ROLE OF CORE RADIATION LOSSES FROM PLASMA AND ITS IMPACT ON ST REACTOR DESIGN PARAMETER CHOICES

SHISHIR DESHPANDE[1*]

CO-WORKERS

P. N. MAYA[1], A.K. TYAGI[2], U. PRASAD[1], P. CHAUDHURI[1] AND S. B. PADASALAGI[2]

[1]INSTITUTE FOR PLASMA RESEARCH, BHAT, GANDHINAGAR, 382428, INDIA

[2] ITER-INDIA, INSTITUTE FOR PLASMA RESEARCH, GANDHINAGAR, 382428, INDIA

(*PRESENTER)

Track: Fusion Energy Technology | Session: TECH/2-5 DEMO & Advance Technology | Contribution ID 1261

PLAN OF PRESENTATION

- Introduction
- Equations/ definitions & Assumptions
- Results
- Summary & Future Work
- References

INTRODUCTION

- Spherical Tokamak (ST) represent an advancing front in fusion sciences today.
    - Attractive physics features
    - New developments (HTS, novel divertor designs)
    - Potentially lower costs
- Challenges
    - Extreme heat flux
    - Tight space on the inboard side for CP, OH, shielding
    - Replaceability and pulsed operations
    - And of course, getting the plasma parameters for a reactor

- This work is about parameter space, not about any specific configuration
- We expect ST to have intense plasma-wall interactions, causing generation of impurities. In addition, one could have externally injected impurities to control the transport power flux at the separatrix
- Furthermore, the ratio of fusion- α Larmor radius to minor radius will be significant (for compact devices) and so fraction of power deposited within the plasma can be small
- Consequently, the α-incidence can happen all over the first-wall, not just divertor, creating additional sources for impurities

Equations/ definitions & Assumptions

$$q = \frac{5RB_t\, S_\kappa}{A^2 I_p}$$

The shape-factor involves κ, δ and A

$$\beta_N = \beta\,(aB_t)/I_p$$

(β is in %)

$$W_\beta = 3\,nT = \frac{3\pi}{8}\,\frac{\kappa S_\kappa}{qA^3} R^3 B^2$$

Stored energy (calculated for given β)

$$P_h - P_r = P_L$$

In steady-state, the heating is balanced by core-radiation and transport,

$$P_L = W_\beta/\tau_E$$

with the transport power-loss estimated by a choice of confinement scaling.

$$Q_{LF} = P_L/P_f$$

It is normalized w. r. t. fusion power

$(1-f_r)\, P_h/P_f = P_L/P_f$	Normalization by fusion-power
$f_r = P_r/P_h$	Core-radiation: a fraction of heating-power
$P_h = P_\alpha + P_a$	Heating: sum of α-heating and auxiliary
$P_\alpha = f_\alpha\left(\frac{P_f}{5}\right)$	α-driven heating fraction (ideally 1)
$Q = P_f/P_a$	definition of figure-of-merit
$Q = \dfrac{1}{\left(\dfrac{Q_{LF}}{1-f_r}\right) - \dfrac{f_\alpha}{5}}$	re-expressed in terms of normalized transp. power and core-radiation fraction

- To estimate the transport-power loss at the separatrix, several scaling laws have been used. ITER IPB(98,y2) is taken as a base reference for results. 11 scalings considered are:

  1) ITER IPB
  2) Buxton et al, Plasma Phys. Control. Fusion 61 035006 Eqn. 13
  3) Kaye et al, 2006 Plasma Phys. Control. Fusion 48 A429 Eqn. 1
  4) Petty et al Fus. Sci. Tech. Jan. 2003 Vol. 43 Eqn. 21
  5) Petty et al Phys. Plasmas 15, 080501, 2008 Eqn. 36
  6) Cordey et al., Nucl. Fusion 45 (2005) 1078–1084 Eqn. 9
  7) Cordey et al., Nucl. Fusion 45 (2005) 1078–1084 Eqn. 19
  8) Dnestrovskij et al NF 61 (2019) 055009 Eqn.7 (Globus)
  9) Dnestrovskij et al NF 61 (2019) 055009 Eqn.8 (MAST)
  10) Dnestrovskij et al NF 61 (2019) 055009 Eqn.9 (NSTX)
  11) Nearest integer ratios for ITER-IPB (analytic, this paper)

Caveat:

Since the scaling laws are obtained by regression analysis, it is strictly not possible to associate an analytic (continuous and differentiable function) for $\tau_{E.}$ So while doing the parameter scan, we associate the curves with a sense of being a guiding constraint, and accept solutions only when power-balance constraint is satisfied.

