Performance of the high Q CW prototype cryomodule for LCLS-II at FNAL

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SRF 2017

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Outline

- Cryomodule Cool Down
- Cavity Q_0 Results compared to VTS Results
- Dynamic and Static Thermal Currents
- Cavity Q_0 Comparison under Different Cool Down Rates
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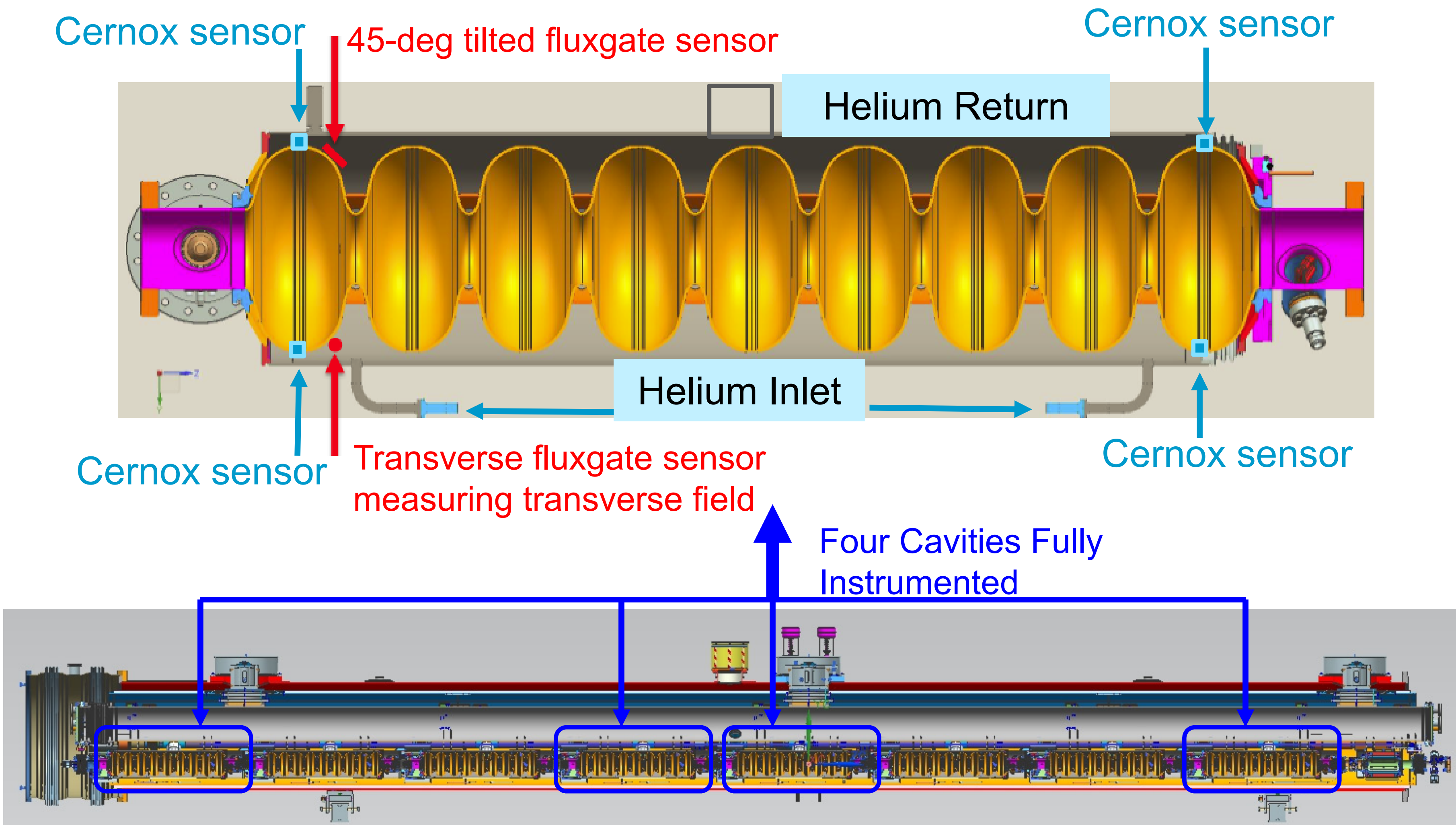
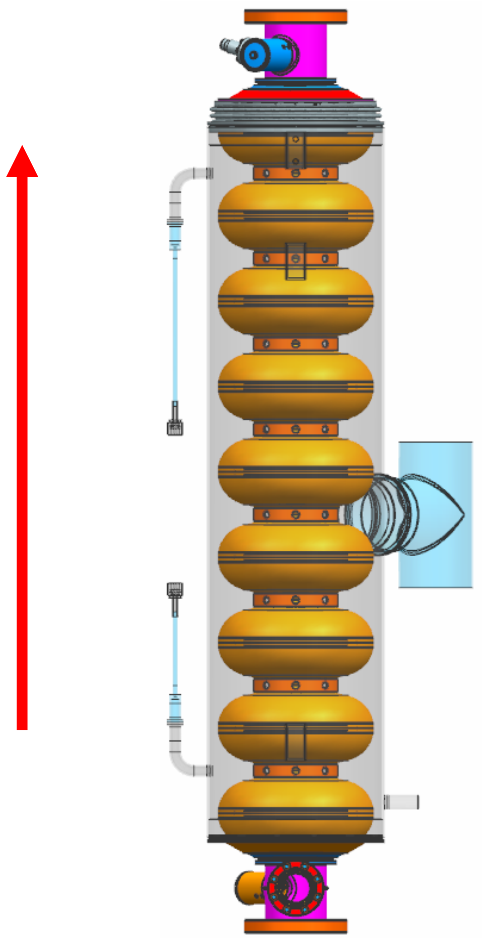
Measurement of Temperature and Magnetic Field

