An Overpressure Furnace:
Understanding Performance and Analysis-led Design Improvements

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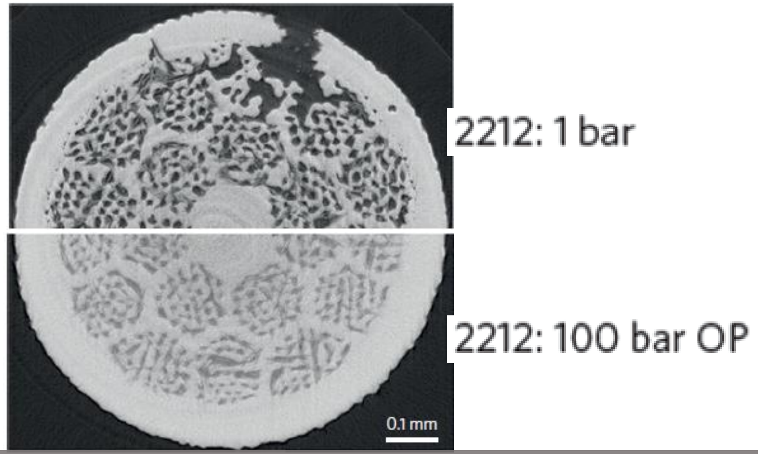
FLORIDA STATE UNIVERSITY

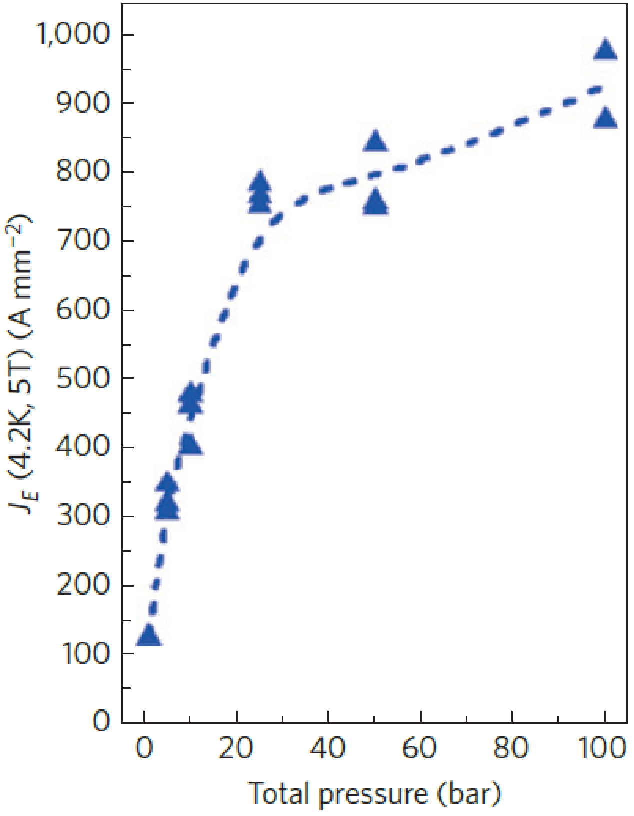
U.S. MAGNET DEVELOPMENT PROGRAM

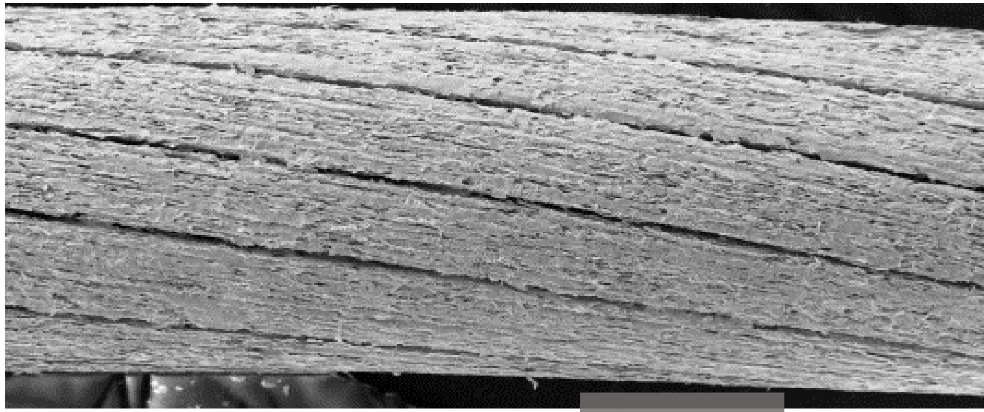
Why Over Pressure Heat Treatment (OPHT)

$Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) is a high temperature superconductor (HTS) with promising application in ultra high field (>25 T) magnet systems. However, it is manufactured as Bi-2212 powder in a silver matrix and requires a heat treatment to connect and texture the powder into long strands of super-current carrying filaments. Gases in the powder-in-tube green wire expand without the OP!



