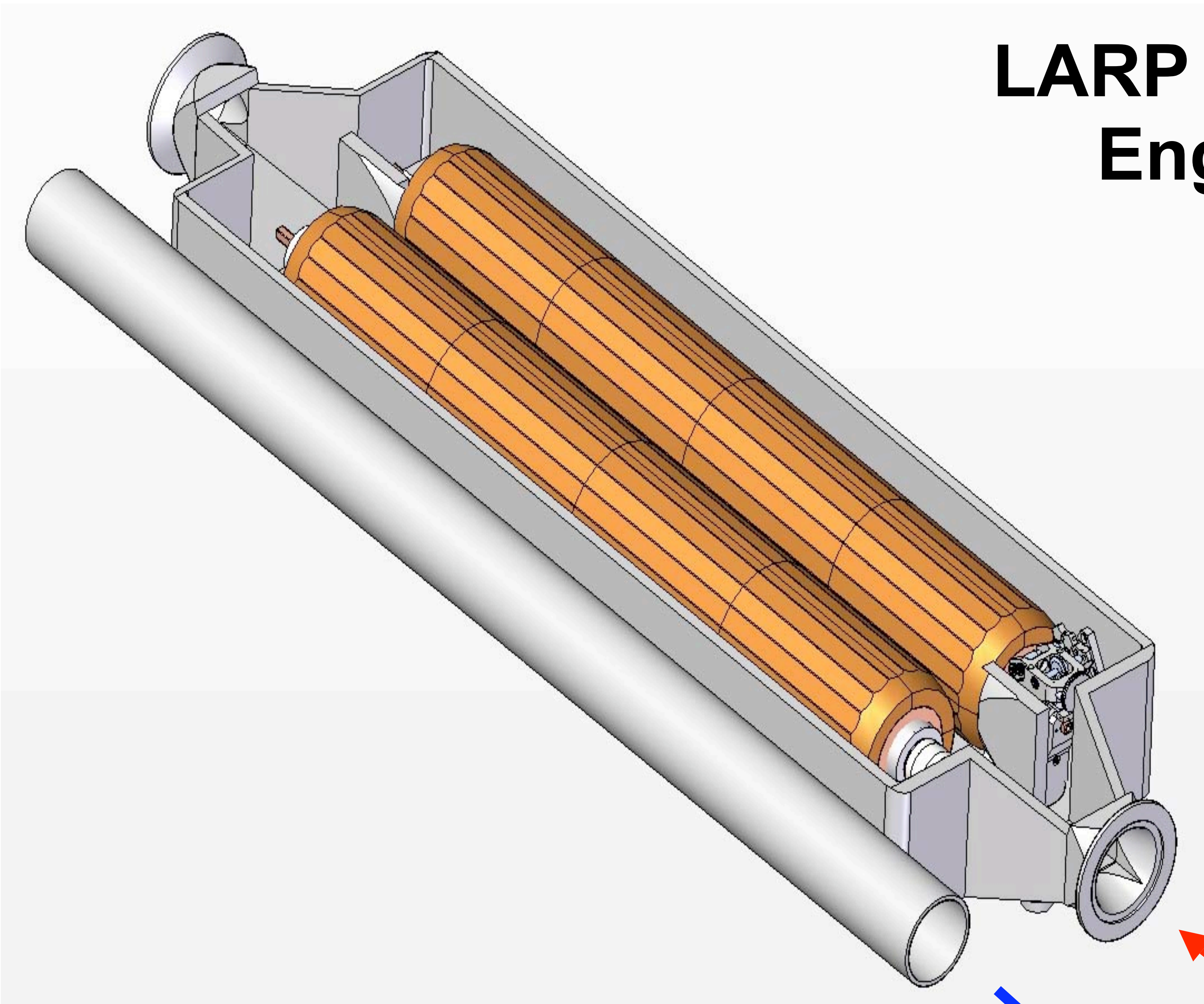
US LHC Accelerator Research Program

BNL - FNAL- LBNL - SLAC



LARP Phase II Collimator Engineering Status

Jeff Smith
SLAC

beam

beam

19 September 2008

CERN Phase II Design Meeting

- Gene Anzalone, Eric Doyle, Lew Keller, Steve Lundgren, Tom Markiewicz, Reggie Rogers & Jeff Smith

