AN INTEGRATED STUDY OF ITER-FEAT DESIGN PHYSICS PERFORMANCE

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MOTIVATION

- ITER-FEAT is more than a factor of 2 smaller than the ITER-EDA design. It is also slightly more elongated and triangular. How would these changes affect the physics constraints, hence machine performance ?
- Consistency of ITER-FEAT design is evaluated based on physics models reflecting our latest understanding from theory and experiment in
  - MHD stability
  - Transport
  - Power exhaust
  - Density Control
- Aspects of ITER-FEAT AT (Advanced Tokamak) are also studied with emphasis on control requirements
- Methodology also used in recent ARIES-AT study [1]

[1] Chan et al, APS 1999

OUTLINE/SUMMARY

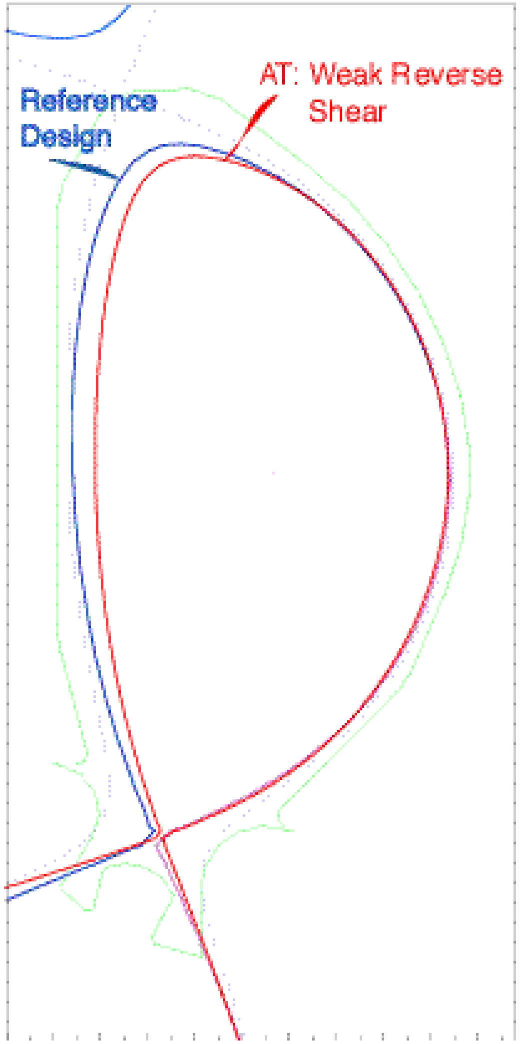
ITER-FEAT Reference Design

- Ideally stable to high, intermediate, and low *n* modes without a conducting wall
- Transport simulations using the GLF23 model indicate that a pedestal temperature of 4.5 keV is required to reach Q = 10 and P_{fus} = 400 MW
- Density can exceed the Greenwald limit while still remain compatible with good confinement and safe heat exhaust with a modest density peaking factor similar to that of a typical DIII-D ELMing H-mode discharge

ITER-FEAT AT Design

- Ideally unstable without a conducting wall and stable with a wall at 1.3a
- *n* =1 resistive wall modes can be completely stabilized with sufficient number and coverage of flux conserving intelligent coils
- Impurity seeding is ineffective to raise the core radiated power due to lower density
- Higher triangularity can affect heat loading at non-divertor locations

ITER-FEAT REFERENCE AND AT EQUILIBRIA ARE ESTABLISHED USING THE CORSICA CODE



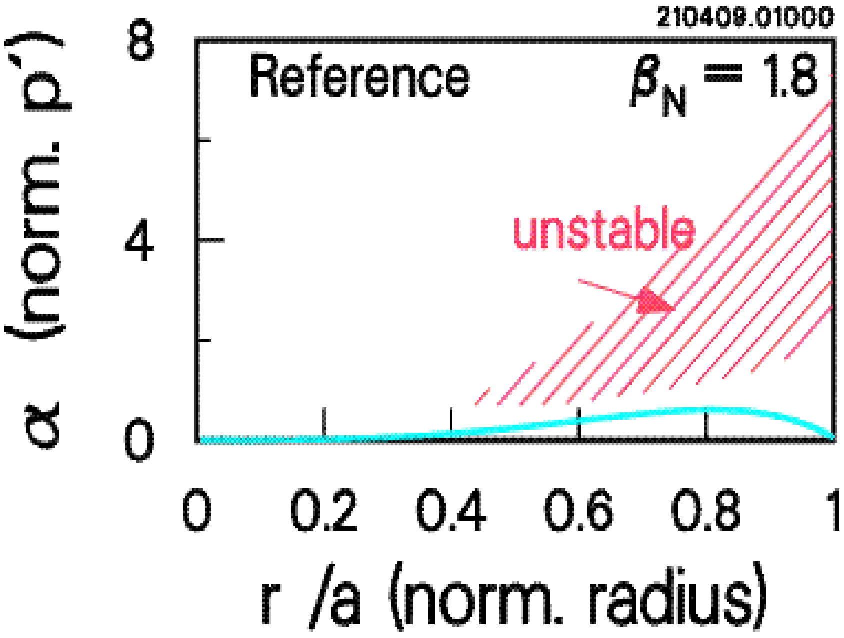
	Campbell*	Corsica	Corsica
	FEAT	FEAT	FEAT-AT
I_p (MA)	15	15	10
B_o (T)	5.3	5.3	5.3
R (m)	6.2	6.2	6.33
a (m)	2.0	2.0	1.87
R/a	3.1	3.1	3.39
κ_x	1.85	1.85	1.93
δ_x	0.49	0.56	0.623
q_0		1.1	2.4
q_{95}	3	2.98	4.29
β_t (%)	2.5	2.5	3.3
β_n	1.8	1.75	3.2