D.Larbalestier *et al*., Nature Materials 2014



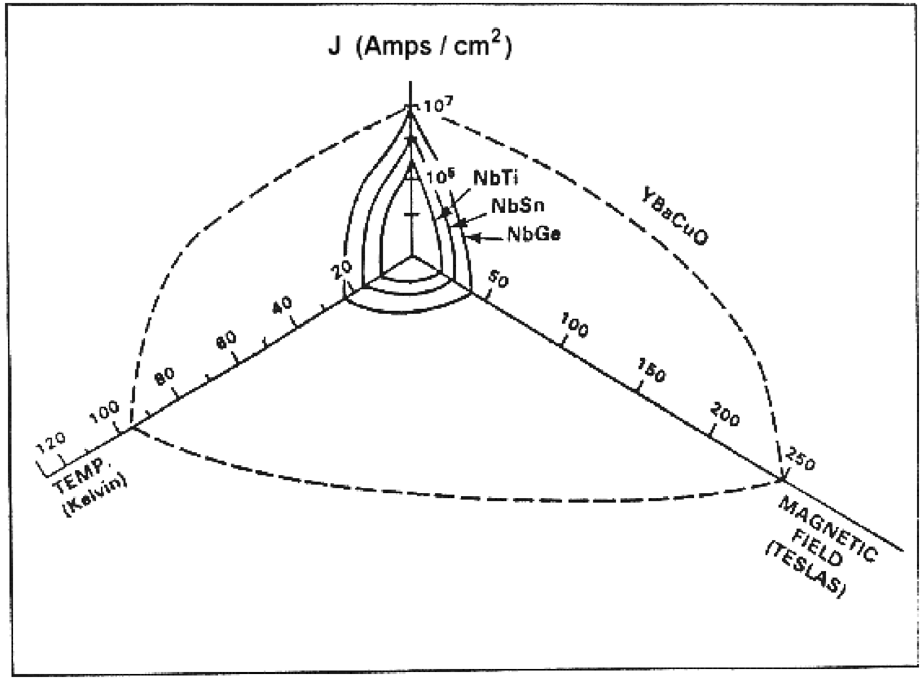


P.Chen

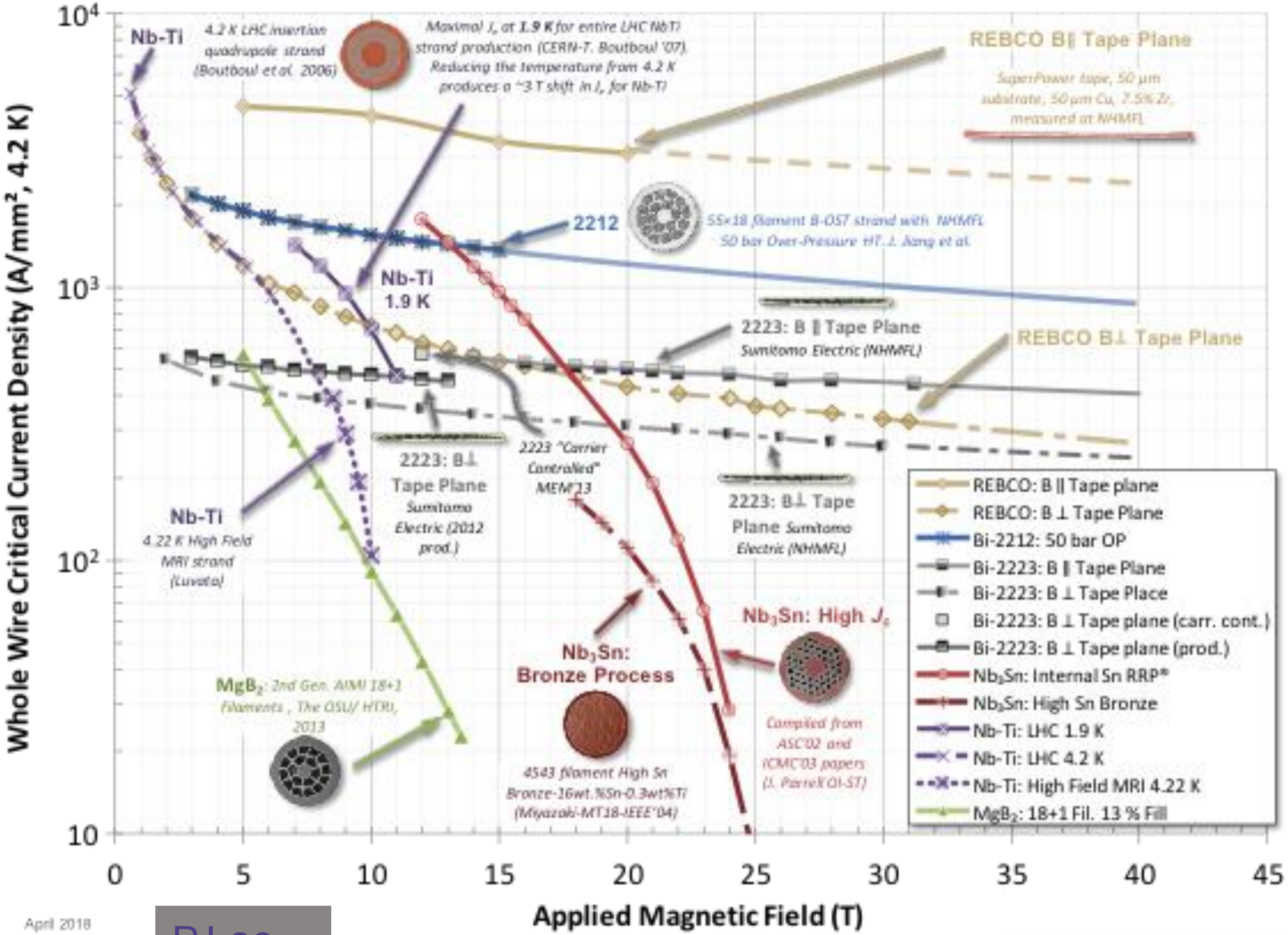
Is Bi-2212 Really Worth the Trouble?