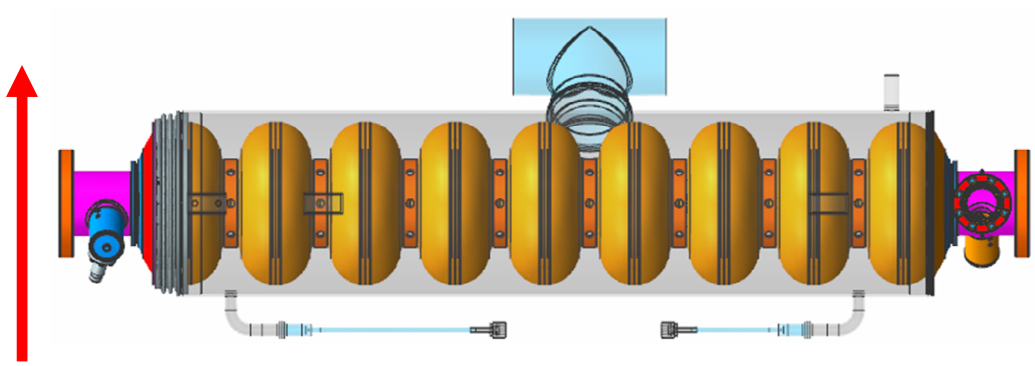


Superconducting Transition

Cool Down in a
Vertical Dewar

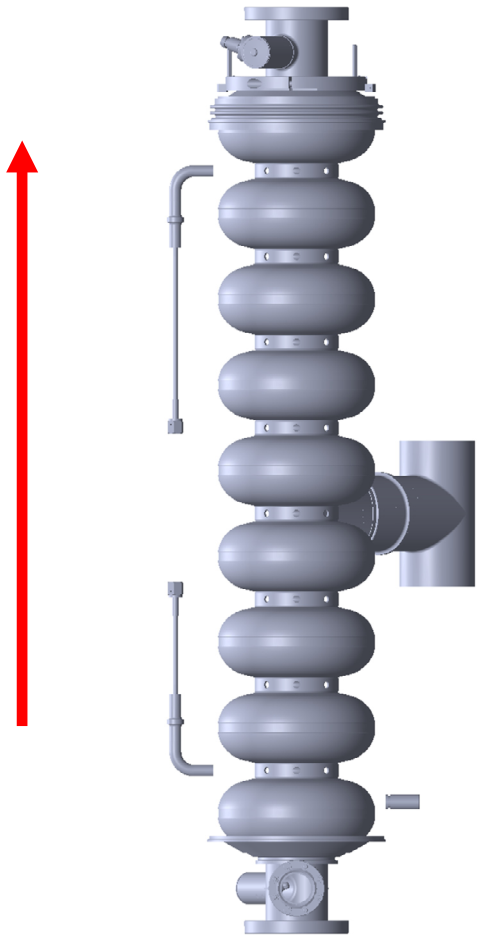


Cool Down in a Cryomodule

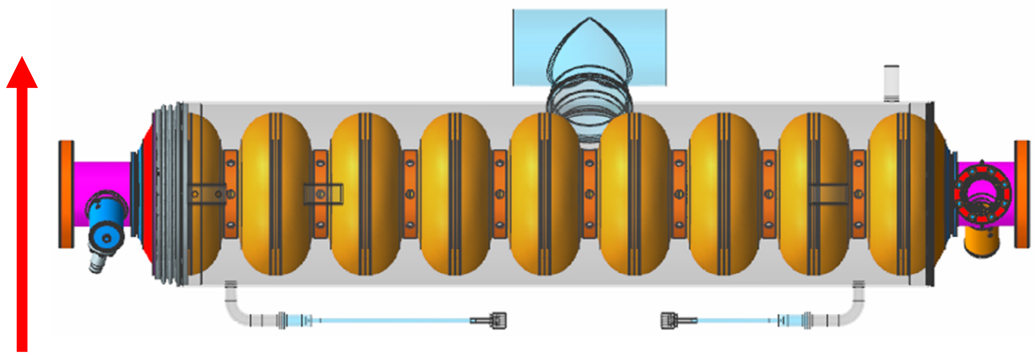


Superconducting Transition

Cool Down in a Vertical Dewar

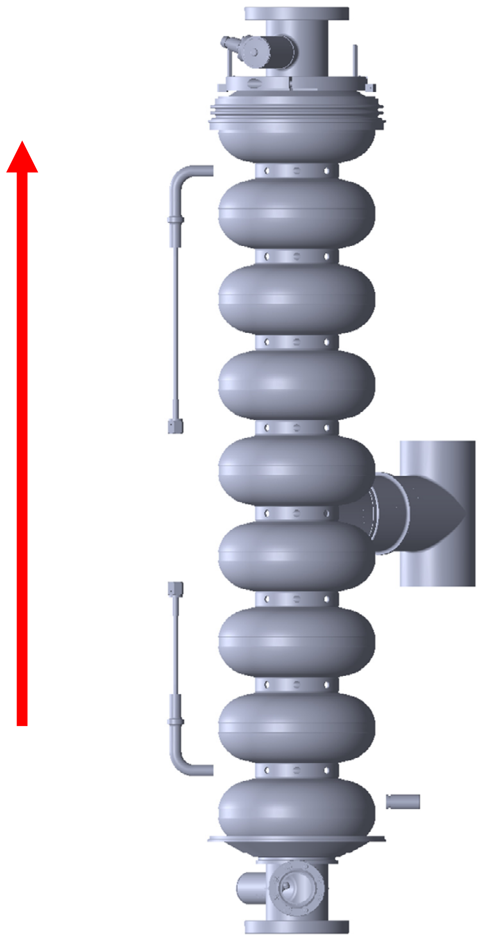


Cool Down in a Cryomodule

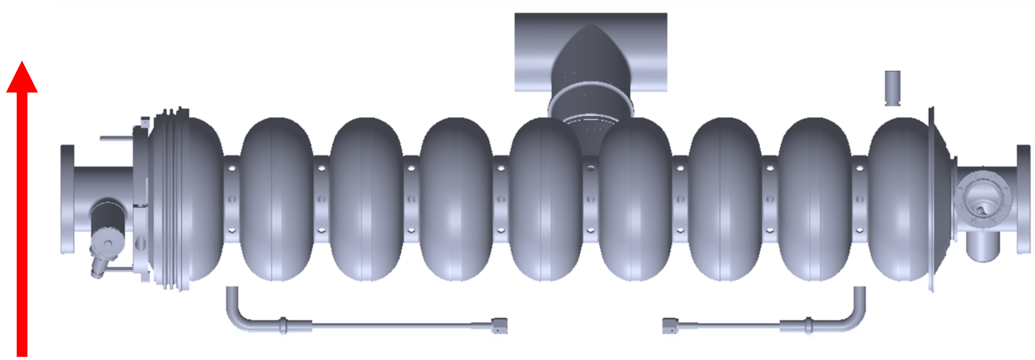


Superconducting Transition

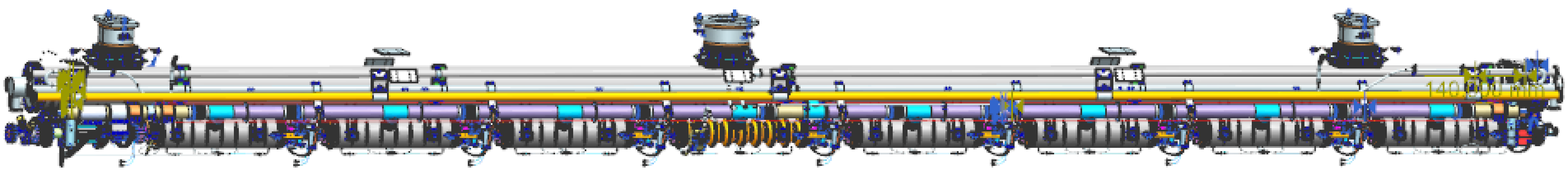
Cool Down in a Vertical Dewar

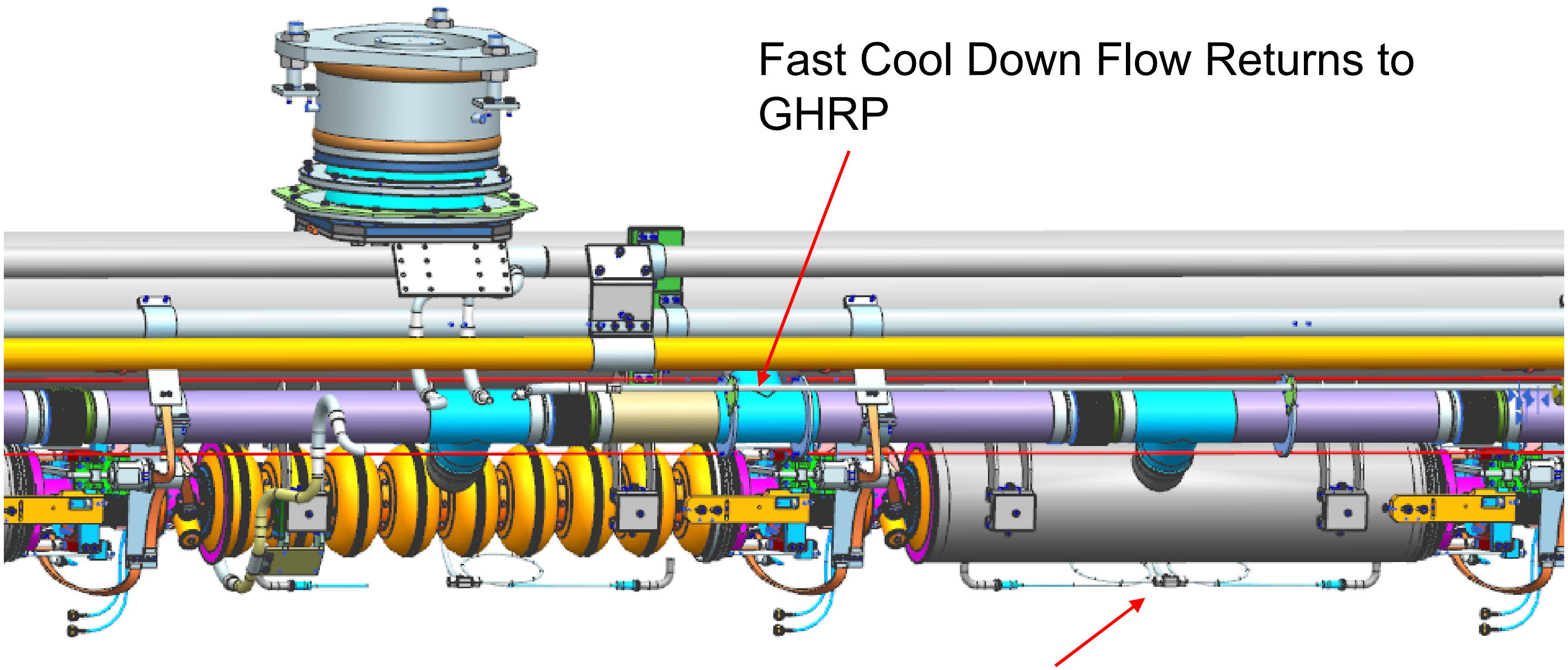


Cool Down in a Cryomodule

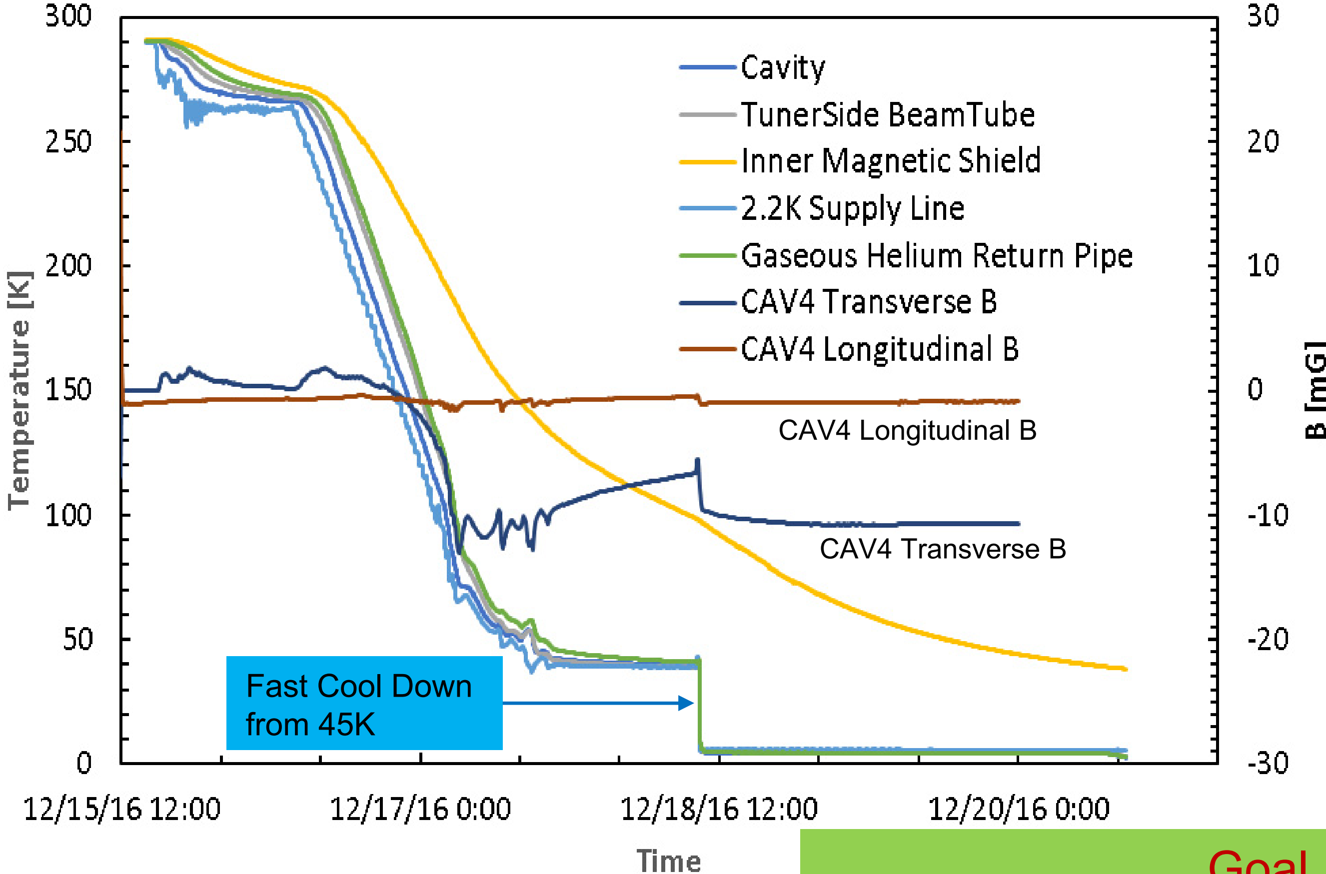


Cryomodule Flow Model





Cryomodule Cool Down – Initial Cool Down



- Initial cool down
  - 300K to 45K
  - 5-7 K/hour
- Soak for 8 hours
- Fast cool down
  - 45 K to 4.5K
  - 10 K/min
  - 35 psi inlet
  - 40-80 g/s

