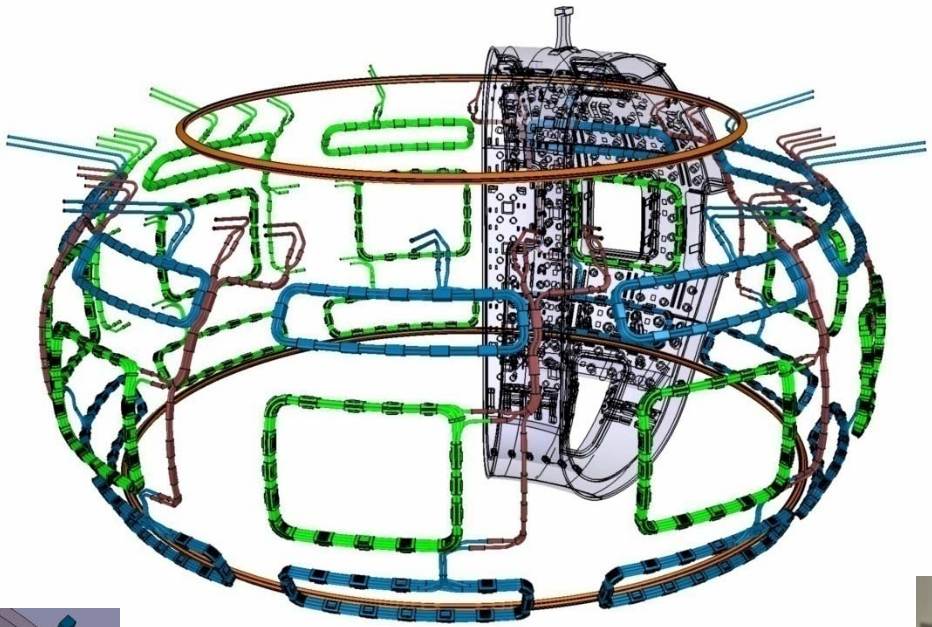
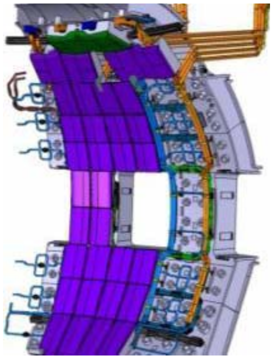
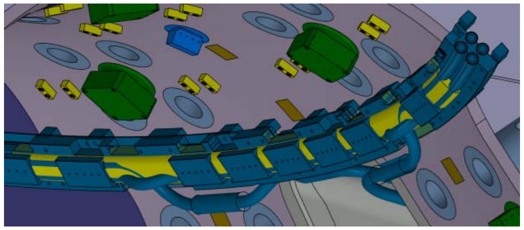
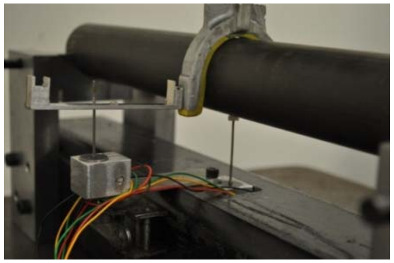








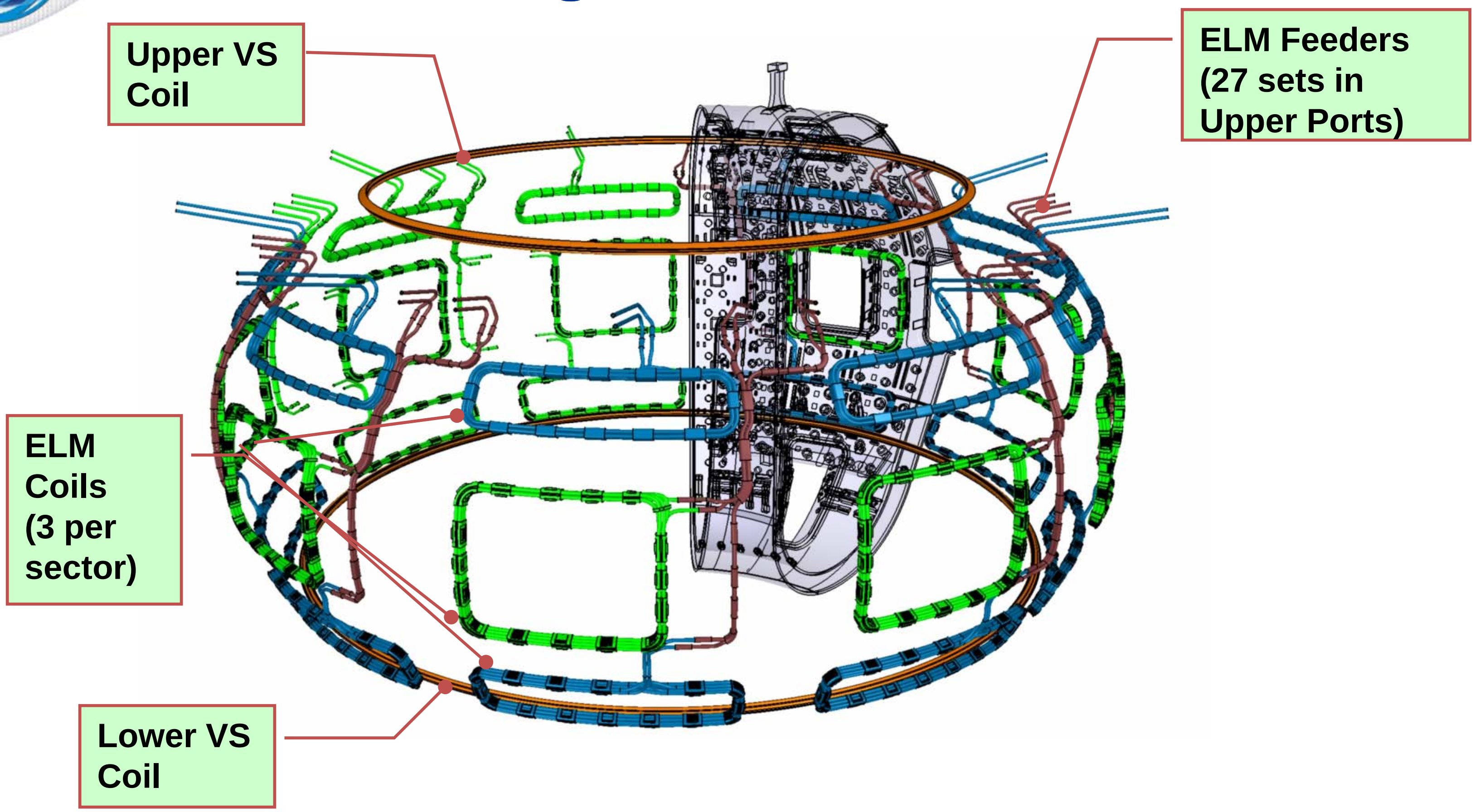
ITER In Vessel Coils Design and R&D

Presented by Mike Kalish for the IVC Team

Outline

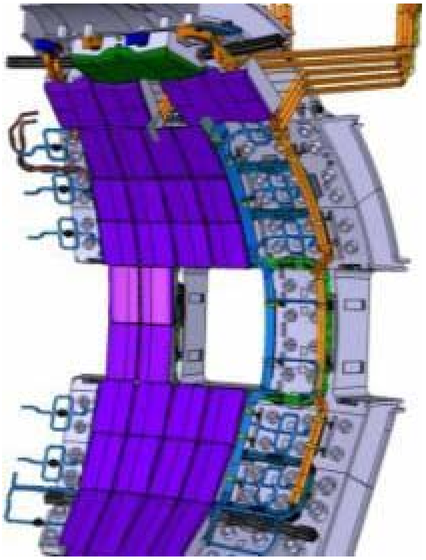
- Design
  - Design Overview
  - SSMIC Development
  - Elm Coils
  - VS Coils
  - Joints
- Analysis
  - Thermal Analysis
  - Electromagnetic Opera Analysis
  - Mechanical Stress Analysis
- Testing
  - Mechanical
  - Electrical
- Summary

Design Overview

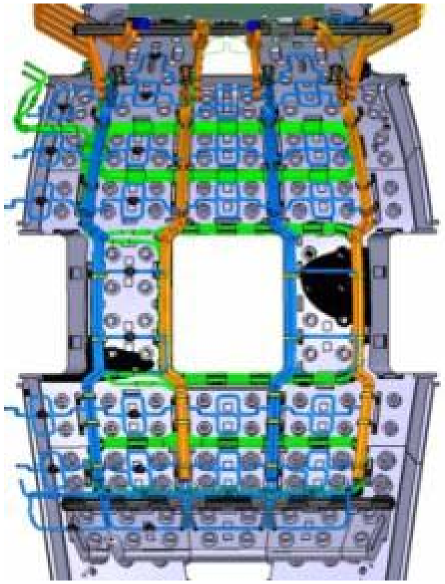


27 ELM (Edge Localized Mode) **2 VS (Vertical Stability)**

In-Vessel Coil Arrangements

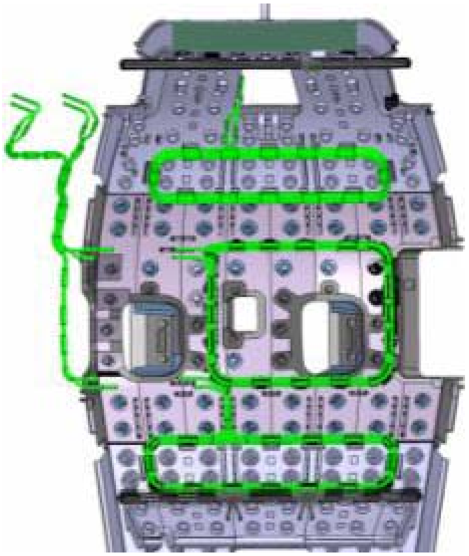


Coils, Manifolds & Blanket



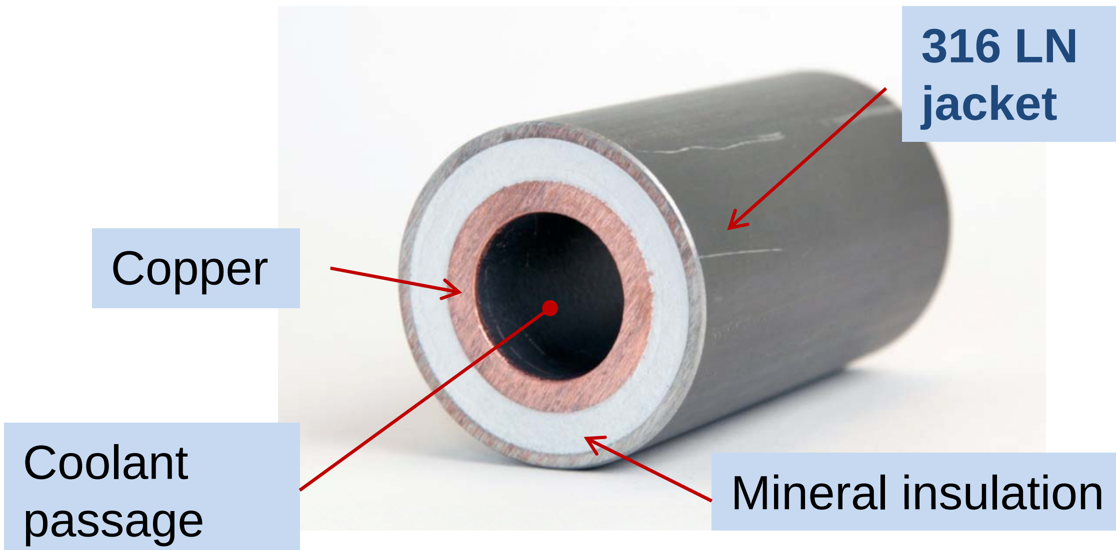
Coils & Manifolds

VS & ELM Coils



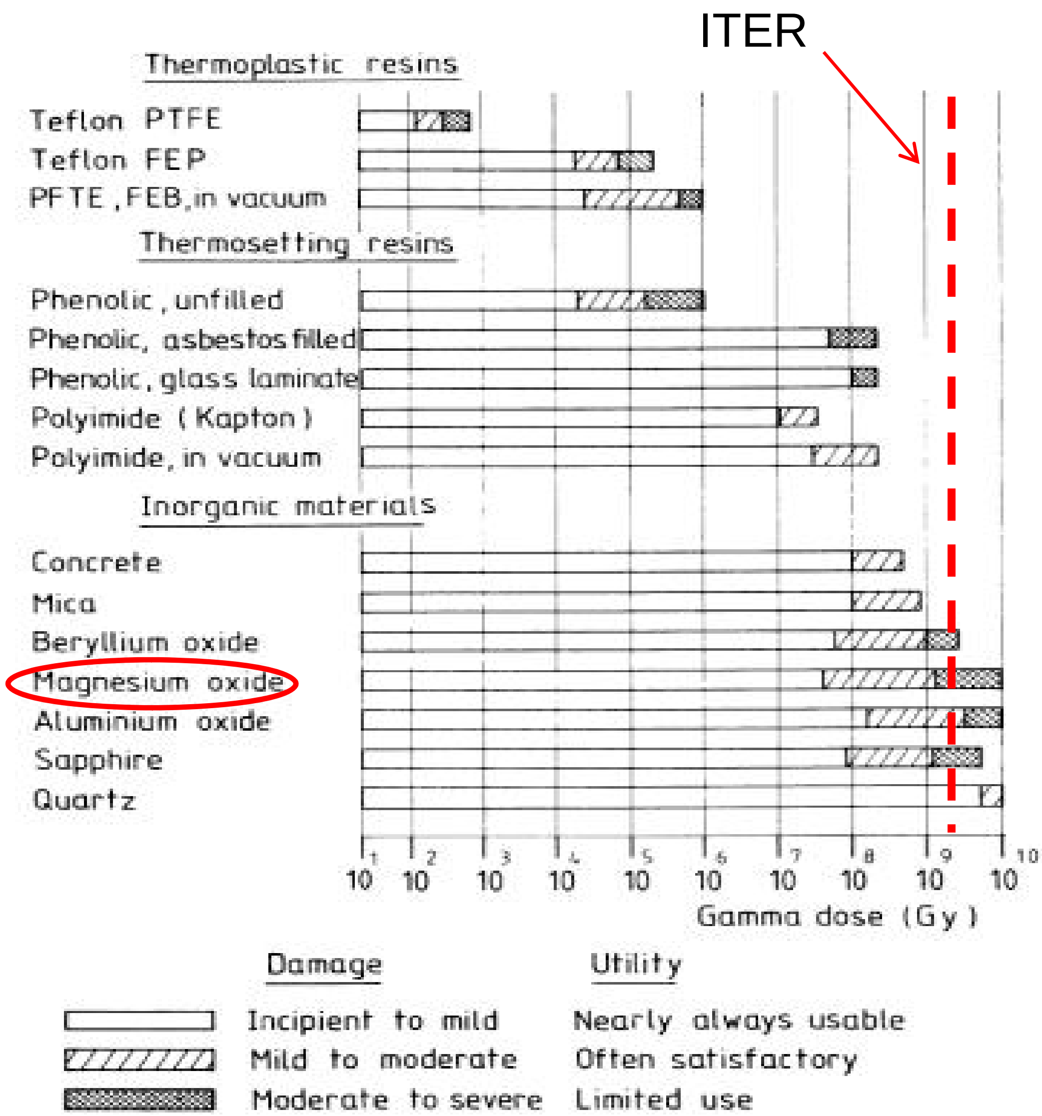
NB sector

SSMIC Conductor Development
(Stainless Steel Mineral Insulated Conductor)



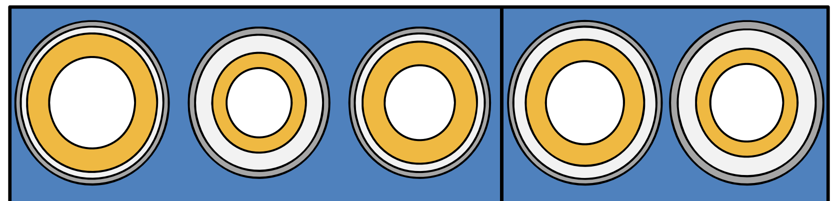
Choice of Magnesium Oxide as Insulation

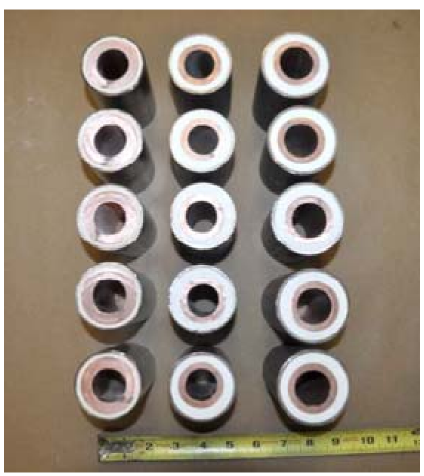
- •Radiation Resistance Required = 3x10^9 Gy
- •High Temperature, Operation = 250C
- •Common Fiberglass Epoxy or Ceramic Polymer systems could not meet these requirements



SSMIC Development
Conductor Prototype Production

- Proof-of-principle production of MIC w/ full-size cross-section
  - ➢2 vendors – TYCO and ASIPP
  - ➢3 conductor sizes
    TYCO (2) and ASIPP (1)

