Role of ECH and ECCD in High-Performance Steady-State Scenarios

by
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GENERAL ATOMICS

Advances in EC Technology and Physics Enhance the Prospects for Steady-state Fusion Energy

Fundamental assumption:
A steady-state fusion energy source is very attractive

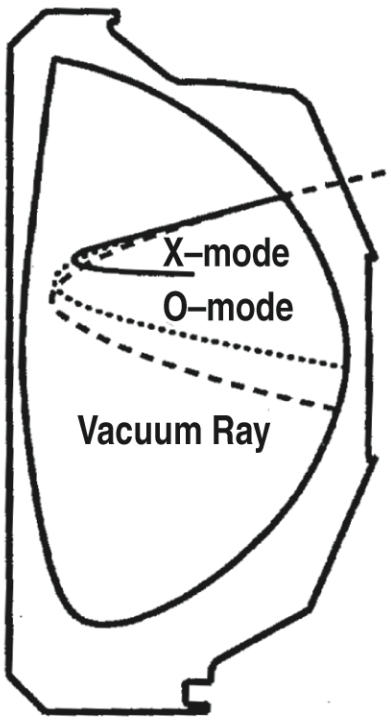
- **Advances in source and transmission line technology give high confidence that EC systems can deliver power in the power plant environment at high power density**
  - Minimal impact on magnet design
  - Minimal impact on blanket/shielding

- **Experiments have validated that ECH/ECCD provides essential and often unique capabiliities to facilitate steady-state operation**
  - Access to relevant conditions
  - Sustaining the desired operating conditions
  - Control of the operating point

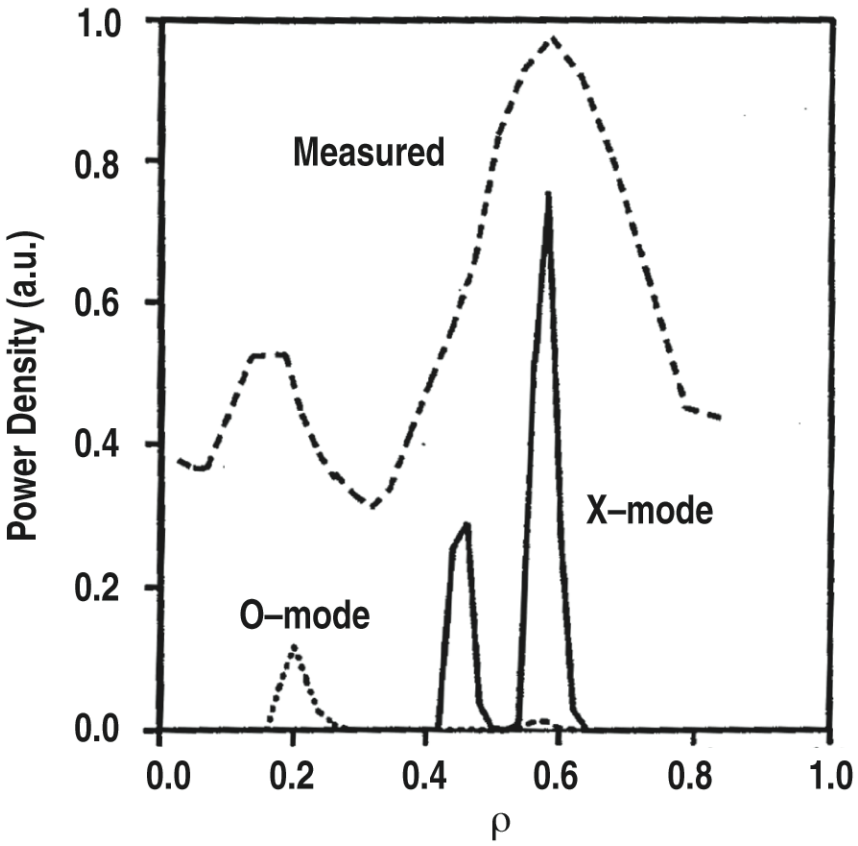
Ray Tracing Provides An Adequate Description of EC Wave Propagation and Absorption

- **Modulation analysis shows the expected response to a mixed polarization beam with weak absorption**

- **Cases with a converging beam require a proper Gaussian beam description up to the beam waist**

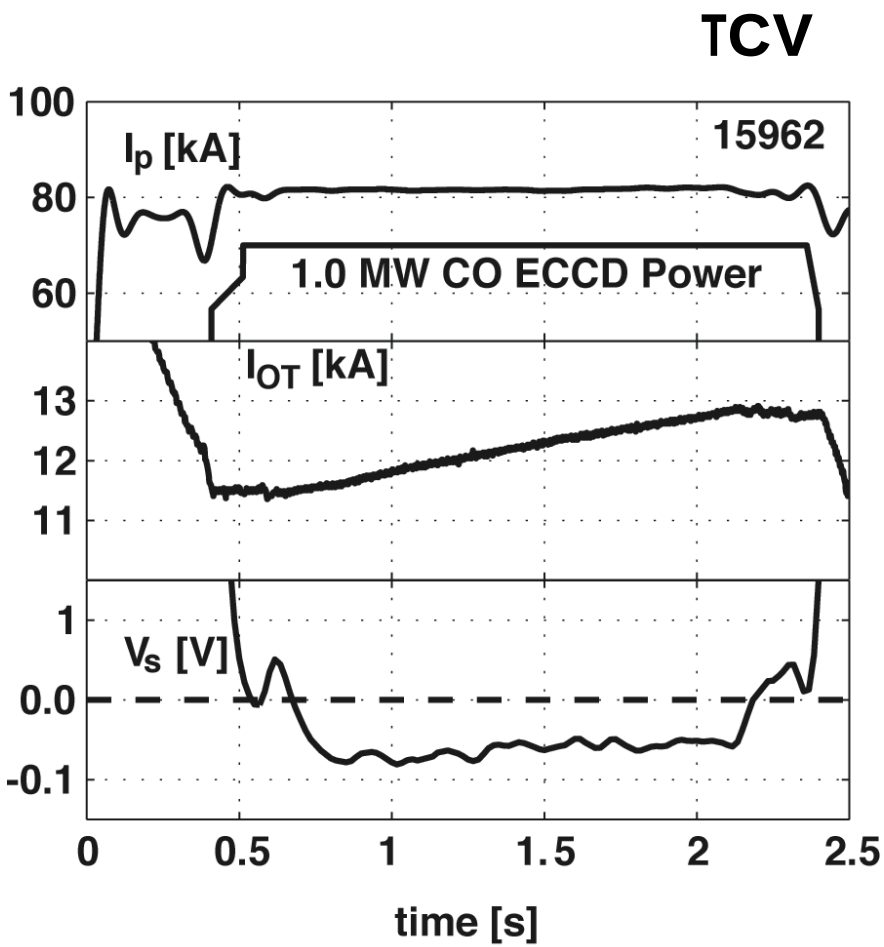


DIII-D



ECCD Has Been Unequivocally Demonstrated

- **ECCD has been observed on many fusion devices**
  - Example shown from the TCV tokamak shows sustainment of the total plasma current by ECCD and bootstrap current
  - To maintain constant current the inductive transformer must induce negative current, indicating overdrive by the non-inductive currents

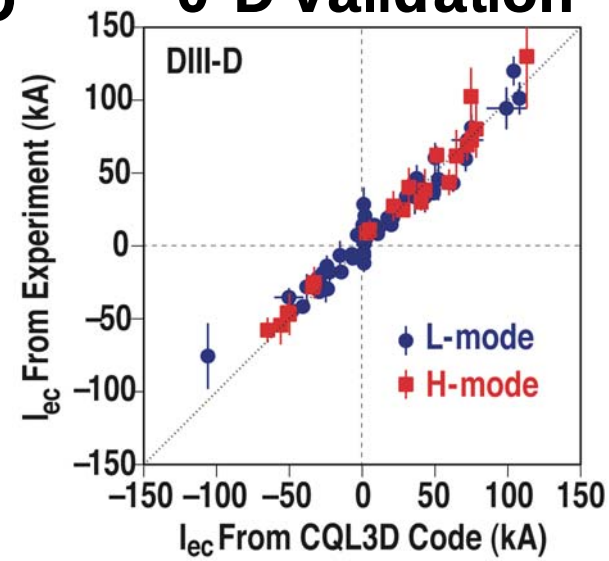


ECCD Theory Has Been Validated by Experiment

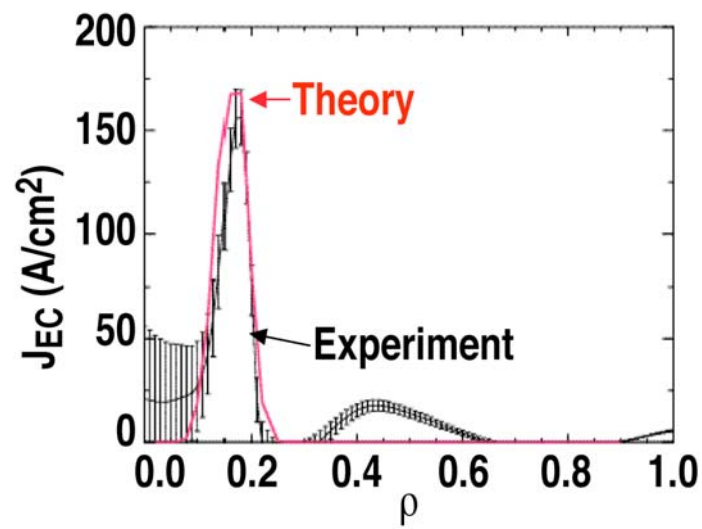
- **Measured driven current agrees well with theory when a full Fokker-Planck treatment with parallel electric field effects are included**
- **Local current density also agrees with predicted ECCD profiles**
- **A validated predictive capability exists for EC deposition and current drive for specified profiles up to conditions relevant for power plants**

DIII-D

0-D validation



1-D validation

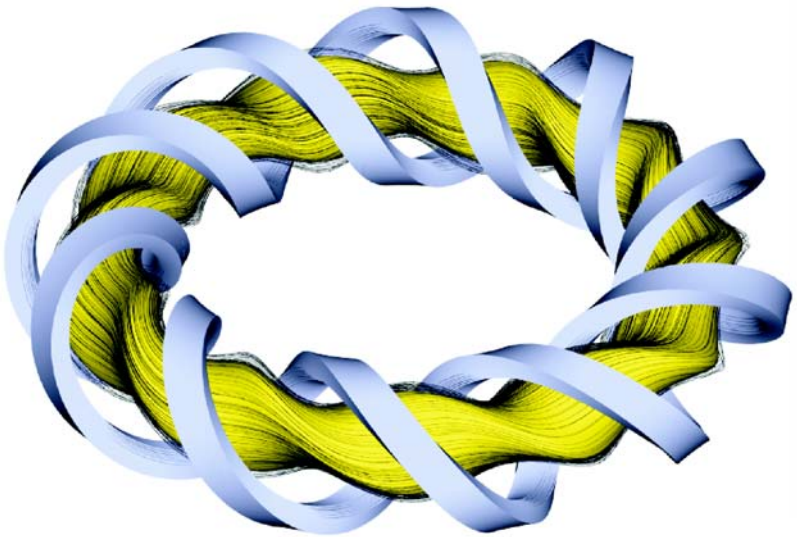


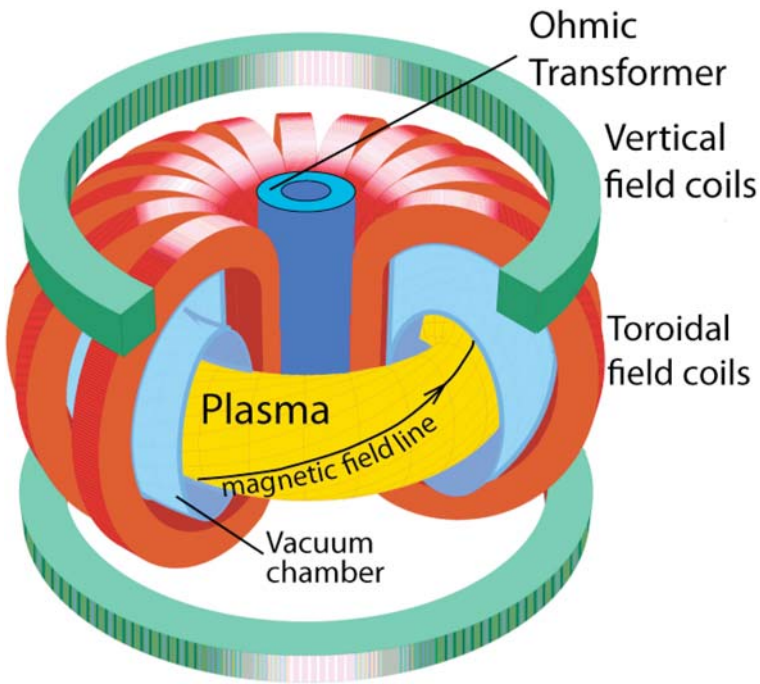
Two Complementary Approaches to Steady-State Magnetic Fusion Are Being Pursued