______Goal______

Achieve >4 K top to bottom temperature difference at the beginning of transition

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Cavity Performance in Cryomodule

Cavity	Cryomodule Max Gradient* [MV/m]	VTS Max Gradient [MV/m]	Usable Gradient** [MV/m]	FE onset [MV/m]	Cryomodule Q_0 @16MV/m*** Fast Cool Down	Q_0 @16MV/m at VTS
TB9AES021	21.2	23.0	18.2	14.6	2.6e10	3.1e10
TB9AES019	19.0	19.5	18.8	15.6	3.1e10	2.8e10
TB9AES026	19.8	21.5	19.8	19.8	3.6e10	2.6e10
TB9AES024	21.0	22.4	20.5	21.0	3.1e10	3.0e10
TB9AES028	14.9	28.4	14.2	13.9	2.6e10	2.6e10
TB9AES016	17.1	18.0	16.9	14.5	3.3e10	2.8e10
TB9AES022	20.0	21.2	19.4	12.7	3.3e10	2.8e10
TB9AES027	20.0	22.5	17.5	20.0	2.3e10	2.8e10
Average	**19.1**		**18.2**	**16.5**	**3.0e10**	**2.8e10**
Total Voltage	**154.6 MV**		**148.1 MV**			

Acceptance = 128 MV

* Administrative limit 20 MV/m
** Radiation <50 mR/h
*** TB9AES028 Q_0 was at 14 MV/m

Unit test heat load (all cavities on) was consistent with the single cavity measurement

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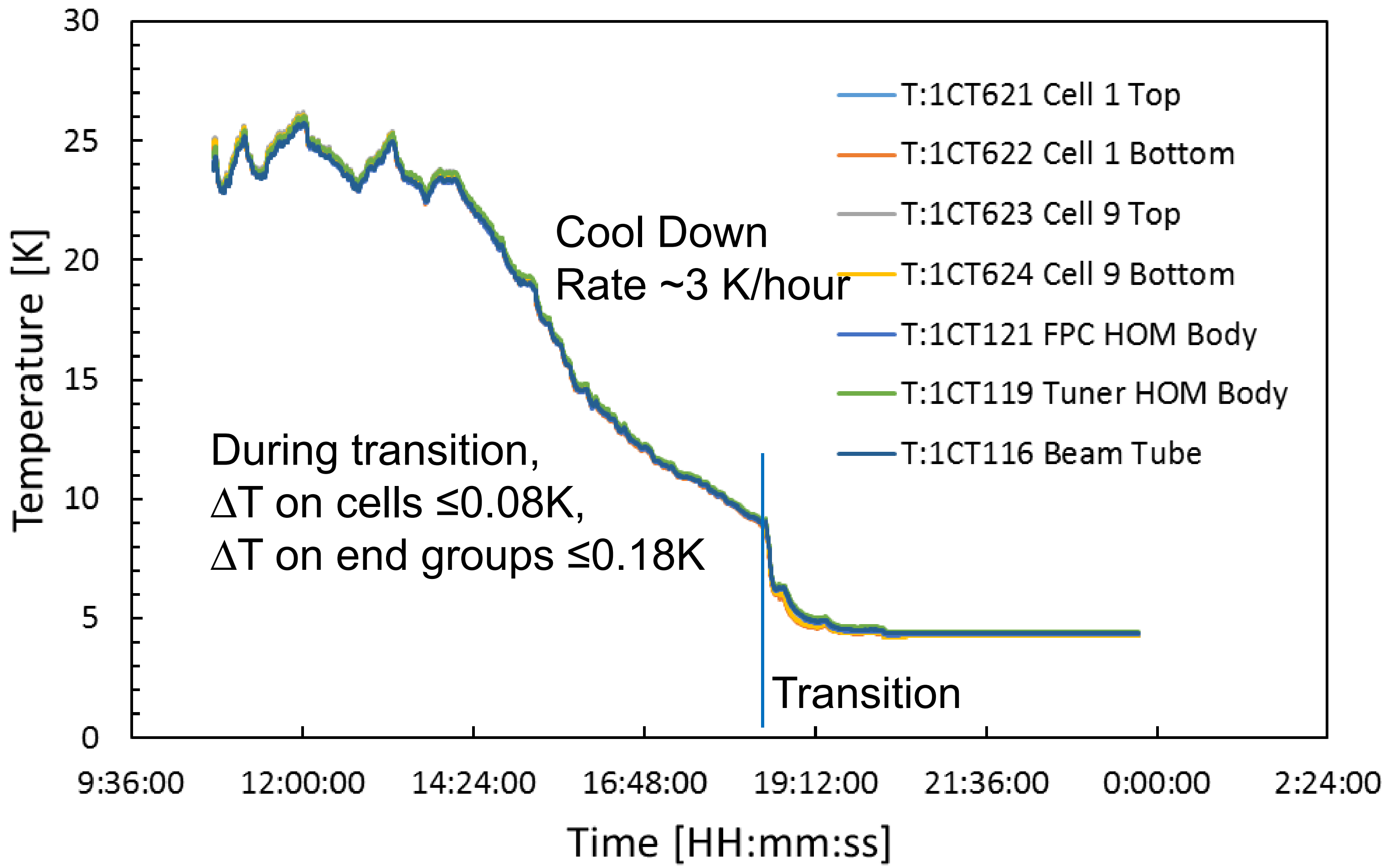
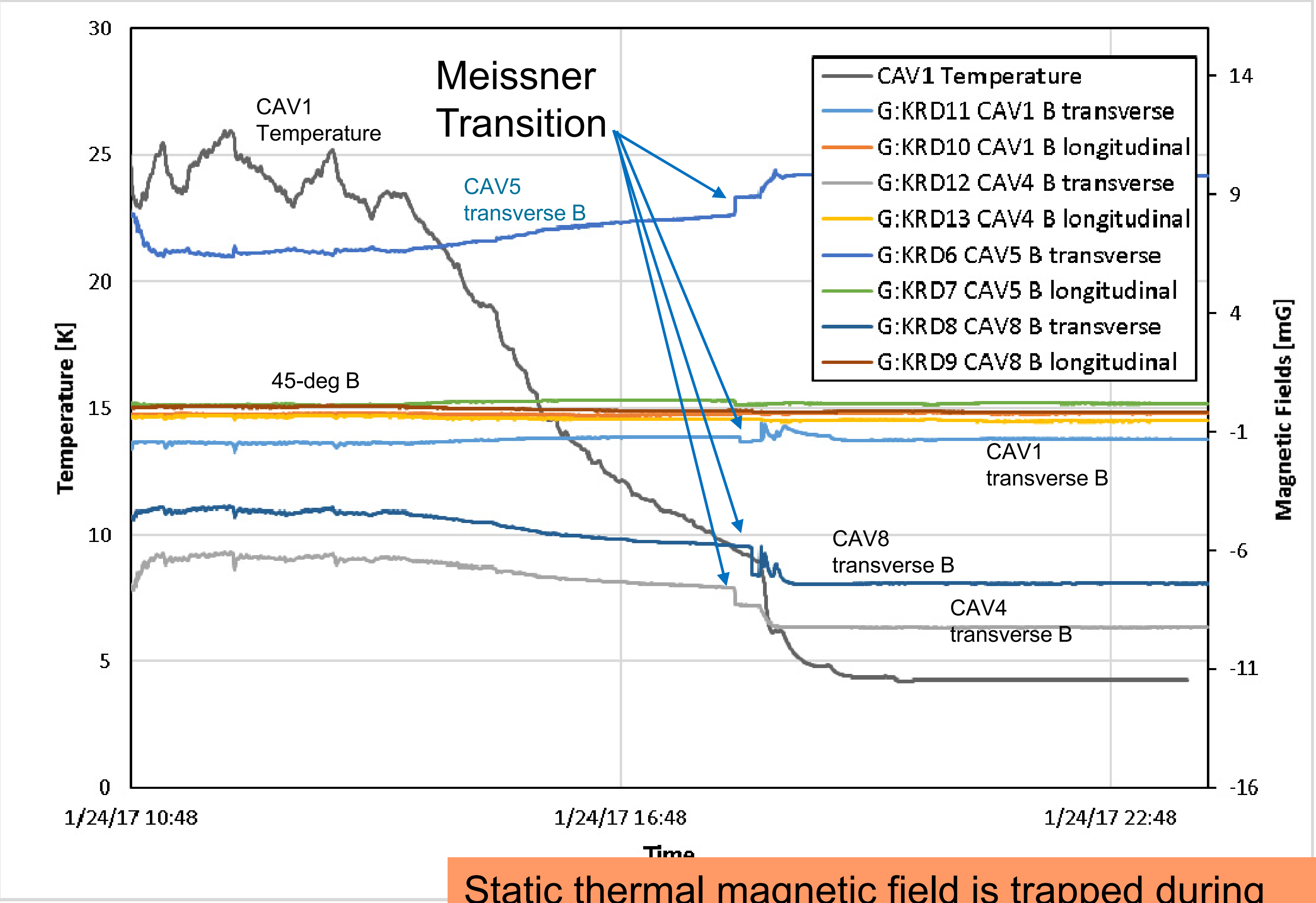
- Thermal currents cause transverse magnetic field
- Dynamic thermal currents are caused by fast cool down
- Static thermal currents are caused by cryomodule thermal gradient

