HES-13 Padua, Italy, May 21-24, 2013

FLUXTROL Inc.
Centre for Induction Technology™

Modeling and Optimization of Cold Crucible Furnaces for Melting Metals

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State of the Art

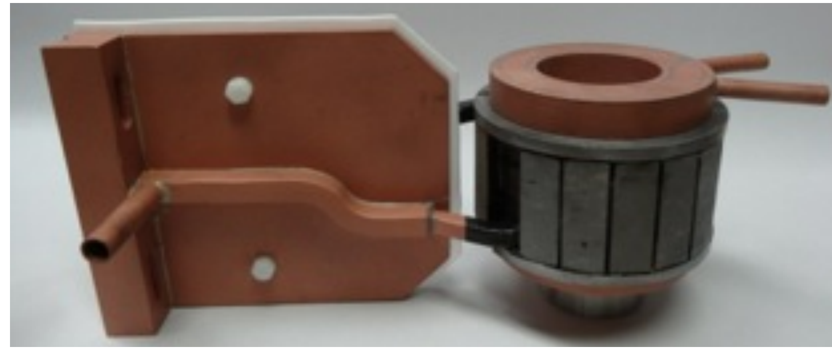
- Induction melting of metals in CC is known since 1931 (Siemens and Halske, Germany)
- Major development of CC melting was made since 1960s in USA, Japan, France and Russia
- In 1988 L. Tir and A. Gubchenko published a fundamental book "*Induction melting furnaces for processes of high cleanness and accuracy*"
- Starting the end of 1980s main research was devoted to MHD processes in cold crucibles (France, Germany, Japan) with much less attention to electrical parameters
- At the beginning of 2000s several very good articles on electromagnetic processes in CC furnaces and methods of their simulation were published by Prof. A. Muehlbauer, E. Westphal et al., Hannover, Germany
- No significant publications on magnetic flux control were found at present time
- This study must show possible improvements due to optimal use of the magnetic controllers

Project Goals and Objectives

- Improve the electrical efficiency of cold crucibles using magnetic flux control
- Evaluate the effects of applying Fluxtrol Controllers in the following ways:
  - Fluxtrol Shunts with Poles added onto the coil
  - Fluxtrol Inserts placed between the cold crucible fingers
  - Magnetic Ring placed between Faraday Ring and CC
- Quantify the effect based on analytical calculations, 2D and 3D FEA simulation and verify the results with experimental data

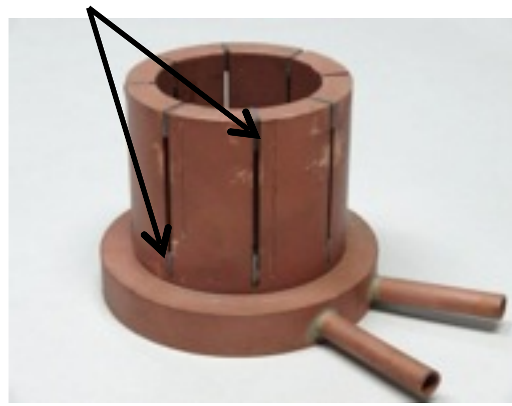
CCF Used in Study

Crucible ID 60 mm, OD 82.5 mm, length 67 mm, number of fingers 8
Coil ID 84 mm, length 54 mm
Load – Stainless steel 304, Dia. 52 mm, length 57 mm
Frequency 10 kHz



5 Turn Coil With Shunts

Inserts Between CC Slits



Faraday Ring

- A mock-up CCF was manufactured with dimensions representing real CCFs used for melting
- Impedance, load resistance, and magnetic field distribution were measured on the setup with the flux control varied

Analytical Calculation for Long System

- With ideal magnetic flux control there are no end effects in a CCF, and it can be considered as a part of an infinitely long system
- Parameters for an infinite CCF were calculated to determine the threshold parameters of real system