Both schemes apply a strong external toroidal field for good confinement:

- **Stellarator achieves equilibrium with 3-D magnets**
  - Magnetic configuration is inherently steady-state
  - Confinement reduced due to loss of axial symmetry
  - Stellarator research is studying "quasi-symmetry" to improve confinement while maintaining steady state capability

- **Tokamak uses plasma current to achieve equilibrium with axial symmetry**
  - Good confinement, but inductive current drive precludes steady state
  - Non-inductive current generation is essential for steady-state operation





Stellarator Requirements for Steady State

- **Accessing the steady-state regime**
  - Plasma startup
  - Heating to burn
  - H mode?
- **Sustaining the steady-state regime**
  - Community vision is ignited operation, so no external power is needed to sustain the plasma
- **Control of the operating point**
  - Key issue may be assuring the magnetic configuration matches the design of the structures in the vessel that handle the heat and particle fluxes

Tokamak Requirements for Steady State

- **Accessing the steady-state regime**
  - Plasma startup
  - Heating to burn
  - H mode access
  - Formation of the required current profile

- **Sustaining the steady-state regime**
  - Fully non-inductive operation
  - Stable operating point

  } Requires flexible current drive location and magnitude

- **Control of the operating point**
  - Impurity accumulation
  - Instability control

Outline

- **Accessing the steady-state regime**
- **Sustaining the steady-state regime**
- **Control of the operating point**
- **Prospects for steady-state operation on future devices**

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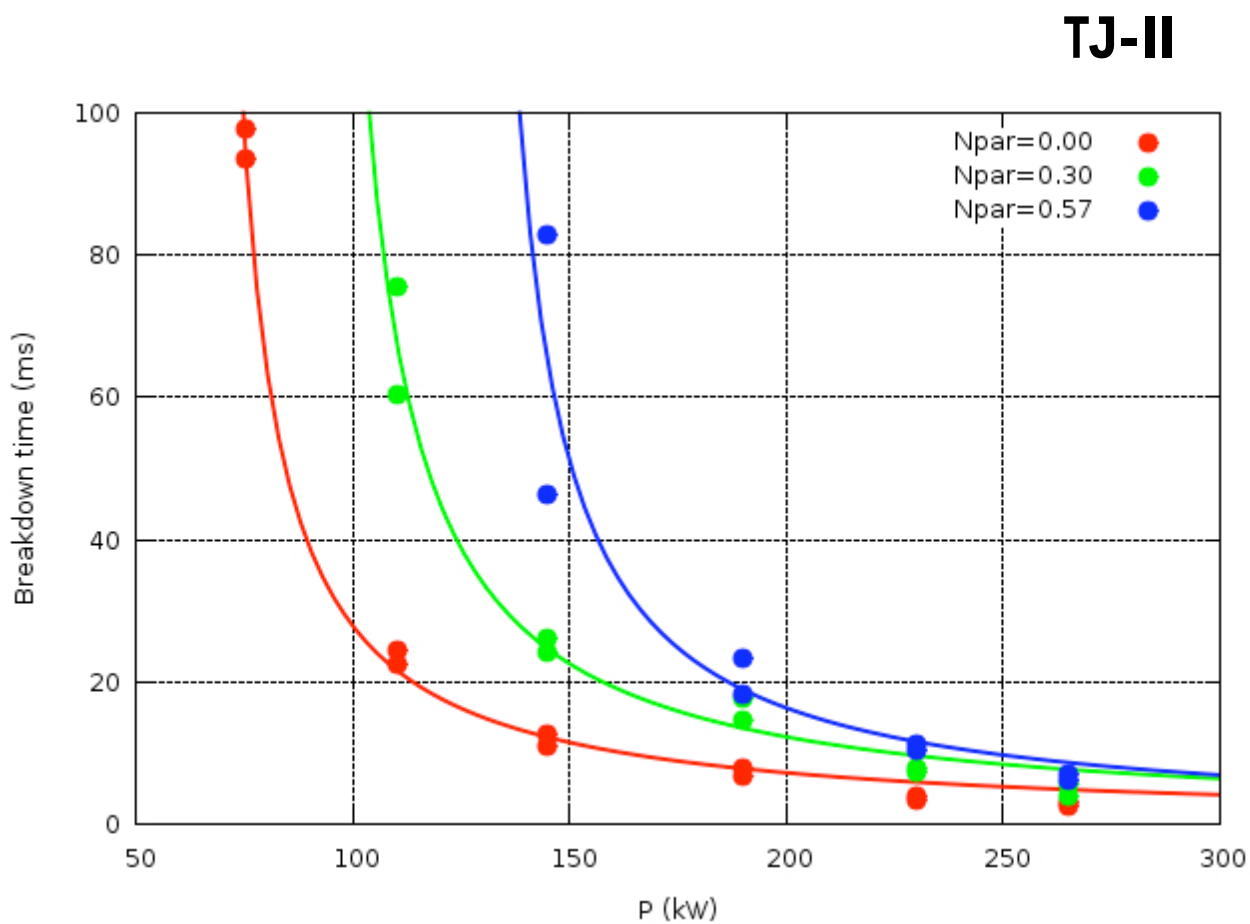
Plasma Startup With EC In Stellarators Is Routine

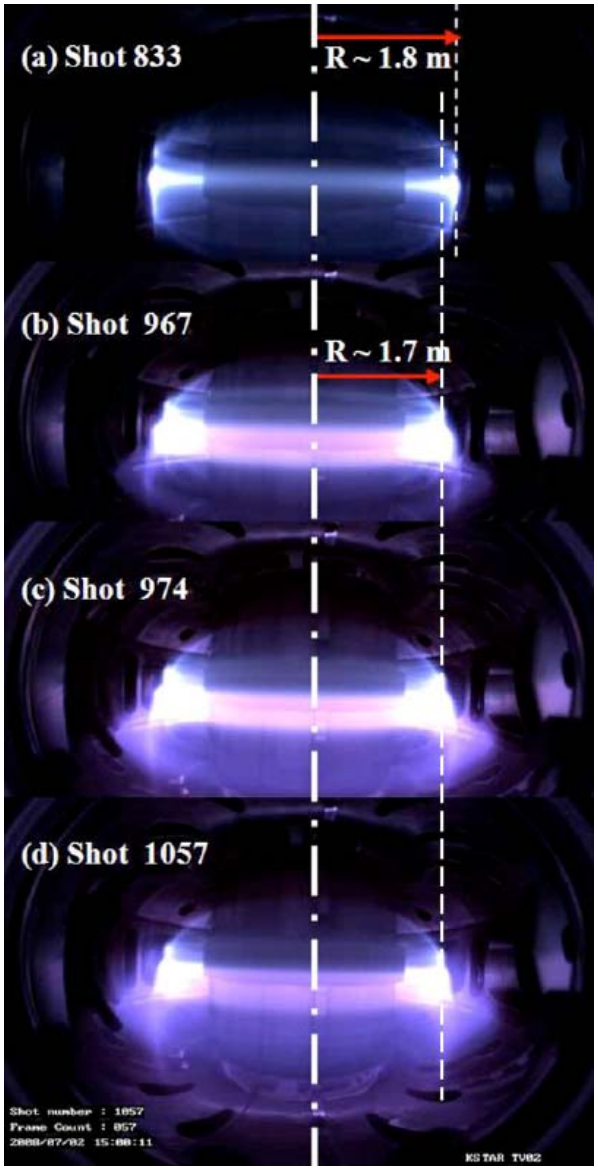
- **Vacuum magnetic configuration confines plasma, but plasma must be made**
  - Not obvious that EC absorption on neutral gas and low density plasma would be sufficient for burning through the radiation barrier
- **Startup results show strong dependence on $n_{\parallel}$ as expected from EC absorption**



EC Startup Assist Is Essential for Superconducting Tokamaks

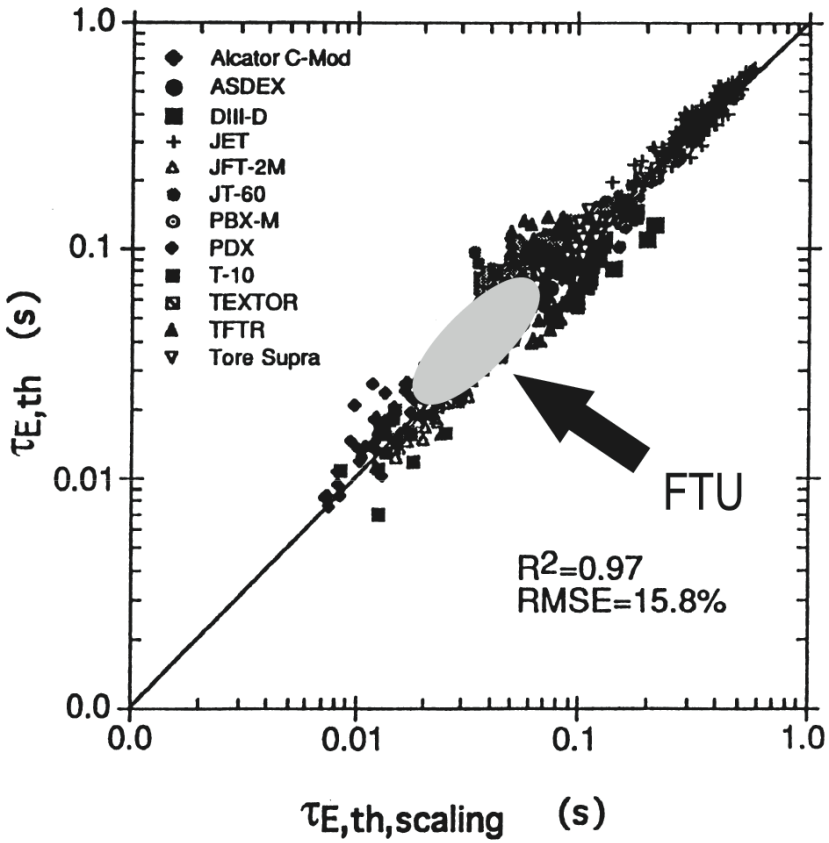
- **Steady-state tokamaks will likely have superconducting magnets**
  - Superconducting magnets limit the voltage that can be generated by the central solenoid
  - Blankets and shielding further decrease the peak voltage induced
  - Limits on wall conditioning techniques to clean the first wall further complicate startup
- **EC startup assist allows robust and reproducible initiation of the plasma**
  - Pre-ionization
  - Burnthrough the impurity radiation barrier

