Recent experiments towards to the steady-state operation in the EAST and HT-7 superconducting tokamaks

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for EAST and HT-7 Teams and collaborators

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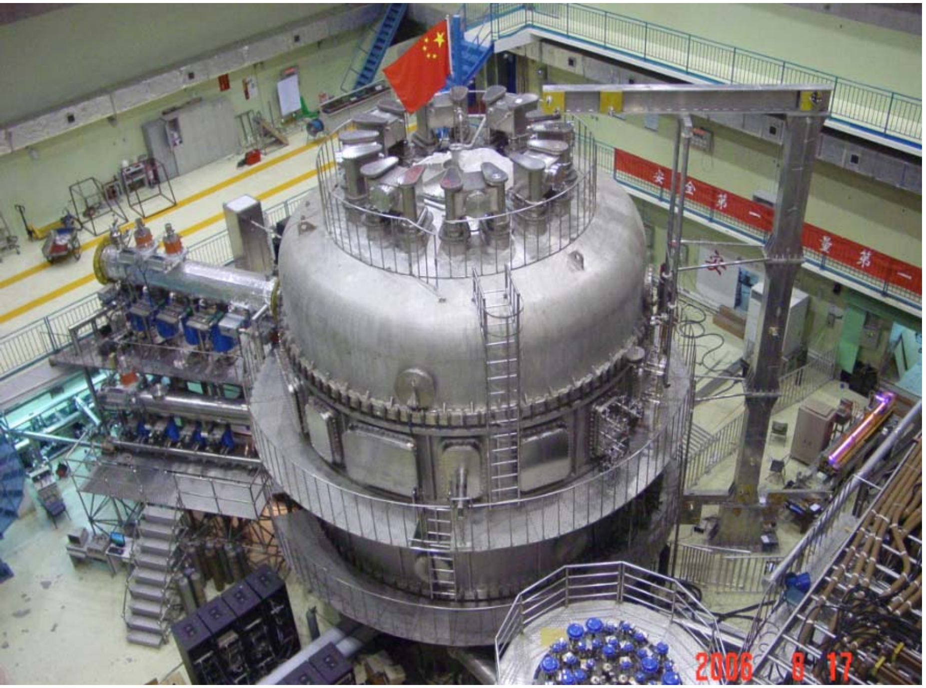
Outline

- Introduction
- Recent progress on EAST
- Long Pulse Operation HT-7
- Summary and near future plan

Institute of Plasma Physics

one of main Fusion Research Center in China

EAST(1MA/3.5T/Divertor)



HT-7(0.25MA/2.5T/Limiter)

Key words of EAST: Steady-state; high-performance; physics and technologies

Milestone of EAST operation

- **Feb.- Mar. 2006 engineering commissioning**
- **Apr. -Jul. 2006 installation of in-vessel components and diagnostics**
- **Sept.-Oct. 2006 second engineering commissioning & first experiments**

  BT = 3.5 T at 1.7 m and $\Delta\Phi$ ~ 13 vs achieved
  first hydrogen plasma in day-one operation
  pre-programming controlled: Ip~220kA, t~2.7s
  Ip, RZ and Ne feedback controlled: Ip~500kA, t~5s

To address the feasibility of the full superconducting magnets and control algorithm with new features

- **Dec. 2006 - Jan.2007 Second experimental campaign**

  highly shaped plasma at various configurations
  To validate reliability of the superconducting magnets

- **Apr.2007-Jun. 2008 fully actively water cooled in-vessel components**
- **Jun.2008-Aug.2008 Third experimental campaign**

  Isoflux-REFIT plasma control
  LHCD experiments: P~800kW, Ip~250kA for 23 s
  Physical engineering effect validation

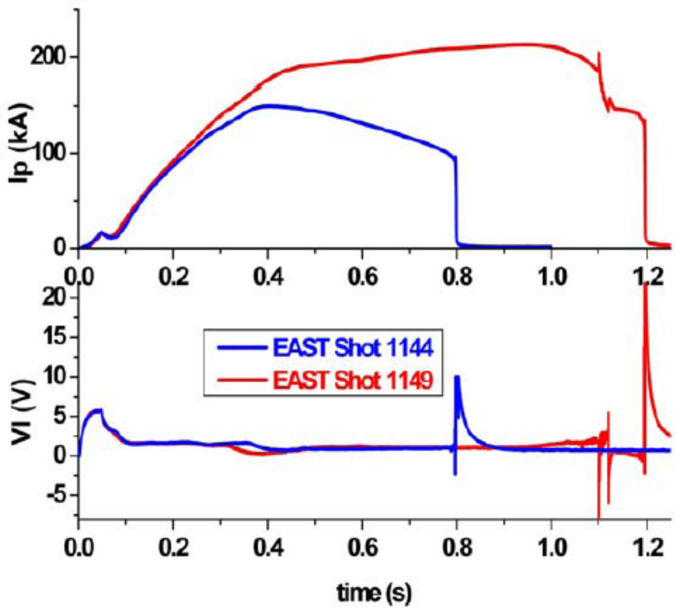
New features

•Full superconducting magnets; flexible divertor configurations and actively water cooled in-vessel components. →**reliable and anti-noise detection of fault and protection**

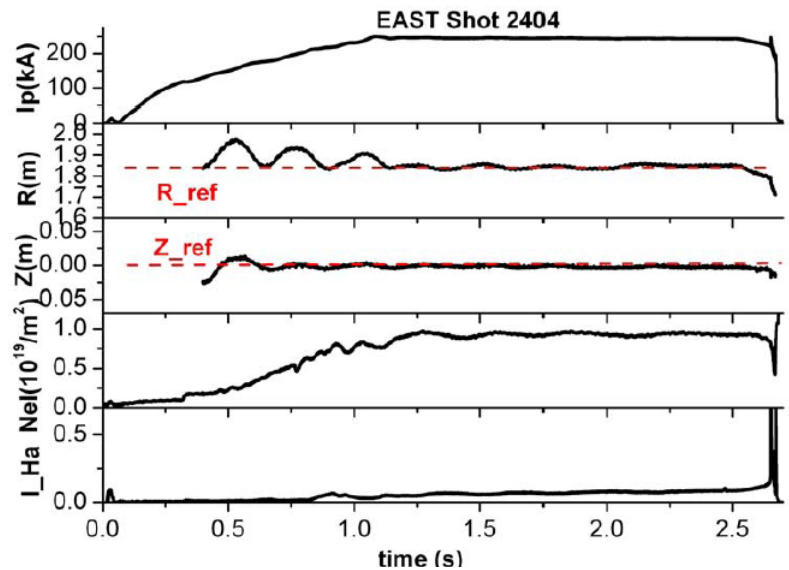
•Limited PF current varying rates, weak coupling between PF coils and plasma →**new algorithm for plasma control**, **optimization of operation scenario to minimize the AC loss**

•The toroidal resistance of the vessel ~80 μΩ can induce the an eddy current up to 150 kA at breakdown and delay breakdown by about 25 ms; →**careful design of initial magnetization for break down and ramping up**