Impedance of Load:

$$Z_w = R_w + jX_w = \frac{\pi D_{ci} \rho_w N^2 (G + jQ)}{\delta_w L}$$

Impedance of Fingers:

$$Z_f = R_f + jX_f \qquad R_f = \frac{\rho_{cu} \Pi_{eq} N^2}{\delta_{cu} L} \qquad X_f = R_f \frac{\Pi_f}{\Pi_{eq}} + \frac{\pi f \mu_0 h M N^2 (D_{ce} - D_{ci})}{\mathrm{L}}$$

Impedance of Coil Winding and Coupling Gap:

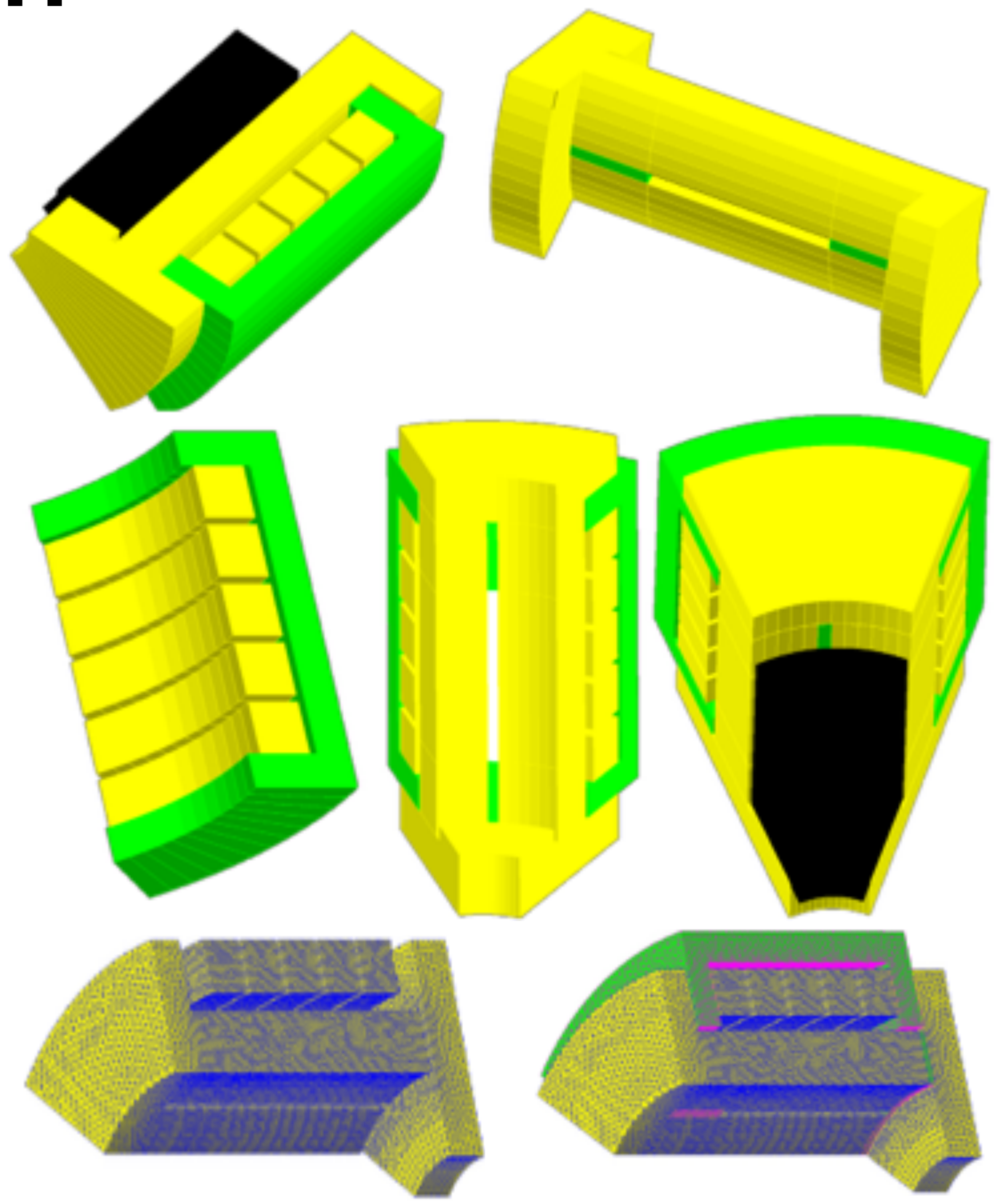
$$Z_c = R_c + jX_c \quad R_c = \frac{\pi \rho_{cu} N^2 (D_i + \delta_{cu})}{g \delta_{cu} L} \quad X_c = R_c + \frac{\pi \mu_0 \omega N^2 \left(\left({D_i}^2 - {D_{ce}}^2 \right) + \left({D_i}^2 - {D_w}^2 \right) \right)}{4\mathrm{L}}$$

