Material, Design, and Cost Modeling for High Performance Coils

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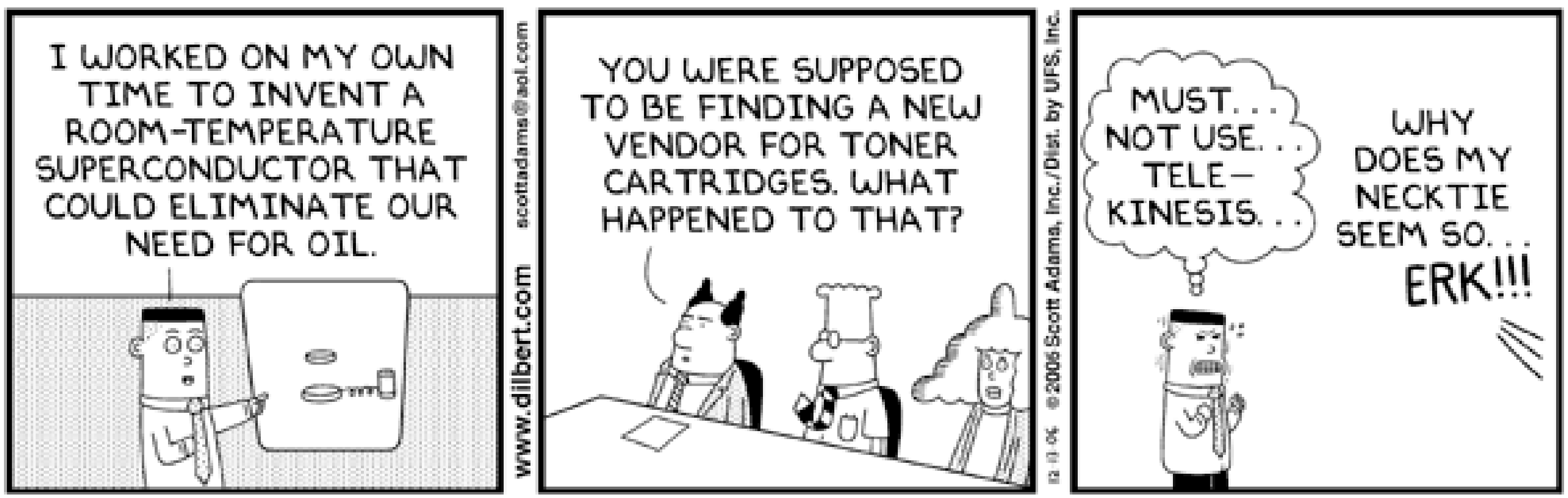
ARIES meeting

Tokamak Concept Improvement

- Cost minimization
  - Decrease cost of final product (10th of a kind)
  - Decrease cost of development path…
- Conventional magnet cost minimization
- Use of HTS superconductors
  - Demountable magnets



LTS

- Improved characterization of CICC concept and winding/insulation methods
- Demonstrate segregation of protection/stability with segregated SC strands
  - Separate superconductor from copper required for protection, to minimize cost
- Improved quench detection
  - Faster detection of quench to minimize protection requirements
- Improved protection
  - Internal vs external dump

LTS requirements

- Issues of use of LTS
  - Neutron damage to the superconductor
  - Neutron and gamma heating
  - Irradiation damage to the stabilizer/quench protection
  - Irradiation damage to the insulation
  - Magnet protection

- For LTS, all for limits occur at close fluences (a few times 10^{18} n/cm^2)

Replacement of LTS with HTS in Fusion Reactor Tokamak designs

- Physics:
  - Operation at higher fields
    - ARIES-RS design optimized at moderate magnetic field
    - Decreased size (ARIES 1, ARIES RS)
    - Longer pulse length from inductively driven plasmas
  - Eliminate ramping limitations
  - Superconducting plasma stabilizer (C. Bolton)
- Engineering:
  - Operation at higher temperatures
    - If operation is possible at liquid nitrogen temperature, cryogenic environment is much easier (YBCO HTS, and other materials that are even at earlier stages of development that YBCO)
  - Decreased sensitivity to heating of cryogenic environment
  - Decreased superconductor, normal conductor and cooling fractions in TF magnet

Option for TF magnets

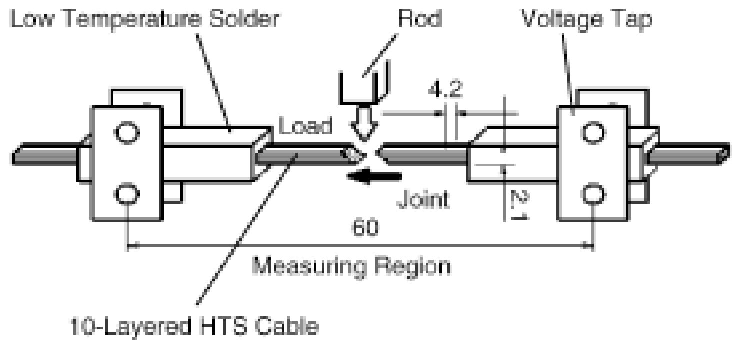
- Superconductor vs normal
  - Multiple options for the superconductor, including LTS, HTS and MgB_2
  - If resistive, cryogenic or water cooled
- Bucked vs wedged
- Radial plates (present ITER) vs shells (ARIES-RS, Rebut-ITER) vs case (TPX)
- Bending free vs increased bending for reduced size TF coil