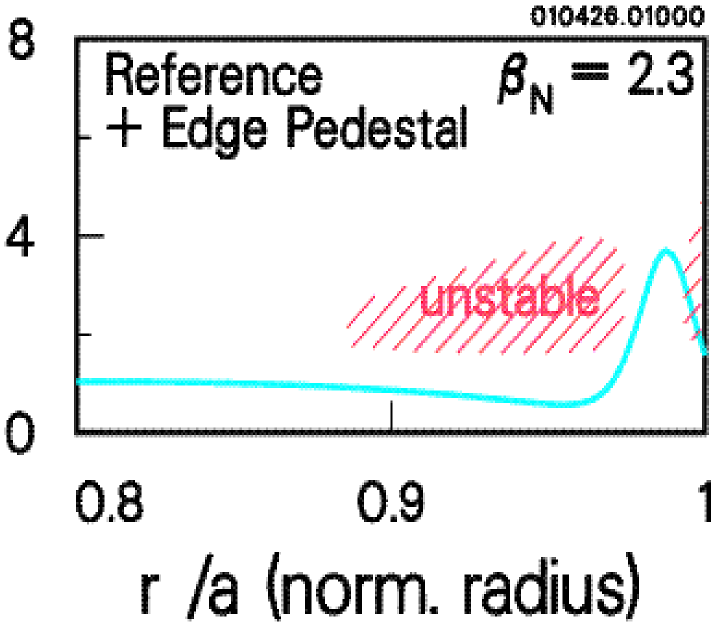
*** Campbell, APS 2000**

Gribov et al, IAEA 2000

BOTH THE REFERENCE AND THE AT DESIGNS ARE STABLE TO THE HIGH *n* IDEAL BALLOONING MODES

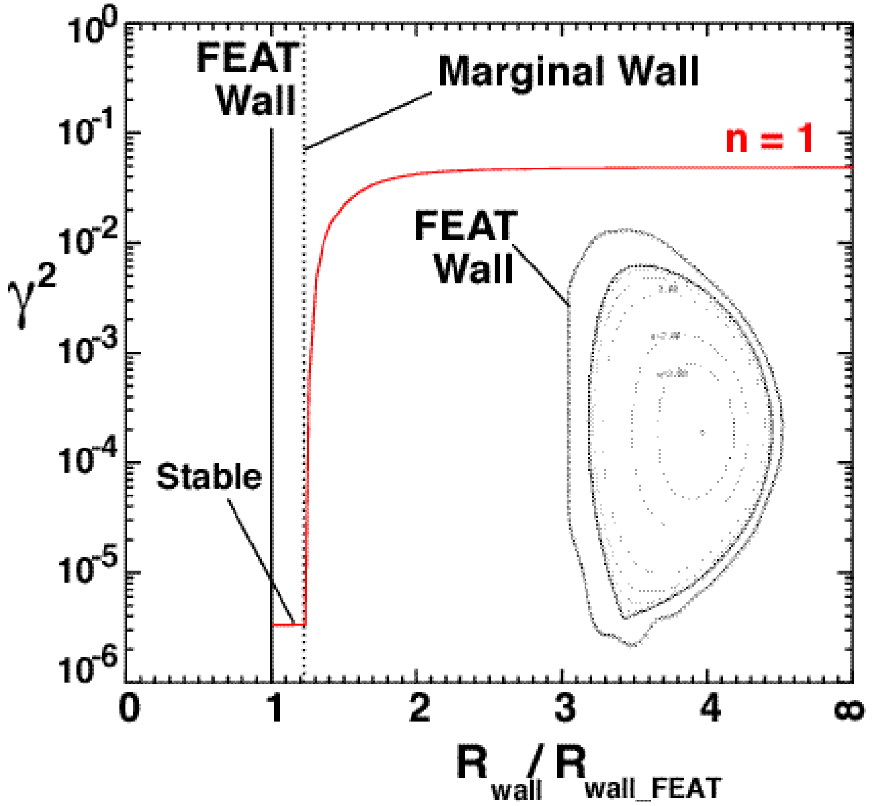
- **Also stable to intermediate *n* modes**
- **Low *n* modes are stabilized by a close fitting conducting wall**
- **Plasma edge opens up to second ballooning stability region when an edge pedestal is added to the reference design**

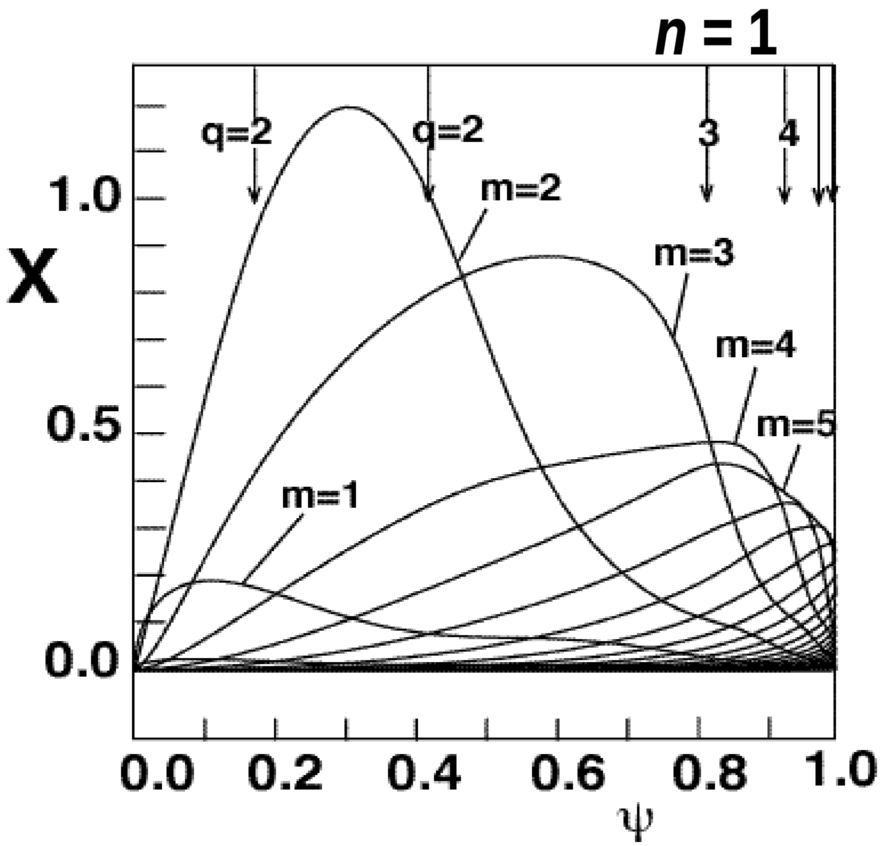




THE AT DESIGN IS UNSTABLE TO *n* = 1 MODE WITHOUT A CONDUCTING WALL AND STABLE WITH A WALL

- $\beta_N^{NO\_WALL}$= 2.45 for AT equilibrium, reference design is stable without a wall
- AT design stable to *n* = 2,3 modes without a wall at β_N = 3.2
- Low *n* modes computed using GATO

