ARIES-Stellerator studies
Magnet issues

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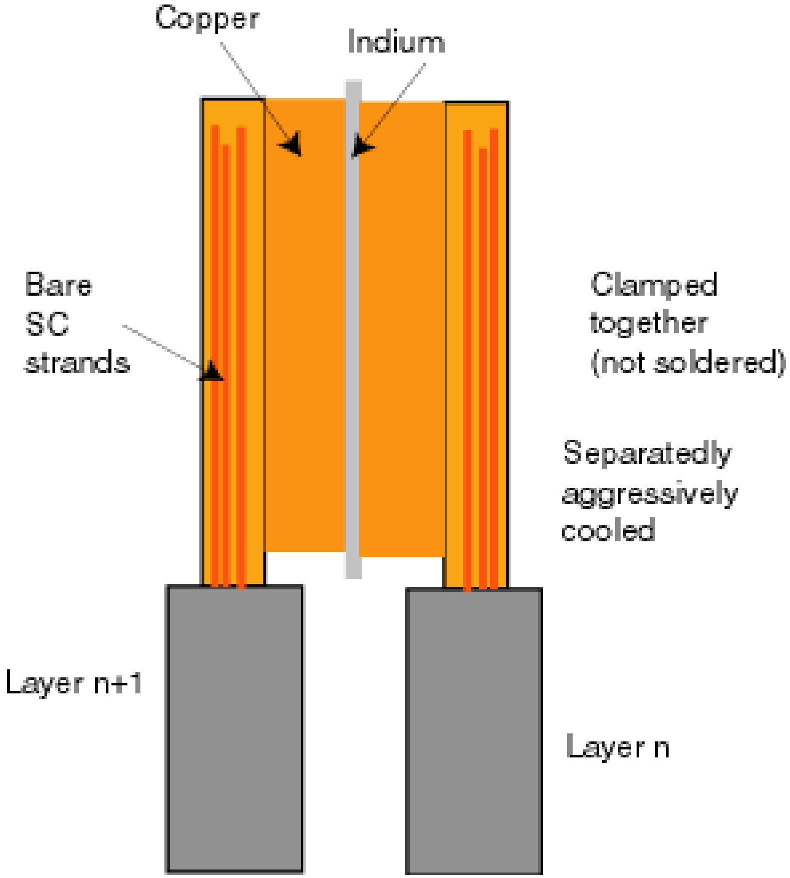
Topics

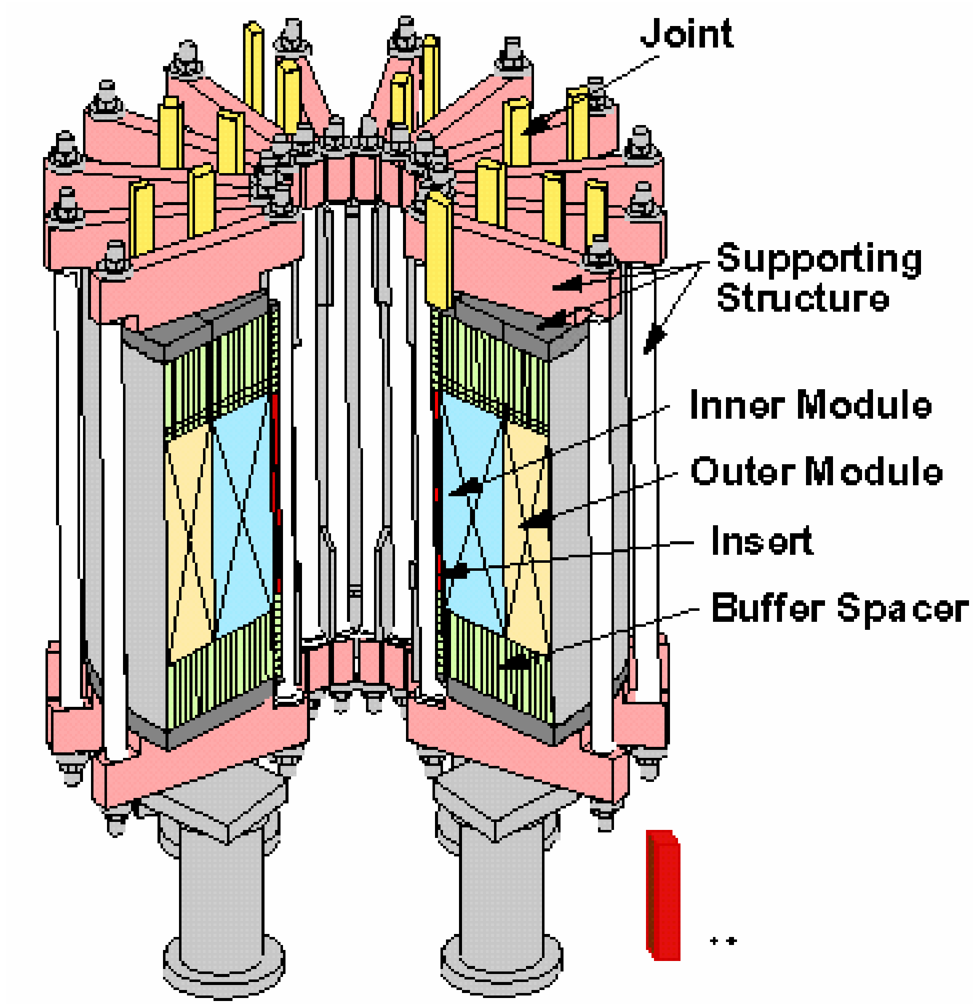
- Design criteria for LTS for system code
  - Minimum bending radius
  - Current density
- Maintenance
  - Demountable magnets?
    - Evaluation of joints
    - Evaluation of cryogenic system
    - Evaluation of external structure
- Most of the discussion relevant to LTS

SC Joints?