KSTAR



Heating Effectiveness With EC Waves Is Comparable To That With Neutral Beams

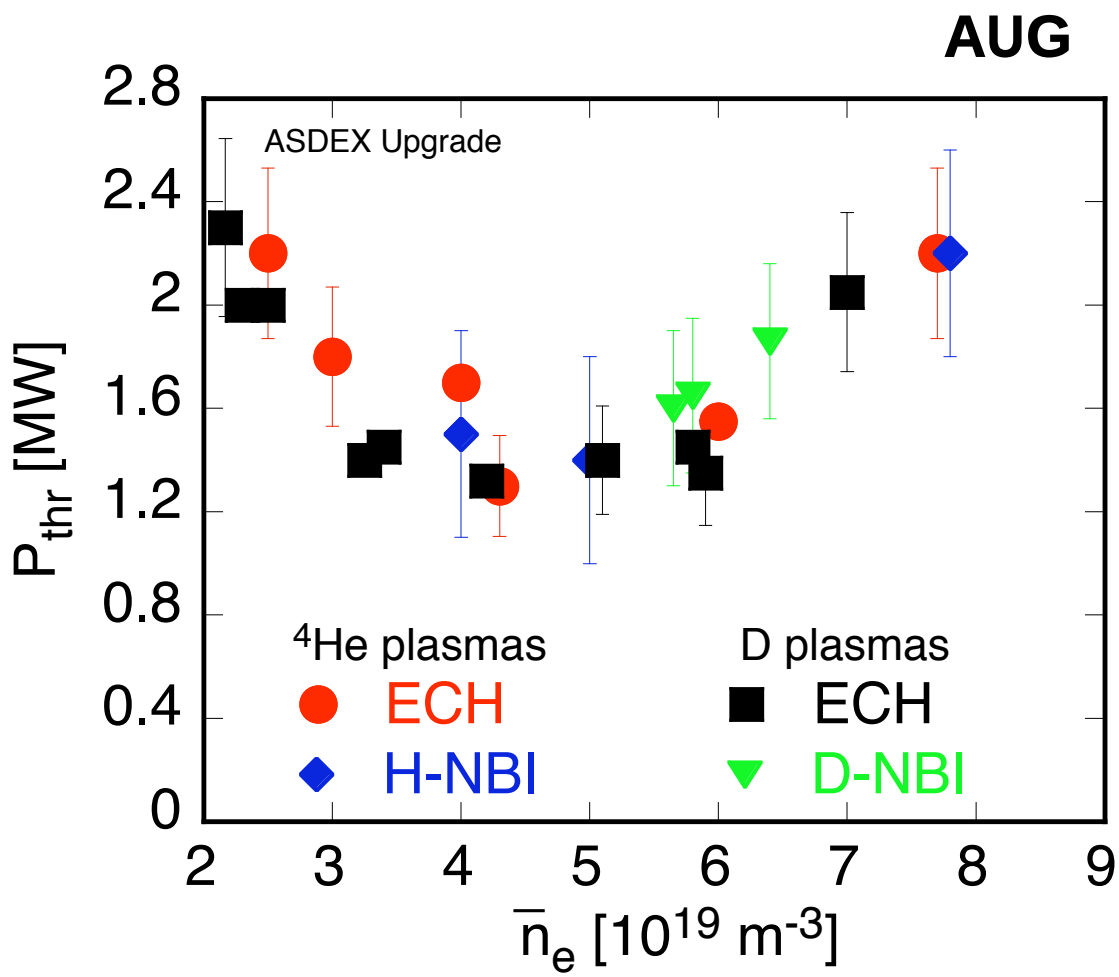
- **Neutral beam heating has higher global confinement due to the fast ion content**
- **Thermal confinement scaling is in better agreement**
  - Example here is FT-U L-mode data plotted over the ITER database compared to the ITER-97L scaling
- **Heating comparisons in high performance plasmas are limited due to lack of high power EC systems**
  - NBI heated high performance plasmas have enhanced confinement due to $T_i > T_e$ and strong rotation



Burning plasmas heated by α particles will be similar to EC heated plasmas
$\Rightarrow$ demonstration needed in present-day experiments

Access to H Mode with ECH Is Similar To NBI Heating

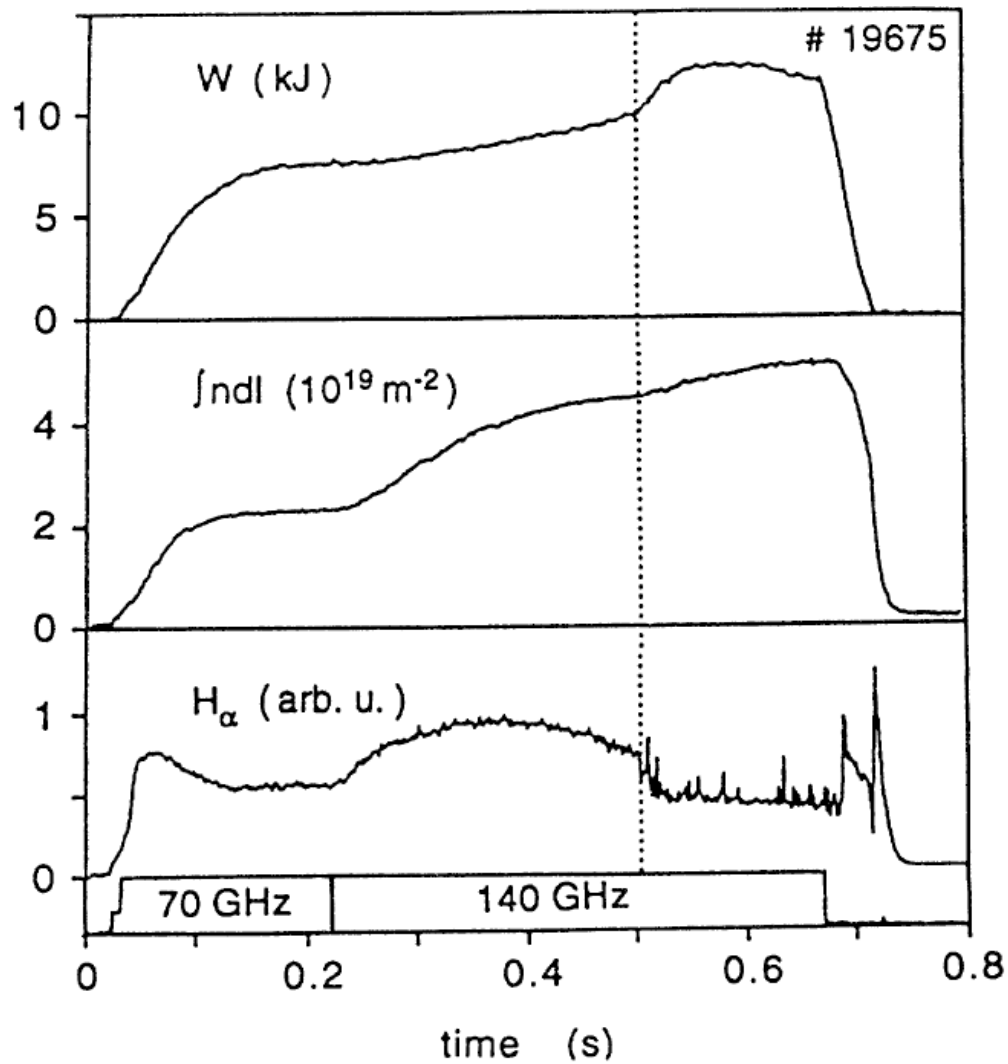
- **H mode confinement is required for steady-state tokamak scenarios**
  - ECH can be applied in a wider variety of conditions than other auxiliary heating methods
- **Access to H mode in tokamaks is characterized by a power threshold**
- **At comparable densities, no difference in power threshold is observed between ECH and NBI**



Stellarators Also Have Accessed H Mode with ECH

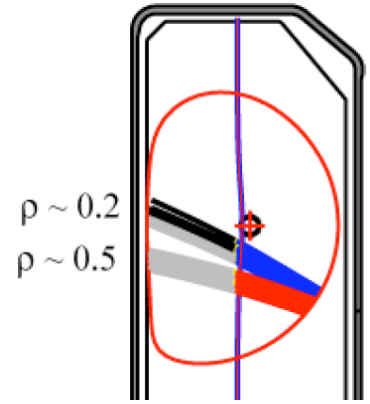
- **Confinement improvement for stellarators is highly desirable**
  - Non-axisymmetry intrinsic to stellarators leads to reduced confinement relative to similar sized tokamaks
- **H mode behavior in stellarators is similar to tokamaks**
  - Stored energy and density increase
  - ELM-free regimes have impurity accumulation
  - ELMing regimes will have the same issues as tokamaks
- **Access is not characterized by a power threshold**

WVII-AS

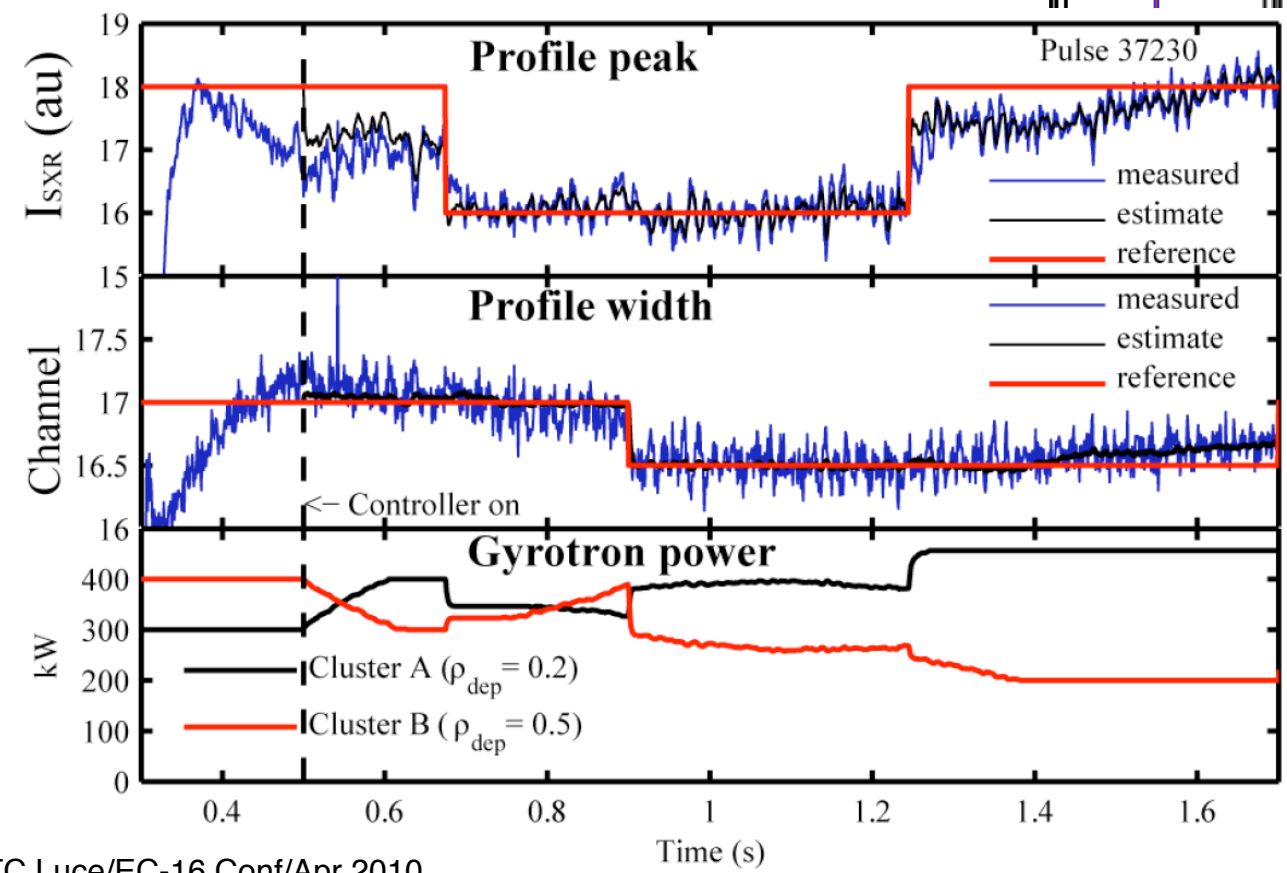


Multiple EC Systems Allow Control of Multiple Variable Quantities Such as Profile Shape

- **Control of the temperature profile during the current formation phase may be needed to access advanced scenarios**
  - In the absence of current profile measurements, the resistivity profile may be a suitable proxy
- **MIMO control successful due to development of an efficient model of the plasma response**