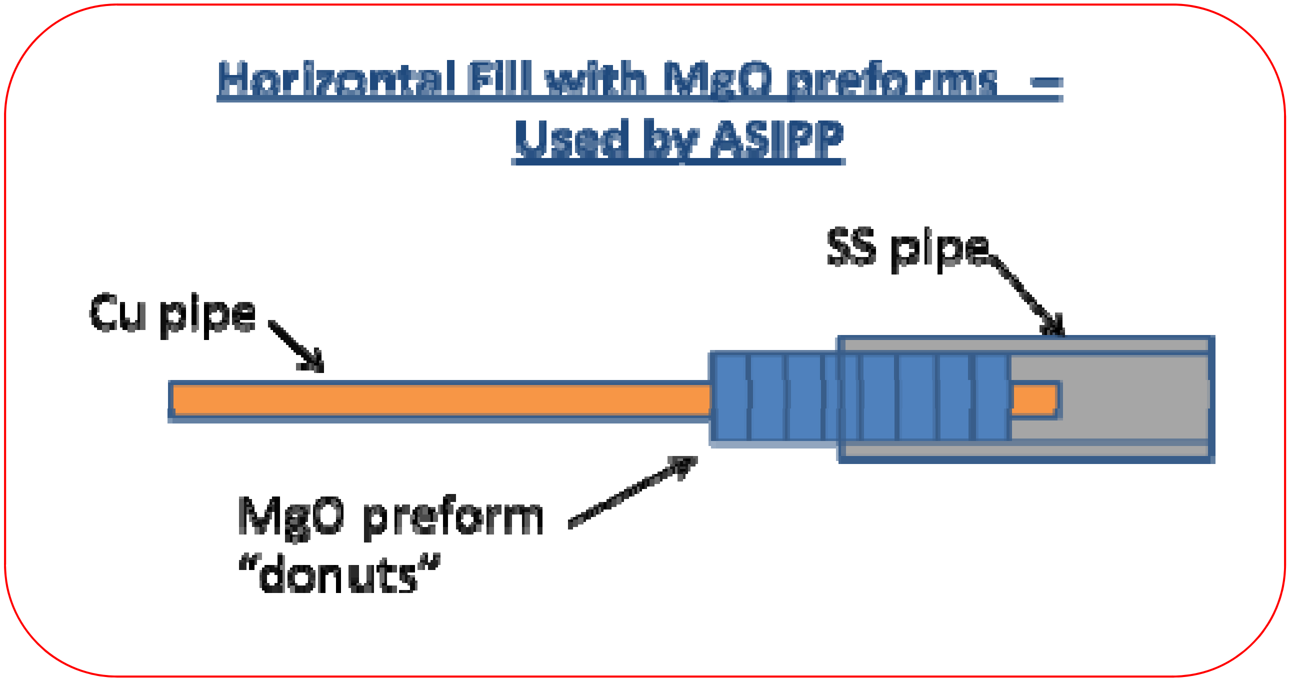




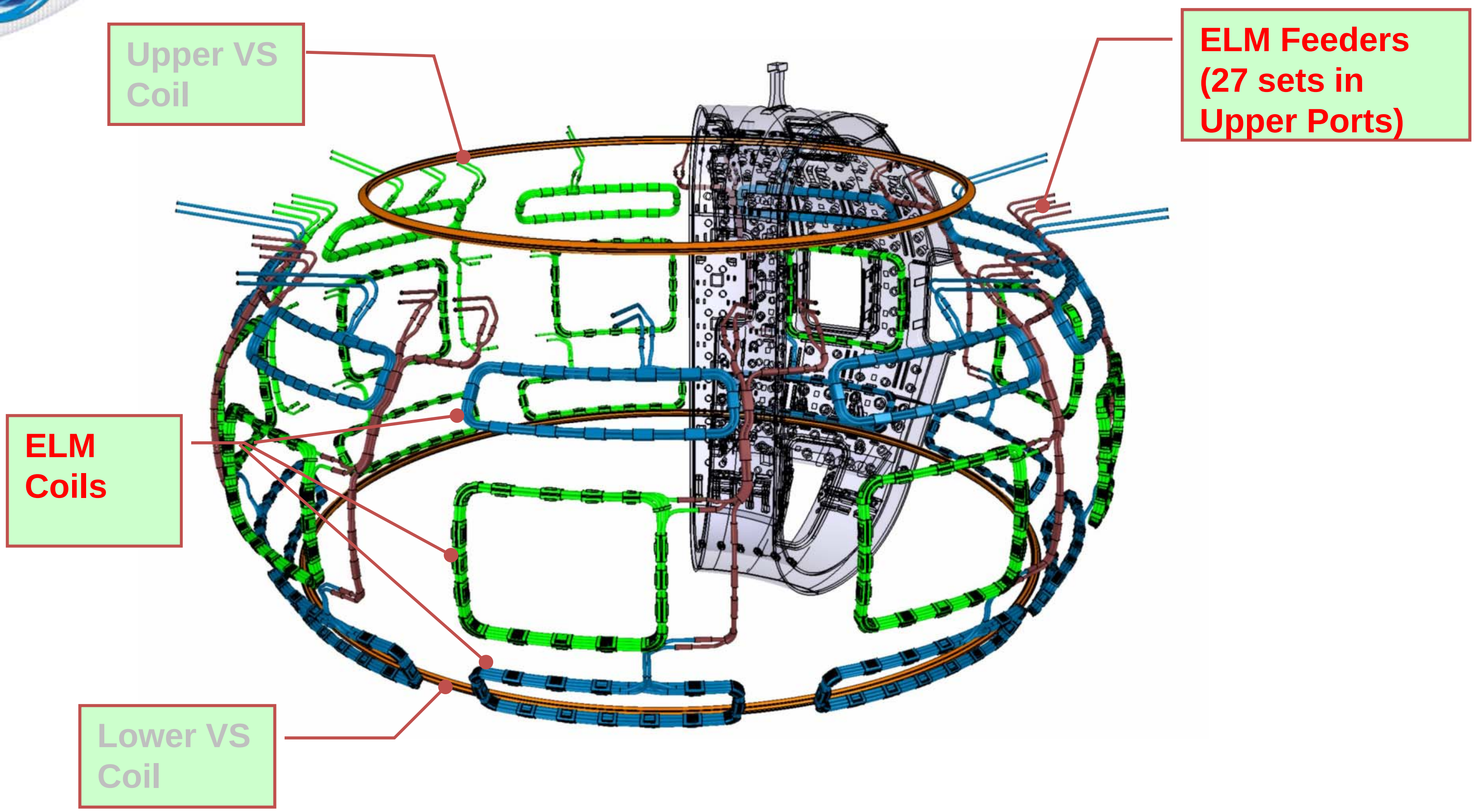
		ELM Design Point	ELM Proto (Tyco)	ELM Proto (ASIPP)	VS Design Point	VS Proto (Tyco)
Jacket	OD (mm)	59	54	54	59	59
	ID (mm)	55	49	50	55	53
	Thickness (mm)	2.0	2.5	2.3	2.0	2.9
	Material	316LN (IG)	304L	316LN	316LN (IG)	304L
Insulation	OD (mm)	55	49	50	55	53
	ID (mm)	50	36	44	45	39
	Thickness (mm)	2.5	6.7	2.5	5.0	7.1
	Material	MgO			MgO	
Conductor	OD (mm)	50	36	44	45	39
	ID (mm)	33	25	27	30	28
	Thickness (mm)	8.3	5.4	8.9	7.5	5.4
	Material	CuCrZr	Cu (C102)	Cu (C102)	Cu (C107)	Cu (C102)
Length	(m)	Coil: 65m	8m	4 @ 5m	Turn: 47m	9m

SSMIC– Conductor Development

- SSMIC is made by cantering a copper pipe in a stainless steel pipe, filling the annulus with magnesium oxide (MgO), and then drawing the assembly in dies or pressing the assembly between rollers to compress the MgO



ELM Coil Design



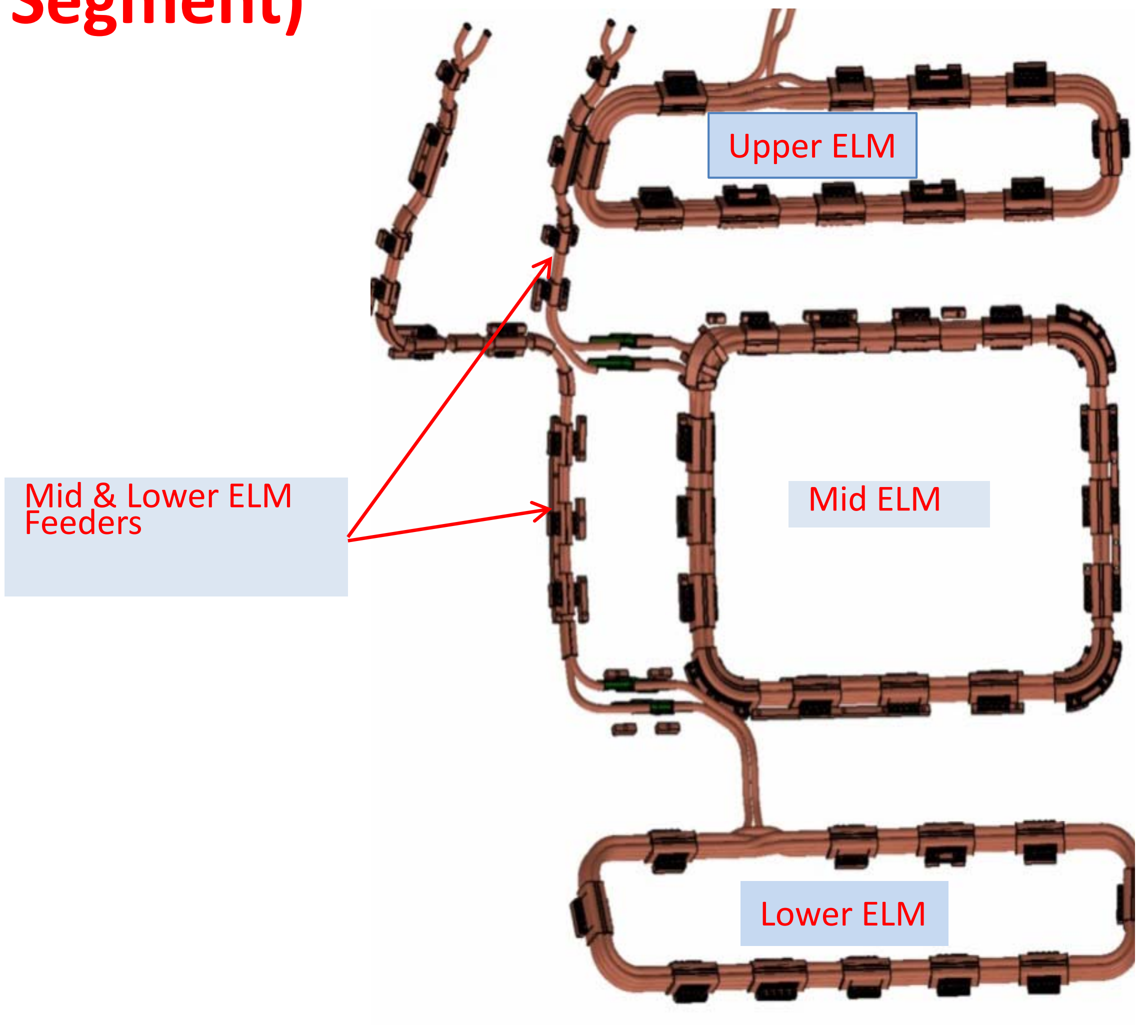
27 ELM (Edge Localized Mode) water-cooled "picture frame" coils

- 9 lower, 9 equatorial, and 9 upper coils
- 6 turns/coil 1 flow path/coil

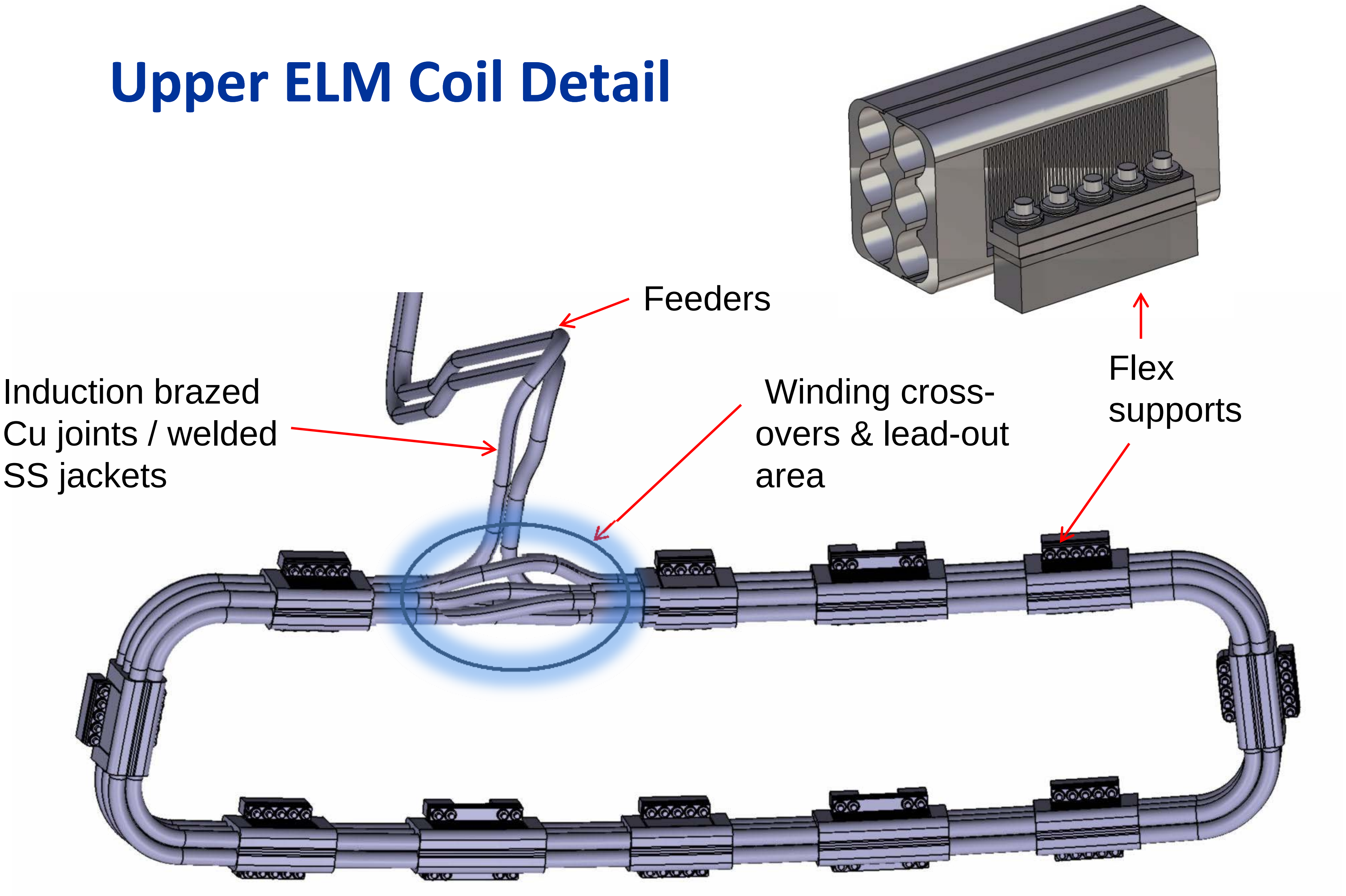
ELM Coil Design with Feeders (40 Degree Segment)

- 9 each
  Upper ELM coils
  Mid ELM coils
  Lower ELM coils

- 9 each
  Feeder Assemblies

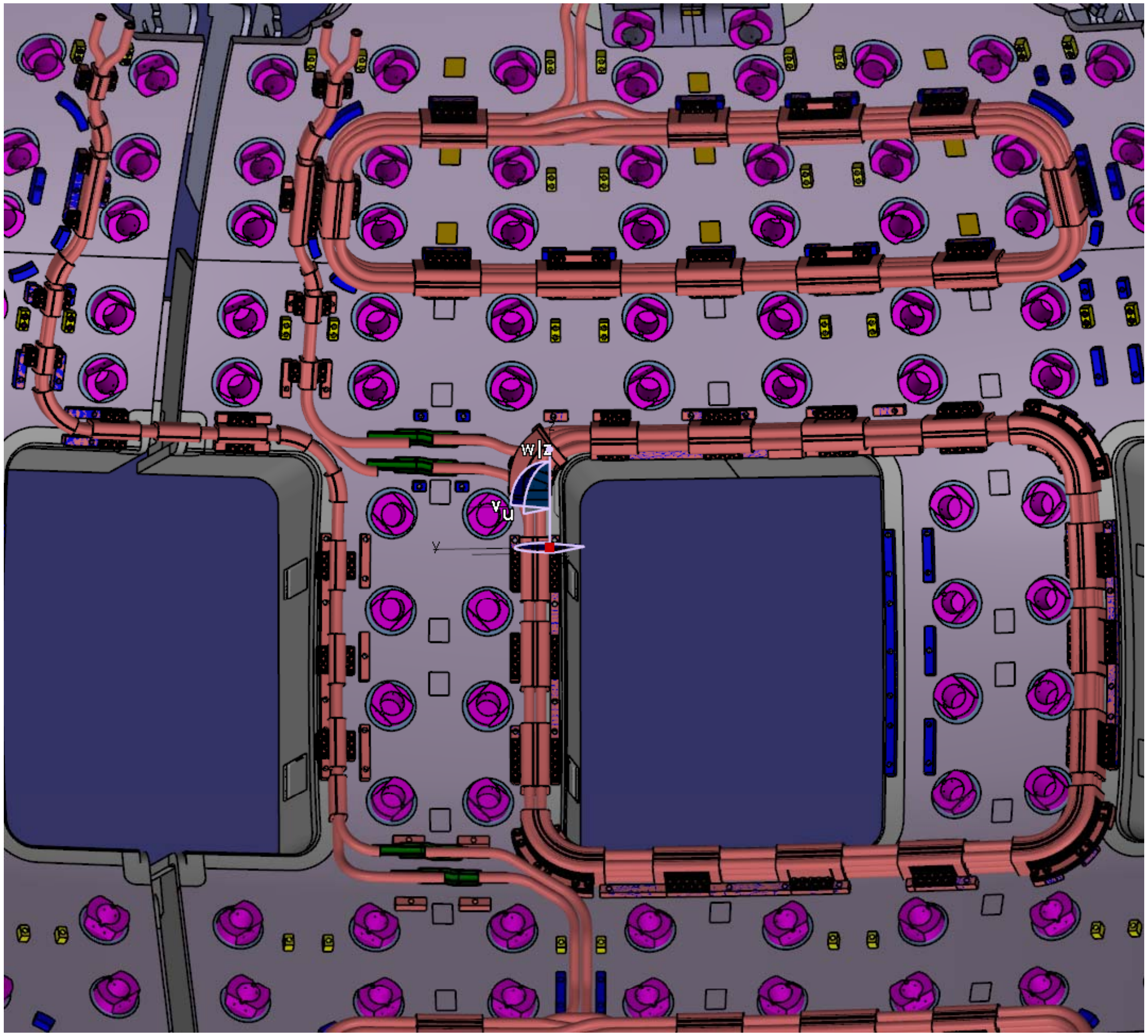


Upper ELM Coil Detail

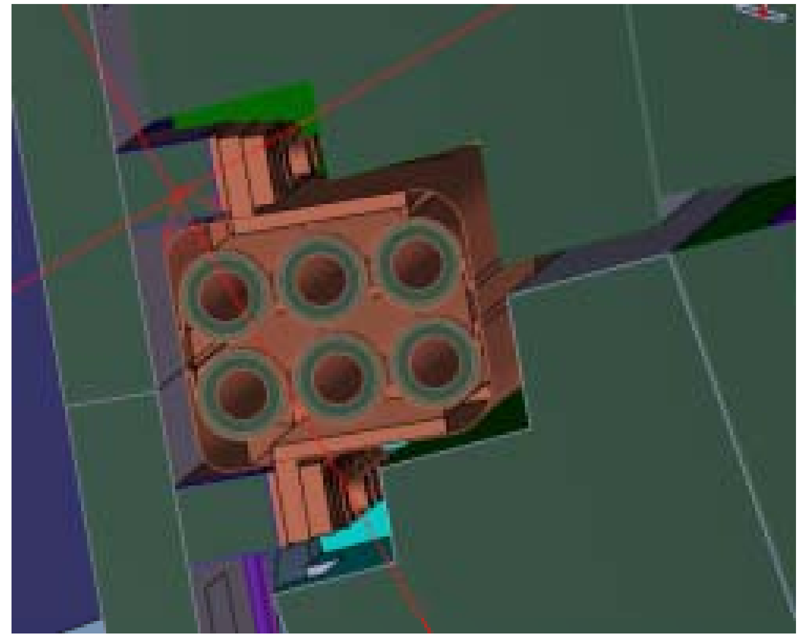


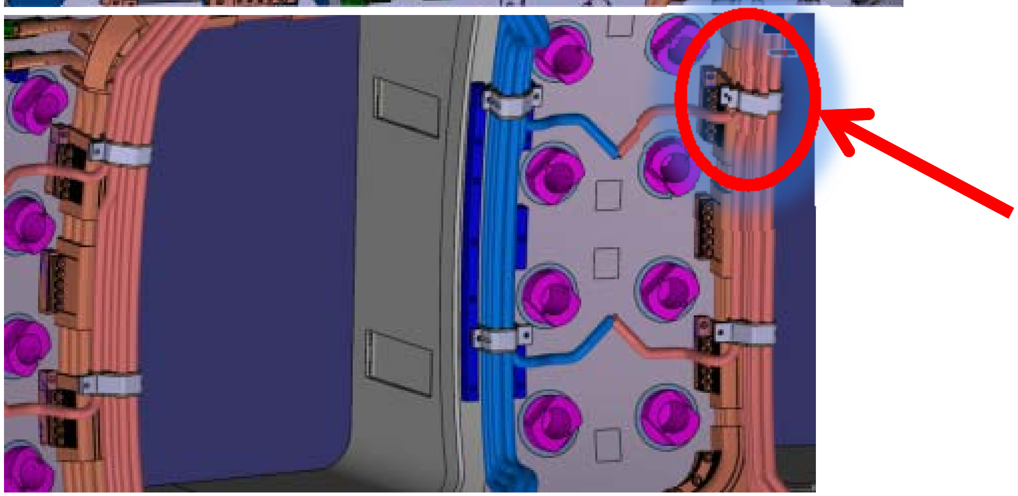
Vacuum Vessel Integration with IVCs

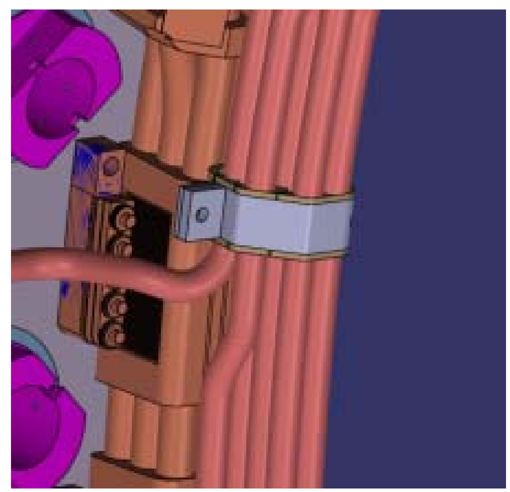
- Coils fit into vacuum vessel late in the design cycle
- Limited space for support points
- Conductor cross section challenged by interferences with blanket shield modules



