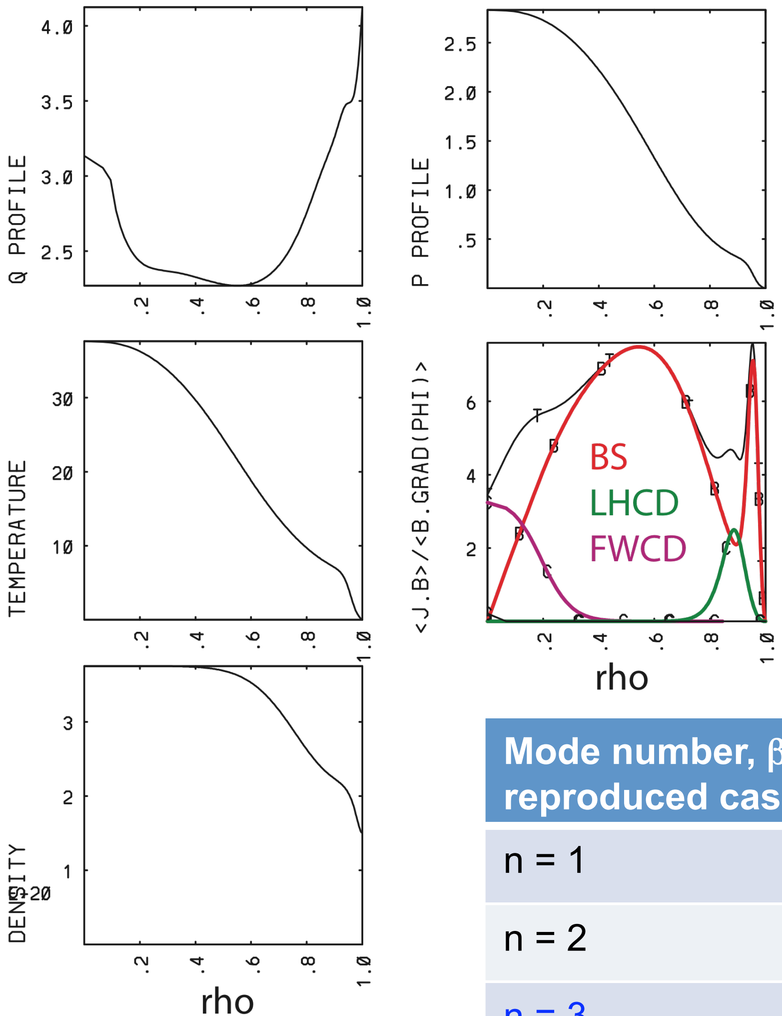
ARIES ACT1 Core Physics Updates and Systems/1.5D comparisons

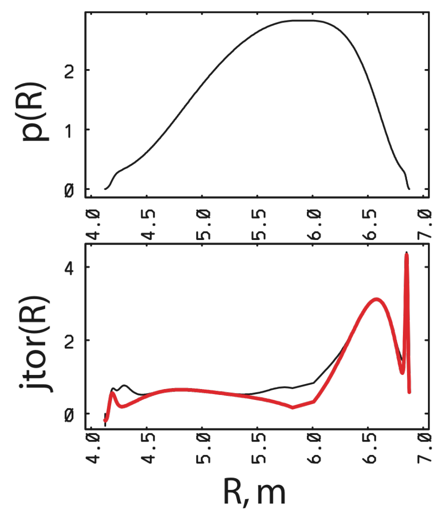
1) ideal MHD stability ACT1
2) TSC time-dependent simulation of ACT1
3) fueling and exhaust estimate
4) systems code and 1.5D comparison

