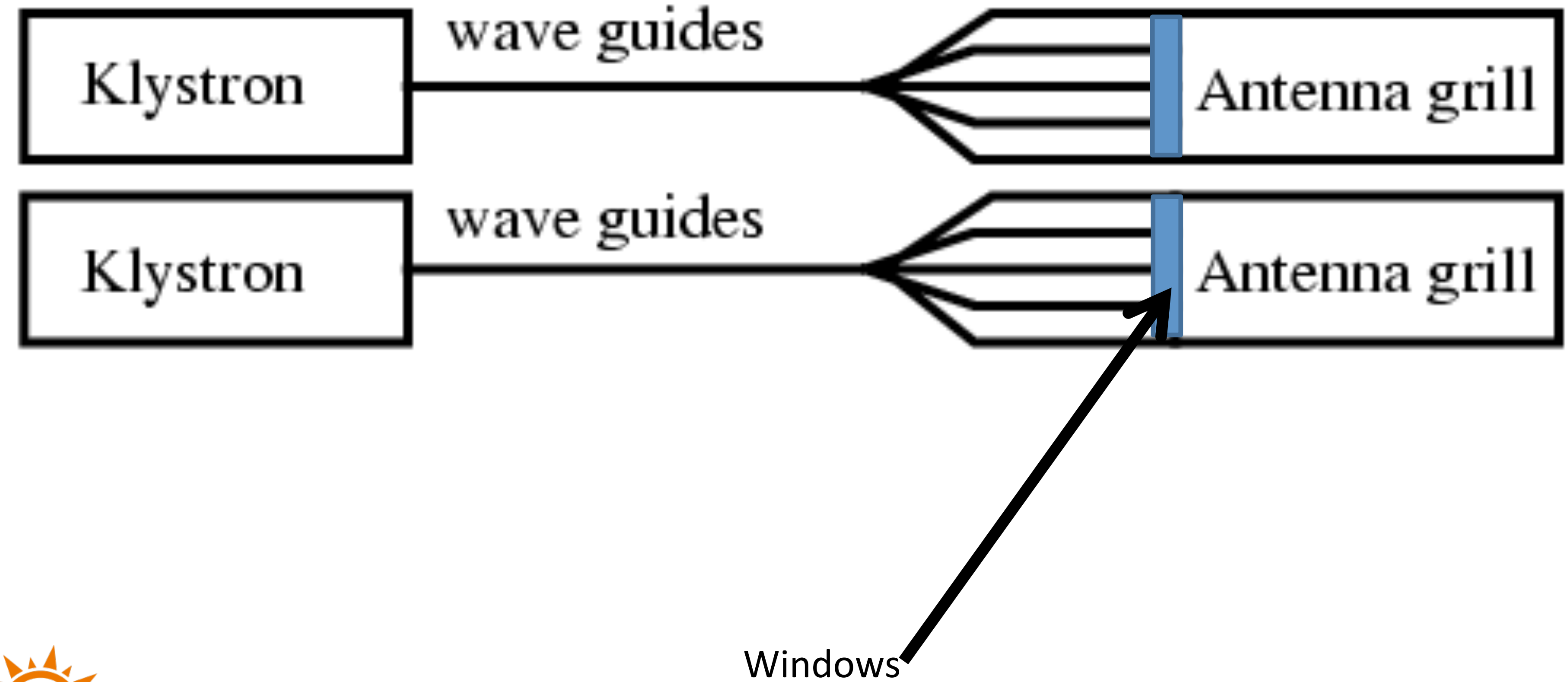
	Parameter	Values
	$<n_e>$	2×10^{13} cm^{-3}
	$<T_e>$	1 keV
	B_t	3 T
	R_0	1.1 m
SST1 machine	a	0.2 m
	I_p	220 kA
	K	1.7–1.9
	δ	0.4–0.8
	Configuration	Double null type
	Gas	Hydrogen

Non-inductive CD with LHCD

- Lower Hybrid Current Drive (LHCD) system is the main system which aims to drive plasma current non-inductively for its CW operation, after Ohmic phase.

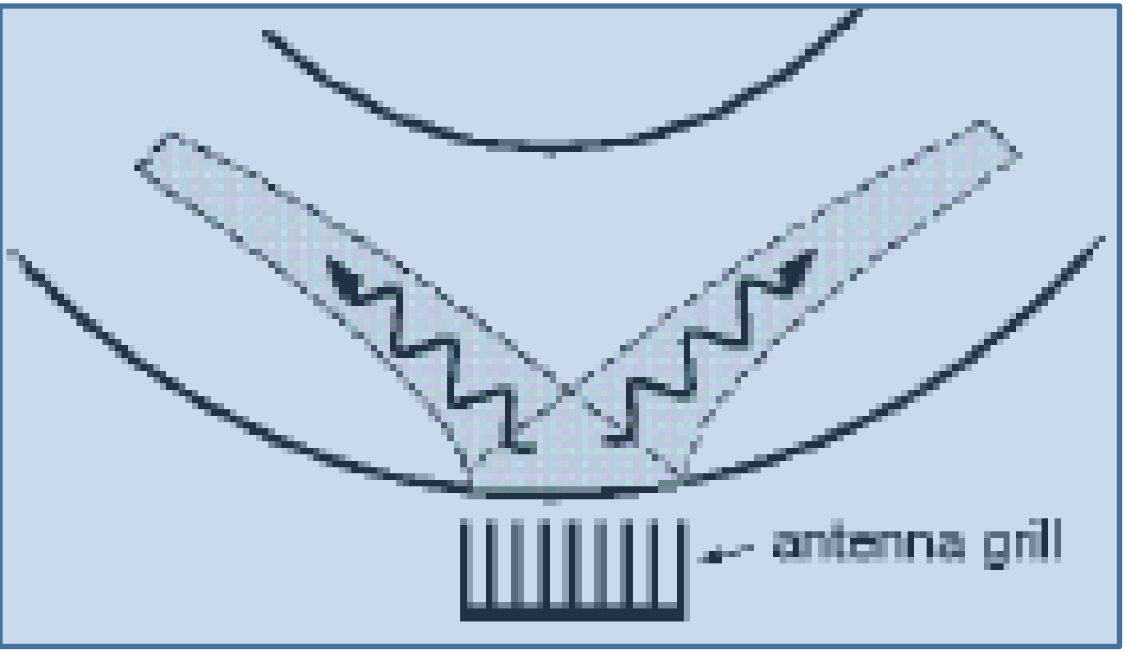
	Parameter	Values
LHCD system	f_0	3.7 GHz
	Power	2.0 MW (CW)
	Antenna type	Conventional grill
	No. of sub-waveguides	32 nos. × 2 rows (64 nos.)
	Periodicity	9 mm
	Sub-waveguide size	76 mm × 7 mm
	Septa thickness	2 mm
	$\Delta\phi$	60°–160°
	$n_{\|\|}$	1.5–4.0
	Power flux	3 kW/cm^2

LHCD Scheme



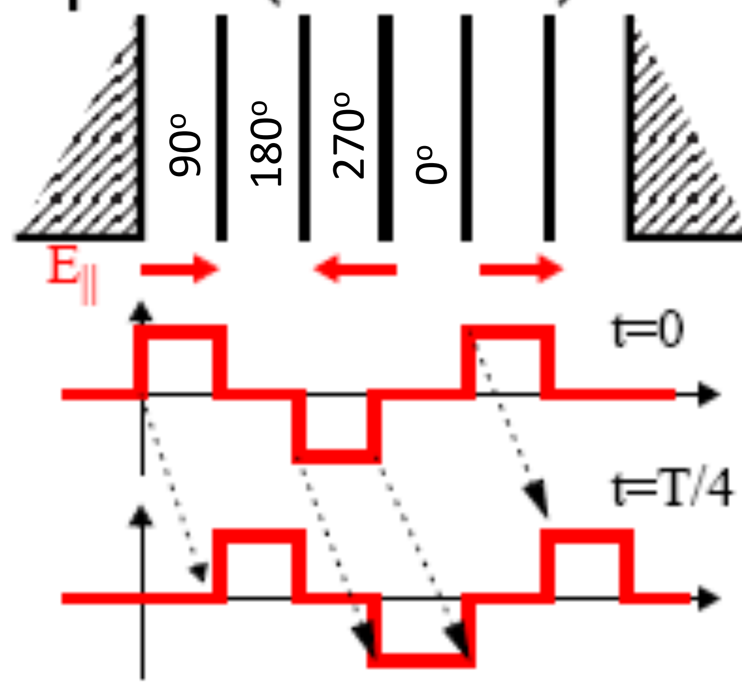
Klystron
wave guides
Antenna grill
Klystron
wave guides
Antenna grill
Windows

How to launch travelling waves



antenna grill:

top view (schematic):



phasing for asymmetric launch

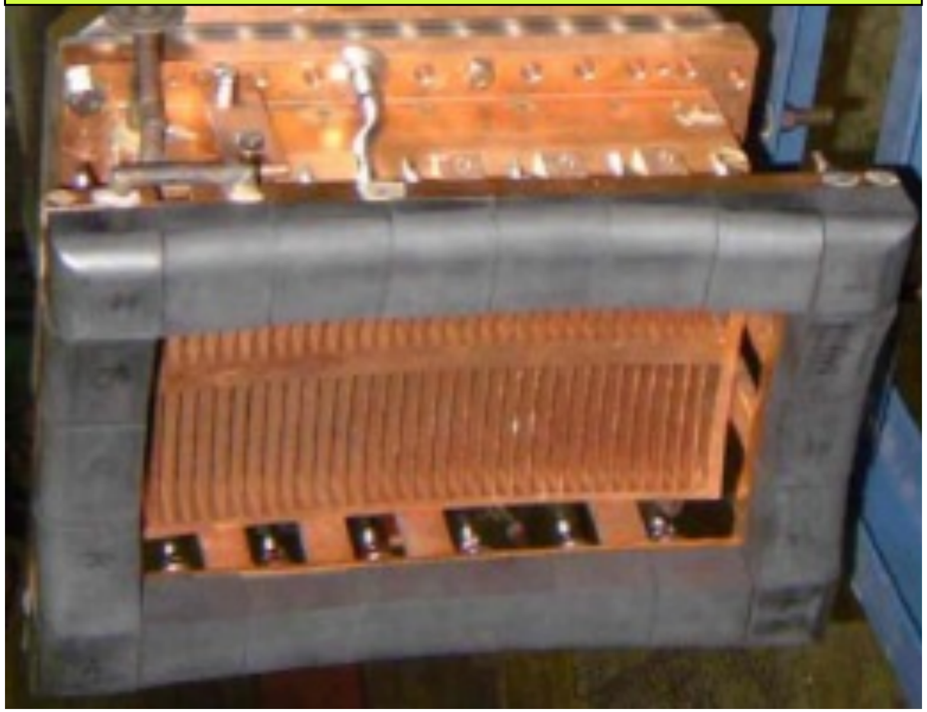
Importance of phasing

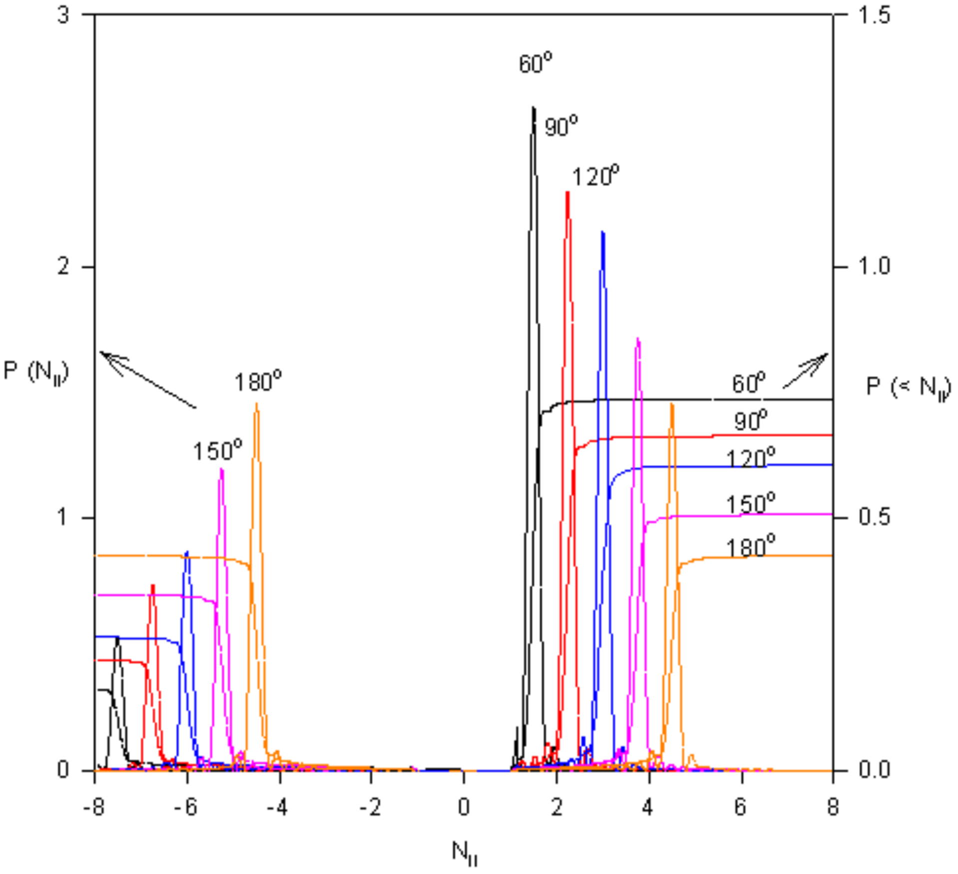
- Phasing steers the wave in preferred direction.
- Higher the waveguide elements better is the representation of the wave (more close to true wave representation) i.e. sharp spectrum.
- $N_{//} = ck_{//}/\omega$

  $= c/f * 1/\Delta * \Phi/360^o$ here Δ is periodicity of antenna
- $\Delta N_{//} = N_{//} /W$ here W is total width of antenna