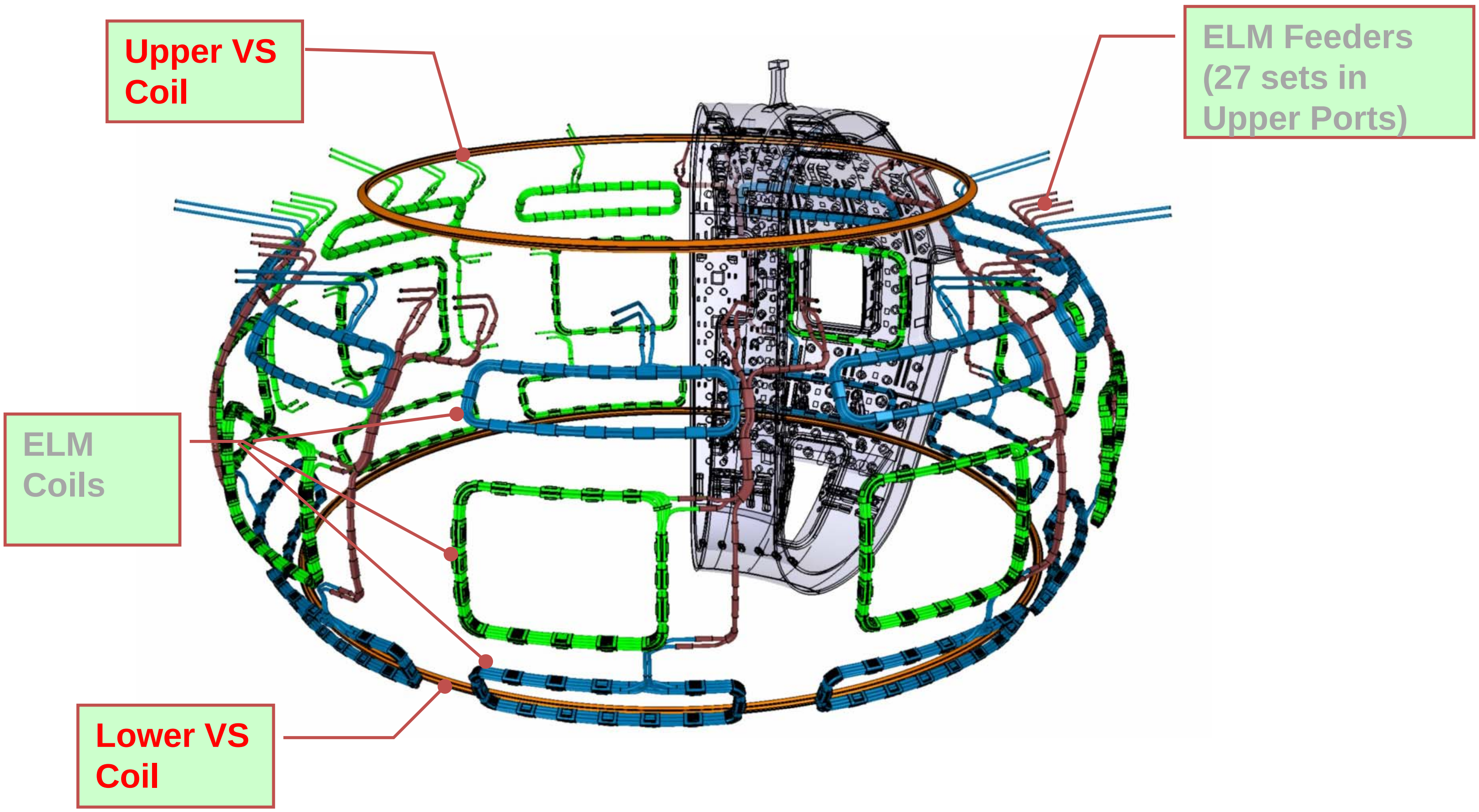
Mid ELM Coil - Interfaces







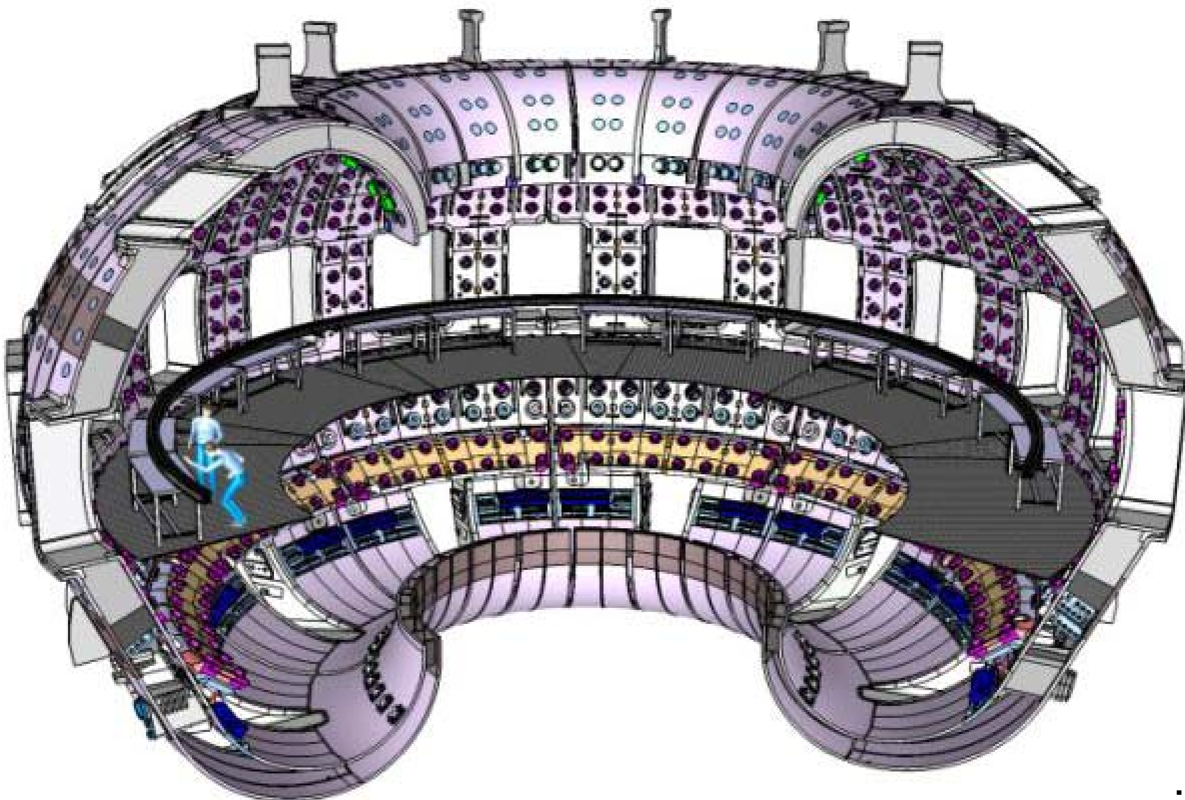
Upper and Lower
Vertical Stabilization Coils Design

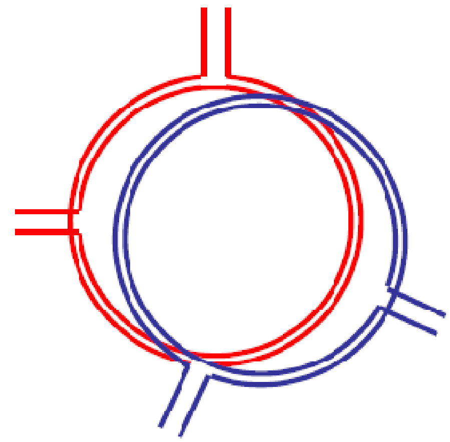


<u>2 VS (Vertical Stability) "ring coils"</u>

- 4 turns/coil   1 flow path/coil

VS Coil Details





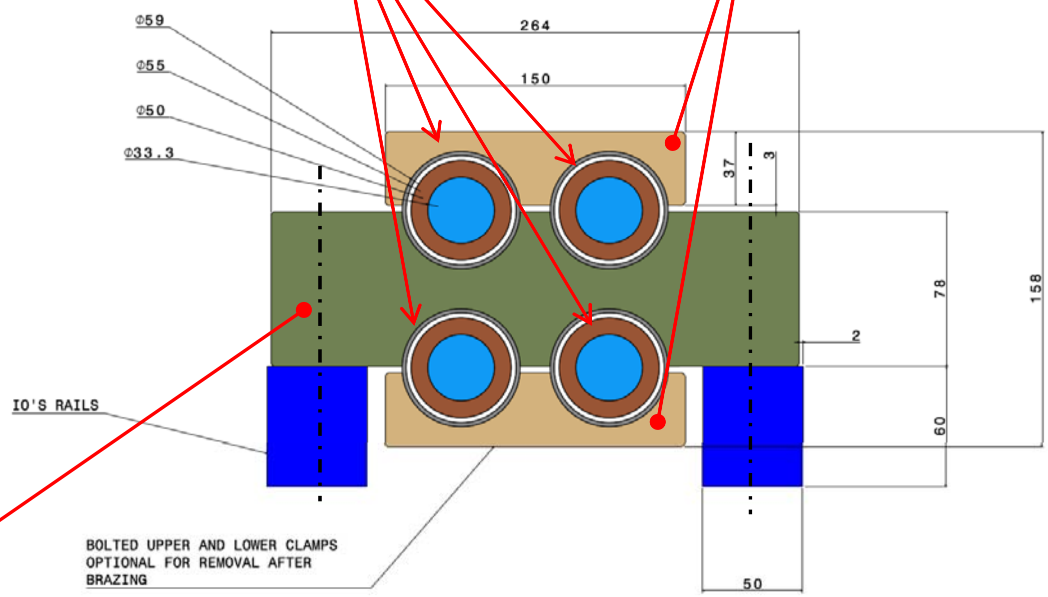
Coil is constructed as 4 individual turns for failure recovery in the event of a turn failure.

The VS coils will be constructed in the VV from pre-formed segments

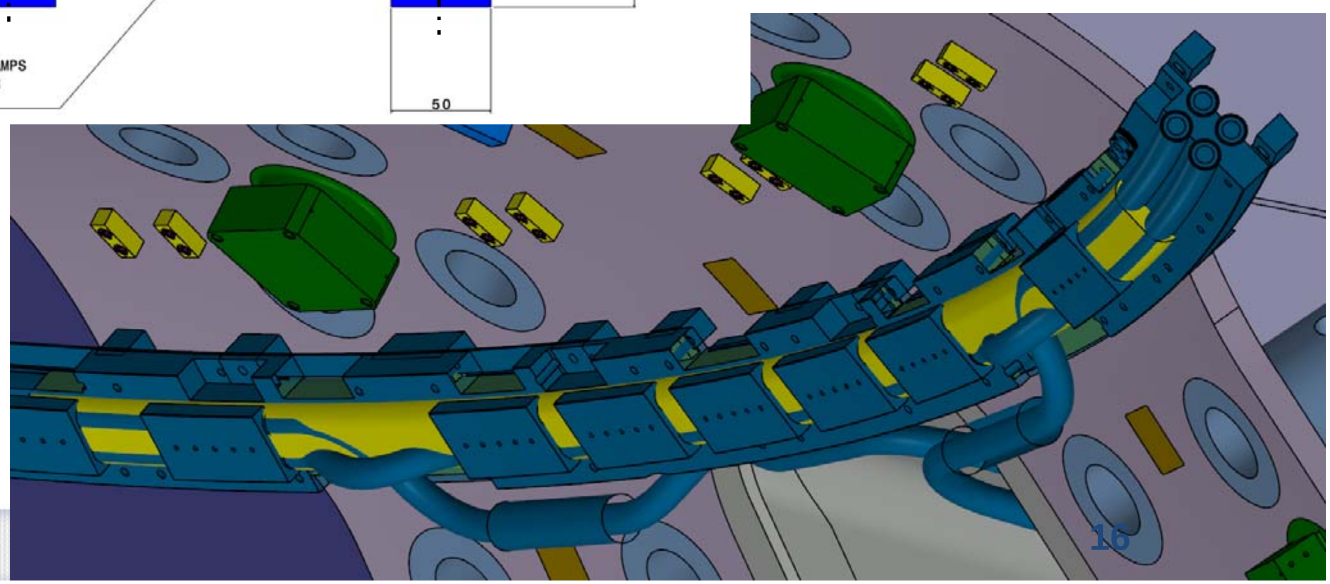
VS Coil Detail

SS jacketed MgO insulated cables w/ 5 mm insulation

Bolted and brazed cable clamping bars

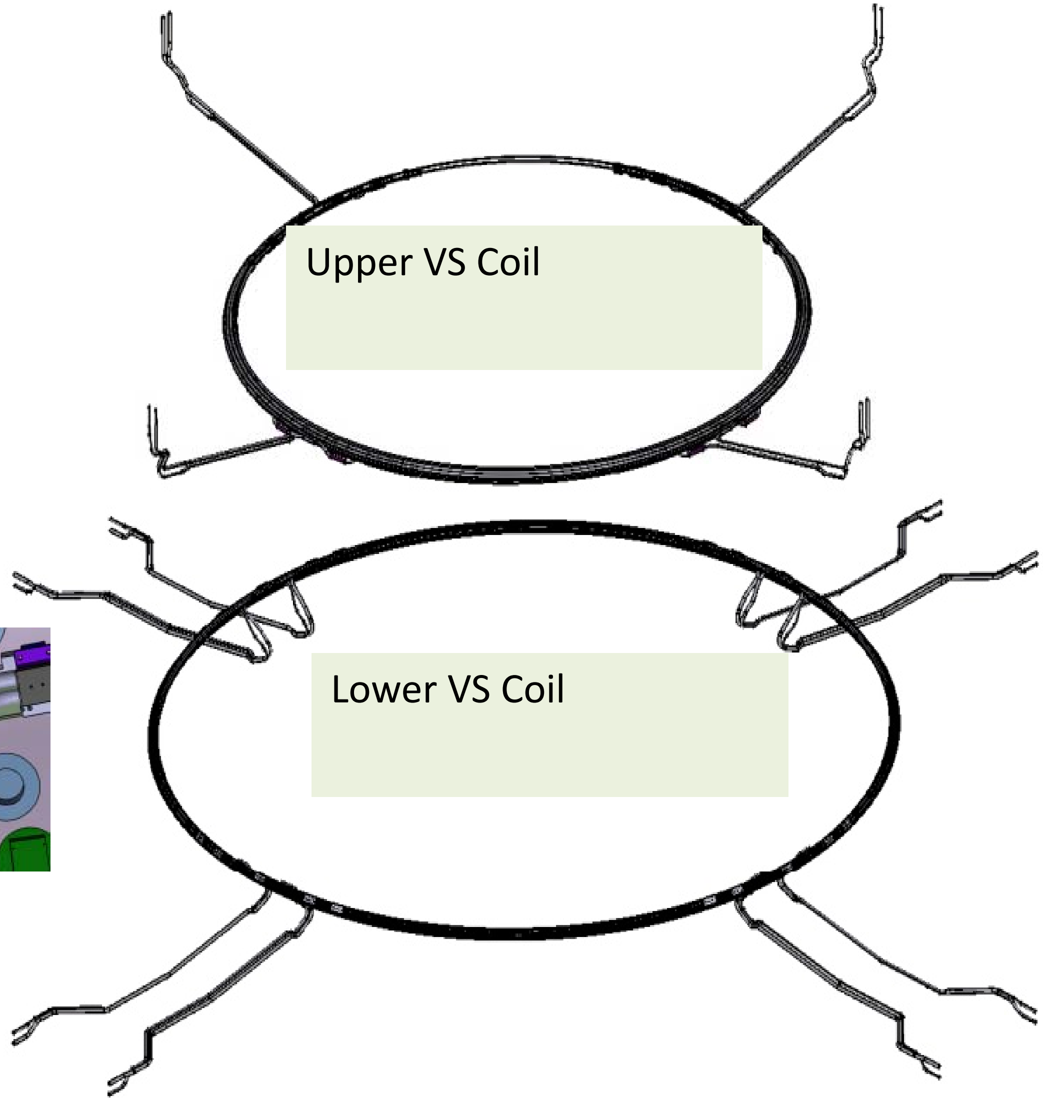


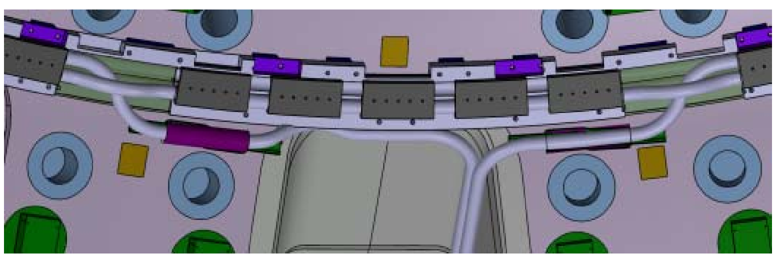
Continuous forged SS “spine”

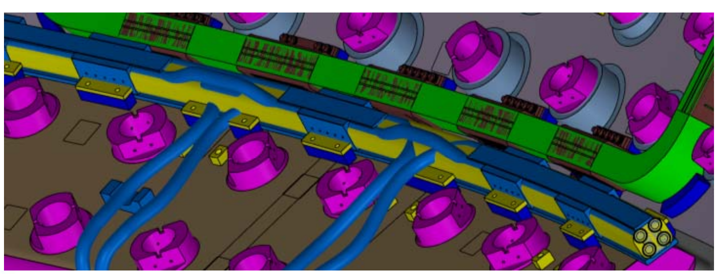


VS Coils with VS Coil Feeders

Eight feeder assemblies to provide power to each VS turn individually. These will extend through the chimney.







