THE OPTIMAL TOKAMAK CONFIGURATION NEXT-STEP IMPLICATIONS

by
R.D. STAMBAUGH

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San Diego, California

*Most calculations reported herein were done by Y-R. Lin-Liu.
†Work supported by General Atomics Internal Funds.

May 1, 2001

GENERAL ATOMICS

ANY NEXT STEP DEVICE SHOULD BE FORWARD LOOKING AND CARRY FORWARD THE CURRENT RESEARCH ISSUES OF THE DAY

- Any Next Step Device Will Have a 20–30 Year Research Period
- For its research program to remain vital over that length of time, we must design the device so that it can carry forward the most up-to-the minute research issues of today
- Current research issues need a future to expand into
- If we design the device based on the physics we are currently sure of, then, considering current research progress, we have to look carefully at whether the device once built will be able to address the issues of that future day

WHAT ARE THE CURRENT PHYSICS RESEARCH LINES THAT NEED TO BE CARRIED FORWARD?

Current Research Line	Machine Design Feature Implied
Improved Confinement Through Transport Barriers	Maximization of the E×B Turbulence Shearing Rate
Understanding Transport	Suitable Diagnostics and Operational Flexibility
Steady-state Through High Bootstrap Fractions	1. Ability to Handle and Maintain Equilibria with Hollow Current Profiles 2. Wall Stabilization for Higher Normalized Beta Operation
Operation Above the Free Boundary Beta Limit	Wall Stabilization Through Feedback and Plasma Rotation
Resolution of the Disruption Issue	1. Long Pulse, Precise Plasma Control Near Understood Stability Limits 2. Ability to Handle Disruptions 3. Mitigation of Disruptions by Massive Gas Puffs or Liquid Jets
Profile Control for higher beta and advanced confinement	1. Auxiliary Systems to Provide Local Control of Pressure, Current, and Rotation Profiles 2. Diagnostic Systems To Measure the Resulting Profiles
Detached Divertor Solutions	Divertors Capable of Detached Operation at Densities Compatible With Steady-State
ELM-free Operational States	Ability to realize the EDA and/or QH–mode regimes
Erosion and Redeposition of First Wall Materials	High Particle Fluences to Surfaces and In-vessel Access For Inspection

WE ARE READY TO TAKE UP BURNING PLASMA AND STEADY-STATE ISSUES

Alpha Issues

More Gain ↓

- DT plasma properties
  - Alpha confinement
    - Alpha ash exhaust
      - Remote maintenance
        - Alpha driven instabilities
          - Self-heated profiles
            - High gain burn control

Steady State Issues

Fluence

- High bootstrap fractions (AT)
  - Steady-state magnets
    - Steady-state current drive
      - Tritium inventory
        - Hour long pulses
          - Resolve disruption issue
            - Blanket development
              - Low activation materials
                - Tritium breeding
                  - Month long operation
                    - First electric output

WHAT IS THE OPTIMUM TOKAMAK?

- Lin-Liu constructed equilibria with
  - Bootstrap fraction 99%, fully aligned
  - Found ballooning limit
    - ★ A point near edge
  - $p' = 0$ at separatrix
  - Wall stabilization assumed for kinks

- Spanned $1.5 \leq \kappa \leq 6$
  $1.2 \leq A \leq 7$

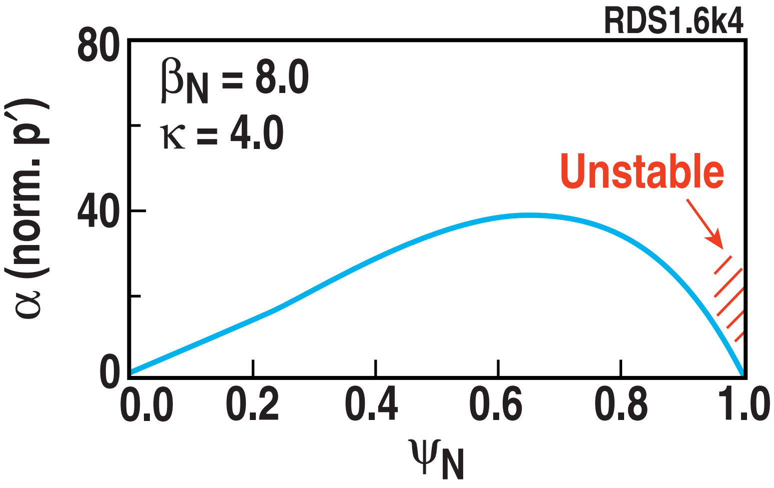
$$\beta_T \, \beta_p = 25 \left(\frac{1-\kappa^2}{2}\right)\left(\frac{\beta_N}{100}\right)^2$$

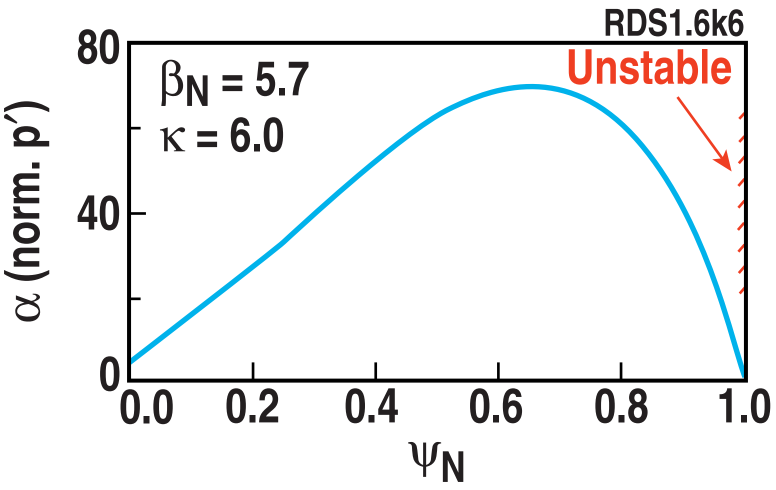
$$f_{bs} = c_{bs}\beta_p / \sqrt{A}$$

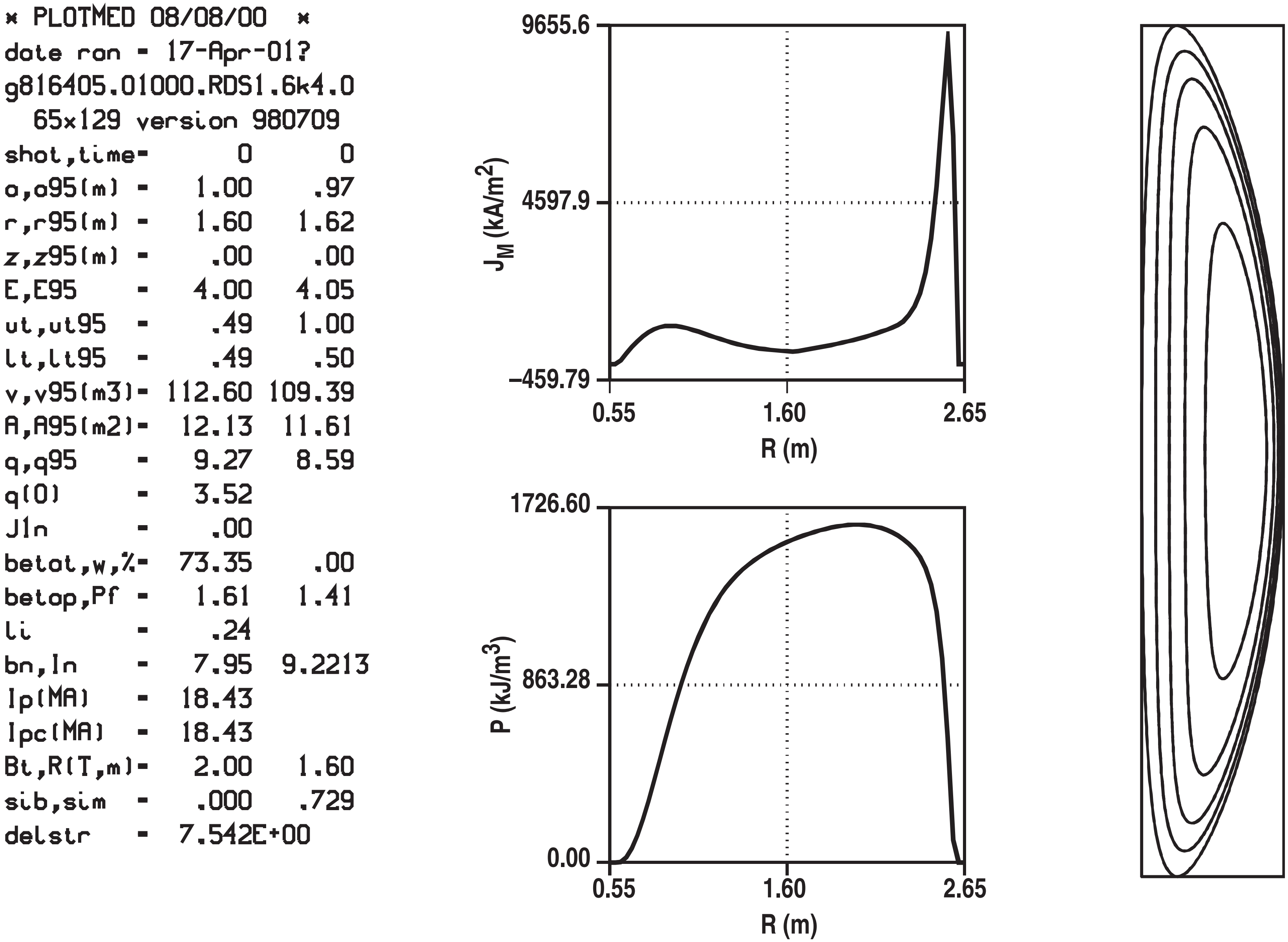
$$P_F \propto \beta_T^2 B_T^4$$

GENERAL ATOMICS

THE LIMITING EQUILIBRIA HIT THE BALLOONING LIMIT AT A POINT NEAR THE EDGE







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  65x129 version 980709
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r,r95(m) -    1.60    1.62
z,z95(m) -     .00     .00
E,E95    -    4.00    4.05
ut,ut95  -     .49    1.00
lt,lt95  -     .49     .50
v,v95(m3)- 112.60  109.39
A,A95(m2)-   12.13   11.61
q,q95    -    9.27    8.59
q(0)     -    3.52
J1n      -     .00
betat,w,%-   73.35     .00
betap,Pf -    1.61    1.41
li       -     .24
bn,In    -    7.95  9.2213
Ip(MA)   -   18.43
Ipc(MA)  -   18.43
Bt,R(T,m)-    2.00    1.60
sib,sim  -    .000    .729
delstr   -   7.542E+00
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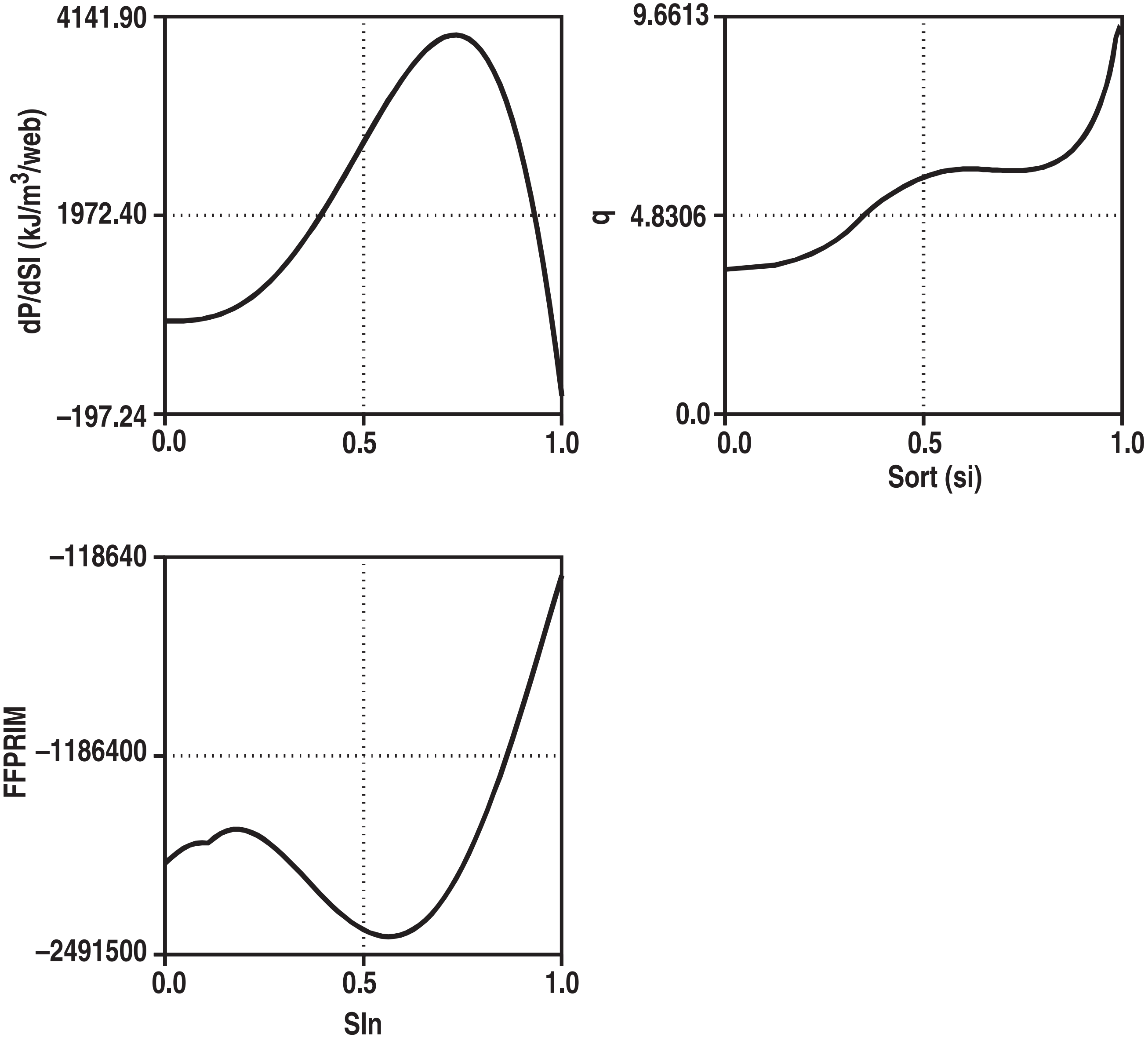