- **Fusion power calculations:**
  - Cross-section data from Bosch & Halle
  - Profiles of density and temperature are parabolic in *r* with an exponent given by S_n and S_T respectively (0.5 and 1.0 resp.)
  - Elongation is linearly interpolated on the magnetic surface
  - Fusion power is calculated from each annular toroidal shell and summed up
  - Helium driven fuel dilution effect is also taken into account
- **Radiative power loss:**
  - Average-Ion Model (D. Post et. al, At. Data and Nucl. Data Tables, 20(5) 1977) & Bremsstrahlung radiation

INPUT PARAMETERS USED BY THE PROGRAM

- q : MHD safety factor (incl. elongation and aspect ratio factor)
- β_N : Normalized toroidal beta
- κ, δ and A : the elongation, triangularity and aspect ratio
- f_r : fraction of the heating power, escaping as radiation
- f_{bs} : fraction of the current driven by bootstrap
- f_G : fraction of the Greenwald density limit
- f_α : fraction of the alpha power deposited in the plasma
- H_h : The H-enhancement factor
- M : the average mass, taken as 2.5 (D and T)
- S_n : 0.5 (parabolic density profile exponent)
- S_T : 1 (parabolic temperature profile exponent)
- fz_Fe, fz_Ne and fz_W: impurity concentrations for iron, neon and tungsten

All the above 16 parameters are held constant in R-Bt space scan

Results

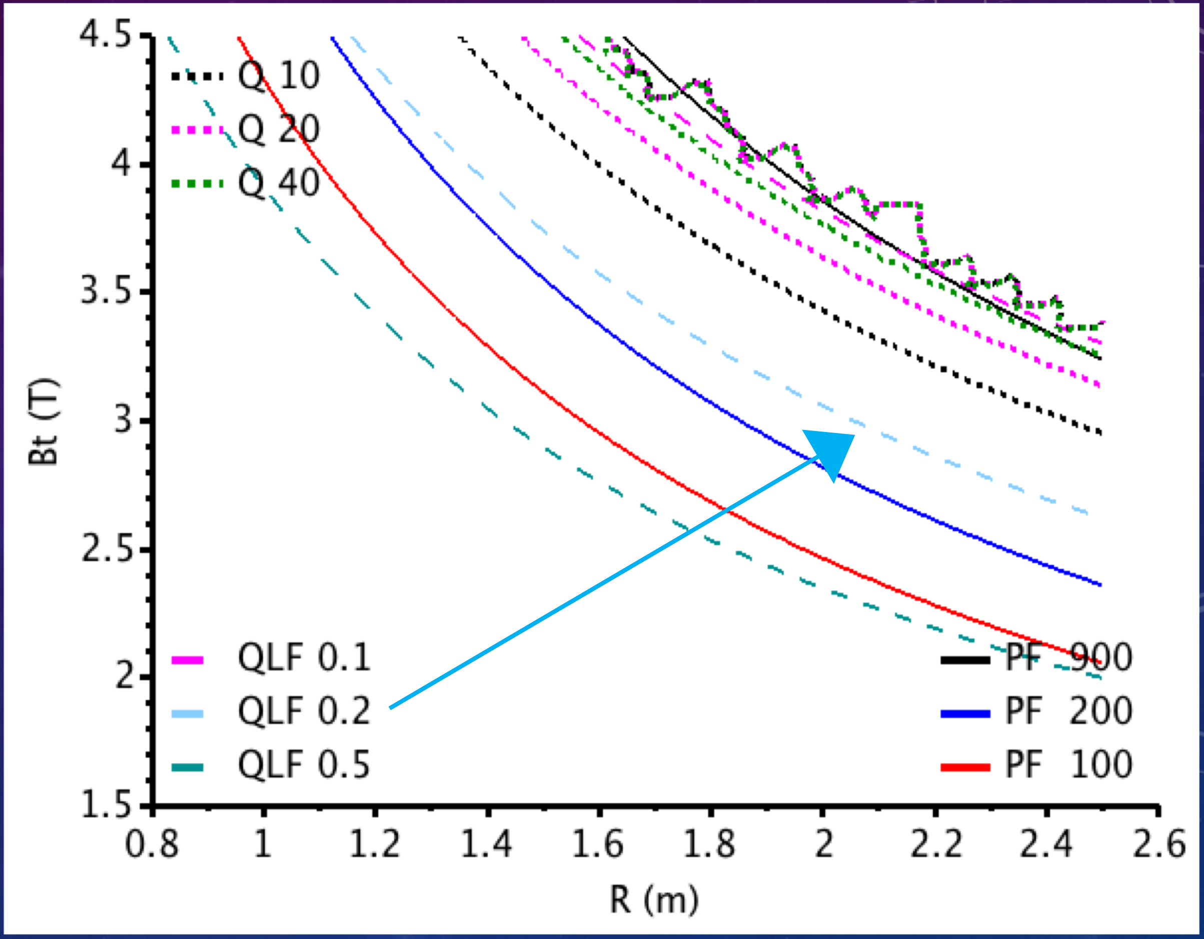
Contours of fusion gain and normalized power across separatrix

