ACT2 Systems and Physics Progress

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Examination of ARIES-I, “conservative” operating point

ARIES-I is a first stability plasma operating point, similar to what we are trying to establish in ACT2

ARIES-I: (from aries website)

R = 6.75 m
a = 1.5 m (A = 4.5)
κ_x = 1.8
δ_x = 0.7
β_N^{tot} = 3.2
B_T = 11.3 (21 T at coil)
Ip = 10.2 MA
Z_{eff} = 1.65
f_{BS} = 0.68
$\langle n \rangle = 1.45\text{x}10^{20}$ /m^3
$\langle T \rangle_n$ = 19.3 keV
τ_E = 2.5 s
f_O = 1.0%
τ_p^*/τ_E = 4
f_{He} = 10%
W_{th} = 618 MJ
T(0)/<T> = 36.6/17.4 = 2.1
n(0)/<n> = 1.89/1.45 = 1.3
n/n_{Gr} = 1.1
Plasma vol = 489 m^3

Present systems code reproduction

κ = 1.7
δ = 0.55
β_N^{th} = 2.7 (β_N^{fast} = 0.53, β_N^{tot} = 3.23)
Z_{eff} = 1.57
f_O = 0.7%
f_{He} = 8.8%
τ_E = 2.3 s
H_{98} = 1.49
W_{th} = 586 MJ
T(0)/<T> = 2.15
n(0)/<n> = 1.29
Plasma vol = 473 m^3

Examination of ARIES-I, cont'd

Power related quantities and engineering solution

<u>ARIES-I:</u>

$Q = 19.9$
$P_{fus} = 1925$ MW
$P_{CD} = 102$ MW
$P_{alpha} = 385$ MW
$P_{brem} = 49$ MW
$P_{cycl} = 195$ MW
$P_{line} = ?$
$\eta_{CD} = 0.32$

SiC structure
$\eta_{th} = 0.49$
$P_{wall\text{-}plug,\ aux} = 141$ MW ($\eta_{aux} = 0.72$)
$P_{pump} = 54$ MW
$P_{subsystems} = 52$ MW
$M_n = 1.3$

$q_{div}^{peak} = 3.88$ MW/m^2

Present systems code reproduction

$Q = 17$
$P_{fus} = 1826$ MW
$P_{CD} = 106.6$ MW ($P_{aux} = 107.3$ MW)
$P_{alpha} = 365$ MW
$P_{brem} = 46$ MW
$P_{cycl} = 170$ MW
$P_{line} = 3.3$ MW
$\eta_{CD} = 0.37$

Use same settings as ARIES-I

Get 916 MW of electric power

$q_{div}^{peak} = 15.3$ MW/m^2

Examination of ARIES-I, discussion

ARIES-I uses a SiC structural material, and has higher thermal conversion efficiency, we are using DCLL in ACT2

The plasma can be reproduced in the present systems code

Higher H_{98} (1.49 vs 1.3) and η_{CD} (0.37 vs 0.175) than we are using in ACT2

Higher η_{aux} giving much lower $P_{wall\text{-}plug,aux}$
Lower additional recirculating powers assumed in ARIES-I

Taking credit for very high field at TF coil, 21 T (at 27 MA/m^2), in ACT2 we are trying to keep this value lower (ITER values are 12-13 T at 15 MA/m^2)

Estimate of divertor heat flux is very low, but this was in early 1990's

Applying ARIES-I engineering/power balance data to our ACT2 physics database gives solutions at 6 m

Comparison of ARIES-I and ACT2 assumptions on operating space

ACT2:

DCLL, Ferritic structure

$\eta_{th} \sim 0.44$

$\eta_{aux} = 0.40$

$P_{pump} = 0.04xP_{fus}$

$P_{subsystems} = 0.04xP_{elec,gross}$

$M_n = 1.1$

ARIES-I:

SiC structure

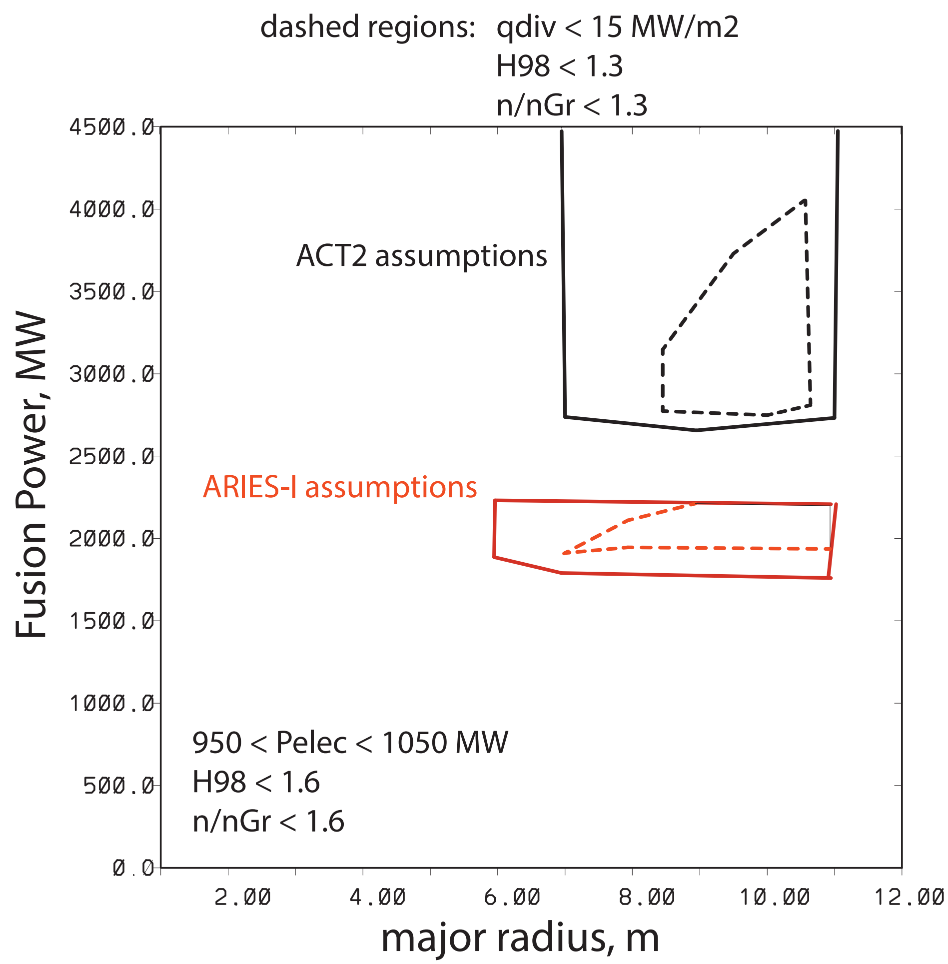
$\eta_{th} = 0.49$

$\eta_{aux} = 0.72$

$P_{pump} = 0.03xP_{fus}$

$P_{subsystems} = 0.03xP_{elec,gross}$

$M_n = 1.3$



Both assume 90% radiated power in divertor

ACT2 Systems Scan Updates

Mark and I have worked through the ACT2 database, but found that the interesting region was too sparsely represented since the scan was very broad in R, B_T, etc

The scan was focused on the promising R,q_{95}, and B_T, and more profiles were included

$8.0 \leq R \leq 10.5$ m
$7.25 \leq B_T \leq 8.75$
$2\% < \beta_N^{th} < 3.25\%$
$6.5 \leq q_{95} \leq 9.0$
$0.9 \leq n/n_{Gr} \leq 1.4$
$1.27 \leq n(0)/\langle n \rangle \leq 1.41$
$2.14 \leq T(0)/\langle T \rangle \leq 3.02$

The main filtering constraints are:

$950 \leq P_{elec} \leq 1050$

$\beta_N^{th} + \beta_N^{fast} < 3.25\%$

$H_{98} \leq 1.3$

$n/n_{Gr} \leq 1.3$

$q_{div} \leq 15$ MW/m2

R	B_T	I_p	β_N^{th}	q_{95}	n_G	Q	H_{98}	P_{aux}	f_{BS}	B_{Tc}	q_{div}	Nw	Z_{eff}
9.0	7.75	13.1	2.75	7.0	1.3	32.5	1.21	85	0.82	13.3	14.9	1.80	1.79
9.0	8.0	13.5	2.75	7.0	1.3	32.5	1.25	87.5	0.82	13.7	13.8	1.85	1.81
9.0	8.25	13.9	2.75	7.0	1.3	25.0	1.26	120	0.82	14.2	14.6	1.95	1.97
9.0	8.25	13.0	2.75	7.5	1.3	32.5	1.30	86.2	0.88	14.2	13.8	1.83	1.81
9.0	8.5	14.3	2.75	7.0	1.3	25.0	1.29	125	0.82	14.6	14.3	2.03	1.99
8.5	8.5	13.5	2.75	7.0	1.3	30.0	1.29	93.7	0.82	14.9	13.2	2.06	1.83
9.0	8.75	13.8	2.50	7.5	1.3	30.0	1.24	96.0	0.80	15.0	13.1	1.88	1.82
8.5	8.75	13.9	2.75	7.0	1.3	32.5	1.29	93.5	0.82	15.3	14.1	2.22	1.99