First plasma

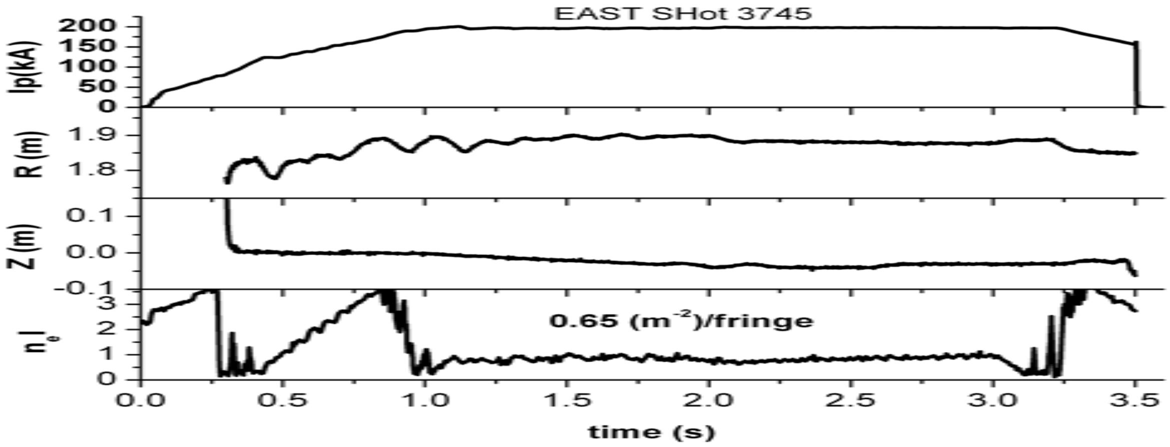


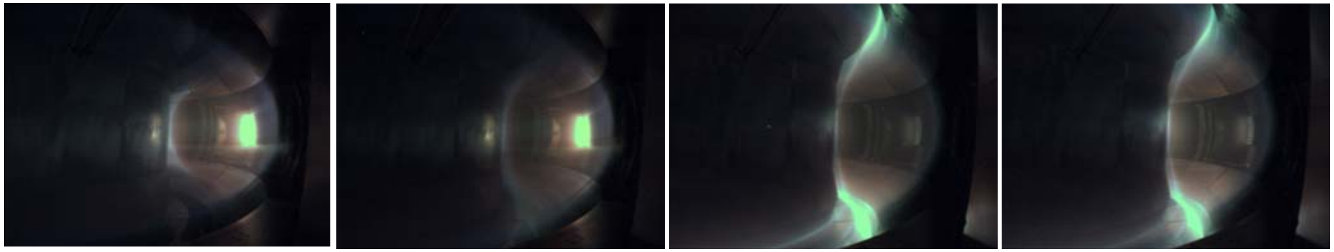
By reducing the current ramping rate and optimizing control, plasma current and position as well as density were well controlled!



Plasma discharges in day-one operation. Pre-program controlled, plasma current up to 220kA has been achieved

Shaped plasma





A well stably controlled plasma with (near) double null configuration. Shaping during flat-top phases. **(pre-programming shaping + RZIp feedback control)**

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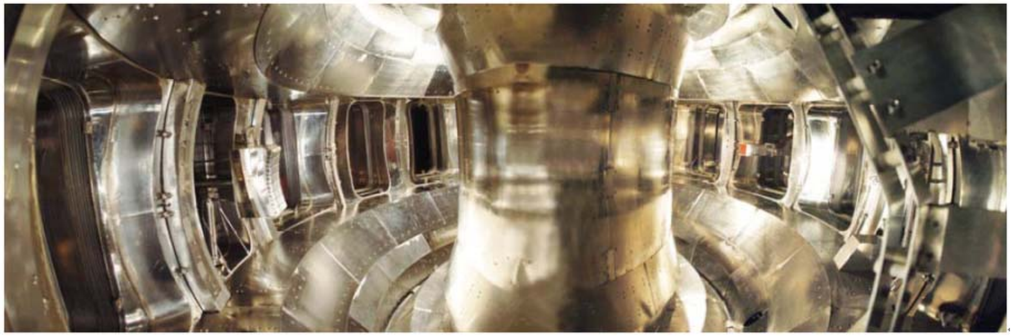
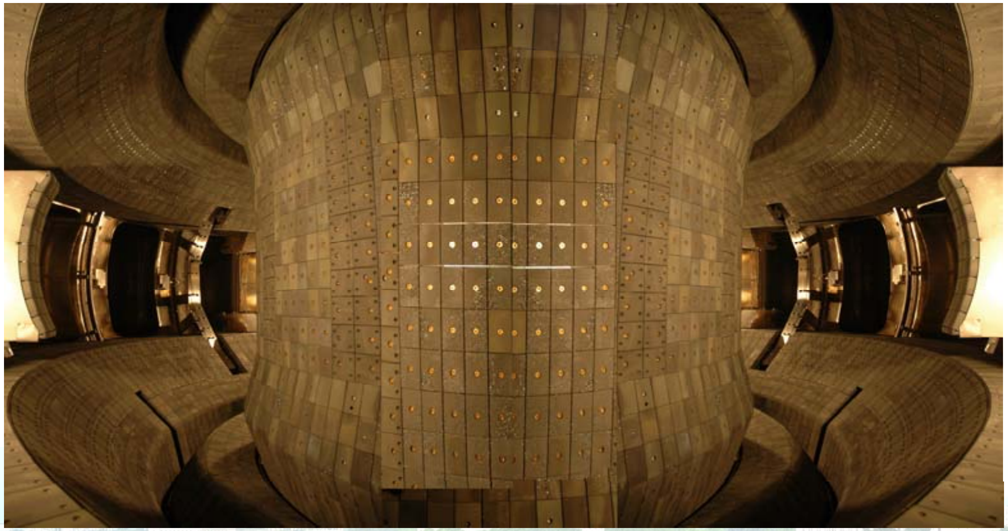
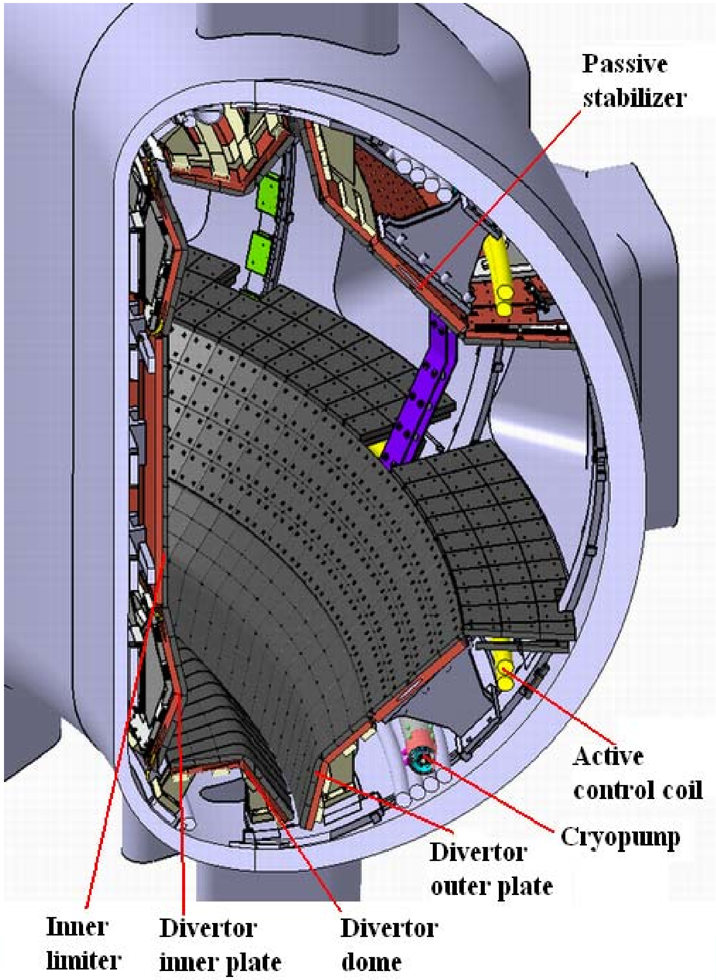
Actively Water-Cooled PFCs

