Optimization of a Steady-State Tokamak-Based Power Plant

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Electronic copy: http://aries.uscd/edu/najmabadi/
ARIES Web Site: http://aries.ucsd.edu/ARIES/

Physics analysis of power plants continue to improve and power plant studies provide critical guidance for physics research

- Identify key impact of physics configuration on power plant performance
  - ✓ High power density
  - ✓ Low recirculating power
  - ✓ Self-consistency of overall configuration

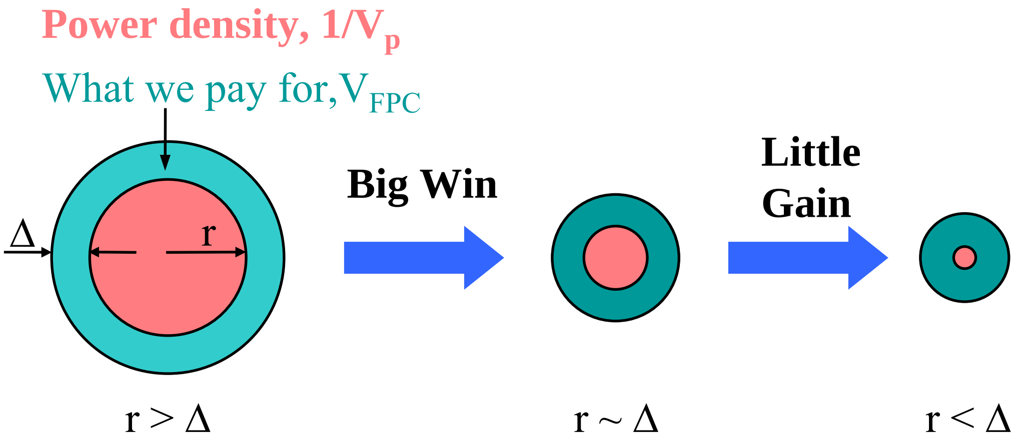
Improvements “saturate” after certain limit

- Understand trade-offs of physics/engineering constraints:
  - ✓ Location of conductor/stabilizer (blanket constraints *vs* allowed κ)
  - ✓ Core/divertor radiation *vs* in-vessel components constraints

- There is a **big difference** between a **physics optimization** and an **integrated systems optimization**

Directions for Improvement

Increase Power Density



Power density, $1/V_p$

What we pay for, V_{FPC}

- ✓ Improvement "saturates" at ~5 MW/m^2 peak wall loading (for a 1GWe plant).
- ✓ A steady-state, first stability device with Nb_3Sn technology has a power density about 1/3 of this goal.

Decrease Recirculating Power Fraction

- ✓ Improvement "saturates" about Q ~ 40.
- ✓ A steady-state, first stability device with Nb_3Sn Tech. has a recirculating fraction about 1/2 of this goal.

High-Field Magnets

- ✓ ARIES-I with 19 T at the coil (cryogenic).
- ✓ Advanced SSTR-2 with 21 T at the coil (HTS).

High bootstrap, High β

- ✓ 2nd Stability: ARIES-II/IV
- ✓ Reverse-shear: ARIES-RS, ARIES-AT, A-SSRT2

Reverse Shear Plasmas Lead to Attractive Tokamak Power Plants

First Stability Regime

- Does Not need wall stabilization (Stable against resistive-wall modes)
- Limited bootstrap current fraction (< 65%), limited β_N= 3.2 and β=2%,
- **ARIES-I:** Optimizes at high A and low I and high magnetic field.

Reverse Shear Regime

- Requires wall stabilization (Resistive-wall modes)
- Excellent match between bootstrap & equilibrium current profile at high β.
- Internal transport barrier
- **ARIES-RS** (medium extrapolation): β_N= 4.8, β=5%, P_{cd}=81 MW (achieves ~5 MW/m^2 peak wall loading.)
- **ARIES-AT** (aggressive extrapolation): β_N= 5.4, β=9%, P_{cd}=36 MW (high β is used to reduce peak field at magnet)