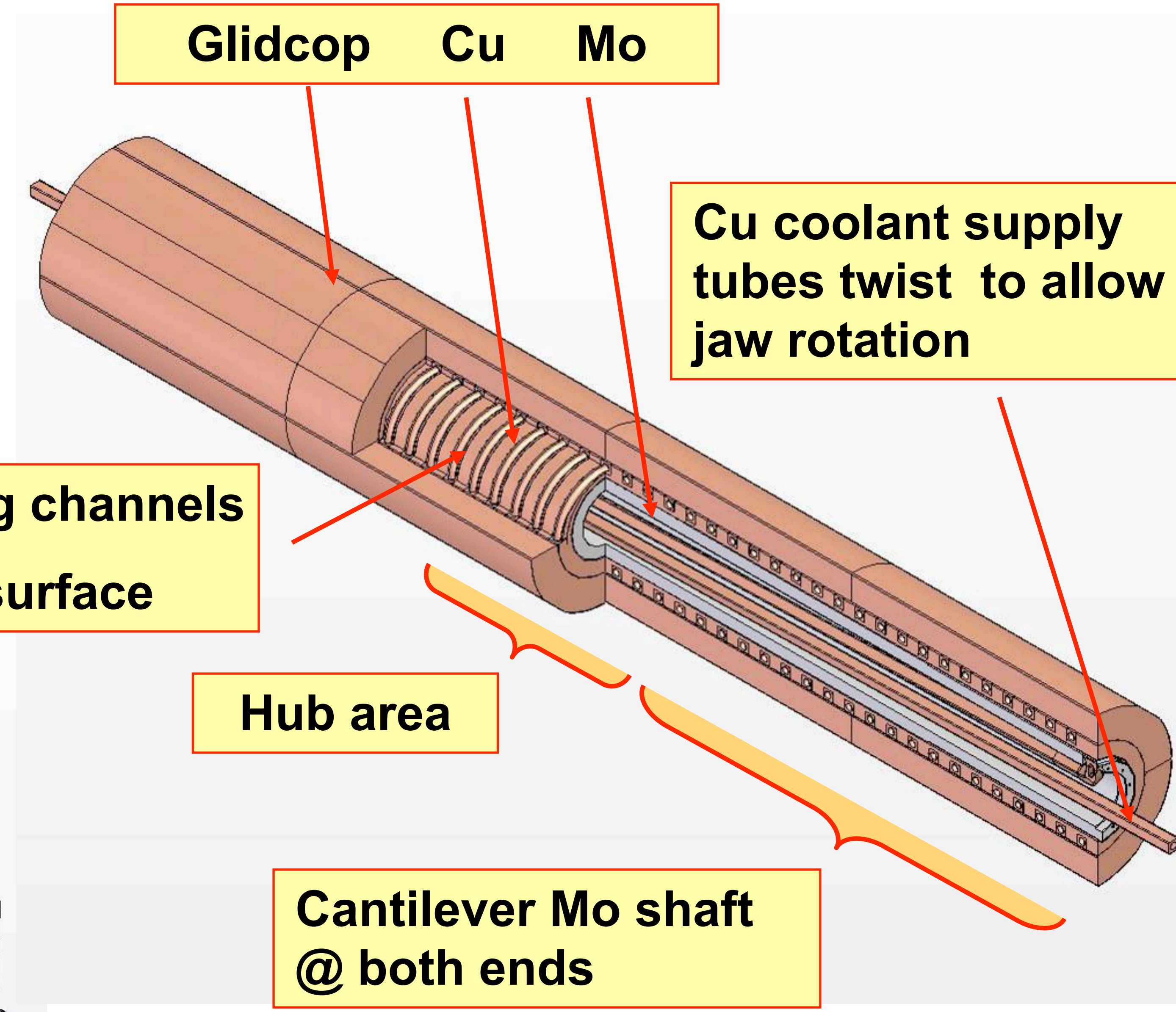
Design Overview

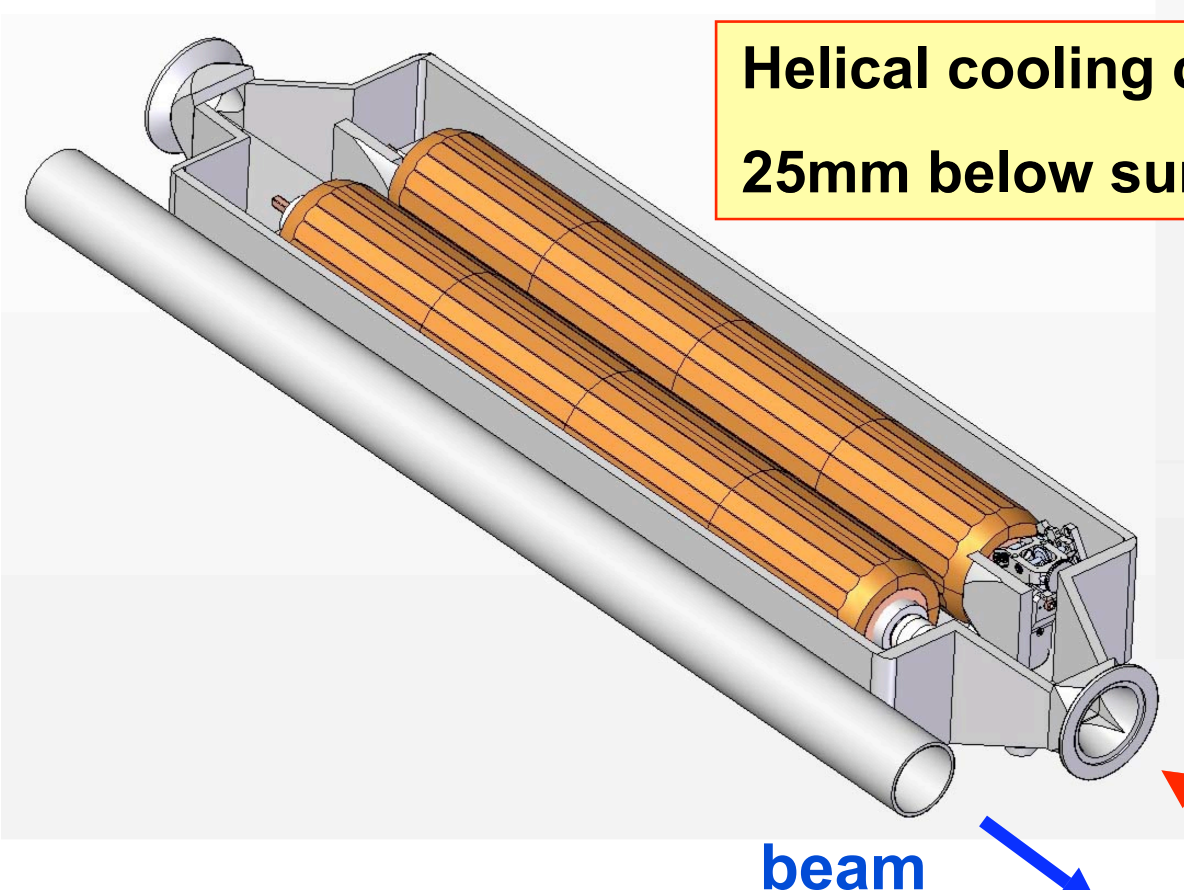
LARP

LHC Phase II Base Concept

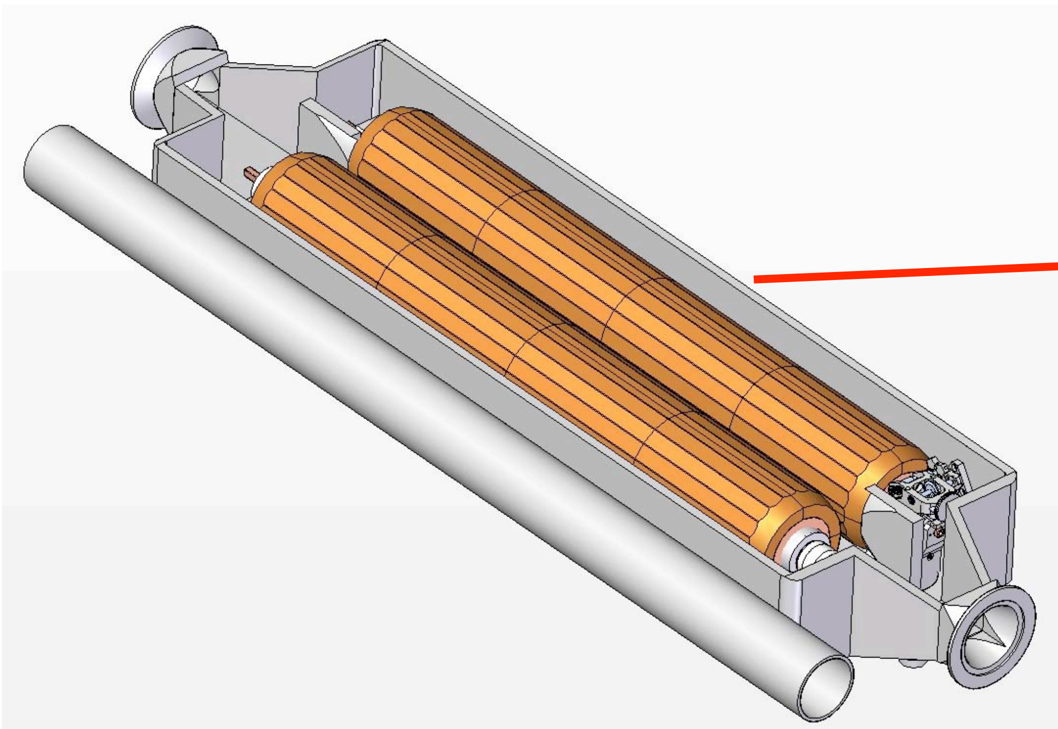
physical constraints
current jaw design

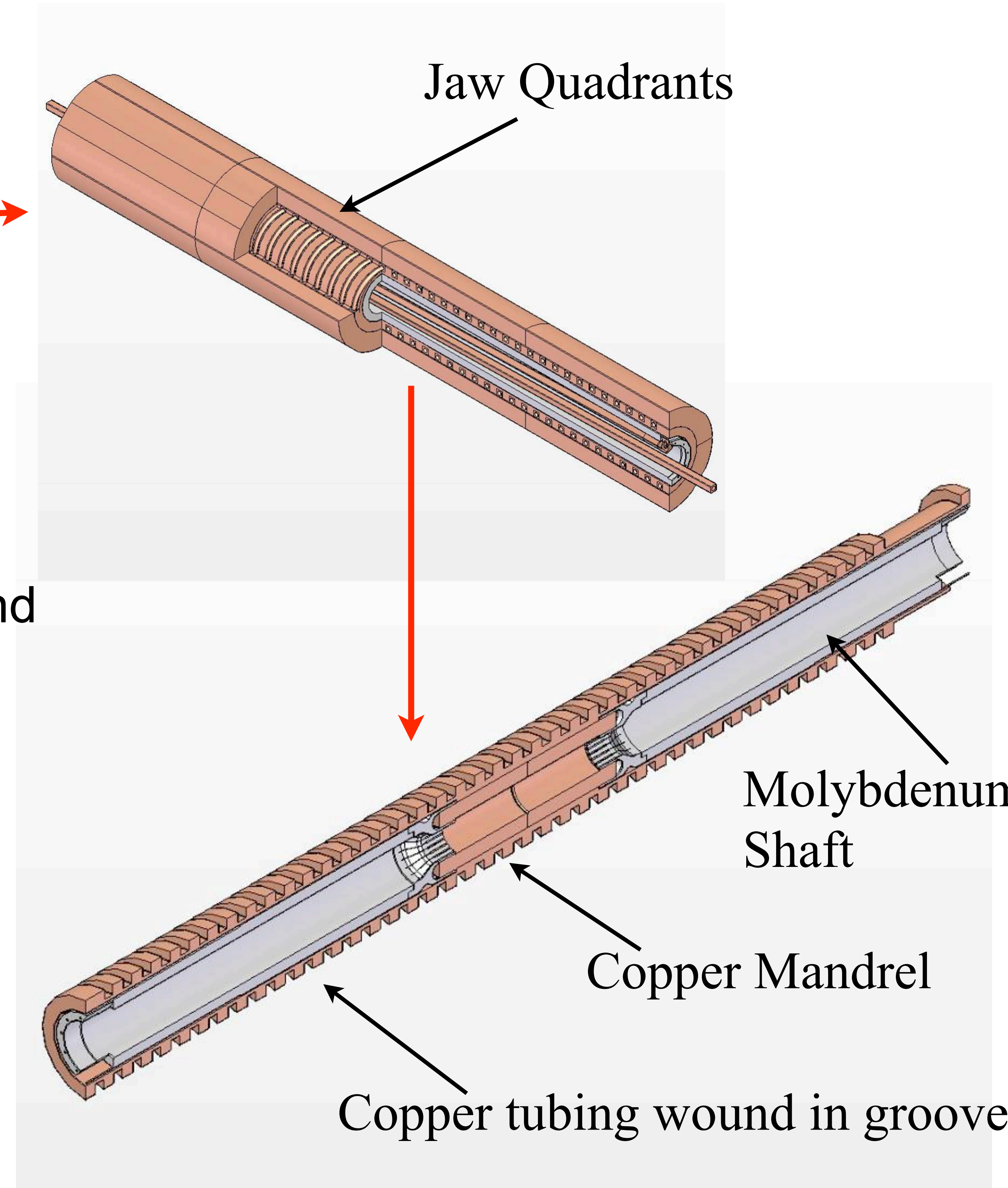
- beam spacing: geometrical constraint
- Length available 1.47 m flange - flange
- Jaw translation mechanism and collimator support base: LHC Phase I
- >10 kW per jaw Steady State heat dissipation (material dependent)





