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Recent Advances in the HL-2A Tokamak Experiments

HL-2A team(Presented by Yong LIU)

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GA, San Diego, USA
JAERI, Naka, Japan
Kurchatov Institute, Russia
Kyushu University, Japan

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OUTLINE

- Introduction &Mission of HL-2A Project
- Engineering progress of the HL-2A
- Experiment Progress

Overview of HL-2A Tokamak

HL-2A is a divertor tokamak constructed at SWIP new site based on original ASDEX main components(magnet coils and vacuum vessel) and based on the experiences from HL-1/1M.

Up to now, HL-2A has operated at Ip = 320 kA, Bt = 2.2T, $n_e=4.2\times10^{13}cm^{-3}$ and discharge duration T_d = 1580 ms with both divertor and limiter configuration. FB control and siliconization have been used to enhance the performance of discharge.

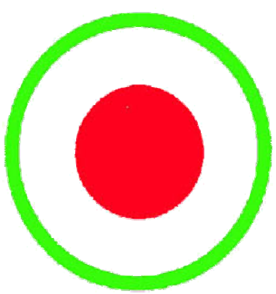
Further experiments will be carried out on the device in near future. Then HL-2A will be modified to be a much more flexible and elongated divertor plasma device with much large plasma volume.(HL-2M)

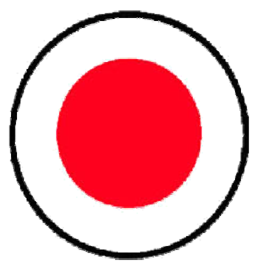
Tokamak Program in SWIP

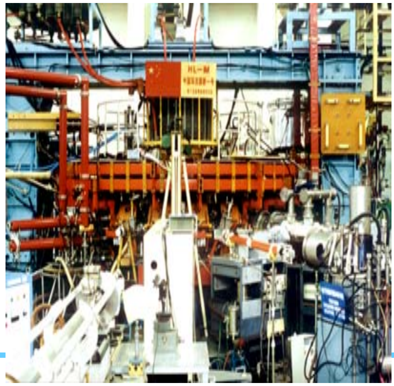
HL-1
1984-1992
R=1.02m
a=0.2m
Mo Limiter

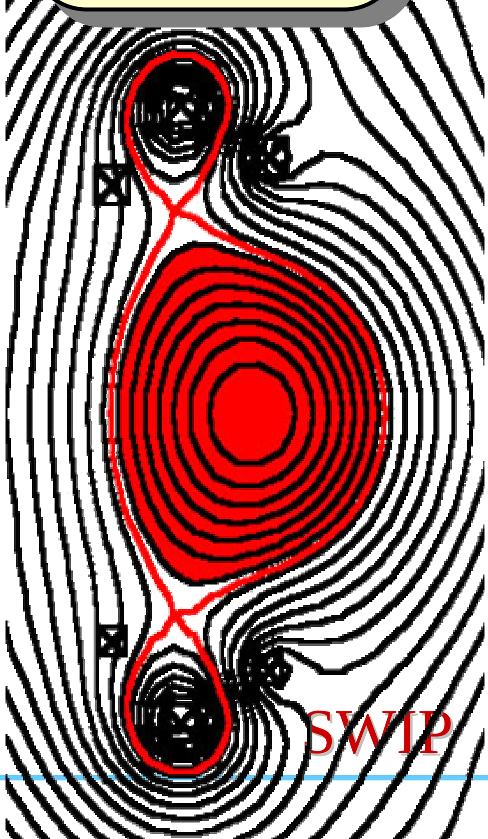
HL-1M
1994-2001
R=1.02m
a=0.26m
Graphite Limiter

HL-2A
2002-
R=1.65m
a=0.45m
Divertor









Mission of HL-2A Project

- Exploring physics issues which results could contribute to the database for the design and operation of a fusion reactor.
- Developing the scientific understanding on the key issues such as divertor plasma and elongated plasma control.
- Personal development in fusion research

Physics issues of HL-2A

- **Plasma control technique**

  Technique development of feedback control on plasma position and shaping with elongated divertor plasma

- **Core Plasma**

  Confinement improvement & transport

  Auxiliary heating & current drive

  MHD instabilities

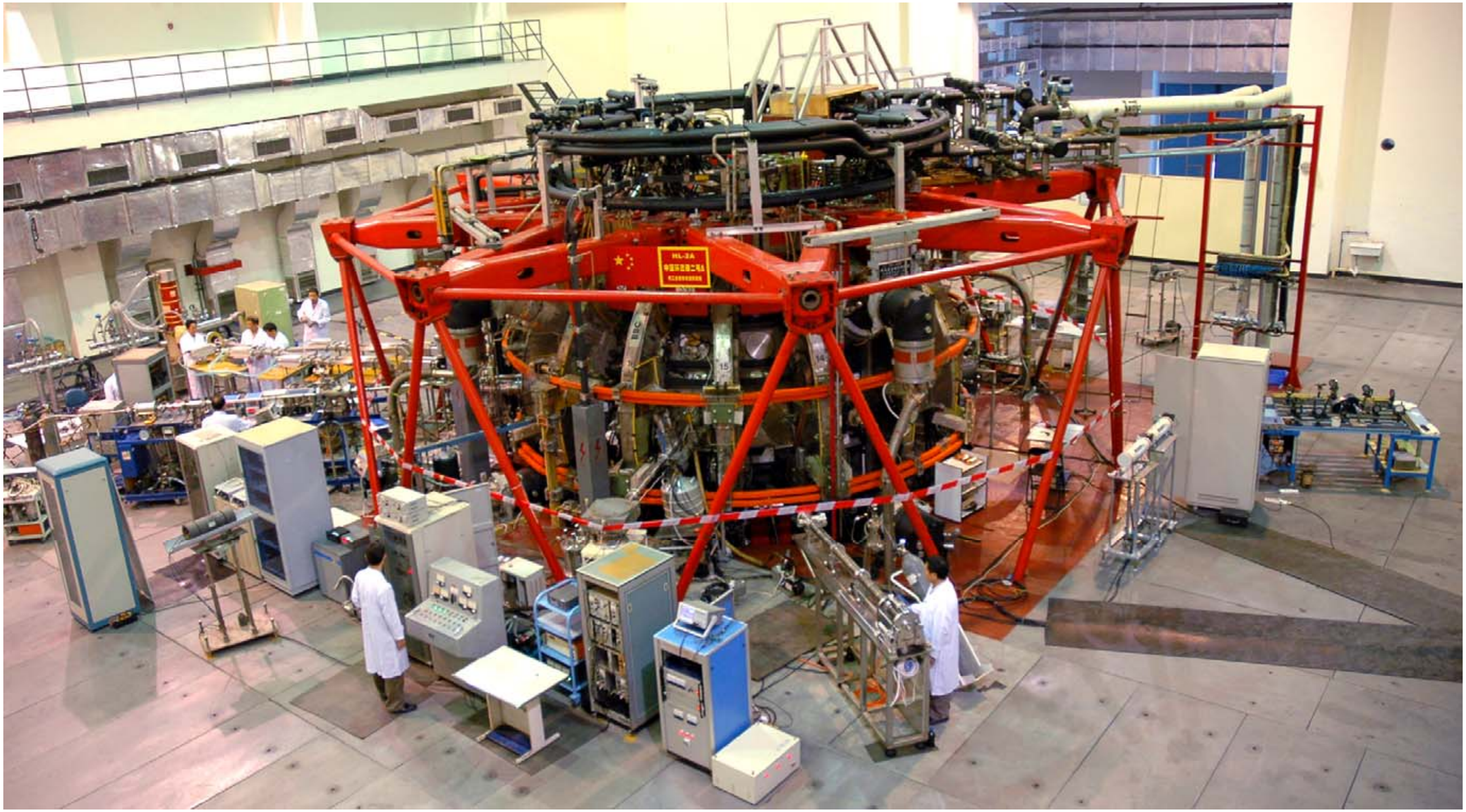
- **Divertor/Edge Plasma**

  Divertor & particle control

  Wall conditioning

  PSI and PFM development

Main issues of Fusion Phys.
Confinement & transport
MHD instabilities
Divertor
Energetic particle
(Except) Steady state



Photograph of the HL-2A Tokamak

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HL-2A Tokamak System

- Main machine & pumping system

  Reconstruction of the former ASDEX, Pumping 8×3500l/s, 2cryo-pump

- Power supply & control system

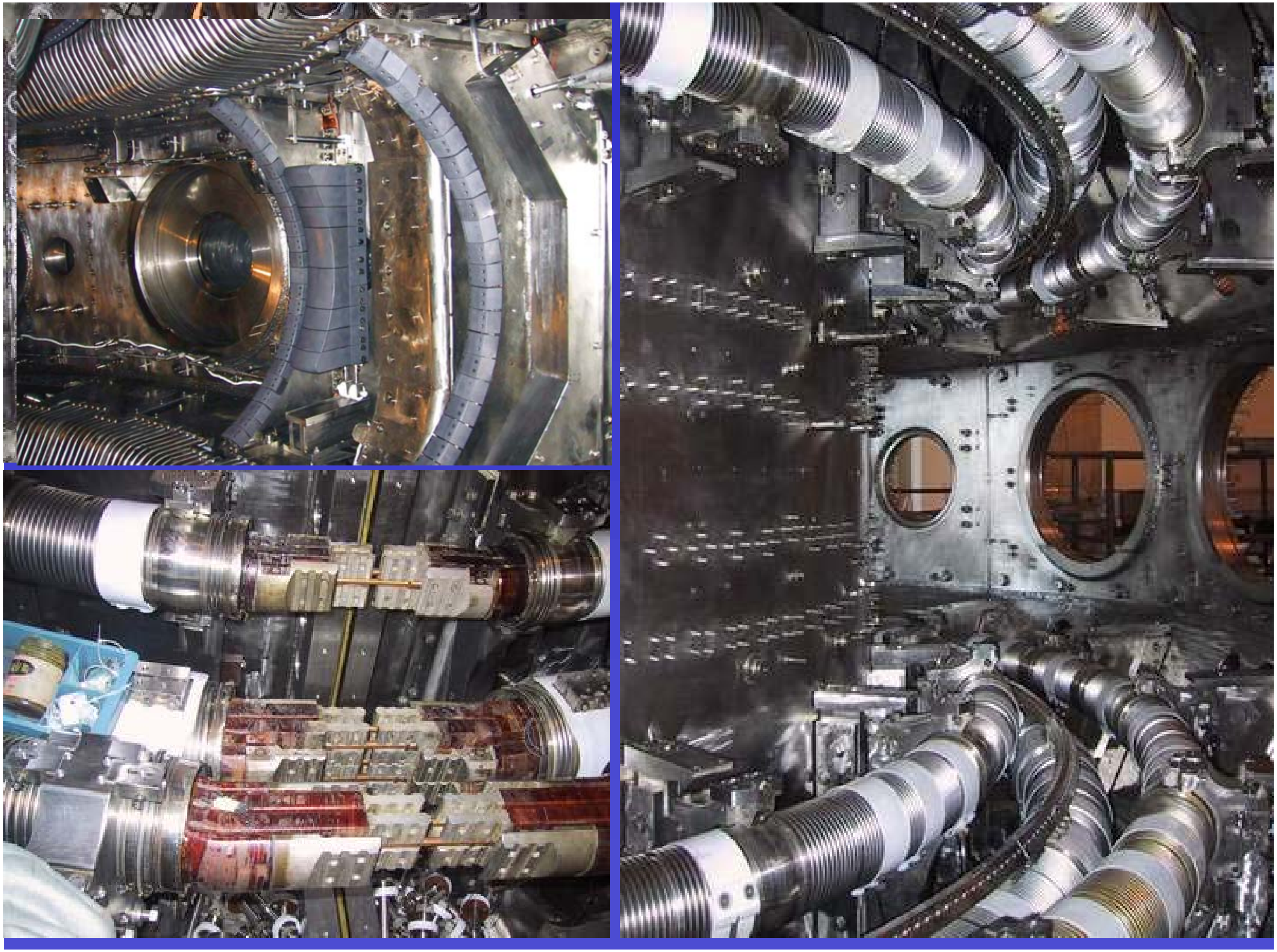
  305MW,1200MJ/shot, 8 sets PS, Logical protection & FB control

