Physics in ARIES Tokamak Power Plant Design

C. E. Kessel, for the ARIES Physics Team

Princeton Plasma Physics Laboratory

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ARIES Has Examined Several Physics Configurations

ARIES-I (q_o=1.3, dq/dr > 0)
- $\beta_N \le 3$, I_{NI}/I_P = 100%, β = 2%, B_T = 9 T, $P_{CD} \ge$ 200 MW

PULSAR ($q_o \approx$1, dq/dr > 0)
- $\beta_N \le 3$, $I_{NI}/I_P \le$ 35%, β = 2.8%, B_T = 7 T, P_{CD} = 0 MW

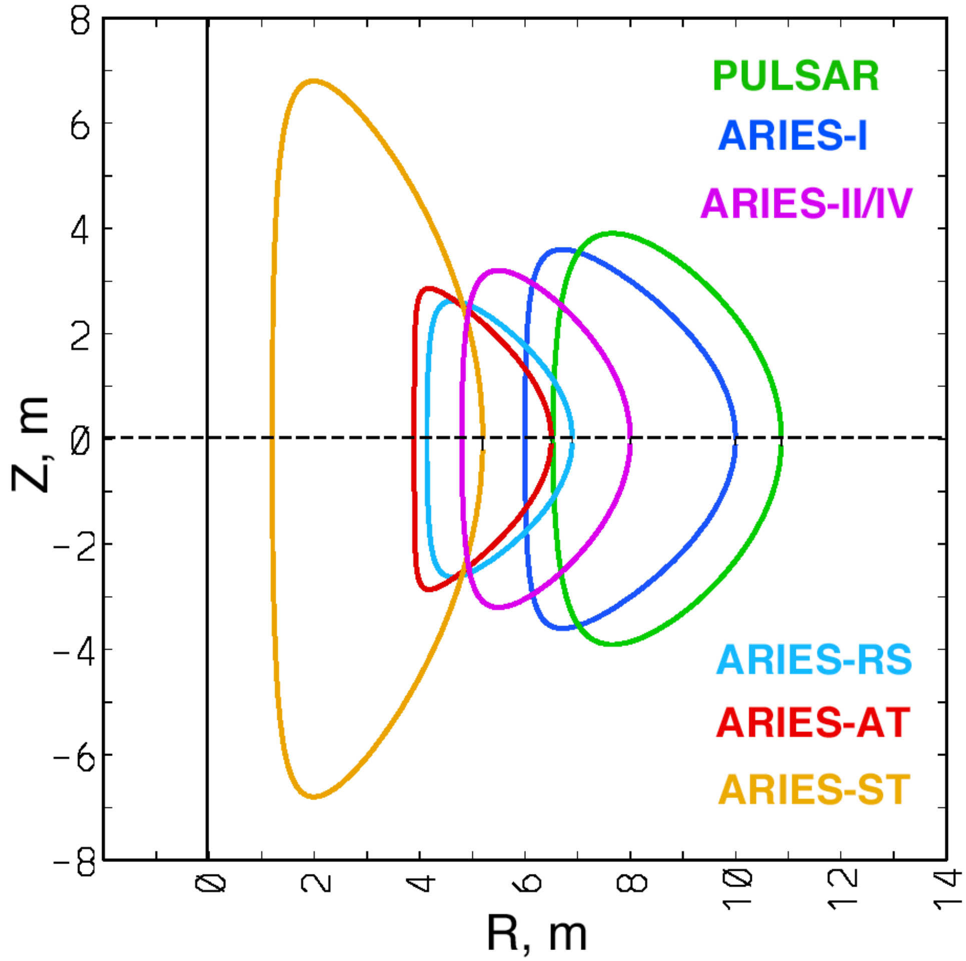
ARIES-II/IV (q_o=2, dq/dr > 0)
- $\beta_N \approx 5.9$, $I_{NI}/I_P \ge$ 100%, β = 3.4%, B_T = 7.85 T, $P_{CD} \le$ 200 MW

ARIES-RS (q_o=2.5, dq/dr < 0)
- $\beta_N \approx 5.4$, I_{NI}/I_P = 100%, β = 5.1%, B_T = 8 T, $P_{CD} \le$ 100 MW

ARIES-AT (q_o=3.5, dq/dr < 0)
- $\beta_N \approx 6.0$, I_{NI}/I_p = 100%, β = 10.5%, B_T = 5.6 T, $P_{CD} \ge$ 40 MW

ARIES-ST (A = 1.6)
- $\beta_N \approx 8.3$, I_{NI}/I_P = 100%, β = 60%, B_T = 2.14 T, P_{CD} = 31 MW

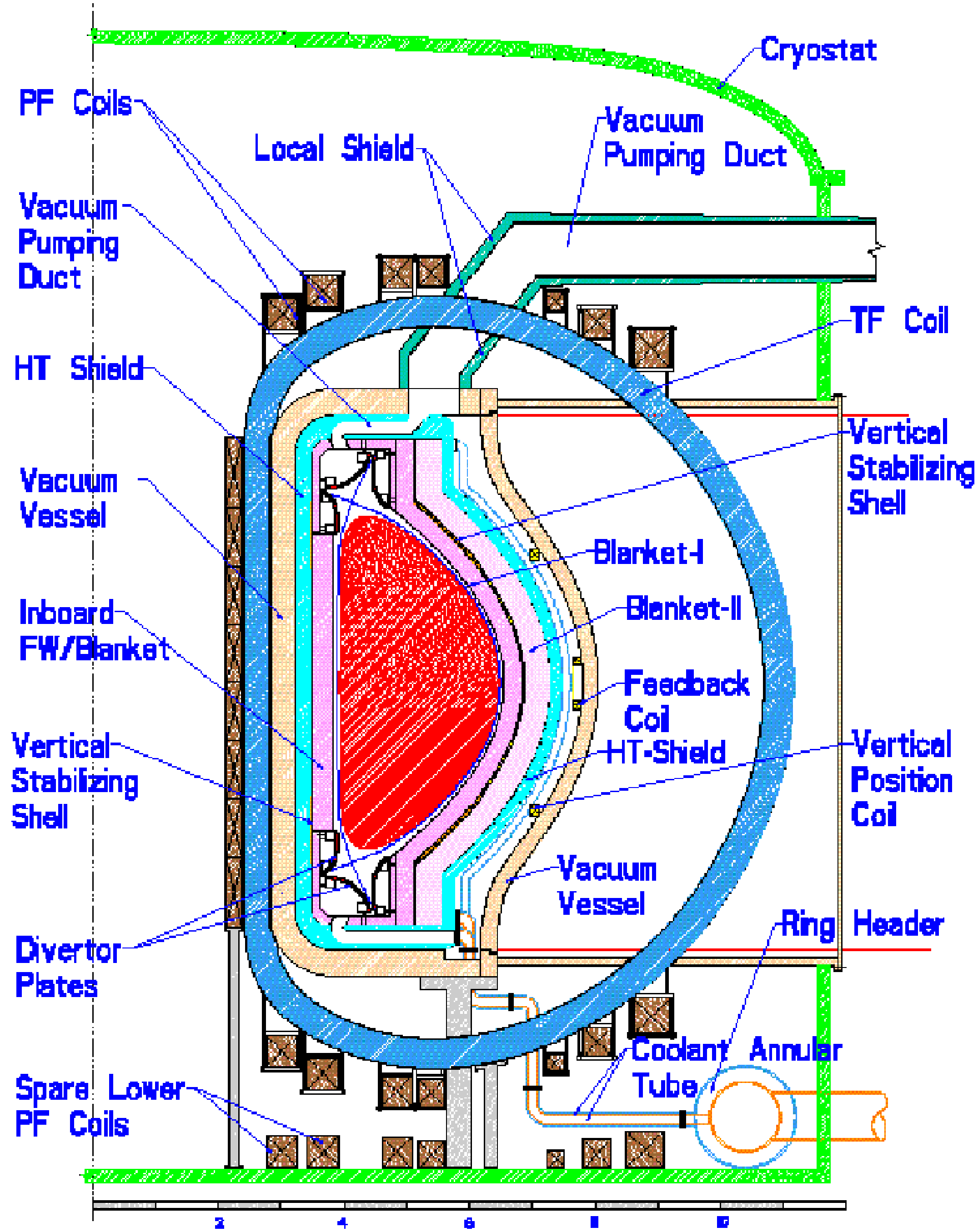
Plasma Boundaries



$P_{electric}$ = 1000 MW

ARIES-AT

$Ip = 12.8$ MA
$B_T = 5.86$ T
$R = 5.2$ m
$a = 1.3$ m
$\kappa_X = 2.2$
$\delta_X = 0.9$
$\beta_p = 2.28$
$\beta = 9.1\%$
$\beta_N = 5.4$ ($\beta_N^{max} = 6.0$)
$q_{axis} = 3.5$
$q_{min} = 2.4$
$q_{edge} \leq 4$
$f_{bs} = 0.89$
$li(3) = 0.3$
$p_o/\langle p \rangle = 1.9$



ARIES Power Plant Studies Utilize a Basic Sequence for Tokamak Design (Iteration)

detailed physics analysis

- MHD stability
- Vertical stability
- NB/RF heating & CD
- Divertor and SOL power
- Plasma equilibrium & PF coil optimization
- ....

detailed engineering analysis

- Neutronics
- Magnet design
- FW/blanket/shield thermal design
- Materials
- Divertor design
- ....

systems analysis

- Plasma power & particle balance
- Thermal cycle
- 2D device layout
- Costing
- ....Parametrics

Configuration optimization

Machine geometric layout

Balance of plant requirements

Machine costing and cost of electricity

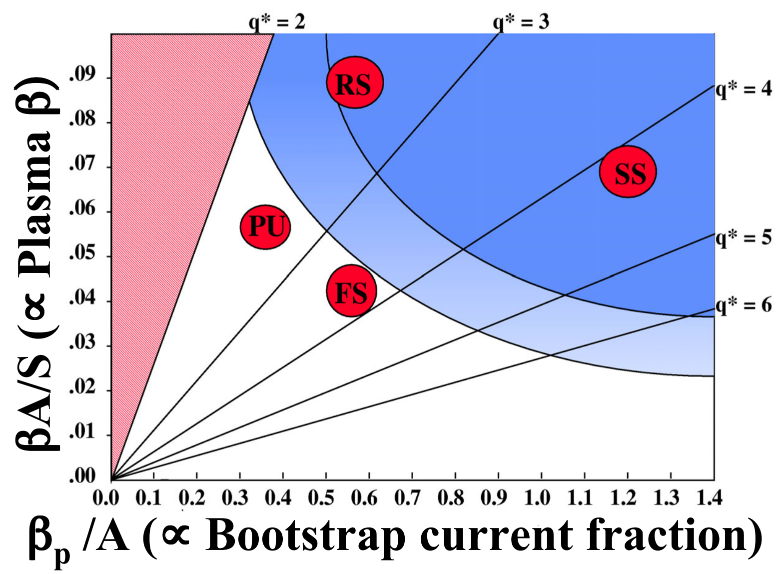
Specific Plasma Configuration Determines the Trade-Offs in Physics Design

Talk Outline

Equilibria
Ideal MHD Stability
Neoclassical Tearing Modes
Heating & Current Drive
Plasma Rotation
Vertical Stability and Control
PF Coil Optimization
Plasma Transport Comparison
Plasma Edge/SOL/Divertor
Fueling
Ripple Losses
Other Physics Issues & Analysis

Increase $P_{fus}/V_p \propto \beta^2 B^4$

Decrease $P_{recirc} \approx P_{CD} \approx (1-f_{BS}) I_P / \zeta_{CD}$



Develop as comprehensive a physics description as possible

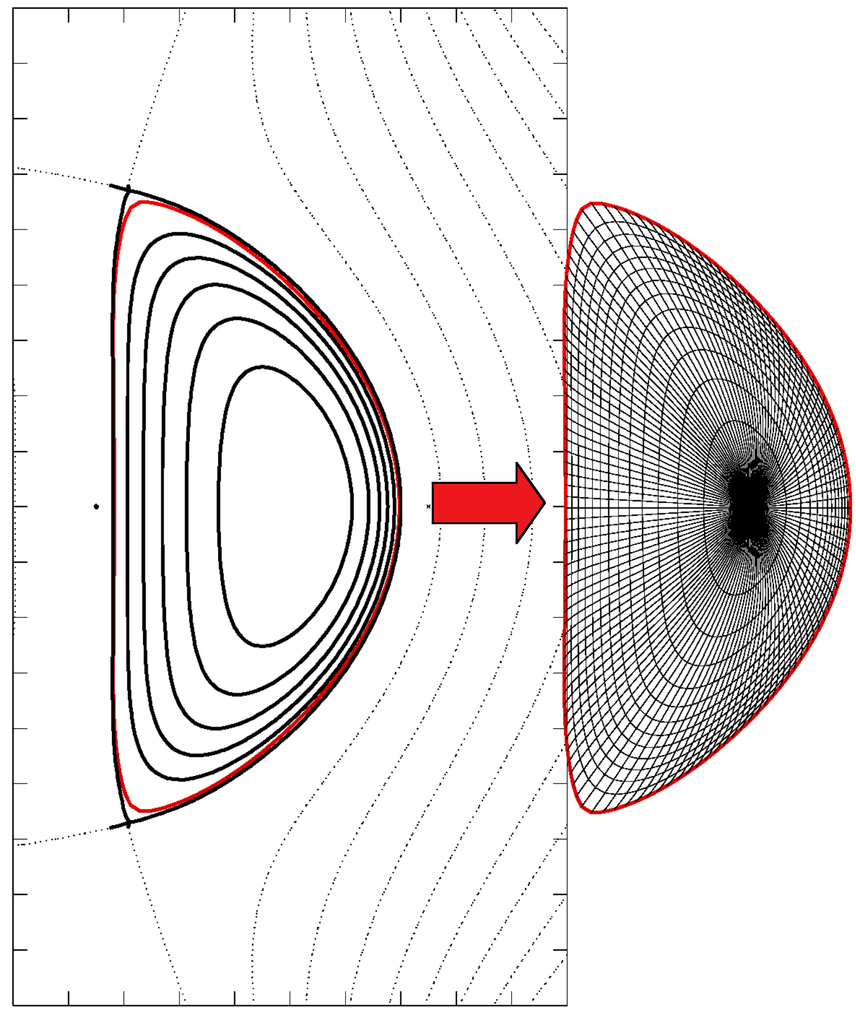
Identify high leverage physics for improving fusion viability and competitiveness

