Operation of Pegasus-III Spherical Tokamak at 0.6 T for Non-Solenoidal Startup Development

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Pegasus-III Experiment

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Pegasus-III: A dedicated platform for solenoid-free startup

Develop helicity injection and microwave-based initiation:
- Local Helicity Injection
- Coaxial Helicity Injection
- Microwave heating, sustainment in over-dense plasmas

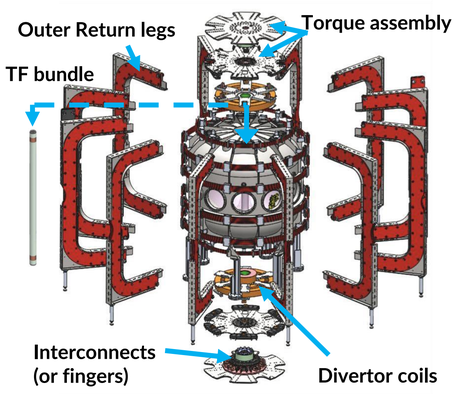
Field diagnostics relevant to tokamak startup conditions

Develop startup methods and components consistent with relevant material, accessibility constraints

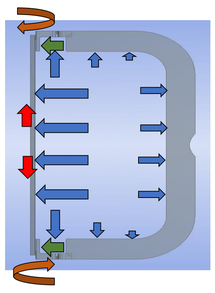
Requires operation at relevant toroidal magnetic field for MA-class STs and Advanced Tokamaks
- Helicity injection scales with initial toroidal flux
- Wave resonances set by field
- Toroidal Field coil upgraded to 0.6 T



Toroidal field coil designed for higher field

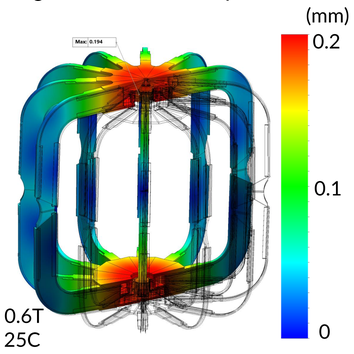


Factor of 4 increase in B_T with 8 × increase in forces [1]
- 24-turn coil with 48 kA per turn for 1.15 MA rod current
- Maintain low aspect ratio ($A_{min} = 1.2$)
- Centerstack solenoid removed for larger, water-cooled 24-turn copper conductors in TF bundle
- Outer return legs significantly bigger and reinforced
- Interconnects need to handle electromagnetic forces at 3 T



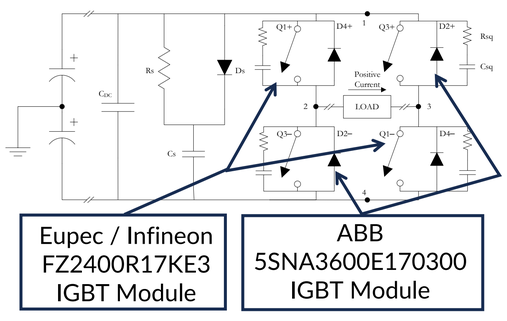
Forces on TF coil accommodated in design [1]:
- Magnetic self-expansion force ($\sim 200\ kN$)
- Interconnect clamping force ($\sim 30\ kN$)
- Thermal expansion of TF bundle ($\sim 12\ kN$)
- Magnetic overturning force ($\sim 4\ kN$)

Midplane flex joint relieves stress from magnetic & thermal expansion



- I-beams supporting TF outer return conductors are split at the midplane
- TF outer return conductors act as a hinged clamp relieving ~ half of the strain on the TF bundle
- Finite Element Analysis shows ~100 μm displacements and ~100 μm/m strain at key locations on the coil structure
  - Suggests measurement locations

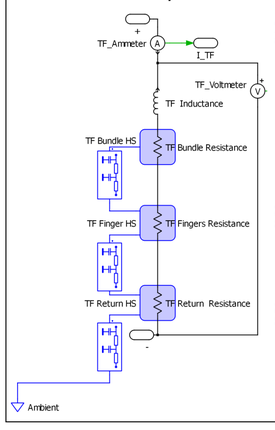
Power supply and coil evaluated for 48 kA operation

