Progress on Engineering and Costing Algorithms for ARIES Systems Code

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Overview of Recent Work

- Costs of TF and PF coil magnets and their impact on the cost of electricity were thoroughly investigated, as prompted by the feedback from the previous meeting.
  - An error in the code was identified and fixed.
- A new TF Coil Algorithm was built in collaboration with Leslie Bromberg.
  - Winding pack calculations are done in detail.
  - Structural calculations based on a simple beam theory are included.
- Shield thickness is estimated based on the average neutron wall load, as recommended by Laila.
- Cost of electricity was obtained for HTS and Nb3Sn and these two compared.

TF Coil Algorithm – Overview of the Previous Version

- In the previous version, TF coil thickness was calculated based on the procedure outlined by Chuck Kessel.
- Maximum toroidal magnetic field is obtained as shown below:

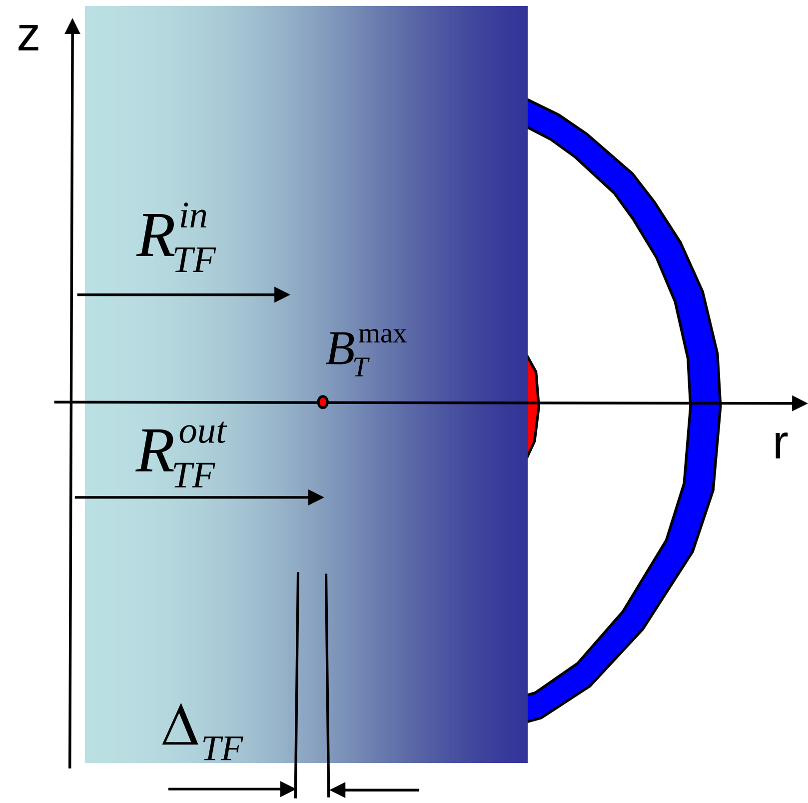
Current in the TF coil, needed to produce the field B_T in a plasma with the major radius R.

$$I_{TF} = B_T \frac{2\pi R}{\mu_o N_{TF}}$$

Outer radius of the inner leg of the TF coil. Summation goes over the inboard thicknesses of the power core, including gaps.

$$R_{TF}^{out} = R - a - \sum_{i=1}^{n} \Delta_i^{inboard}$$

Maximum toroidal magnetic field is located at the outer radius of the TF coil inner leg.



$$B_T^{max} = \frac{\mu_o N_{TF} I_{TF}}{2\pi R_{TF}^{out}} \leq 21T$$

Reject the operating point if the inequality is not satisfied.

TF Coil Algorithm – Overview of the Previous Version, Continued

- In the previous code, the current density that corresponds to the maximum toroidal magnetic field was defined as:

$$J_{TF}^{overall} = \frac{0.9\sigma_{all} - \frac{(B_T^{\max})^2}{2\mu_o}}{\sigma_{all}\left(\frac{1}{J_{SC}} + \frac{1}{J_{Cu}} + RB_T^{\max}\right)\ln\left(\frac{R_{TF}^{outboard}}{R_{TF}^{inboard}}\right) - \frac{\sigma_{Cu}}{J_{Cu}}}$$

Current density that corresponds to the entire cross-section of the TF coil.