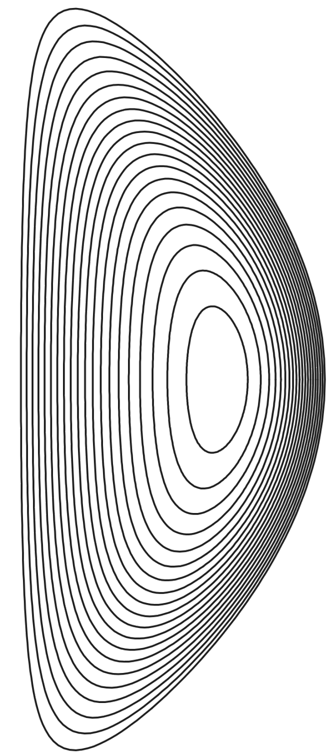
C. Kessel, PPPL

ARIES Project Meeting, Gaithersburg MD
May 31 – June 1, 2012

1) JSOLVER equilibria and stability…reproduce a TSC case



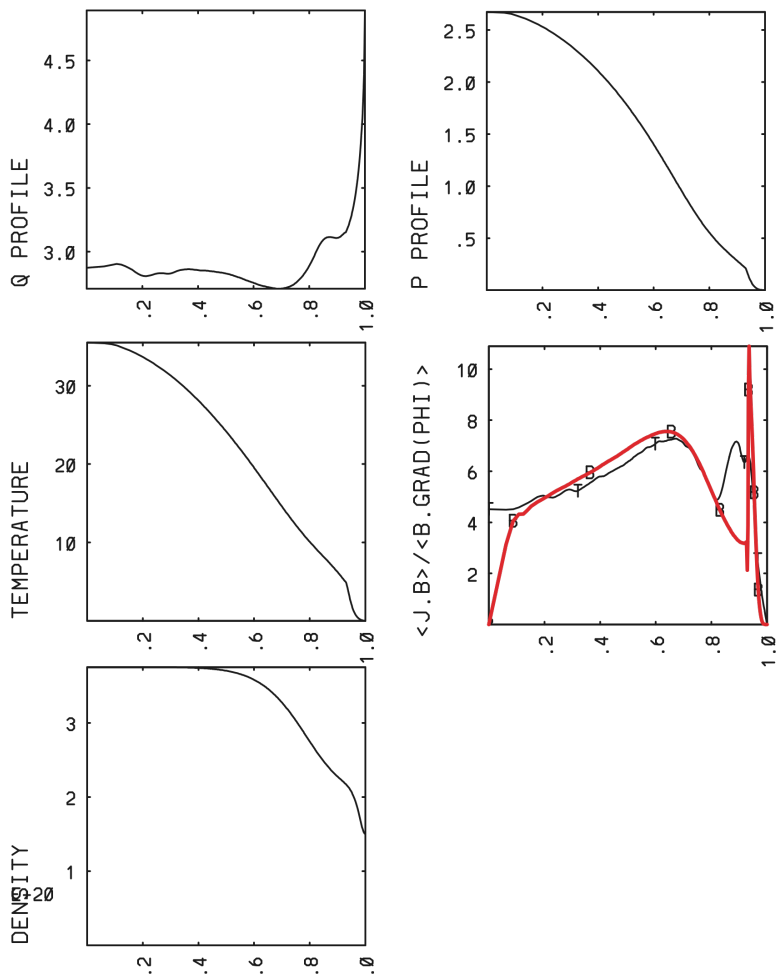




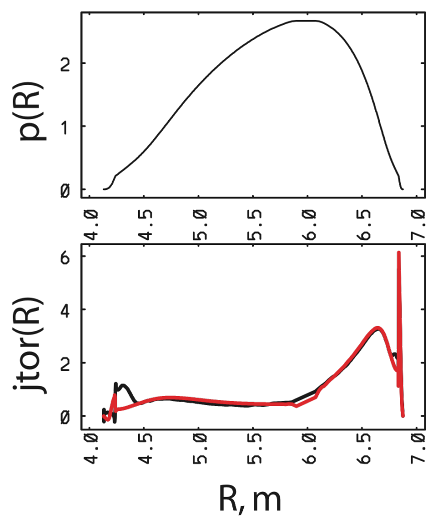
Ballooning stable

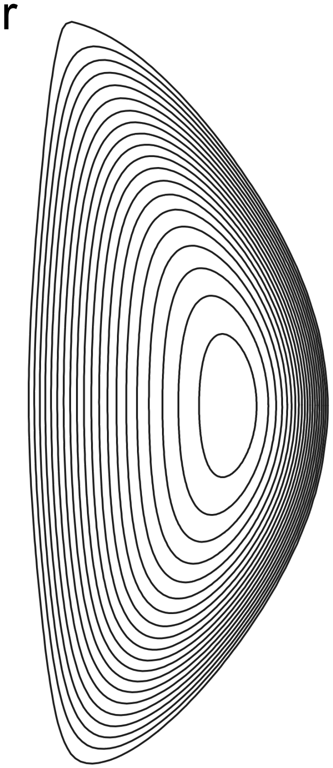
Mode number, β_N ~ 5.67, reproduced case from TSC	b/a to stabilize (real distance from plasma surface)
n = 1	0.500 (0.69 m)
n = 2	0.385 (0.529 m)
n = 3	0.365 (0.502 m)
n = 4	0.385 (0.529 m)

1) JSOLVER equilibria directly from TSC simulation….still converging for stability analysis



Need to decrease fraction of separatrix flux to smooth out corner





99.98% of separatrix flux

1) Ideal MHD Stability

Extract plasma from TSC simulation and analize, and separately produce a very close match in JSOLVER

The $\beta_N = \beta_{N,th} + \beta_{N,fast}$ which is > 5.5 or so, making $\beta_{N,th}$ ~ 4.5

Previous case analyzed

Mode number, β_N ~ 4.5	**b/a to stabilize (real distance from plasma surface)**
n = 1	0.46 (0.633 m)
n = 2	0.45 (0.619 m)
n = 3	0.425 (0.584 m)

Very similar to ARIES-AT, so we should assume the same b/a ~ 0.33….vertical shell is in the same location

Mode number, β_N ~ 5.67, reproduced case from TSC	**b/a to stabilize (real distance from plasma surface)**
n = 1	0.500 (0.69 m)
n = 2	0.385 (0.529 m)
n = 3	0.365 (0.502 m)
n = 4	0.385 (0.529 m)