Low temperature superconductors (LTS) cannot exceed fields above 25 T

The HTS materials are thus required, and Bi-2212 is a very promising choice



Phase Diagram

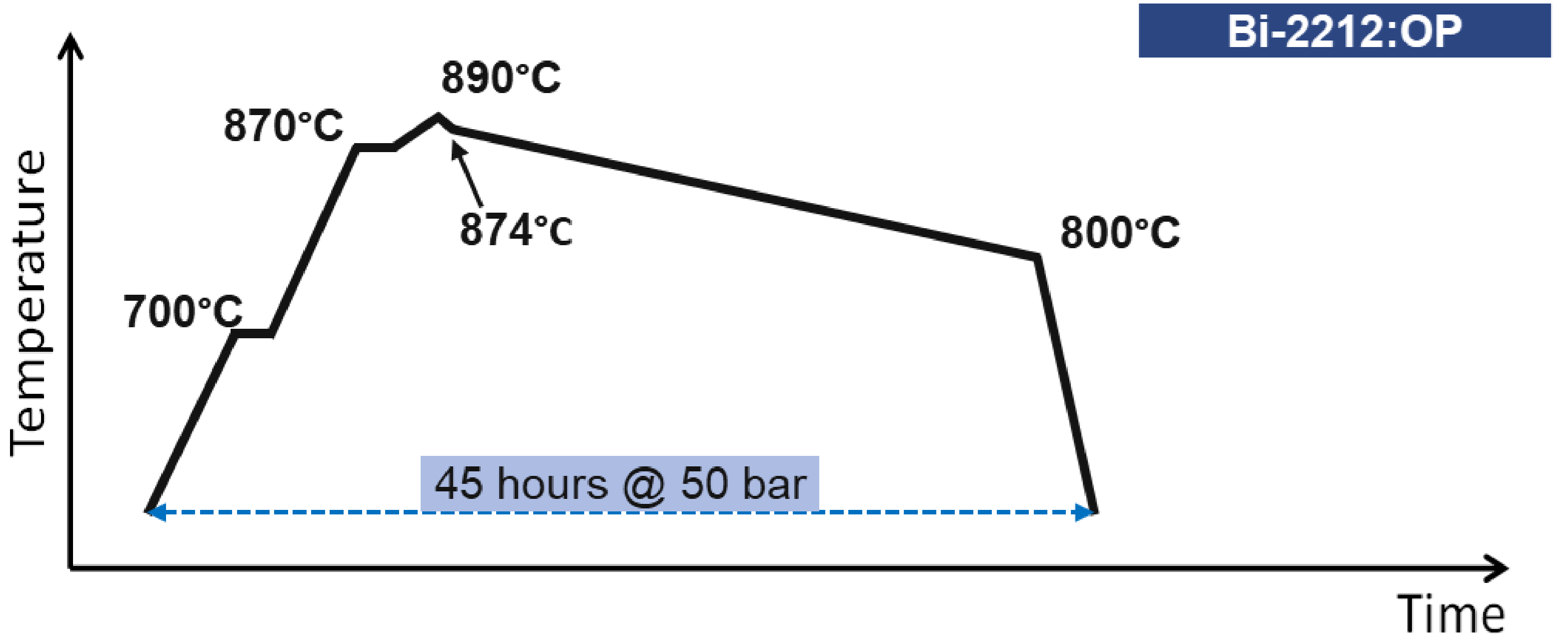


Wind-and-React OPHT

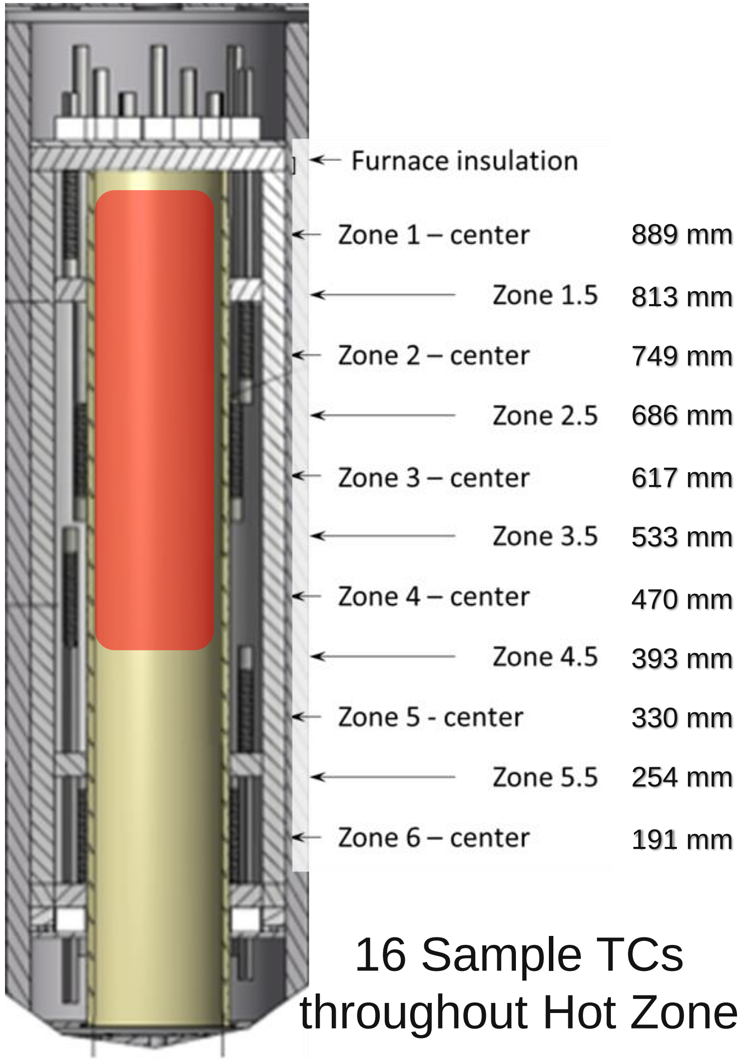
The $Bi_2Sr_2CaCu_2O_{8+\delta}$ powder breathes during the reaction, giving up oxygen in its melting phase (> 883 °C) and picking up oxygen during its re-crystallization phase (< 874 °C).

Therefore, the furnace is an open system. A back pressure regulator maintains the OP at 50 bar, while a high precision flow controller feeds 2%-O_2 in Ar (to maintain 1 bar O_2), at a steady rate of 5 L/min.

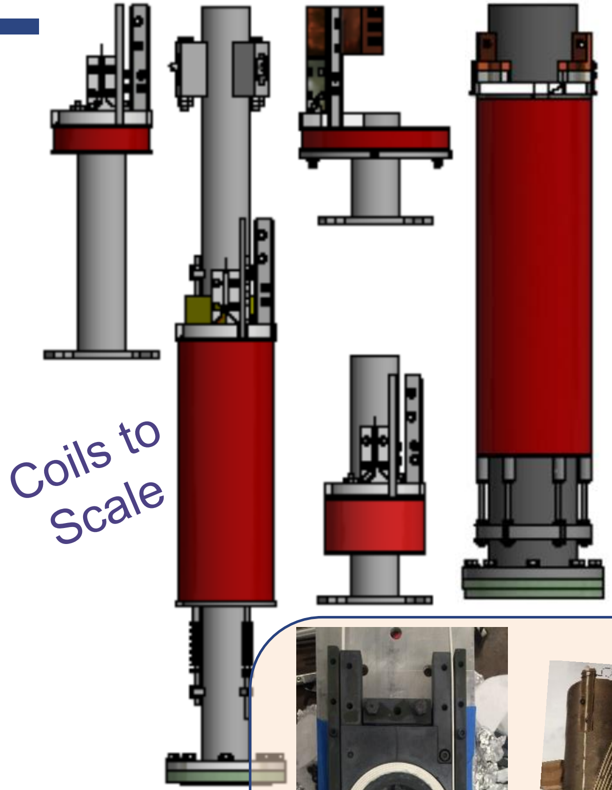
Illustrated below is the now established ramp schedule for the OPHT reactions.



The Existing OP Furnace (Deltech)