- Instead of simply using this formula, we wanted to establish a procedure for calculating the cross section of the winding pack and the procedure for providing the necessary structural support to the TF coil.

$$A_{TF} = \frac{N_{TF} I_{TF}}{J_{TF}^{overall}}$$

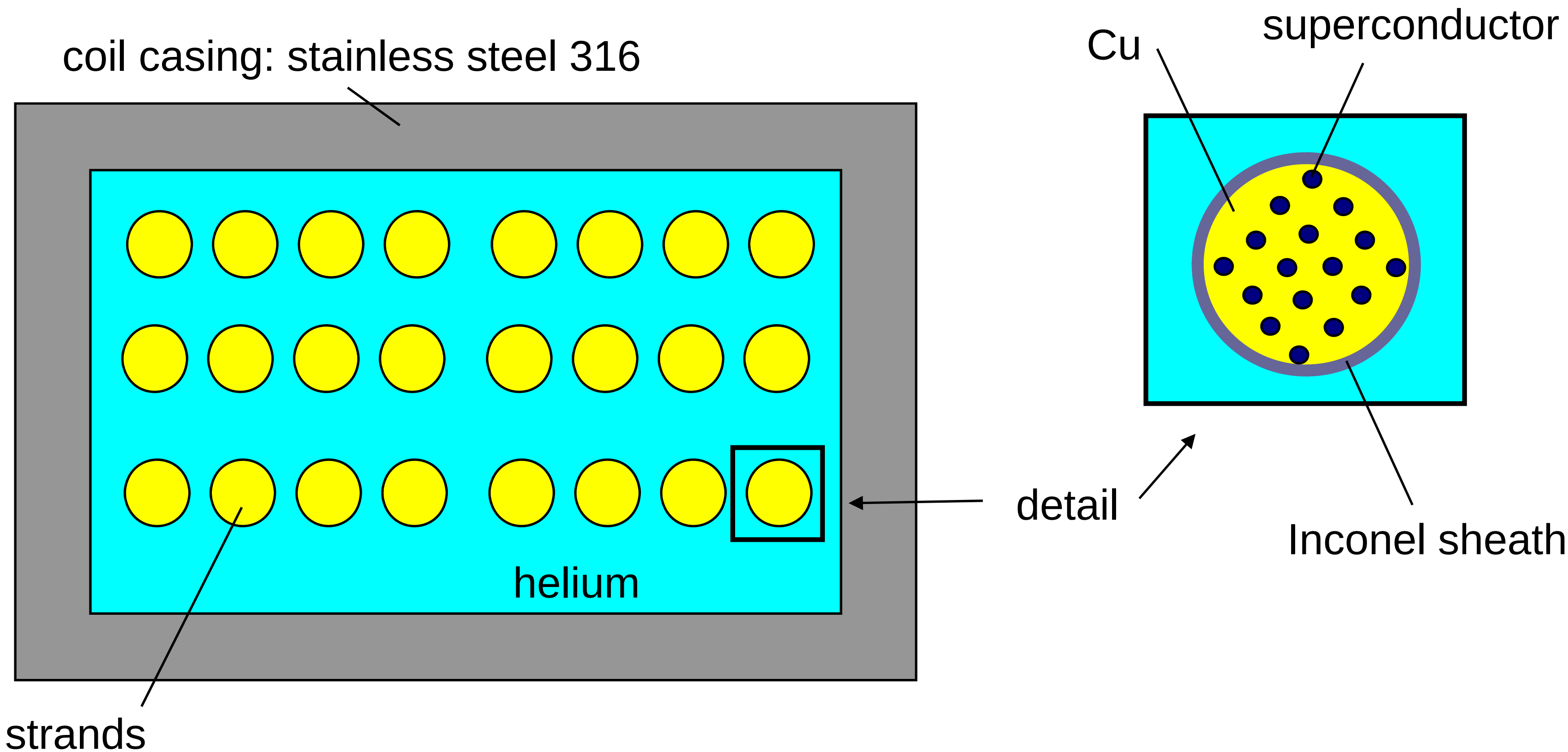
Cross-section of the inboard part of the entire TF torus.

$$R_{TF}^{in} = \sqrt{(R_{TF}^{out})^2 - \frac{A_{TF}}{\pi}} \Rightarrow \Delta_{TF} = R_{TF}^{out} - R_{TF}^{in}$$

Thickness of the TF coil.