- Diagnostics: Up to 30 kinds

- Auxiliary heating & current drive system

  LHCD, NBI, ECRH

- Fueling system: GP, MBI, PI



View in Vacuum Chamber

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Power supply system of HL-2A

Two existing MG were modified for the toroidal field coils. 90MW×2, 500MJ×2

A MG is used to power the poloidal field coils. 125MW, 200MJ

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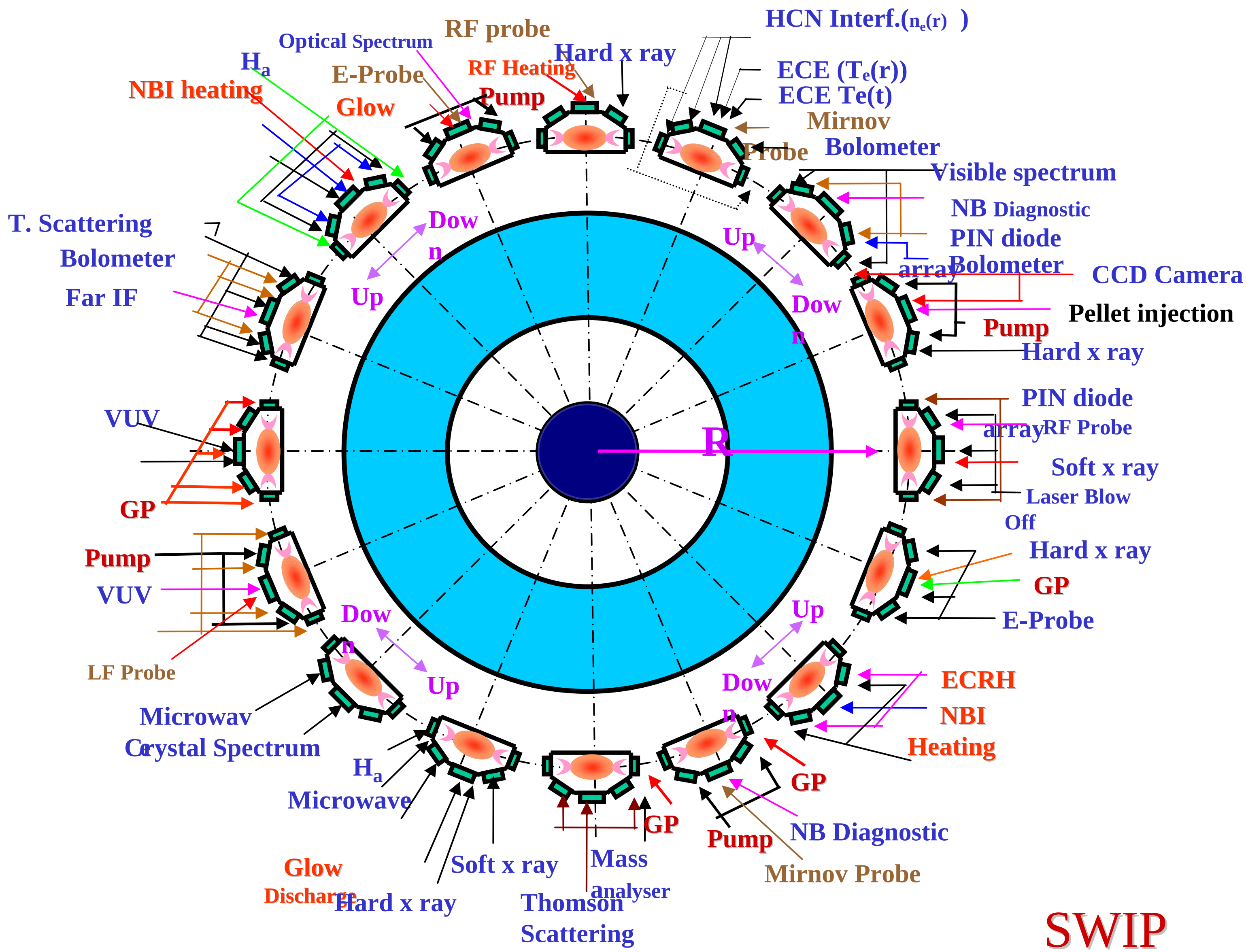
Control systems of HL-2A

Auxiliary Heating and Current Drive System

	Power (MW)	Energy/Freq.	Pulse Duration (s)
NBI	4(2)	60keV	2
LHCD	3(2)	2.45GHz	2(1)
ICRH	3(0)	80-100MHz	2
ECRH	1(1)	68GHz	1

The parameters in ( ) is for the Phase I

Diagnostics Layout on the HL-2A Tokamak



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Main diagnostics for the core plasma

- Thomson Scattering & ECE for $T_e(r)$
- Multi-channel HCN laser interferometer for $n_e(r)$
- SXR array for MHD & internal magnetic structure
- Bolometer array for radiation profile
- Visible & VUV spectrum
- Neutral particle charge exchange (and/or, charge exchange recombination radiation) for T_i (r)
- MSE (in plan) for j(r)

Main diagnostics for the edge plasma

- **Probe array**
- **Optical spectrum(such as H_{α})**
- **Infrared camera**
- **Bolometer array**
- **Neutral gas pressure measurement**
- **Ion species by mass spectrum (Omegatron)**

Progress of HL-2A Project

- The development and installation of the facilities were finished in September of 2002. The first plasma was obtained with limiter configuration in December 2002.
- Discharge with 170kA/920ms was achieved and divertor configuration operation achieved with SN up to October 2003.
- 320kA/2.2T/1.5s/ $4.2\times10^{13}cm^{-3}$ has been reached up to October 2004. FB control and siliconization have been used to enhance the performance of discharge. LHCD & pellet experiments are on going.

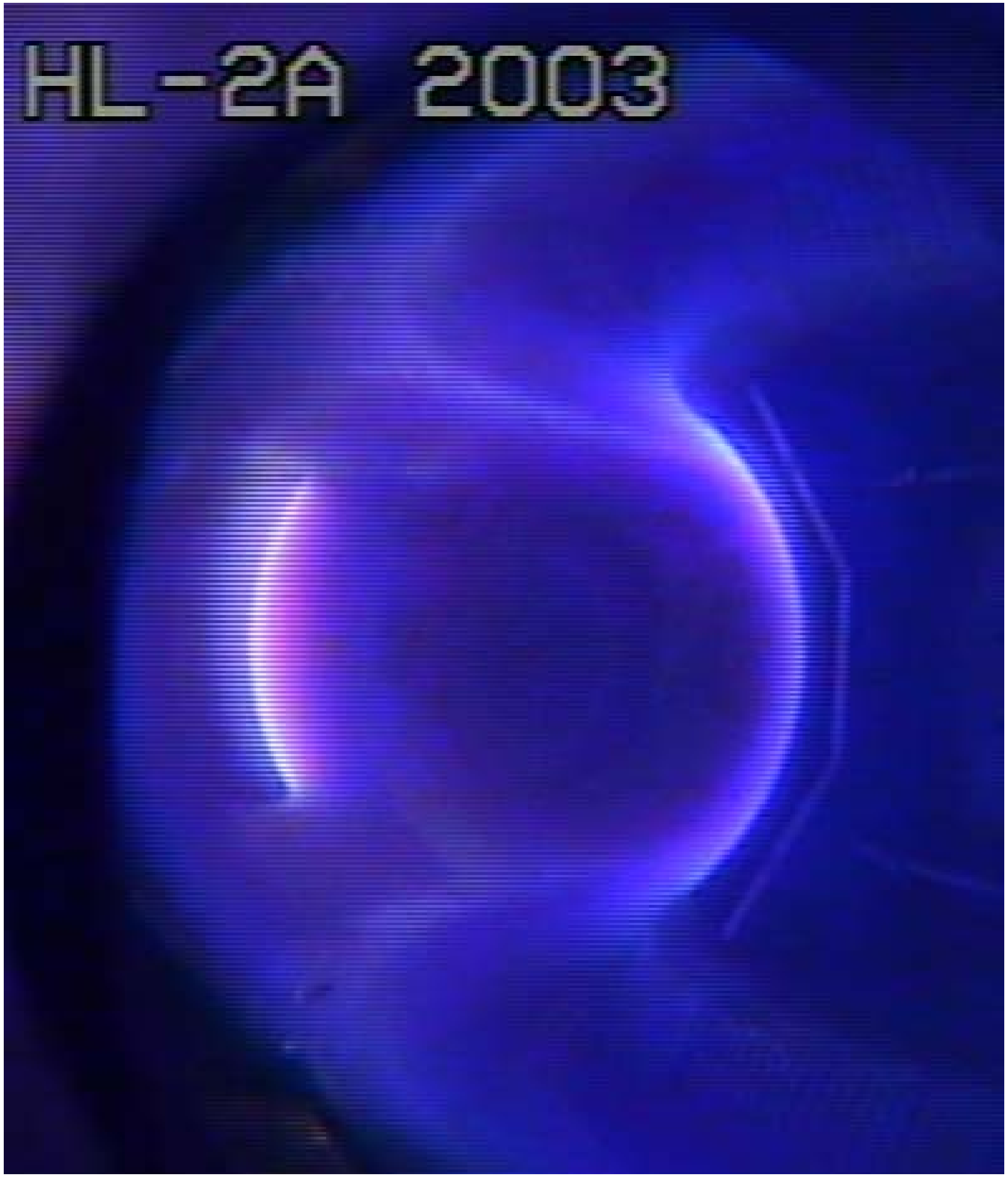


Image of a discharge with limiter configuration


HL-2A 2003
Video, SH:02033

Plasma boundary identification

- The plasma boundary has been reconstructed by CF code and FBI code.
- The identification results are consistent with the images by CCD camera.

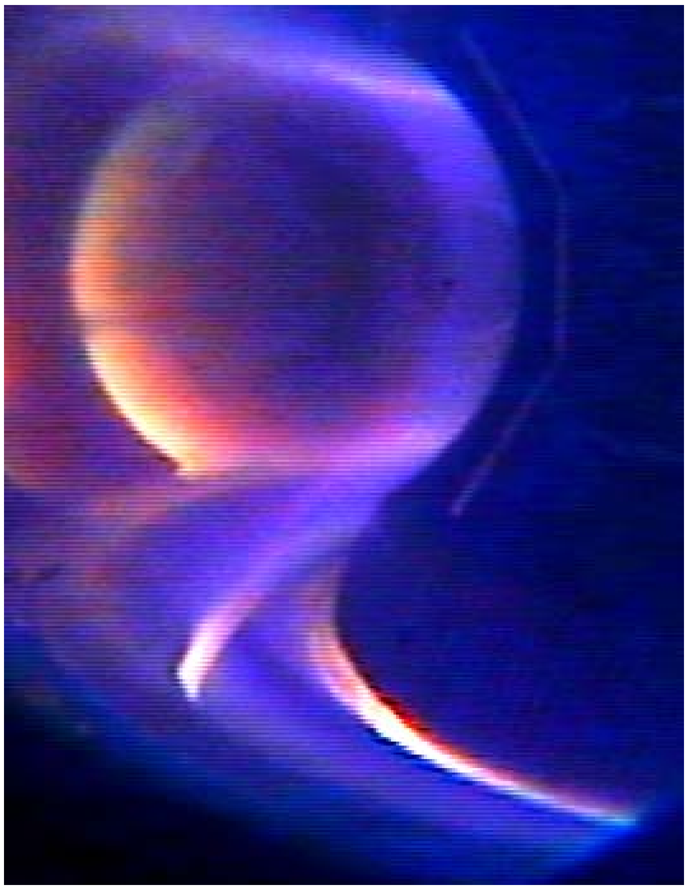
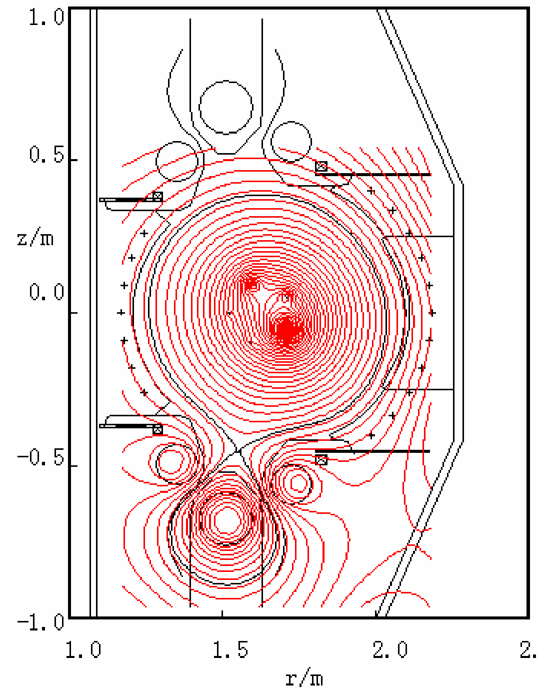


