PPCA.O-5
Proceedings of the 2nd IAEA Technical Meeting on First Generation of Fusion Power Plants: Design & Technology

The Benefits of Different Options for a European DEMO

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This work was jointly funded by the EPSRC and by EURATOM

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What Key Parameters are Explored?

- Systems code studies using the code PROCESS, particularly looking at:
  - Divertor heat flux
  - Steady state versus pulsed operation
  - Inboard radial build (steady state)
  - Flux swing (steady state and pulsed)

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Divertor Heat Flux

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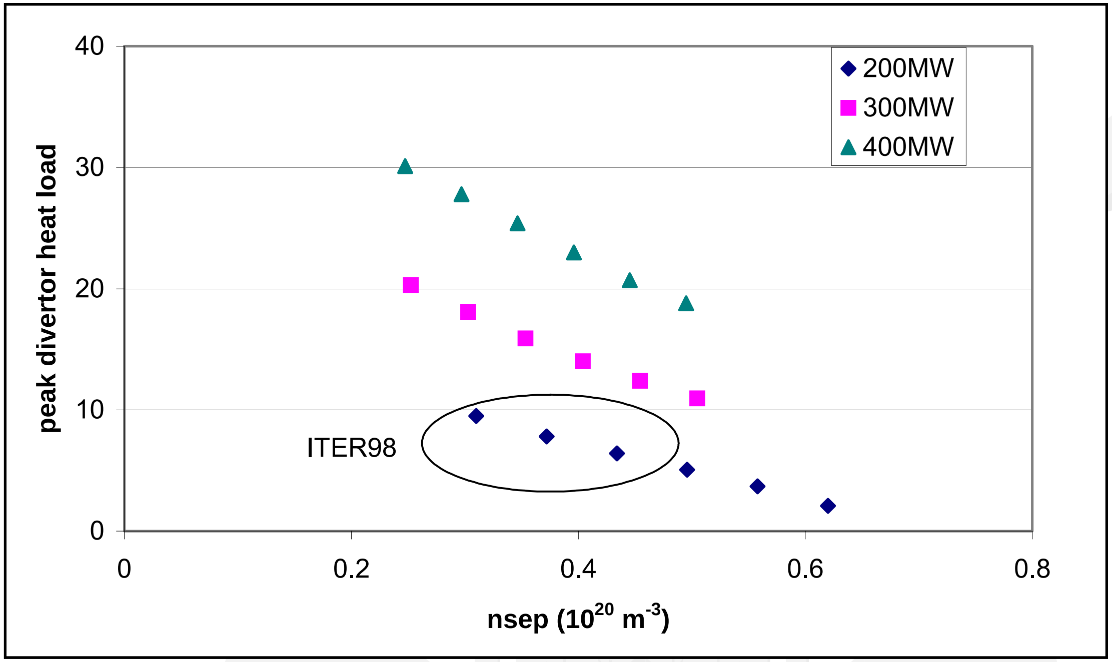
What Power Across the Separatrix Can be Handled?



R=8.2m

300 MW looks to be the highest possible P_{sep} in an ITER(98) sized machine, even allowing for impurity seeding of the divertor. If this were a DEMO, producing 3GW fusion power, this would require ~60% radiation from the core.

Constraint less severe in Double Null (if balanced power flow can be attained) but complexity increased.

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Pulsed or Steady State?

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Pulsed or Steady State?

- Pulsed:
  - Long pulse length, larger solenoid, larger R (larger aspect ratio)
  - Pulsed heat and stresses
  - Energy storage
  - Large power supplies for fast recharge of OH coil
- Steady state
  - Current drive efficiency and reliability
  - Ports, neutron streaming
  - Increased power density and divertor loading
- Hybrid design? (pulsed with some supporting CD)
  - Worst of both worlds?

Pulsed Operation of a Power Plant

- Assume that the electrical power must be steady state
- Match pulsed plasma to steady power with a thermal (or other) buffer
- The energy storage adds a significant cost but this is offset by the reduced current drive system
- Then why is a pulsed power plant always said to be more expensive than a steady state one?

Pulsed Operation of a Power Plant

1. Pulsed operation induces cyclic stresses which require reduced thermal and electromagnetic loads
2. Restricting the number of pulses over the device lifetime requires a long pulse length.

- 1 and 2 are consistently satisfied by a large bore device with reduced power density, (and correspondingly reduced divertor heat flux).
- e.g. lifetime made up of 30,000, 8 hour pulses.
- Large machine size increases cost substantially although in power plant studies coe ‘only’ ~20% higher.
- This requires high duty cycle, fast transformer recharge and large power supplies. (Probably inadequately treated).

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Example of a Pulsed DEMO

R(m)	9.55
Aspect ratio	4
I (MA)	15.5
B(T)	7.4
q	3.4
<T> (keV)	15.6
<n> ($10^{19}m^{-3}$)	0.95
Z_{eff}	1.77
P_{fus} (GW)	2.03
P_e (GW)	1.0
Av neutron wall load (MW/m^2)	1.2
Peak div heat load (MW/m^2)	5.1
Bootstrap fraction	0.43
β_N thermal, total	2.4, 2.6
β_N limit (thermal)	3.0
H factor	1.3
Pulse time (hours)	8.5

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What is the Effect of Adding CD to a Pulsed Device?

