ADVANCED TOKAMAK RESEARCH IN DIII–D

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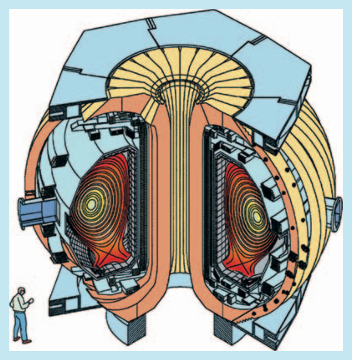
INTRODUCTION

THE TOKAMAK IS THE LEADING CONCEPT FOR FUSION ENERGY PRODUCTION USING MAGNETIC CONFINEMENT

- Fusion has the potential to provide plentiful energy
- The challenge: Need to confine fusion fuel (plasma) long enough for it to fuse
- The Tokamak confines plasma with:
  - Toroidal magnetic field (driven by external coils)
  - Poloidal magnetic field (driven by electrical current in the plasma)
    - Plasma current is usually driven as the secondary of a transformer
    - This approach makes the "conventional" tokamak inherently pulsed

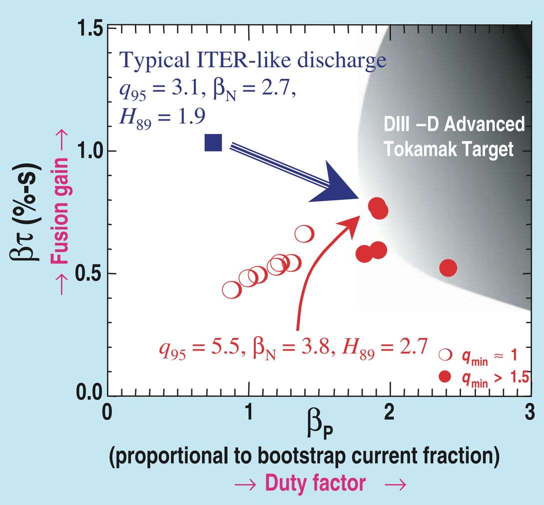


Cutaway view of the DIII–D tokamak

ADVANCED TOKAMAK RESEARCH ON DIII–D: REALIZING THE ULTIMATE POTENTIAL OF THE TOKAMAK

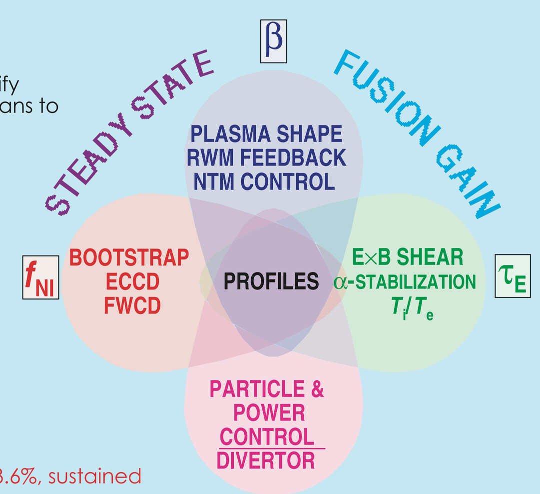
The Advanced Tokamak (*AT*): Improvement of the tokamak concept toward:

- Steady state: Replace transformer driven current with:
  - Self-generated bootstrap current
    - ⇒ Requires high β_P (ratio of plasma pressure to poloidal magnetic field pressure)
  - External current drive
- High fusion power density
  - ⇒ Requires high β_T (ratio of plasma pressure to toroidal magnetic field pressure)
  - ⇒ Requires improved stability
- Maintaining sufficient fusion gain with reduced engineering parameters
  - ⇒ Requires high confinement time τ_E