Lots more solutions with R = 8.5, 8.75, and 9.0 m

B_T = 7.75, 8.0, 8.25, 8.5, and 8.75 T

β_N^{th} = 2.5 and 2.75

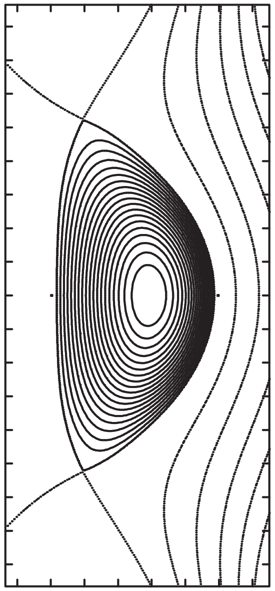
Q = 20, 22.5, 25, 27.5, 30, and 32.5

q_{95} = 6.75, 7.0, 7.25, 7.5, and 7.75

R	B_T	I_p	β_N^{th}	q_{95}	n_G	Q	H_{98}	P_{aux}	f_{BS}	B_{Tc}	q_{div}	Nw	Z_{eff}
9.25	8.0	13.4	2.75	7.25	1.3	32.5	1.30	85.2	0.85	13.6	12.4	1.71	1.97
9.25	8.75	13.7	2.50	7.75	1.3	30.0	1.28	93.9	0.82	14.9	11.9	1.74	1.98
9.25	8.75	14.2	2.50	7.50	1.3	27.5	1.27	106	0.79	14.9	12.1	1.79	1.83
9.50	7.75	13.8	2.75	7.0	1.3	32.5	1.28	86.7	0.82	13.1	12.1	1.65	1.82
9.50	8.5	14.1	2.50	7.5	1.25	30.0	1.29	93.1	0.80	14.4	11.7	1.63	1.83
9.50	8.5	14.1	2.50	7.5	1.30	27.5	1.27	105	0.80	14.4	11.8	1.68	1.83
9.50	8.75	15.6	2.50	7.0	1.20	22.5	1.30	136	0.74	14.8	12.5	1.79	2.02
9.50	8.75	14.5	2.50	7.5	1.30	27.5	1.29	108	0.80	14.8	11.2	1.74	2.15
9.50	7.75	14.3	2.75	6.75	1.30	27.5	1.28	104	0.79	13.1	11.4	1.67	2.12
9.50	8.0	14.8	2.75	6.75	1.30	25.0	1.28	122	0.79	13.5	12.4	1.79	2.14
9.50	8.5	13.7	2.50	7.75	1.30	32.5	1.26	87.4	0.82	14.4	12.3	1.66	1.83
9.50	8.75	14.1	2.50	7.75	1.30	32.5	1.29	91.2	0.82	14.8	12.2	1.74	1.83

$q_{div} \leq 12.5$ MW/m2

Free-boundary Solution and Setting Up for TSC



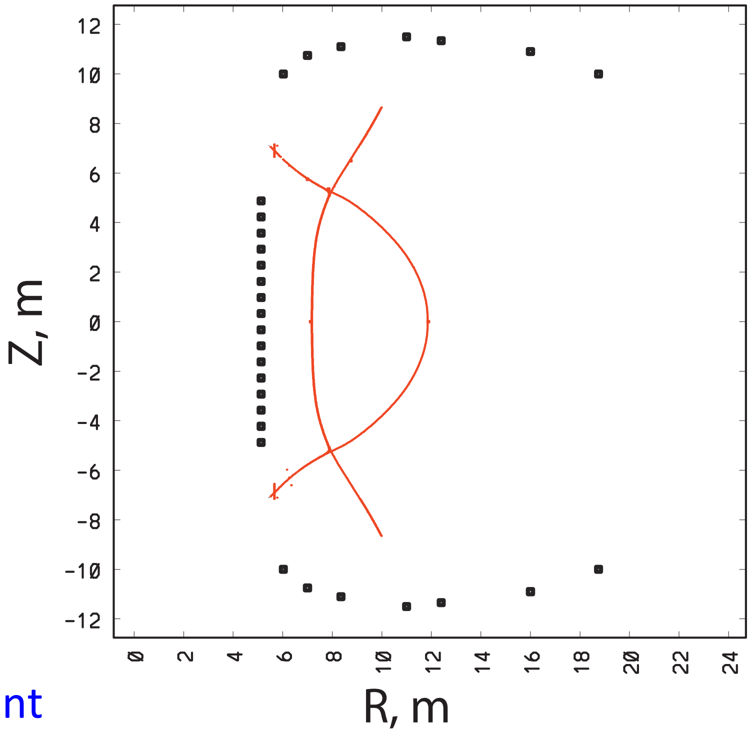
Tentative Plasma Parameters for Equilibria