Slow Cool Down



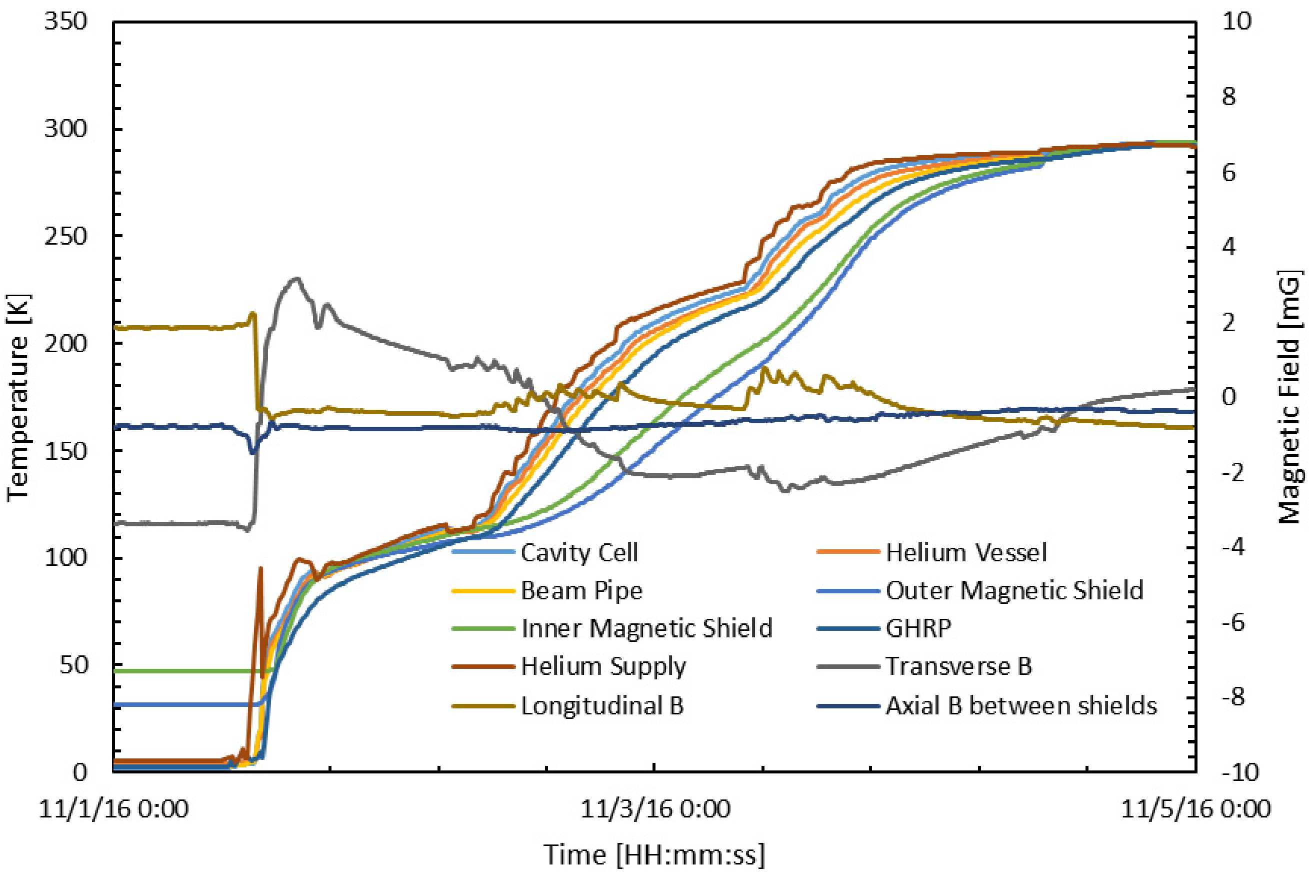
Slow cool down created a uniform temperature on cavity

Static Thermal B Field



Static thermal magnetic field is trapped during superconducting transition (Slow cool down)

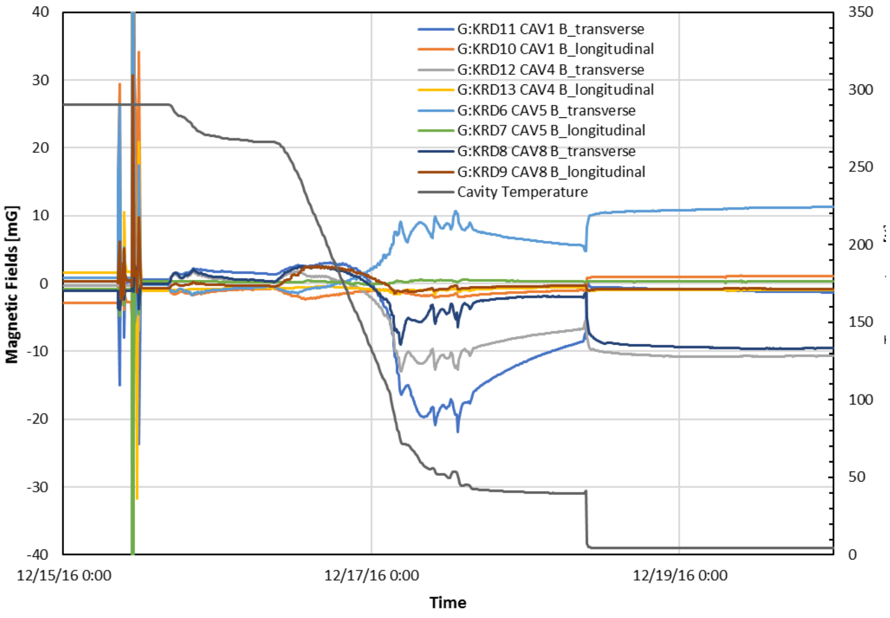
Static Magnetic Field Resets at Room Temperature