AT RESEARCH RELIES ON INTEGRATION OF ADVANCES MADE IN SEVERAL SCIENTIFIC AREAS

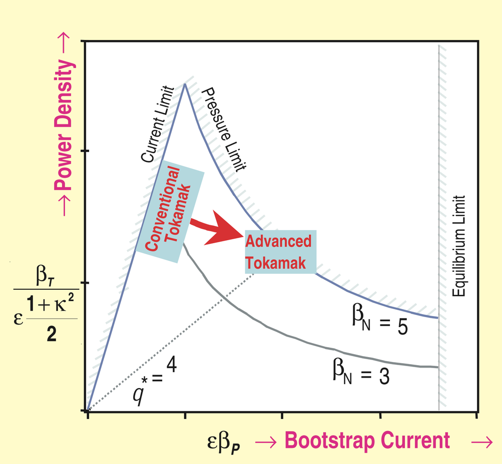
- Focused tool development
  - Individual tools developed separately
  - Detailed physics studies identify operational limits and the means to expand them
- Complex interactions between scientific areas ⇒ *the challenge is integration*
  - Sophisticated plasma control system
  - Integrated modeling used to design experiments and interpret results
  - Fusion Collaboratory tools used for analysis and collaboration
    - Will use for modeling in future research
- Recent highlights:
  - Plasmas with f_{NI}=100% and $\beta_T \leq 3.6$%, sustained for several confinement times



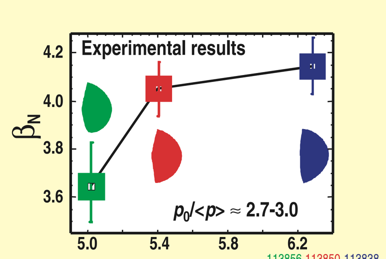
TOOL DEVELOPMENT

A STEADY STATE TOKAMAK REQUIRES OPERATION AT HIGH β_N

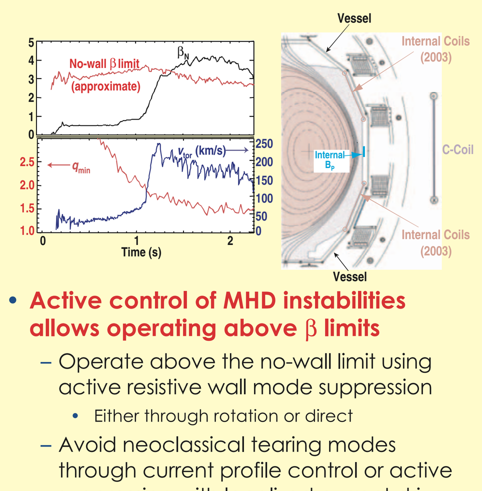
- Advanced Tokamak regimes operate at the pressure limit
  - Need to optimize for high normalized beta $\beta_N = \beta_T/(I_P/aB_T)$
- Methodology:
  - Maximize β limits by optimizing geometry and pressure profile shape
  - Active control of MHD instabilities
    - Operate above the no-wall limit using active resistive wall mode suppression
    - Avoid neoclassical tearing modes through current profile control or active suppression



SEVERAL TOOLS FACILITATE ACCESS TO HIGH β_N



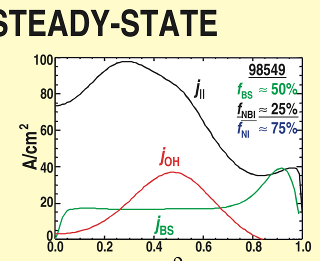
- Maximize β limits
  - Optimizing geometry: "strong" shaping
  - Broad pressure profile

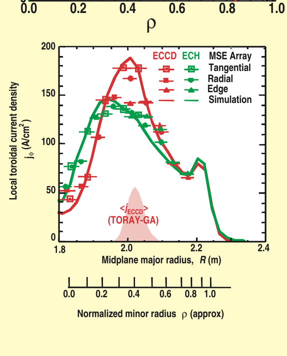


- Active control of MHD instabilities allows operating above β limits
  - Operate above the no-wall limit using active resistive wall mode suppression
    - Either through rotation or direct
  - Avoid neoclassical tearing modes through current profile control or active suppression with localized current drive

