Maximising fusion power density in compact beam driven tokamaks

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Abstract

For a number of non-power fusion applications high fusion power density, not high energy multiplication, is the primary measure of performance. It is well established that the fusion power density can be raised above the thermonuclear level using NBI [Jassby, D. L, Nuc Fus 15(3) 1975], and in the beta limited devices investigated fusion power density was found to be inversely related to energy multiplication.

Recently continued progress on spherical tokamaks and in magnet technologies have lead to the development of a new class of high field, compact STs. Such devices could achieve high first wall neutron fluxes while operating below beta stability limits, making them ideally suited to many non-power applications. However, limits on divertor power loadings place restrictions on the allowed external power and it is this that will ultimately limit performance. It is therefore necessary to revisit the subject of maximising fusion power density under the new constraint of fixed divertor loading.

Motivation

- New high field STs create the possibility of a *super compact* neutron source with major radius $R_0 \leq 0.5\text{m}$
- Growing need for a component test facility to investigate materials under fusion relevant conditions
- Compact size means commercial competitiveness, quick development and good accessibility to research community

Relationship between fusion power density and energy multiplication

Fixed pressure (fraction of beta limit):

$$P_f \sim \frac{1}{Q^{2/3}} \quad \text{but} \quad P_{NBI} \sim \frac{1}{Q^{5/3}}$$

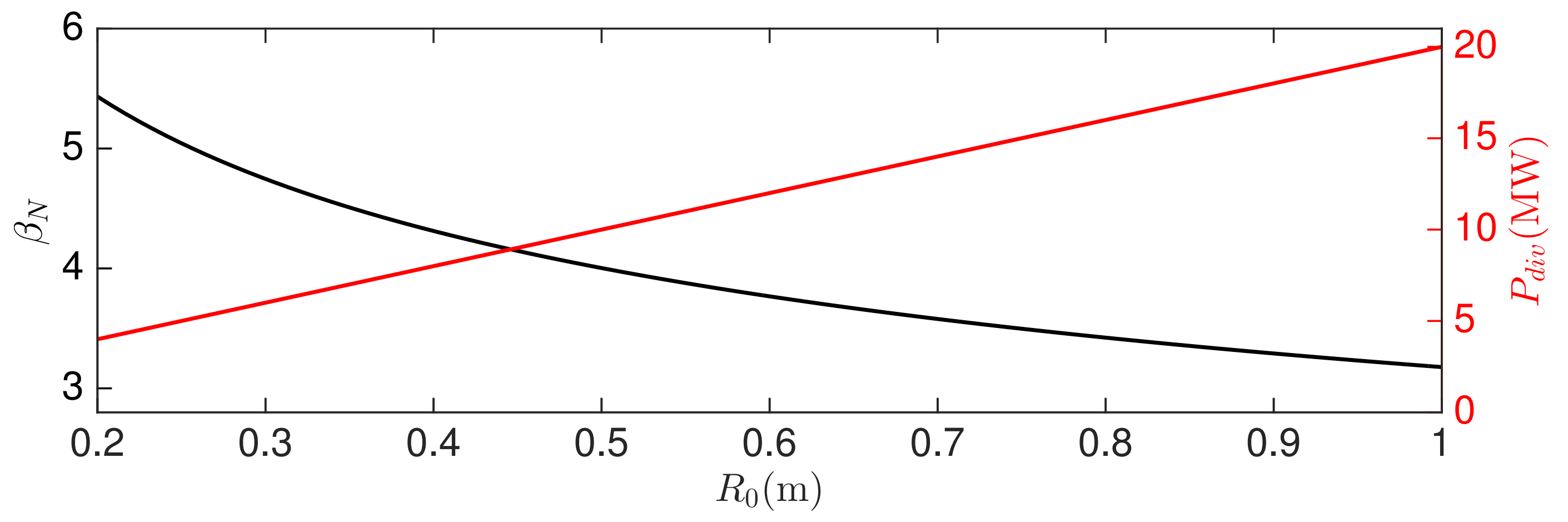
- Fusion power can be increased by reducing confinement
- However this requires an increase in NBI power

Fixed wall or divertor power load:

$$P_f \sim \frac{Q}{(1+Q)} \quad \text{and} \quad P_{ext} \sim \frac{1}{(1+Q)}$$

- Fusion power is positively correlated with Q
- However this requires good plasma confinement

Which limit is relevant in compact devices?