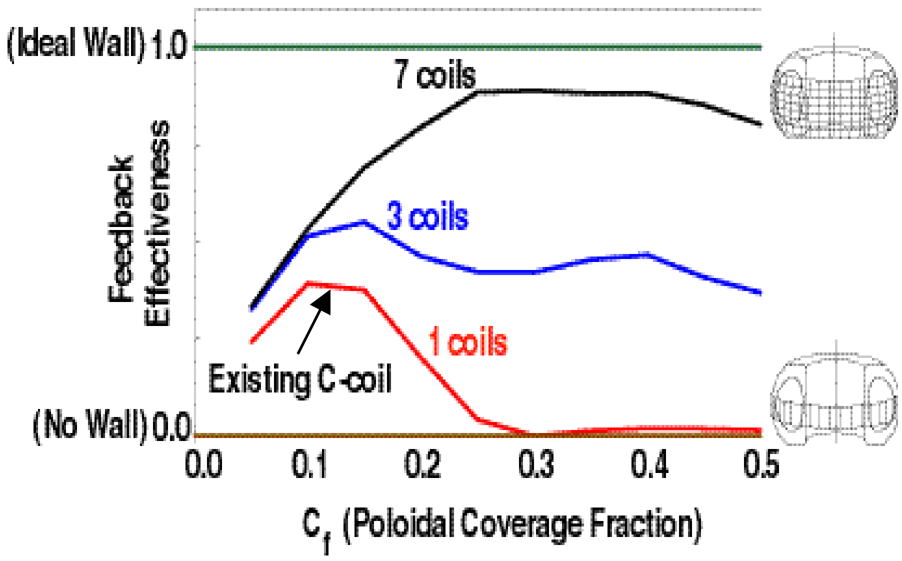




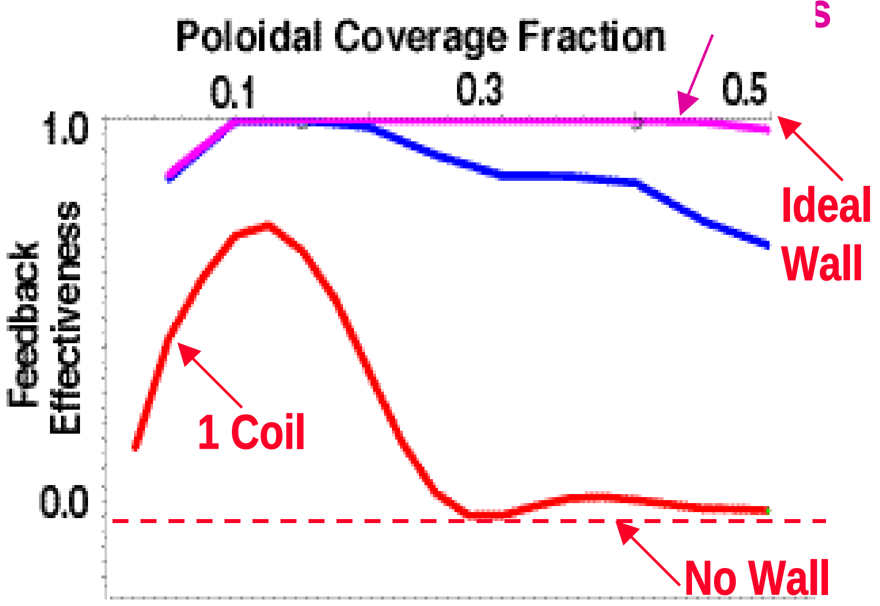
n = 1 RESISTIVE WALL MODES CAN BE COMPLETELY STABILIZED BY FLUX CONSERVING INTELLIGENT COILS

- **Currents in the coils are utilized to replenish the perturbed radial flux diffused through the resistive wall**
- **Evaluated using GATO and VACUUM with an extended energy principle**
- **Unstable modes can slip through 1 coil at large poloidal coverage**