- COIL FEATURES, AS REST OF THE SYSTEM, DEPENDS ON MISSION…

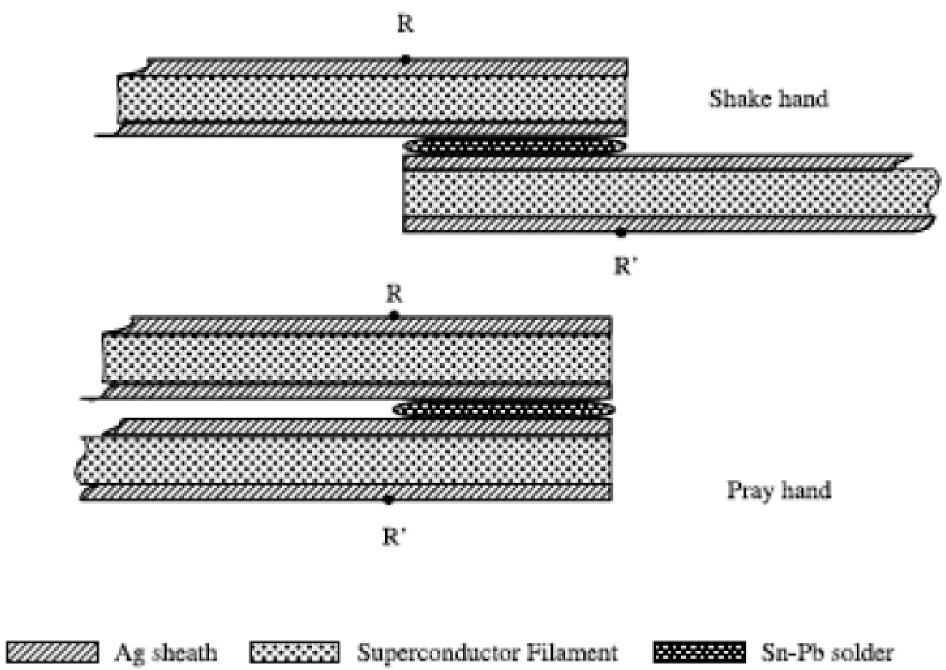
HTS: Demountable TF magnets

- In the past, demountable HTS magnets for tokamaks have been advocated:
  - Absence of flux jumping voids the requirement of very thin filaments that is required for LTS!
- HTS thick tapes of even monoliths can be used
- Based upon ALCATOR C-MOD geometry
  - structural plates with superconducting coatings
- MIT has preliminarily investigated joints between sections
  - BSCCO butt joints already good enough.
  - BSSCO lap joints show improved performance
  - YBCO lap joints show very good performance (~100 nΩ per tape, ~1 nΩ per joints for 10 kA cable, at 77K)