- The same pulse length can be achieved with a smaller flux swing. This is more beneficial than might be expected because up to 50% of the current is driven by the bootstrap effect already, so only ~50% is inductive even in the “fully” pulsed case.
- In the following, the systems code, PROCESS, is used to carry out systematic scans but without the normal iteration and refinement that is carried out for “point designs”. Details should not be taken too seriously; it is the trends that are important.

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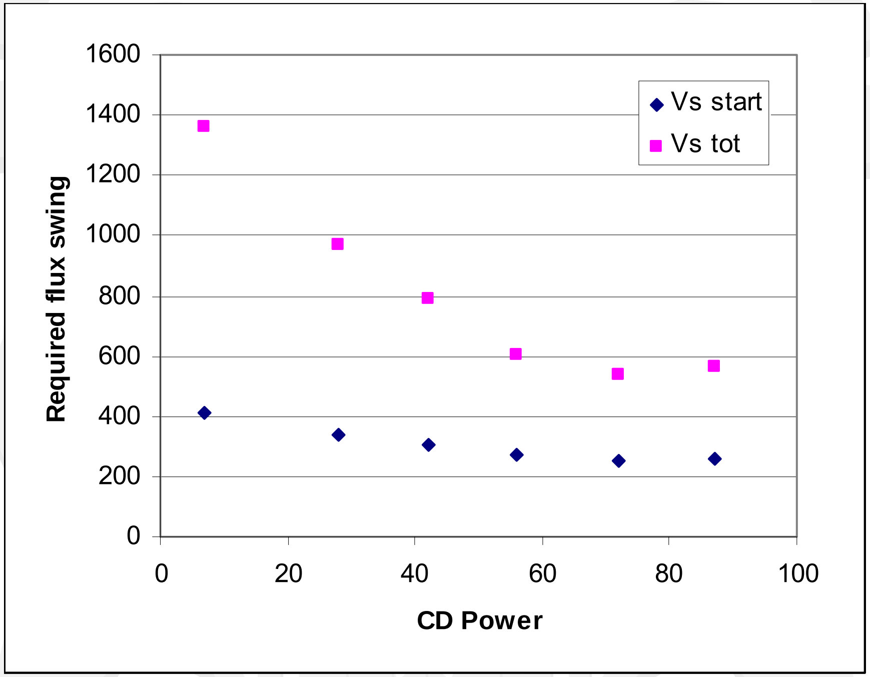
Adding CD Power Naturally Reduces Flux Swing Requirements



Current drive sustains some of the current reducing the voltage requirements and reduces the required flux swing

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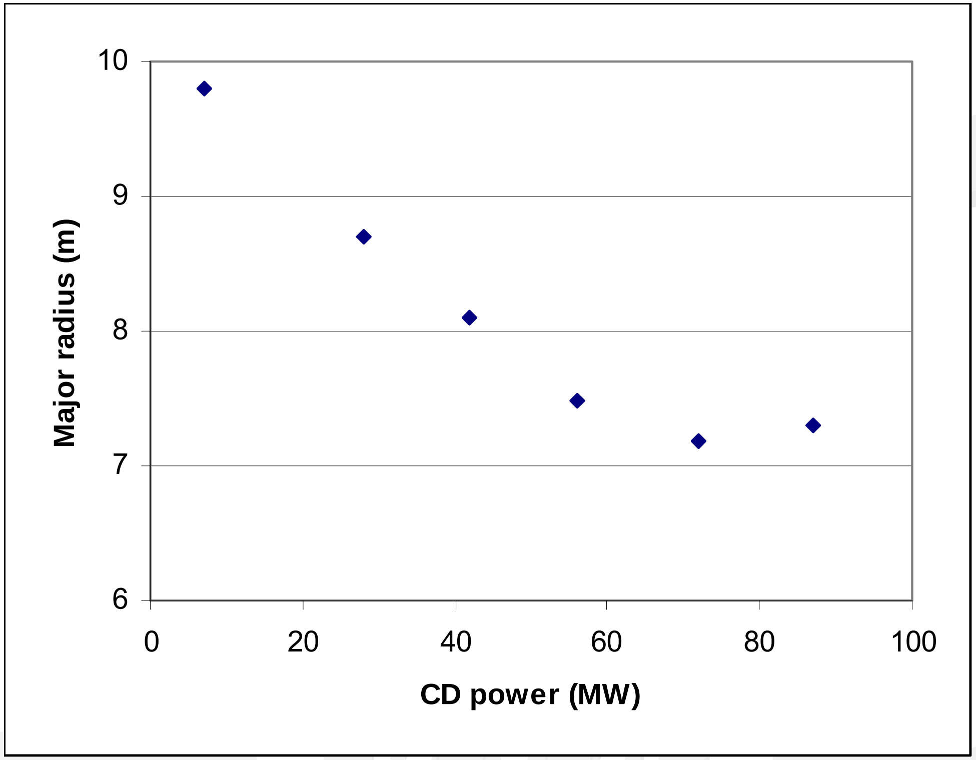
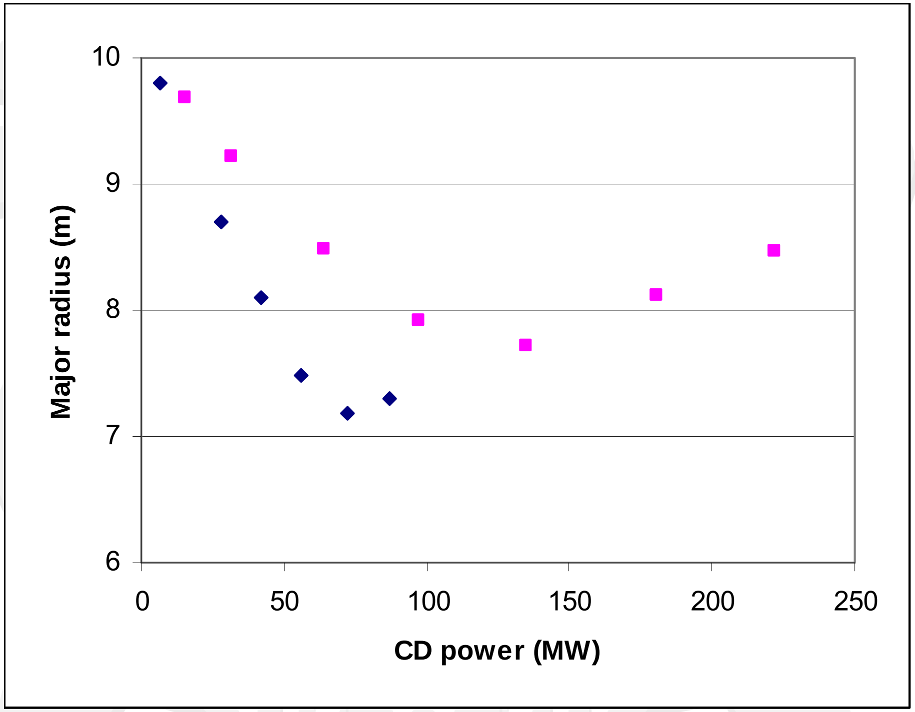
Adding CD to a Pulsed Device Reduces the Size