DIII-D

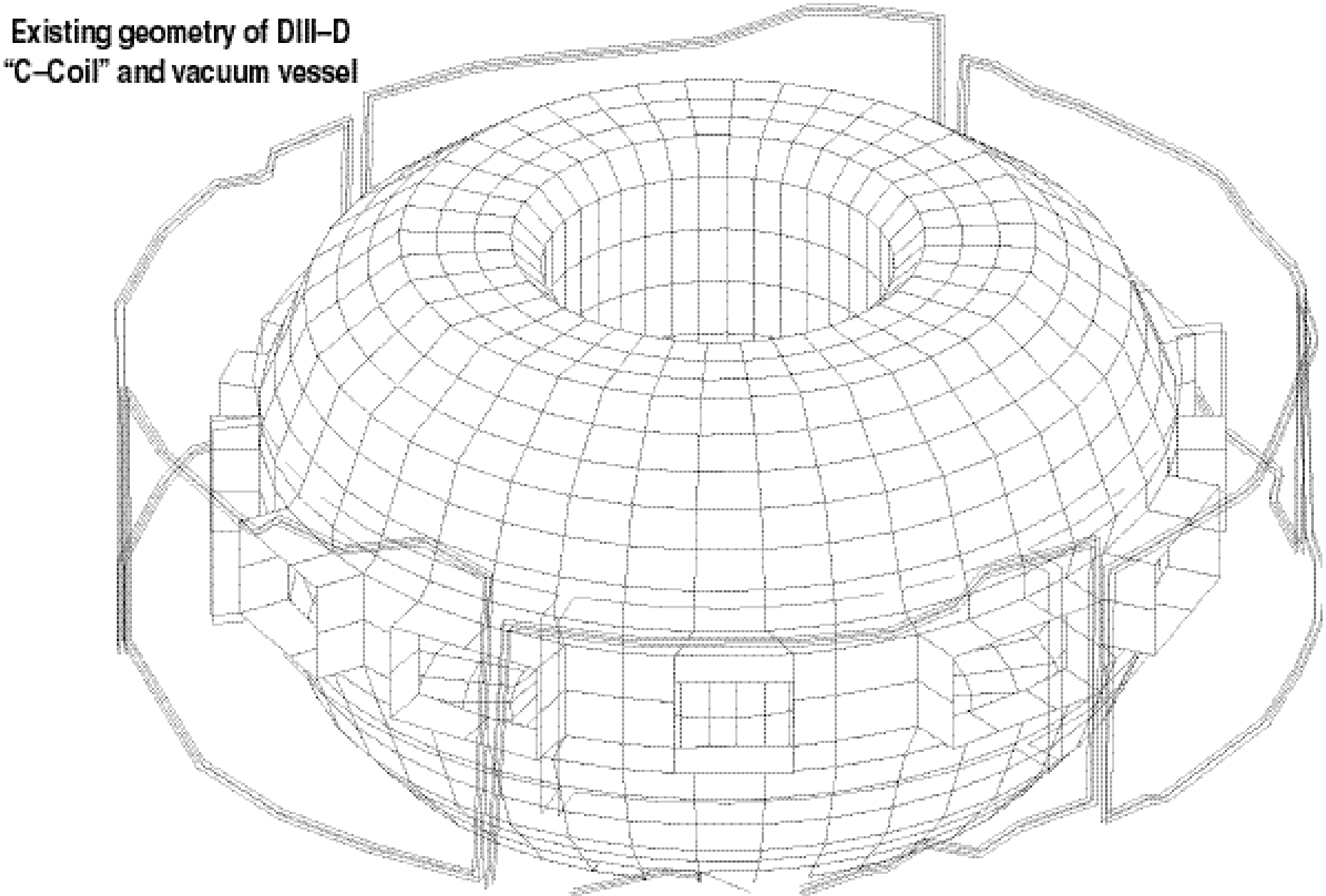


ITER-FEAT



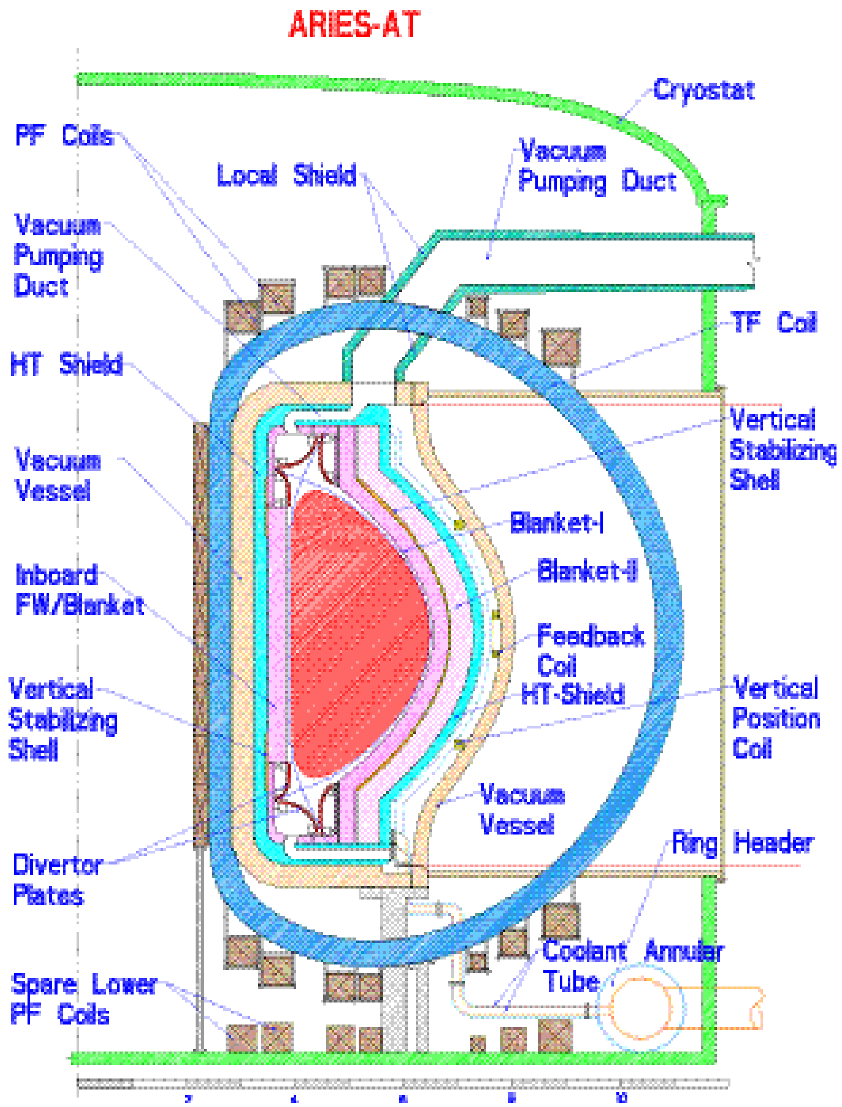
RESISTIVE WALL MODES ARE CONTROLLED IN DIII-D USING THE C COILS

- 6 segments connected to produce a $n = 1$ magnetic field



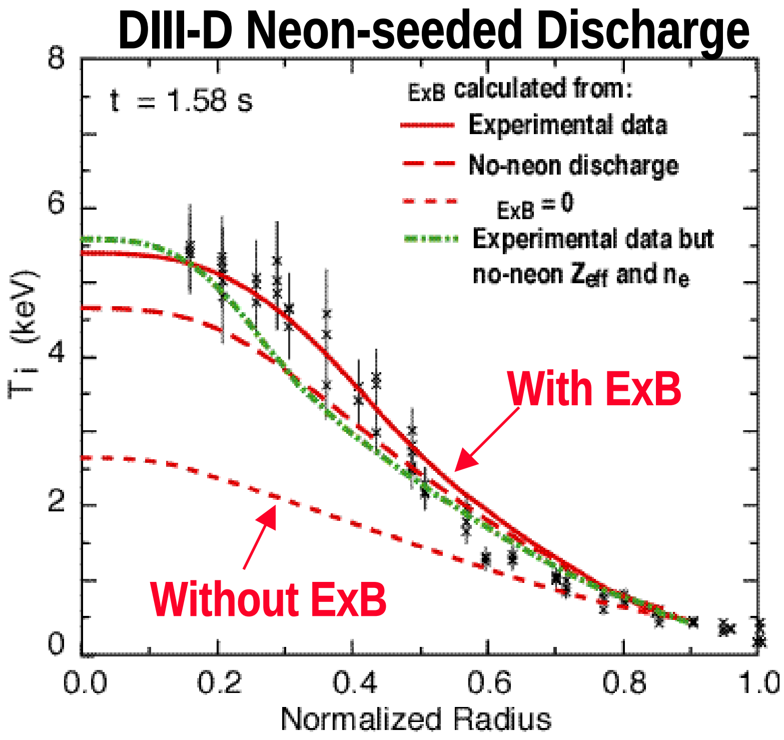
ARIES-AT RWM FEEDBACK COIL DESIGN IS BASED ON THE DIII-D C-COIL CONFIGURATION

- 16-22.5° wide toroidally, 60° wide poloidally, outboard
- $\delta B_R \sim 150$ G at vessel
- 8 MW reactive power, 6 MW dissipated power
- δB_R sensor loops needed as close to plasma as possible