Impedance of Loaded Coil:

$$Z_i = \sqrt{{R_i}^2 + j{X_i}^2} = \sqrt{\left(R_w + R_f + R_c\right)^2 + \left(jX_w + jX_f + jX_c\right)^2}$$

3D Simulation

- A 1/8 wedge of the CCF modeled using periodicity with the mesh on the sides of the wedge equal
- BH Curve for Fluxtrol 100 applied to flux concentrator components
- Power in the melt or coil current are held constant while flux control is varied

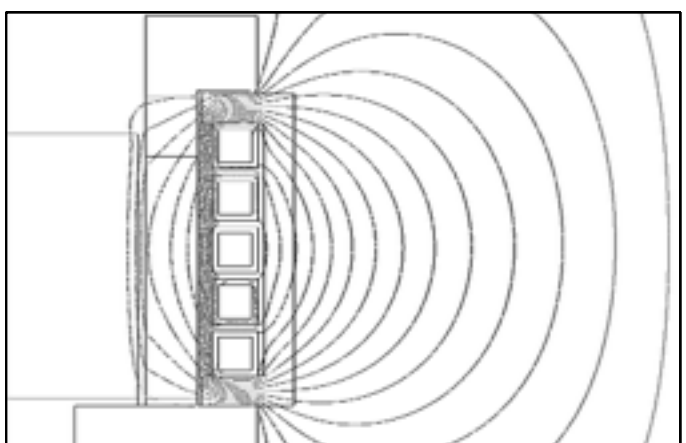


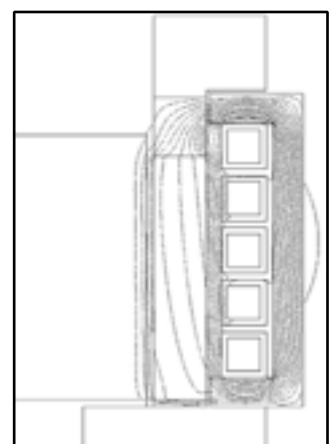
2D Simulation

- A method was developed and used in practice at Fluxtrol to make 2D CCF simulations
- 2D simulation is a good engineering tool for matching calculations but it does not account for the axial component of current in fingers
- To account for the reluctance of the magnetic flux path through the finger regions, equivalent permeabilities were calculated:

$$\mu_{eq,radial} = \frac{\mu_{r,slit} h + \delta_{cu}}{b} \qquad \mu_{eq,axial} = \frac{\mu_{r,slit} ht + \delta_{cu}(t + s - \delta_{cu})}{bt}$$