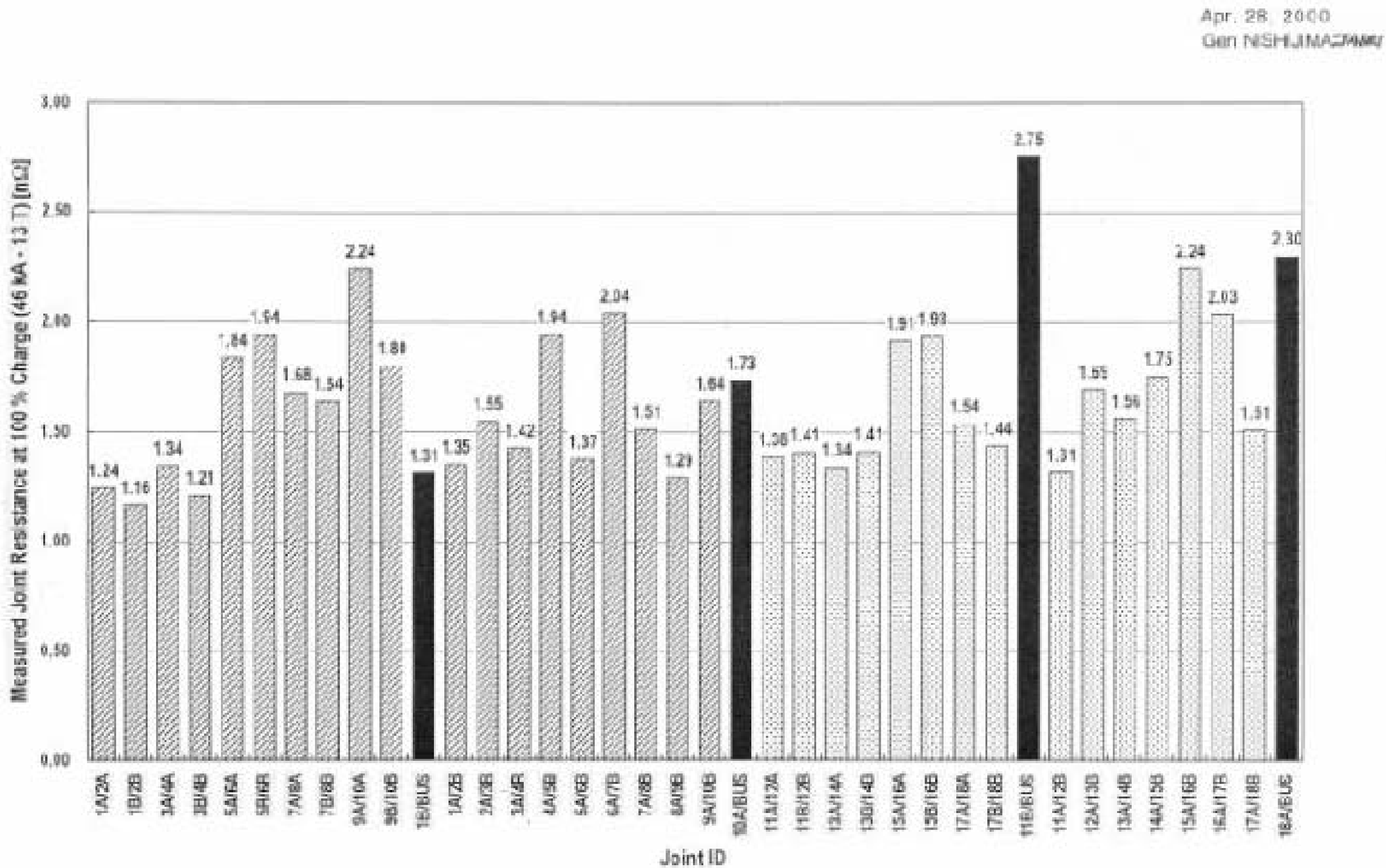
- Most large SC coils have joints
- Conductor can not be obtained in large enough lengths.
- Illustration:
  - ITER CS model coil
    - 37 joints
    - 46 kA
    - 4 W/joint, corresponding to ~ 1 nΩ (nOhm)
    - Joint resistance ~ 2 micro-Ohm/mm^2
      - Cross sectional area of joint determined by space/dissipation (joints are normal!)