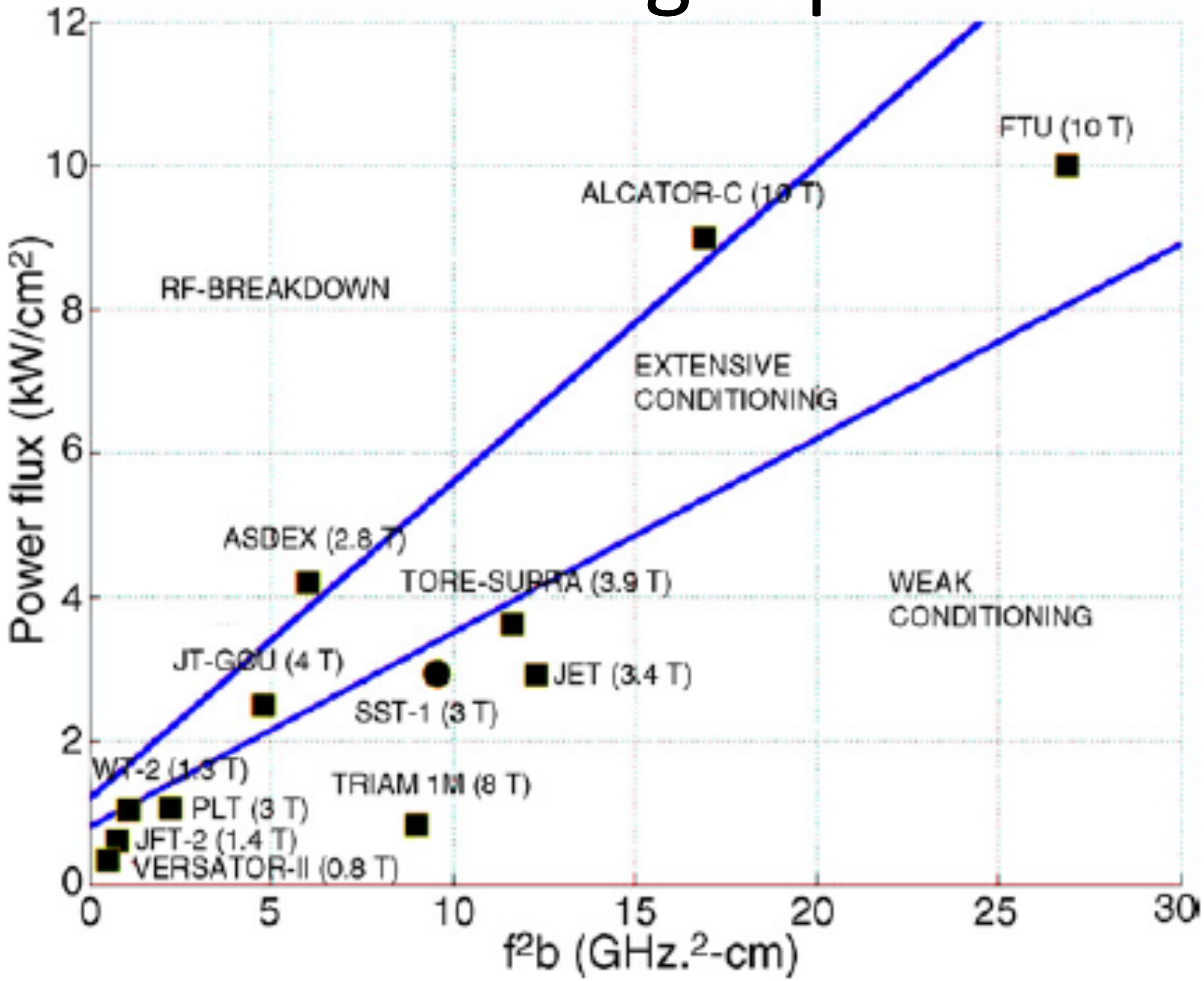
LH antenna on SST1

2 × 32 grill antenna for SST1 machine





Power handling capabilities



Theoretical background

- Incremental power absorbed by the electron is

$$\Delta P \sim n m_e v_{||} \Delta v \ \nu_{coll}$$

- Incremental change in current is

$$\Delta J \sim ne\Delta v.$$

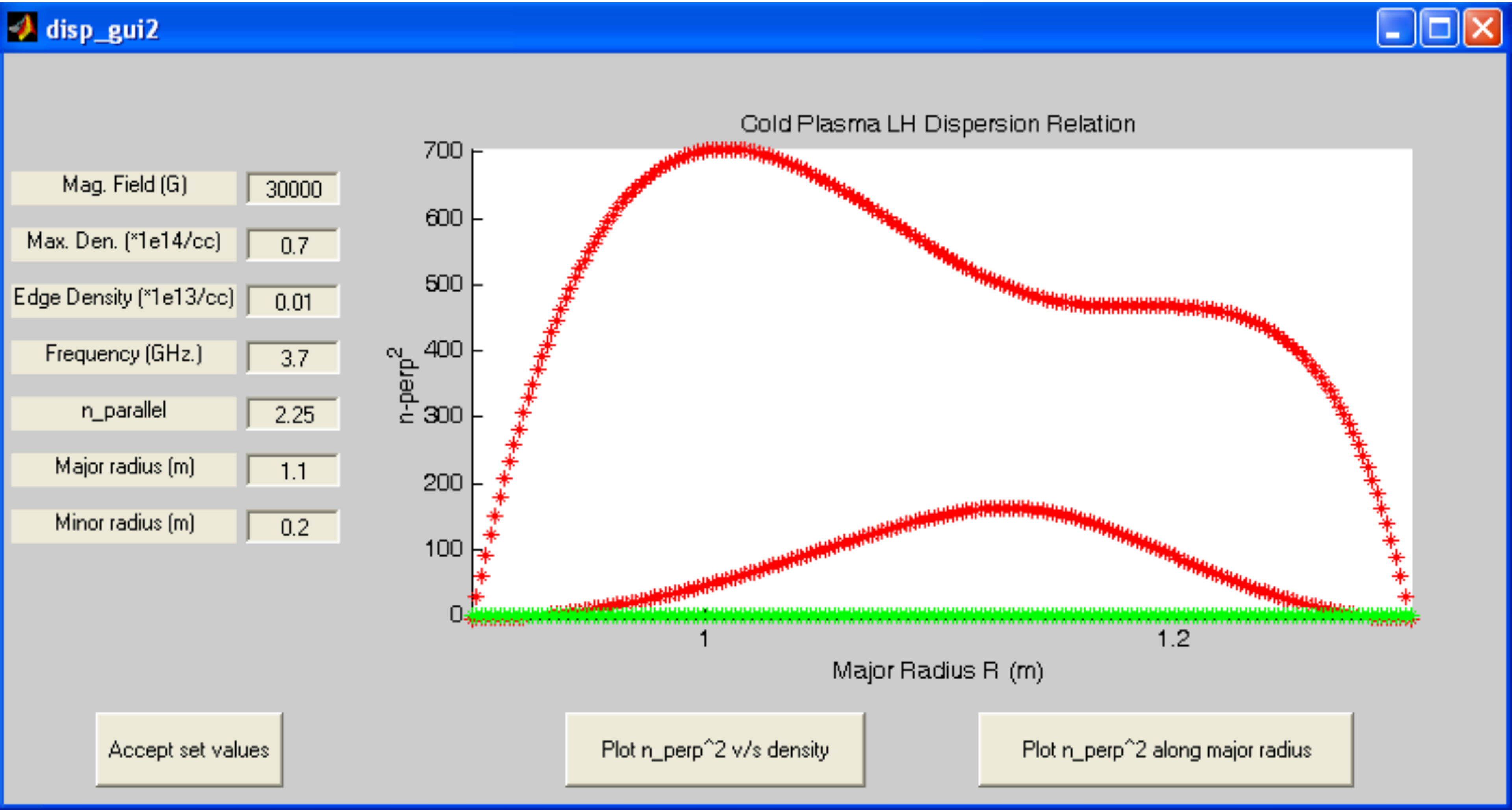
- The efficiency of LHW is

$$\Delta J/\Delta P \quad \sim e/\, m_e v_{||} \nu_{coll}$$
$$\propto e\, v_{||}^2/\, n\, m_e$$
$$\propto N_{//}^{-2} \ \text{(for fixed density)}$$

- As for suprathermal electrons ($v_{||} >> v_{te}$), the collision frequency is proportional to $n/v_{||}^3$

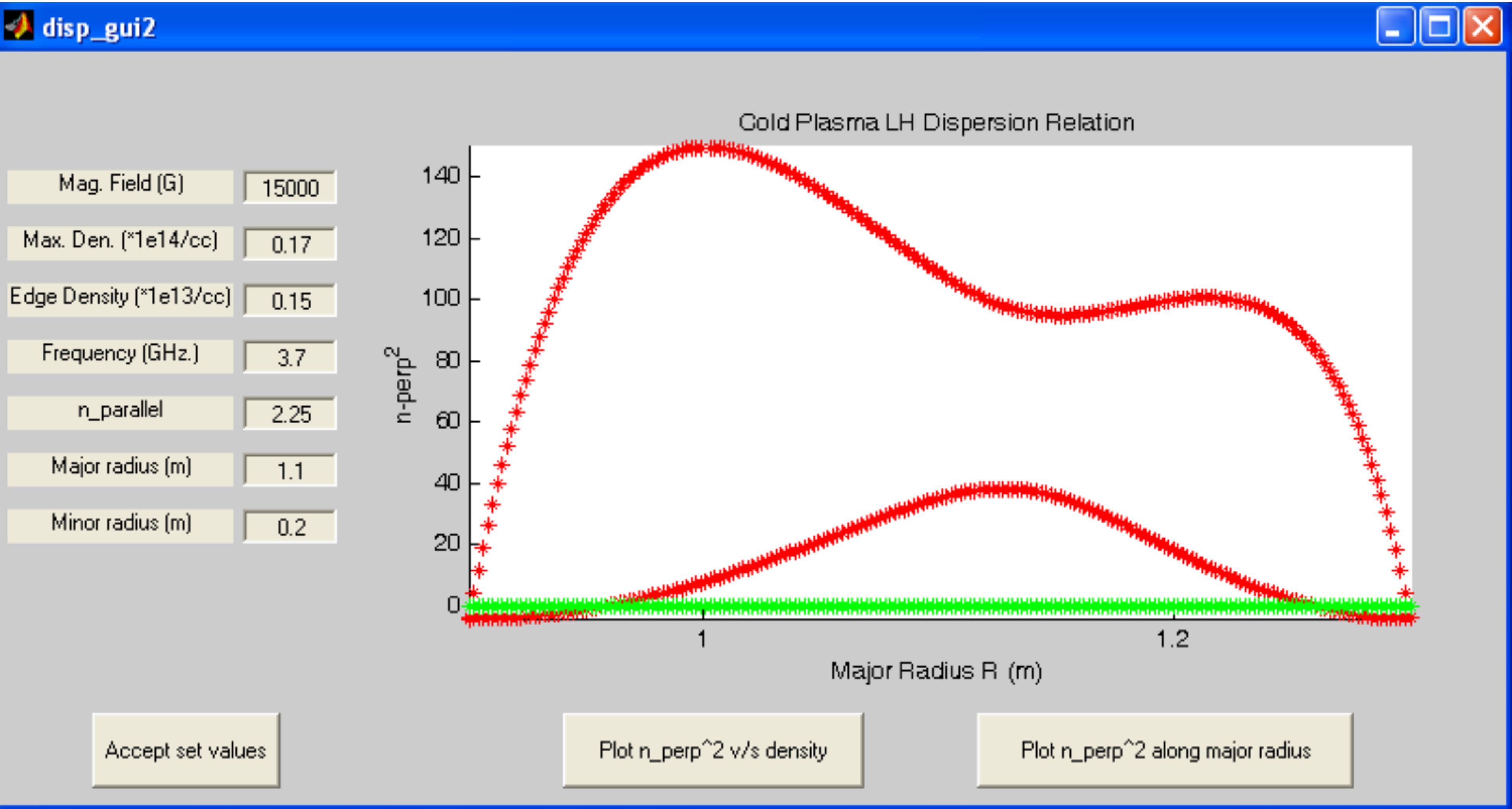
For SST1

$n_e <= 7 \times 10^{13}\ cm^{-3}$; $B_t = 3T$



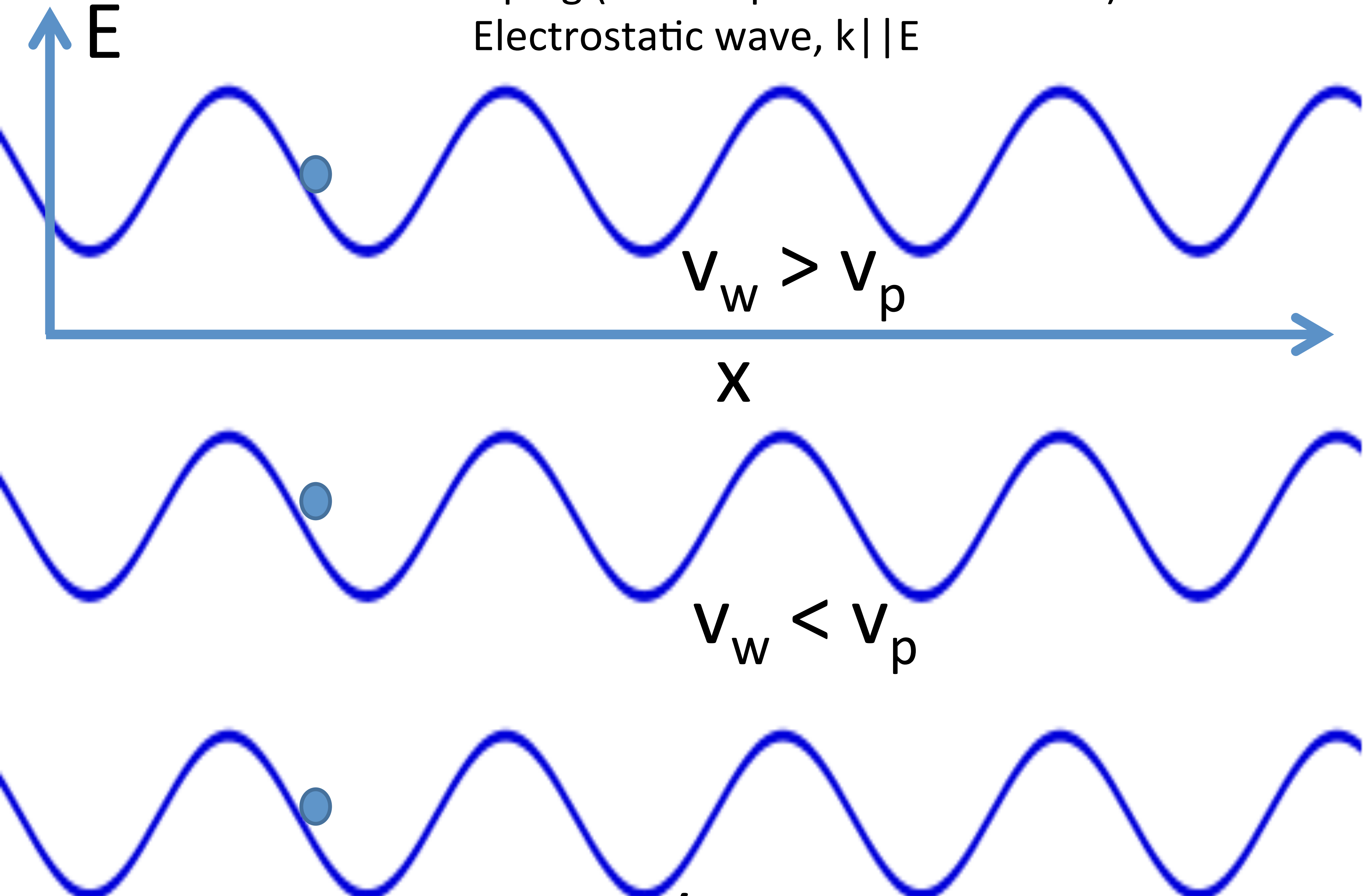
For SST1

$n_e <= 1.7 \times 10^{13}\ cm^{-3}$ $B_t = 1.5T$



Landau damping (wave – particle interaction)

Electrostatic wave, k||E



$v_w = v_p \Rightarrow \omega/k = v_p$ strong interaction

Wave absorption

ν: collision frequency

ω≤ν: low temperature plasmas

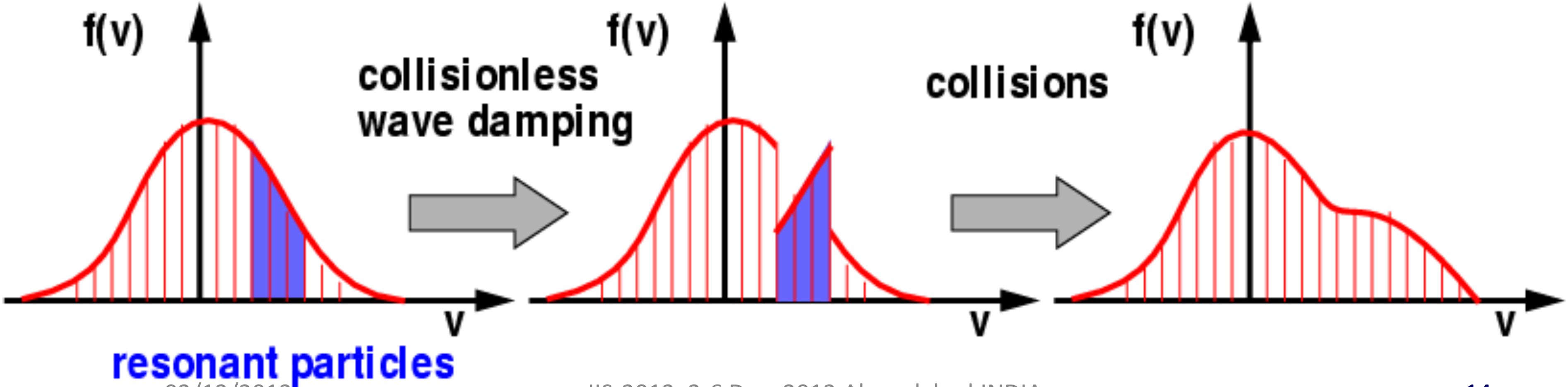
collisional damping

all particles involved

ω≥ν: fusion plasmas

collisionless damping

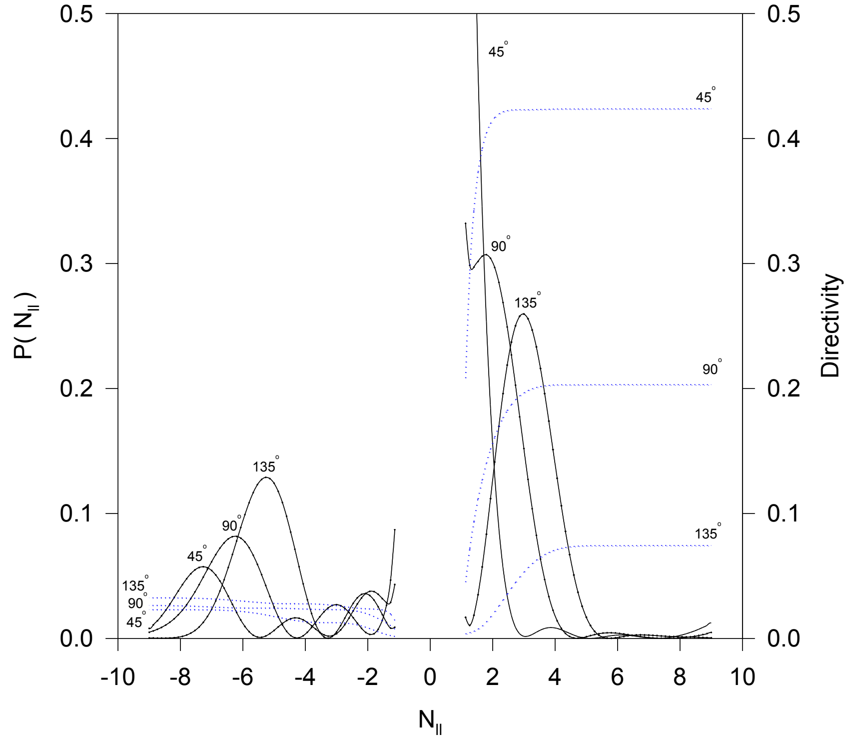
only some resonant particles (electrons, ions) involved

