Utilization of ARIES Systems Code

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Discussion Topics

- Rationale for improvement of systems code capabilities.
- Discussion of code improvements and increased capabilities
- Presentation of results and parameter scans
- General Discussion
- Publication Options
  - TOFE
  - FESAC
  - ANS

Rationale for improvement of systems code capabilities.

- New systems code was developed as a tool for exploring the most influential parameters in transition from experimental facilities to viable commercial power plants.
- The systems code integrates physics, engineering, design and costing algorithms in order to establish an operational design space that sheds light on the most attractive trade-offs in this transition.
- The structure of the systems code is modular and the modules are composed from the toolbox of generic building blocks that were specially designed for this purpose. One can easily put a code together in a fashion analogous to building objects from Lego blocks.
- Ingredient algorithms:
    - The physics module captures the current Tokamak physics knowledge database including modeling of the most-current Fusion Ignition Research Experiment (FIRE).
    - The engineering model accurately reflects the intent and design detail of the power core elements including accurate and adjustable 3-D Tokamak geometry and complete modeling of all the power core and supporting systems.
    - The plant cost accounts have been revised to reflect a more functional cost structure, supported by an updated set of costing algorithms for the direct, indirect, and financial cost accounts.
- All the features of the code were exercised and validated against the well documented ARIES-AT baseline.

Discussion of code improvements and increased capabilities compared to the version prior to “Next Step”

- Better code structure:
  - Object oriented data structures are used as generic building blocks instead of code segments that are “glued” on top of each other through if-then statements, commenting out, etc.
  - Library of reusable algorithms that can easily be plugged into other codes.
- Accurate geometry of the power core.
- State-of-art physics, engineering and costing algorithms.
  - Greater level of detail is included.
  - TF Magnet is re-designed from the previous version and validated.
  - Power flow algorithm built with a higher attention to detail.
    - Inboard and outboard segments of the power core separated from each other.
    - Calculation of radiation flux on the first wall is more accurate, etc.
    - Maximum heat flux on divertor is more accurate.
- Computational efficiency.
  - 2 seconds per data point on a dual-core processor, ~7 seconds on a Pentium with 2 GHz (typical desktop). How fast was the earlier code?
- Advanced post-processing of data
  - Several different visualization methods are implemented.

Presentation of Results and Parameter Scans

- ARIES-AT design space.
  - Physics database was obtained by scanning the following parameters:
    - R: 4.5 – 9 [m]
    - B_T: 5-10 [T]
    - βn: 0.03 – 0.06
    - fracGw: 0.4 – 1.1
    - q_{cyl}: -3.2 - -4.6
    - δ: 0.6 – 0.8
    - Q: 20 – 40
    - a_k: 1.8 – 2.2
    - f_{imp}: 0.001: 0.003
  - 253,467 data points generated after applying the physics rejection criteria.
  - Engineering Filters Triggered:
    - B_T^{max} out of range.
    - Maximum flux on divertor exceeds limit. Three limits were imposed for a scan:
      - 8 MW/m^2
      - 12 MW/m^2
      - 16 MW/m^2
      - Electric power departs for more than 10% from 1 GW .
- ARIES-AT With DCLL blanket design space.

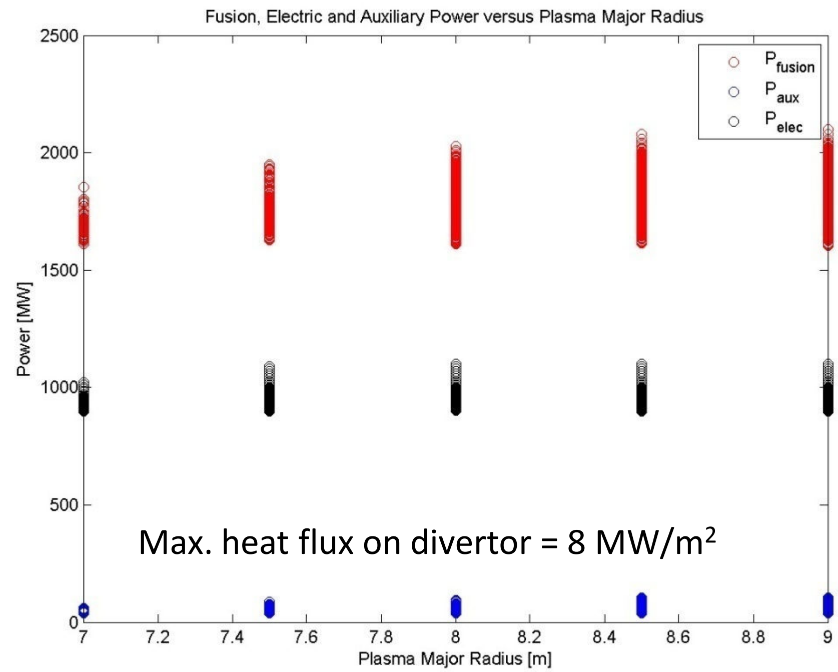
Data for ARIES-AT Based Design

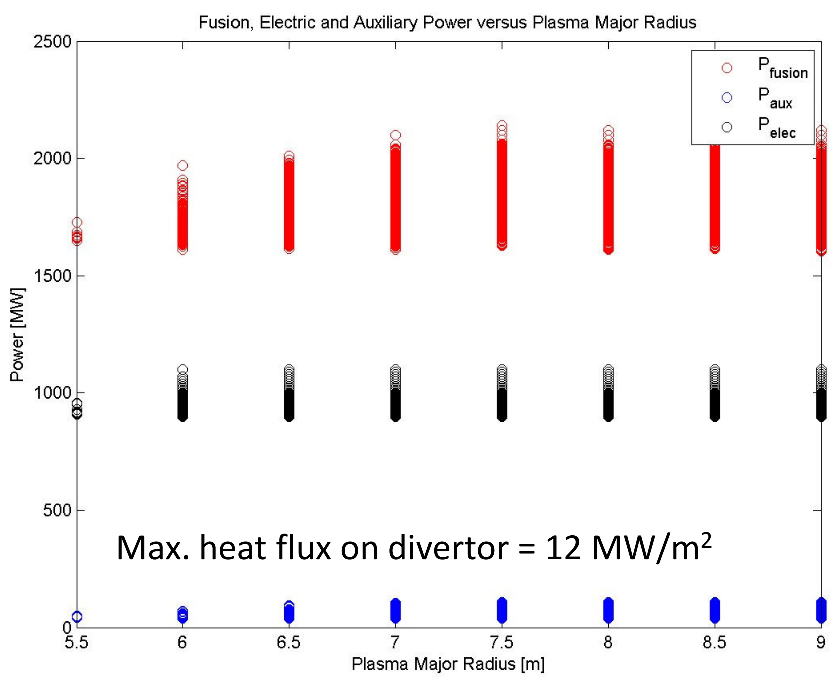
- Powers versus plasma major radius and magnetic field at plasma major radius:
  - Fusion, electric and auxiliary power versus plasma major radius.
  - Electric, thermal and recirculation power versus plasma major radius.
  - Electric, thermal and recirculation power versus magnetic field at plasma major radius.
- Physics operating space and how it relates to COE:
  - βn versus bootstrap current fraction.
  - βn versus Q_{mhd}.
  - βn versus toroidal field at plasma major radius.
  - Volume averaged temperature versus volume averaged density.
  - Multiplier on energy confinement scaling versus Greenwald density fraction.
  - COE versus R, B_T and βn.
  - COE versus R, B_T and Greenwald density fraction.
- Fluxes that impact the first wall and divertor across the plasma major radius:
  - Average neutron wall load versus plasma major radius.
  - Peak inboard heat flux on divertor versus plasma major radius.
  - Peak outboard heat flux on divertor versus plasma major radius.
  - Peak radiated heat flux on the first wall versus plasma major radius.
- Recommendation for optimal design.

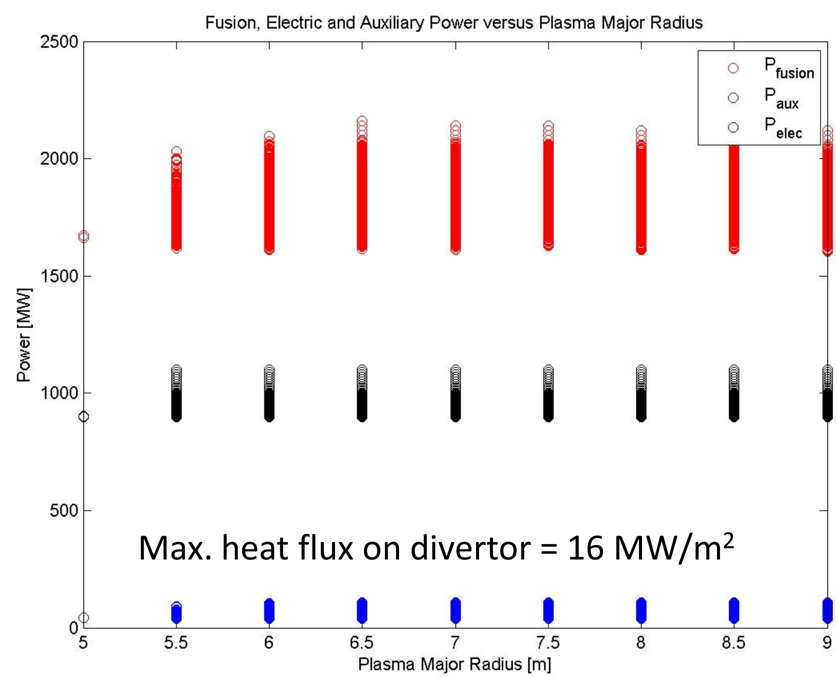
Powers versus plasma major radius and magnetic field at plasma major radius

Fusion, Electric and Auxiliary Power Versus Plasma Major Radius

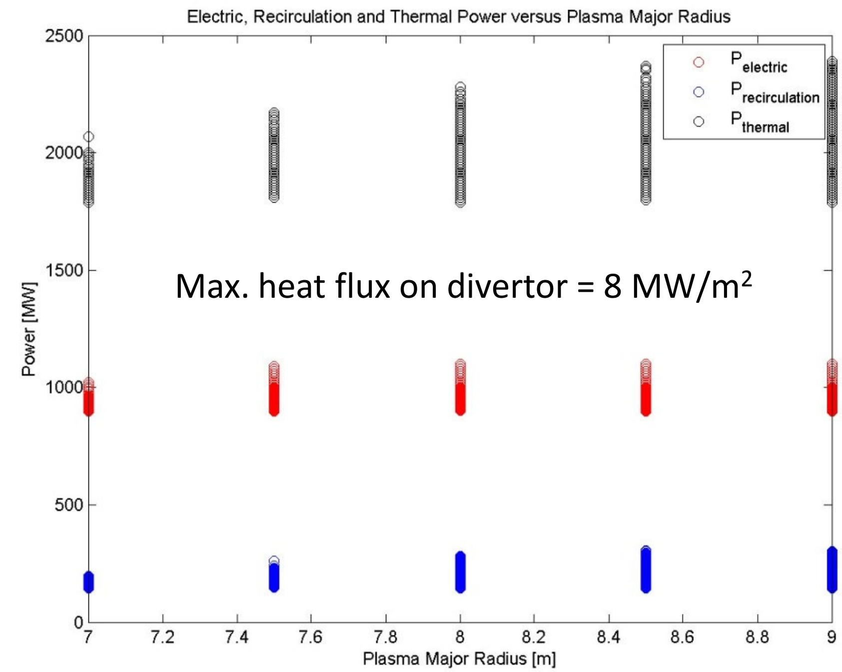
- The intervals of powers are uniform across the plasma major radius, as expected.
- As the divertor heat flux limit increases, the smaller plasma sizes become available.

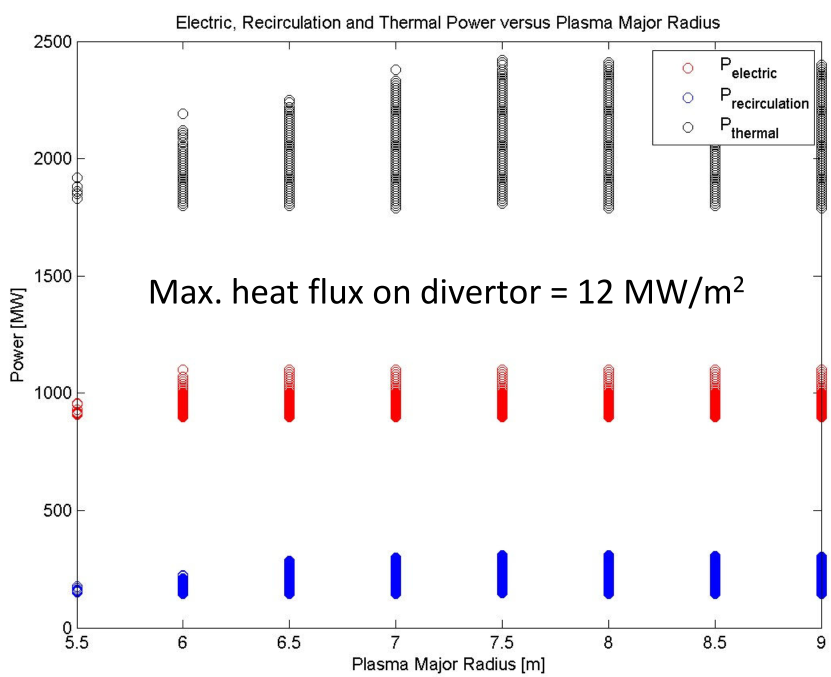


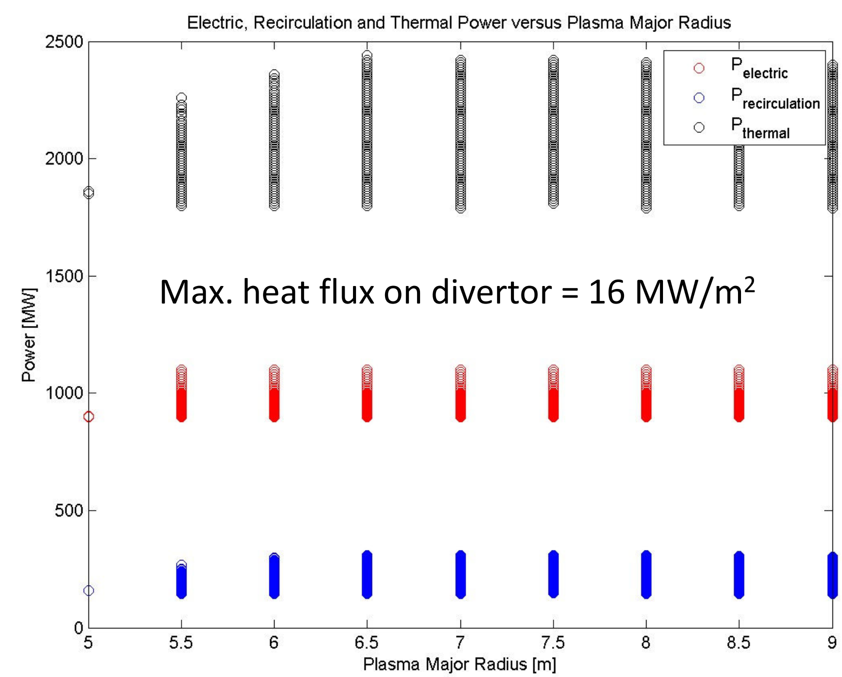




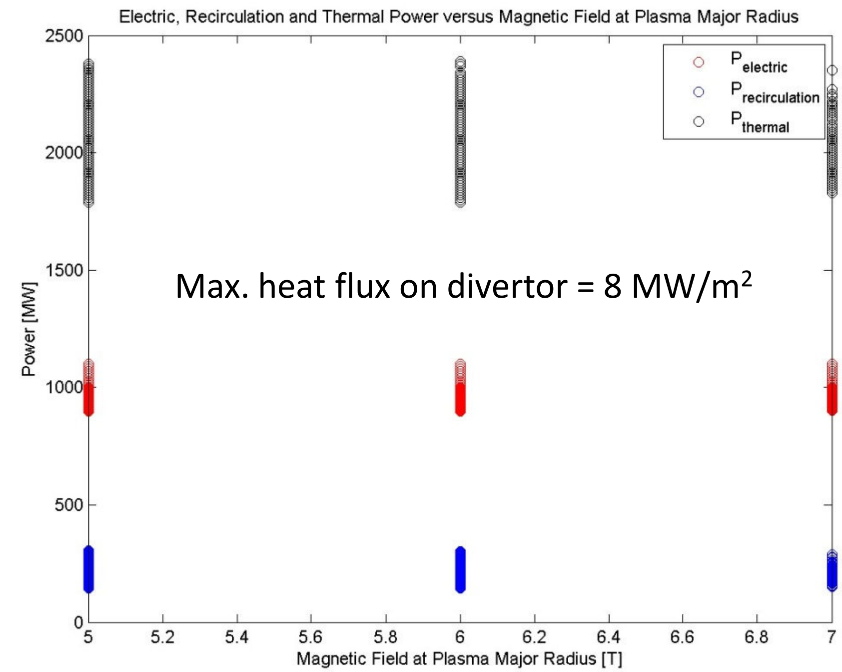
Electric, Recirculation and Thermal Power Versus Plasma Major Radius