Evolution of ARIES Designs

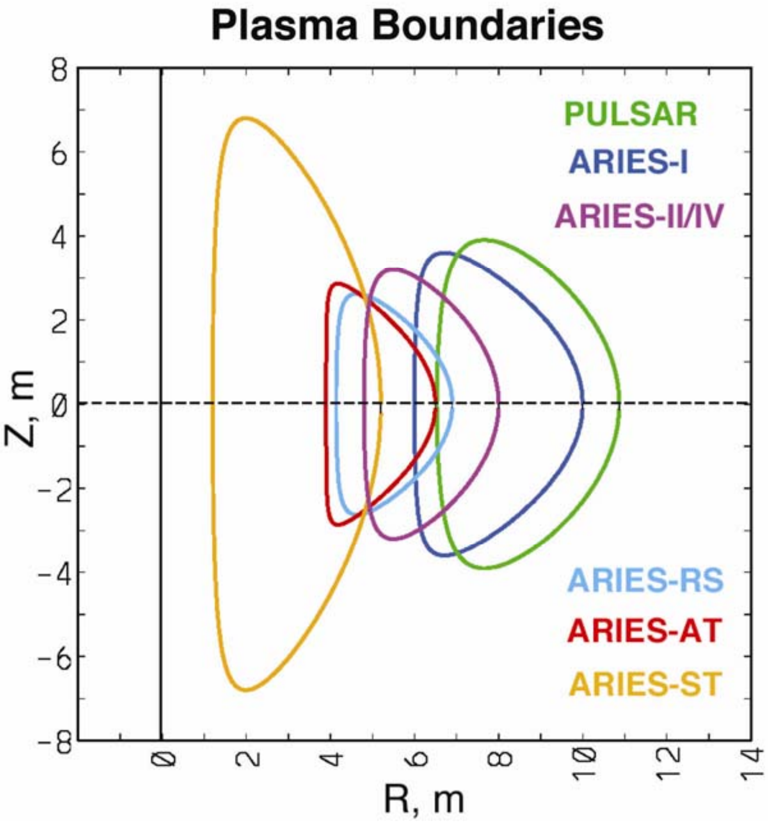
	1st Stability, Nb$_3$Sn Tech.	**High-Field Option**	**Reverse Shear Option**	
	ARIES-I’	**ARIES-I**	**ARIES-RS**	**ARIES-AT**
Major radius (m)	8.0	6.75	5.5	5.2
β (β_N)	2% (2.9)	2% (3.0)	5% (4.8)	9.2% (5.4)
Peak field (T)	16	19	16	11.5
Avg. Wall Load (MW/m^2)	1.5	2.5	4	3.3
Current-driver power (MW)	237	202	81	36
Recirculating Power Fraction	0.29	0.28	0.17	0.14
Thermal efficiency	0.46	0.49	0.46	0.59
Cost of Electricity (c/kWh)	10	8.2	7.5	5

Approaching COE insensitive of power density

Approaching COE insensitive of current drive

ARIES Aspect Ratio Optimization

- For first-stability devices (monotonic q profile), optimum A is around 4 mainly due to high current-drive power.
- For reverse-shear, system code calculations indicate a broad minimum for A ~ 2.5 to 4.5
- Detailed engineering design has always driven us to higher aspect ratios (A ~ 4).
  - ✓ Inboard radial build is less constraining;
  - ✓ More "uniform" energy load on fusion core (lower peak/average ratios).



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- Understand trade-offs of physics/engineering constraints:
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Major Plasma Parameters of ARIES-AT