OFF-AXIS CURRENT DRIVE IS NEEDED TO BRING DIII–D *AT* TARGET DISCHARGE TO STEADY-STATE

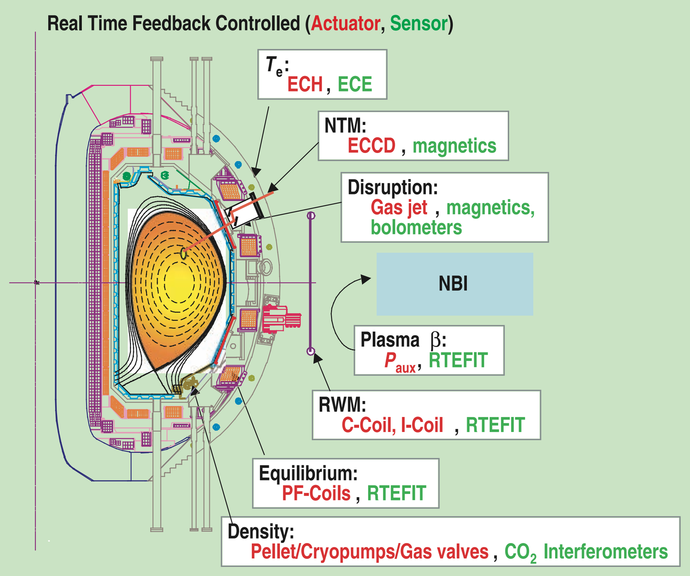
- All inductively driven current j_{OH} must be replaced to reach steady-state
  - *AT* target discharge: Remaining inductive current concentrated near mid-radius
  - Self-generated bootstrap current provide most of the current
- Electron cyclotron current drive (ECCD) can provide most of the rest
  - Example: 130 kA of current driven by 2.5 MW of ECCD
    - Well understood: good agreement between experiment and simulation
  - Long-term plan for DIII-D: 10 s pulse length with (powers given at source):
    - ECCD: 9 MW
    - Fast Wave Current Drive (FWCD) for additional control of the current profile in the vicinity of the magnetic axis: 5 MW





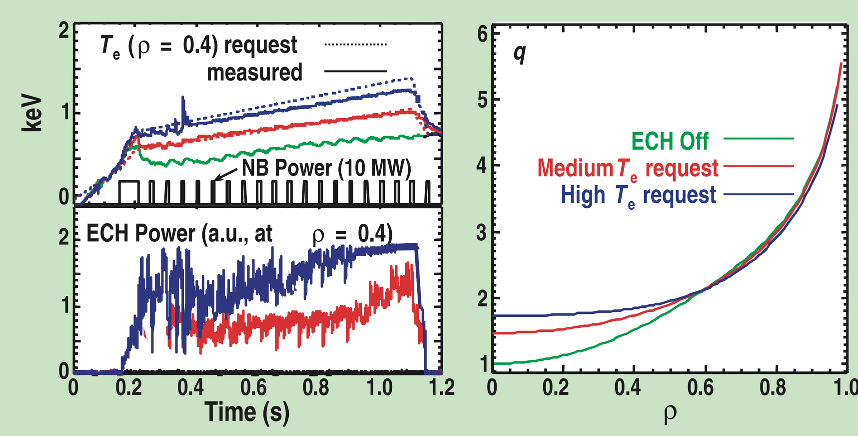
INTEGRATED SCENARIO DEVELOPMENT

INTEGRATED PLASMA CONTROL IS KEY TO THE DIII–D *AT* PROGRAM



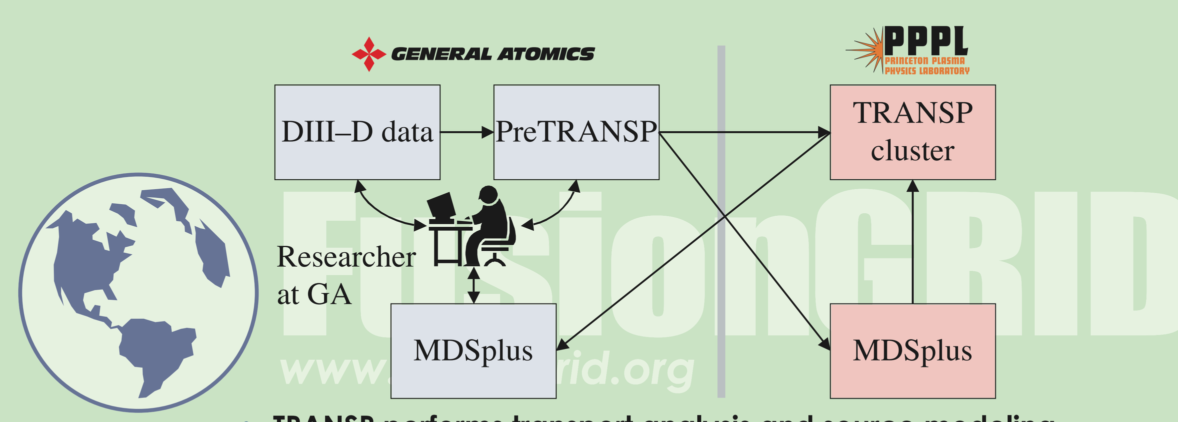
- Long experience: Global parameters and equilibrium
- Recent progress:
  - Single-point T_e and current profile control
- Under development: Real-time, multi-point profile control
  - $T_e(\rho,t)$: ECH, ECE, Thomson scattering
  - $j(\rho,t)$: ECCD, MSE
  - …