Dependence of β_N *limit and maximum allowed divertor power on device size when operating with* $q_a = 2.2$*. Divertor power limit taken as* $P_{div}/R_0 = 20\text{MW/m}$*.*

A 0-D scoping model

Prescribe:

- Temperature, $T_i = T_e = T$
- Electron density, n_e
- Beam injection current, $I_b = P_{NBI}/W_0$

Beam density:

$$n_b \sim \frac{I_b T_e^{3/2}}{n_e}$$

Quasi-neutrality:

$$n_e = n_i + n_b$$

Edge safety factor:

$$q_a = \frac{5 B_{T0} \epsilon^2 R_0 \kappa}{I_p}$$

Bootstrap current:

$$f_{bs} = 0.04 \epsilon^{-0.5} \beta_N q_a$$

External current drive:

$$P_{CD} = [1 - (f_{bs} + f_{NBI})] \frac{33 n_{20} I_p R_0}{\xi_{eff} T_e(\text{keV})}$$

Power balance:

$$\underbrace{P_{NBI} + P_{CD}}_{P_{ext}} = \frac{3(n_e T_e + n_i T_i)V}{2\tau_E}$$

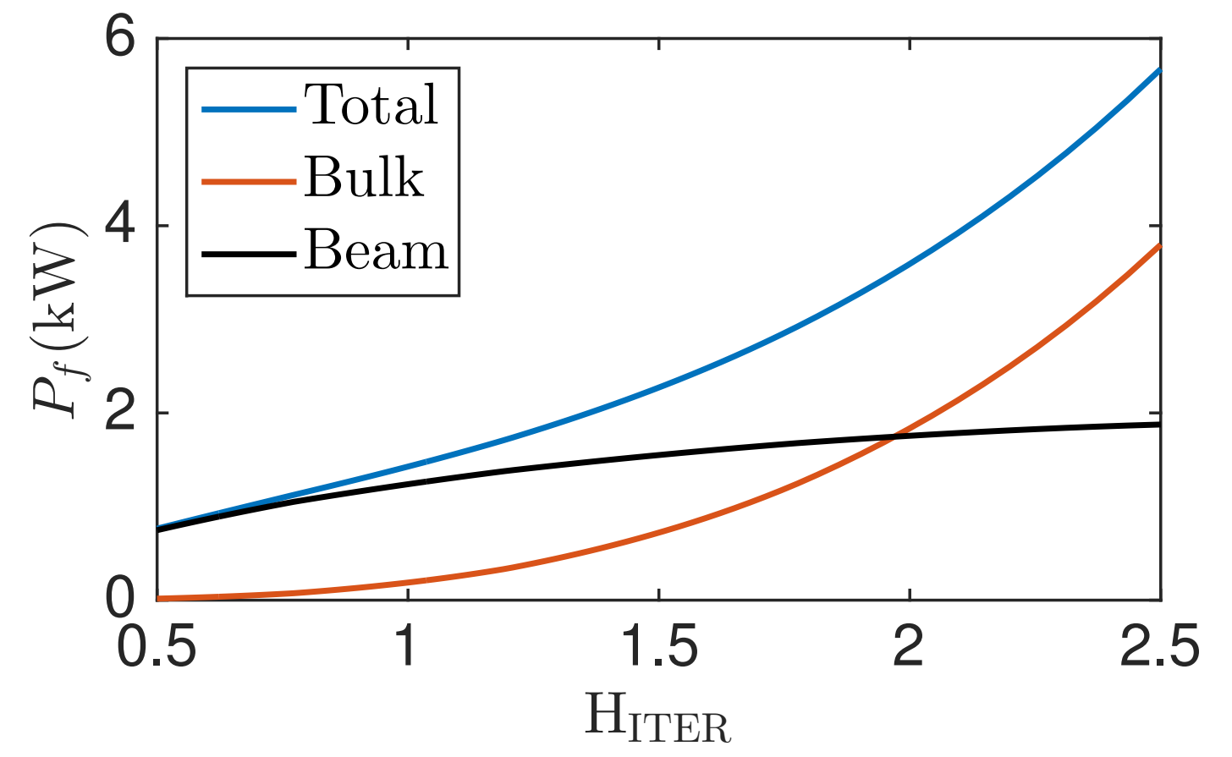
Power to divertor:

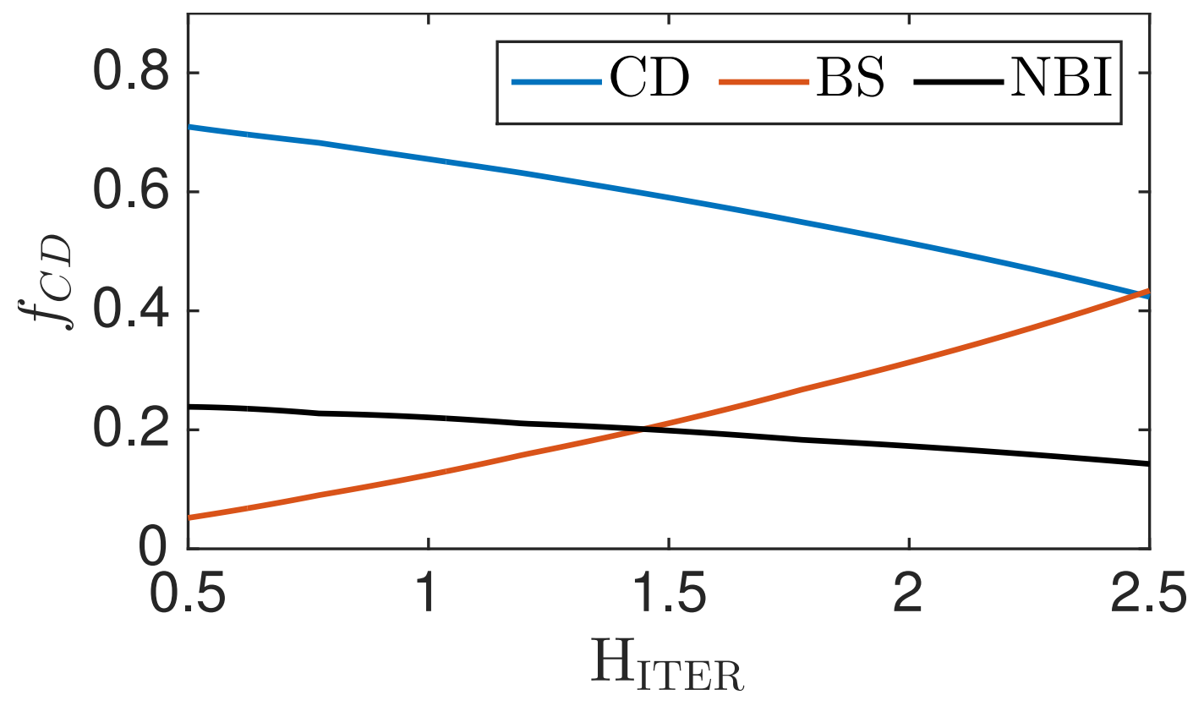
$$P_{div} = P_{ext} + P^{+}_{fusion} - P_{rad}$$

Deuterium-deuterium device

- Compact, high field ST, based on ST40 device designed by Tokamak Energy:

$R_0(\text{m})$	ϵ	κ	$B_{T0}(\text{T})$	$I_p(\text{MA})$	$P_{NBI}(\text{MW})$	$P_{CD}(\text{MW})$	ξ_{eff}
0.4	1/1.8	2.5	3	2	2	6	0.5