$A = 4$
$R = 5.2$ m
$a = 1.3$ m
$I_p = 12.8$ MA
$B_T = 5.9$ T

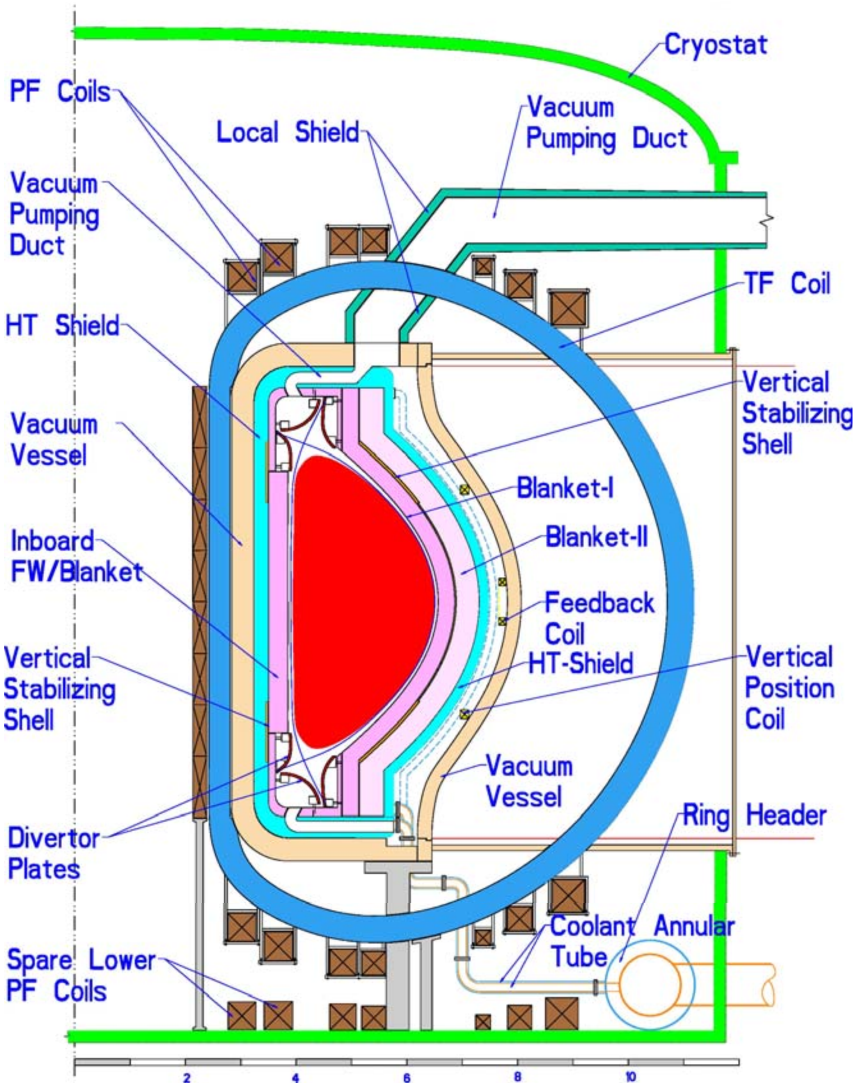
$\kappa_x = 2.2$
$\delta_x = 0.84$
$q_{axis} = 3.5$
$q_{min} = 2.4$
$q_{edge} \leq 4$
$li(3) = 0.3$
$p_0/<p> = 1.9$

$\beta = 9.2\%$
$\beta_N = 5.4$ ‡
$\beta_p = 2.8$

$f_{BS} = 0.89$
$P_{CD} = 36$ MW

$n_e = 2 \text{ X}10^{20} \text{ m}^{-3}$
$H_{ITER\text{-}89P} = 2.6$

$P_f = 1755$ MW



‡ ARIES-AT plasma operates at 90% of maximum theoretical limit

Detailed plasma analysis performed for ARIES-AT and critical issues and trade-offs were identified*

- ✓ Equilibria
- ✓ Ideal MHD Stability
- ✓ Neoclassical Tearing Mode
- ✓ RWM and Plasma Rotation
- ✓ Heating & Current Drive
- ✓ Vertical Stability and Control
- ✓ PF coil Optimization
- ✓ Plasma Transport
- ✓ Plasma edge/SOL/Divertor
- ✓ Fueling
- ✓ Ripple losses
- ✓ 0-D Start-up with and without solenoid
- ✓ Disruption and thermal transients