No Flux Controllers





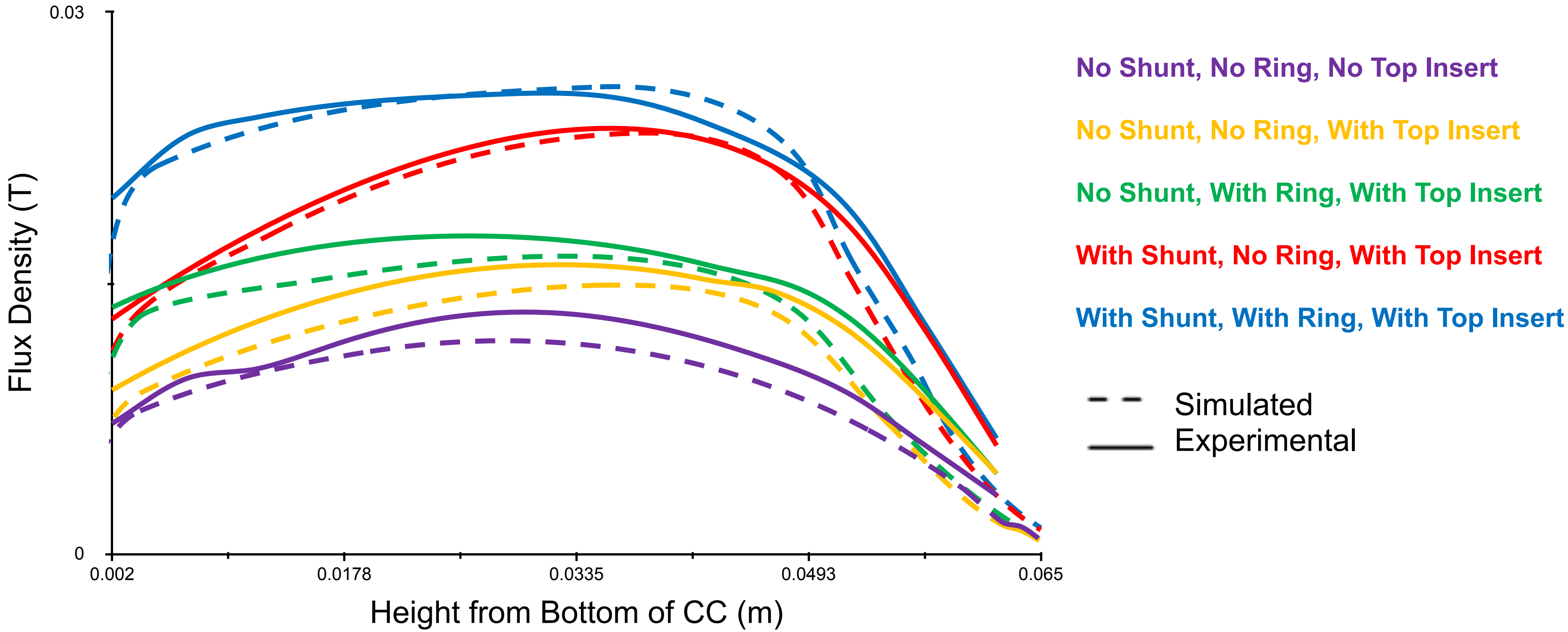
With Shunts, Top Inserts, And Fluxtrol Ring

Comparison of Results

Shunt	No		No		No		Yes		Yes		-
Top Insert	No		Yes		Yes		Yes		Yes		-
Fluxtrol Ring	No		No		Yes		No		Yes		-
Experiments E; 3D Simulated S,	E	S	E	S	E	S	E	S	E	S	I
Impedance (Ohm)	42.9	41.6	48.3	45.9	49.5	47.6	68.6	72.0	73.0	76.1	77.2
Load Resistance (Ohm)	1.61	1.70	2.84	2.66	3.55	3.50	5.10	6.48	7.16	8.92	12.9
Efficiency (%)	-	25.4	-	35.3	-	42.5	-	43.9	-	52.7	53.2
Power Factor	-	0.16	-	0.16	-	0.17	-	0.21	-	0.22	0.31