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  65x129 version 980709
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a,a95(m) =    1.00     .97
r,r95(m) =    1.60    1.62
z,z95(m) =     .00     .00
E,E95    =    6.01    6.08
ut,ut95  =     .50    1.00
lt,lt95  =     .50     .50
v,v95(m3)= 168.65  163.86
A,A95(m2)=   18.15   17.37
q,q95    =   13.36   11.98
q(0)     =    4.84
J1n      =     .00
betat,w,%=   80.86     .00
betap,Pf =    1.57    1.41
li       =     .23
bn,In    =    5.68 14.2320
Ip(MA)   =   28.36
Ipc(MA)  =   28.37
Bt,R(T,m)=    2.00    1.60
sib,sim  =    .003    .776
delstr   =   6.788E+00
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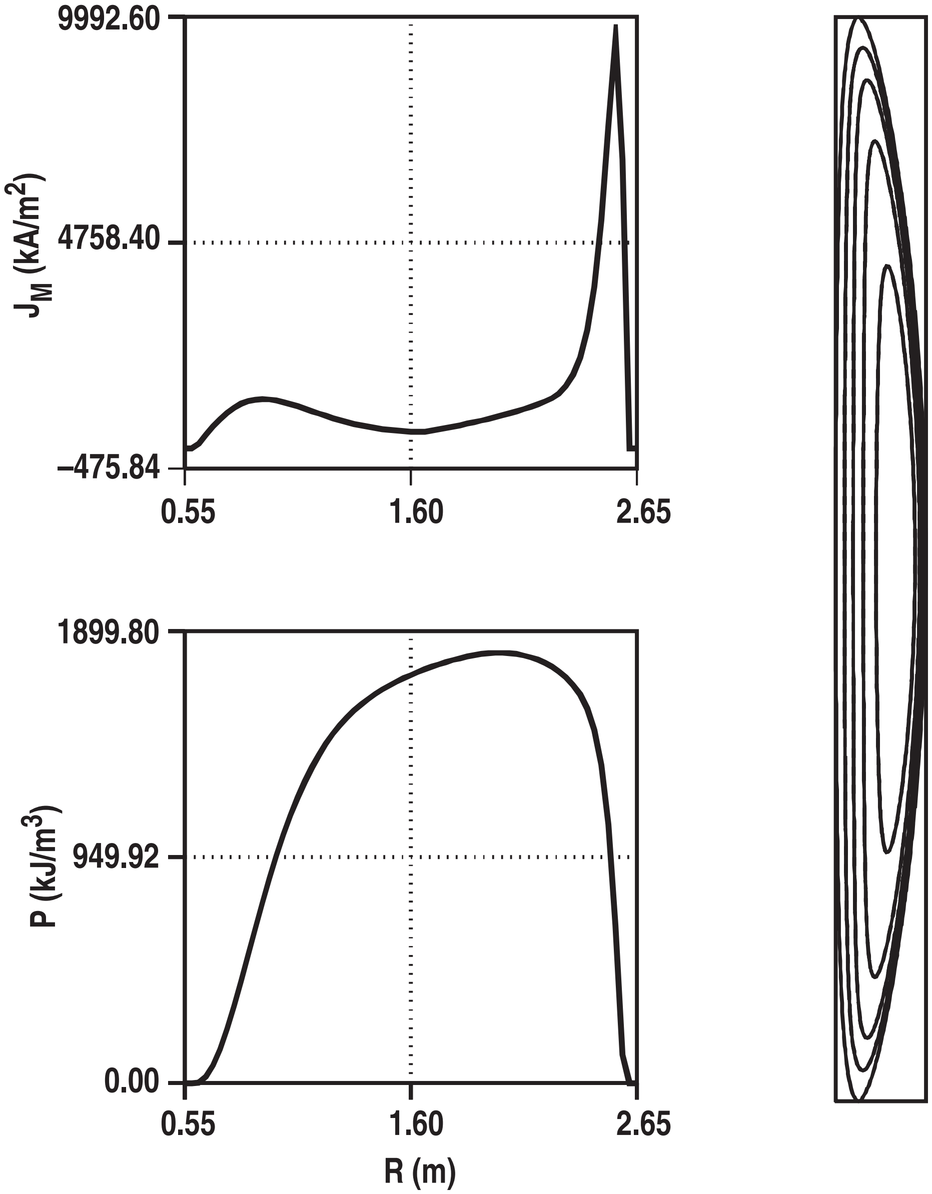

× PLOTMED 08/08/00 ×
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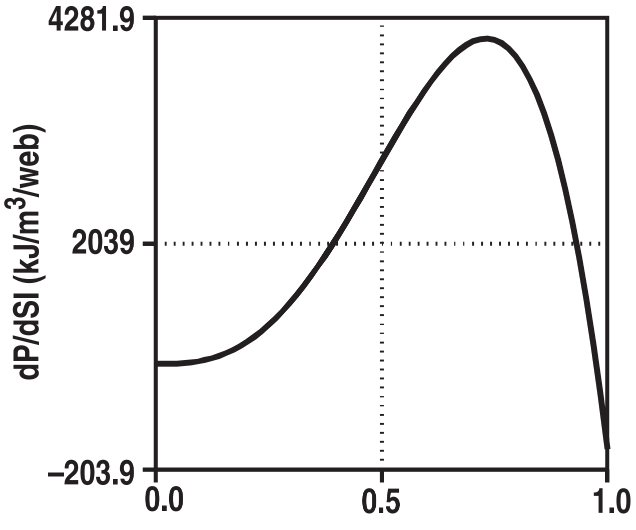
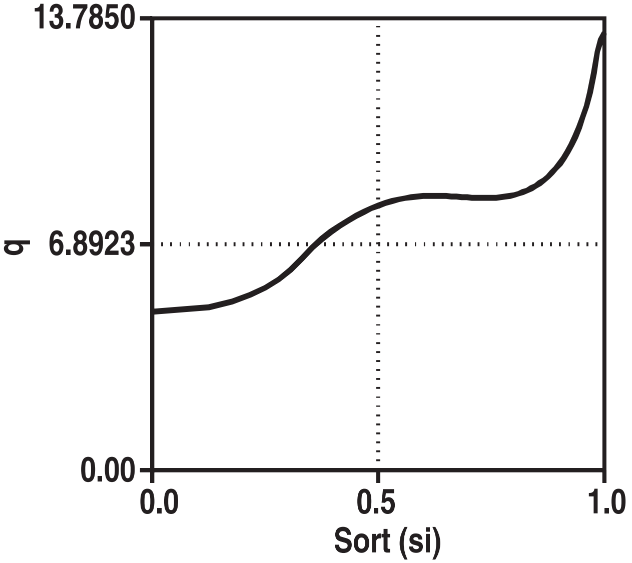
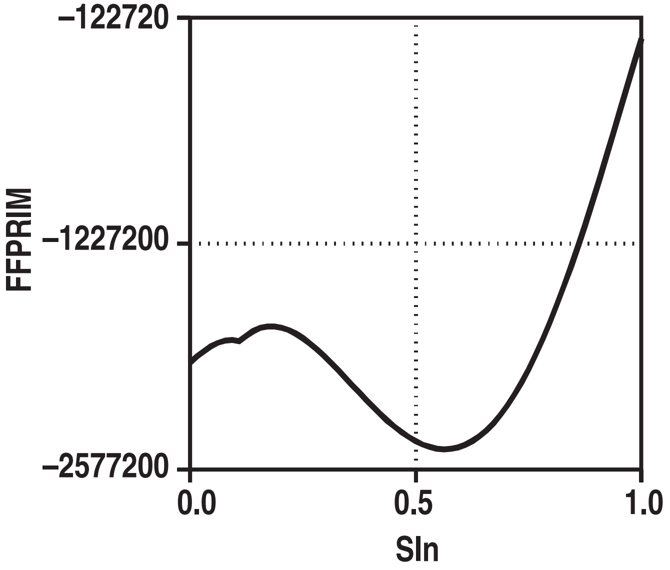


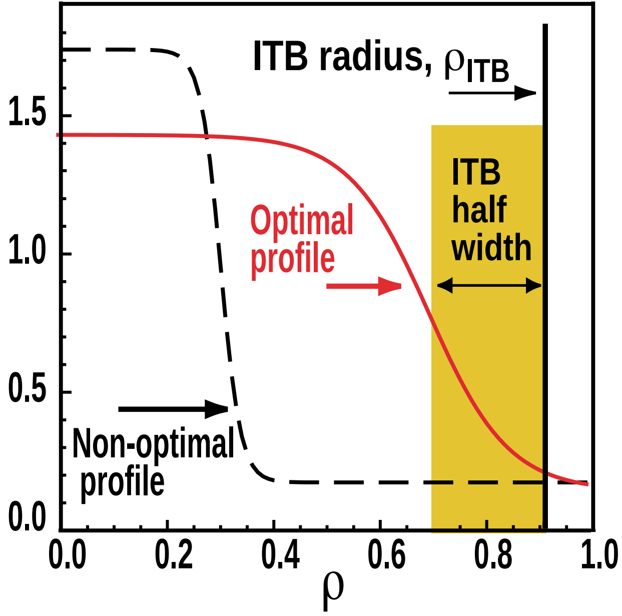




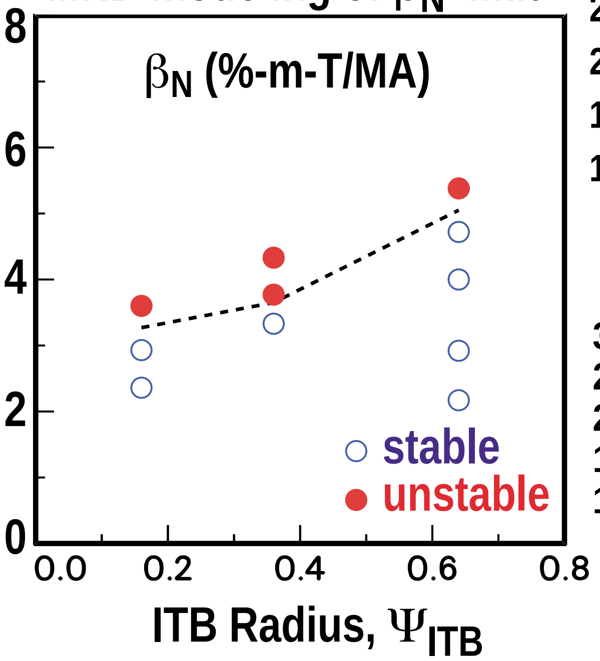
“ULTIMATE” AT PRESSURE PROFILES WILL REQUIRE AN ITB AT LARGE RADIUS, CONSISTENT WITH MHD STABILITY AND HIGH BOOTSTRAP FRACTION

- Modeling indicates that increasing ITB radius and barrier width is consistent with:
  - Higher fusion performance (larger high confinement volume)
  - Improved MHD stability limits
  - High bootstrap fraction and improved bootstrap current alignment