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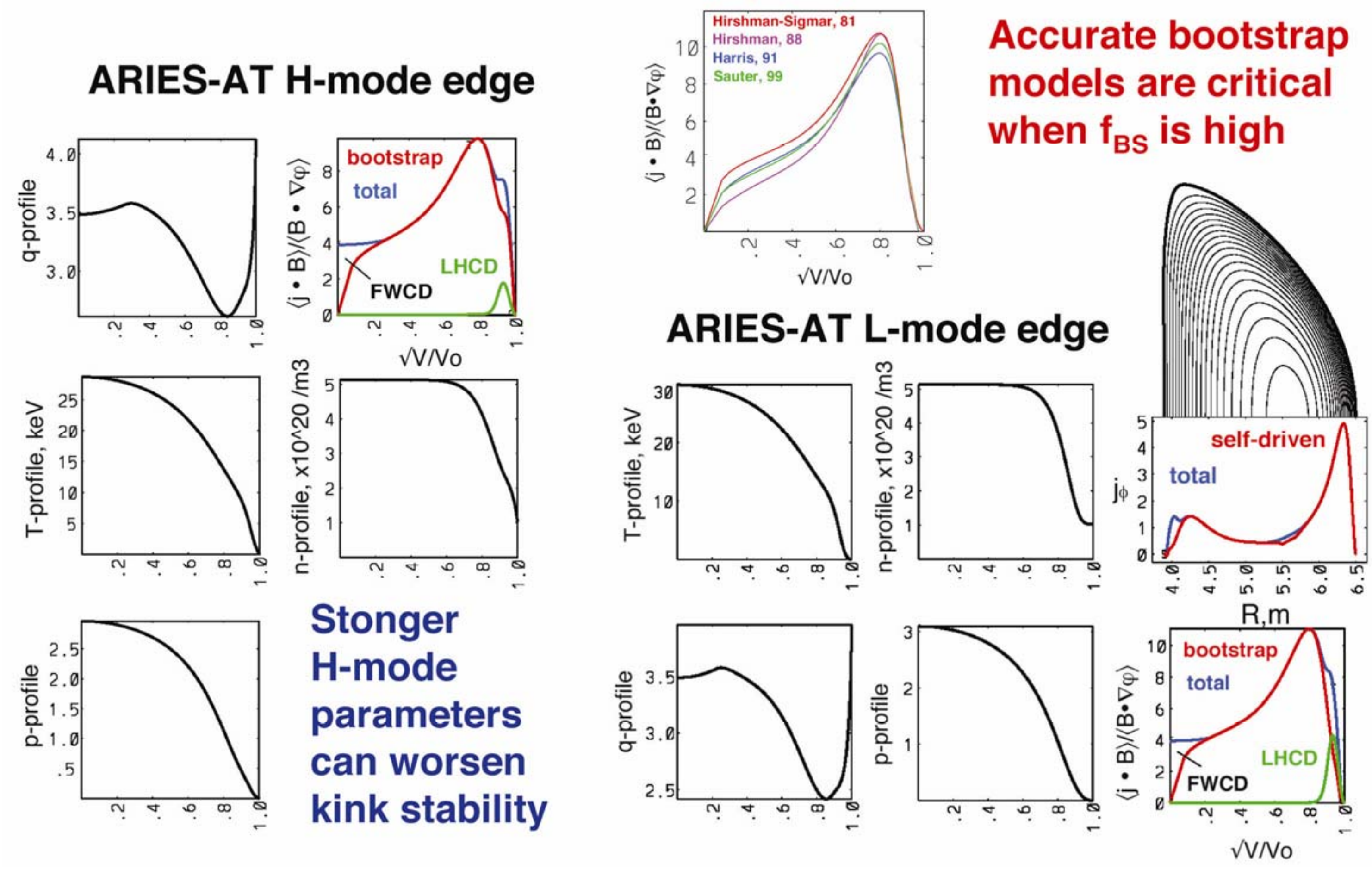
* See ARIES Web Site for details

Equilibria were produced to provide input to current-drive, Stability and Systems Studies*



