Design Status of the PEGASUS-III ST

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University of Wisconsin-Madison

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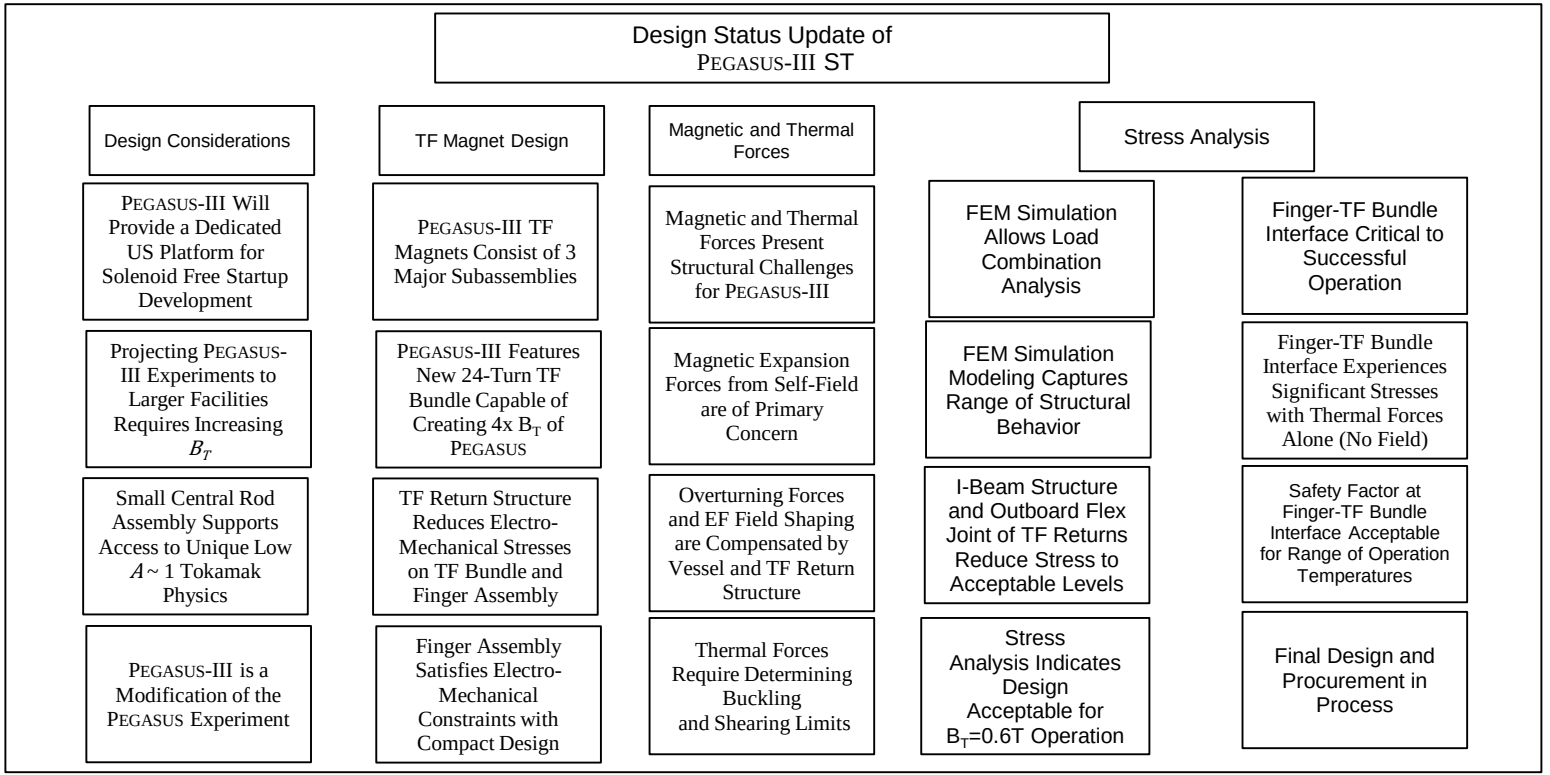
PEGASUS Toroidal Experiment

Layout

12:1 scale Panel size: 8’ x 4’

US Legal
8.5 x 14”

US Letter
8.5 x 11”



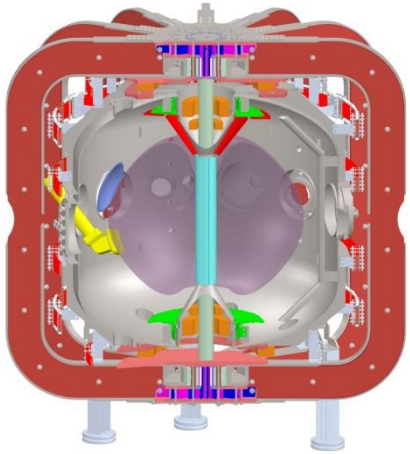
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Design Considerations

PEGASUS-III Will Provide a Dedicated US Platform for Solenoid Free Startup Development

- Compare/contrast/combine concepts for solenoid-free startup in a dedicated facility
  - Local Helicity Injection
  - Coaxial Helicity Injection (Transient, Sustained)
  - EBW assist and sustainment
  - Future: EC, NBI heating and current drive
- Goal: develop validated concept, equipment for 1 MA startup on NSTX-U and beyond
- Construction underway, operational in 2020

PEGASUS-III: US Startup Development Station



Collaborative Enterprise

WISCONSIN UNIVERSITY OF WISCONSIN-MADISON

UNIVERSITY of WASHINGTON

OAK RIDGE National Laboratory

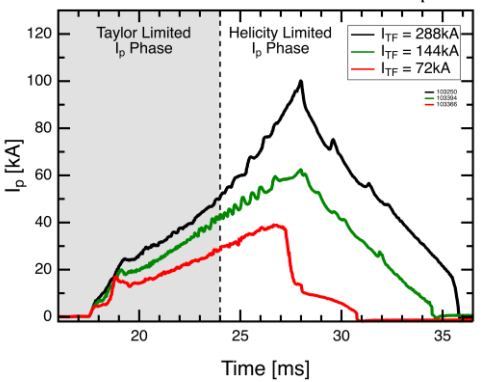
PPPL

Projecting PEGASUS-III Experiments to Larger Facilities Requires Increasing B_T

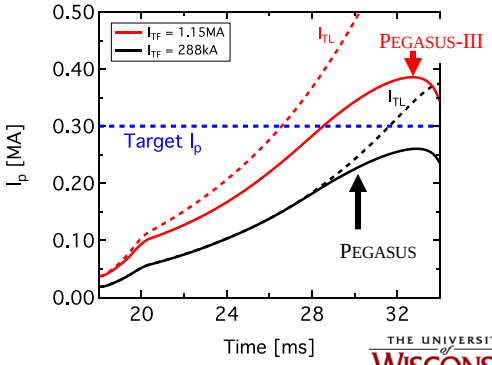
- Increasing B_T is a path to higher I_p
  - I_p constrained by Taylor limit: $I_{TL} \sim \sqrt{I_{TF}}$
  - Increasing initial Taylor limit leads to strong I_p gains
  - New CHI and RF methods require higher B_T

- Physics variations with B_T
  - Magnetic reconnection and current drive mechanisms
  - Effects of stochastic edge on transport properties
  - Current stream stability and edge properties
  - Demonstration of achieving increased I_p