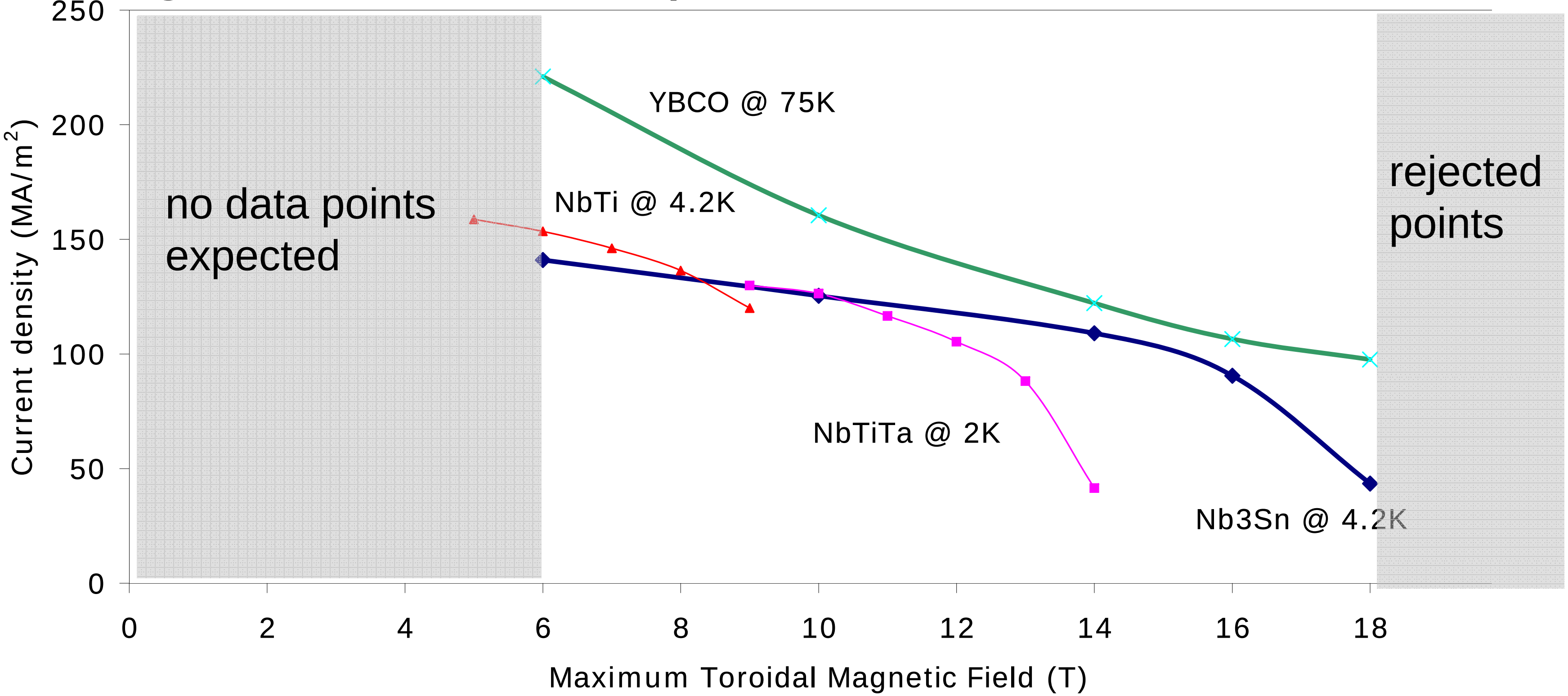
- The costing was based on the density and cost per unit mass of the composite material. In a better approximation, the volume fractions of the composition are not fixed and depend on the plasma parameters.

Cross Section of the TF Coil



- The strands are composed from the superconductor and copper, which are wrapped together into a thin sheath made of Inconel. The volume of copper is twice as large as the volume of the superconductor in order to insure the adequate quenching protection.
- The winding pack is submerged into helium in order to provide cooling to the cryogenic temperatures.
- Structural support to the TF coil is provided by a coil casing made of stainless steel 316.

Current Density Dependence on Peak Toroidal Magnetic Field in Superconductors We Modeled



- The experimental data depicted above were used to determine the current density in the superconductor, given the peak toroidal magnetic field. For this study, YBCO @ 75K (green curve) and Nb3Sn @ 4.2K were used.
- The range of data for these two cases requires that all the physical operating points that produce $B_T^{max} > 18$ T be rejected. The same is true for $B_T^{max} < 6$T, even though we do not expect to see those values.

Effective Current Density in the Winding Pack

- The algorithm starts by calculating the peak magnetic field B_T^{max} at the outer radius of the inner cross section, as previously shown.
- The winding pack consists of the superconductor, copper, helium and inconel sheath. The procedure to determine the effective current density is outlined as:

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1. Calculate the current density in the superconductor by interpolating from the experimental curves. Reject all the points with peak magnetic field out of range.