We should be using this range of betaN

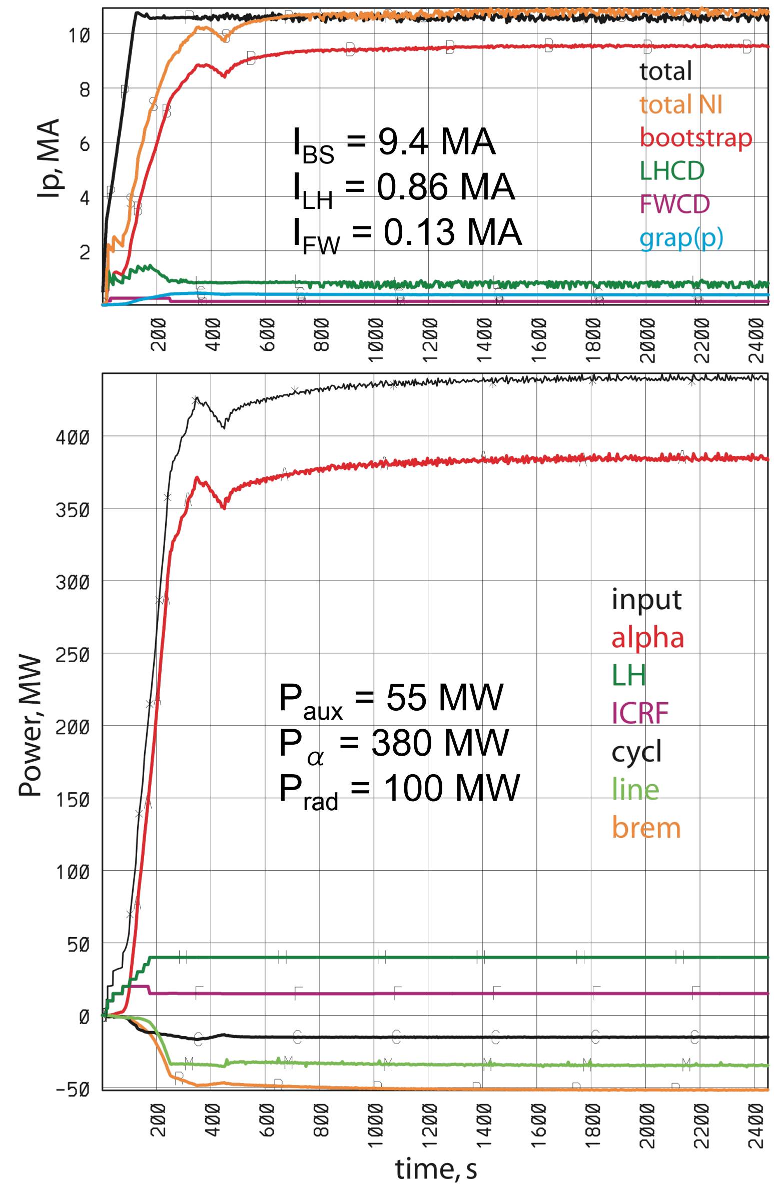
2) TSC 1.5D free-boundary simulations

Have established 100% non-inductive plasmas at