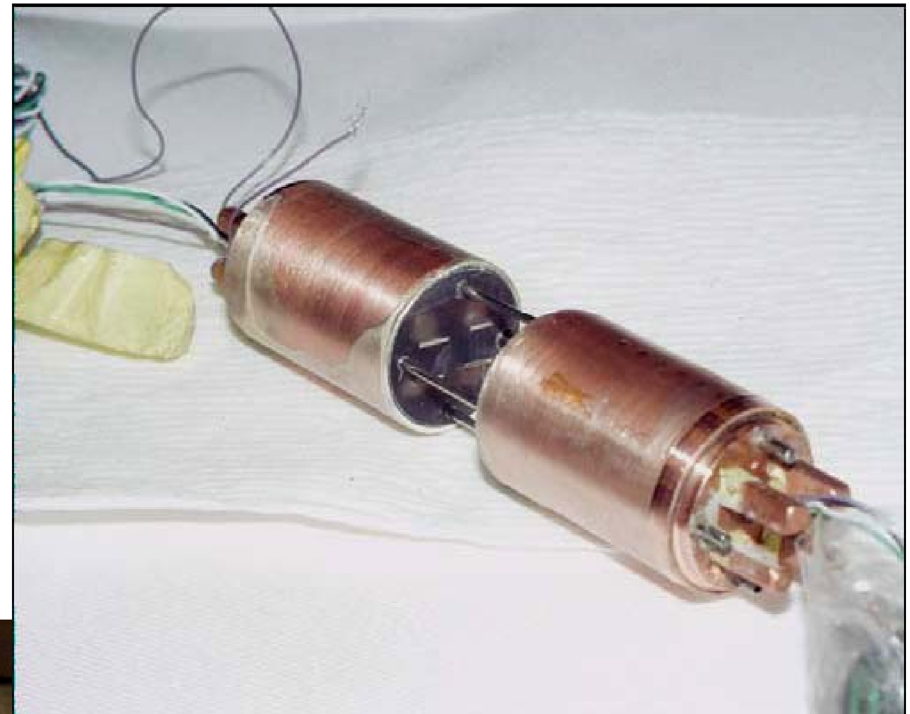
Butt joint

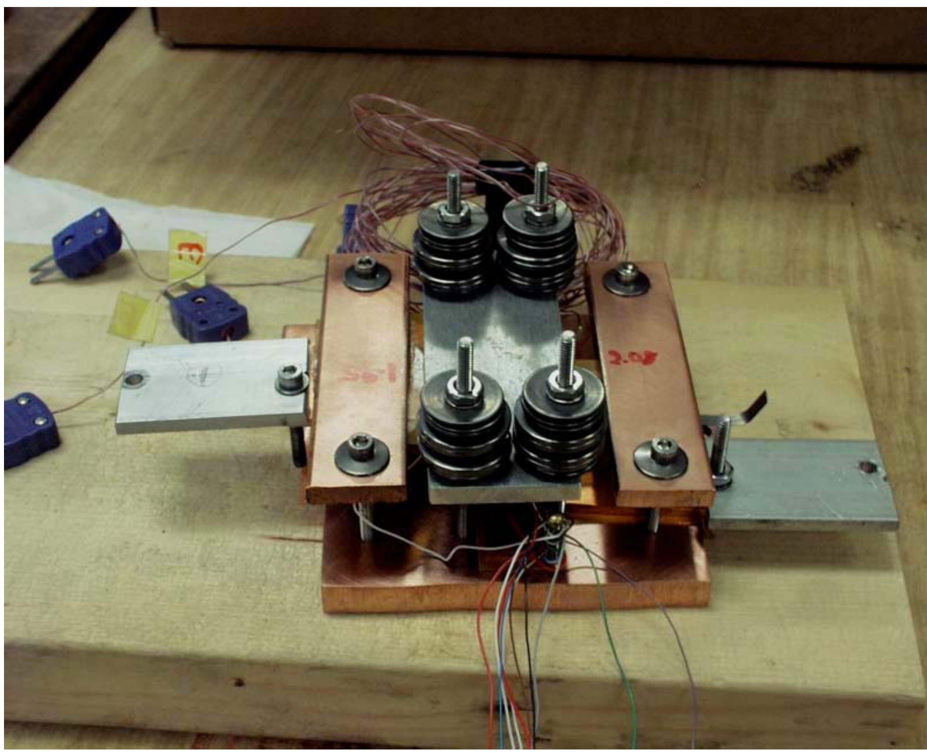


Lap joints

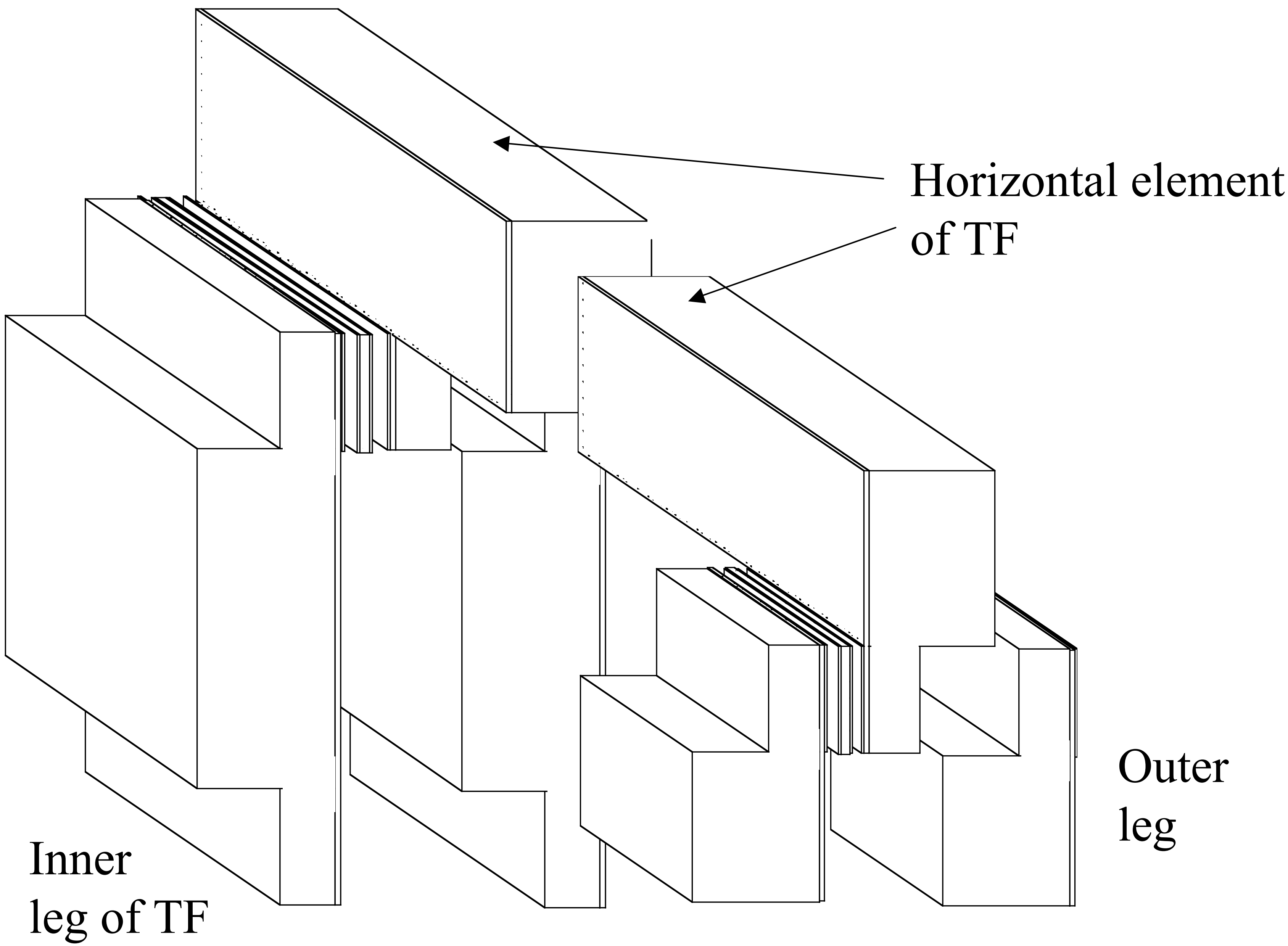


Butt joint





Lap joint



Horizontal element
of TF
Outer
leg
Inner
leg of TF

System code development

- There is a good number of models for designing toroidal and poloidal field coils