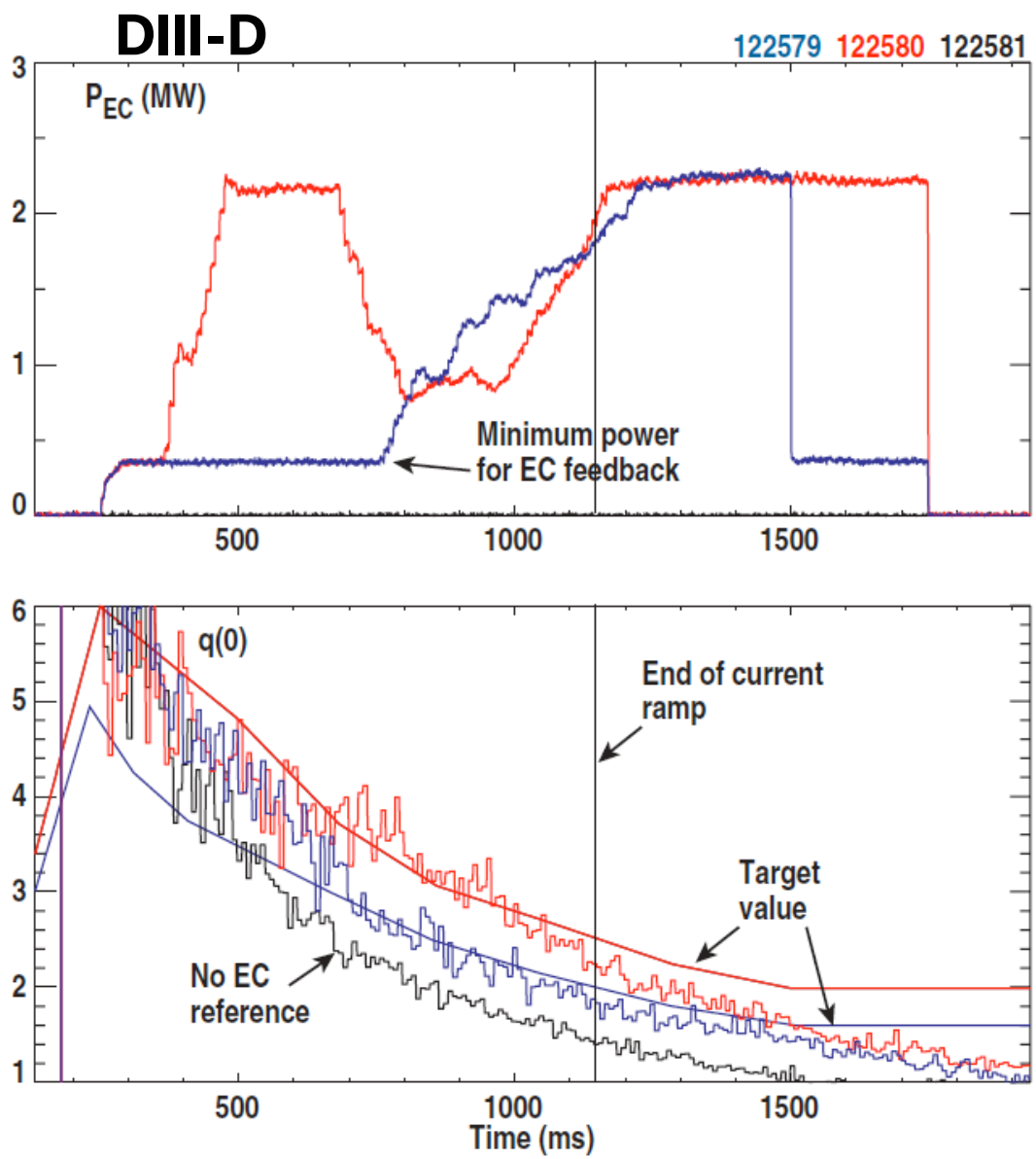


TCV Closed-loop case



Feedback Control of q(0) Is Possible with Real-Time q Measurements and ECH

- **Access to steady-state scenarios requires forming the desired q profile before start of burn**
  - Hot plasma during burn precludes modification of the q profile
  - ECH is the ideal tool because other heating schemes have limitations during the current rise
- **Example shown is single-input single-actuator control**
  - More sophisticated MIMO and model-based feedback schemes are under development



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- **Sustaining the steady-state regime**
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High Bootstrap Current Fraction Is Needed To Reduce The Recirculating Power Fraction

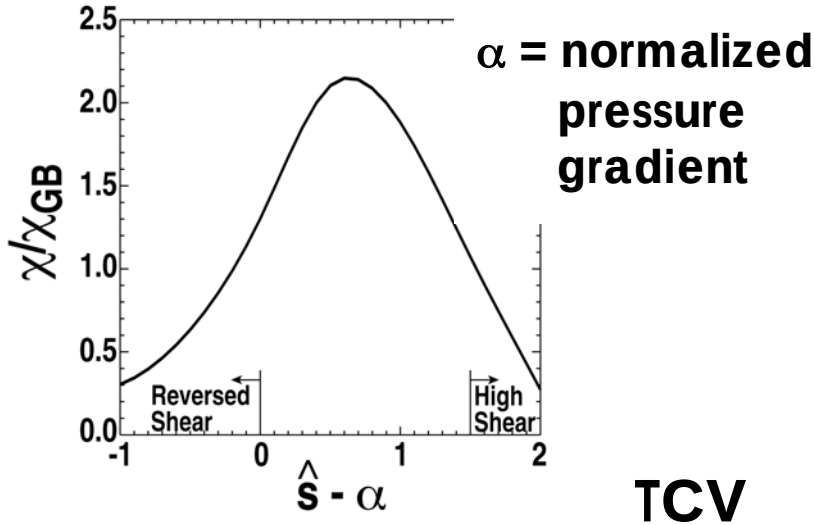
- **Electron cyclotron current drive efficiencies under fusion conditions yield γ_{CD} < 0.05 A/W**

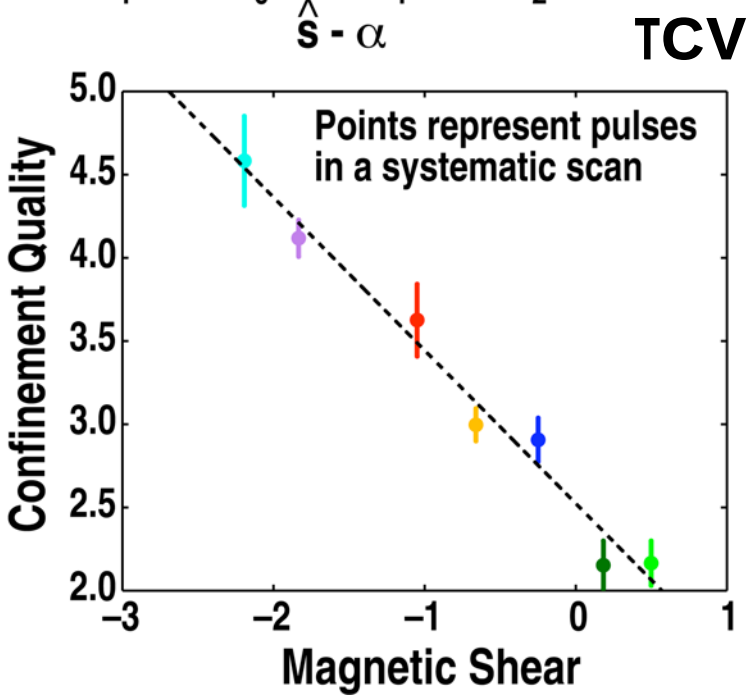
- **Recirculating power fraction is given by:**
  - $f_{recirc} = P_{CDe} / P_{plant,}$ where $P_{CDe} = (I_{CD} / \gamma_{CD}) / \eta_e$
  - Take I_{CD} = 12.5 MA and η_e = 0.5
  - For P_{plant} = 1000 MWe, the recirculating power fraction f_{recirc} = 50% ➔ much too high for a practical power plant

- **To make the target of f_{recirc} = < 20%, it is necessary to find a factor of 2.5:**
  - Increase in γ_{CD} ➔ higher T/n, which means lower density at fixed β
    Unattractive due to smaller increase in the fusion power with temperature and additional stress on the solution to handle heat and particle flux at the boundary

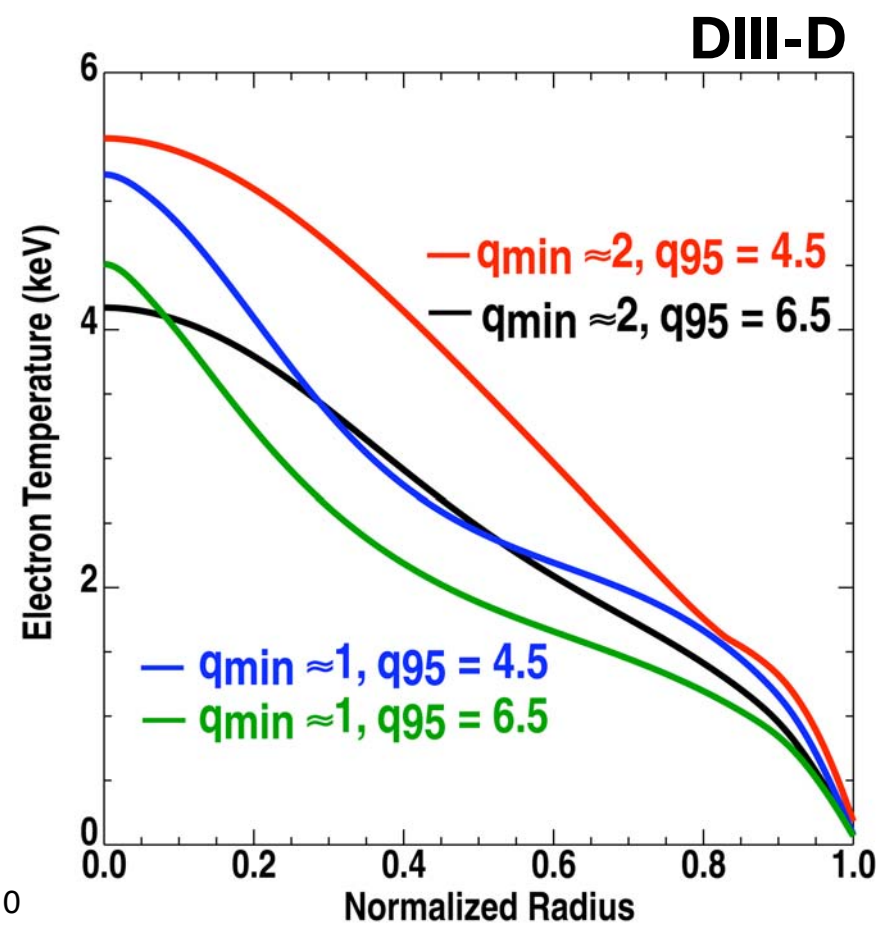
  or
  - Reduction in the demand for external current drive ➔ higher bootstrap current fraction

Bootstrap Current Profile Depends On Transport Which Depends On the Total Current Profile