β_N = 5.5-5.7 with Ip = 10.6 MA, R = 5.5 m, a = 1.375……ACT1

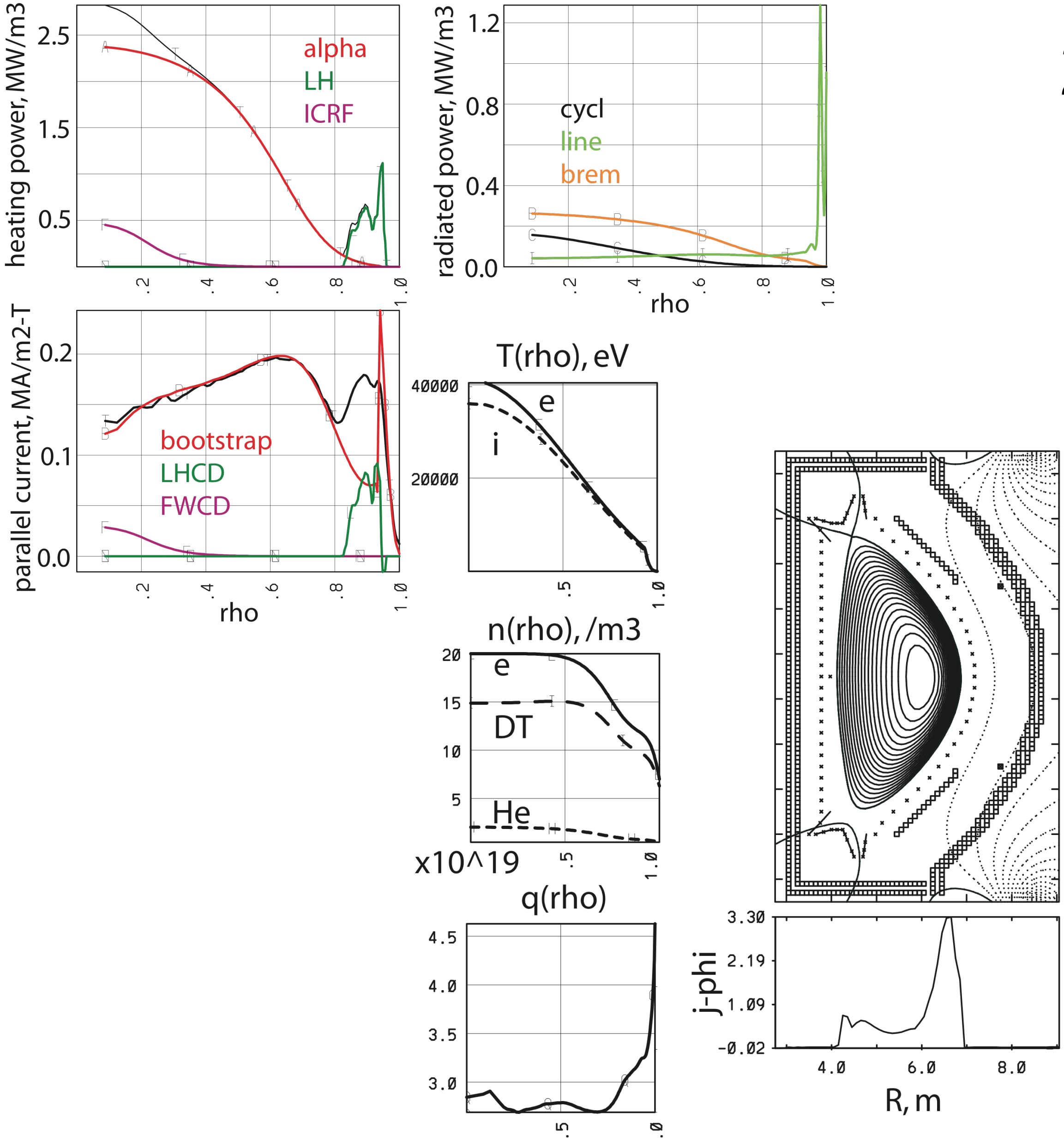
LHCD and ICRF FW, will run thru TRANSP to determine FWCD and EC