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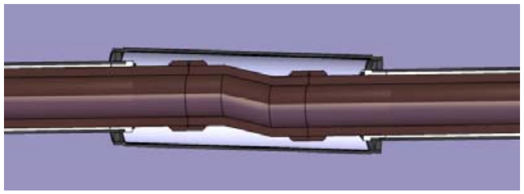
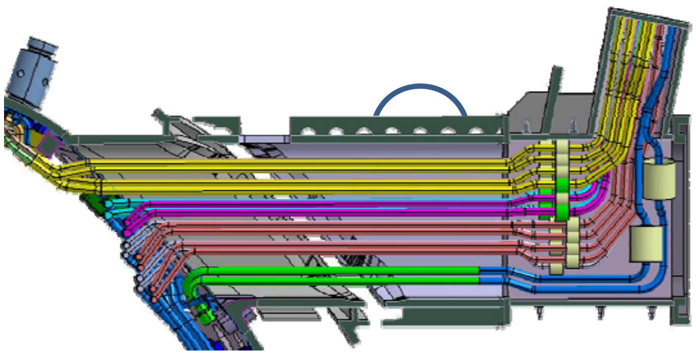
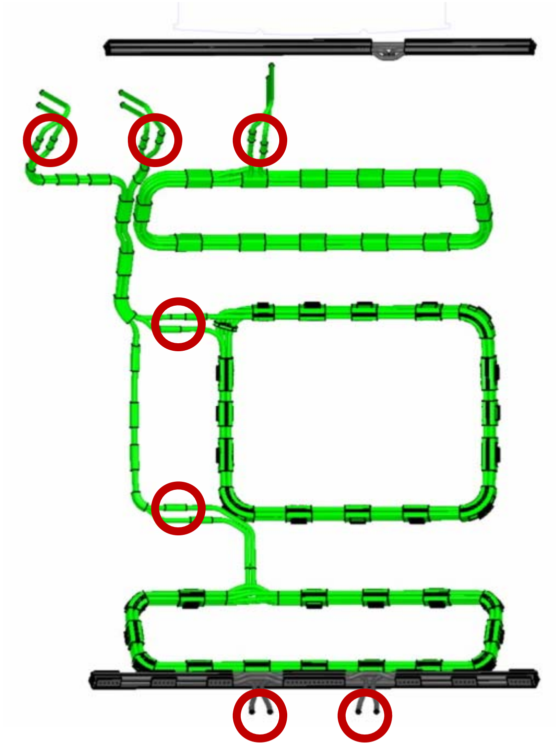
Coil to Feeder Joints

Roughly 176
Coil to Feeder Joints Required



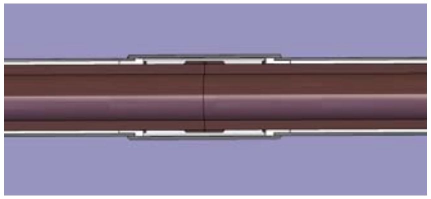


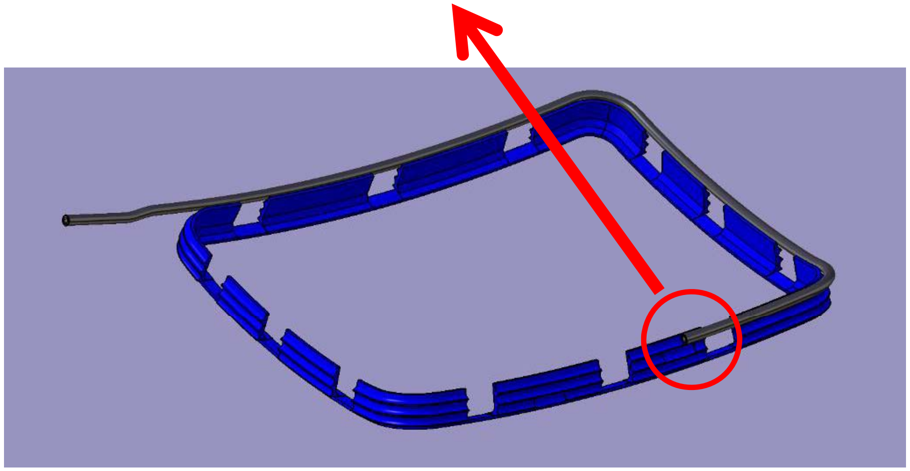


Chimney area:
ELMs 6/sector x 9 sectors =54
VS: 8/coil x 2 coils =16

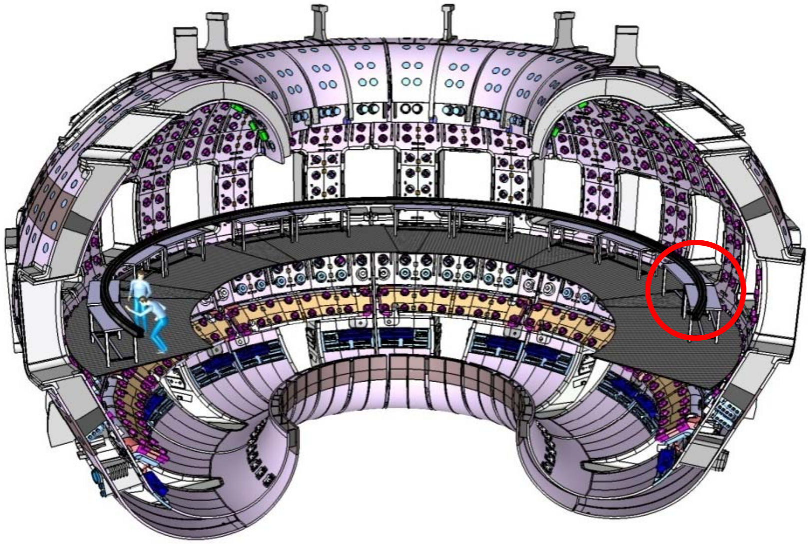
ELM coil to feeders:
10/sector x 9 sectors =90
VS coil to feeders:
8 (4 lead pairs per coil) x 2 coils =16

Inline Coil Joints





- **ELM coils:** the SSMIC length that can be manufactured is currently limited to ~15 m.
- With half turn SSMIC lengths 27 ELM coils x 11 joints/coil=**297 joints**.
- **VS coils:** are manufactured in quadrants which will be assembled in the vacuum vessel. This will require 6 joints / quadrant x 4 quadrants x 2 coils =**48 joints.**

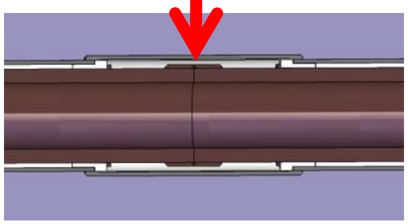


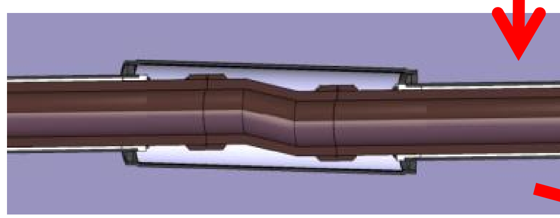
Joint Design & Prototype

- Large number of joints so high reliability required
- Induction silver brazing for copper conductor
- Tig welding for stainless steel sleeve
- NDT (non-destructive testing) development required

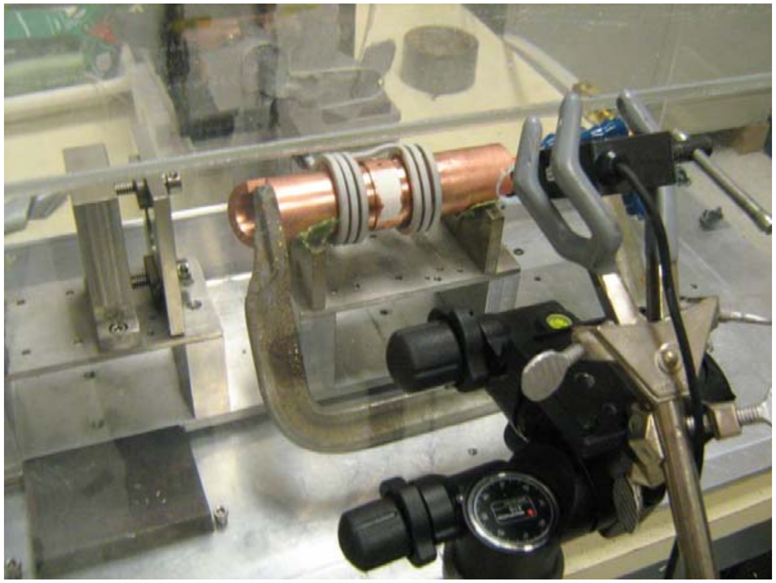
- **In Line Joint**
- Ends precisely aligned in the factory.
- Compact as possible to fit the coil.

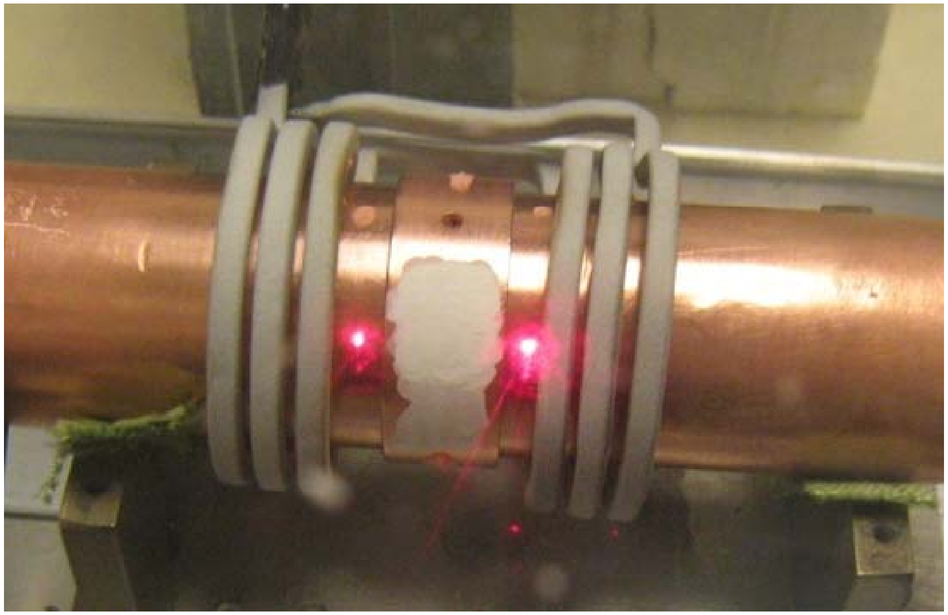
- **Coil To Feeder Joint**
- Joined in VV with limited space
- Adaptable to RH methods





Joint Development

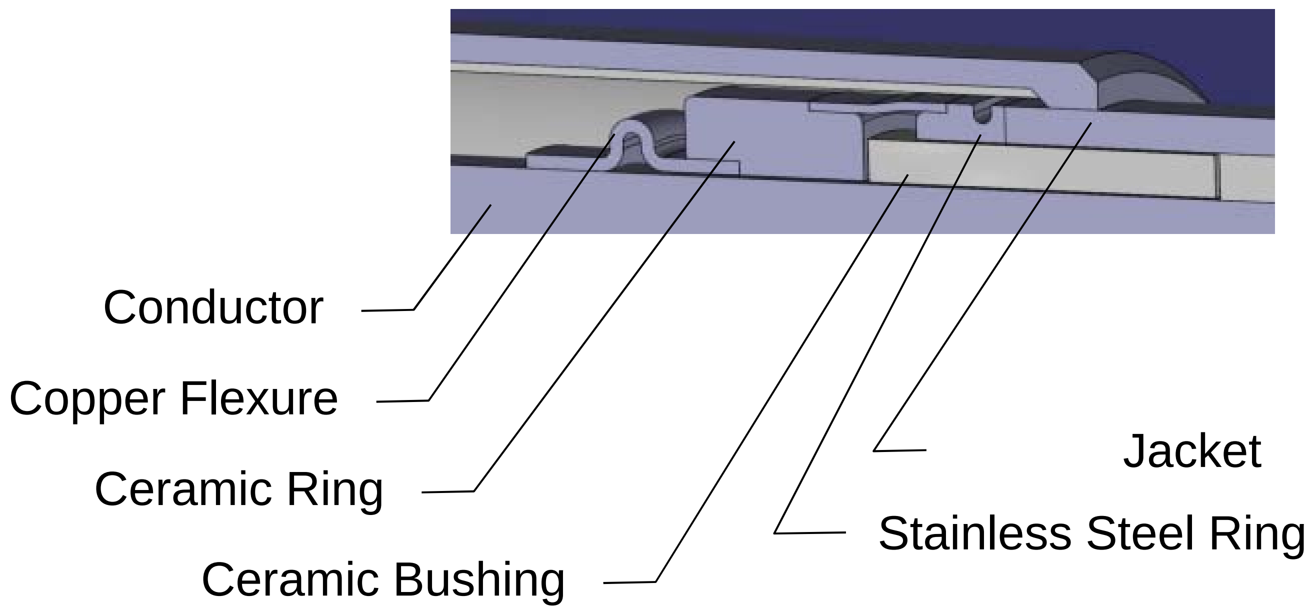




- Basic joint configurations and fabrication methods were demonstrated during the PDR phase at Edison Welding Institute. Remote handling compatibility studies were also performed

Ceramic Bushing Design

- Requirements
  - Hermetic seal for MgO insulating space
  - Electrical Stand-off
  - Mechanical compliance



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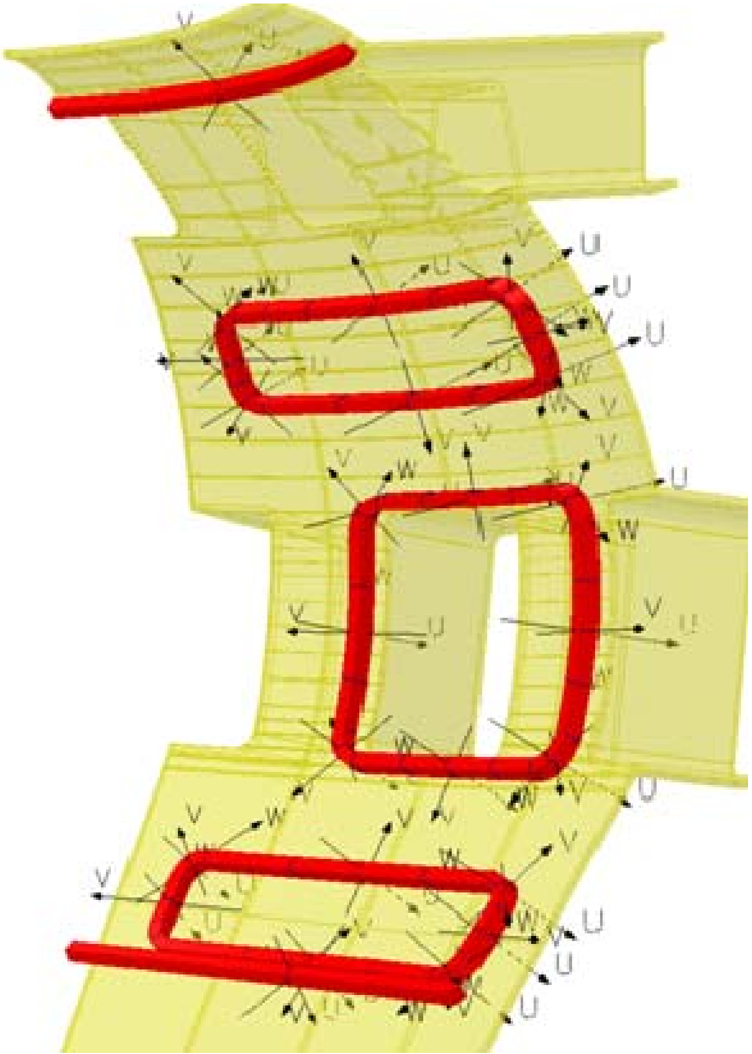
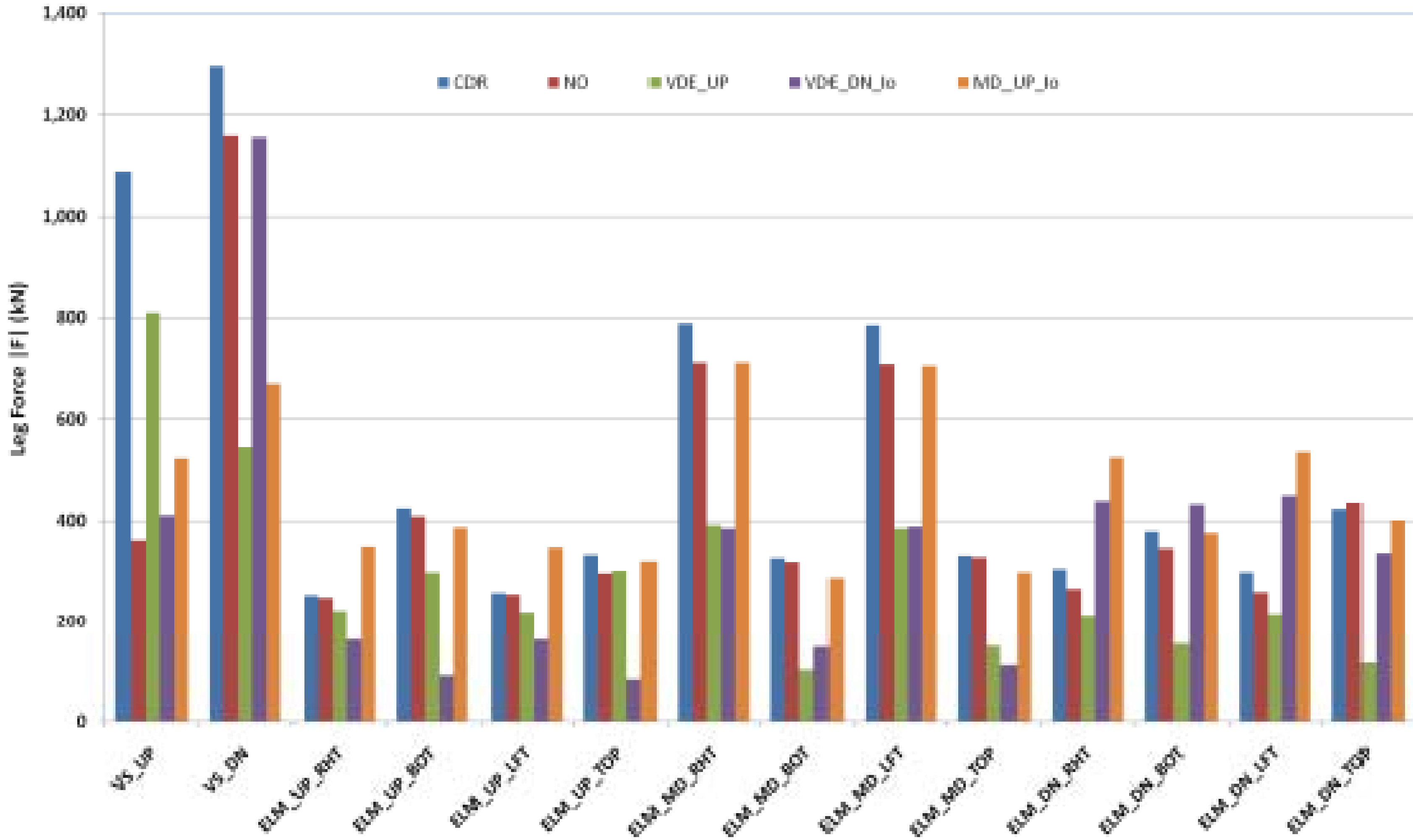
EM Analysis Model

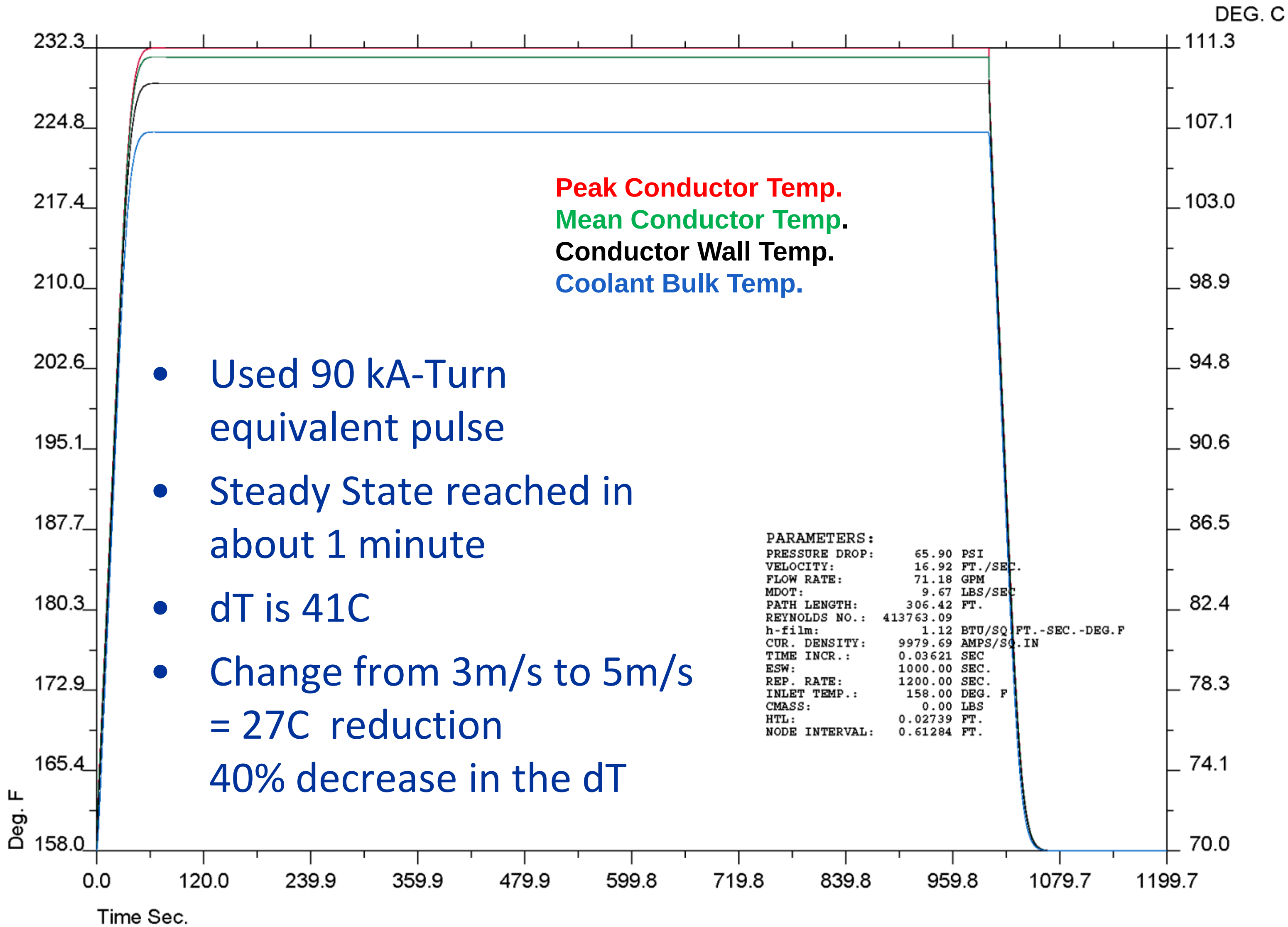


- Normal and Disruption loads were analyzed using DINA Inputs for OPERA simulations
- Survey of load cases reduced inputs down to critical worst case disruption and operating loads for analysis