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

Stonger H-mode parameters can worsen kink stability

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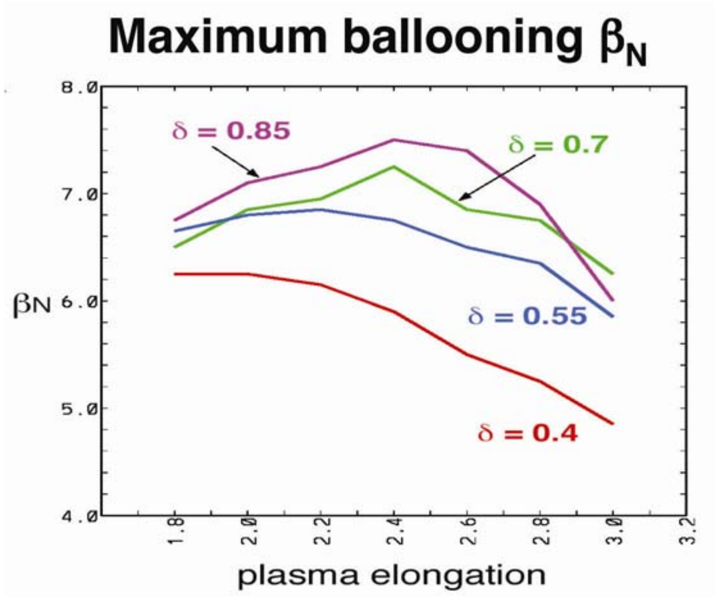
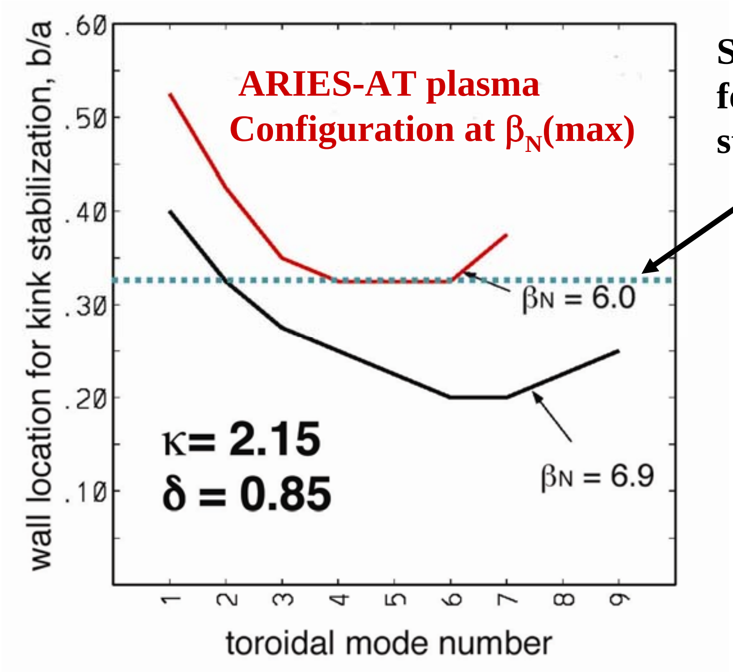
* High resolution Equilibria are essential. Plasma boundary was determined from free-boundary equilibrium with the same profiles at ~ 99.5% flux surface.

Plasma elongation and triangularity strongly influence achievable β

- Low-n link and high-n ballooning was performed by:
  - ✓ PEST2 for $1 \leq n \leq 9$
  - ✓ BALMSC for $n \to \infty$
  - ✓ MARS for $n = 1$ rotation
- Examined the impact of plasma shape, aspect ratio, and j and p profiles.
- A data base was created for systems analysis.