- Structural constrains for TF coils
  - Inplane loads
  - Out-of-plane loads

Materials
Design criteria for external support

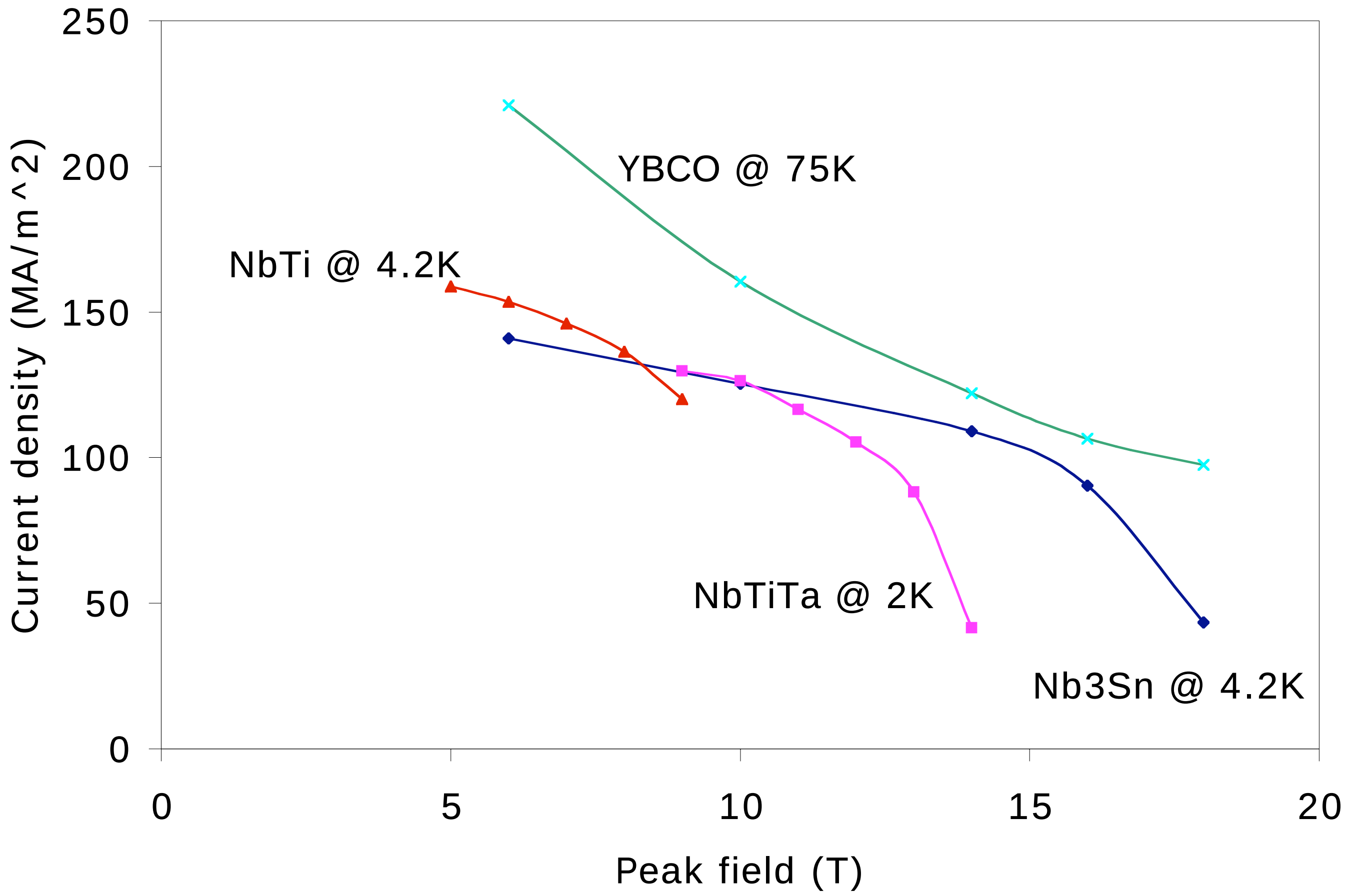
- Use SS-316 because of the large amounts of materials required could have substantial cost penalty
- Cross section of support determined by bending
  - Maximum stress by lowest of 1.5 x greater of (2/3 σ_y or 1/3 σ_u)
  - Use around 600 MPa (for SS-316)
    - SS-316: (1400 MPa yield, 1800 MPa ultimate)

Bucking cylinder and total structure cost

Bucking cylinder		
Inner pressure	Pa	3.22E+07
Force	Pa m	2.00E+08
thickness	m	3.34E-01
Volume	m^3	1.80E+02
Total structure volue	m^3	1.11E+03
Weight	tones	8.87E+03
Assume $50/kg		50
cost of structure		4.43E+08

- Large structure with tight tolerances

Simple code for system code



PF analysis

Nb3Sn
INPUTS

Peak field of coil	T	6
Radius of coil (m)	(m)	12
Current in conductor (A)	(A)	50000
Current in coil A	(A)	4000000
SC current density	A/m^2	1.50E+09
J2 tau	(A/m^2)s	5.00E+16
tau	s	2.00E+00
Current density in Copper	A/m^2	2.24E+08
Helium fraction		0.25
Stress in sheath	Pa	8.00E+08
Area of sheath	m^2	2.25E-03
Area of strands	m^2	2.57E-04
Area of strands + Helium	m^2	3.43E-04
Area of conductor		2.59E-03
Area of coil	m^2	2.07E-01
Volume	m^3	1.56E+01
weight	kg	1.20E+05
Cost per unit	$/kg	7.00E+01
Total cost of coil		8.38E+06

Ripple

- TF outer boundary determined by ripple considerations

$$\delta_{\text{peak to average}}(\%) \leq \frac{a}{(N_{\text{TF}} q_{95} R)^{0.6}} \frac{\sqrt{\frac{1+\kappa_{95}^2}{2}}}{\sqrt{0.36+0.64\kappa_{95}^2}} \left(\frac{R+a}{R+0.8a}\right)^{N_{\text{TF}}}$$

- Simple model can be build using simple model of TF coils
  - 2-D (cylindrical approximation) of finite cross section TF coils or stick model
- Use magnetic elements to compensate for coil ripple?