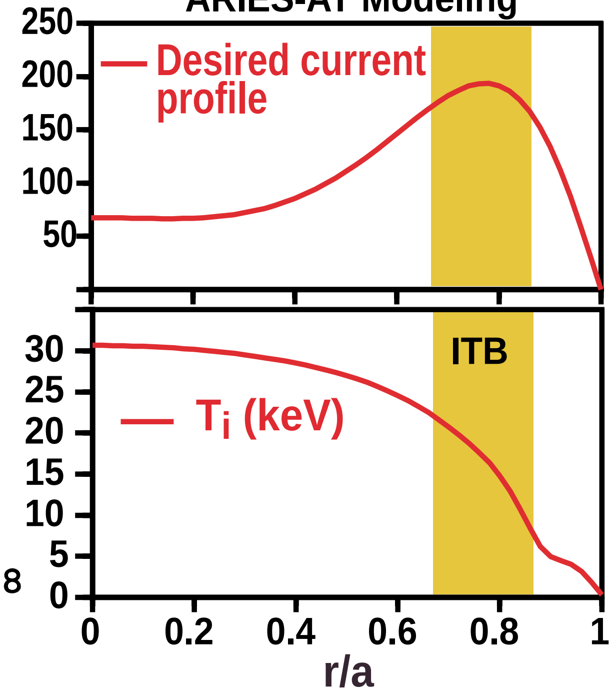
Schematic ITB T_i profiles



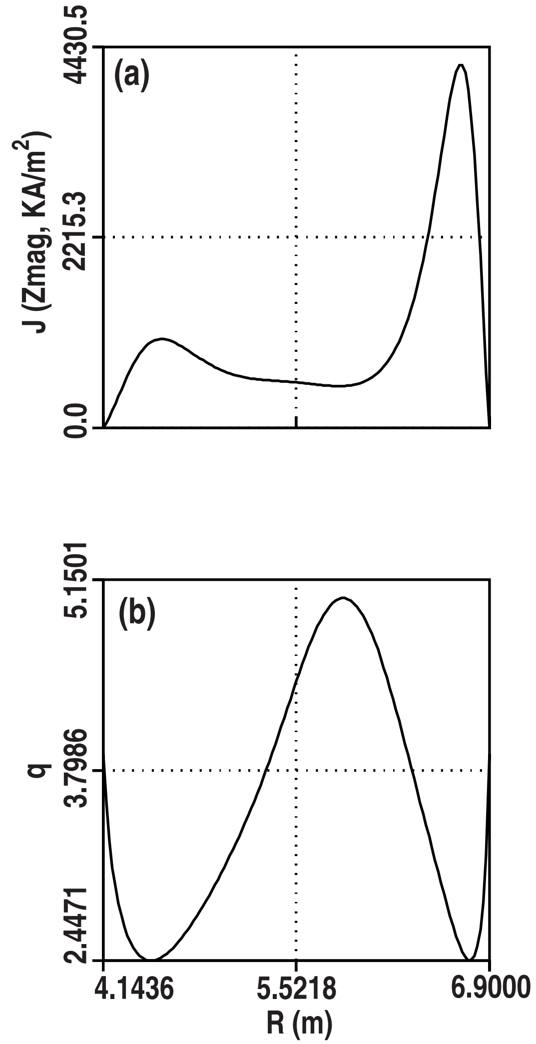
MHD modeling of β_N limit



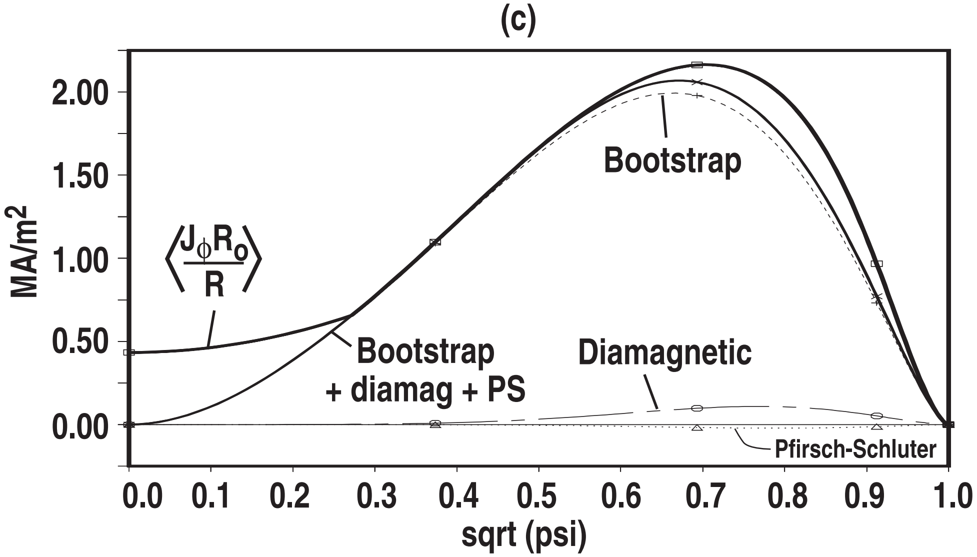
ARIES-AT Modeling



HIGH BOOTSTRAP FRACTION ARIES-AT SCENARIO DEMONSTRATES NEED FOR TRANSPORT CONTROL AT LARGE BOOTSTRAP FRACTION

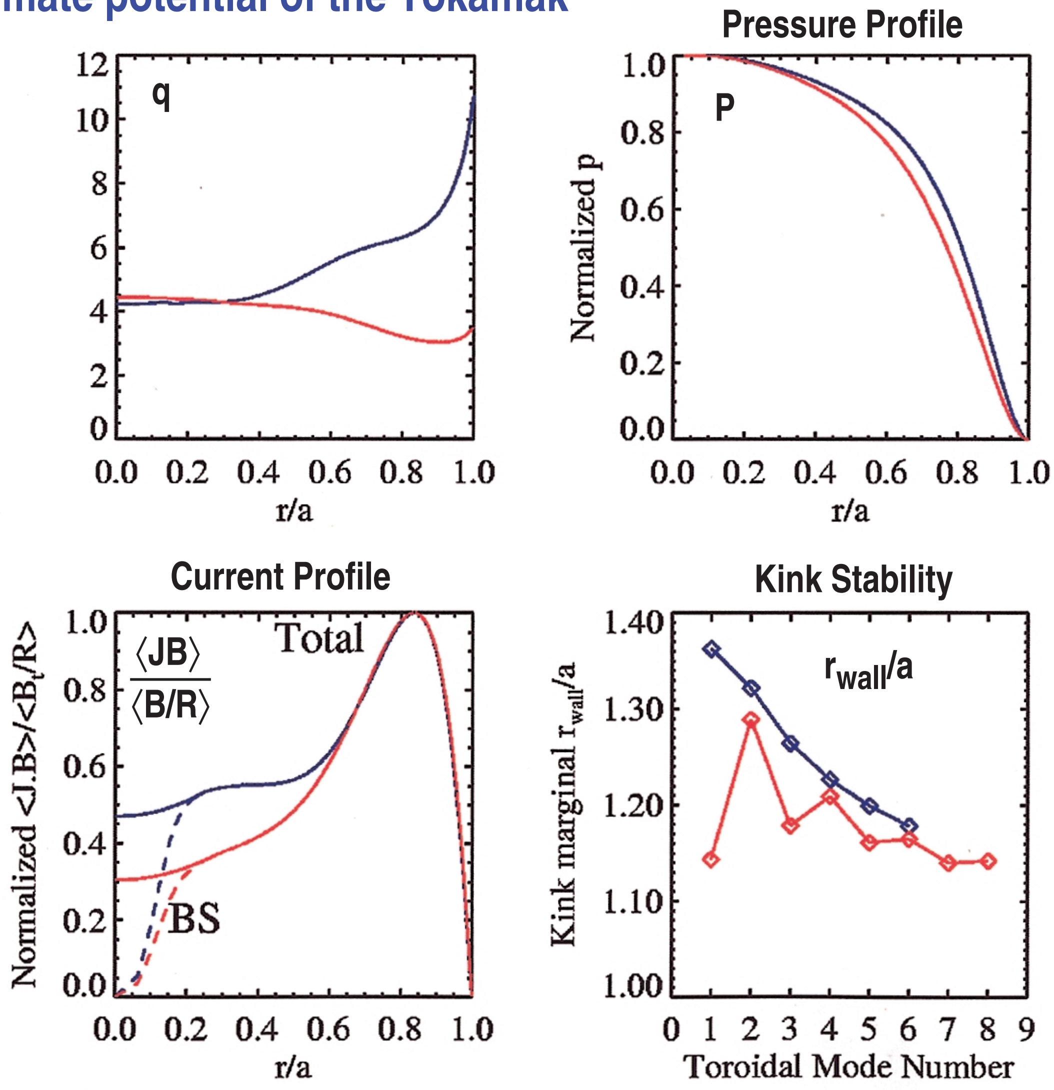


- AT large boostrap (I_{BS}/I) → 100%
  - J becomes naturaly hollow (NCS)
  - Alignment of J_{BS} with J_{total} requires broad pressure profile
  - Control of J requires control of transport profiles



THE FUTURE

- Advanced Tokamak stability theory points to states with very broad pressure profiles and hollow current profiles and nearly 100% bootstrap current as perhaps the ultimate potential of the Tokamak