- Current in the coil is held constant (200 A)
- There is good agreement between experiments and 3D simulation
- With shunts, top insert, and Fluxtrol ring efficiency is 52.7%, compared to 25.4% for the case with no flux controllers
- The results came very close to the infinite case showing maximum possible improvements in electrical efficiency

Magnetic Field Distribution



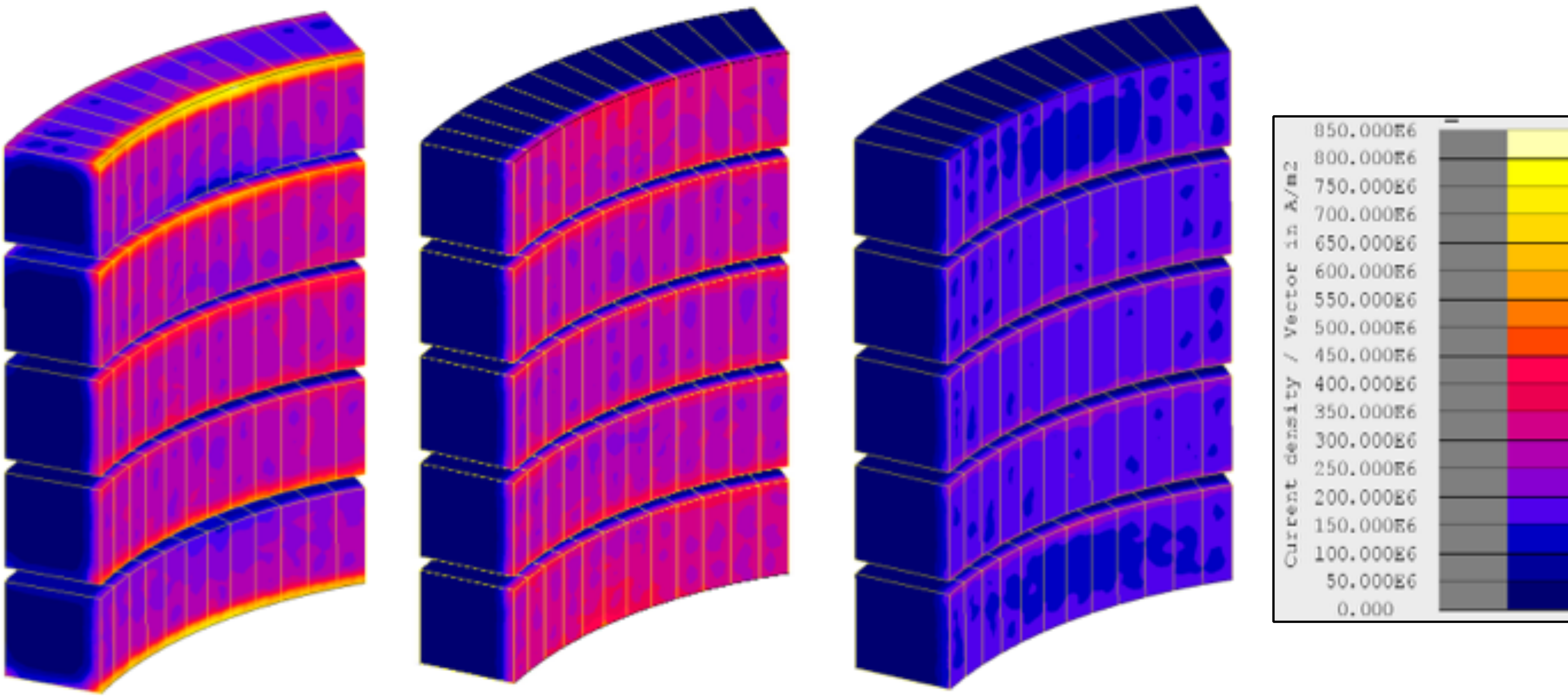
- Current in the coil is held constant (200 A)
- There is good agreement between the experimental and 3D simulated results
- Flux density is more than doubled when all forms of flux concentrator are used