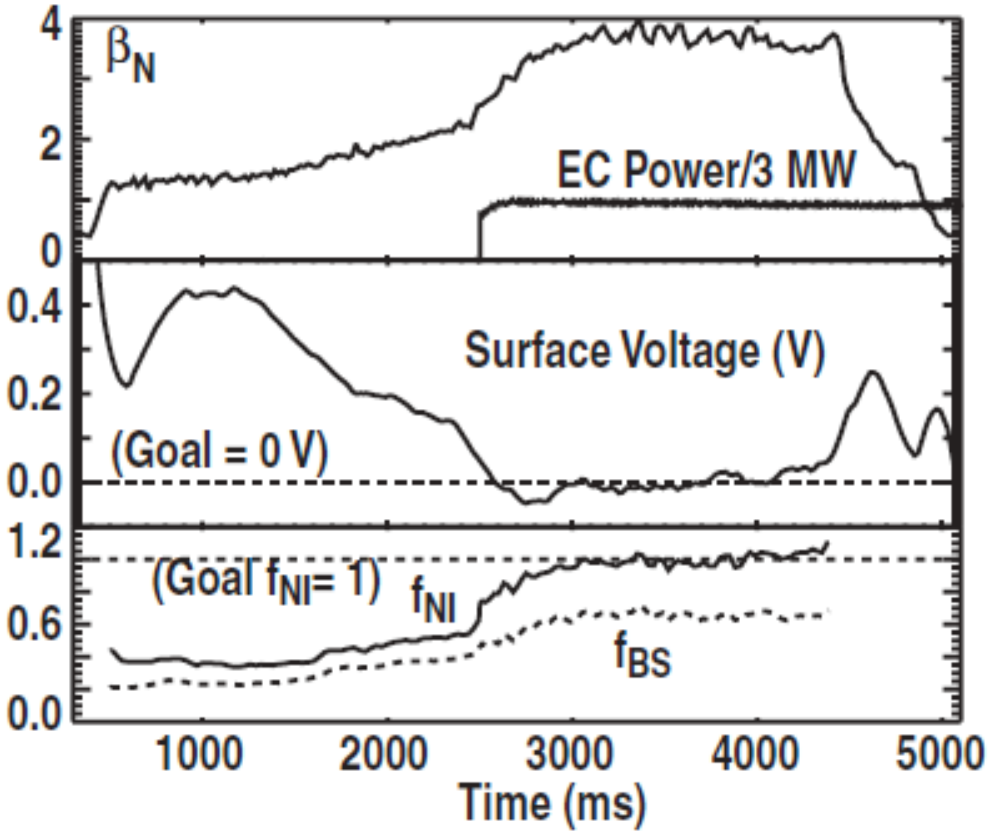


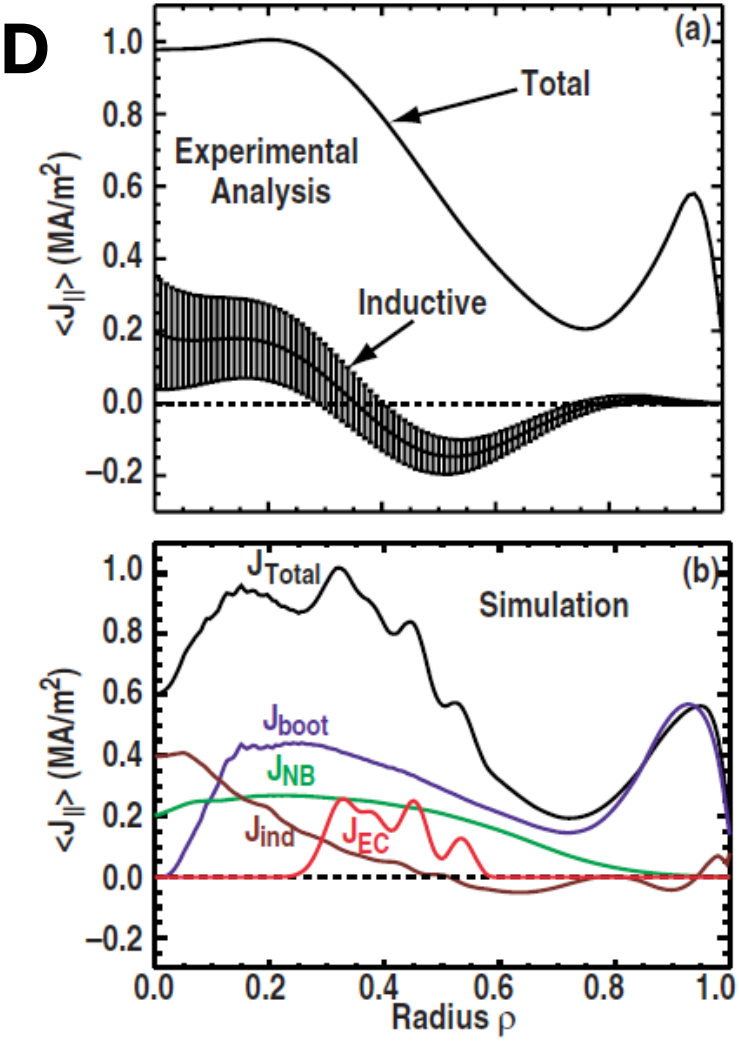
- **For example, energy transport depends on magnetic shear**
  - Theory and experiment show strong dependence



Steady-state Tokamak Operation Requires Sustaining the Plasma Current Non-inductively

β_N=3.7, H=1.5, f_{BS}=0.65, q_{95}=6.3 **DIII-D**



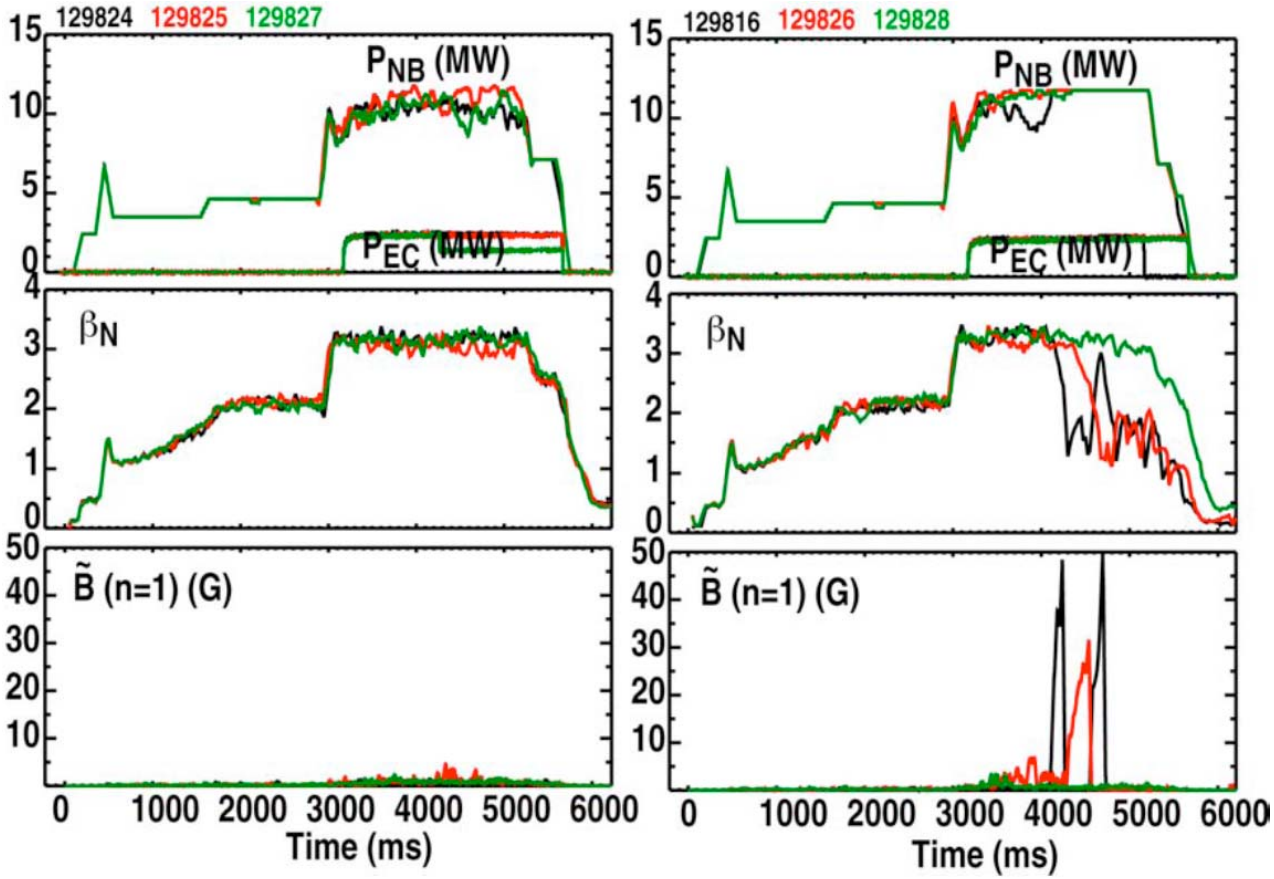


- **EC system plays two key roles:**
  - Driving ~10% of the total current where other current drive sources do not
  - Varying position to optimize ideal and resistive stability

Optimization of ECCD Location and Deposition Profile Leads to Operation at Higher Pressure

All cases stable at β_N=3.2

Only broad deposition case is stable at β_N=3.4



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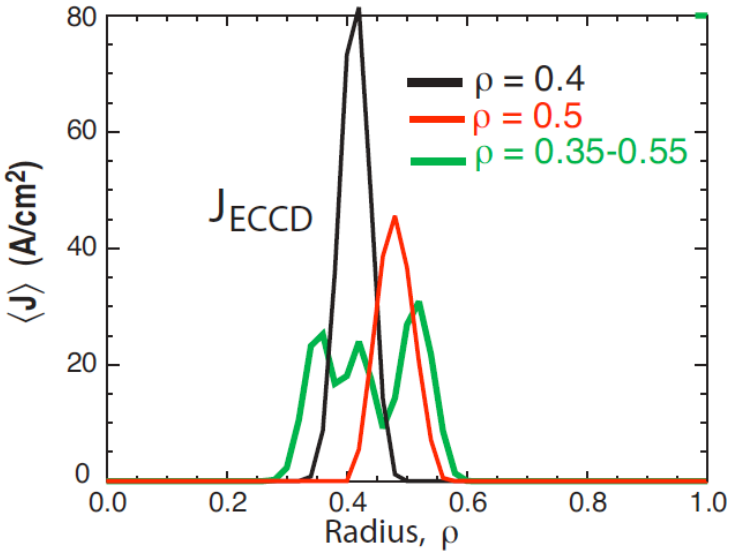

Not direct stabilization like stabilization of an existing island

Predictive model of resistive stability and the effects of ECCD on it is needed to optimize steady state scenarios

Outline

- Accessing the steady-state regime
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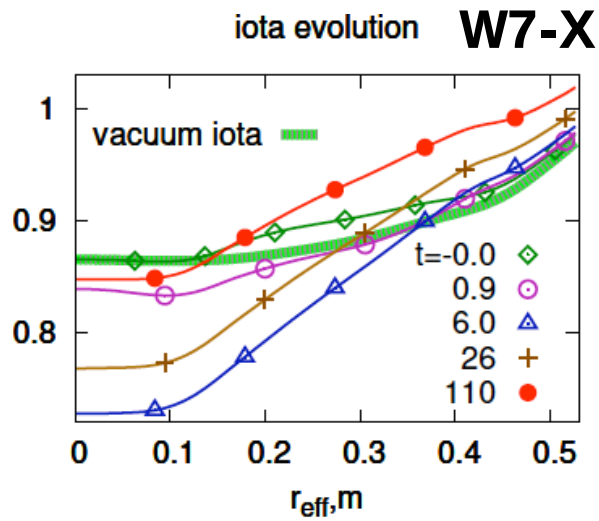
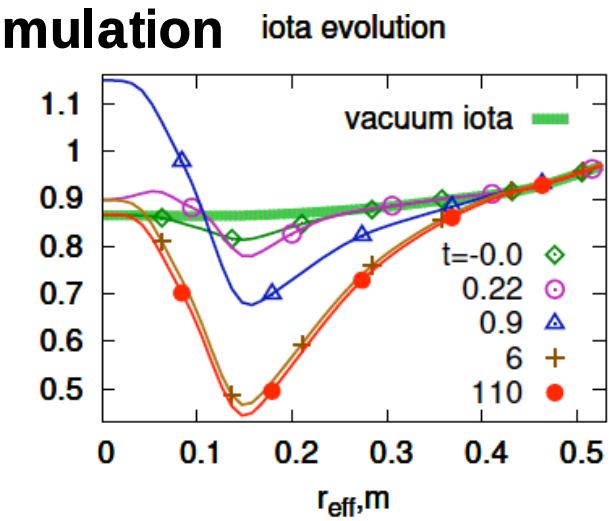
Stellarator Divertor Solutions May Require Careful Control of the Edge Rotational Transform