Major radius is substantially reduced by adding CD power (here 2 MeV NNBI, but what if lower CD efficiency?).

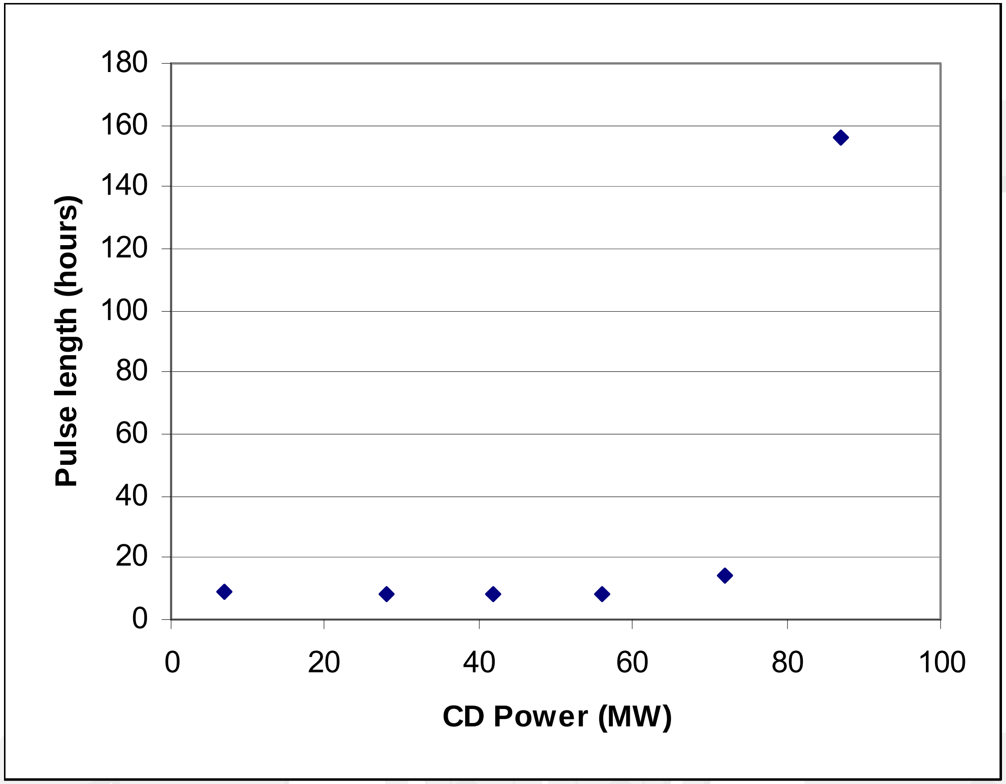
What if the CD System is not as Efficient as 2 MeV NNBI?



Reducing γ_{CD} **by a factor of 5** changes results but still full non-inductive plant is smaller than full inductive. Possible optimum at less than full CD but this is not a proper comparison of pulsed vs steady-state.

It is **not true** that steady state plants cannot be built using less efficient CD systems.

Pulse Length Approaches Infinity at High CD Power



Although still a pulsed plant, it approaches almost 100% CD.