Power Distribution between Components

Shunt		No	Yes	No	Yes
Inserts (Top and Bottom)		No	No	Yes	Yes
Power (kW)	Load	7.4	7.4	7.4	7.4
	Coil	10.6	7.7	5.1	2.5
	Faraday Ring	1.0	0.4	0.7	0.7
	Cooling Head	0.6	0.3	0.5	0.1
	Fingers	11.0	11.5	5.2	4.9
	Total Losses	23.2	19.9	11.5	-
	Total	30.6	27.3	18.8	14.7

- Power in the melt is held constant (7.4 kW)
- Total Power is reduced 52% using shunts and inserts

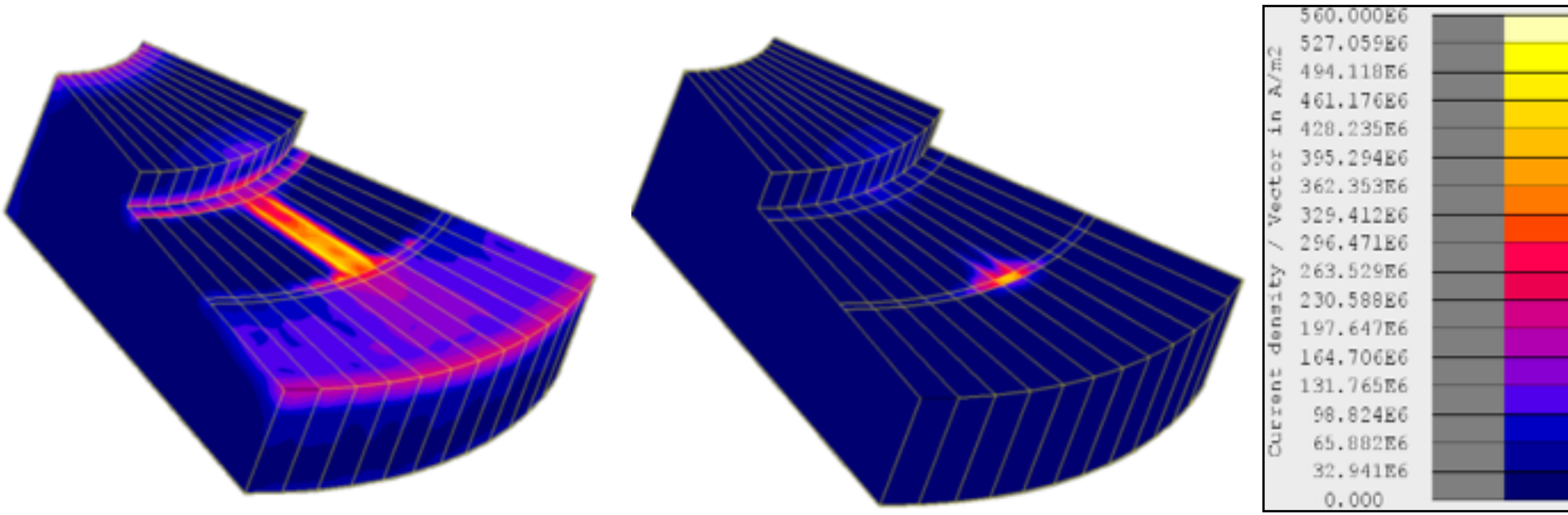
Current Density in the Coil



No Shunts or Inserts **2205 A** | With Shunts No Inserts **1653 A** | With Shunts and Inserts **933 A**

- Power in the melt is held constant (7.4 kW)
- Adding flux concentrator reduces current in the coil **2.4 times**