κ =2.75, δ=0.5, A=1.8, β_N =3.3, f_r =0.54, f_G =0.8, Hh=1.2, f_α =1

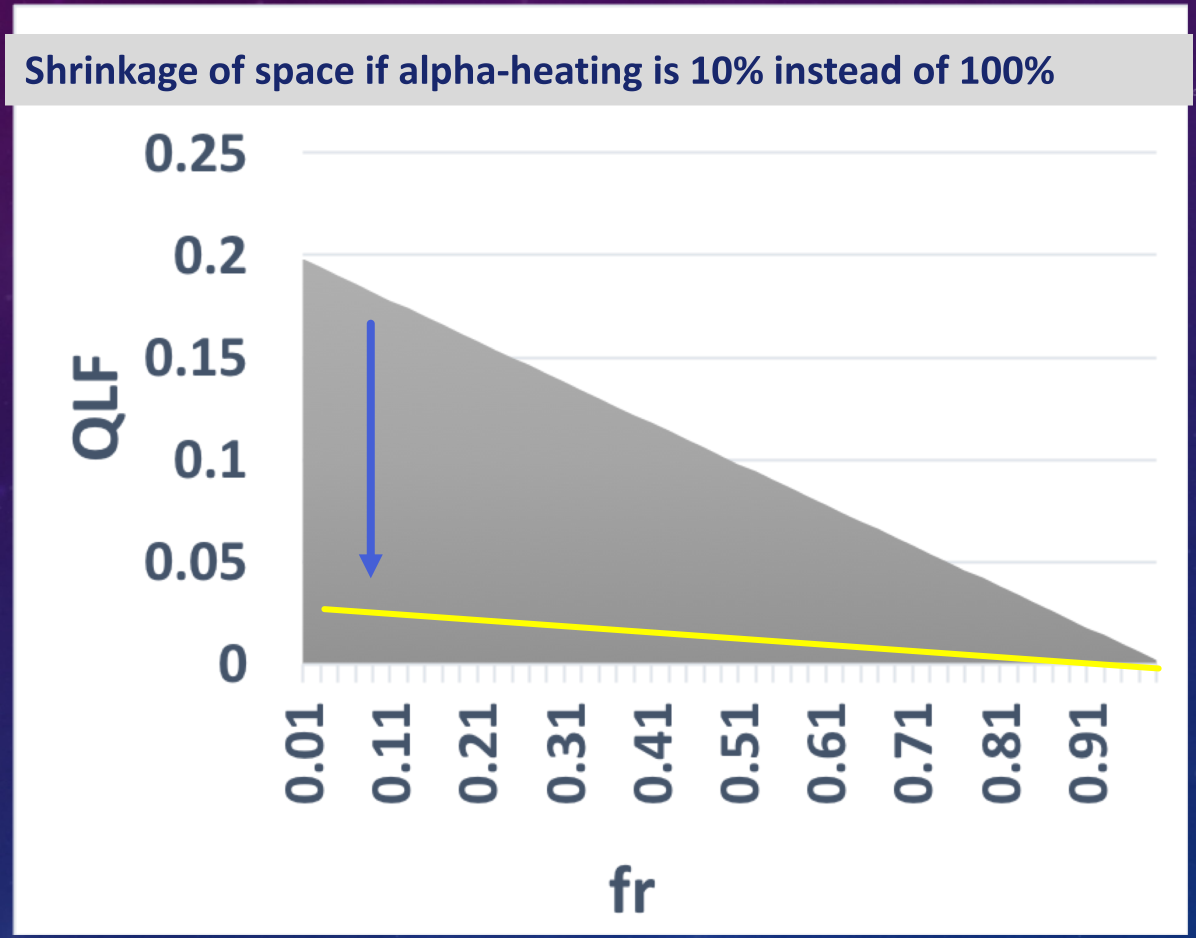
An important delimiter:

QLF=0.2

if f_r=0 and full α heating, then this the ignition boundary



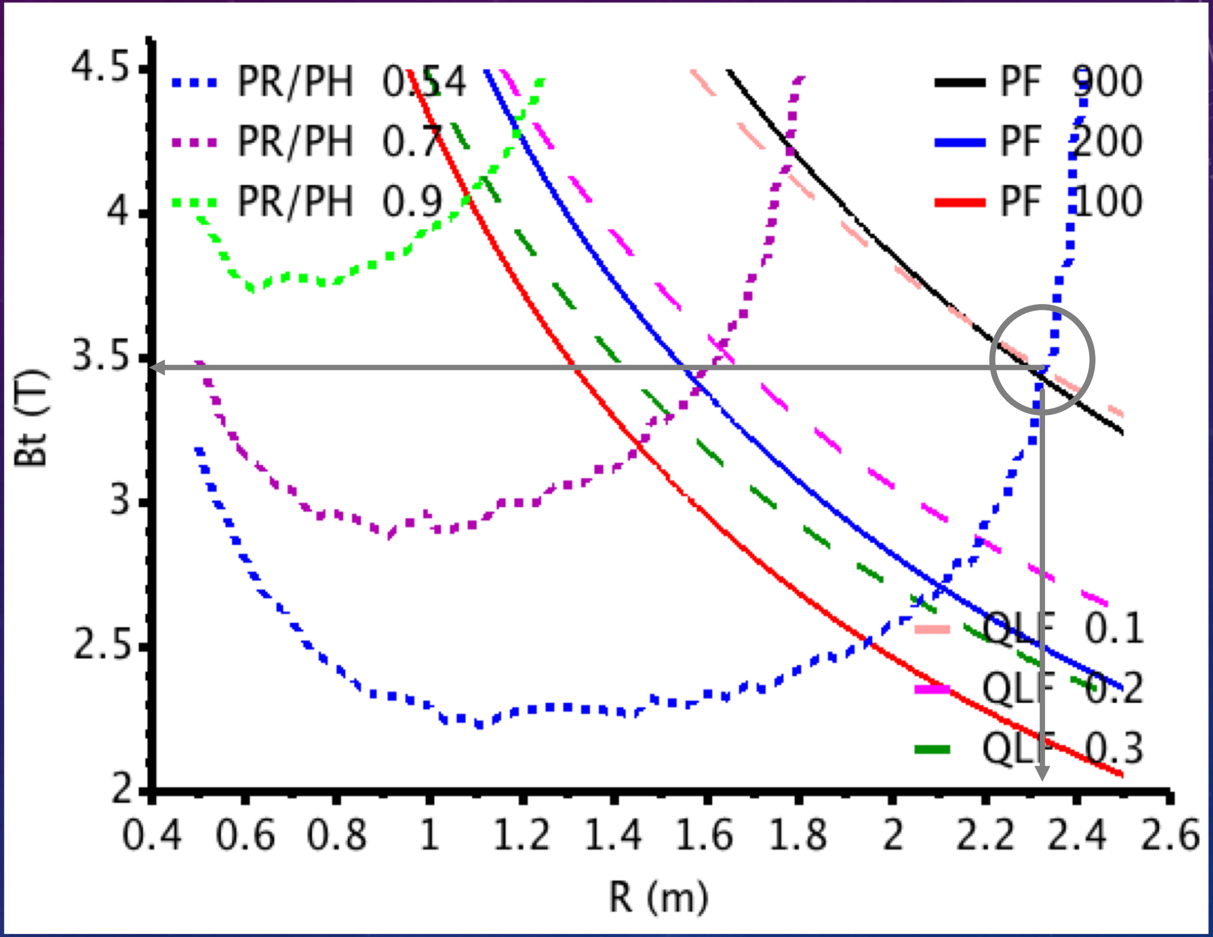
The resonance point (or large Q) will require smaller Q_{LF} values