High Accuracy Equilibria are Essential to Assess Stability

JSOLVER fixed boundary flux coordinate equilibria

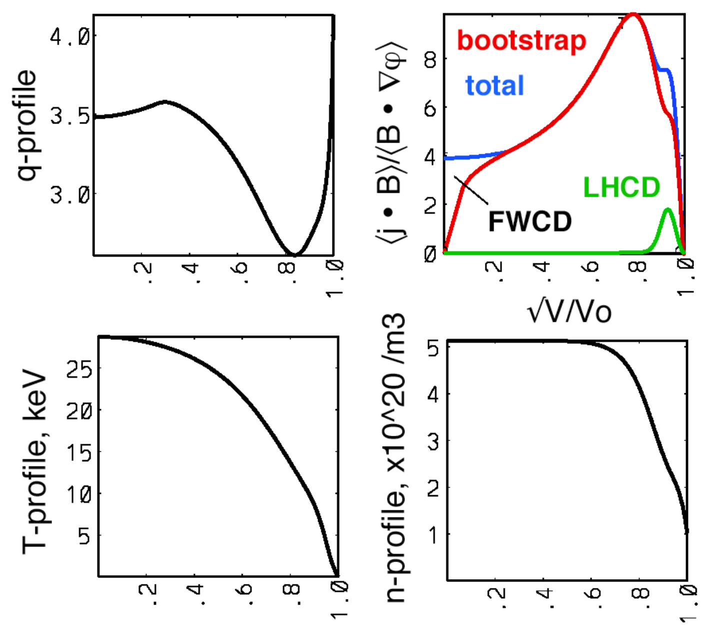
- **High resolution (257ψ × 257θ)**
- **p(ψ) and ⟨ j•B ⟩ are input**
- **Includes bootstrap current, multiple CD sources, and loop voltage self-consistently**
- **Plasma boundary determined from free-boundary equilibria with same profiles, at ≈ 99.5% flux surface**
- **Iterate between RF,NB analysis and equilibria**

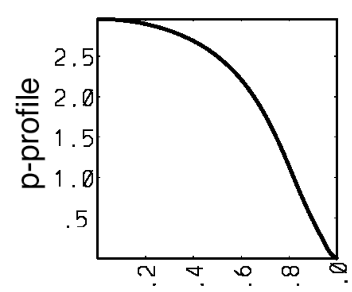
Free-boundary R×Z **Fixed-boundary ψ×θ**



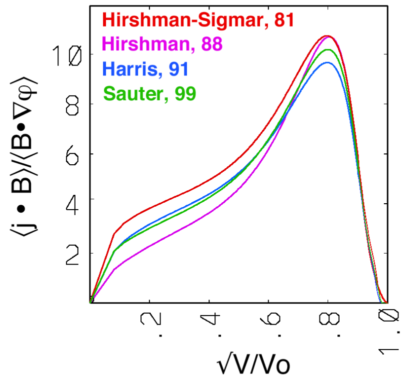
Equilbria Are Produced to Provide Input to RF, Stability and Systems Studies

ARIES-AT H-mode edge

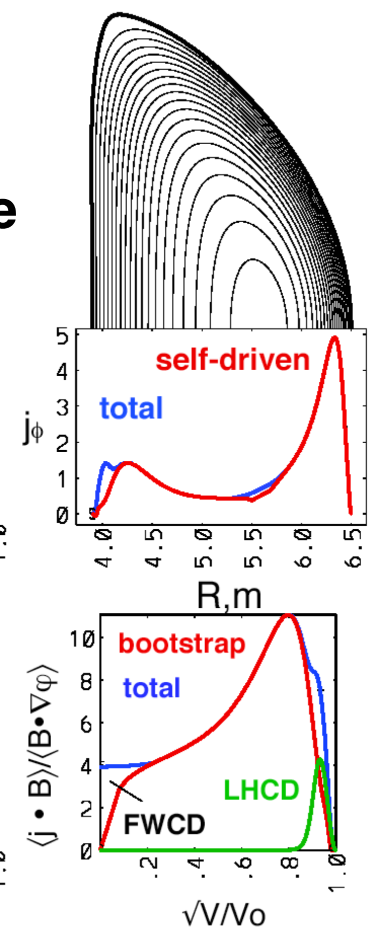




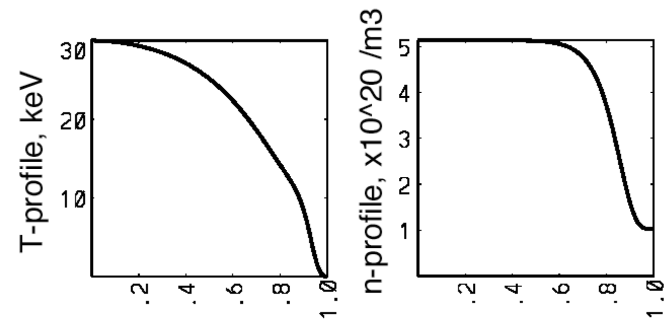
Stonger H-mode parameters can worsen kink stability

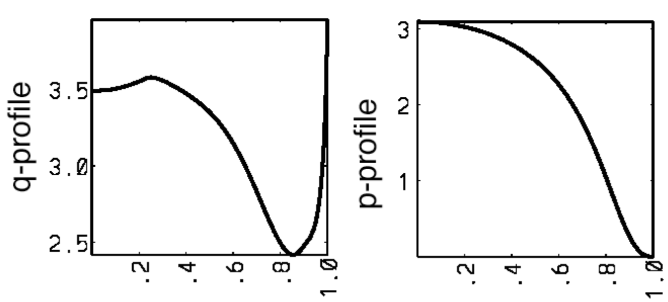


Accurate bootstrap models are critical when f_{BS} is high



ARIES-AT L-mode edge





Extensive Ideal MHD Stability Analysis

Low-n kink and high-n ballooning stability

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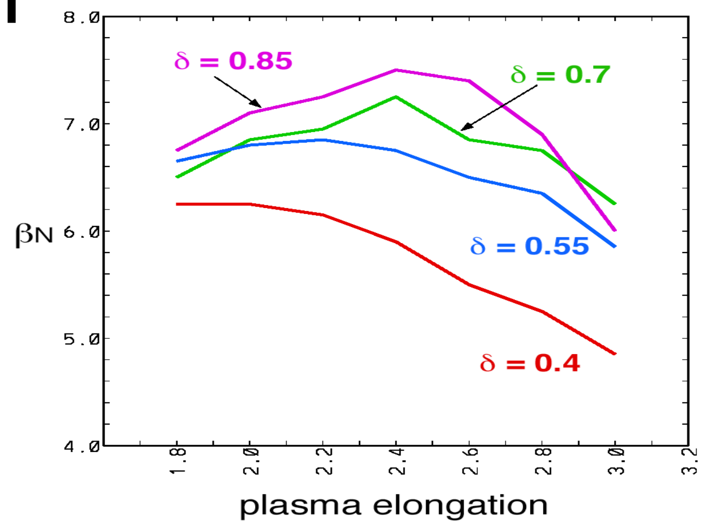
PEST2 for 1 ≤ n ≤ 9
BALMSC for n = ∞
ELITE for 10 ≤ n ≤ 30 (ELMs)
MARS for n=1, 2 rotation

Examine the impact of plasma shape, aspect ratio, and j-profiles and p-profiles

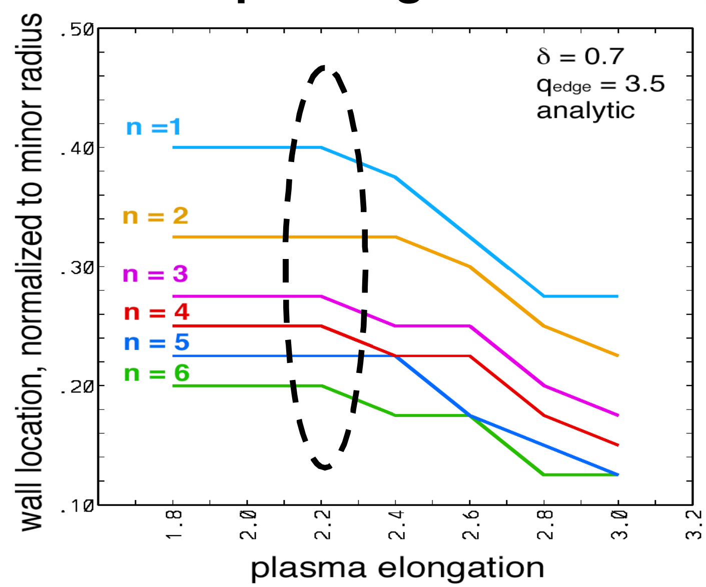
Determine maximum $\beta_N(n=\infty)$

Determine conducting wall location for low-n stabilization (with rotation or feedback)

Maximum ballooning β_N

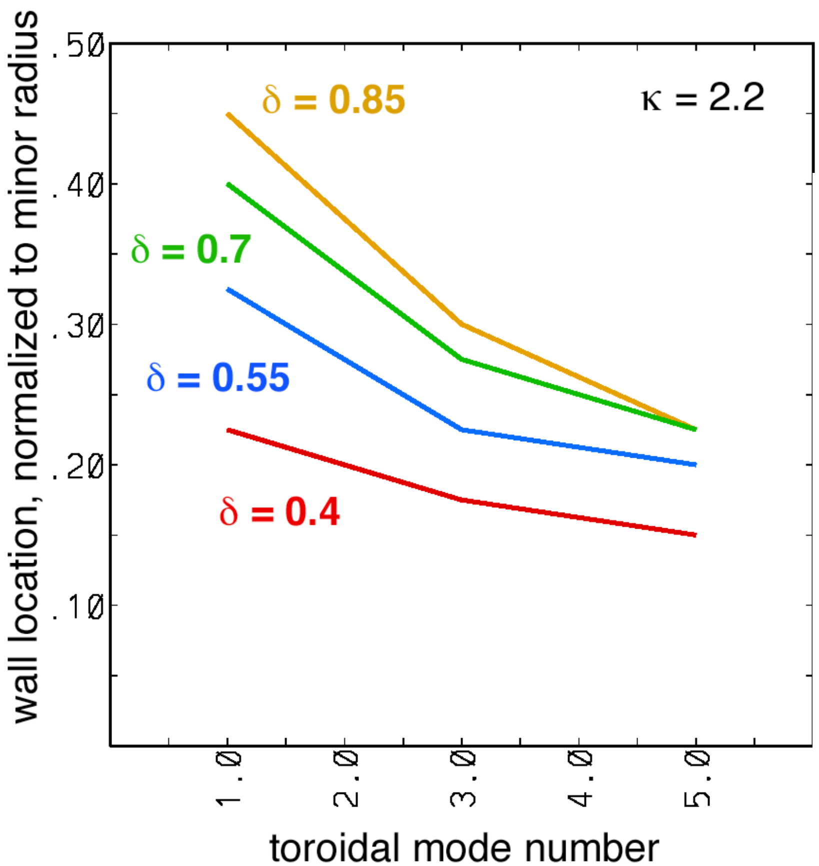


Corresponding kink stability

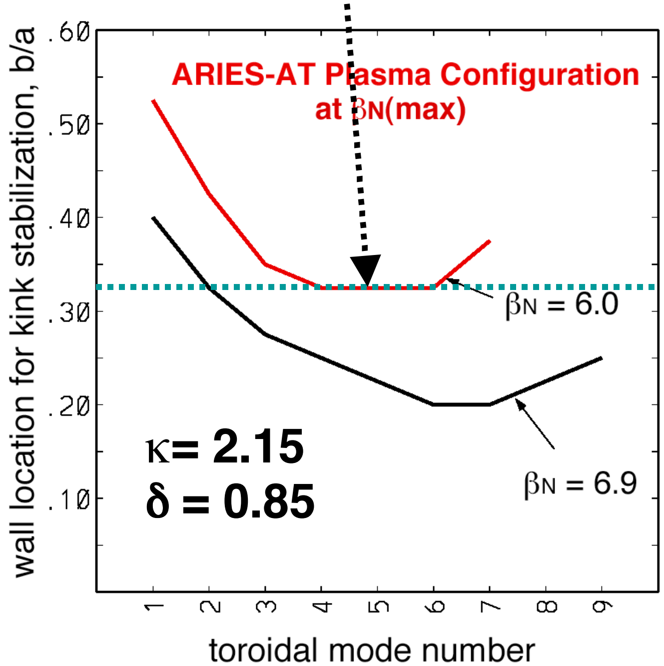


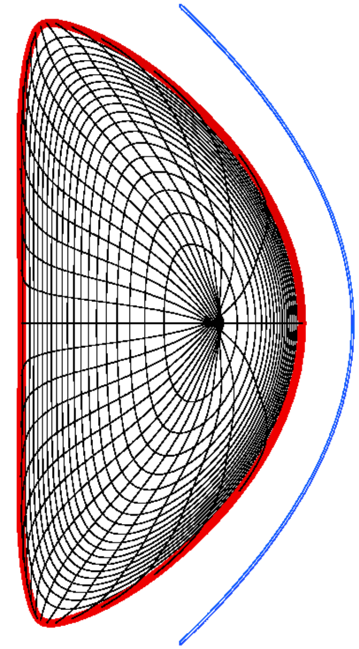
Plasma Elongation and Triangularity Strongly Influence Achievable β