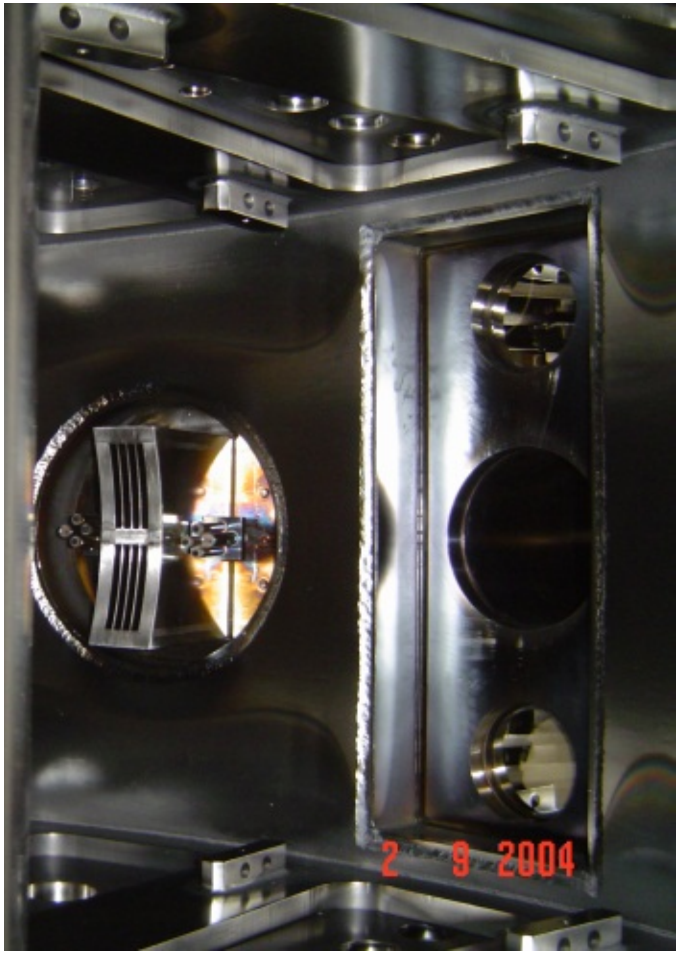


Prototype LH system

LH Antenna on ADITYA

2 × 4 grill antenna placed Inside ADITYA

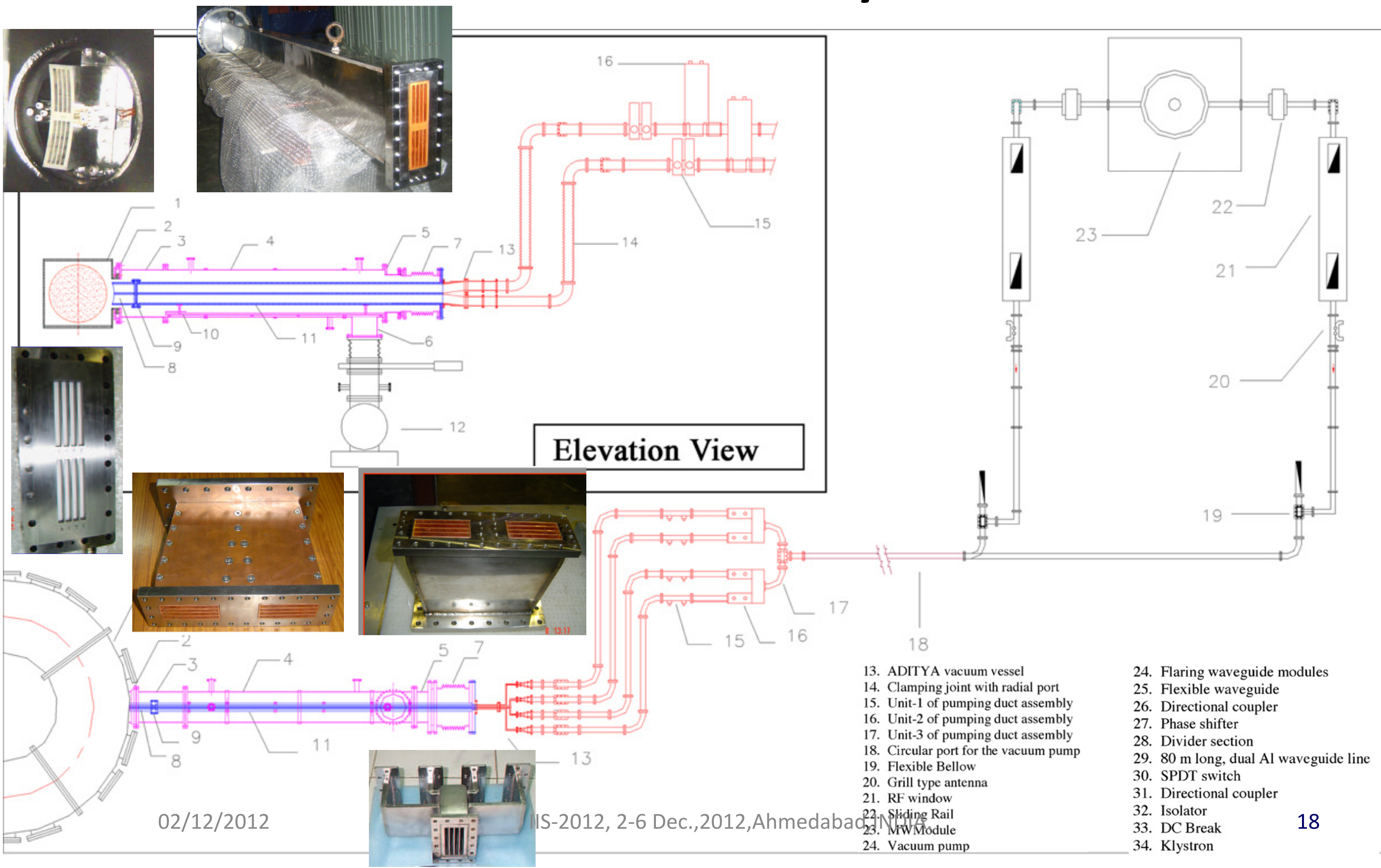




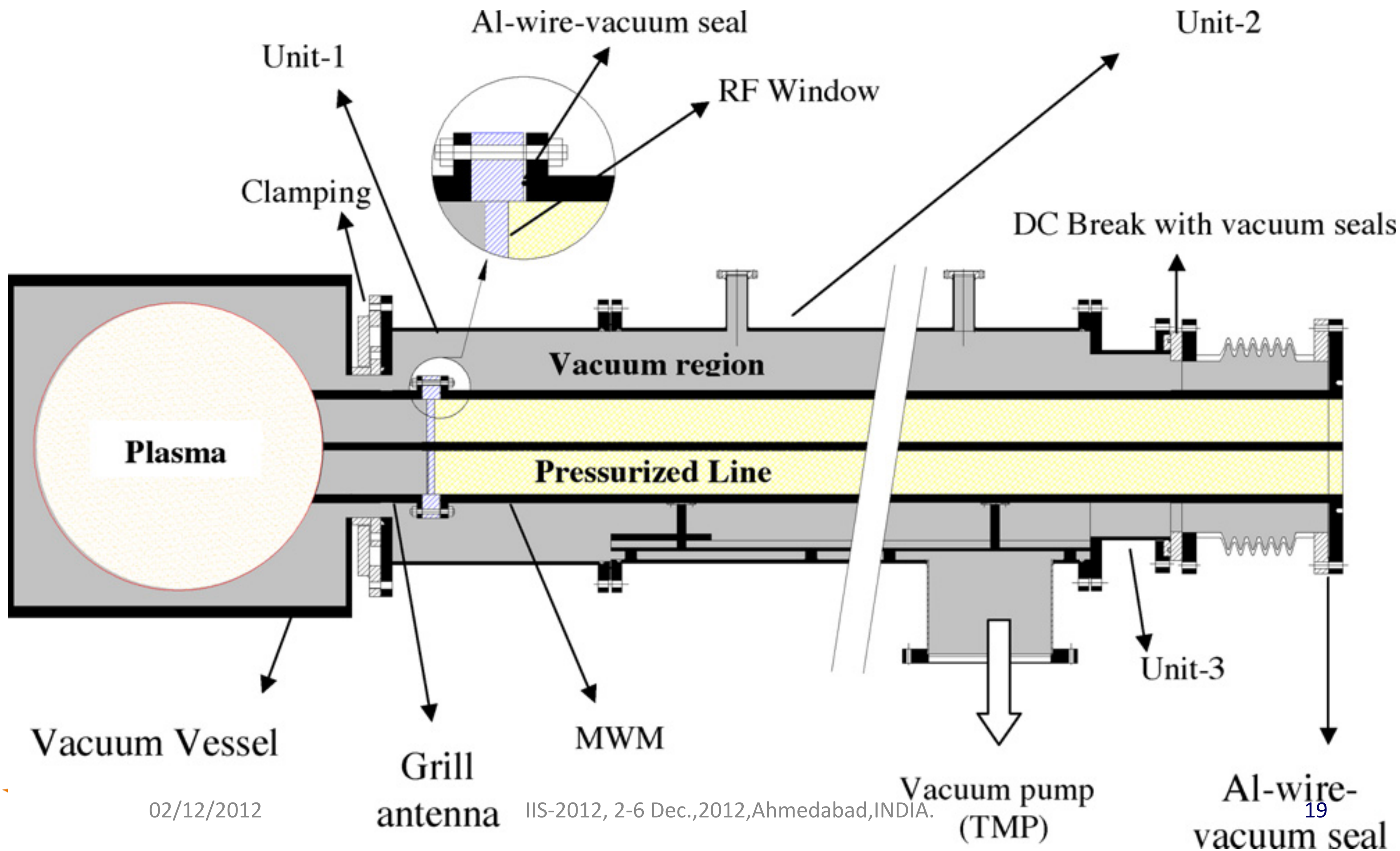
ADITYA & LHCD parameter

ADITYA Tokamak	Major radius	0.75 m
	Minor radius	0.25 m
	Toridal magnetic field	0.8 T
	Density	$\sim 2 \times 10^{13}$ cm^{-3}
	Temperature	$\sim$400 eV
	Plasma current	200 kA max.
	Plasma shape	Circular
	Loop voltage	24 V max.
	Plasma duration	200 ms max.
	Additional heating	ICRH, LHCD & ECRH
LHCD parameter	Frequency	3.7 GHz
	Power	120 kW
	Antenna type	Grill antenna
	Antenna position	2 mm behind LCS
	Total no. of sub-waveguides	8 (2 rows $\times$ 4 columns)
	Sub-waveguide dimensions	76 mm $\times$ 7 mm
	Pulse width	$\sim$1 s
	Output mode	TE_{10} (0-degree phasing)
	RF source	Klystron based (500 kW CW)
	Critical crater energy	10 J
	HV protection device	Rail gap type crow bar system