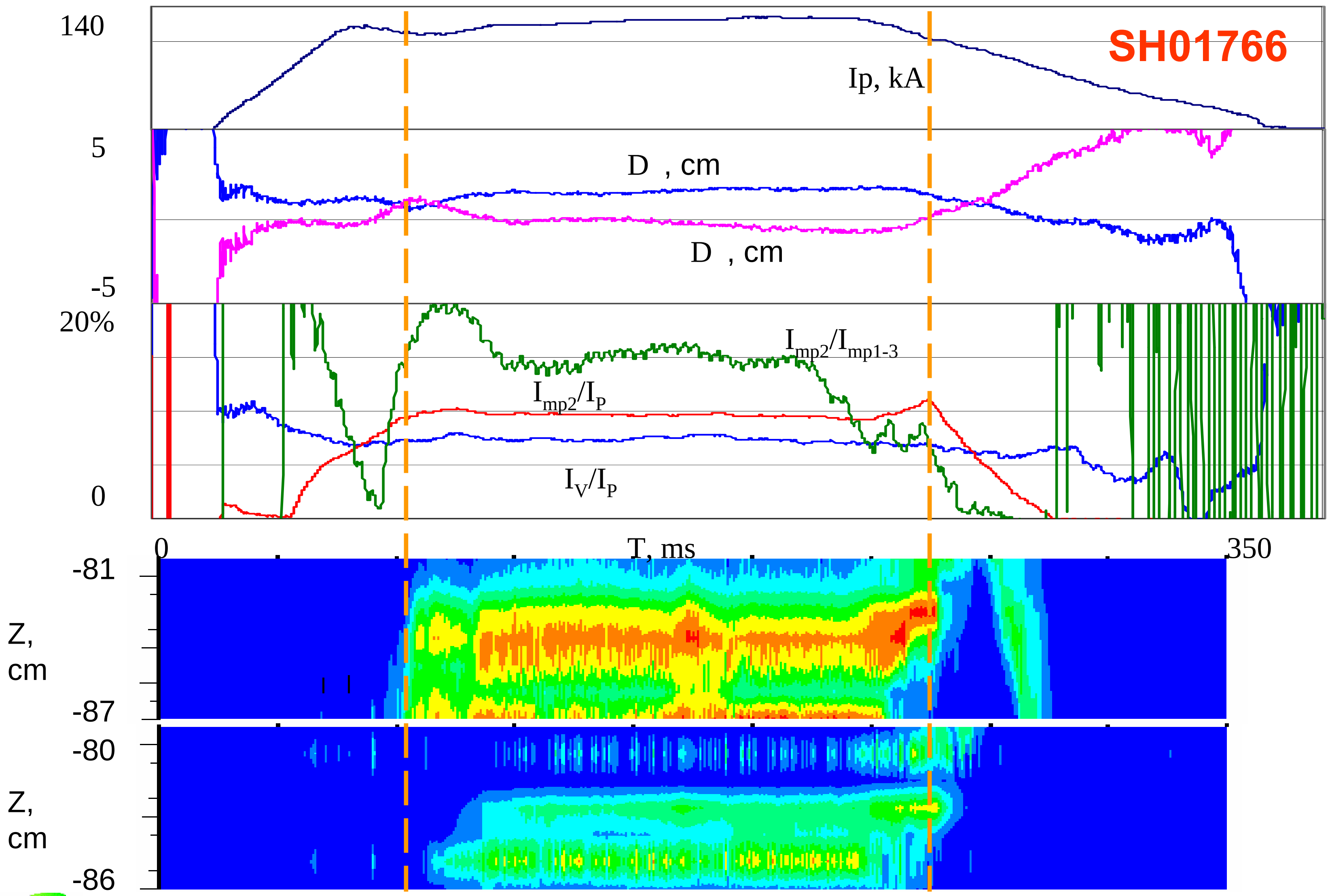
Image of the discharge with divertor configuration



1533 shot T(ms)= 200
Ip(kA)= 69.6905
Xr(m)= 1.5480 Xz(m)= -0.4560
xmax(m)= 2.03824 xmaxz(m)= -0.02400
xmin(m)= 1.26310 xminz(m)= 0.02400
Rp(m)= 1.6507 Zp(m)= -0.0331
ap(m)= 0.3876 k= 1.0911

[For the detail, see B.S.Yuan, EX/P5-35]

Divertor configuration achieved and sustained



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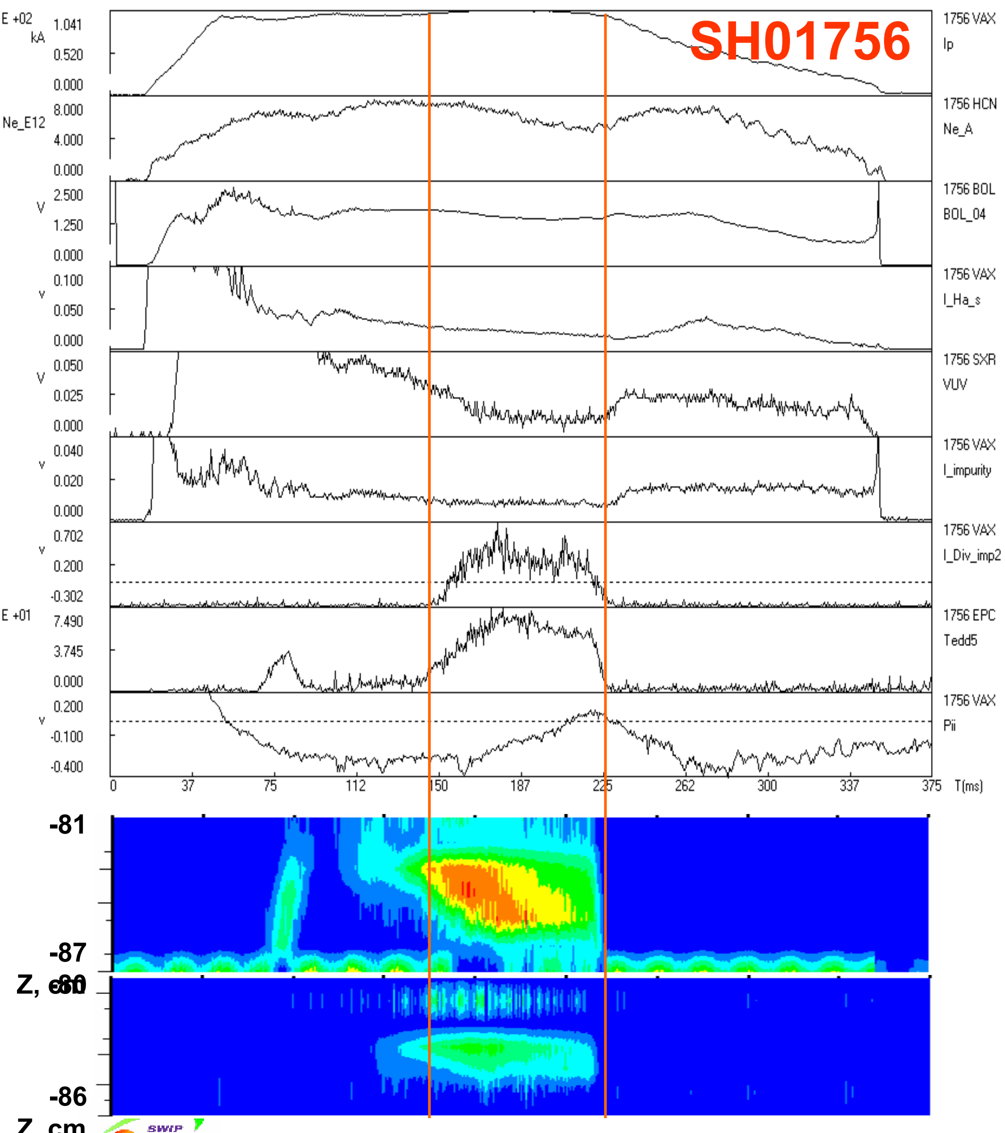
Transition between divertor and limiter configuration



During the divertor configuration operation:

- The impurity and Hα radiations in the divertor chamber increase.
- The plasma radiation, impurity and Hα emissions in the main plasma region decrease.
- The plasma density decreases due to reduction of the wall recycling in the main plasma region.
- The neutral gas pressure in the divertor chamber increases.
- The bolometer measurements show that the radiation near X-point increases.