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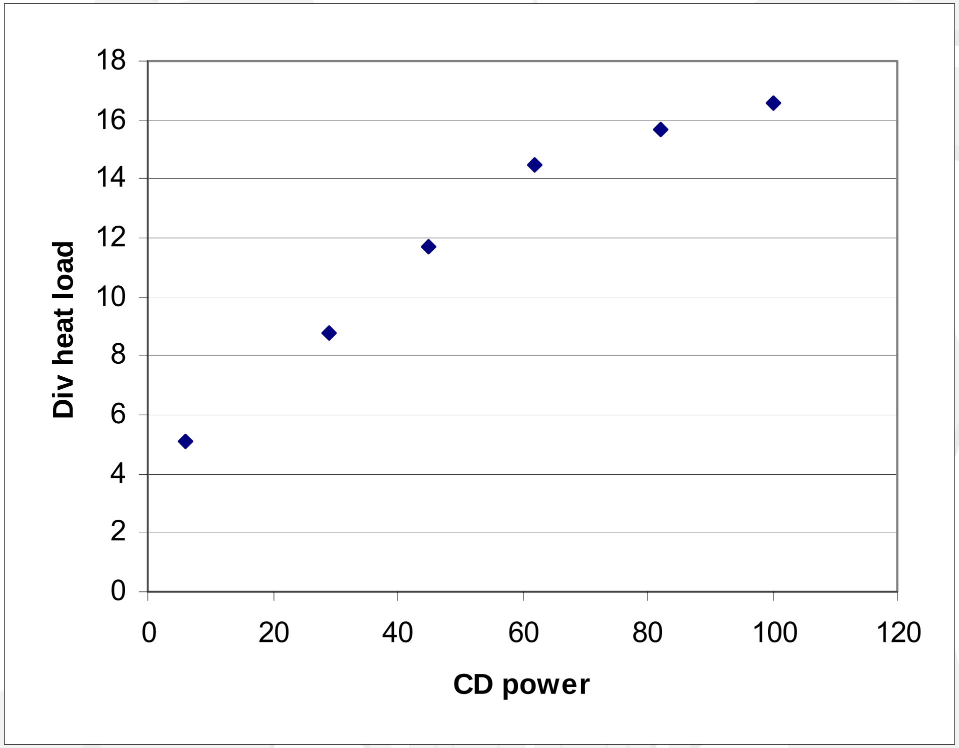
Increasing Power Drives Pulsed Device Towards Power Densities Characteristic of Steady-State Devices



Increasing CD power reduces size (cost) and increases power density. This is not heading to an optimum steady state plant as the basic assumptions are still characteristic of a pulsed plant (aspect ratio, energy storage…)

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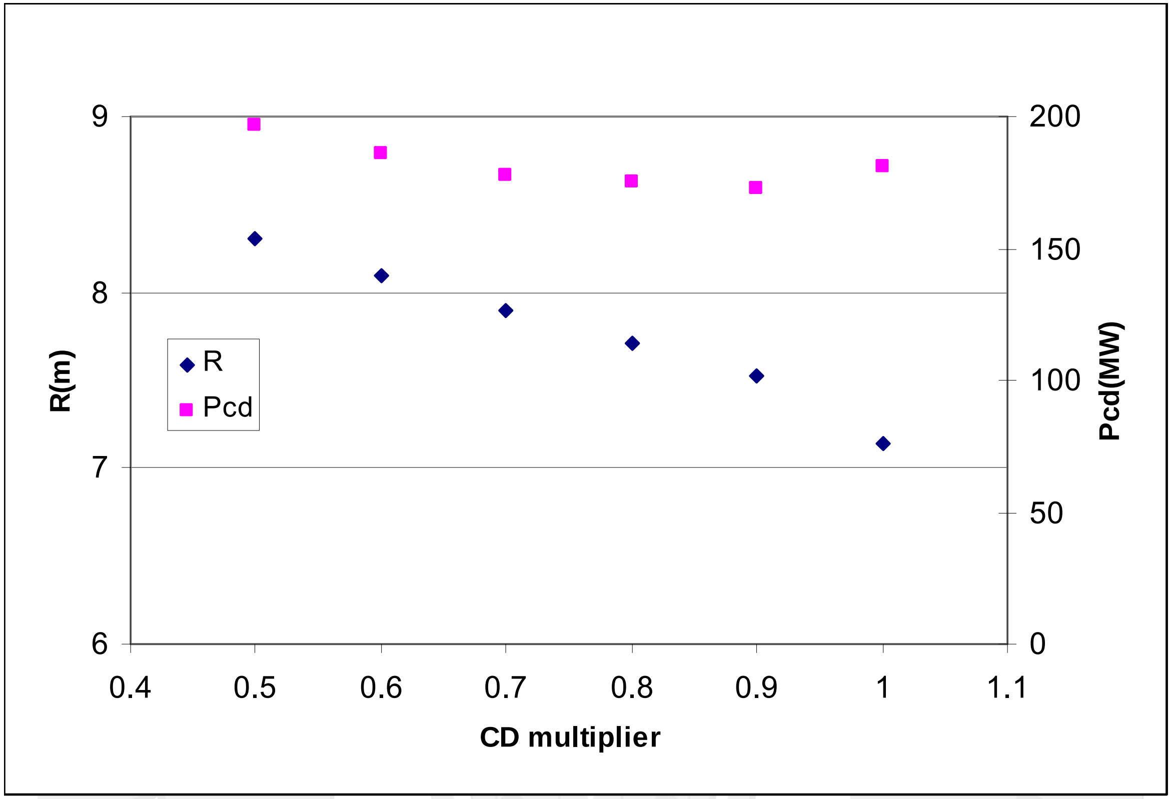
What is the Result of Reduced CD Efficiency on a Steady State Design?