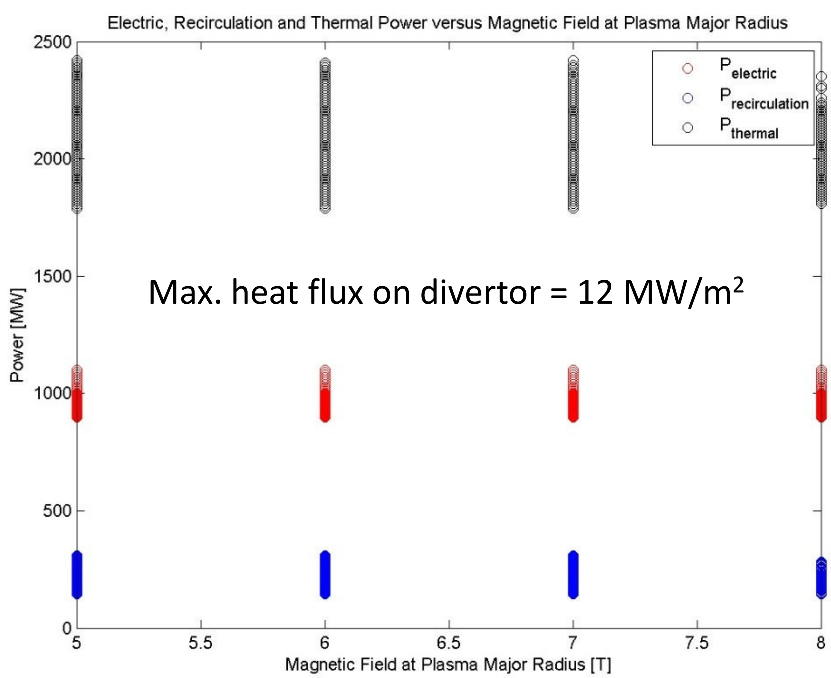


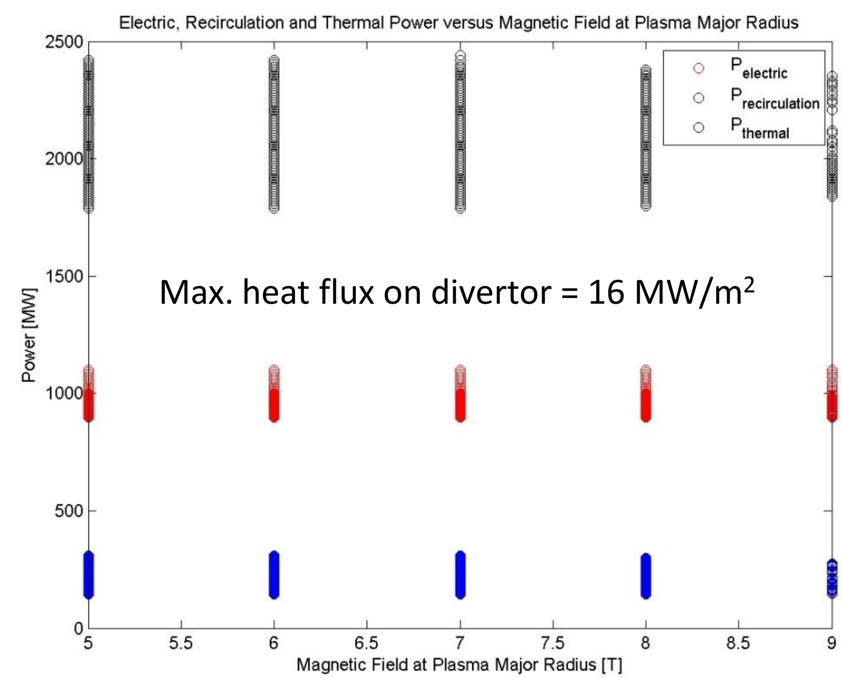




Electric, Recirculation and Thermal Power Versus Magnetic Field at Plasma Major Radius



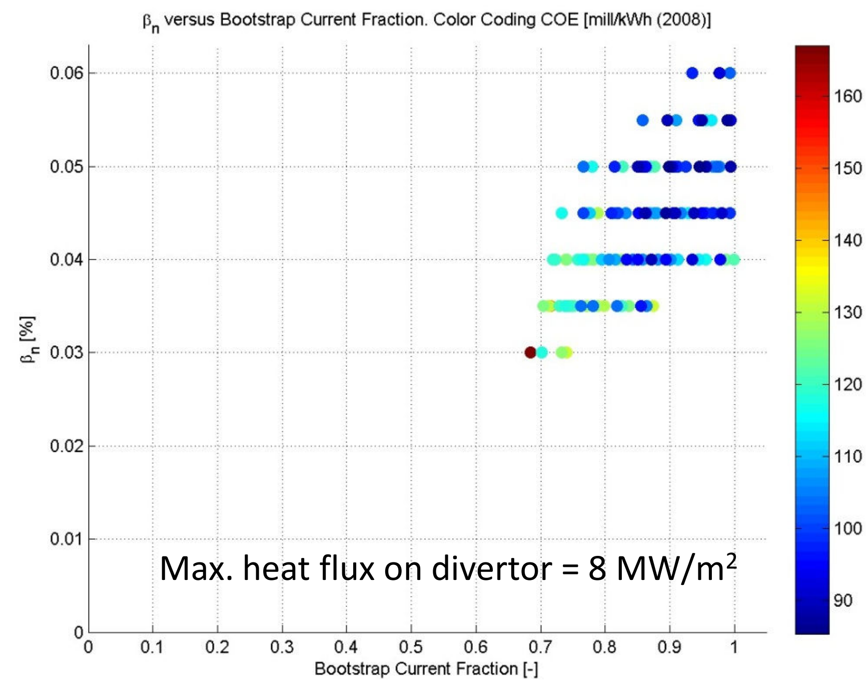


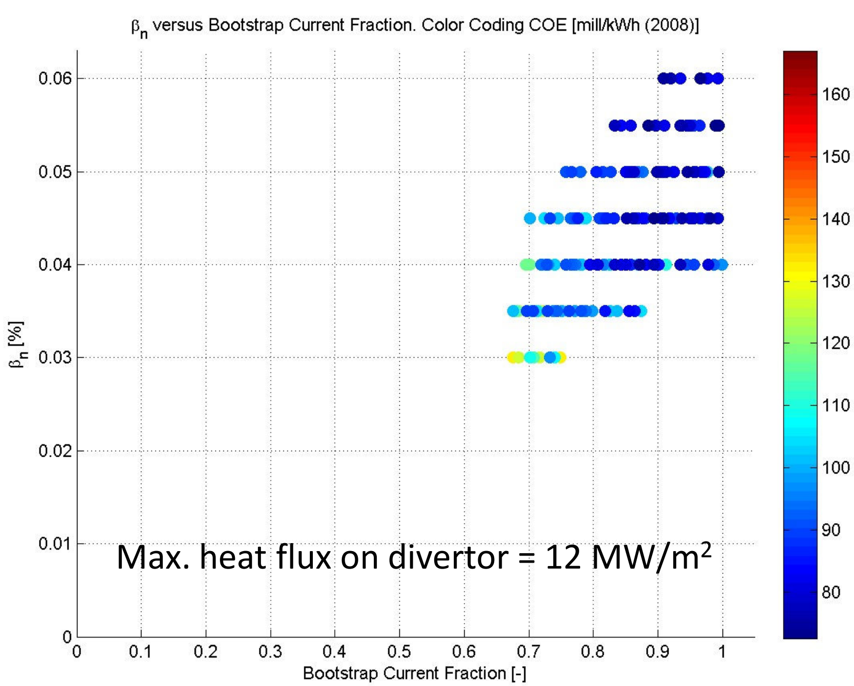


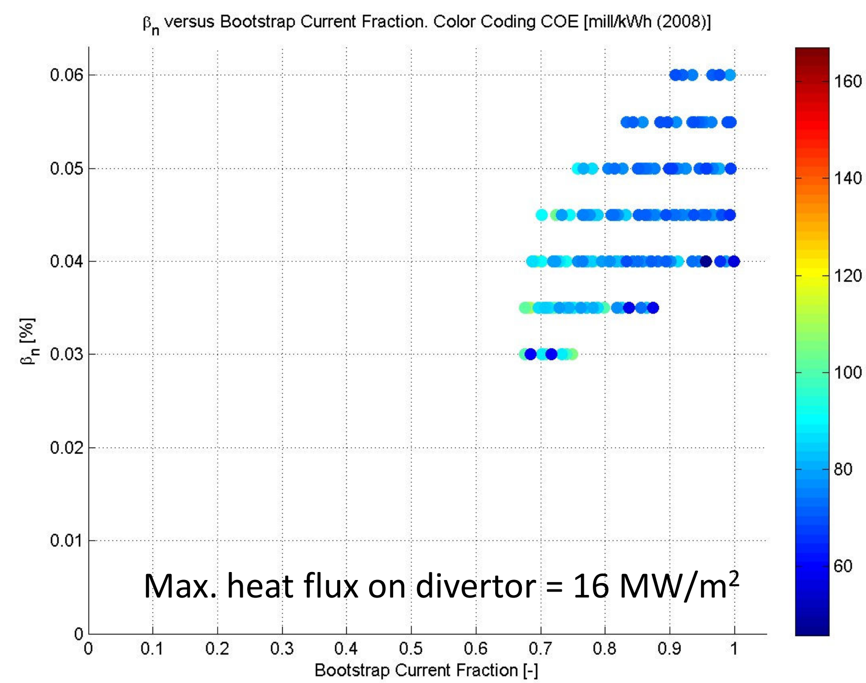
Physics operating space and how it relates to COE

β_n Versus Bootstrap Current Fraction

- In all 3 scans, the viable data points populate the same operating space in (bootstrap current fraction, β_n) parametric plane.
- Color coding is in COE [mill/kWh]

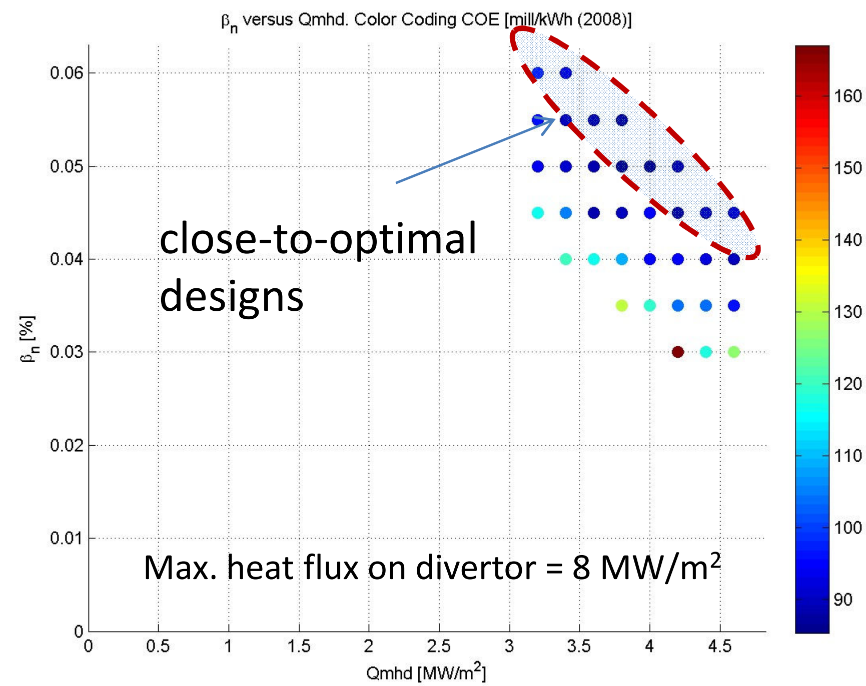


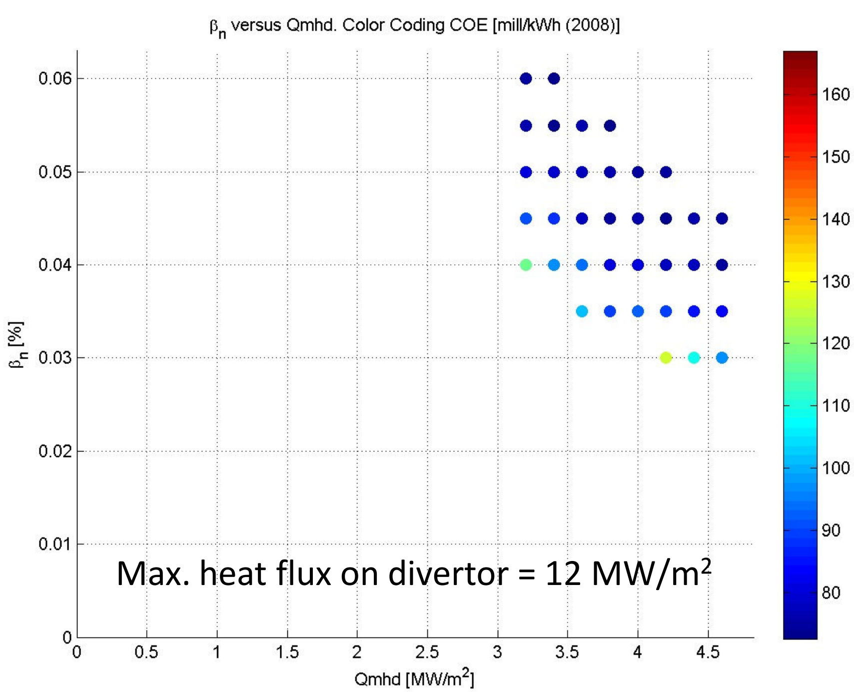


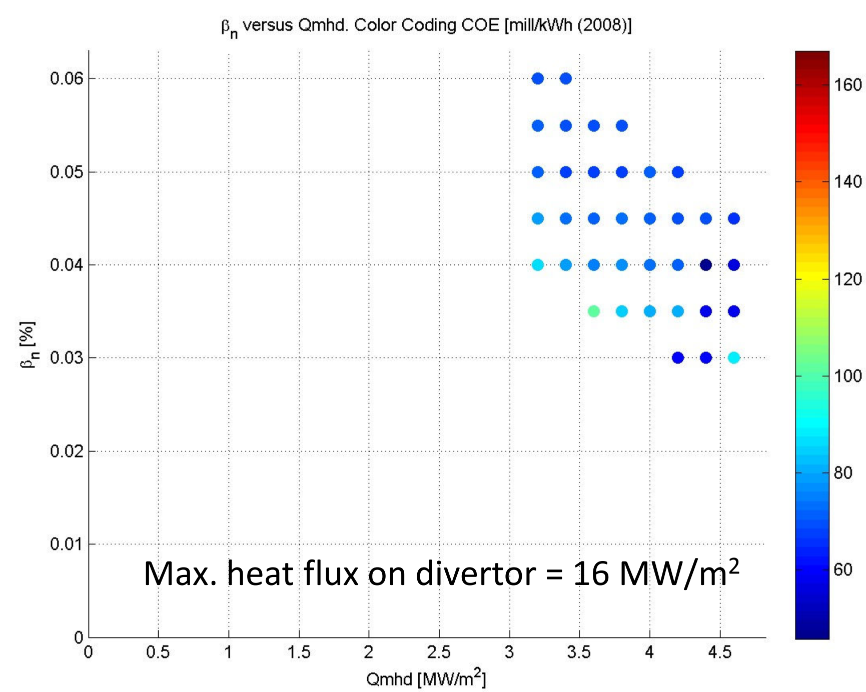


β_n Versus Q_{mhd}

- The operating space populated by viable data points is the same for all 3 scans.
- COE is inversely proportional to β_n and this dependence is the strongest in case of the scan with the lowest limiting flux to divertor (upper left corner).
- Qmhd = q95 – flux at the surface enclosing 95% of the total flux.