PEGASUS B_T Scaling Experiment: Varying Initial I_{TL} Raises Final I_p



0-D Power-Balance Projections for LHI on PEGASUS-III

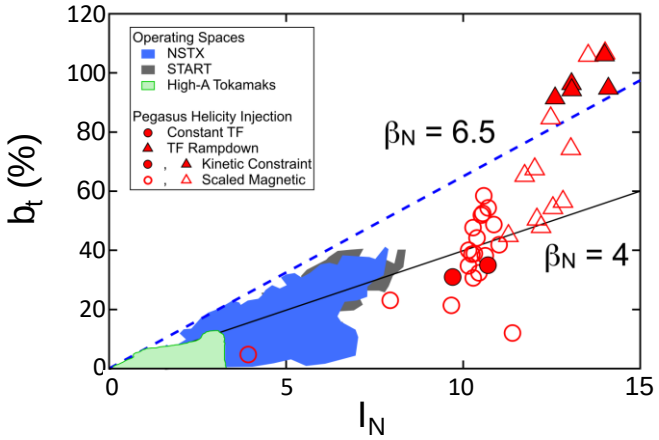


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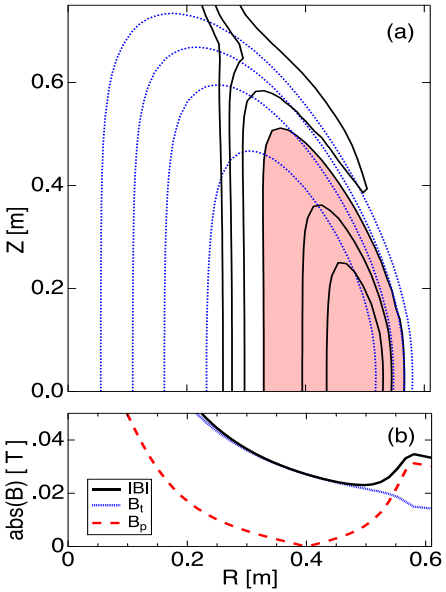
Small Central Rod Assembly Supports Access to Unique Low $A \sim 1$ Tokamak Physics

- Relaxed edge diagnostic requirements
  - Ability to diagnose high I_p plasmas at low B_T with insertable probes
- High-β_t Operating Space*
  - Min $|B|$ well configuration
  - MHD limits at high toroidicity
  - Micro-tearing mode turbulence

Troyon Stability Diagram for Tokamaks, STs



Min $|B|$ Well in $\beta_t \sim 100\%$ Plasma

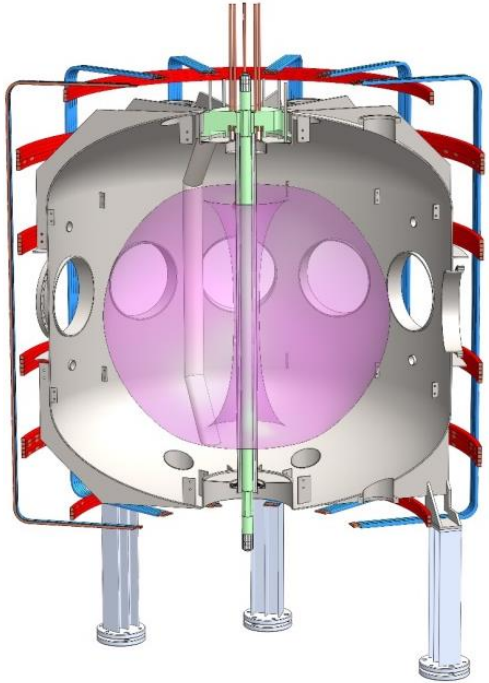


*Schlossberg et al., Phys. Rev. Letters **119** 035001(2017)
*Reusch et al., Phys. Plasmas **25** 056101 (2018)

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PEGASUS-III is a Modification of the PEGASUS Experiment

PEGASUS

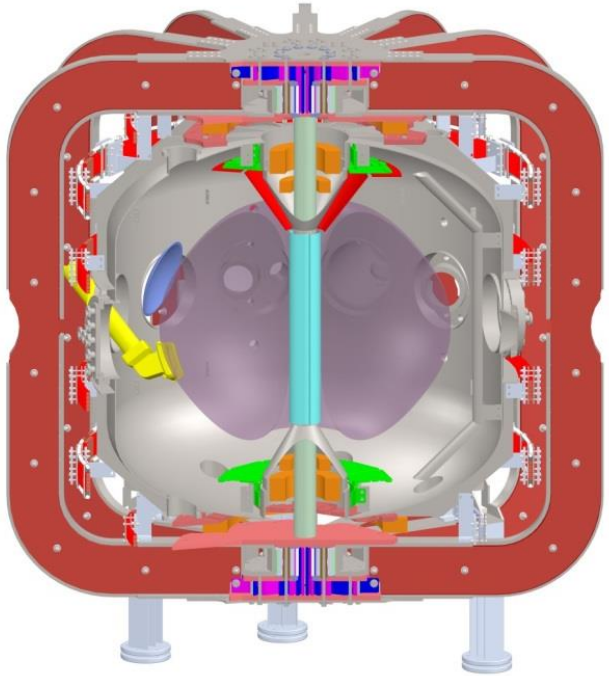


2 m

- Solenoid-free central column
- Stronger, less resistive TF returns
- Torque frame and divertor coils
- CHI, RF, and next generation LHI

Parameter	PEGASUS	PEGASUS-III
I_{TF}	0.288 MA	1.15 MA
N_{TF}	12	24
ψ_{sol} (mWb)	40	0
R_{inner} [cm]	5.5	7.0
TF Conductor Area [cm^2]	13.2	72
$B_{T,max}$ [T] at R_0~0.4 m	0.15	0.58
B_T Flattop [ms]	25	50-100
ΔT_{bundle}	< 10℃	< 20℃
R_0 [cm]	45	45
A	1.15–1.3	1.18–1.35