Pressure Profile

Current Profile

Kink Stability

ARIES–AT

$A=3.3$

$\kappa=2.5$

$\delta=0.6$

$\beta=14\%$

$\beta_N=6$

ARIES–ST

$A=1.6$

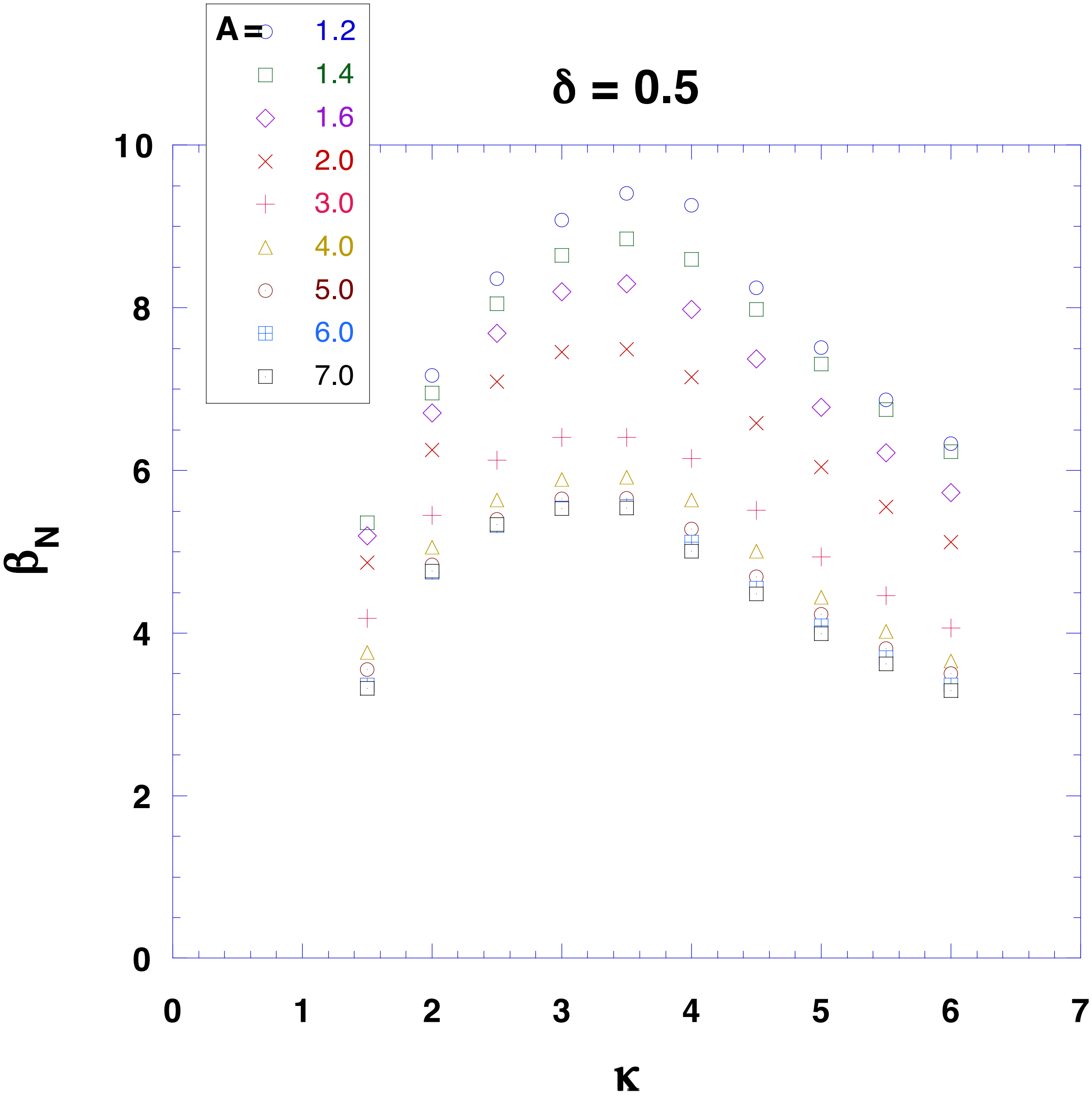
$\kappa=3.6$

$\delta=0.64$

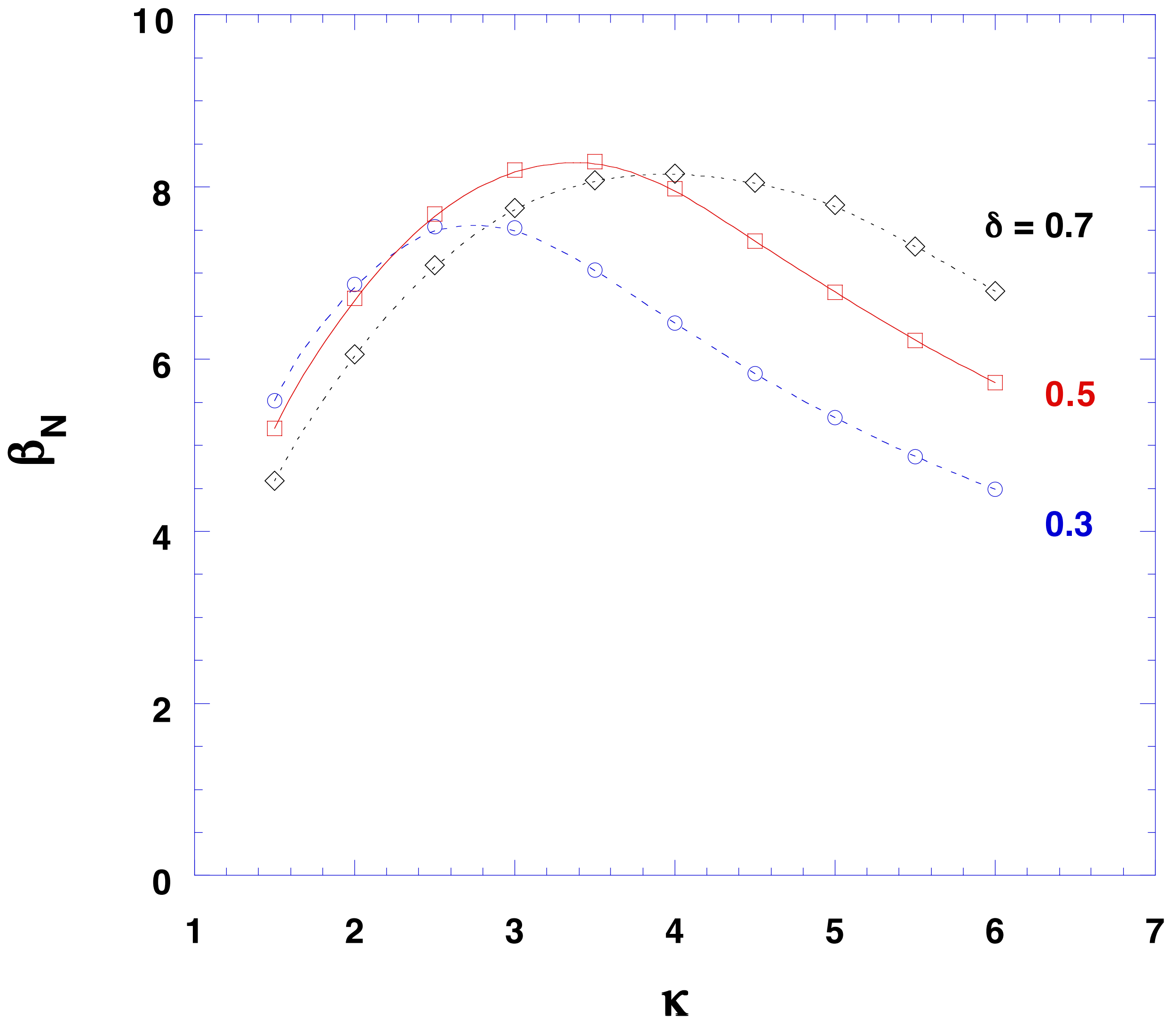
$\beta=56\%$

$\beta_N=8.2$

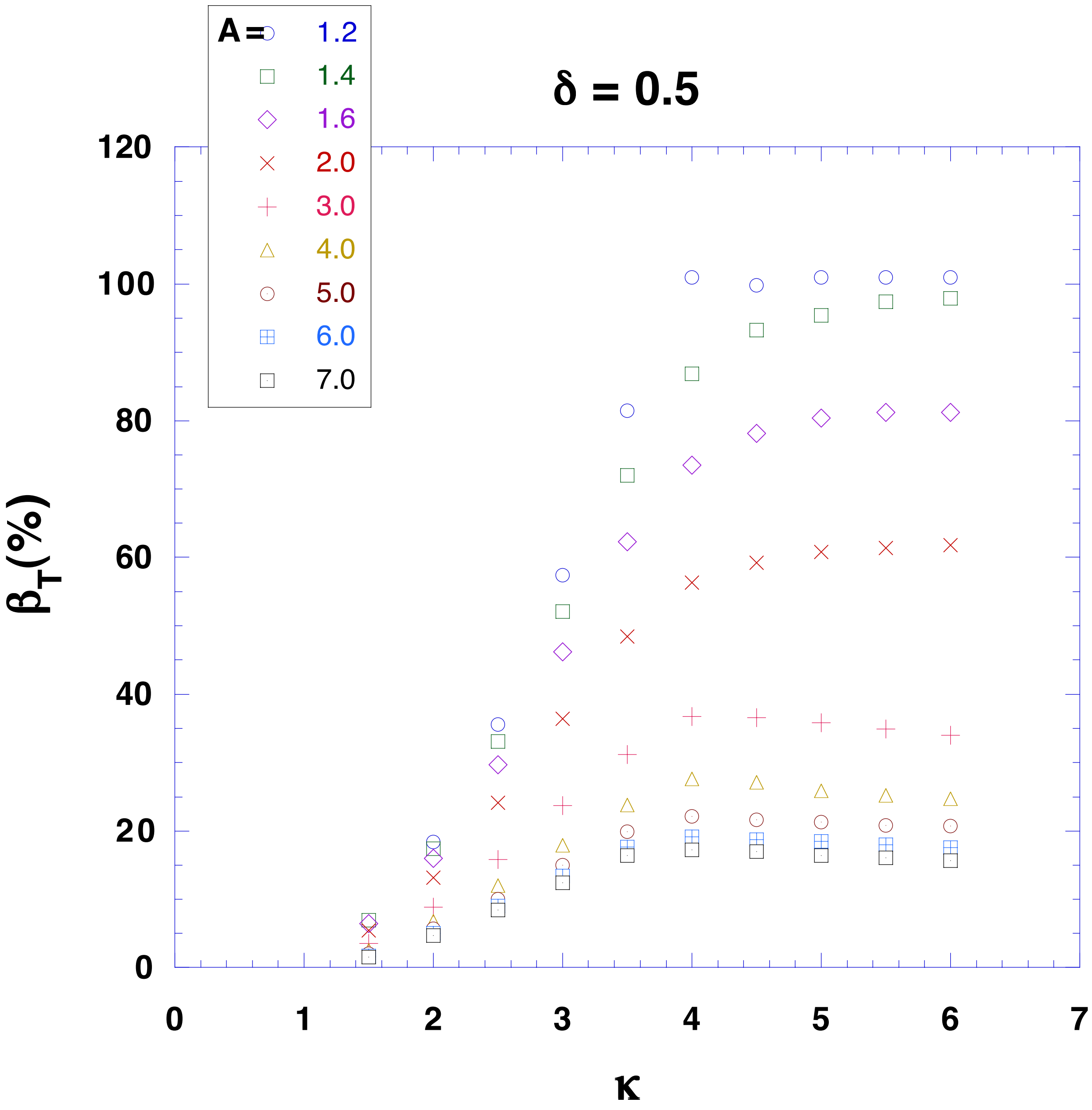
(J. Menard, S. Jardin, J. Manickam)

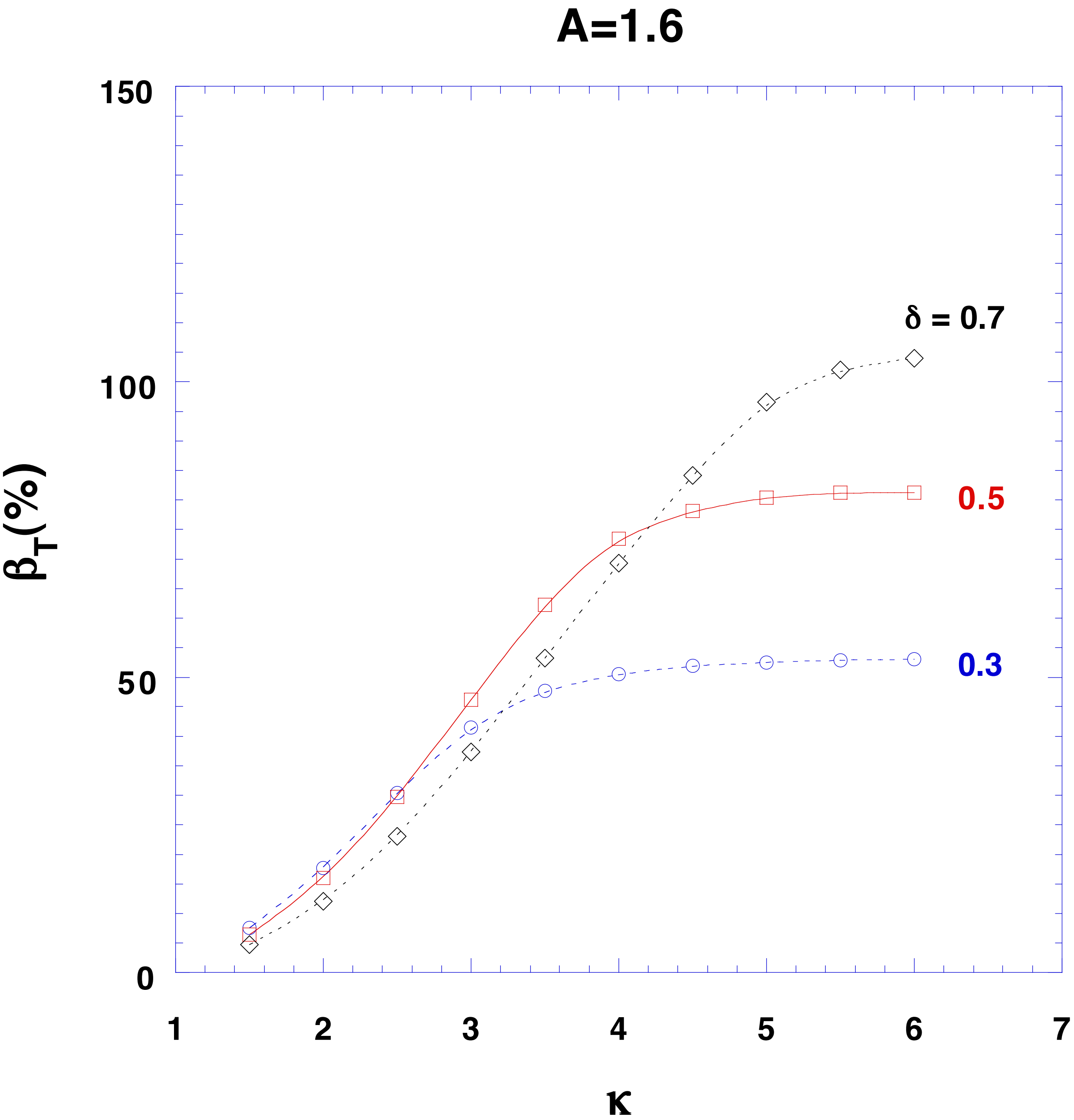


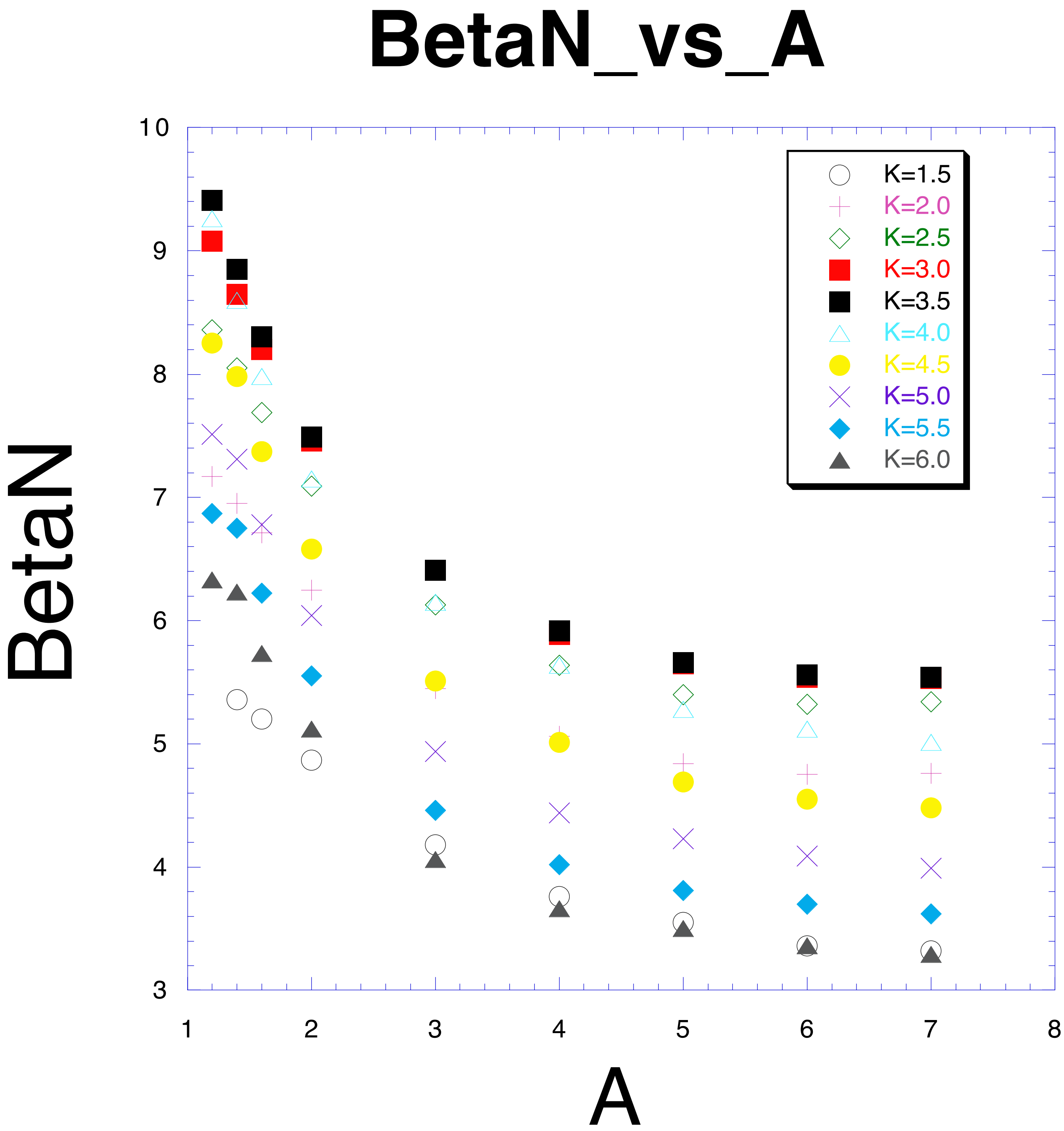
A =
○ 1.2
□ 1.4
◇ 1.6
× 2.0
+ 3.0
△ 4.0
○ 5.0
⊞ 6.0
□ 7.0
δ = 0.5
β_N
κ
0
2
4
6
8
10
0
1
2
3
4
5
6
7



A=1.6


A =
○ 1.2
□ 1.4
◇ 1.6
× 2.0
+ 3.0
△ 4.0
○ 5.0
⊞ 6.0
⊡ 7.0
δ = 0.5
β_T(%)
120
100
80
60
40
20
0
0
1
2
3
4
5
6
7
κ


A=1.6
β_T(%)
κ
150
100
50
0
1
2
3
4
5
6
7
δ = 0.7
0.5
0.3


BetaN_vs_A
BetaN
A
10
9
8
7
6
5
4
3
1
2
3
4
5
6
7
8
K=1.5
K=2.0
K=2.5
K=3.0
K=3.5
K=4.0
K=4.5
K=5.0
K=5.5
K=6.0

OPTIMIZING Q IN A STEADY-STATE MACHINE

$$Q = \frac{P_F}{P_{CD}} = \frac{\gamma_{CD} P_F}{nIR(1 - f_{bs})} = \frac{\gamma_{CD}\, \beta_N^2\, \kappa B_c^2 \left(1 - \frac{1}{A}\right)^2 Ra^2}{f_{GR}\, R(1 - f_{bs})}$$