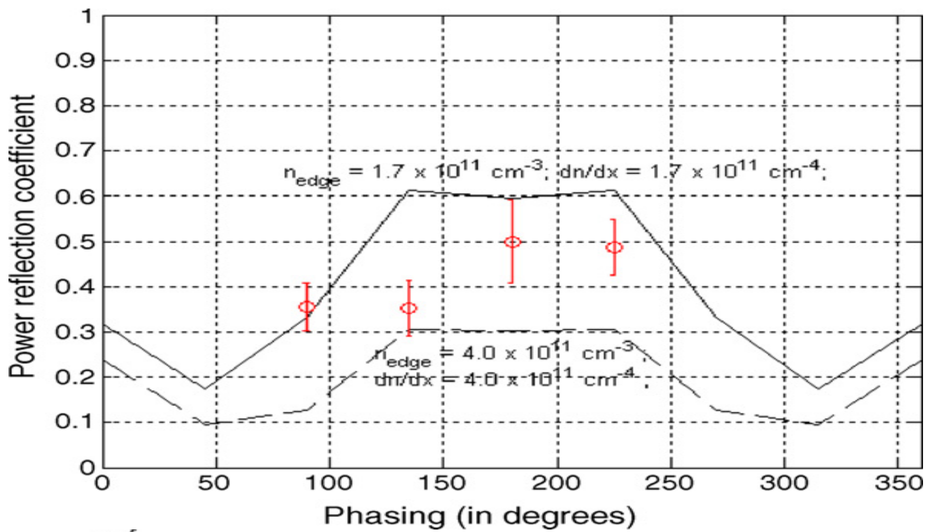
ADITYA-LH Layout

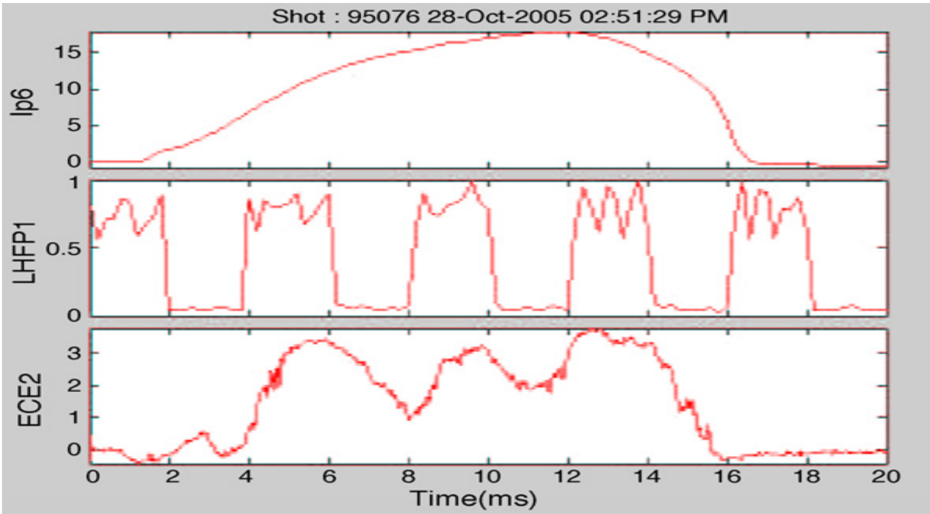


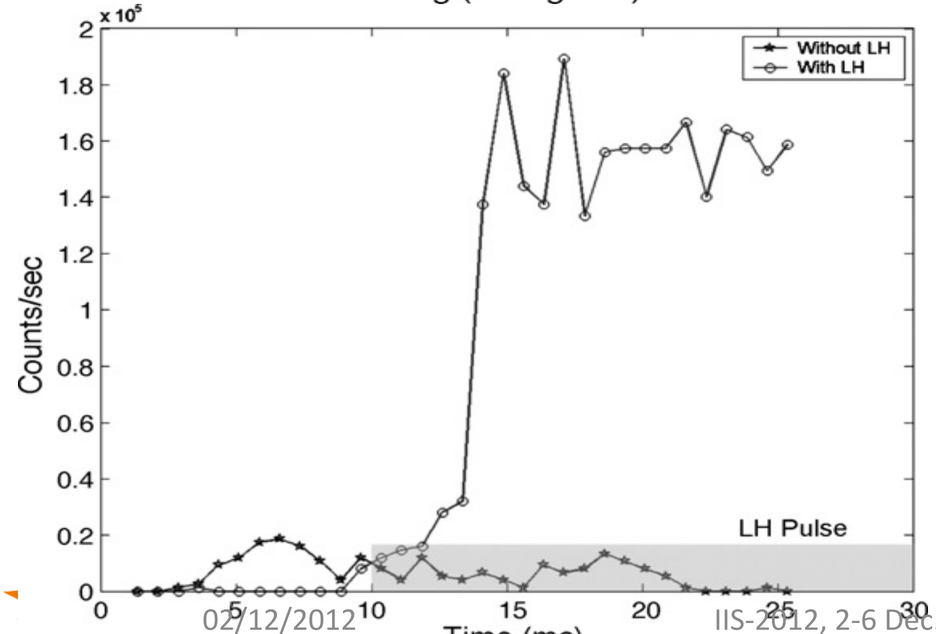
In-vessel description

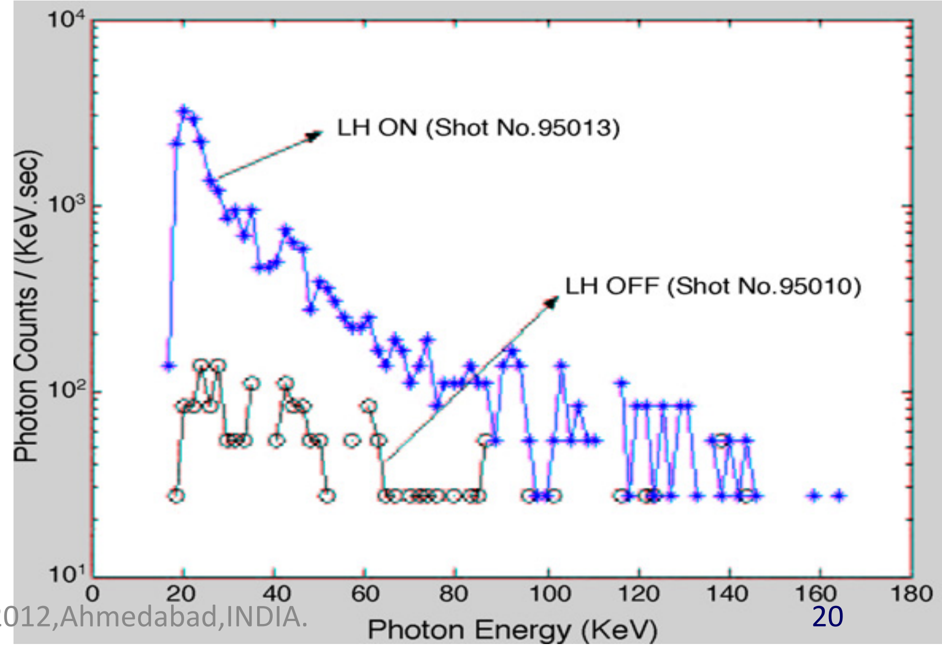


Plasma response to LH power

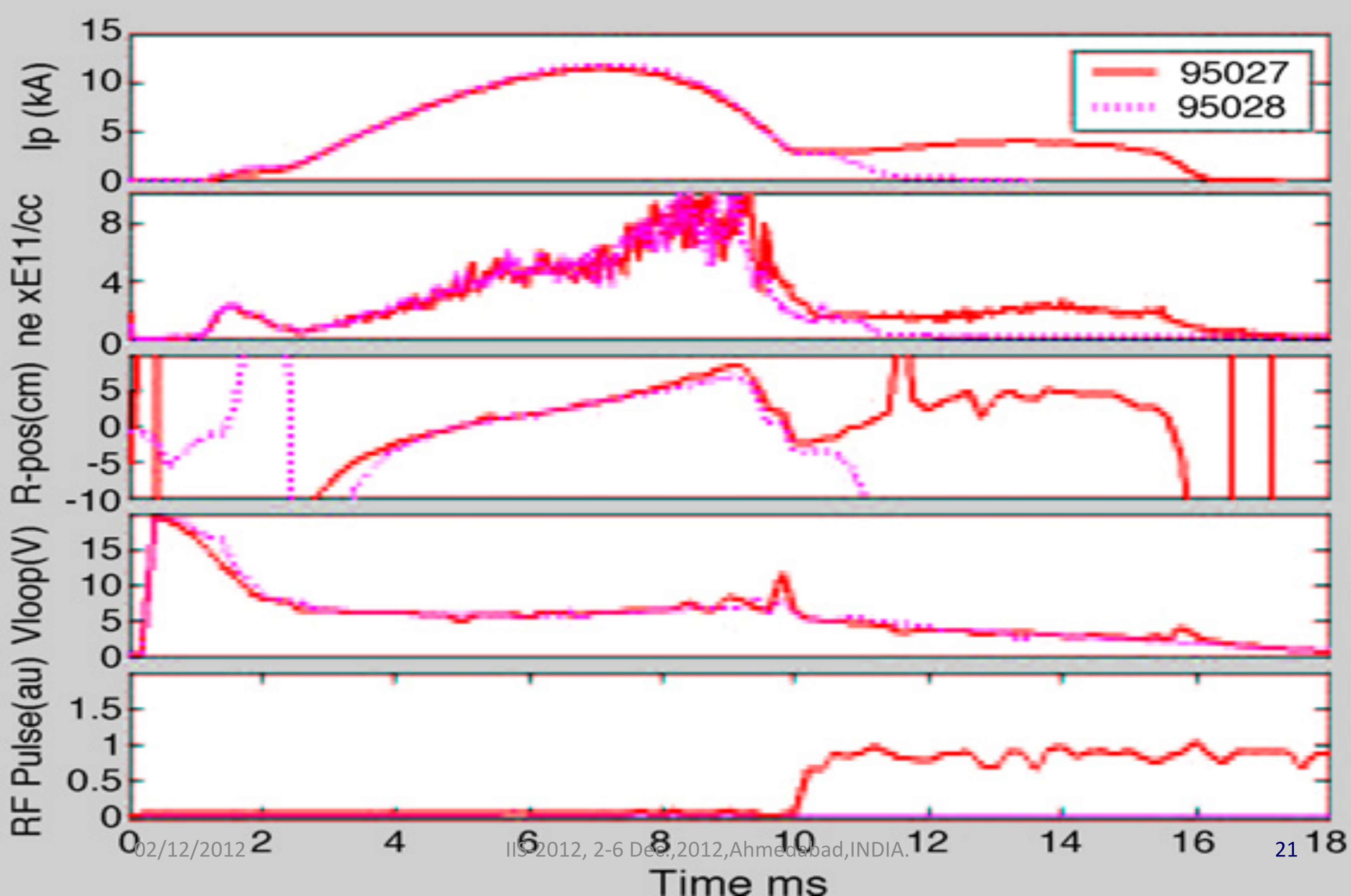




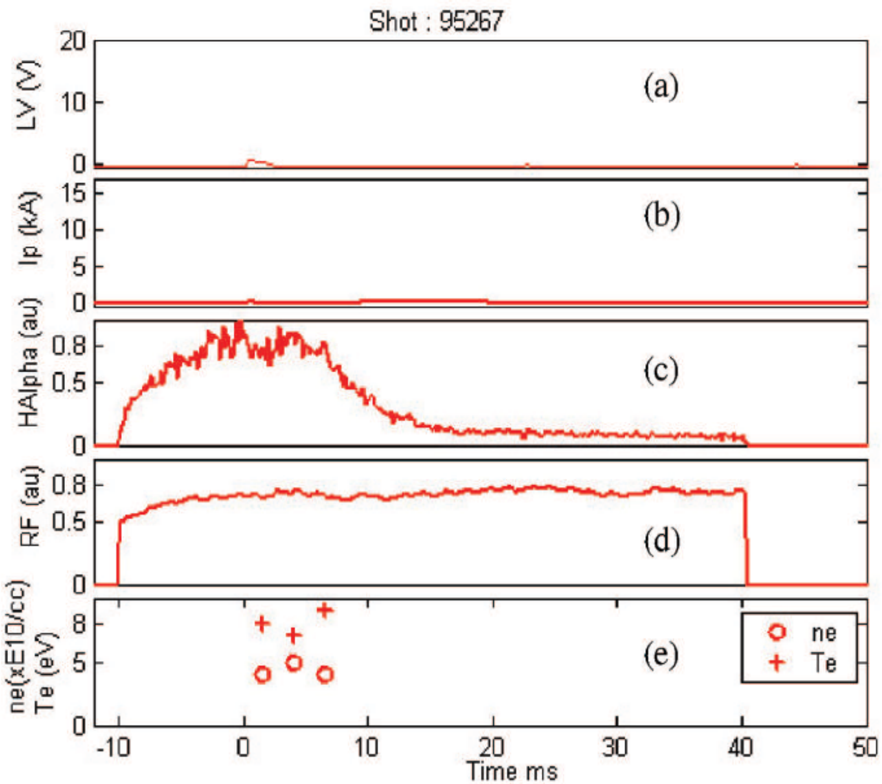


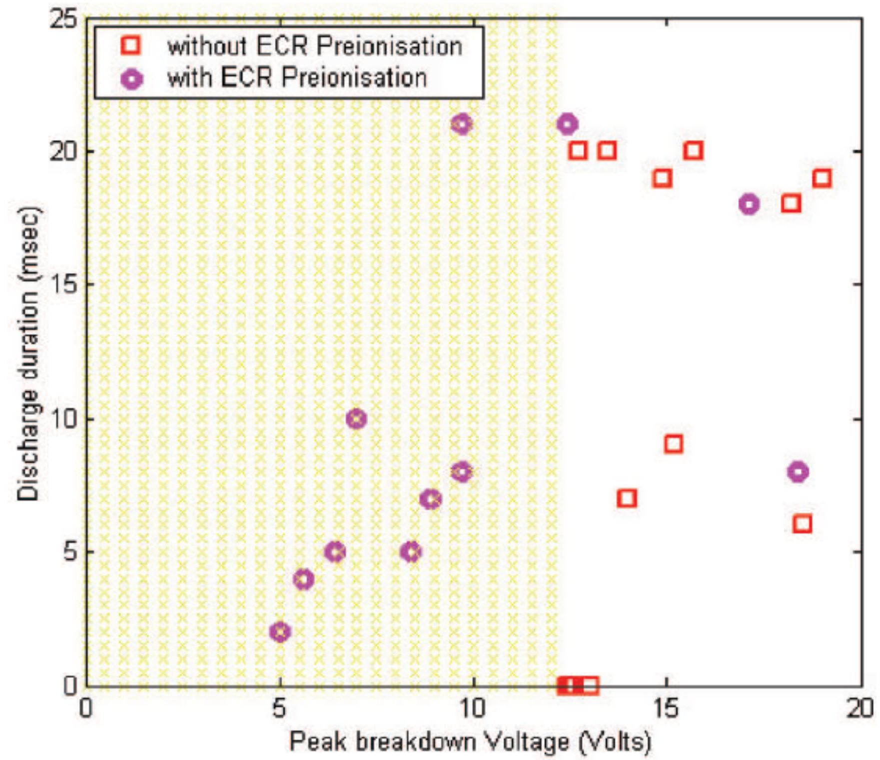


More power needed ….

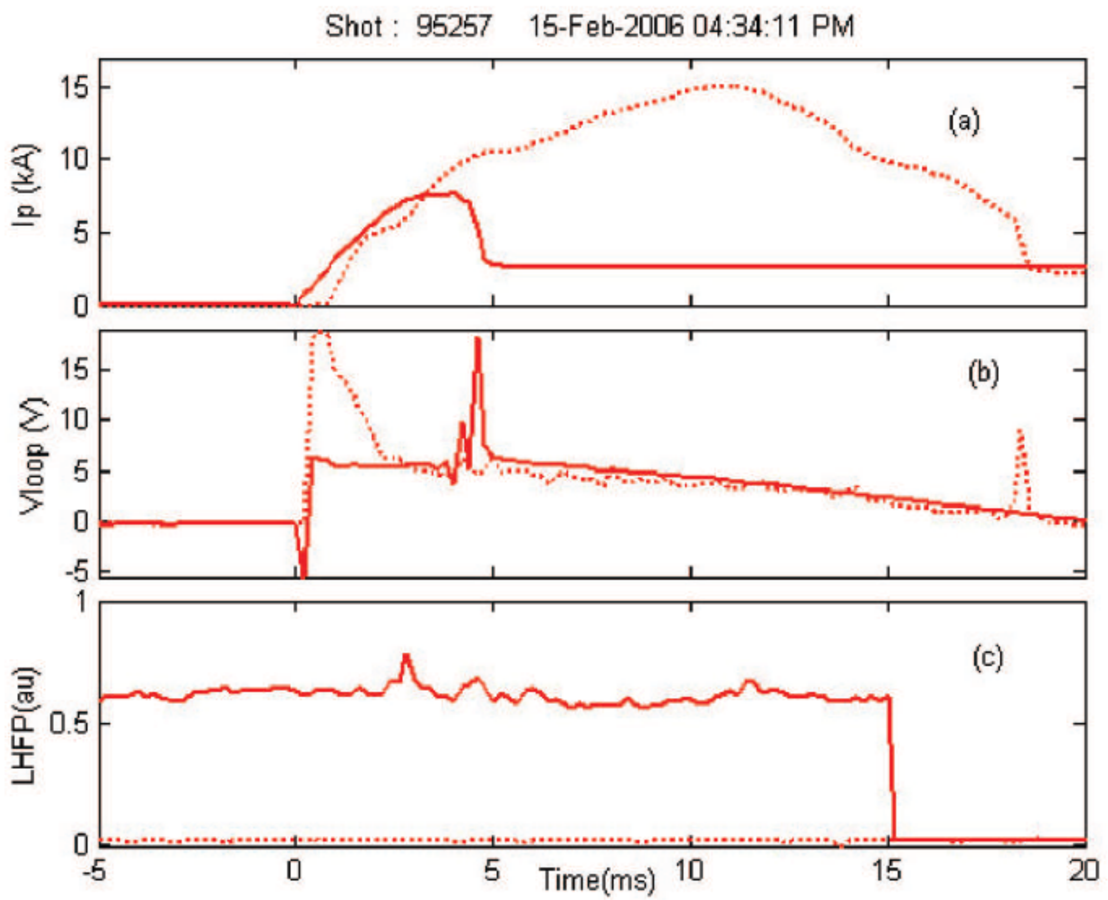


LHCD system used for ECR breakdown studies at lower toroidal magnetic field

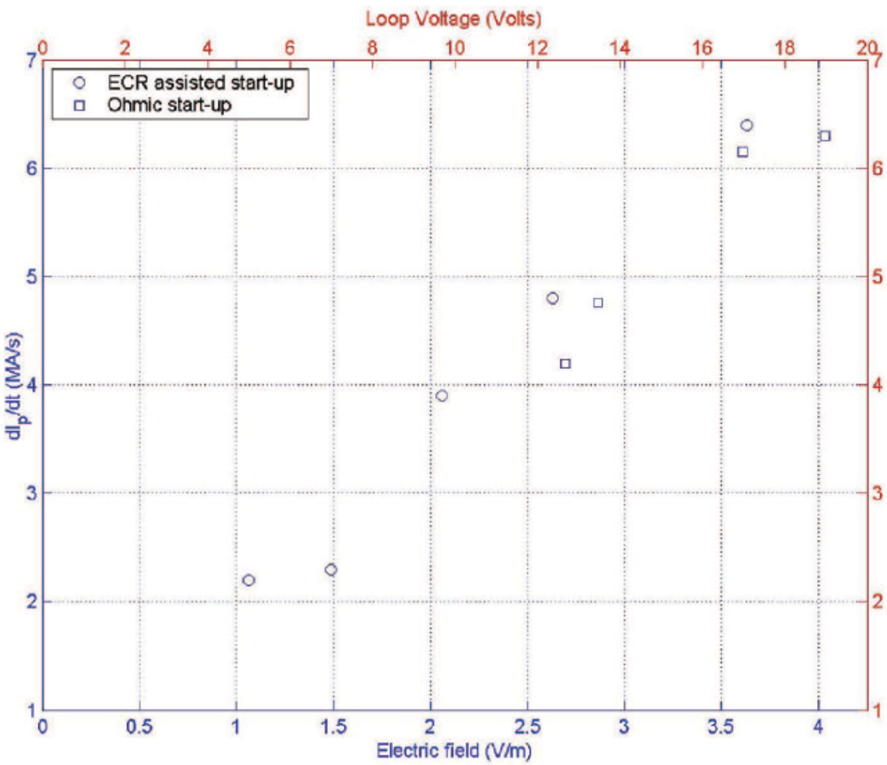


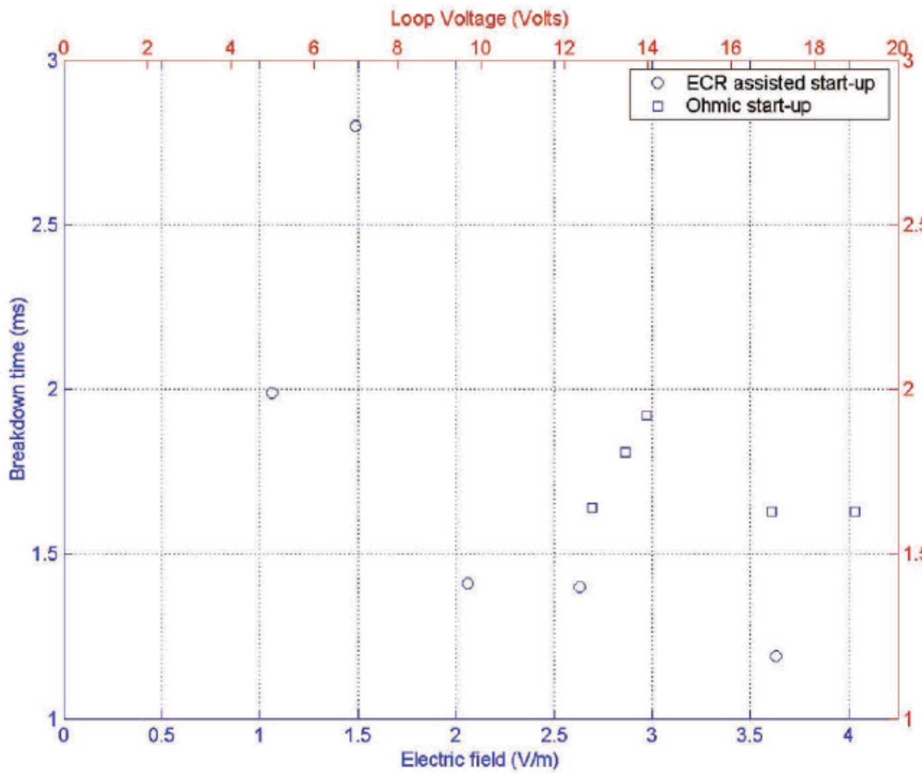


Comparison between ECR assisted/ unassisted startup



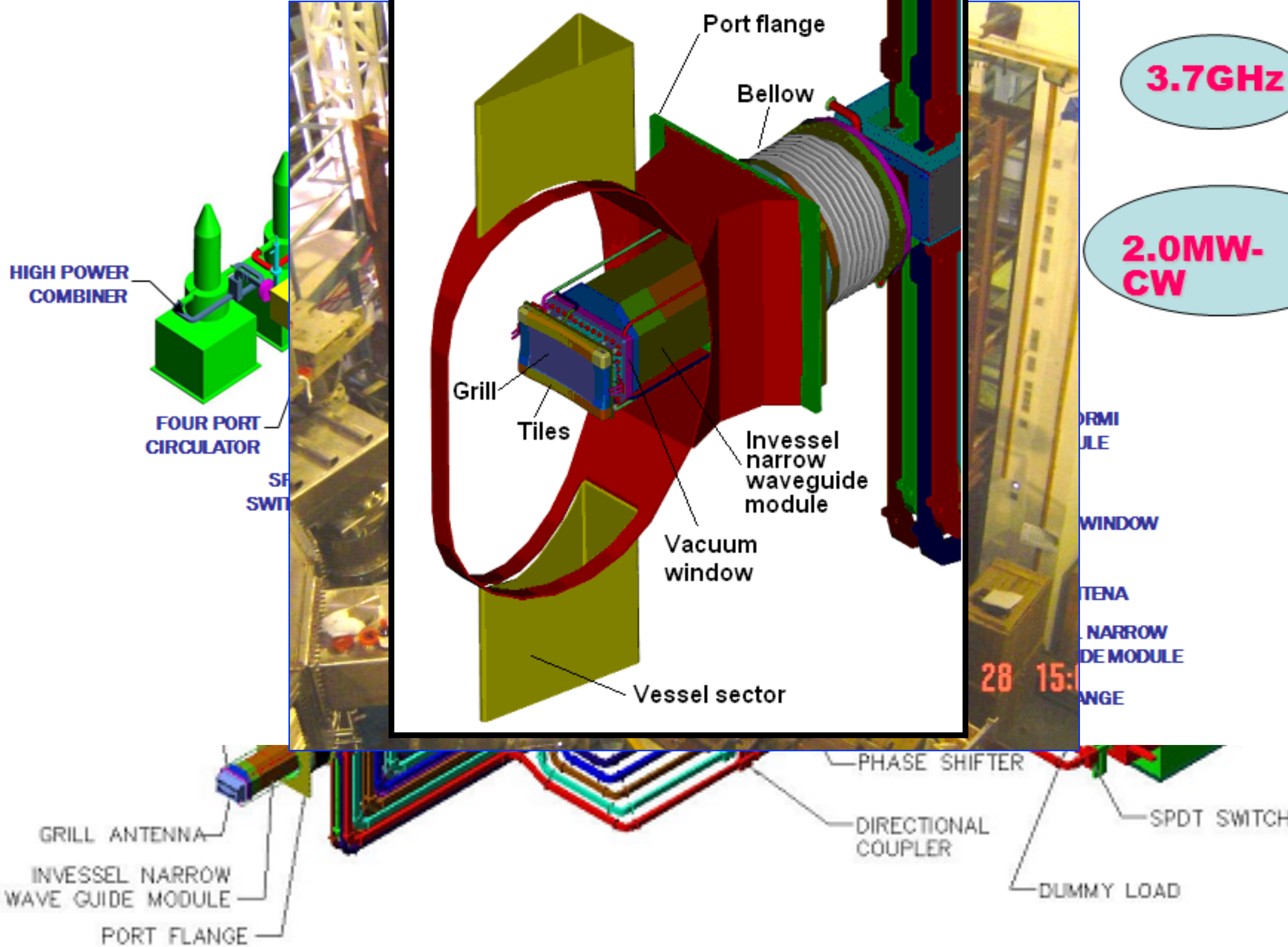
DI/dt and breakdown time





3.7GHz

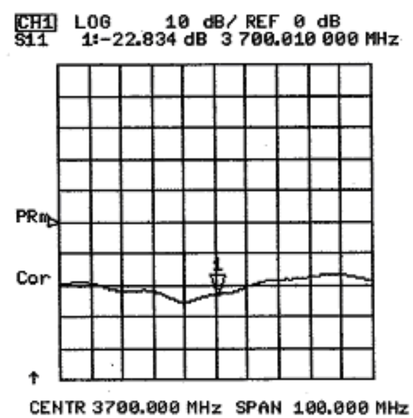
2.0MW-CW

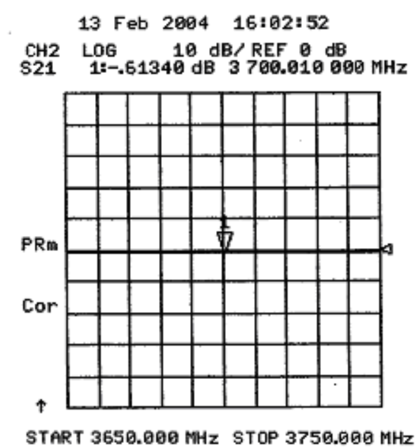


HP Divider section

Transforming module

- The length of the transmission line is ~2.0m
- Unique process - CNC milled long copper plates are stacked sequentially
- Enclosed in SS enclosure for pressure compatibility.
- Avg. insertion loss of –0.6 dB, and avg. return loss of –20 dB.
- Measured cross talk is ~ -45 dB.
- Actively water cooled for CW operation.