R = 9.5 m
a = 2.375
kappa = 2.2
delta = 0.625
B_T = 8 T
betaN = 3.26
li(1) = 0.72

PF coils shifted from ACT1 solution

Have calculated equilibria at
0, 0.5, 2.5, 3.5, 4.5, 6.5, 9, and 12/14 MA

Need to set up TSC simulation



*final PF solution will likely be different

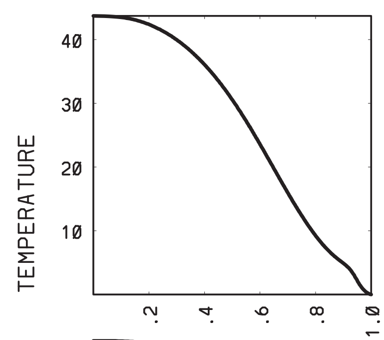
Ideal MHD Stability

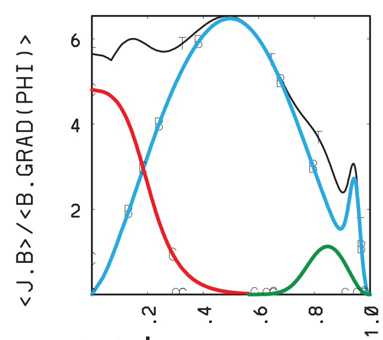
Pressure-current consistent no wall stable equilibria are very hard to find

The current profile is still dominated by bootstrap current, and so the current and pressure profiles are coupled…..our only other CD components are ICRF FW, ECCD, and LHCD

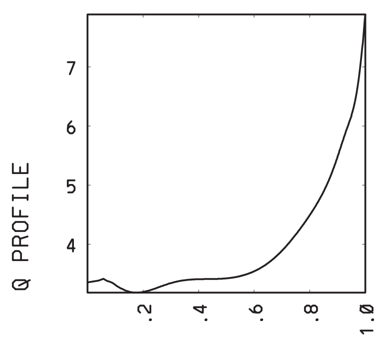
May still take credit for wall at Ring Structure, intrinsic rotation, kinetic stabilization effects….which are used in experiments

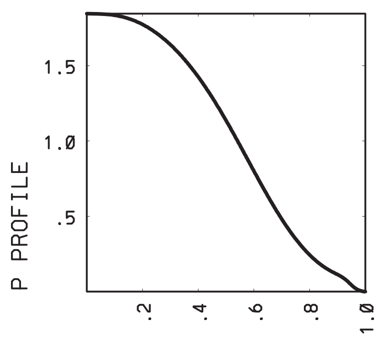
b/a = 0.45, corresponds to 1.07 m, which is behind the blanket, from the plasma boundary, most cases are stable with this wall