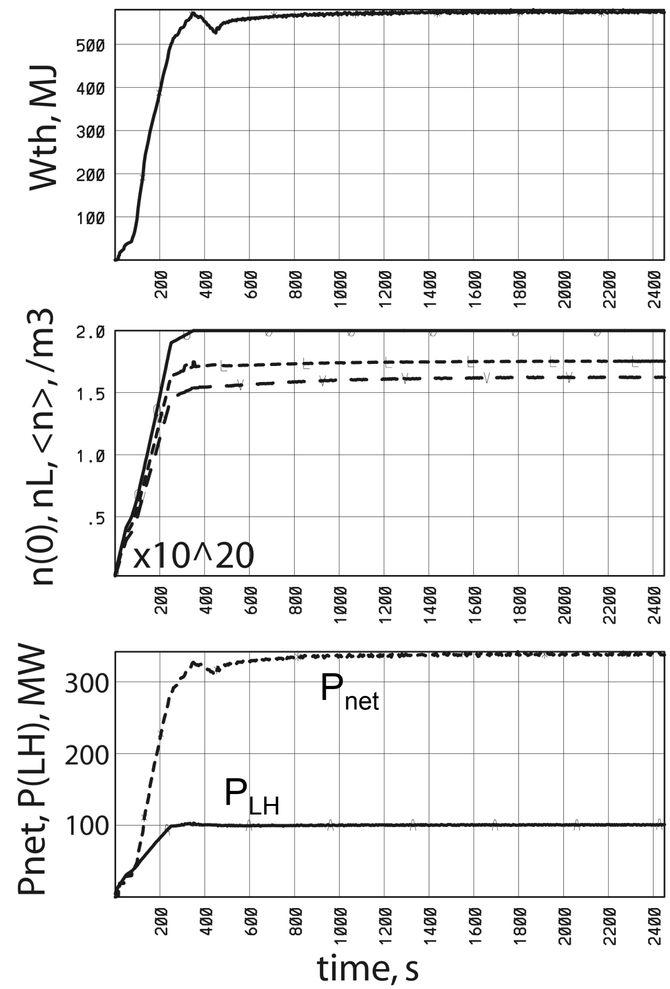
Examining broader and more peaked T profiles, including ITB, and an n profile with gradient spread across the minor radius

With EPED pedestal, n_{ped} ~ 1.1×10^{20} /m^3 and T_{ped} ~ 5 keV …..require H_{98} ~ 1.5