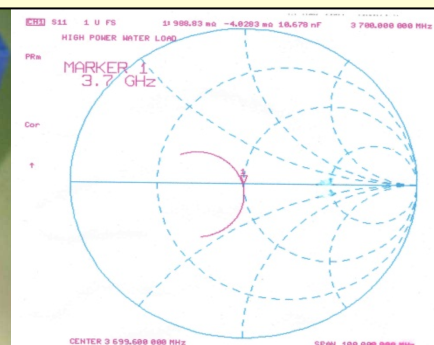
HP component development

HP Transformer

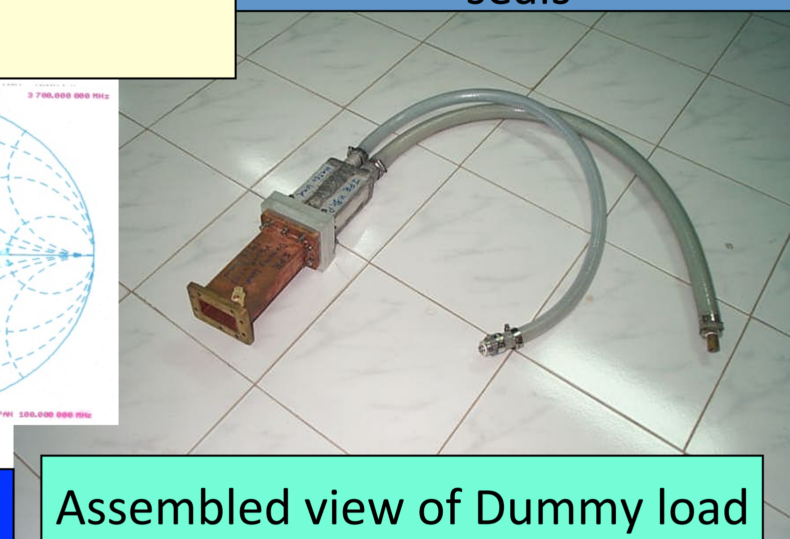
High Power Magic Tee

Radiation tight conducting seals

High Power CW water dummy load developed & tested at 3.7 GHz in IPR

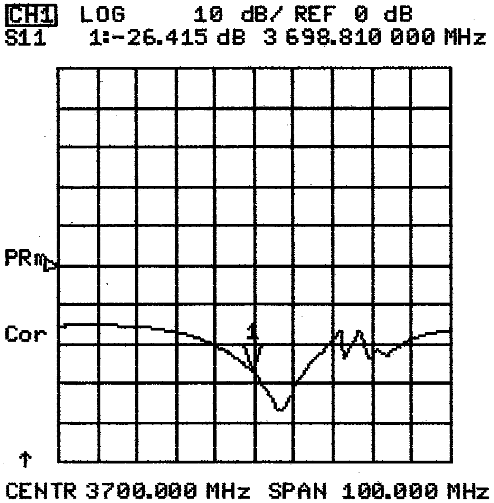


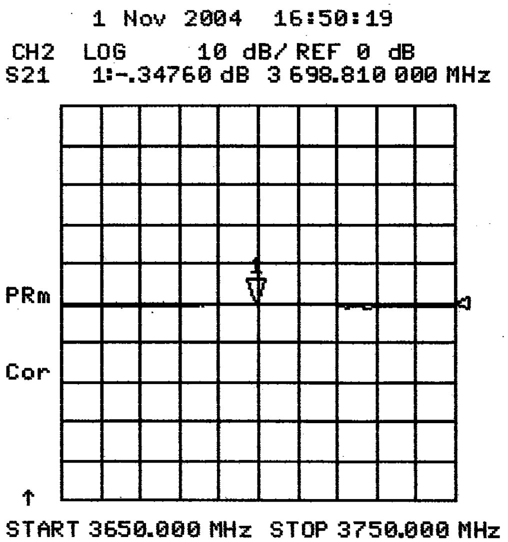
VSWR at I/P



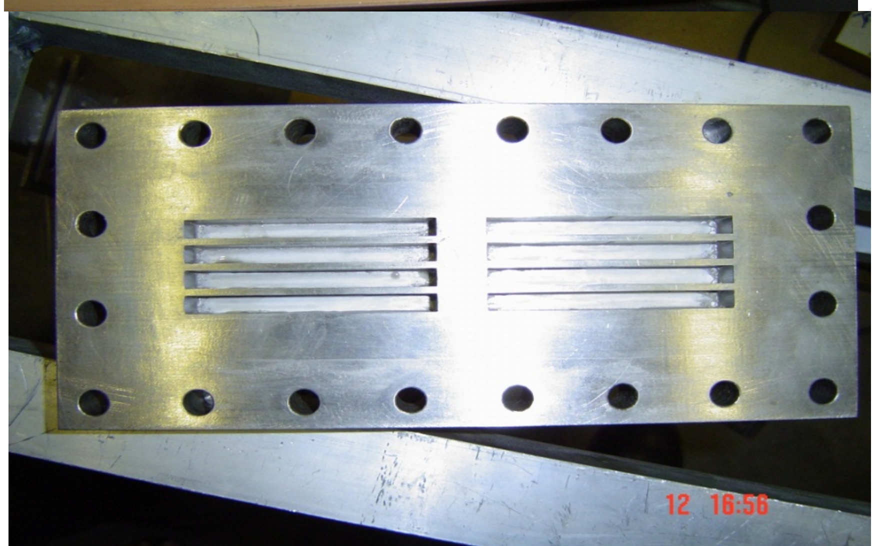
Assembled view of Dummy load

Invessel multiwaveguide module





Vacuum window development



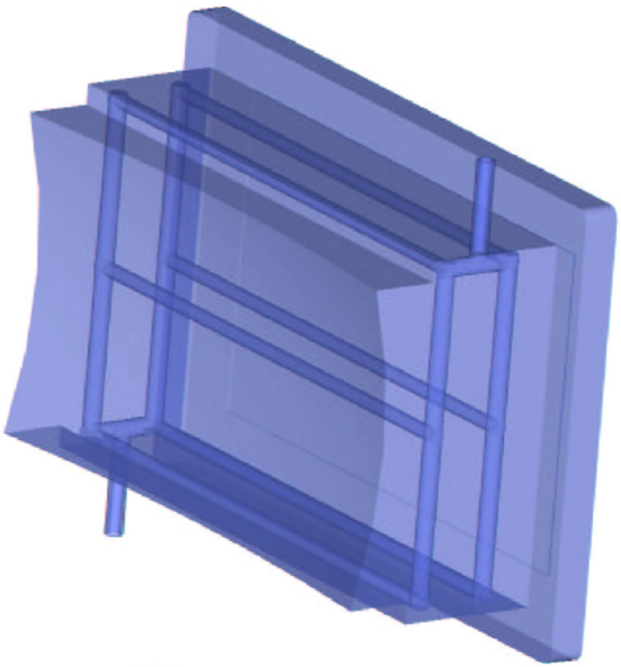
Vacuum windows, a very important part of LHCD system is designed, developed & tested at IPR.

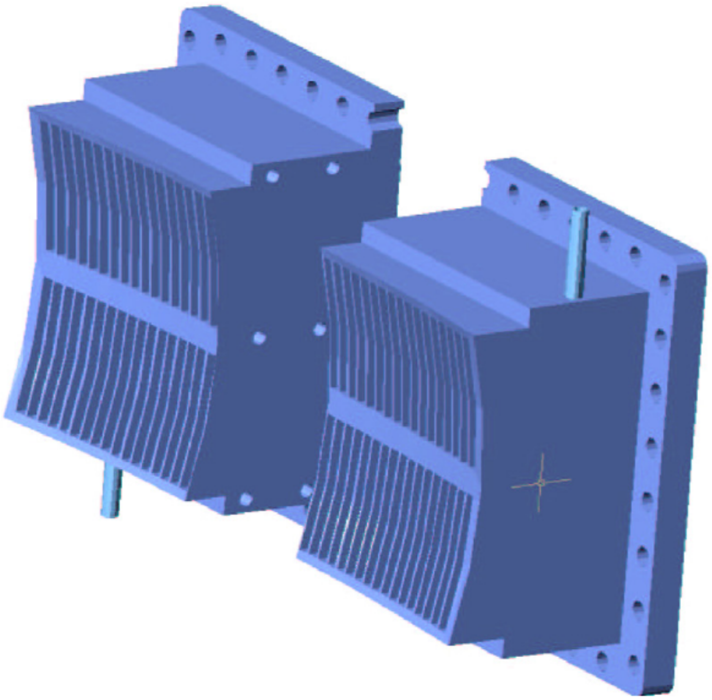
Single and multiple windows, comprising of ceramic material (Al_2O_3) and different flange materials like copper, copper alloy, SS, titanium, etc. developed successfully.

Vacuum brazing of multiple window carried out successfully in collaboration with CEERI.

The window showed an insertion loss of about 0.15 dB with a return loss of better than 25 dB

Thermal management of grill antenna



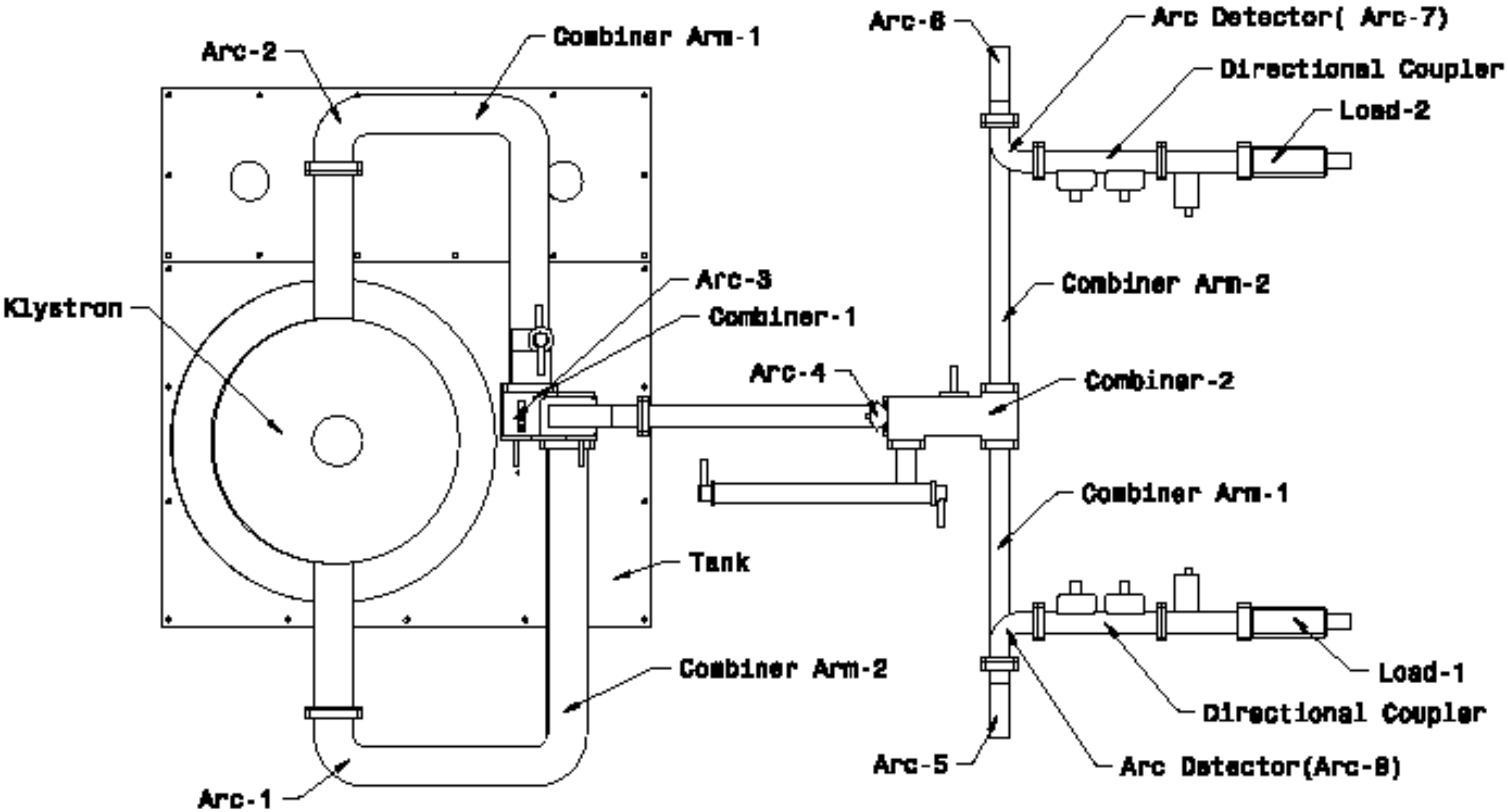


Typical tube parameter

Main characteristics of the klystron tube

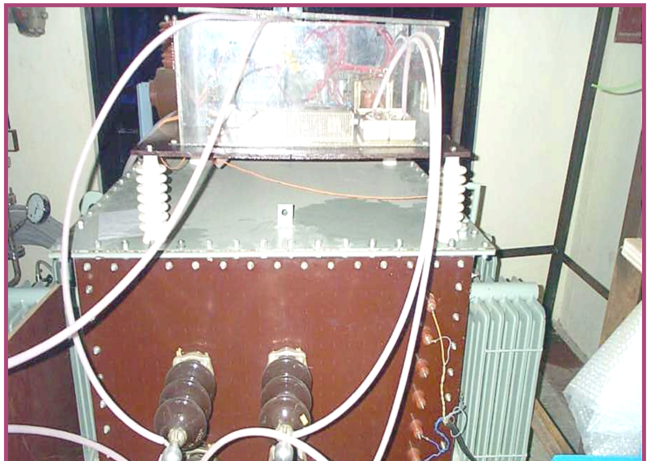
Frequency (GHz)	3.7	Max. load VSWR	~1.2
Power (kW-CW)	500	Type of drive	Solid state
Beam voltage (kV)	65	Efficiency (%)	~40
Beam current (A)	20	RF drive power (W)	5–7
Gain (dB)	~47		

High Power Klystron Test Bed



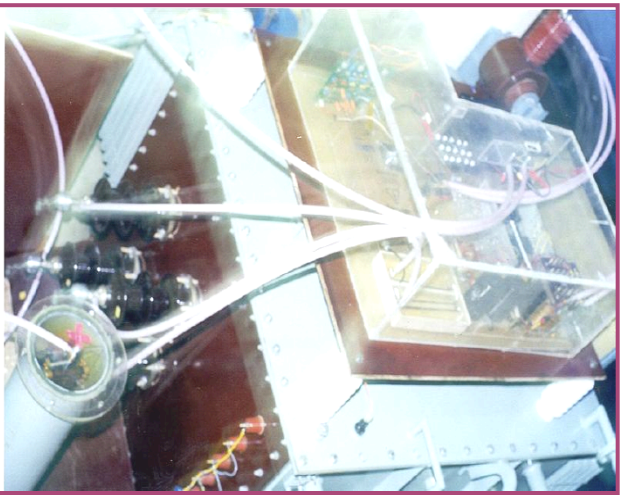
Auxiliary PS

11kV (ac) Voltage Variation system: It varies input ac voltage for HV DC PS.



YU155 tetrode based AMPS (0-60kV, 50ms–1000s). Remote control & monitoring.