PEGASUS-III



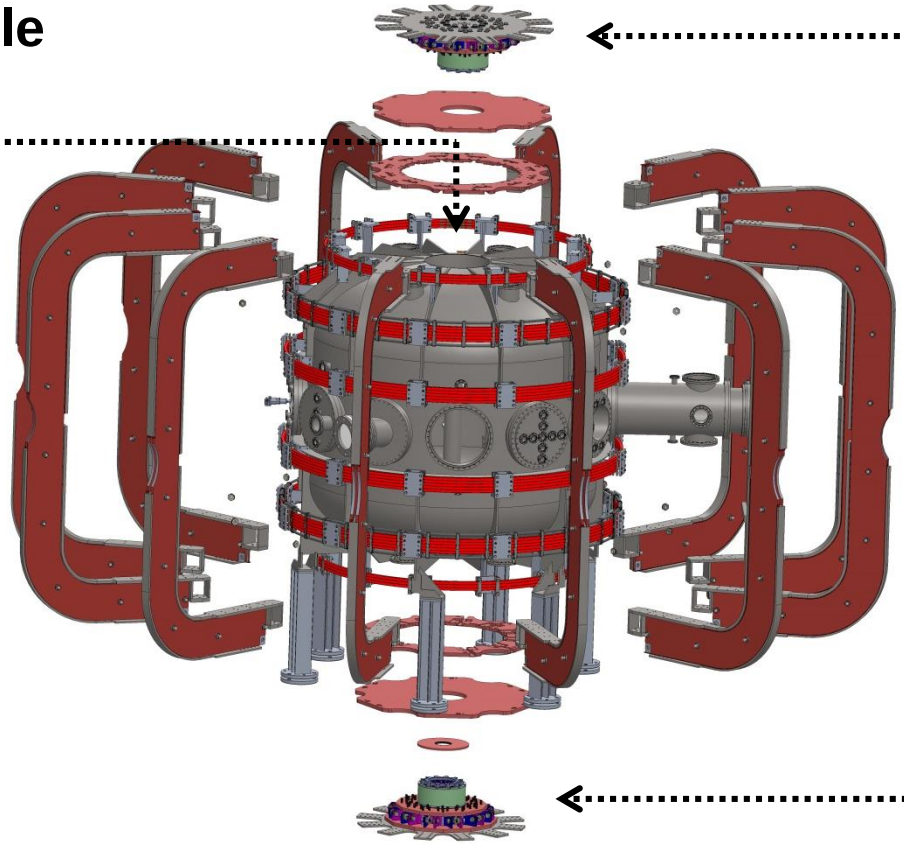
2 m

TF Magnet Design

PEGASUS-III TF Magnets Consist of 3 Major Subassemblies

TF Bundle
(24 turn)





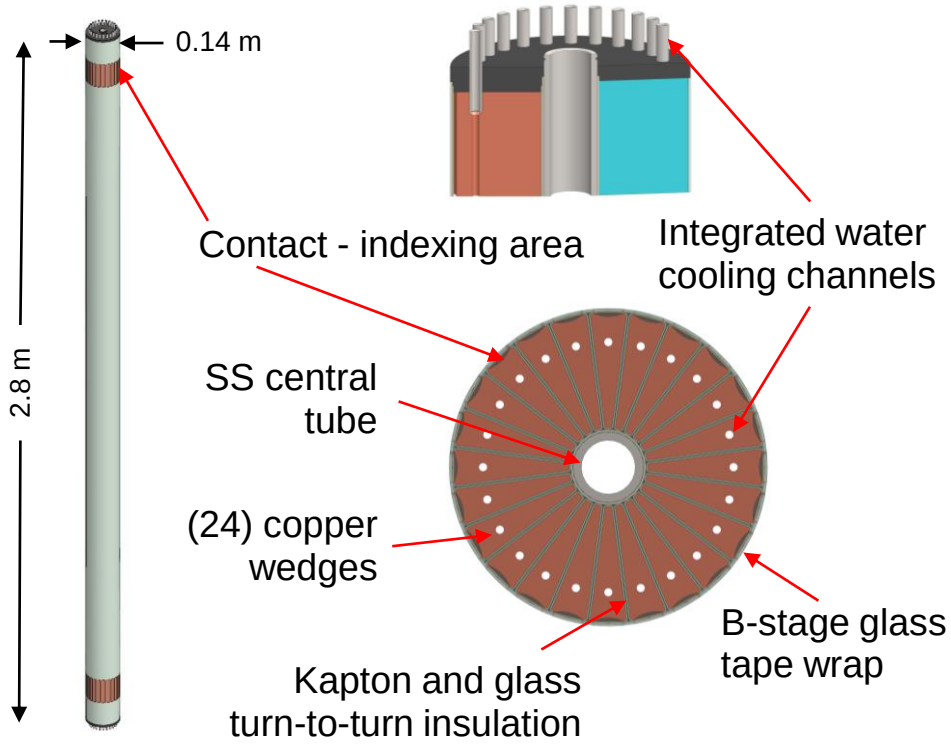
Finger Assembly
(top and bottom)

TF Return Structure
(12 Red “C-Packs”)

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PEGASUS-III Features New 24-Turn TF Bundle Capable of Creating 4x B_T of PEGASUS

TF Bundle



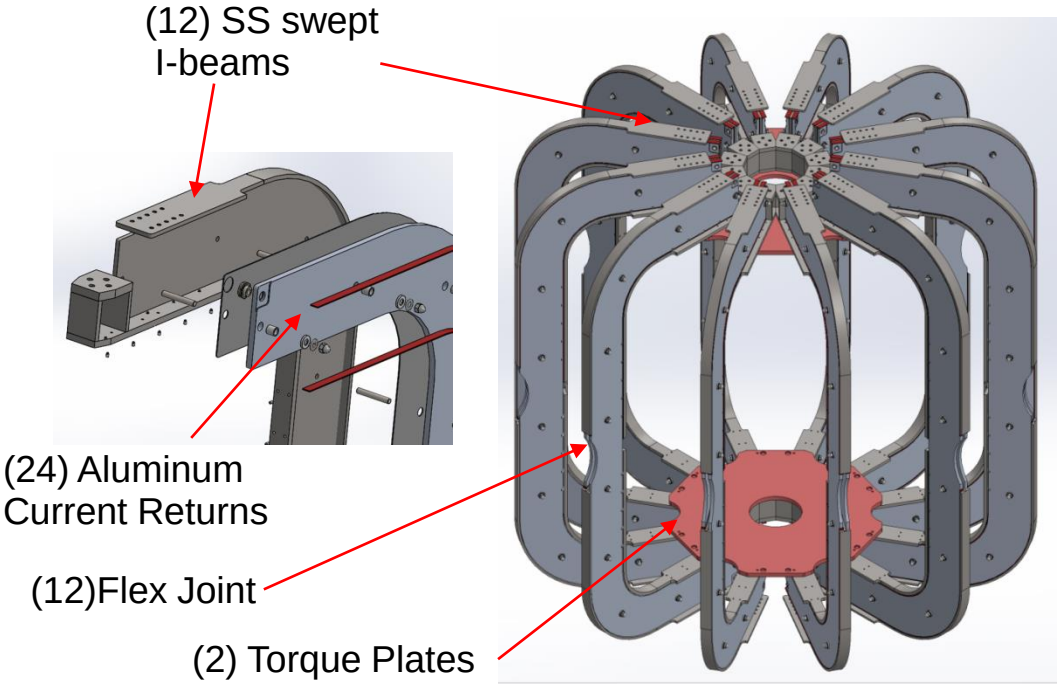
- Maintains access to low-A physics: Diameter 11cm → 14 cm
- Doubles number of turns: 12 → 24
- Expands capability to B_T = 0.6T
- 24 Conductors add significant mechanical strength (72cm^2 area)
- Currently in fabrication

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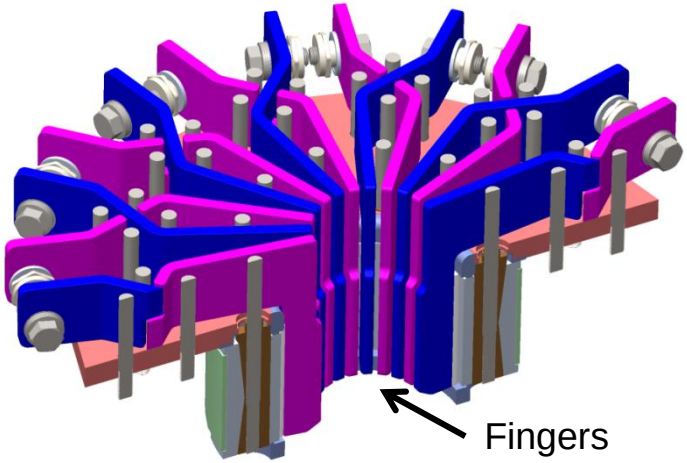
TF Return Structure Reduces Electro-Mechanical Stresses on TF Bundle and Finger Assembly