J_{SC} by interpolation

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2. Estimate the current density in copper while having in mind that copper needs to provide quenching protection to the superconductor. For HTS, this is done by setting the current density in Cu as half or the value in the superconductor. For Nb3Sn, a quenching time of 2 seconds is desired.

$$J_{Cu} = \frac{J_{SC}}{2}$$ HTS

$$J_{Cu} = \sqrt{\frac{2J^2\tau}{\tau}}, \quad \tau = 2s$$ Nb3Sn

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3. Volumetric fraction of helium is fixed to 0.25 while the volumetric fraction of the inconel sheath is calculated based on the structural support requirements. The stress in sheath is 1.6 10^9 Pa.

$$d_{sheath} = \frac{(B_T^{max})^2}{2\mu_o \sigma_{sheath}}$$

$$f_{sheath} = 1-(1-d_{sheath})^2$$

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4. The effective current density is given as:

$$J_{effective} = \frac{(1-f_{He})(1-f_{sheath})}{\frac{1}{J_{SC}}+\frac{1}{J_{Cu}}}$$

Electric Current in TF Coil and Cross-Sectional Areas of Components

- Leslie Bromberg's recommendation for the electric current in the TF coil was I_{TF} = 40 kA. This choice has to do with the ability to dissipate the energy out of the magnet at times when quench protection may be necessary. The estimated value originates from the Stelarator design, which has 36 electrical circles and discharges 50 GJ of energy into an external resistor during the quench protection. The optimal discharge time is 2s.
- The cross sectional areas of different components can be recovered from previously calculated current densities:

$$A_{turn} = \frac{I_{TF}}{J_{effective}} \quad \Rightarrow \quad A_{TF} = A_{turn} N_{turns}$$ Total area of the TF coil.

$$A_{strands} = \frac{I_{TF}}{\frac{1}{J_{SC}} + \frac{1}{J_{Cu}}}$$ Conductive area that includes the superconductor and copper.

$$A_{strands+He} = \frac{A_{strands}}{(1 - f_{He})}$$ Strands + He $$\Rightarrow \quad A_{sheath} = A_{turn} - A_{strands+He}$$

$$A_{Cu} = \frac{I_{TF}}{J_{Cu}}$$ Copper.

$$A_{SC} = \frac{I_{TF}}{J_{SC}}$$ Superconductor.

External Structure of the TF Coil

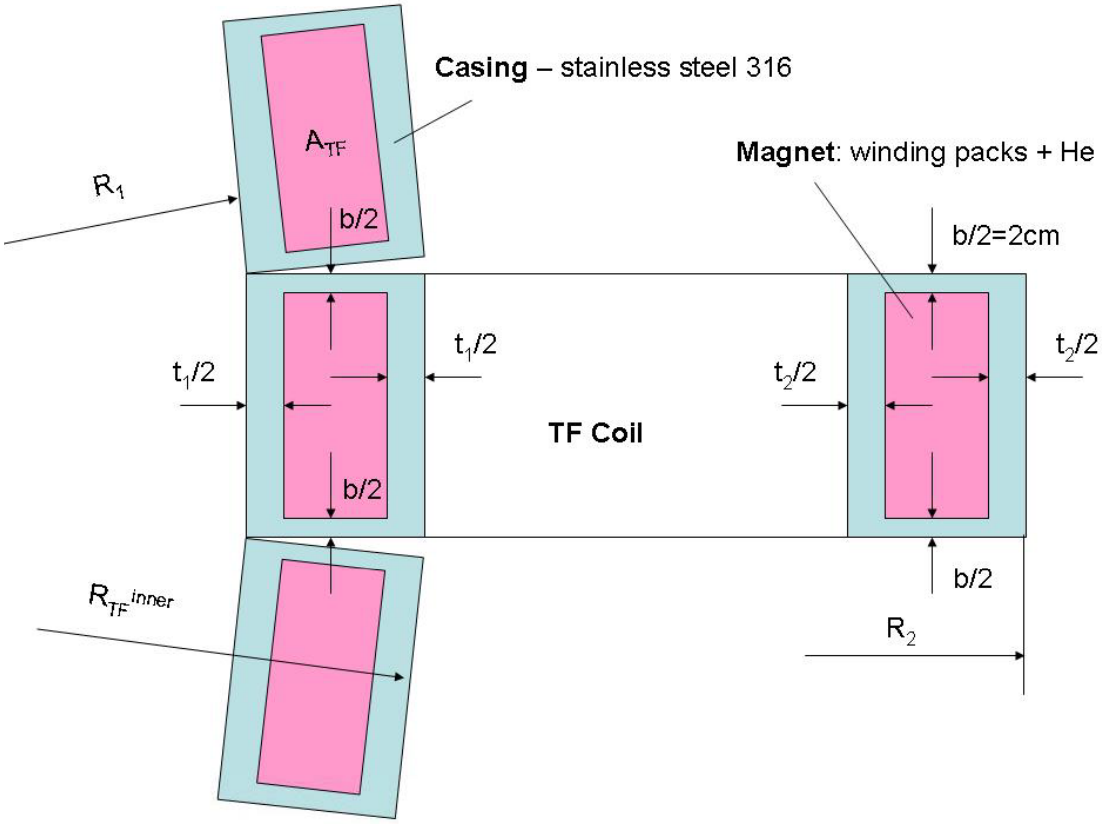
- Calculations of the external structure (casing) are based on the simple beam theory.
- The thicknesses of the inner leg (t_1), outer leg (t_2) and the top of the coil (a) are obtained by solving the following set of equations:

$$A = \frac{B_T^2 R^2}{2\mu_o}$$

$$S_1 = A\frac{R_2 \ln\left(R_2/R_1\right) - R_2 + R_1}{R_1\left(R_2 - R_1\right)}$$

$$S_2 = A\frac{R_2 - R_1 - R_1 \ln\left(R_2/R_1\right)}{R_2\left(R_2 - R_1\right)}$$

$$R_3 = \frac{S_1 R_1^2 + S_2 R_2^2}{A\ln\left(R_2/R_1\right)}$$



$$t_1 = \frac{S_1}{\sigma_m} \qquad t_2 = \frac{S_2}{\sigma_m}\cdot 1.5 \qquad a = \sqrt{\frac{3}{8}\frac{S_2 R_2\left(R_2 - R_3\right)}{\sigma_b R_3}}$$

Connecting the Winding Pack and External Structure Calculations Together

- The algorithm that puts the TF coil structure together consists of an inner and outer iterative loop. The inner loop is based on the B_T^{max} estimated at the fixed distance from the plasma, determined by the inboard radial build as previously shown. The outer loop is done in order to place the B_T^{max} at the center of the TF coil.
- Overview of the inner loop:
  1. Estimate the cross-sectional area enclosed within the coil casing and the corresponding areas of the components: A_{TF}, A_{SC}, A_{Cu}, etc.
  2. Assume a value of the outer external structure radius R_2 that gives a sufficient space for the power core and satisfies maintenance requirements.
  3. Make an initial guess for t_1, t_2, a and calculate the inner external structure radius R_1.
  4. Based on the radii R_1 and R_2 solve the structural equations for the coil casing and repeat the steps 3 and 4 until the values for t_1, t_2 and a converge.
- Overview of the outer loop:
  1. Estimate the B_T^{max} at the center of the TF coil instead of the edge and repeat the inner loop until all the values converge.
- The final outcome of the iterative loops are the volume of the TF coil and the volumetric fractions of the components. Even though the algorithm is iterative in nature, the values converge to the 4th decimal within only 3 iterations.

Costing of the TF Magnet

Material	Density [kg/m^3]	Cost per unit mass [$/kg] (1992)
YBCO	6200	92.7
Nb3Sn	7500	92.7
Cu	7300	65.4
Inconel	8440	50.912
Stainless Steel 316	7860	68.657

- We have confidence in densities but not in costs of these materials.
- Nb3Sn, Cu and stainless steel costs are obtained from the unpublished ARIES II-IV studies, which are the most up to date.
- YBCO and Inconel costs are guessed.

HT Shield Thickness as a Function of Average Neutron Wall Load

- Inboard shield thickness:

$$\Delta_{shield}^{inboard} = 0.24 + 0.067\ln(nwl/3.3)\ \ [\mathrm{m}]$$

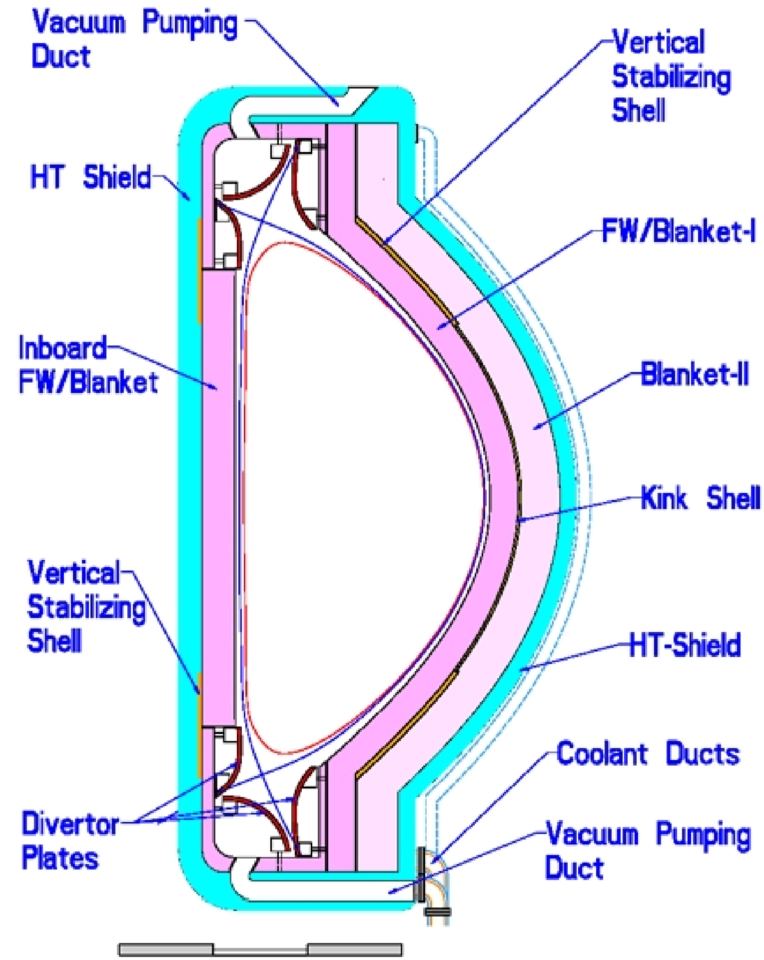
- Outboard shield thickness:

$$\Delta_{shield}^{outboard} = 0.15 + 0.0664\ln(nwl/3.3)\ \ [\mathrm{m}]$$

- Divertor shield thickness:

$$\Delta_{shield}^{divertor} = 0.30 + 0.07\ln(nwl/3.3)\ \ [\mathrm{m}]$$

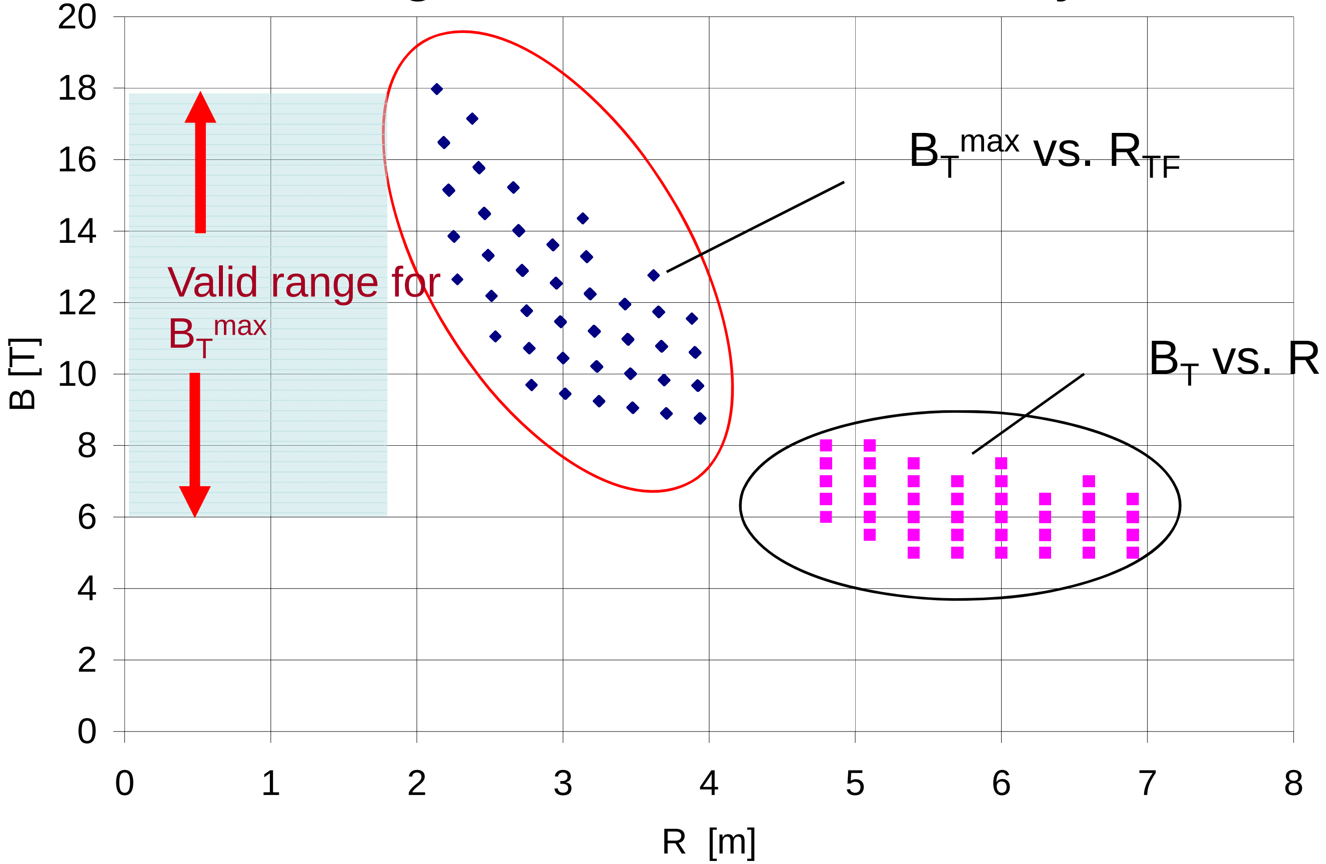
- The average neutron wall load (*nwl*) is given in MW/m^2



