Impact of H&CD Technology on DEMO Scenario Choice (Impact of DEMO Scenario on Choice of H&CD Technology)

By
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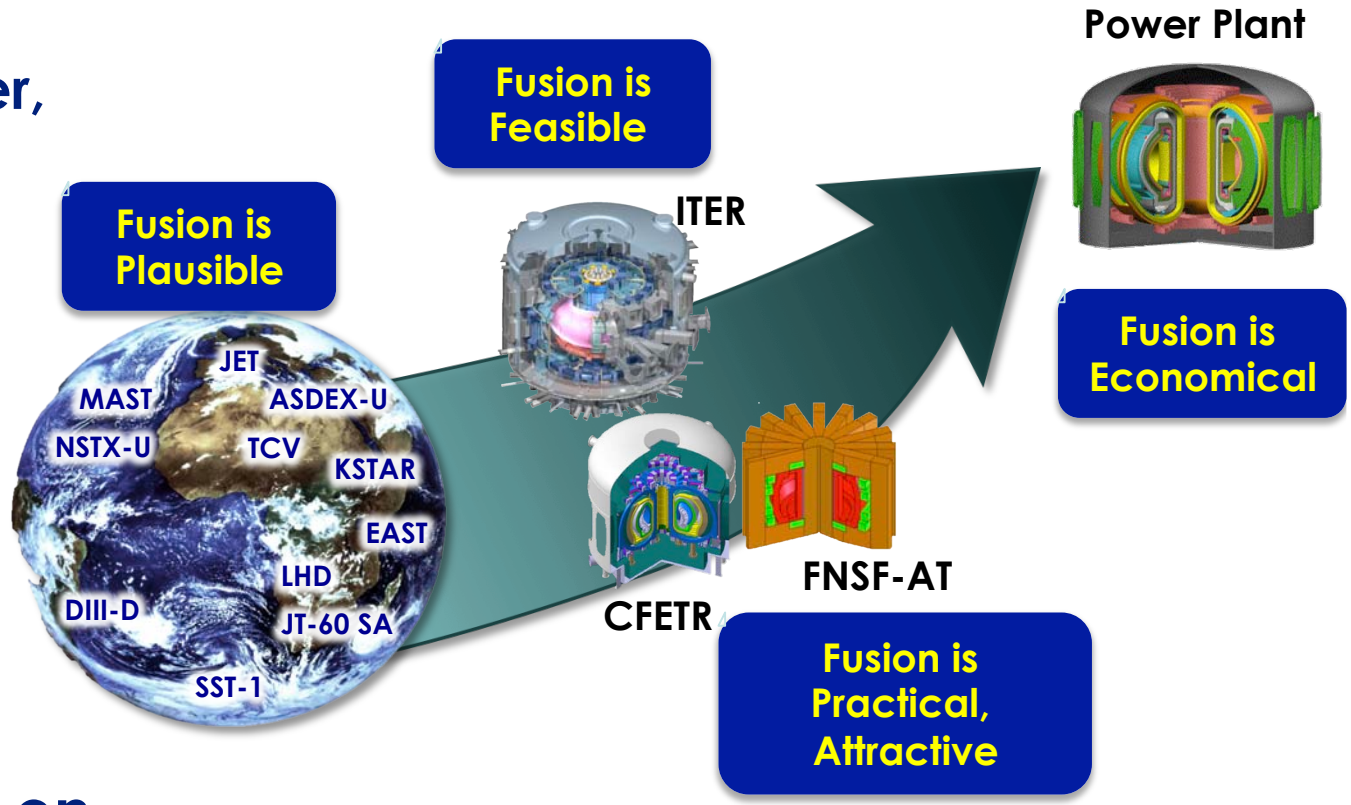
V.S. Chan, R.I. Pinsker,
G. Staebler, T.S. Taylor,
C.P.C. Wong
(General Atomics)



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13-14 March 2014
University of California San Diego, USA

Different DEMO Scenarios Push Against Different Limits

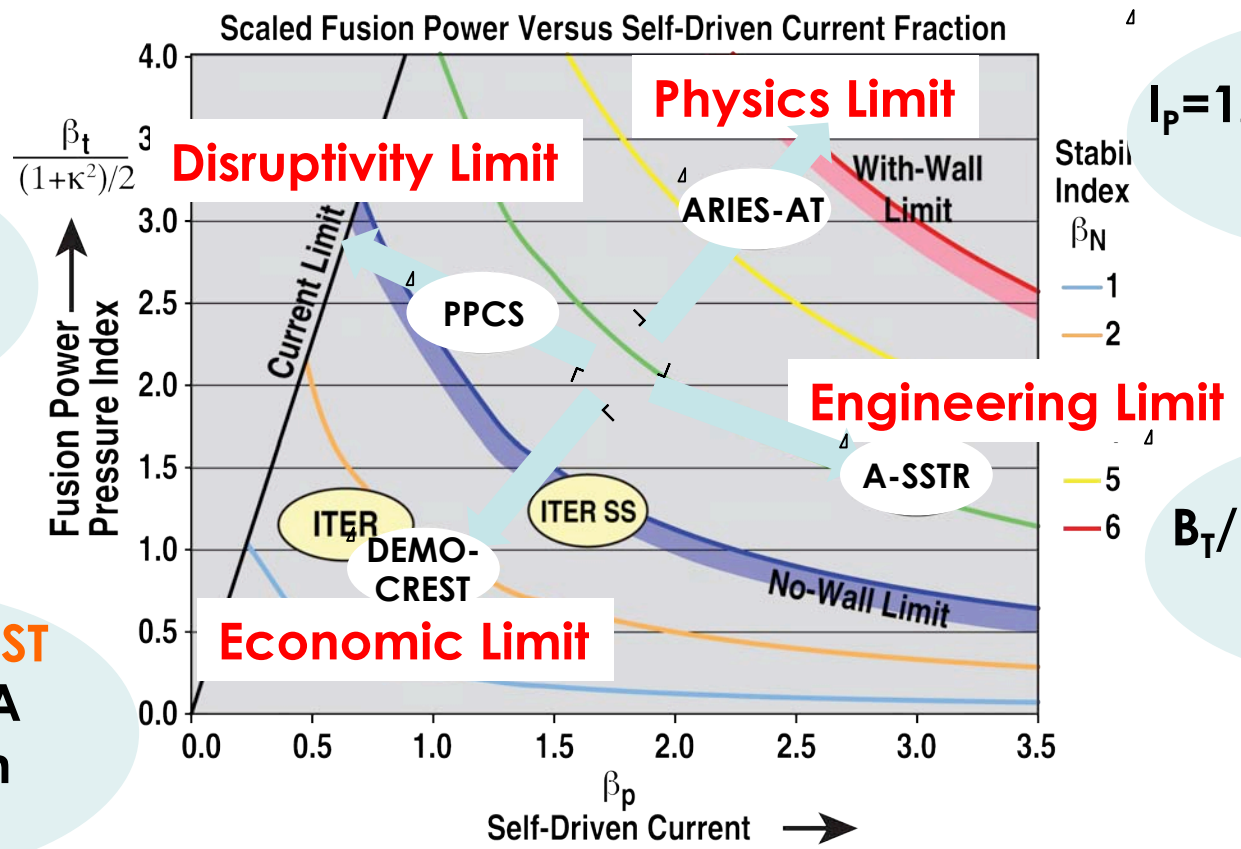
- ITER Q=10 will show fusion is feasible
- DEMO should show fusion can be economically attractive

PPCS
I_P=30.5 MA
R_P=9.55 m
Q=20

Maisonnier, NF 2007

Hiwatari, NF 2005

DEMO-CREST
I_P=15.9 MA
R_P=7.25 m
Q=6.7



ARIES-AT
I_P=12.8 MA, B_T=5.9 T
R_P=5.2 m
Q=50

Jardin, FE&D 2005

A-SSTR
$B_T/B_{T,Max}$=11/20.5 T
R_P=6 m
Q=75

Kikuchi, FE&D 2000

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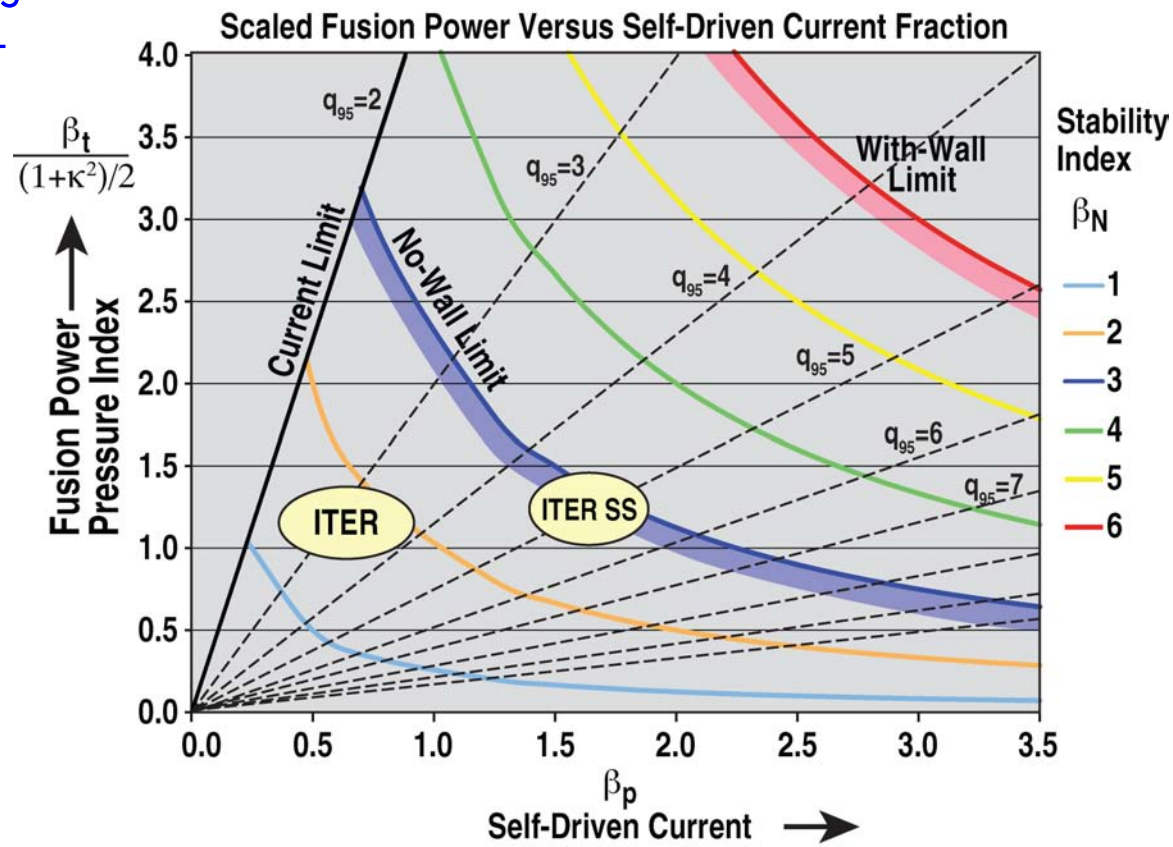
Added lines of constant q95



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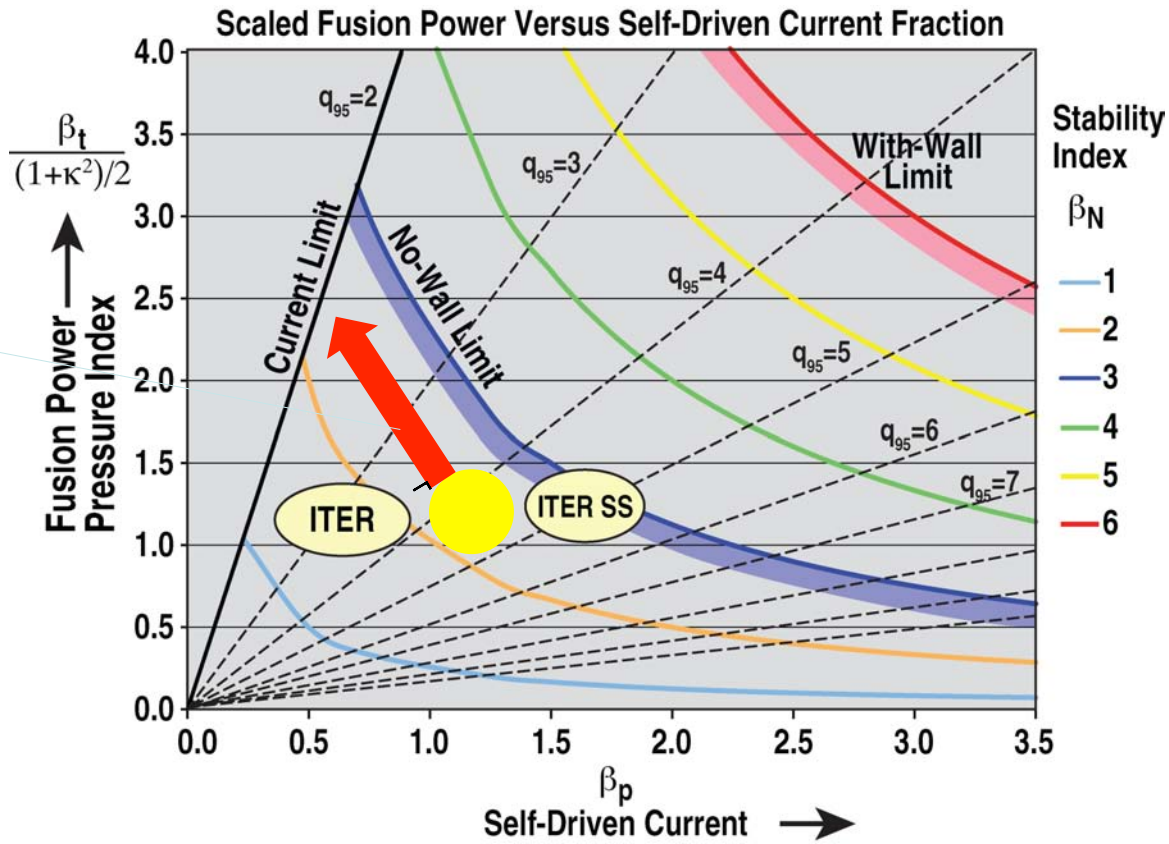
Increase β_T by lowering q_{95} – Standard Tokamak Approach