Solid state based crow bar system (Thyristor based)



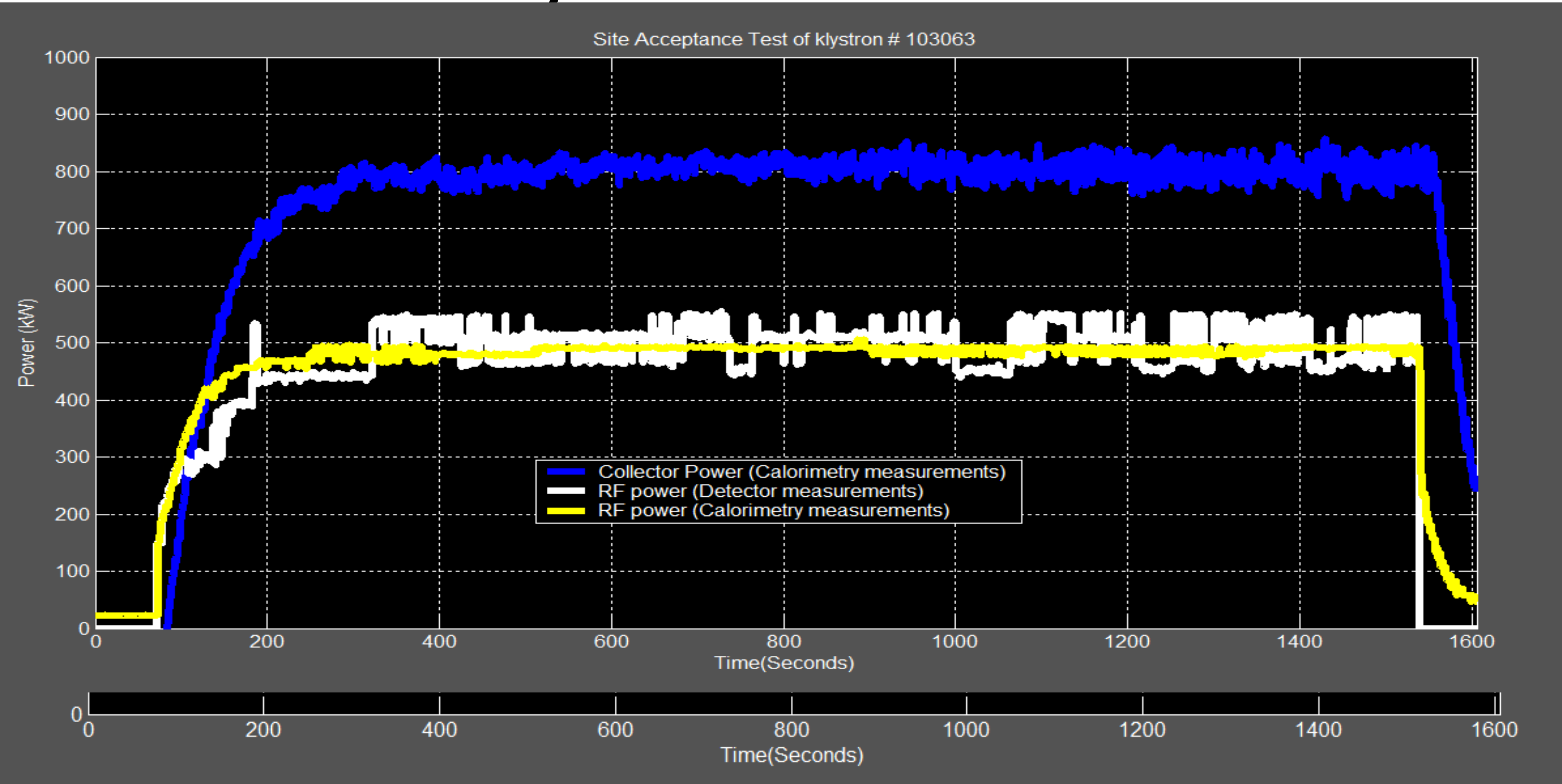
2kV, 100mA Bias Voltage PS: **It is used to suppress dark current that flows when anode pulse is absent. This power supply is designed to float at 120kV DC.**

AMPS Control Panel: **For synchronization if necessary and controls Tetrode, operating in its linear range.**

Filament PS: **12V, 50A, Soft Start 130kV DC Isolation Over Voltage & Over Current Protection.**

Magnet PS: **Provides beam collimation.**

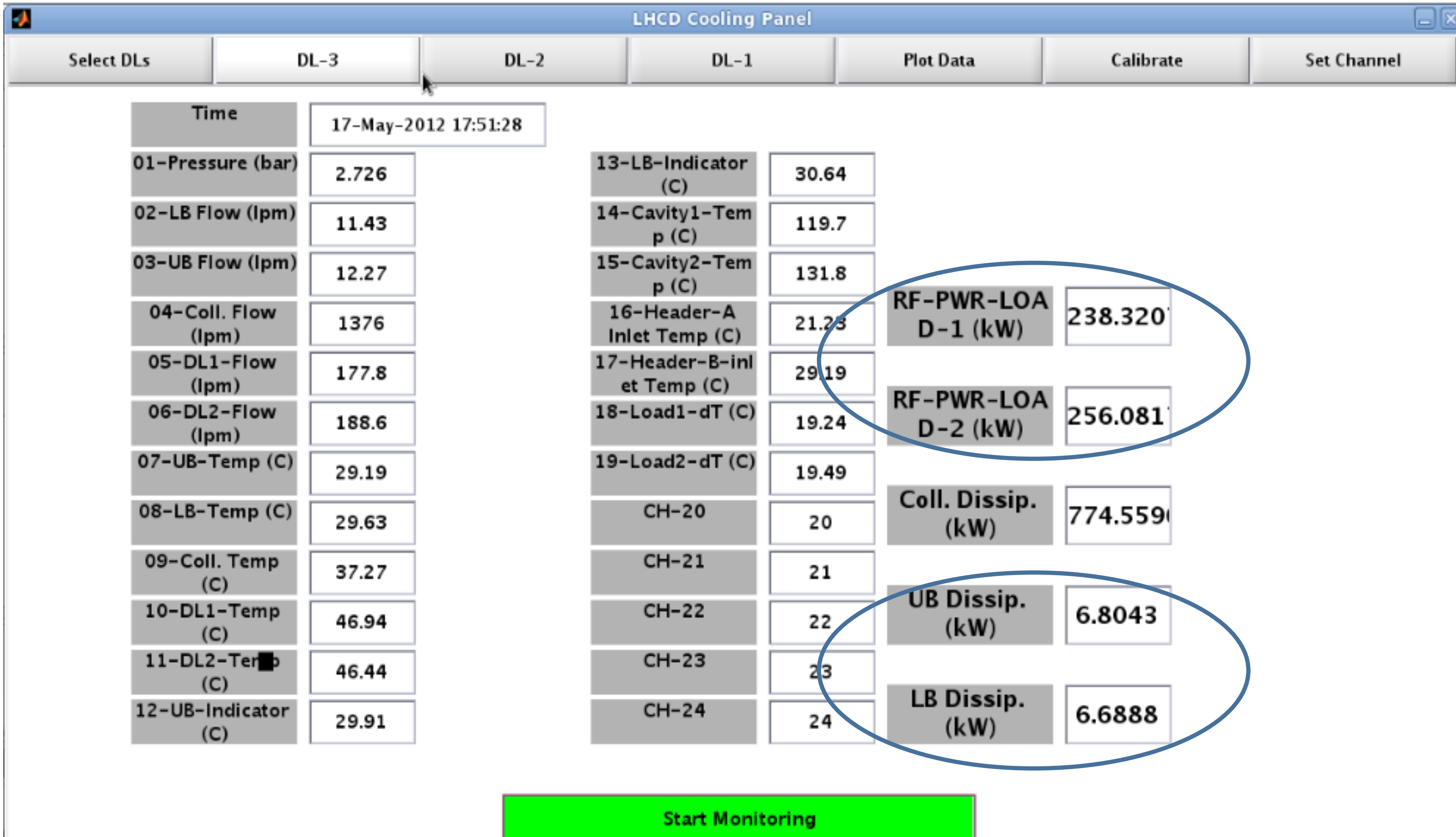
HP Klystron test results



Immediate response during HP operation

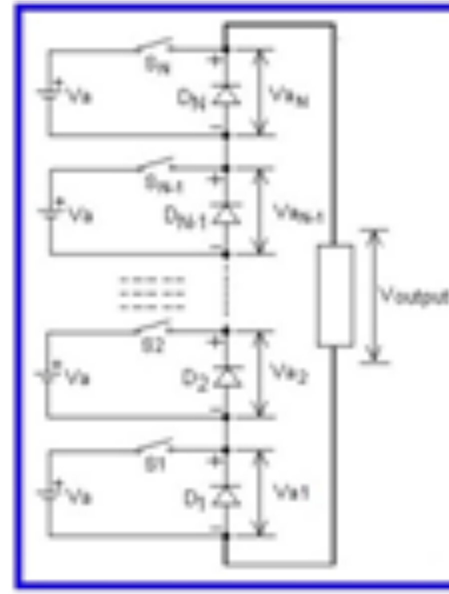
Stationary & efficient thermal management

On-line display of important parameter

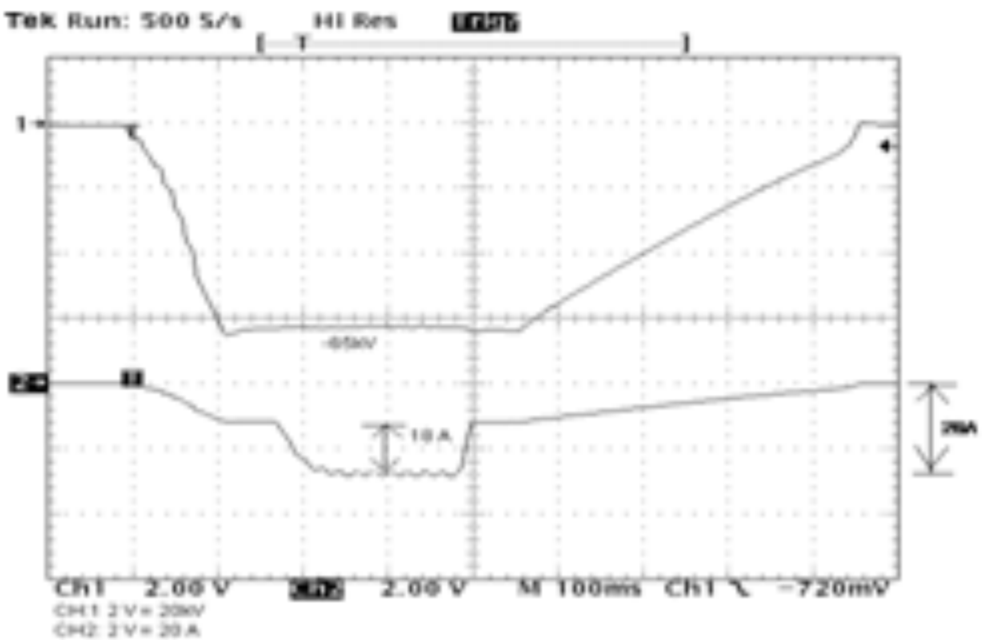


RHVPS details

Multi-secondary tx-former

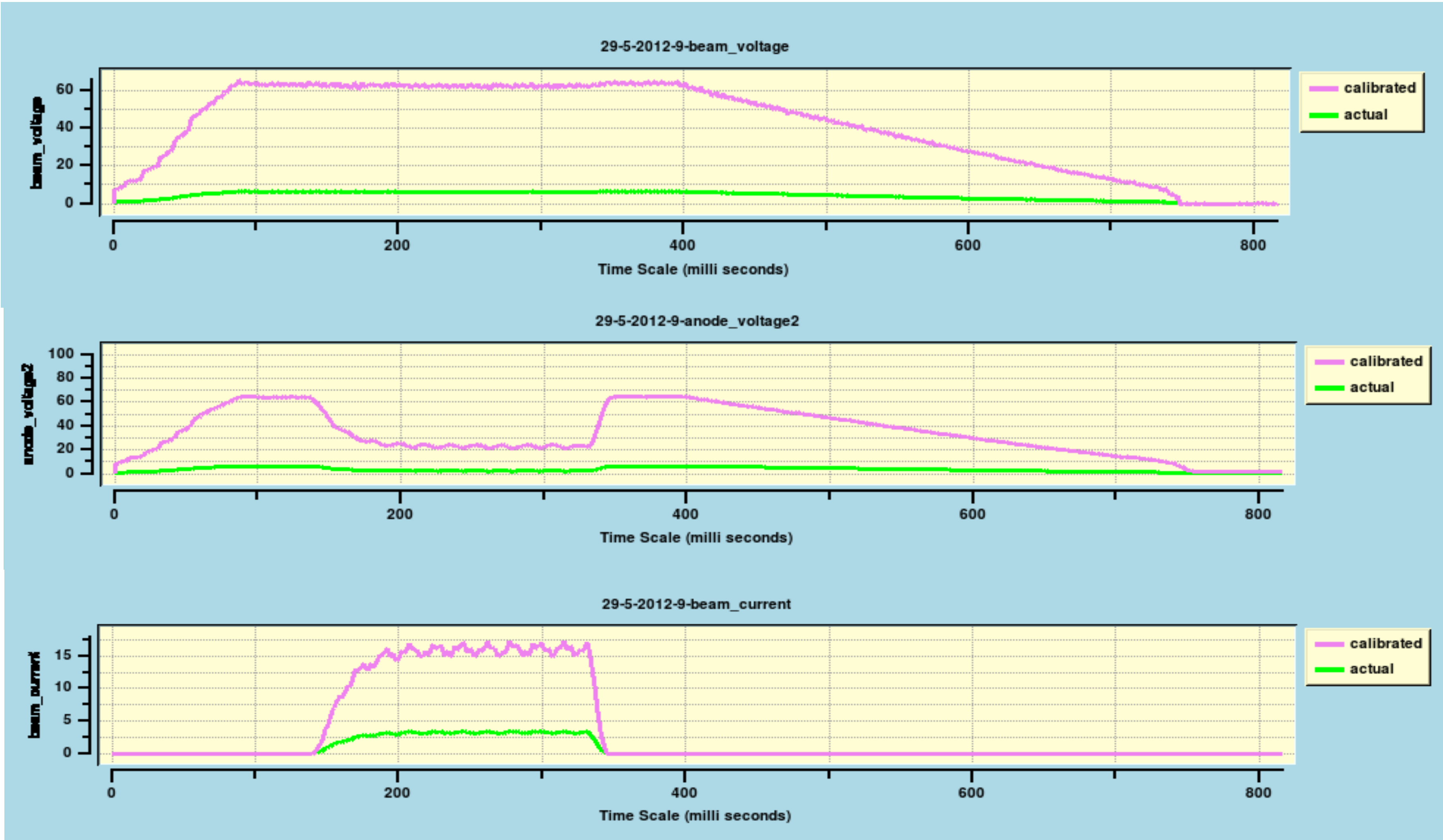


RHVPS working principle

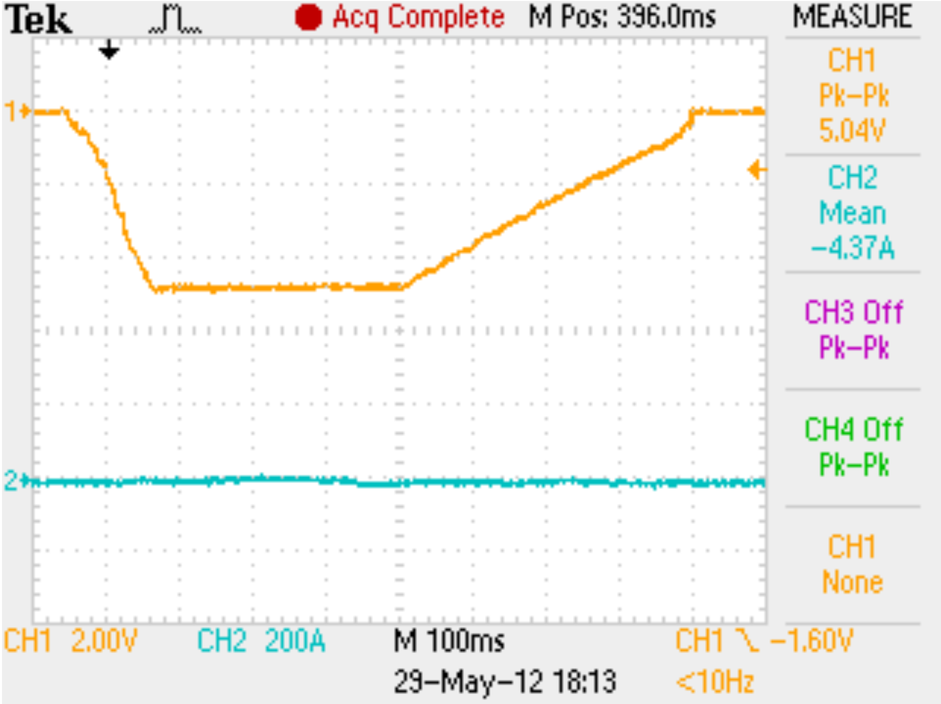


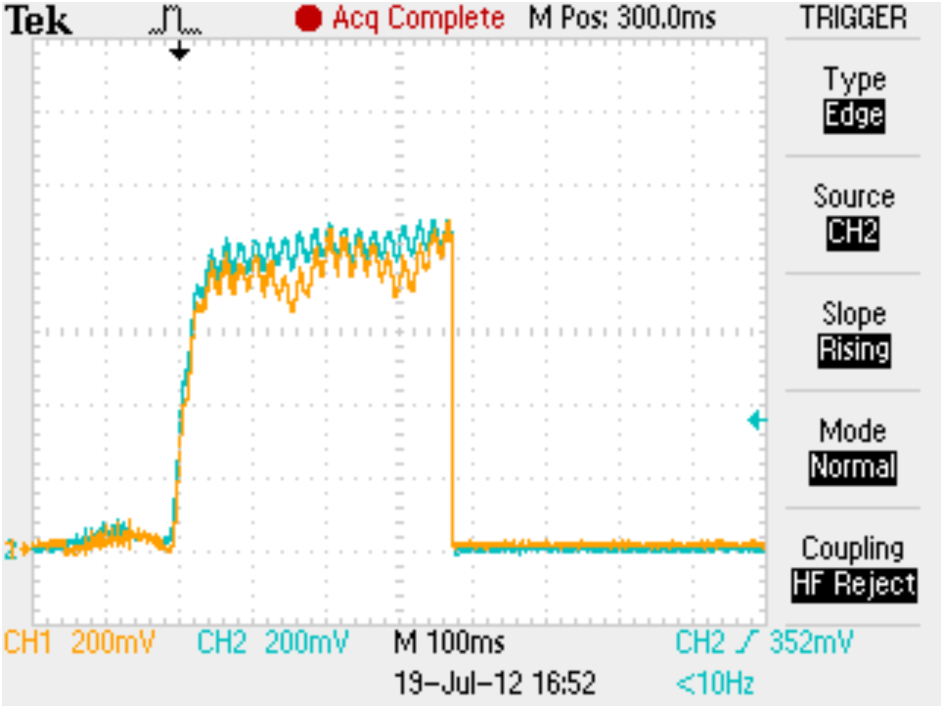
Parameters		Values
Input		11kV, (+/-)10 % , 50 Hz, THD < 5%, P. F. >0.9
Output Voltage	Range	Up to (+/-) 100 kV
	Stability	< 1 %
	Ripple	< 1%
Voltage Rise/fall times		~10 μsec to 100 mSec (Settable)
Transient Response		< 50 mSec
Duty Cycle		1000:5000 S (CW possible)
Load/Line Regulation		0.5 %
Max. Output Current		75A
Overall Efficiency		97 %
Fault Shutdown time		< 2 μSec
Fault Energy		< 10 Joules