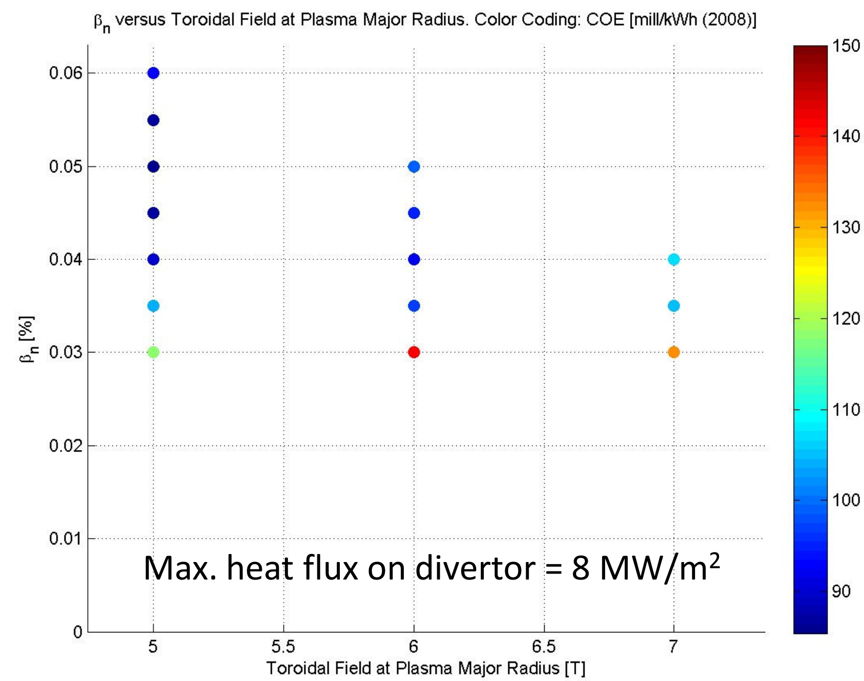


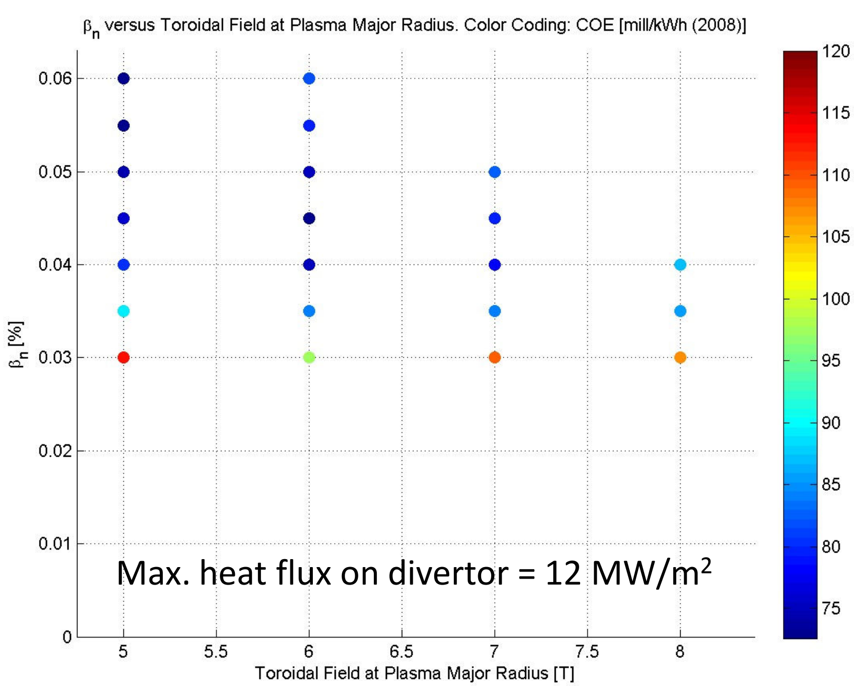


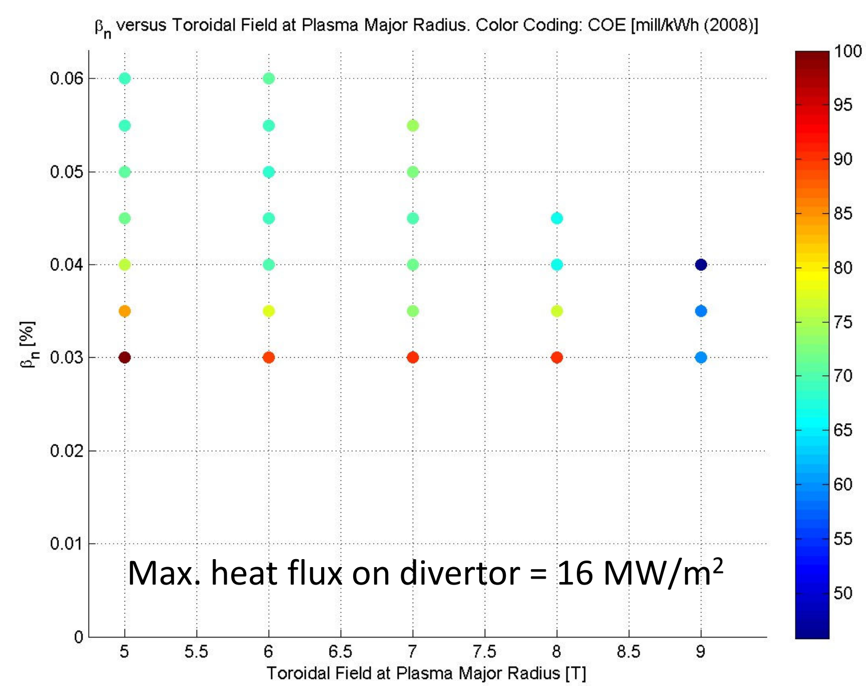


β_n Versus Toroidal Field at Plasma Major Radius

- Tradeoffs that can be observed here:
  - For a given toroidal field at plasma major radius, we can increase β_n and obtain a lower cost of electricity.
  - By increasing the admissible heat flux on divertor, we are allowing for designs with higher toroidal fields and lower plasma major radii, that also have a low cost of electricity.

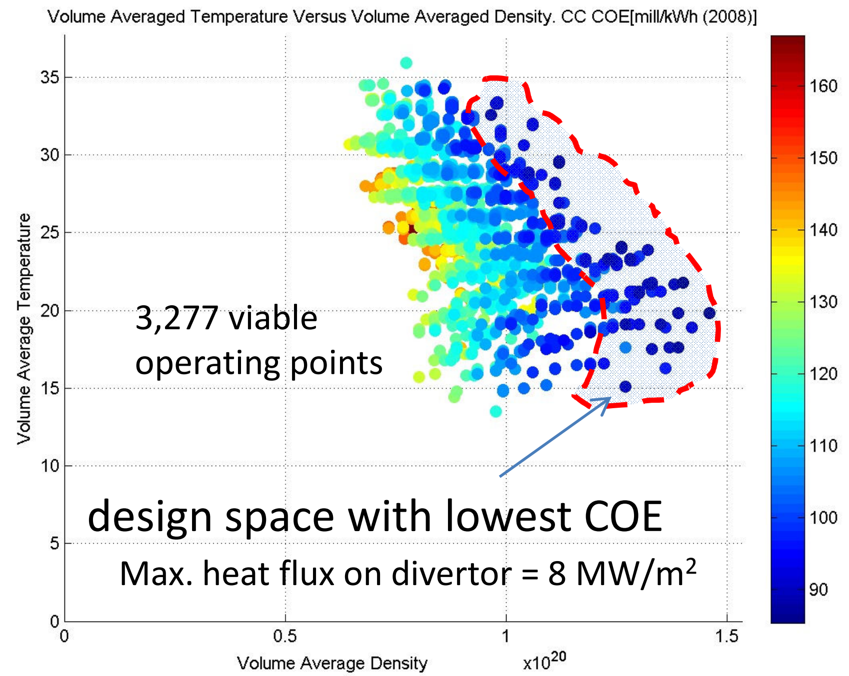


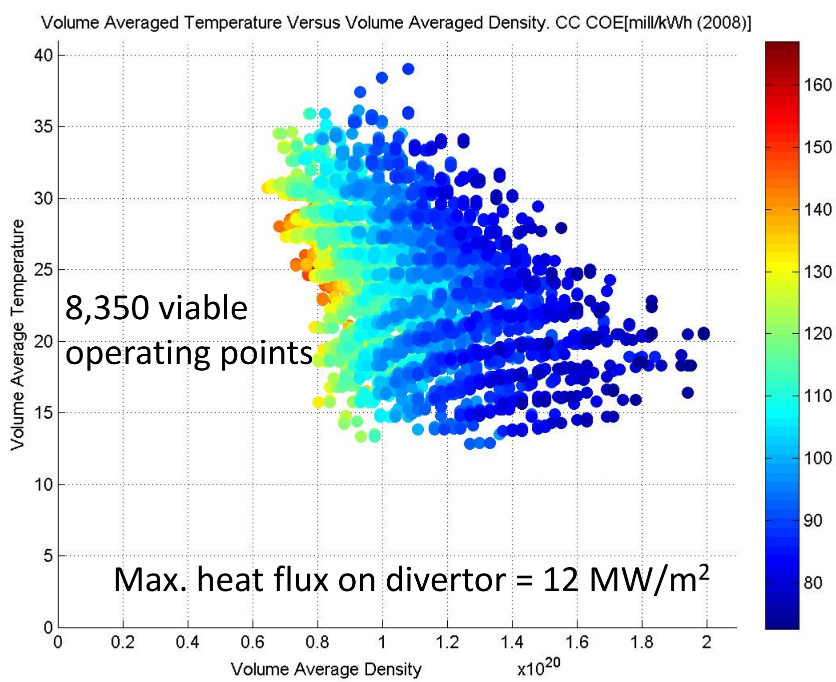


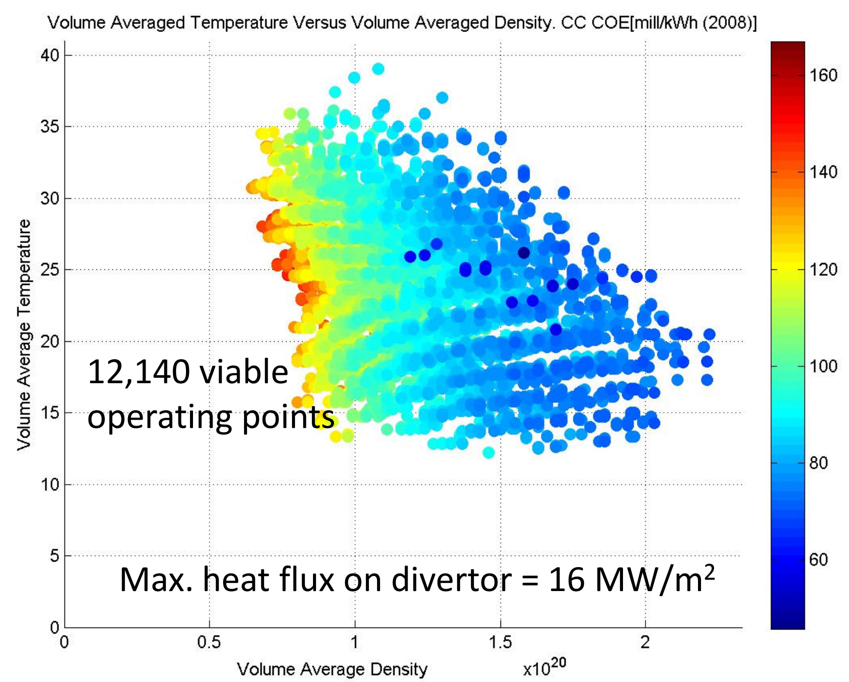


Volume Averaged Temperature Versus Volume Averaged Density

- COE significantly drops with the increase of the volume average density. This is possibly due to the fact that design points with high volume average density tend to have a high β_n and/or a low plasma major radius.
- The 3 scans "paint" the same picture, except that the number of viable data points quadruples when the divertor flux limit goes from 8 to 16 MW/m^2.