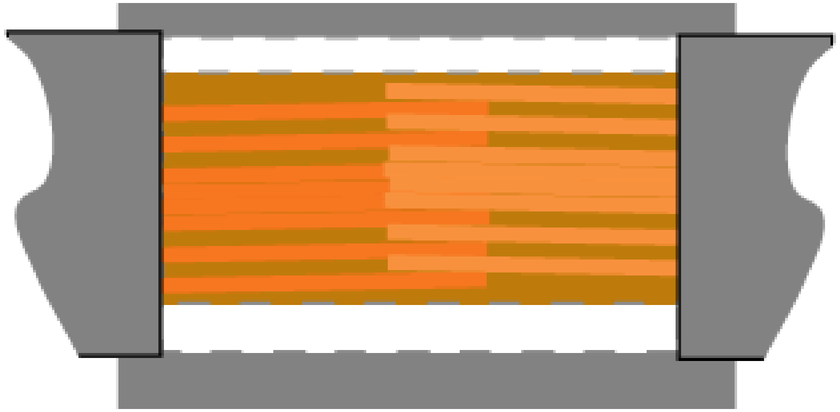
Schematic of joint



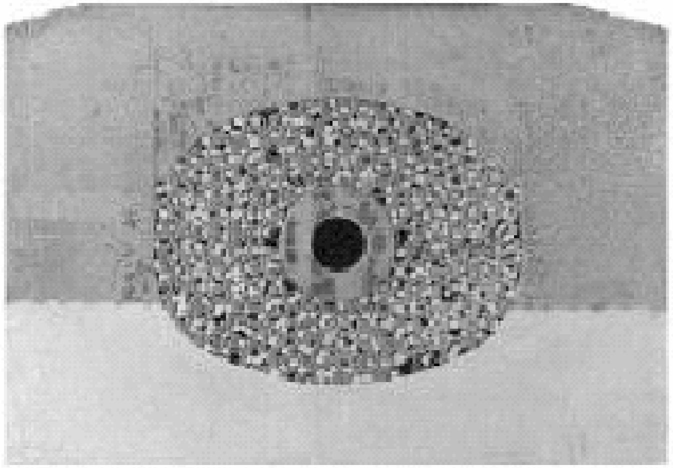
Resistance of Both Lap and Butt Joints Were Within Design Range



ITER TF model coil joint (not “very” demountable)



TF model coil joint



- Twin terminals at both conductor ends, soldered together
- joint cooled in series with the conductor,
- Avids handling of the brittle Nb3Sn cable

TF model coil joints

Sample Joint resistance (n Ohm)	2T	7 T
SS-FSJS	0.84	1.34
TFMC-FSJS	1.96	2.51
TF-FSJS	1.28	1.87

Point calculation of joints stellerator coil systems

QA2

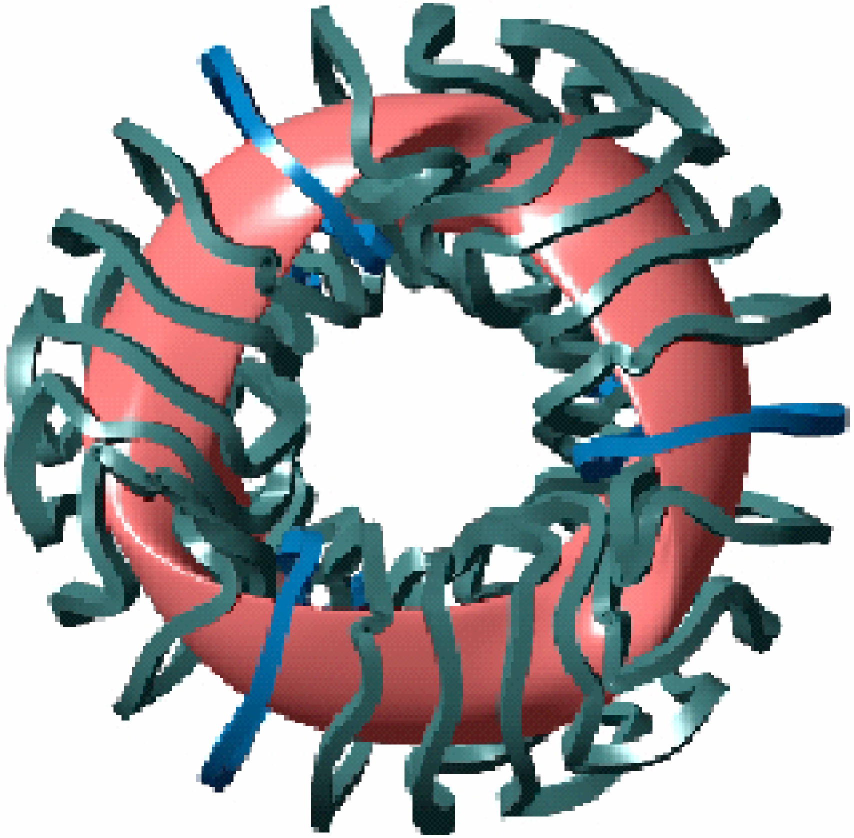
R	m	10
B-sxis	T	5.6
A	R/ap	4.4
a	a	2.27
plasma-coil	m	1.5
Bmax	T	8.99
Single turn current	KA	280000
Pack current	KA	50
coil turns	TURNS	5600
joints/coil	JOINTS	2
total number of joins		11200
Power per joint	W	2.5
Total refrigeration power	W	28000