Operation with RHVPS (Relevant for ADITYA operation)



Typical RF output @ 50kV

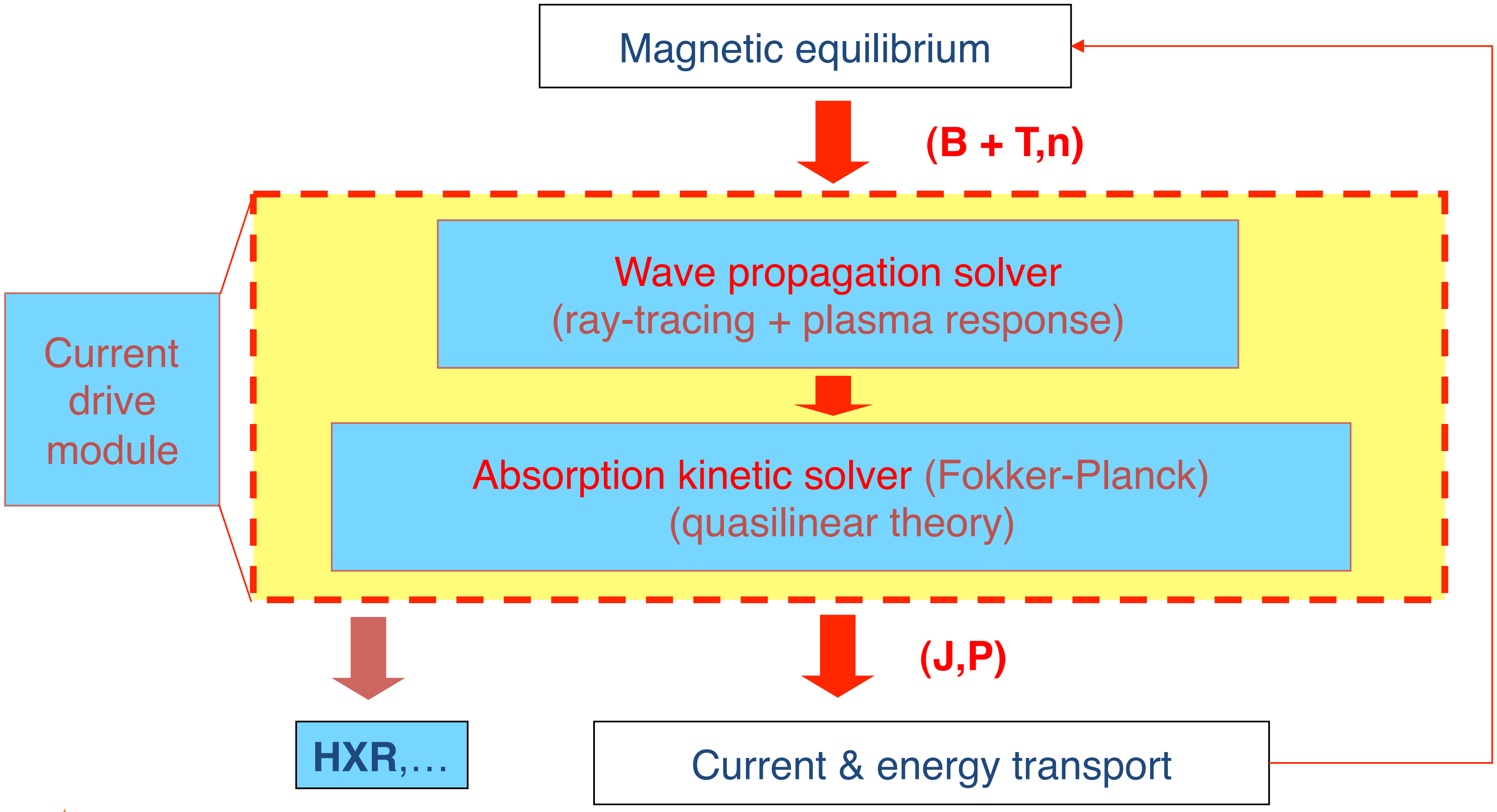




Simulation work

- Several simulation codes have been used to establish LHCD performance.
  - ACCOME
  - TSC/LSC
- Under collaboration with CEA for LHCD activities (A. Becoulet, G. T. Hoang, Y. Peysson, J. Decker, V. Basiuk, M. Goniche, et. al.), recently we have modelled LHCD performance using CRONOS package.

The Current Drive Module



A set of three tools

- C3PO: Universal ray-tracing

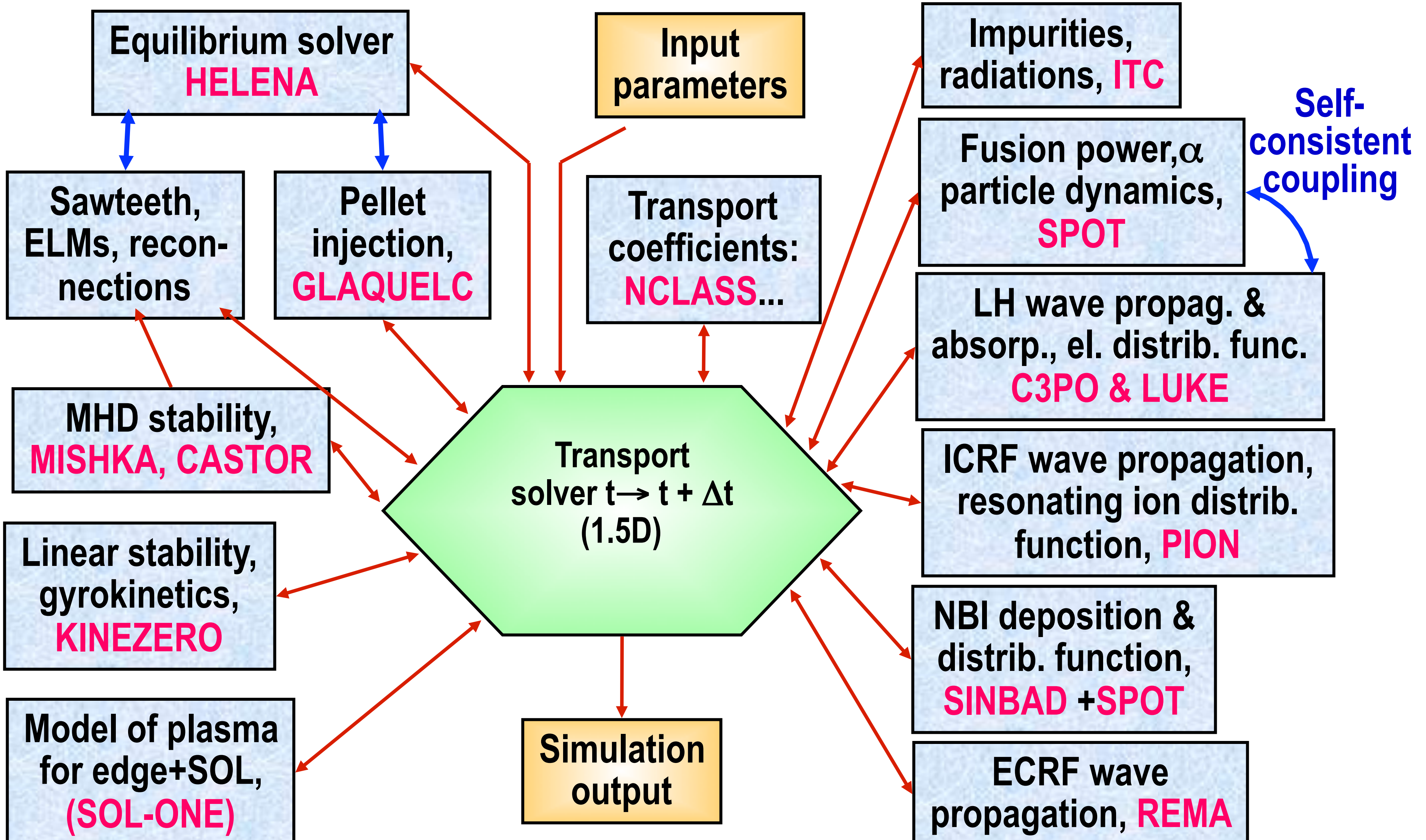
multi-wave (LH, EC, EBW, light)
arbitrary dielectric tensor (cold, warm, hot, relativistic)
arbitrary vectorial tokamak magnetic equilibrium

- LUKE: 3-D relativistic bounce-averaged drift kinetic solver: *thin banana limit, arbitrary tokamak magnetic equilibrium, anomalous fast electron radial transport consistent with quasilinear theory, multi-wave (LH, EC, EBW), runaway electron avalanches, bootstrap current. Time evolution (Crank-Nicholson), fully implicit or reverse time scheme ($t=+\infty$), incomplete LU matrix factorization, parallel + distributed processing (MUMPS, PETSc,…)*

-R5-X2: Relativistic bremsstrahlung (e-i + e-e)

multi-model (classical, semi-quantic, fully quantic)
arbitrary tokamak magnetic equilibrium and diagnostic configuration. Pile-up modeling.

The CRONOS Platform



Typical simulation scenarios considered for SST1

	Case 1	Case 2	Case 3
κ	**1**	**1.8**	**1.8**
δ	**0**	**0.7**	**0.7**
B_t (T)	**1.5**	**1.5**	**3.0**
I_p (kA)	**110**	**150**	**220**
n_{e0} (10^{19} m^{-3})	**0.75**	**1.2**	**1.5**
T_{e0} (keV)	**1.37**	**1.7**	**3.1**
T_{i0} (keV)	**0.55**	**0.67**	**1.2**

Typical profiles parameter assumed for LUKE input

$$T\left[n\right]\left(\psi_n\right) = T_0\left[n_0\right]\left(1 - T_1\left[n_1\right]/T_0\left[n_0\right]\right)\left(1-\psi_n^2\right)^{\alpha_{T[n]}} + T_1\left[n_1\right]$$

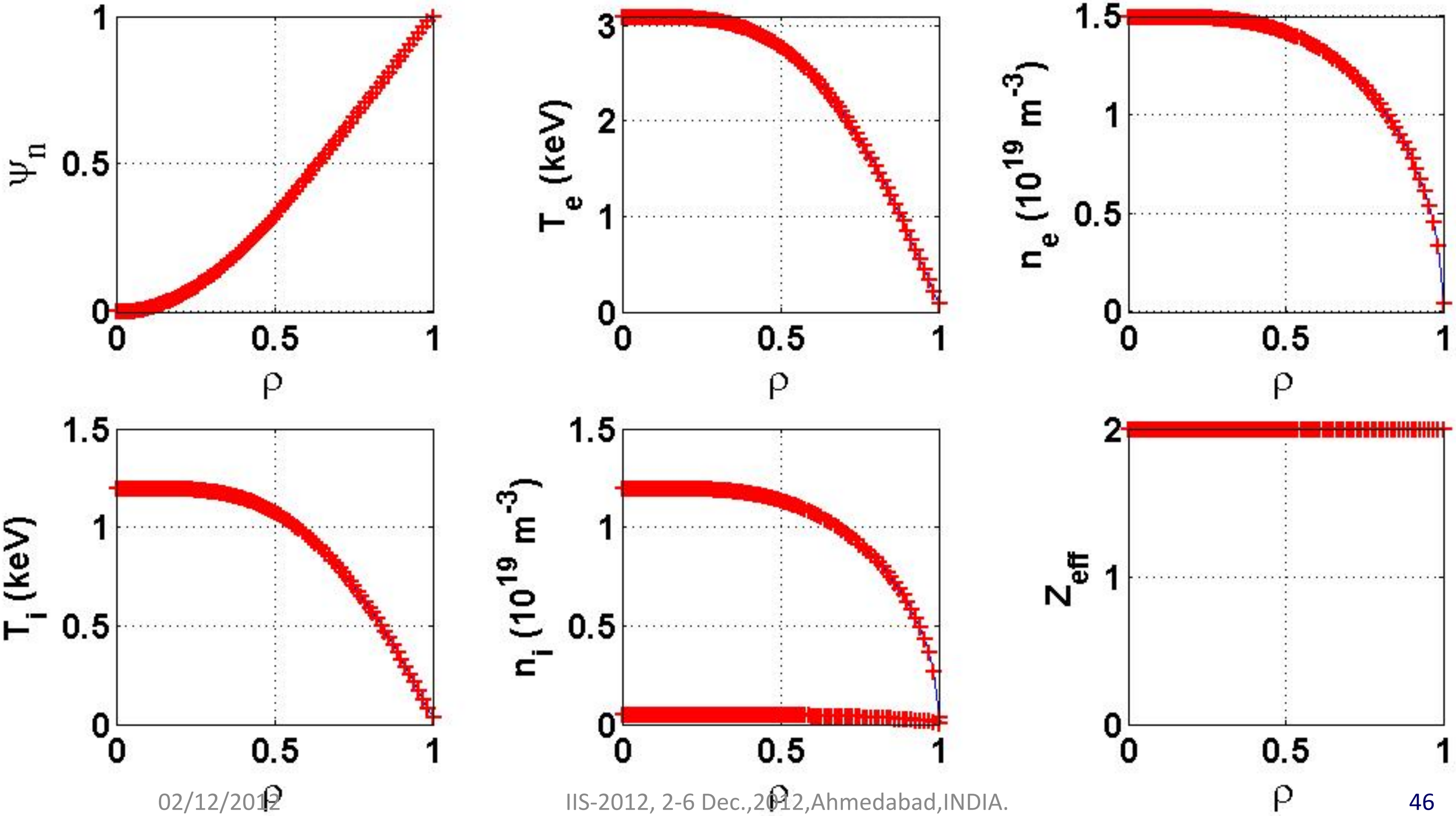
$T_1[n_1]/T_0[n_0] = 0.03$

$\alpha_T = 1$ and $\alpha_n = 0.5$, either for ion or electron populations.

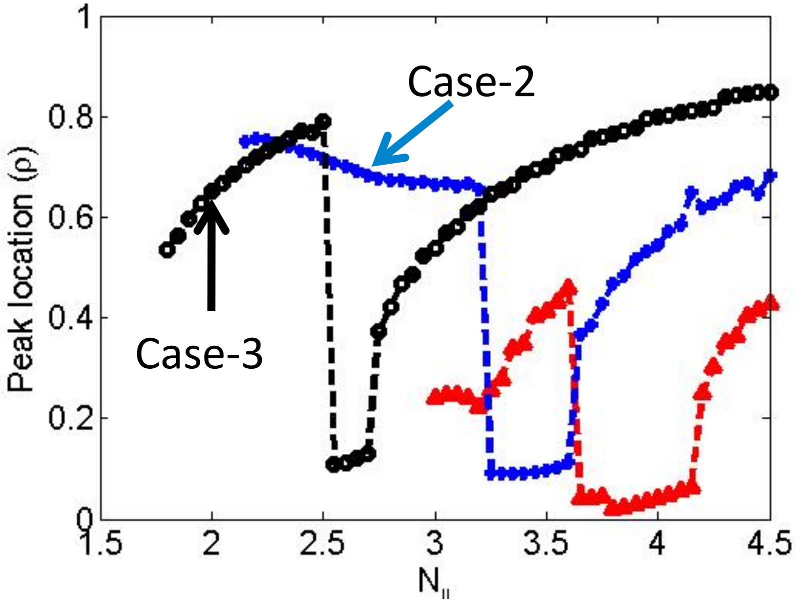
For all simulations, $Z_{eff} = 2$, and its profile is considered to be flat.

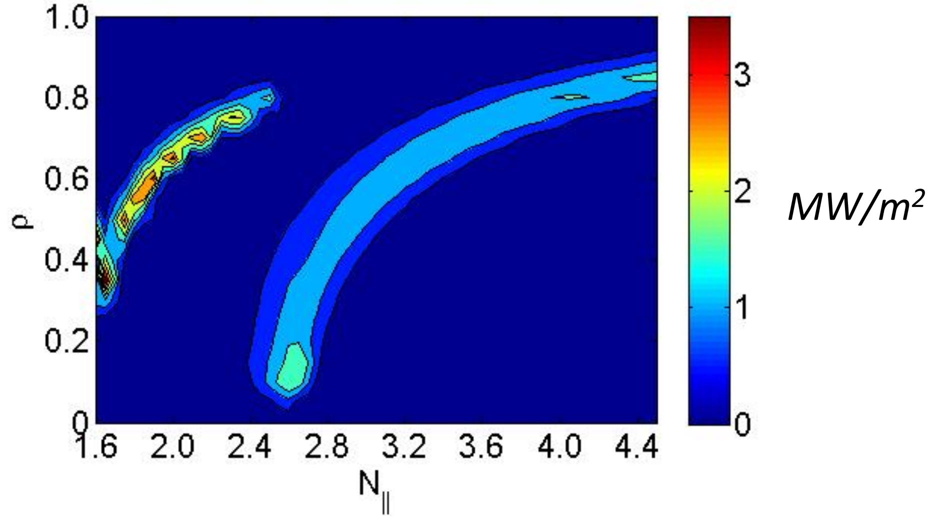
Calculations are performed for a hydrogen plasma with carbon as the single fully stripped impurity. From the effective charge Z_{eff} and the electron density profile, it is possible to calculate the corresponding ion density profile, without the use of an impurity transport model.