Reduce CD efficiency by a multiplier. Design optimisation changes size (and q and bootstrap fraction) to avoid excessive CD Power. Self consistent plant couples changes and outcomes often non-intuitive.

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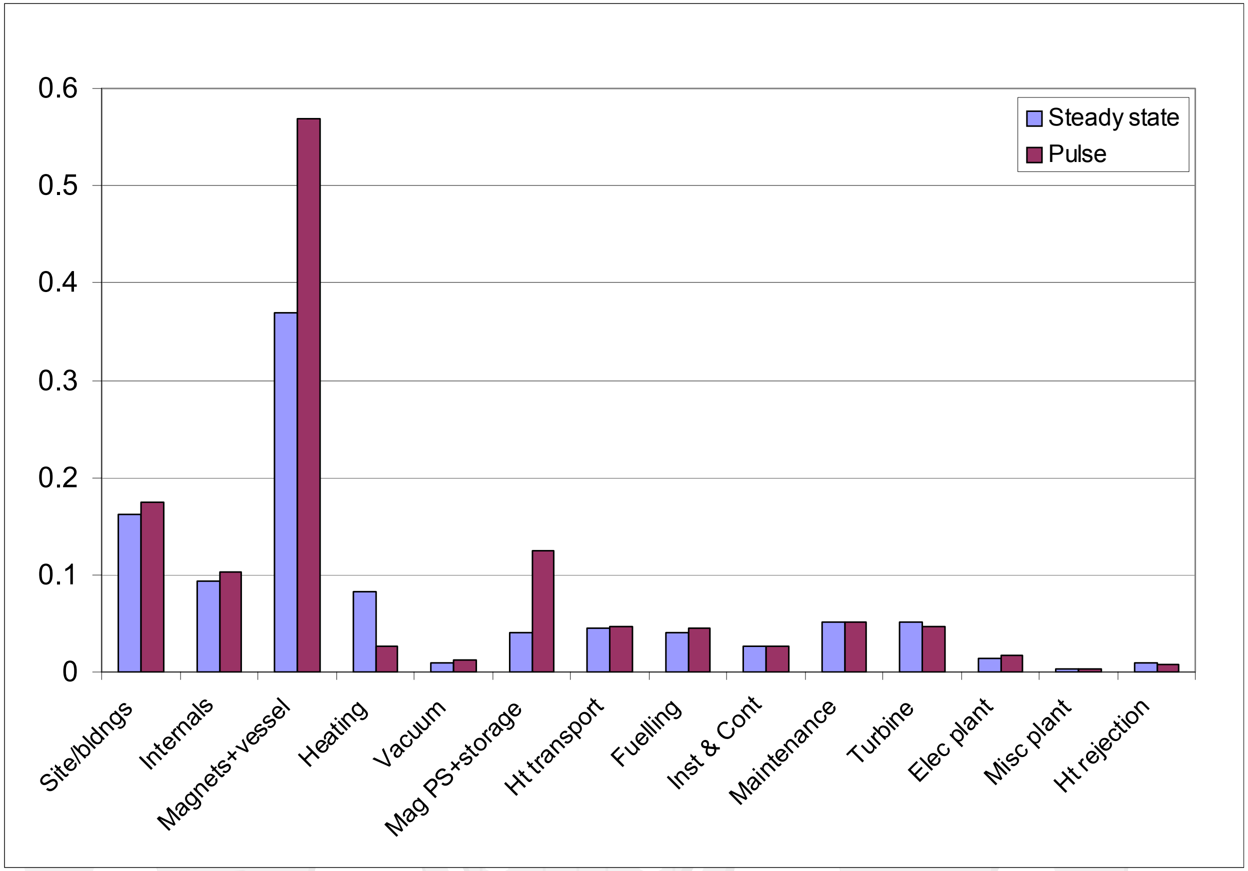
Cost Comparison – Pulsed vs Steady State