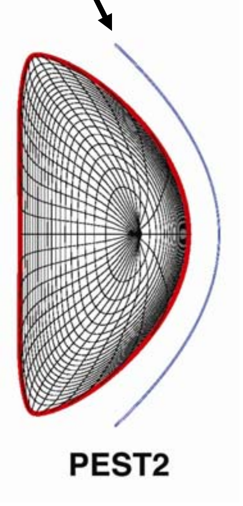


High elongation requires high triangularity



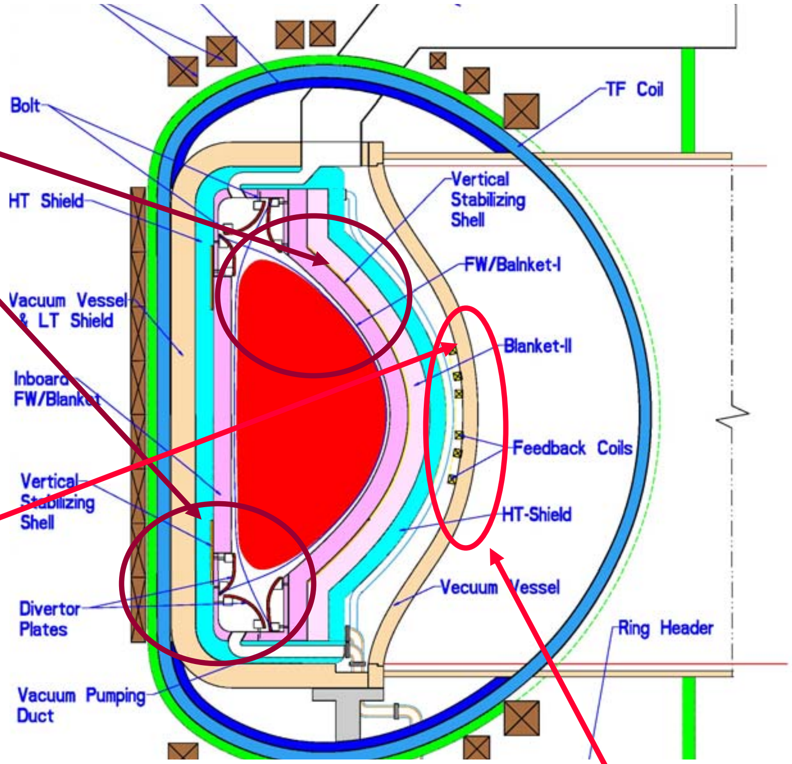
Intermediate n is most restrictive

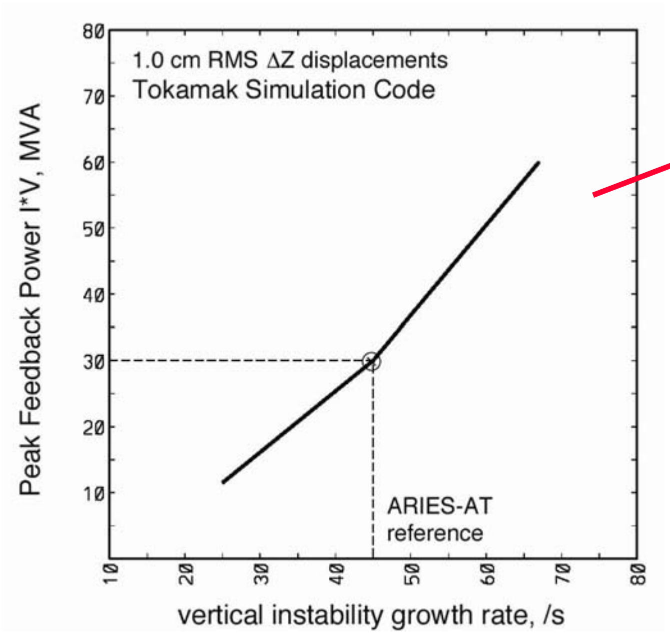
Same wall location for kink and vertical stability



Location of shell and feedback coils is a critical physics/engineering interface

- Passive stability is provided by tungsten shells located behind the blanket (4 cm thick, operating at 1,100^{o}C)
- Thinner ARIES-AT blanket yields κ_x = 2.2 and leads to a much higher β compared to ARIES-RS





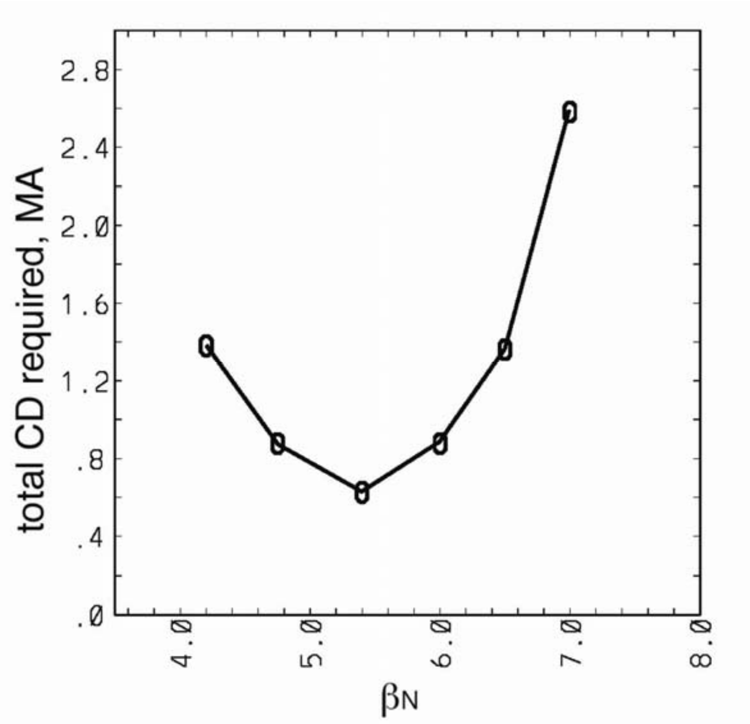
Using DIIID C-coil as basis for RWM stabilization