- Al current returns (24 total) are fastened to both sides of a SS swept I-beam
- Radial and vertical magnetic forces counteract, reducing stress on bundle
- Flex joint at mid-plane minimizes thermal stresses
- SS Swept I-Beam provides both rigidity and torsional stability to return structure

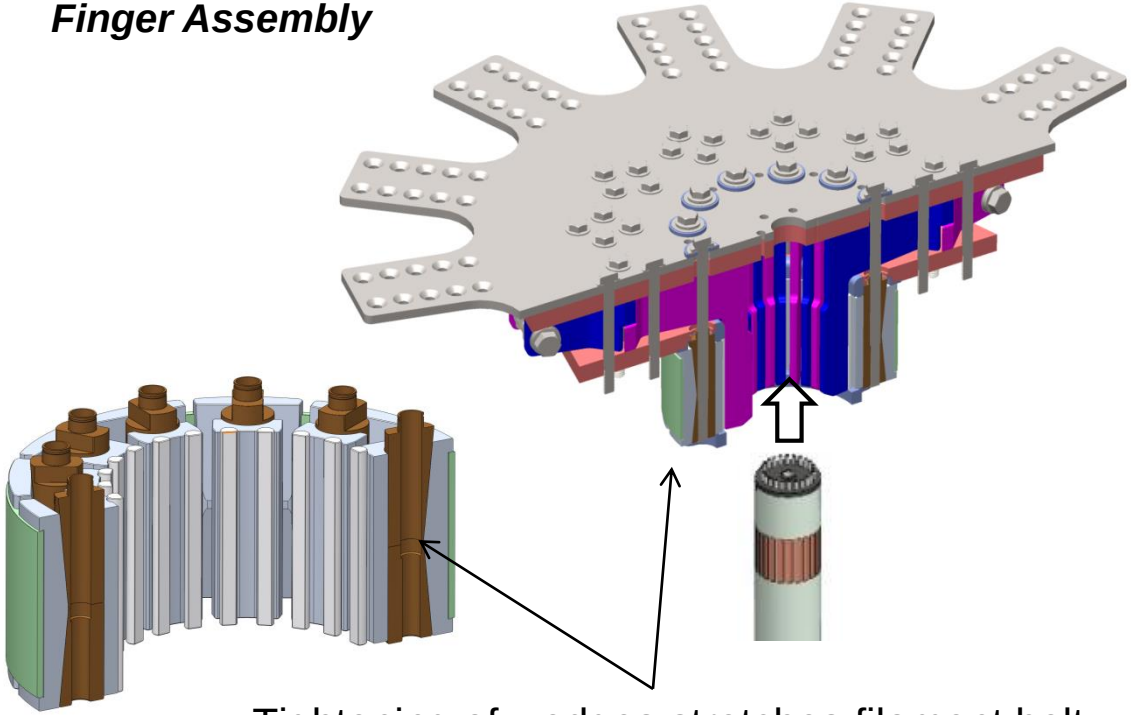
TF Return Structure



Finger Assembly Satisfies Electro-Mechanical Constraints with Compact Design



Finger Assembly



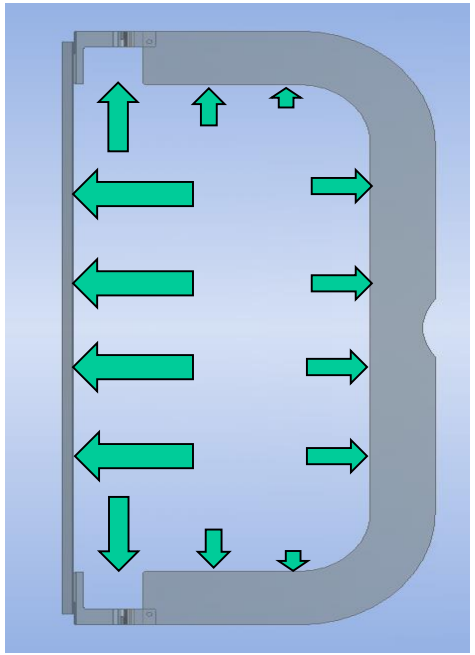
- 30N/mm^2 compressive pressure provided by Finger Assembly
- Minimizes electrical resistance and prevents slipping of Finger at TF Bundle Interface
- Tightening of wedges stretches filament belt and produces radial compression

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Magnetic and Thermal Forces

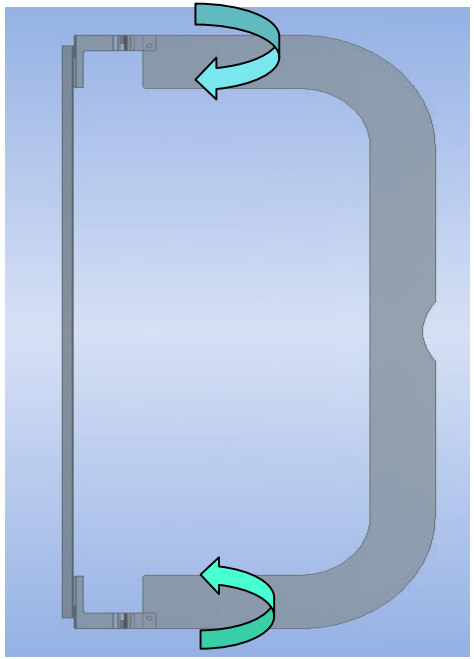
Magnetic and Thermal Forces Present Structural Challenges for PEGASUS-III TF Assembly

Magnetic Self Expansion



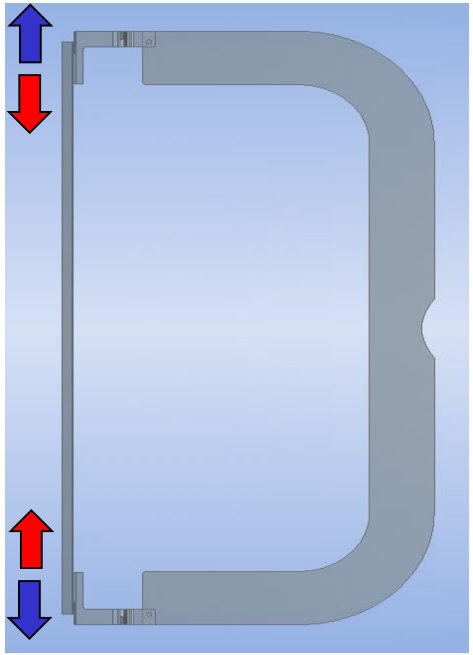
I_{TF} interacting with B_T

Overturning



I_{TF} interacting with B_V

Thermal



OH heating - or -
pre-chilled Bundle

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Magnetic Expansion Forces from Self-Field are of Primary Concern