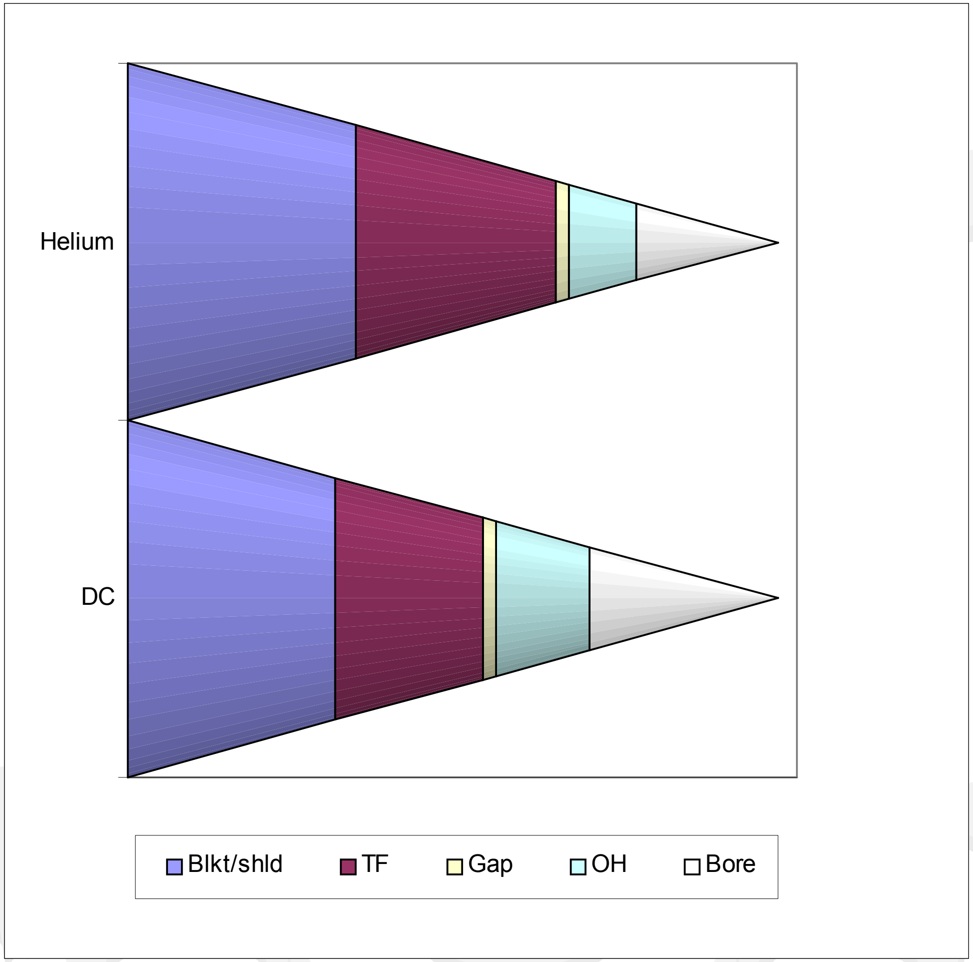
Normalised cost



Only approximate, both normalised to same total cost (steady state plant). Direct costs, first of a kind, 1GWe plant.

Radial Build

Helium Cooled Plant Radial Build More Challenging



Potential for reduced OH coil size with helium coolant than with Dual Coolant concept. This is only an example.

Flux Swing

Example of Flux Swing

- Details depend on detail of inboard radial build which may still change slightly.
- This level of detailed calculation should be done outside a systems study, then integrated.
- For illustration, PROCESS estimates OH coil can provide up to ~120Wb whilst plasma startup needs approx 320 Wb (250 inductive plus 70 resistive).
- However PROCESS estimates flux swing available from remainder of PF set is (more than) 300 Wb (but does not calculate accurate wave-forms).
- This remains uncertain – how much inductive flux is needed for start-up and can this be supplied by a reasonable PF set?

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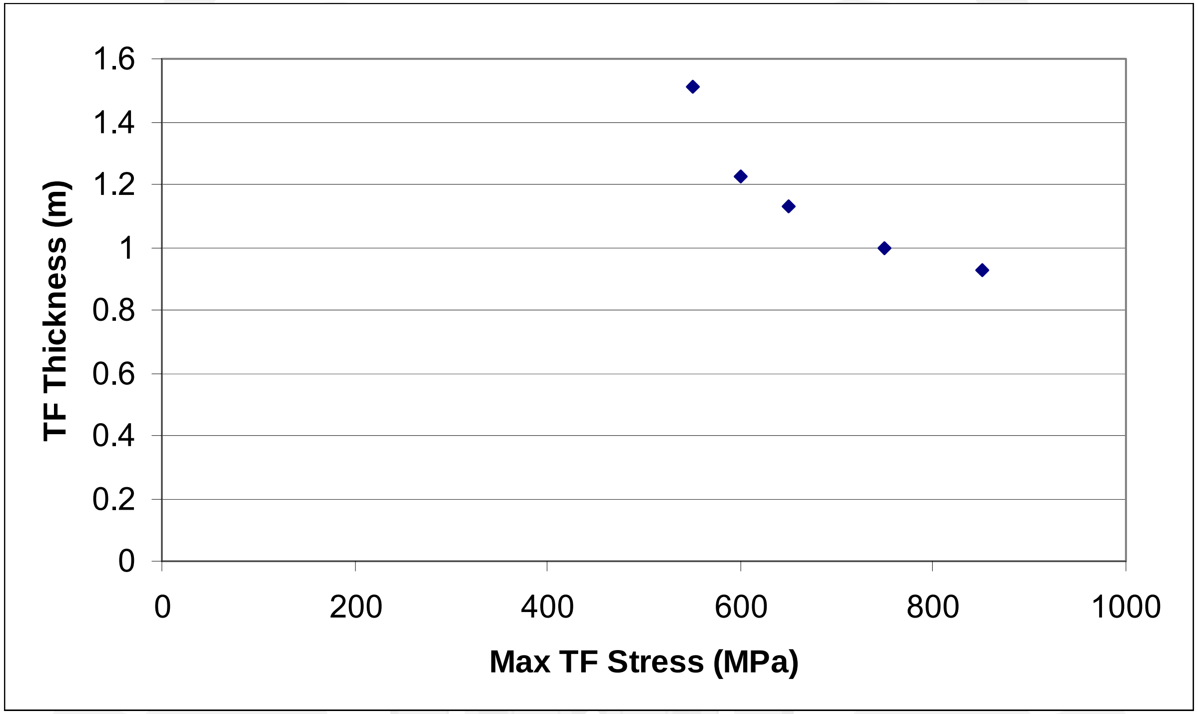
How Do Other Assumptions Impact?