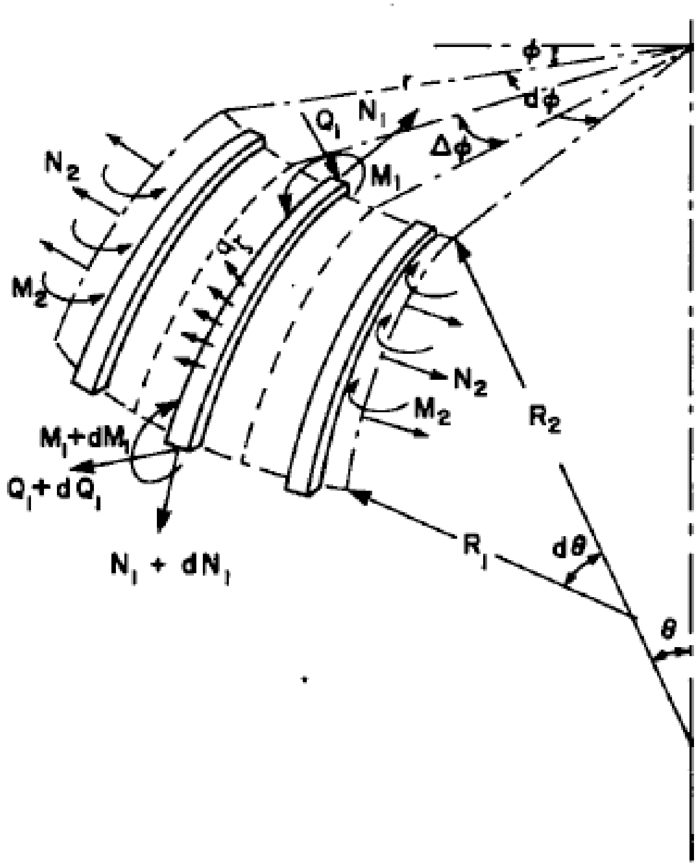
Structural approach

- Simple modeling of the coils, using minimal number of beams and shells
- Simple shell model results in relatively simple analysis of the structure
  - Coupled differential equation, capable to analyzing

Calculation of external structure

- Using simple beam theory (good for system analysis)
  - $A = B_0^2 R_0^2/2\ \mu_0$
  - $S_1 = A\ (R_2 \ln(R_2/R_1) - R_2 + R_1)/(R_1\ (R_2 - R_1))$
  - $S_2 = A\ (R_2 - R_1 - R_1 \ln(R_2/R_1))/(R_2\ (R_2 - R_1))$
  - $t_1 = S_1/\ \sigma_m$; $t_2 = S_2/\ \sigma_m$ *1.5 (as strongback)
  - $R_3 = (S_1 R_1^2 + S_2 R_2^2)/(A \ln(R_2/R_1))$
  - $a = \sqrt{3/8\ S_2 R_2\ (R_2 - R_3)/\sigma_b\ /\ R_3}$
  - R_2: outer external structure radius
  - R_1: inner external structure radius

Toroidal shell model
In-plane analysis



$$N_1 = \int_A \sigma_1 \mathrm{d}A, \qquad M_1 = \int_A \sigma_1 \zeta \mathrm{d}A,$$

$$N_2 = \int_{-h/2}^{h/2} \sigma_2 (1 + \zeta/R_1) \mathrm{d}\zeta,$$

$$M_2 = \int_{-h/2}^{h/2} \sigma_2 \zeta (1 + \zeta/R_1) \mathrm{d}\zeta,$$

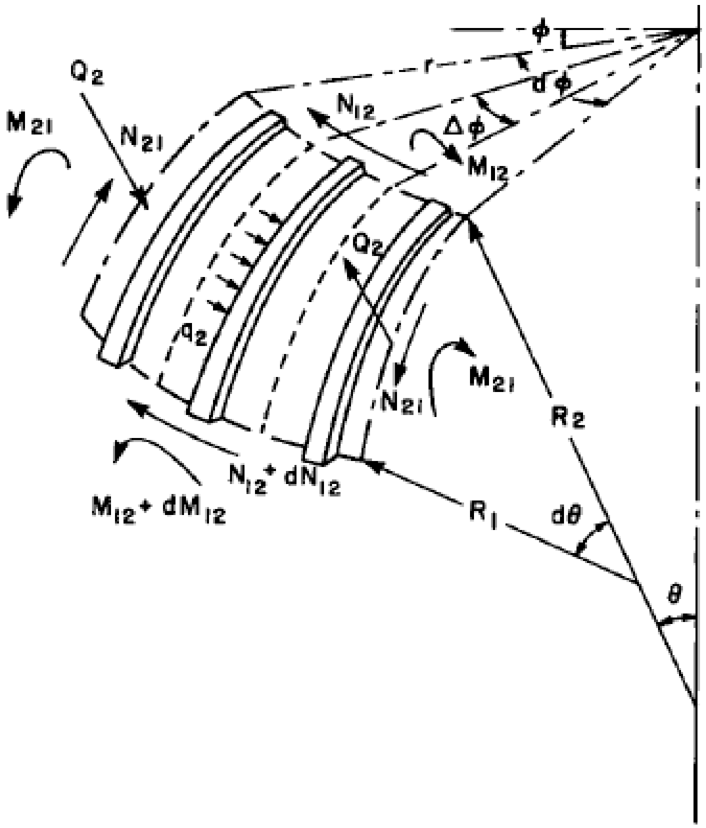
$$Q_1 = \int_A \tau_{1\zeta} \mathrm{d}A,$$