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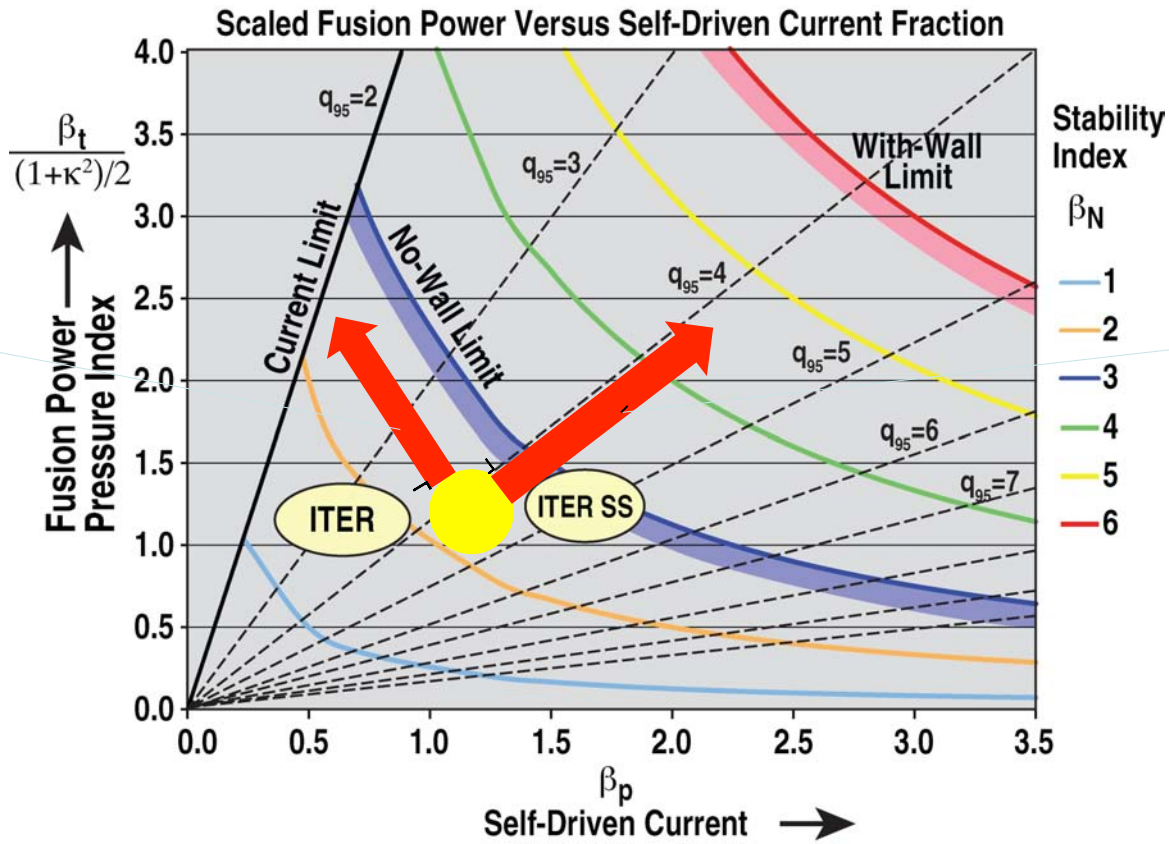
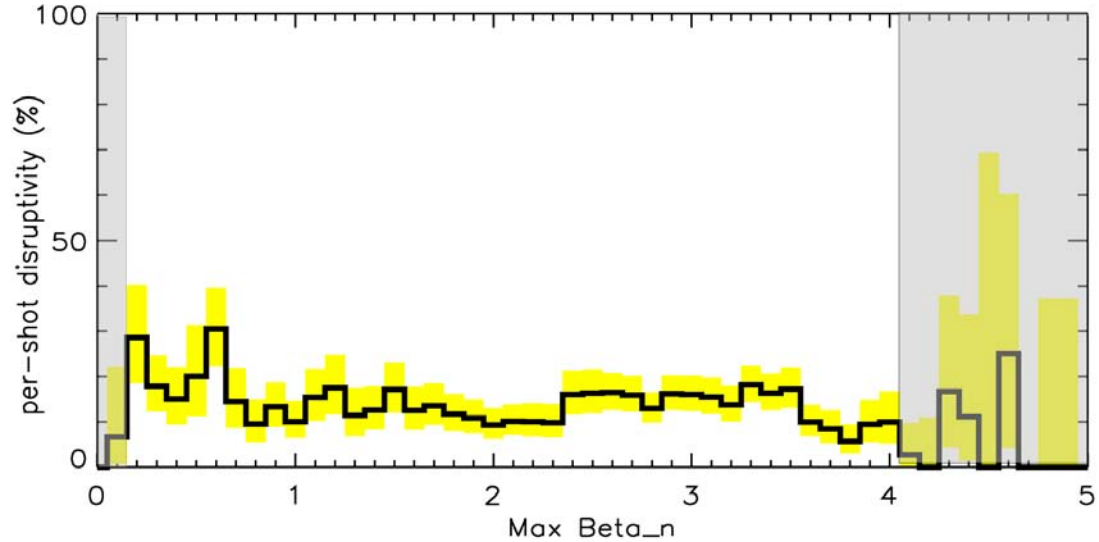


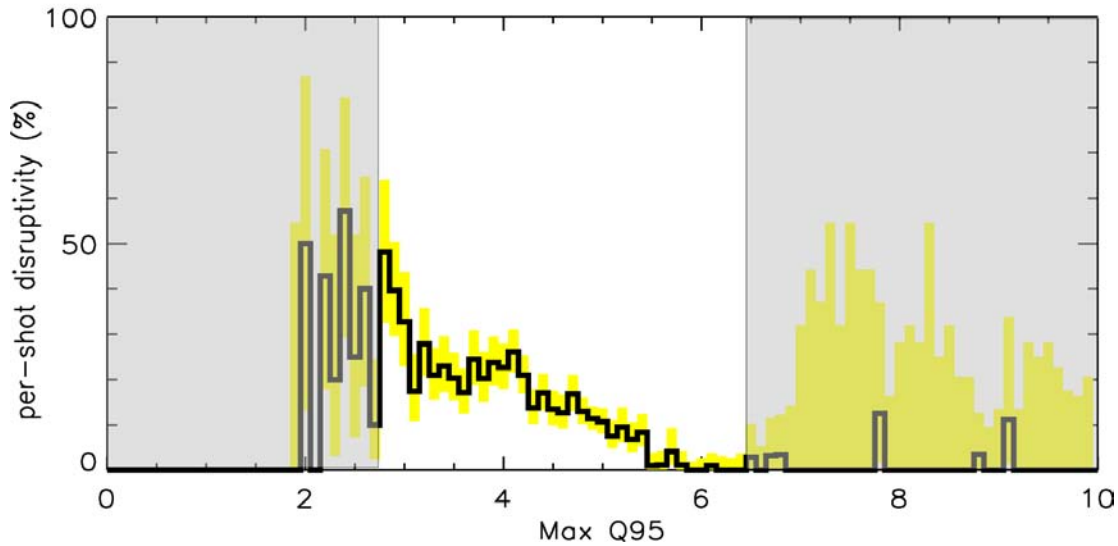
Increase β_T by increasing β_N – Advanced Tokamak Approach

AT Physics Trades Lower q95 for Higher β_N – Strong Reduction of Disruption Risk

Courtesy of A.W. Hyatt

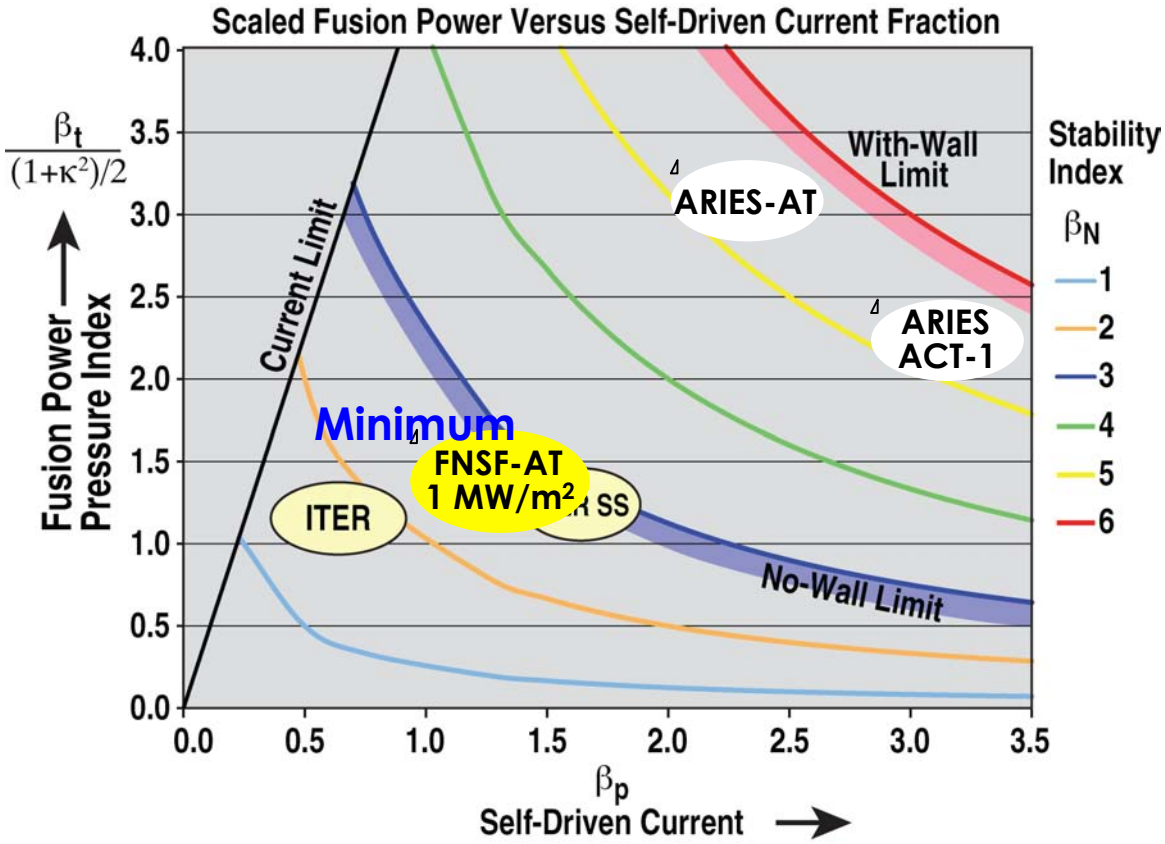
- **Disruption occurrence database from DIII-D: ~6000 discharges**
  - All flattop disruptions, not caused by operator error or PS failures
- **Disruptivity is constant or decreasing with higher betaN**
  - Wall stabilization leads to "softer" limits
- **Disruptivity decreases strongly with increasing q95**
  - Higher safety factor adds resilience to disturbances





A FNSF with Advanced Tokamak Capability Is the Appropriate Step on the Path to an Attractive DEMO

- **1 MW/m² Scenario sufficient to meet nuclear science mission of FNSF**
  - Performance already achieved in fully noninductive DIII-D discharges



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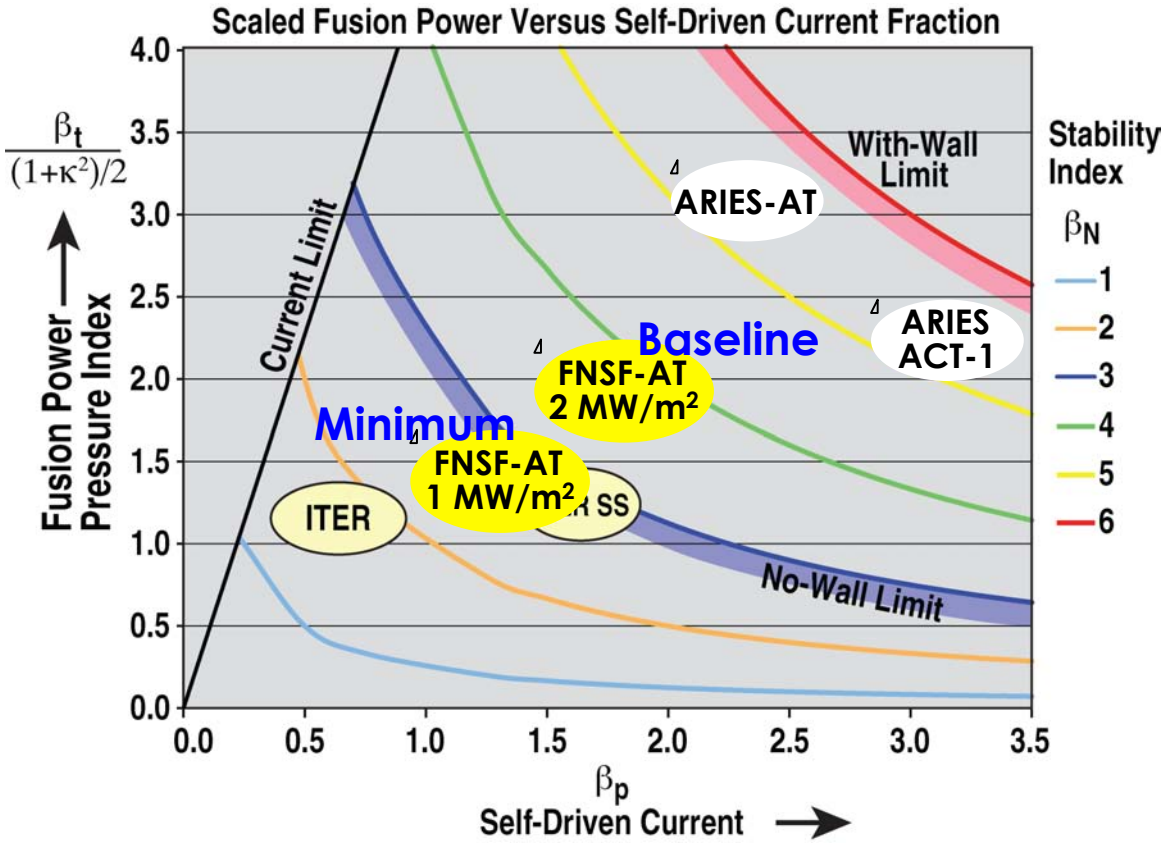
- **More advanced scenarios can close physics gaps to DEMO**