Kink stability at corresponding maximum ballooning β_N, with varying triangularity



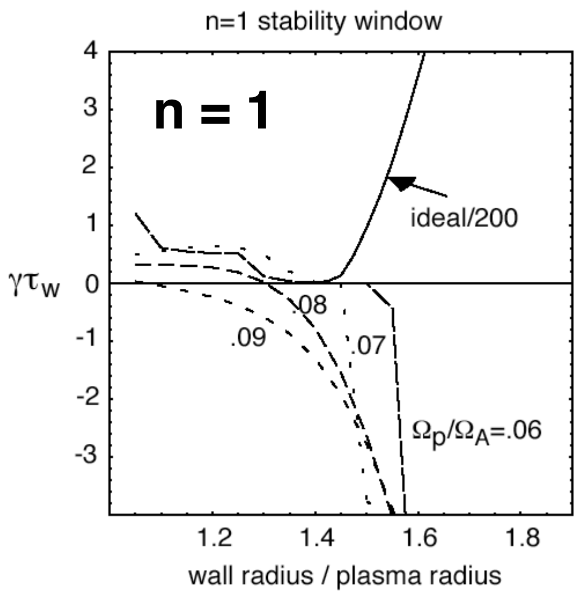
Similar wall location for kink modes and vertical stability

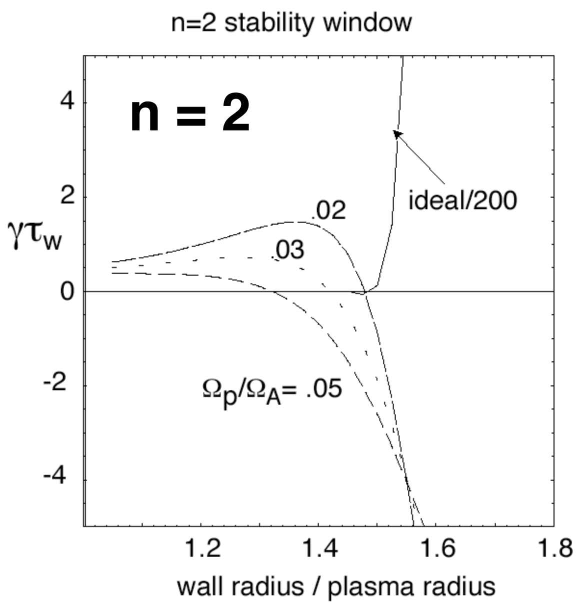




PEST2

MARS Analysis Indicates $V_\phi \leq 0.09 V_{Alfven}$, So ARIES-AT Relies on RWM Feedback





Using DIII-D C-coil as basis for RWM feedback coils

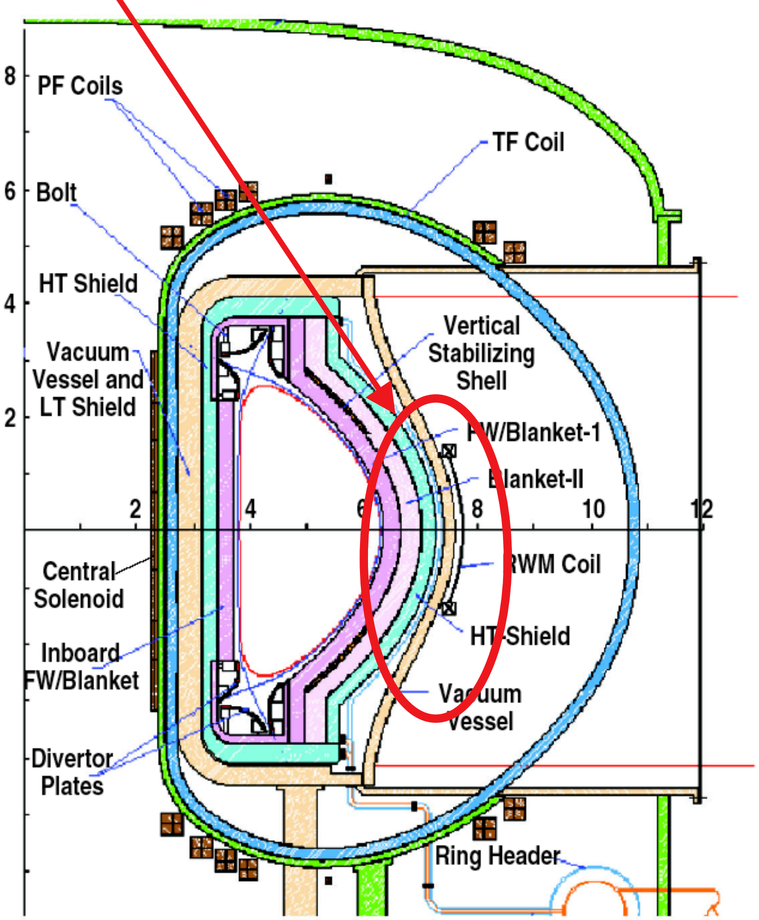
8 or 16 coils

50 kA-turns

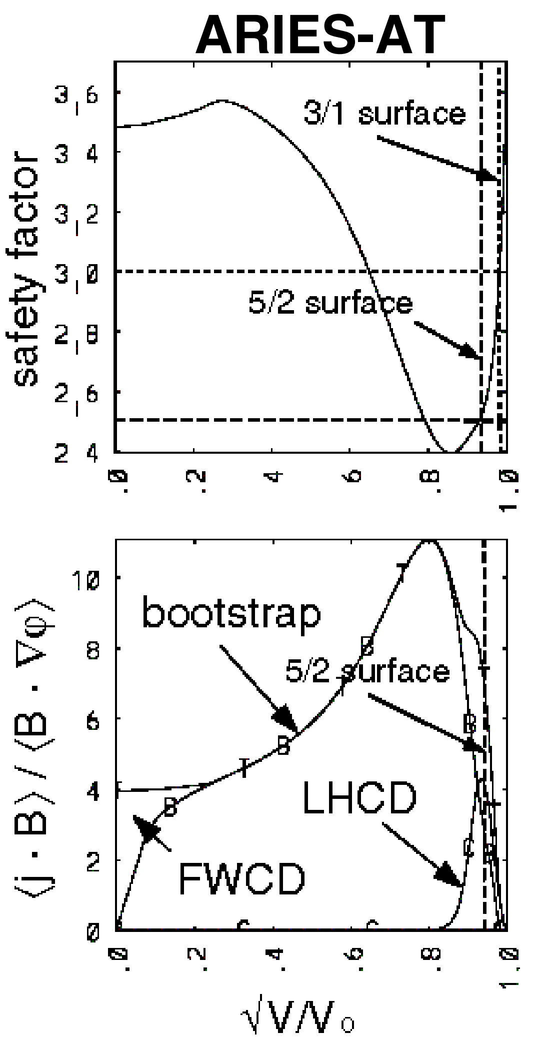
$\omega\tau_{wall} = 3$

$P_{total} \approx 10$ **MW**

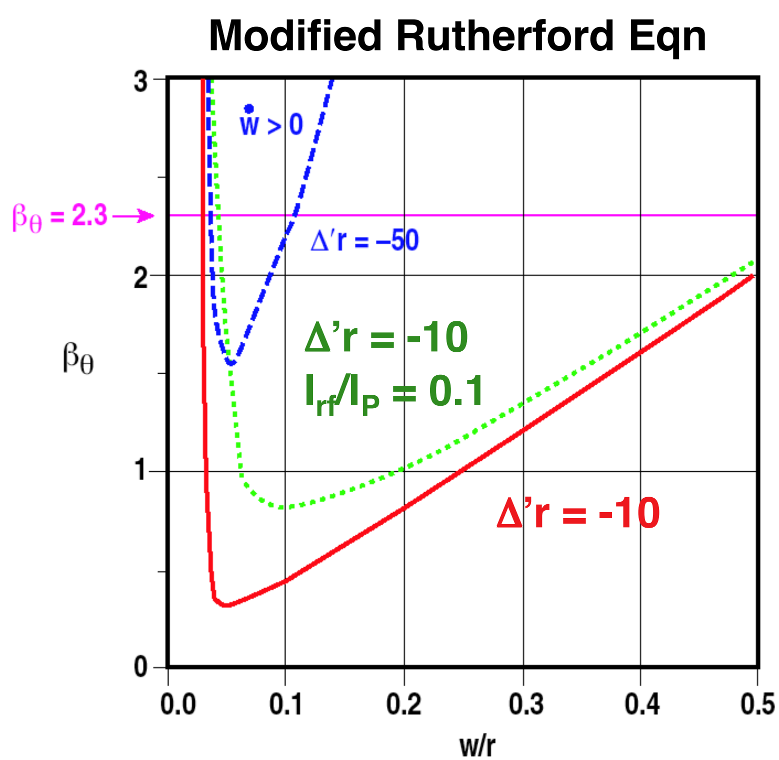
Only n=1 considered

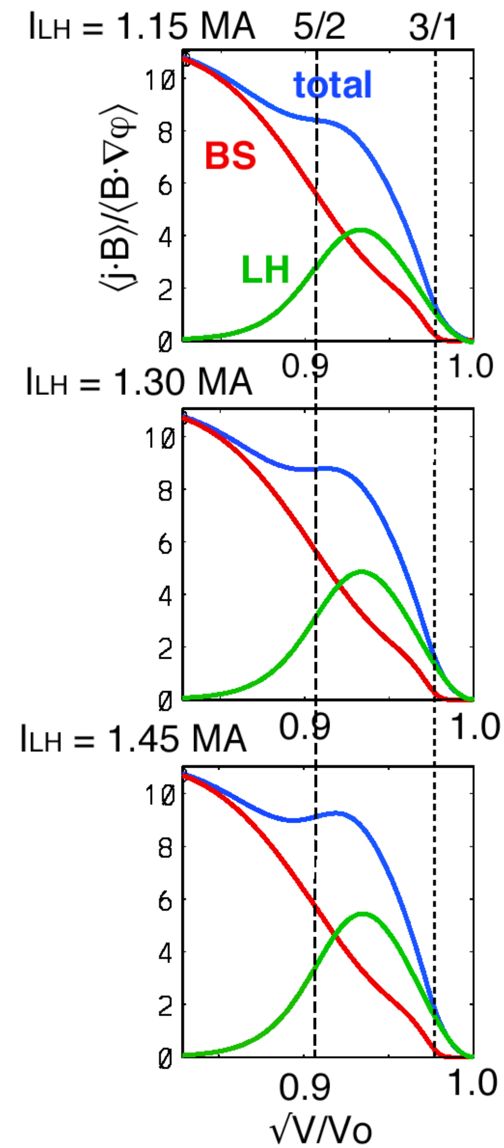


Neoclassical Tearing Modes Must be Stabilized to Access Ideal MHD Limits



ECCD current and power is excessive to stabilize 5/2, so that **LHCD profile modification may be more effective,** still needs to be seen if LH can make Δ'r ≈ -50