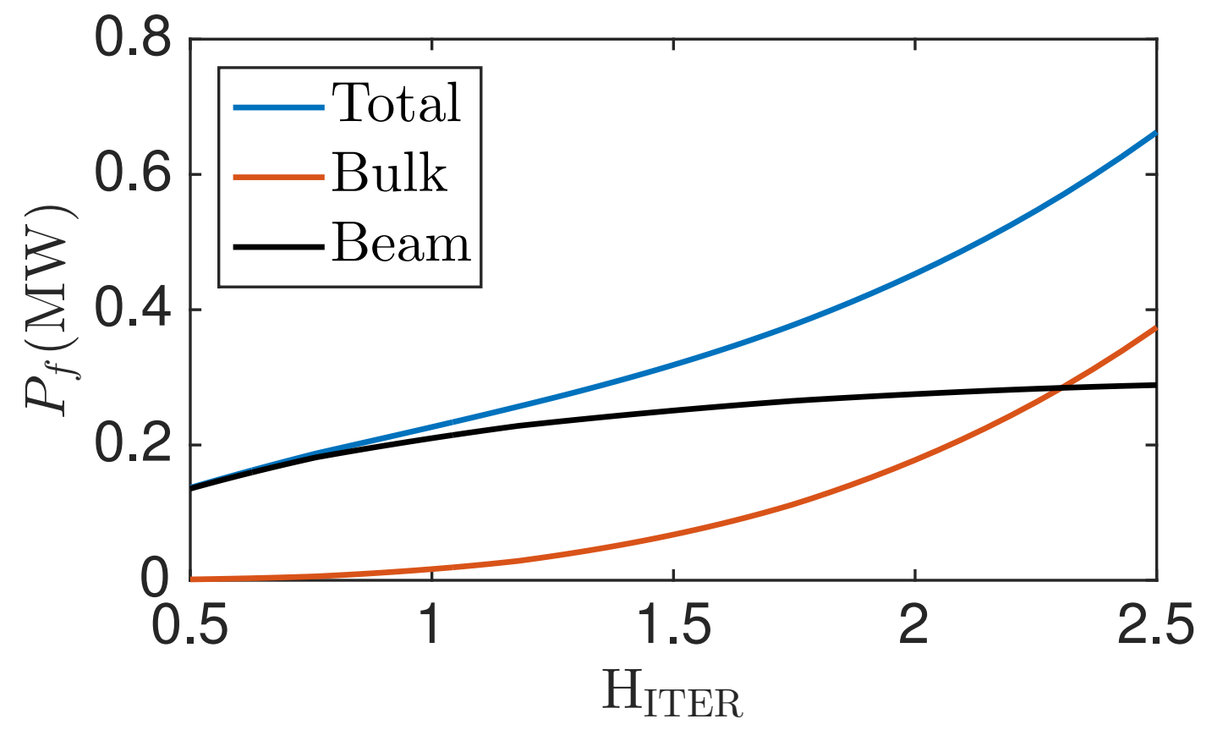


H_{ITER}	$\text{n}(2.45) \times 10^{15}/\text{s}$	$\text{n}(14.1) \times 10^{13}/\text{s}$	$\beta/\beta_{max}(B_{T0} = 3\text{T})$	$\beta/\beta_{max}(B_{T0} = 1.5\text{T})$
1	1.28	2.48	0.33	0.62
1.5	1.99	5.00	0.44	0.81
2	3.09	9.02	0.59	1.06
2.5	4.81	15.3	0.76	1.34

- Performance very sensitive to H_{ITER}
- High field allows higher performance operation while remaining beta stable
- High current means high fraction of fast tritons will be confined (requires high B_{T0} to ensure $q_a > 2$)
- Current drive is dominated by external power as $f_{bs} < 40\%$. Therefore a high efficiency is required to keep P_{div} within limits

Seeding with a small amount of tritium

- Tritium is expensive, difficult to handle and heavily regulated
- With a small amount of tritium, $n_T/n_i = 15\%$
  - 50% of the optimum thermonuclear power (1:1 D:T)
  - 15% of optimum beam-on-bulk fusion power (100%T)
  - Approximately $100\times$ increase in fusion power over pure deuterium operation



H_{ITER}	$P_f(\text{MW})$	$\text{n}(14.1) \times 10^{17}/\text{s}$	$\text{m}_{\text{T}}(\mu\text{g})$
1	0.27	0.80	48.6
1.5	0.32	1.12	70.3
2	0.45	1.60	94.3
2.5	0.66	2.33	124.6

- 14.1MeV neutron outputs suitable for a number of applications including: materials and PFC testing
- Performance can be further increased by raising the tritium concentration
- Beam contribution to total fusion power increases with tritium concentration
- Options for further optimisations include constant:
  - H_{ITER}
  - Fusion power
  - Energy multiplication

Conclusions

- In power limited devices fusion power density is positively correlated to energy multiplication
- A super compact MW range neutron source is feasibly with ITER like divertor loadings, assuming transport scalings do not change significantly as device size is reduced
- Fusion power is very sensitive to H_{ITER}
  - Bulk fusion power $\sim \text{H}^3_{\text{ITER}}$
  - For $\text{H}_{\text{ITER}} \gtrsim 1$ beam fusion power is only weakly dependent on H_{ITER}
- Divertor loadings are dominated by external power. Therefore maximising current drive efficiency is crucial
- Tritium seeding can greatly increase performance without the need for high tritium concentrations

Further work

- Complete scoping study by fully investigating DD and DT devices, including the effects of: T_i/T_e, P_{NBI}, W_0 and B_{T0}
- Use results as basis for a more detailed design study of a super compact neutron source