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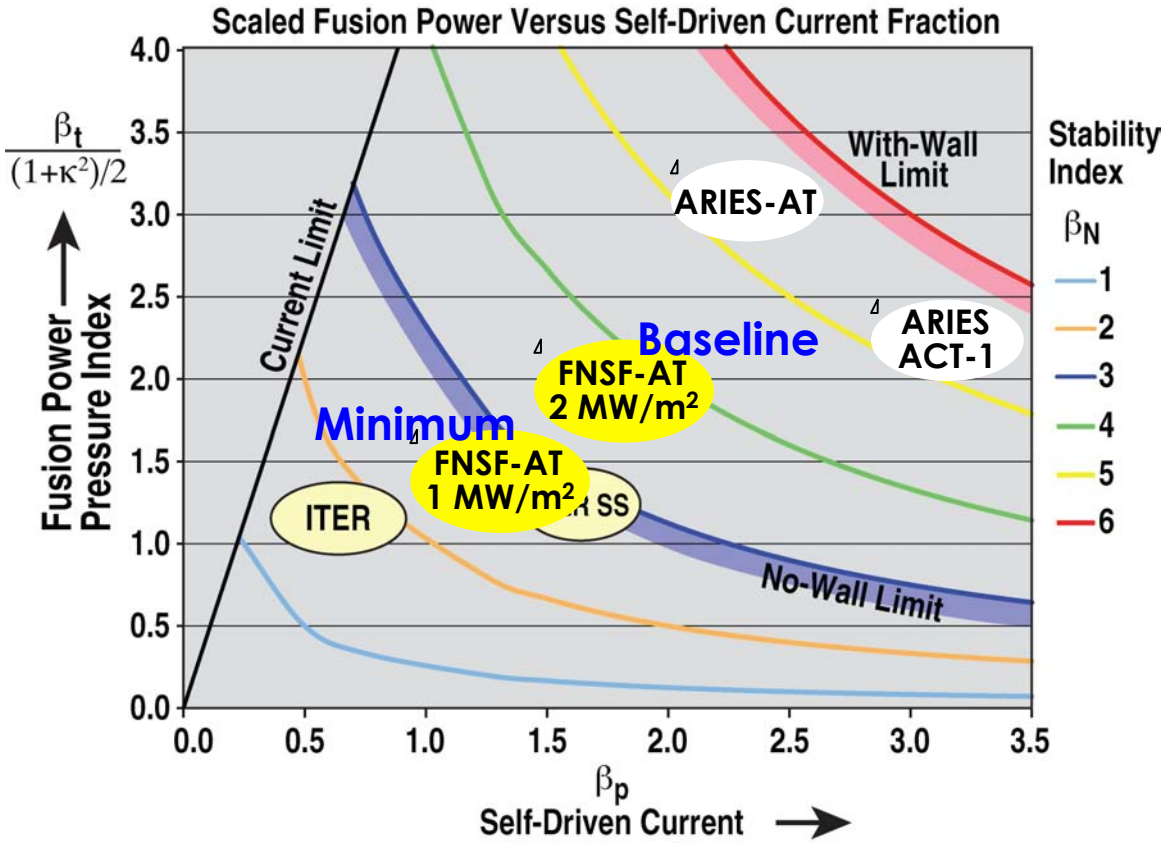


- **Key Challenge is to extend to $\tau_{DUR} >> \tau_{CR}$**
  - Hardware limitations: heating and off-axis current drive power

Outline

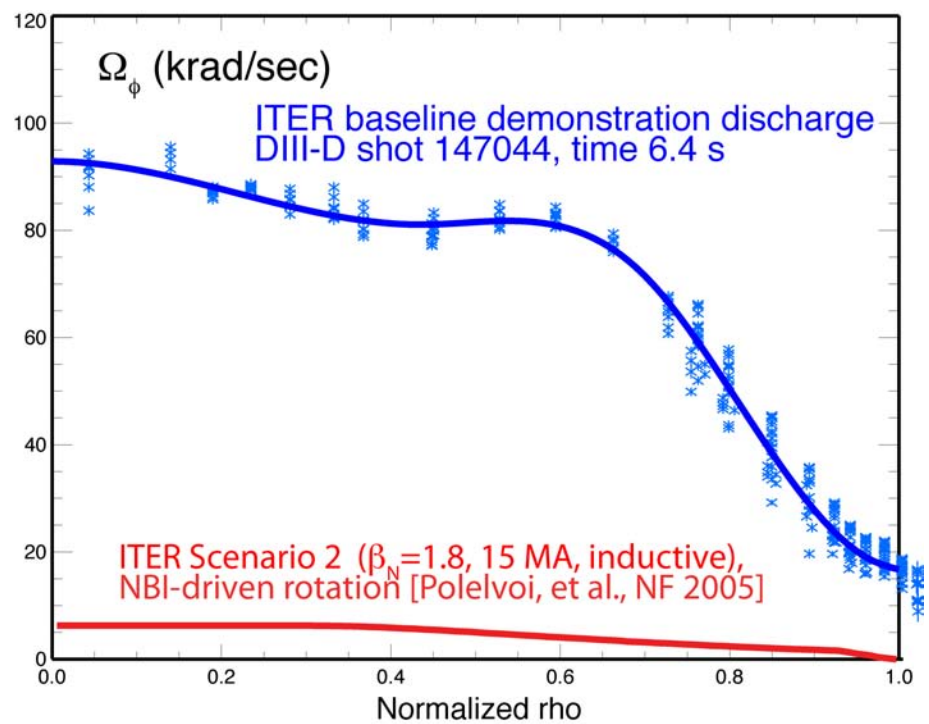
- **Choice of technique for off-axis current drive (NBI, EC, LH, Helicon) has implications beyond simply the auxiliary power requirement and its effect on energy gain**
  - Torque injection and effect on confinement/stability
  - Impact on TBR, neutron shielding, tritium containment, remote maintenance, and lifetime.
  - Compatibility with high density operation, improving survivability of the divertor
- **Two attractive, no-torque alternatives to NBI H&CD**
  - Top launch ECH/ECCD
  - Helicon (very high harmonic fast wave)
- **DIII-D to validate Helicon H&CD in 2016**

Driving Strong Toroidal Rotation in a Demo Plasma Would Be a Significant Challenge, Even with NBI

- **What is the NBI torque required to drive in DIII-D the same rotation expected in ITER?**
- **$T_{NB,\,ITER}$ ~ 35 Nm, $\omega_{NB} = T_{NB}\tau_L/I$, $\tau_{L,ITER}/\tau_{E,ITER} \sim \tau_{L,D3D}/\tau_{E,D3D}$**

$$\omega_{NB,ITER} = \omega_{NB,D3D} \Rightarrow T^{e}_{NB,D3D} = T_{NB,ITER}\frac{I_{D3D}}{I_{ITER}}\frac{\tau_{E,ITER}}{\tau_{E,D3D}}$$

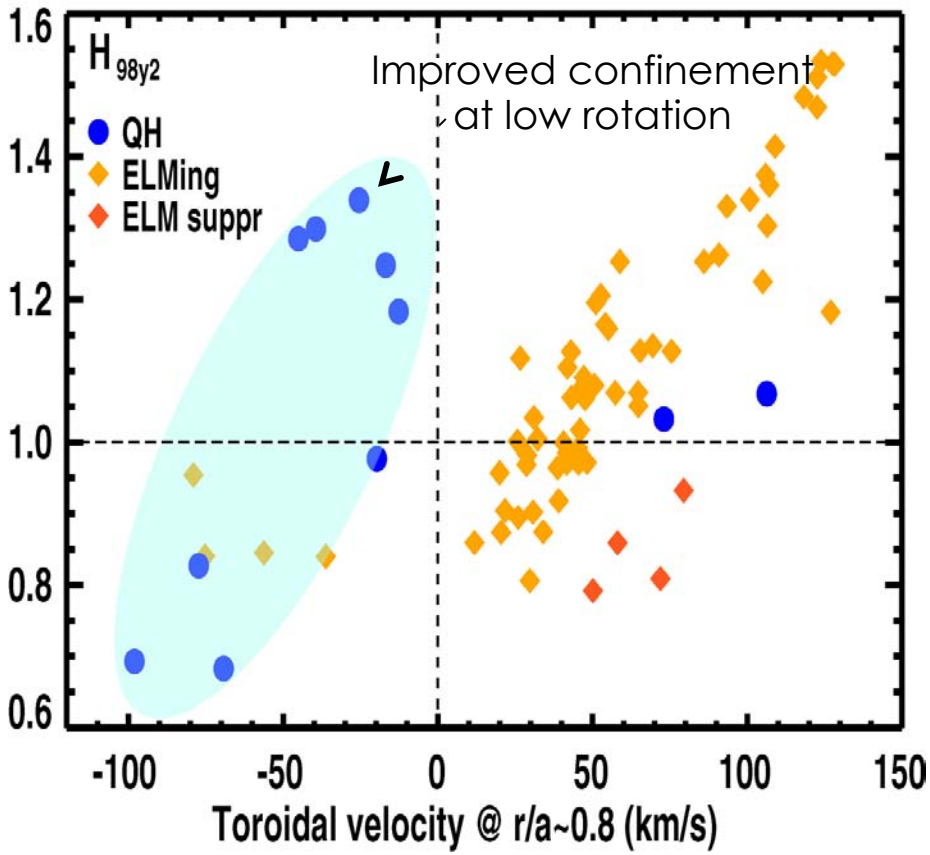
- **It takes only $T_{NB,D3D}$ ~0.35 Nm to drive expected ITER rotation in DIII-D**
  - Standard DIII-D operation uses T_{NBI} ~3-10 Nm



NBI-driven angular rotation predicted for ITER (ASTRA, $\chi_i=\chi_\phi$) compared to ITER baseline demonstration discharge in DIII-D (T_{NBI}~3 Nm)

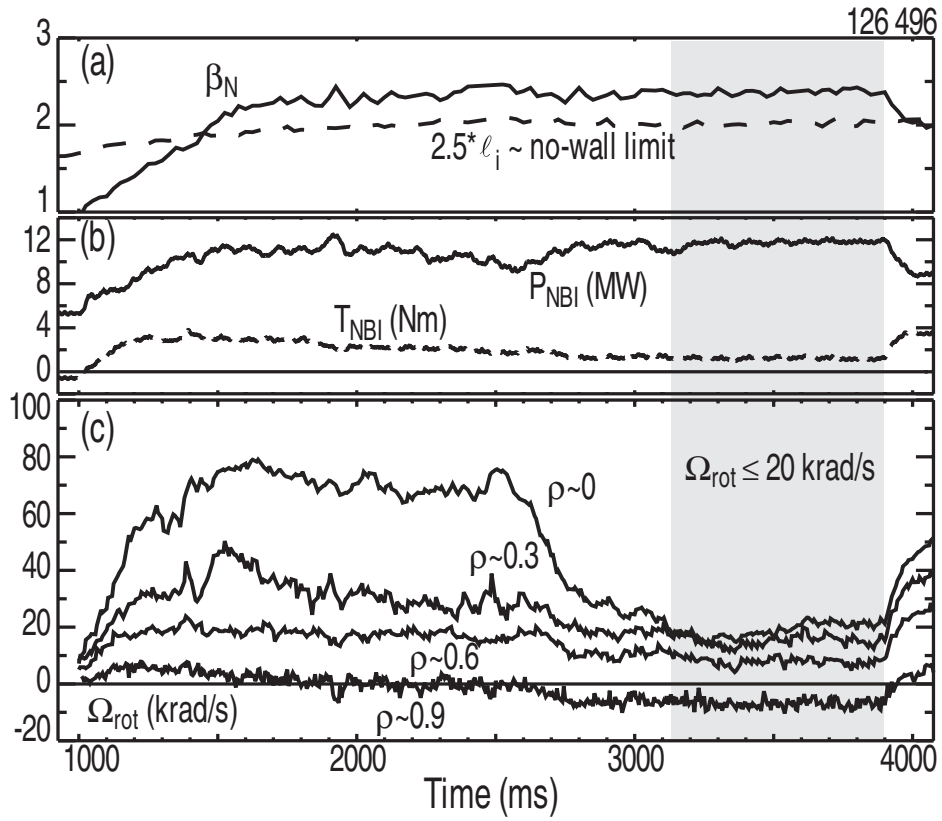
Good Confinement and Stability Have Been Demonstrated at Low NBI Torque and Rotation

- **QH-mode shows improvement in confinement at low rotation**



[Solomon et al., TTF (2012)]

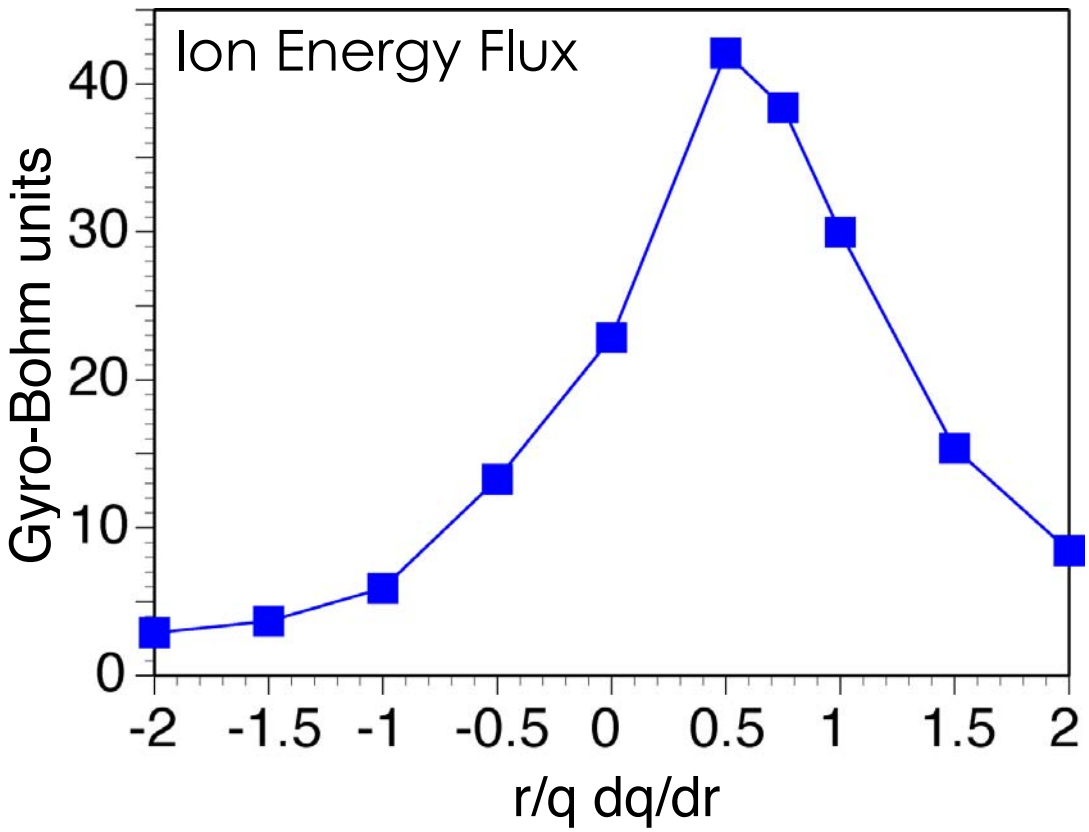
- **Kinetic stabilization of resistive wall mode shown in DIII-D experiments at ~zero plasma rotation**



[Reimerdes, et al., PRL (2007)]

Weak Or Negative Magnetic Shear and High β Predicted to Yield Higher Energy Confinement

- **Negative global magnetic shear** $\hat{s} = r/q\, dq/dr < 0$ **reduces the ion energy transport at fixed plasma pressure profile.**