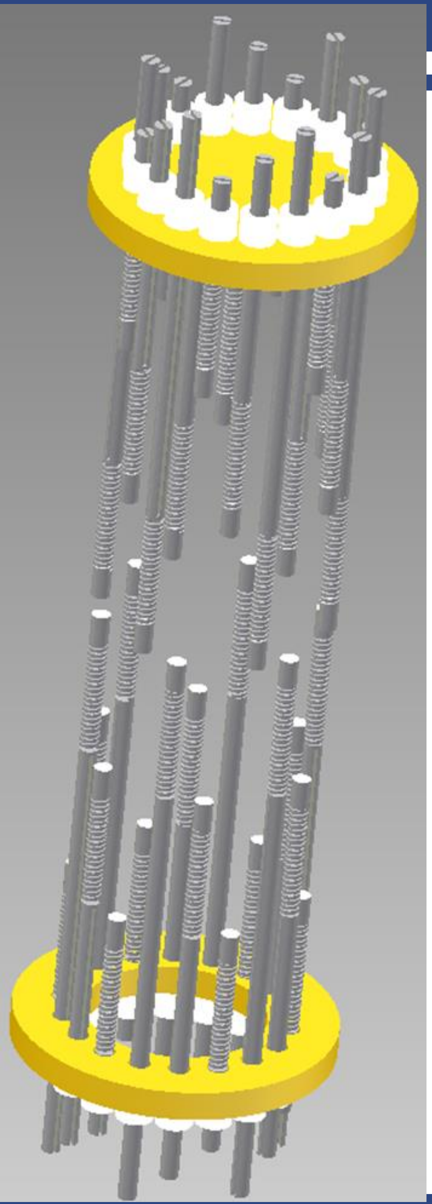


16 Sample TCs throughout Hot Zone



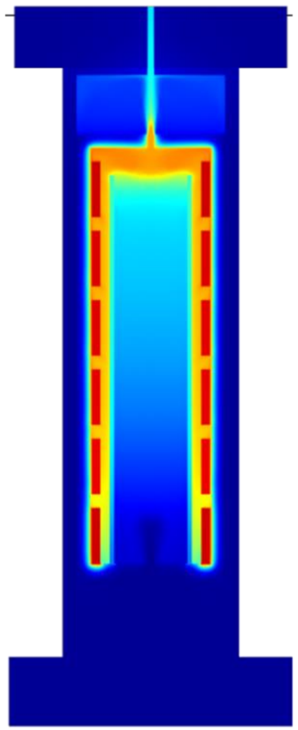
02/18/15	Pup1
02/23/15	Pup2
06/01/15	Pup3
06/23/15	Compression Coil
08/31/15	Platypus
04/01/16	Riky1
04/28/16	Riky2
06/09/16	LBNL RaceTrack1
07/26/16	LBNL RaceTrack2
10/25/16	RIKEN
01/07/17	CERN/Twente Rutherford Cable
01/12/17	OI Coil
02/27/17	Pup4
03/28/17	LBNL RaceTrack3
04/18/17	Riky3
04/26/17	Riky4
07/06/17	Platypus-II Dummy
08/14/17	LBNL RaceTrack4
08/17/17	LBNL RaceTrack5
12/05/17	Riky5 & Pup5
01/24/18	LBNL RaceTrack6
06/04/18	Riky6 & RikySRW2
09/10/18	Riky7 & Riky8
01/15/19	Pup6 & Cryomagnetics1
01/22/19	Cryomagnetics2
01/29/19	LBNL RaceTrack7
02/07/19	LBNL RaceTrack8
05/14/19	Pup7
05/22/19	LBNL CCT BIN5a-OL
05/26/19	LBNL CCT BIN5b-OL
09/12/19	Dingo

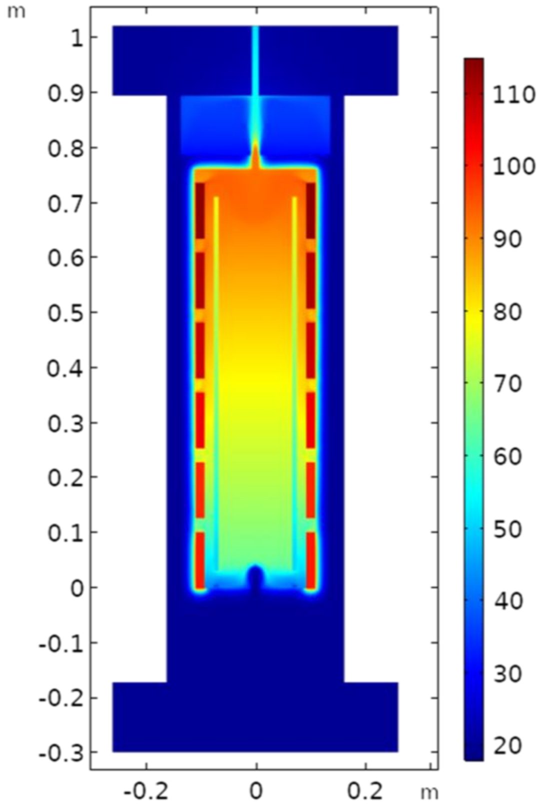
nitf – Nonisothermal Flow

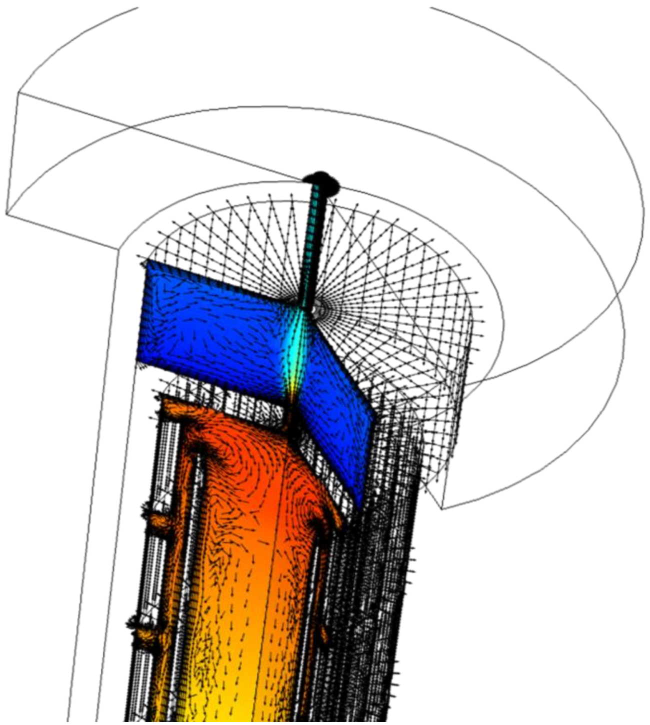


Originally worried about line of sight, we introduced a homogenizing tube between the working hot zone and the bare SiC heating elements.

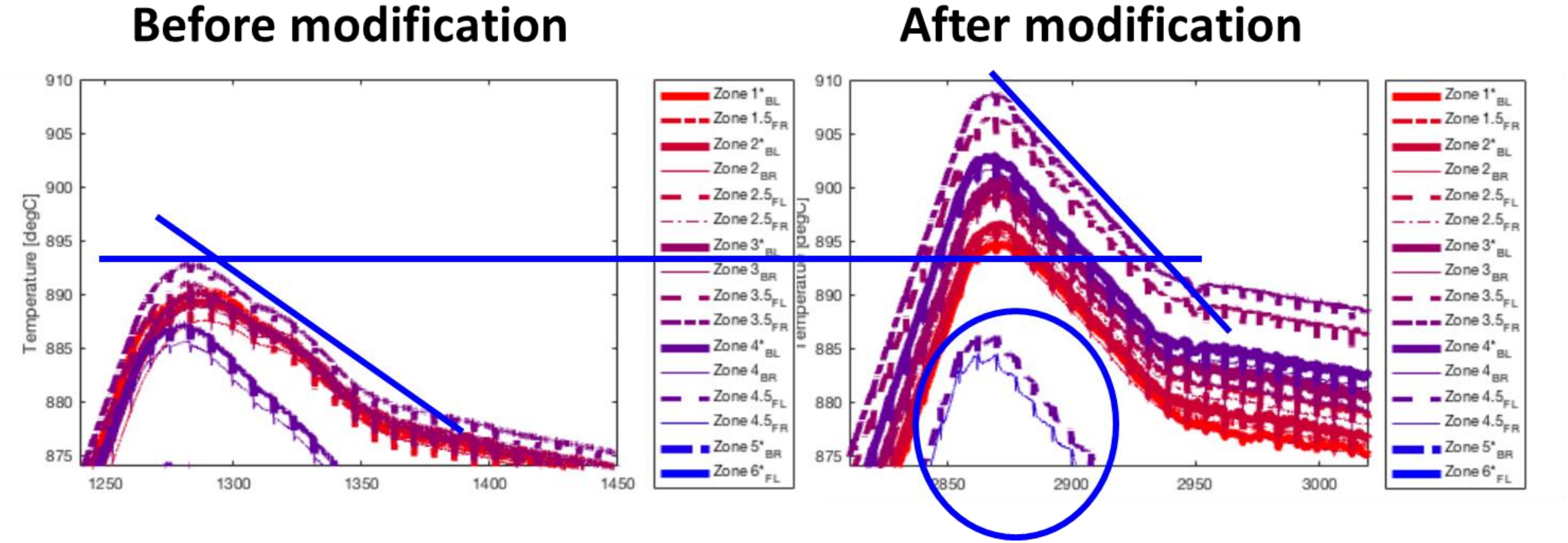
Illustrated below is the effect of the homogenizing tube w.r.t. to the temperature profile, followed by a modification to that tube, and followed by the fully resolved flow profile