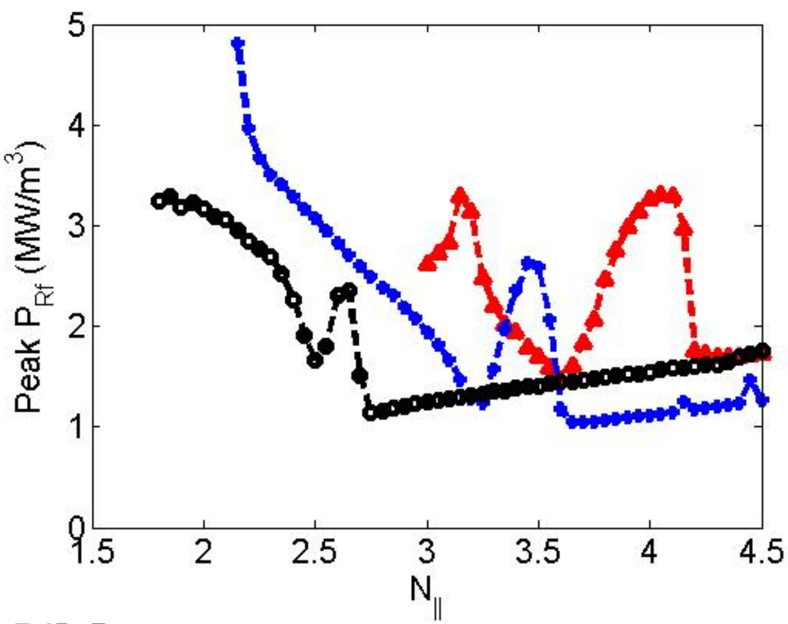
Typical plasma parameter (case-3) for SST1

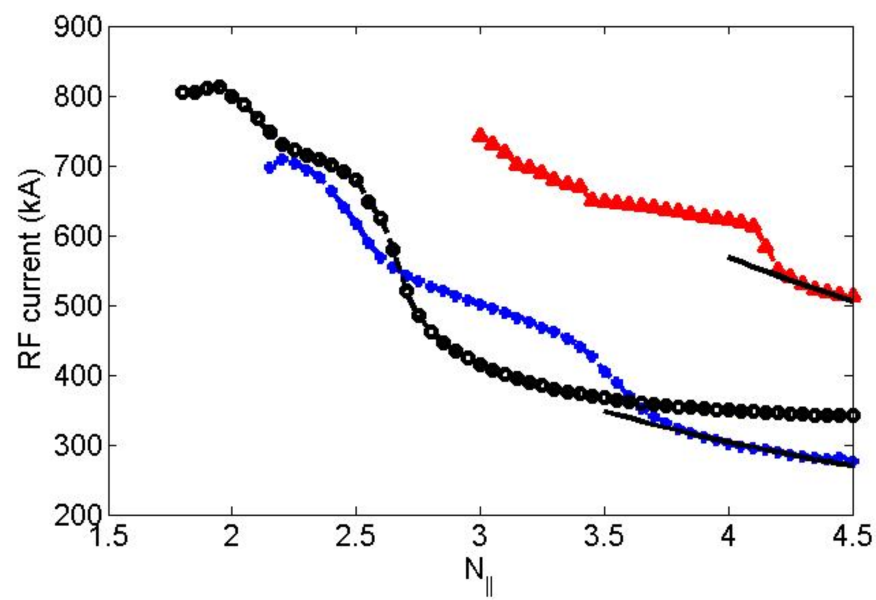


Observation of two distinct regime (single pass & multipass)

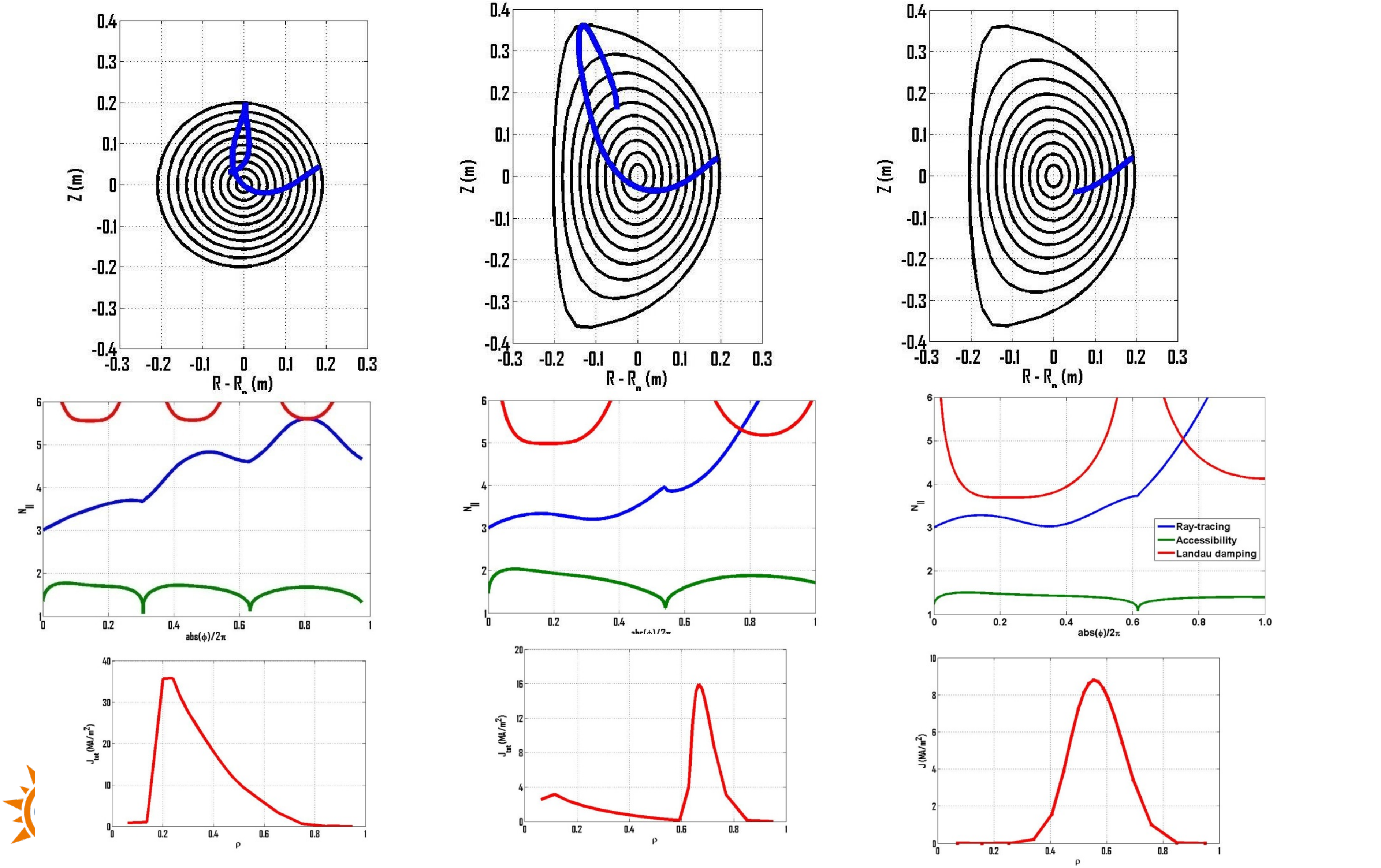




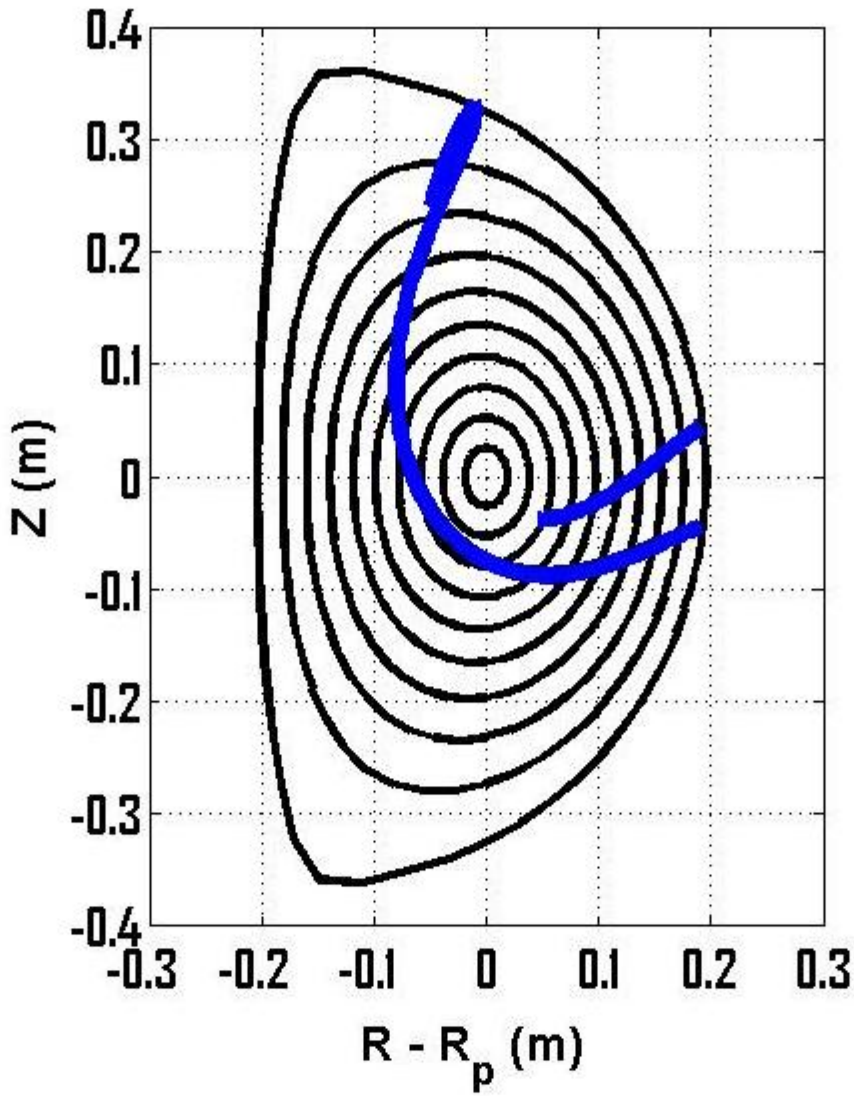


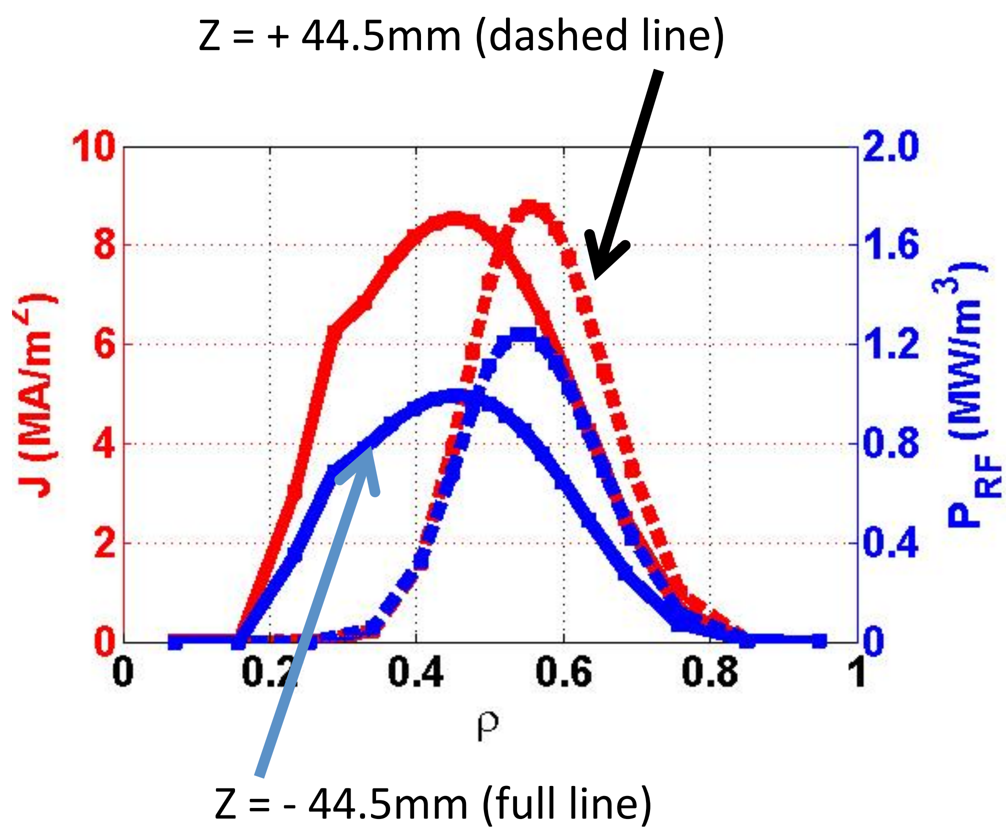


Ray trajectories, upshift of $N_{||}$ and deposition profile for various cases



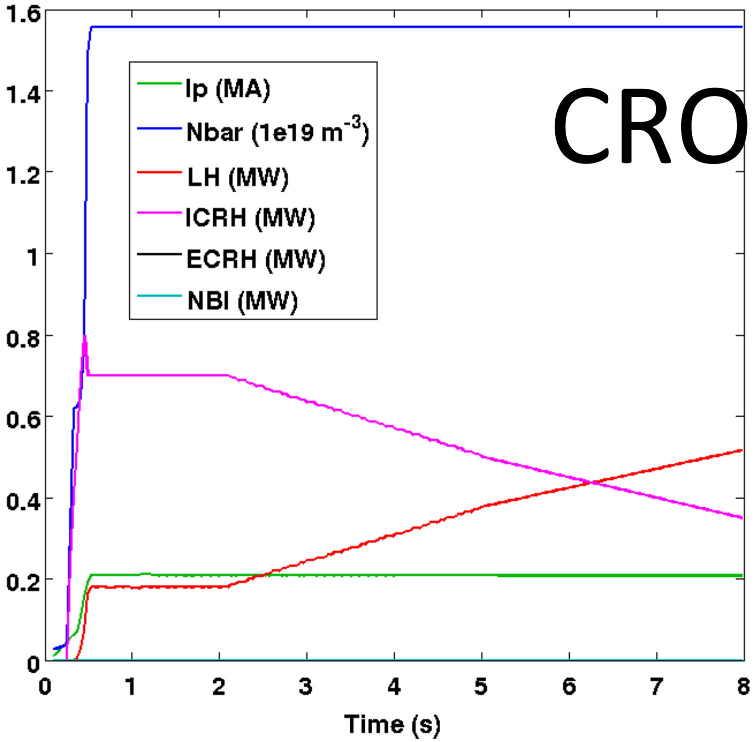
Up-down launch

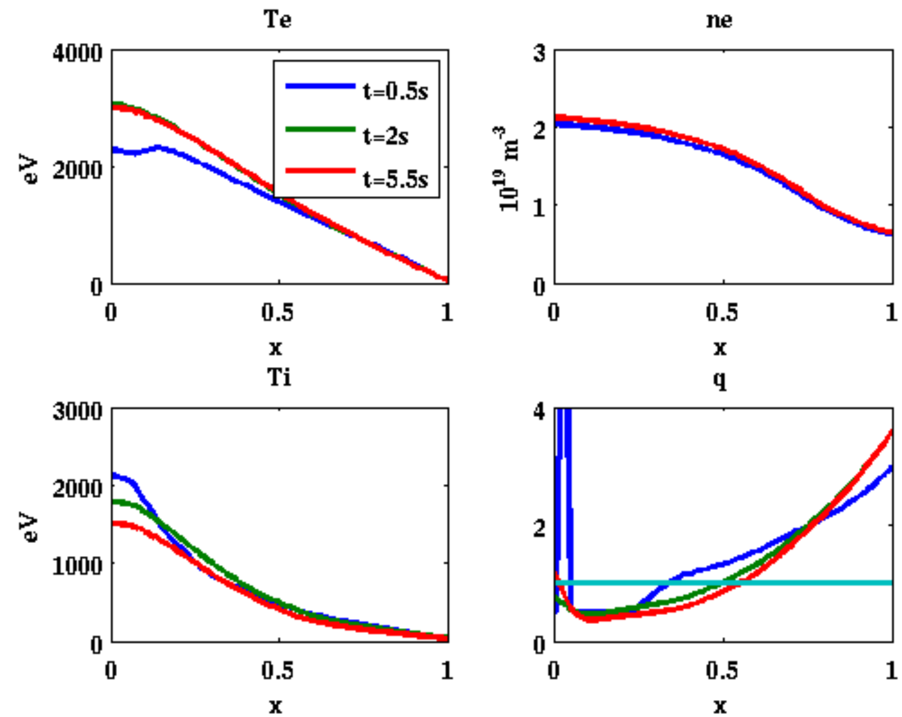


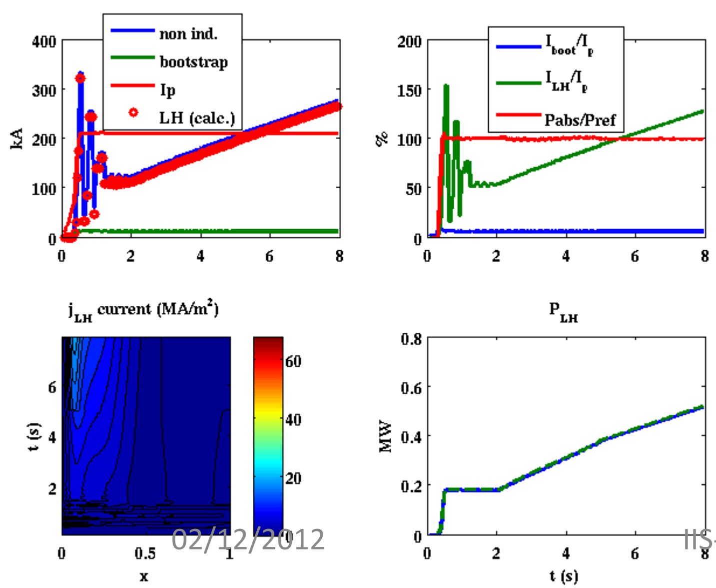


Profile is broader and radially in for bottom launch

CRONOS results for SST1







Conclusions and future plans

- ❑ LHCD is a mature method used in a large number of tokamaks
- ❑ In India, we have developed two LHCD systems for ADITYA and SST1 tokamak
- ❑ Design criterion for LHCD system is highlighted.
- ❑ A test bed to validate HP CW klystrons for rated power has been successfully developed.
- ❑ The klystrons have been tested for CW operation at rated power on water loads.
- ❑ At present two klystrons would be operated using a single modulator.
- ❑ If successful, all the four klystrons would be operated with single modulator.
- ❑ Finally all the four klystrons would be operated by single RHVPS.
- ❑ The LHCD components (inside machine) is being integrated for

Thank you for your kind attention