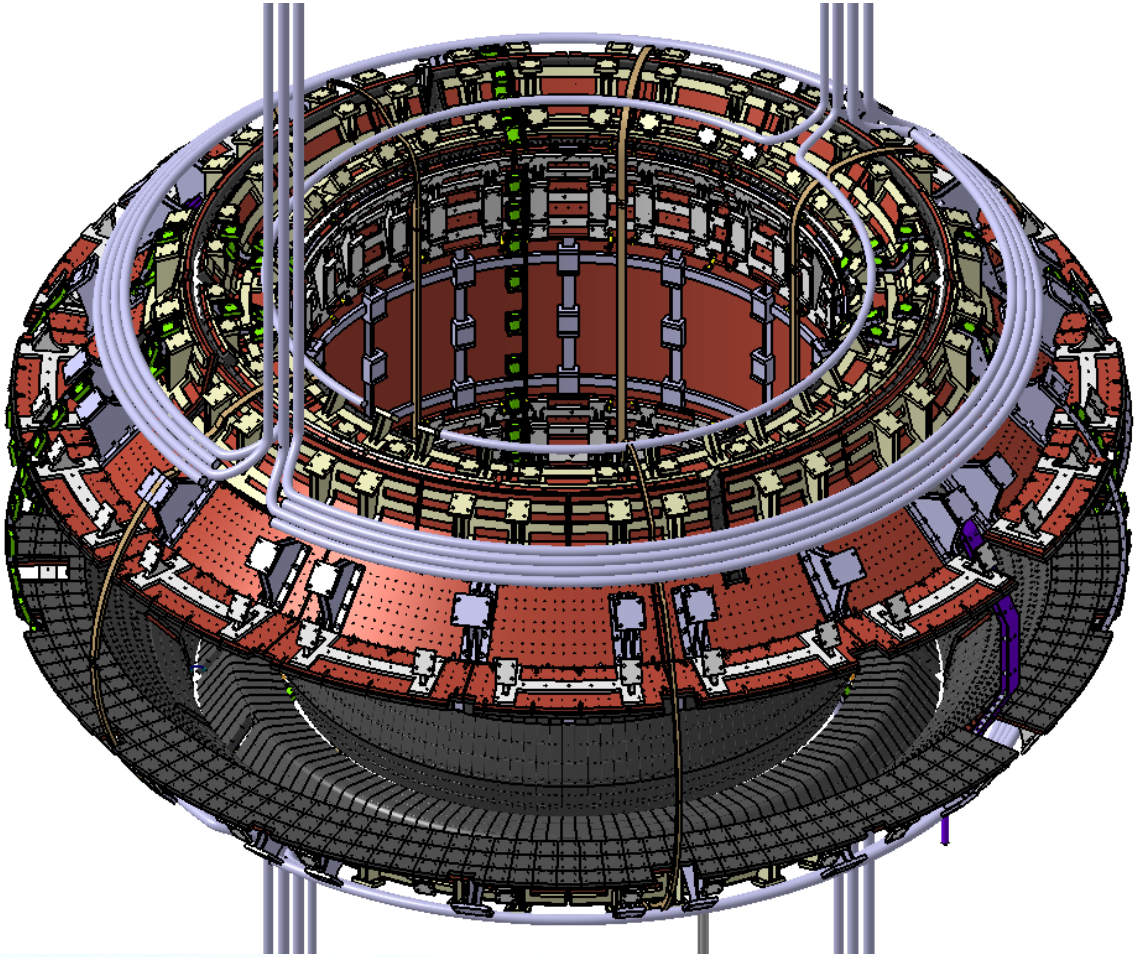


Since the 3rd Campaign changed to full graphite's





Integration



- Magnetics
- Cryo-pump
- Thermal couple
- Water cooling
- Anodes of DC GD
- Internal coils
- RF antenna
- Poloidal limiters
- Divertor probes
- Support structures
- Heat sink
- Graphite titles

Wall Conditioning

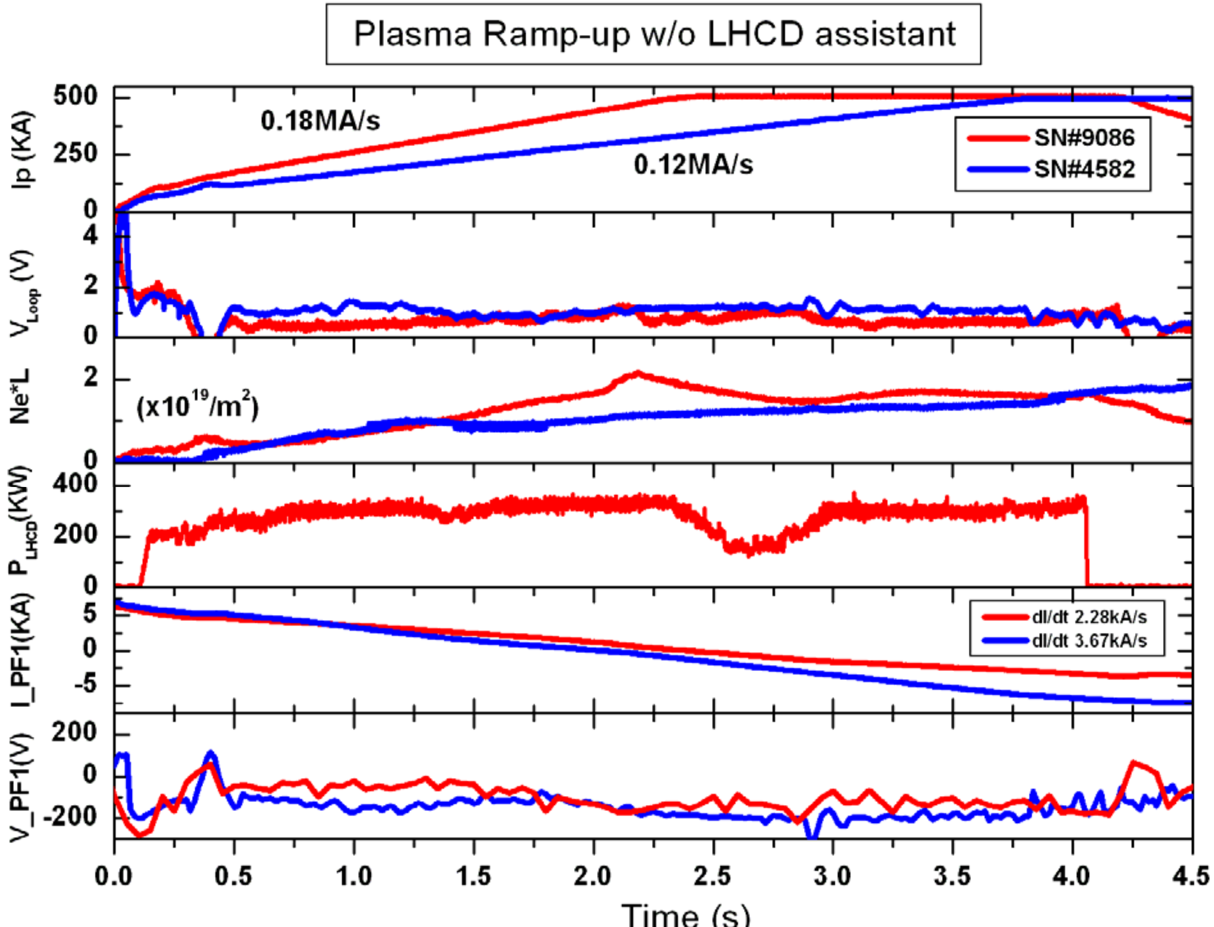
- Baking, Tmax: 350^{o}C
- Glow Discharge Cleaning
- RF Wall Conditioning