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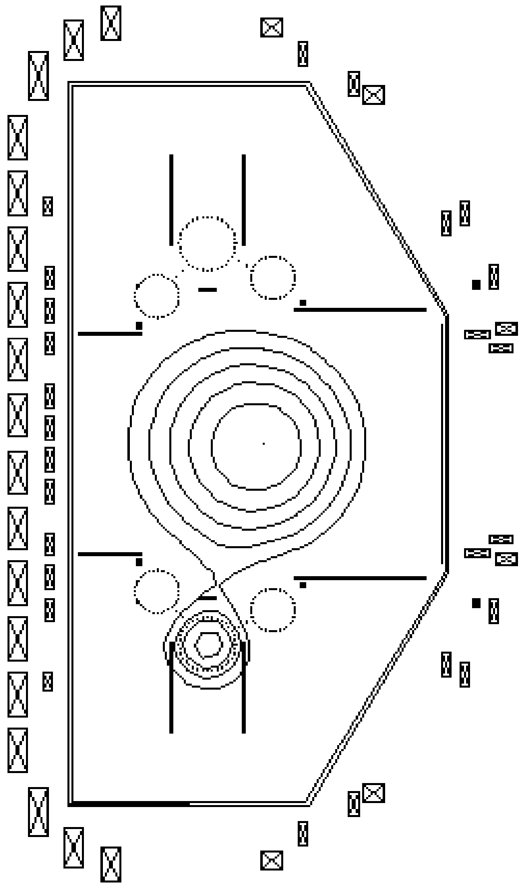
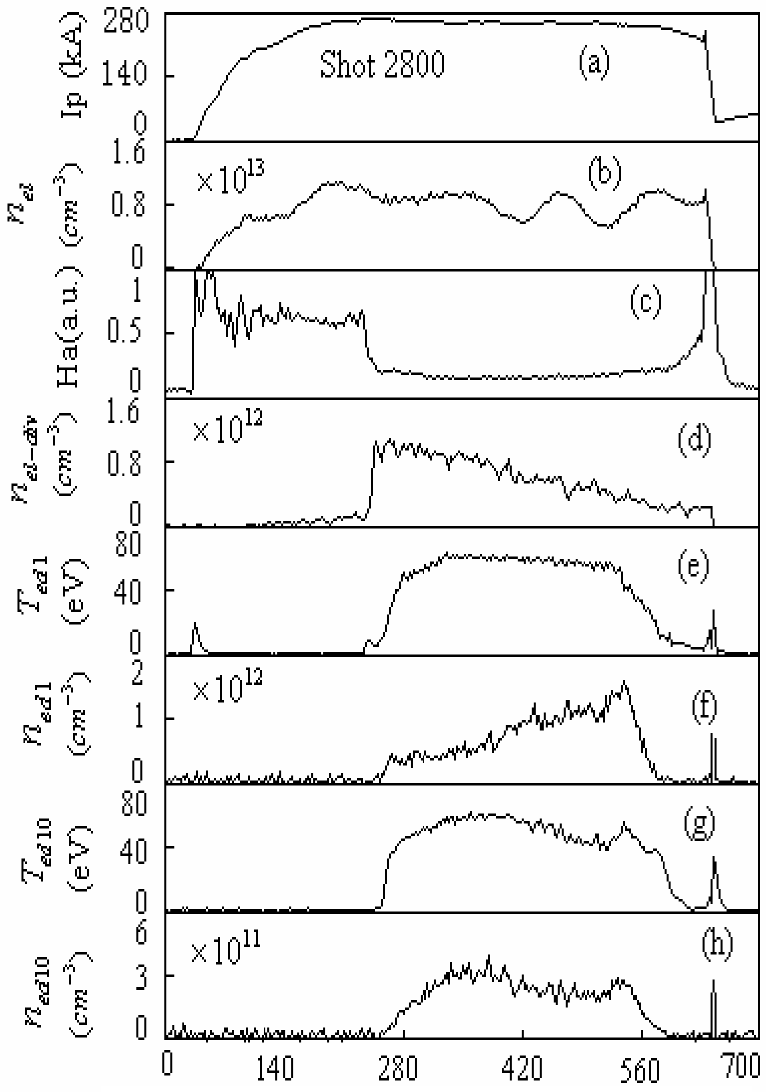
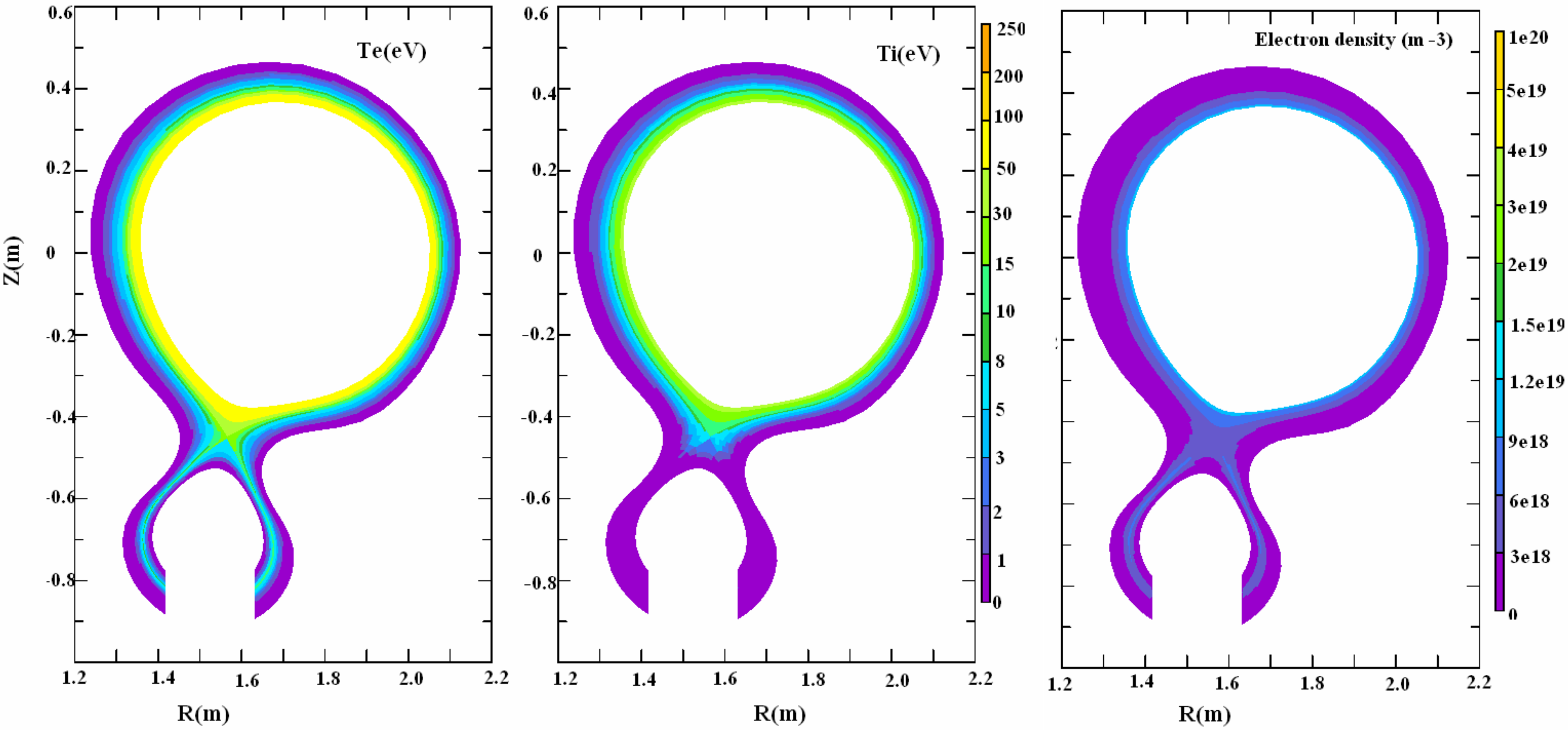
Divertor configuration simulated with SWEQU code





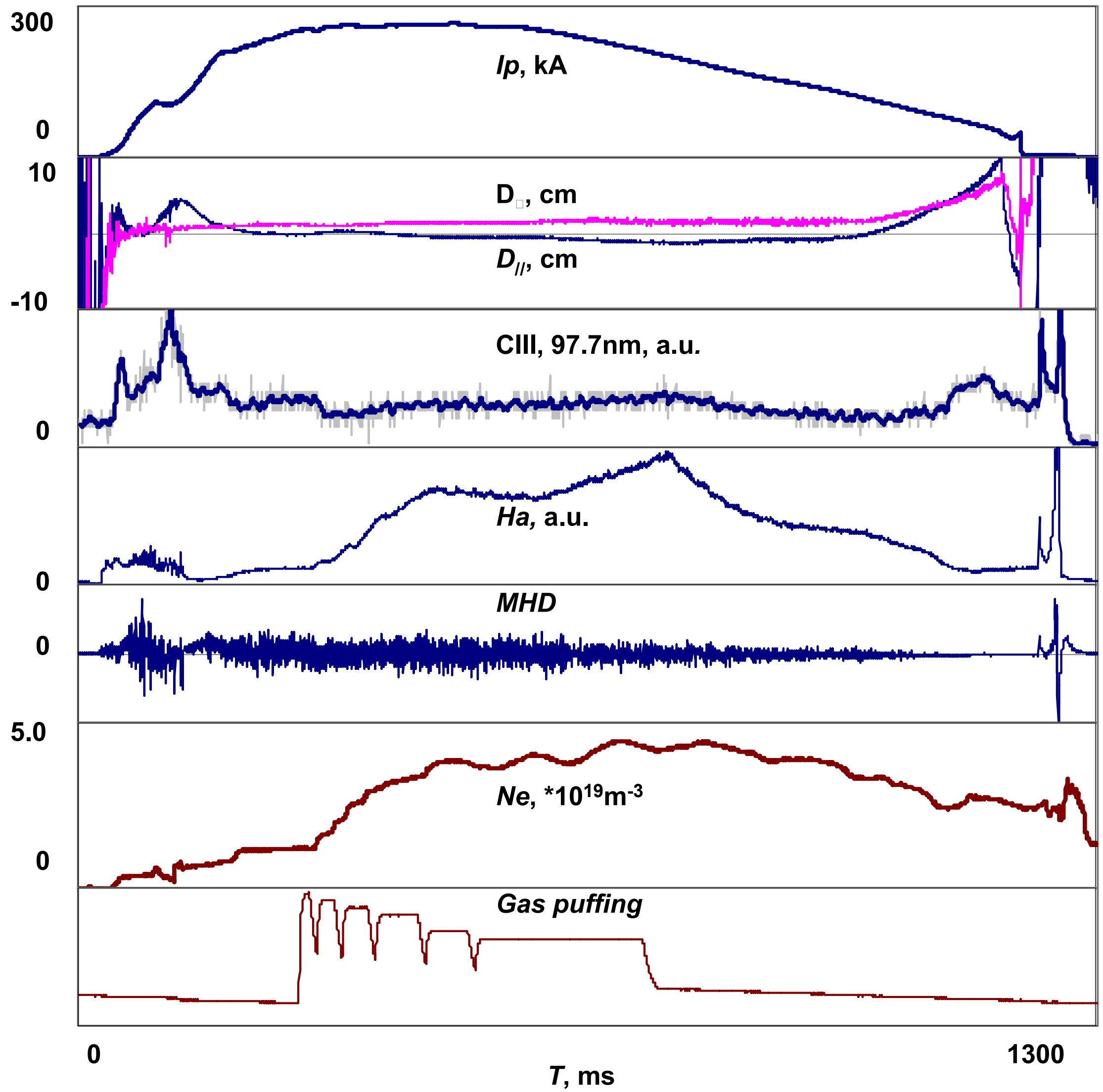
Plasma evolution of divertor discharge

2-D edge plasma distribution



2-D spatial profile of the edge Te,Ti,and ne for the typical higher density HL-2A discharge (Ip=300kA, Bt=2.2T, $\bar{n}_e = 3\times10^{19} m^{-3}$)