$$Q = \frac{1}{\left(\frac{Q_{LF}}{1-f_r}\right) - \frac{f_\alpha}{5}}$$

Radiated fraction and normalized power across separatrix

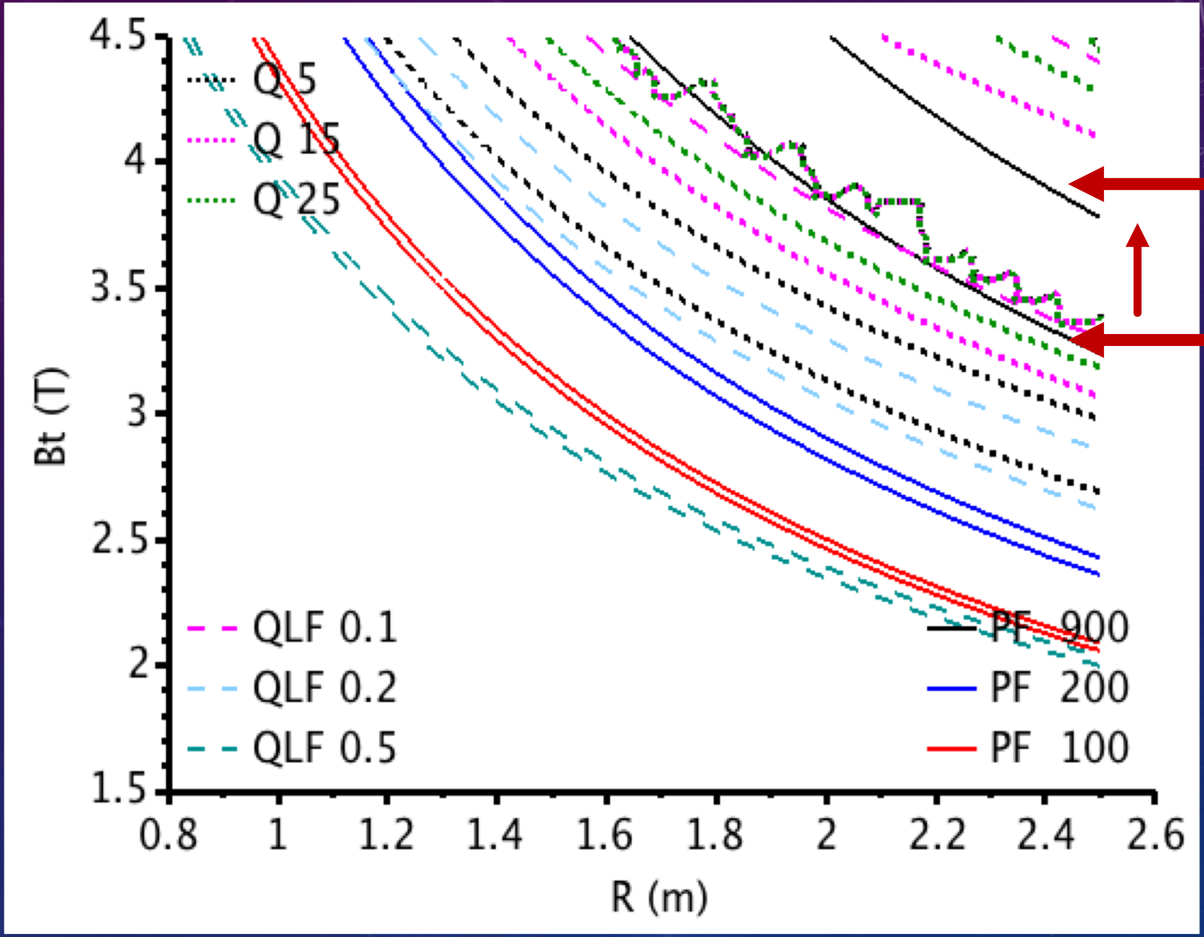
κ =2.75, δ=0.5, A=1.8, β_N =3.3, f_r =0.54, f_G =0.8, Hh=1.2