EM Analysis – Disruption Force Summary



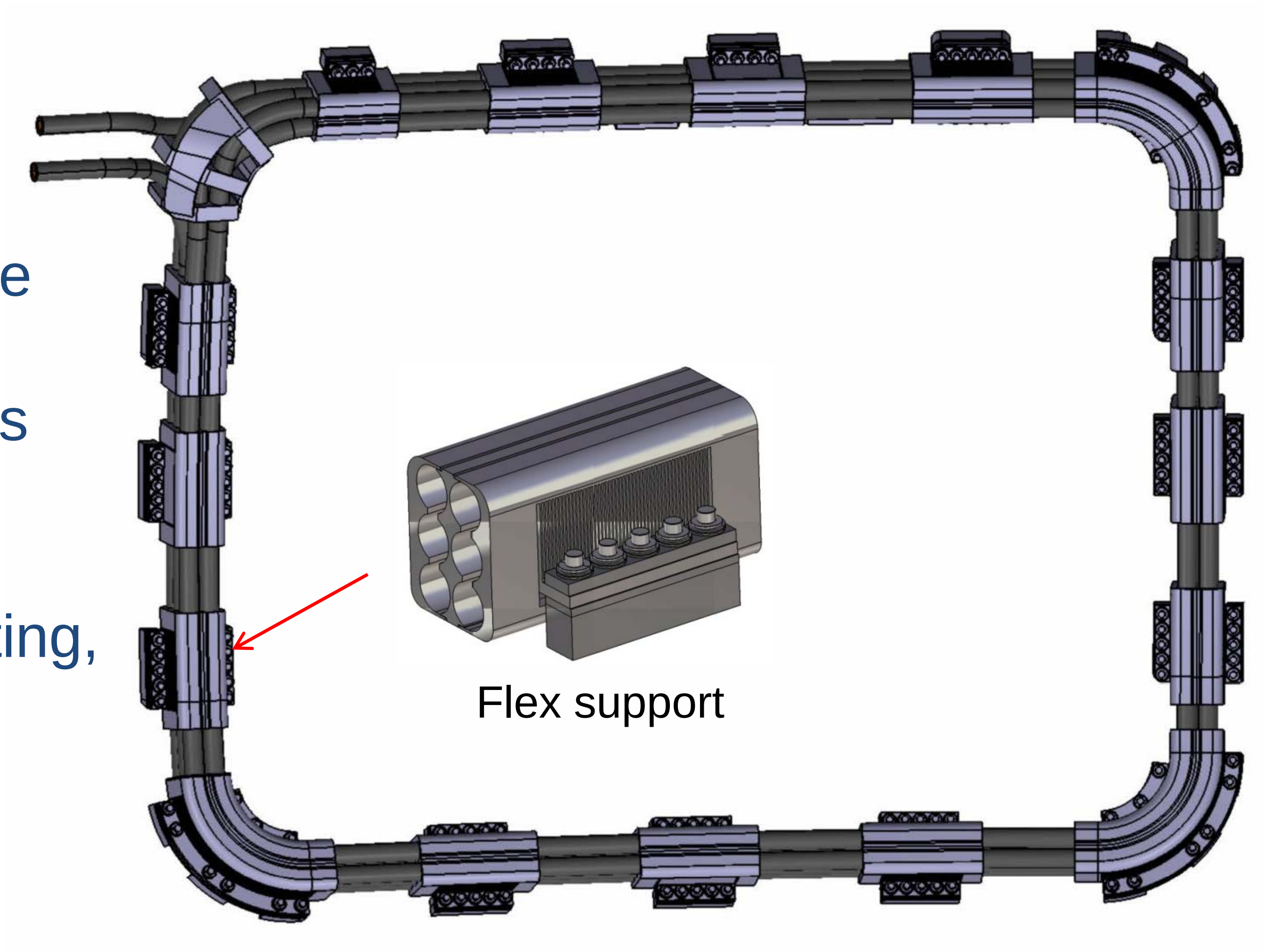
ELM Coil and Feeders With Nuclear Heating Steady State RMS Square Wave Input 5m/s at 70C Input



- Used 90 kA-Turn equivalent pulse
- Steady State reached in about 1 minute
- dT is 41C
- Change from 3m/s to 5m/s = 27C reduction
  40% decrease in the dT

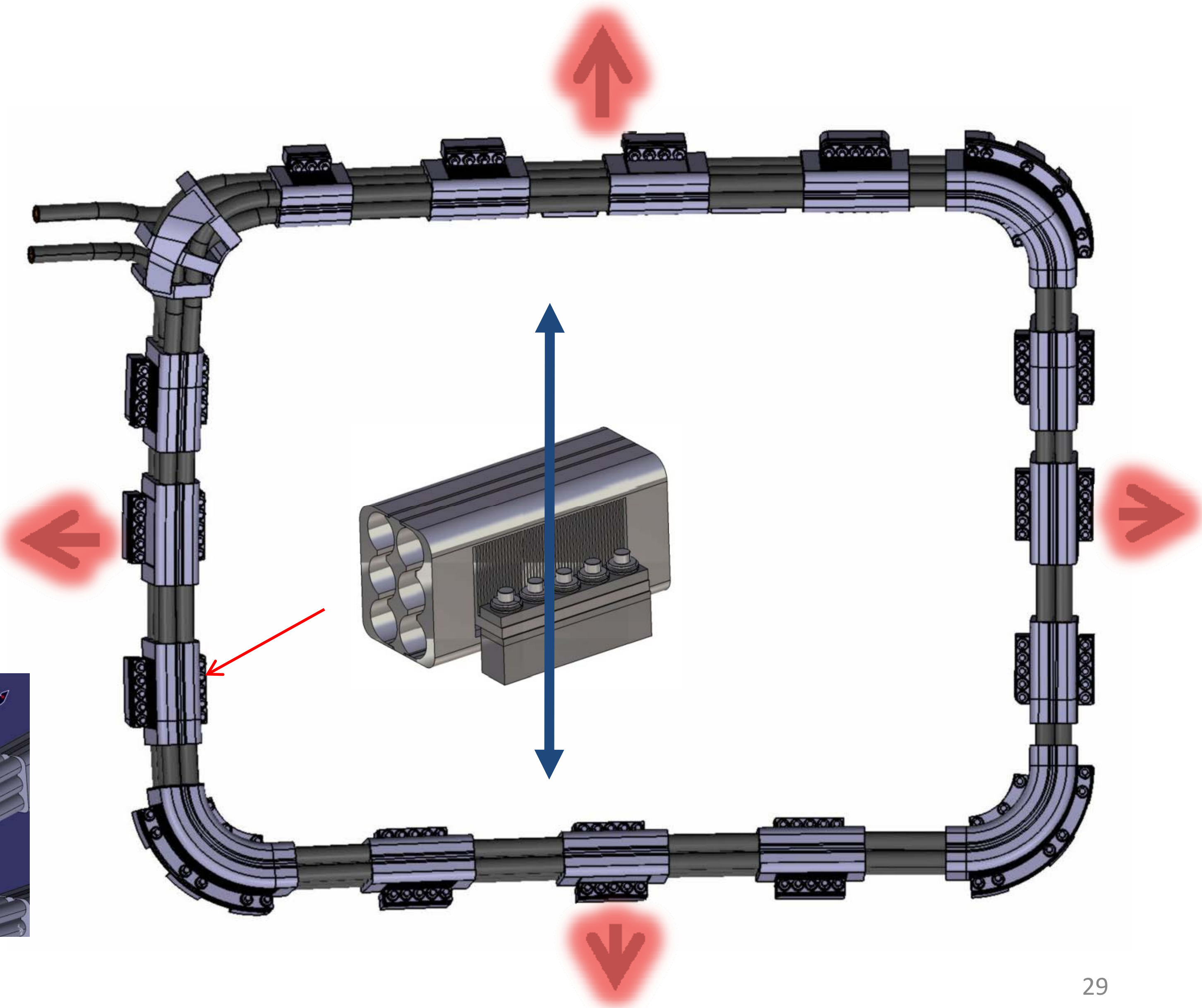
Mid ELM Coil Model

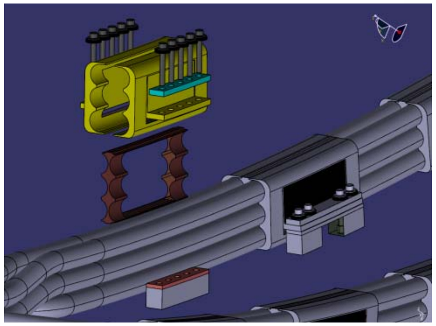
- EM Loads were mapped into ANSYS models along with Neutronics, Resistive Heating, and Thermal Hydraulic boundary conditions



ELM Coil Bracket Restraint

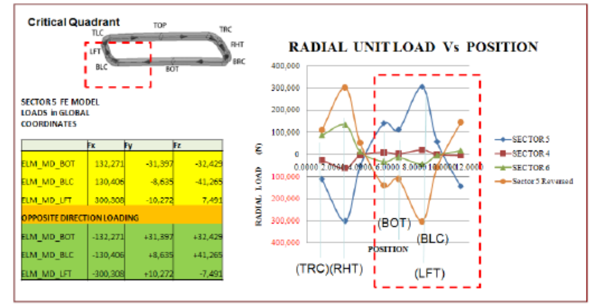
- FLEX
  Thermal Growth
- RESTRAIN
  Upward EM Forces



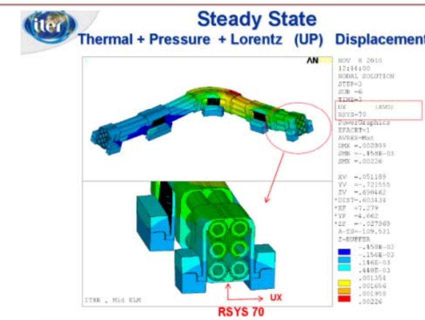


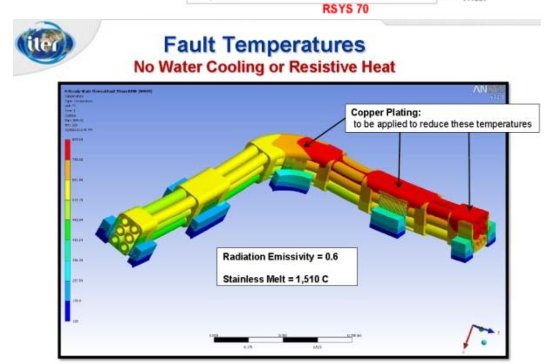
ELM Coil Analysis Result

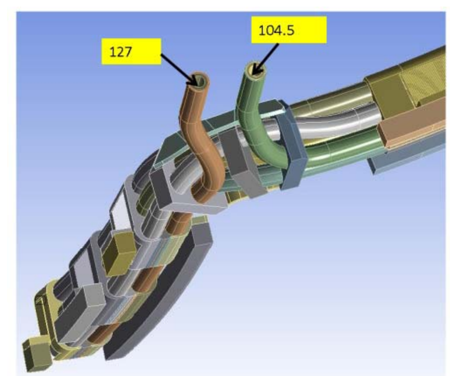
- Low Allowable Design Stress
  - 5Hz operation results in millions of cycles
  - Crack propagation criteria requires very low design allowable
  - For Stainless Steel design allowable is only between 44MPa and 84MPa as a stress range depending on the R Value (ratio of alternating stress to mean stress)



	Fx	Fy	Fz
ELM_MD_BOT	132,271	-31,397	-32,429
ELM_MD_BLC	130,406	-8,635	-41,265
ELM_MD_LFT	300,308	-10,272	7,491
OPPOSITE DIRECTION LOADING			
ELM_MD_BOT	-132,271	+31,397	+32,429
ELM_MD_BLC	-130,406	+8,635	+41,265
ELM_MD_LFT	-300,308	+10,272	-7,491

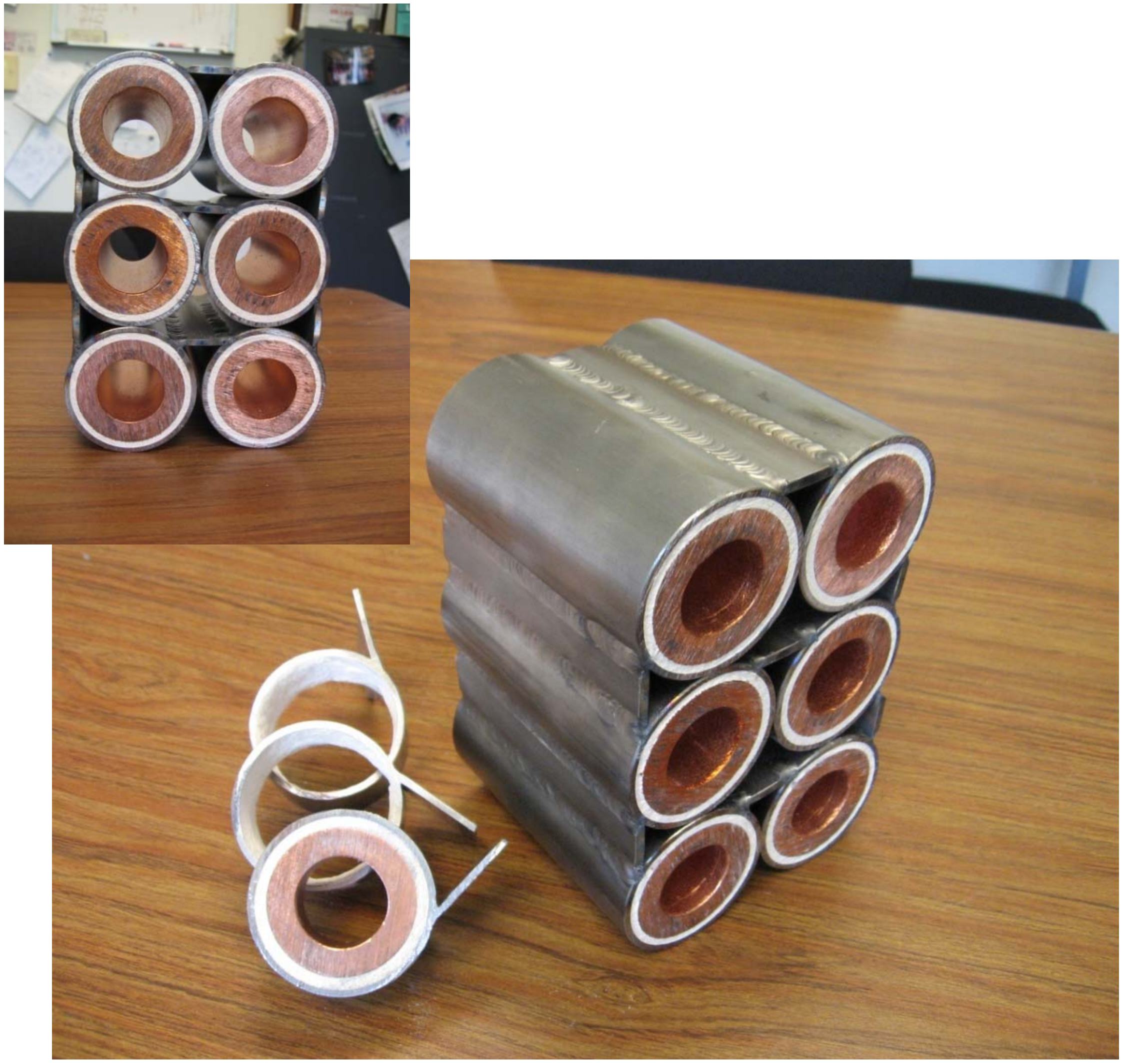




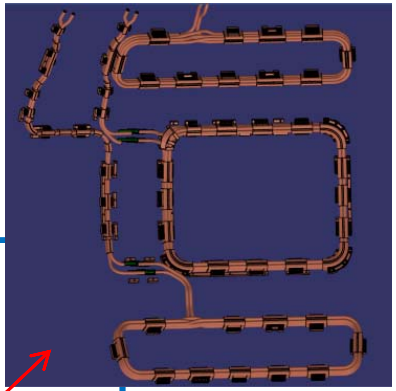


ELM Coil Welded Brackets

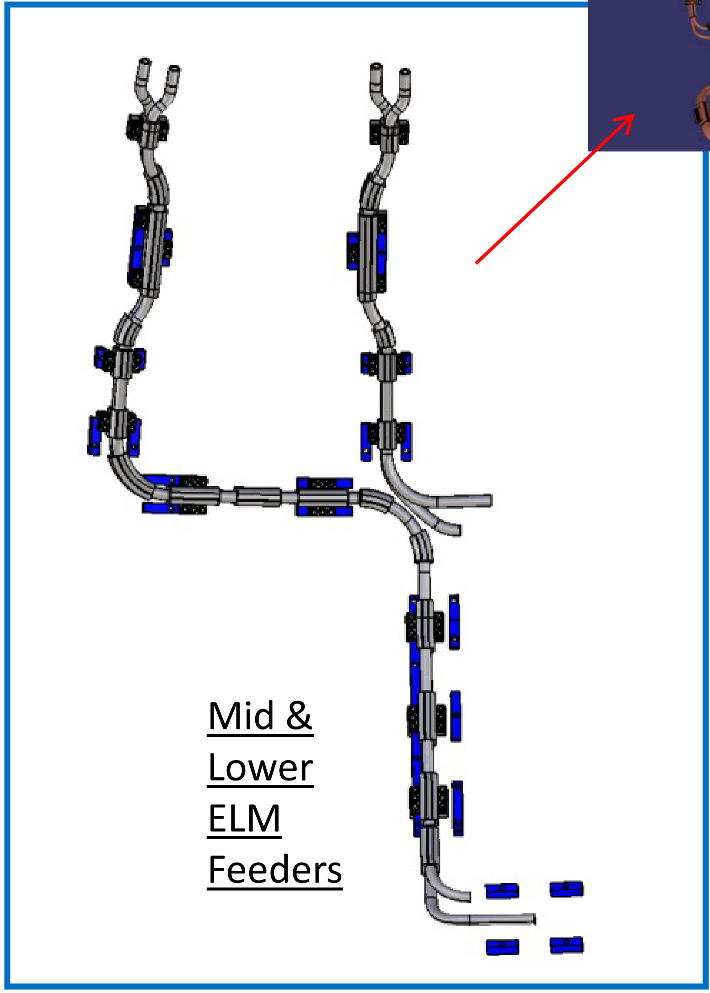
- Welding brackets to the SS jacket may be required to improve coil stiffness for resisting EM loads.