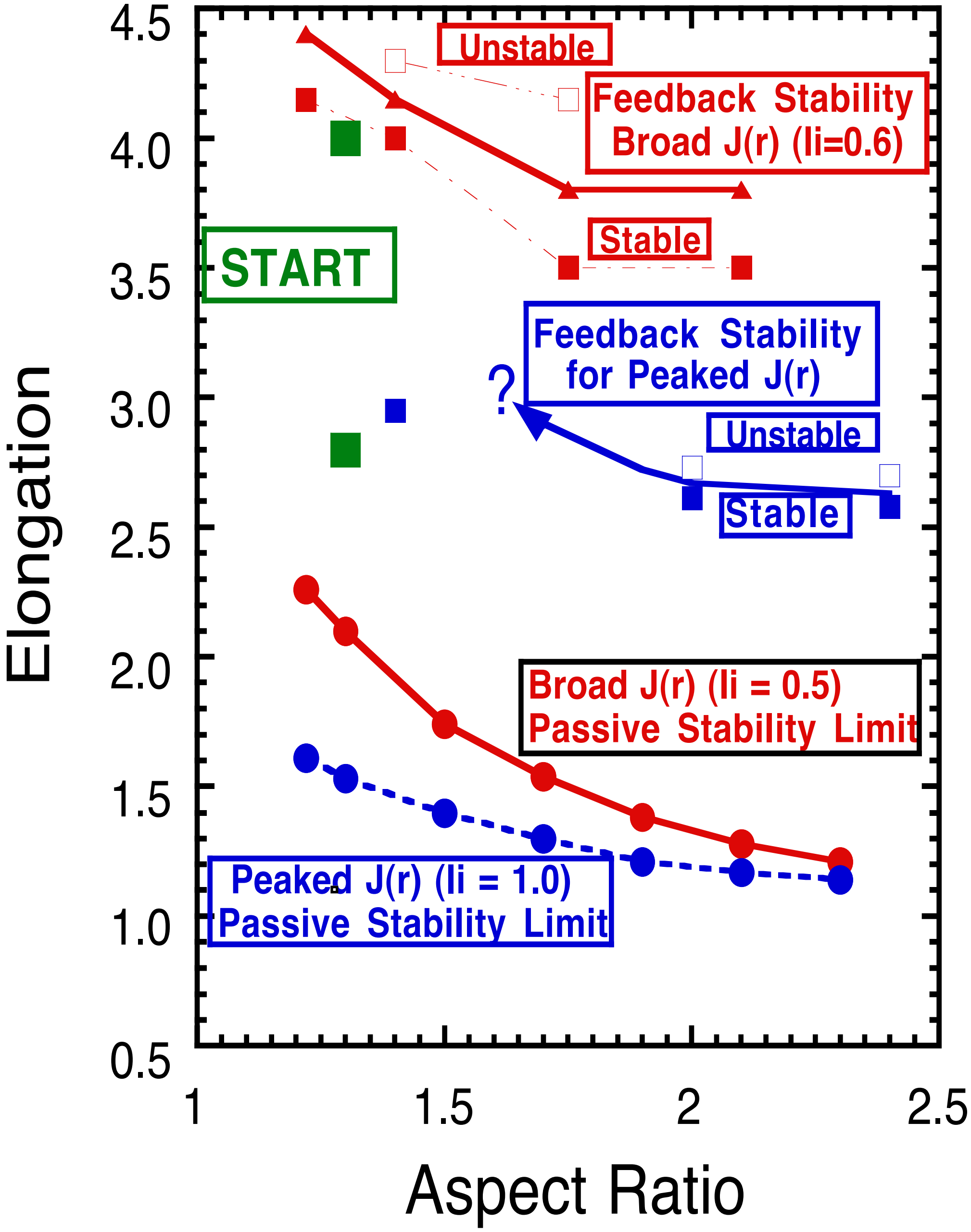
- $n = f_{GR}\, \frac{I}{\pi a^2}$
- B_c = field at centerpost (fixed maximum from stress)
- $f_{bs} = c_{bs}\, \beta_p / \sqrt{A} = \frac{c_{bs}}{20} \sqrt{A}\;\; q_{cyl}\;\; \beta_N$
- Express $\beta_N(A)$ as $\beta_{NO} A^{-\alpha}$ and κ as $\kappa_O A^{-\phi}$
- Optimize the function $$\frac{A^{-2\alpha}\left(1 - \frac{1}{A}\right)^2 A^{-\phi}}{\left(1 - \frac{c_{bs}}{20}\, q_{cyl}\;\; \beta_{N0}\; A^{1/2-\alpha}\right)}$$

for $\alpha = 1/2$; $\phi = 1/2$ $A_{max} = 2.3$
$\alpha = 1$; $\phi = 1/2$ $A_{max} = 1.5$

GENERAL ATOMICS

086–01/RDS/wj

Passively Stable κ goes like 1/A
A Reasonable Assumption for Feedback Stabilized κ is $A^{-0.5}$



1) Passive stability results from A. Sykes, "Progress on Spherical Tokamaks," Plasma Phys. and Contr. Fusion **36**, B93 (1994).

2) Feedback stability results for peaked profiles from R. D. Stambaugh, et. al., "Relation of Vertical Stability and Aspect Ratio in Tokamaks," Nucl. Fusion **32**, 1642 (1992).

3) Feedback stability results for broad profiles from recent work by L. Lao.

GENERAL ATOMICS

OPTIMIZING Q IN A STEADY-STATE SYSTEMS (Continued)

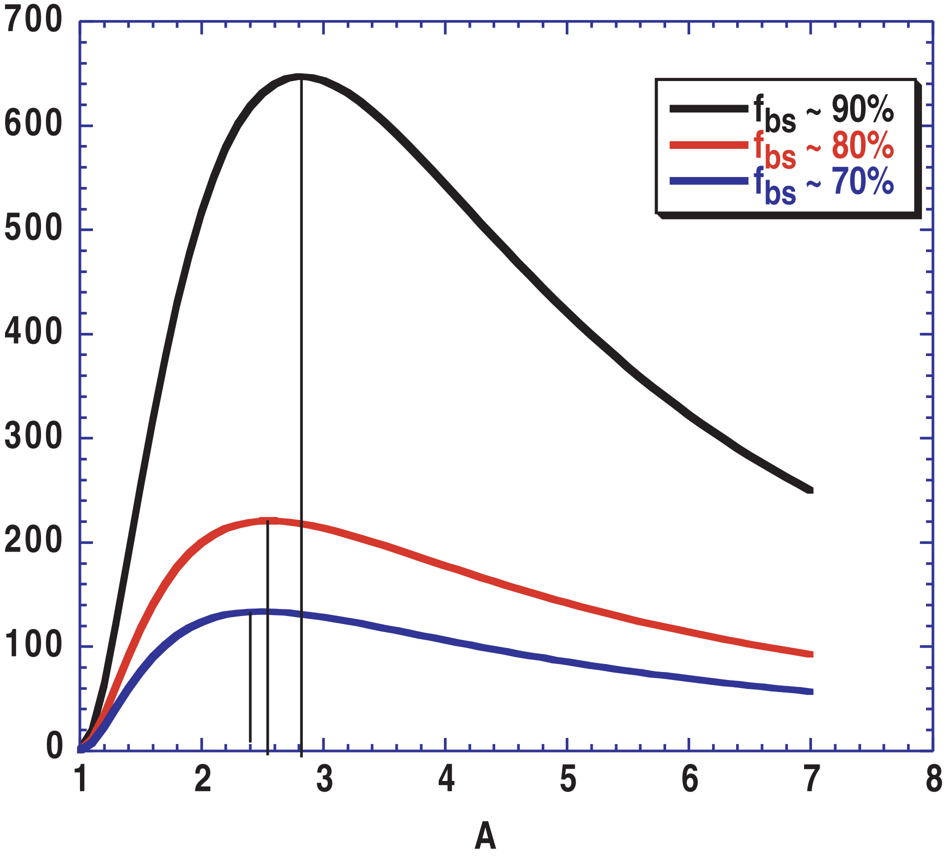
- Fit Lin-Liu's data to

  $\beta_N = \beta_{N0}\, A^{-(a+b\kappa)}\, (c + d\kappa + e\kappa^2)$

- Use this β_N in ratio for Q
- Use $\kappa \propto A^{-0.5}$

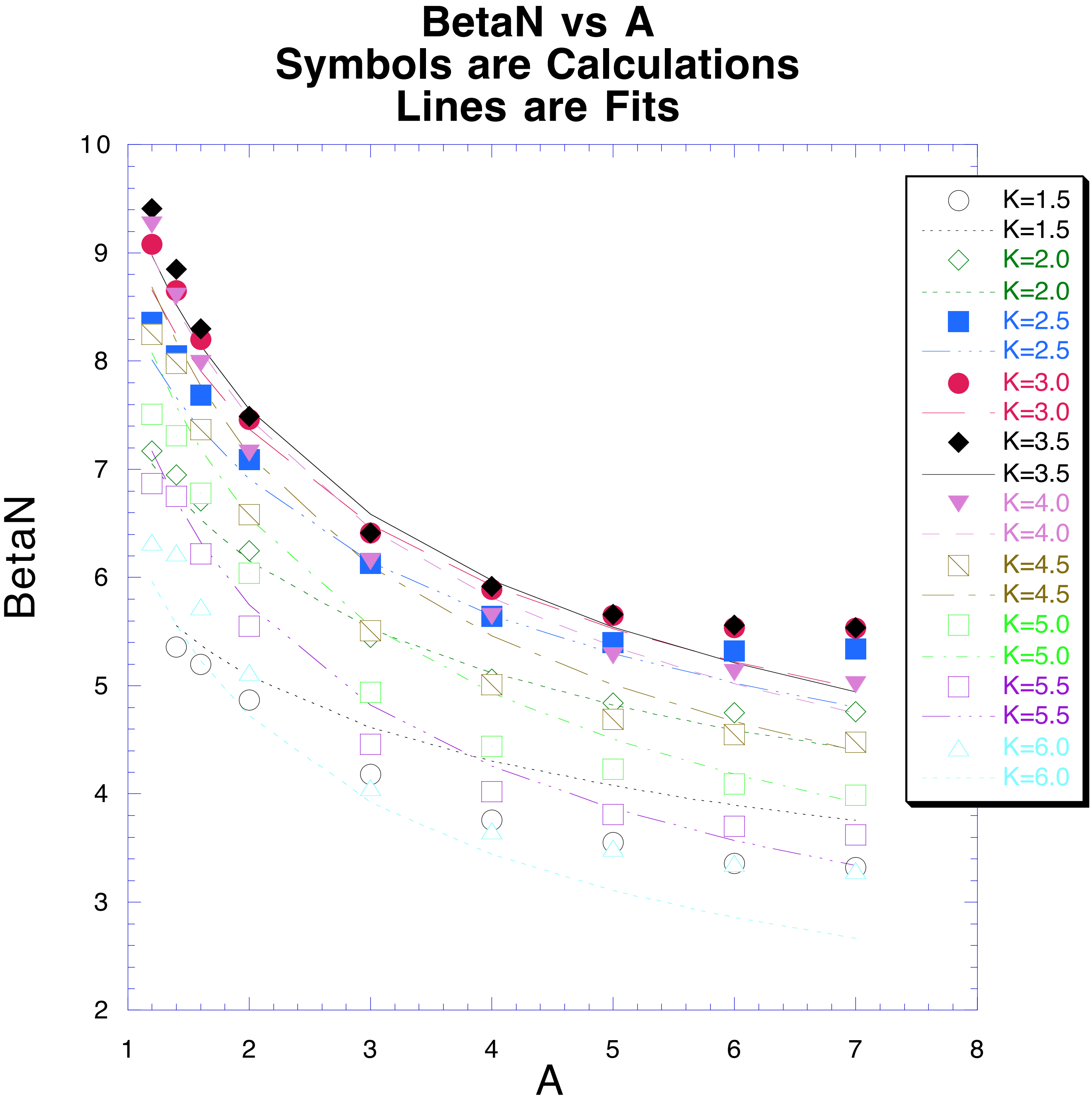
  Q index optimizes for A = 2.4–2.8 depending on the bootstrap fraction

Fusion Power/Current Drive Power Index

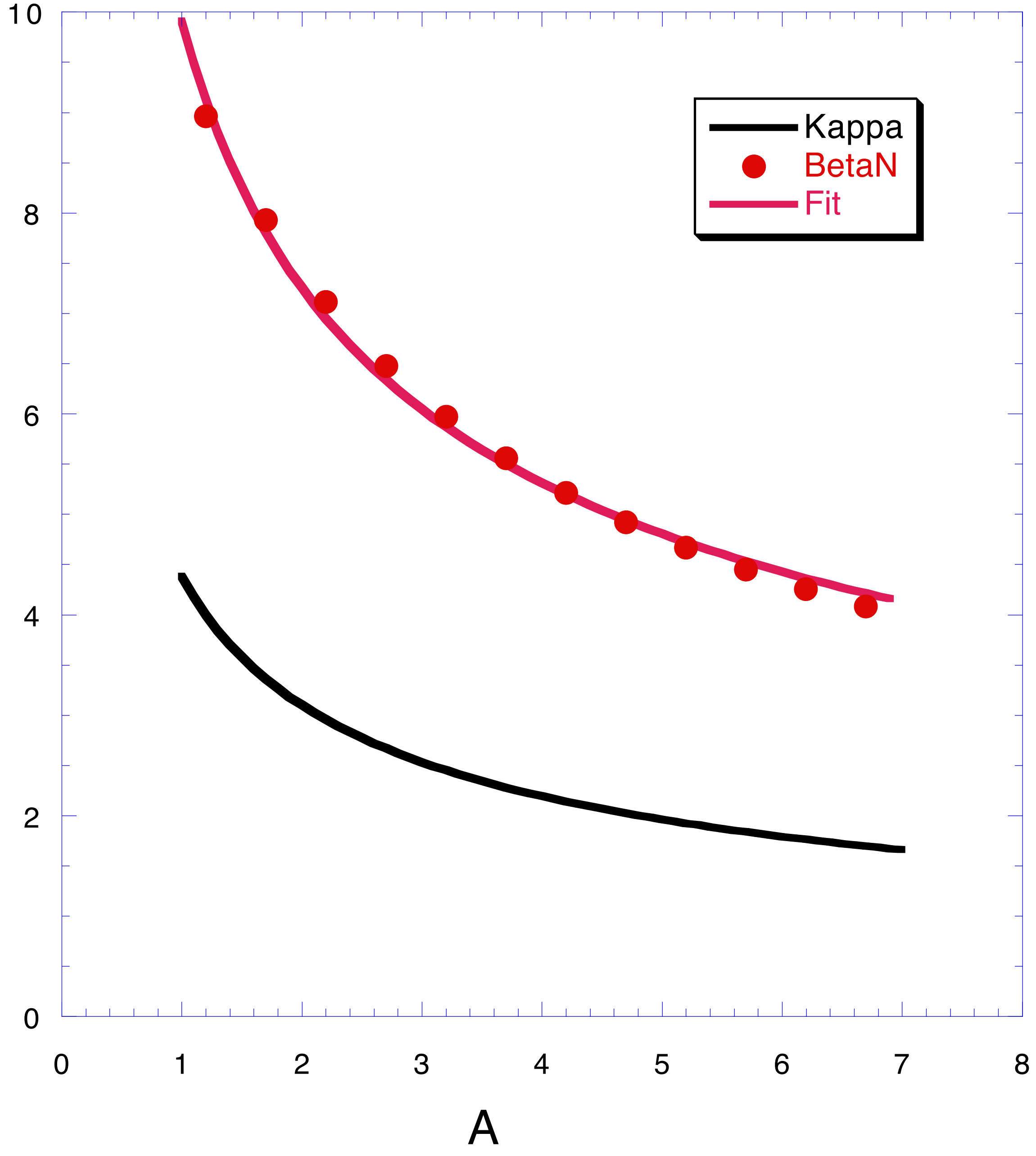


GENERAL ATOMICS

086–01/RDS/wj


BetaN vs A
Symbols are Calculations
Lines are Fits
BetaN
A
10
9
8
7
6
5
4
3
2
1
2
3
4
5
6
7
8
K=1.5
K=1.5
K=2.0
K=2.0
K=2.5
K=2.5
K=3.0
K=3.0
K=3.5
K=3.5
K=4.0
K=4.0
K=4.5
K=4.5
K=5.0
K=5.0
K=5.5
K=5.5
K=6.0
K=6.0