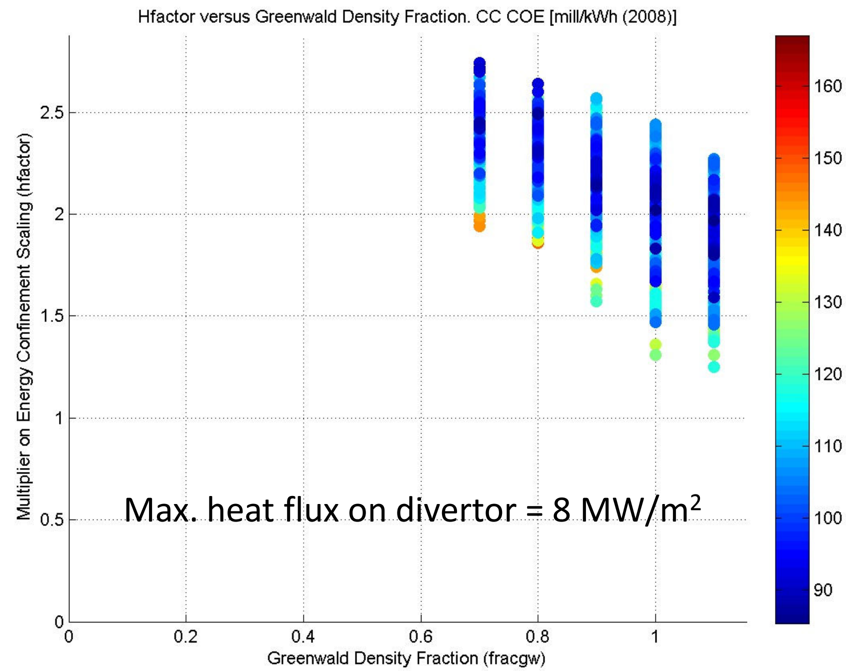


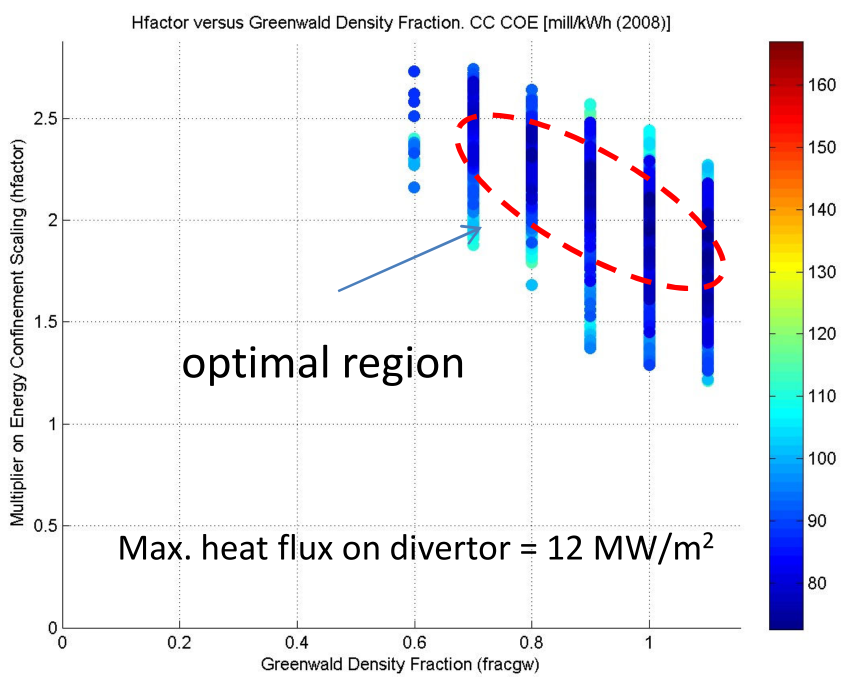


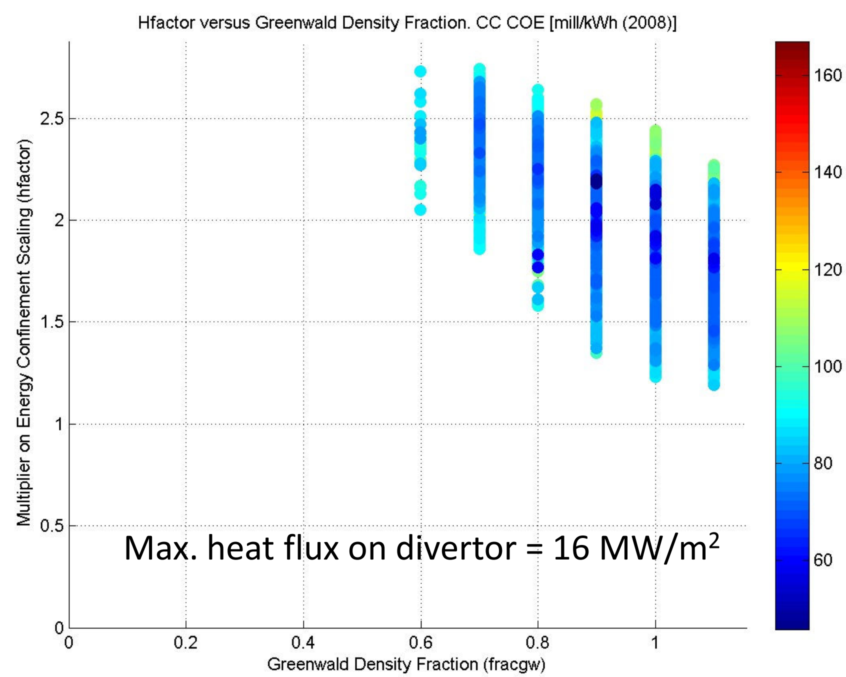


Multiplier on Energy Confinement Scaling Versus Greenwald Density Fraction

- The operating space is the same for all 3 scans.
- The optimal operating space can be distinguished from these plots. COE tends to be low in the middle and high at the border.



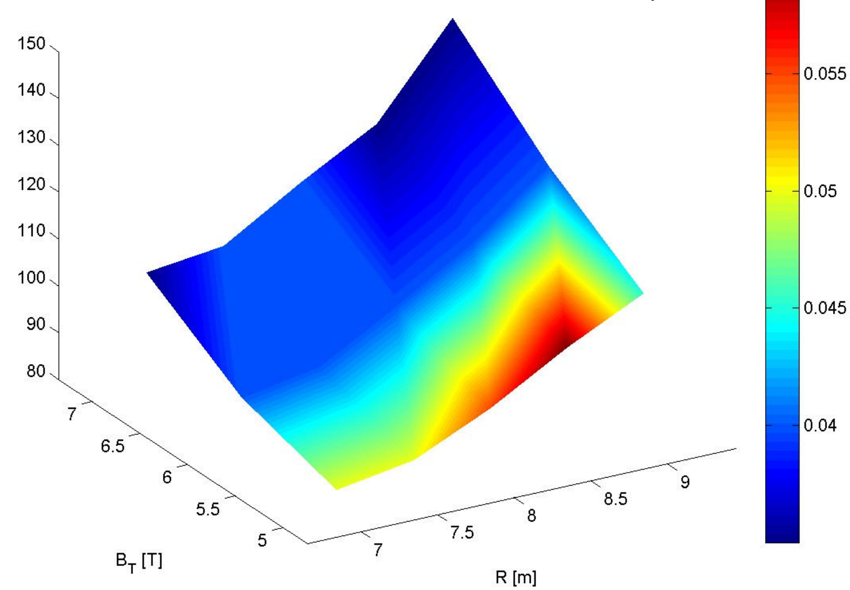




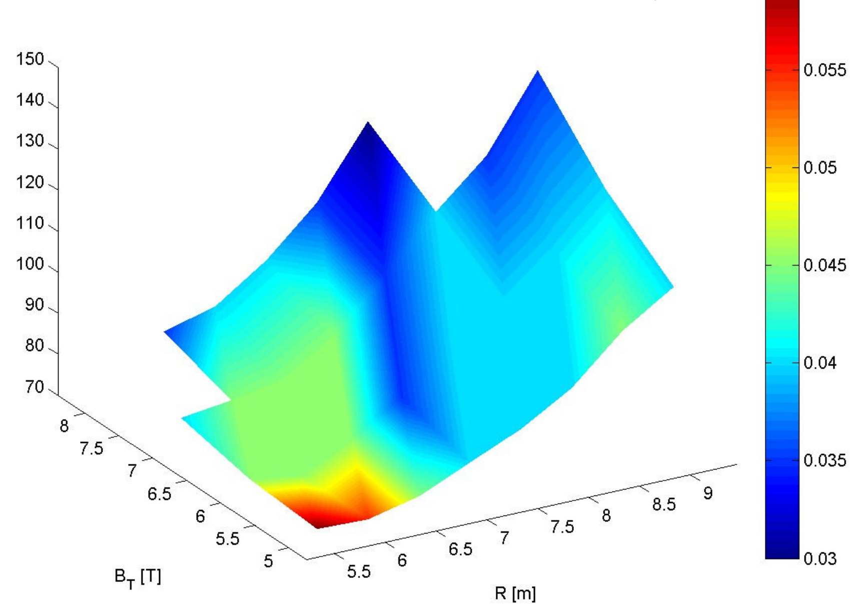
Local Minimum of COE Versus Plasma Major Radius, Toroidal Field at Plasma Major Radius and β_n

- The surface represents the local minimum of COE over the plane of plasma major radius and toroidal field at plasma major radius. The magnitude of β_n that corresponds to this particular COE is shown in colors.
- The top value of βn of 0.06 is a hard limit imposed by the physics database.
- As we allow more data points to survive by increasing the divertor heat flux limit, we can clearly observe regions of close-to-optimal tokomaks with small sizes, low COE and high βn values.

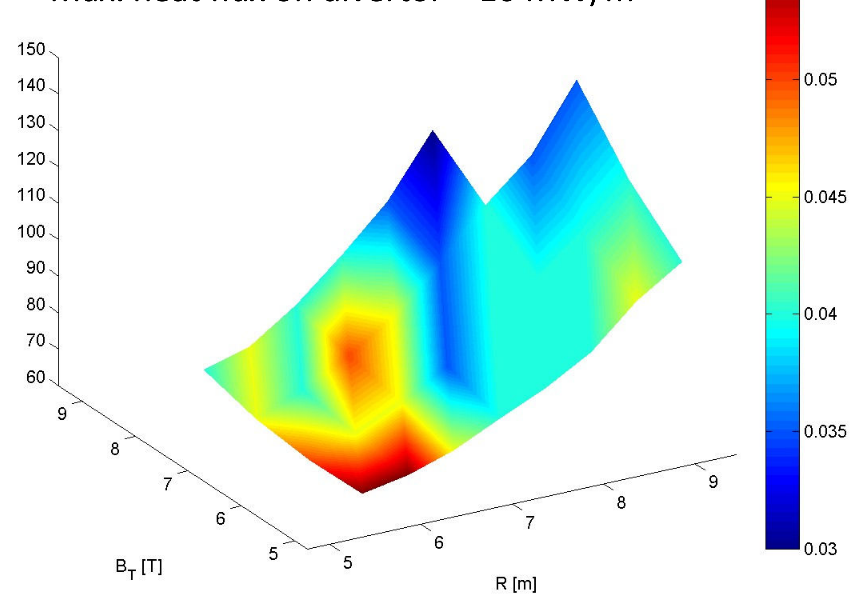
Max. heat flux on divertor = 8 MW/m²



Max. heat flux on divertor = 12 MW/m²

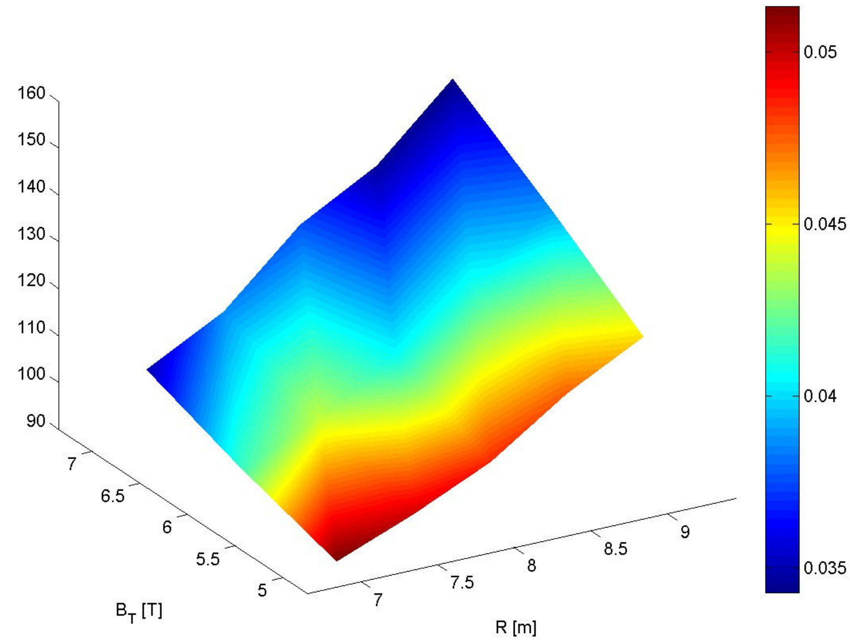


Max. heat flux on divertor = 16 MW/m²

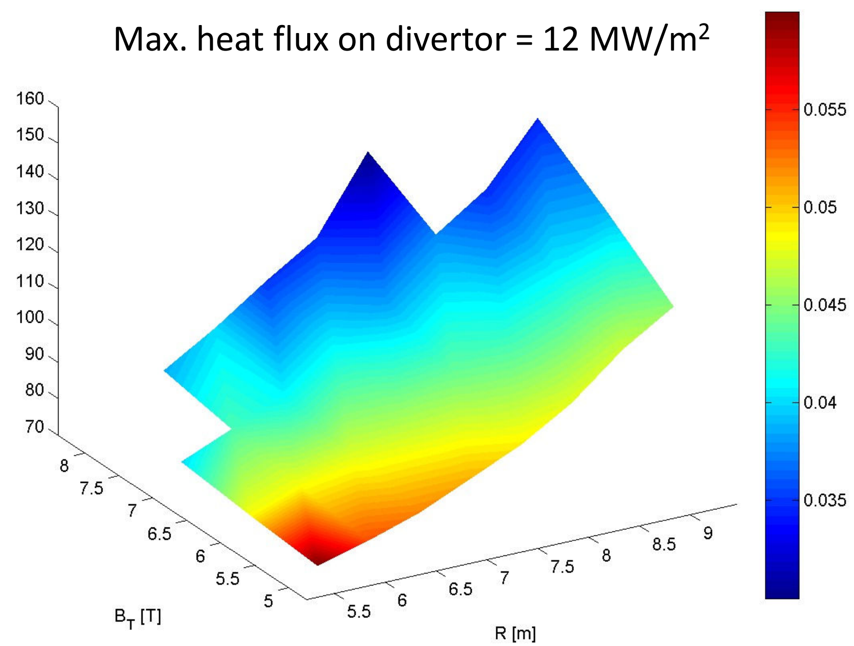


Locally Averaged COE Versus Plasma Major Radius, Toroidal Field at Plasma Major Radius and β_n

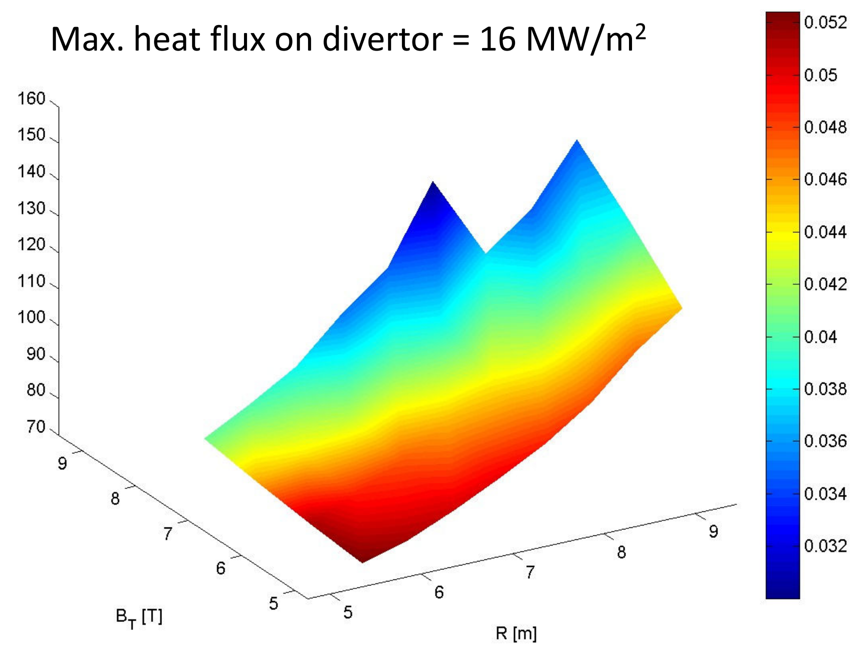
- The surface represents the locally averaged COE over the plane of plasma major radius and toroidal field at plasma major radius. The locally averaged β_n is shown in colors.
- This way of presentation eliminates the irregularities of βn on the COE surface due to independent engineering filters and gives a much better view of the important tradeoffs between B_T, bn and R.