✓8-16 coils, 50 KA-turns

✓$\omega\ \tau_{wall} = 3$

✓P_{total} = 10 MW

Other parameters also influence plasma configuration and optimization



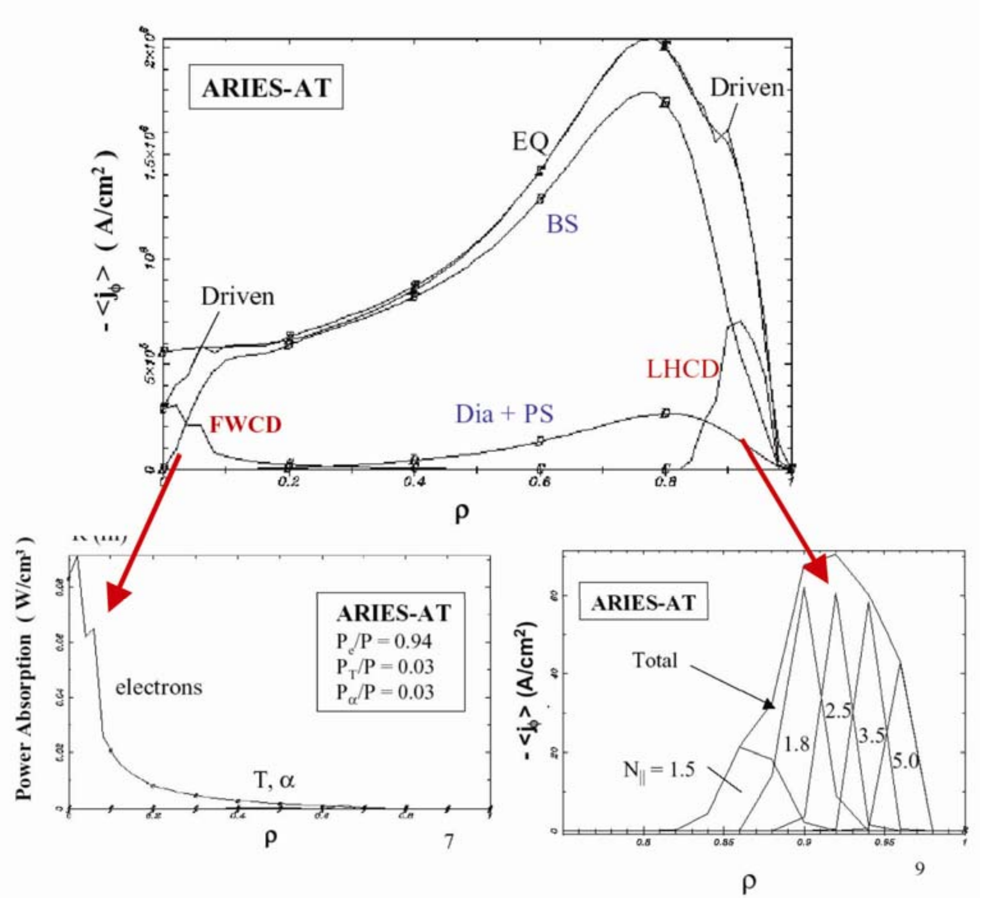
Minimum current-drive power does not occur at highest β_N