First full length Jaw Construction

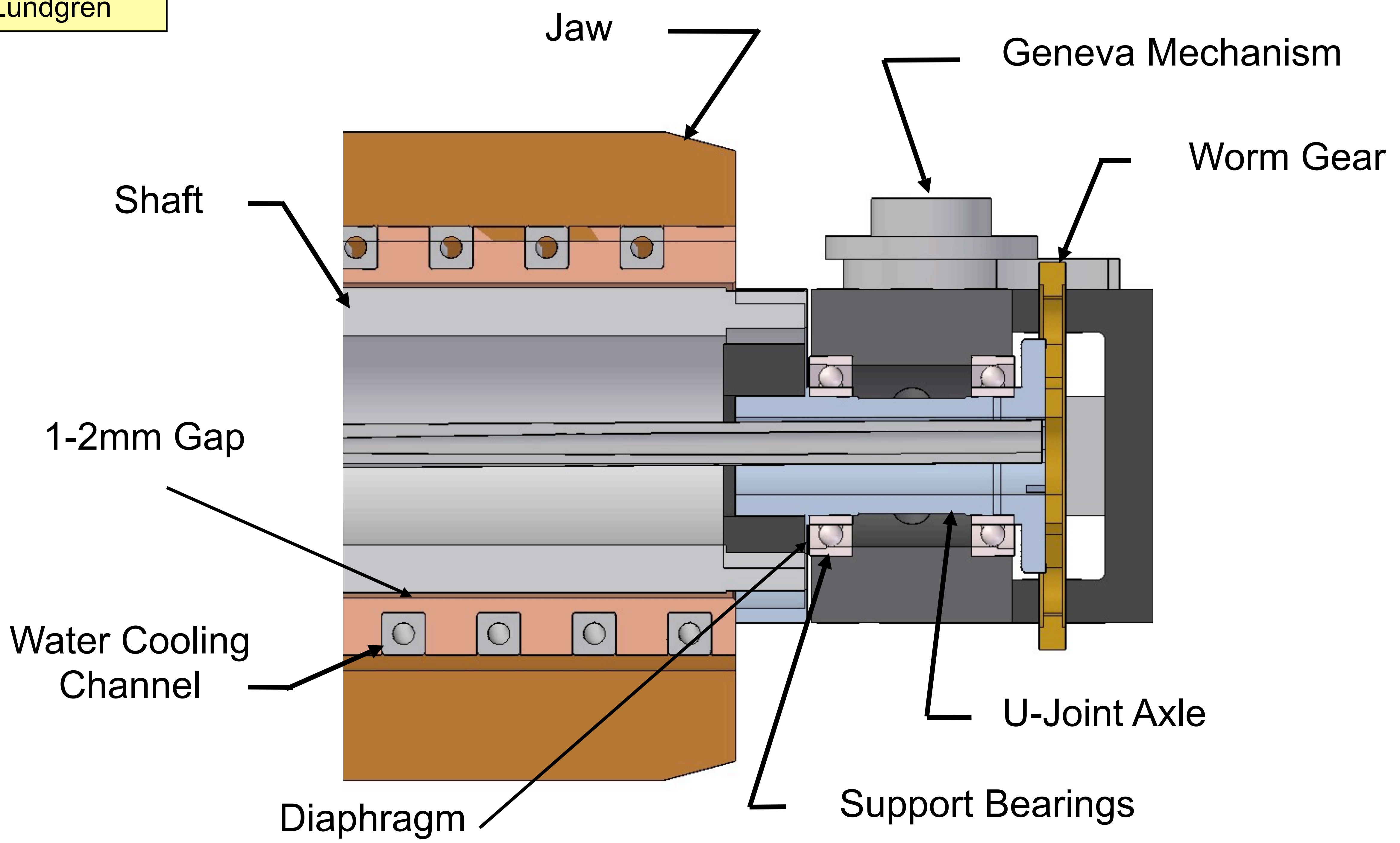




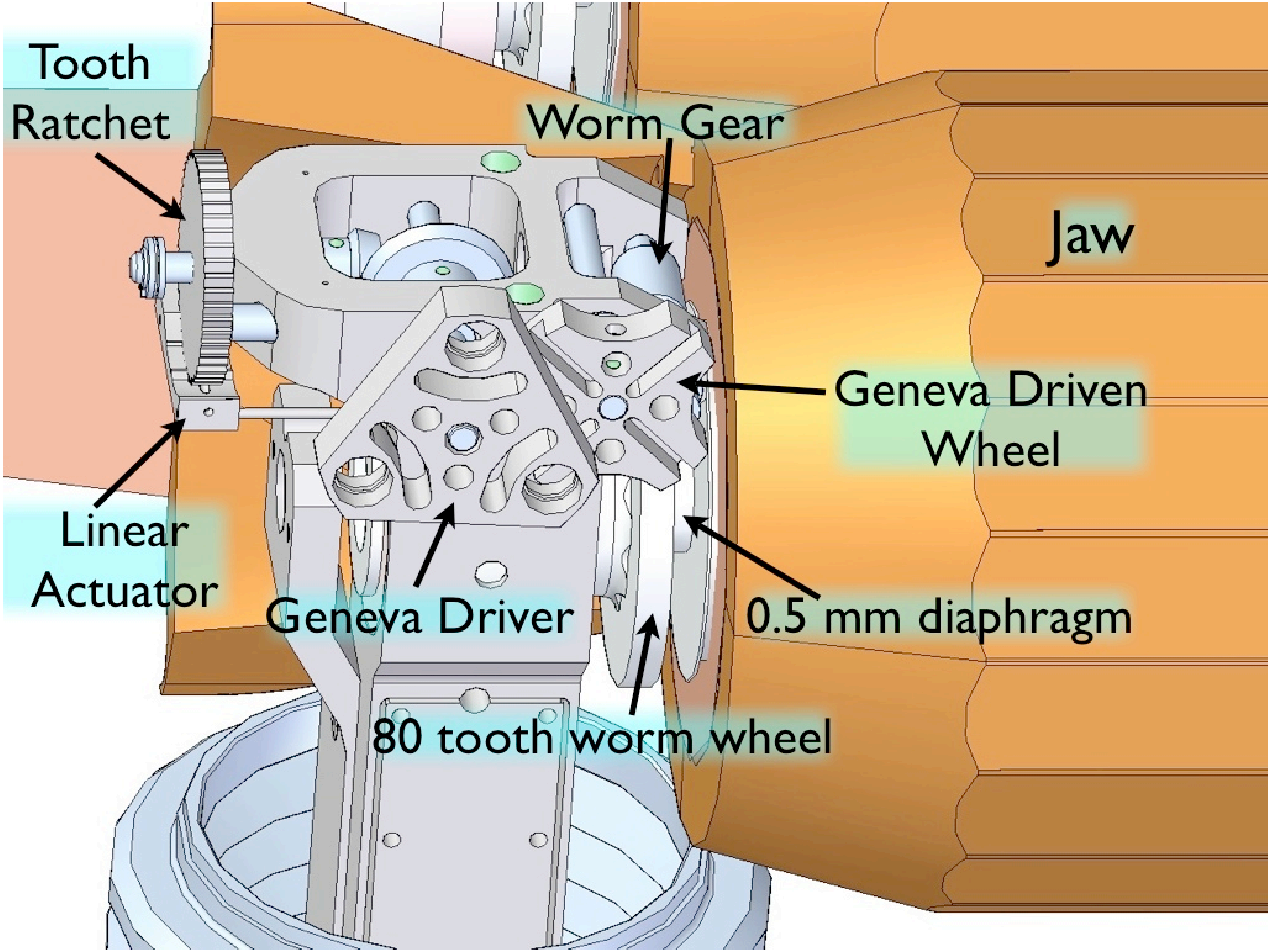
- Jaw composed of molybdenum shaft and copper mandrel wound with copper tubing for cooling. Exterior Jaw quadrants brazed on top of mandrel

Upstream end vertical section

Lundgren



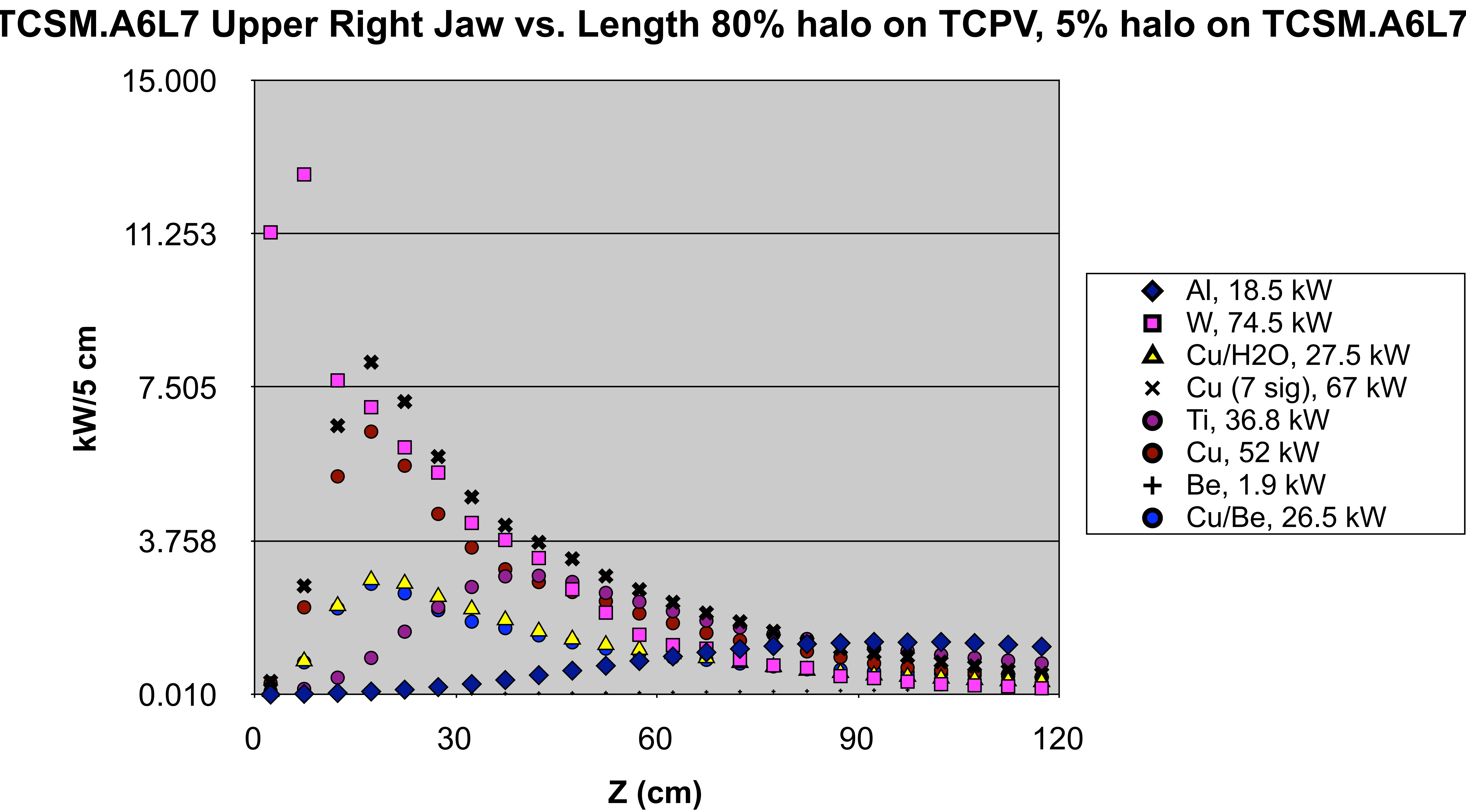
Rotation Mechanism



Thermal Considerations

FLUKA Results - Power Deposited vs. Length

- Ist secondary collimator
- Various materials



LARP

Material thermal performance

- Hollow Cylinder Model
- O.D = 150 mm, I.D. = 100 mm, L = 1.2 m
- NLC-type edge supports
- aperture 10σ

10σ, primary debris + 5% direct		SS @ 1 hour beam life					transient 10 sec @ 12 min beam				
material	cooling arc (deg)	power (kW) per jaw	Tmax (C)	defl (um)	Tmax water side(C)	max flux (W/m^2)	power (kW)	Tmax (C)	defl (um)	Tmax water side(C)	max flux (W/m^2)
Al	360	3.7	33	143			18.5	73	527		
2219 Al	360	4.6	34	149	26	7.1E+04	23	79	559	46	3.1E+05
BeCu (94:6)	360	0.85	24	20			4.3	41	95		
C R4550	360	0.6	25	5			3.0	41	20		
Cu	360	10.4	61	221	43	2.7E+05	52	195	829	117	1.2E+06
Cu - 5mm	360	4.5	42	117	39	2.3E+05	22.4	129	586	117	1.2E+06
Cu/Be (5mm/20mm)	360	5.3	53	161							
Super Invar	360	10.8	866	152 [1]	60						
Inconel 718	360	10.8	790	1039	66		54	1520	1509	85	
Titanium	360	7.4	214	591	42		36.8	534	1197	77	
Tungsten (.48 m L)	360	13.5	183	95	79		67.5	700	335	240 [2]	2.6E+06
Al - solid core	36	3.7	40.8	31			18.5	80	357		
2219 Al	36	4.6	43	31			23	89	492		
BeCu (94:6) *	36	0.85	27	2			4.3	46	101		
Cu	36	10.4	89	79	67	5.6E+05	52	228	739	139	1.4E+06
Cu - solid core	36	10.4	85	60	65	5.3E+05	52	213	542	120	1.2E+06