Tungsten concentration (n_W/ne) ~ 10^{-5}

Contours of fusion gain and normalized power across separatrix

κ =2.75, δ=0.5, A=1.8, β_N =3.3, f_r =0.54, f_G =0.8, Hh=1.2



Effect of He dilution is most visible for 900 MW case. Curve moves upwards

Neutron wall-load and Divertor Load

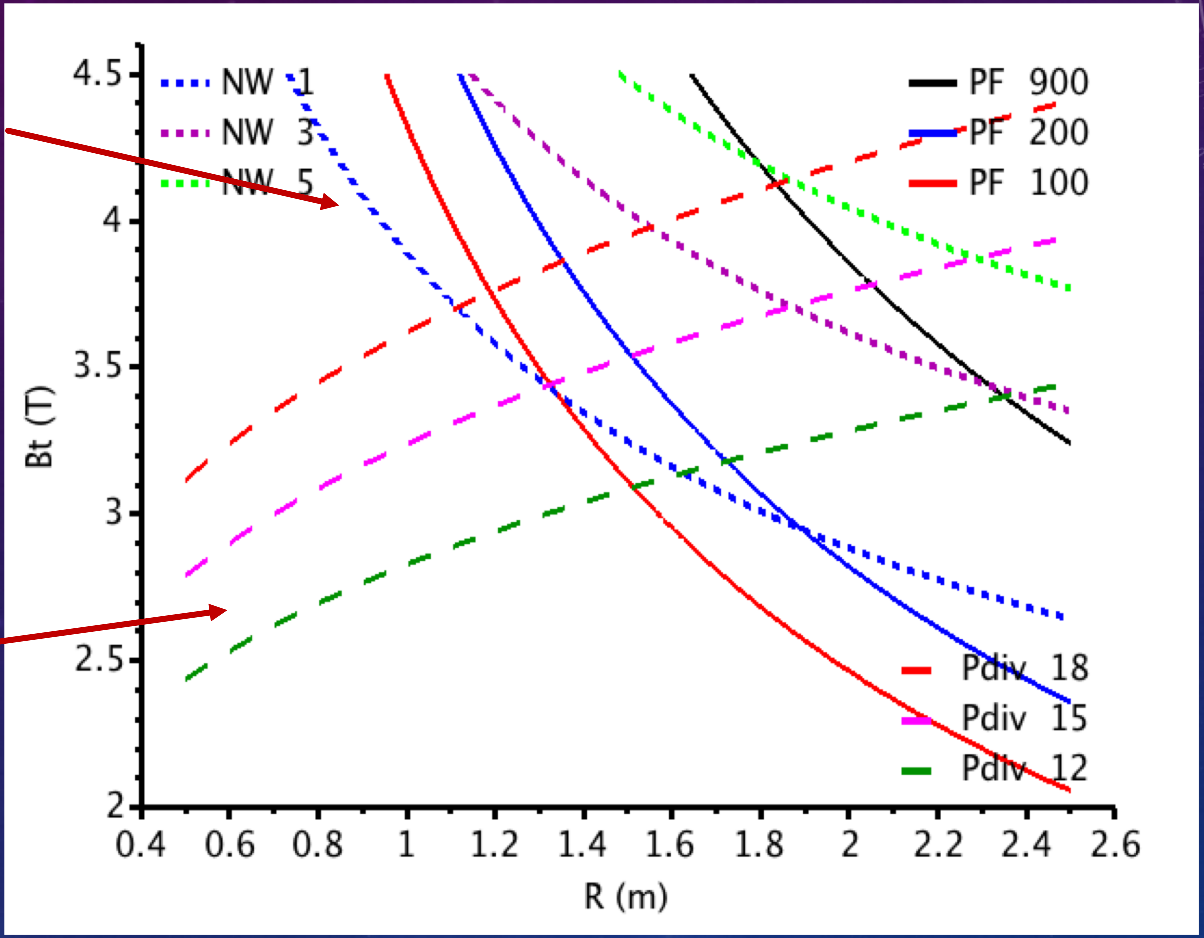
- Pdiv indicates the “divertor challenge parameter” (MW/m^2).
- NW indicates the neutron wall load (MW/m^2)

The divertor challenge parameter is not the actual divertor heat load, but a basis which spells out the actual design requirement. The number actually is Pdiv= Pseparatrix/(4*pi*R*a/5), suited for a double-null plasma.