Plasma parameters evolution for high density discharge



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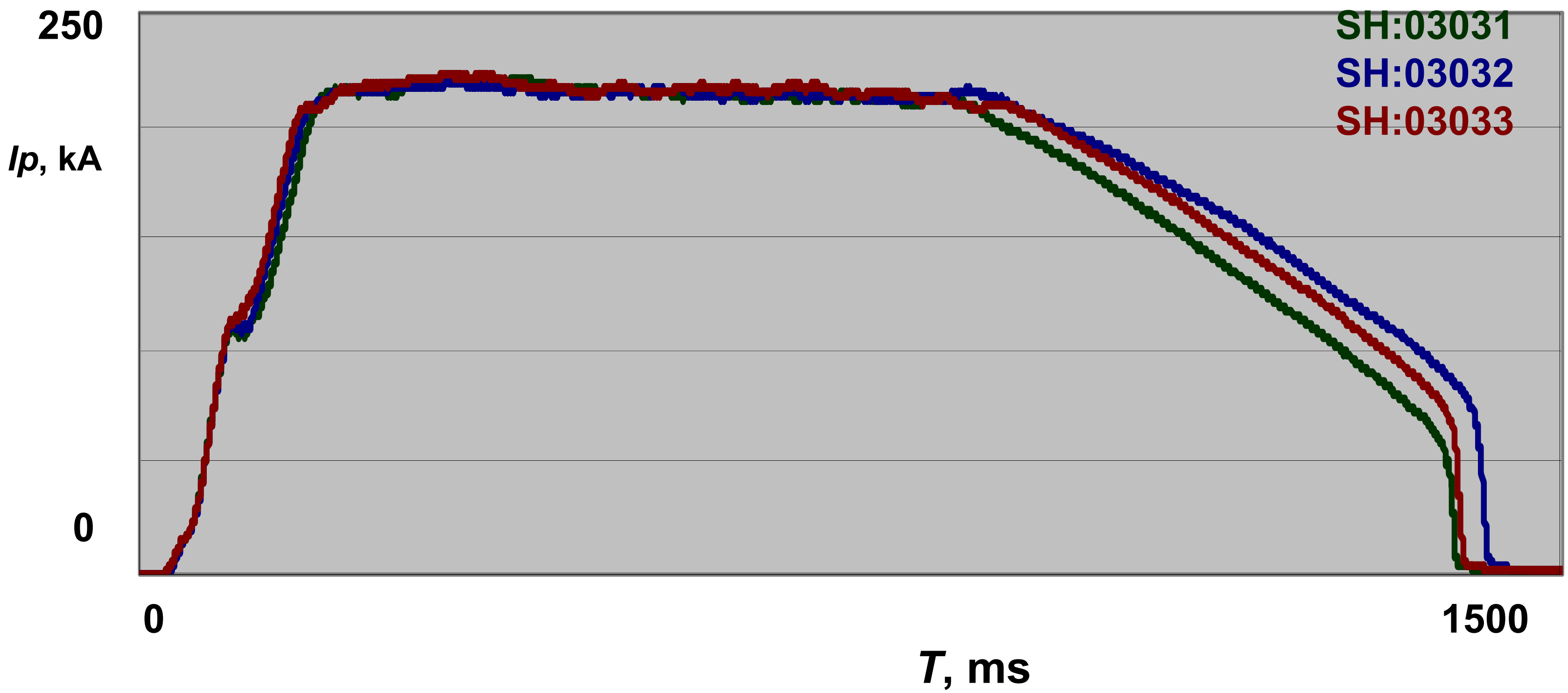
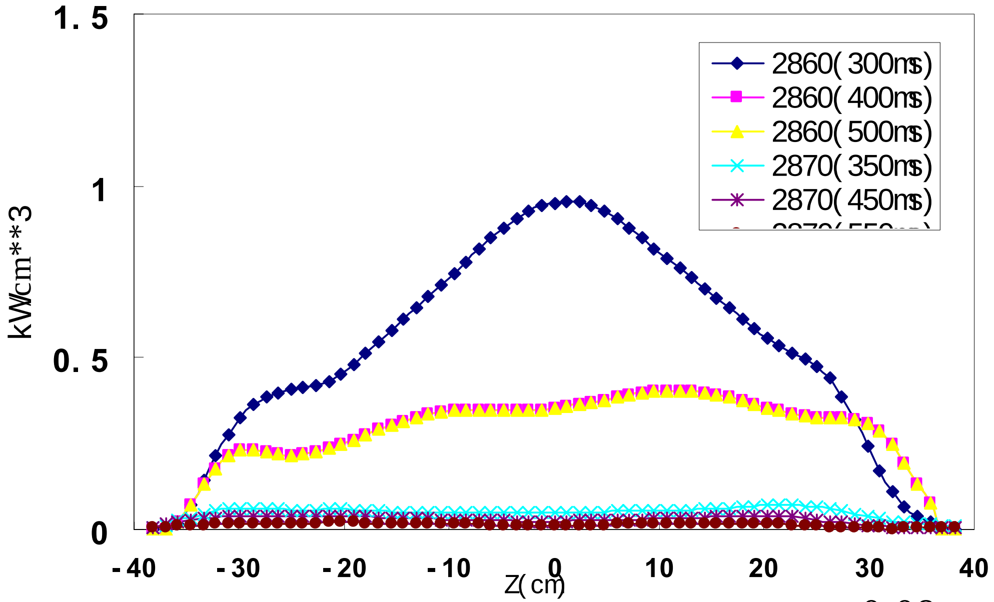
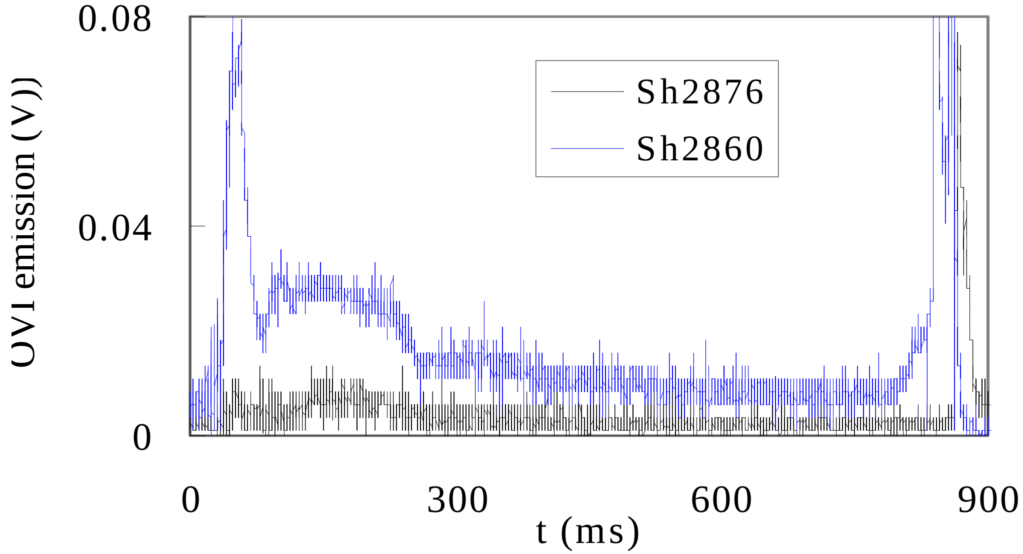
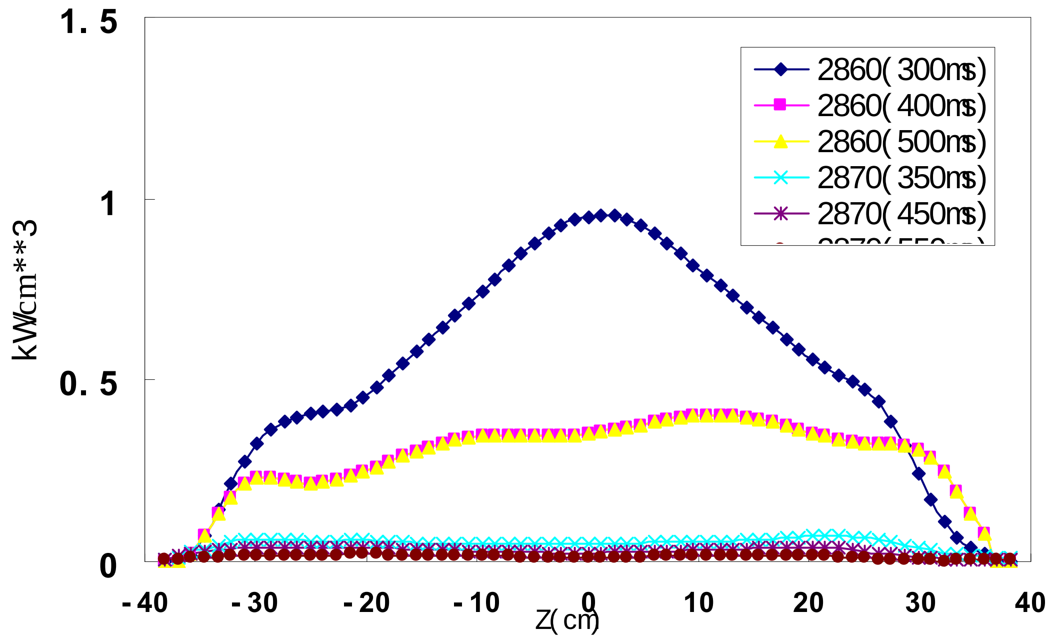


Repeatability of discharge on HL-2A

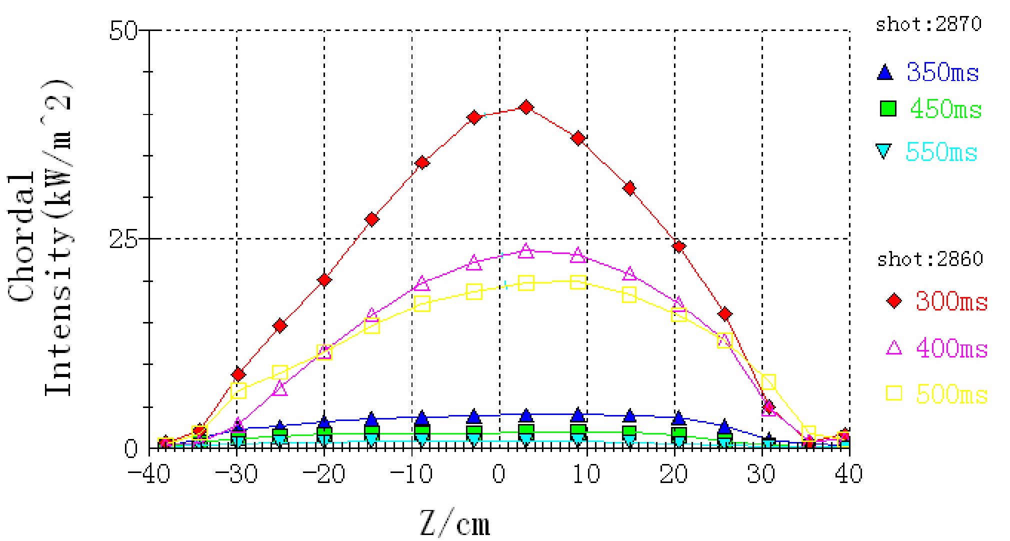
Comparison of radiation and impurity before and after siliconization







1. 5
1
0. 5
0
kW/cm**3
- 40
- 30
- 20
- 10
0
10
20
30
40
Z(cm)
2860(300ms)
2860(400ms)
2860(500ms)
2870(350ms)
2870(450ms)



50
25
0
Chordal Intensity(kW/m^2)
-40
-30
-20
-10
0
10
20
30
40
Z/cm
shot:2870
350ms
450ms
550ms
shot:2860
300ms
400ms
500ms

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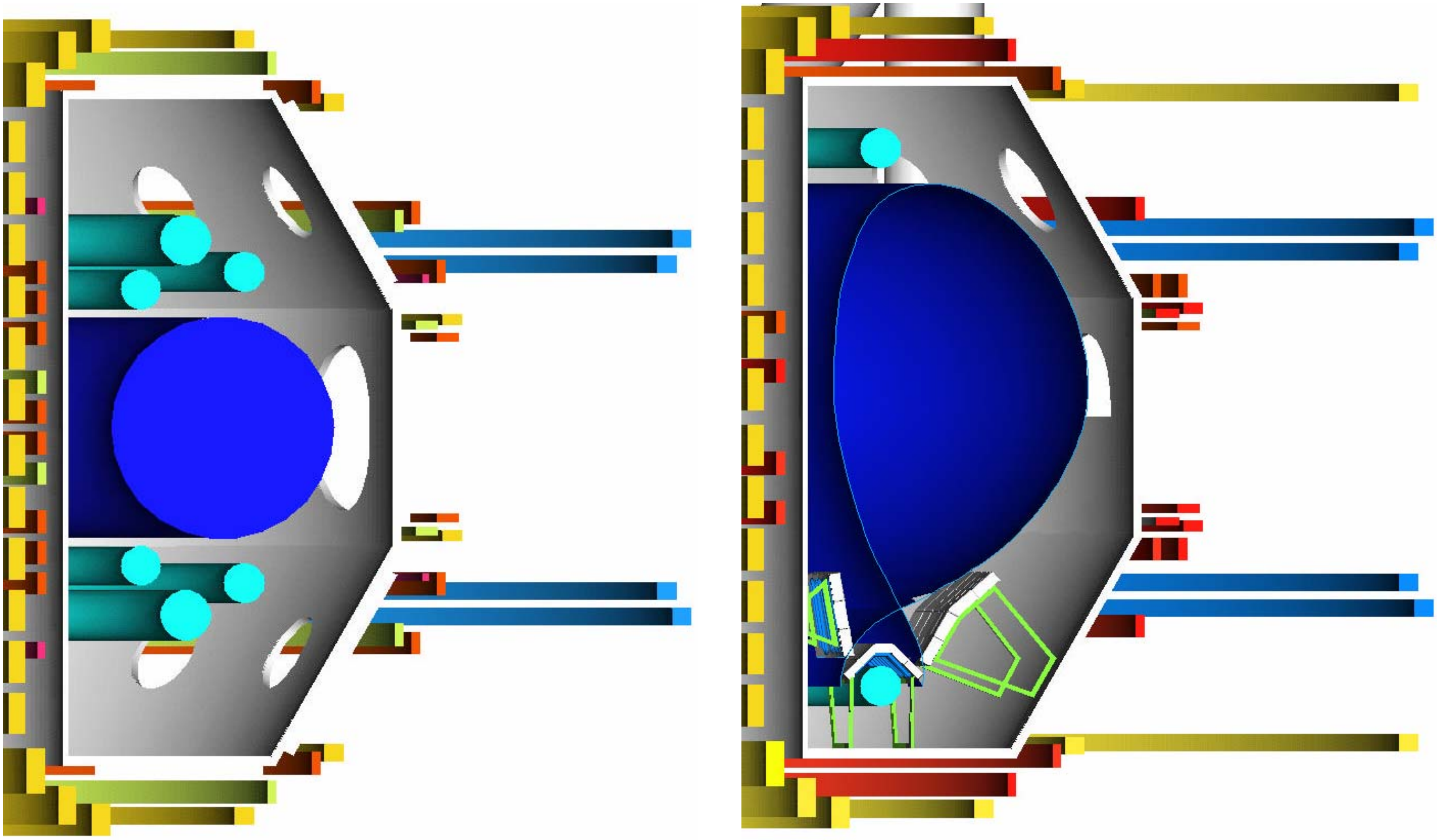
Experiment plans for next step

- Higher plasma parameters performance are expected:
  $I_P \sim 400\mathrm{kA}$, $B_T \sim 2.5\mathrm{T}$, $n_e \sim 6*10^{13}\mathrm{cm}^{-3}$, $T_e \sim 1\mathrm{kev}$, $\tau_{plas.} \sim 3$ sec.
- Plasma feedback control techniques will be developed further.
  plasma current, position, plasma shape/configuration
- Wall conditioning, Fueling & high density operation(up to $6\times10^{13}\mathrm{cm}^{-3}$):
  Boronization / siliconization, Pellet, MBI
- Confinement improvement and energetic particle behavior
  with LHCD and ECRH(1MW/68GHz). [for detail, see Gao Q.D. EX/p4-21]
- Modification From close to open divertor.


a Present b After modification

The concept design for the modification of HL-2A

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SUMMARY

- Former ASDEX has been reconstructed successfully as HL-2A tokamak at SWIP of in China for exploring the physics issue of fusion plasma.
- The sub-system of HL-2A, including pumping system, power supply, diagnostics, auxiliary heating subsystem, has been designed and constructed, to meet the requirements of the experiment program of HL-2A. The first plasma of HL-2A has been obtained just ahead of the schedule at the end of 2002.