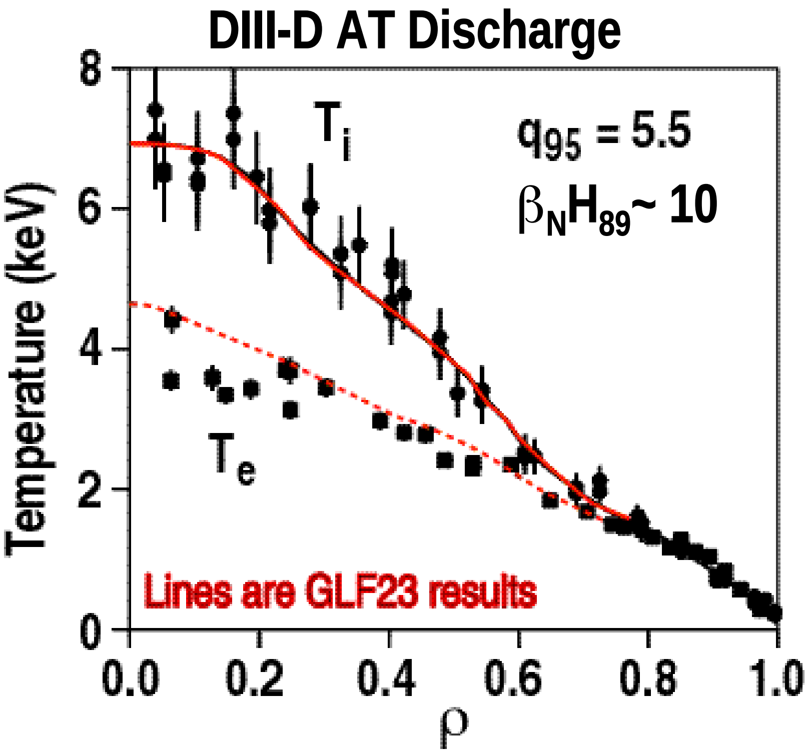


DRIFT-WAVE BASED TRANSPORT MODELS LIKE GLF23 ARE APPROACHING A PREDICTIVE CAPABILITY FOR CORE TEMPERATURE PROFILES

- Transport fluxes due to drift wave turbulence are computed using quasi-linear theory and a saturation rule
- Linear ITG, TEM, ETG modes are computed using the gyro-Landau fluid approximation
- The quench rule is used to include the effect of ExB flow shear