[Staebler et al, Phys. Plasmas 2007]

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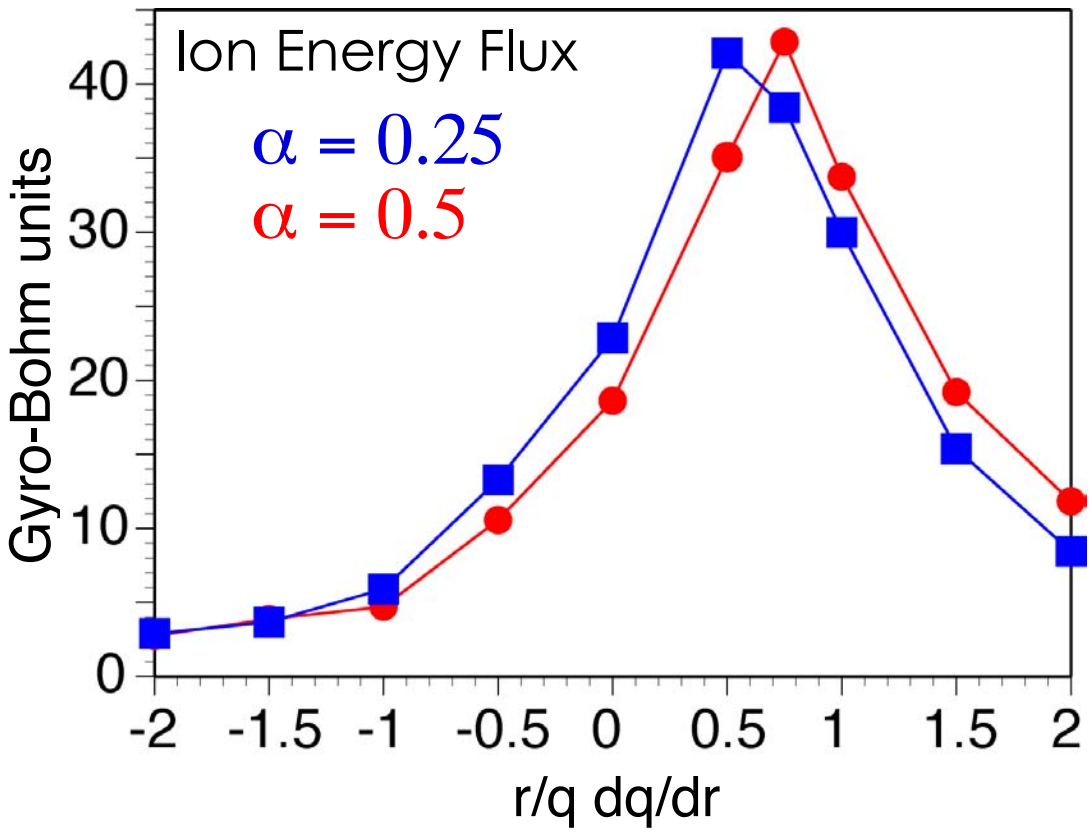
- **Increasing β also reduces ion energy transport through the Shafranov shift**

$$\alpha = -q^2 R\, d\beta/dr$$

if the local magnetic shear satisfies:

$$\hat{s} - \alpha < 0.5$$



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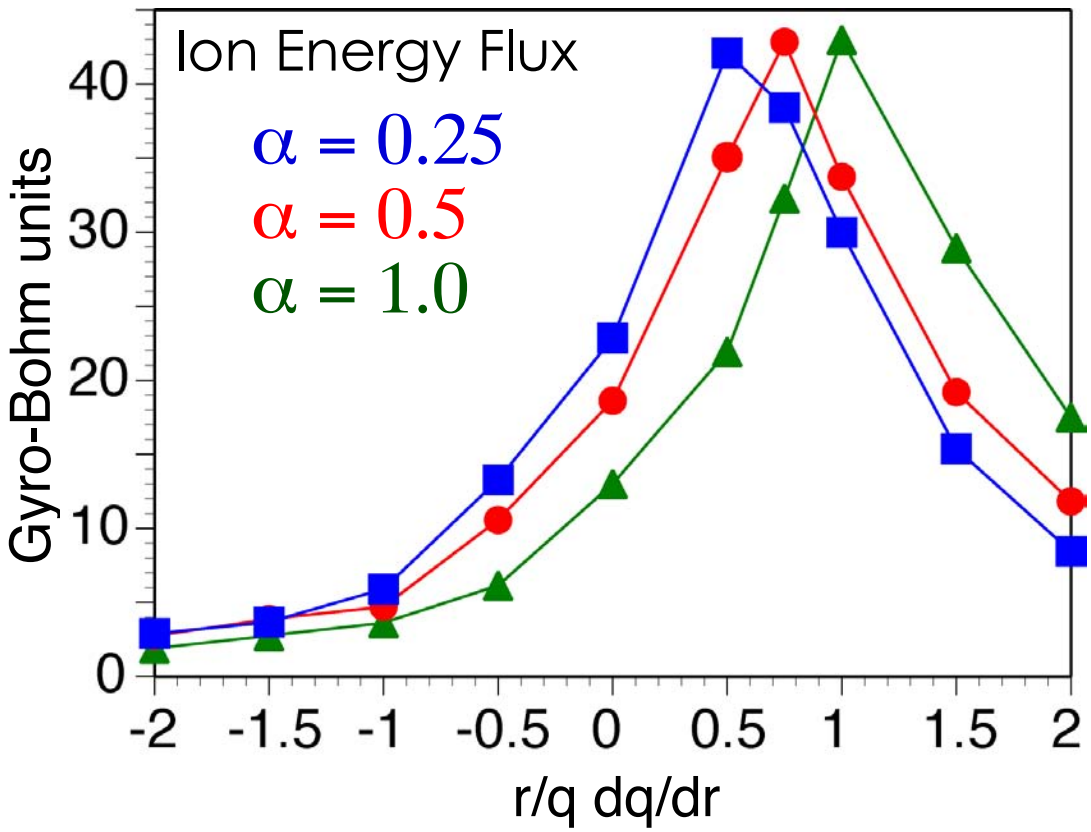


[Staebler et al, Phys. Plasmas 2007]

Impact On TBR, Neutron Shielding, Tritium Containment, Remote Maintenance, and Lifetime

- **Comparison of RF and NBI shows that RF offers considerable advantage in terms of lower shielding requirements and easier control of radiation dose in reactor building** [Jung and Abdou, Nuclear Technology, 1978]
- **Premise that FNSF/DEMO should have very low release rates of tritium, and a very high factor of safety, greatly impacts overall facility cost**

  → **Tritium containment leads to largest unit cost for NBI** [Waganer, "ARIES Cost Account Documentation", 2013]
- **Neutron damage/activation are serious issues for all H&CD tools: accelerator grids for NBI sources, waveguides for EC, antennae for FW, LH**
- **Impact of penetrations on TBR is small: 0.02-0.03. However, this is subtracted from a TBR already very close to 1.0** [El-Guebaly et al, Fusion Science and Technology, 2013]
  - Helicon with traveling wave antenna may have least impact (many radiators connected inductively, only one feedthrough at one end)

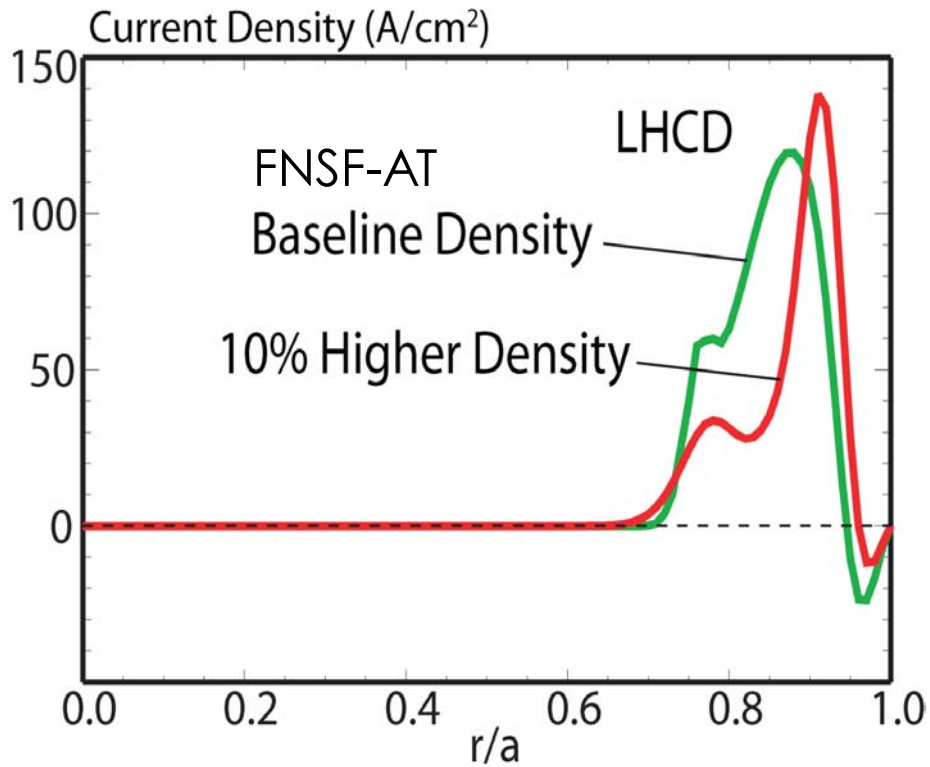
Compatibility with High Density Operation (Divertor Survivability) Narrows the CD Options

- **Non-inductive current drive efficiency**

  I_{driven}/P_{CD} **(Amps/W) ~** $n_e^{-1}R_0^{-1}$ **,**

  so high density, necessary for divertor survivability, poses a challenge for driven steady-state devices

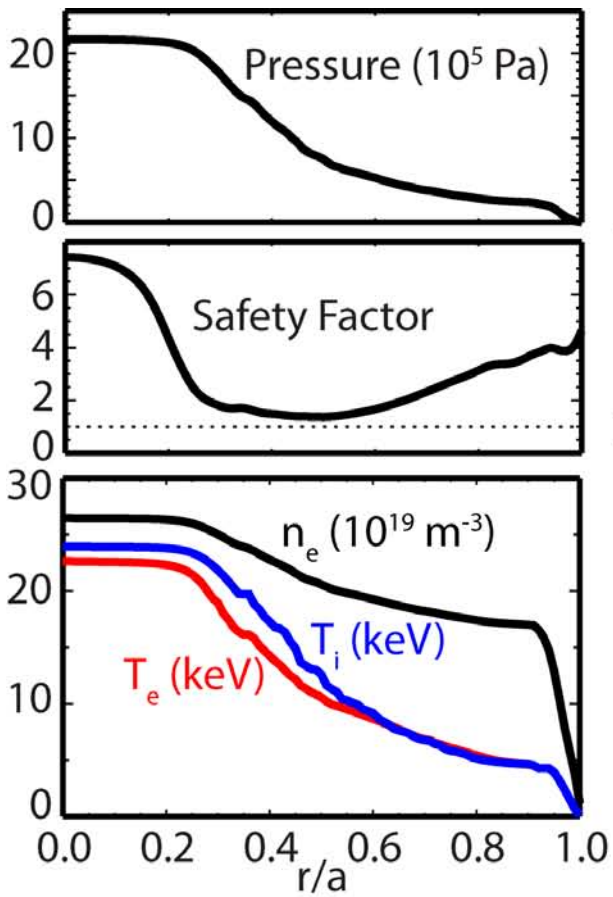
- **While Lower Hybrid Current Drive can be quite efficient in high-field devices, high density sets limits on LHCD in a reactor:**
  - High pedestal density means radial penetration can be very slow, so that the wave is fully absorbed very close to the last closed flux surface at reactor-relevant T_e

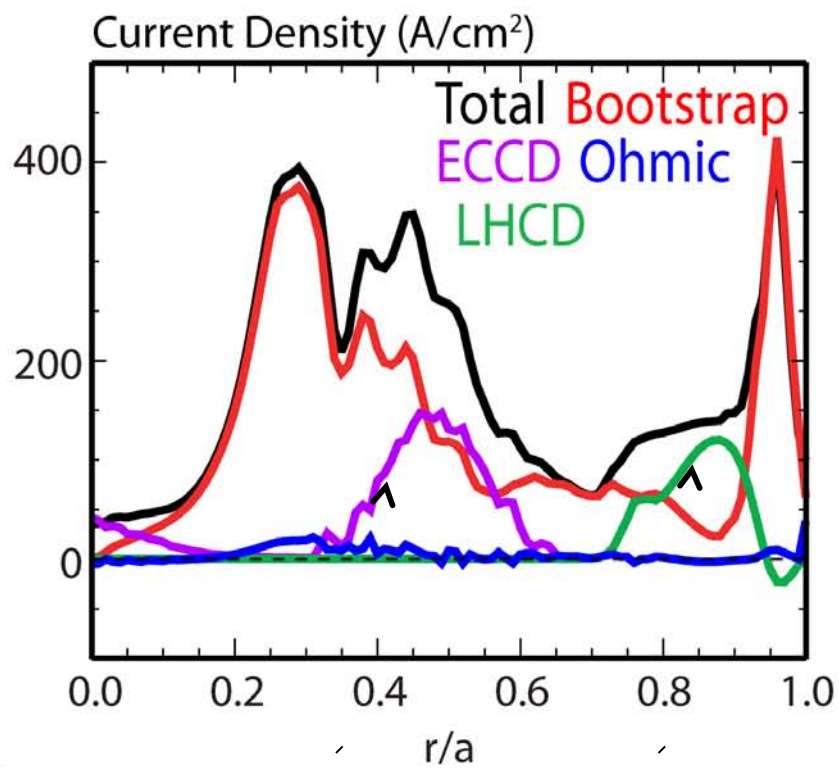


Steady-state FNSF-AT Equilibrium at Baseline Performance Obtained with LH and EC H&CD

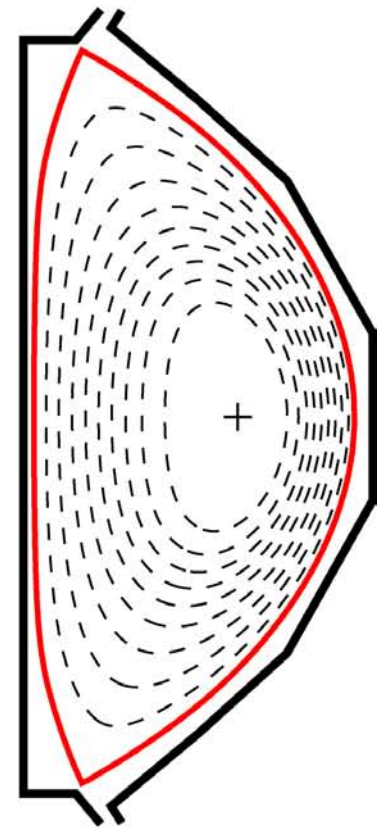
- **Broad current profile (l_i~0.63) with negative central shear, essential for good stability and controllability even at high β_N**
- **β_N=3.7, β_T=5.8%, f_{BS}~70%, Q~3, P_{fus}~230 MW**
- **Good confinement (H_{98y2}~1.2) even without rotation**