Experimental Validation of Better Natural Convection

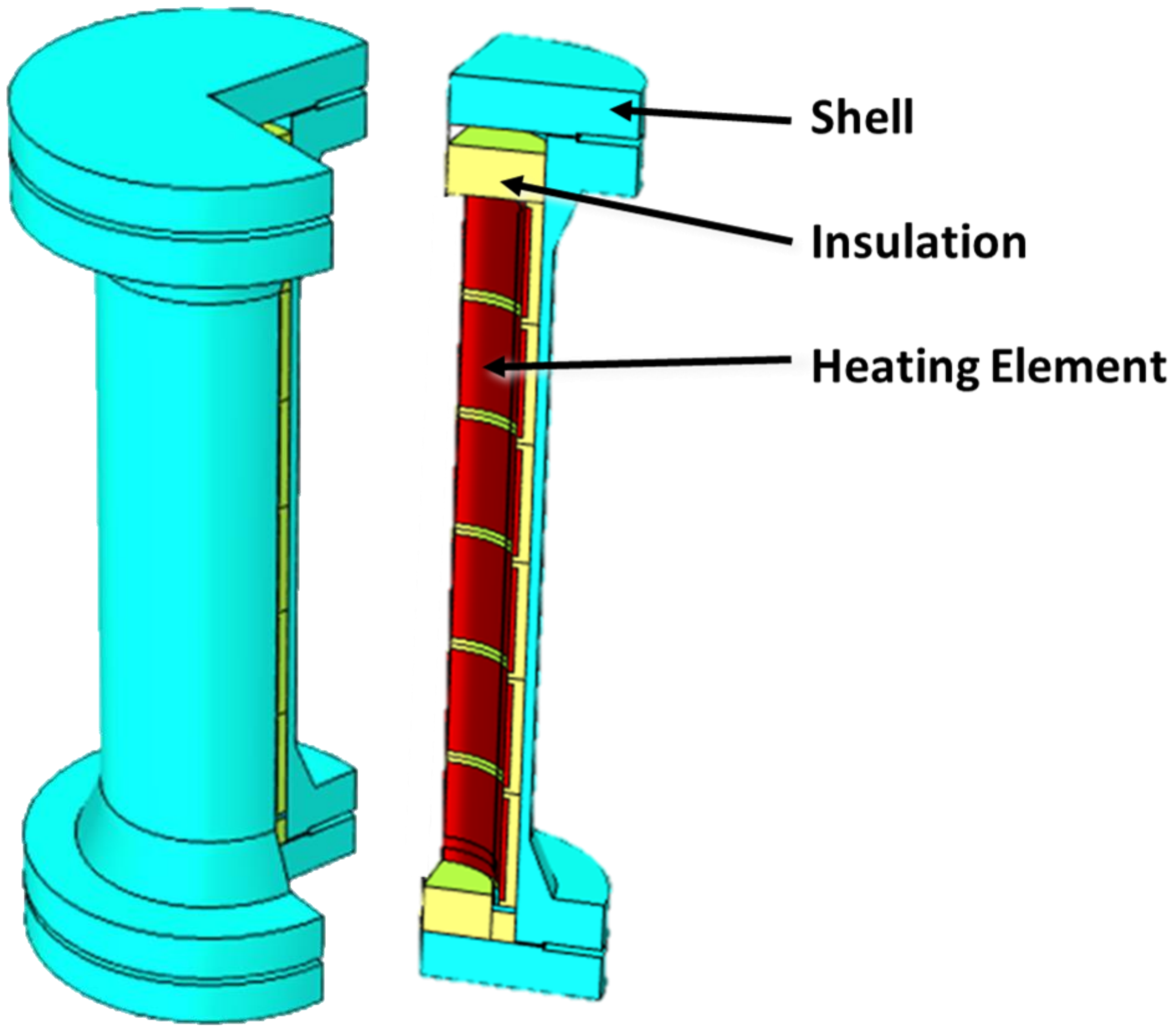


Used same furnace settings and essentially identical thermal mass before and after modifications

Improvements after modifications:

- Increased temperature in uniform hot zone
- Provided more precise control of cooling rates
- Raised temperature of lower zones - lengthened hot zone

Now for the Details Behind the Finite Element Modeling



A few notes about the modeling:

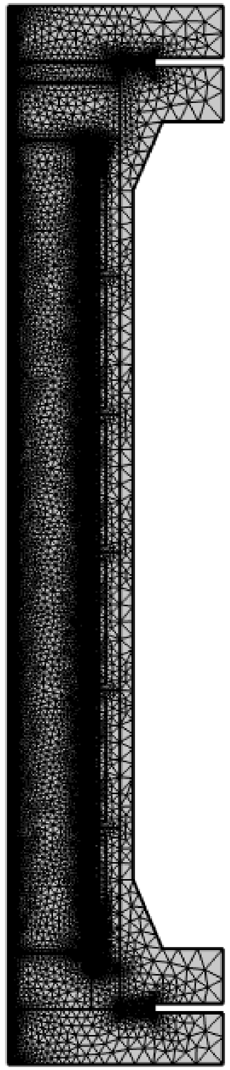
All material and geometric features of the furnace are modeled as close to reality as possible

2D Aximsymmetric

Initial Conditions:
- Heating elements off
- Temp everywhere 20 degC

Boundary Conditions:
- Non-isothermal flow of 50 atm Argon
- Inlet mass flow rate of 5 L/min (bottom middle)
- Exhaust fixed to Set Point pressure of 50 atm (top middle)
- Internal natural convection established via density gradients
  - (not highlighted is the vertical baffle recently introduced)
- **Heaters ramped up to 3 kW (3.8 kW for bottom zone) in 10 s**
- Shell cooled by ambient natural convection

Mesh and Study Steps

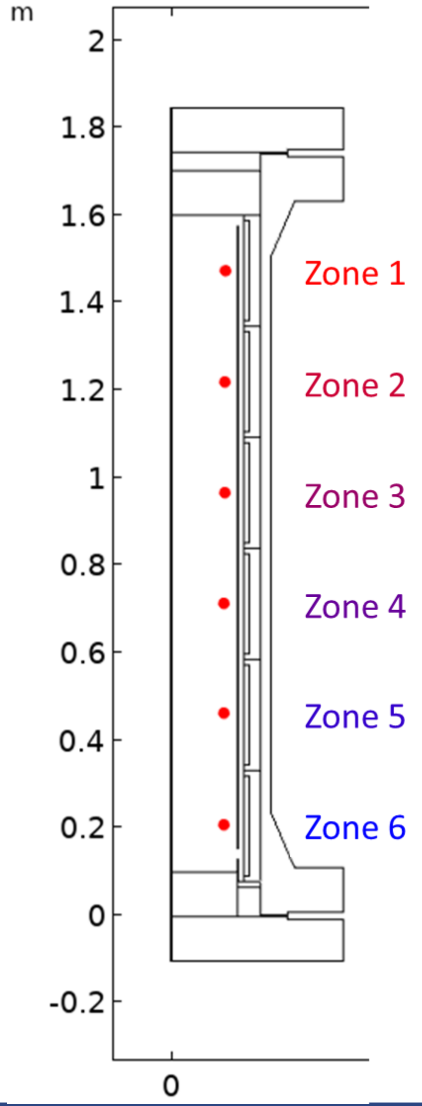


A ‘normal’ mesh for fluid flow was used.
Study1 examines one second of heating, with 0.1 [s] time steps.
Study2 examines the first minute of heating, with 1 [s] time steps, using the Study1 solution as a first step.
Study3 examines the first hour of heating, with 60 [s] time steps, using Study2 solutions.
Study4 examines the second hour, using Study2 solutions
Study5 examines cooling for 25 [min], using Study4 solutions.