BetaN vs A
Using Limiting Kappa (A) , (SQRT(1/A))
Best Fit is BetaN (A) = 9.9 A-0.45



OPTIMUM ASPECT RATIO ST IS 1.5

- Optimize $\dfrac{P_{FUSION}}{P_{CENTERPOST}}$ as
  - Stambaugh et al., Fusion Technology 33, 1 (1998)

- $\dfrac{P_F}{P_C}$ at constant bootstrap fraction is

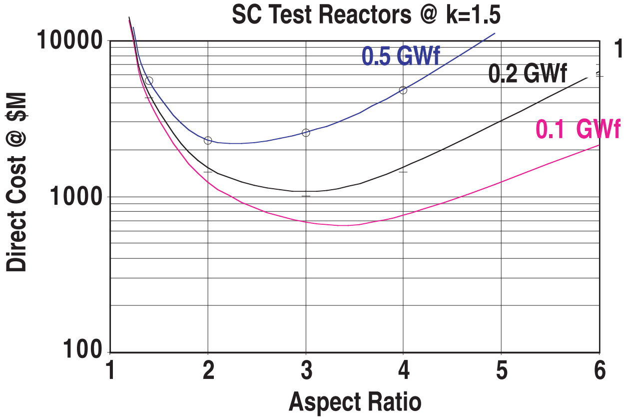
$$\propto (1 + \kappa^2)\ \beta_N^4 \left(\frac{A - 1}{A}\right)^2$$

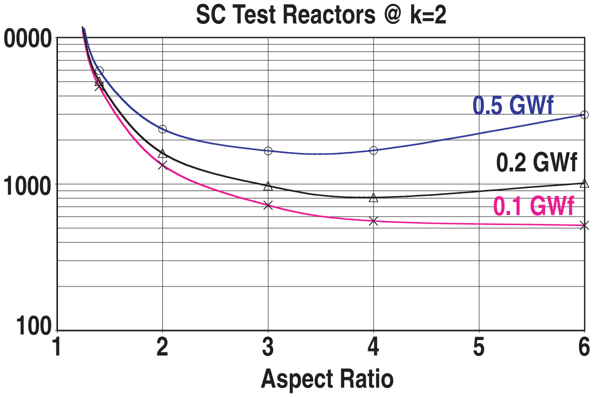
- Use $\kappa \propto A^{-1/2}$ and $\beta_N \propto A^{-1/2}$

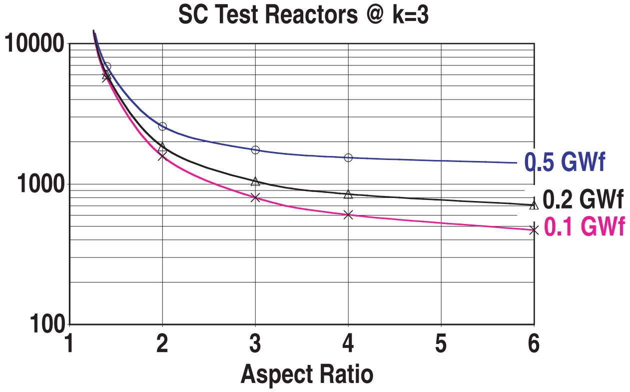
- Optimum of $\left(\dfrac{A - 1}{A^6}\right)^2$ is $A = 1.5$

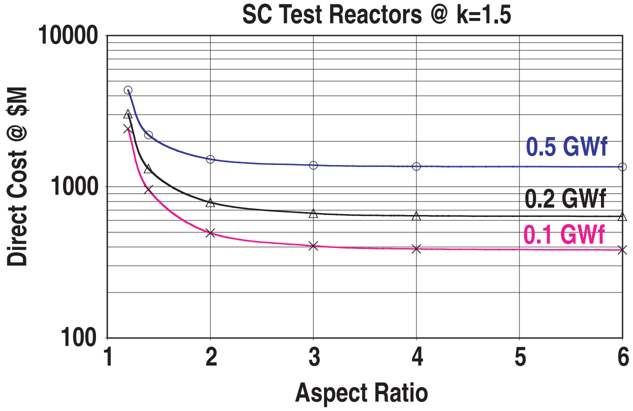
SC AND NC TEST REACTORS

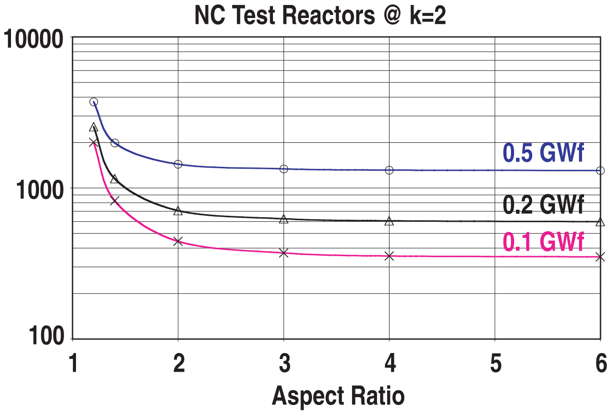
(T-peak at 20 keV, f_{bs} = 90%, and S_n=0.25, S_t = 0.25)

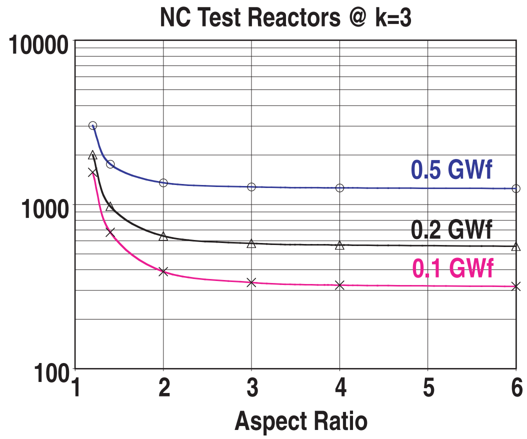












18th IAEA Fusion Energy Conference, Sorrento, Italy 2000

GA Wong 2000

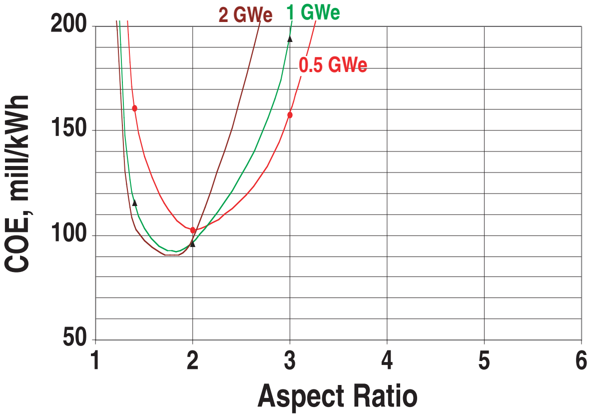
GENERAL ATOMICS

233-00 jy

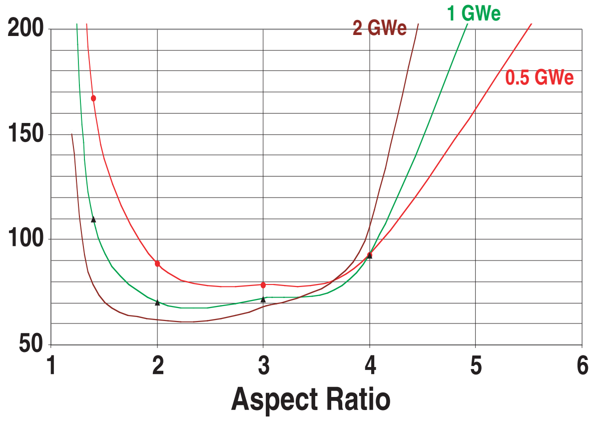
SC AND NC POWER REACTORS

(T-peak at 20keV, fbs=90%, and Sn=0.25, St=0.25)