Murakami, IAEA 2000



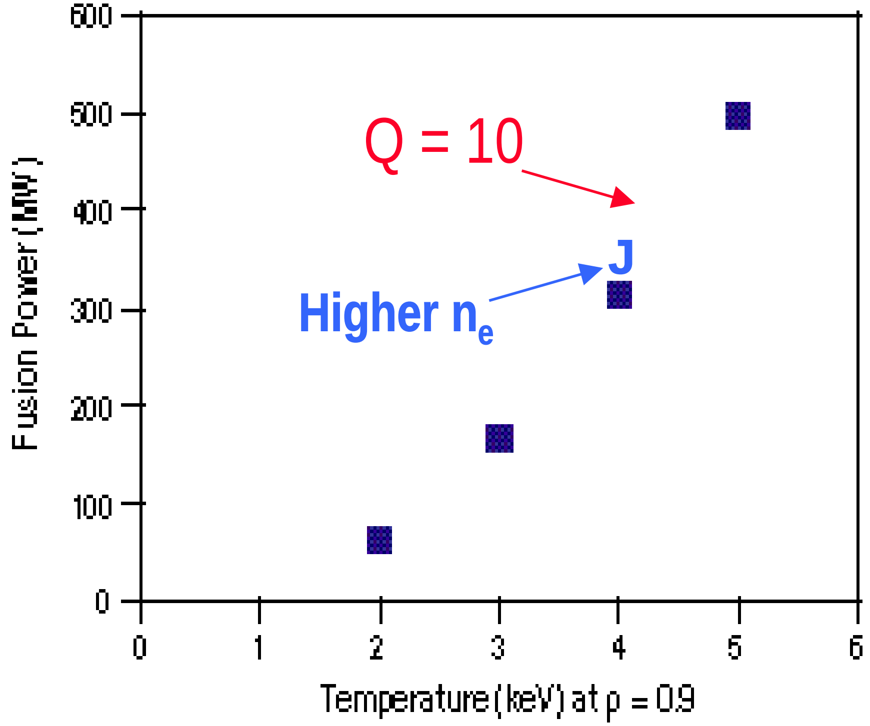
Luce, IAEA 2000

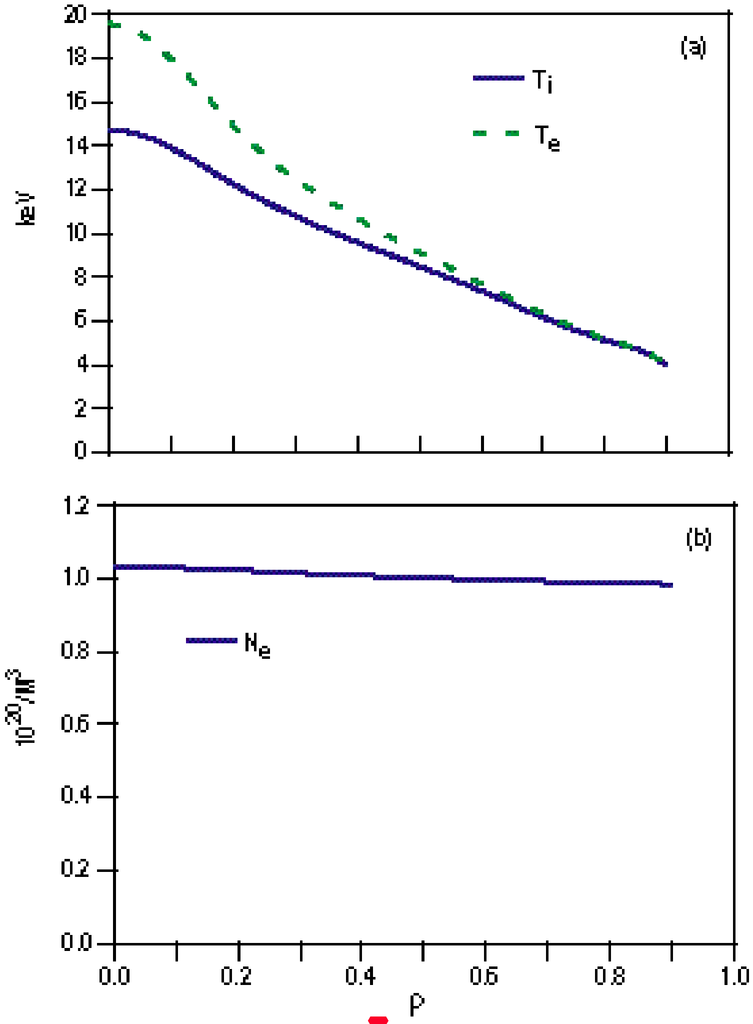
GENERAL ATOMICS

GLF23 SIMULATIONS INDICATE THAT A PEDESTAL TEMPERATURE OF 4.5 keV IS REQUIRED TO REACH Q = 10

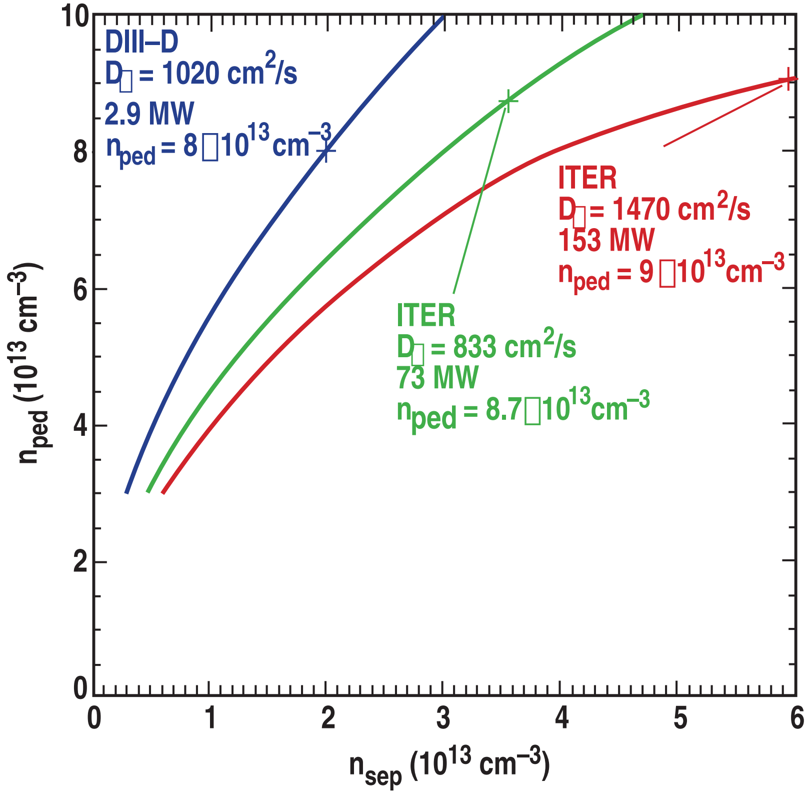
- **Predicted pedestal temperature requirement of 4.5 keV is higher than the 3.5 keV estimated for the original ITER**
- **A too peaked n_e profile lowers performance, destabilization of TEM**
- **Higher n_{PED} may reduce required T_{PED}**

GLF23 Predicted Performance of ITER-FEAT





ITER-FEAT CAN OPERATE ABOVE GREENWALD IN H–MODE



Experiment shows H_{89P} □ 2 is compatible with $\bar{n}_e$ □n_{GW} ∫ $10^{14} \frac{I_p}{\square a^2}$ m^{-3}

Divertor power balance limit requires $n_{sep}^{(MAX)}$ µ $P_{\square}^{5/7}$

Experiment and theory show with gas fueling

n_{PED} µ $n_{SEP}^{1/2}$

– n_{PED} □ 0.75 n_{GW} possible in ITER-FEAT

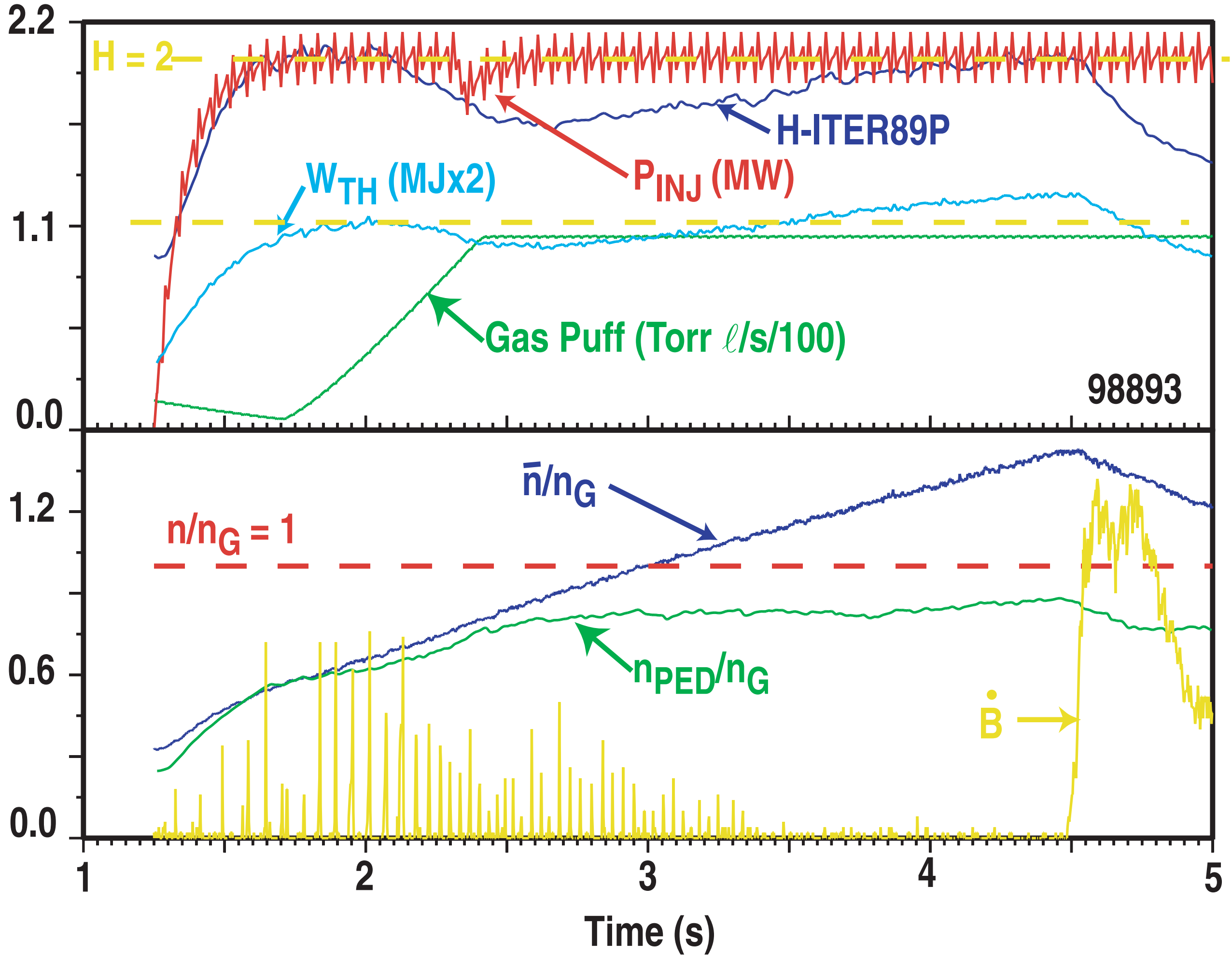
Modest peaking allows $\bar{n}_e$ □n_{GW}