[Garofalo, IAEA 2012]

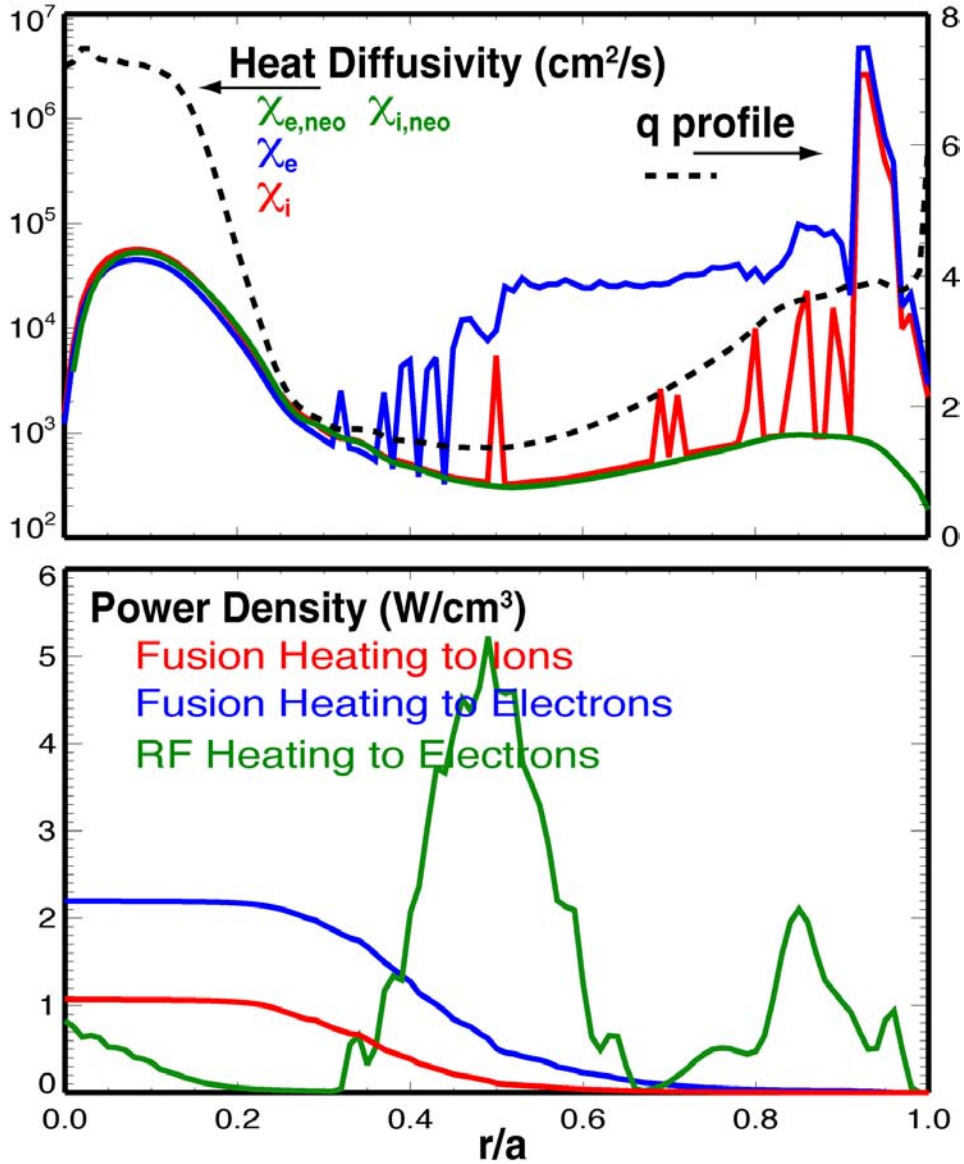




P_{EC}=55 MW P_{LH}=25 MW



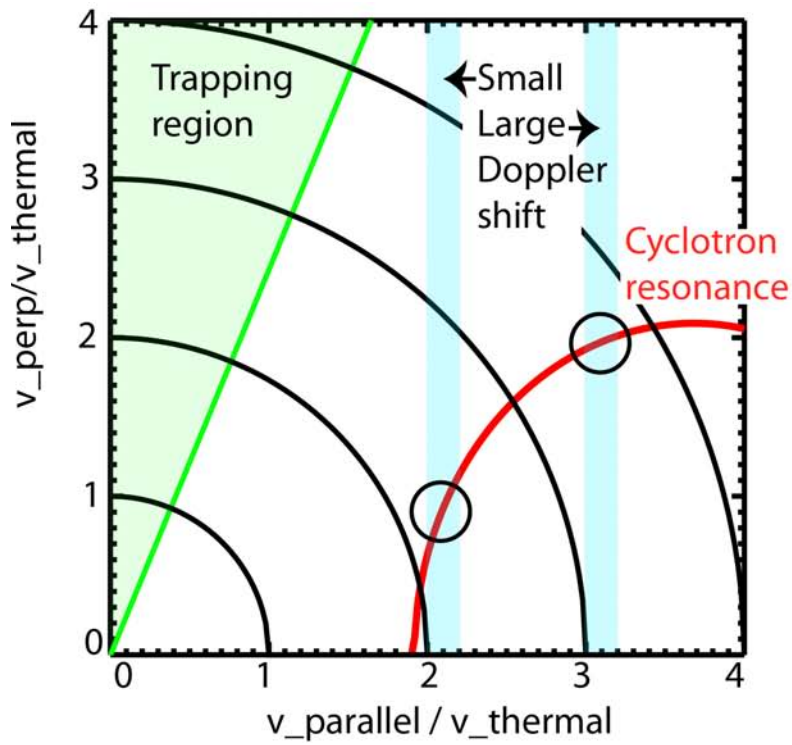
Negative Central Magnetic Shear Enables Neoclassical Transport In Plasma Core



- **Energy transport is electron dominated**
  - Most direct heating goes in through the electrons, comes out through the electrons
- **ETG modes stabilized inside $\rho(q_{min})$ by negative magnetic shear and alpha-stabilization**
- **ITG modes marginally stable at all radii**
  - Neoclassical ion transport in core & high edge pedestal are sufficient to maintain power balance
- **Most RF power mainly used for CD**
  - More efficient CD scheme would reduce RF power waste

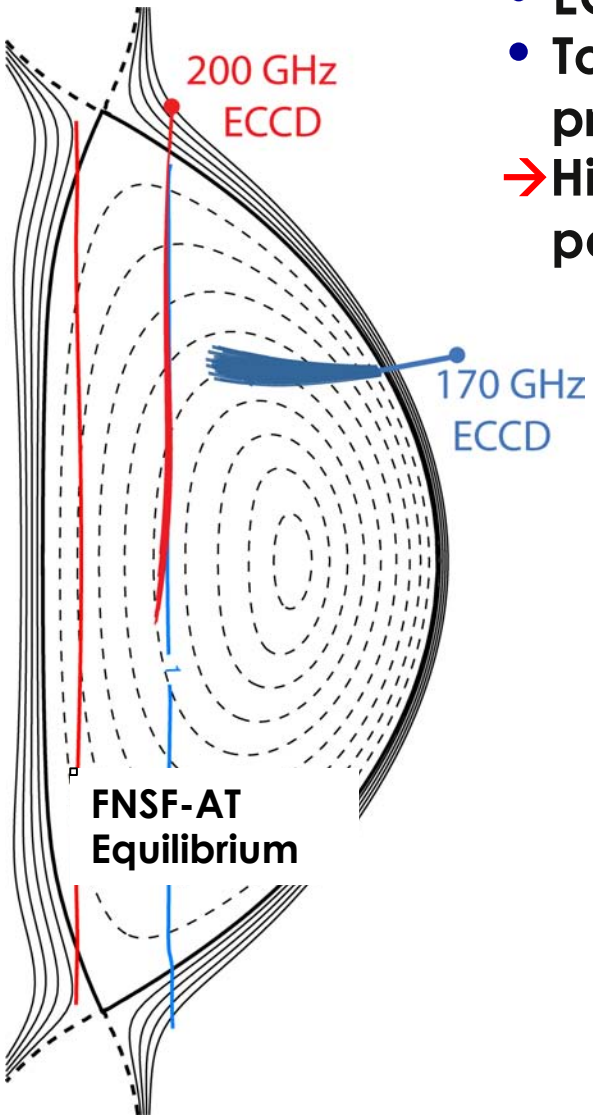
Top Launch Instead of Outside Launch Can Improve ECCD

- **Near mid-plane launchers depend only on Doppler shift to interact with the high-energy electrons**
  - May suffer from parasitic losses at Doppler shifted 2nd harmonic
- **Top launchers can also use nearly vertical trajectories to increase interaction at large Doppler shift**
- **Top launchers can use very large toroidal component to steering angle, which contributes to larger Doppler shift**
- **A large Doppler shift is beneficial because waves will interact with higher energy electrons, which are less collisional and provide larger ECCD**



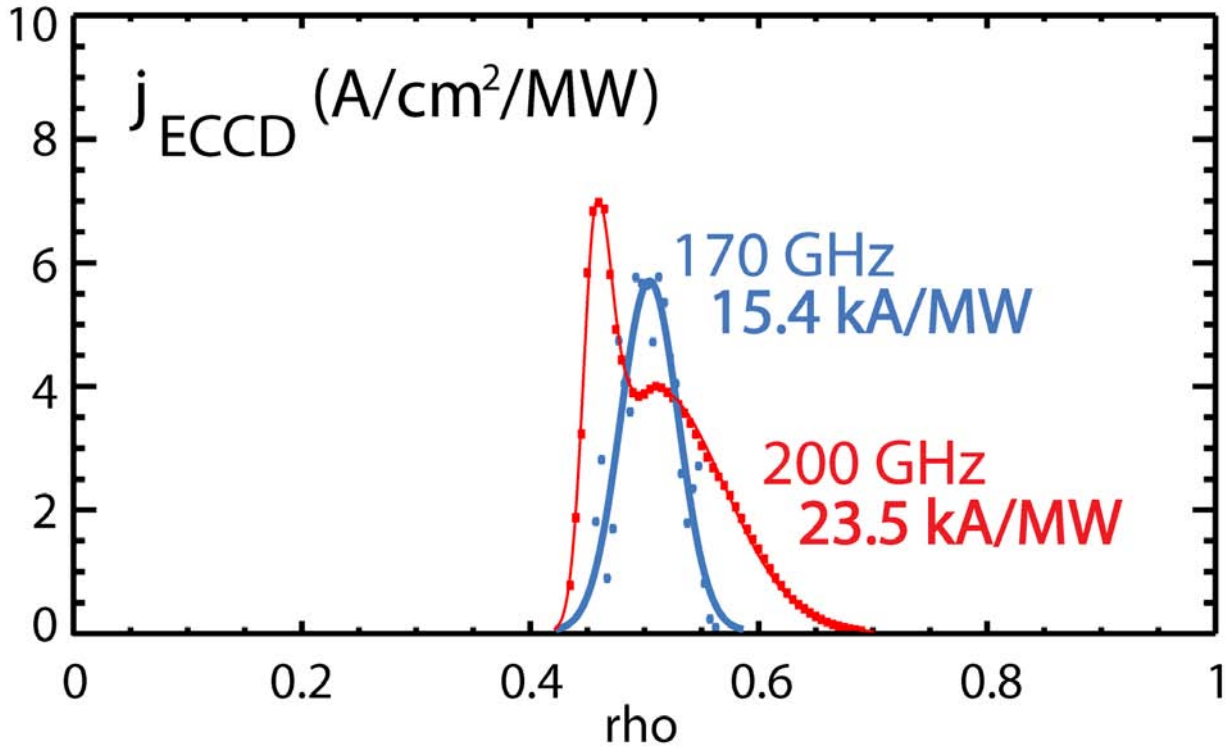
Cyclotron Doppler resonance: $\omega - \Omega_e = k_{||} v_{||}$

Optimization of EC Frequency and Launch Location Yields 50% Increase for Off-axis CD

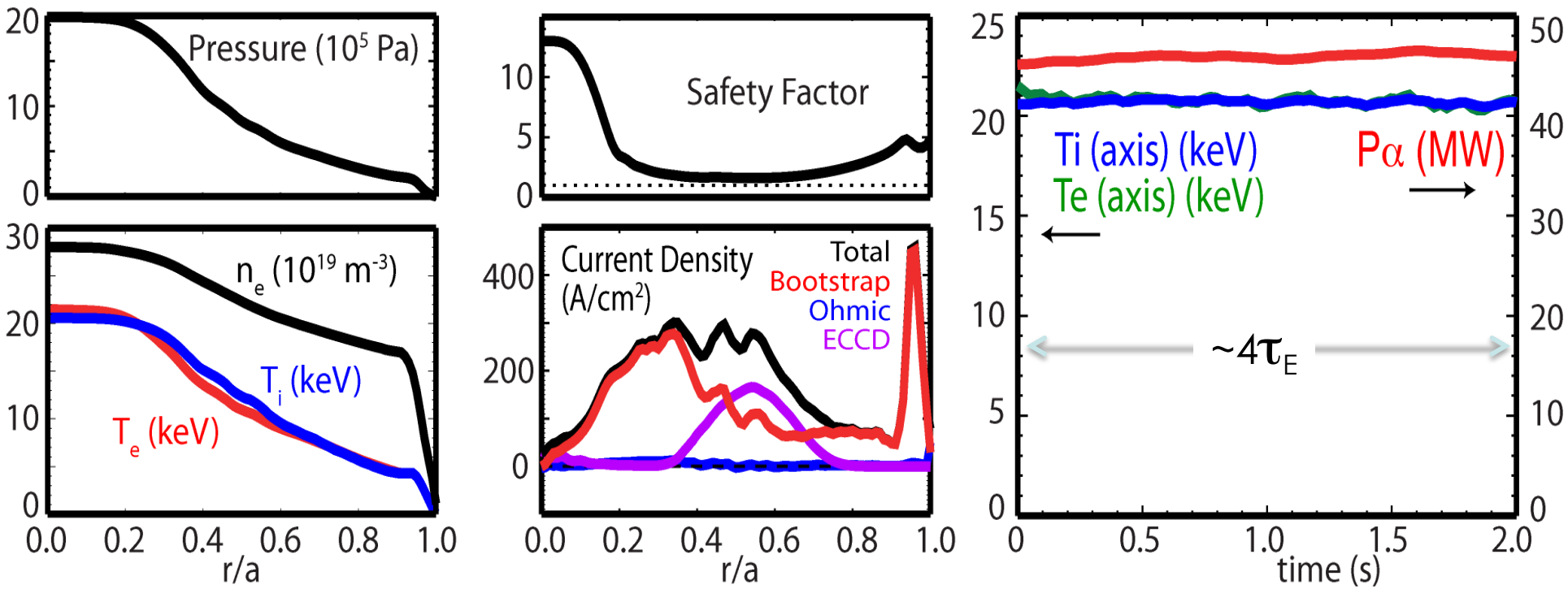


- EC frequency =200 GHz
- Top launch with vertical launch angle so that rays propagate nearly parallel to resonance