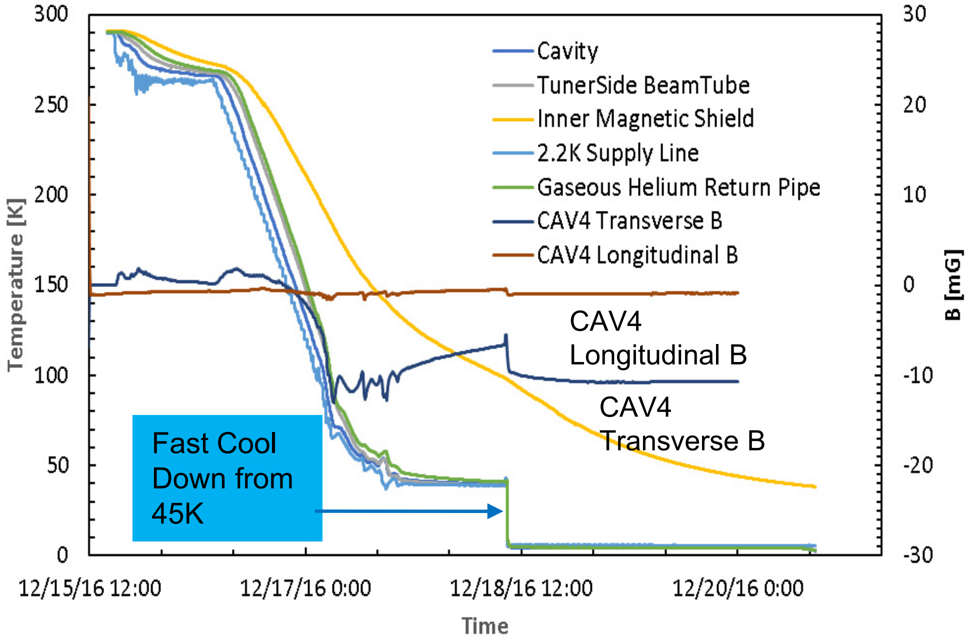


Static magnetic fields were restored to near zero as Cryomodule warmed up

Cryomodule Cool Down – Magnetic Field

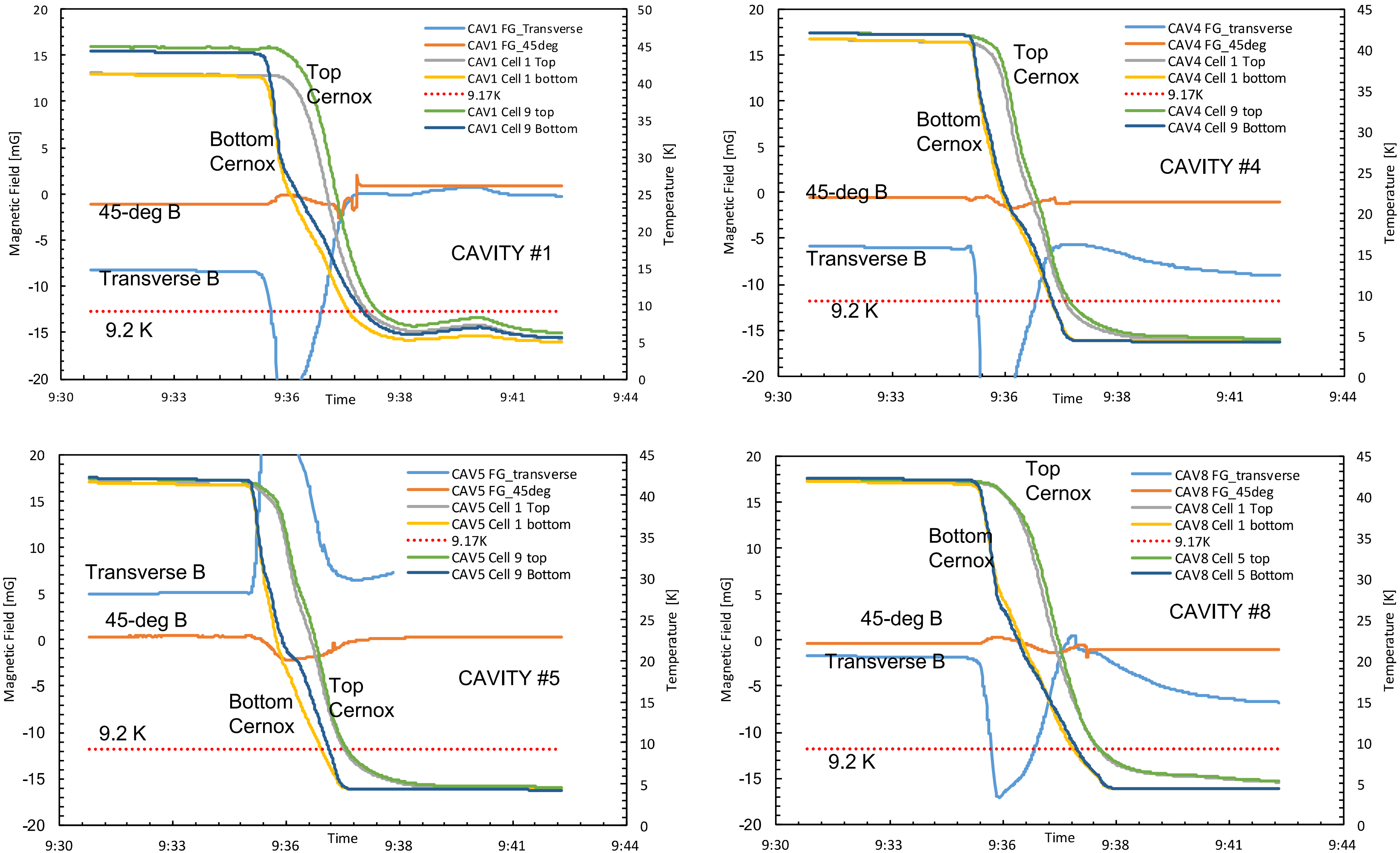
Five fluxgate sensors outside of cavity read negligible fields throughout the cool down.





Static thermal magnetic field is trapped during superconducting transition (Slow cool down)

Temperatures and Magnetic Fields During Fast Cool Down



Temperature Gradient and B field at Cavities

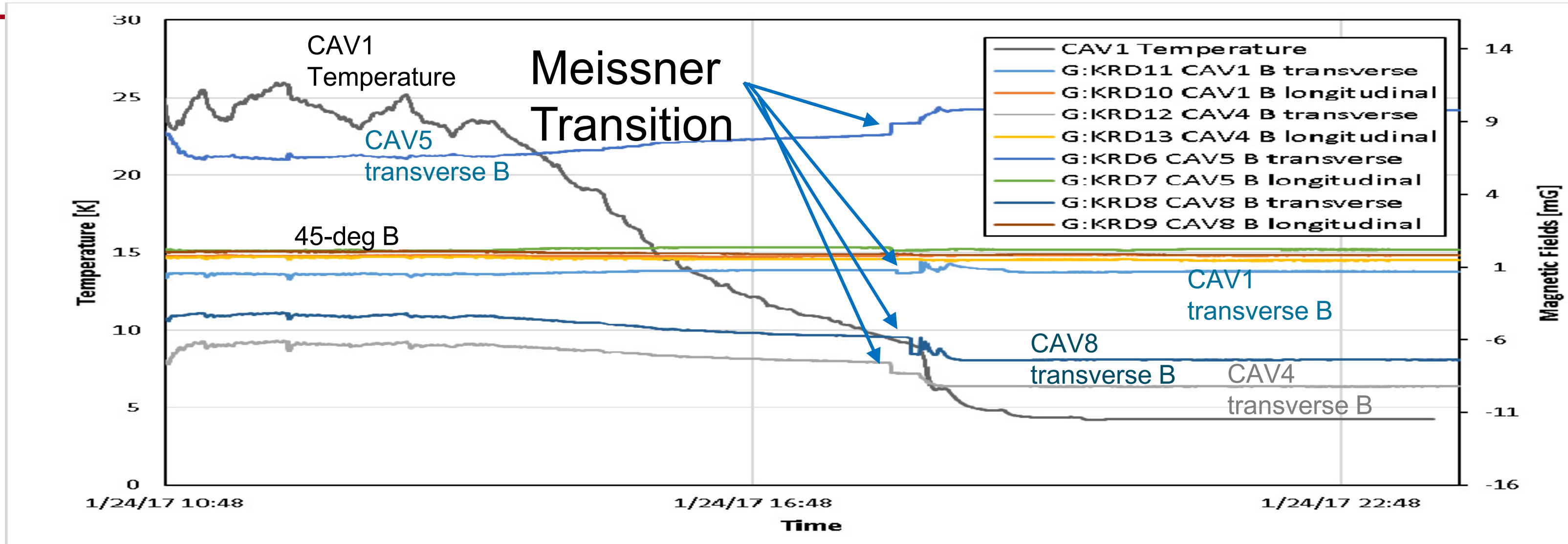
TABLE I. Temperature difference and B field for four cavities when cavity bottom passed Tc during fast cool down

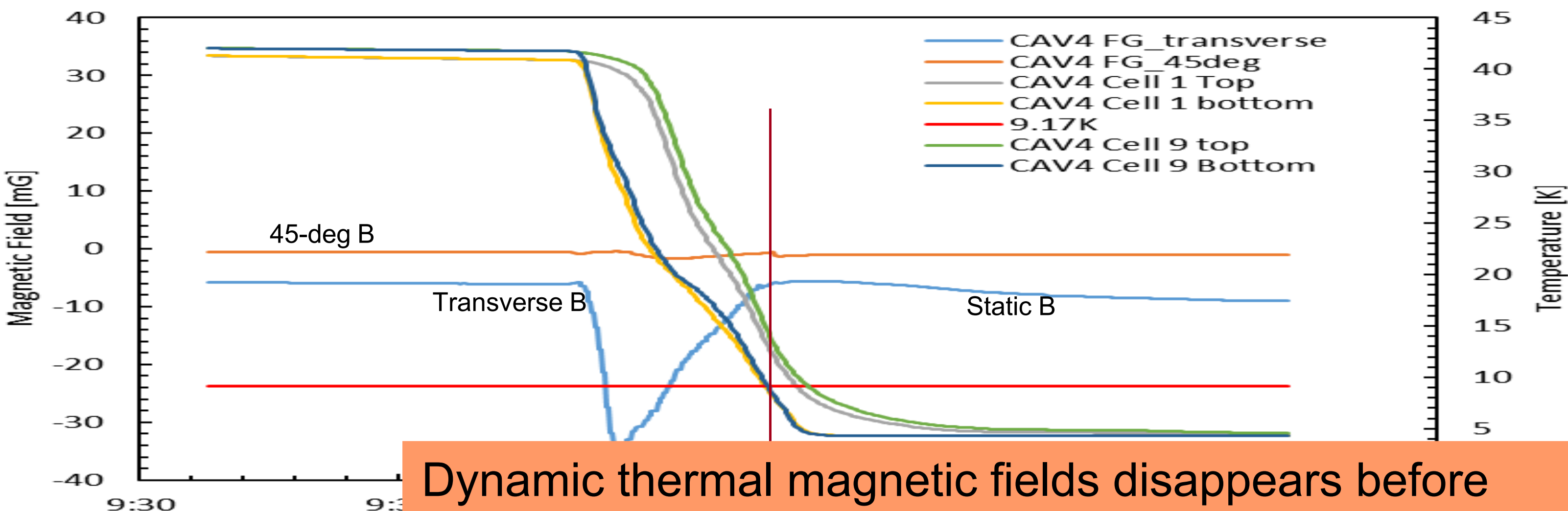
Cavity number	Top Bottom Temperature Difference [K]	Longitudinal B field [mG]	Transverse B field [mG]
1	4.1	1	5
4	4.3	1	7
5	6.8	2	8
8	5.1	1	1

Remnant field from other components cannot be measured other than at the sensor locations.

80 g/s

Dynamic Thermal Current vs. Static Thermal Current





Dynamic thermal magnetic fields disappears before superconducting transition

Cavity Q_0 Comparison

Cavity	Usable Gradient [MV/m]	Q_0 @16MV/m* Fast Cool Down	Q_0 @16MV/m* Slow Cool Down
TB9AES021	18.2	2.6E+10	1.8E+10
TB9AES019	18.8	3.1E+10	1.5E+10
TB9AES026	19.8	3.6E+10	3.3E+10
TB9AES024	20.5	3.1E+10	2.1E+10
TB9AES028	14.2	2.6E+10	1.9E+10
TB9AES016	16.9	3.3E+10	2.0E+10
TB9AES022	19.4	3.3E+10	2.1E+10
TB9AES027	17.5	2.3E+10	1.8E+10
Average	**18.2**	**3.0E+10**	**2.1E+10**
Total Voltage	**148.1 MV**		

* TB9AES028 was at 14 MV/m

Slow cool down results the trapping of static thermal magnetic field

Dynamic Thermal Current vs. Static Thermal Current

- ✓ Dynamic thermal magnetic field not harmful
  - ✓ Induced from cavity and helium vessel thermal gradient during fast cool down
  - ✓ Dissipates quickly as the cavity reaches equilibrium before superconducting transition and can be expelled during fast cool down
  - ✓ Does not appear during slow cool down
- × Static thermal magnetic field can be trapped if no flux expulsion
  - × Induced from various current loops in a cryomodule
  - × Requires fast cool down to achieve flux expulsion
  - × Proper heat treatment of niobium cavity material is a necessity.