Summary of the Systems Algorithm With Latest Modifications Included

- Generate a set of viable operating data points based on plasma physics – PPPL code.
- Generate the inboard radial build by using relevant engineering modules and filters – PPPL code. Exceptions:
  - HT shield inboard thickness is replaced by the scaling law recommended by Laila El-Guebaly and described on the previous slide – UCSD code.
  - TF coil inboard thickness is replaced by the value obtained from the new TF coil algorithm – UCSD code.
- Generate complete TOKAMAK geometry starting from the inboard radial build – UCSD code.
  - In the new TF coil calculations, both geometry and internal composition of the TF magnet depend on the parameters from plasma physics.
- Generate all the costing accounts and cost of electricity based on TOKAMAK geometry, internal composition of the elements and their costs. – UCSD code.

Magnitudes of Peak Toroidal Magnetic Field – They are all are in the range of the current density curves.



- Peak toroidal magnetic field at the center of the TF coil inner leg is depicted by blue dots while the corresponding values of B_T at plasma major radii are represented by pink dots.
- Only two data points from the initial set of 1452 were filtered out by being out of the range defined by the current density curves. For the HTS and Nb3Sn magnet, this range is 6T-18T. The remaining data for B_T^{max} are evenly distributed between 8T and 18T
- It appears that there is a very few data points here, however this is a full set of 1452 data points. A very large number of them overlap and appear as one dot.

Comparison of Previous and New TF Coil for a Single Data Point: R=5.7m, B_T = 5T.

	Previous TF Coil Algorithm	New TF Coil Algorithm
Volume [m^3]	23.237	15.4453
Cost [M$ (1992)	163.04	136.112
Total Direct Cost [M$ (1992)]	1847.27	1821.21
Total Capital Cost [M$ (1992)]	3797.27	3742.37
Cost of Electricity [mill/kWeh]	72.4151	71.5175

- The rather large difference in volumes can be explained by different procedures to calculate the cross-sectional areas. The coil thickness in the r-z plane is comparable between the versions but the width in the r-θ plane was previously over-estimated.
- Costing calculation is completely different between the versions. In the old version, a single density and cost per unit mass is given for the entire magnet, while in the new version each material is separately taken into account.
- Cost of the magnet is less than 10% of the total direct and total capital cost. Therefore there is only a small difference in the cost of electricity.

Comparison of Previous and New TF Coil for Multiple Data Points at B_T = 5.5T

Major Plasma Radius R [m]	Cost of the TF Coil [M$ (1992)] old	new	Cost of Electricity [mill/kWeh] old	new
5.1	162.352	109.931	68.8909	67.635
5.7	179.62	147.674	71.9178	70.967
6.0	188.997	169.786	72.8458	72.2869
6.3	198.888	194.008	74.5461	74.4132
6.9	219.464	249.92	79.8121	80.7548

- The difference between the old and new cost of the TF coil is significant and reverses the sign as the plasma major radius increases. At the lowest radius, the old TF cost is over-estimated by 50% while at the highest radius, the old TF cost is under-estimated by 12%.
- The reason for the differences mentioned above is due to the fact that the new TF coil has a significantly different thickness and width from the old TF coil. The new thickness and width are significantly impacted by a detailed winding pack calculation, as well as the structural based estimate of the casing.
- On the range of radii considered and for the given value of B_T, there is a rather low impact of the cost of TF magnet on the cost of electricity.

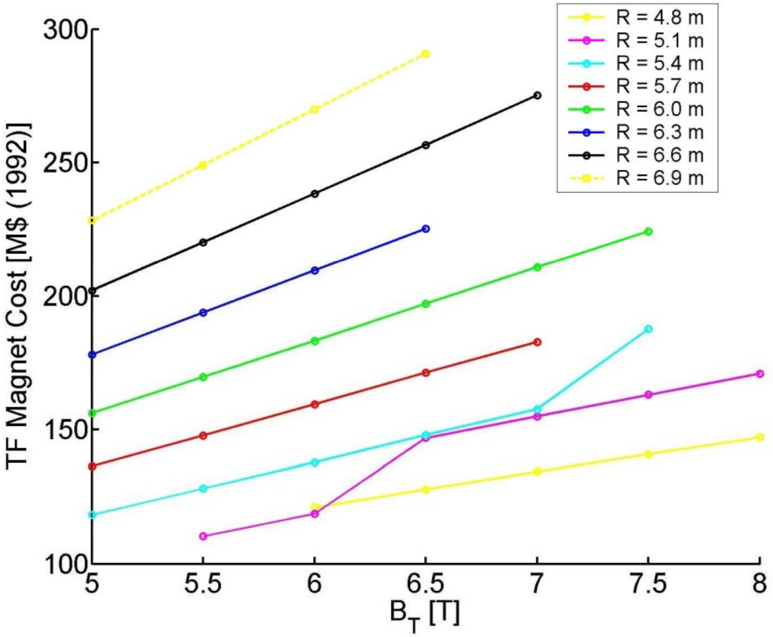
Comparison of Previous and New TF Coil for Multiple Data Points at R = 5.7m