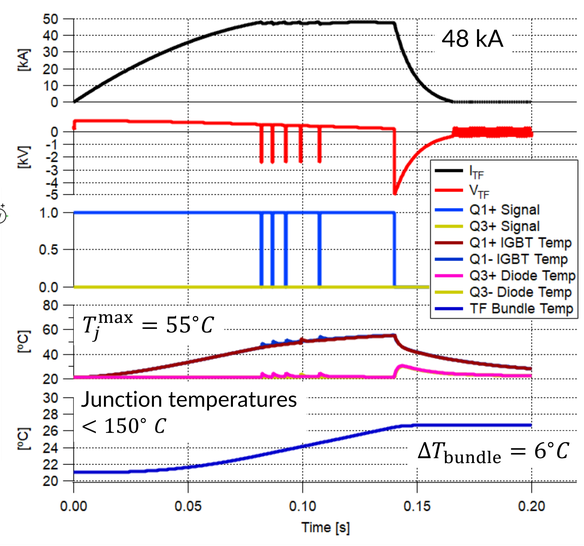


- IGBT modules rated for 3.6 kA steady-state [2]
- Operation at 4 kA per device for > 10 ms is greater than specification for transient pulse
- Need to model switching losses to predict junction temperatures

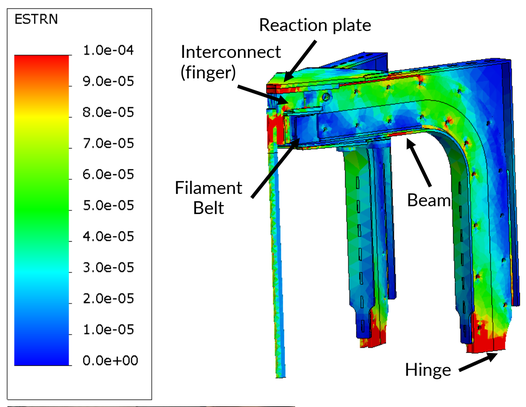
Electrical and thermal circuit modeling of TF coil and power supply shows H-bridges capable of desired pulse

TF coil modeled as separate resistive elements to predict thermal conduction between components

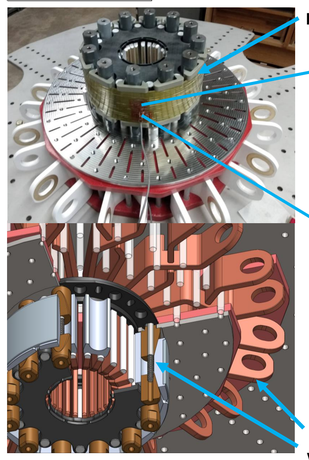




Finite element analysis validated against strain measurements

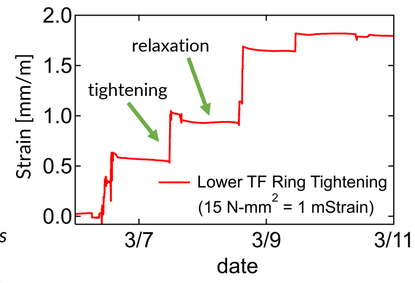


- Thermal expansion creates strain primarily at the interconnects and reaction plate
- Magnetic overturning forces create strain on the beam and at the hinge
- Filament belt applies compression force on interconnects
  - Expected strain on belt $\sim 1 - 2$ mm/m
- Typical predicted maximum strain at key locations is 100 μm/m
  - Gauge sensitivity ~10 μm/m
  - Metals plastically deform at ~ 1 mm/m



Dual-layer strain gauges are affixed to coil structures and wired with shielded twisted pair