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Q_0 under Different Cool Down Mass Flow

Temperature difference from top of the cavities and bottom of cavities

Mass Flow	80 g/s	47 g/s	25 g/s	Slow Cool Down
Cavity	Δ T(K)	Δ T(K)	Δ T(K)	Δ T(K)
CAV1	4.1	3.3	2.6	≤0.08
CAV4	4.9	4.7	4.4	≤0.08
CAV5	7.0	7.1	7	≤0.08
CAV8	5.6	5.6	2.89	≤0.08
Average Q0	2.99e10	~2.46e10	~2.26e10	2.06e10

Linac cryogenic capacity 120 g/s

Sensors are at limited locations.

Fast cool down with sufficient mass flow can achieve effective flux expulsion

Q_0 under Different Cool Down Mass Flow

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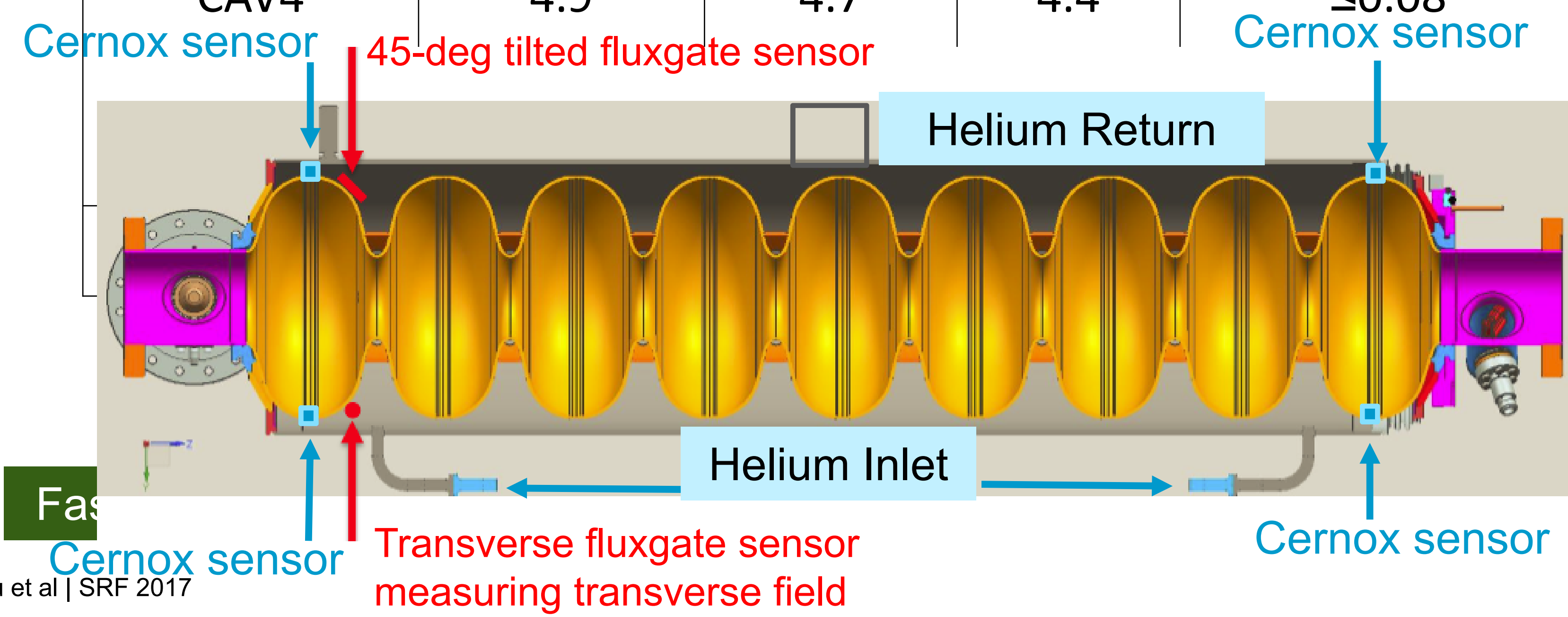
CAV4	4.9	4.7	4.4	≤0.08



Fas

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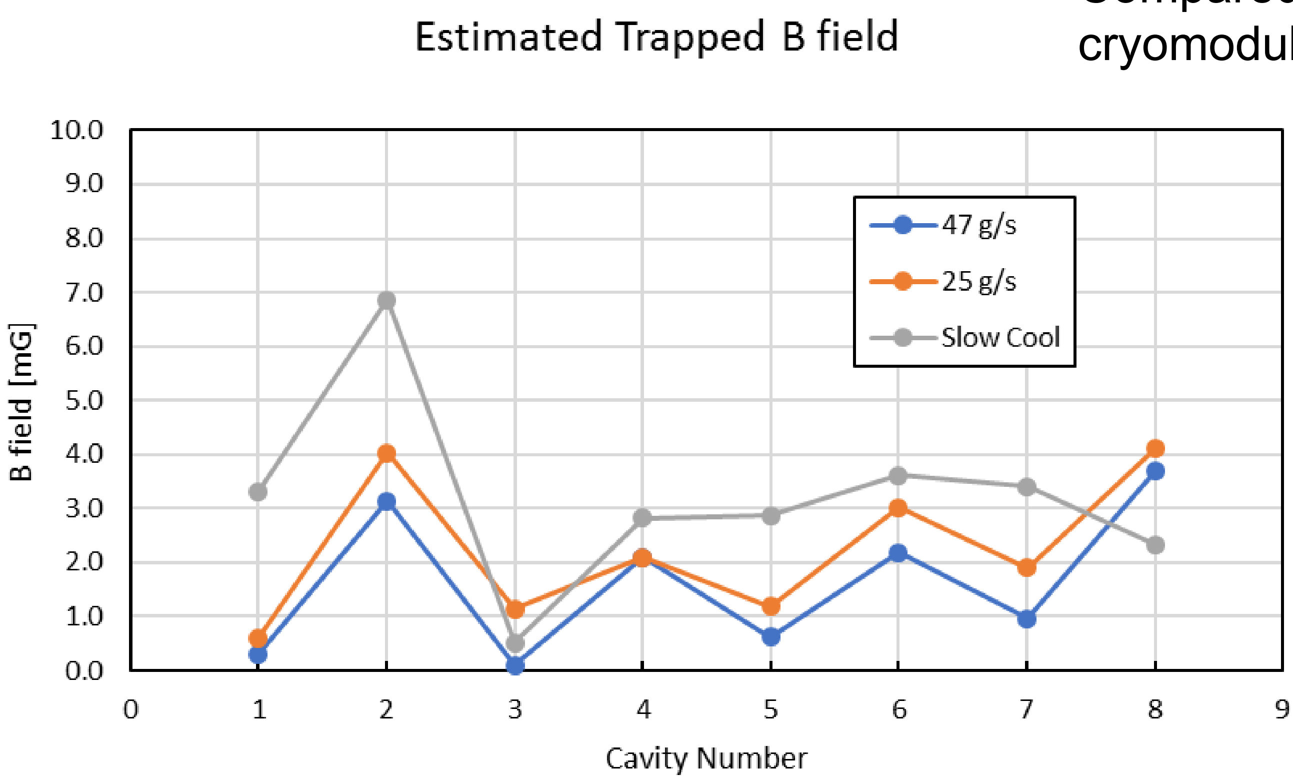
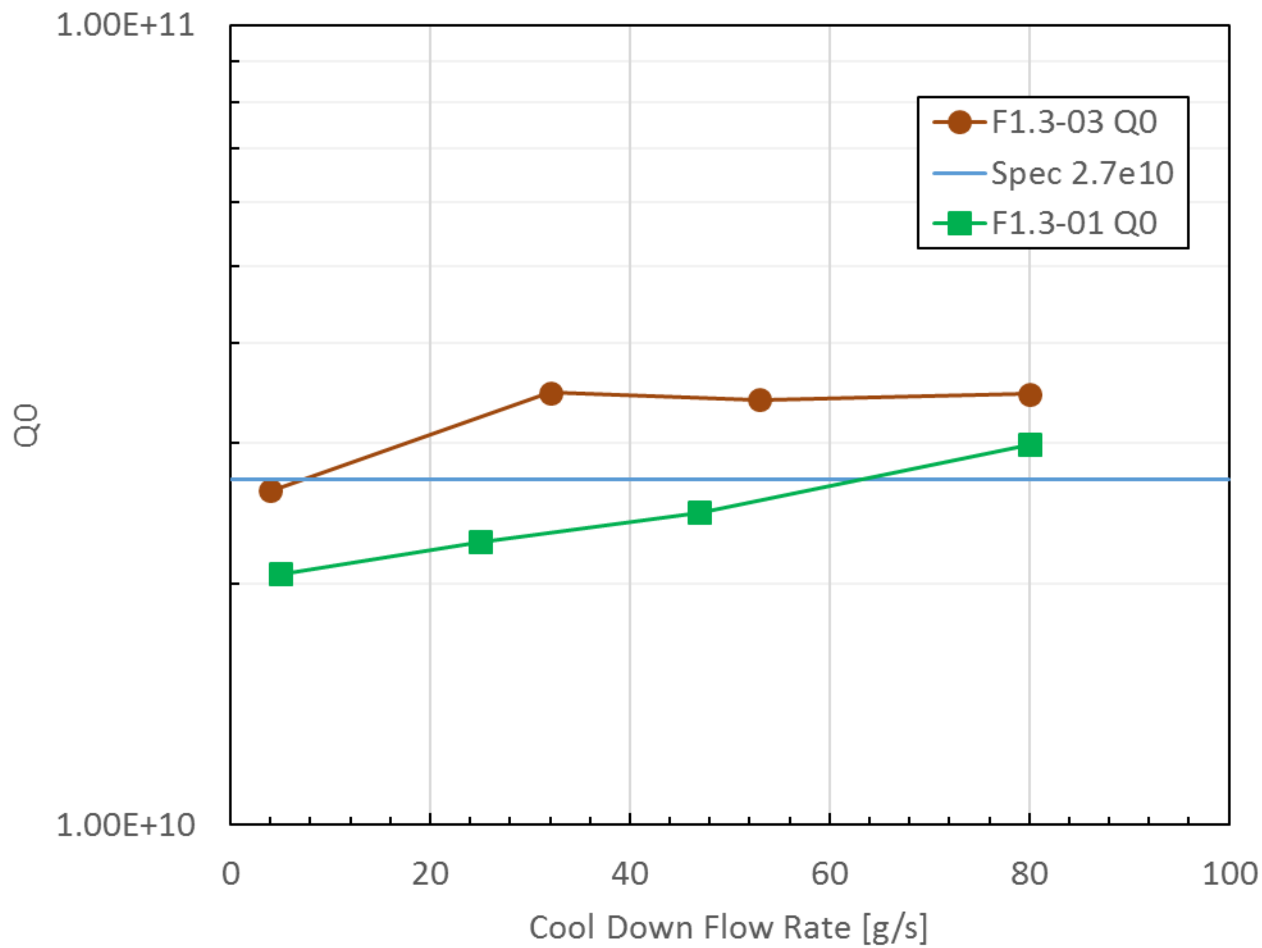
Estimated Trapped Magnetic Field F1.3-01 (pCM)