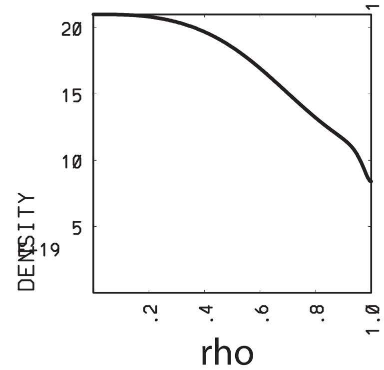




total
ICRF/FW
BS
LHCD







Ip = 13-14 MA

R = 9.5 m

a = 2.375

I_{LH} ~ 0.5-1.5 MA

I_{FW} ~ 0.9 MA

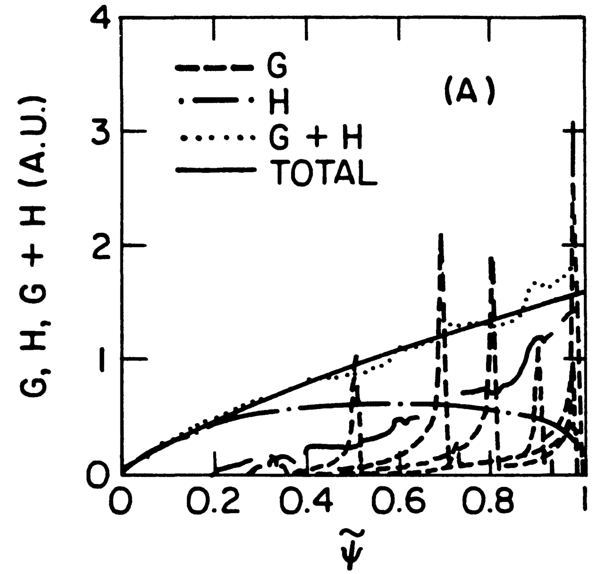
Heating and Current Drive

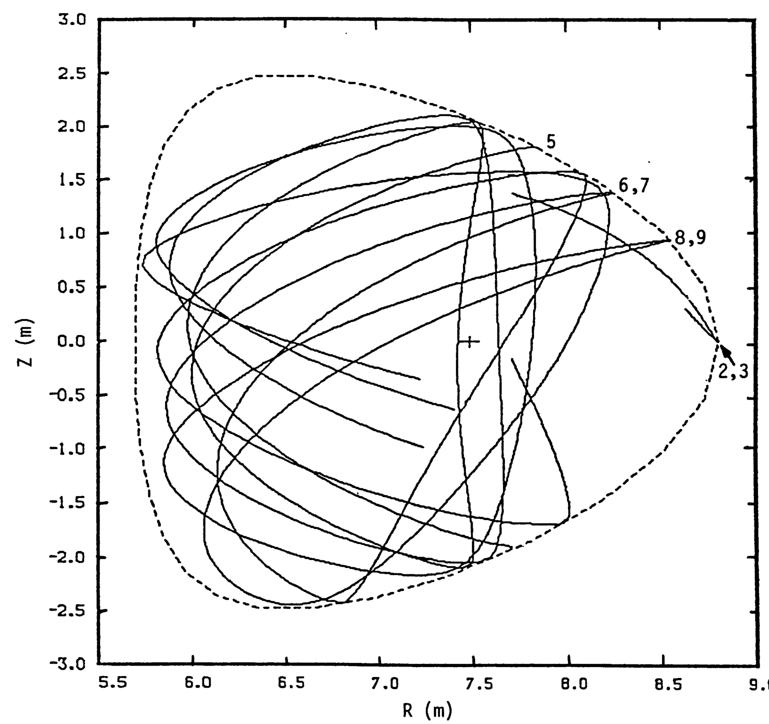
ARIES-I CD was achieved with ICRF FW launched from off the midplane, with multiple reflections from the separatrix…leading to multiple damping locations off-axis

This is generally a poor way to achieve good power absorption, as it leads to parasitic absorption mechanisms….these optimistic results are likely due to assumptions in ray-tracing analysis

Better to have single pass absorption as we had in ACT1, as this provides the most reliable behavior from experiments…..however then there is no off-axis absorption

We will check with full wave analysis if off-midplane can provide off-axis damping





ACT2 Pedestal Estimate

$$p_{ped} = 2410\left(\frac{M}{n_{ped,20}}\right)^{0.33} \frac{R^{1.33}}{a^4} \frac{I_p^2}{\left(\frac{1+\kappa^2}{2}\right)^{2.33}} (1+\delta)^{3.2} \kappa^{3.62} A^{-2.94} \left(\frac{P_{tot}}{P_{L-H}}\right)^{0.06}$$

Using Sugihara 2003 with

- M=2.5
- n_{ped} ~ 0.65 x 10^{20} /m^3
- R = 9.5
- a = 2.375
- Ip = 13.5 MA
- κ = 2.2
- δ = 0.63
- A = 4
- P_{tot} = 750 MW
- P_{LH} = 330 MW

I get ~ 45 kPa, and T_{ped} ~ 2 keV

Due to our keeping Ip low in order to keep recirculating power low, while making R (and a) large to provide P_{fus} high and q_{div} low enough…..

Recall for ACT1, p_{ped} ~ 160 kPa

n_{Gr} = Ip/(πa^2), increasing a is driving n_{Gr} down

Implications are that LHCD could damp deeper in the plasma

The Physics Basis for an Advanced Physics and Advanced Technology Tokamak Power Plant Configuration, ARIES-ACT1

I. Introduction
II. Systems Identification of Physics Operating Point
III. Time-Dependent Free Boundary Simulations ←
IV. Ideal MHD Stability of low-n kink, high-n ballooning, peeling-ballooning, and vertical
V. Fast Particle Stability
VI. Approaching or Exceeding the Greenwald Limit
VII. Poloidal Field Coils
VIII. Heating and Current Drive
IX. Scrape-off Layer and Divertor Plasma Simulations
X. Heat Flux for Steady State, Transient, and Off-Normal Loading ←
XI. Small and No ELM Regimes ←
XII. Tritium Burnup ←
XIII. Conclusions and Discussion ←

← More work