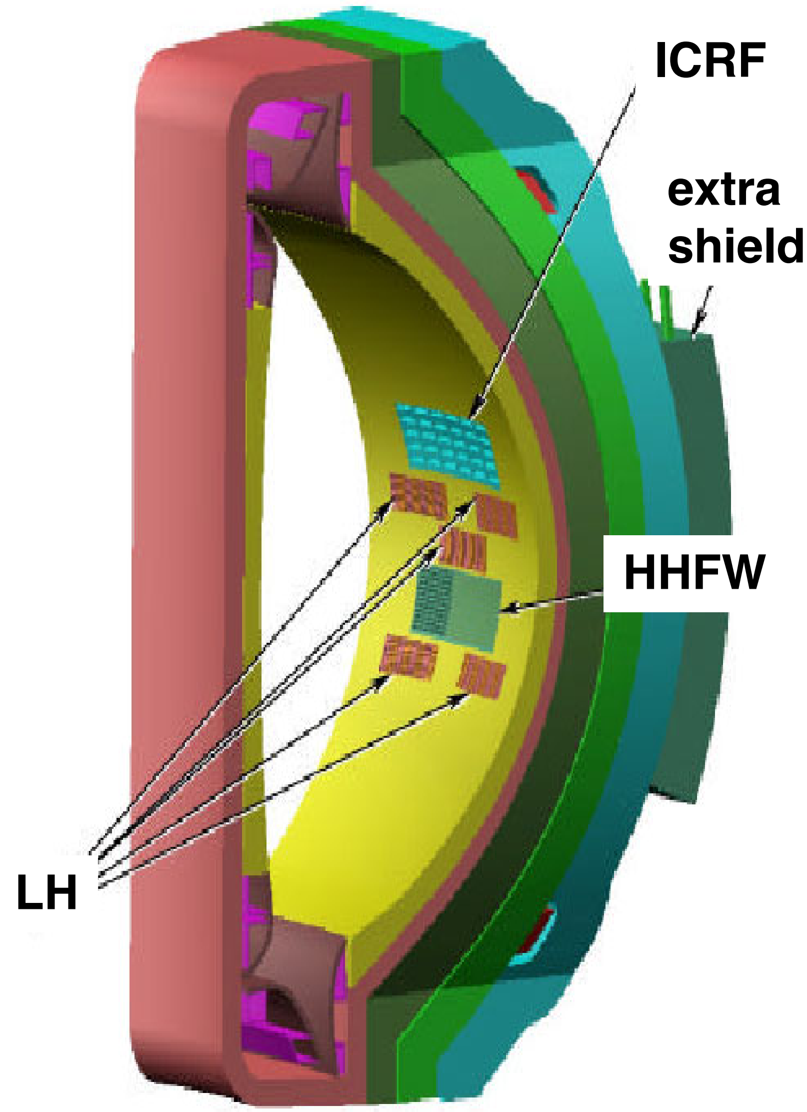




Heating and Current Drive Analysis

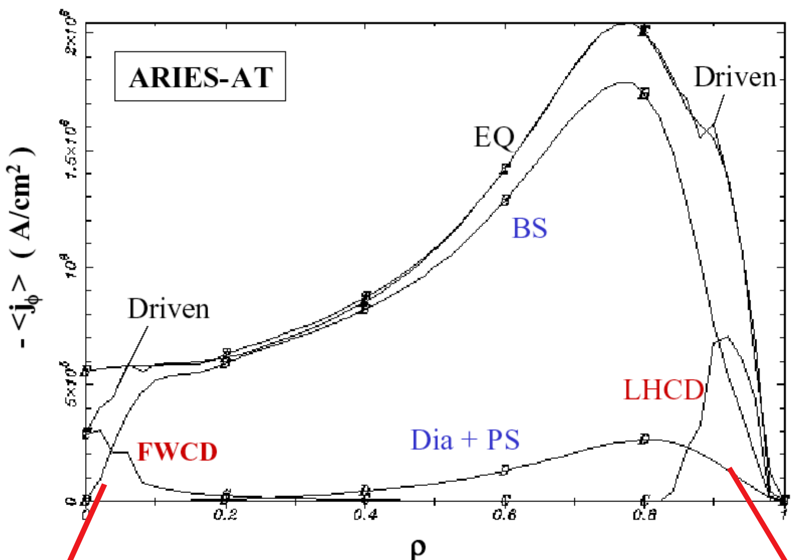
Determine viable CD schemes and determine CD power requirement

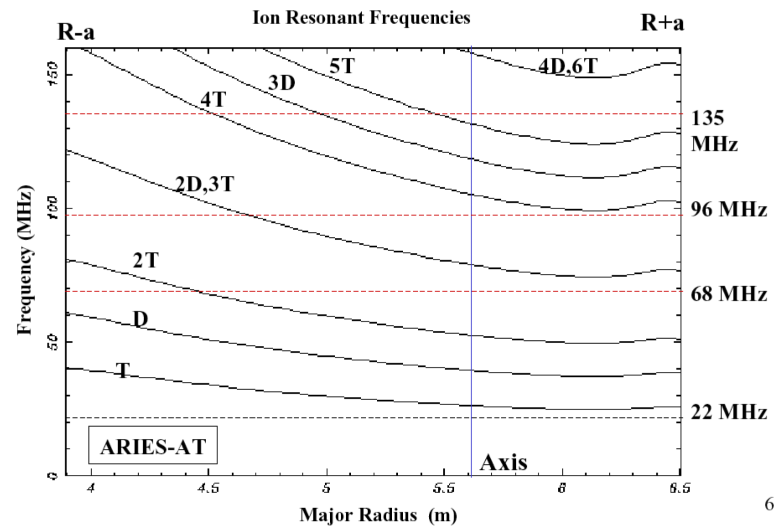
- **CURRAY ray-tracing for ICRF, LHCD, and HHFW**
- **NFREYA for NB**
- **Establish CD source and launcher requirements (ω, $n_{||}$, $\Delta n_{||}$, θ_{RF}, E_{beam}, R_{tan}, θ_{beam})**
- **Examine effects of T_e, Z_{eff}, L or H-mode edge**
- **CD power contributes to recirculating power, so minimized while maintaining some CD for j control**

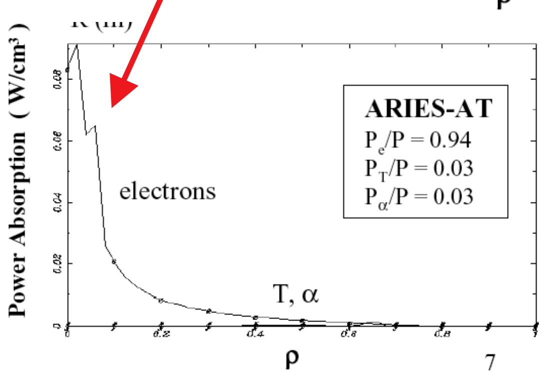


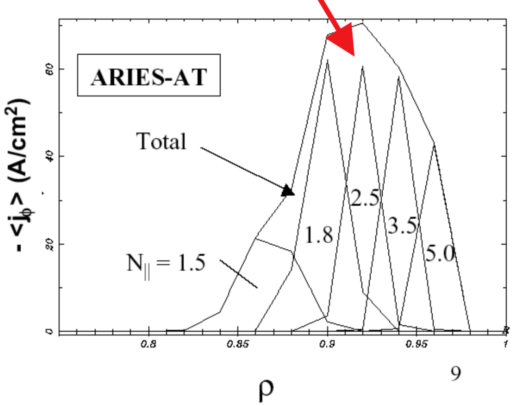
ARIES-AT Utilizes ICRF/FW and LHCD

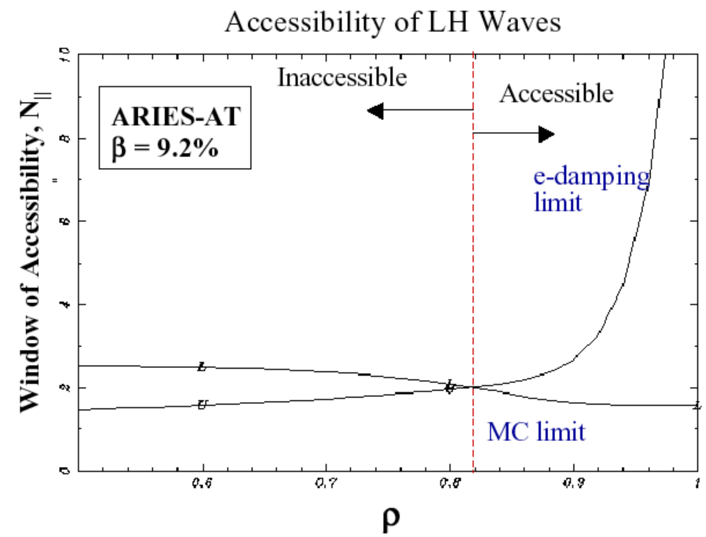
ICRF/FW, P_{FW} = 5 MW, 68 MHz, $n_{||}$ = 2
LHCD, P_{LH} = 37 MW, 3.6 & 2.5 GHz, $n_{||}$ = 1.65-5.0









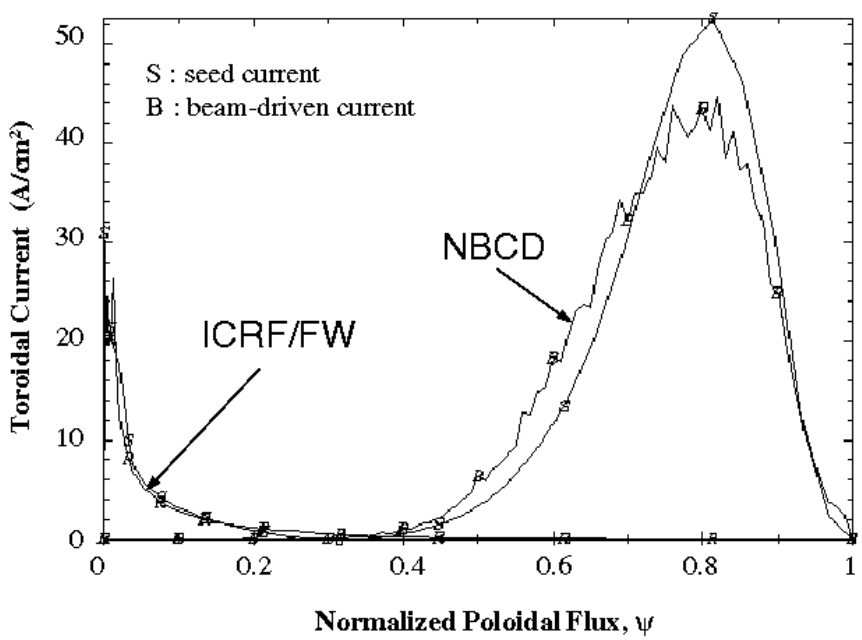


Alternate CD Sources are Examined for Current Profile Control and Rotation

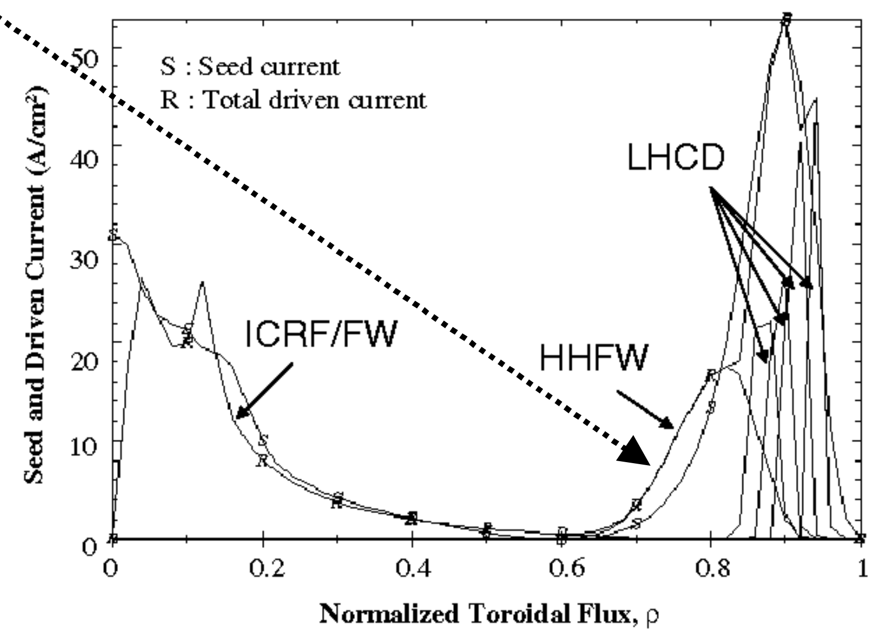
120 keV NBI provides plasma rotation and CD for ρ > 0.6, P_{NB} = 44 MW, P_{FW} = 5 MW (NFREYA)

HHFW at 20ω_{ci} provides current at ρ > 0.7 - 0.9, P_{LH} = 20 MW, P_{HHFW} = 20 MW, P_{FW} = 5 MW