GREENWALD LIMIT IS EXCEEDED IN HIGH CONFINEMENT H–MODE

During density rise, stored energy increases monotonically after an initial dip, eventually exceeding its peak value at low density

Density rises monotonically during gas fueling, with no evidence of sturation

High confinement phase is terminated after the onset of 3/2 MHD mode

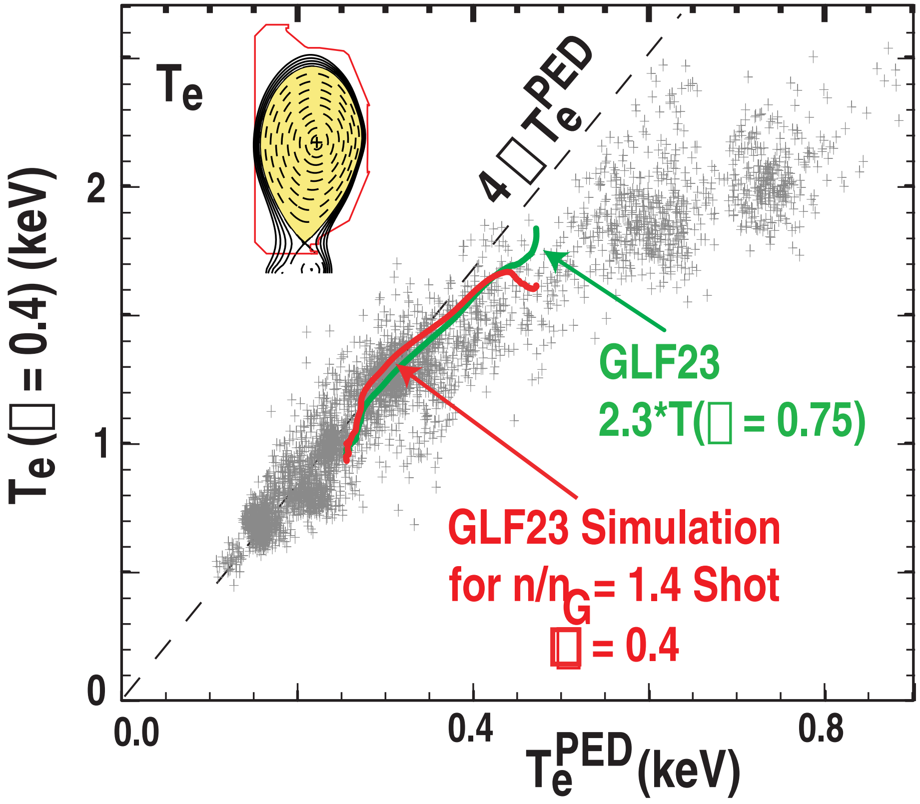


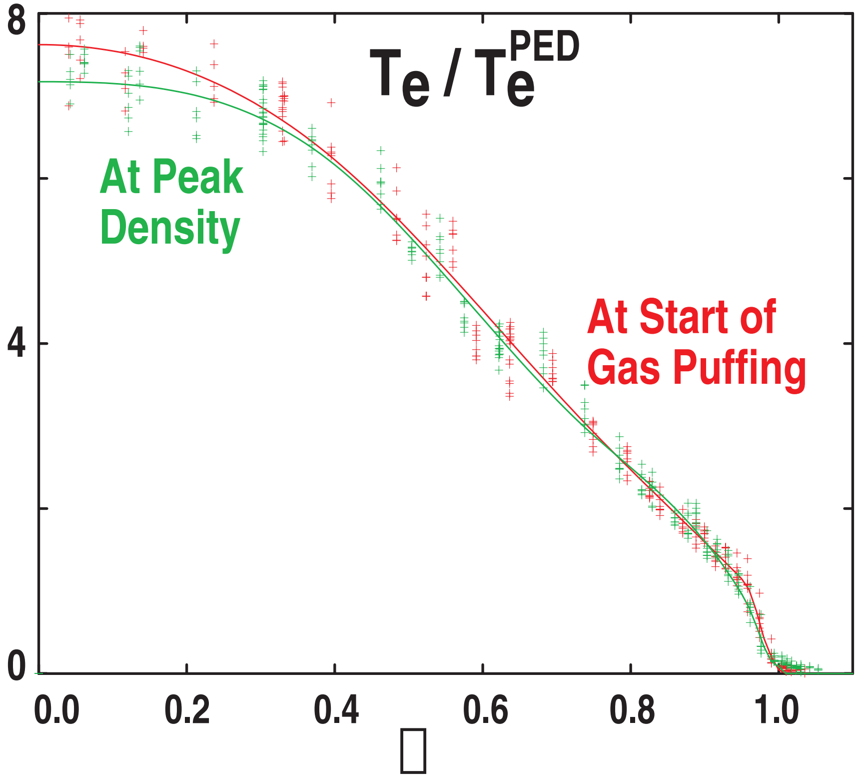
DIII–D
NATIONAL FUSION FACILITY
SAN DIEGO

Mahdavi IAEA 2000 GENERAL ATOMICS

STORED ENERGY IS PROPORTIONAL TO THE PEDESTAL PRESSURE AND INSENSITIVE TO DENSITY

$$T(\square) = T^{PED}\,\square(\square)\ \square\quad W_{Total}\,\square\ p^{PED}\, g(n^0/n^{PED})$$





GKS indicates ITG is fastest growing mode

□ GLF23 transport simulation gives stiff T profile in agreement with experiment

DIII–D
NATIONAL FUSION FACILITY
SAN DIEGO

CAN A RADIATIVE CORE SIGNIFICANTLY REDUCE EXCESS POWER FLOW TO THE ITER-FEAT AT DIVERTOR ?