REAL-TIME CONTROL OF T_e RESULTS IN SLOWER CURRENT PENETRATION



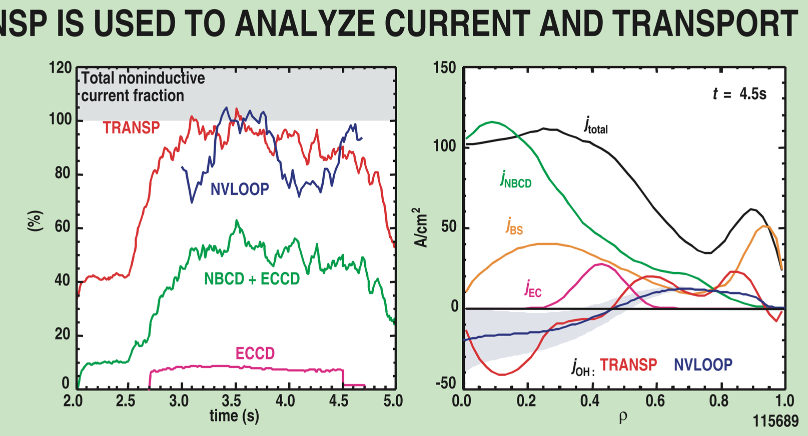
- Real-time T_e control for improved control over *AT* target plasma formation:
  - T_e control → q profile evolution control during current ramp

GRID ENABLED TRANSP PROVIDES CRITICAL ANALYSIS SERVICES FOR *AT* RESEARCH



- TRANSP performs transport analysis and source modeling
  - Future: Improved simulation capability
- Other codes being made available through the FusionGrid for stability, turbulence, transport,…

TRANSP IS USED TO ANALYZE CURRENT AND TRANSPORT PROFILES



MODELING AND SIMULATION GUIDE THE DIII–D ADVANCED TOKAMAK PROGRAM

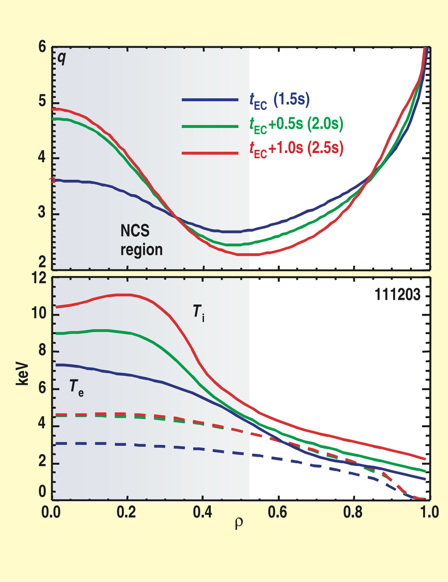
- Integrated modeling used to develop detailed plans for AT experiments
  - Successfully predicts main features of the experiment
- Improvements and integration of modeling tools are crucial to a predictive understanding of physics issues critical to Advanced Tokamak and fusion science
  - Emphasizing physics based rather than empirical models
- Long-term objective is a fully predictive understanding of integrated Advanced Tokamak scenarios
  - Validated models needed for projection of advanced scenarios in burning plasma experiments

CONTROL OF THE *AT* MUST BE ACHIEVED WITH AWARENESS AND UNDERSTANDING OF TRANSPORT MECHANISMS

- Transport impacts both the duty factor and the fusion gain:
  - Pressure profile ⇒ β, bootstrap current,…
  - Confinement (τ_E)
- Direct control of transport is difficult in present day devices, and likely more so in a burning plasma
  - Largest external source of power in next-step devices will probably be the current profile control tool
  - Other tools are being evaluated as control tools in DIII–D
  - Challenge: These tools typically impact multiple transport channels simultaneously