κ =2.75, δ=0.5, A=1.8, β_N =3.3, f_r =0.54, f_G =0.8, Hh=1.2

N-wall load MW/m²

Divertor load MW/m²



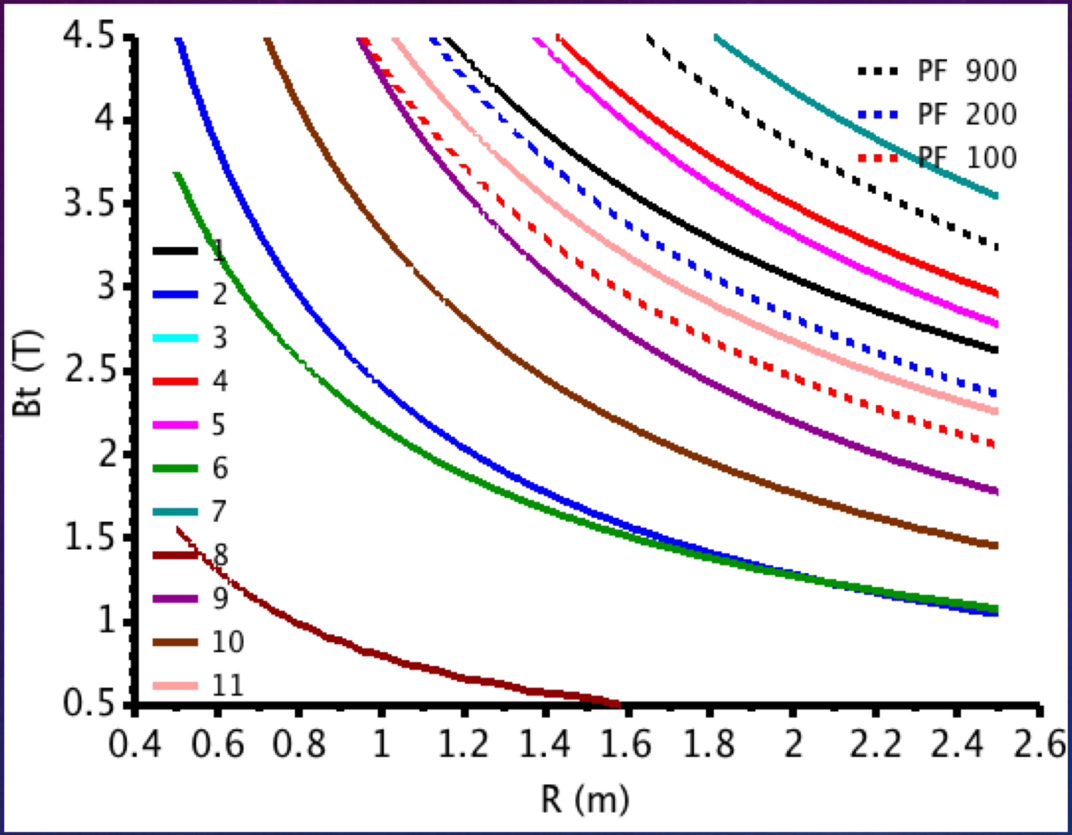
THE ST CONFIGURATIONS BEING EXPLORED HAVE THE FOLLOWING CONSIDERATIONS

- A low-power, low-cost configuration has an advantage of demonstrating a potential (policy level decision) which can start a program towards larger devices
- If sufficient pulse length is feasible (depending on the flux stored in CS/ space available / HTS capability), then component-test facility can be foreseen, as also the novel breeding-blanket ideas (outboard-side)
- For a grid-level operation, multiple STs in tandem can be foreseen, with ESS (Energy Storage Systems) so that grid receives a steady supply.

Three configurations analyzed (using ITER IPB scaling)