A powerful tool to suppress impurity and control recycling for the fusion devices in the presence of permanent toroidal magnetic field

Wall Cleaning
- Wall Coating
- Recycling and Isotopic Control
- RF Oxidation

RF Plasma

Plasma Ramp-up w/o LHCD

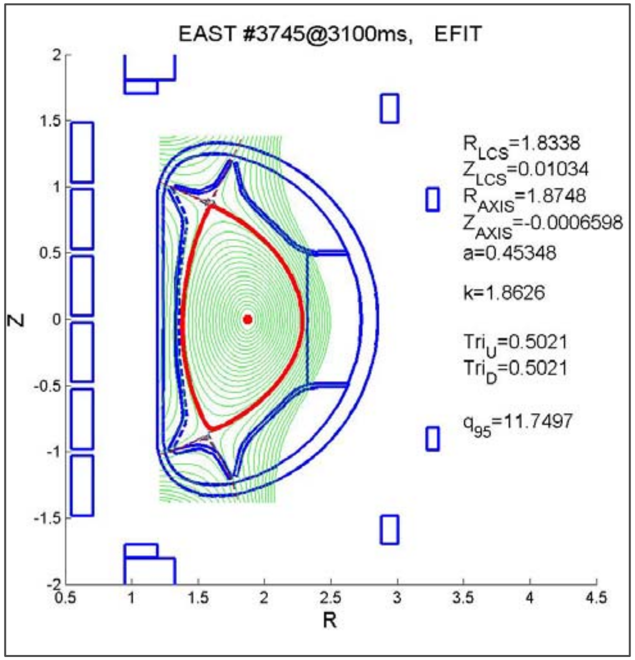


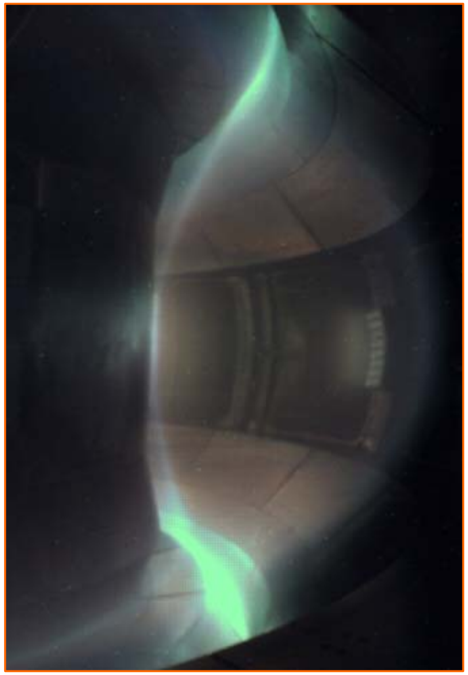
Maybe a scenario for ITER start up

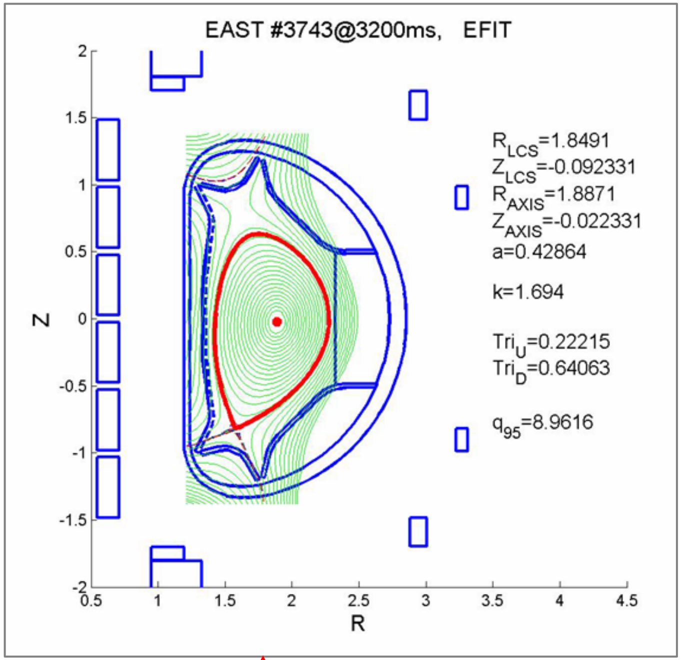
LHCD applied at plasma start up phase can significantly reduce the current ramping rate in PF coils and voltage applied at PF coils, which increases the safety margin of SC magnets and provide larger margin for plasma control

DN & SN configurations

A double null plasma having elongation of kappa = 1.8 and delta = 0.5,
EAST SN #3745 @ Ip = 0.2 MA, Bt = 2 T, t = 3.1s







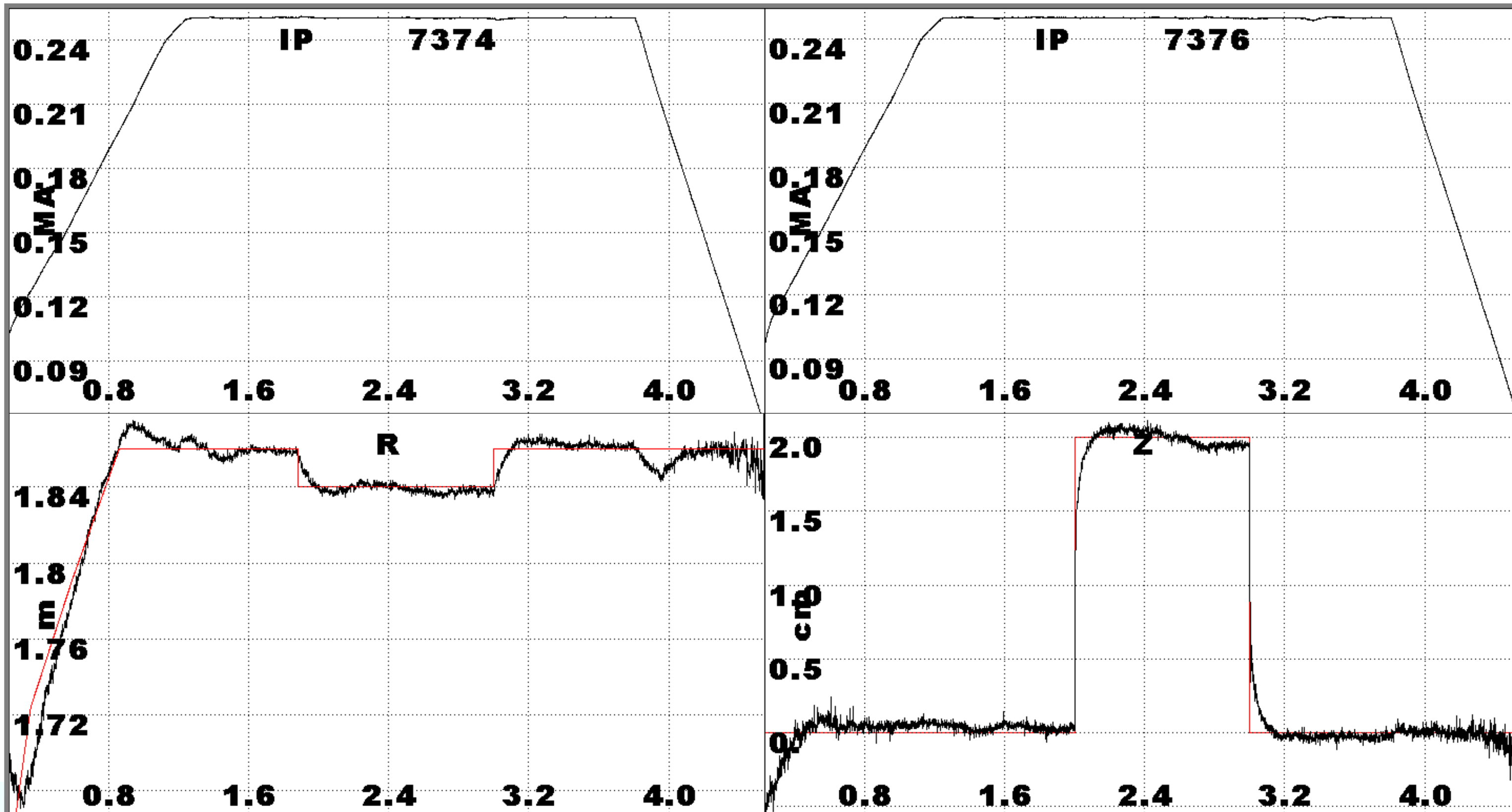
A single null plasma having elongation of kappa = 1.7 and delta = 0.64,
EAST SN#3743 @ Ip = 0.2 MA, Bt = 2 T, t = 3.2s