Current Density in the Faraday Ring

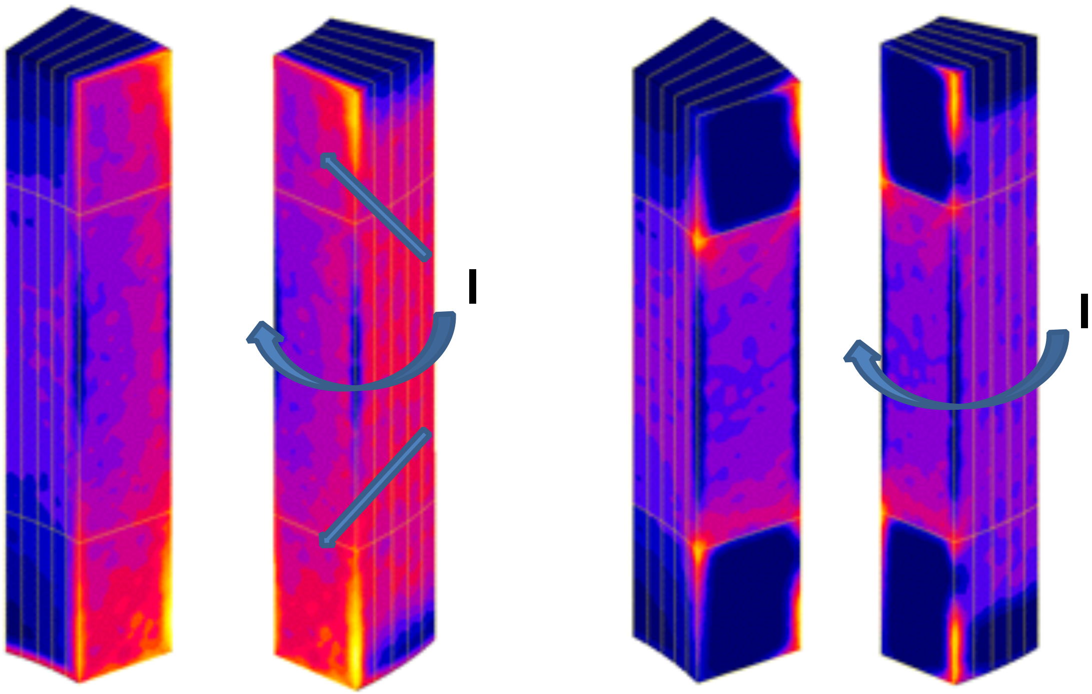


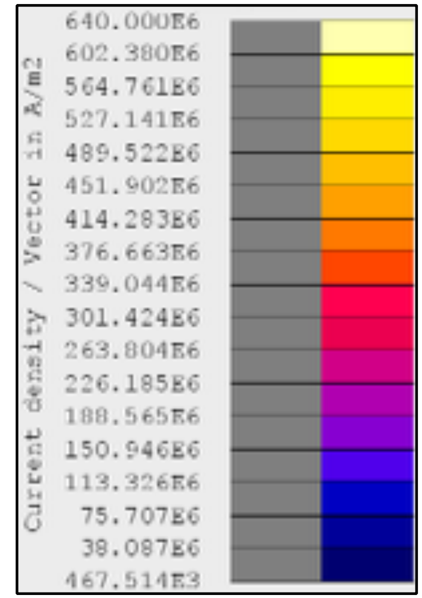
No Controllers

With Controllers

- Power in the melt is held constant (7.4 kW)
- Applying controllers reduces losses in the Faraday ring