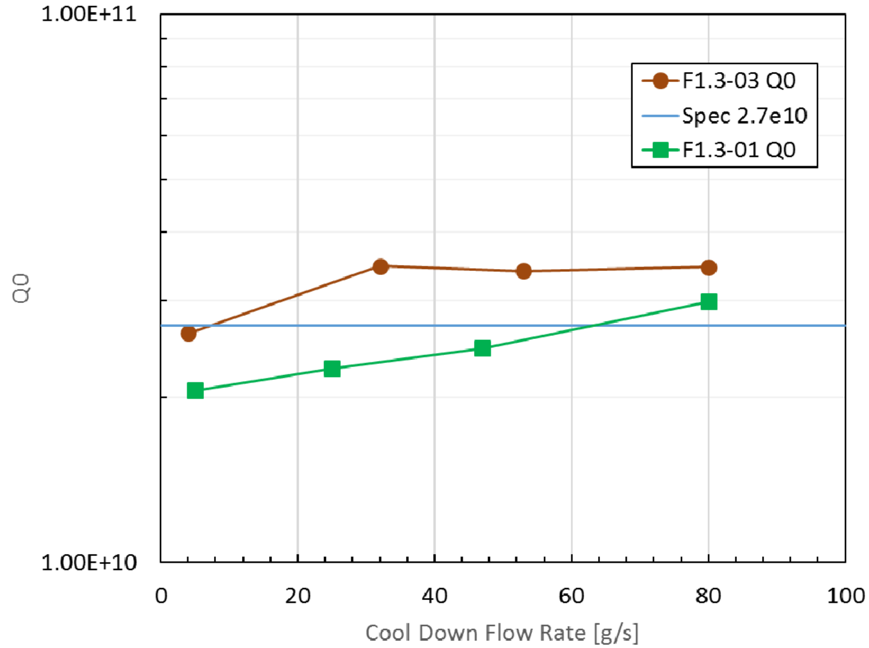
Compared to the fastest cryomodule cool down

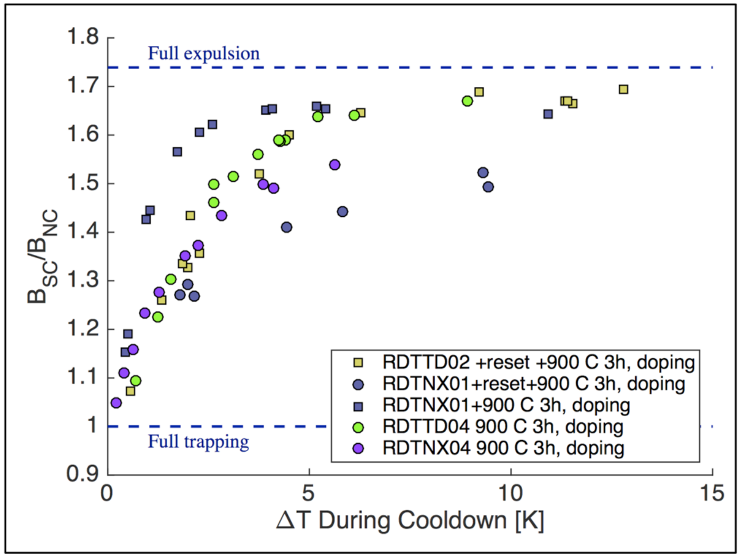
Slow Cool Down Trapped 3.2 mG in average

Q0 under Different Cooldown Mass Flow



Q0 under Different Cooldown Mass Flow





Courtesy of S. Posen (see Posen's talk on Tuesday)

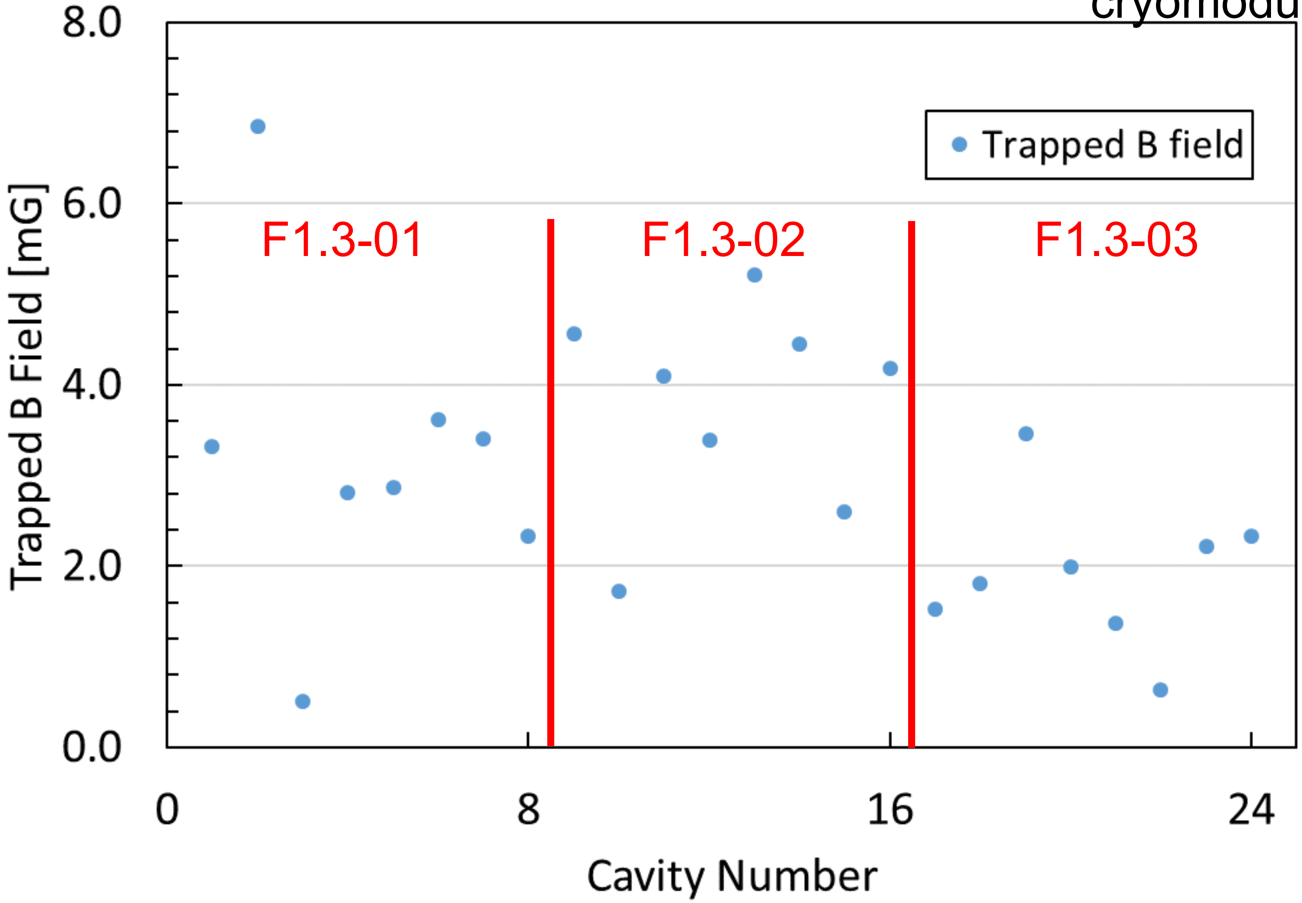
pCM cavities have been 800C heat treated
CM03 cavities have been 900C heat treated