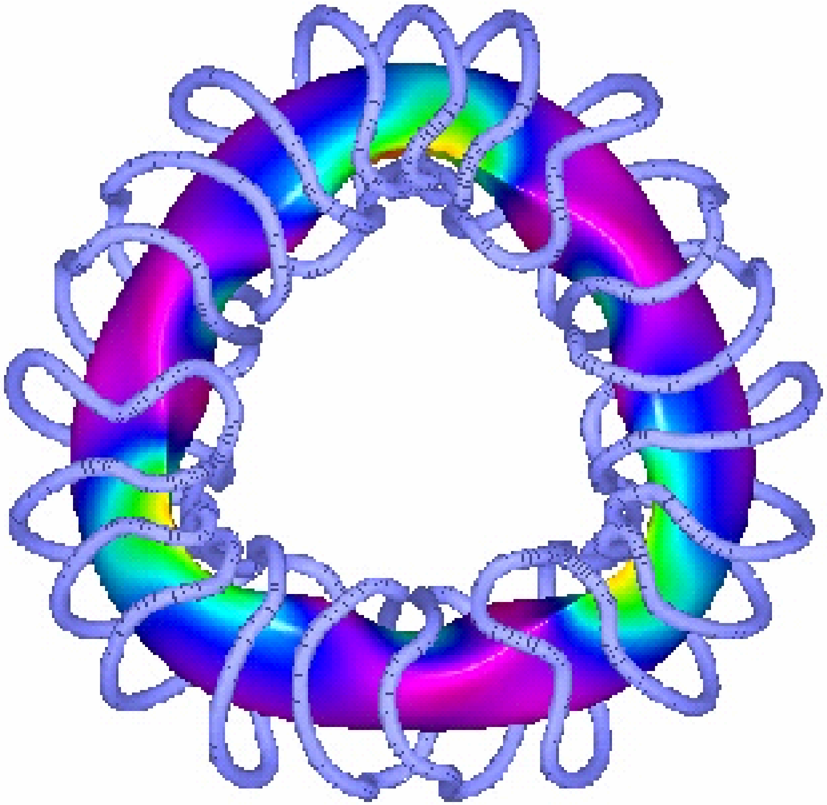
Demountable coil
Evaluation of joint implications

- Although large refrigeration, the first view results in a refrigeration power that is one order of magnitude too high
- Options:
  - Increased cross section area of joints
  - Decreased number of joints

  - Do you need joints in all coils?