Toroidal Magnetic Field BT [T]	Cost of the TF Coil [M$ (1992)] old	new	Cost of Electricity [mill/kWeh] old	new
5.0	163.04	136.112	72.2127	71.3984
5.5	179.62	147.674	71.2345	70.2969
6.0	196.288	159.212	71.7299	70.6416
6.5	213.302	170.696	73.8045	72.5142

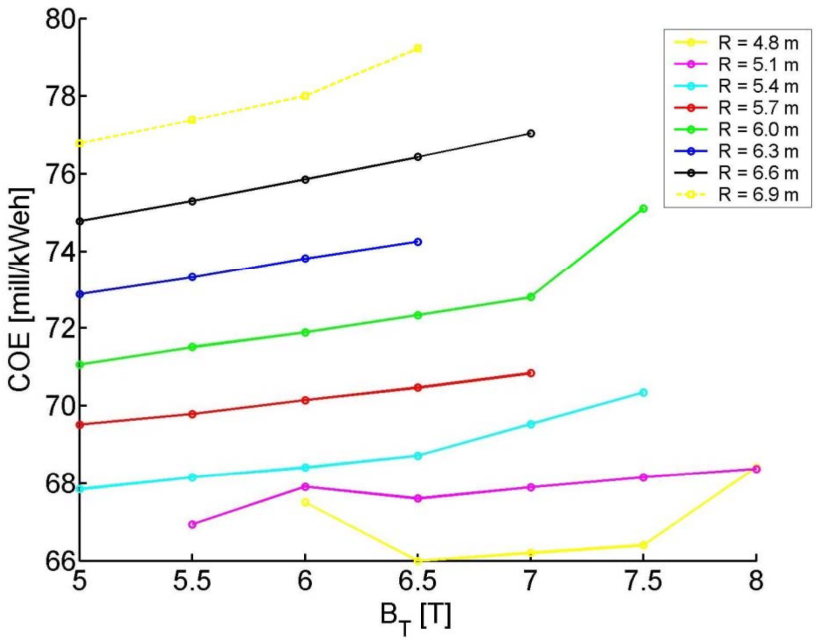
- For a fixed plasma major radius and variable magnetic field, the old algorithm is consistently over-estimated by about 20-25% on the entire range of data points. This confirms that the main source of differences is in geometry. The way the cross section is estimated impacts the volume and the total cost of the coil.

TF Magnet Cost and Cost of Electricity for Nb3Sn Superconductors

TF Magnet Cost that Corresponds to Minimum Cost of Electricity



Minimum Cost of Electricity



- For each pair of values R, B_T, there are several data points with different costs of electricity. Among those points, the ones with the minimum COE are plotted on the right. The cost of TF magnet that corresponds to the points with the minimum COE is plotted on the left.
- Cost of the TF magnet increases linearly with the toroidal magnetic field at plasma major radius and it also with that radius.
- Cost of electricity behaves similarly with respect to B_T and R, except at the lowest radius of 4.8 m, where there is a slight drop in COE at B_T = 6.5 T.

Conclusions and Future Work

- New TF coil algorithm includes detailed calculations of the winding pack and the structural support. Do we have a sufficiently good approximation of this magnet?
  - We would like to include the calculations of the bucking cylinder, wedged support and compare the two options but we need the appropriate procedures.
  - Some structure needs to be placed between the magnets in order to encase the power core elements. A thin shell made of steel 316 can be used or we can extend the magnet casing into a smooth surface.
  - The cost of different magnet materials needs to be obtained/verified. Based on that, we can compare the costs of electricity for Nb3Sn and HTS.
- HT shield is now properly estimated, after the recent inclusion of the scaling law for thickness, based on the average neutron wall load.
- PF coil algorithm is the work in progress.
- Any other engineering algorithms that we need to include / haven't included properly?
- Need to identify the important trends that these algorithms need to capture in order to use them with confidence.