$$\frac{\mathrm{d}N_1}{\mathrm{d}\theta} - \frac{2\pi R_1}{n} \cos\theta\, N_2 + Q_1 = 0,$$

$$-rN_1 - \frac{2\pi r R_1}{n} \sin\theta\, N_2 + r\frac{\mathrm{d}Q}{\mathrm{d}\theta} = -FR_1,$$

$$-R_1 Q_1 + \frac{\mathrm{d}M_1}{\mathrm{d}\theta} - \frac{2\pi R_1}{n} \cos\theta\, M_2 = 0.$$

Toroidal shell model
Out-of-plane analysis



$$N_{12}=\int_{-h/2}^{h/2}\tau_{12}\left(1+\frac{\zeta}{R_2}\right)\mathrm{d}\zeta,$$

$$N_{21}=\int_{-h/2}^{h/2}\tau_{12}\left(1+\frac{\zeta}{R_1}\right)\mathrm{d}\zeta,$$

$$M_{12}=\int_{-h/2}^{h/2}\tau_{12}\zeta\left(1+\frac{\zeta}{R_2}\right)\mathrm{d}\zeta,$$

$$M_{21}=\int_{-h/2}^{h/2}\tau_{12}\zeta\left(1+\frac{\zeta}{R_1}\right)\mathrm{d}\zeta,$$

$$Q_2=\int_{-h/2}^{h/2}\tau_{2\zeta}\left(1+\frac{\zeta}{R_2}\right)\mathrm{d}\zeta \quad (\tau_{2\zeta}=0 \text{ at } \zeta=\pm h/2)$$

$$r\frac{\mathrm{d}N_{12}}{\mathrm{d}\theta}+R_1\sin\theta\,(N_{12}+N_{21})+R_1\sin\theta\,Q_2 = -\frac{R_1 n}{2\pi}q_2,$$

$$r\frac{\mathrm{d}M_{12}}{\mathrm{d}\theta}+R_1\sin\theta\,(M_{12}+M_{21})-rR_1Q_2=0,$$

$$N_{12}-N_{21}+\frac{M_{12}}{R_1}-\frac{\sin\theta\,M_{21}}{r}=0.$$

Toroidal shell model
In-plane results

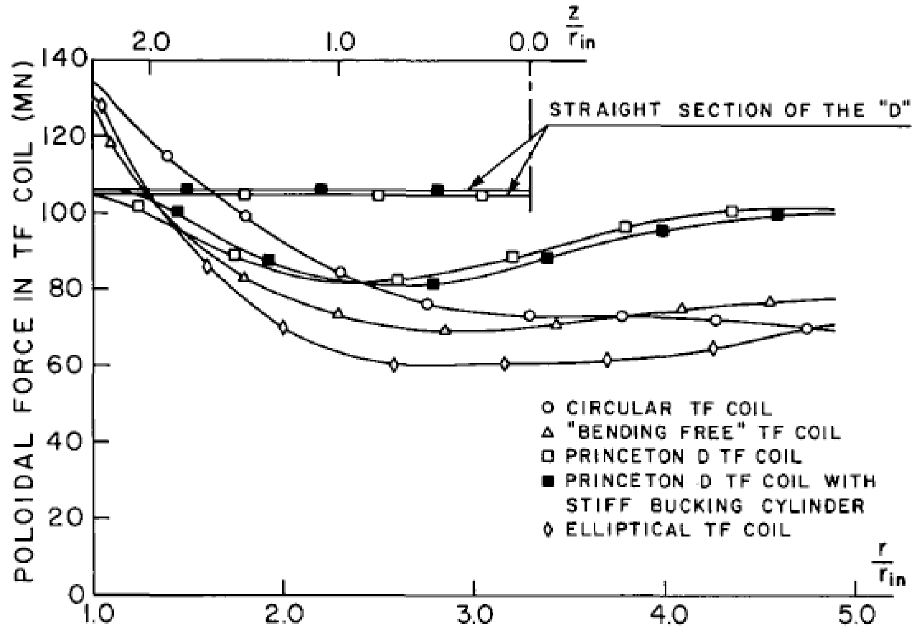
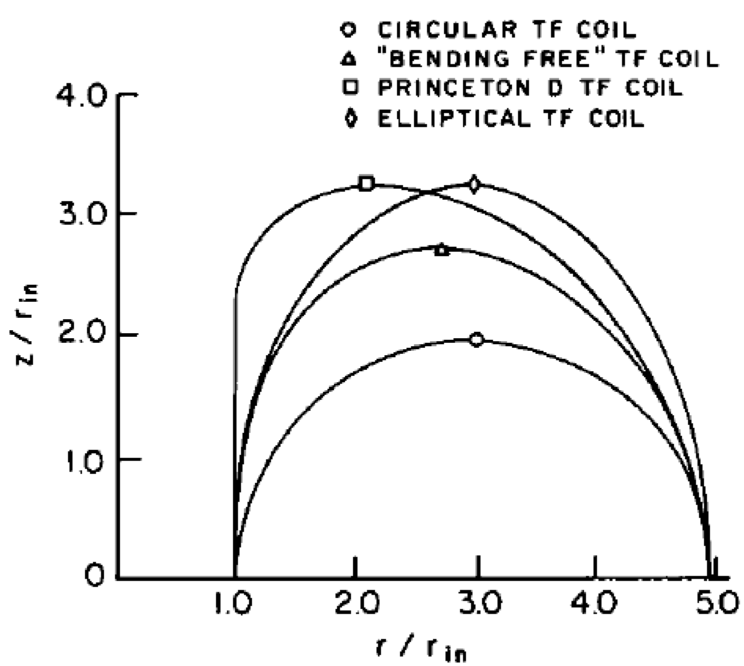