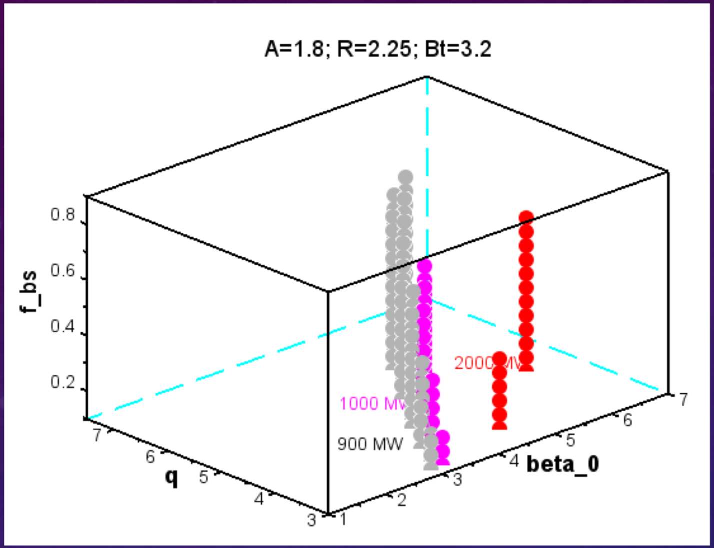
Parameters	R175	R125	R225
PFUSION (MW)	100	200	900
A	1.5	1.5	1.8
Kappa	2.75	2.5	2.7
q	6	4.2	5.2
H_h	1.2	1	1.2
f_{bs}	0.5	0.1	0.5
β_N	2.9	1.8	3.3
I_p (MA)	19.7	25.2	21.4
Q	1.3	3.5	40
f_r	0.56	0.3	0.54
P_{sep} (MW)	38	43	90

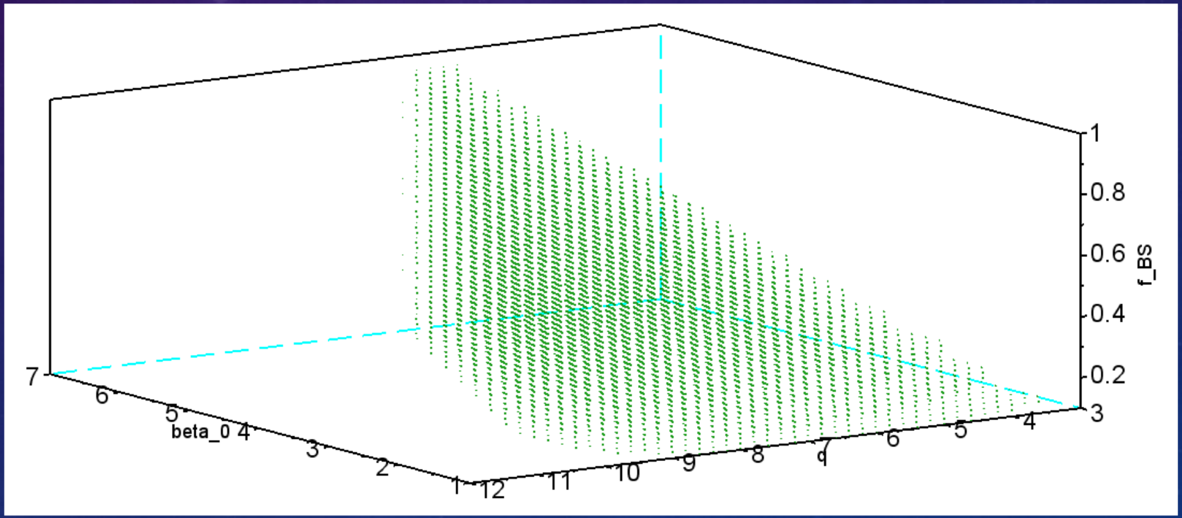
How various scaling laws affect the shape of QLF=0.2 curve



1) ITER IPB
2) BuxtonPPCF61
3) KayePPCF48
4) PettyFST43
5) PettyPP15
6) CordeyNF45
7) CordeyNF45Eq19
8) DnestrovskijNF61Eq7
9) DnestrovskijNF61Eq8
10) DnestrovskijNF61Eq9
11) Nearest integer ratios for ITER-IPB (this paper)

Allowed solutions zone, bounded in beta- q plane for various bootstrap fractions





SUMMARY

- Parameter space studies for ST based fusion reactor show a constraint arising from the radiative power loss from the core
- An important parameter characterizing the convergence for reasonable Q values is the ratio QLF (P_{sep}/P_{fusion})
- The uncertainties in confinement scaling (the exact exponent for the power) cause a large variation in QLF
- Reasonable Q seems possible only at high I_p
- The auxiliary power requirement (due to poor alpha confinement) will adversely affect Q
- High values of f_r are needed for those cases where QLF is significantly less than $f_\alpha/5$

THANK YOU

STAY SAFE !