Achieved and well controlled plasma shapes almost cover all designed configuration

In collaboration with GA & PPPL

RZIP Control algorithm

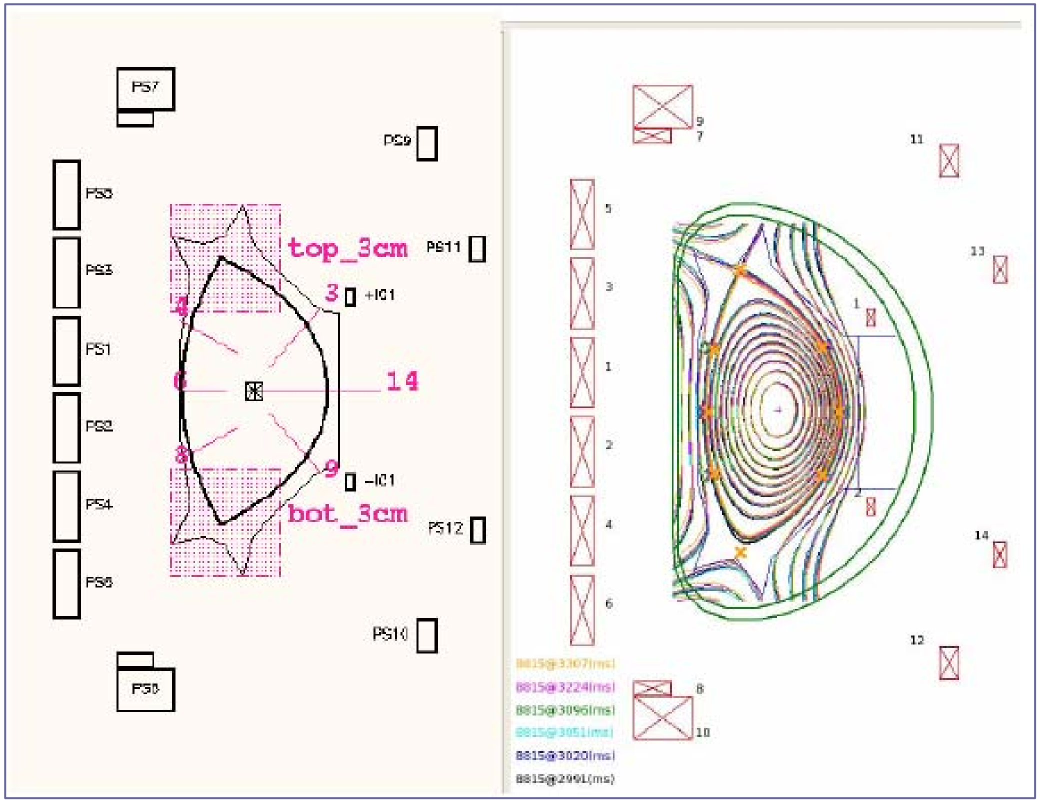
IP：1 kA, R: 0.3%(6 mm), Z: 0.6 mm has been achieved with well aligned and calibrated magnetic diagnostics