→ High dimensional efficiency for broad ECCD profile peaked off-axis



Using Optimized ECH/ECCD, EC-only Steady-state Scenario Possible with Good Confinement

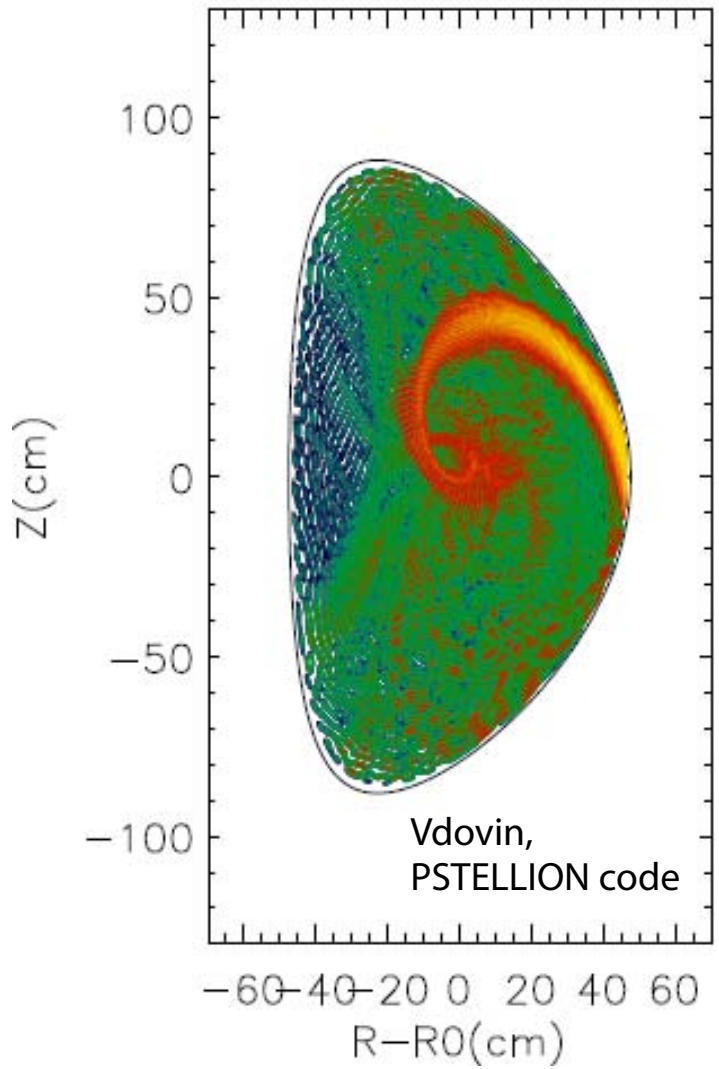


- **Equilibrium evolution is approaching steady-state**
- **Q~3, P_{fus}~230 MW, P_{EC}=75 MW, β_N~3.7, β_T~5.8%, H_{98y2}~1.2, f_{BS}~74%**

[Garofalo, IAEA 2012]

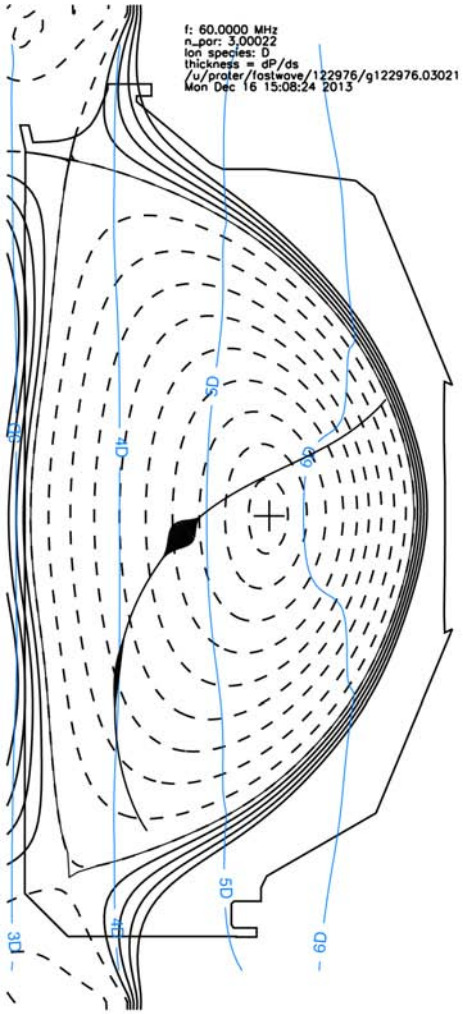
High Harmonic Fast Waves (Helicons) Are Effective at Driving Off-axis Current in High Beta Tokamaks

- **Helicons are fast waves at a high harmonic (30-50) of the ion cyclotron frequency**
- **The high frequency does two important things:**
  - Gives waves whistler-like quality of primarily following field lines, with also a small radial component, so waves spiral around and toward magnetic axis
  - Improves damping, so high performance plasma conditions can provide full damping on first pass
- **Launching the helicon benefits from use of a Traveling Wave Antenna**
  - Sequence of many radiators coupled inductively with only the end element powered



High Frequency Causes Spiraling Ray Trajectory

60 MHz



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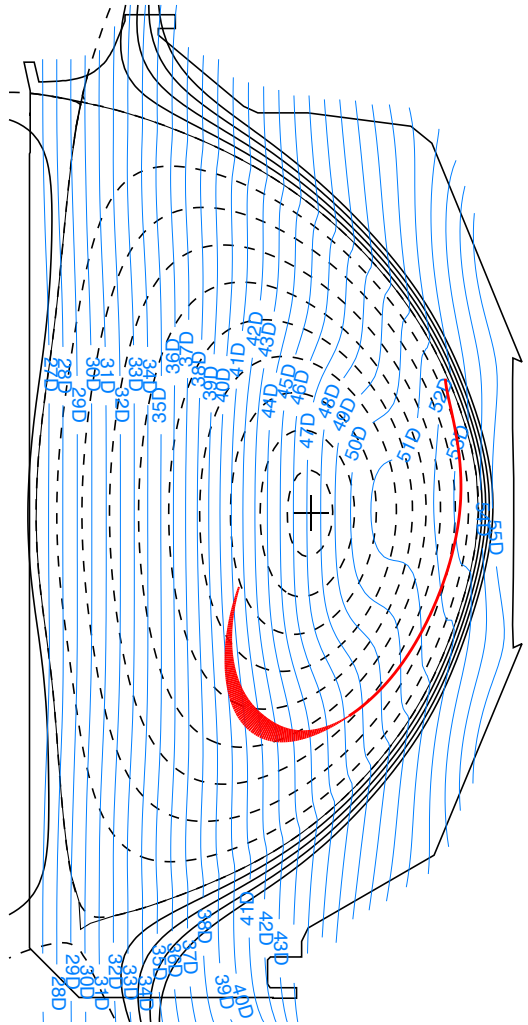
500 MHz

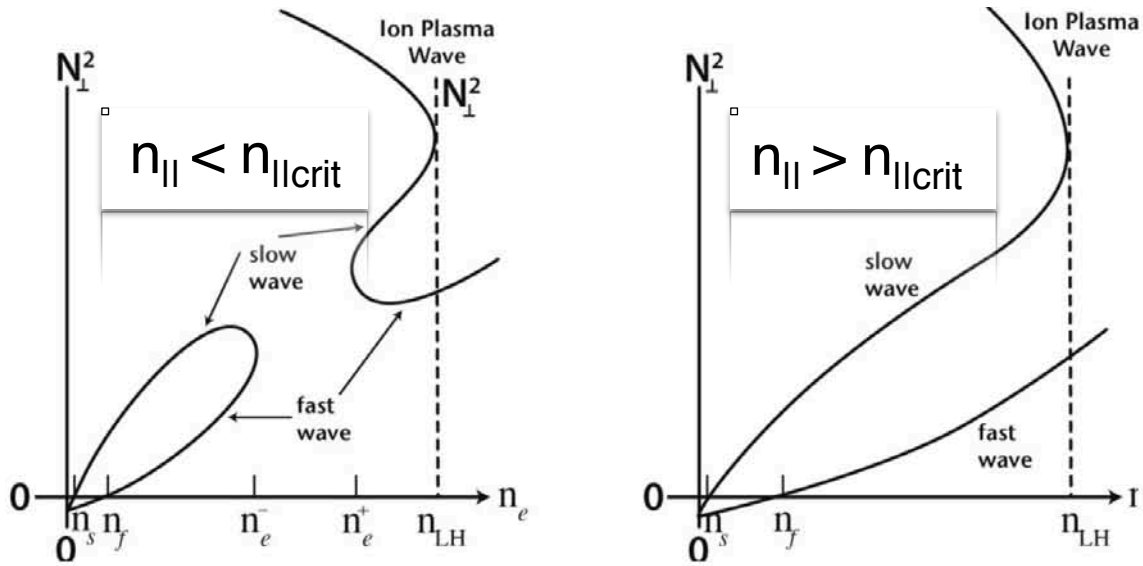


- **The spiral trajectory plus single pass damping imply off-axis interaction**
- **Single pass damping also implies minimum interaction with boundary**
- **Modeling shows that 1.2 GHz is best frequency for FNSF-AT**

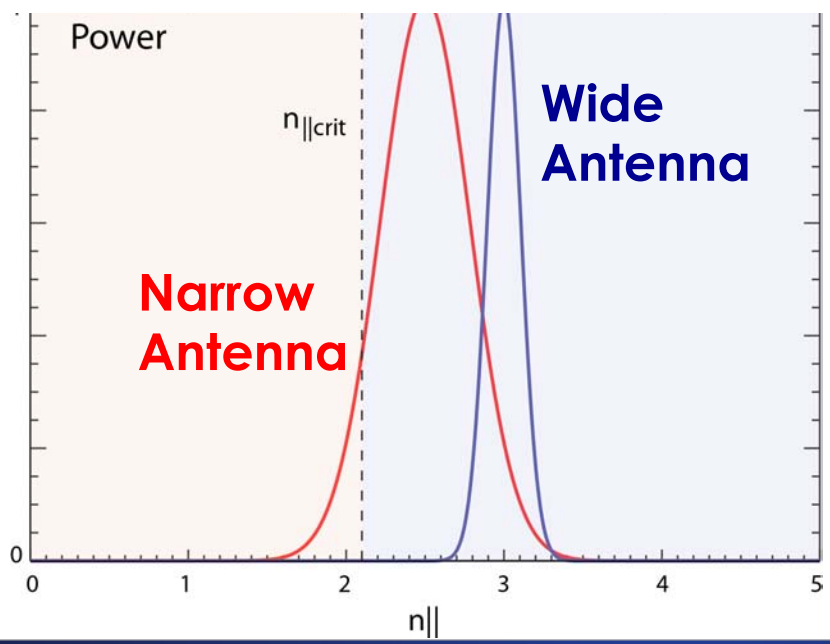
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Traveling Wave Antenna Keeps Power in Desirable Range of $n_{||}$, Avoiding Problems with Accessibility

V. Golant, 1972

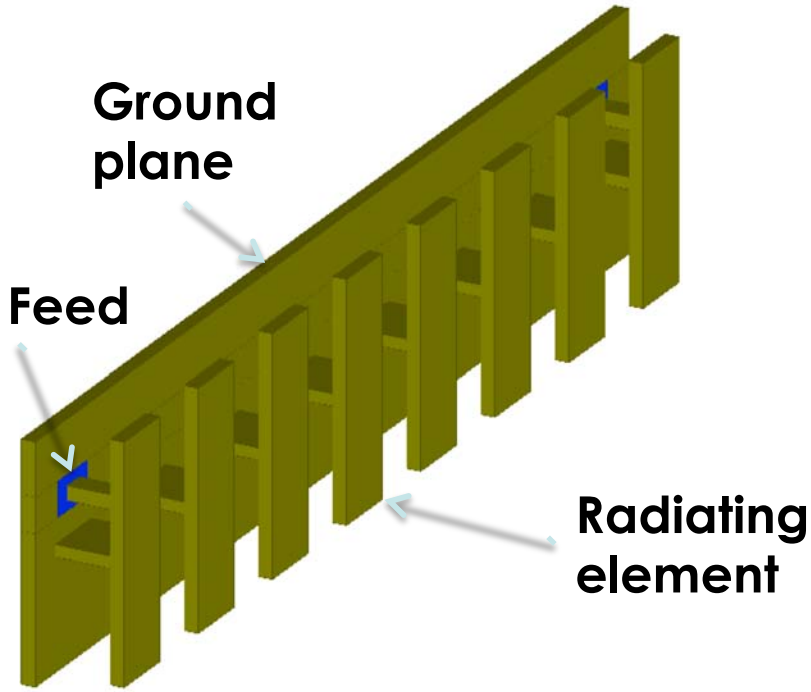


$$n_{||cri} \sim \left[1 - \frac{\omega^2}{\omega_{ce}\omega_{ci}}\right]^{-1/2} \approx 2.1$$

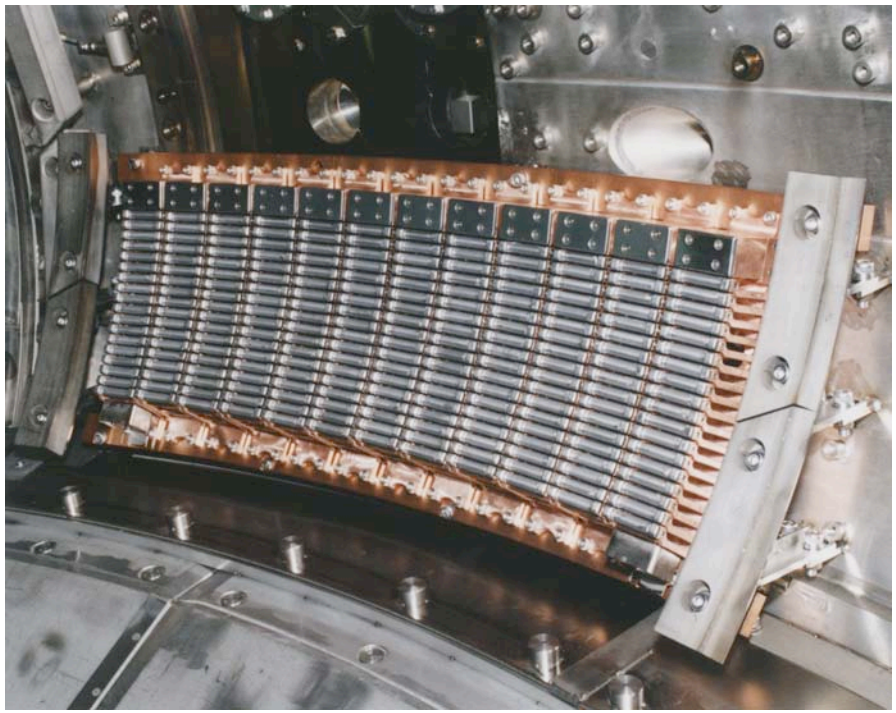


- Traveling wave antenna has narrow $n_{||}$ spectrum
- Implies highly reduced mode conversion