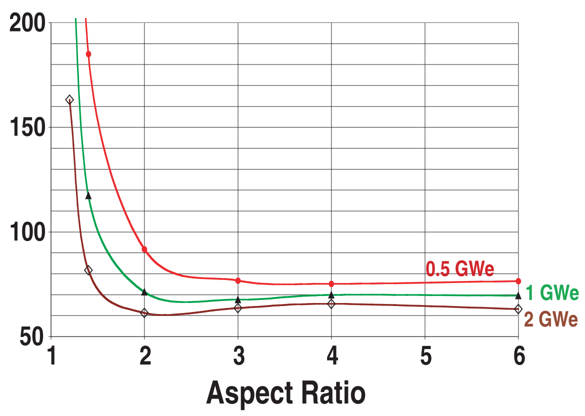
SC Power Reactors
@ k=1.5



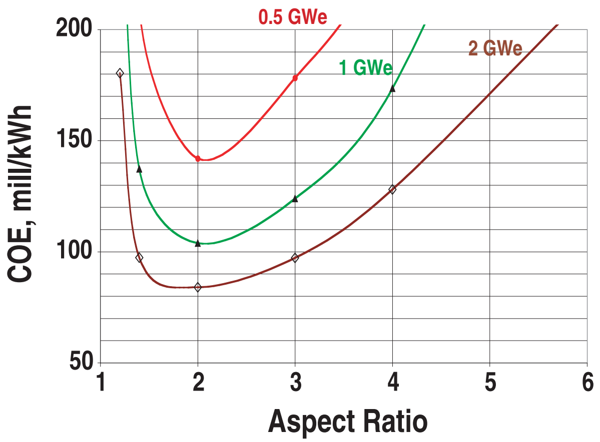
SC Power Reactors
@ k=2



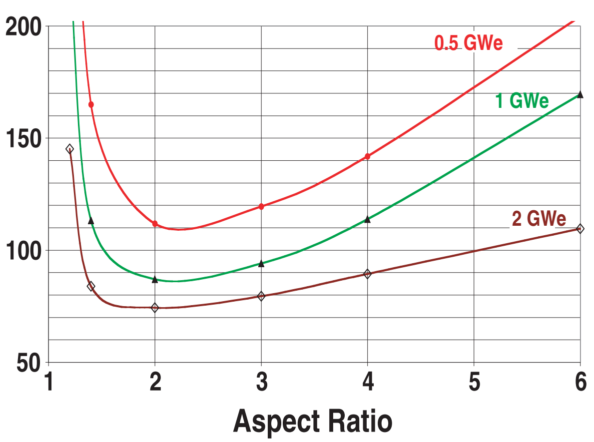
SC Power Reactors
@ k=3



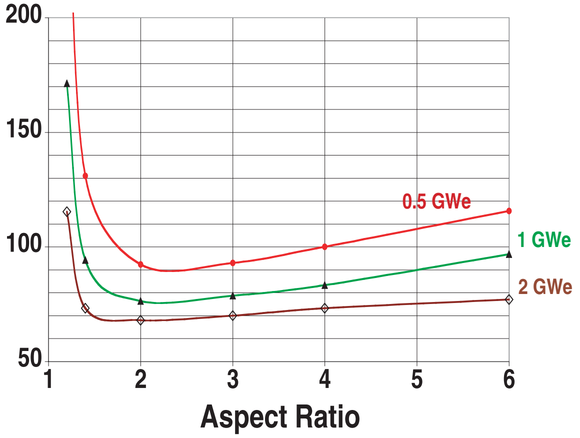
NC Power Reactors
@ k=1.5



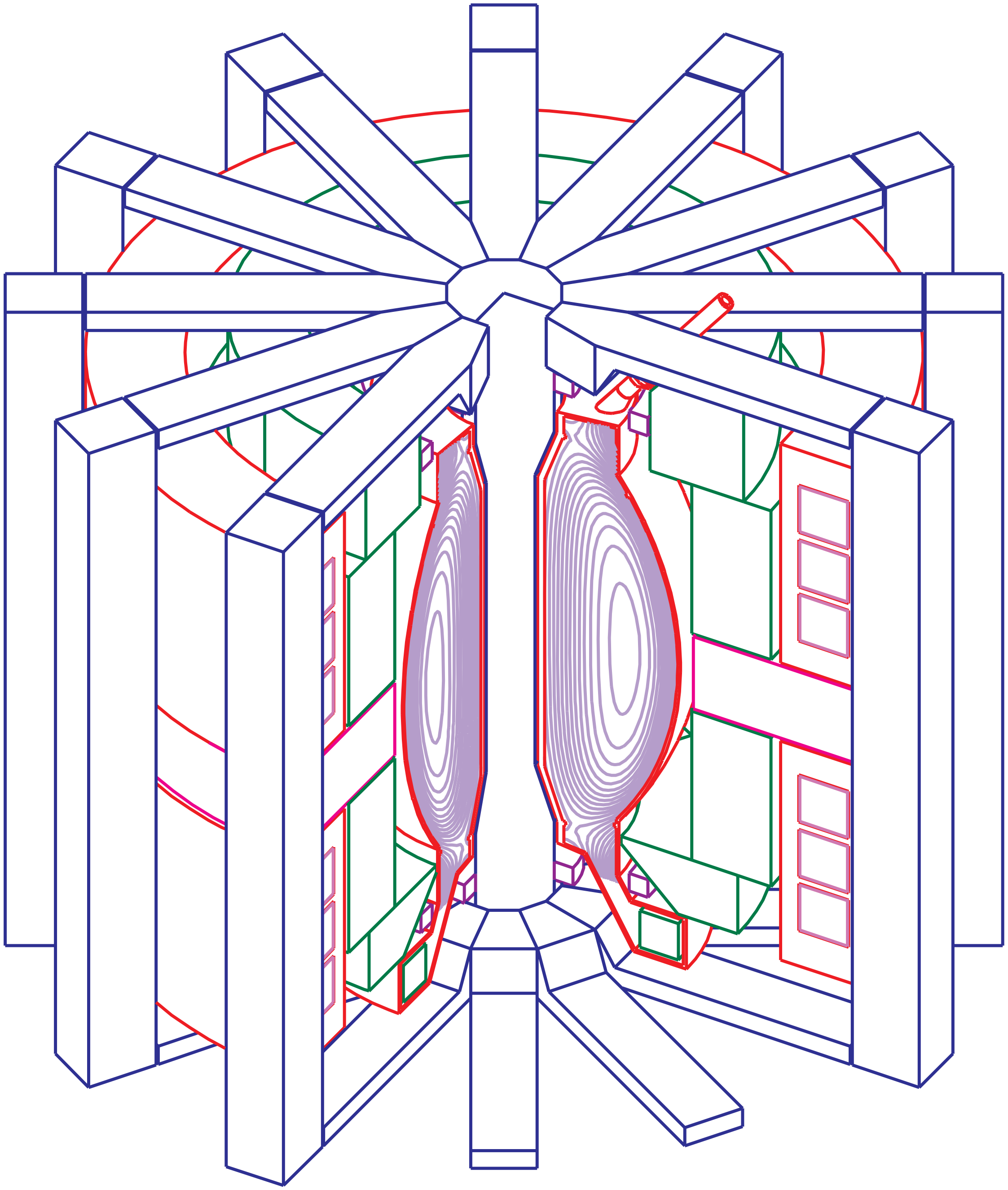
NC Power Reactors
@ k=2



NC Power Reactors
@ k=3

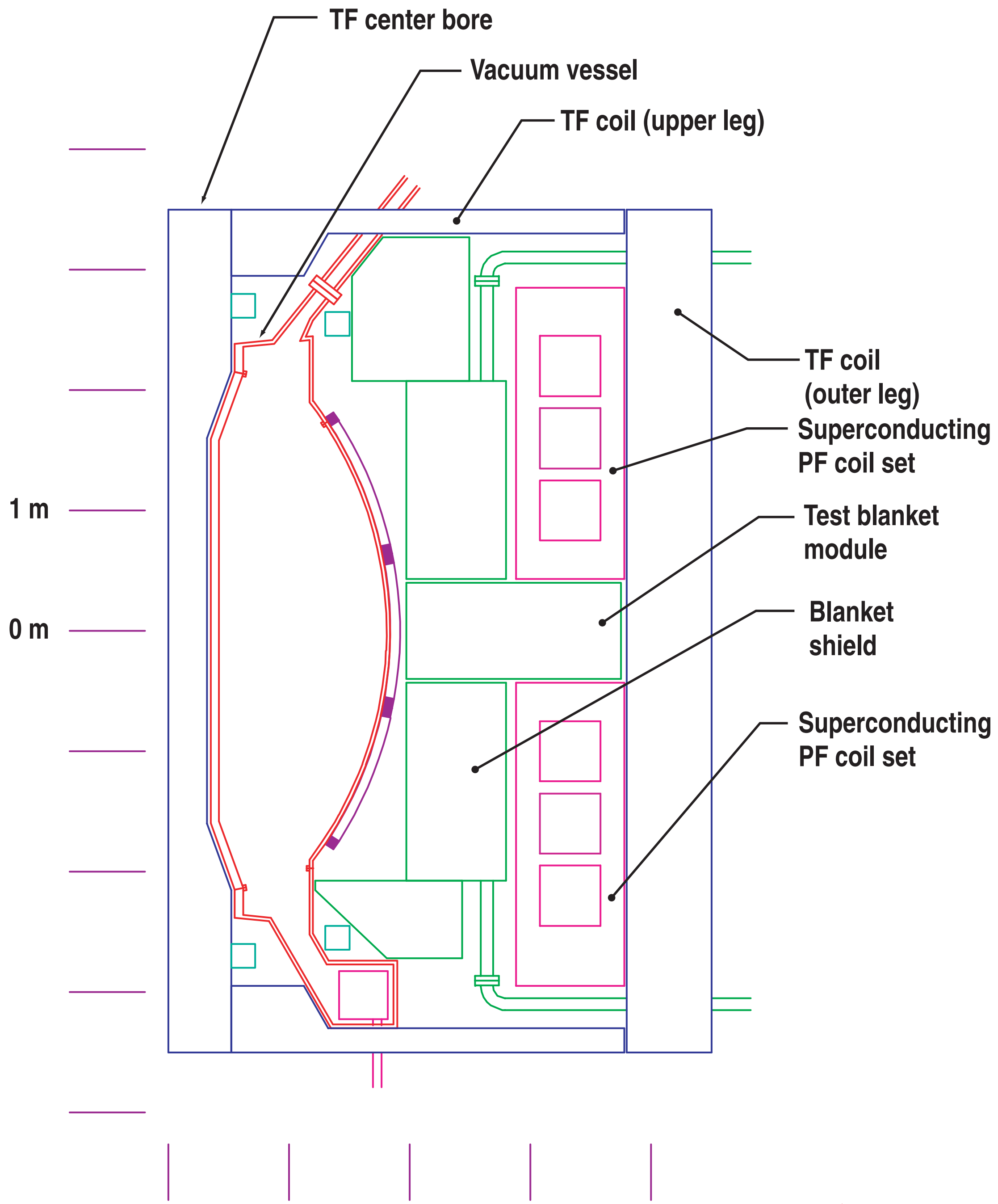


18th IAEA Fusion Energy Conference, Sorrento, Italy 2000

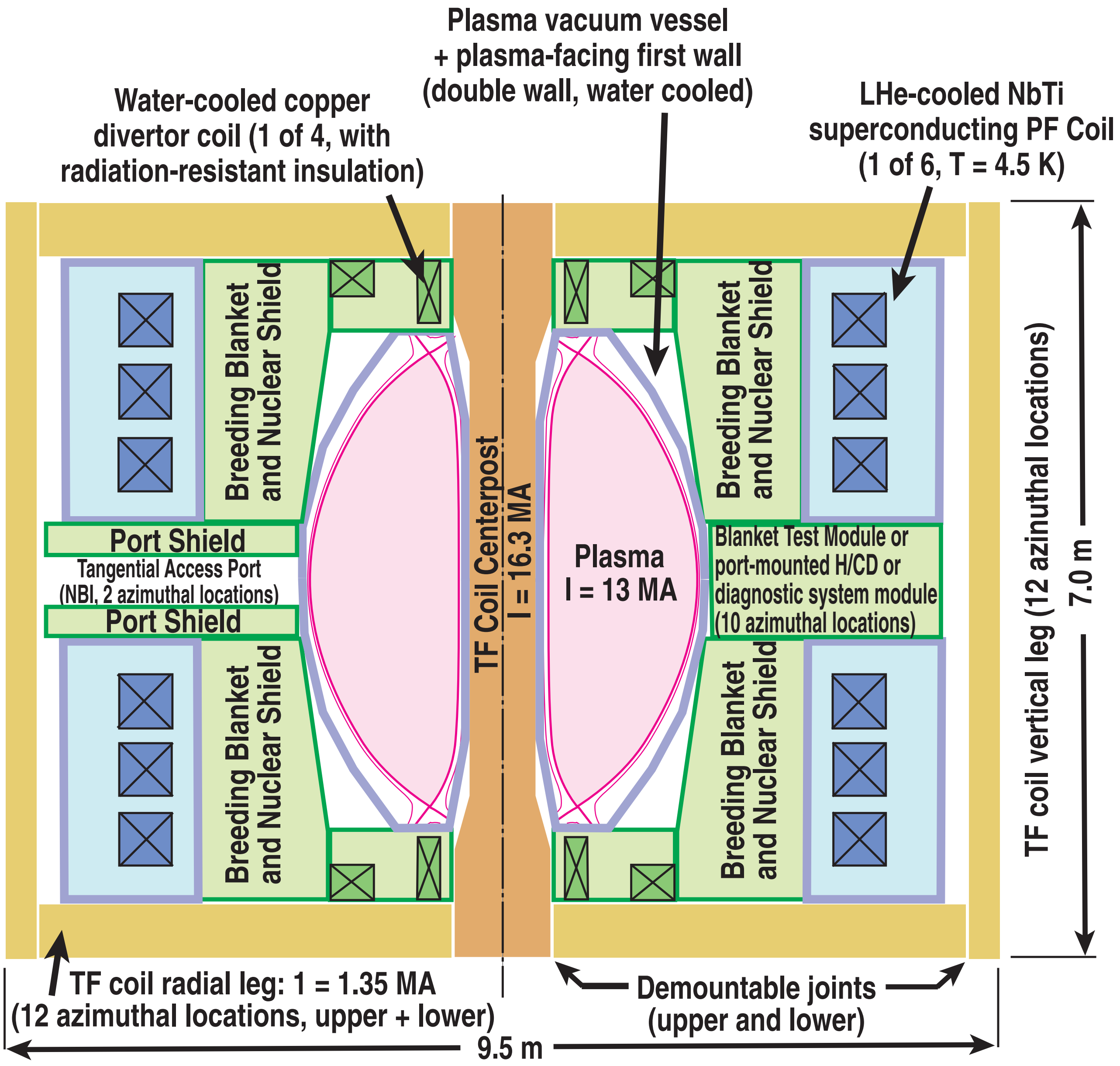


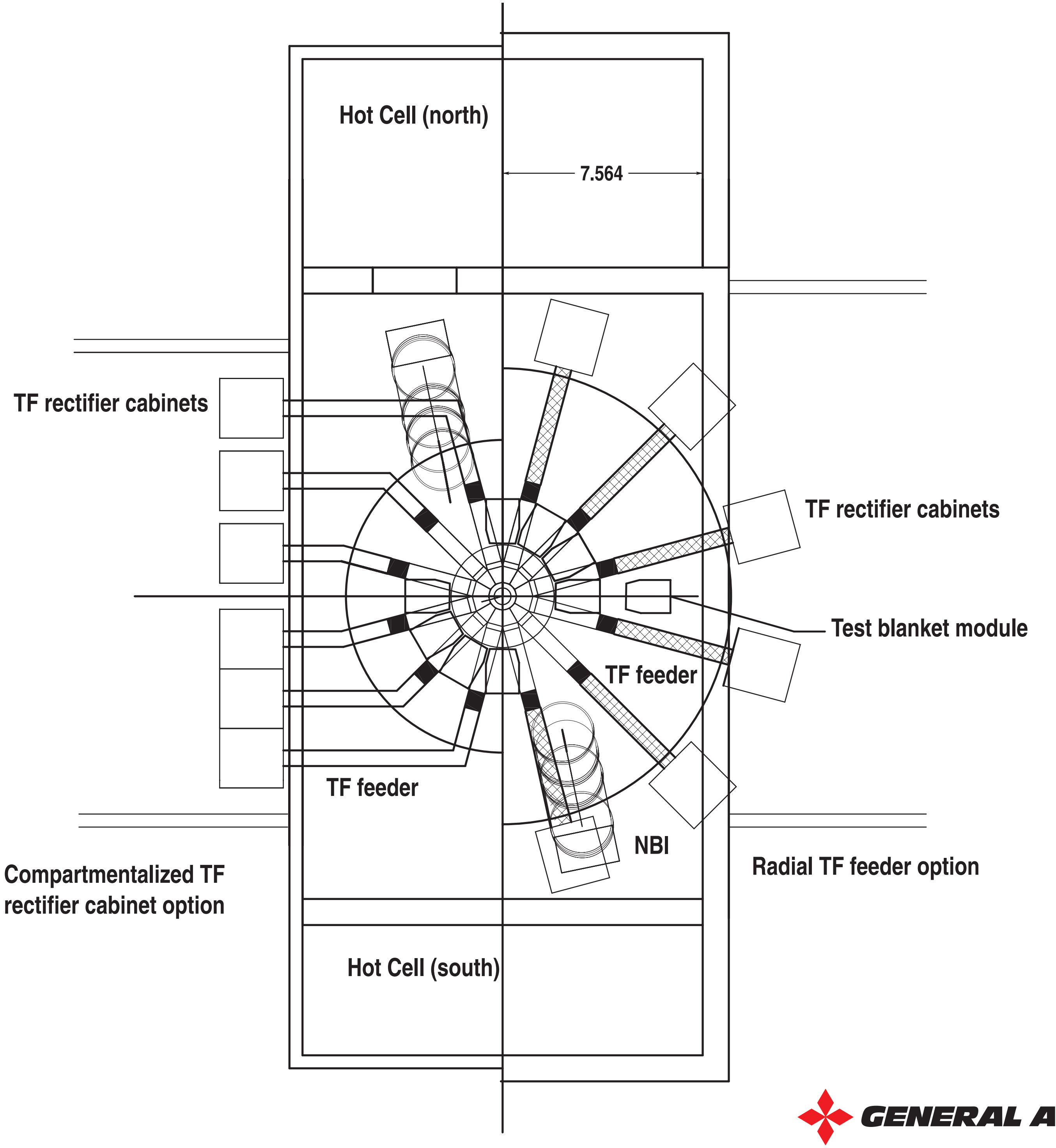
093–01/RDS/df

GENERAL ATOMICS


TF center bore
Vacuum vessel
TF coil (upper leg)
TF coil (outer leg)
Superconducting PF coil set
Test blanket module
Blanket shield
Superconducting PF coil set
1 m
0 m