Reactors Based on NCSX & QPS





NCSX variant

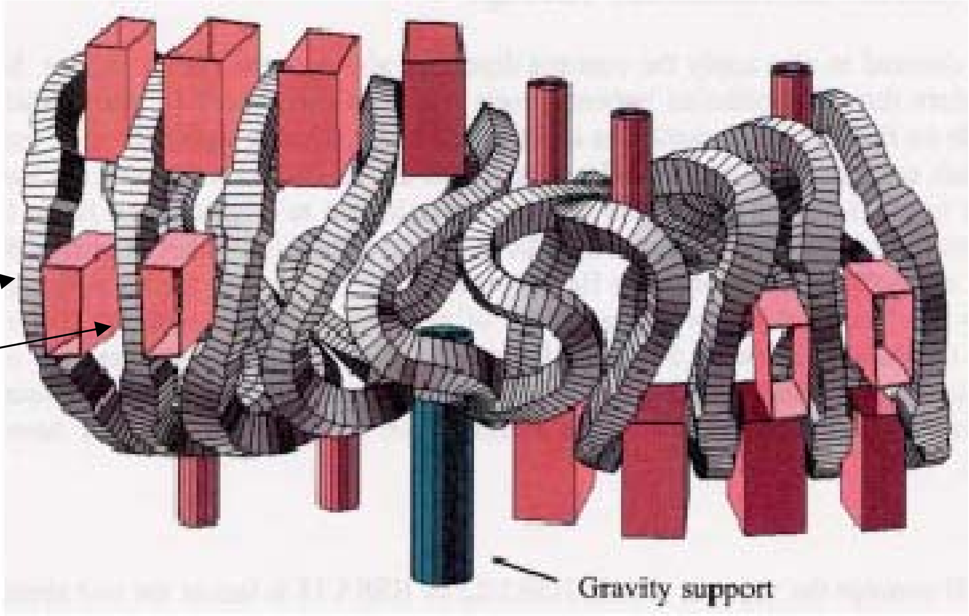
Quasi-Axisymmetric

QPS variant

Quasi-Poloidal

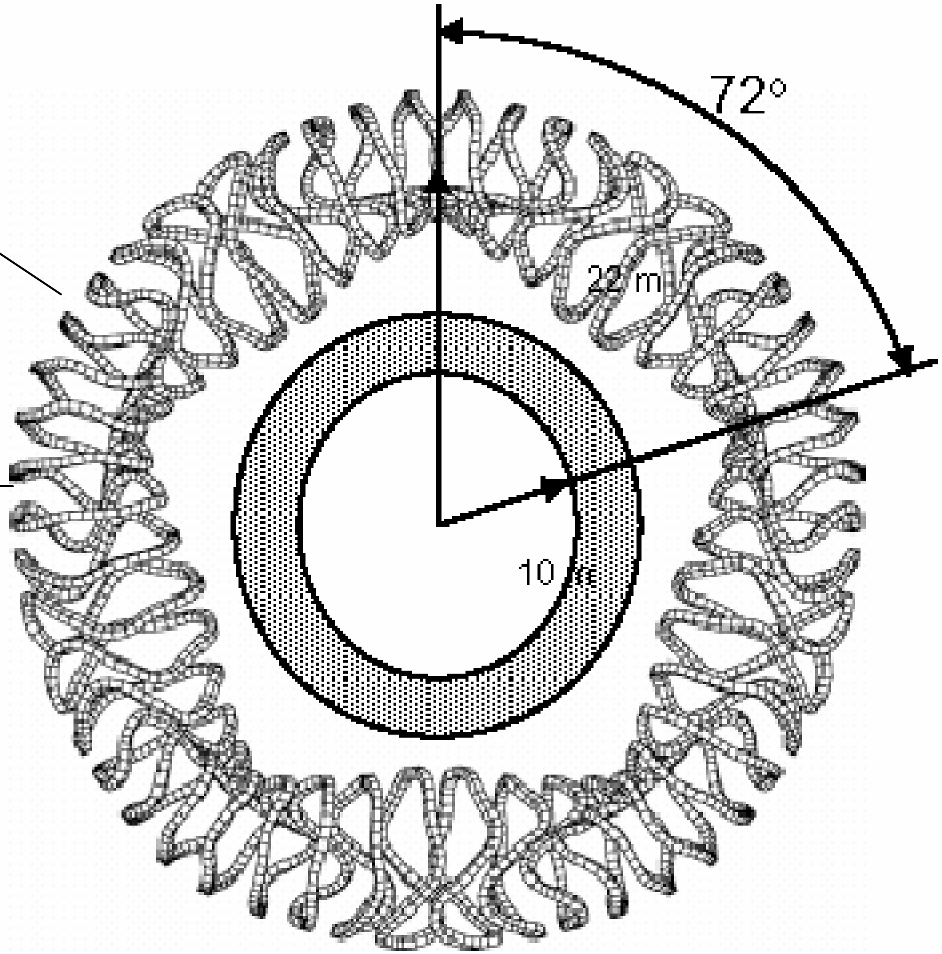
HSR5/22

Relatively straight coils with widest gap between coils

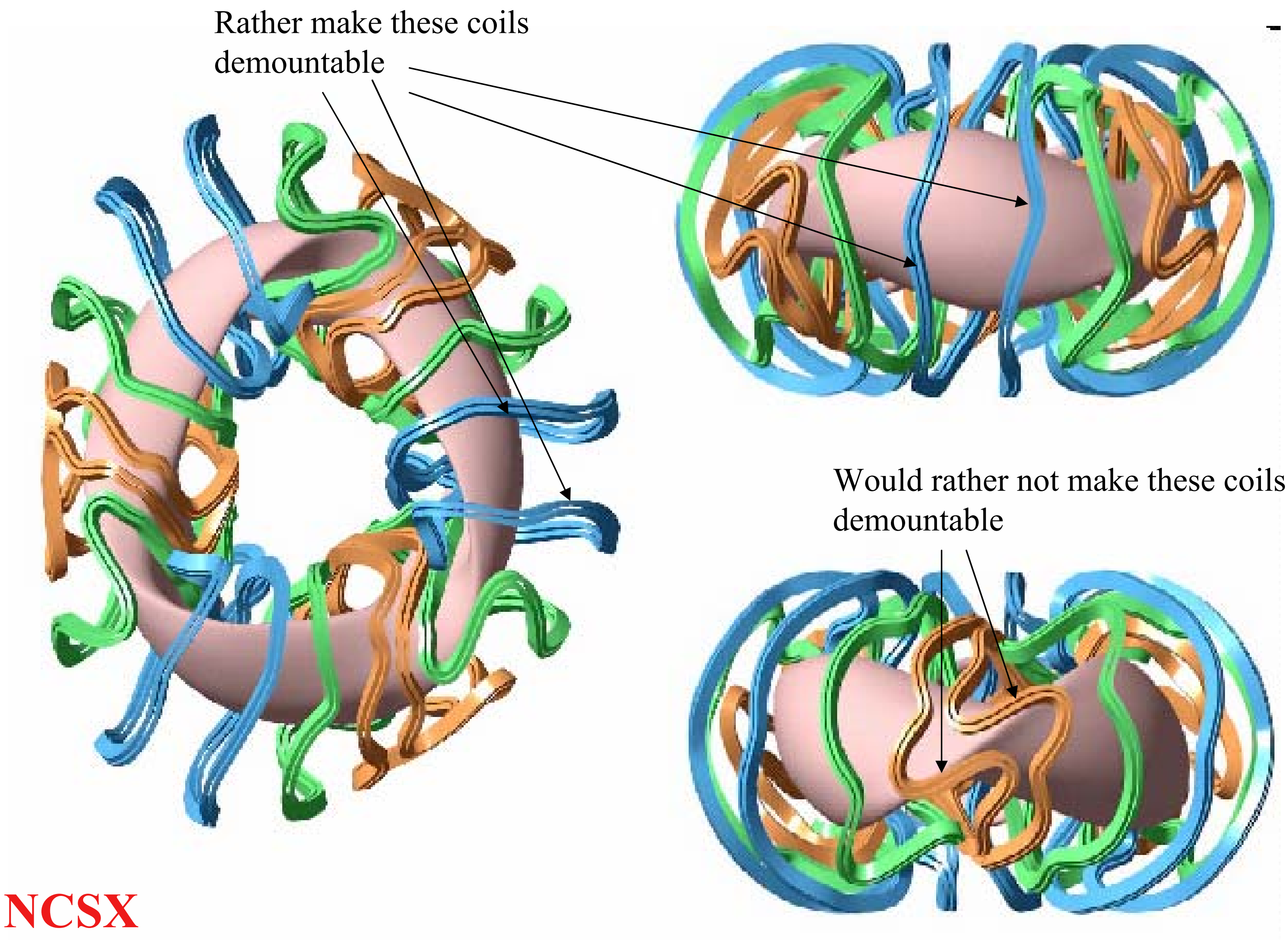


One field period of the coil system with ports

Relatively straight coils



Do all need to be removed?