Traveling Wave Antenna Tested on JFT-2M in 1996



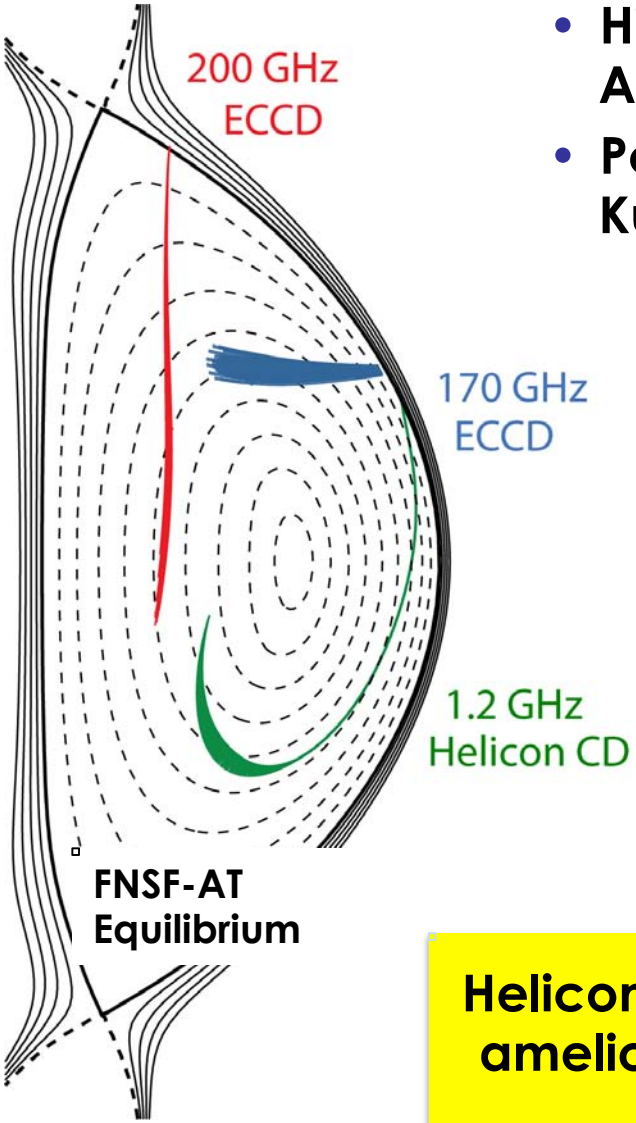
- 10-50 radiators
- Feedthroughs only at ends
- Matched impedance minimizes voltage
- Radiators connected inductively
- 4 or more straps per parallel wavelength



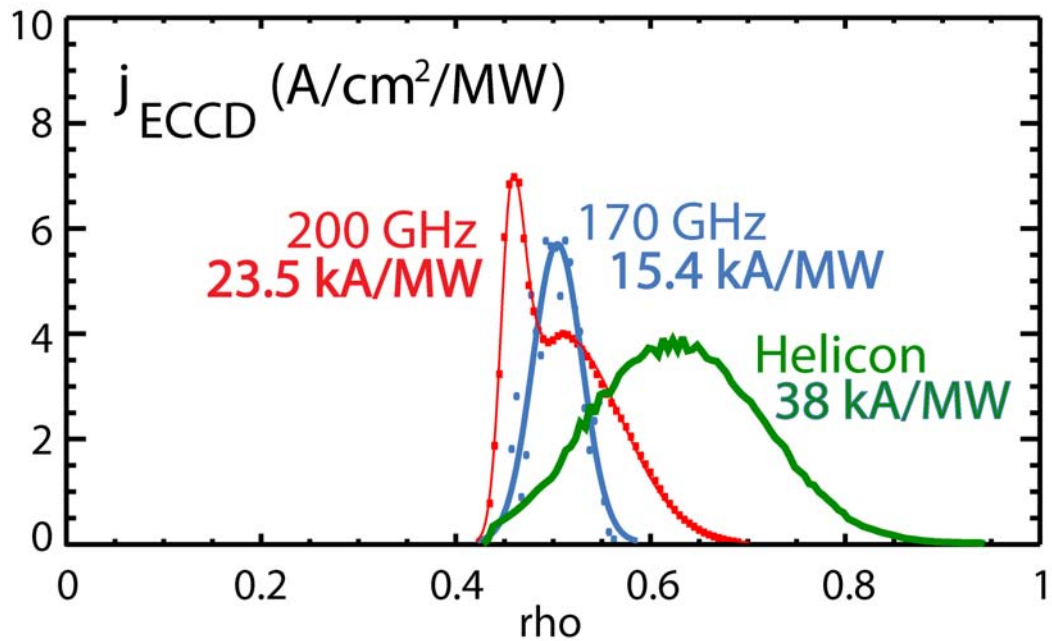
- 12 radiating straps
- Tested at voltages corresponding to 800 kW
- Experimentally successful at launching the fast wave
- Designed and built by GA

[Moeller, 1993; Pinsker, 1996; Ogawa, 2001]

Helicons Are Predicted to Drive 1.5-2.5 Times More Off-axis Current than ECCD in FNSF-AT

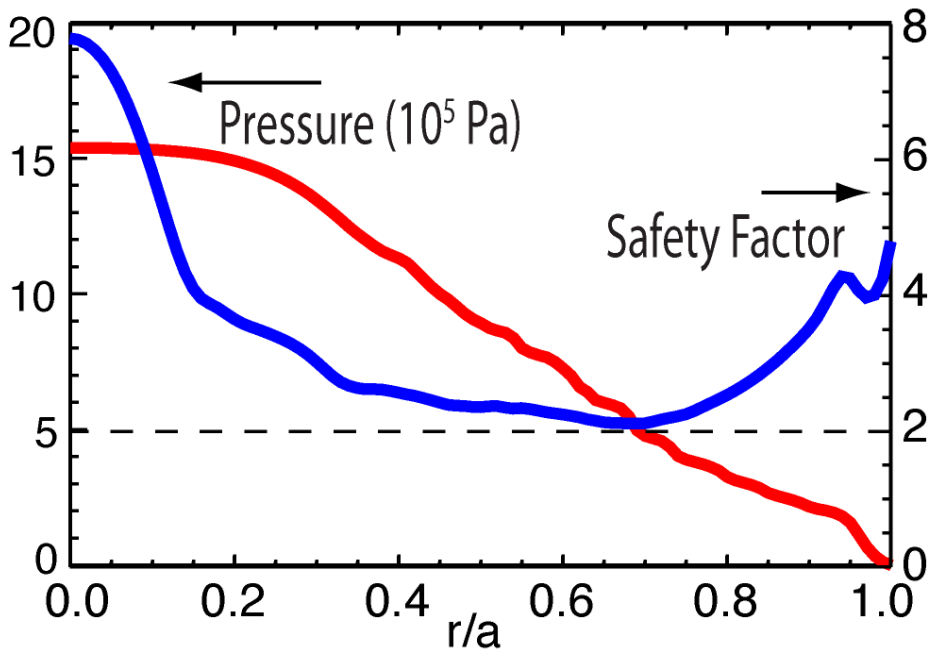


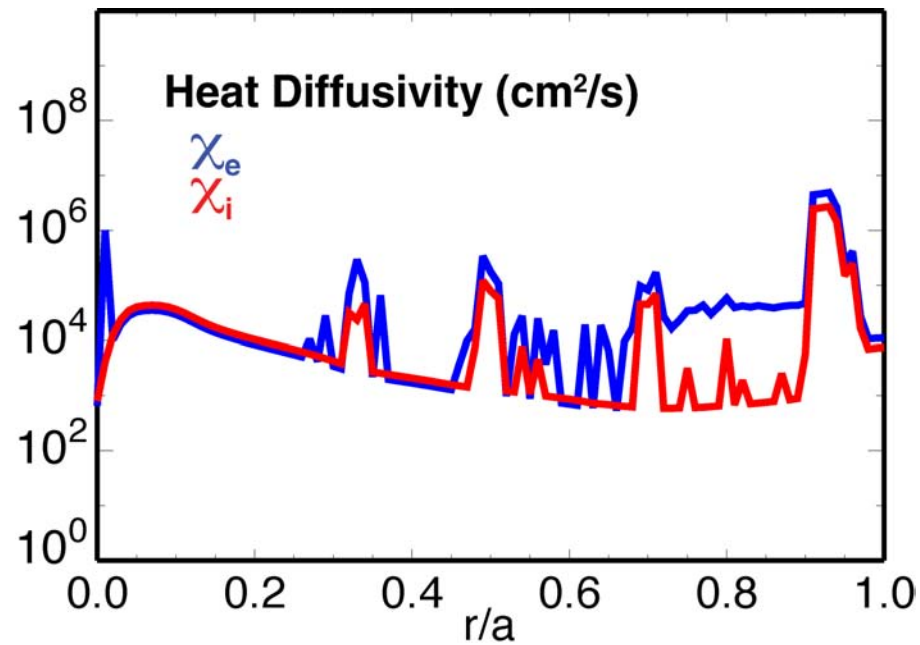
- **Higher CD efficiency is why helicons were chosen for ARIES-RS** [Jardin, FED 1997]
- **PoP tests on DIII-D in 2016 in collaboration with Kurchatov Institute**



Helicons may reduce the tension between high density for ameliorating the power exhaust issue and low density for improving current drive efficiency

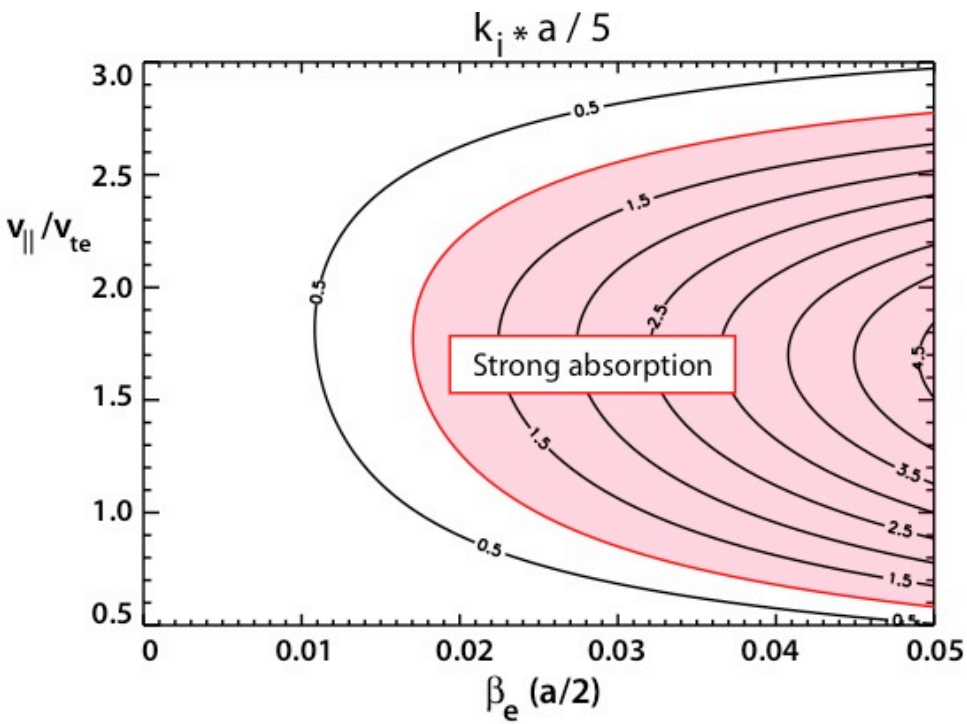
FNSF-AT Scenario Using Helicon Still Under Development



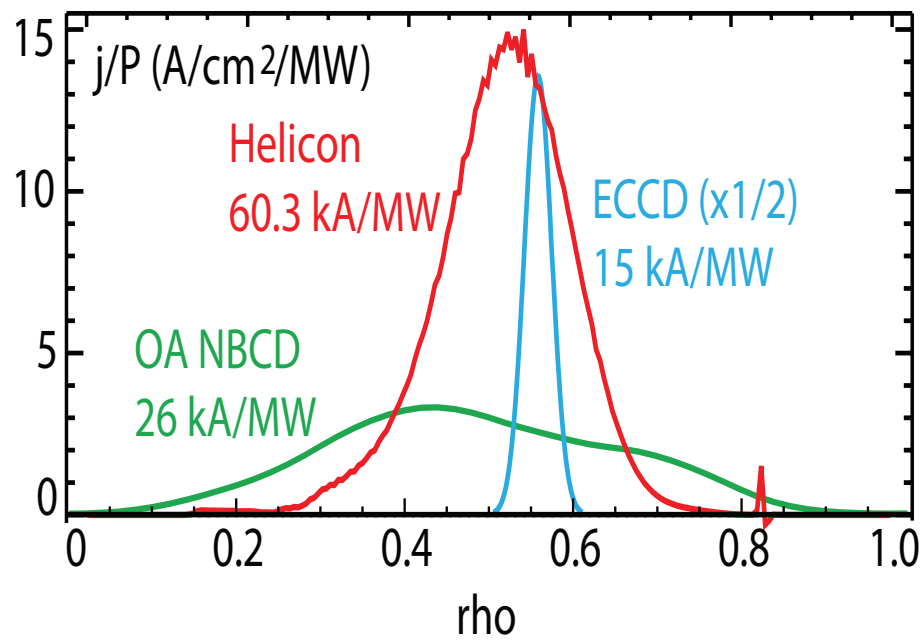


- **Pressure profile is very broad**
- **q-profile has higher q_{min} and broader radius of q_{min}**
- **Neoclassical transport extends to larger radius**

DIII-D Can Provide Target Discharges with the High β_e Needed for Successful Helicon Demonstration



- $n_{||}(a) = 3.0$, f=500 MHz
- $\beta_e(\rho=0.5) = 3.2\%$ (Discharge #122976)