e.g. TF stresses affect inboard radial build

Thickness of i/b TF coil increases as allowable TF stress reduces

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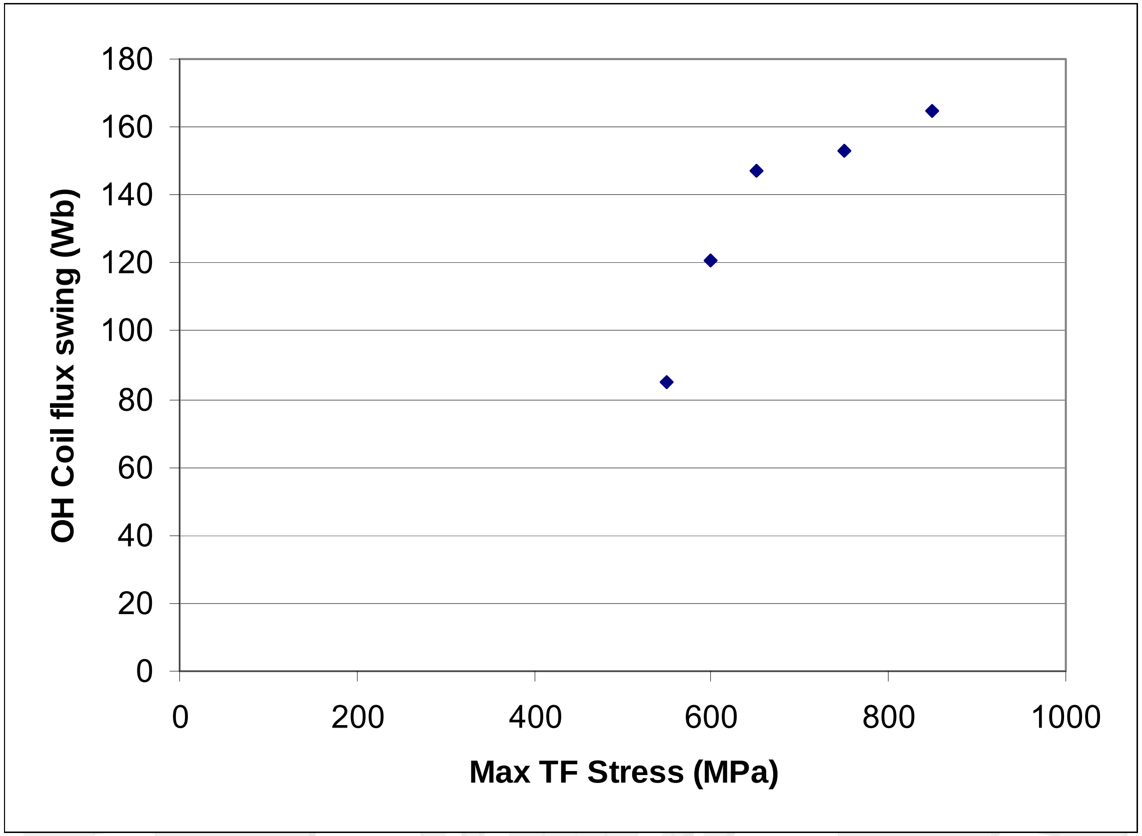
Allowable TF Stress Strongly Affects OH Flux Swing



OH coil size can be substantially changed by relatively small change in allowable TF stress

Starting Point for DEMO Based Around Helium Cooled Lithium Lead Concept

R (m)	7.5
I (MA)	19.4
B (T)	5.9
P_{add} (MW)	142+40
β_N (thermal)	3
H factor	1.3
P_e, P_{fus} (GW)	1.0, 2.40
Divertor heat load	10

Still expect to iterate this design as a result of other information.

Single null, steady state design.

Technology studies underway.

Also consider a pulsed machine as an alternative?