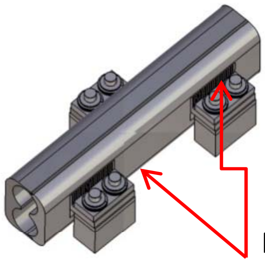


Analysis of ELM coil feeders



- The (+) and (-) legs of the feeders have opposite forces
- Clamping them together results in almost zero net force



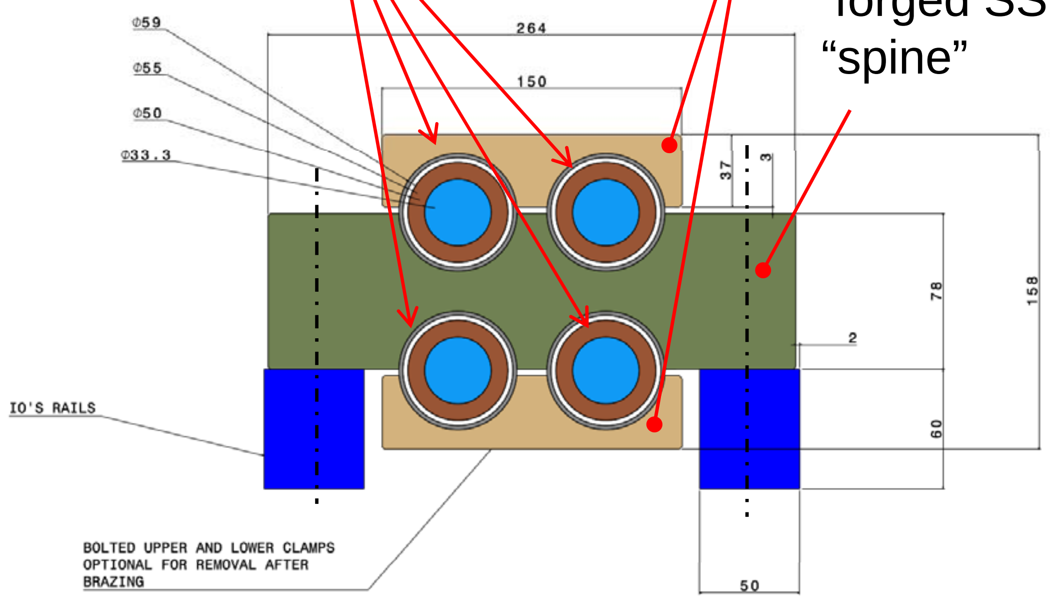


VS Coil Analysis

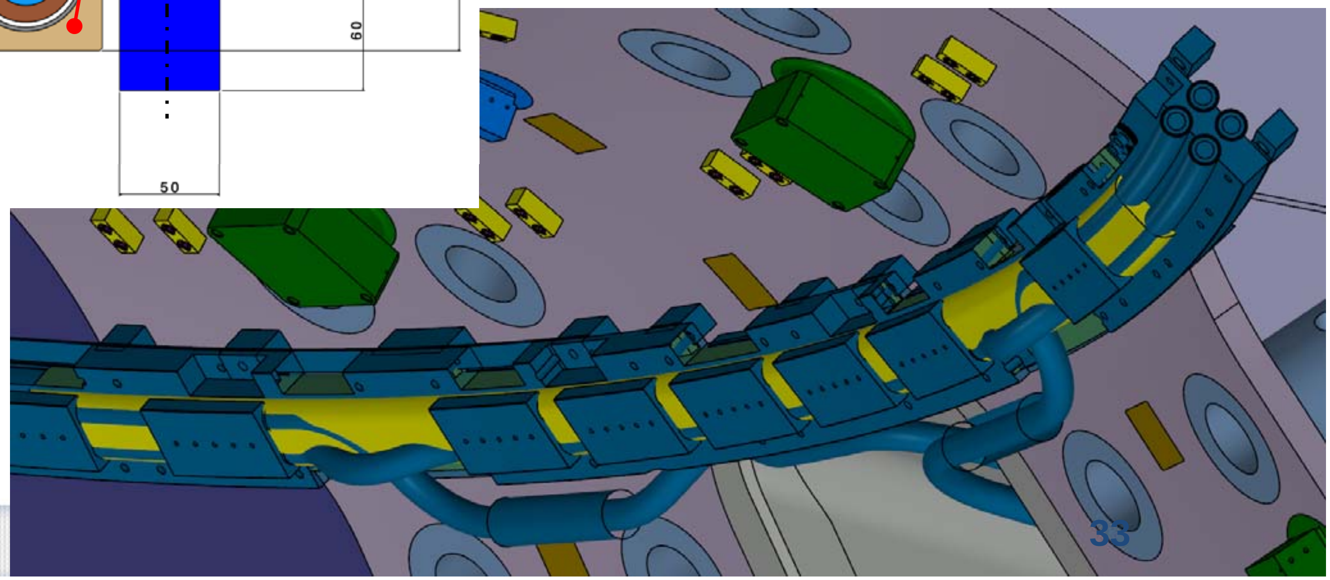
SS jacketed MgO insulated cables w/ 5 mm insulation

Bolted and brazed cable clamping bars

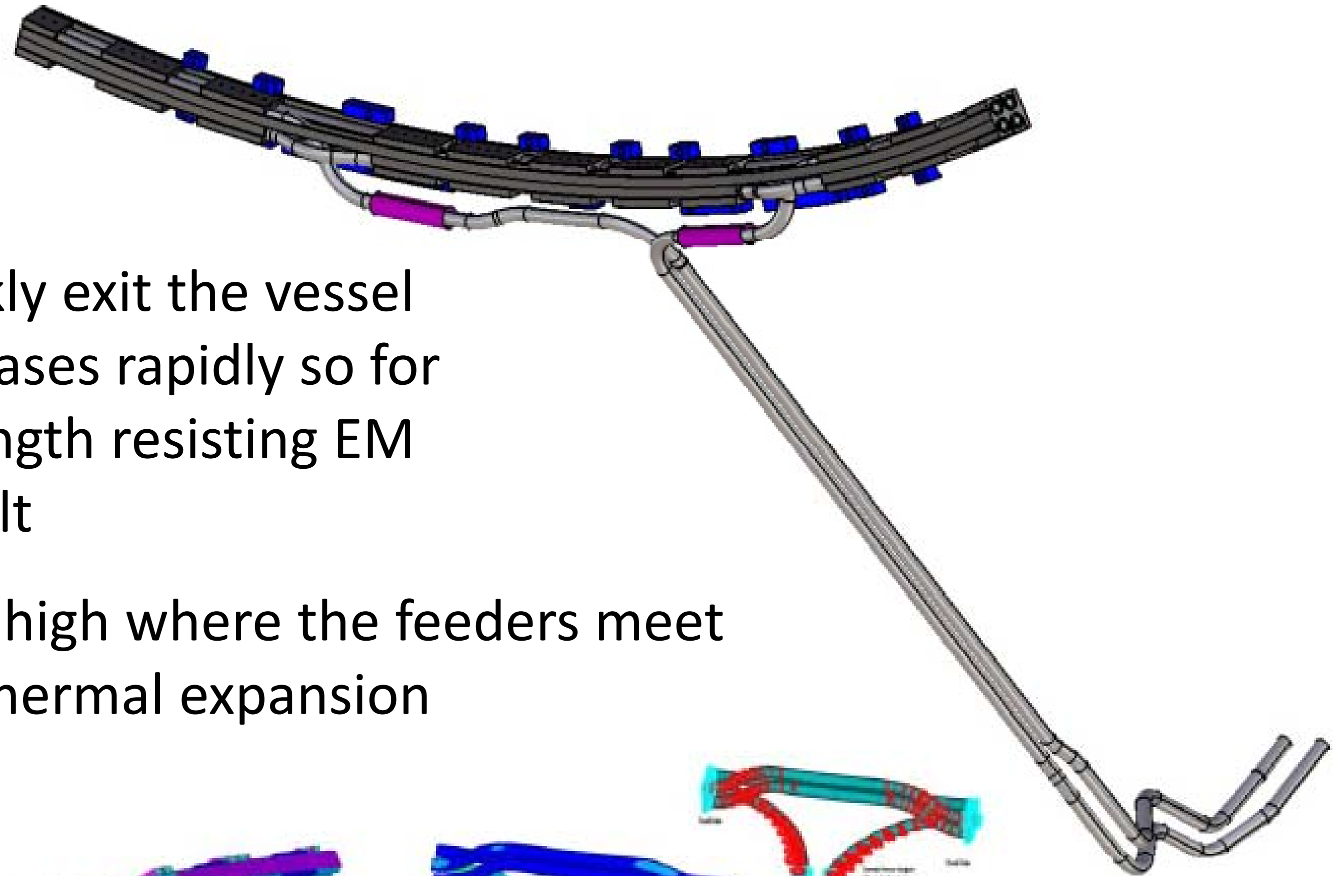
Continuous forged SS "spine"



The circular geometry of the VS coil results in more benign thermal hoop compression due to thermal expansion as compared to an ELM coil, whose rectangular geometry results in high bending stresses in the corner regions.

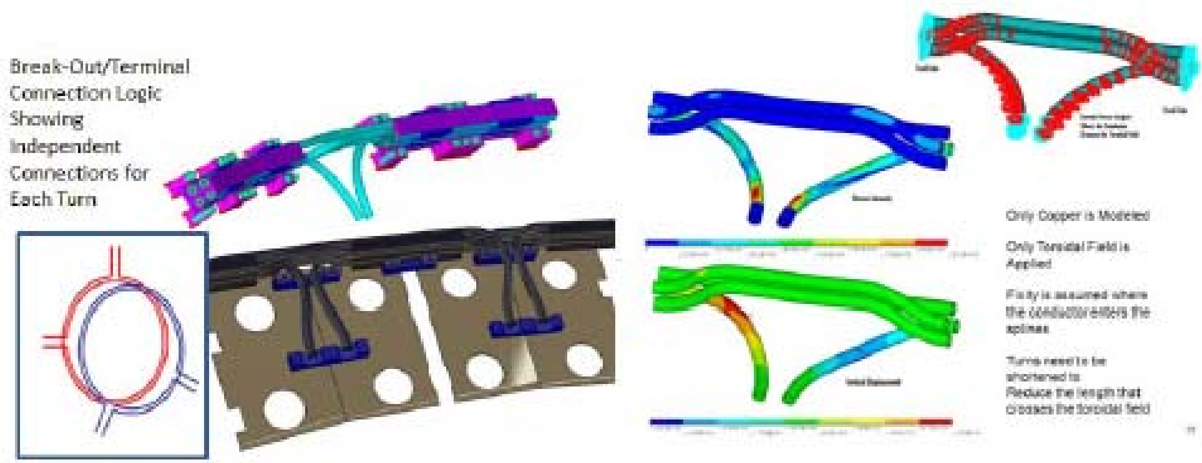


VS Feeder Analyses



The Elm feeders quickly exit the vessel where the field decreases rapidly so for most of the feeder length resisting EM forces is not as difficult

However stresses are high where the feeders meet the fixed coil due to thermal expansion

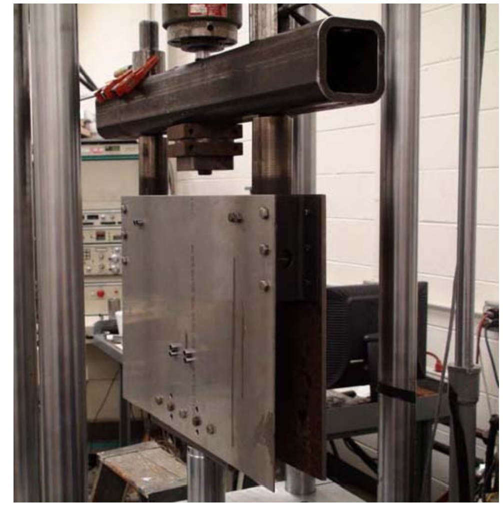


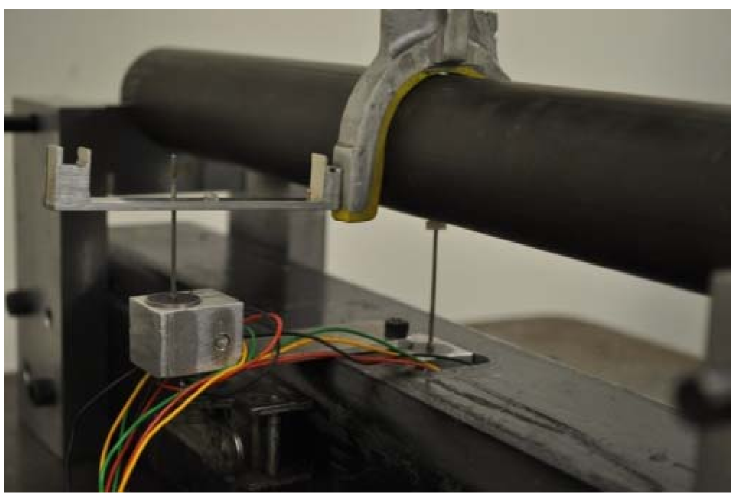
Outline

- Design
  - ➢Design Overview
  - ➢SSMIC Development
  - ➢Joints
- Analysis
  - ➢Thermal Analysis
  - ➢Electromagnetic Opera Analysis
  - ➢Mechanical Stress Analysis
- **Testing**
  - ➢Mechanical
  - ➢Electrical
- Summary

Mechanical Testing

- Shear Test
- Compression Test
- UBend Cyclical Test
- Bend Test

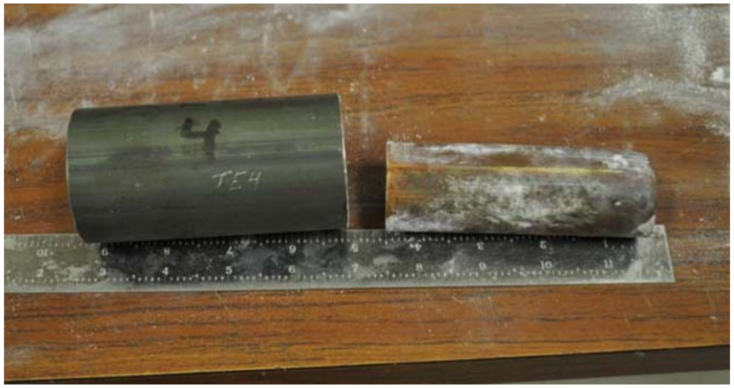




Mechanical Testing

Shear Testing

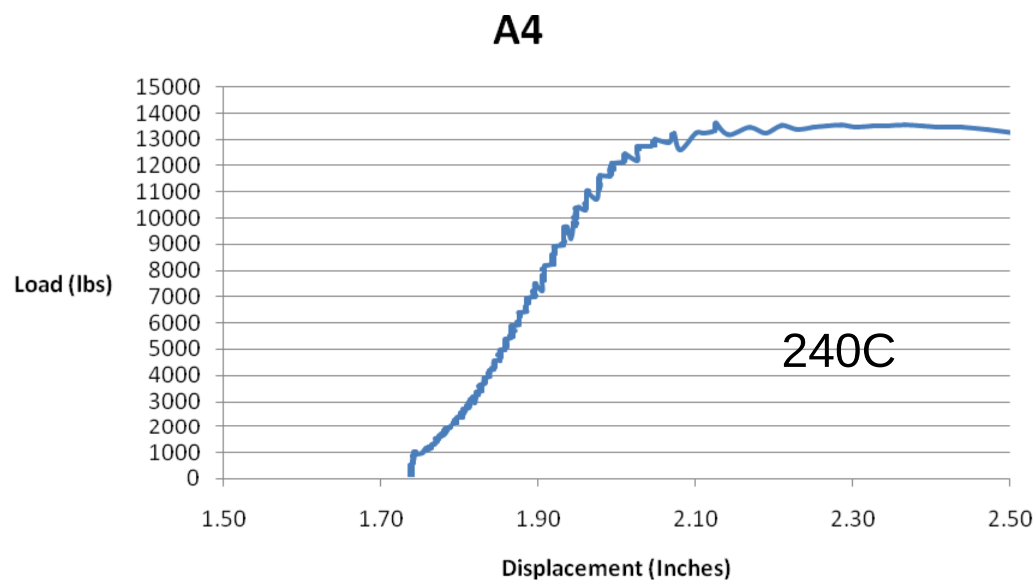
- Samples placed in chamber with actuator positioned through hole in top of oven
- Copper is pressed out of the MgO and load displacements are recorded
- Repeated for 3 temperatures

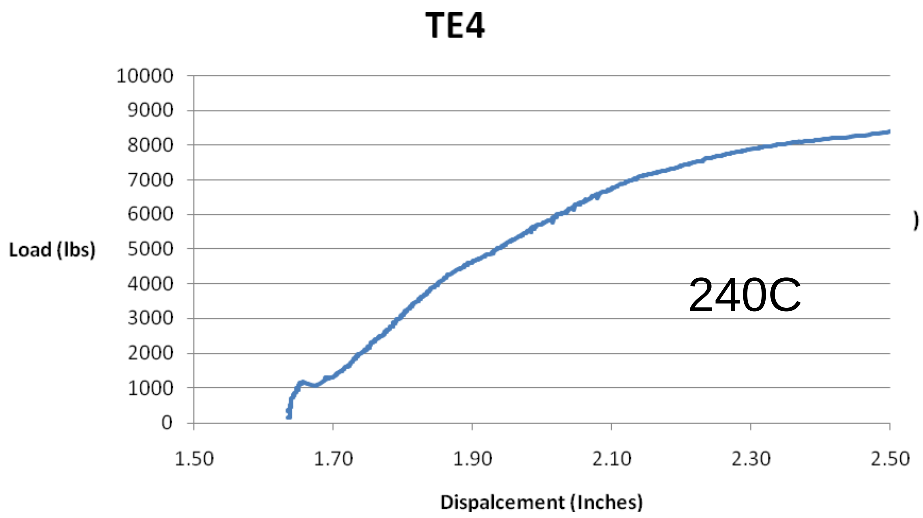


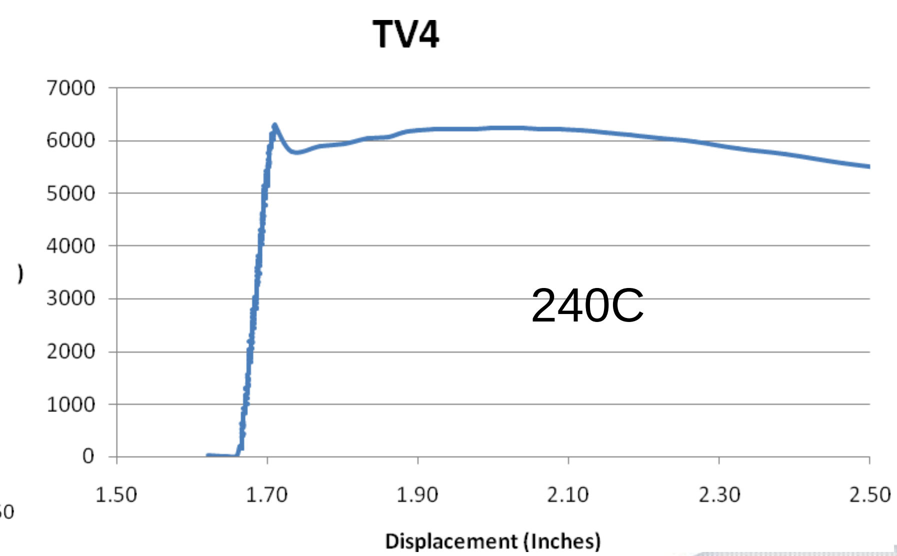
Mechanical Testing

Shear Test

- Slip begins at a low shear strength of approximately
  .3MPa for the ELM samples
  2.1MPa Tyco VS samples
- Calculations show that shear strength does not effect deflection or bending stress for the coaxial SSMIC



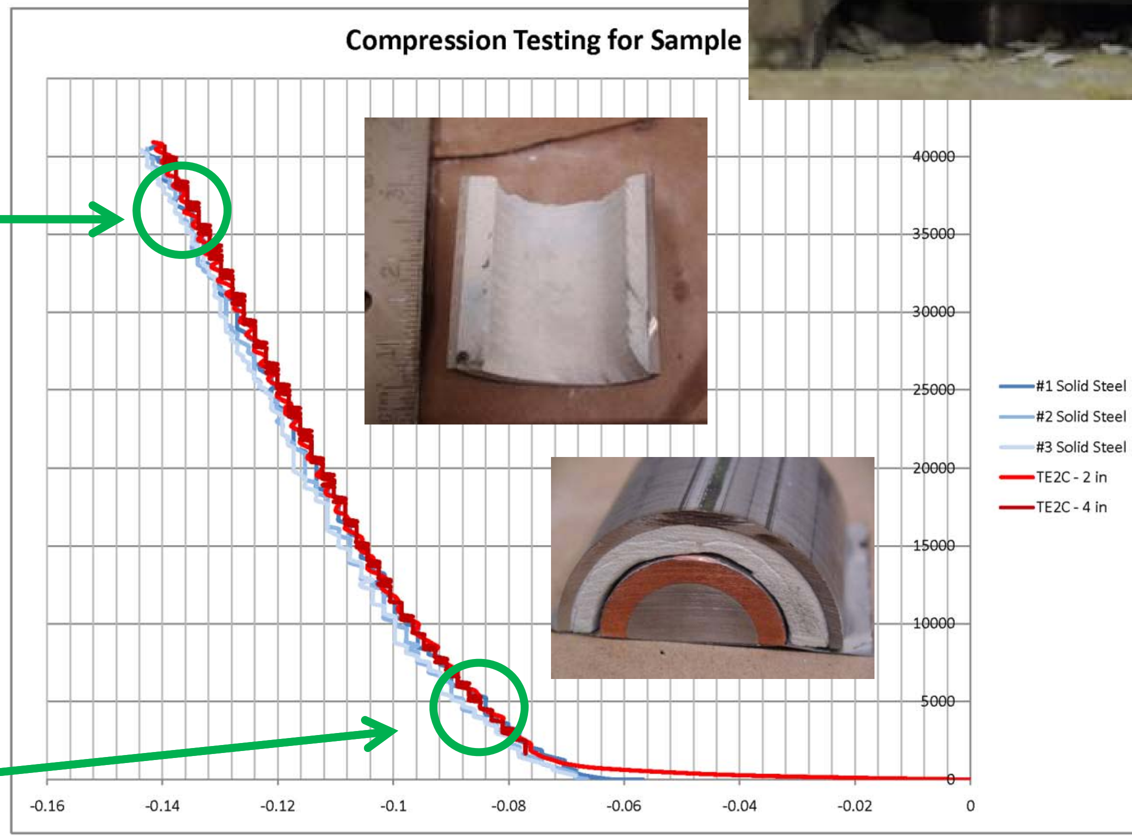




Mechanical Testing

Compression Test

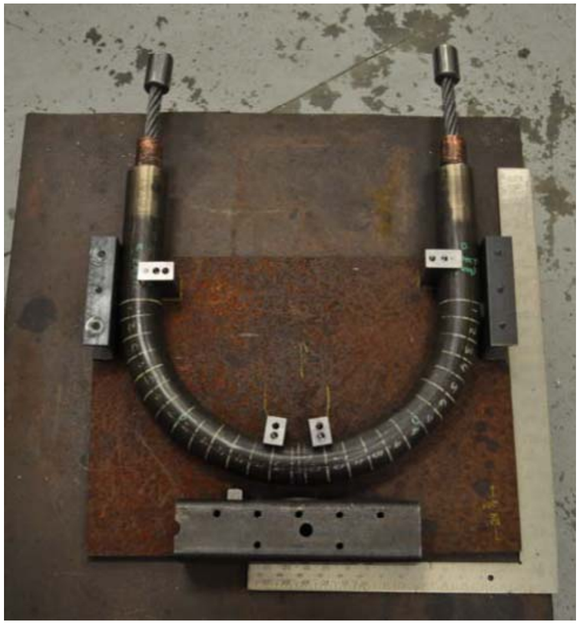
- No Apparent failure of MgO at pressures as high as 65MPa
- FEA analysis shows Mid ELM Coil max operating compressive MgO loading is less than 7MPa