- **Confinement in a shearless stellarator optimizes near a low-order rational**
  - Divertor solutions take advantage of this to expand the flux with the nearby vacuum island
  - Small changes in the edge rotational transform can affect the plasma boundary strongly
- **Compensation with ECCD is possible**

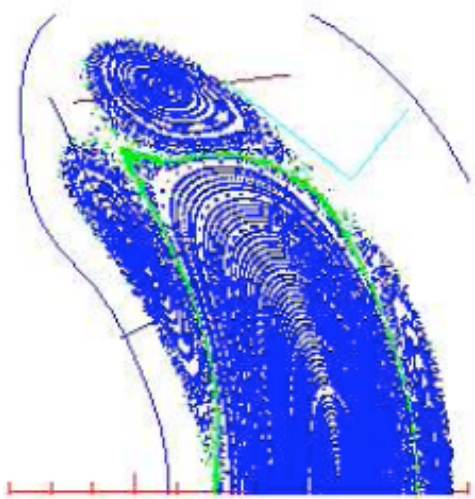
W7-X Simulation

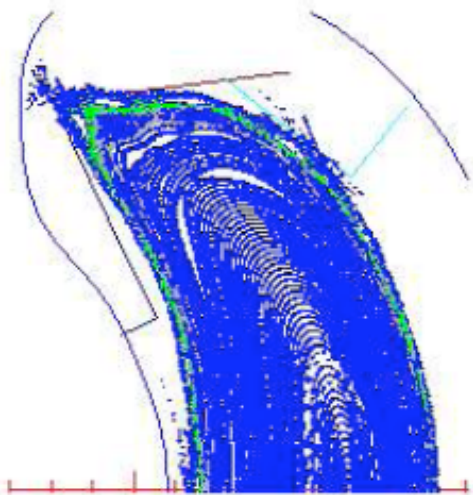


$I_b = 43$ kA



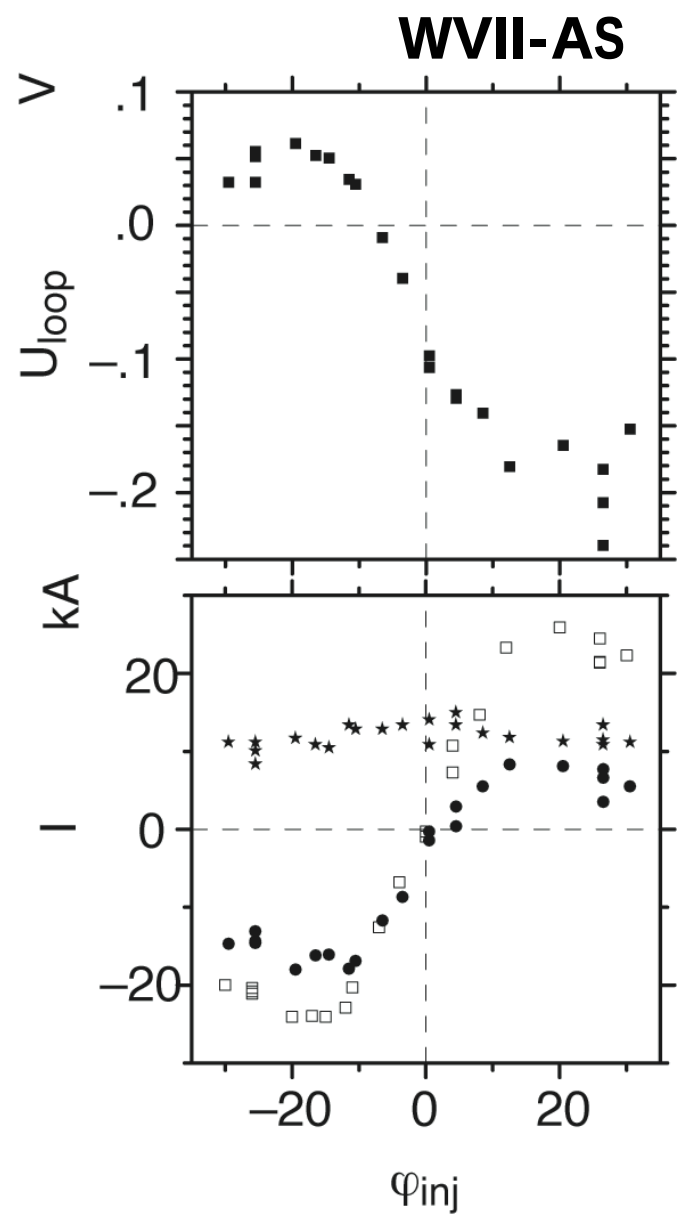
$I_b = 0$





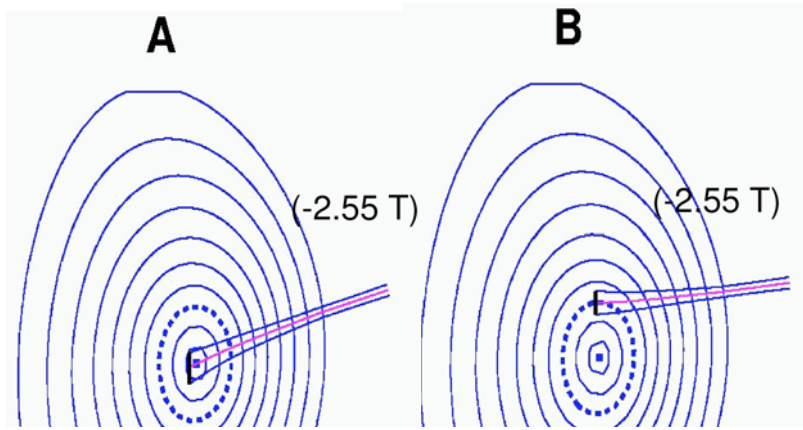
Bootstrap Current Compensation By ECCD Has Been Demonstrated

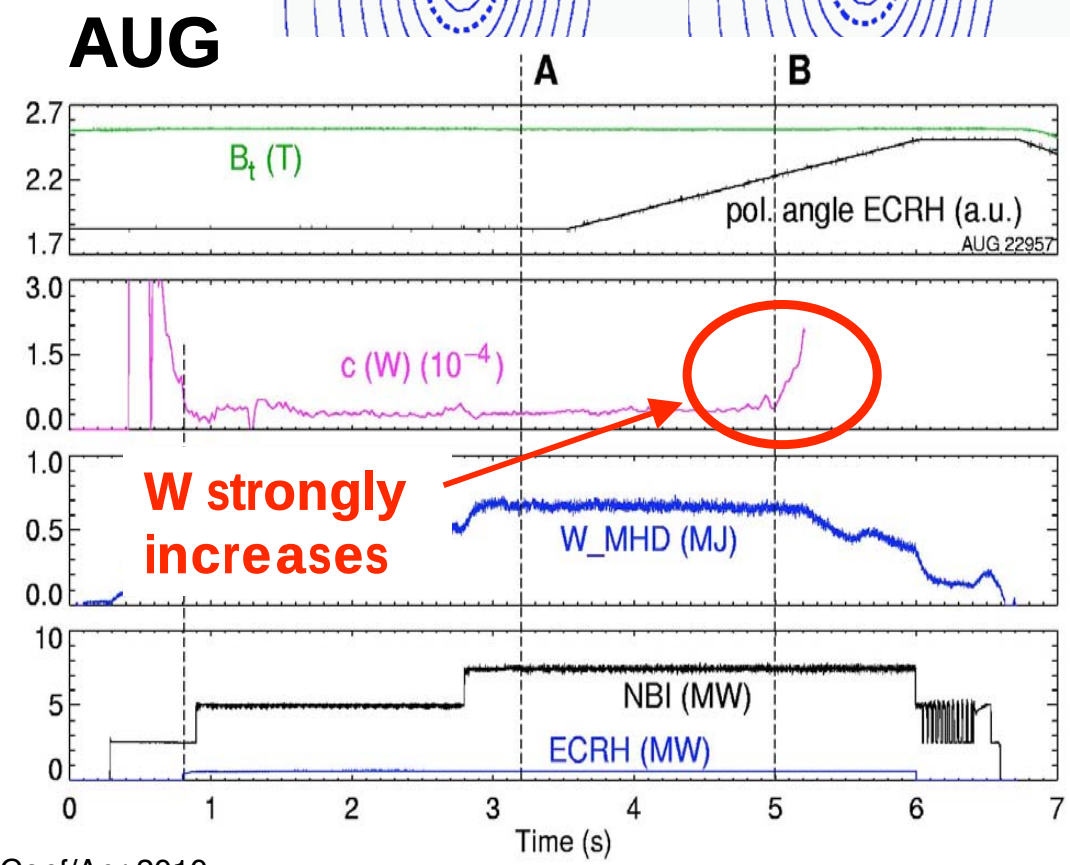
- All cases have ~10 kA of bootstrap current
- Scan of the injection angle parallel to the field lines varies the amount of ECCD for fixed power
- Inductive current is applied to yield no net current
- When no inductive current is applied, then the bootstrap current is compensated by ECCD



Intense Central Heating Counteracts the Effects of Metallic Impurity Accumulation

- **Power plants are likely to have a metallic first wall**
  - Neoclassical impurity transport yields very peaked impurity density ($n_Z \propto n_e^Z$)
  - High Z impurities can radiate intensely in power plant conditions
- **Cental EC heating mitigates the effects of W accumulation**
  - Physics mechanism still unclear:
    - Support power balance against radiation?
    - Enhanced particle flux?
  - Same spatial dependence seen for radial shift of heating

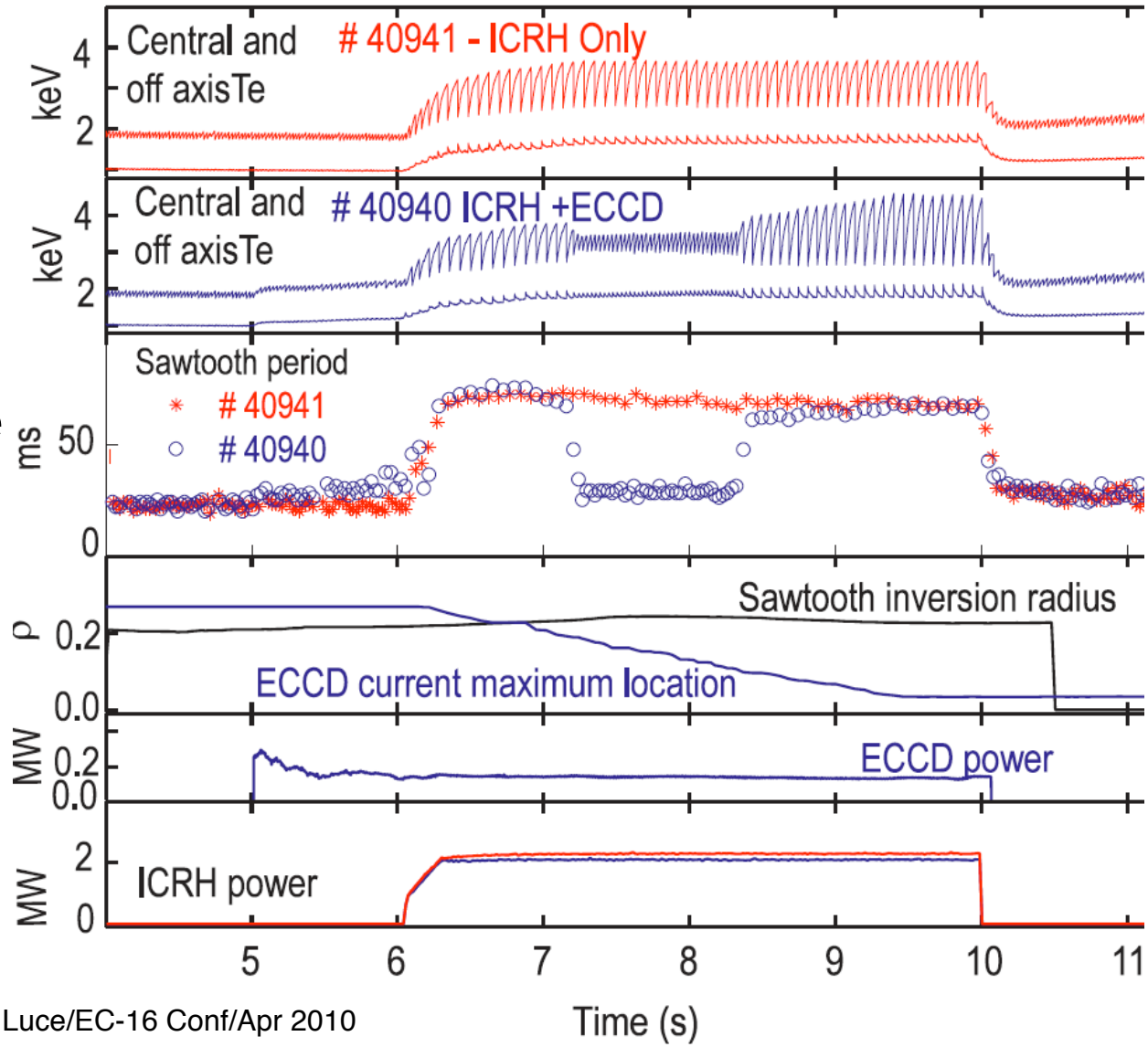




Localization and Control of the ECCD Deposition Allows Feedback Control of Instabilities