Consider ARGON, KRYPTON, and XENON as “seed” candidates

- Assume $n_{He}/n_e = 0.04$ and $n_{Be}/n_e = 0.02$
- Maintain $Z_{eff} \leq 2$
- Reliance only on core radiation

R/a	(m)/(m)	6.6/1.6
B_T	(T)	4.98
I_p	(MA)	7.8
$<n_e>$	(10^{20} m^{-3})	0.78
β_N		3.17
$P_\alpha + P_{aux}$	(MW)	121
$Q = P_{fus}/P_{aux}$		5,2
Z_{eff}		1.66
I_{CD}/I_p	(%)	46.4
I_{bs}/I_p	(%)	53.6
q95		4.1
$H_{H(98y,2)}$		1.49

$$P_{R,core} = \int n_e n_{imp}\, f_{rad}(T_e)\, dV$$

$$q_{\parallel}^{P} \approx \frac{(P_{IN} - P_{R,core}) \times f_{out/T} \times (1 - f_{PFR}) \times \sin\theta}{2\pi\, R_{osp} \times \lambda \times f_{exp}}$$

Where

$P_{IN} = 121$ MW

$f_{out/T} \approx 0.6$

$f_{PFR} \approx 0.1$

$\theta = 30°$

$R_{osp} \approx 5.5$ m

$\lambda \approx 1.3$ cm

$f_{exp} \approx 5$

GENERAL ATOMICS

IMPURITY RADIATION FROM THE MAIN PLASMA WOULD NOT BY ITSELF BE SUFFICIENT TO REDUCE PEAK HEAT FLUX TO □ 5 MW/m^2 UNDER ATTACHED DIVERTOR CONDITIONS

For the low density ITER-FEAT AT, core impurity radiation by itself would not be adequate to reduce q $^{p}_{\square}$ 5 MW/m^2

- Kr best, but still $q^{p}_{\square}$ □ 10 MW/m^2
- "Radiating mantle" is more effective at higher densities (e.g., ARIES-AT)

Modeling based on a device similar to ITER-FEAT* suggests that a detached solution for the 120 MW example may be possible in producing required lower heat flux

- Divertor connection length in ITER-FEAT AT greater than modeled case □ Additional cooling expected between X–point and divertor

Critical issue: Is detachment consistent with an AT "high performance" edge plasma?

* A. Kukushkin, as shown in Technical Basis for ITER-FEAT Outline Design, (G A) R1 2 00-01018 R1-0), Chapter 1 , Section 2.

GENERAL ATOMICS

CHANGES IN THE UPPER TRIANGULARITY OF ITER FEAT-AT PLASMAS AFFECT HEAT LOADING AT NON-DIVERTOR LOCATIONS

Good economics for future tokamak designs depend on sufficiently high $\square_E$ and $\square_T$ □ increase plasma triangularity ($\square_T$)

One cost of raising $\square_T$ in an ITER FEAT AT device: Higher heat loading at a non-divertor location

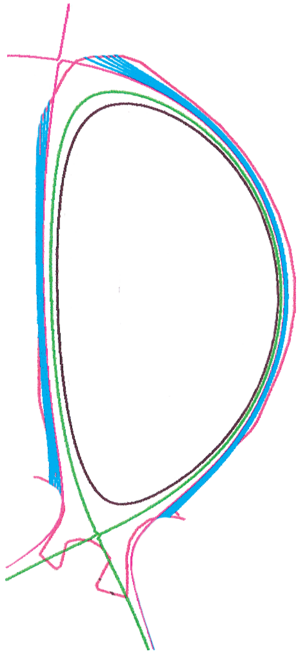
Estimate heat loading near the upper inboard corner for an ITER FEAT AT plasma at maximum $\square_T$ but preserving LSN shape

GENERAL ATOMICS

PRELIMINARY RESULTS SUGGEST THAT CAUTION IS NEEDED WHEN EXTENDING ITER FEAT-AT PLASMA PERFORMANCE BY INCREASING UPPER TRIANGULARITY

Nominal Case

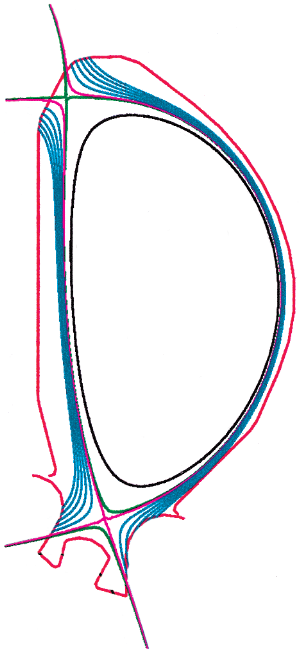
$\square_{UP,95} = 0.34$
dRsep □ 4 cm
frad □ 0.2
f_{PFR} □ 0.1
□ □ 45°
R □ 4.6 m
□□ 1.3 cm
f_{exp} □ 13



$q_{\square}^{p}$ 0.2 MW/m^2
$P_{div,up}$ 5 MW

Highest Triangularity

$\square_{UP,95} = 0.46$
dRsep □ 0 cm
frad □ 0.2
$f_{PFR} = 0.1$
□ □ 65°
R □ 4.45 m
□□ 1.3 cm
f_{exp} □ 12



$q_{\square}^{p}$ □ 6 MW/m^2
$P_{div,up}$ □ 50 MW

GENERAL ATOMICS

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SUMMARY

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- Ideally stable to high, intermediate, and low *n* modes without a conducting wall
- Transport simulations using the GLF23 model indicate that a pedestal temperature of 4.5 keV is required to reach Q = 10
- Pedestal density can exceed the Greenwald limit by 30% while still remain compatible with good confinement and safe heat exhaust with a density peaking factor similar to that of a typical DIII-D ELMing H-mode discharge

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- Impurity seeding is ineffective to raise the core radiated power due to lower density
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CONTROL AND DESIGN ISSUES

- Stabilization of resistive wall modes for AT design
  - Feedback control using external coils, magnetic sensors
    - A major element of DIII-D AT program
  - Error fields, NTM
  - Rotational source ?
- Scaling of edge pedestal width and height
  - Improved understanding of edge stability
  - Trade off between confinement and heat flux requirements
- Acceptable divertor heat flux
  - Consistency of detached or partially detached divertor with AT edge
    - Current drive, bootstrap current
  - Increase of localized heat loading with higher upper triangularity
  - Improved understanding of ELM physics