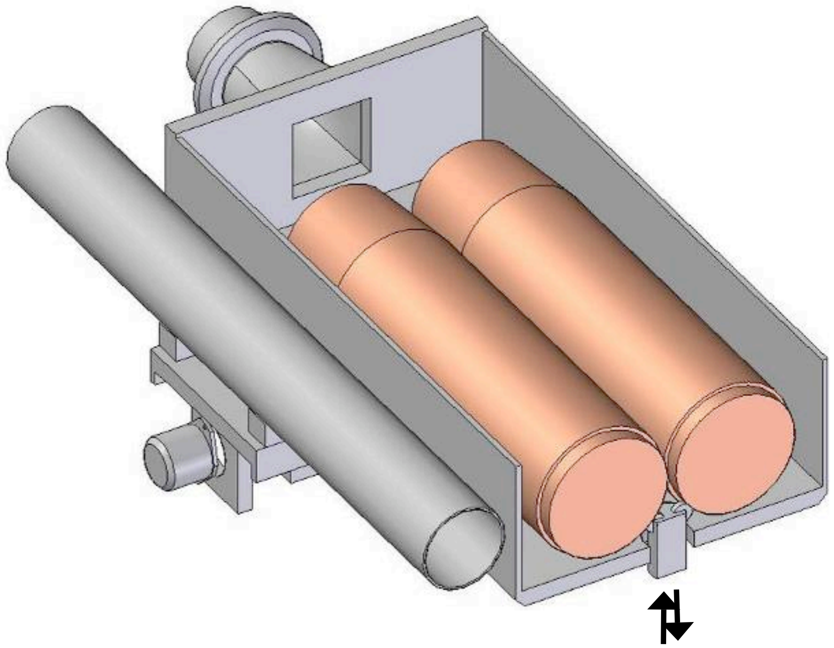
1. deflection not valid, super invar loses its low c.t.e. at 200C
2. pressure > 30 bar needed to suppress boiling

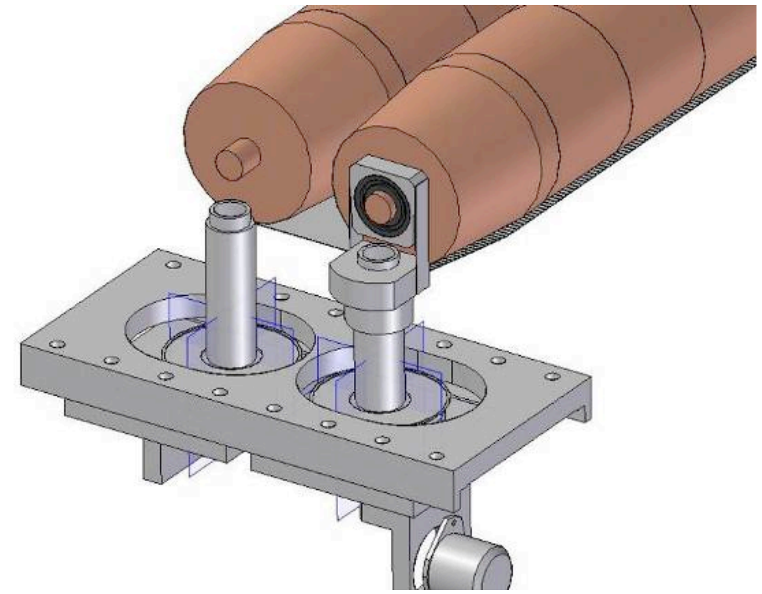
* **Promising but no practical implementation**

Cu chosen – balance of efficiency, deflection and manufacturability

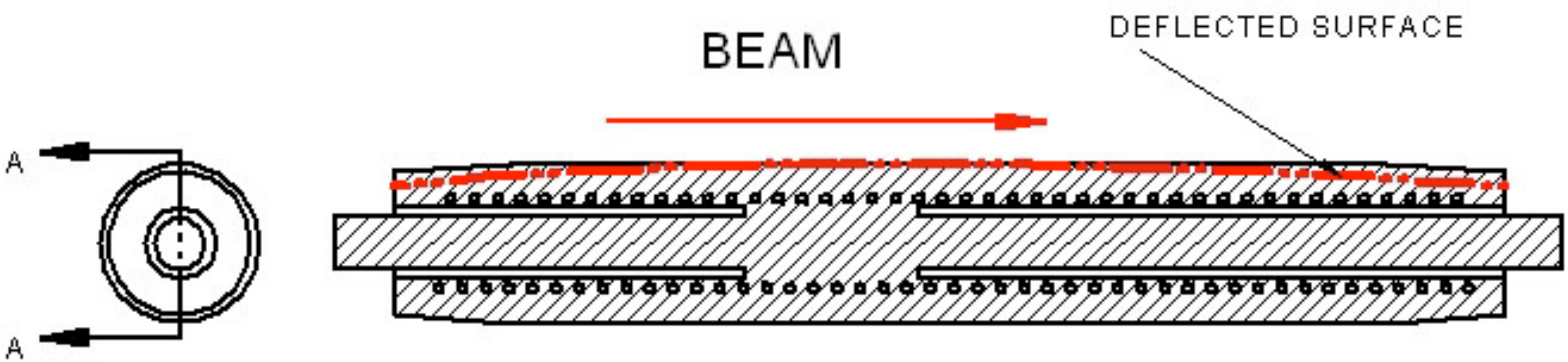
June 2006

Introduce new **jaw-hub-shaft** design which eliminates central stop & flexible springs





x5 improvement in thermal deformation
1260 um → 236 um (60kW/jaw, τ=12min)
426 um → 84 um (12kW/jaw, t=60min)

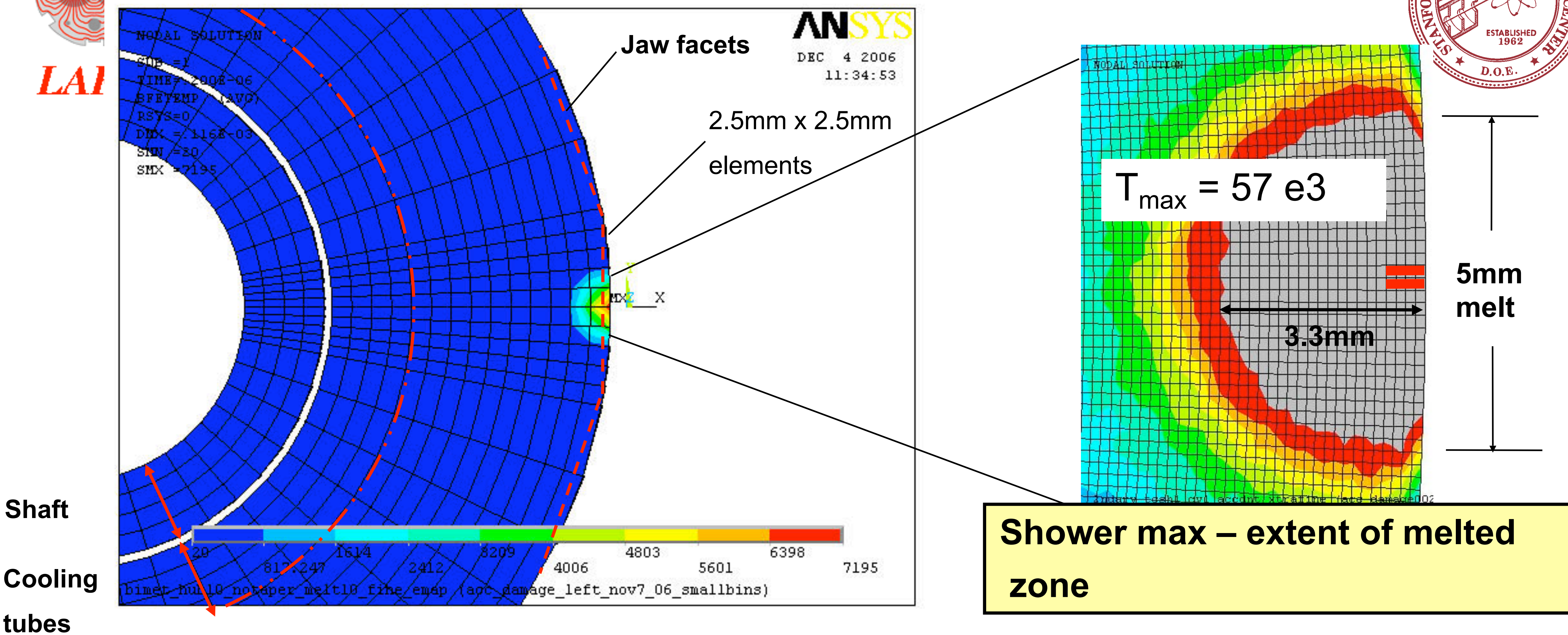


Comparison of Hollow Moly shaft to Solid Copper Shaft: Improved deflections but necessitated Moly/Cu Brazing R&D

	Solid Cu, 75cm tapered jaw, asymmetric hub		Tubular Moly, 95 cm straight jaw, symmetric hub	
	Steady State τ=1 hour	τ = 12 min for 10 sec	Steady State τ=1 hour	τ = 12 min for 10 sec
Gravity sag	200 um		67.5 um	
Power absorbed	11.7 kW	58.5 kW	12.9 kW	64.5 kW
Peak Temp.	66.3 °C	197 °C	66 °C	198 °C
Midjaw Δx	100 um	339 um	83.6 um	236 um
Effective Length	51 cm	25 cm	74 cm	39 cm
Sagitta	221 um	881 um	197 um	781 um

Note that to preserve the maximum deflection toward beam of 25 microns requires retracting jaw from nominal sigma position.