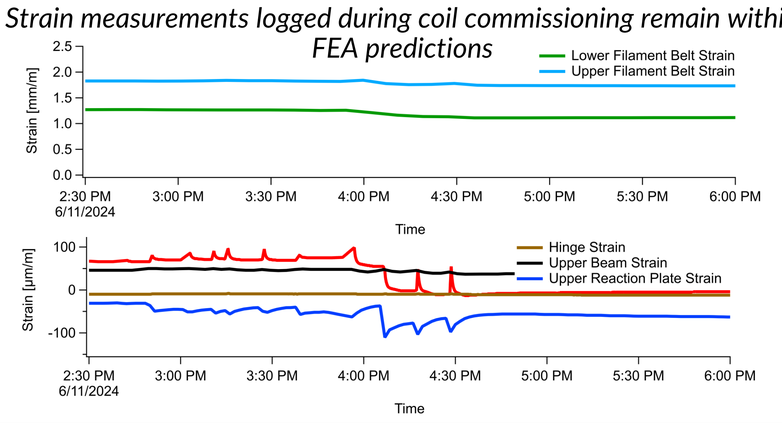
TF Magnet Interconnect Assembly Tightening Achieved Desired Pressure



Strain gauges are wired as Poisson half-bridge to increase sensitivity

Shielded twisted pair wiring for EMI

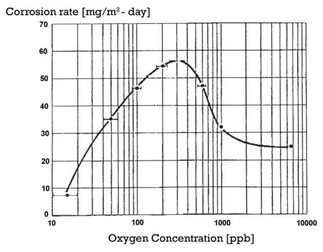
Strain measurements logged during coil commissioning remain within FEA predictions



Chilled water system designed to limit copper corrosion

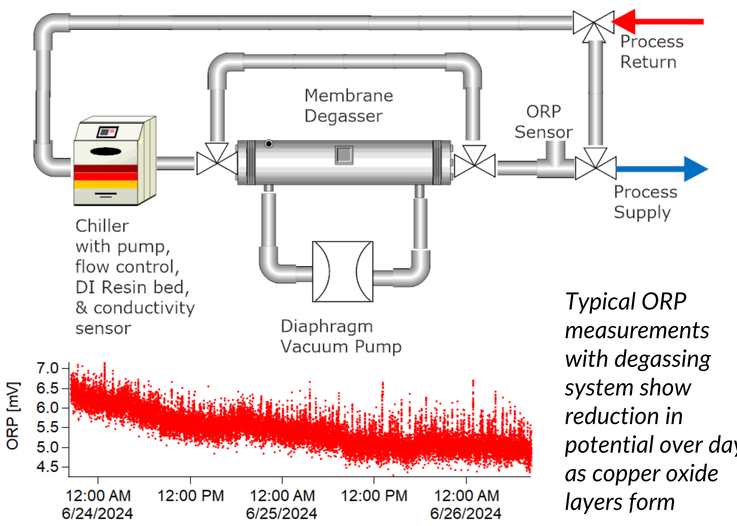
Implement ThermoFlex 10 kW Chiller
- Flow and temperature control
- Conductivity control via DI resin bed

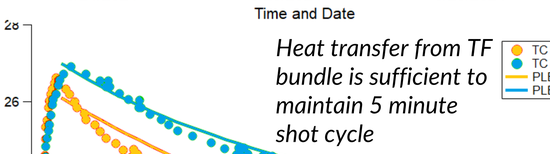
Low conductivity water is highly corrosive
- Reduce corrosion rate by removing dissolved gasses using a 3M Liqui-Cel Membrane Contactor with diaphragm vacuum pump
- Reduce erosion by limiting flow velocity ~ 1 m/s
- Monitor water quality:
  - Conductivity measurement
  - Oxidation Reduction Potential (Cu_2O *vs.* CuO formation)



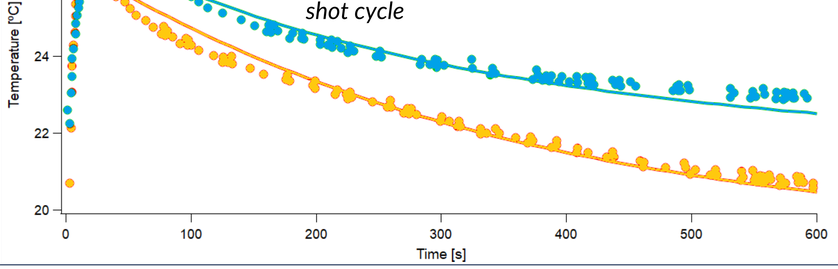
Preferred chilled water operating regime [3,4]:
- Low conductivity
- Neutral to moderately alkaline (low dissolved CO_2)
- Reducing environment (low dissolved O_2)