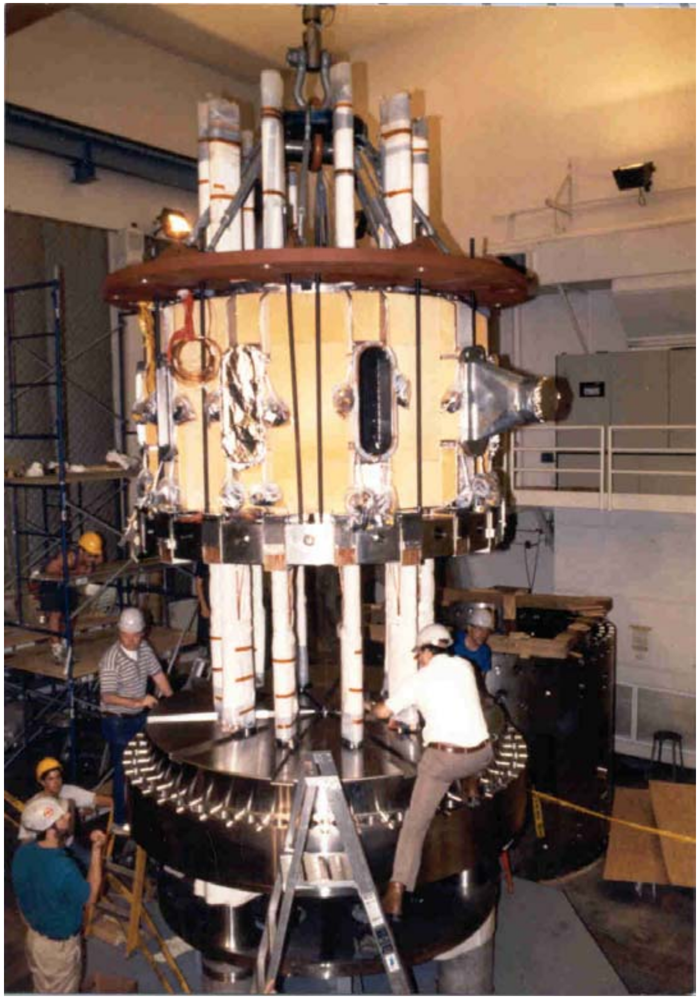

Rather make these coils
demountable
Would rather not make these coils
demountable
NCSX

Joint location

- If joints:
  - Top/outboard side
    - More real estate
      - for large cross section required for joints
      - For structure required to immobilize the joints
    - Lower fields (at least, TF fields)
- If large number of joints are used, it may be possible to use less expensive conductor
  - NbTi in the outboard side, Nb_3Sn in the inboard side??

Demountable magnets
Structural issues

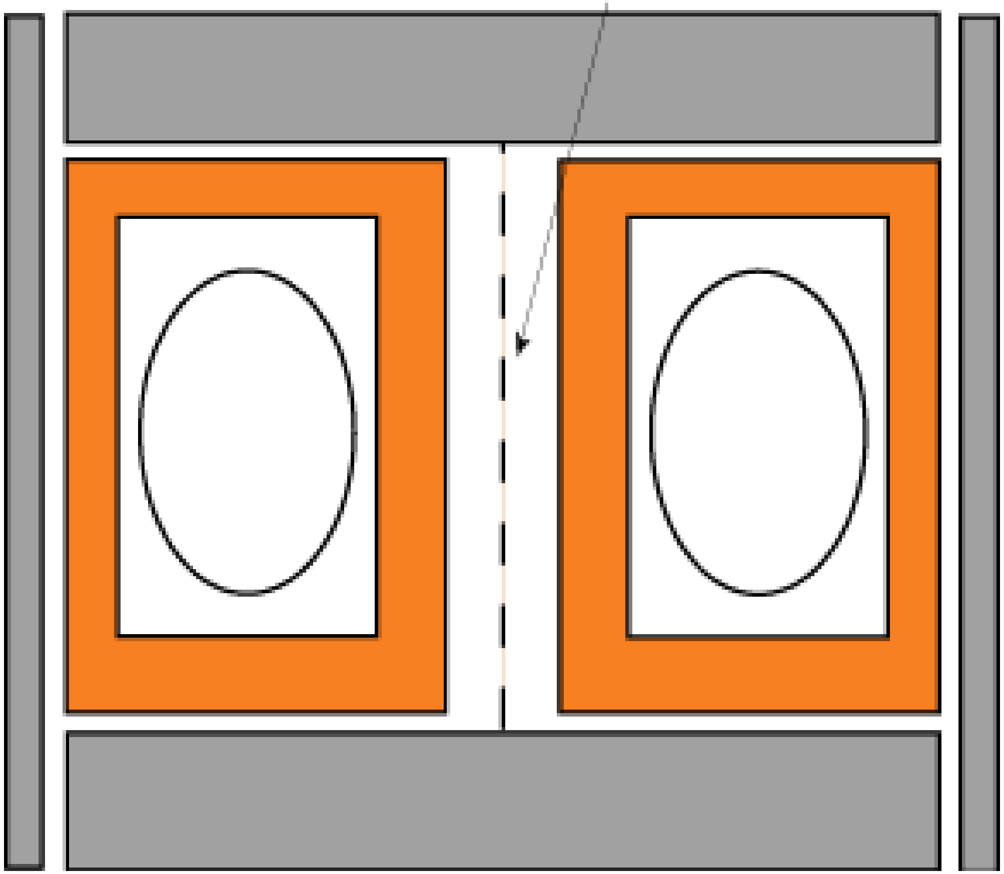
- Demountable magnets lower the mechanical efficiency of the structure
  - holes/structures for load transfer between segments
  - The region of the joint is also less efficient structurally