⇒ Another variable in the optimization

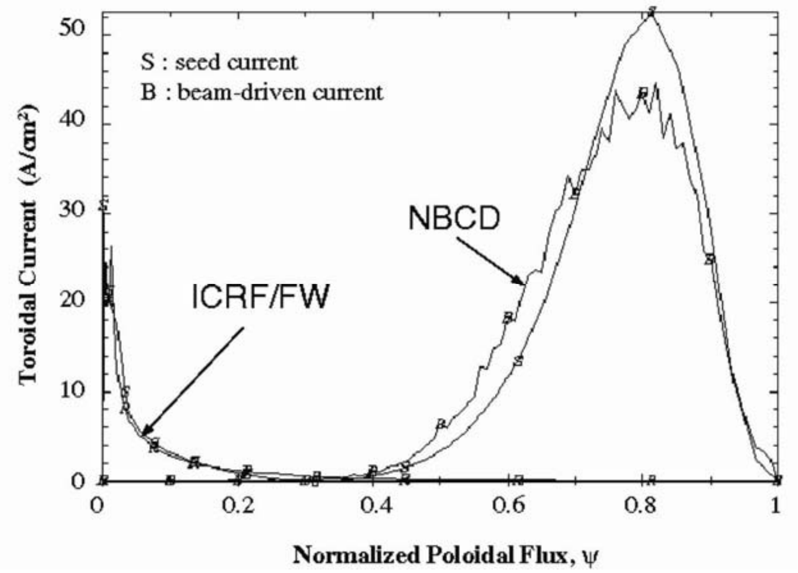
ARIES-AT utilizes ICRF/FW and LHCD

ICRF/FW: $P_{FW} = 5$ MW, 68 MHz, $n_{||} = 2$

LHCD: $P_{LH} = 37$ MW, 3.6 & 2.5 GHz, $n_{||} = 1.65–5.0$



Alternative scenario with NBI



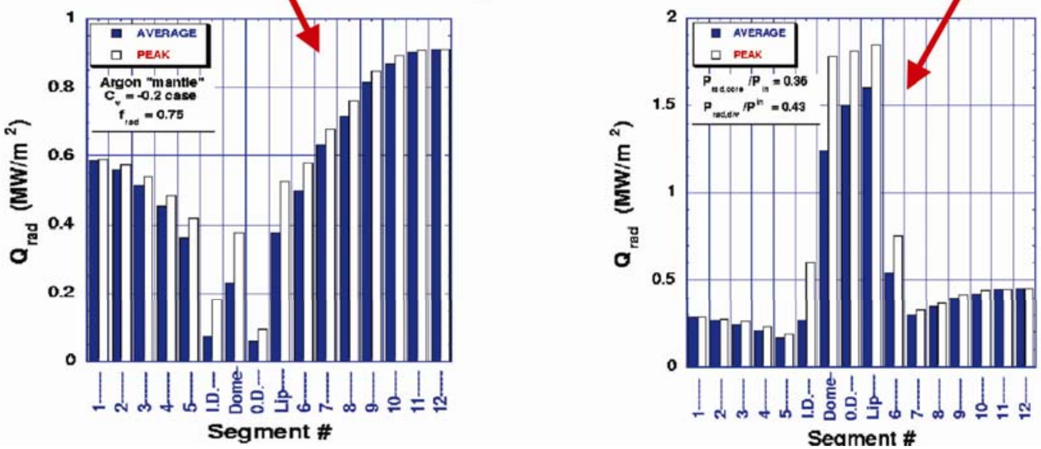
120 keV NBI provides rotation and current drive for ρ > 0.6 with $P_{NB} = 44$ MW and $P_{FW} = 5$ MW (NFREYA)

Radiated power distribution should balanced to produce optimal power handling

- A highly radiative mantle is NOT the optimum solution. First wall usually has a much lower heat flux capability than the divertor:
  - ✓ For ARIES AT: $Q_{FW}^{peak} \leq 0.45$ MW/m^2 while $Q_{DIV}^{peak} \leq 5$ MW/m^2
- L-Mode Edge is preferable (higher edge density, no pedestal at the edge).

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



Summary

- ➢ Advanced mode improve attractiveness of fusion through higher power density and lower recirculating power. However improvements "saturate" after certain limits:
  - ✓ Neutron loading of ~ 3-4 MW/m^2 (higher β is then used to lower magnet cost)
  - ✓ Very little incentive for plasmas with $Q > 40$.
- ➢ For reverse-shear, system code calculations indicate a broad minimum for A ~ 2.5 to 4.5
  - ✓ Detailed engineering design has always driven us to higher aspect ratios (A ~ 4).
- ➢ Understanding trade-offs of physics/engineering constraints is critical in plasma optimization, *e.g.*,
  - ✓ Location of conductor/stabilizer (blanket constraints *vs* allowed κ)
  - ✓ Core/divertor radiation *vs* in-vessel components constraints
- ➢ There is a **big difference** between a **physics optimization** and an **integrated systems optimization**