Accident Case: Permanent deformation AND Molten copper



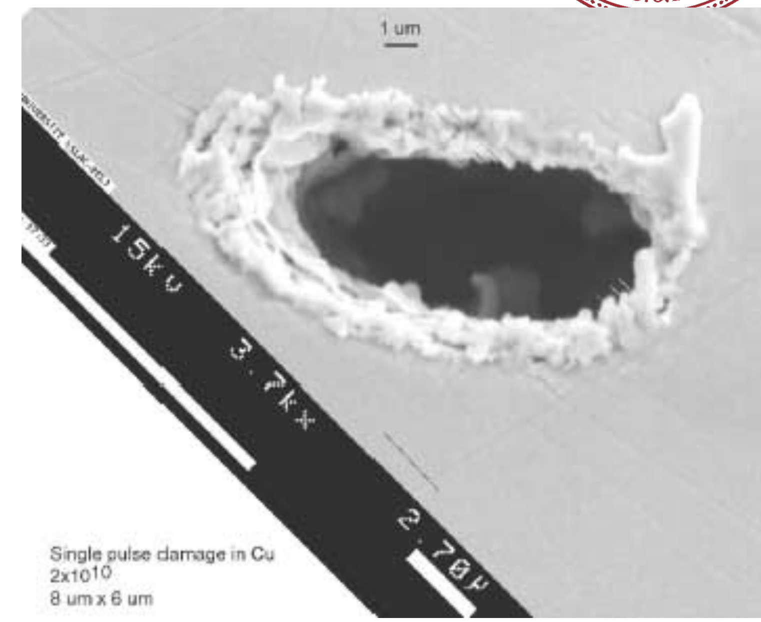
Case: beam abort system fires asynchronously, **8 full intensity bunches into jaw**

Model: - increased resolution 3-D ANSYS & FLUKA models
- Thermal heating/cooling analysis followed by quasi-static stress analysis
- Jaw ends constrained in z during 200 ns, released for 60 sec cool-down
- 0.27 MJ deposited in 200 ns
- Molten material removed from model after 200 ns

Result: - 57e3 peak temperature (ultra fine model)
- **54 μm permanent deformation** (concave)

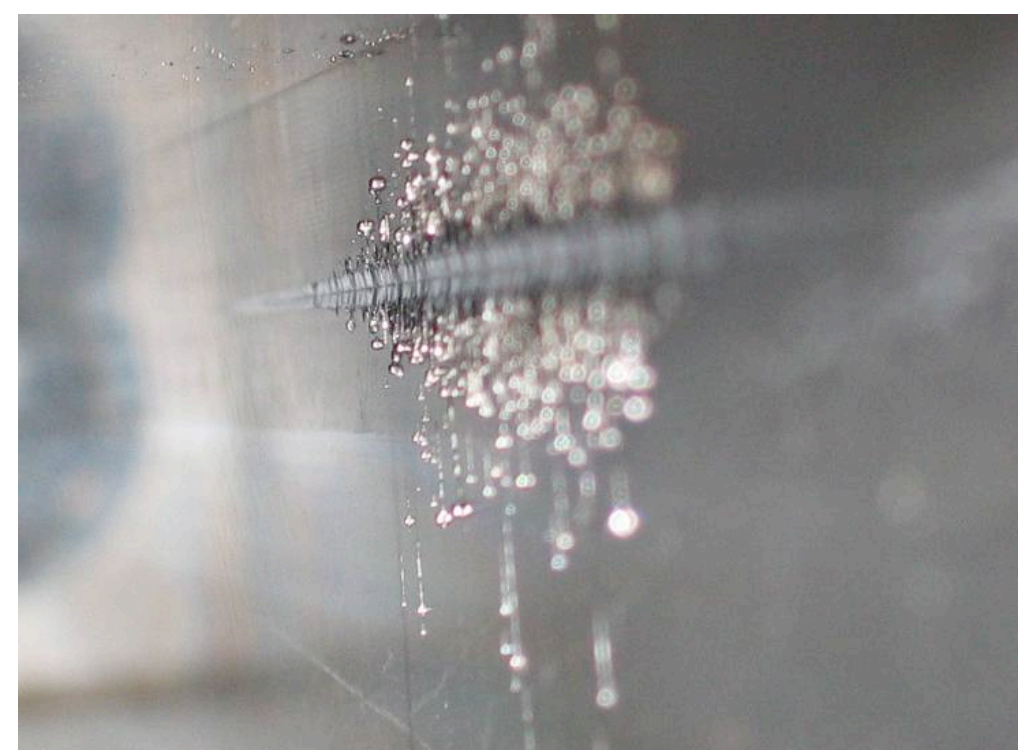
Exact Nature & Extent of Damaged Region still not really known well. We need beam tests with prototype.

Thin Cu sample in FFTB electron beam at SLAC
Hole = Beam Size



2000um 500 kW 20 GeV e- beam hitting a 30cm Cu block a few mm from edge for 1.3 sec (0.65 MJ)

FNAL Collimator with .5 MJ



Jaw Construction and Brazing Considerations

Brazing and Construction R&D

- Last couple years a lot of R&D performed to determine how to:
  - Braze molybdenum to copper
    - different thermal expansion rates
  - Braze copper tube to copper and remove gaps around braze
  - Wind copper tube around helical mandrel groove
- Won’t go into all of this.
- Will just show the steps taken to manufacture our first full length jaw
  - From winter 2007 - summer 2008

Three Braze Cycles

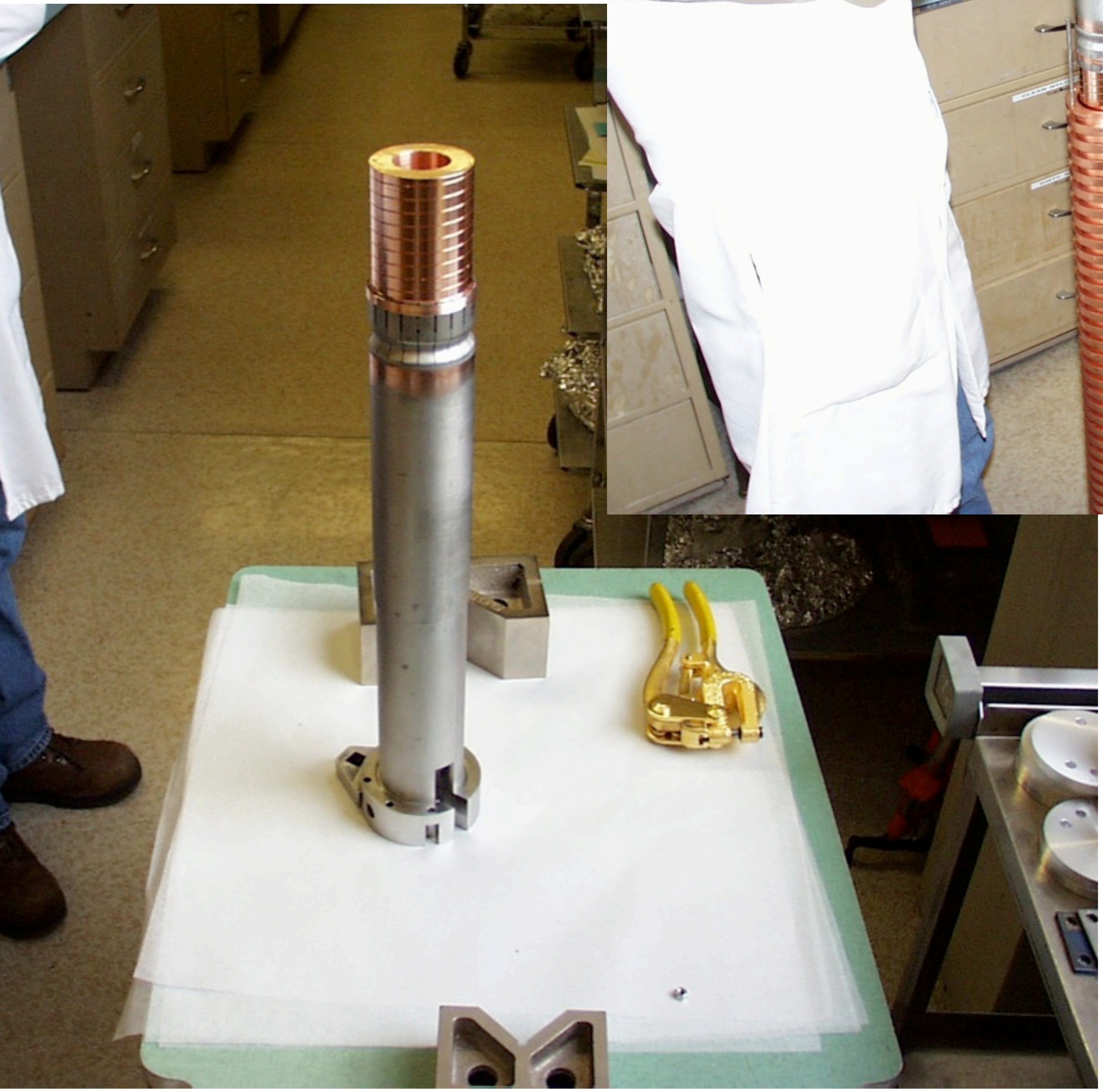
- Three brazing steps.
  - Brazing materials set to melt at gradually lower temperature.

  1. Braze Moly shaft and hub to Mandrel
     - 25% Gold, 75% Copper
  2. Braze copper coil to Mandrel
     - 35% Gold, 65% Copper
  3. Braze jaw quadrants to mandrel surface
     - 50% Gold, 50% Copper