ARIES-AT

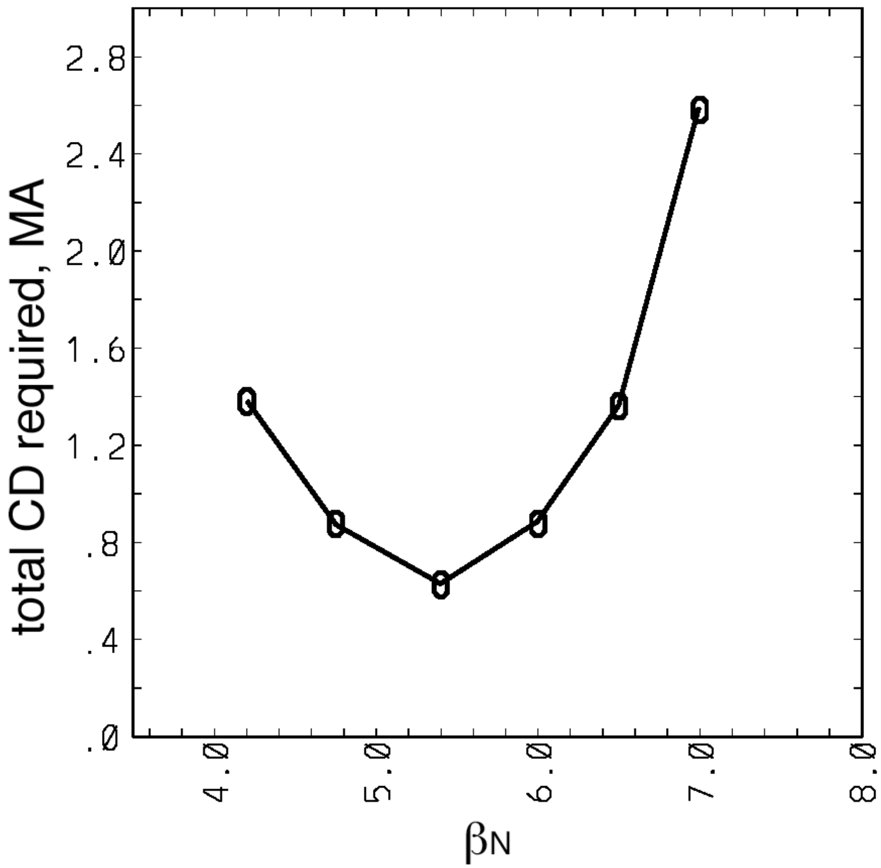


ARIES-AT

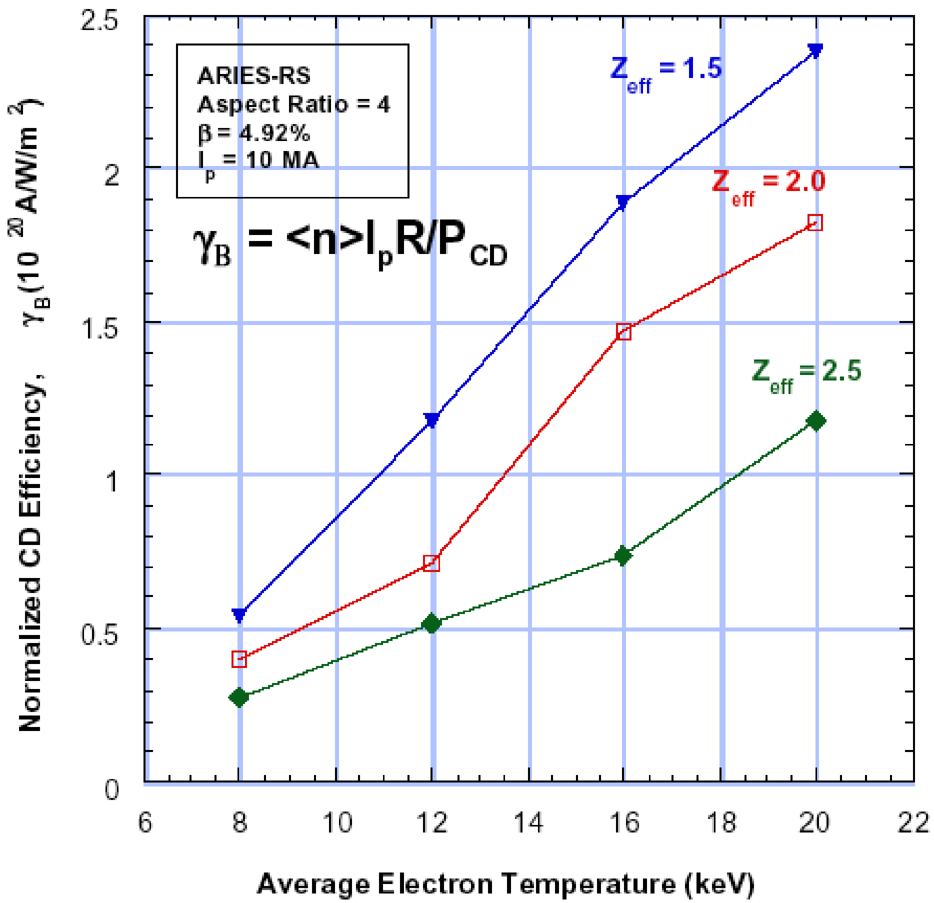


Heating and CD Analysis Show the Impact of β_N, Z_{eff}, and T_e

ARIES-AT study showed that minimum CD power DOES NOT occur at the highest β_N



ARIES-RS shows that some increase in Z_{eff} from intentional impurities (Ar) can be tolerated



Plasma Rotation is Probably Too Small for RWM Stabilization

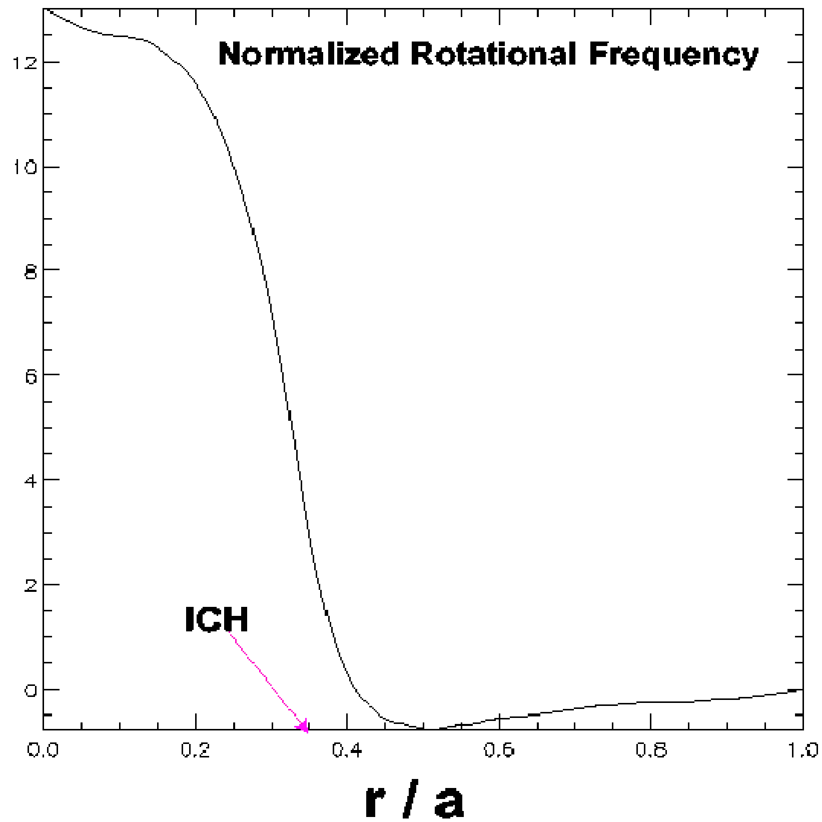
$$\frac{m_i \langle v_\phi \rangle}{\tau_E} \approx \frac{P_b (2m_b / E_b)^{1/2}}{V_p \langle n_i \rangle}$$

gives about 82 km/sec, which is 1.6% of the Alfven speed

XPTOR (GLF23) in conjunction with ONETWO estimates that the plasma rotation near or outside q_{min} will be very small

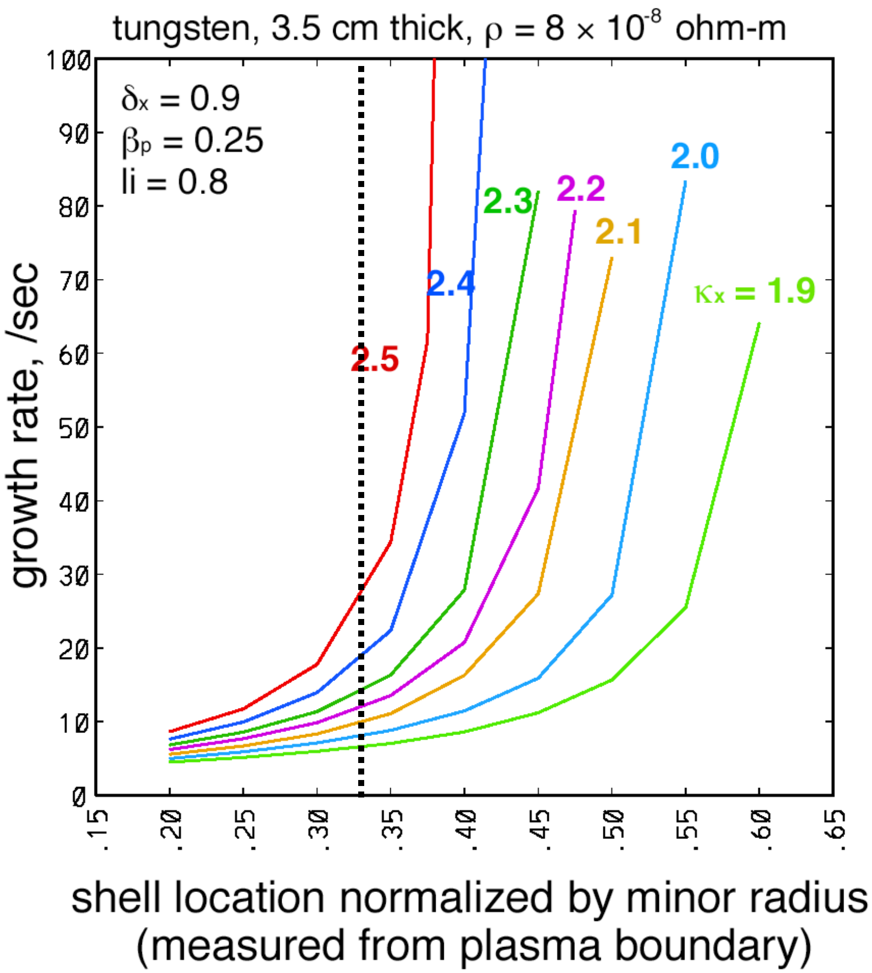
Examination of the rotation provided by IC heating off-axis indicates this mechanism is not effective, although there is considerable uncertainty in modeling

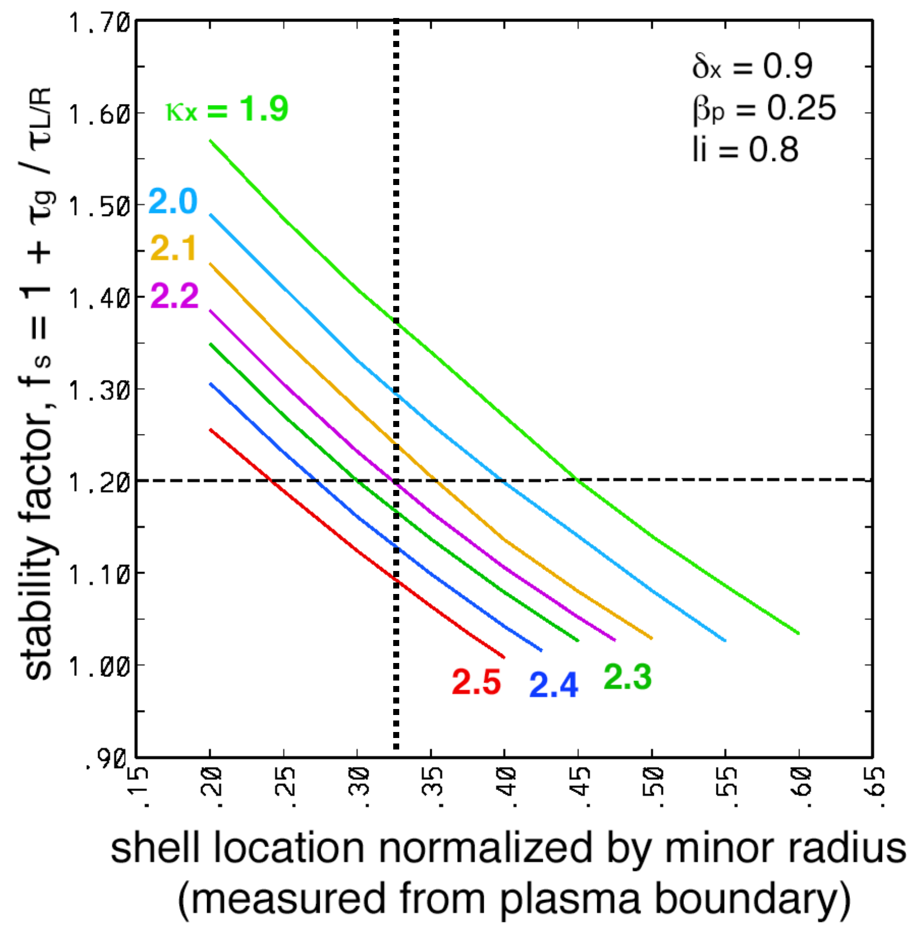
Plasma rotation profile generated by ICH deposition at ρ = 0.34, with volume integrated torque density equal 0