Current Density in CC Fingers





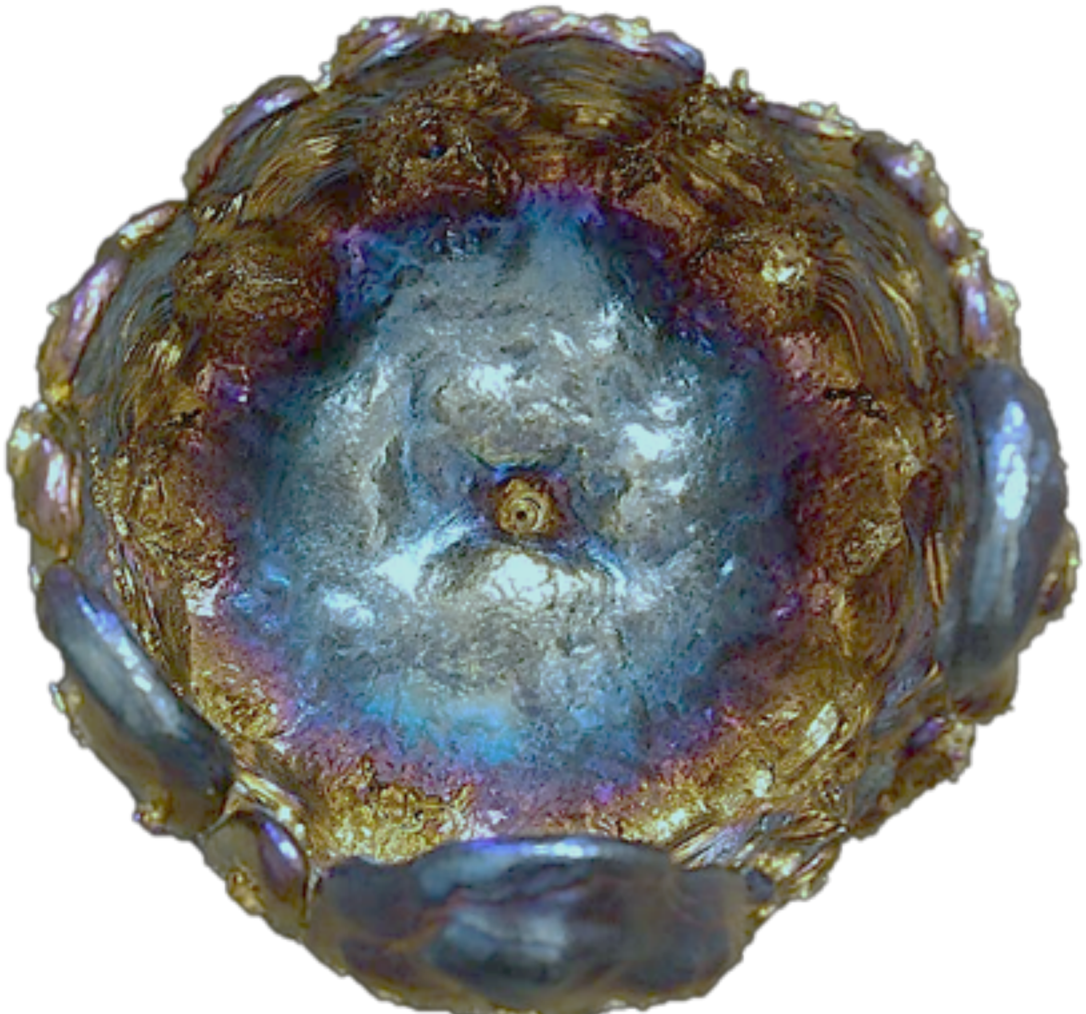
No Inserts With Inserts

- Power in the melt is held constant (7.4 kW)
- Applying inserts reduces losses in the CC fingers more than two times (for this furnace design)

Conclusion

- Magnetic flux controllers can dramatically improve efficiency of Cold Crucible furnaces and provide desirable power distribution in the load
- Magnetic shunts reduce coil current, losses in supplying circuitry and size of generator and capacitor battery
- Slit inserts strongly increase efficiency and reduce coil current
- Combination of inserts and shunts provide larger effect than a sum of the effects of inserts and shunts separately
- For the same power in the melt magnetic control can reduce the generator power and size of capacitor battery more than 2 times
- Industrial tests confirmed effectiveness and reliable work of magnetic shunts and inserts in furnaces for melting Ti alloys
- Present study does not give overall solution for CC furnace optimization; it pays attention of designer to potential improvements due to magnetic flux control.

THANK YOU!



Skull of Ti after bottom pouring, courtesy R. Haun