- **Most of the important issues of fusion physics, such as confinement, divertor, MHD instability and energetic particles, will be studied and explored on the HL-2A through the progressively improvement of the hardware.**
- **The divertor(S-N) operations have been achieved and sustained on HL-2A, in 2003. The feedback control of the plasma current and the plasma position were used for both limiter and divertor operations.**
- **320kA/2.2T/1.5s/ $4.2\times10^{13}cm^{-3}$ has been reached up to Oct.2004. Improved FB control and siliconization have been used to enhance the performance of discharge.**

- **Both configuration simulation(with SWEQU) and plasma boundary identification (with CFc and FBI) have been made. The reconstruction results indicate that the good SN divertor structure has been obtained. B2 code also was used for simulation of the divertor plasma behavior.**
- **For near future, the plasma parameters and performance are expected to be greatly enhanced with powerful auxiliary heating and current drive. For long term, the modification to the device will be made for obtaining more flexible and elongated divertor plasma device with much large plasma volume.**
- Next

Overview of the last HT-7 experiments

Baonian Wan and HT-7 Team

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University of Science and Technology of China, Hefei, China
Institute of Physics, Chinese Academy of Sciences, Beijing, China
Institute of Carbon Chemistry, Chinese Academy of Sciences, Taiyuan, China
Huazhong University of Science and Technology, Wuhan, China
Department of Physics, East China University of Science and Technology

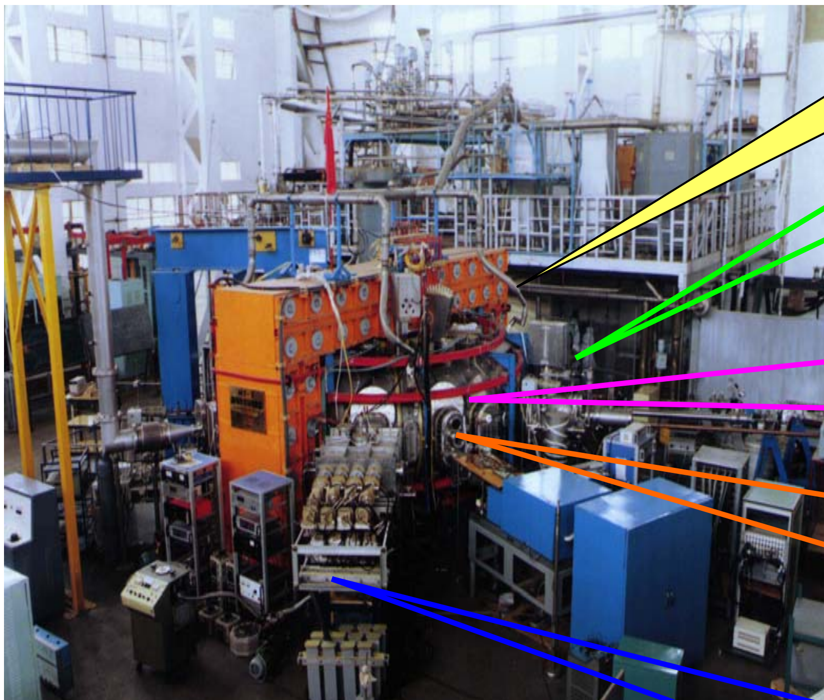
Fusion Research Center, UT at Austin, USA
General Atomic, San Diego, USA
National Institute for Fusion Sciences, Toki, Japan
Advanced Fusion Research Center, Kyushu University, Japan
Kuchatov Institute, Russia

FEC-2004

Outline

- HT-7 mission and R&D
- Confinement improved scenarios
- High performance under steady state
- Long pulse discharges
- Summary

Main Mission: Steady-state high performance operation and related physics and technologies



SS real-time PF PS&control

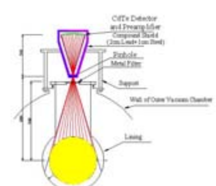
RF: 18-30MHz

350 kW CW

IBW, FW antenna

Graphite (P, T)

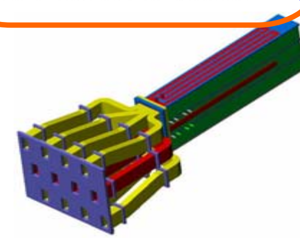
Water cooled



Schematic diagram of vertical CdTe detector array on HT-7

>30 diagnostics

Steady-state



f: 2.45 GHz

1.2 MW CW

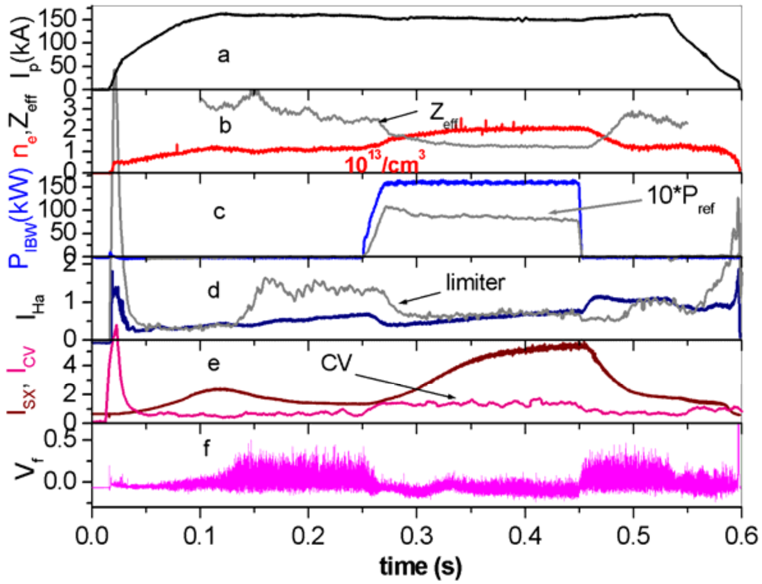
Multijunction

$R = 1.22m$, $a = 0.27m$,

$Ip = 100\sim250$ kA, $B_T = 1\sim2.5T$

H-mode by IBW at 30 MHz

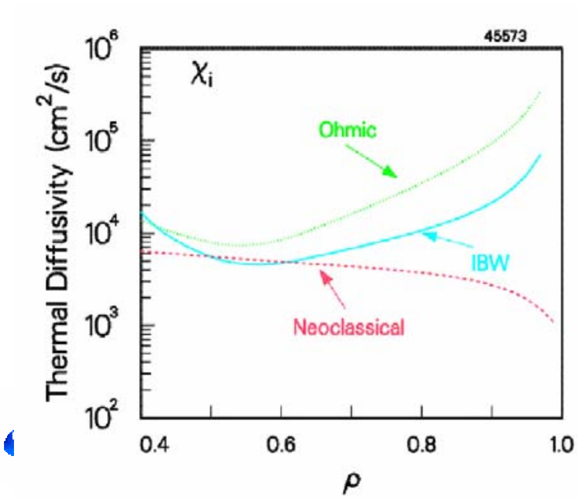
HT-7

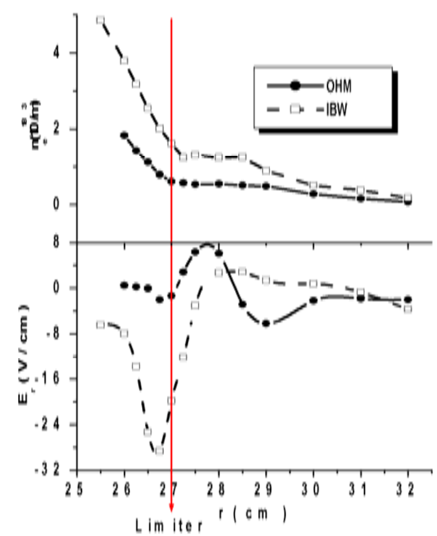


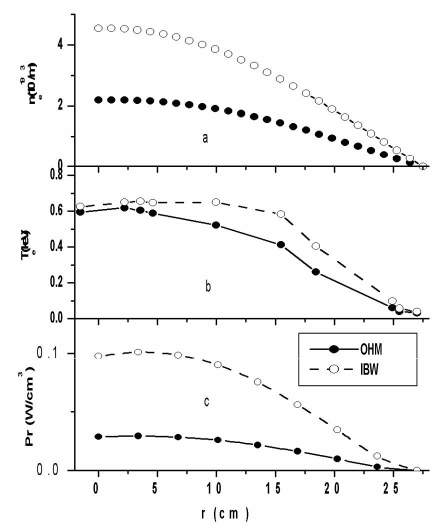
IBW enhanced the edge E_r shear,
$\omega_{E\times B} > \Delta\omega_t \sim ck_\theta T_e/eBL_n$ (for drift–wave-like turbulence)