EAST

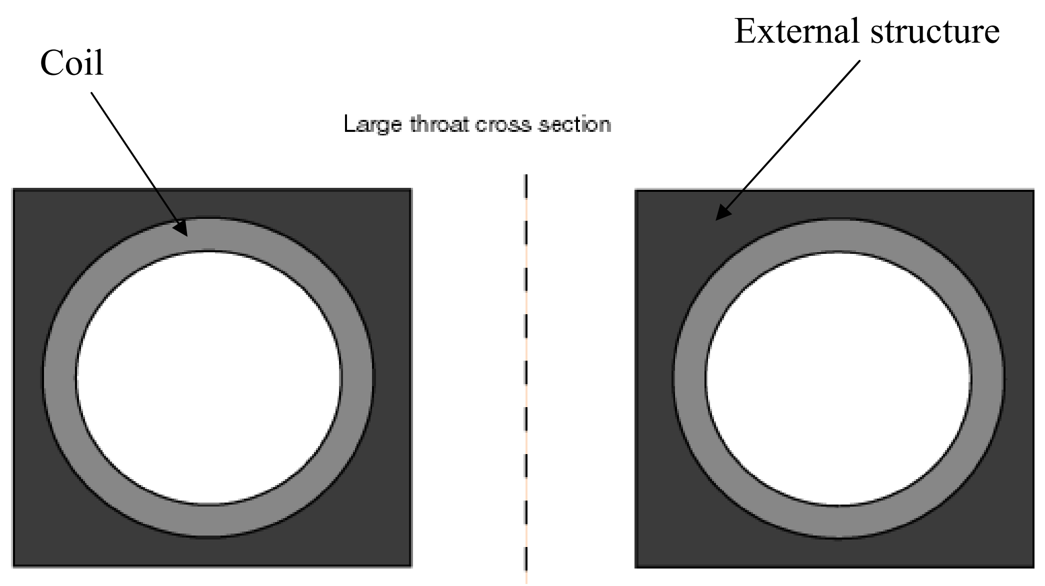
C-MOD support

- In C-Mod, throat too small for supporting bolt
  - "beam" length very long, requiring very thick plate for support



Stellerator

- For devices with higher aspect ratio, structural elements can exist through throat
- Much reduced scale of “beam” means much reduced thickness of horizontal plates



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 800 MPa (for SS-316)
    - SS-316: (1400 MPa yield, 1800 MPa ultimate)

External support

- Cross sectional material required:
  - Top/bottom determined by bending
  - Inner/outer determined by principal stress

Calculation of external structure

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

- QA 2
- Uniform thickness top/bottom plates
- “educated” guesses to some dimensions and stresses

Bo	T	5.6
Ro	m	10
ASPECT		4.4
INBOARD	m	1.5
OUTBOARD	m	2.5
Rout		6.23
Rin		14.77
A		2.50E+09
S1		1.98E+08
S2		6.26E+07
sigma m	Pa	6.00E+08
sigma b		9.00E+08
tin	m	3.30E-01
tout	m	1.04E-01
half thickness	m	0.87
Volume:		
top/bottom	m^3	1966
outside	m^3	55
inside	m^3	110