Water quality process monitoring:
- Conductivity < 50 μS/cm
- Oxidation Reduction Potential (ORP) < 100 mV



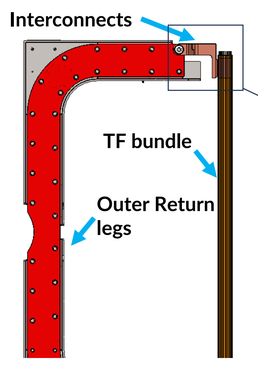


Typical ORP measurements with degassing system show reduction in potential over days as copper oxide layers form

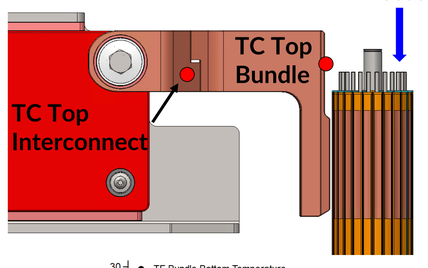


Heat transfer from TF bundle is sufficient to maintain 5 minute shot cycle

Thermocouples used to validate thermal model of TF coil



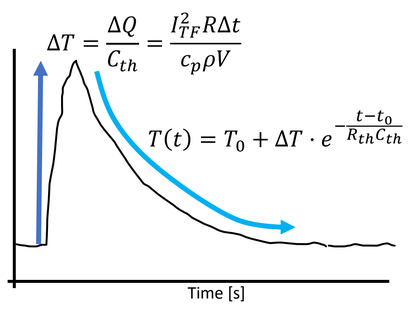
Type T (Constantan-copper) thermocouples
NI 9213 Thermocouple module
- Sensitivity of 0.02°C
- Accuracy of 1°C

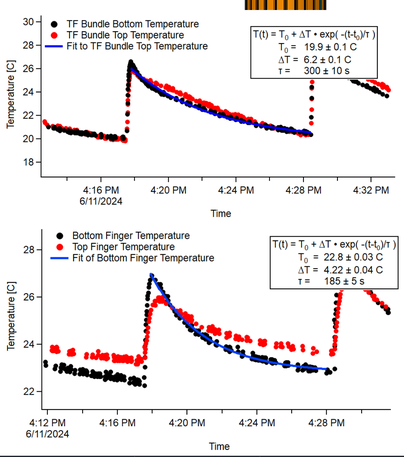


Instantaneous resistive heating provides a way of measuring thermal capacitance and resistance

$$\Delta T = \frac{\Delta Q}{C_{th}} = \frac{I_{TF}^2 R \Delta t}{c_p \rho V}$$

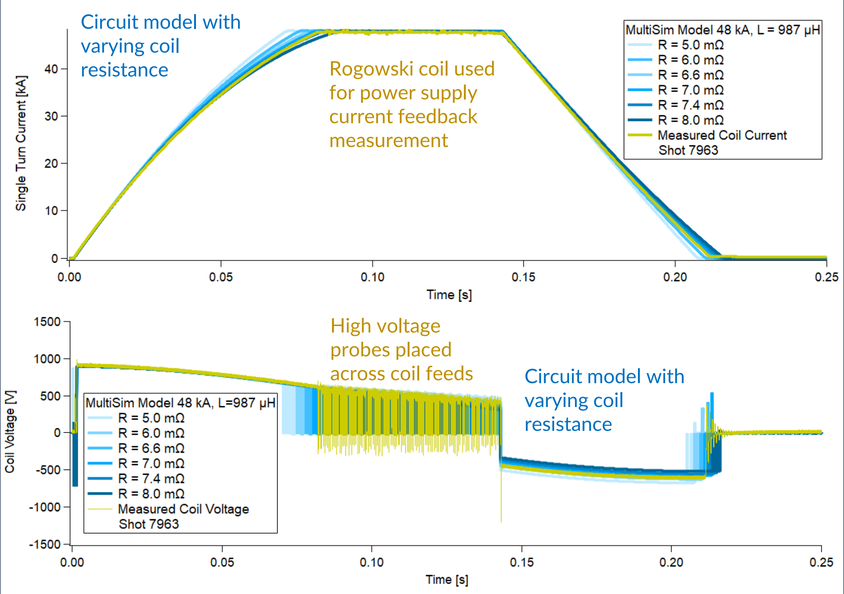
$$T(t) = T_0 + \Delta T \cdot e^{-\frac{t - t_0}{R_{th} C_{th}}}$$