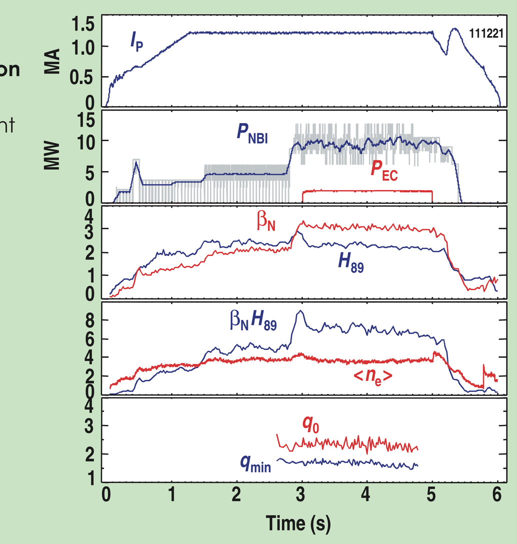
CURRENT PROFILE MODIFICATION CAN ALSO IMPACT TRANSPORT BEHAVIOR

- Transport can be modified through the current profile
  Example:
  - ECCD added to target plasma with slight negative central shear (NCS) at ρ ≈ 0.4
  - ⇒ Current drive makes q profile more reversed
  - ⇒ which triggers formation of an internal transport barrier (ITB; most obvious in the ion thermal transport channel)
    - α-stabilization and NCS

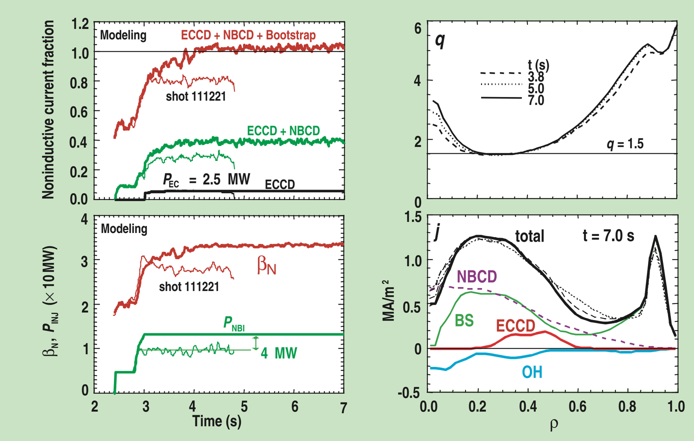


DISCHARGE WITH 85% NONINDUCTIVE CURRENT FRACTION SERVES AS THE STARTING POINT…

- Early H–mode used to slow evolution of q profile
  - High power heating and current drive delayed until $q_{min} < 2$
- NBI feedback maintains $\beta_N \approx 3.1$, $H_{89} \approx 2.3$
- ECCD applied at ρ ≈ 0.4 after 3 s arrests q profile evolution
  - Noninductive current fraction $f_{NI} \approx 85$%
  - Terminated after 1 second by small (m,n) = (5,3) NTM



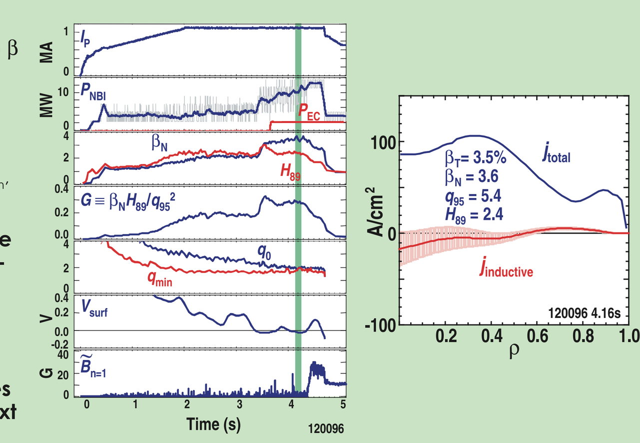
PREDICTIVE SIMULATIONS INDICATE EARLIER ECCD DISCHARGE COULD BE EXTENDED TO 100% NONINDUCTIVE WITH INCREASED NBI POWER



- Initial calculations conservative: used $H_{98(y,2)}$ scaling ($\chi \propto \chi_{exp} \bullet P^{0.69}$)
- Later calculations with recalibrated GLF23 transport model in agreement