2) TSC 1.5D





$$P_{net} = P_{input} - P_{rad} - dW_{th}/dt$$

2) Parameters of TSC operating point

I_p = 10.6 MA
B_T = 5.5 T
I_{NI} = 10.8 MA
I_{BS} = 9.4 MA
I_{LH} = 0.86 MA
I_{FW} = 0.13 MA
$I_{grad(p)}$ = 0.4 MA

$q(0)$ = 2.85
q_{95} = 3.4
$li(1)$ = 0.46
β_N = 5.8
W_{th} = 580 MJ
$n_e(0) = 2\times10^{20}$ /m^3
$\langle n\rangle = 1.67\times10^{20}$ /m^3

τ_E = 1.7 s
H_{98} = 1.57
$T_{e,i}(0)$ = 40, 36 keV
$T(0)/\langle T\rangle$ = 2.15
Z_{eff} = 2.02 (0.3% Ar)
T_{ped} = 5 keV
$n_{ped} \sim 1.1\times10^{20}$ /m^3
f_{He} = 0.077

P_α = 380 MW
P_{aux} = 55 MW
P_{brem} = 50 MW
P_{line} = 35 MW
P_{cycl} = 15 MW
P_{LtoH} = 100 MW
P_{net} = 339 MW

R = 5.5 m
a = 1.375 m
κ = 2.18
κ_{95} = 2.11
δ = 0.68
δ_{95} = 0.58

3) Plasma Fueling and Exhaust (consistency with UEDGE analysis)

ACT1 has a fusion power of 1804 MW, which means we produce 6.4×10^{20} He / s which we must exhaust at the same rate…we ignore here implantation losses

The helium fraction in the core ($f_{He} = n_{He}/n_e$) is 0.073
The DT fuel fraction in the core is ($f_{DT} = n_{DT}/n_e$) is 0.8….we will neglect impurities for this case, then $f_{DT} = 1 - 2f_{He}$

In the divertor the fractions of He and DT can be different, so there is a He enrichment factor, $\eta = (n_{He,o}/n_{DT,o})/(n_{He}/n_e)$…..can UEDGE tell me this??

Exhaust rate of He needs to be equal to the production rate, $E_{He} = 6.4\times10^{20}$ /s, and the DT exhaust rate is related, $E_{DT} = (f_{DT}/f_{He})\, E_{He}$……but we want to include the He/DT fractions in the divertor where particles are pumped

$E_{DT} = (1-2f_{He}\eta)/(f_{He}\eta)\, E_{He} = 7.5\times10^{21}$ /s @ $\eta=1$ and 4.3×10^{22} /s @ $\eta=0.2$
(actual DT particles pumped is ½ of this since they are molecules, D_2, T_2, DT)

Fueling is then the sum of the exhausted DT plus the burned DT,
$F_{DT} = (7.5\text{-}43 \times 10^{21} + 2\times6.4 \times 20^{20}$ /s$) = 8.8 - 44.3 \times 10^{21}$ /s

4) Topics for detailed physics and systems code comparisons

- Plasma temperature profile originally used in systems scan is too broad, T(0)/<T> = 1.8, lowest from 1.5 D is about 2.10

- Discrepancy in β_N tracked down to T and n profiles representations and volumes in systems code
  - Profiles from 1.5D have finite n at separatrix, and finite T at pedestal, BUT systems code in scans is assuming these are going to zero at the plasma edge (nrat and trat)
  - Volumes in physics module use elongated plasma formulas, so $V = 2\pi^2 R a^2 \kappa$

- It is more accurate to use 95% shape parameters with full major and minor radius in the systems code, to infer a viable 1.5D operating point

- Assuming that η_{CD} ($n_{20} R I_{CD}/P_{CD}$) in plasma for Lower Hybrid is 0.27 (ARIES-AT), but 1.5D analysis indicates this is ~ 0.15 (amp/m^2-W x10^{20})