093–01/RDS/df


Plasma vacuum vessel
+ plasma-facing first wall
(double wall, water cooled)
Water-cooled copper
divertor coil (1 of 4, with
radiation-resistant insulation)
LHe-cooled NbTi
superconducting PF Coil
(1 of 6, T = 4.5 K)
Breeding Blanket and Nuclear Shield
Breeding Blanket and Nuclear Shield
Breeding Blanket and Nuclear Shield
Breeding Blanket and Nuclear Shield
Port Shield
Tangential Access Port
(NBI, 2 azimuthal locations)
Port Shield
TF Coil Centerpost
I = 16.3 MA
Plasma
I = 13 MA
Blanket Test Module or
port-mounted H/CD or
diagnostic system module
(10 azimuthal locations)
TF coil vertical leg (12 azinuthal locations)
7.0 m
TF coil radial leg: 1 = 1.35 MA
(12 azimuthal locations, upper + lower)
Demountable joints
(upper and lower)
9.5 m



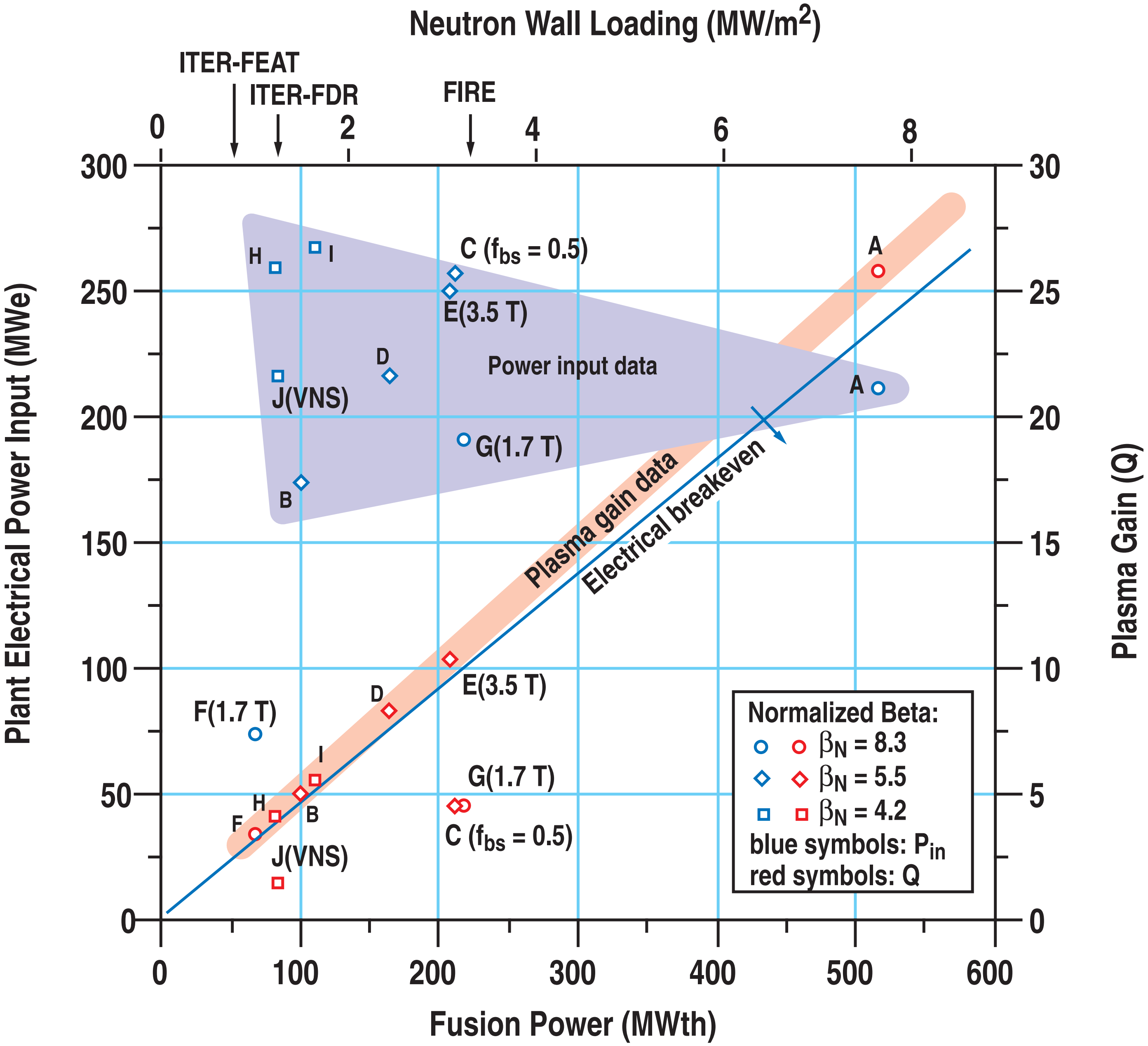
093–01/RDS/df

GENERAL ATOMICS

			A	B	C	D	E
	FDF Base Case and		Net Electric!	OK Blanket	OK Blanket	OK Blanket	OK Blanket
	No Wall Stabilization Cases		10 cm	No Wall Stabilization			
			Inboard	BetaN down	fbs 0.5	fbs 0.7	Turn up B
A	aspect ratio		1.6	1.6	1.6	1.6	1.6
a	plasma minor radius	m	0.70	0.70	0.70	0.70	0.70
Ro	plasma major radius	m	1.12	1.12	1.12	1.12	1.12
κ	plasma elongation		3.00	3.00	3.00	3.00	3.00
Rhole	Hole Size	m	0	0	0	0	0
Jc	centerpost current density	MA/m2	50	50	45	50	60
framp	induct ramp frac		0.000	0.000	0.000	0.000	0.000
Pf	fusion power	MW	516.69	99.63	211.78	164.69	206.58
Pc	power dissipated	MW	84.45	84.45	68.40	84.45	121.60
Pinternal	power to run plant	MW	211.99	174.35	256.84	215.77	250.47
Qplant	gain for whole plant		1.12	0.26	0.38	0.35	0.38
Qplasma	Pfusion/Paux		25.83	4.98	4.51	8.23	10.33
Pnetelec	net electric power	MW	25.69	-128.53	-159.42	-140.02	-155.44
Pn/Awall	Neutron Power at Blanket	MW/m2	7.77	1.50	3.18	2.48	3.11
BetaT	toroidal beta		0.54	0.24	0.43	0.31	0.24
BetaN	normalized beta	mT/MA	8.30	5.50	5.50	5.50	5.50
fbs	bootstrap fraction		0.90	0.90	0.50	0.70	0.90
Pcd	current drive power	MW	13.65	3.97	46.92	19.70	6.86
Ip	plasma current	MA	13.19	8.74	14.16	11.24	10.49
Bo	field on axis	T	2.87	2.87	2.59	2.87	3.45
Bc	field at conductor	T	10.05	10.05	9.05	10.05	12.06
Ti(0)	Ion Temperature	keV	20.00	20.00	20.00	20.00	20.00
Te(0)	Electron Temperature	keV	20.00	20.00	20.00	20.00	20.00
n(0)	Electron Density	E20/m3	4.62	2.03	2.96	2.61	2.92
nbar/nGR	Ratio to Greenwald Limit		0.43	0.29	0.26	0.29	0.34
Zeff			2.40	2.40	2.40	2.40	2.40
W	Stored Energy in Plasma	MJ	82.22	36.10	52.64	46.42	51.99
Pheat	Total Heating Power	MW	123.34	39.93	89.27	52.94	61.32
TauE	TauE	sec	0.67	0.90	0.59	0.88	0.85
H	H factor over 89P L-mode		4.81	5.47	3.47	4.89	5.18

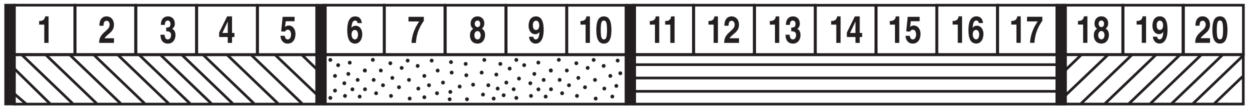
			A	H	I	J
	ST FDF Base Case and		Net Electric!	Q=4, Blanket	OK Blanket	Driven VNS
	Low BetaN Cases		10 cm	Cases at BetaN 4.15		
			Inboard	BetaN lower	fbs 0.7	Get to H=2
A	aspect ratio		1.6	1.6	1.6	1.6
a	plasma minor radius	m	0.70	0.70	0.70	0.70
Ro	plasma major radius	m	1.12	1.12	1.12	1.12
κ	plasma elongation		3.00	3.00	3.00	3.00
Rhole	Hole Size	m	0	0	0	0
Jc	centerpost current density	MA/m2	50	63	60	30
framp	induct ramp frac		0.000	0.000	0.000	0.000
Pf	fusion power	MW	516.69	81.39	110.70	84.75
Pc	power dissipated	MW	84.45	134.07	121.60	30.40
Pinternal	power to run plant	MW	211.99	259.64	266.78	216.30
Qplant	gain for whole plant		1.12	0.14	0.19	0.18
Qplasma	Pfusion/Paux		25.83	4.07	5.53	1.42
Pnetelec	net electric power	MW	25.69	-222.20	-215.86	-177.31
Pn/Awall	Neutron Power at Blanket	MW/m2	7.77	1.22	1.66	1.27
BetaT	toroidal beta		0.54	0.14	0.18	0.61
BetaN	normalized beta	mT/MA	8.30	4.15	4.15	4.15
fbs	bootstrap fraction		0.90	0.90	0.70	0.20
Pcd	current drive power	MW	13.65	3.41	14.63	59.72
Ip	plasma current	MA	13.19	8.31	10.18	17.81
Bo	field on axis	T	2.87	3.62	3.45	1.72
Bc	field at conductor	T	10.05	12.67	12.06	6.03
Ti(0)	Ion Temperature	keV	20.00	20.00	20.00	20.00
Te(0)	Electron Temperature	keV	20.00	20.00	20.00	20.00
n(0)	Electron Density	E20/m3	4.62	1.83	2.14	1.87
nbar/nGR	Ratio to Greenwald Limit		0.43	0.27	0.26	0.13
Zeff			2.40	2.40	2.40	2.40
W	Stored Energy in Plasma	MJ	82.22	32.63	38.05	33.30
Pheat	Total Heating Power	MW	123.34	36.28	42.14	76.67
TauE	TauE	sec	0.67	0.90	0.90	0.43
H	H factor over 89P L-mode		4.81	5.19	4.75	2.15
VH	Tau over 0.85 ELM Free		3.82	3.89	3.47	1.72

			A	F	G
	ST FDF Base Case and		Net Electric!	~OK Blanket	Really High
	Low BT Cases		10 cm		Beta
			Inboard	Low BT	fbs=0.5
A	aspect ratio		1.6	1.6	1.6
a	plasma minor radius	m	0.70	0.70	0.70
Ro	plasma major radius	m	1.12	1.12	1.12
κ	plasma elongation		3.00	3.00	3.00
Rhole	Hole Size	m	0	0	0
Jc	centerpost current density	MA/m2	50	30	30
framp	induct ramp frac		0.000	0.000	0.000
Pf	fusion power	MW	516.69	66.96	216.96
Pc	power dissipated	MW	84.45	30.40	30.40
Pinternal	power to run plant	MW	211.99	73.80	190.69
Qplant	gain for whole plant		1.12	0.42	0.52
Qplasma	Pfusion/Paux		25.83	3.35	4.54
Pnetelec	net electric power	MW	25.69	-43.00	-90.89
Pn/Awall	Neutron Power at Blanket	MW/m2	7.77	1.01	3.26
BetaT	toroidal beta		0.54	0.54	0.98
BetaN	normalized beta	mT/MA	8.30	8.30	8.30
fbs	bootstrap fraction		0.90	0.90	0.50
Pcd	current drive power	MW	13.65	2.95	47.78
Ip	plasma current	MA	13.19	7.92	14.25
Bo	field on axis	T	2.87	1.72	1.72
Bc	field at conductor	T	10.05	6.03	6.03
Ti(0)	Ion Temperature	keV	20.00	20.00	20.00
Te(0)	Electron Temperature	keV	20.00	20.00	20.00
n(0)	Electron Density	E20/m3	4.62	1.66	2.99
nbar/nGR	Ratio to Greenwald Limit		0.43	0.26	0.26
Zeff			2.40	2.40	2.40
W	Stored Energy in Plasma	MJ	82.22	29.60	53.28
Pheat	Total Heating Power	MW	123.34	33.39	91.17
TauE	TauE	sec	0.67	0.89	0.58
H	H factor over 89P L-mode		4.81	5.96	3.75
VH	Tau over 0.85 ELM Free		3.82	4.90	3.09


Neutron Wall Loading (MW/m²)
ITER-FEAT
ITER-FDR
FIRE
0
2
4
6
8
300
250
200
150
100
50
0
30
25
20
15
10
5
0
Plant Electrical Power Input (MWe)
Plasma Gain (Q)
H
I
C (f_bs = 0.5)
E(3.5 T)
D
Power input data
J(VNS)
A
G(1.7 T)
B
Plasma gain data
Electrical breakeven
A
E(3.5 T)
D
F(1.7 T)
I
G(1.7 T)
H
F
B
C (f_bs = 0.5)
J(VNS)
Normalized Beta:
○ ○ β_N = 8.3
◇ ◇ β_N = 5.5
□ □ β_N = 4.2
blue symbols: P_in
red symbols: Q
0
100
200
300
400
500
600
Fusion Power (MWth)

FUSION DEVELOPMENT FACILITY

- Steady progress through sequenced objectives



PHASES	D-D PHYSICS	DT PHYSICS	BLANKET DEVELOPMENT	TRITIUM SELF SUFFICIENCY
FUSION POWER (MW)	~0	10 → 300	400	500
ELECTRIC POWER (MW)	–200	–250	–250	–50
DUTY CYCLE	0.4%	0.4%	0.4% → 10%	100%
	60 SECOND PULSES	60 SEC — 5 MIN.	~ WEEK LONG RUNS	STEADY-STATE
NEUTRON WALL LOAD (MW/m^2)		5	6	8
TRITIUM PER YEAR				
BURNED (kg)	~0	0.1	2.7	27
PRODUCED [NET] (kg)	0	0	3.1 [0.4]	31 [4]