Max. heat flux on divertor = 12 MW/m^2

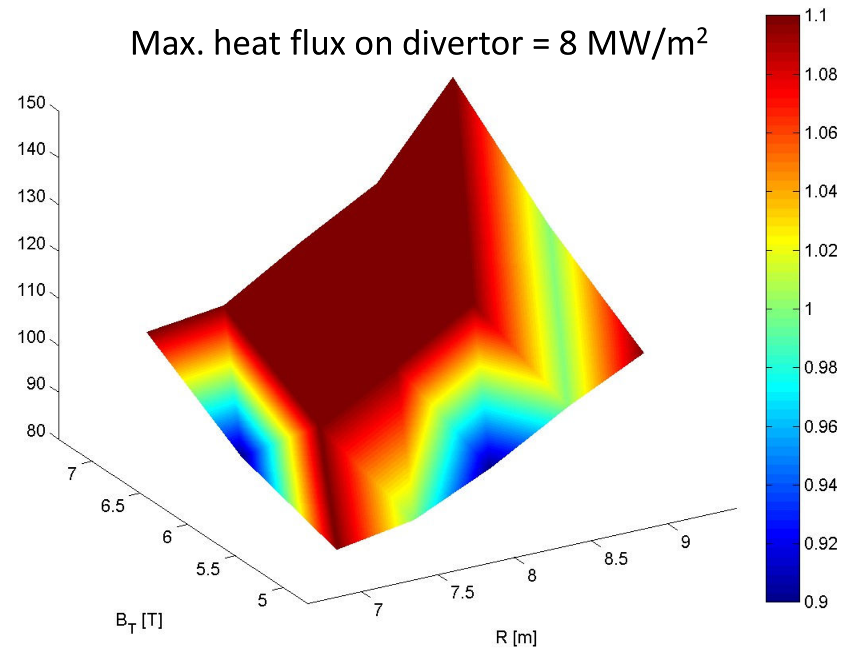


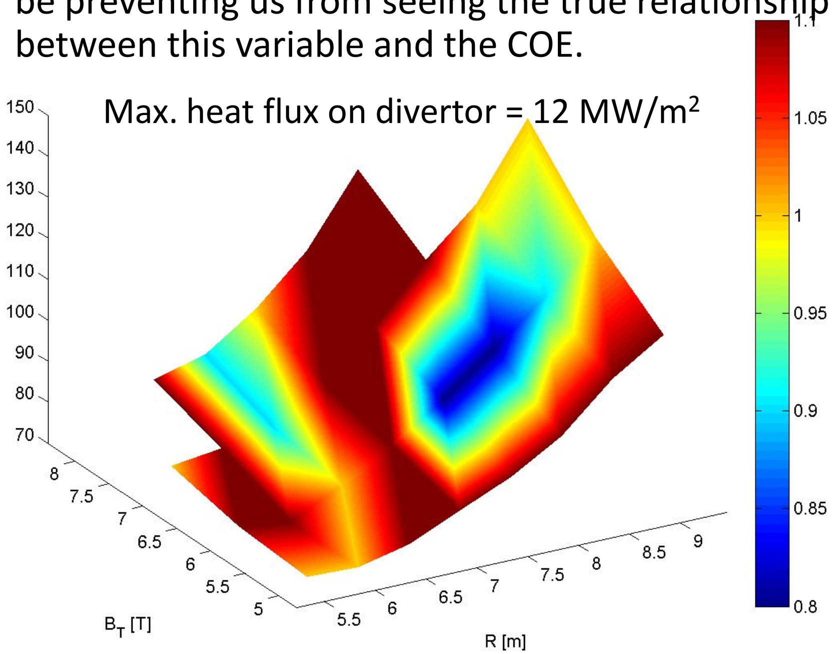
Max. heat flux on divertor = 16 MW/m^2

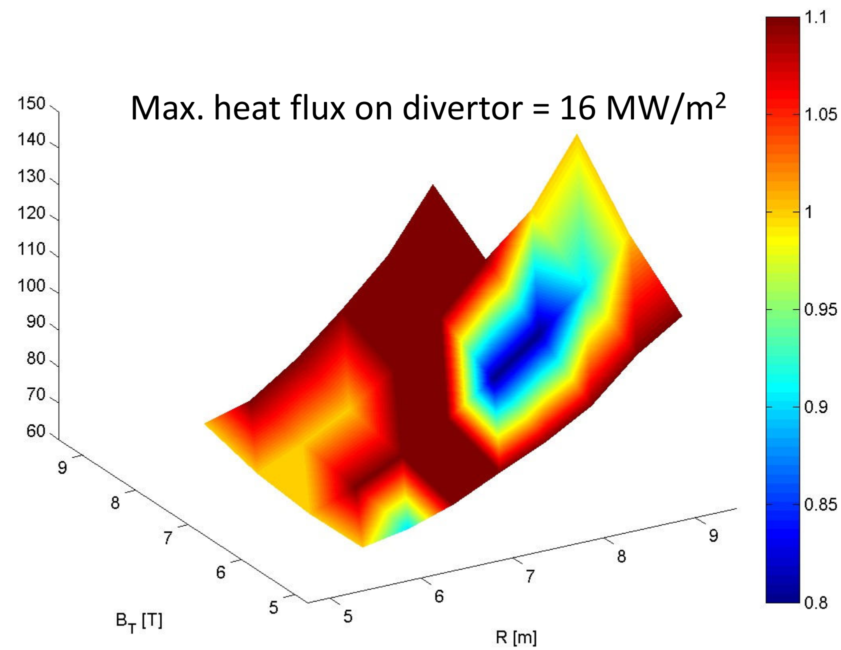


COE Versus Plasma Major Radius, Toroidal Field at Plasma Major Radius and Greenwald Fraction

- The surface represents the local minimum of COE over the plane of plasma major radius and toroidal field at plasma major radius. The magnitude of Greenwald Fraction that corresponds to this particular COE is shown in colors.
- The top value of Greenwald Fraction of 1.1 is a hard limit imposed by the physics database. This variable is allowed to vary between 0.4 and 1.1. What the plots are telling us is that majority of the data points on the COE optimal surface have reached the limit in Greenwald Fraction. This may be preventing us from seeing the true relationship between this variable and the COE.



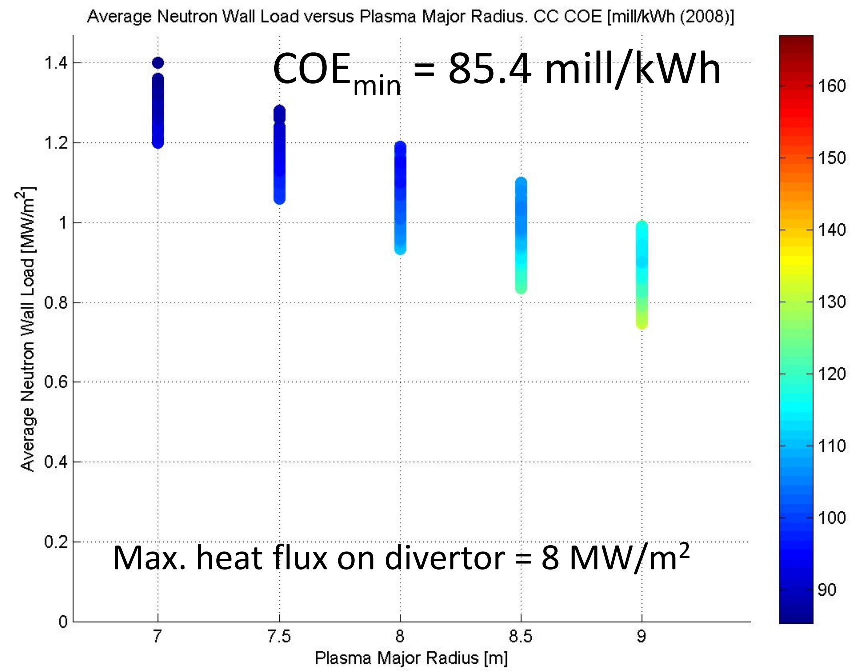


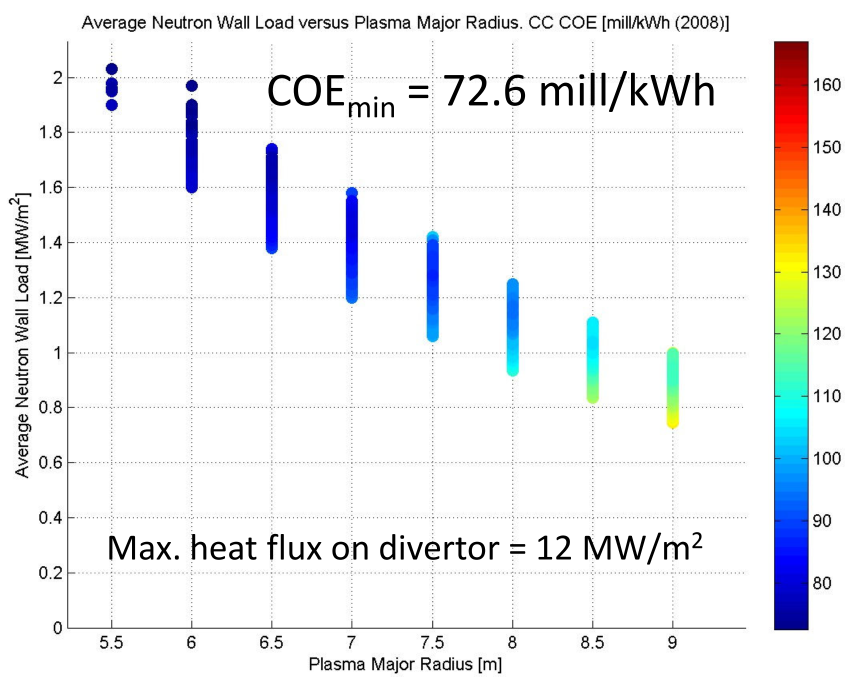


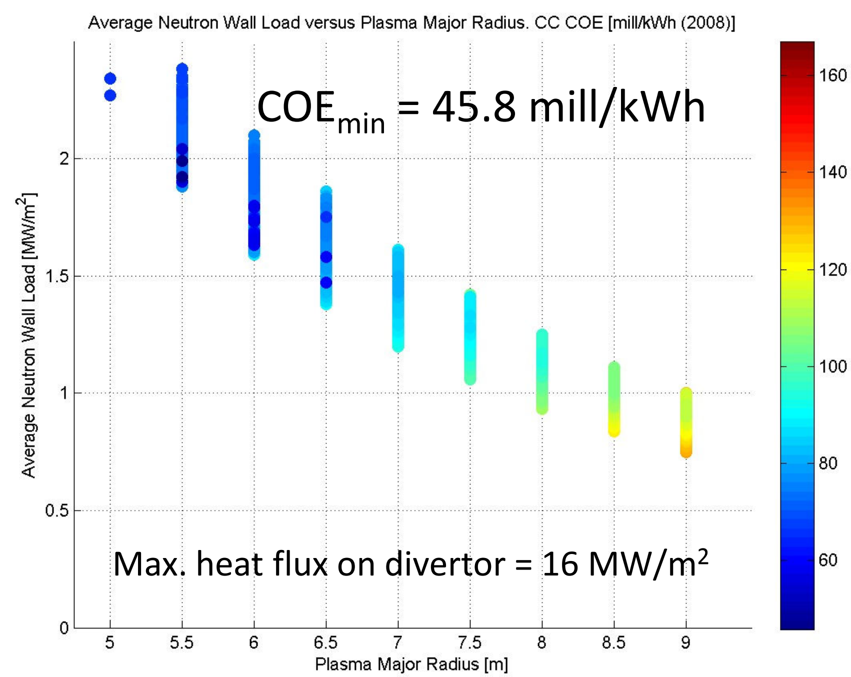
Fluxes that impact the first wall and divertor versus plasma major radius

Average Neutron Wall Load Versus Plasma Major Radius

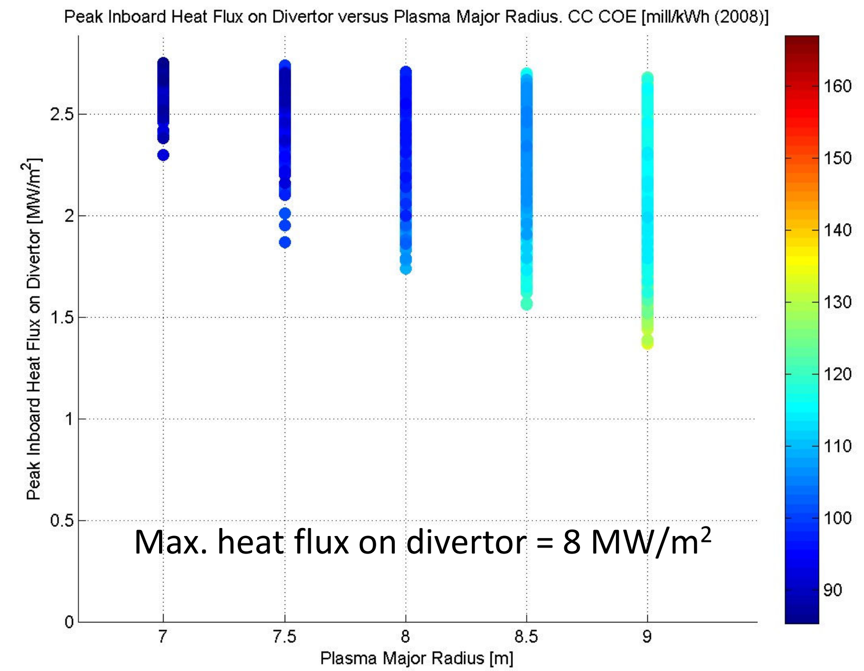
- Three scans of data points are obtained by increasing the limit of the heat flux on divertor from 8 MW/m^2 to 16 MW/m^2.
- Average neutron wall load behaves reasonably along the plasma major radius. Data points are color coded in COE.
- At present 8 MW/m^2 is the most realistic limit to heat flux on divertor. However, increasing this limit could lead to significant savings in COE.