External structure optimization

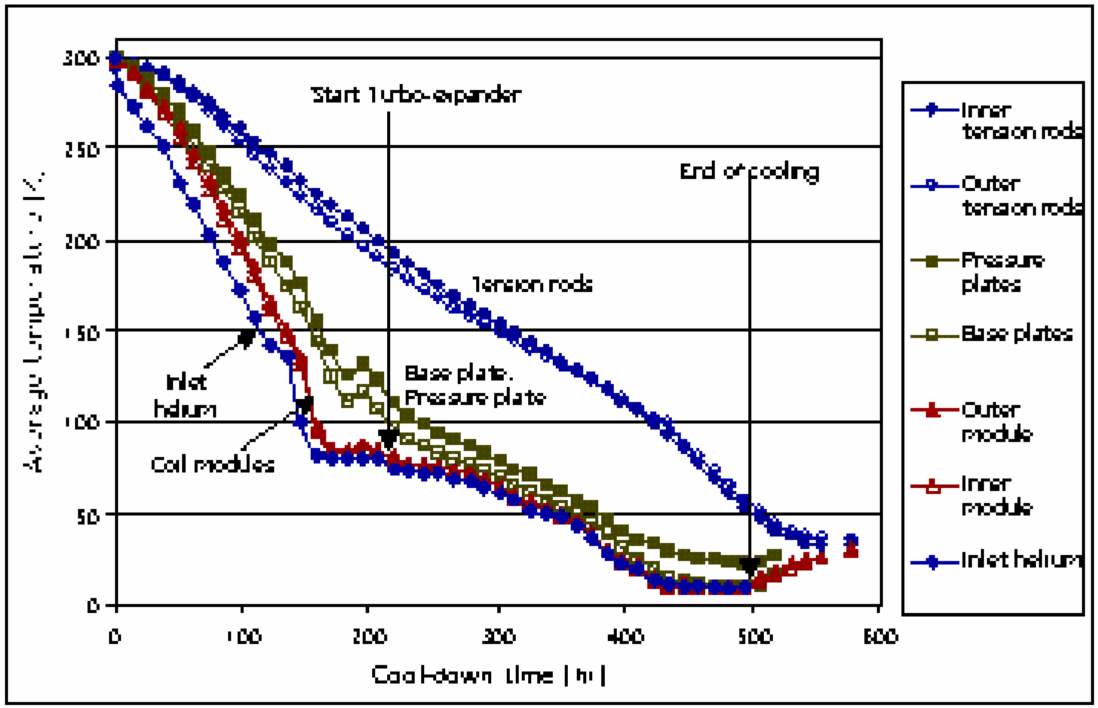
- It is possible to minimize the mass of the external structure
  - Trade off thickness vs coverage
    - Thicker structure but not covering all poloidal planes (discrete structure)
    - Plates do not have to be constant thickness
- Possible to decrease mass of external structure by factor of 2-3

Cryogenic considerations for demountable coils

- Prior to demounting the coils, it is necessary to warm up the coil and structure.
- Similarly, after reassembling coil, it is necessary to cool down

- How long does it take to cool down/warm up? (Thermal effects, not joint disassembly/ assembly)

Cooling down times



ITER CS model coil cool down

Cooling down time constrain

- Thermal stresses in magnet
  - Temperature differential conservatively set to 50 K
- Refrigerator power
  - At liquid He temperature, refrigeration "efficiency" is about 1/300 (300 We/1 W@ 4K)
  - Refrigerators on the order of 5-10 kW
- Cooling down time constant ~ 0.5 K/hr
  - At the higher temperatures, refrigerator "efficiency" is higher, but materials have greater heat capacity.
  - Cooling down time (heating up) ~ 600 hrs (2-3 weeks)

Refrigerator power required

- Rate of temperature: 0.5 K/hr
- Energy ~ 100 GJ
- Volume ~ 300 m^3
- Cold mass ~ 2500 ton
- Power for reducing temperature (not accounting for heating losses)
    - ~ 250 kWe @ RT
    - ~ 500 kWe @ 77 K
    - ~ 400 kWe @ 20 K
- Most designs/studies use a refrigerator that can remove 5 kW at 4K
- If only part of the system is disassembled, additional cooling available
    - Need to improve thermal time constants, though.

Magnet design criteria systems code

- Previously, design criteria has been provided for HTS
  - Arbitrarily small bending radius (determined by current density, which is high if YBCO thick films are used)
  - Using epitaxial techniques, bending strain is not relevant

Low Tc Superconductor Winding pack design criteria

- Winding pack design criteria:
  - Use 0.7 $J_{\text{current sharing}}$
  - Use 3:1 copper to superconductor (some laced)
  - Use 50% packing factor (determined by pushing strands through sheath, requirement for cooling (CICC)
  - Assume that conductor is 50% of cross section (rest is conductor sheath and insulation)
  - Loads transferred to structure outside winding pack
  - Average winding pack current densities as high as 30 MA/m^2 are possible (for comparison, NCSX has 14 MA/m^2)

Structure

- In stellerators studies the structure, to first order, does not affect size of system, but it impacts cost
- To accurately calculate required structure, sophisticated stress analysis is required
- Simple method:
  - Estimate stored energy in magnets
  - Use “virial stress” of, say, 300 MPa
  - Calculate volume of structure using ratio of energy to virial stress
  - Double for out-of-plane loads
  - Not applicable for demountable!
    - Use algorithm described above.

Bending radius

- If NbTi is used, make sure that conductor can wrap around itself:
  - Use filament conductors (is this what the system code uses?)
  - Determine the cross section of the winding pack from average current density in winding pack (as indicated in a previous vuegraph)
  - Allow for a bending radius that is a number times the winding pack characteristic dimension
    - How about 3x?
- If thick Nb_3Sn is used, determined by strain:
  - $t/R_{c,min} < .02$ (with margin of safety for other strains, such as cooldown) (t: conductor width, $R_{c,min}$ radius of curvature of innermost turn in bend)

Summary

- Demountable coils investigated
  - Joints described
  - Cryogenic system evaluated
  - Demountable coils can not be discarded on cursory look
    - Lots of joints if all coils are demountable
    - One order of magnitude too high thermal load
    - How about limited demountable coils?
- Design criteria for system code using LTS
  - Applicable for investigation of demountable coils