- Bootstrap current comparison indicates a correction should be applied

I_p = 10.6 MA
B_T = 5.5 T
R = 5.5 m
a = 1.375 m
n/n_{Gr} = 0.95

Inpar changes:
1) ali = 0.5 → 0.47
2) tpote = 5.09 → 5
3) etacd = 0.27 → 0.15
4) ak, akx = 2.2 → 2.1
5) delta = 0.7 → 0.575
6) qcyl = -4.0 → -3.725
7) **an = 0.3 → 0.55**
8) **drat = 0 → 0.4**
9) **at = 0.8 → 1.7**
10) **trat = 0 → 0.15**
11) Q = 40 → 33
12) rcd = 0.7 → 0.85

Sysplas changes:
1) vol, area
2) f_{BS}

Need to watch $\beta_N^{th} + \beta_N^{fast} < \beta_N^{limit}$

	ACT1 sys	TSC 1.5D	New ACT1 sys
κ (κ_{95})	2.2	2.2 (2.1)	2.1
δ (δ_{95})	0.7	0.7 (0.58)	0.575
q_{95}	**4.4**	**3.3**	3.7
β_N	**4.5**	**5.5**	5.5
P_α	361	365	364
P_{brem}, MW	50.6	50	53.7
P_{line}, MW	29.2	34.6	23.7
P_{cycl}, MW	12.	13.5	20.
P_{aux}, MW	45.1	55.0	55.
P_{CD}, MW	26.9	40.0 (LH)	43.
Q	40	33	33
f_{BS}	0.90	0.85	0.89
H_{98}	1.44	1.5	1.59
W_{th}, MJ	513	544	553
$n_o/\langle n \rangle$	1.29	1.26	1.27
$T_o/\langle T \rangle$	1.79	2.14	2.15
V_{plas}, m^3	451	391	396
T_{edge}/T_o	**0**	**0.15**	0.15
n_{edge}/n_o	**0**	**0.38**	0.40
T_o, keV	26.7	36.7	39.

4) Systems scan with the new physics inputs and updates….1000 MW_e

Input fixed:

$A = 4$
$\delta = 0.575$
$\kappa = 2.1$
$\alpha_n = 0.55$
drat = 0.40
$\alpha_T = 1.70$
trat = 0.15
$\tau_p^*/\tau_E = 5.0$
$l_i = 0.5$
$\eta_{CD} = 0.15$
$r_{CD} = 0.85$
$f_{Ar} = 0.3\%$

Scanned parameters:

$B_T = 4.5 – 7.5$ T
$\beta_N = 0.04 – 0.06$
$q_{95} = 3.25 - 5.50$
$n/n_{Gr} = 0.85 – 1.05$
$Q = 20 – 45$
$R = 4.0 – 8.0$ m

Background:

ARIES TF coil algorithm
Includes bucking cylinder
ARIES PF coil algorithm

$\Delta_{SOL} = 0.10$ m
$\Delta_{blanket} = 0.35$ m
$\Delta_{shield} = 0.24 + f(\langle N_w\rangle)$ m
$\Delta_{VV} = 0.40$ m
Δ_{gaps} (total) = 0.07 m

$f_{div,rad} = 0.95$

$P_{subs} = 0.05 \times P_{elec,gross} \sim 55$ MW
$P_{pump} = 0.01 \times P_{fusion} \sim 20$ MW
$\eta_{aux} = 0.4$
$\eta_{pump} = 0.9$
$\eta_{th} = 0.58 + f(\langle N_w\rangle, q_{peak}^{FW})$

$q_{div}^{peak} \leq 10$ MW/m^2
$f_{BS} \leq 0.9$
$n/n_{Gr} \leq 1.0$
$\beta_{N,th} + \beta_{N,fast} \leq 5.5$

Low radius solutions

1) Higher R → due to lower CD efficiency, f_{subs} weaker effect
2) Higher B_T → compensate lower $\beta_{N,th}$
3) Higher P_{fusion} → compensate the higher recirculating power (including lower f_{BS})