Component	Calculated Electrical resistance [mΩ]	Calculated Thermal Capacitance [kJ/K]	Measured Thermal Capacitance [kJ/K]	Estimated Thermal Resistance [K/kW]	Measured Thermal Resistance [K/kW]
TF Bundle	3.5	70	79 ± 1	2 to 20	3.8±0.1
Interconnects	0.78	49	50 ± 0.5	2 to 20	3.7±0.1
Returns	0.69	1250	NA	0.18	NA

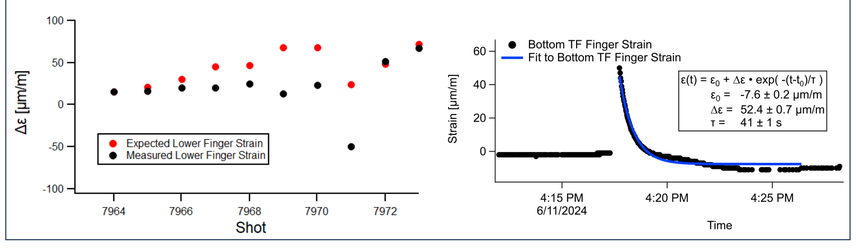
Coil current and voltage measured to verify circuit model



Strain changes within expected range of stress analysis

Finite Element Analysis results for 48 kA coil current with heating scaled by $I_{TF}^2 \times \Delta t$ to estimate anticipated temperature and strain measurements

I_{TF} [kA]	Field on-axis [T]	Demand pulse length [ms]	Expected/Observed max interconnect strain [με]	Expected/Observed max beam strain [με]	TF bundle ΔT [C]	Shot number
24	0.3	50 / 50	15 / +15	12 / +5	1.8 / 1.1	7964
24	0.3	70 / 70	21 / +16	12 / +1	2.5 / 1.5	7965
24	0.3	100 / 100	30 / +20	12 / +2	3.6 / 2.0	7966
24	0.3	150 / 149	45 / +25	12 / +2	3.6 / 2.9	7967
30	0.36	100 / 90	47 / +25	19 / +3	7.1 / 3.1	7968
36	0.45	100	68 / +23	27 / -6	12 / 4.7	7970
48	0.6	82 to 101	24/ -50	48 / +6	15 / 5.0	7971
48	0.6	82 to 121	48 / +51	48 / +4	16 / 6.6	7972
48	0.6	50 / 60	72 / +67	48 / +5	17 / 8.2	7973



Summary

- Pegasus Toroidal Field coil has been upgraded for operation up to 0.6 T
- Electromagnetic and thermal stresses remained within predictions from FEA
- Modelled junction temperatures on IGBTs and diodes remained low enough for operation above steady-state ratings
- A chilled water system was fielded to maintain a 5 minute shot cycle and limit corrosion of the copper components in the TF bundle
- A simple thermal model of the TF coil components is adequate to provide information on thermal stresses and heat transfer characteristics

References: [1] A.C. Sontag *et al.*, IEEE Trans. Plasma. Sci. (2022), DOI: 10.1109/TPS.2022.3184626; [2] M.W. Bongard *et al.*, IEEE Trans. Plasma. Sci. **50**, 4021 (2022) DOI:10.1109/TPS.2022.3165694, [3] Svoboda, R., Power Plant Chem. **16**, 352 (2014); [4] R. Svoboda, B.A. Reinbooth, M. Svoboda, Power Plant Chem. **13**, 496-502 (2011).