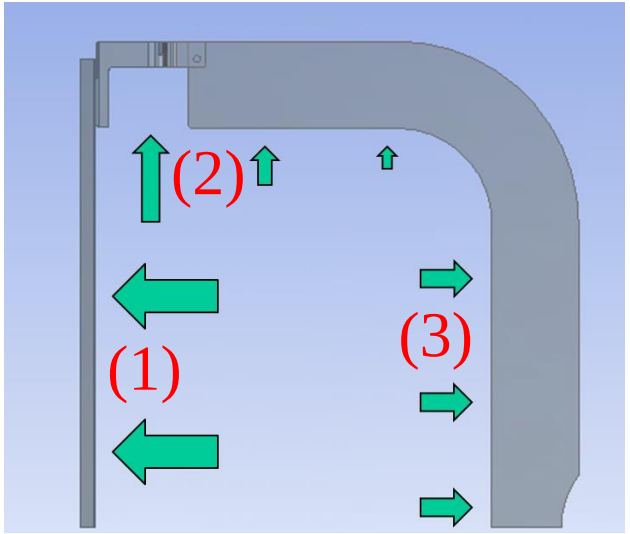
Magnetic Expansion Force:

$$(1),(3)\quad d\boldsymbol{F}_M = \frac{\mu_0}{4\pi}\frac{NI^2}{R}dz \qquad (2)\quad d\boldsymbol{F}_M = \frac{\mu_0}{4\pi}\frac{NI^2}{R}dR$$

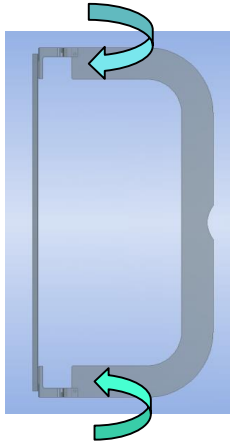
(Stacey, Fusion: an introduction to the physics and technology of magnetic confinement, p.105)

Force Location	Force Magnitude B_T =0.6T	Force Magnitude B_T =0.9T	Units
(1) Inner Leg	201	452	kN/Turn
(2) Horizontal Leg(s)	17	38	kN/Turn/Side
(3) Outer Leg	9	20	kN/Turn

Forces Applied to Single Turn:



Overturning Forces and EF Field Shaping are Compensated by Vessel and TF Return Structure

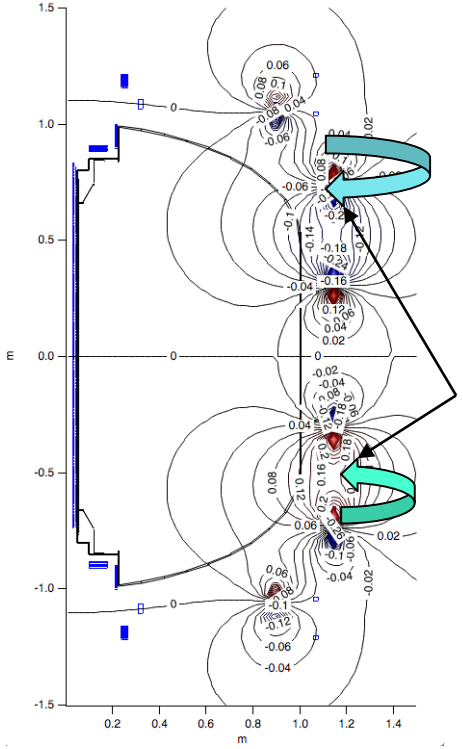


Overturning Force and Torque:

$$\frac{d\boldsymbol{F}}{dR} = I_{TF}B_V \qquad \frac{d\boldsymbol{\tau}}{dR} = I_{TF}B_V R$$

Force/Torque Considered	Magnitude B_T =0.6T	Units
Overturning F	6	kN/turn/side
Overturning τ	4.5	kN-m /turn/side
EF Field Shaping	2.3	kN/turn

EF Field Shaping:



- Force/torque on outer leg of return

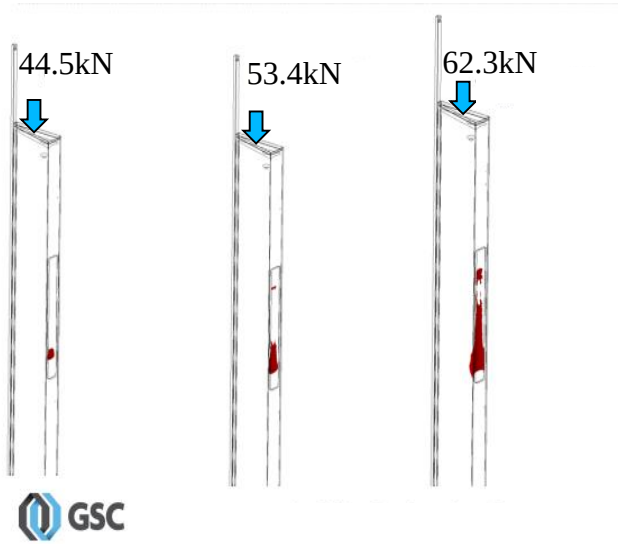
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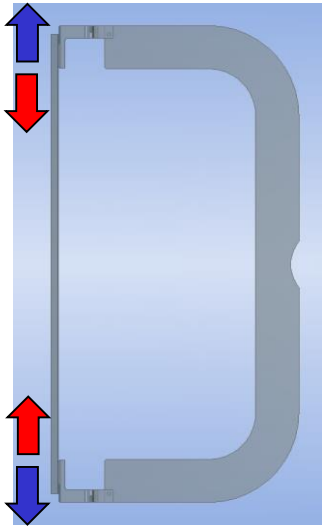
Thermal Forces Require Determining Buckling and Shearing Limits

TF Bundle is Composite Structure:

- Act as single member in compression? Multiple members?

Type of Member in Compression	Buckling Limit
All 24 Turns Act as Single Member ($72cm^2$)	230kN/Turn
Single Turn ($3cm^2$ each)	1kN/turn
Composite Structure	90kN/turn





- Commercial GSC analysis indicates shearing of conductor will occur at ≈ 40kN/turn
- Shearing limit < buckling limit