Is a low Q machine acceptable? (here Q~15)

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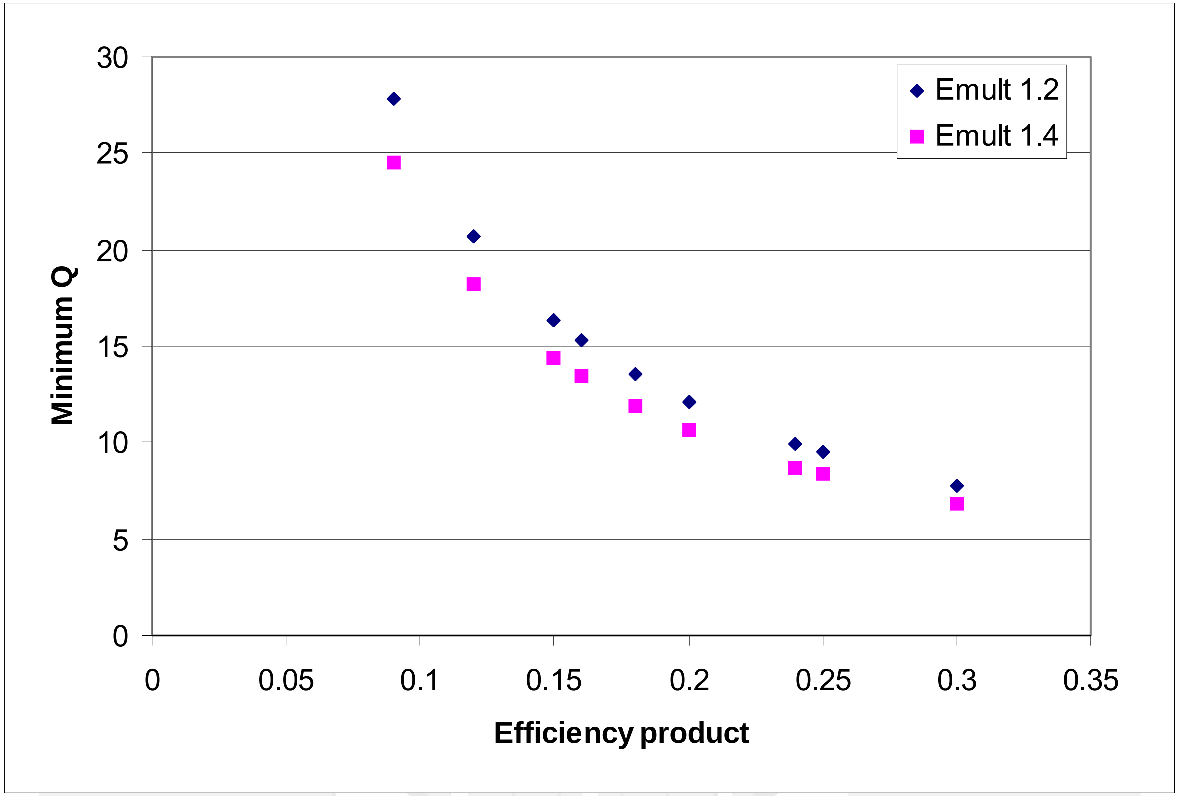
Minimum Q for a Power Plant



Efficiency product multiplies CD wall plug efficiency and plant electrical conversion efficiency.

Requires less than 33% recirculating power, and includes energy multiplication in the blanket, contribution of heating to high grade thermal power etc.

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Conclusions

- With optimised impurities in a plant based on a hybrid plasma, a steady-state DEMO appears feasible. A 7.5m major radius, single null, steady state device has been proposed as a starting point.
- In a pulsed machine the issues are entirely different: flux swing, pulse length, fatigue life and increased cost become most important; divertor heat load is relatively unimportant. A pulsed machine appears to be up to 2m larger in major radius although this can be reduced by adding some current drive.
- A Helium cooled plant has a more challenging inboard radial build than a liquid cooled plant and may reduce the available flux swing. This is part of the ongoing investigations.
- A pulsed device may still be considered as an alternative.

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SPARES

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Energy Storage Study - Electrowatt

- Two main options studied:
  - 1. Fast restart, use thermal storage, only for reactor down time of up to 100s
  - 2. Slow(er) restart, auxiliary heat source, studied for a down time of up to 300s.
- Capital and O&M costs estimated.
- Option 1 required for each plant built
- Option 2 could be shared between multiple units.
- This is modelled in PROCESS as an additional cost.

EWE-2913 1992

Hybrid Plasma with Model C Technology

R (m)	7.5
I (MA)	17.6
B (T)	6.1
P_{add} (MW)	137
β_N (thermal)	3
H factor	1.28
P_e, P_{fus} (GW)	1.0, 2.55
Divertor heat load	10

Illustrative results with protected divertor

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	Pulsed	Steady-state	Steady-state (low CD effic)
R(m)	9.55	6.91	8.77
Aspect ratio	4	3	3
I (MA)	15.5	19.0	19.2
B(T)	7.4	5.8	6.5
q	3.4	4.0	5.6
P_{fus} (GW)	2.03	2.82	2.84
P_e (GW)	1.0	1.0	1.0
Av neutron wall load (MW/m^2)	1.2	2.2	1.35
Peak div heat load (MW/m^2)	5.1	10	10
Bootstrap fraction	0.43	0.44	0.55
β_N thermal, total	2.4, 2.6	3.0, 3.5	2.76, 3.45
H factor	1.3	1.05	1.3
H factor limit	1.3	1.3	1.3
Pulse time (hours)	8.5	∞	∞
γ_{NB} ($10^{20} A/Wm^2$)	-	0.44	0.29
P_{CD} (MW)	-	237	238

Here optimised against size. Smallest plant could not be built with HCLL technology due to radial build constraints

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