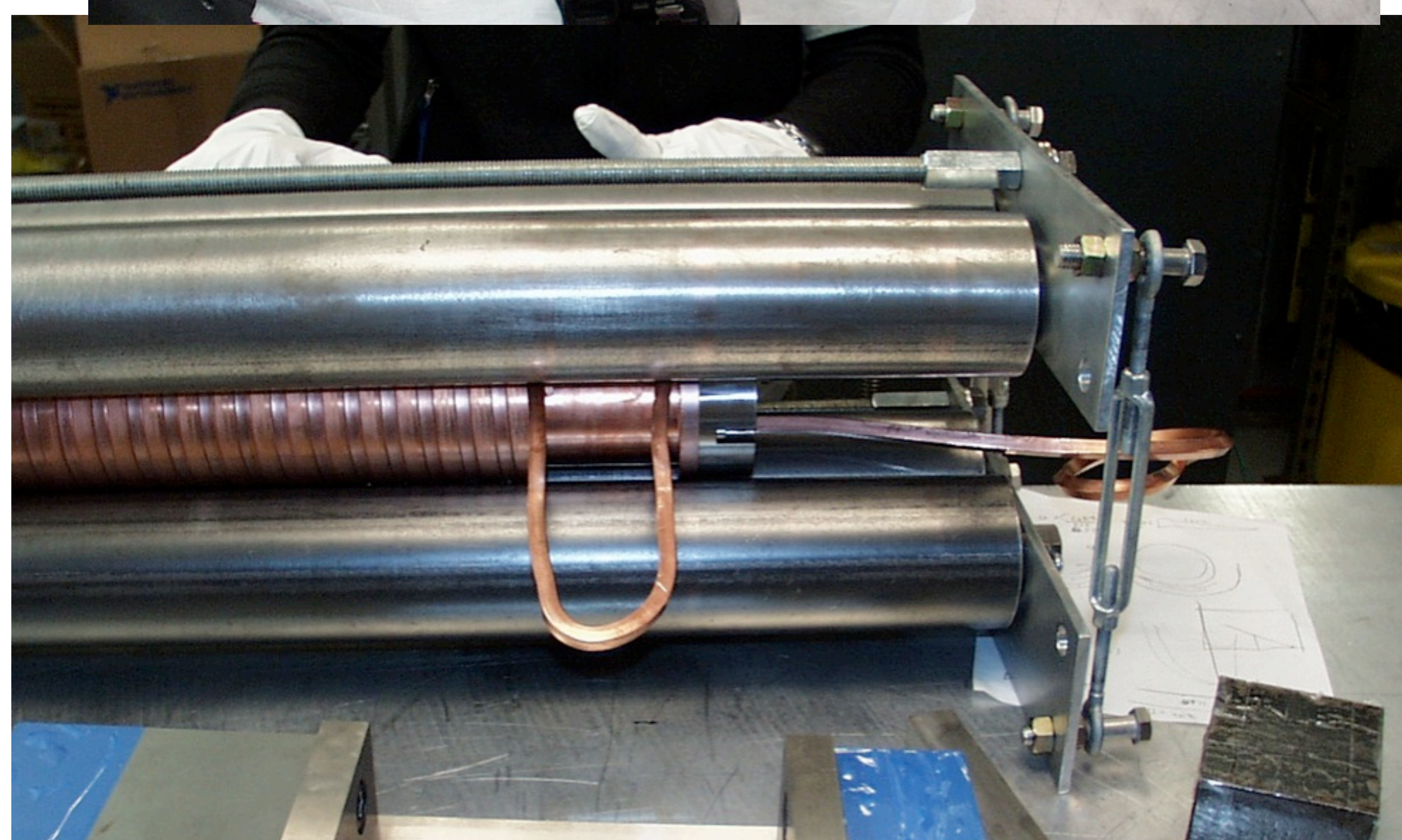
First Braze: Brazing Moly Shafts

- After much R&D developed method to braze molybdenum to copper for inner shafts
- Molybdenum (and some other components) from Eagle Alloys Corp. www.eaglealloys.com

Inserting molybdenum shaft into Mandrel



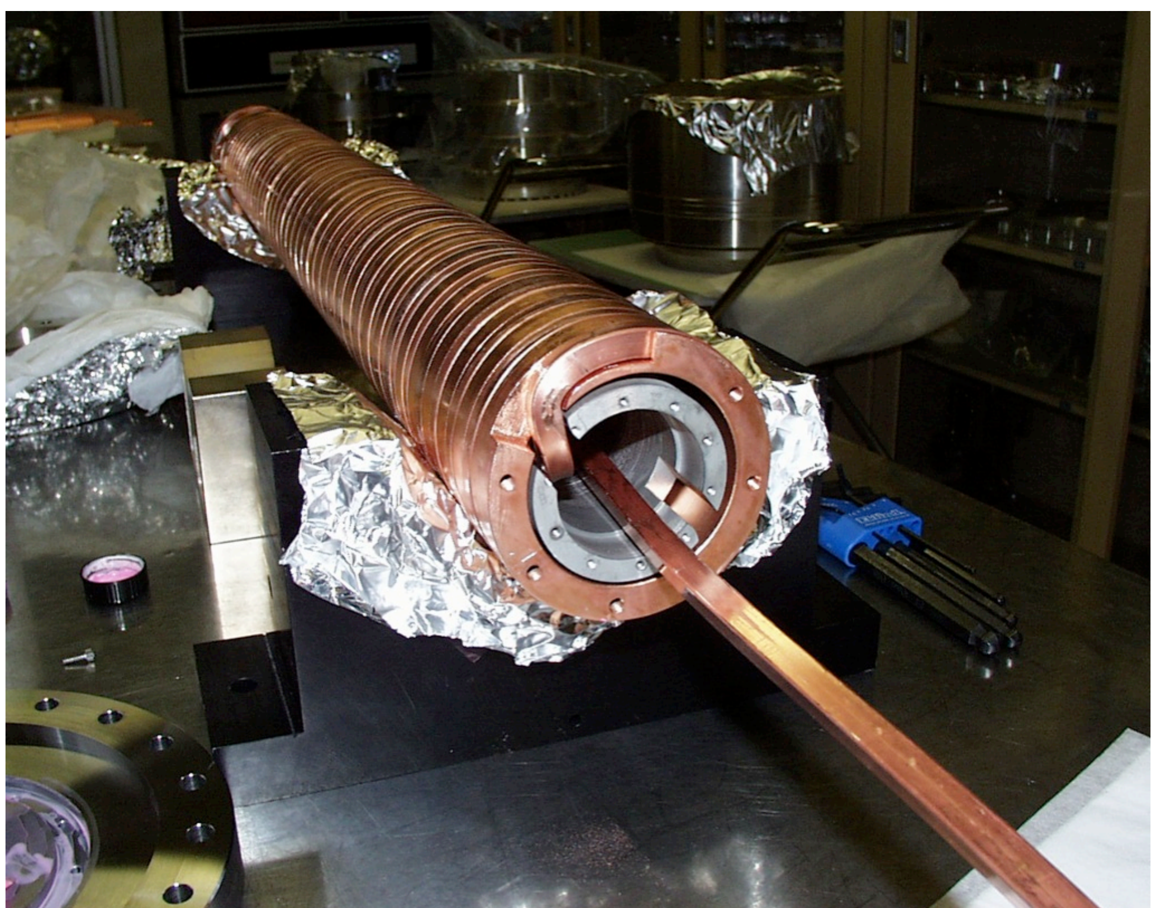
Coil Winding



Second Brazing Preparation

LARP

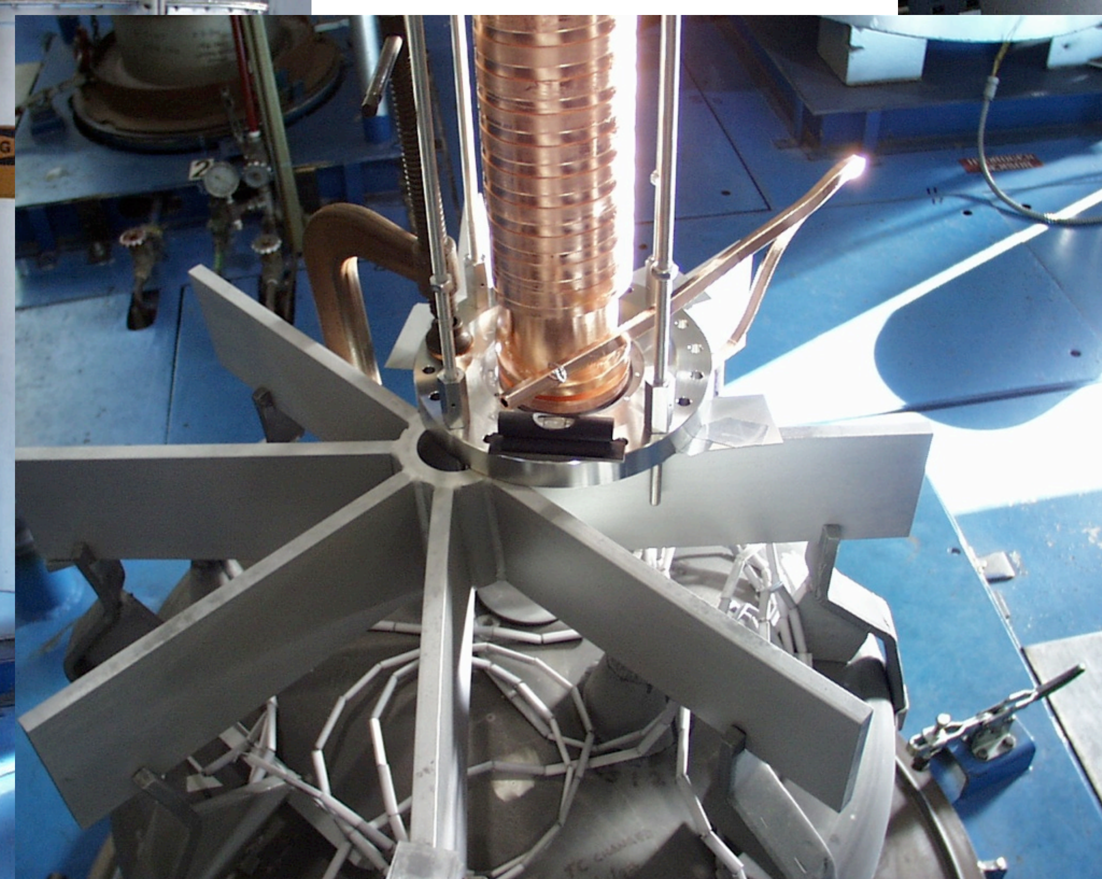
- Here are pictures showing preparation for second brazing
- Here on support stand and ready for insertion in baking oven
  - Carbon block used to hold thermally expanding copper against central hub and shaft (moly and copper)
  - Next time may use carbon block full length of mandrel