Vertical Stability Analysis Shows $\kappa_x = 2.2$ is Possible for ARIES-AT

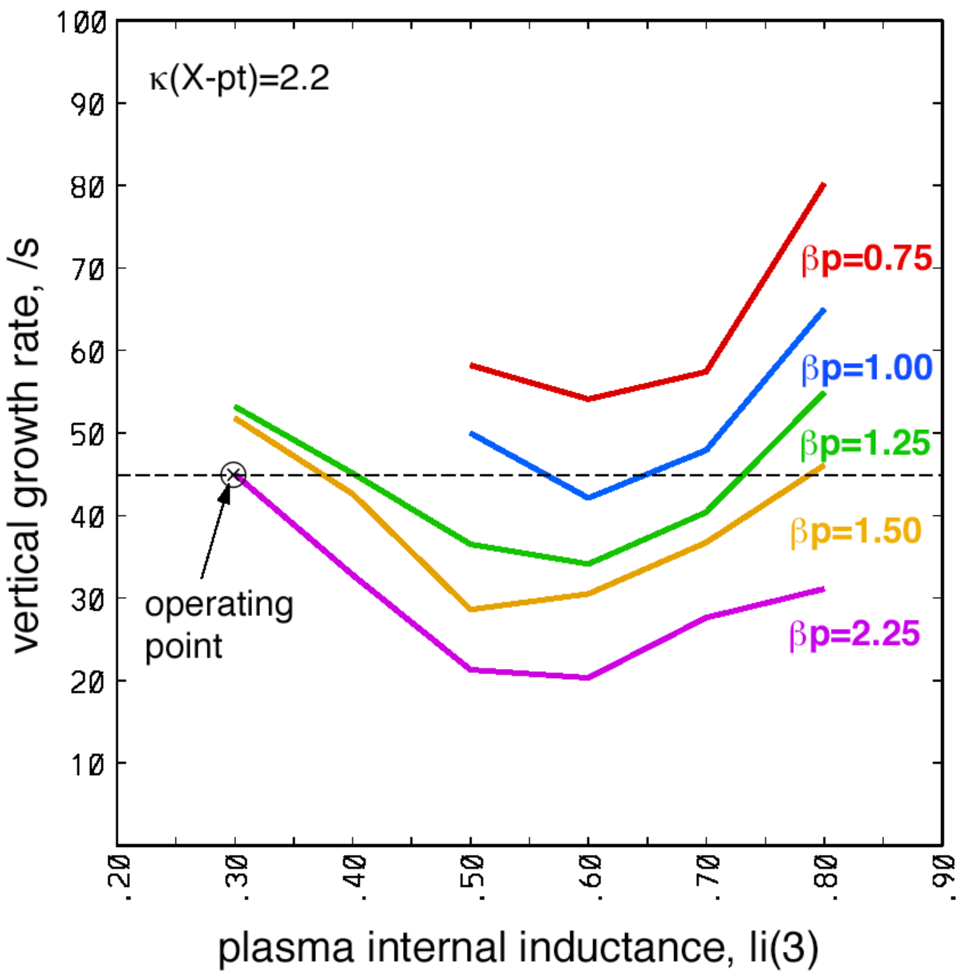
ARIES-RS had $\kappa_x = 1.9$, neutronics indicated the conducting structures could be closer to plasma in ARIES-AT yielding $\kappa_x^{max} = 2.2$

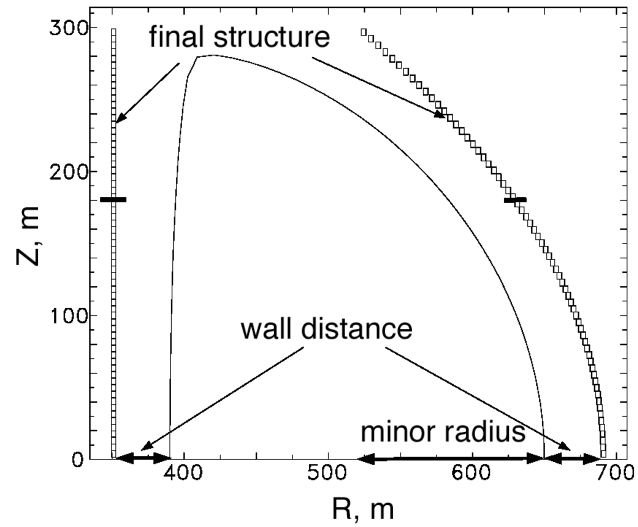


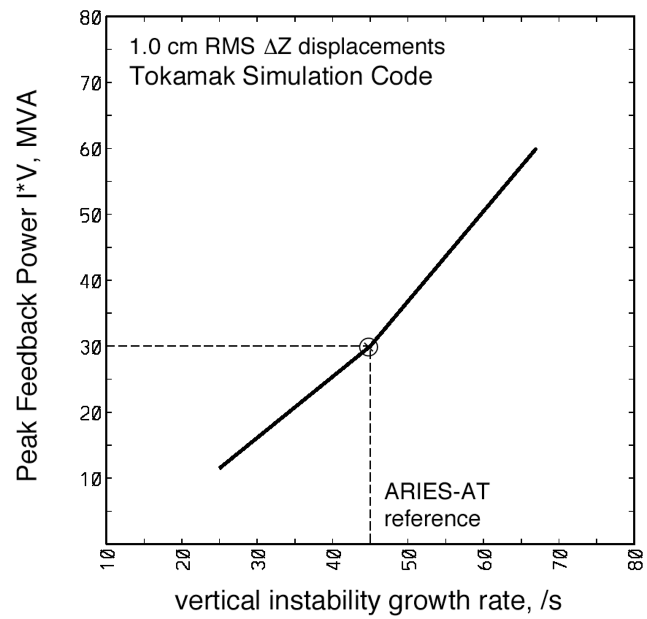


Vertical Stability and Control of Final Design Show Viable Operating Space

Tungsten shells located behind 1st blanket, 4 cm thick, operating at 1100°C

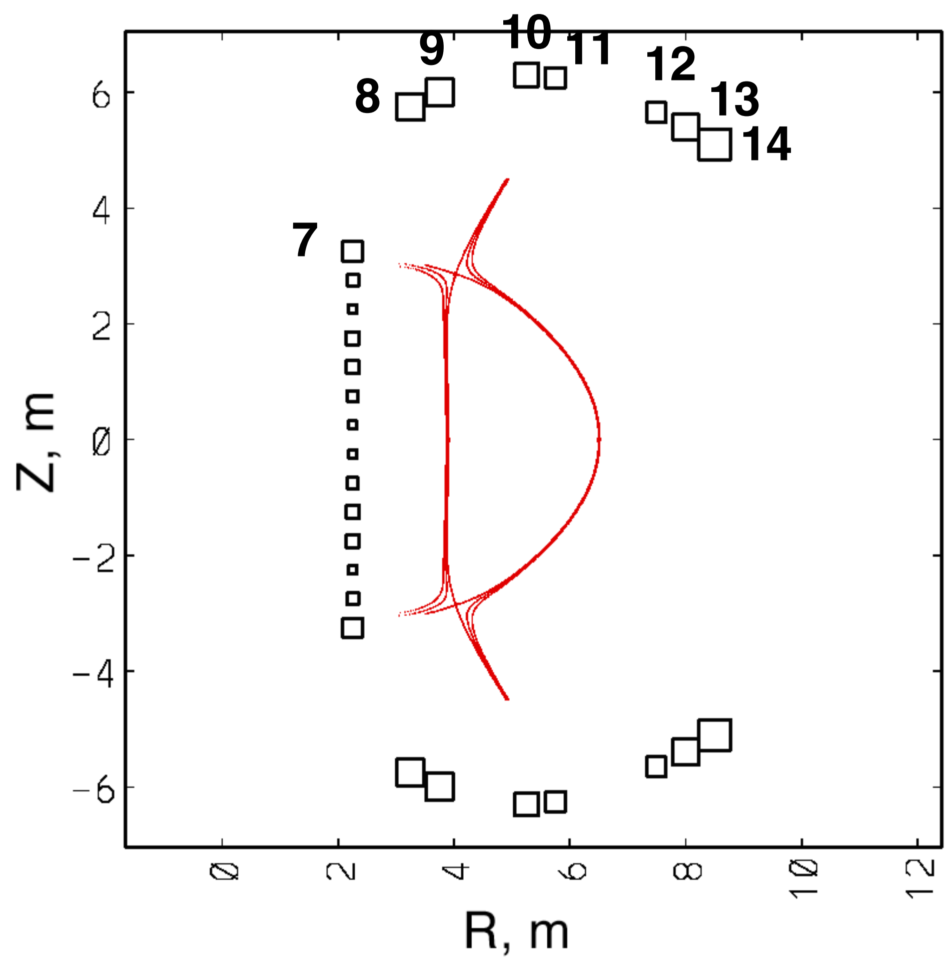


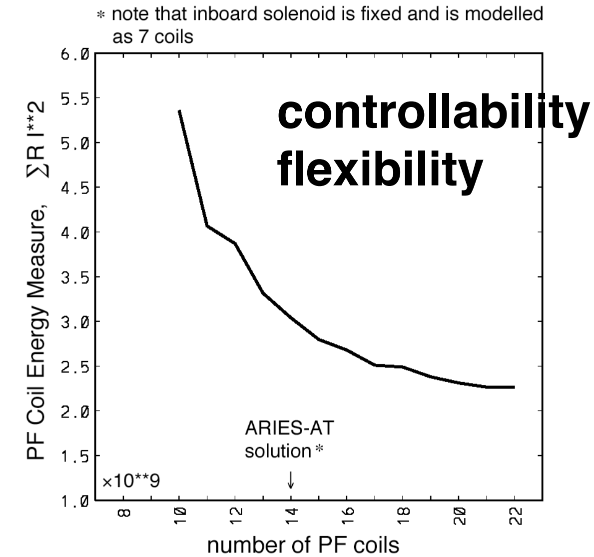


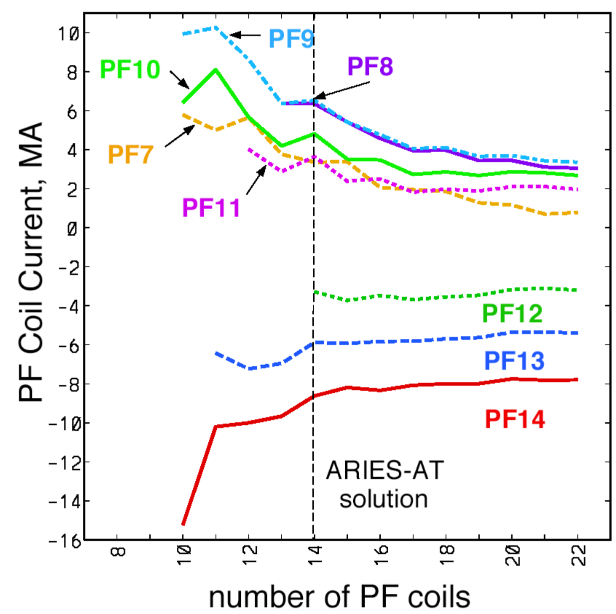


PF Coil Optimization Shows All Coil Currents Below 10 MA in ARIES-AT

All accessible PF coil locations are filled with coils, and one by one, are eliminated in order to yeild the least increase in $\sum RI^2$







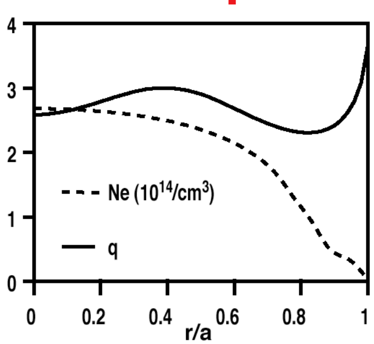
Examine Transport Assumptions Against GLF23 Predictions

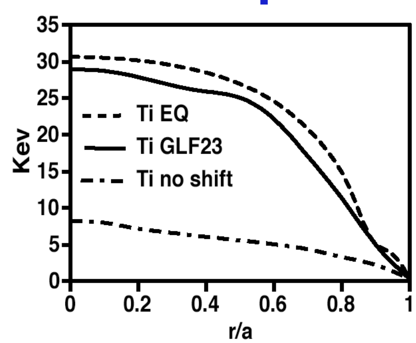
1) **Agreement is good for the assumed ARIES-AT profiles, however improved transport is due to Shafranov shift not ExB shear, ion transport above neoclassical**

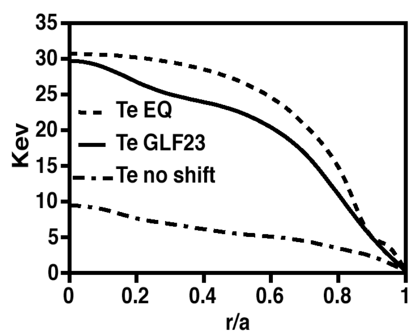
2) **Very broad density profile produces 30% reduction in electron and ion temperatures, profiles are similar**

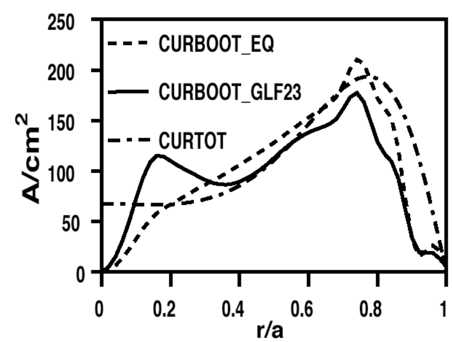
3) **Very broad density profile in combination with plasma rotation similar to DIII-D recovered temperatures, but still did not suppress all ITG turbulence**

Need expt’s with no external momentum input to benchmark GLF23 predictions for dq/dr < 0 and Shafranov shift stabilization