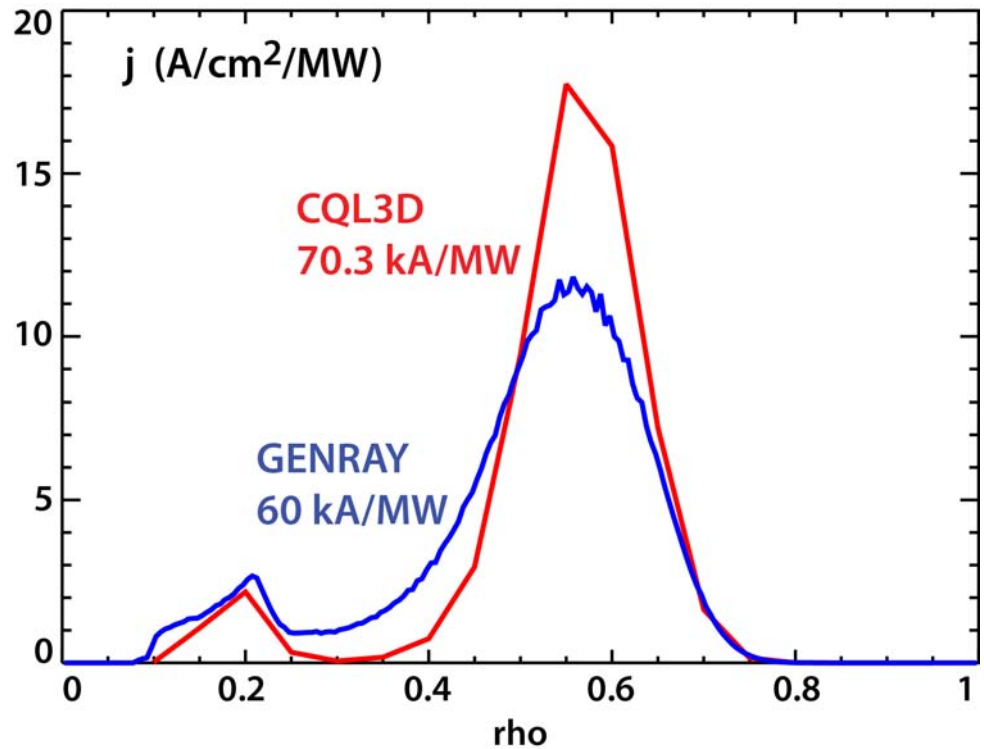


- **Minimum β_e for strong absorption is around 2%**
  - $n_{19}(a/2)=5$, $B_t=1.6$ T, f=500 MHz [Chiu, Chan, Harvey, Porkolab, NF 1989]

- **Helicon current drive in target DIII-D discharge is more effective than ECCD by 4x and than NBCD by 2x**

CQL3D Fokker-Planck Code Validates Absorption and Current Drive Models in GENRAY

- **CQL3D uses completely different models than GENRAY for absorption and current drive**
  - inputs to CQL3D are the wave trajectory and electric field polarization from GENRAY
- **Agreement between CQL3D and GENRAY is very good**
  - Raising power level in CQL3D does not increase difference between its prediction and (linear) GENRAY prediction, verifying that quasilinear effects are unimportant



DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Klystrons Appear to Be Available from the SLAC B-Factory

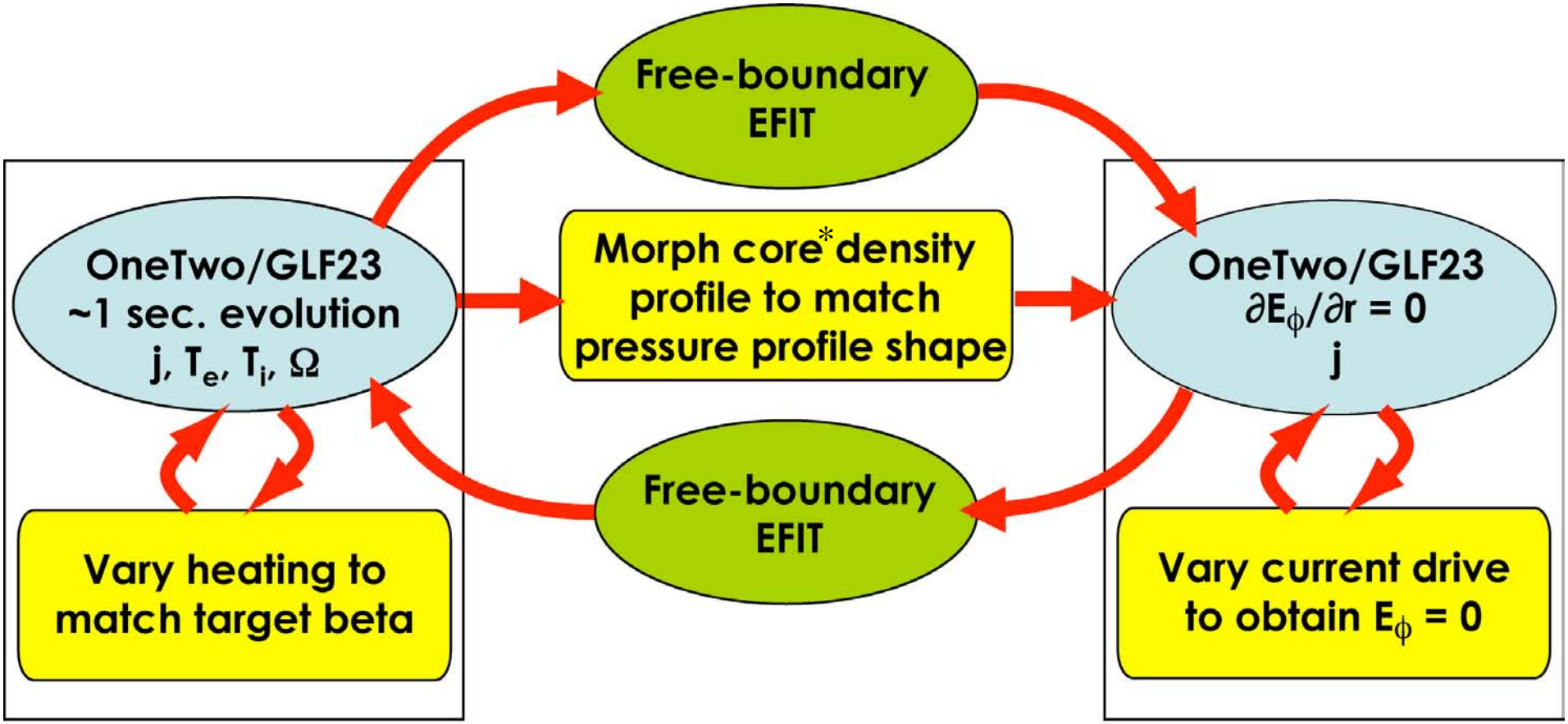
- **SLAC (Stanford Linear Accelerator Center) has multiple klystrons from the B-Factory they have indicated they are willing to transfer to DIII-D**
  - B-factory operated 1998-2008
- **Klystrons are 1.2 MW cw at 476 MHz**
  - Operate at 84 kV (compatible with gyrotron power supplies at DIII-D)
  - Electrical efficiency is high, above 60%
- **Related equipment is also available: heater power supply, magnet, circulator, waveguide, dummy load,…**

Efficient Off-axis CD Is a Key Technology Issue for Advanced Tokamak Scenarios on FNSF and DEMO

- **Advanced Tokamak approach reduces disruption risk, requires efficient off-axis current drive**
- **Self-consistent steady-state AT scenarios calculated for FNSF-AT using ECCD+LHCD or ECCD-only**
  - Good confinement without toroidal rotation
  - Good MHD stability without internal control coils (n=0 and n>0)
- **Helicons offer significant improvement in off-axis current drive efficiency over ECCD and NBCD**
  - May reduce tension between high density for ameliorating power exhaust issue and low density for improving current drive efficiency
  - Fewer vessel penetrations, reduced impact on TBR, neutron shielding
- **DIII-D is an excellent facility for testing Helicon current drive due to high β_e and antenna expertise (and CD measurement capability)**

Additional Material

Steady-state Is Found Via Iteration of Alternating Temperature Profiles and Current Profile Evolution



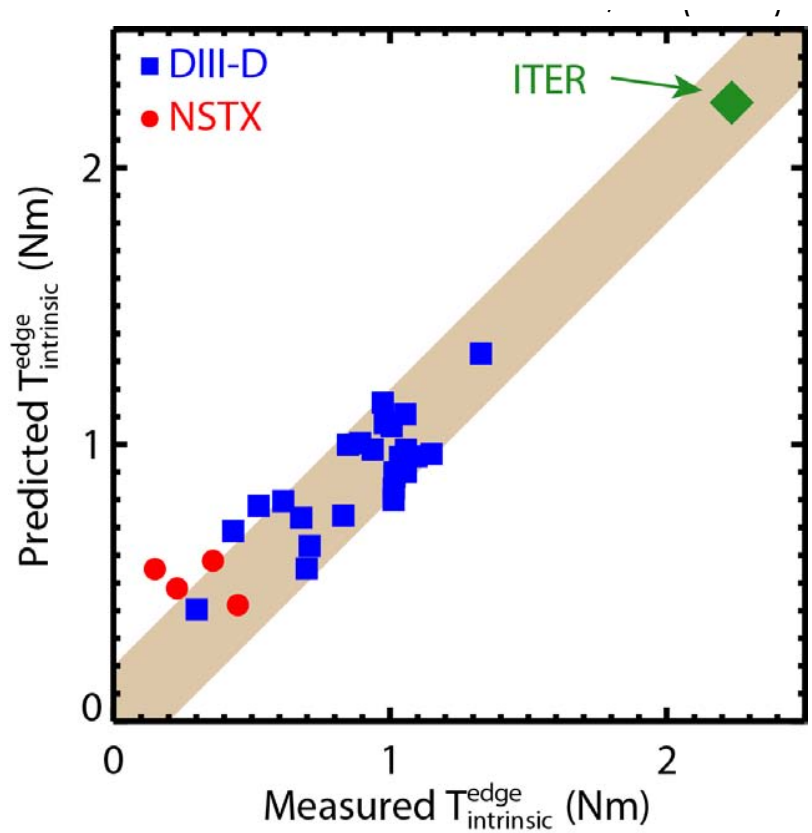
* Density pedestal fixed at EPED value, density peaking fixed at international database value

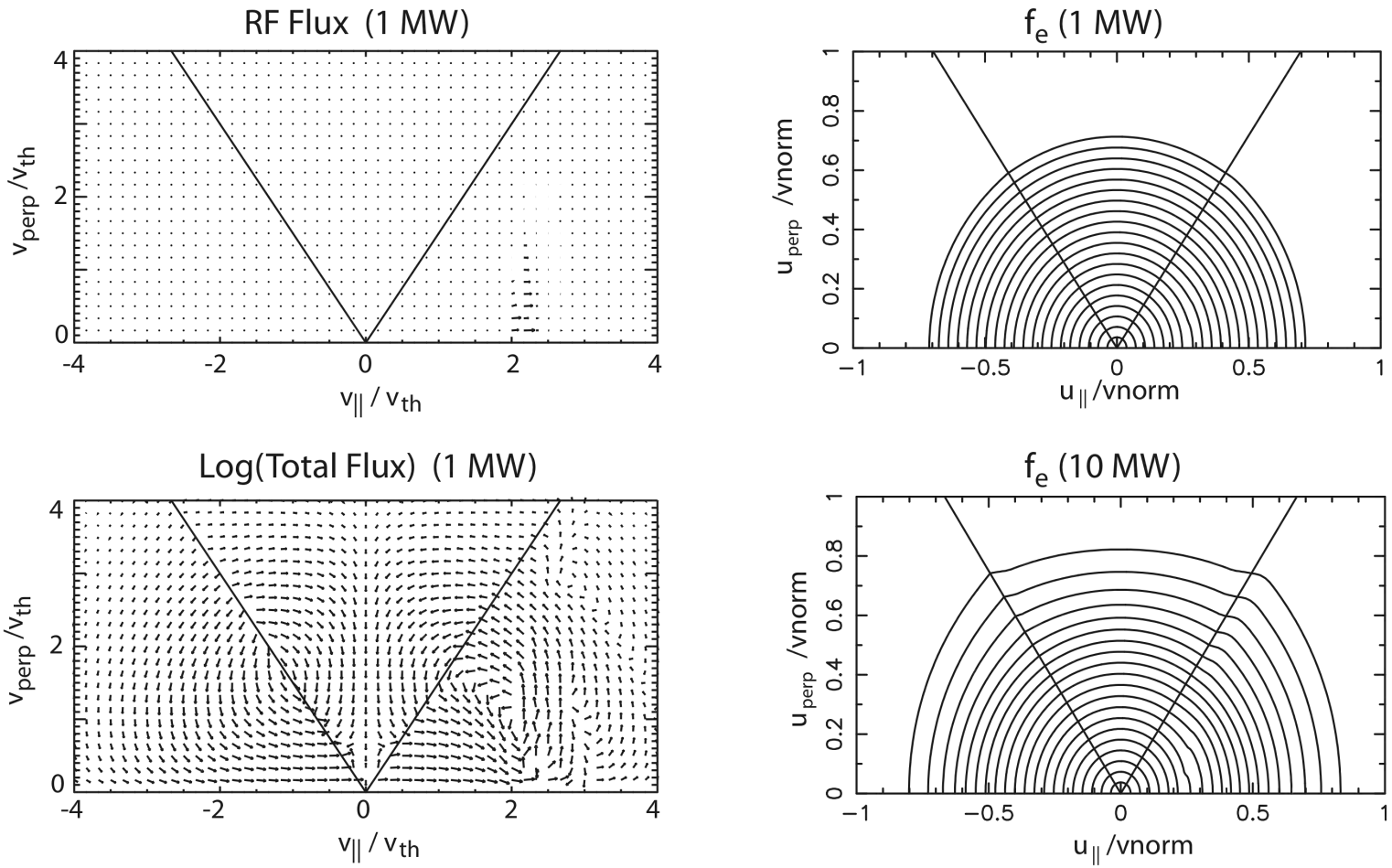
Negligible Intrinsic Torque expected in ITER

- **An excellent predictor of edge intrinsic torque has previously been established for DIII-D H-modes**
  - Empirically includes physics associated with turbulent Reynolds stress and thermal ion orbit loss
    [Solomon et al., *Nucl. Fusion* (2011)]

- **Intrinsic torque calculated to be only 2 Nm**

- **Much smaller than even NBI torque (~35 Nm)**



CQL3D shows that the effect of waves is a parallel flux in a small region of v_parallel and low v_perp

- **Only electrons with v_parallel near 2v_thermal and small v_perp are directly affected by the wave**
- **No direct interaction with trapped electrons**