Suppression of edge turbulence leading to improved confinement

Reduced transport in $\rho > 0.5$

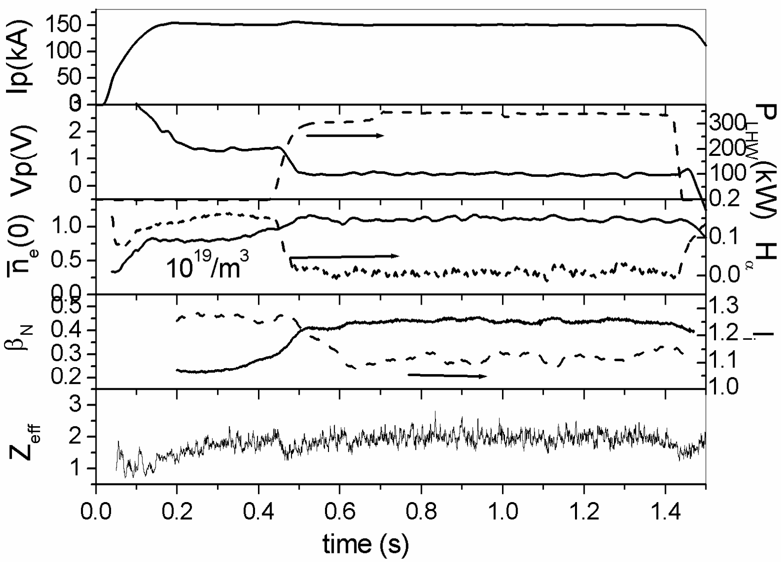




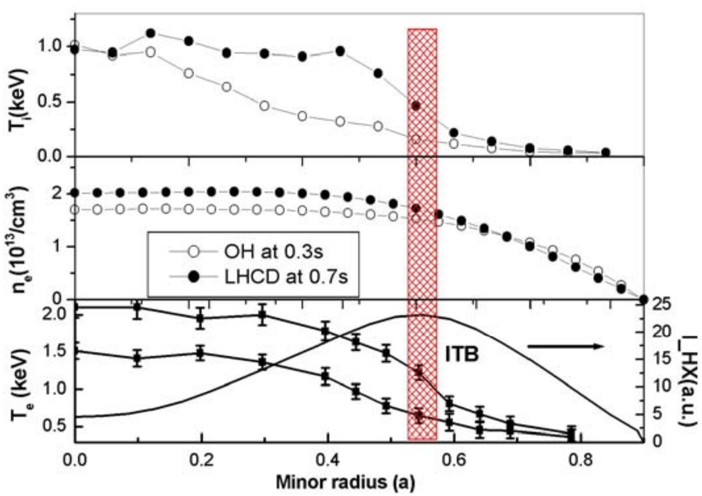


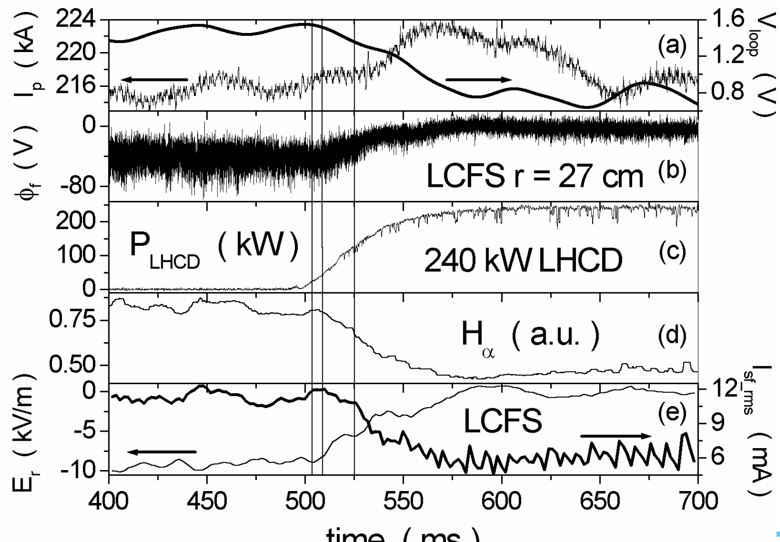
H-mode by off-axis LHCD

HT-7



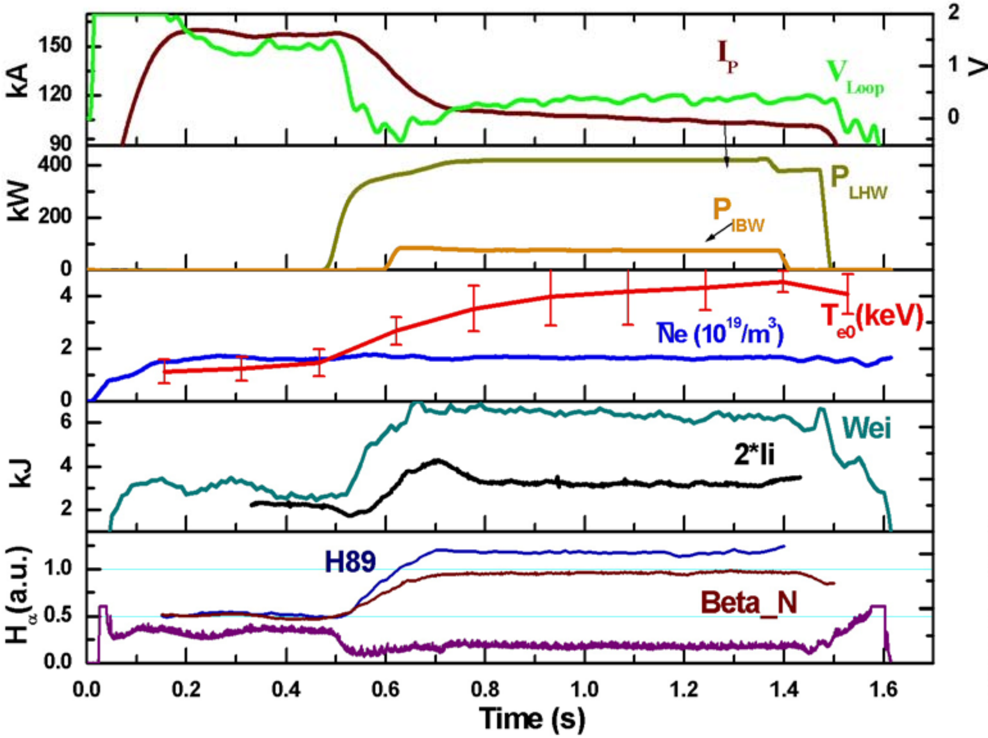
- Current density profile control by changing $n_{||}^{LHW}$
- $H_{89} \leq 2$, with potential steady-state capability, but low β
- Enhanced edge E_r shear led to suppression of edge turbulence
- Improved confinement



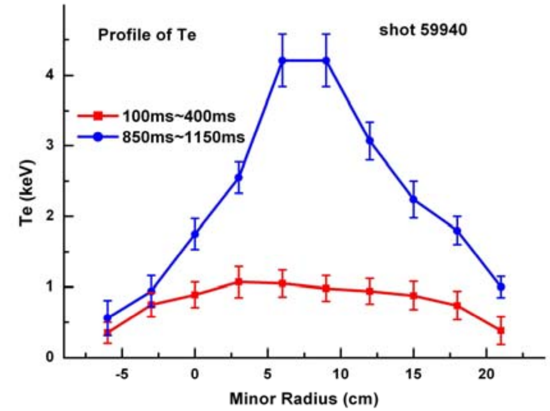


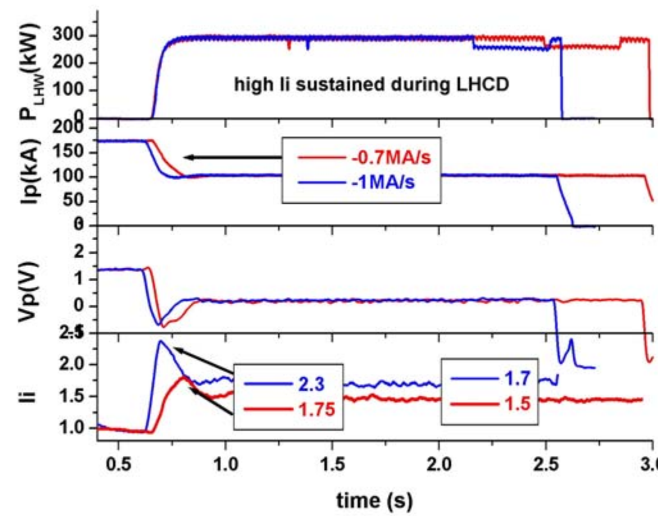
High li mode

HT-7



Improved core confinement





Ip ramp-down at rate of -0.5~ 1.2MA/s

Highest Te(0) ~ 4.5keV

Steady-state high li 1.3-1.8 for up to 3s

Better confinement for higher li

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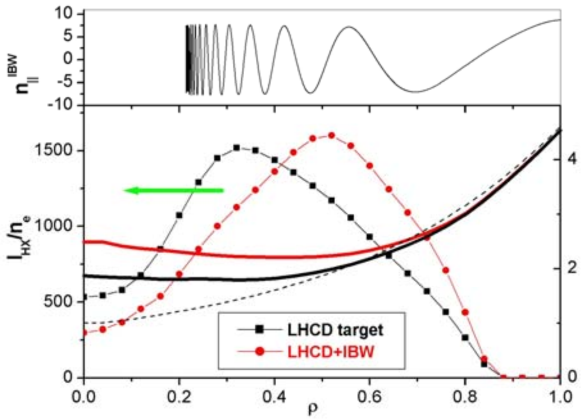
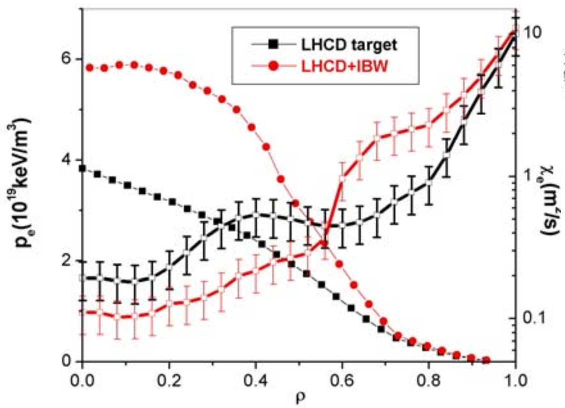
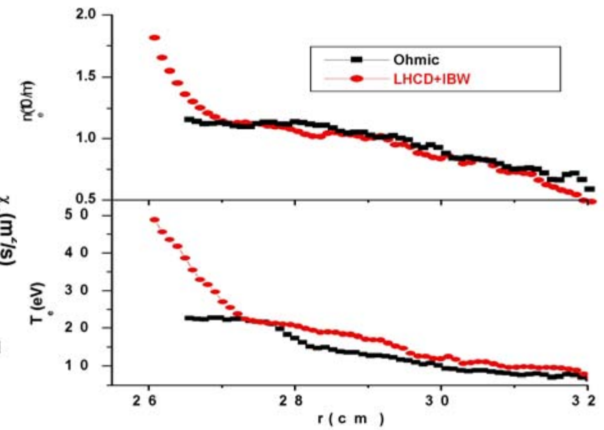
HT-7