R, m	B_T, T	Ip, MA	$\beta_{N,th}$	q_{95}	f_{BS}	n/n_{Gr}	Q	P_{aux}, MW	H_{98}	$\langle N_w \rangle$	B_{tmax}, T	q_{div}
6.5	6.0	11	4.5	4.5	0.86	1.0	28	71	1.5	2.4	10	8.6
6.2	6.3	11	4.5	4.5	0.86	1.0	30	68	1.5	2.8	11	9.6
6.2	6.6	11	4.3	4.8	0.85	1.0	30	66	1.5	2.7	12	9.2
6.5	6.9	12	4.0	5.0	0.85	1.0	28	74	1.5	2.5	12	8.7
6.2	6.9	11	4.3	5.0	0.90	1.0	42	45	1.7	2.6	12	7.5
6.0	7.2	11	4.3	5.0	0.90	1.0	42	47	1.6	2.9	13	8.7
6.0	7.5	11	4.0	5.2	0.89	1.0	38	51	1.6	2.8	13	8.4
ACT1												
5.5	5.5	10.6	4.5	4.4	0.9	0.95	40	45.1	1.44	2.74	10	6.7
ACT-SA1, 1b?												
5.75	5.5	11.0	4.5	4.4	0.9	0.9	35	54	1.48	2.9		6.7

4) PF Coil solution…Volt-seconds consumption to rampup Ip

TSC shows that about 120 V-s from all the PF coils are necessary to build up the plasma current

The solenoid provides a portion of this

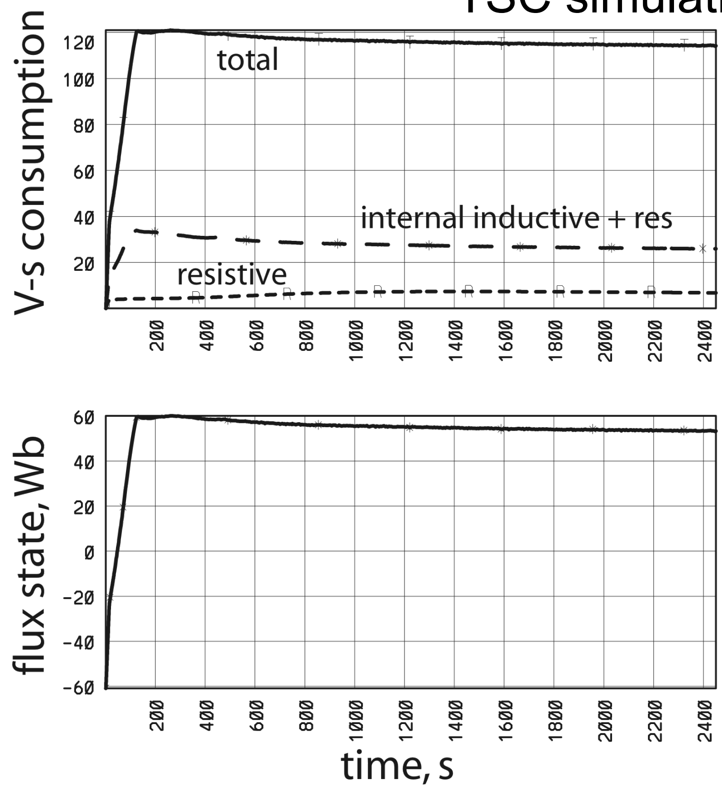
The PF Coil section of the systems code estimates

- For ACT1, 74 V-s from solenoid and 130 V-s from all coils total are needed
- For a new physics point, this is 71 and 140 V-s, respectively

The estimate for the total V-s required is fairly accurate, 120 V-s vs 130 or 140 V-s

The upper value is used to size the solenoid coils, so they are a bit over-built

TSC simulation



4) Systems work to do

Get our assumptions for aggressive and conservative operating points layed out clearly for all 4 corners, check that sys code is doing this

- Recirculated powers
- Physics parameters
- Radial builds
- Etc.

Rerun physics database with changes to input and source code

Can we incorporate any more information from detailed physics or engineering analysis NOW…..edge plasma analysis for example

Rerun engineering, build-out and cost…..need to insert a filtering step after physics module that involves the critical engineering calculations….or run all cases thru the full systems code on PPPL cluster

Perform the focusing on desired operating space for each corner, with higher resolution