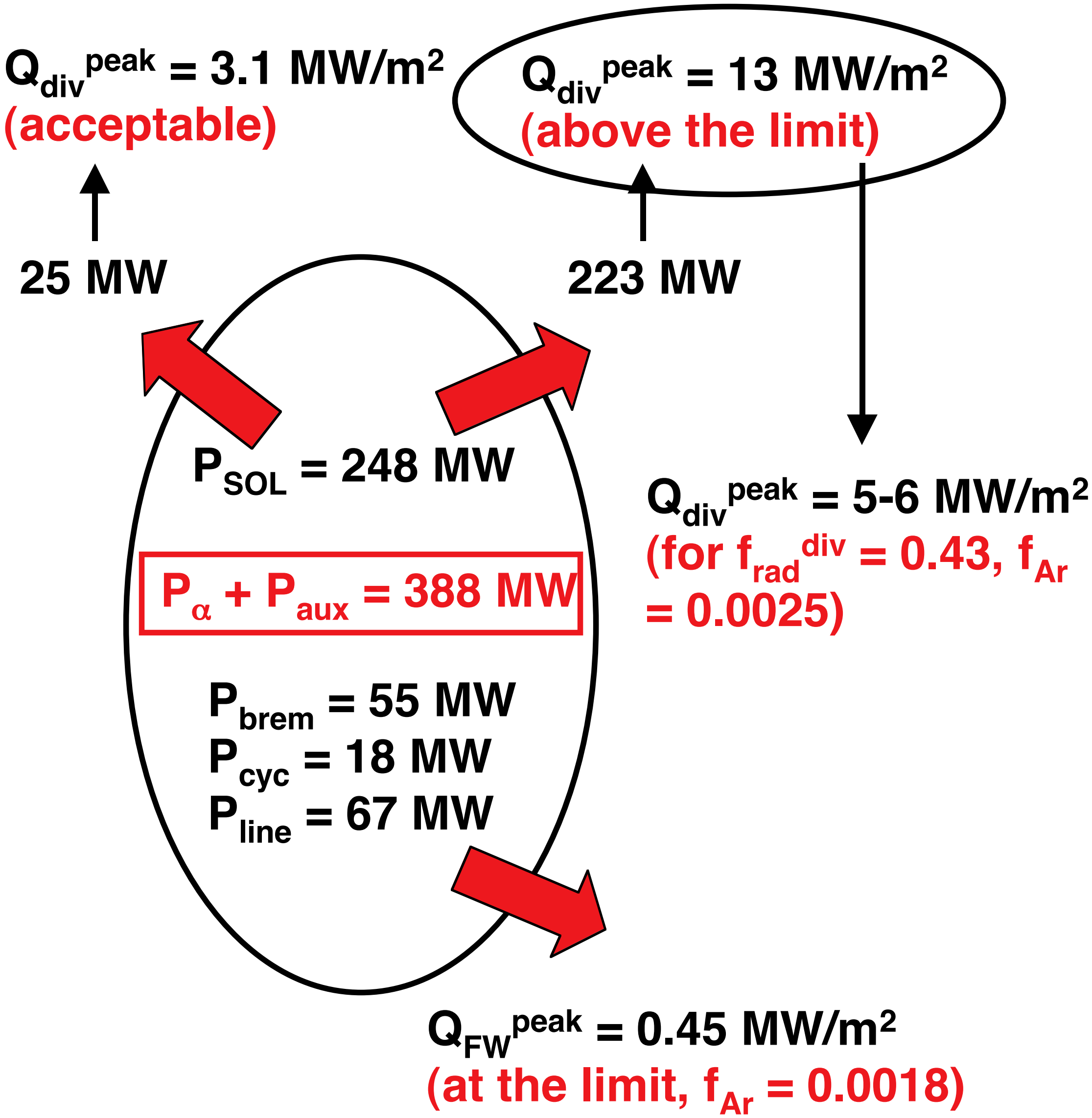








Plasma Edge/SOL/Divertor Solution Must Satisfy Physics & Engr. Constraints



P_{plasma} = 388 MW

Δ_{SOL} = 0.8-2.1 cm (L-mode & H-mode)

90% power to OB and 10% power to IB

$Q_{FW}^{peak} \leq$ 0.45 MW/m^2

$Q_{div}^{peak} \leq$ 5-6 MW/m^2

Enhancing Radiated Power is Critical to Power Handling

$$Q_{div}^{peak} \approx \frac{P_{SOL}(1-f_{rad})f_{pow}^{OB}f_{\nabla B}(1-f_{priv})\sin\alpha}{2\pi R_{strk}f_{\exp}\Delta_{SOL}}$$

$$\Delta_{SOL}^{L} = 6.6\times10^{-4}R^{1.21}q_{95}^{0.59}n_{L}^{0.54}Z_{eff}^{0.61}P_{div}^{-0.19}$$

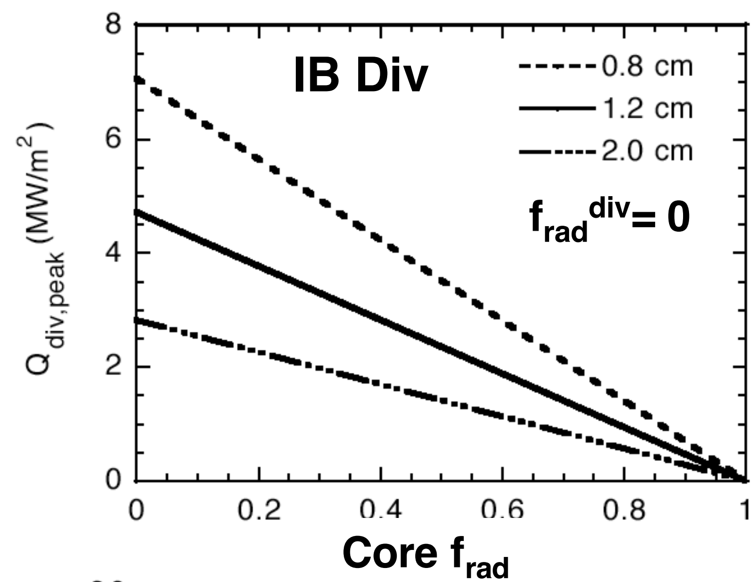
$$\approx 1.4-2.1cm$$

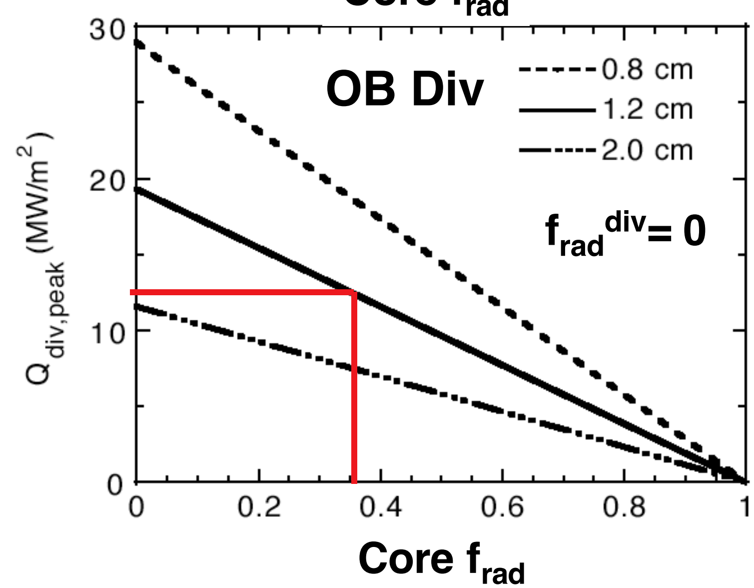
$$\Delta_{SOL}^{H} = 5.2\times10^{-3}P_{div}^{0.44}q_{95}^{0.57}B_{T}^{-0.45}$$

$$\approx 3.8cm$$

Convert these “integral power width” to width of steepest decay near the separatrix, divide by 1.8

Δ_{SOL} = 0.8-2.1 cm, use 1.2 cm in analysis

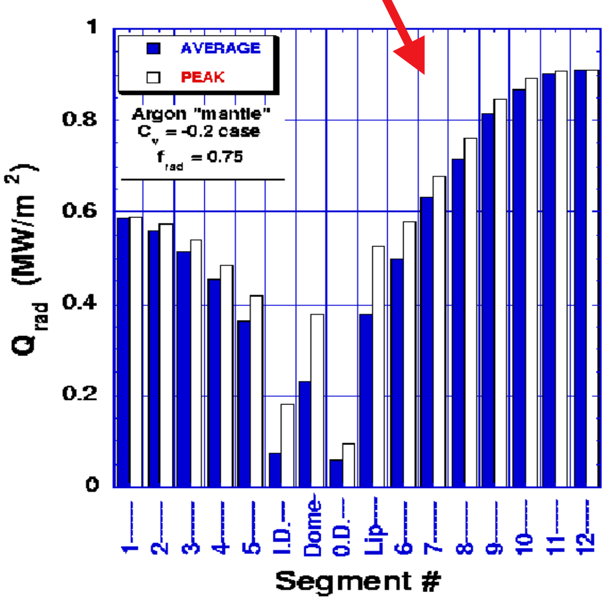


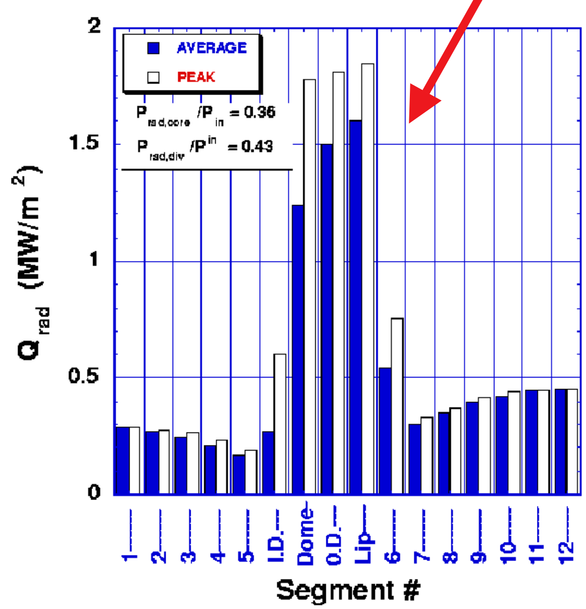


Balancing Radiated Power Distribution to Produce Optimal Power Handling

f_{rad}^{core}	Q_{FW}^{peak}	f_{rad}^{div}	$Q_{div}^{peak,OB}$	$Q_{div}^{peak,IB}$	$f_{Ar}^{core}, f_{Ar}^{div}$
30%	0.37 MW/m^2	0%	14.3 MW/m^2	3.4 MW/m^2	0, 0%
36%	0.45	0	13.0	3.1	0.18, 0
75%	0.90	0	5.0	1.2	0.35, 0
36%	0.45	43	5-6	1.3	0.18, 0.26

Radiated power distributions





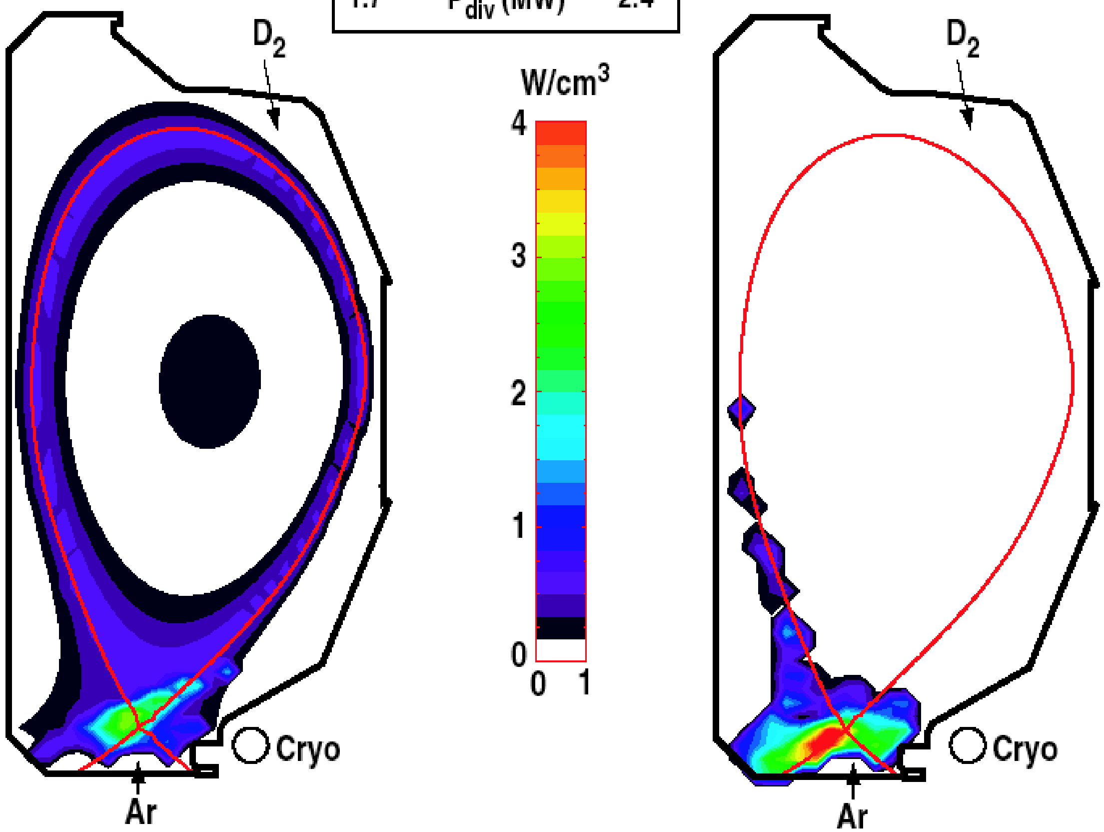
Controlling Impurity Distributions to Achieve the Best Radiation Distribution

DIII-D Puff & Pump Expts.