LARP

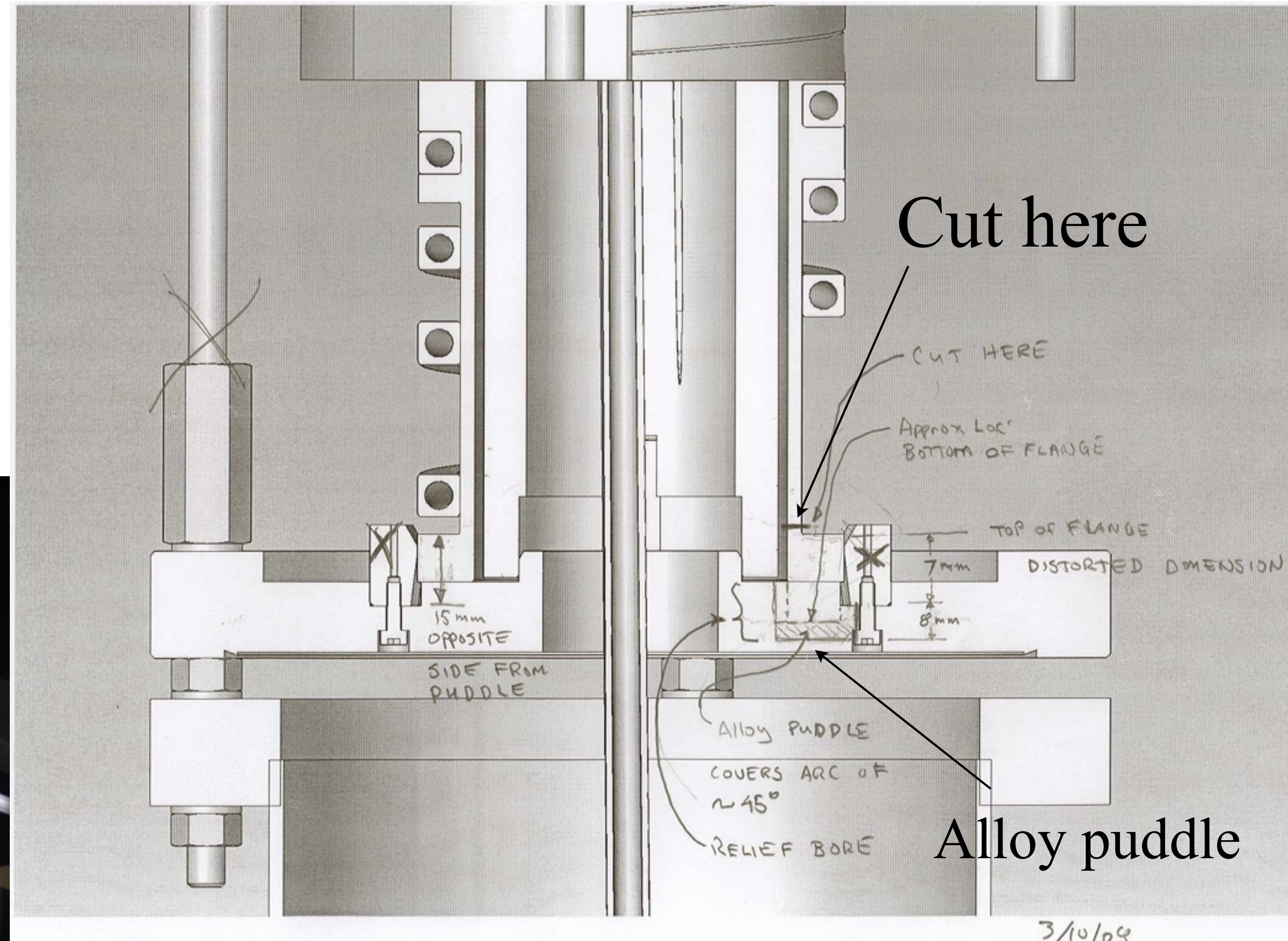
Brazing Coil to mandrel

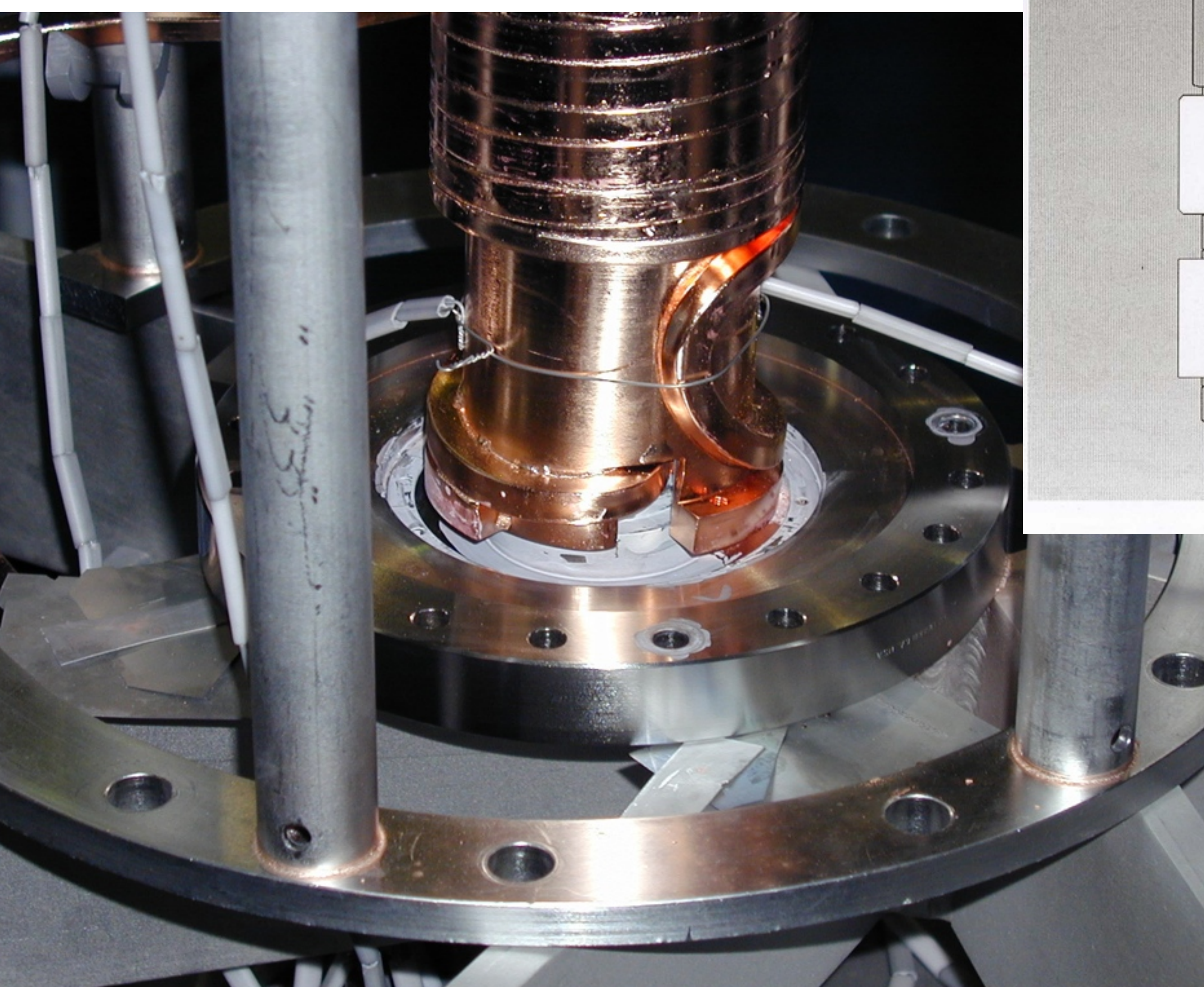
- Brazed coil in three brazing cycles
    - Examined quality of braze between cycles
- Here are pictures for second braze cycle



Mandrel brazing

- Ran into some problems with brazing.
- Too much braze material was apparently used and our mandrel was brazed to the furnace mount during third braze!
- Had to saw off braze flange