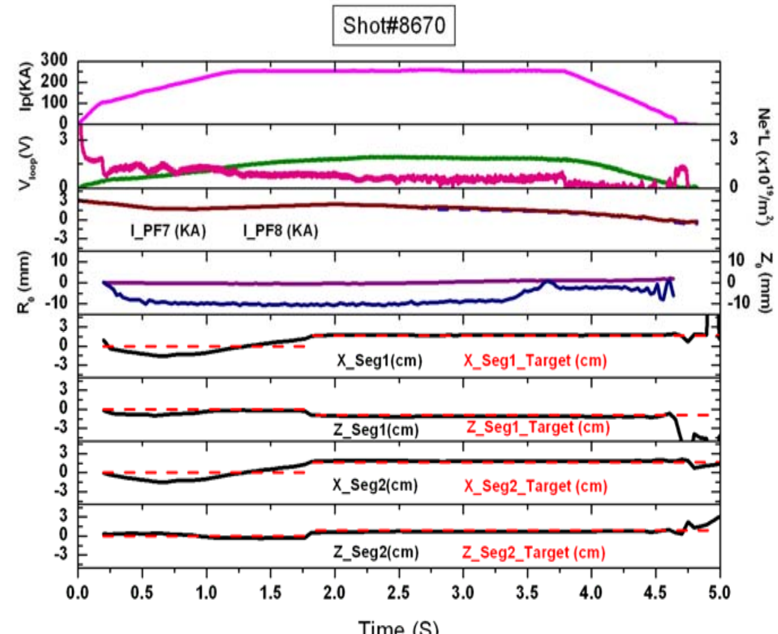


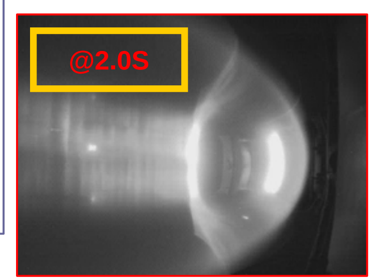
In collaboration with GA

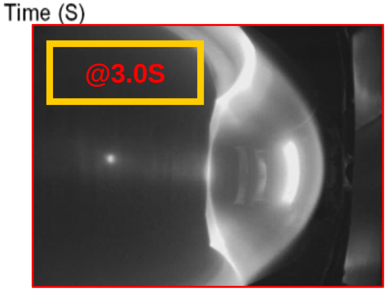
RTEFIT/ISO-flux control

In collaboration with GA



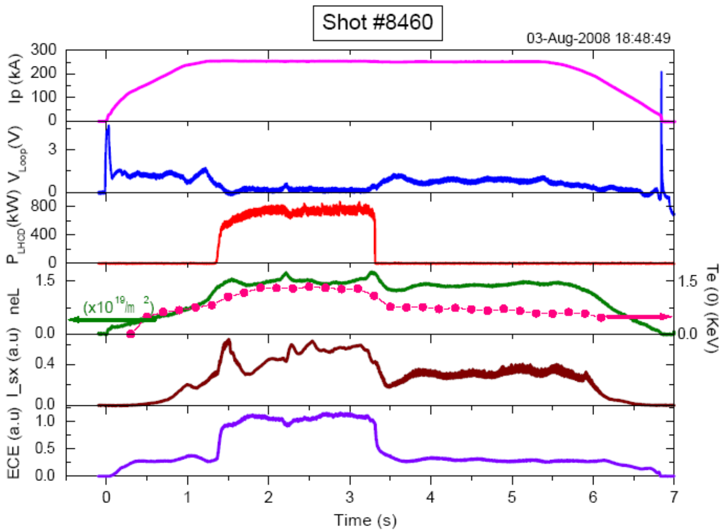


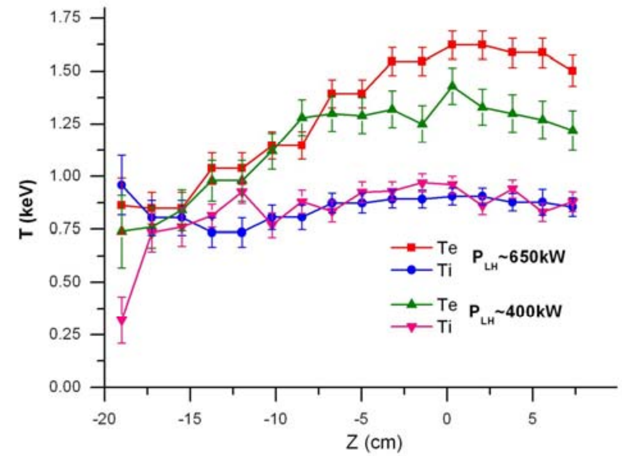


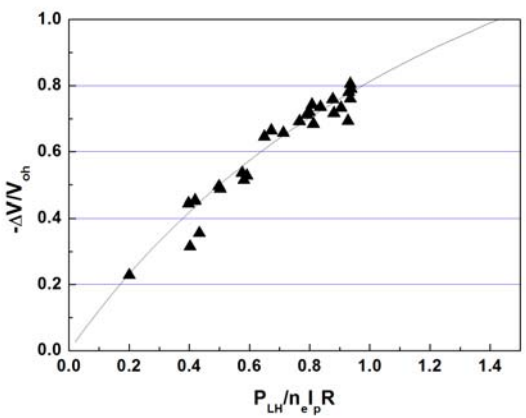


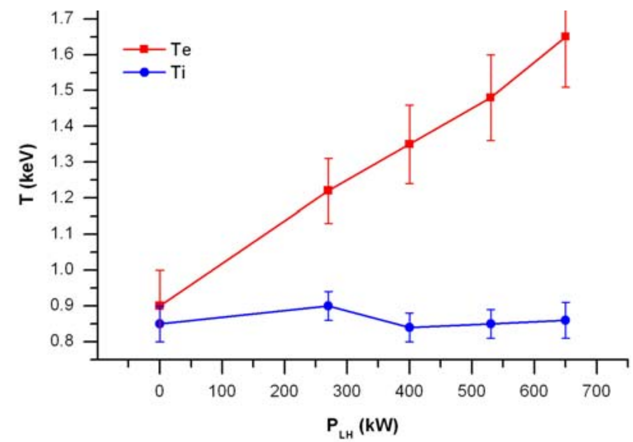
Primarily realization of RTEFIT/ISO-flux control algorithm produced well controlled plasma shapes and provide basis for further experiments

First LHCD experiments







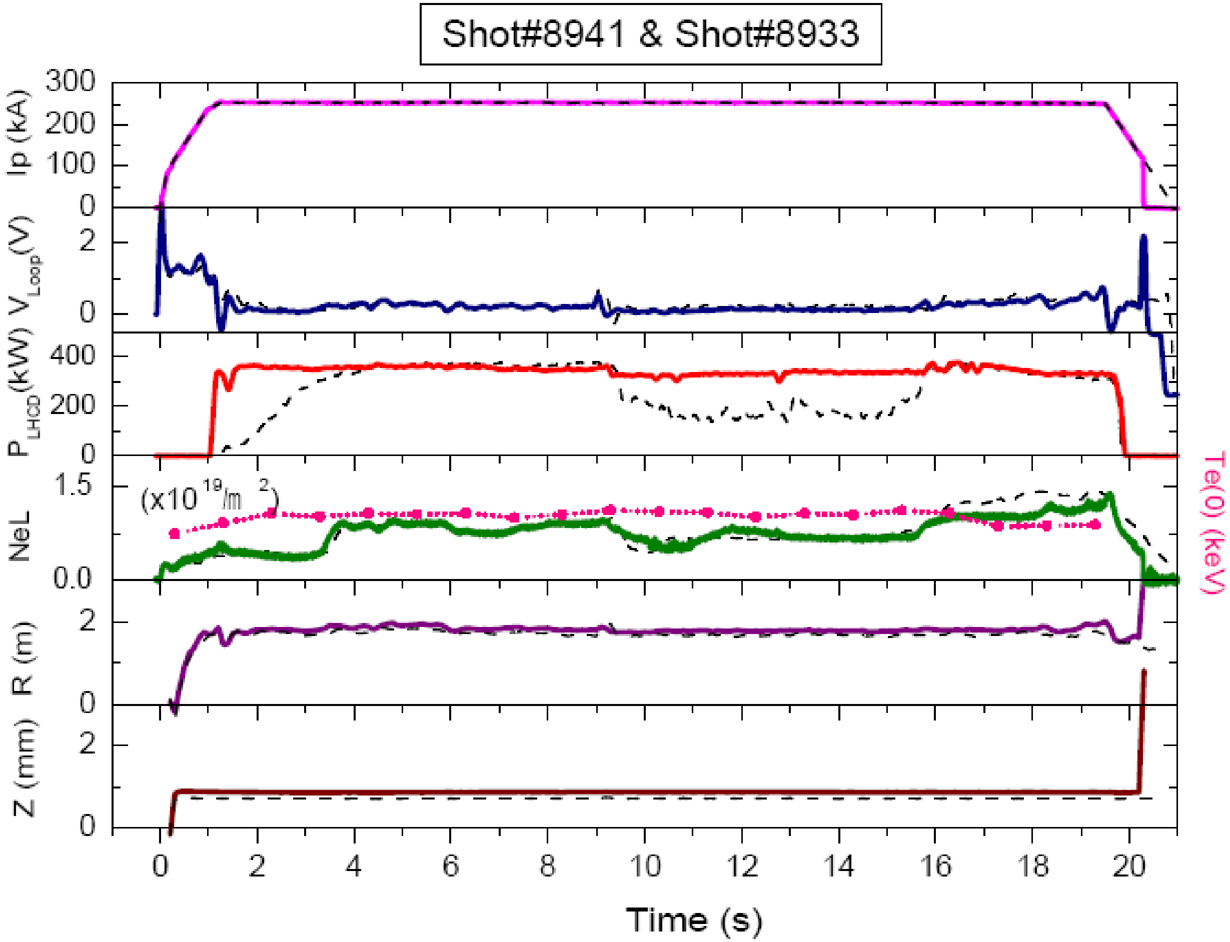


LHCD of 800kW almost sustain a fully non-inductive plasma discharge at Ip=250kA.