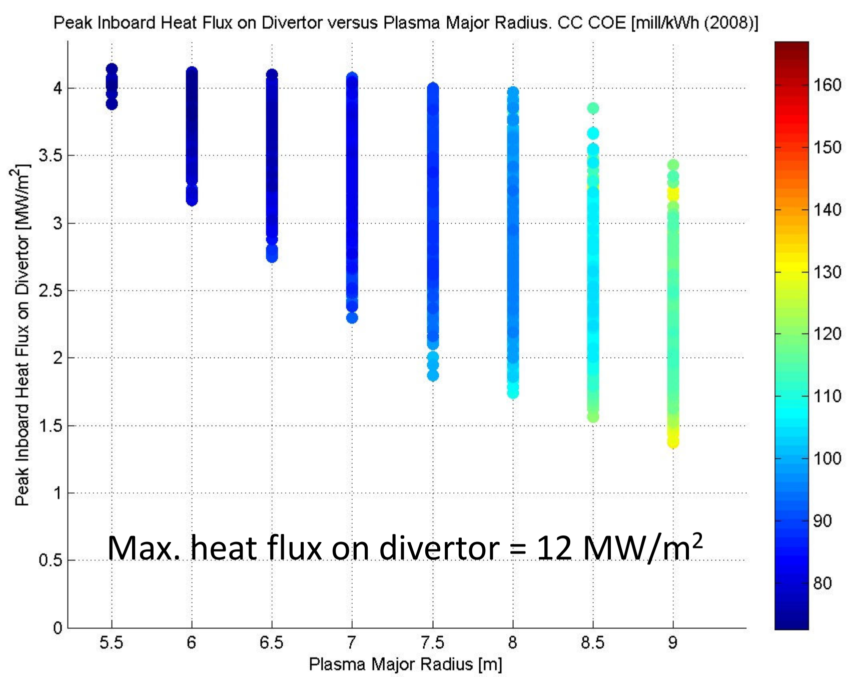


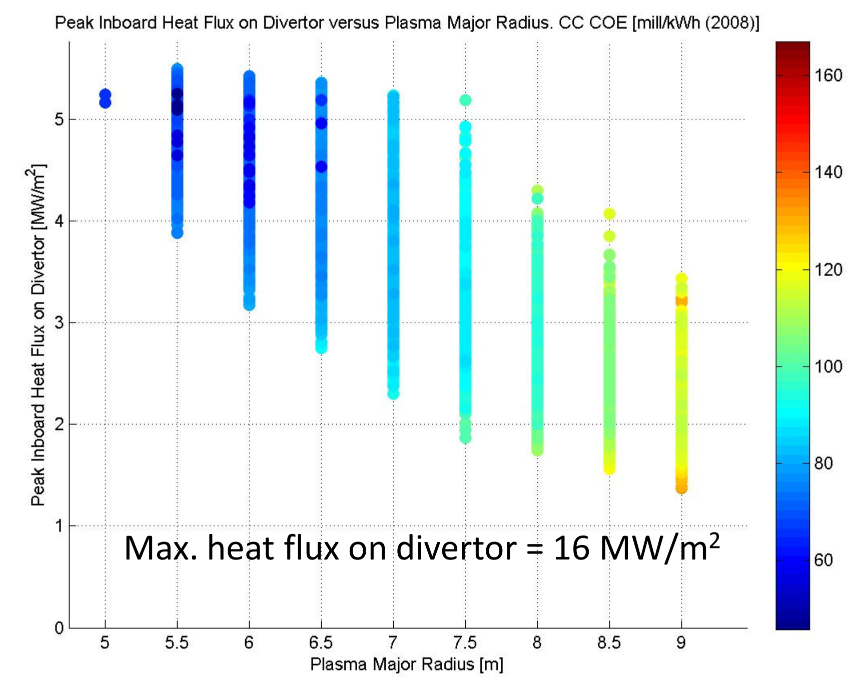




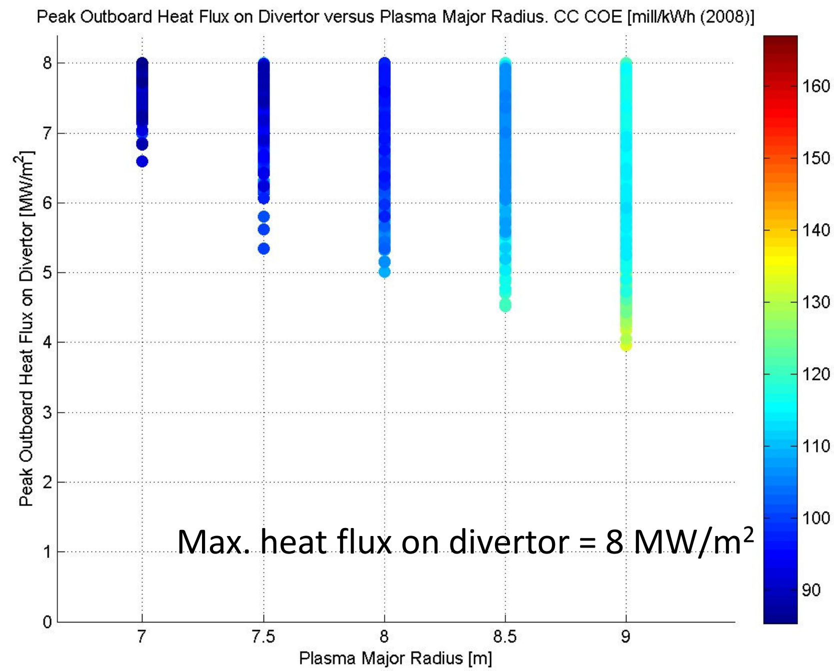
Peak Inboard Heat Flux on Divertor Versus Plasma Major Radius

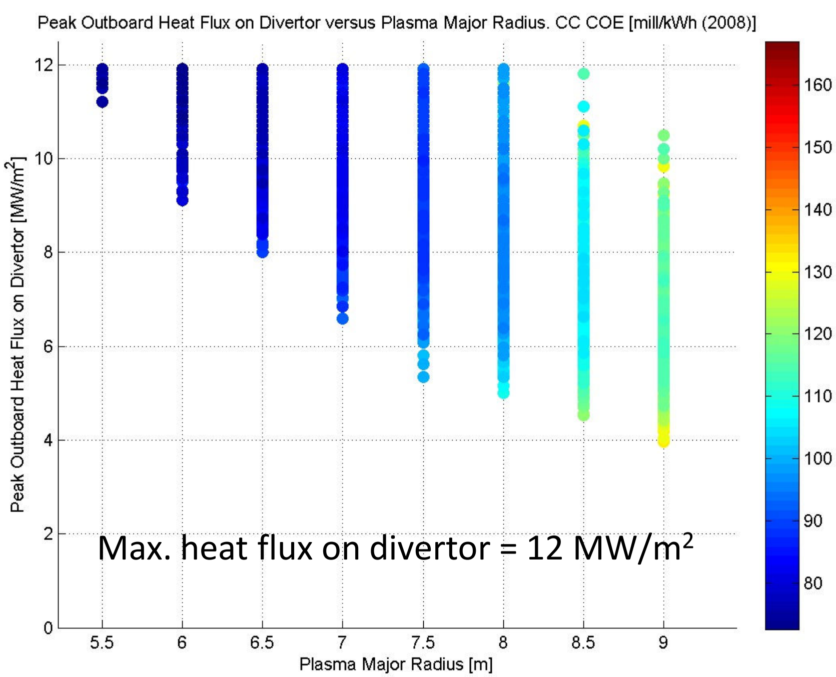


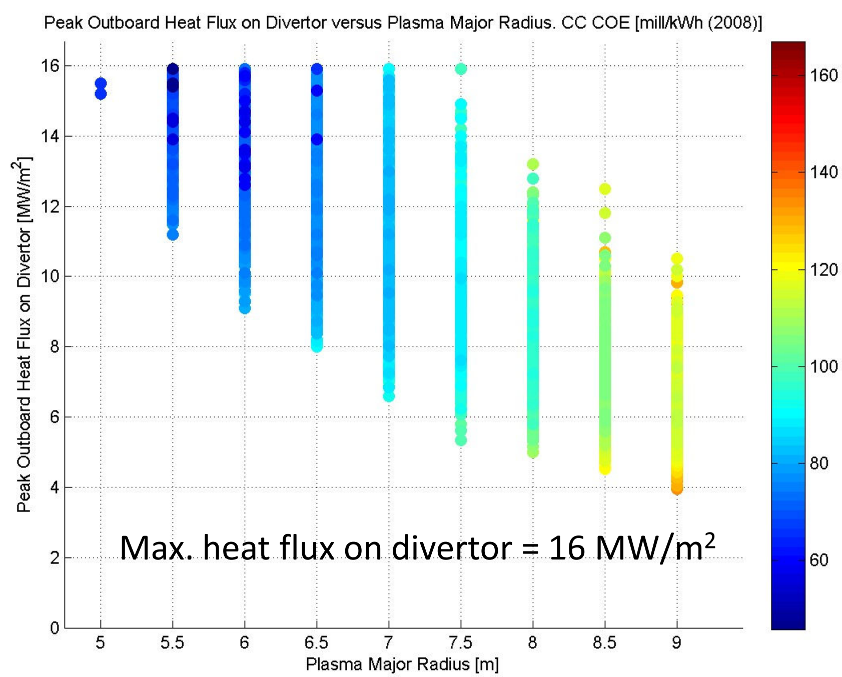




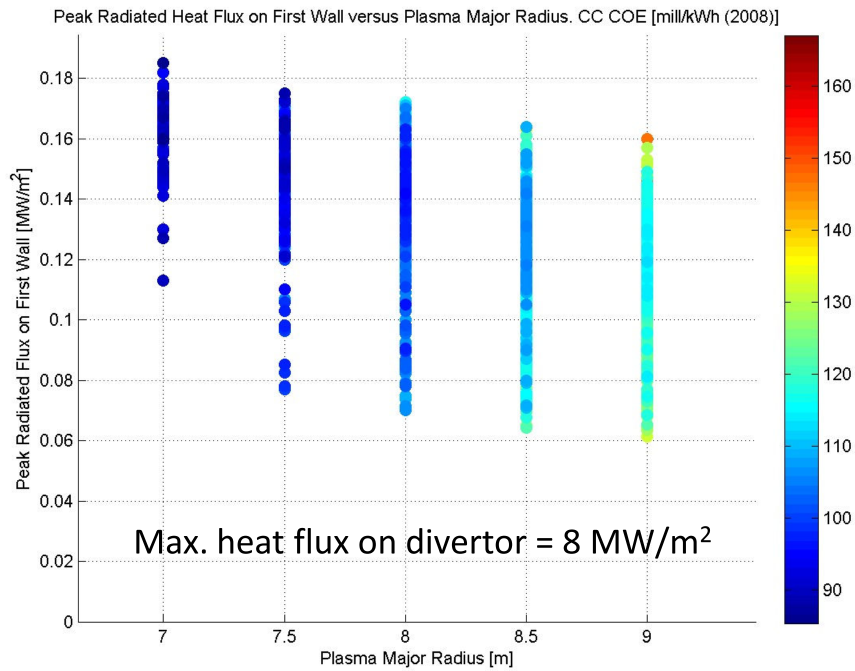
Peak Outboard Heat Flux on Divertor Versus Plasma Major Radius

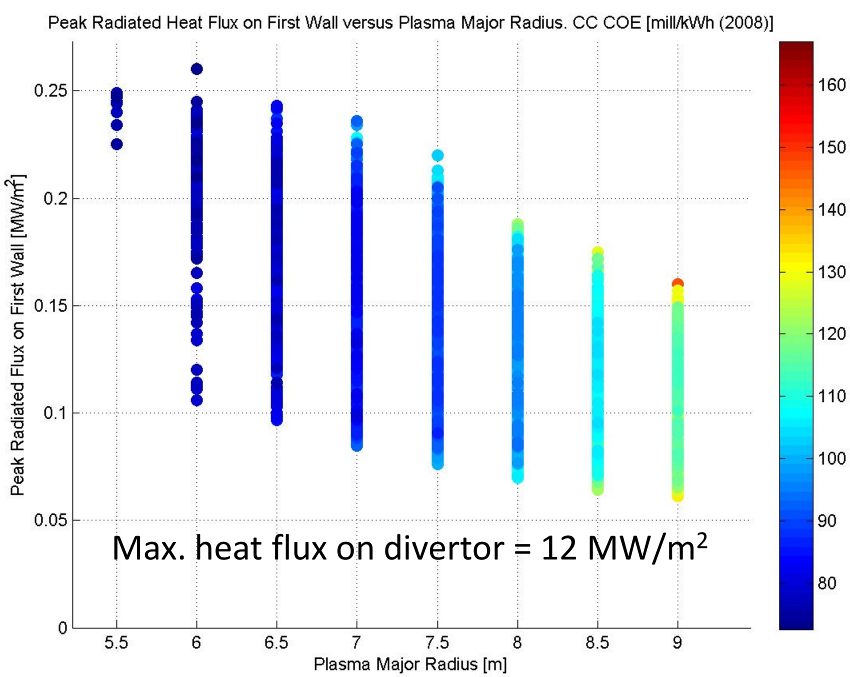


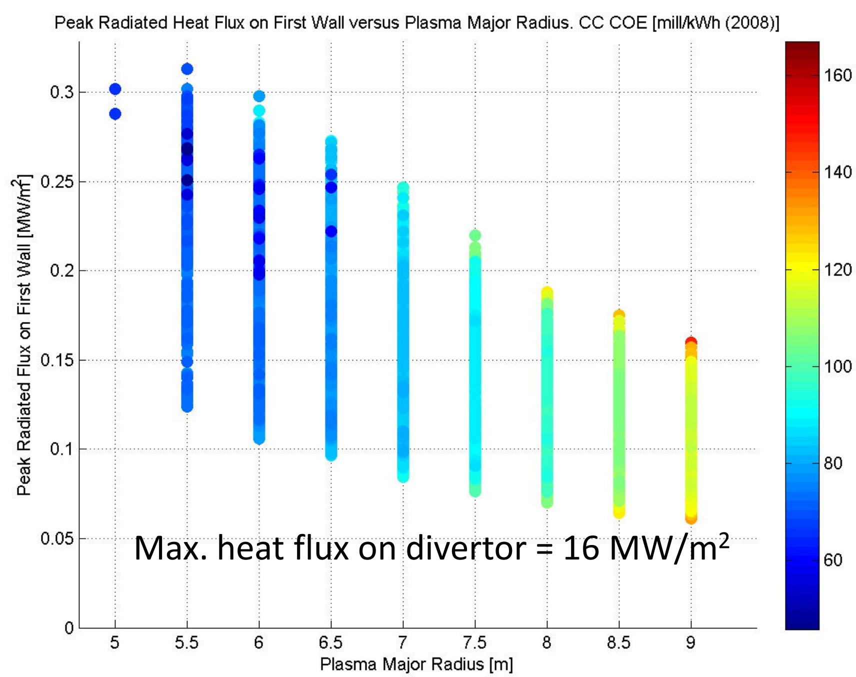




Peak Radiated Heat Flux at the First Wall Versus Plasma Major Radius







Recommendations for Optimal Design

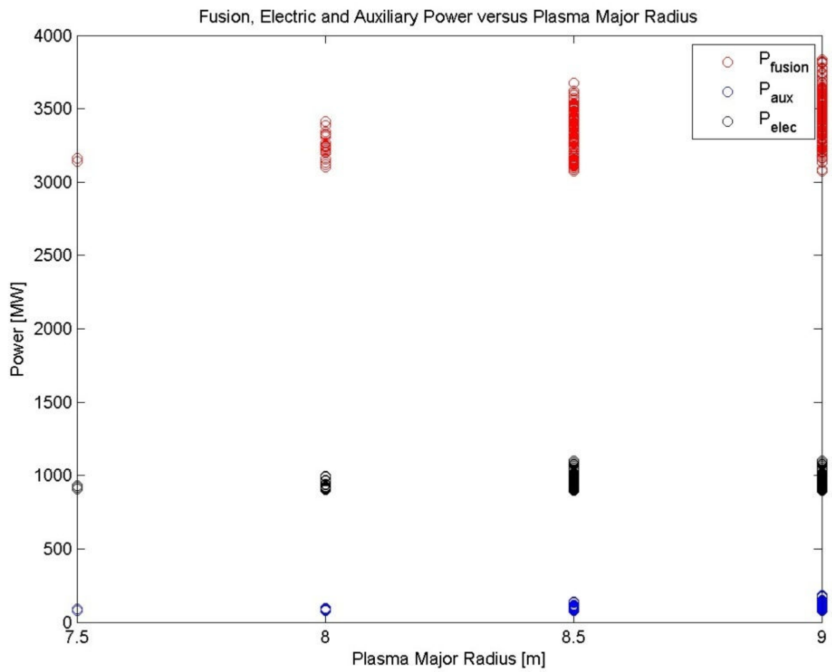
COE [mill/kWh]	R [m]	B_T [T]	βn [-]	FracGW [-]	NWL [MW/m^2]	P_{fusion} [MW]	P_{recir} [MW]
85.4	7	5	0.05	1.1	1.4	1860	180
85.4 - 87.2	7	5	0.045 - 0.055	0.8 - 1.1	1.32 - 1.4	1750 - 1860	153 - 180
85.4 - 90.0	7 - 7.5	5	0.04 - 0.055	0.7 - 1.1	1.26 - 1.4	1680 - 1940	149 - 180
85.4 - 95.0	7 - 7.5	5.0 - 6.0	0.04 - 0.06	0.7 - 1.1	1.16 - 1.4	1620 - 1950	147 - 242
85.4 - 100.0	7.0 - 8.0	5.0 - 6.0	0.035 - 0.06	0.7 - 1.1	1.06 - 1.4	1610 - 2030	145 - 251
85.4 - 167.0	**7.0 - 9.0**	**5.0 - 7.0**	**0.03 - 0.06**	**0.7 - 1.1**	**0.747 - 1.4**	**1600 - 2100**	**144 - 305**
78.39	**5.2**	**5.8**	**0.054**		**3.2**	**1719**	**169.634**