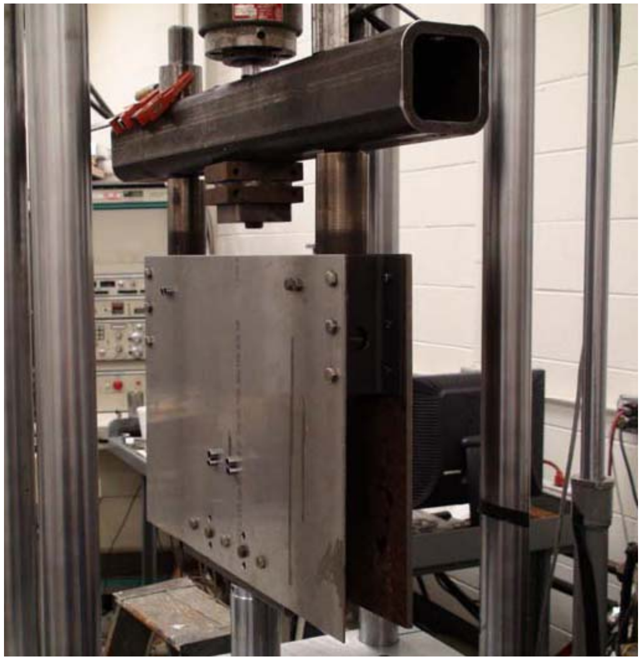


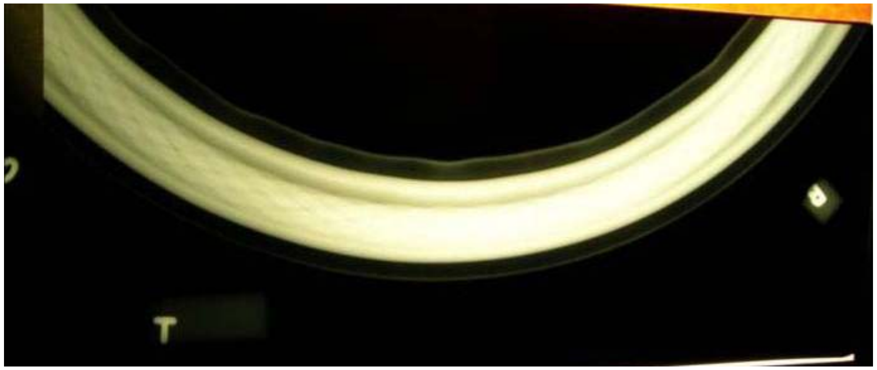
Mechanical Testing

U Bend Cyclical Testing

- 30,000 Cycles applied at 51KN = 1.6x calculated maximum load of 31KN
- X-Ray Shows “No Shifting of Copper”. (smallest feature or porosity X-Ray technique can identify is .75mm)
- Electrical testing and dissection look good

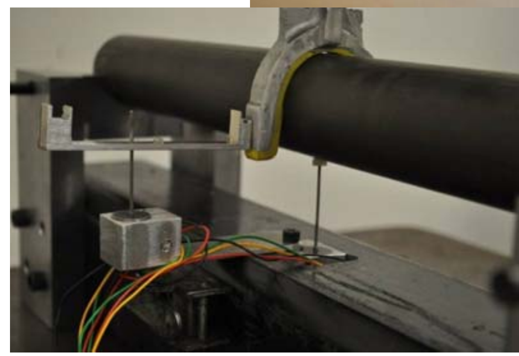


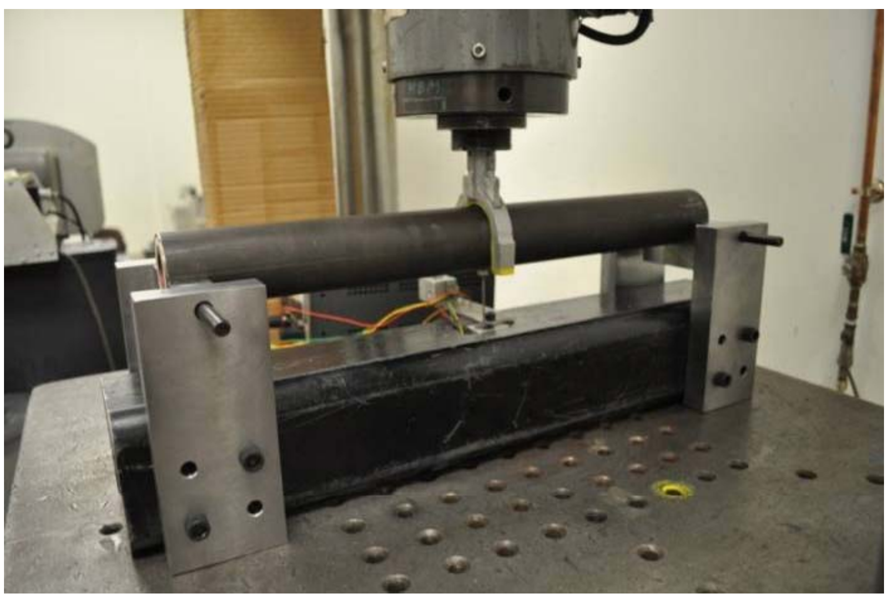


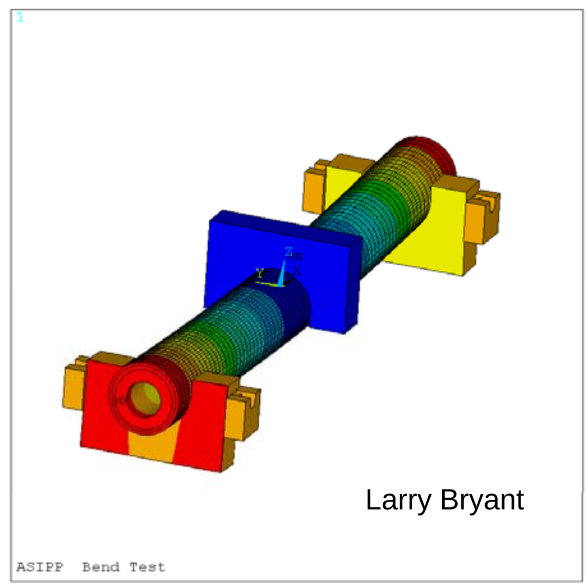


Mechanical Testing Beam Bending

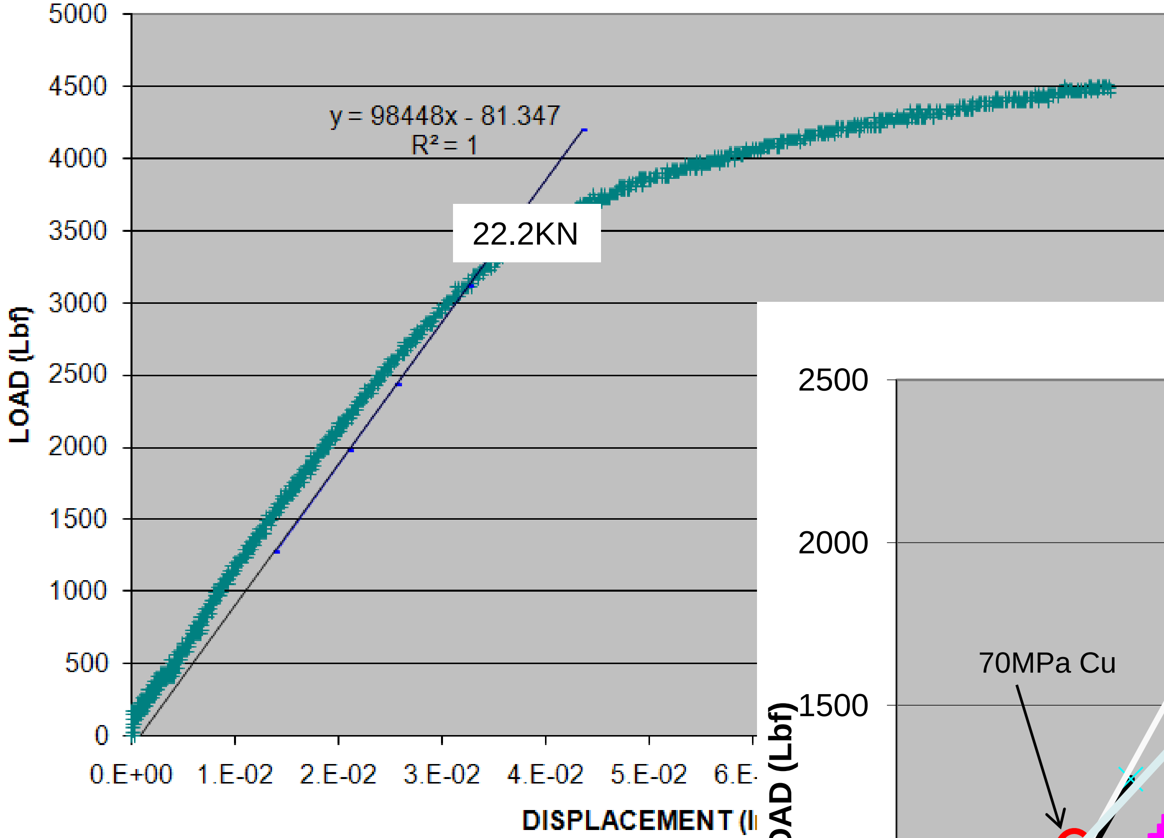
- Three samples tested one of each type all at room temperature
- FEA and Beam formulas used to compare test results to analytical results

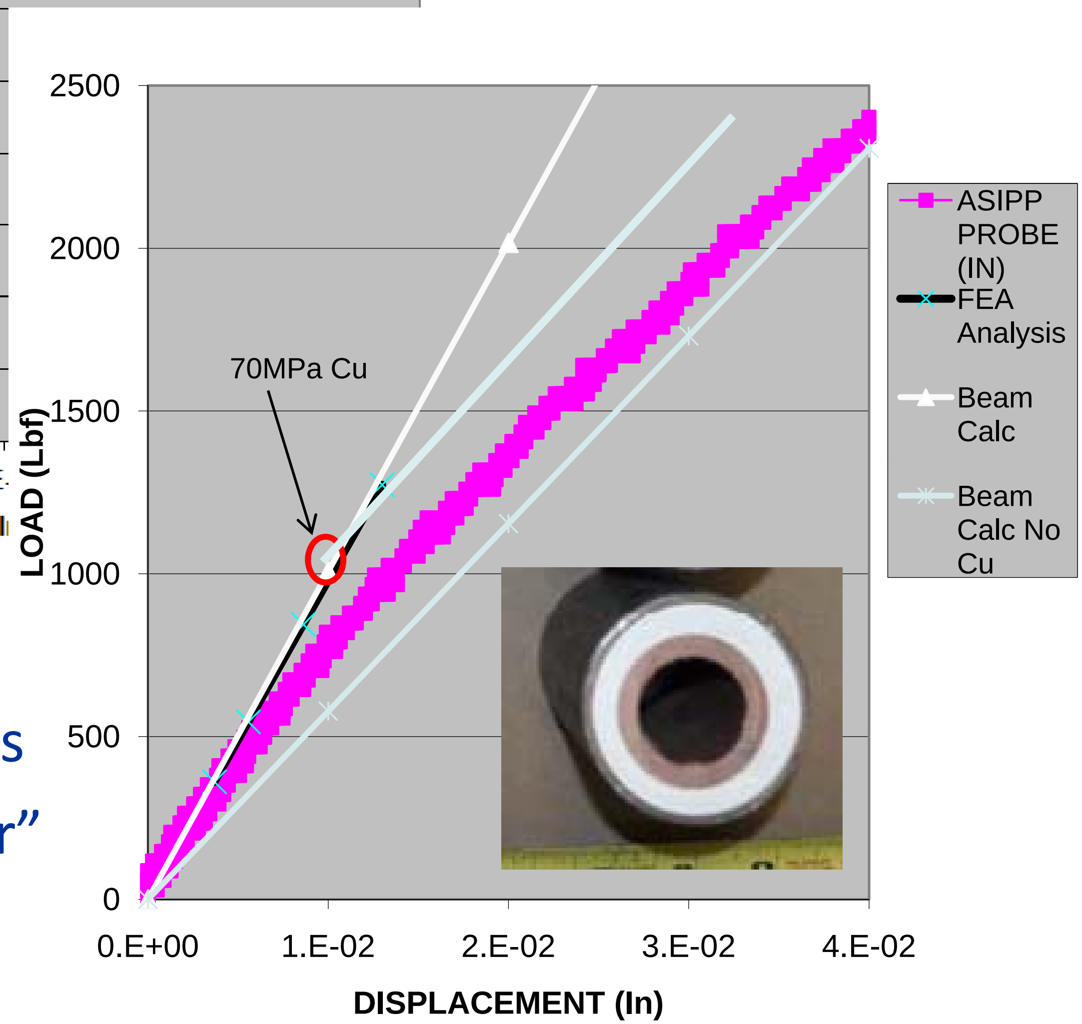






Bend Test Result vs Analytical Prediction





- VS Test Result has good agreement with FEA analysis
- ELM test result looks "softer" than FEA prediction

Mechanical Testing Conclusions

- Shear strength of MgO interface is low however shear strength of MgO interface is not critical. Performance in compression IS critical.
- MgO can handle compression at levels exceeding the design point by a factor of 9 to 10.
- Cyclical loading of bent conductor at 1.6x operating loads does not appear to damage or shift the conductor
- Will repeat bend test to better understand discrepancy with analytic result

Outline

- Design
  - Design Overview
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- Analysis
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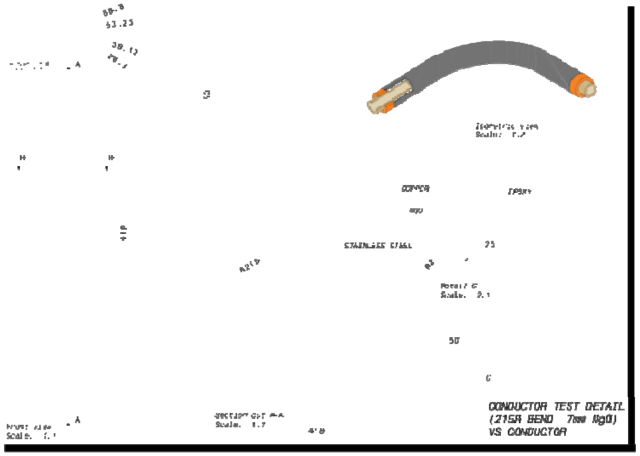
  - Electromagnetic Opera Analysis
  - Mechanical Stress Analysis
- Testing
  - Mechanical
  - **Electrical Testing**
- Summary

Electrical Test Sample Preparation

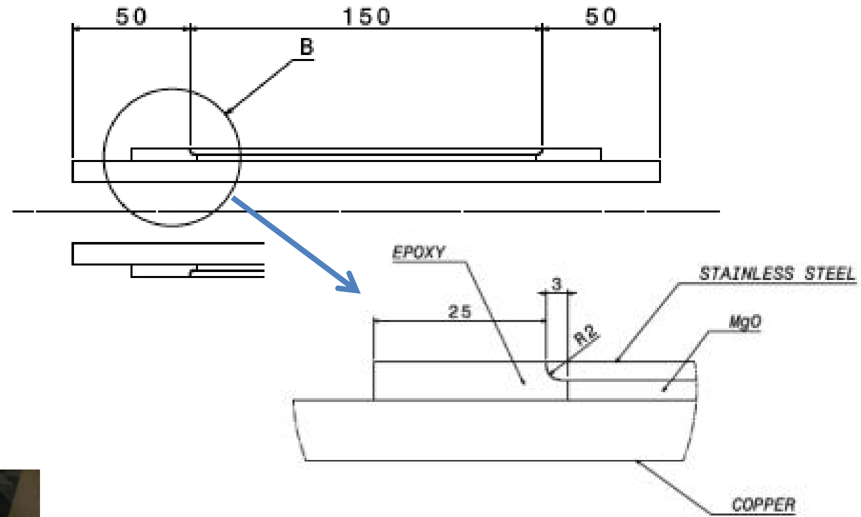
- Samples bent to the design bend radius of 215 mm for electrical testing
- Some ripples were observed in the jacket
  - ➢ Attributed to the use of an existing fixture, utilized to save time / reduce cost
  - ➢ MgO conformed to ripples in Stainless Steel

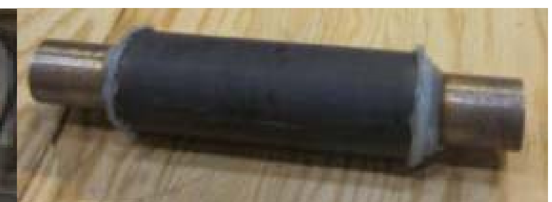


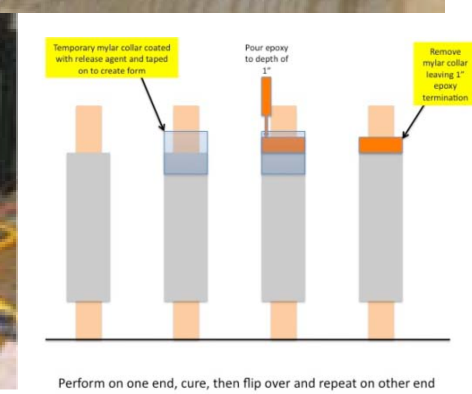
Electrical Test Sample Preparation

- RTV-based sealing method

1)Cut piece
2)Heat to 450°C for 4 hour
3)Remove from oven, place in hood flooded with dry N_2
4)Let cool to 100°C
5)Apply bead of RTV 108

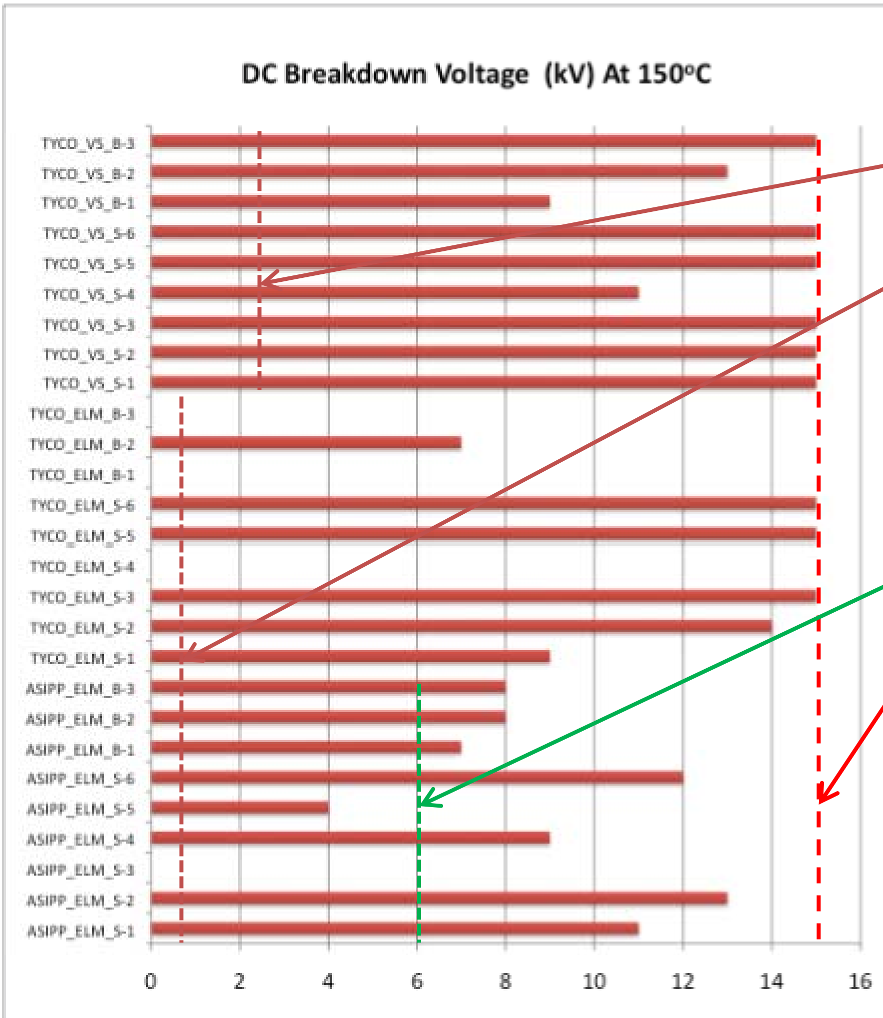






Electrical Testing

- DC Breakdown voltage at 150^{o}C



- ITER Max. Operating Voltages
  - Require VS = 2400 V
  - Require ELM = 180 V

- Based on Tyco Eng Guide data
  - Expect 18 kV from Tyco VS
  - Expect 18 kV from Tyco ELM
  - Expect 6 kV from ASIPP ELM

- Test set limited to 15kV DC

- All samples broke down at ends
  - some at RTV/MgO Interface
  - some creepage flashover

- 23 of 27 samples tested

Electrical Testing- Result

- Electrical test results were favourable - no major surprises were identified.
- Leakage resistance was better than predicted using the TYCO engineering data.
- The DC breakdown tests were mostly better than predicted from TYCO engineering data
- Results exceeded design requirement with margin
- Breakdowns occurred at sample ends underscores importance of end terminations /seals

IVC Summary and Plans

- We have successfully completed production of prototype SSMIC Conductor
  - Mechanical and Electrical Testing show good results
  - Future testing to include proof of radiation resistance
- Preliminary analysis has led to a strong understanding of the EM loading and thermal stress issues
  - High stress regions require further design iterations

IVC Summary and Plans

- Design is continuing into a Final Design Phase in collaboration with ASIPP to include:
  - Fabrication of SSMIC conductor with final SSMIC geometry
  - Full scale Mid ELM Coil prototype
  - VS Coil Prototype Section
  - Final Design and Analysis of all coils
  - Mechanical and Electrical R&D Testing of Prototypes

END

Questions?