ARIES-AT examined Ne, Ar, and Kr ----> Ar appears best

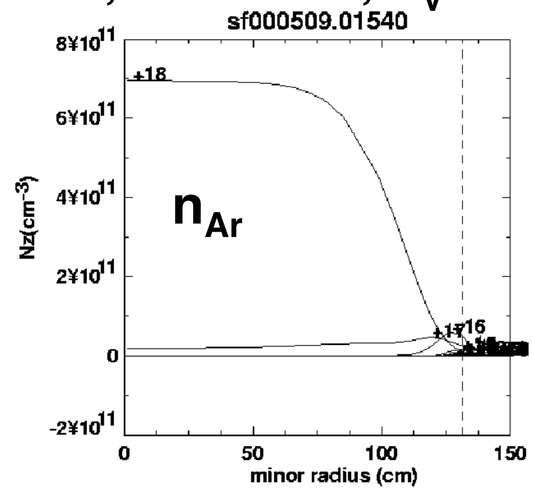
5.4	P_{tot} (MW)	4.5
0.45	P_{core} (MW)	0.3
2.4	P_{mantle} (MW)	0.73
1.7	P_{div} (MW)	2.4

(a) (b)

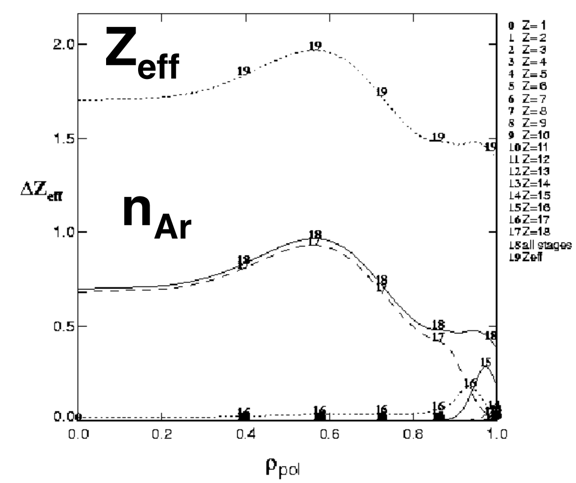


ARIES-AT Impurity Modeling

MIST, D = 1 m²/s, C_V = 1.0

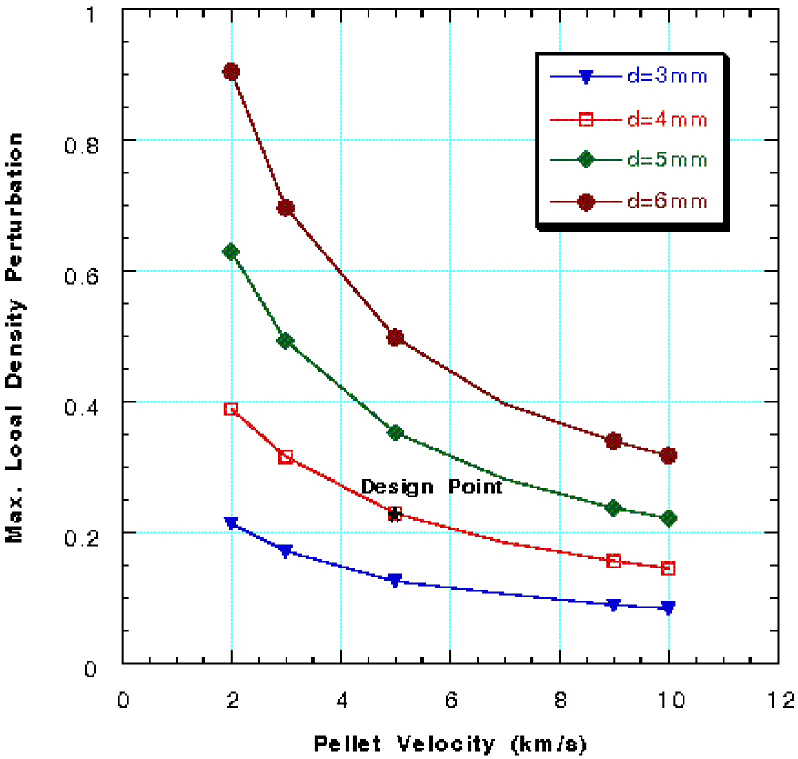


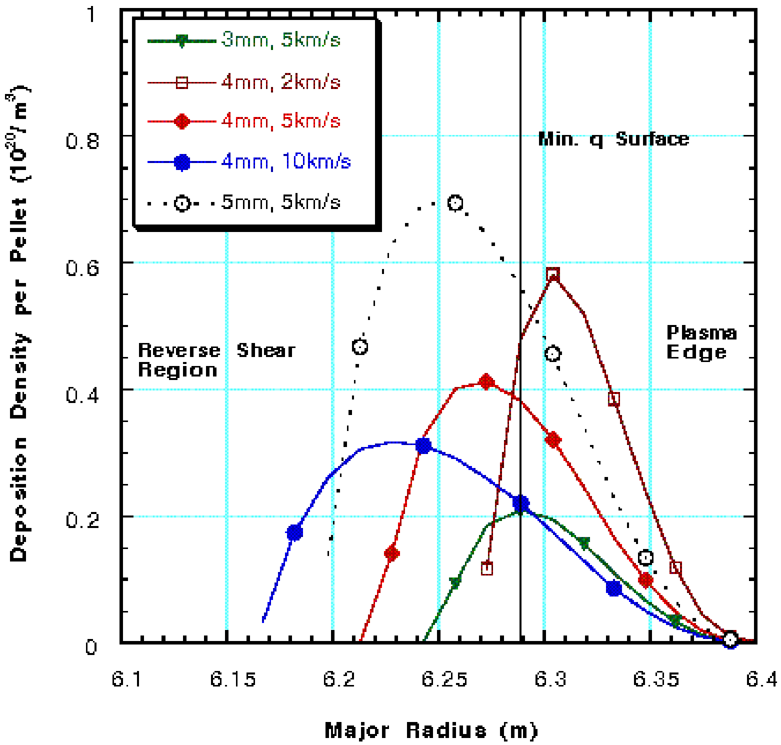
STRAHL, D & v = neo.



Fueling Must Reach Inside ITB With Reasonable Pellet Velocities

Recent advances in High Field Side pellet launching show that much lower velocities are required to access the plasma core, but guide tube must reach IB or vertical access





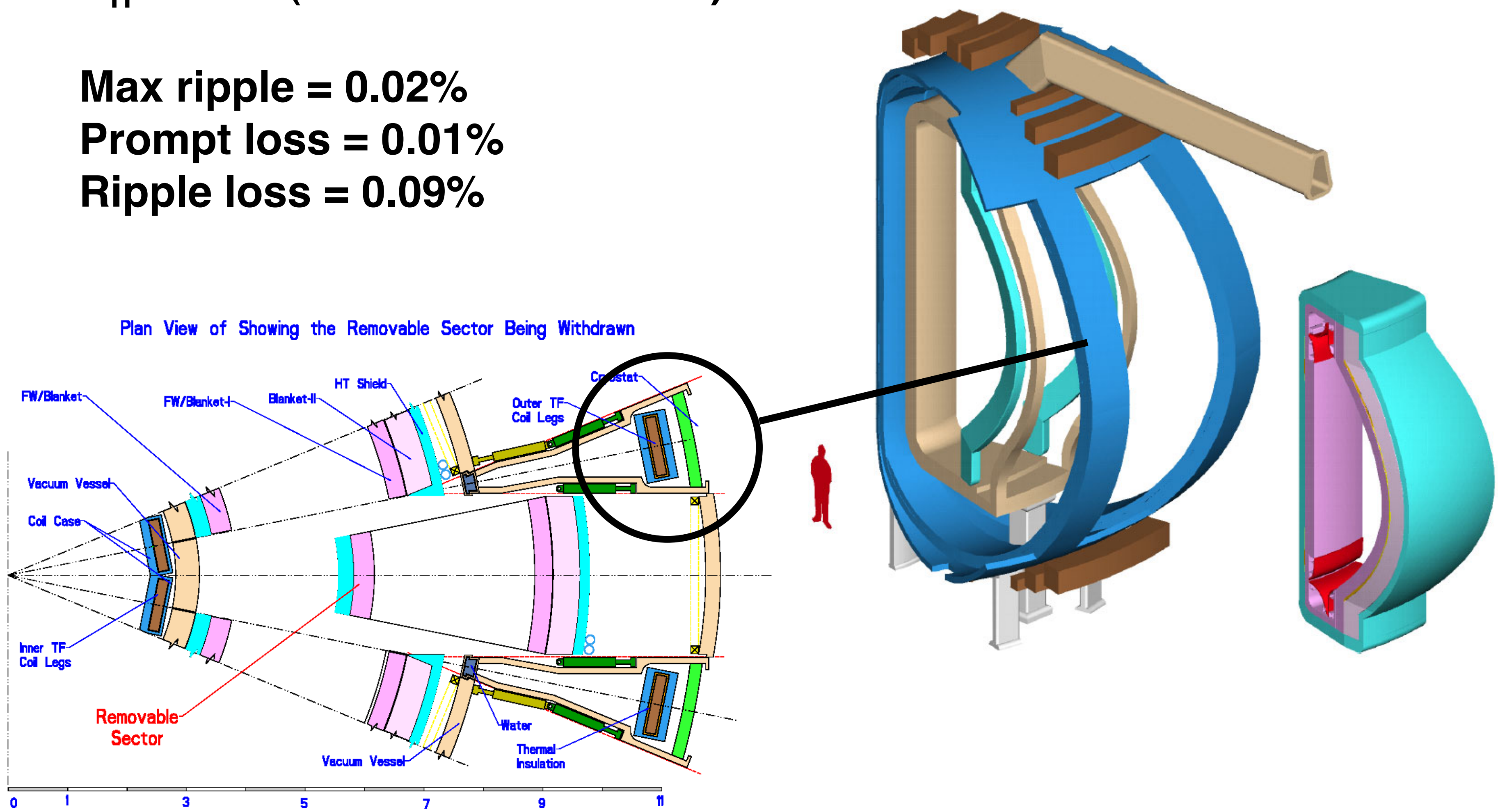
Low Field Side Pellet Simulations for ARIES-RS

Ripple Losses are Small Due to Large Outboard TF Coil Distance Even with High q

R_{TF} / (R+a) = 1.7
b_{TF} / a = 3 (measured from R+a)

Max ripple = 0.02%
Prompt loss = 0.01%
Ripple loss = 0.09%

Full sector maintenance has a positive impact on physics



Other Physics Examinations Performed in ARIES Studies

0D Startup analysis, both including the solenoid and without the solenoid

- Solenoid coils (IB) are made to provide $\Delta\psi$ to ramp up to Ip
- Non-solenoidal current rampup involves bootstrap overdrive technique (heating to produce BS current, LH can be used to assist, current hole formation is likely) ----> leads to long rampup times 90-200 minutes

Disruptions and thermal transients (ELMs) assessment and analysis with DESIRE and A*THERMAL

- Identify operating space with acceptable PFC/divertor lifetime
- Very few disruptions allowed and low amplitude/high frequency ELMs necessary

L-H transition, global energy confinement scaling comparisons, and POPCON for thermal stability and startup

Since no detailed neutral particle/plasma edge analysis done, the particle control requirements are done in Engr. using particle balance and DIII-D expt. experience as part of Divertor design

Other Physics Issues That Significantly Impact Power Plant Design

Control of neutral particles can allow the plasma to operate above the Greenwald density limit (DIII-D and TEXTOR)

Helium particle control is demonstrated in pumped divertor experiments, $\tau_{He}^* / \tau_E \approx$ 3-5 for H-mode, and $\approx$ 5-10 for AT plasmas (DIII-D and JT-60U, ARIES assumes 10)

LHCD (Compass) or bulk current profile modifications (ASDEX & JET FIR-NTMs, DIII-D Hybrid discharges) have growing evidence as a viable method for NTM suppression

Vertical (at $R < R_o$) and inboard (HFS) pellet launch show better penetration with lower pellet velocities

Strongly shaped ---> DN plasmas access Type II ELMs, which significantly reduce the divertor heat load and erosion (JET and ASDEX-U)

Physics Analysis in Power Plant Studies is Continuing to Improve

Identify primary impacts of physics on power plant optimization

- Fusion power density
- Recirculating power
- Self-consistency of overall configurations

Understand trade-offs among plasma configurations

- Pulsed vs steady state
- With and without wall stabilization of kink mode
- Inductive and non-inductive CD

Enable improved solutions thru physics/engineering interactions

- Conductor/stabilizers
- Radiative mantle/divertors

Understand the difference between a physics optimization and an integrated systems optimization