COE [mill/kWh]	P_{recir} [MW]	BoostrapFrac [-]	Q95 [MW/m2]	QpeakDiv [MW/m2]	QpeakFW [MW/m2]	RhoAve [1.e20/m^3]	Tave [kEv]
85.4	180	0.946	4	7.73	0.185	1.46	19.8
85.4 - 87.2	153 - 180	0.894 - 0.989	3.8 - 4.2	7.25 - 8.0	0.16 - 0.185	1.12 - 1.46	17.6 - 29.5
85.4 - 90.0	149 - 180	0.852 - 0.994	3.4 - 4.6	6.84 - 8.0	0.113 - 0.185	0.97 - 1.46	15.1 - 32.6
85.4 - 95.0	147 - 242	0.833 - 0.994	3.2 - 4.6	6.24 - 8.0	0.110 - 0.185	0.915 - 1.46	15.1 - 33.4
85.4 - 100.0	145 - 251	0.766 - 0.994	3.2 - 4.6	5.35 - 8.0	0.0771 - 0.185	0.815 - 1.46	15.1 - 34.3
85.4 - 167.0	**144 - 305**	**0.684 - 1.0**	**3.2 - 4.6**	**3.96 - 8.0**	**0.0613 - 0.185**	**0.645 - 1.46**	**13.5 - 35.9**
78.39	**169.634**	**0.91**	**3.7**	**5**		**1.709**	**18**

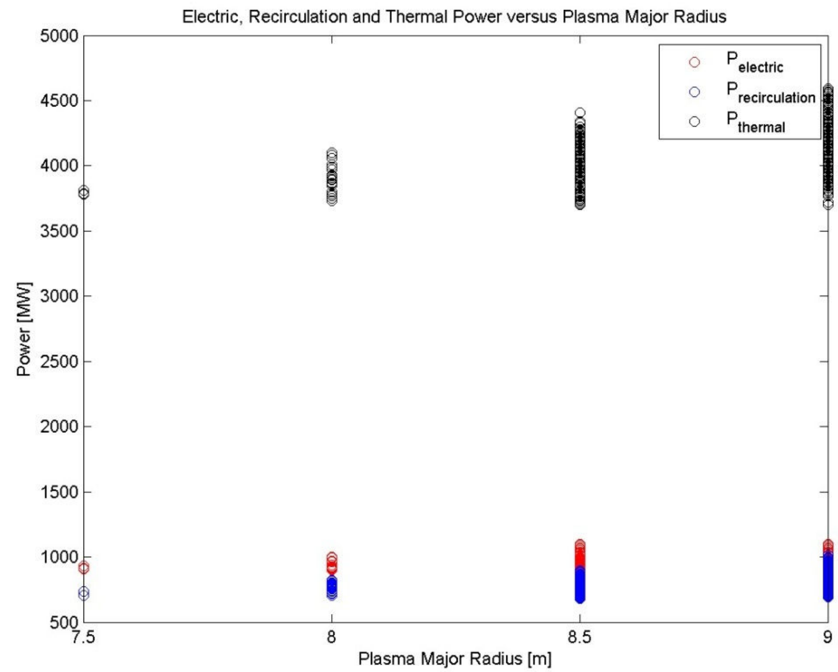
- Parameters for the most optimal design based on the minimum COE are shown in red, on top of the table.
- Lower rows of the table (black fonts) show how the intervals of characteristic parameters widen around the optimal point as we gradually increase the tolerance for the COE from lowest to higher costs.
- The intervals of COE and other parameters across the entire valid database are shown in blue.
- Well documented and highly respected ARIES-AT data are shown in green.

Data for ARIES-AT With Dual Coolant Lithium Lead Blanket Design

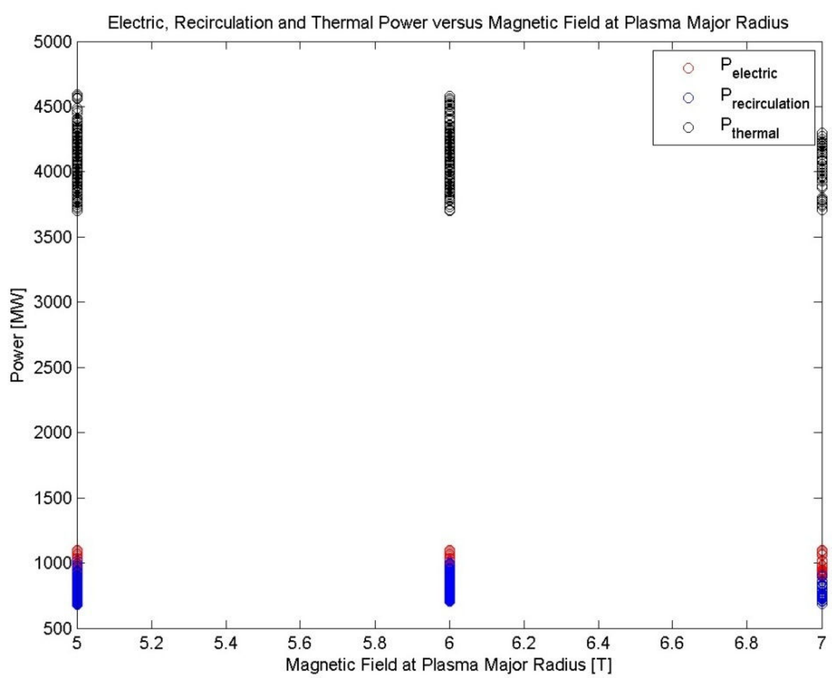
- Powers versus plasma major radius and magnetic field at plasma major radius:
  - Fusion, electric and auxiliary power versus plasma major radius.
  - Electric, thermal and recirculation power versus plasma major radius.
  - Electric, thermal and recirculation power versus magnetic field at plasma major radius.
- Physics operating space and how it relates to COE:
  - βn versus bootstrap current fraction.
  - βn versus Q_{mhd}.
  - βn versus toroidal field at plasma major radius.
  - Volume averaged temperature versus volume averaged density.
  - Multiplier on energy confinement scaling versus Greenwald density fraction.
  - COE versus R, B_T and βn.
  - COE versus R, B_T and Greenwald density fraction.
- Fluxes that impact the first wall and divertor across the plasma major radius:
  - Average neutron wall load versus plasma major radius.
  - Peak inboard heat flux on divertor versus plasma major radius.
  - Peak outboard heat flux on divertor versus plasma major radius.
  - Peak radiated heat flux on the first wall versus plasma major radius.



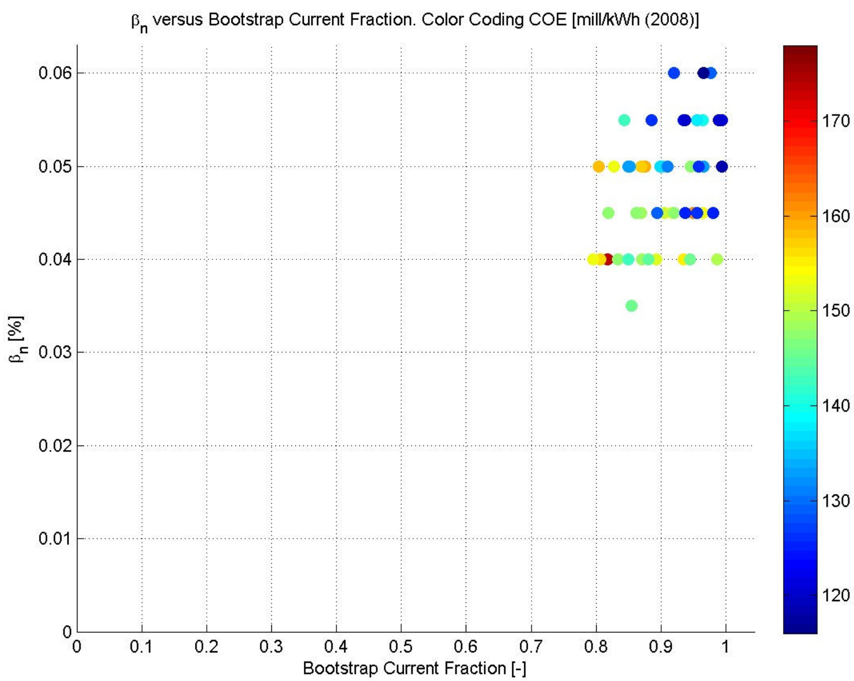
Fusion, Electric and Auxiliary Power versus Plasma Major Radius
Power [MW]
Plasma Major Radius [m]
P fusion
P aux
P elec

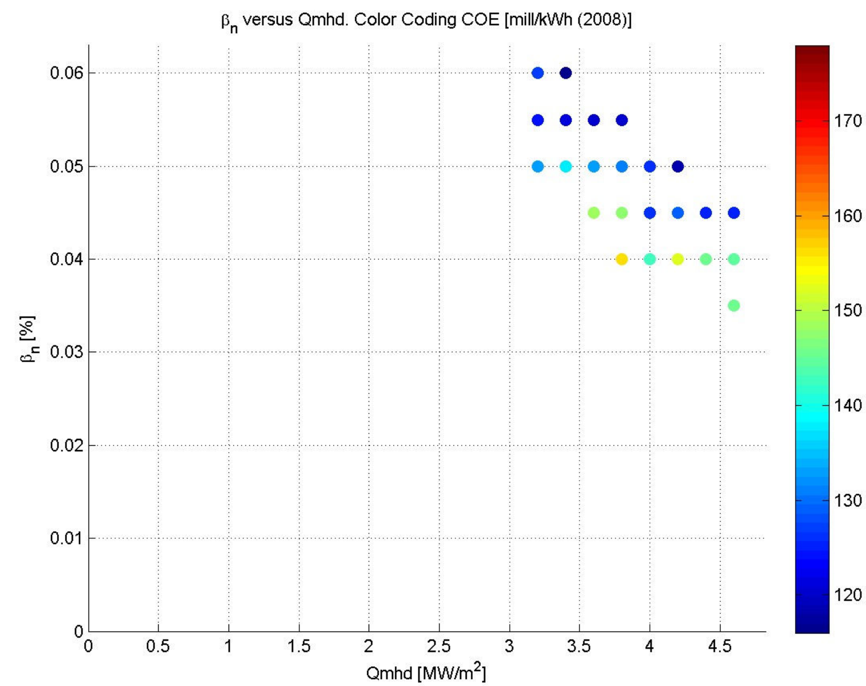


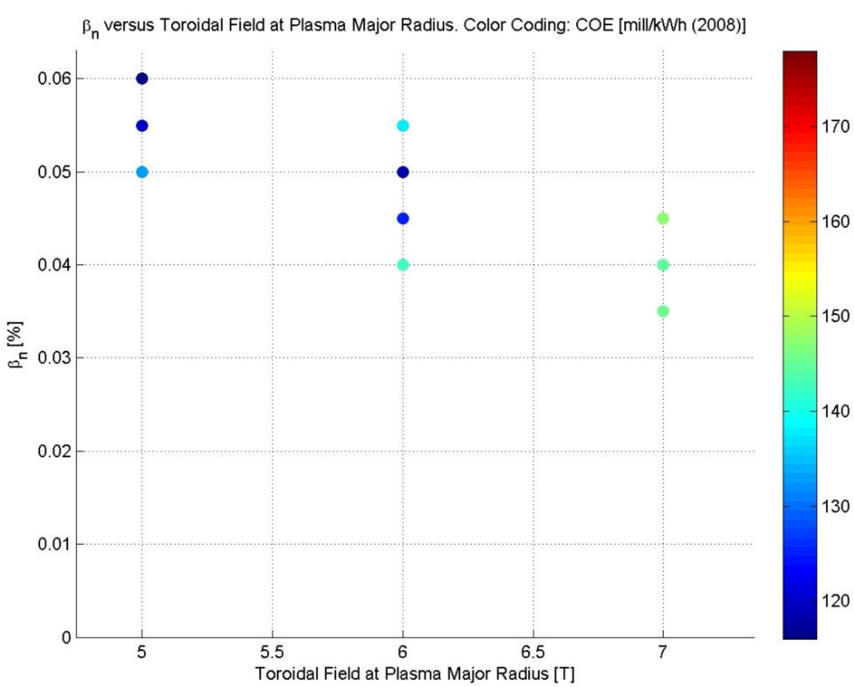
Electric, Recirculation and Thermal Power versus Plasma Major Radius
Power [MW]
Plasma Major Radius [m]
P electric
P recirculation
P thermal