Fig. 4. Poloidal force in the structure of various TF coil configurations.



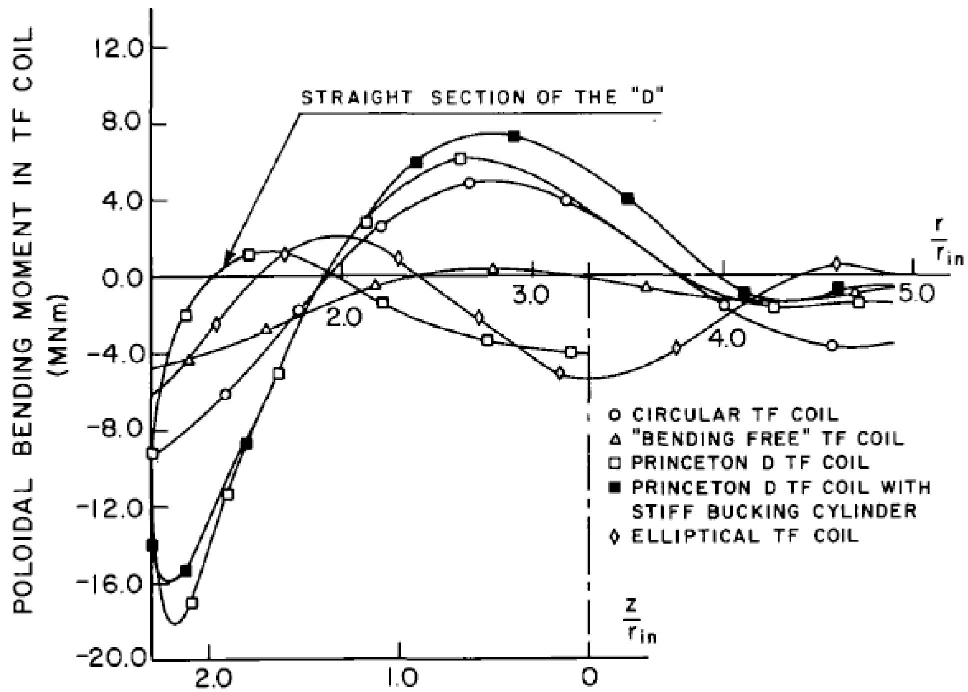
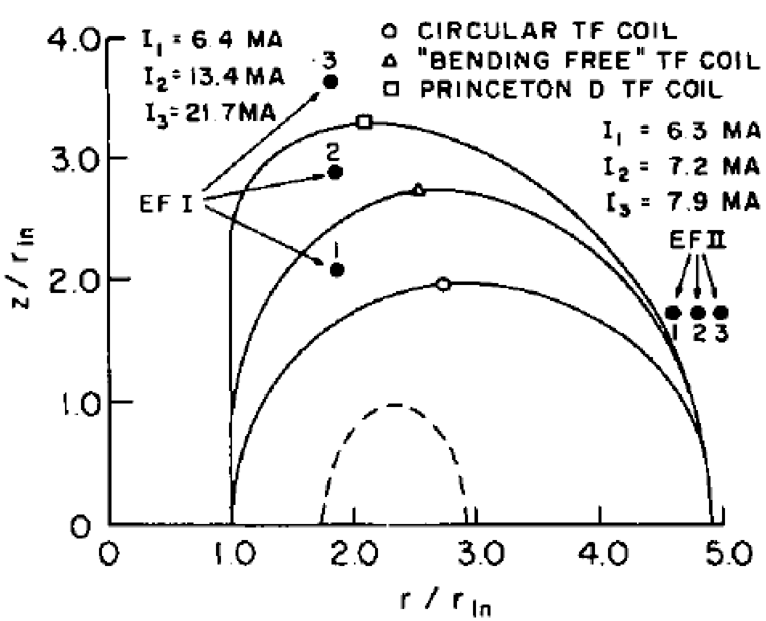


Fig. 5. Poloidal bending moment in the structure of various TF coil configurations.