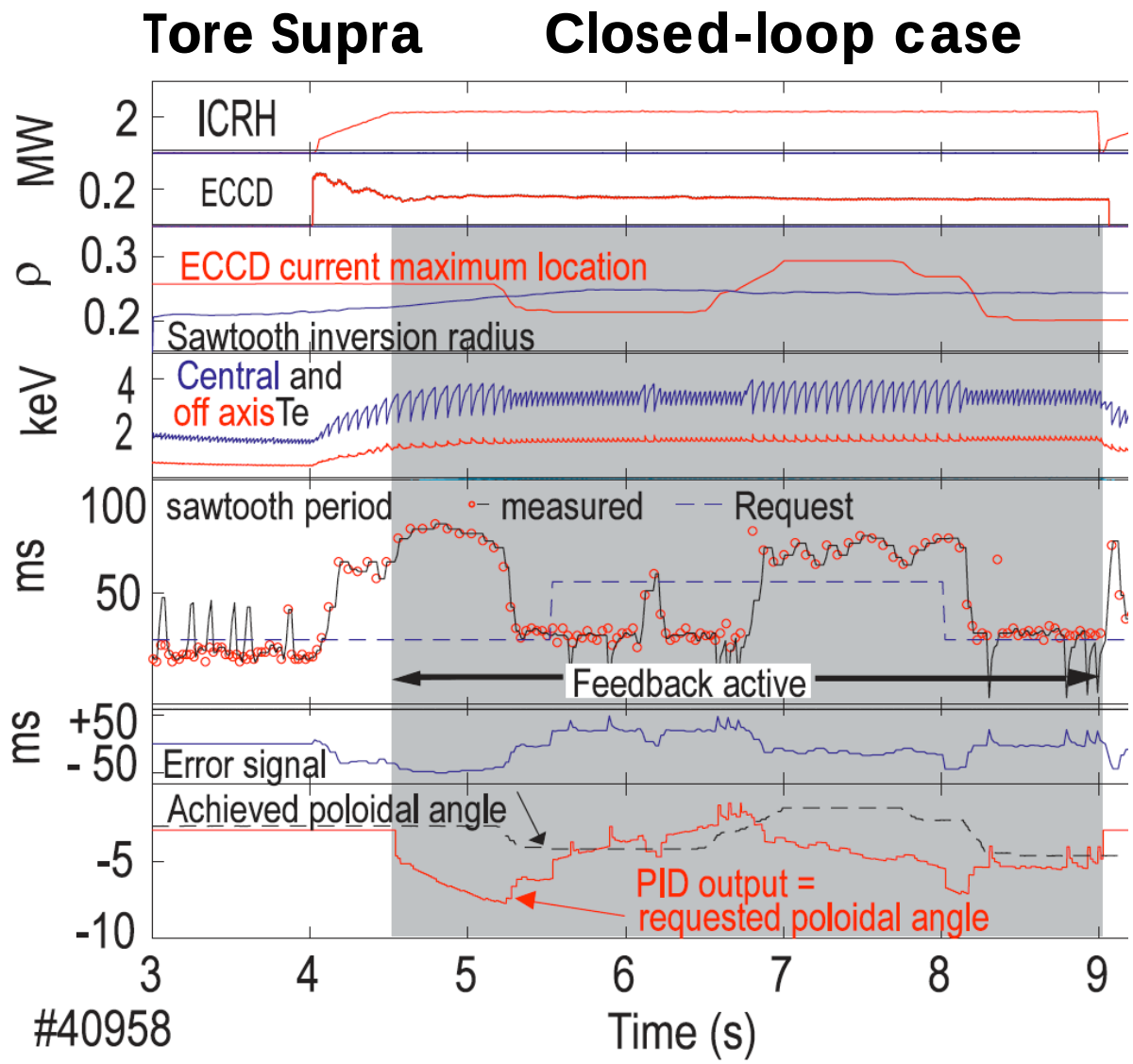
- **Scan of the relative location of the ECCD and the sawtooth inversion radius shows a clear plasma response**
  - Plasma has two distinct states
  - ECCD location determined by change in aiming

Tore Supra **Open-loop case**



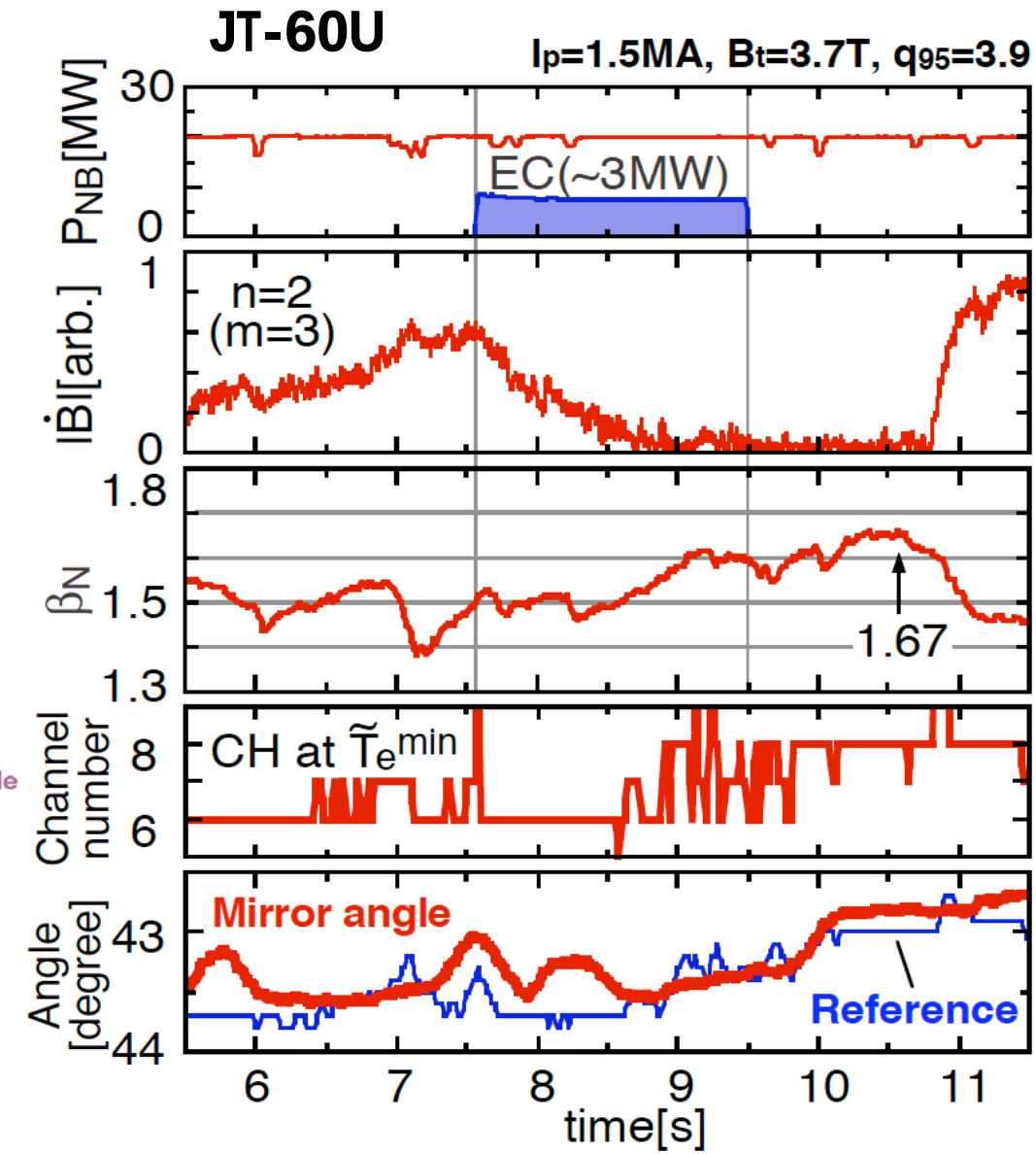
Localization and Control of the ECCD Deposition Allows Feedback Control of Instabilities

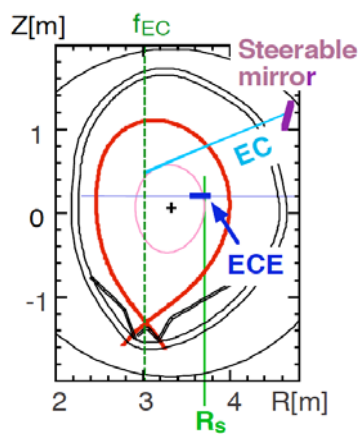
- **Scan of the relative location of the ECCD and the sawtooth inversion radius shows a clear plasma response**
  - Plasma has two distinct states
  - ECCD location determined by change in aiming
- **Proportional-integral controller successfully switches the plasma between the two states**
  - Latency largely due to response time of aiming hardware



Stabilization of Tearing Instabilities With Techniques Relevant to Power Plants Has Been Demonstrated