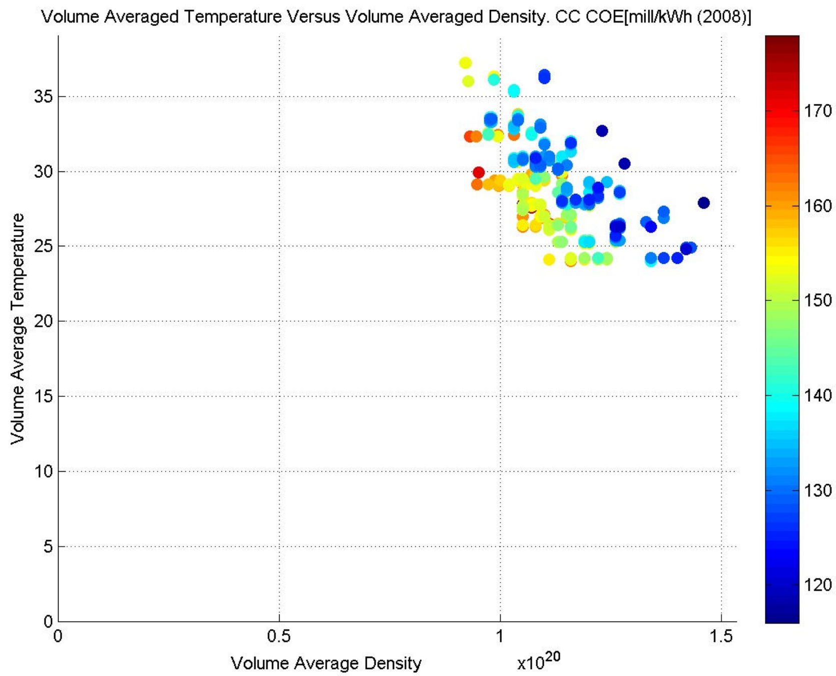


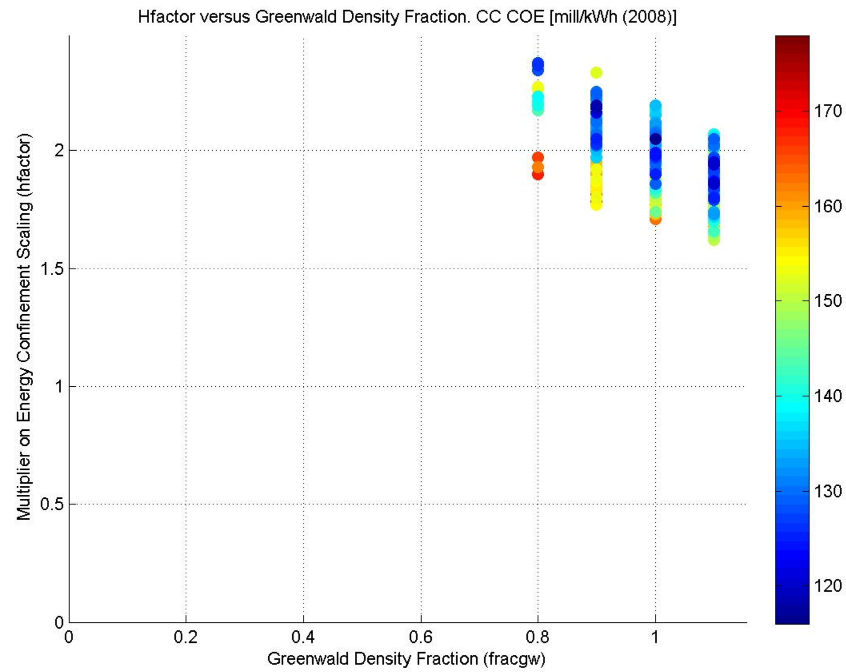
Electric, Recirculation and Thermal Power versus Magnetic Field at Plasma Major Radius
Power [MW]
Magnetic Field at Plasma Major Radius [T]
P electric
P recirculation
P thermal

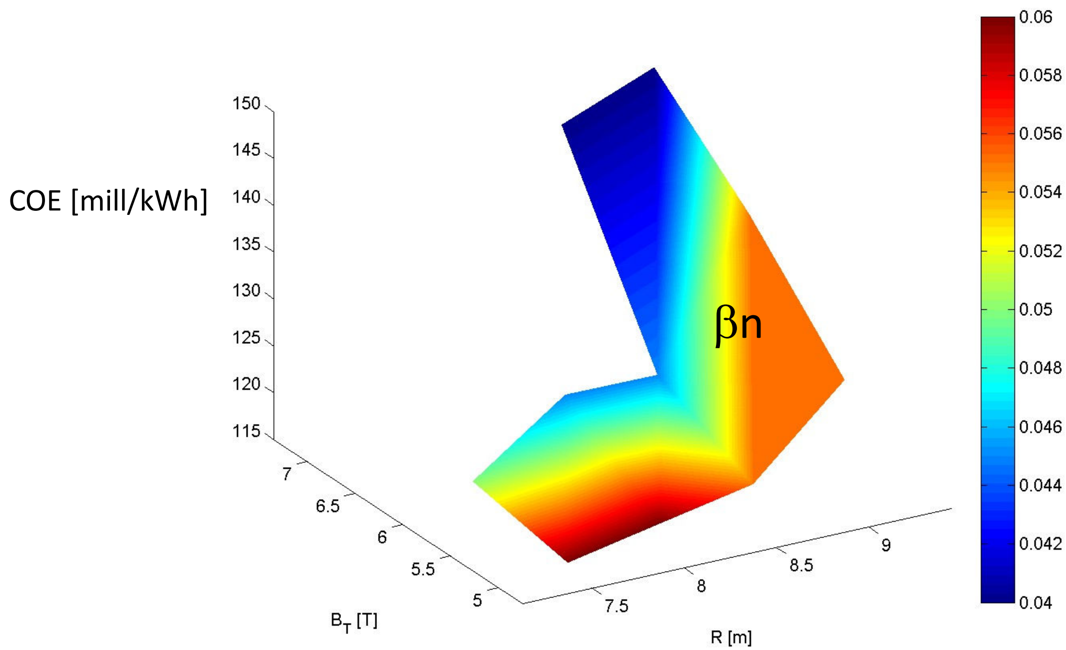

β_n versus Bootstrap Current Fraction. Color Coding COE [mill/kWh (2008)]
β_n [%]
Bootstrap Current Fraction [-]
0 0.01 0.02 0.03 0.04 0.05 0.06
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
120 130 140 150 160 170

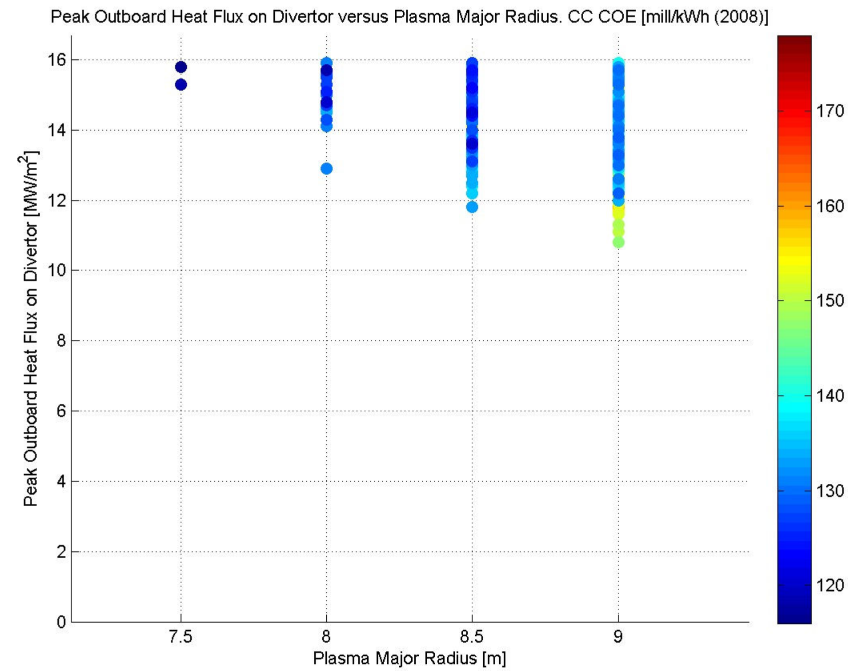

β_n versus Qmhd. Color Coding COE [mill/kWh (2008)]
β_n [%]
Qmhd [MW/m^2]
0 0.01 0.02 0.03 0.04 0.05 0.06
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5
120 130 140 150 160 170

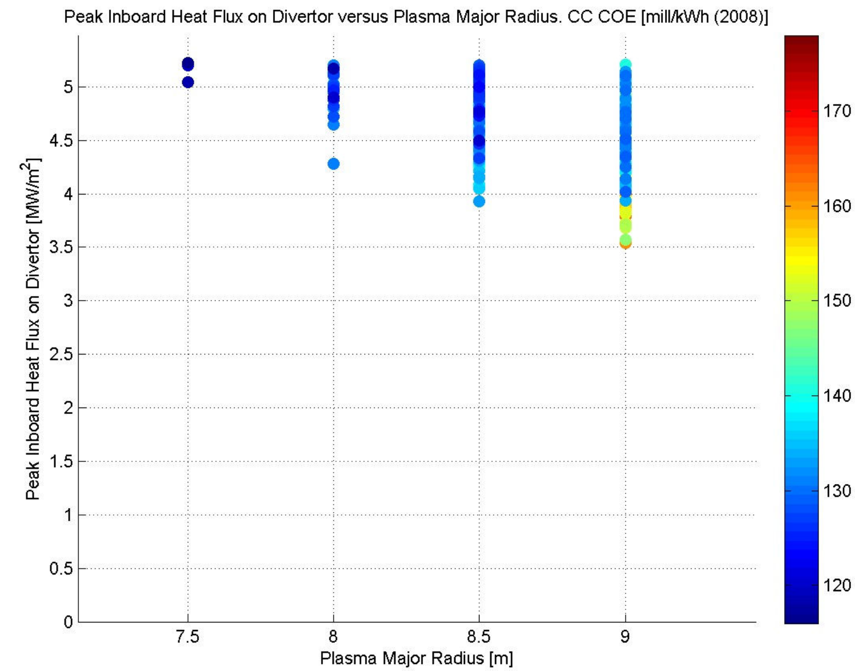

β_n versus Toroidal Field at Plasma Major Radius. Color Coding: COE [mill/kWh (2008)]
β_n [%]
Toroidal Field at Plasma Major Radius [T]
0 0.01 0.02 0.03 0.04 0.05 0.06
5 5.5 6 6.5 7
120 130 140 150 160 170

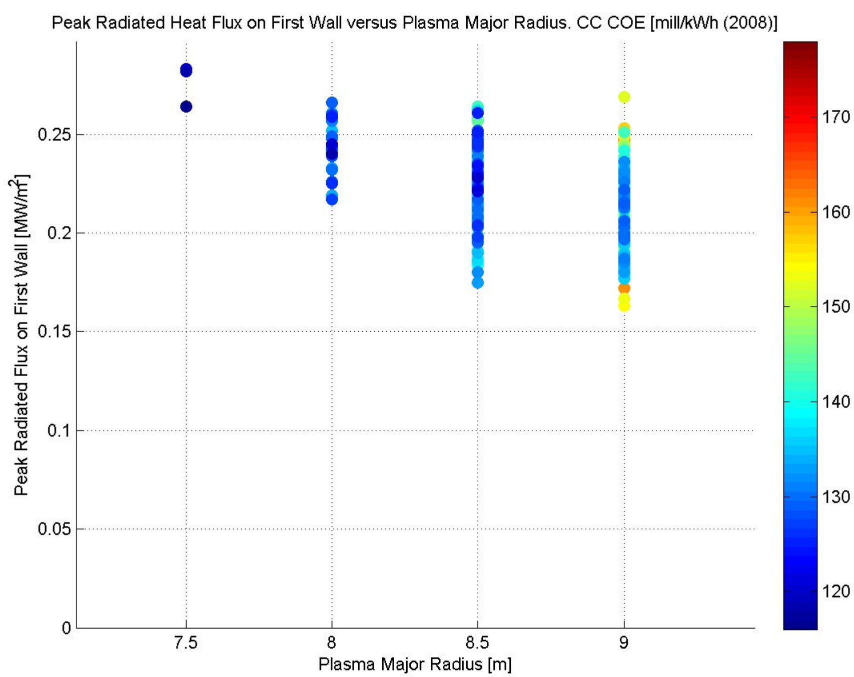

Volume Averaged Temperature Versus Volume Averaged Density. CC COE[mill/kWh (2008)]
Volume Average Temperature
Volume Average Density
x10^20
0
0.5
1
1.5
0
5
10
15
20
25
30
35
120
130
140
150
160
170

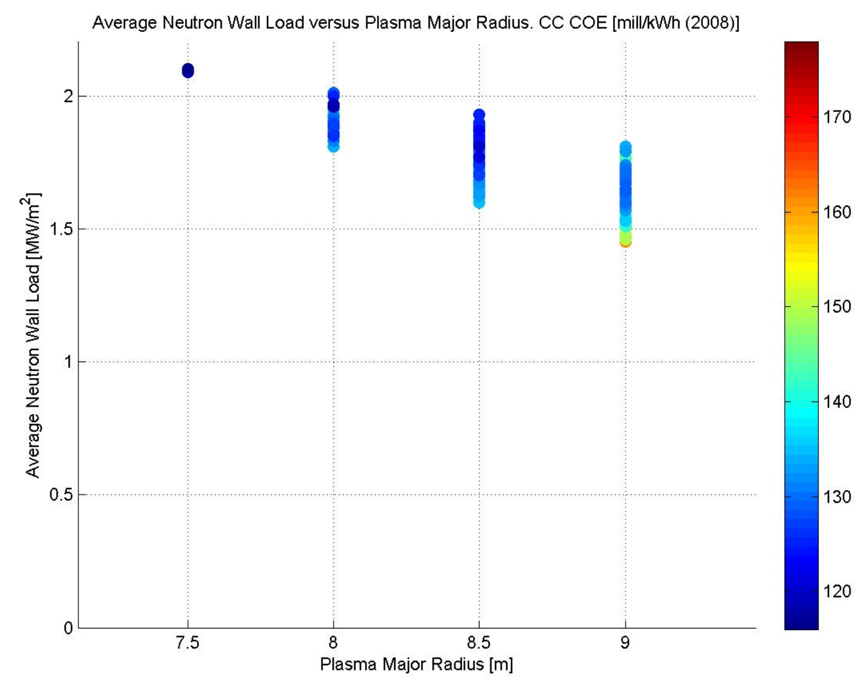

Hfactor versus Greenwald Density Fraction. CC COE [mill/kWh (2008)]
Multiplier on Energy Confinement Scaling (hfactor)
Greenwald Density Fraction (fracgw)
0
0.2
0.4
0.6
0.8
1
0
0.5
1
1.5
2
120
130
140
150
160
170


COE [mill/kWh]
βn
B_T [T]
R [m]
115
120
125
130
135
140
145
150
5
5.5
6
6.5
7
7.5
8
8.5
9
0.04
0.042
0.044
0.046
0.048
0.05
0.052
0.054
0.056
0.058
0.06


Peak Outboard Heat Flux on Divertor versus Plasma Major Radius. CC COE [mill/kWh (2008)]
Peak Outboard Heat Flux on Divertor [MW/m^2]
Plasma Major Radius [m]
0
2
4
6
8
10
12
14
16
7.5
8
8.5
9
120
130
140
150
160
170


Peak Inboard Heat Flux on Divertor versus Plasma Major Radius. CC COE [mill/kWh (2008)]
Peak Inboard Heat Flux on Divertor [MW/m^2]
Plasma Major Radius [m]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
7.5
8
8.5
9
120
130
140
150
160
170


Peak Radiated Heat Flux on First Wall versus Plasma Major Radius. CC COE [mill/kWh (2008)]
Peak Radiated Flux on First Wall [MW/m^2]
Plasma Major Radius [m]
0
0.05
0.1
0.15
0.2
0.25
7.5
8
8.5
9
120
130
140
150
160
170


Average Neutron Wall Load versus Plasma Major Radius. CC COE [mill/kWh (2008)]
Average Neutron Wall Load [MW/m^2]
Plasma Major Radius [m]
0
0.5
1
1.5
2
7.5
8
8.5
9
120
130
140
150
160
170