Toroidal shell model
Out-of-plane results



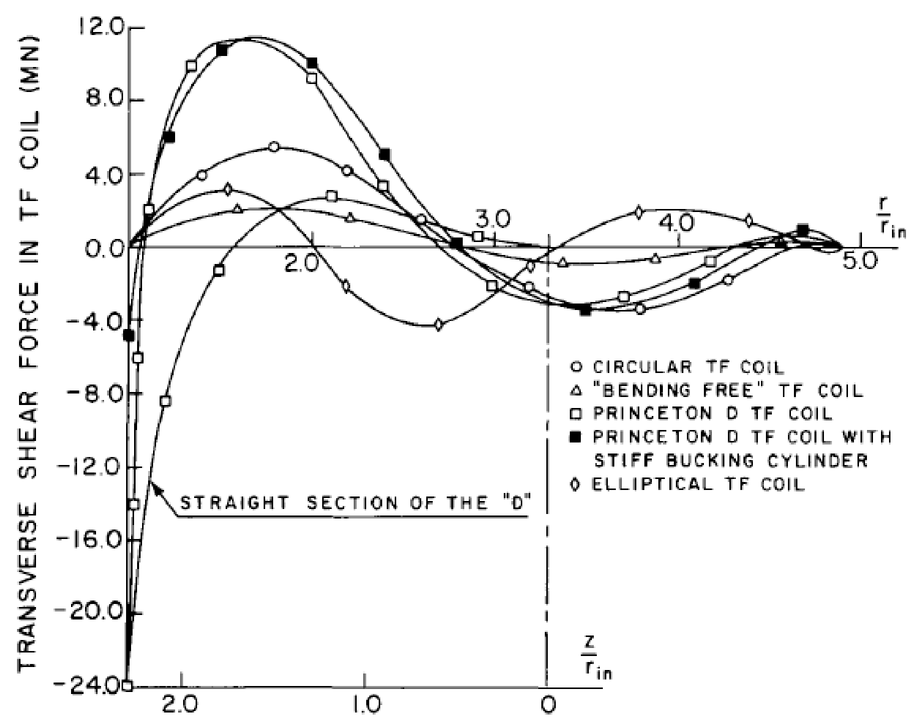
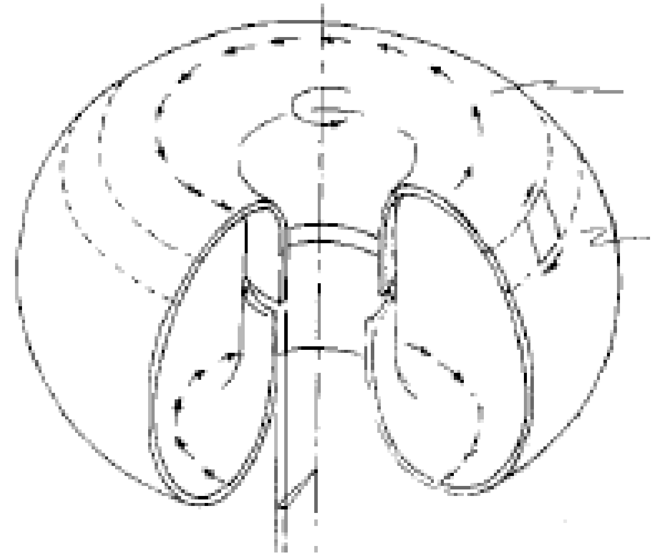
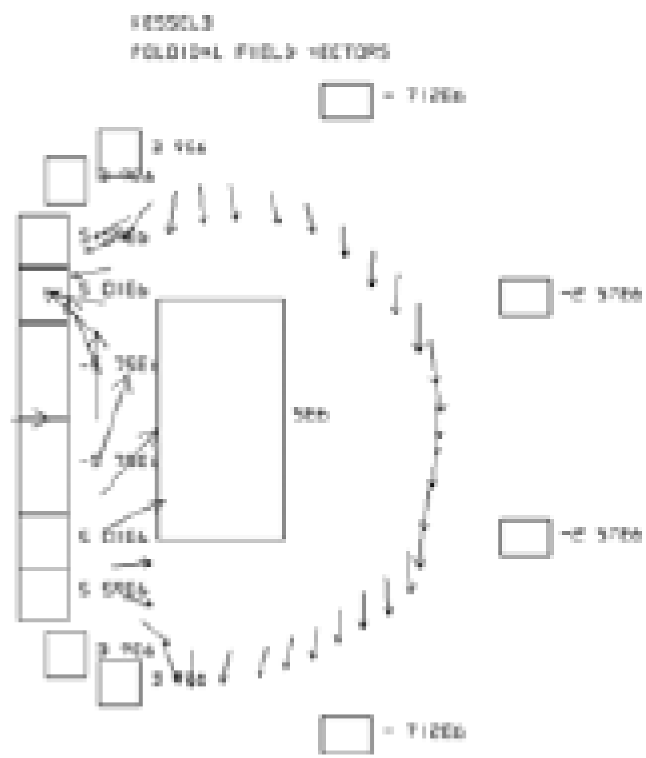


Fig. 6. Transverse shear force in the structure of various TF coil configurations.

Out-of-plane structural model suitable for system codes

- A simplified method for calculating OOP shear stresses and their distributions, suitable for systems codes





OOP simple model

- The TF coil system and structure is modeled as a toroidal shell.
- OOP Lorentz forces are computed by crossing the TF current with the poloidal field calculated at the shell using axisymmetric current loops
- The torsional stiffness of segments of the TF shell is computed, adjusting shear modulus and thickness to simulate the stiffnesses of the tokamak.
- The torsional moment is computed from the force distribution.
- Shear deformations are computed, around the coil shell, from an assumed starting point. There is an incompatibility where the loop should close.
- The total shell stiffness is computed, and the additional moment, to force closure /compatibility of the shell, is superimposed on the torsional moment distribution previously calculated.
- The shear stress can then be computed from the torsional shear.

Summary

- Potential to produce sophisticated system code for investigation tradeoffs
- Need to analyze a large number of magnet configurations
- Team needs to determine how detailed the models need to be…
- A good starting point would be the use of Supercode (???)