The current driving efficiency 0.8*1019 Am-2W-1 at Ip=250kA

Significant electron heating has been observed.

Long Pulse Discharges



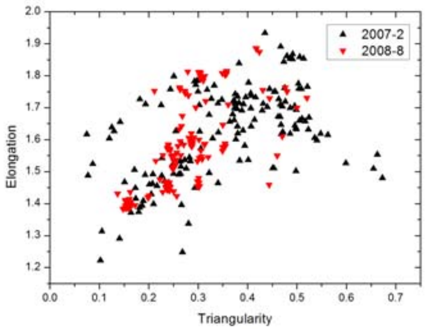
Ip=250kA, Ne~1.5*10^{19}/m^3 >20s

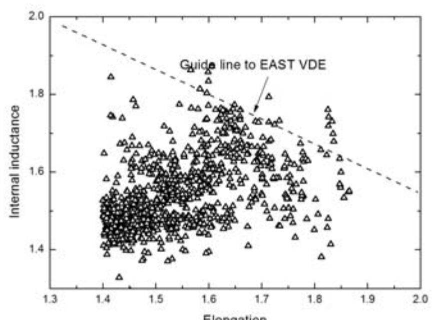
Ip=400kA, Ne~1.5*10^{19}/m^3 >10s

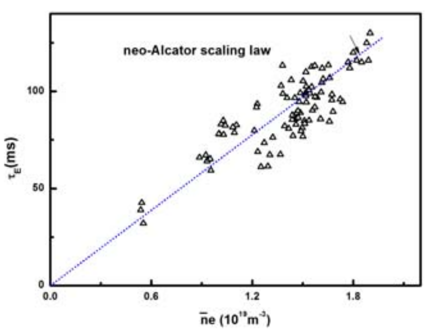
With presently available 2MW LHCD, it is possible to sustain full non-inductive plasma of 500kA

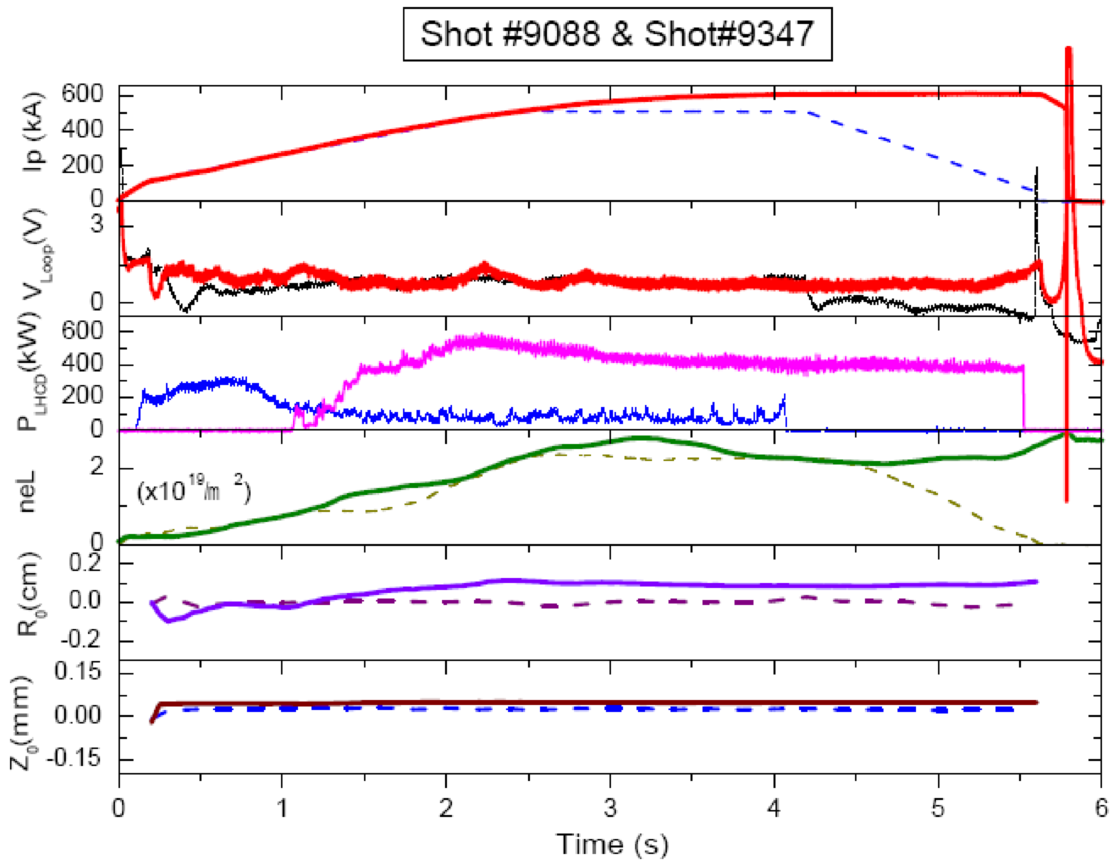
Repeatable long pulse discharges up to 23s has been achieved in elongated plasma. Main limitation…

Operational achievements









Plasmas: Ip~0.6MA, Bt~3T, P_{LHCD}~0.8MW, Td ~23s
Shaping: kappa ~ 1.9, delta ~ 0.65
Control: RZIp feedback + shaping programming (iso-flux)

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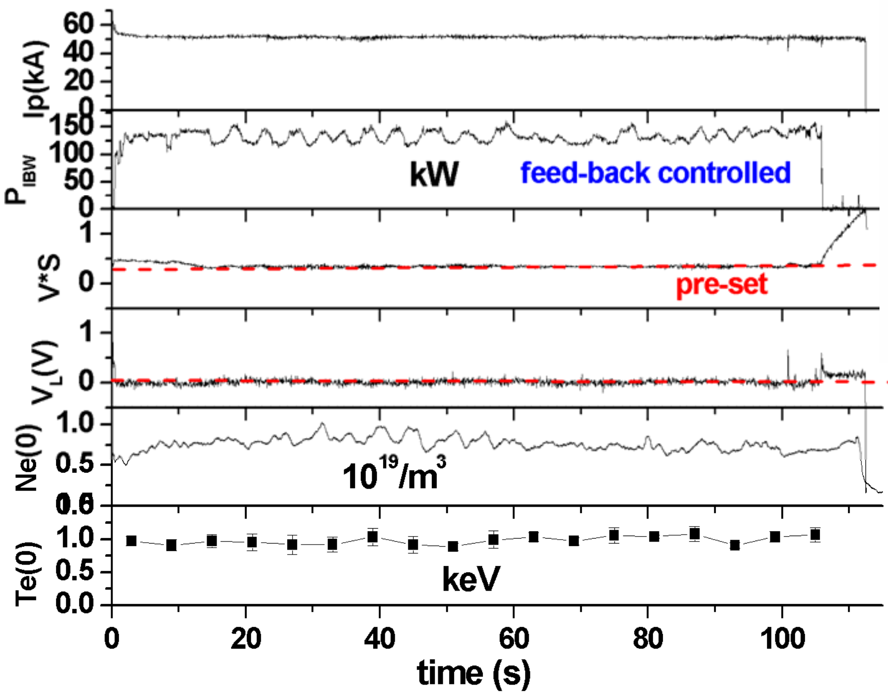
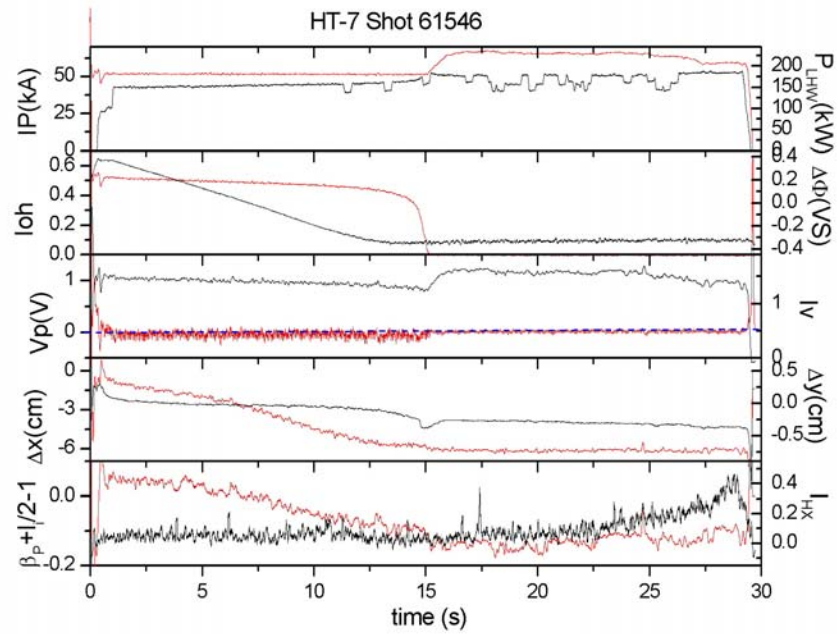
Scenarios for Long Pulse Discharges in HT-7