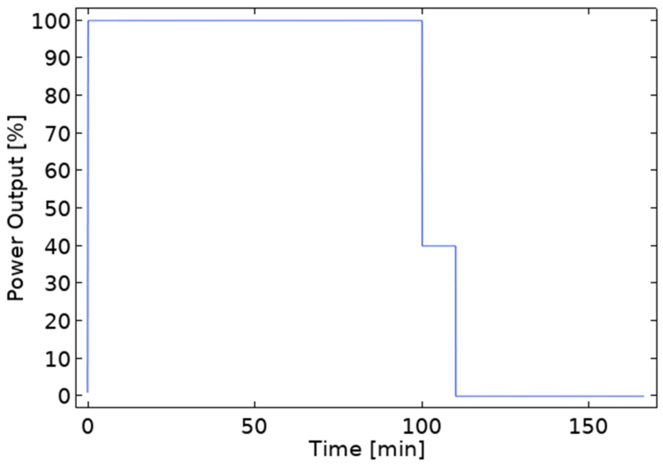
Mesh:	68k DOF
Study1:	57 s, 1 GB
Study2:	4 min, 3 GB
Study3:	10.5 hr, 13 GB
Study4:	8 hr, 11 GB

New heater design – which a 2D axisymmetric model coincidently is modeled better than the previous heaters.

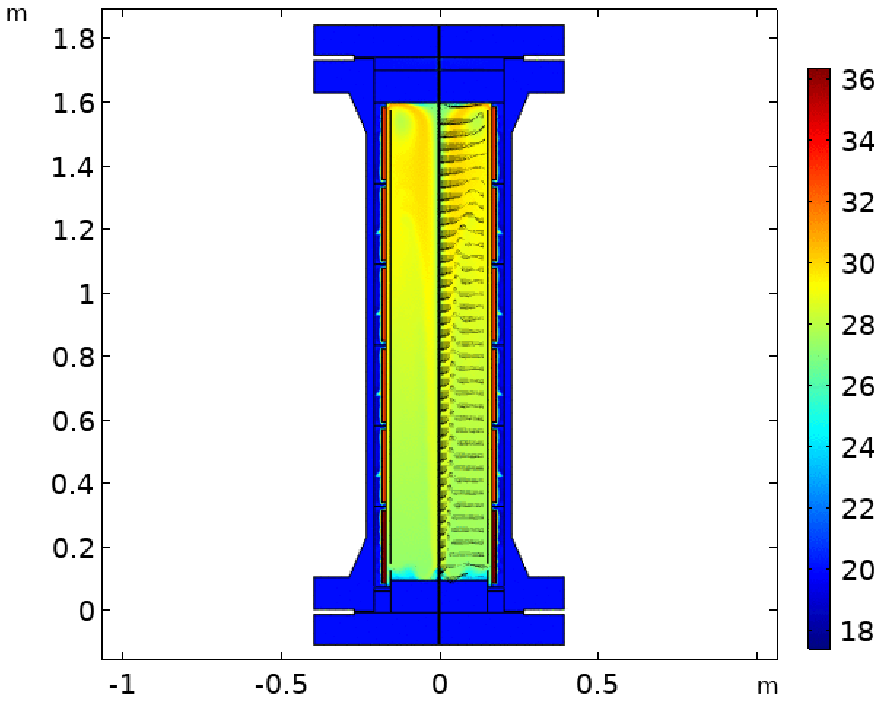
Transient Results of Non-Isothermal Flow Development



Heating Elements turned ON (100%)
and left on until T > 890,
Reduced to 40% for 10 min,
Then turned Off

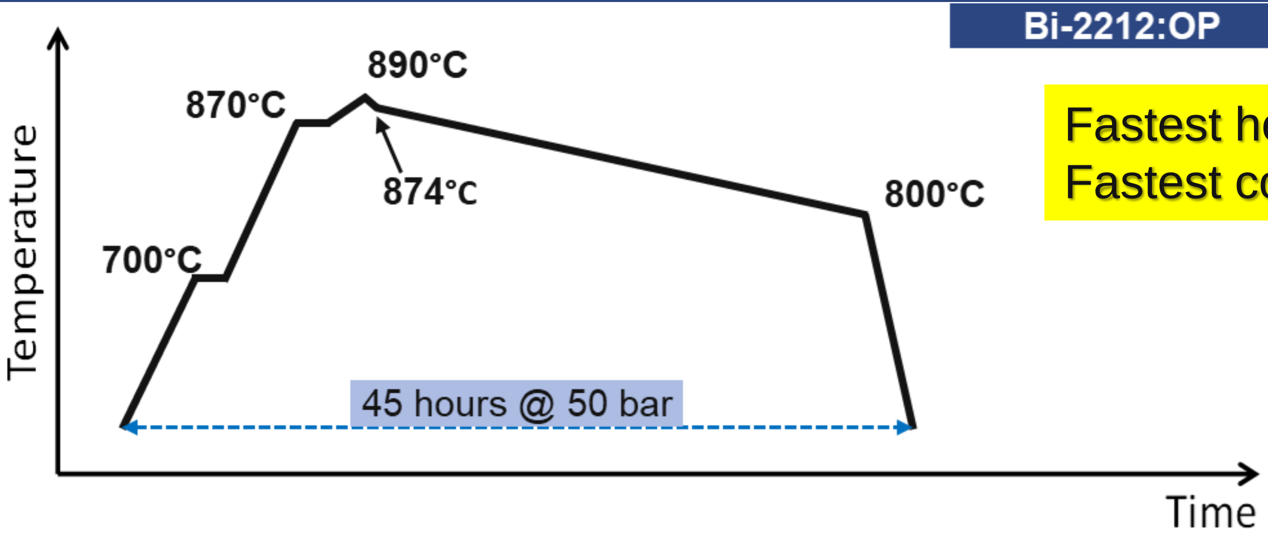


Temperature Evolution & Natural Convection Loop Development During First Hour:



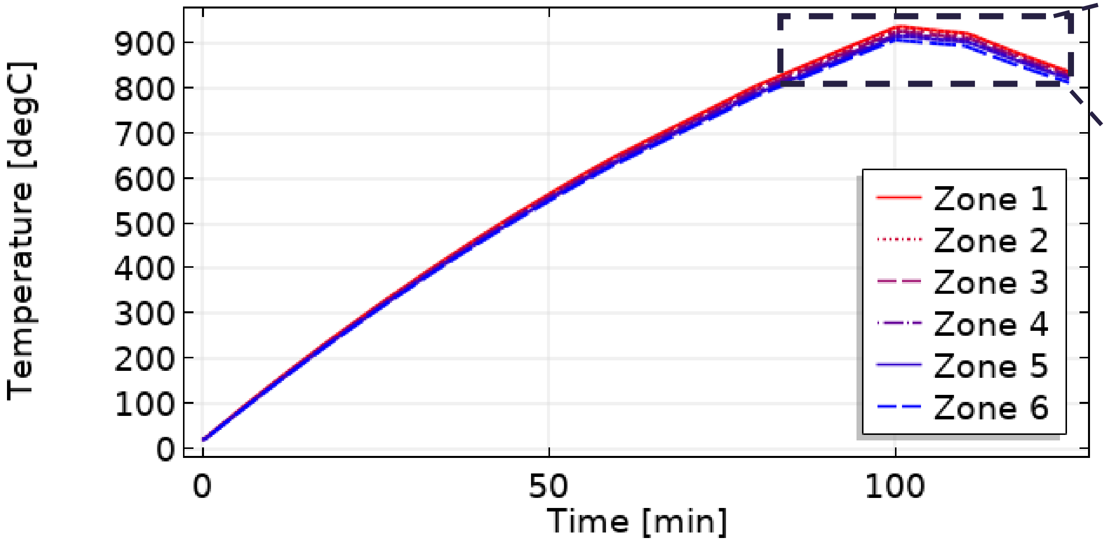
Thermal Map with color scale and
Arrow Plot of flow field
(only superimposed on right half for clarity)

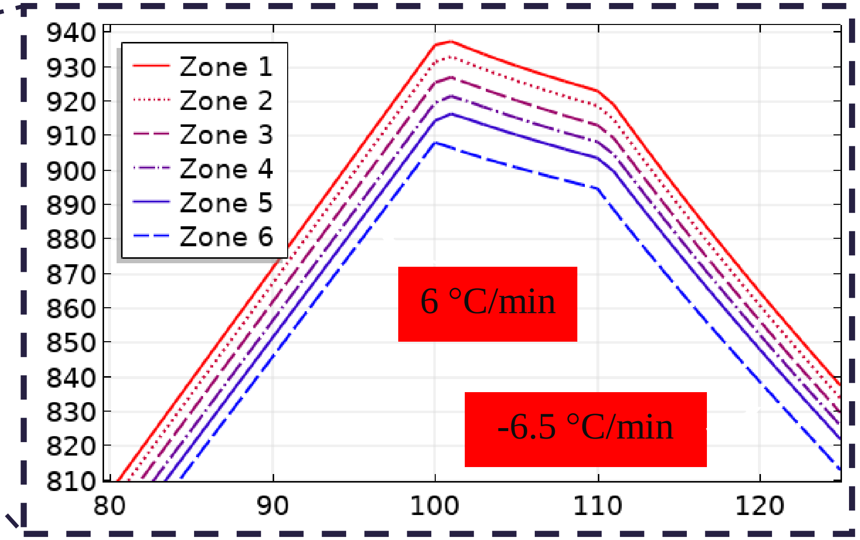
Furnace Capable of Meeting Schedule Needs



Fastest heating rate in schedule: 4 °C/min
Fastest cooling rate in schedule: 1 °C/min

Available heating rate: ≥ 6. °C/min
Available cooling rate: ~ 5.7 °C/min



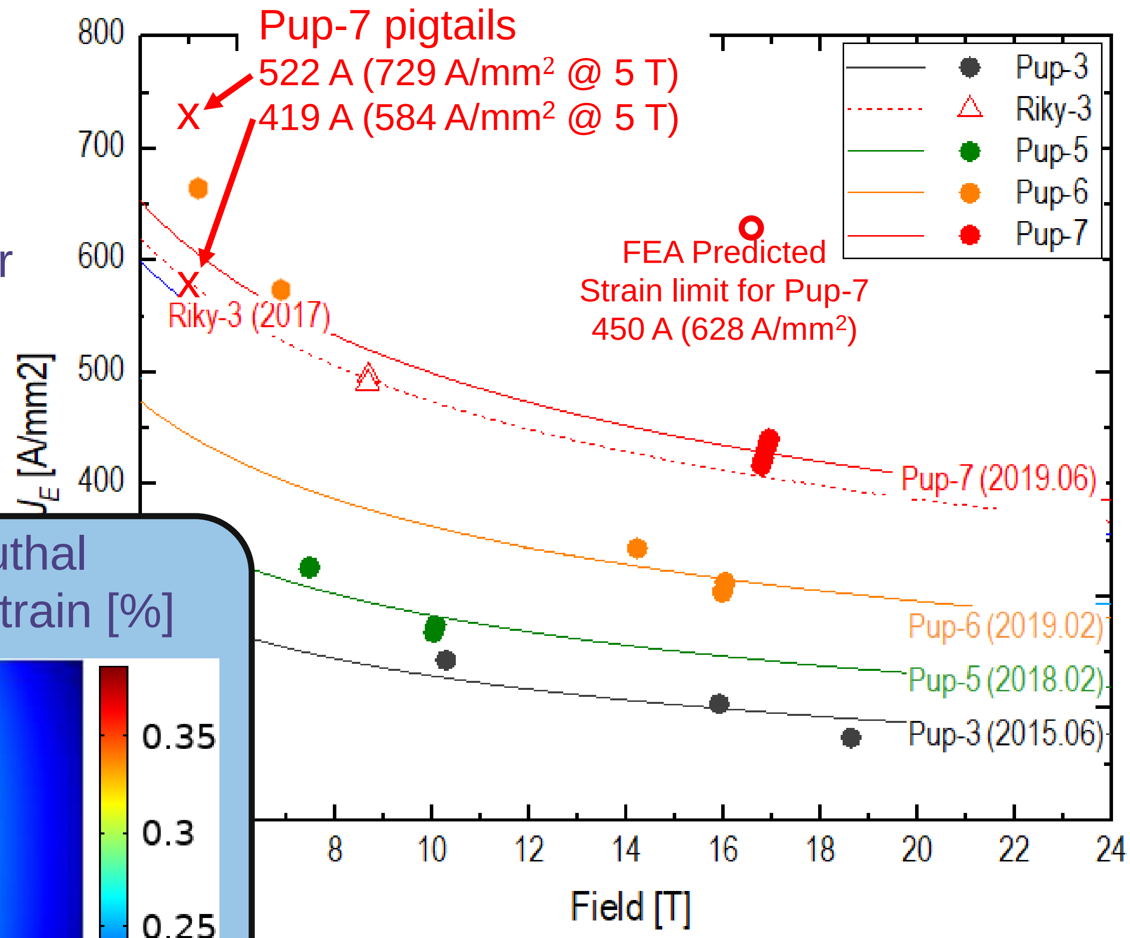


Comparison of Furnace Capabilities

	Deltech	Renegade
Commissioned	c. 2014	c. 2020
HT Pressure	100 bar (typically run at 50 bar)	50 bar
T_max	890 C	890 C
Partial O2 pressure	2%-O_2 in Ar (target 1 atm O_2)	2%-O_2 in Ar
Hot Zone Diameter	130 mm	**250 mm**
Hot Zone Height	450 mm	**1000 mm**
# of Zones	6	6
# of Heaters per Zone	6 individual, spiral SiC elements	**1 single element, embedded in ceramic**
Power to Zones	1.2 kW per Zone w/ bottom Zone = 2 kW	**3 kW per Zone w/ bottom 2 Zones = 3.8 kW**