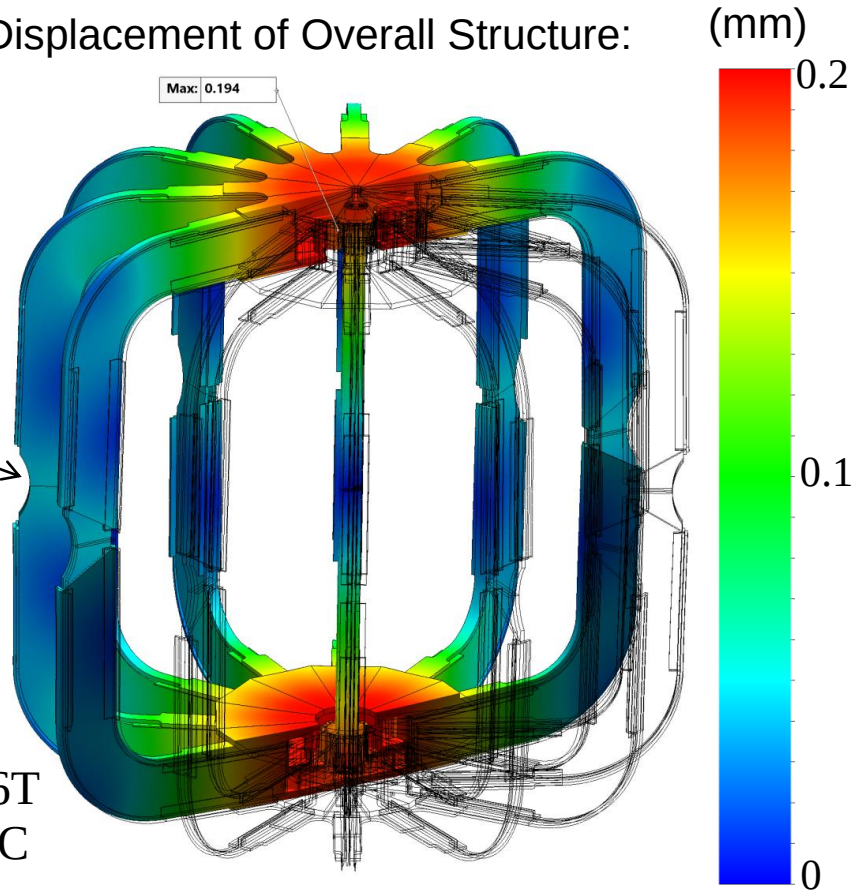
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Stress Analysis

FEM Simulation Allows Load Combination Analysis

- Structure is designed to allow submillimeter displacement
- Semi-Rigid structure opposes magnetic stresses while relieving thermal stresses with outboard flex joint
- Operation temperatures of 10C to 40C analyzed at B_T = 0.6T

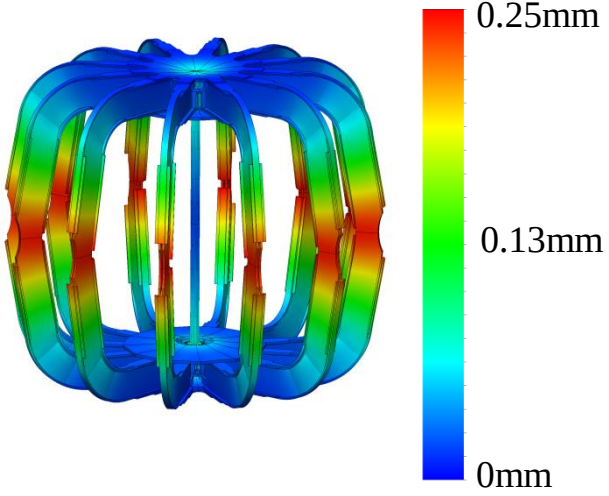
Displacement of Overall Structure:



B_T = 0.6T
T = 25C

FEM Simulation Captures Range of Structural Behavior

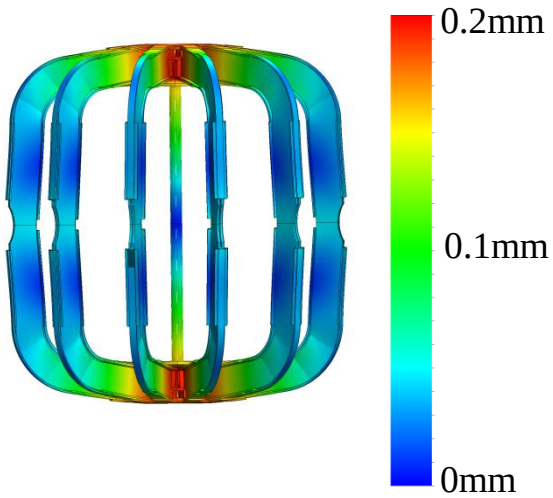
Displacement of Overall Structure:



Cold Bundle

$B_T = 0.6T$

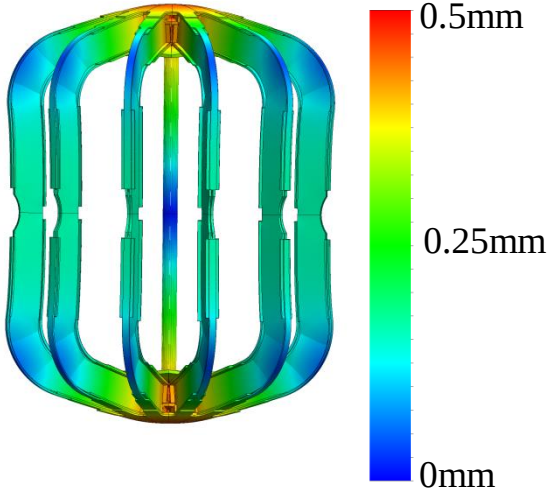
T = 10C



Initial Temperature

$B_T = 0.6T$

T = 25C



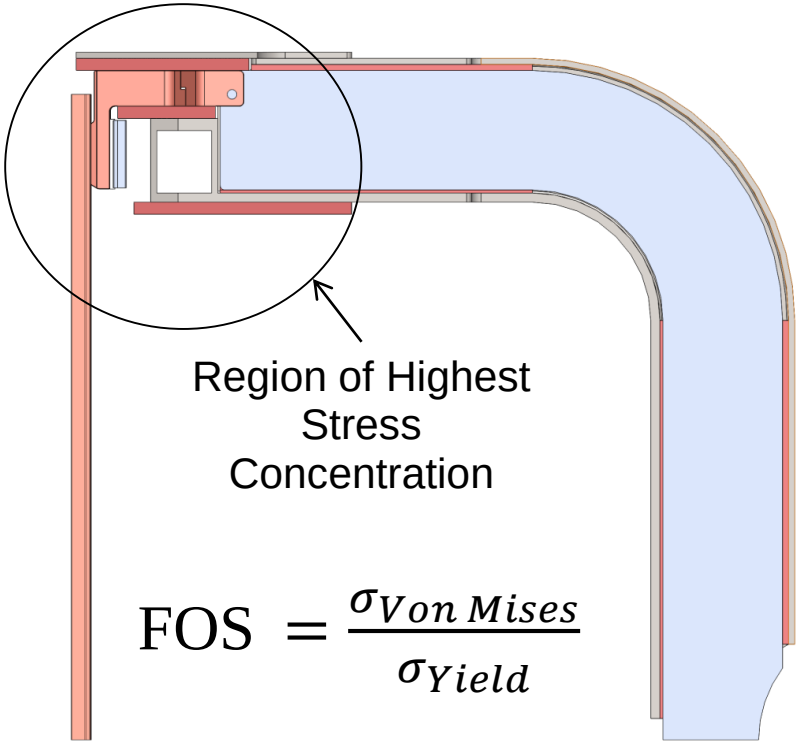
Hot Bundle

$B_T = 0.6T$

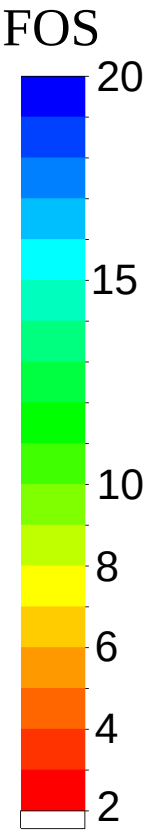
T = 40C

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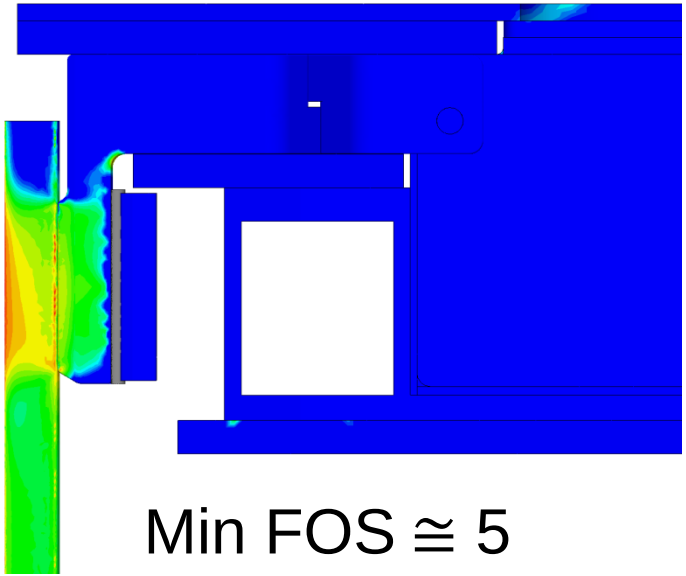
I-Beam Structure and Outboard Flex Joint of TF Returns Reduce Stress to Acceptable Levels



$$FOS = \frac{\sigma_{Von\ Mises}}{\sigma_{Yield}}$$



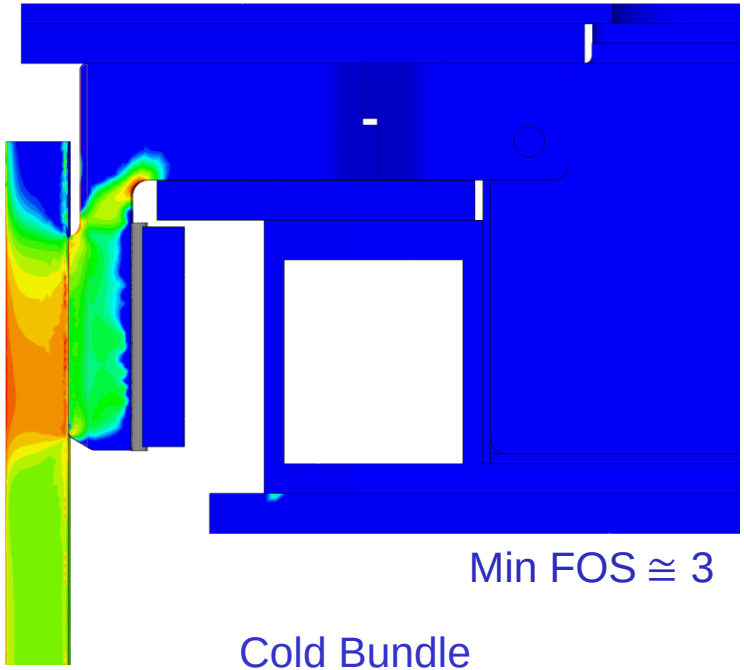
Factor of Safety (FOS) Stress Analysis of Single Turn at **T = 25C**



Min FOS ≅ 5

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Stress Analysis Indicates Design Acceptable for B_T=0.6T Operation

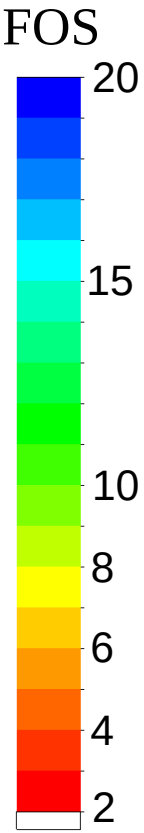


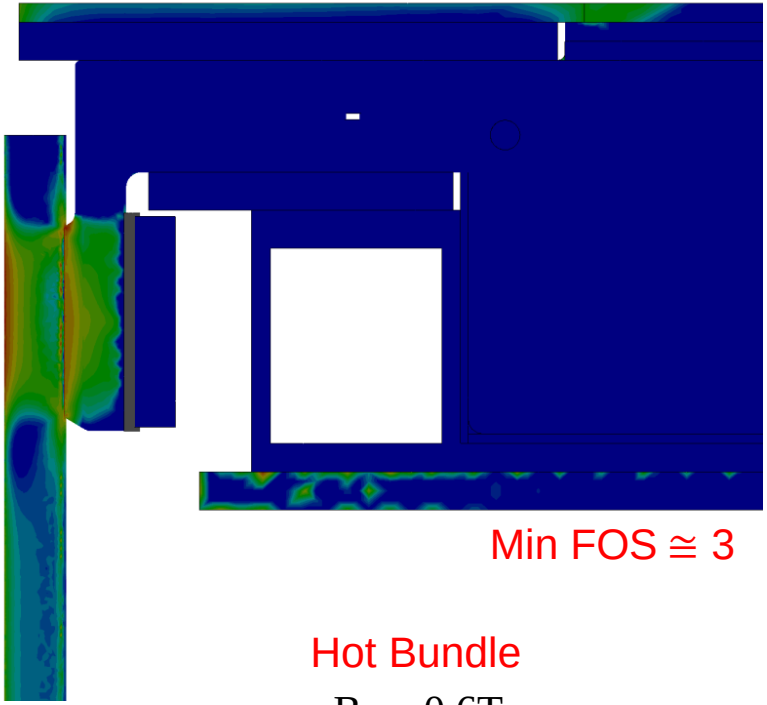
Min FOS ≅ 3

Cold Bundle

B_T = 0.6T

T = 10C





Min FOS ≅ 3

Hot Bundle

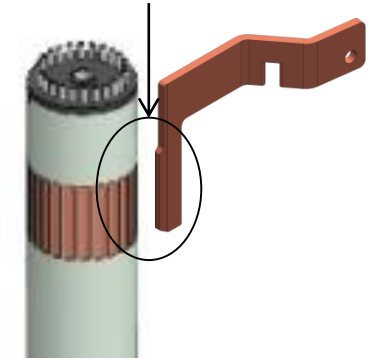
B_T = 0.6T

T = 40C

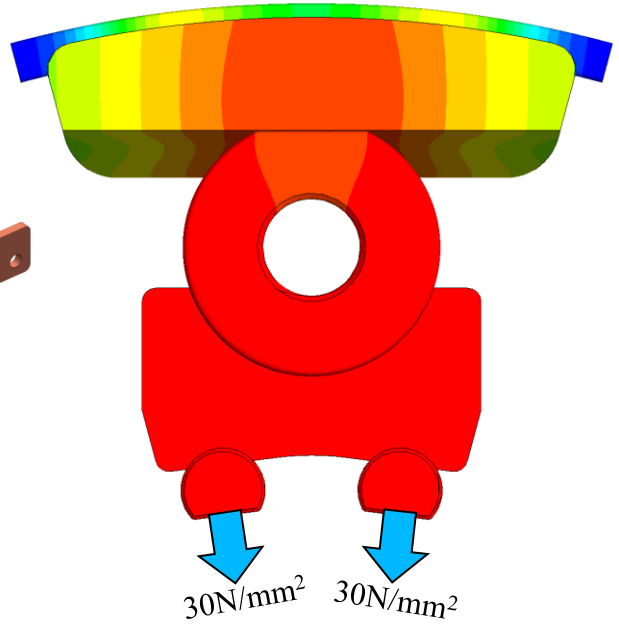
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Finger-TF Bundle Interface Critical to Successful Operation