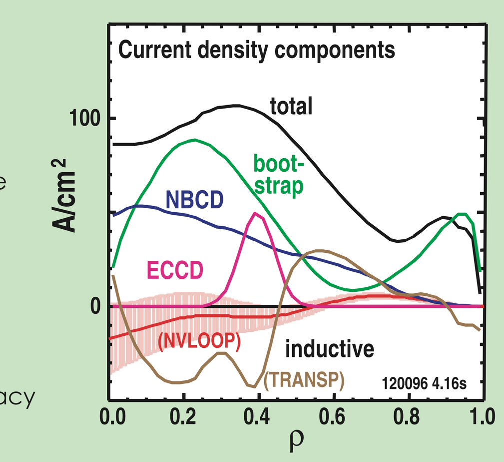
EXPERIMENTS BASED ON SIMULATION RESULTS HAVE DEMONSTRATED FULLY NONINDUCTIVE *AT* CONDITIONS

- Careful preparation of target conditions rely on β feedback initiated early in the discharge
  - Conditions during current ramp become very reproducible
  - Allows adjustment of q_{min}, q_0–q_{min},… prior to high performance phase
- Target q profile is suitable for sustainment using off-axis ECCD
  - Current drive is needed only to sustain rather than to reach desired conditions
- Pressure profile continues to evolve… this is the next challenge

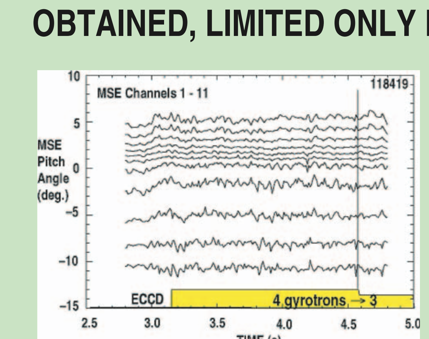


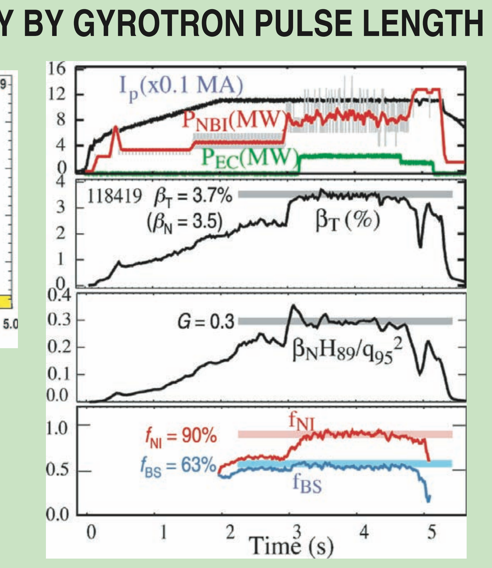
WITH IMPROVED CONFINEMENT, f_{NI}=100% ACHIEVED WITH GOOD CURRENT DRIVE ALIGNMENT

- NVLOOP analysis:
  - f_{OH} = 0.5%, f_{NI} = 99.5%
  - j_{ind} calculated directly from parallel electric field
  - Challenge: Difficult to parameterize current profile details with EFIT
- TRANSP modeling:
  - f_{BS}=59%, f_{NB}=31%, f_{EC}= 8%, f_{NI}= 98%
  - $j_{ind} = j_{total} - j_{BS} - j_{NBCD} - j_{ECCD}$
  - Challenge: In addition to above, depends on accuracy of bootstrap and source models



NEARLY FULL NONINDUCTIVE, STATIONARY DISCHARGE OBTAINED, LIMITED ONLY BY GYROTRON PULSE LENGTH





Slightly lower β request:

- $J_\phi(\rho)$ stopped evolving
- Maintained for $1\times\tau_R$ (≈1.8s)

HIGHLIGHTS OF ADVANCED TOKAMAK PROGRESS ON DIII–D

- 100% noninductively driven plasmas with β_T up to 3.6% and β_N up to 3.5
- Up to 130 kA has been driven by off-axis ECCD in AT plasmas
- Optimized pressure profile and plasma geometry allows operation with β_N > 4
- Detrimental MHD modes can be stabilized through active control
- Integrated modeling successfully predicts main features of experiment
- TRANSP FusionGrid service has been successfully used for data analysis

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