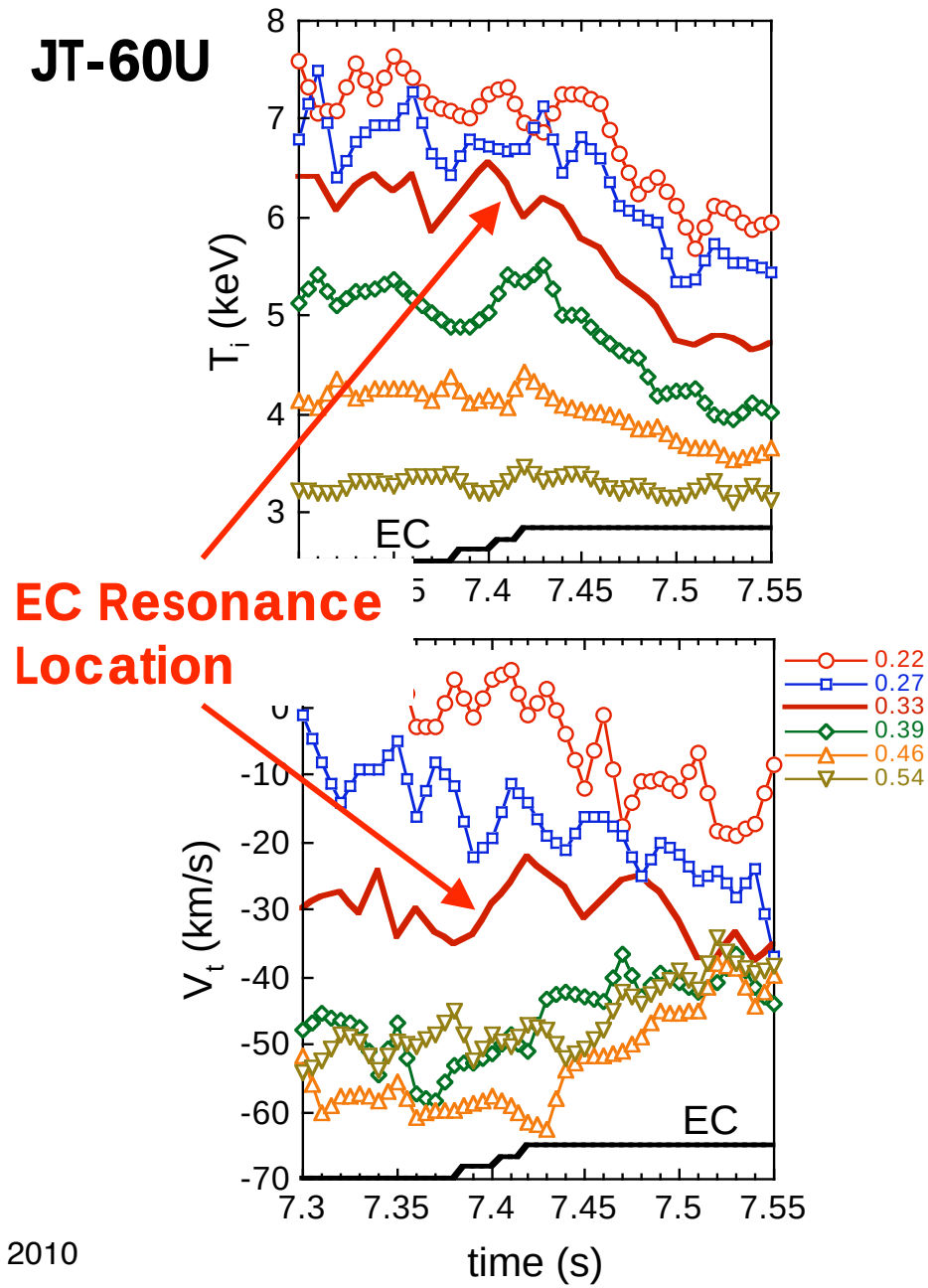
- **Proof of principle had been demonstrated previously**
  - Key advance here is automatic detection and control of the deposition
- **Critical technology for prevention of disruptions in tokamaks**





ECH/ECCD Can Affect Plasma Transport in Advanced Scenarios

- **ECH reduces the strength of an ion internal transport barrier**
  - Likely not due to change in current profile--same result for ECH/ECCD, independent of location, time scale too fast
- **Effect appears to be due to a change in the transport properties**
  - Ion energy transport enhanced
  - Momentum transport affected
  - Electron heating depends on resonance location
  - Large spatial extent of the transport change leads to speculation of a large scale correlation



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Prospects for Steady-State Operation With EC

- **Simple calculations show that EC will be useful in burning plasma regimes**
  - β = 5% implies the density will be below the O mode cutoff value if <T> > 6 keV

- **The primary physics objectives of ITER include steady-state operation with Q=5**
  - ITER will be a critical demonstration of the necessity of EC power
- **Reactor designs have favored lower hybrid current drive due to the high efficiency; however,**
  - Difficult to control the radial deposition to compensate for the actual bootstrap current profile determined by the transport
  - High pedestal temperature needed for high bootstrap current fraction and stability makes LH waves damp very close to the edge

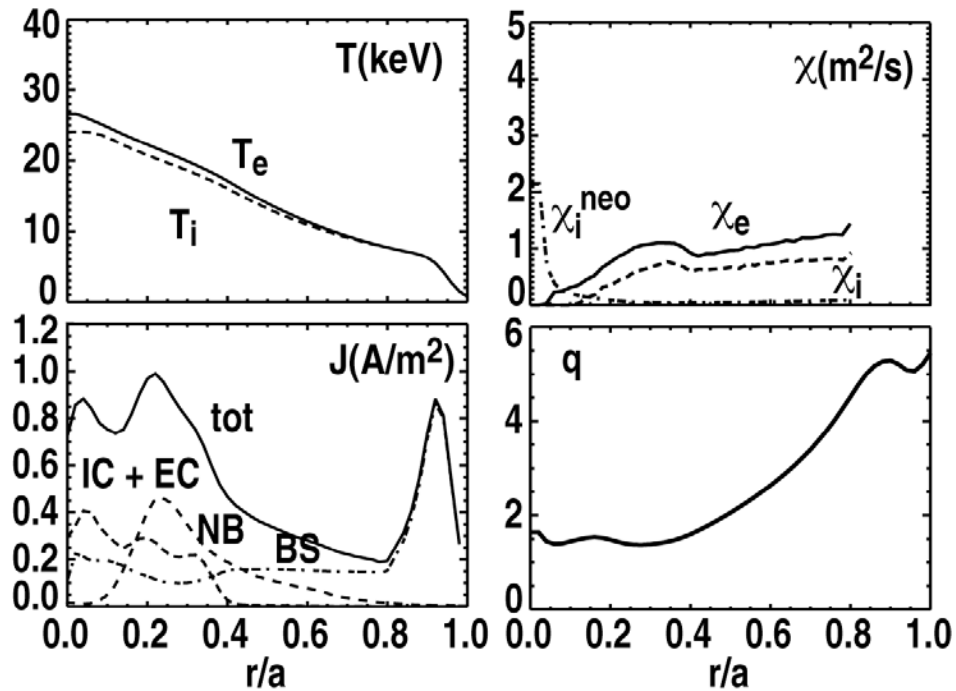
  ➔ Need to reconsider EC waves

Prospects for Using EC in ITER Steady State Scenarios Are Good

- **Role of ECCD is to supply current drive near the half radius**
  - Unfortunately the ITER EC system is not optimized for this application
- **Significant upgrades in power and launcher capability are possible in the lifetime of ITER**
  - Launchers could be optimized for steady-state operation if preliminary experiments are promising

ITER Simulation
Day-1 heating mix:
P_{NBI} = 33 MW, P_{EC} = 20 MW, P_{IC} = 20 MW

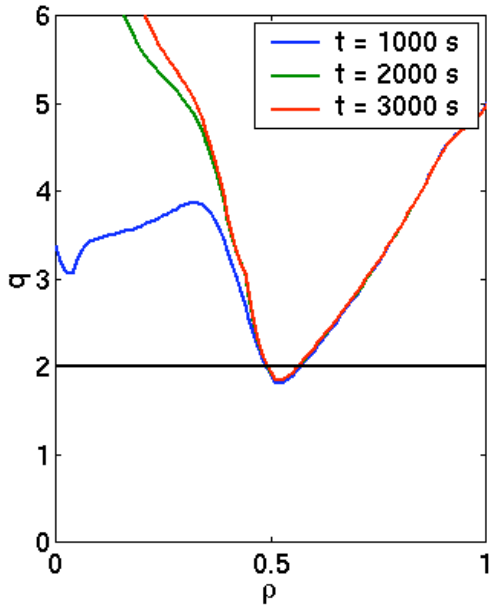
β_N = 2.9 H = 1.4 f_{BS} = 0.57
q_{95} = 5.0 f_G = 0.91 Q = 4.6

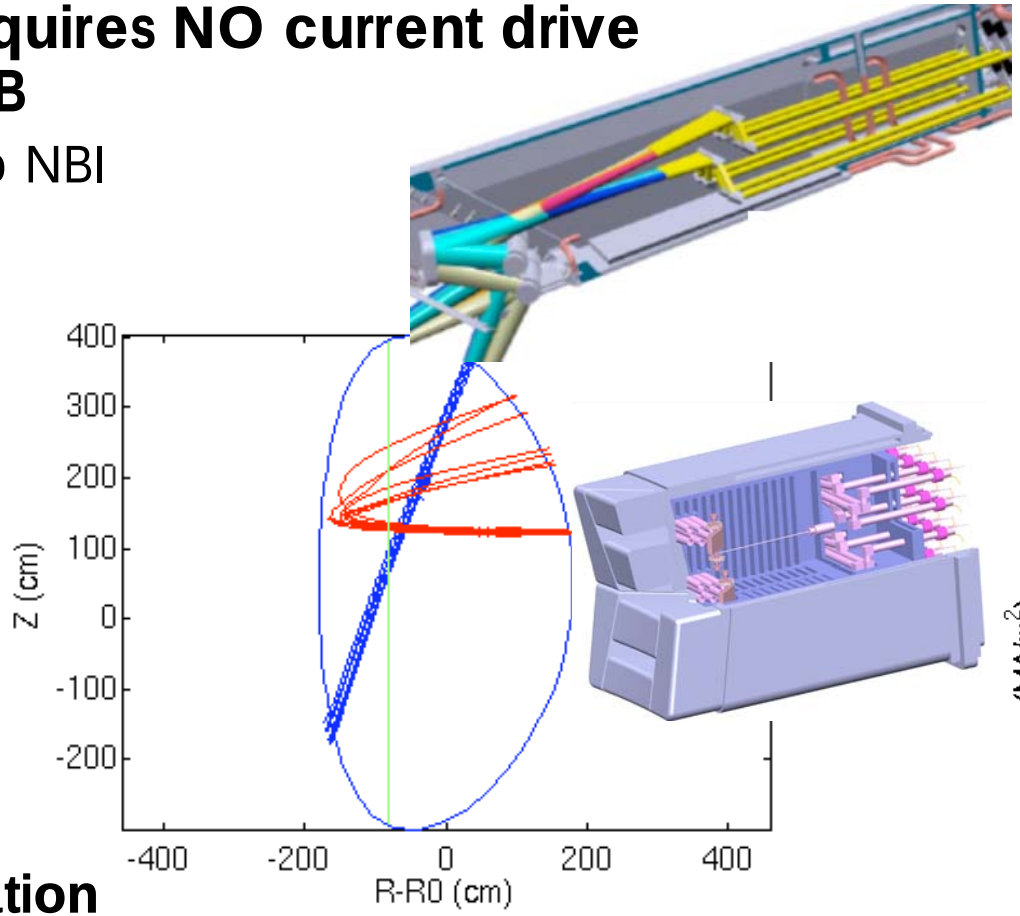


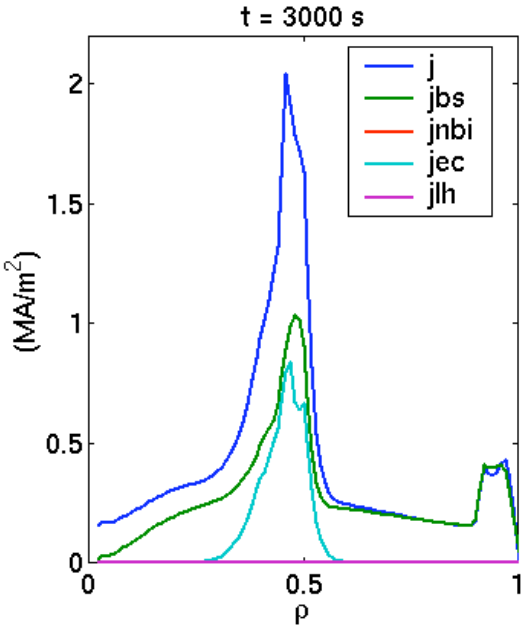
ONETWO Simulation from DIII-D

Prospects for Using EC in ITER Steady State Scenarios Are Good

- **Steady state scenarios with ITB also benefit from ECCD**
  - ECCD triggers the ITB
  - ECCD location fixes the ITB foot
- **Scenario requires NO current drive inside the ITB**
  - Implies no NBI







CRONOS Simulation from CEA

Summary

- **EC heating and current drive physics has been validated to an impressive level**

- **EC applications required for steady-state operation are demonstrated, often on multiple experiments**

- **Heating and current drive by EC waves have significant advantages in the power plant environment**
  - High power density ➔ low impact on blankets and shielding
  - Remote launching and steering ➔ low impact on magnet design

➔ **Heating and current drive with EC waves is a key enabling tool for steady-state generation of fusion power**