- Spring-wedge assembly provide 30MPa compression
- Provides both mechanical and electrical connection
- Friction joint with ≥**30kN** of frictional force available
  - Maximum friction force needed is 3.7kN → FOS ≈ 8
- High Frictional FOS → no Finger slip under EM load



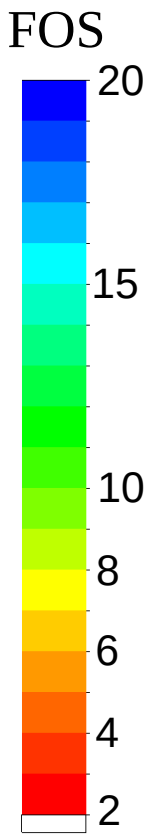
0.5mm displacement from spring-wedge assembly provides 30N/mm^2 on fingers

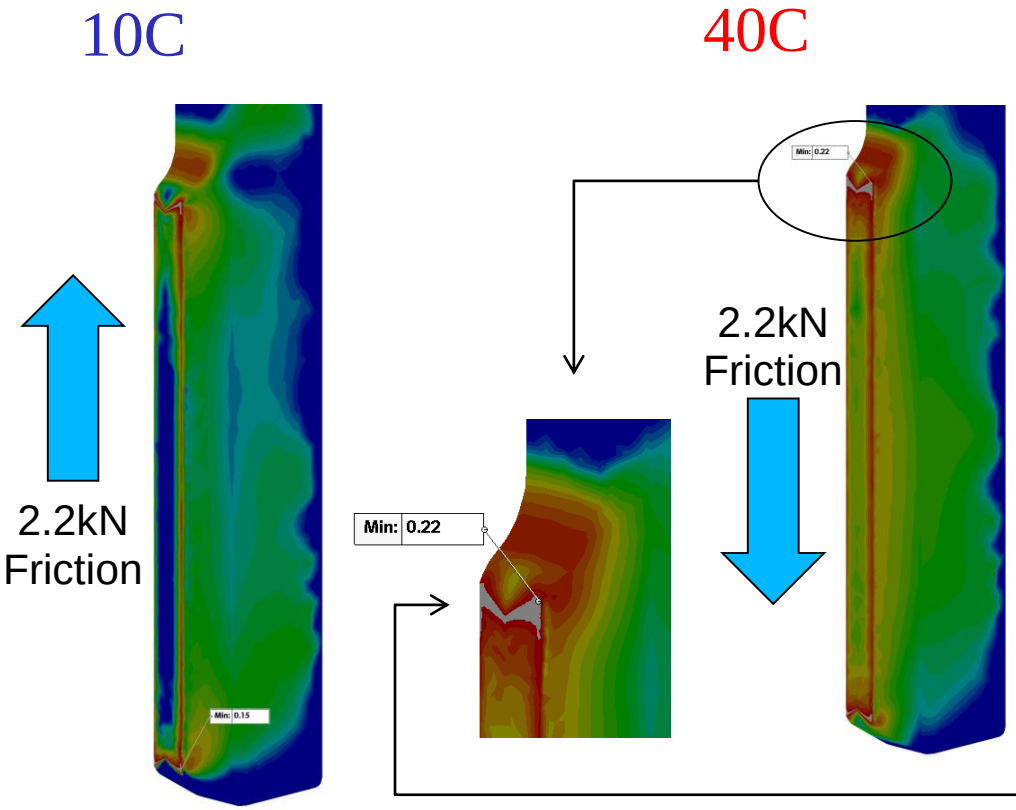


(Finger-TF Bundle Interface)

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Finger-TF Bundle Interface Experiences Significant Stresses with Thermal Forces Alone (No Field)



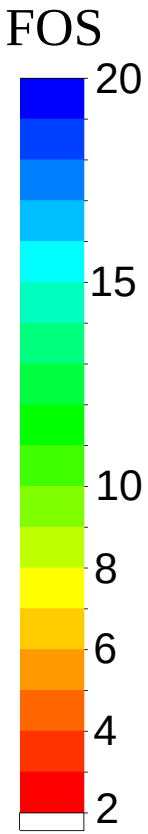


- Thermal expansion of bundle → stress in finger
- Outboard flex joint relieves ≈ 60% of thermal stress
- 30MPa radial compression adds to stress in finger
- Small-region stress concentration will conform finger-surface-profile to the Bundle conductor surface

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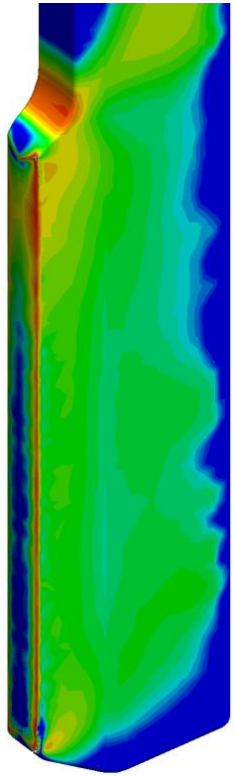
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Safety Factor at Finger-TF Bundle Interface Acceptable for Range of Operation Temperatures



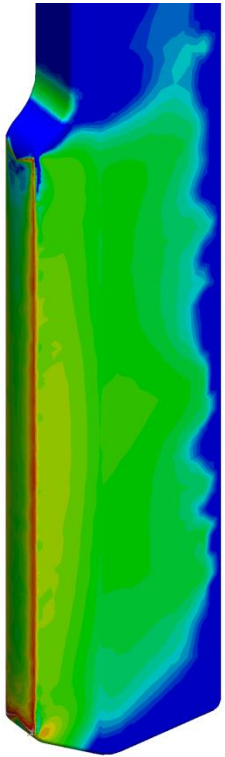
B_T = 0.6T
T = 10C

3.7kN Friction



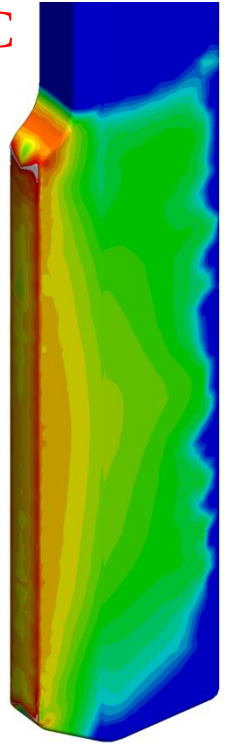
B_T = 0.6T
T = 25C

2.8kN Friction



B_T = 0.6T
T = 40C

1.9kN Friction



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Final Design and Procurement of TF Assemblies in Process

- Conceptual design for TF Magnet capable of 0.6T complete
- Together, structural properties of TF Bundle and Returns minimize stress on TF Bundle
- Novel wedge-spring compression of Finger Assembly provides low contact resistance
- Point design for TF assembly meets desired FOS under expected load conditions