Magnetic swing flux feed back control for fully non-inductive current drive by regulating LHCD power



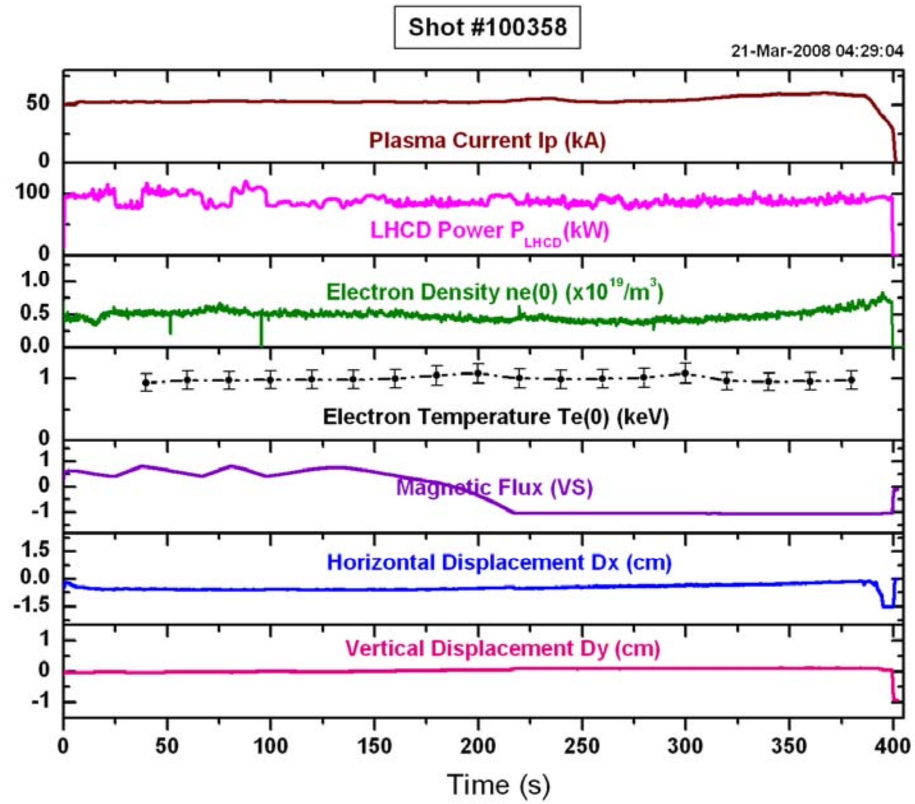


Transformer-less plasma discharges have been controlled by firstly over current drive to reverse saturation of transformer and then switch off current in central solenoid

Long Pulse Discharges in HT-7

I_p~50kA, ne(0)~0.7, Te(0)~1.0keV, Td~400S, I_{OH} (off) >200S

- Upgrade PFMs
- RT iso-flux control
- Water-cooled limiter
- RF wall conditioning
- Full Non-inductive CD
- P_{LHCD} Feed back control
- Fueling and pumping



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Near future plan

- 2(4)MW LHCD @ 2.45GHz √
- 1.5MW ICRF @ 30-110MHz √
- 4.5MW ICRF @ 25-75MHz ~√
- 4MW NBI @ 80keV (2011)
- 4MW LHCD @ 4.6GHz (2011)
- 4MW NBI @ 80keV (?)
- 4MW LHCD @ 3.7GHz （?）
- 2~4MW ECRF (?)

Total heating and current drive power ~16MW in 3~4 years

Additional ~8MW heating and current drive power is proposed

- Diagnostics（2010）→ all key profiles and some of specific measurements for physics understanding
- Upgrade of power supplies (IC, for 1MA operation)
- Upgrade of divertor (before 2011, >5MW/m^2 for SSO)

Research plan

Approach to steady-state operation

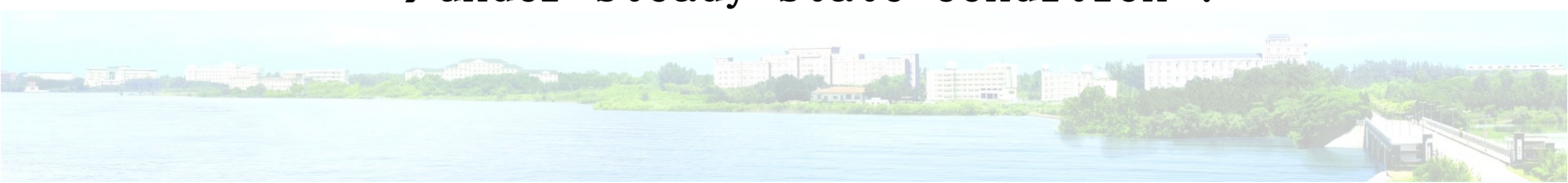
- **Fully non-inductive current drive**
  Mainly LHCD, FWCD, neutral beam CD and BS current

- **Current and pressure profile control**
  Mainly combination of LHCD,FWCD, NBCD

- **Operation scenario**
  Reversed shear or weak shear mode with ITB, high beta ELMy H-mode

Available CD and heating powers are sufficient to reach high performance regimes

→under steady-state condition ?



Summary

- **Control based on RZIP algorithm produced highly shaped plasma configurations. ISOFLUX control algorithm was primarily realized in EAST.**
- **The actively cooled in-vessel components using graphite as PFC and H&CD capabilities in EAST have been primarily validated in long pulse discharges.**
- **Experiments in HT-7 focused on steady-state operation under different scenarios. The long pulse discharges up to 400s renews the records in HT-7.**

- **EAST would be accessible to high performance regime under steady state condition.**
- **It will be fully open for fusion community.**