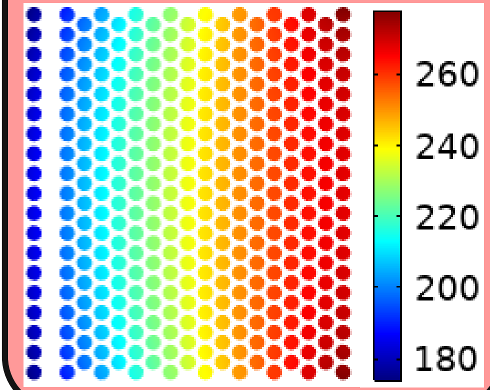
Pup-7 I_c-Limited Actual Performance

Takeaways:
Better coil manufacturing, design, and processing yields pigtails which indicate coil performance
Opportunity still exists to get higher I_c and reach target strain-limits!

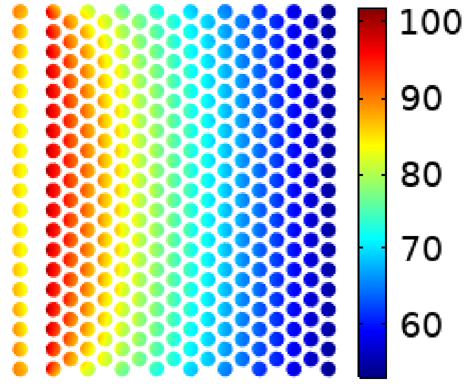


I_{op} = 346 A (483 A/mm²) within the 14 T outsert

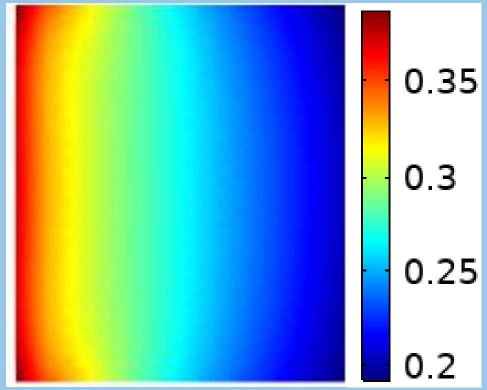
$J_{phi} \cdot B_z \cdot R$ [MPa]



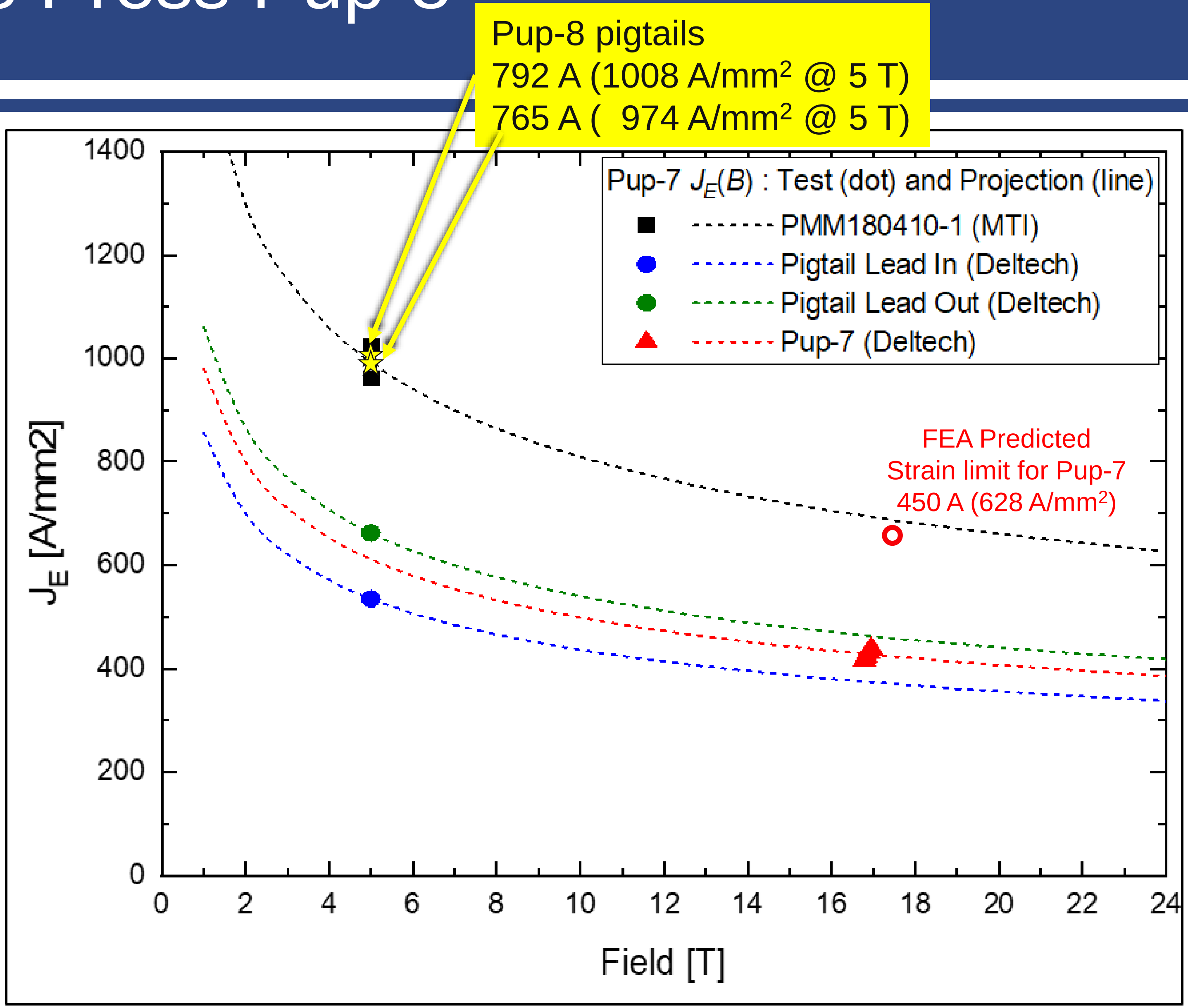
Azimuthal Stress Map [MPa]



Azimuthal Percent Strain [%]



Hot Off the Press Pup-8



Summary

FEA of the furnace (and experience) has provided the confidence to move forward and build a larger facility

We have a great track record of producing successful test coils

Larger furnace for larger magnets online next year

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