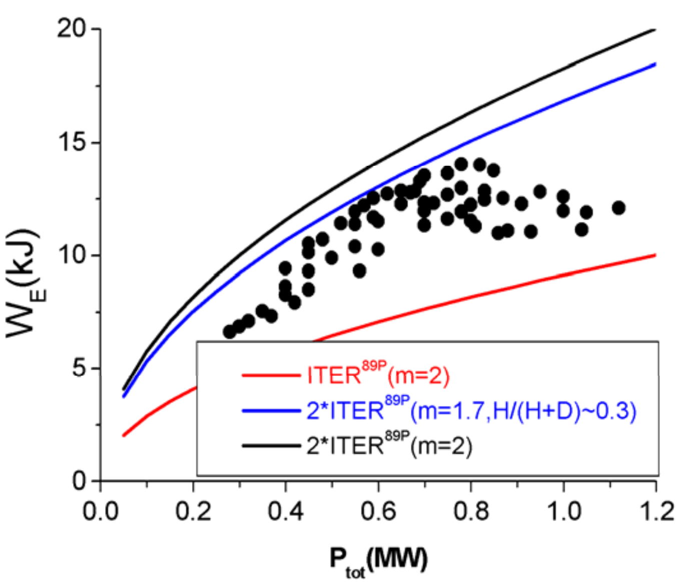
Features of IBW + LHCD synergy

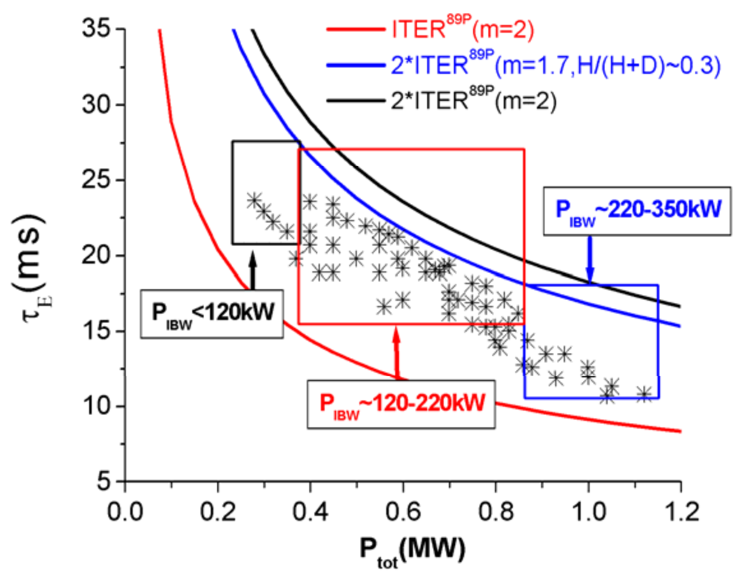






Weak negative shear **ITB at minimal q** **H-mode edge**



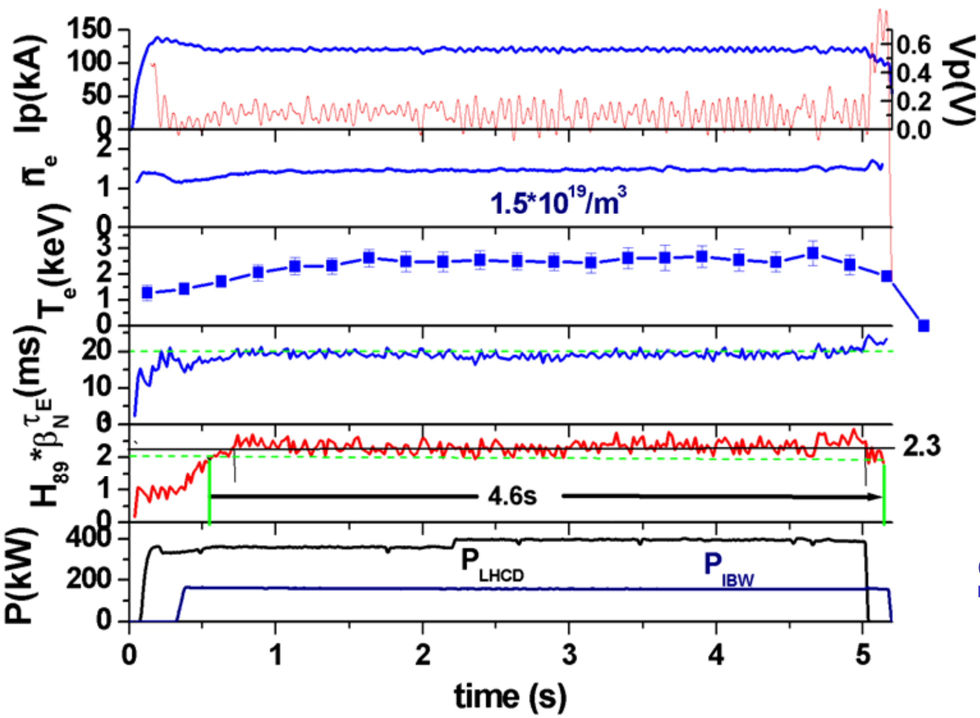


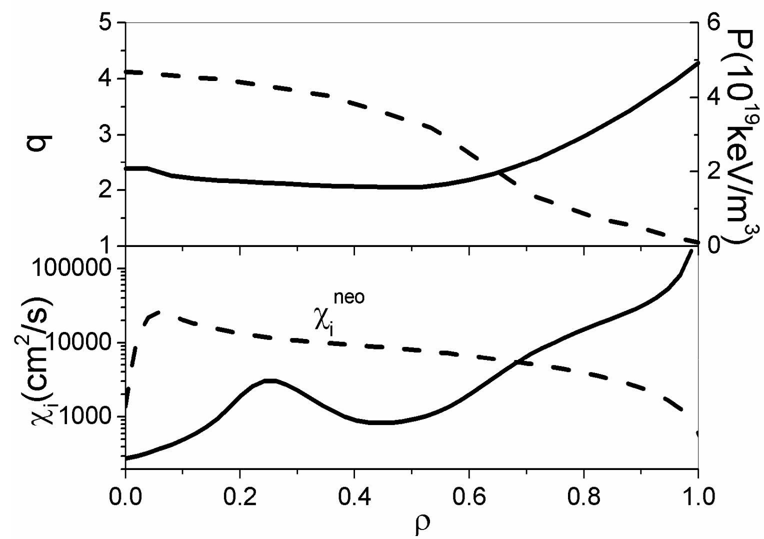
Up to 1 MW good confinement

Integrated high performance

HT-7

H89*β_N >2.2 for ~220τ_E & > 20 τ_{CR} $f_{LHCD}+f_{BS}$ >80%, Vp<0.10V



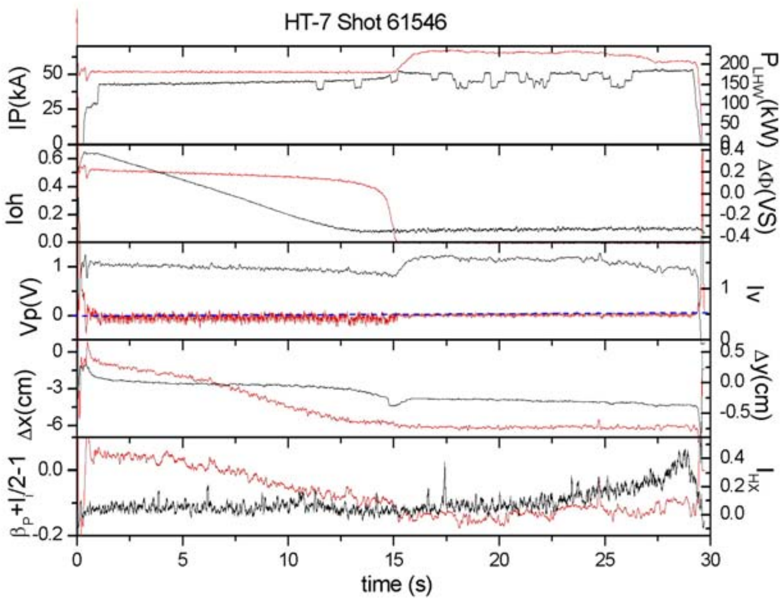


Stationary ITB was formed at footprint of minimal q and sustained during LHCD and IBW, f_{LHCD} ~ 42%, f_{BS}~39%

Discharge w/o ohmic current

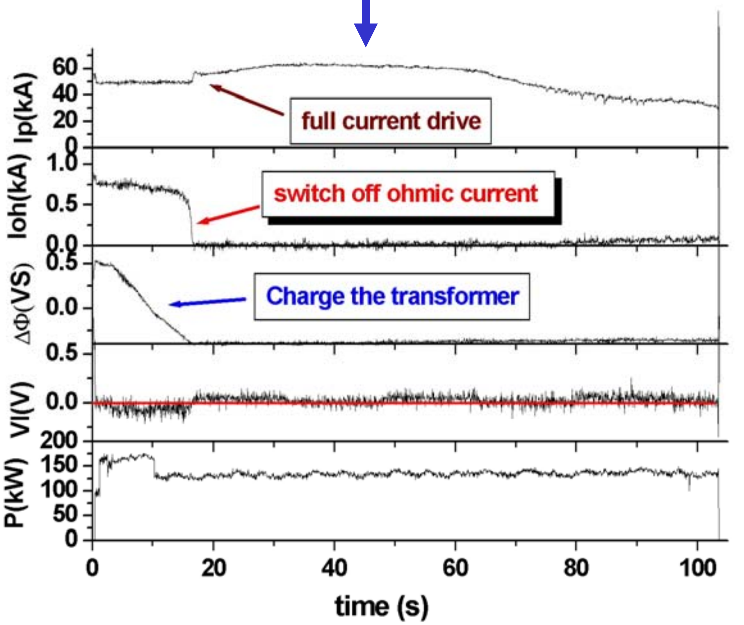
HT-7

Over LHCD recharged the transformer, the current in central solenoid was switched off when the transformer was reverse saturated



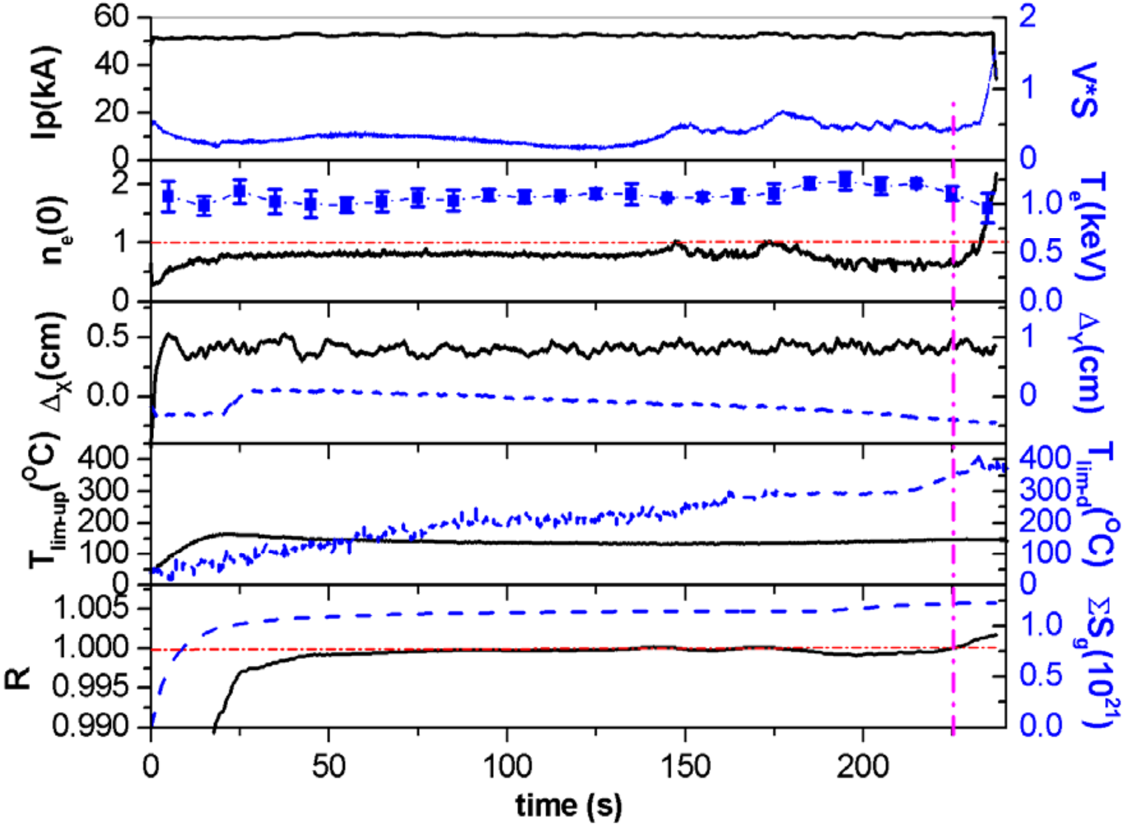
In 2003, sustained for 28 s
Density build-up terminated discharge

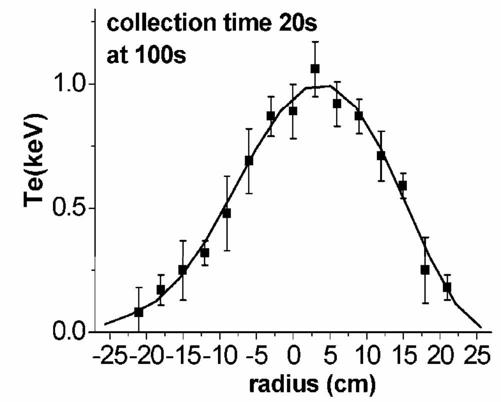
In 2004, sustained for 80s
Reflection protection terminated discharge



Long pulse discharges 4mins in 2004

HT-7





- Ip≥50kA, $n_e(0)$~$0.8\times10^{19}/m^3$, Te(0)~1keV
- Wall saturation at ~80s and refresh at ~180s
- Limiter temperature rise caused uncontrollable density

Power feed back control by switching on/off spare klystrons

Summary

HT-7

- HT-7 experiments are strongly oriented to steady-state high performance plasmas and long pulse discharges.
- Technical improvements made great progress in achieving high performance plasmas under steady-state condition.
- Various scenarios of high performance plasma discharges (including edge H-mode, RS mode, high li mode etc) were realized.
- Stationary high performance plasma with $H_{89}*\beta_N > 2$ has been sustained for > 200 τ_E and >20 τ_{CR}.
- Long pulse discharge up to 4mins is successful with the new up-down toroidal belt limiters.
- Further experiments in HT-7 are strongly oriented to support the EAST project both scientifically and technically. (for the detail,see FT/3-3)