Michael Kalish
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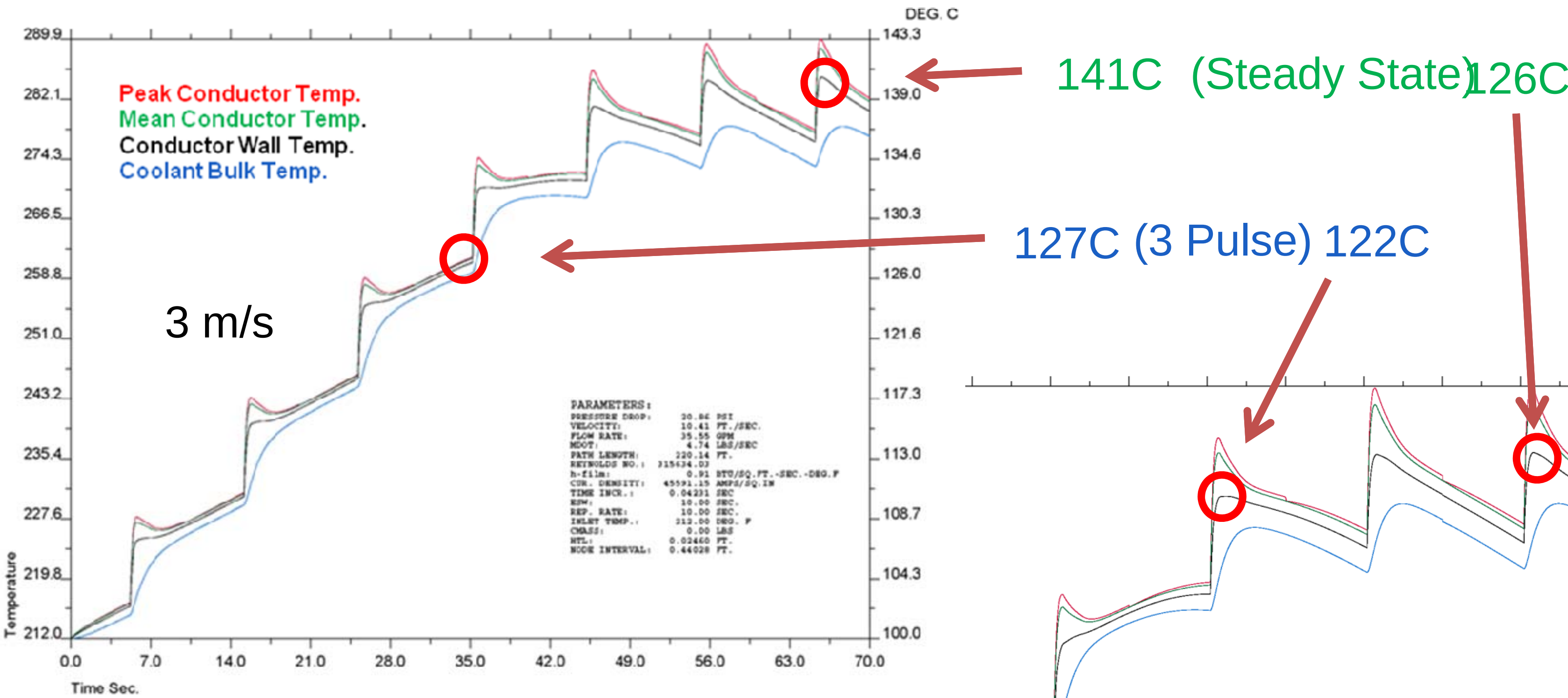
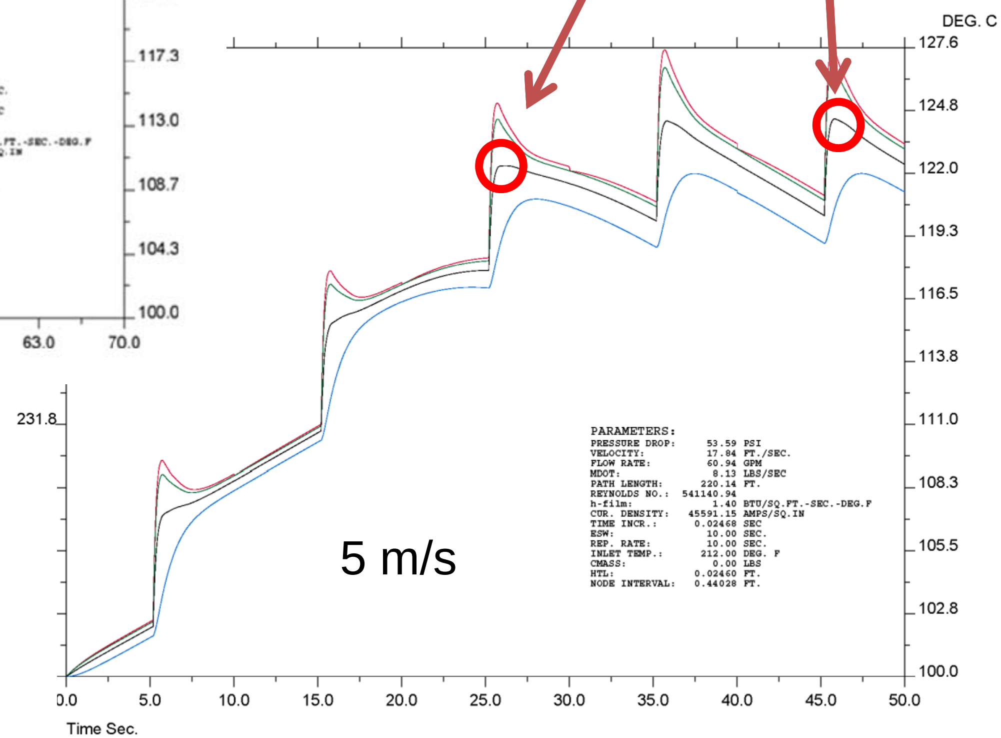
VS Coil and Feeders With Nuclear Heating Pulsed Input



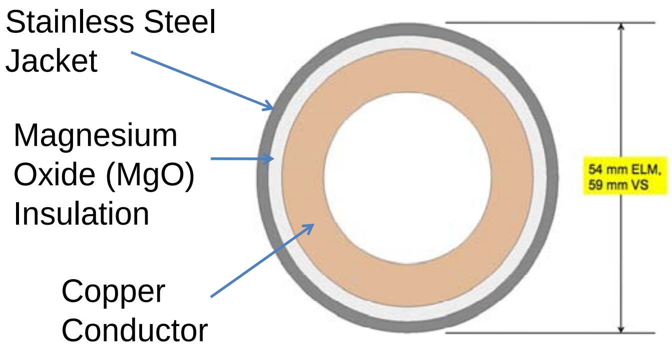


- Increased flow velocity from 3m/s to 5m/s achieves a 15C decrease in the maximum steady state temperature
- Increased flow velocity from 3m/s to 5m/s achieves a 5C decrease in the maximum temperature after 3 pulses

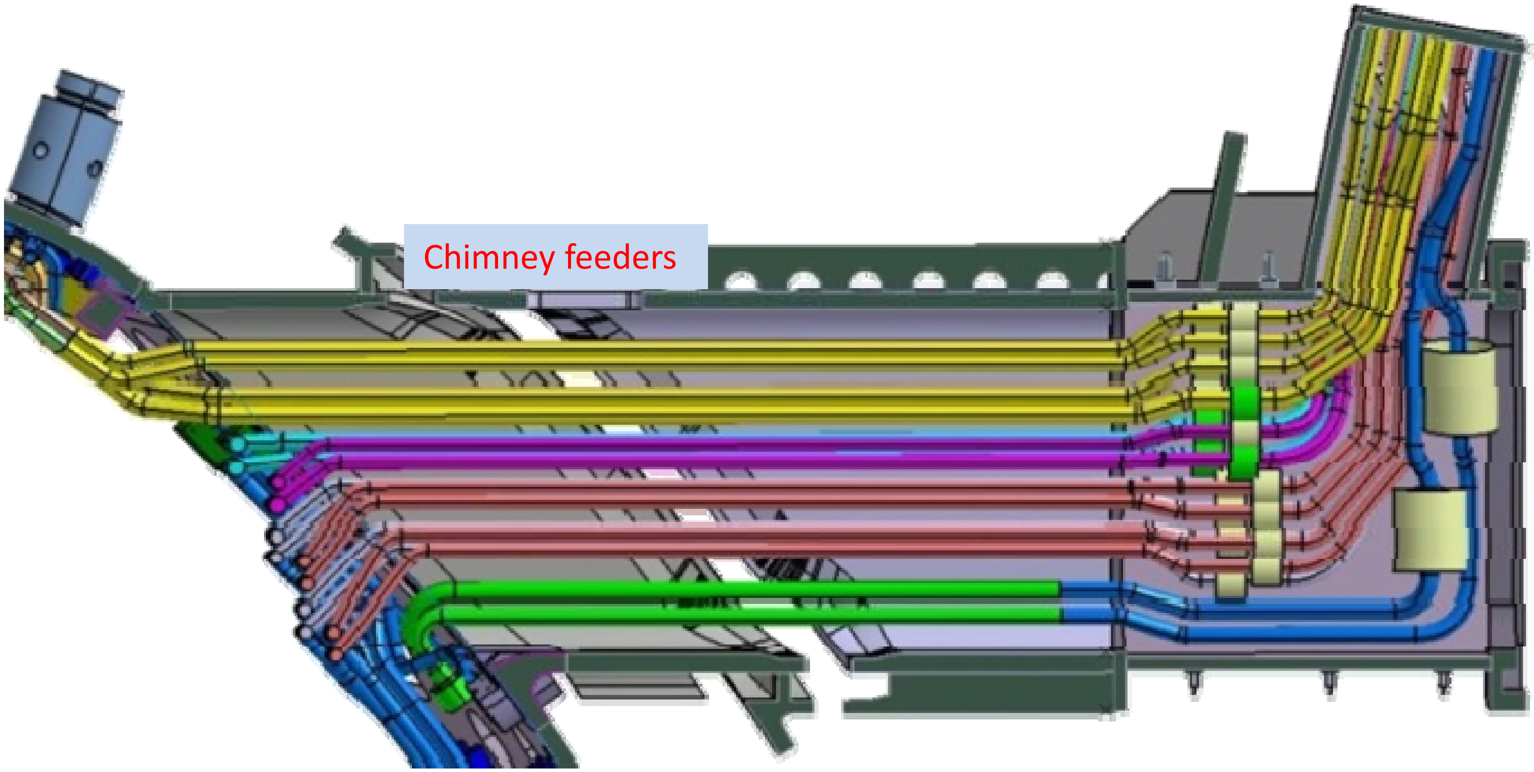
SSMIC Development

- Optimize SSMIC Wall thickness
  - Tradeoff Stainless Steel wall thickness for copper wall thickness. Final jacket thickness will be 4mm
  - More Copper smaller thermal rise and smaller thermal stress but less stainless steel and higher mechanical stress
  - More SS lower mechanical stress due to EM loads but higher Delta T and higher thermal stress

SSMIC Sample Cross Section



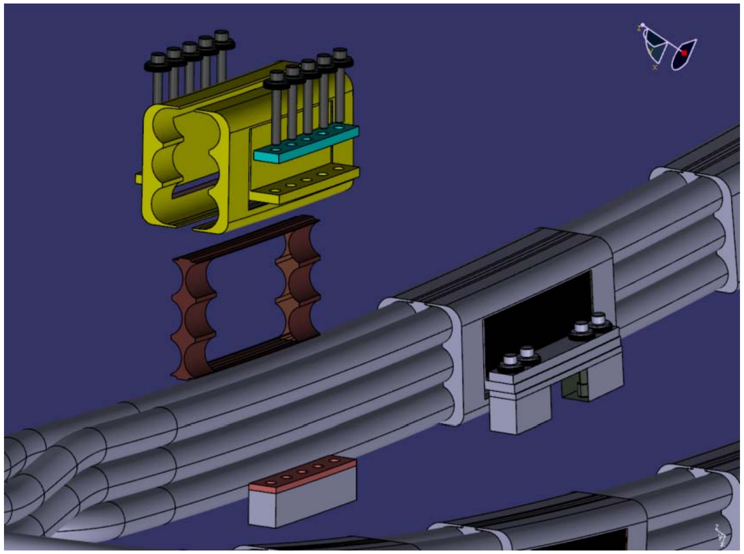
Upper Port Chimney Feeders



•The design of feeder segments in the upper port chimney region which connect to the feeders above and terminate outside the cryostat.

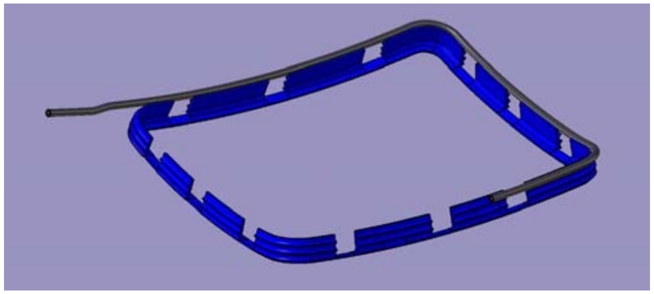
Manufacturing R&D (ASIPP)

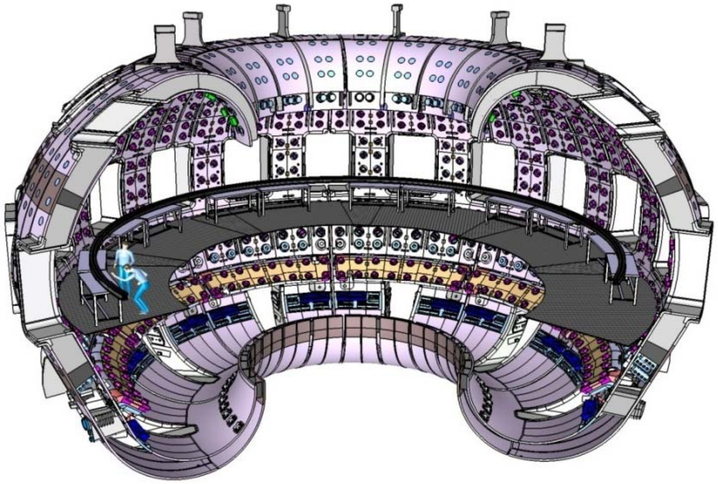
- **Manufacturing Development for Coil Supports & Prototypes:** The coil supports are critical elements of the ELM design. They must reach extremely high electromagnetic loads at frequencies from DC to 5 Hz, must flex to reduce thermal stress, conduct nuclear heat to the SSMIC and VV, and have high fatigue life. The alloy chosen must have good welding and brazing properties and their high numbers require careful development of the manufacturing process to meet technical requirements and cost objectives. In this task, manufacturing processes will be studied, the best option will be identified, and prototypes will be produced that will be used for the prototype mid-ELM coil.



Manufactuing (ASIPP)

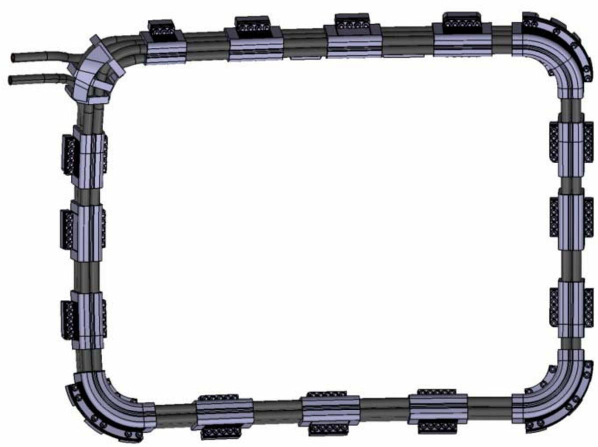
- **ELM and VS Coil Manufacturing Process Development:** This will be a manufacturing study aimed at determining the methods necessary to fabricate the ELM and IVC coils to meet technical and cost objectives. Major areas of study:
  - Precision forming of SSMIC to form the coil turns, joggles, & lead-out areas.
  - Assembly of the ELM coil turns on the coil mandrel, in-place fabrication of coil joints, NDT testing of the joints, and application of the brazing methods developed in the previous task.
  - Coil electrical testing.
  - Measurement of coil tolerances using laser scanners and / or multi-link CMMs.
  - Development of formal coil manufacturing procedures covering all of the above.
  - Developing cost and schedule estimates.
  - Developing plans for a full scale prototype mid-ELM coil and a half scale single turn of a VS coil.
  - Develop QC requirements





Prototypes

- **A full scale prototype mid-ELM coil and a half scale single turn of a VS coil:** These prototypes will use the SSMIC , coil supports, and prototype manufacturing plans developed in the preceding R&D tasks. The prototype ELM coil will be used for the accelerated life test previously described. Or Full Scale 4 turn 90 degrees VS Coil Segment



The ELM prototype will consist of a full size mid-ELM coil, compete with supports.

The VS prototype consist of a single turn, manufactured in quadrants like the VS coil, but half scale. It is still quite large - ~7.5 m. diameter!

SSMIC R&D Results – Mechanical Testing

- Compression
  - ➢ MgO insulation strength in compression is approximately ~10x greater than calculated maximum compressive stresses from combined structural/thermal analyses
- Shear
  - ➢ Low shear strength of MgO bond found during tests has small impact on the behavior of conductor in bending
- Beam Bending
  - ➢ Measured composite beam deflection
  - ➢ Testing and Analysis results in good agreement
- U-bend
  - ➢ Investigated the possibility of the conductor moving within jacket due to shifting of granular MgO
  - ➢ 30,000 cycles at 51 kN (1.6x maximum conductor load, Cat. 3)
  - ➢ No shifting of the copper was observed down level measurable by the X-ray inspection technique (.75 mm)