LCLS-II niobium material
after 900C bake

Flux expulsion efficiency depends on material

Estimated Trapped Magnetic Field all Cryomodules

Compared to the fastest cryomodule cool down

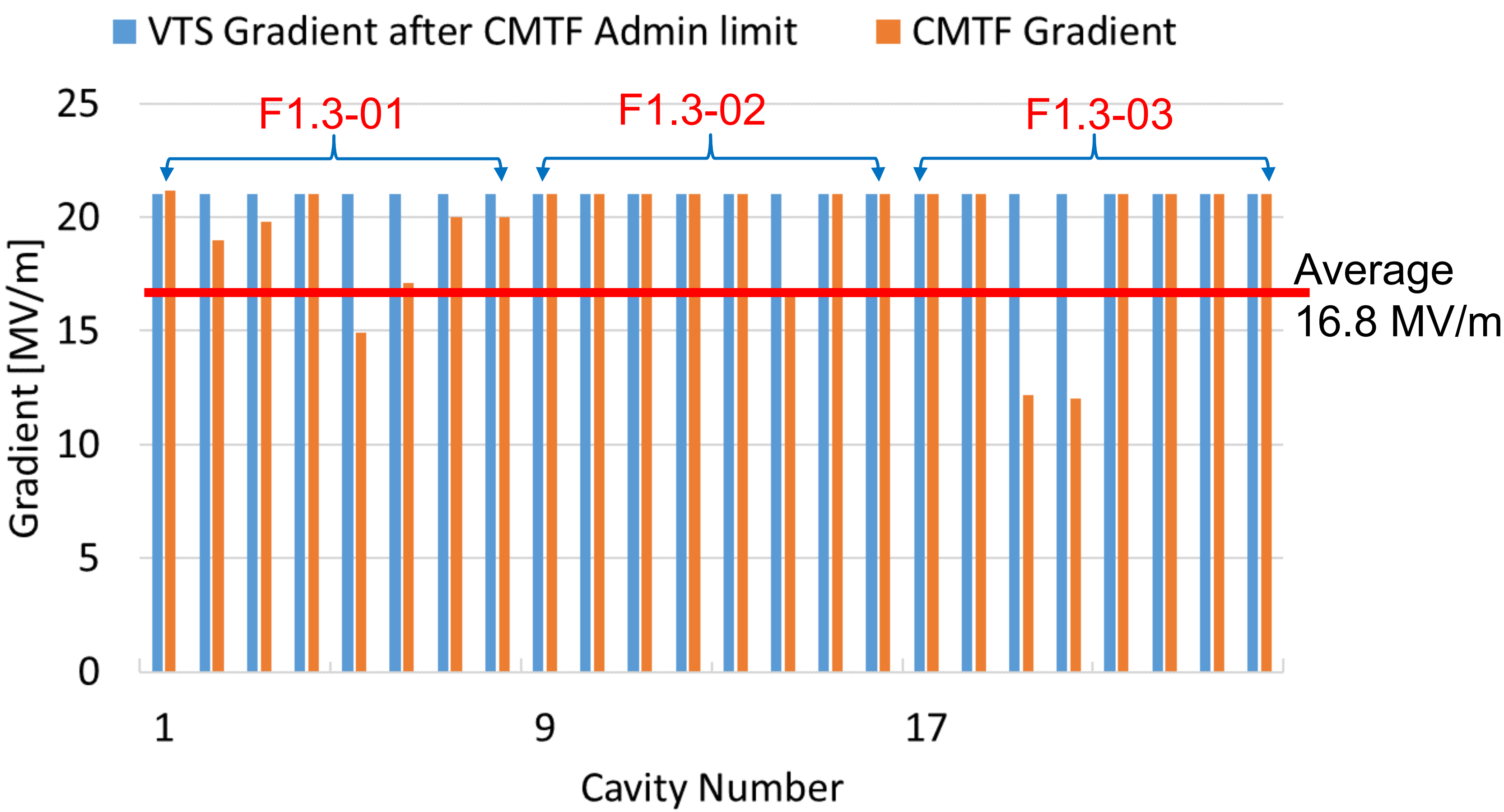


Slow Cool Down Trapped 3.0 mG in average

Another Record High Q0 for a Cryomodule

	VTS		CMTF					
Cavity	**Eacc* [MV/m]**	**Q0@16MV/m**	**Usable Gradient*** [MV/m]**	**Q0 @16MV/m 2K @ 85g/s**	**Q0 @16MV/m 2K @53 g/s**	**Q0 @16MV/m 2K @32 g/s**	**Q0 @16MV/m 2K @4 g/s**
CAV0034	26	3.33E+10	21.0	3.36E+10	3.49E+10	3.54E+10	2.65E+10
CAV0039	24	3.70E+10	21.0	4.17E+10	4.35E+10	3.86E+10	3.00E+10
CAV0040	24.5	3.29E+10	10.0	3.58E+10	2.74E+10	3.54E+10	2.18E+10
CAV0026	21.5	3.73E+10	9.2	3.21E+10	3.19E+10	4.28E+10	2.41E+10
CAV0027	29.7	3.50E+10	21.0	3.25E+10	3.04E+10	3.22E+10	2.64E+10
CAV0029	23.1	3.32E+10	21.0	4.36E+10	4.80E+10	4.21E+10	3.81E+10
CAV0042	24	3.30E+10	16.8	2.77E+10	2.82E+10	2.62E+10	2.10E+10
CAV0032	22.9	2.74E+10	21.0	2.98E+10	2.78E+10	2.53E+10	2.19E+10
Average	**24.5**	**3.4E+10**	**17.6**	**3.5E+10**	**3.4E+10**	**3.5E+10**	**2.6E+10**
Total Voltage	**203.1**		**146.4**				

Performance Comparison between VT and CM



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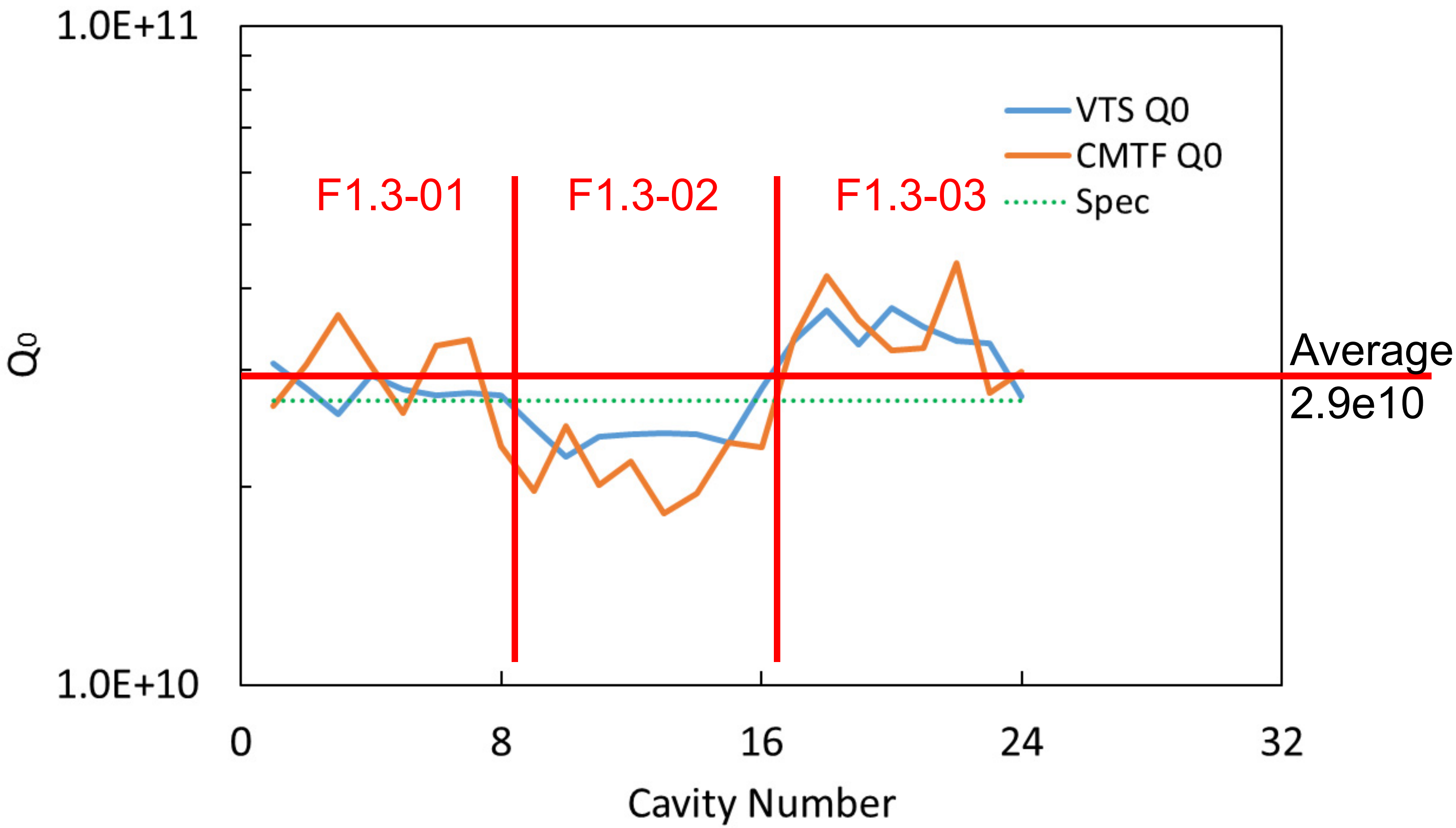
Performance Comparison between VT and CM



Summary

- We have achieved record high Q_0 for production cryomodules
- Q_0 performance maintained from vertical tests to cryomodule
  - Fast cool down and flux expulsion demonstrated in a cryomodule
- Thermal current induced fields are present in cryomodule
  - Dynamic field during fast cool down mostly disappears during superconducting transition and remaining field can be expelled
  - Static field can be expelled during fast cool down
- Slow cool down avoids the dynamic thermal magnetic field, but cannot avoid the static thermal currents in current cryomodule design
- Fast cool down is needed to ensure minimal magnetic field trapping
  - Expel thermally induced field
  - Expel any residual magnetic field by cryomodule components (Limited number of fluxgate sensors)

Acknowledgement

The tests cannot complete without helps from many staff members from Fermilab Accelerator Division and Technical Division, who contributes to mechanical support, system integration support, software support, instrumentation support, safety reviews, inspections and etc.