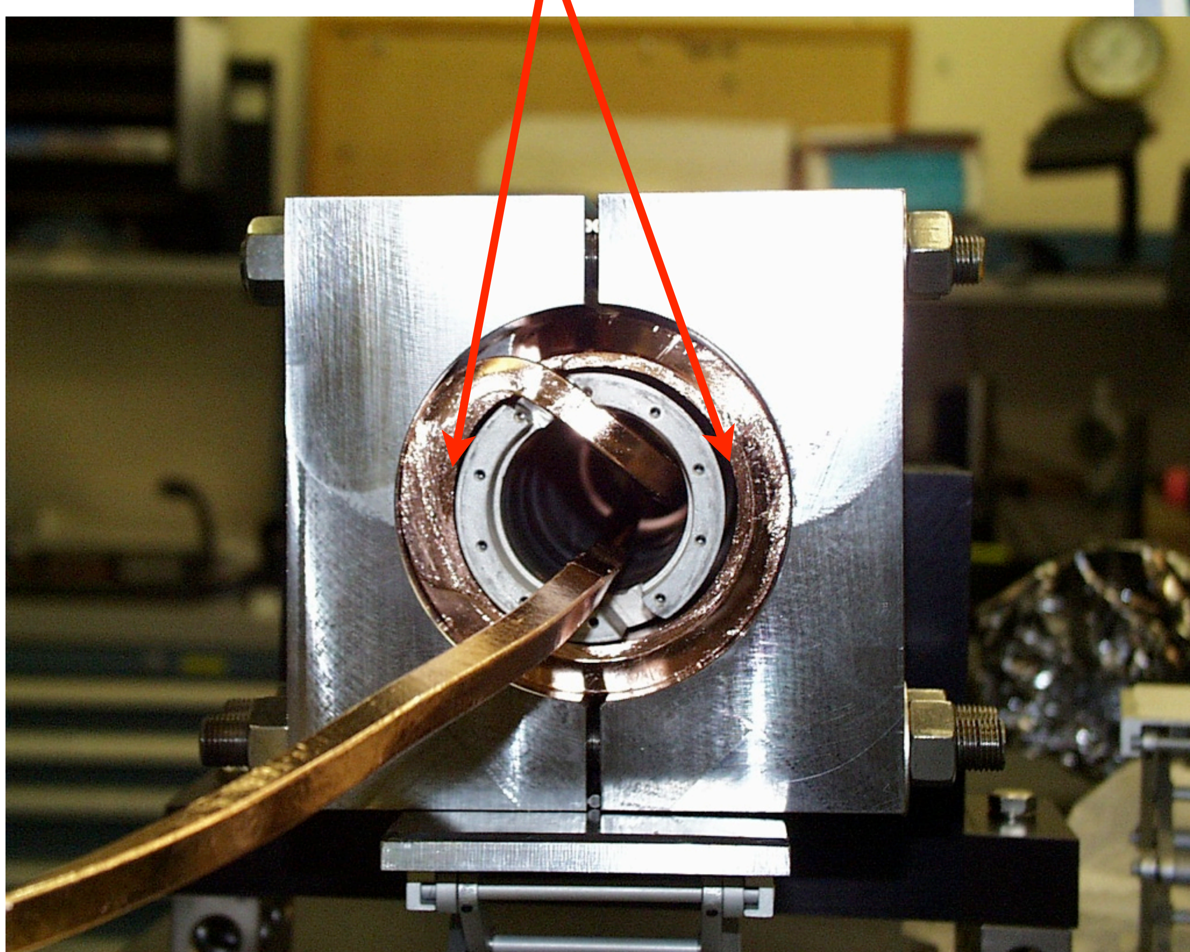


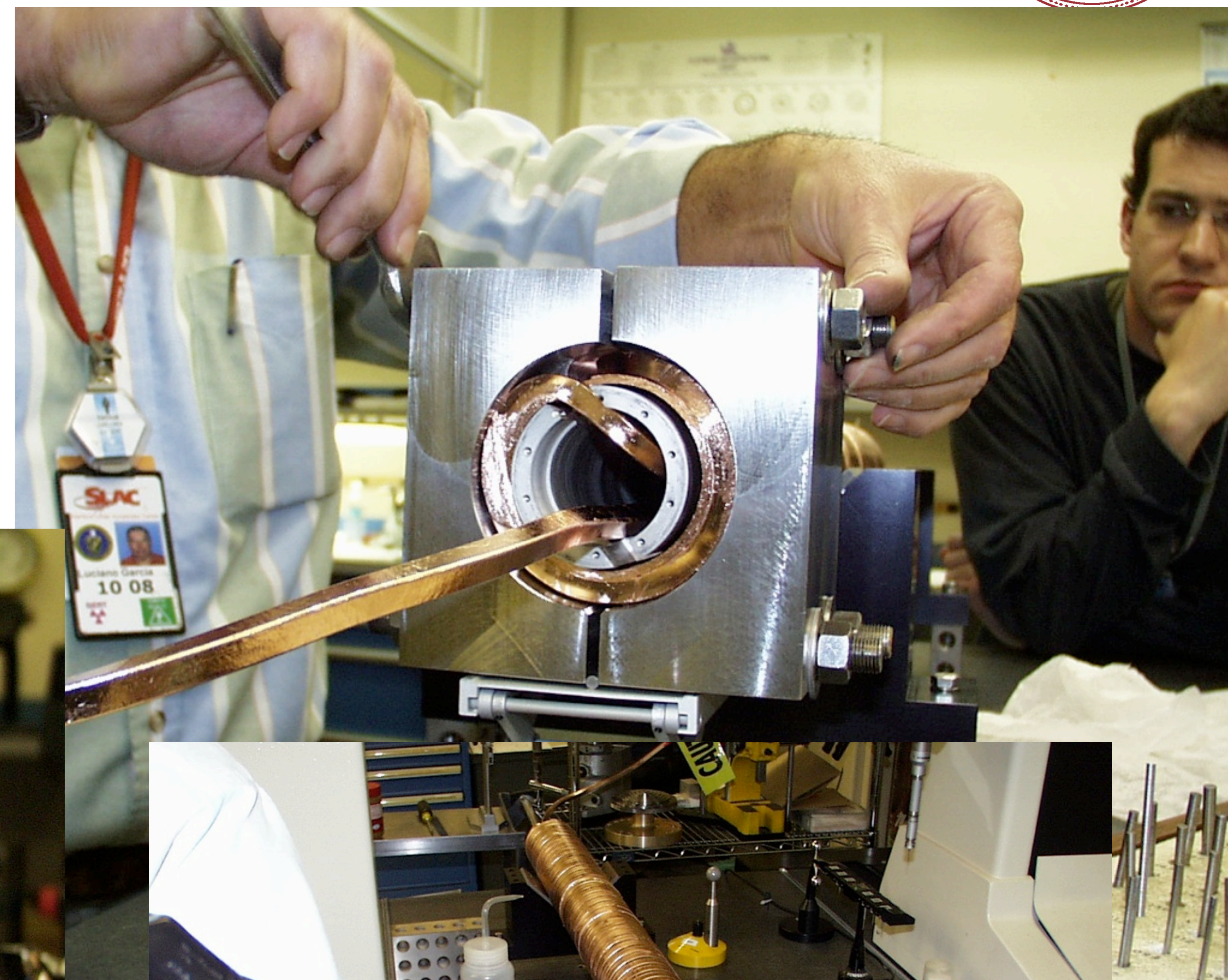
- Brazing error resulted in bending of end of mandrel attached to furnace table.

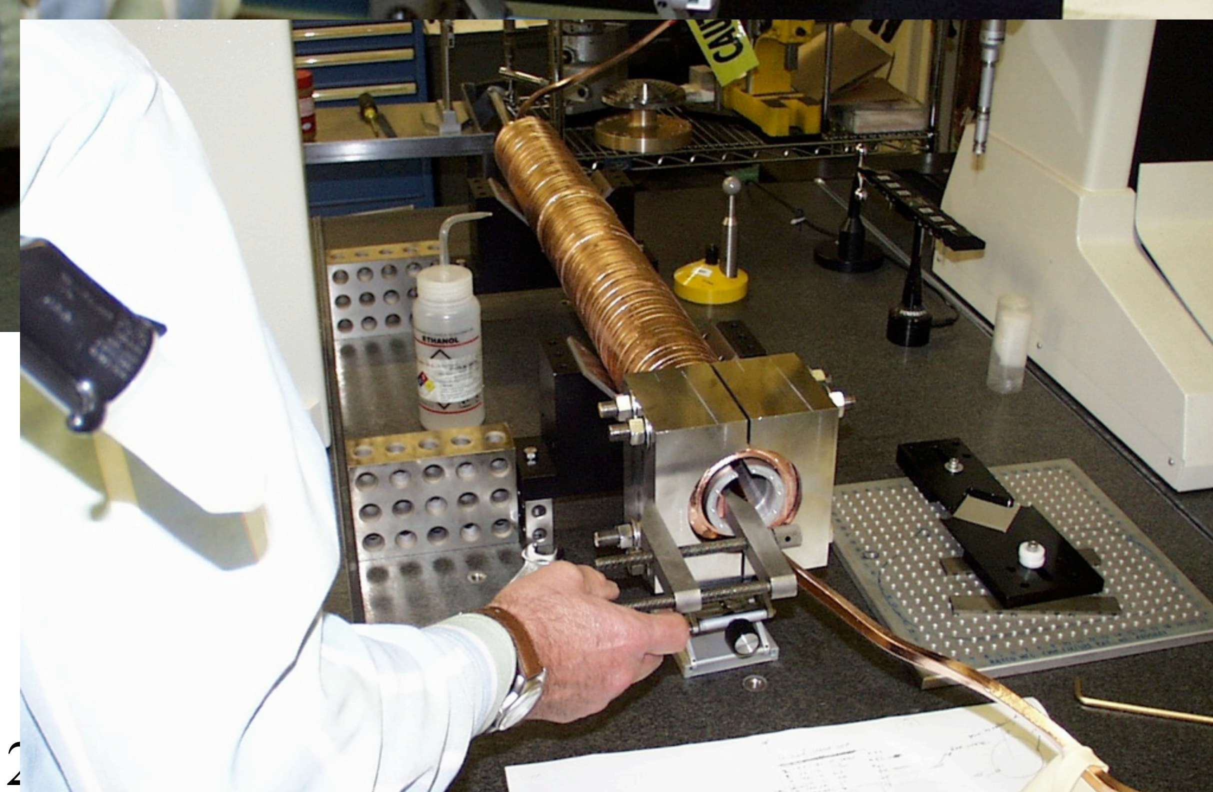
The Aftermath...

- Most of mandrel OK, but end had to be fixed
- Used custom made clamps to “press” mandrel back into shape.

Center shaft not in center of mandrel due to bent mandrel

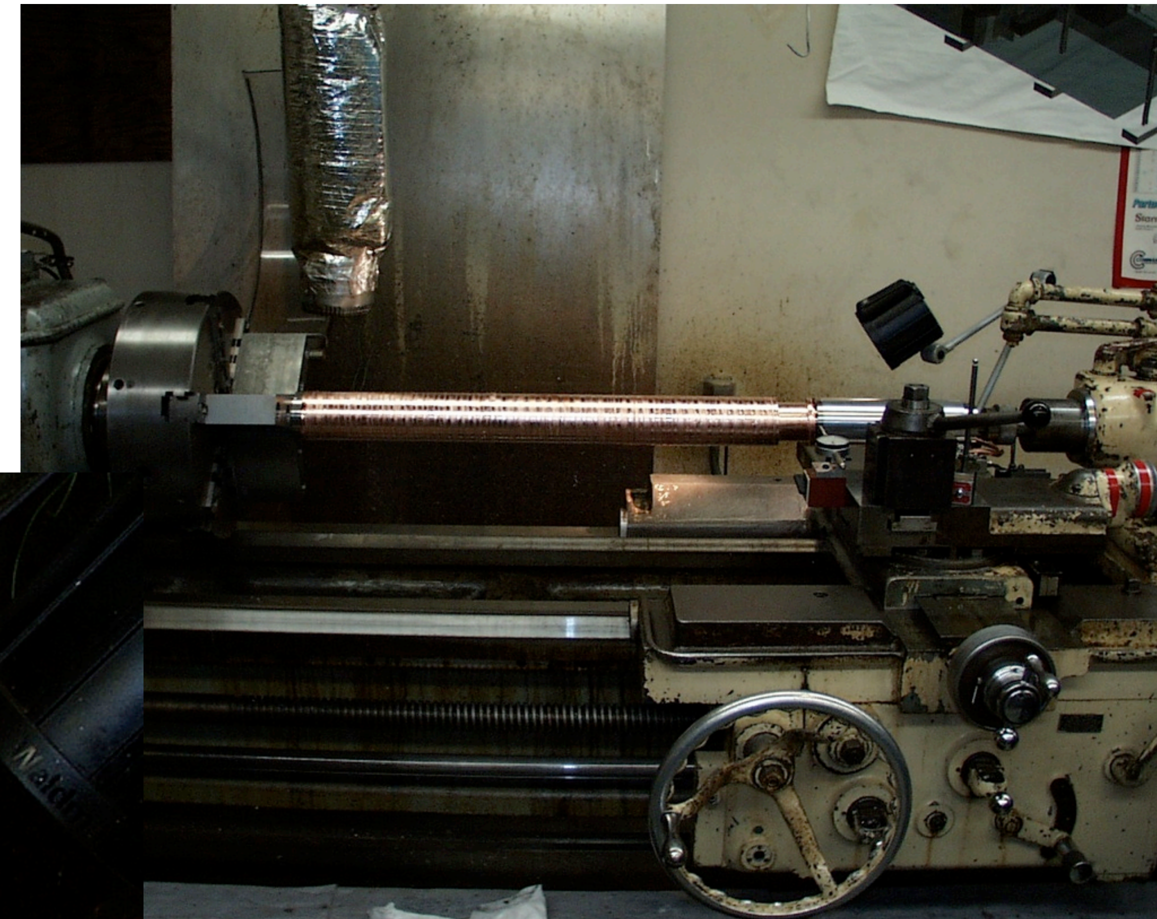


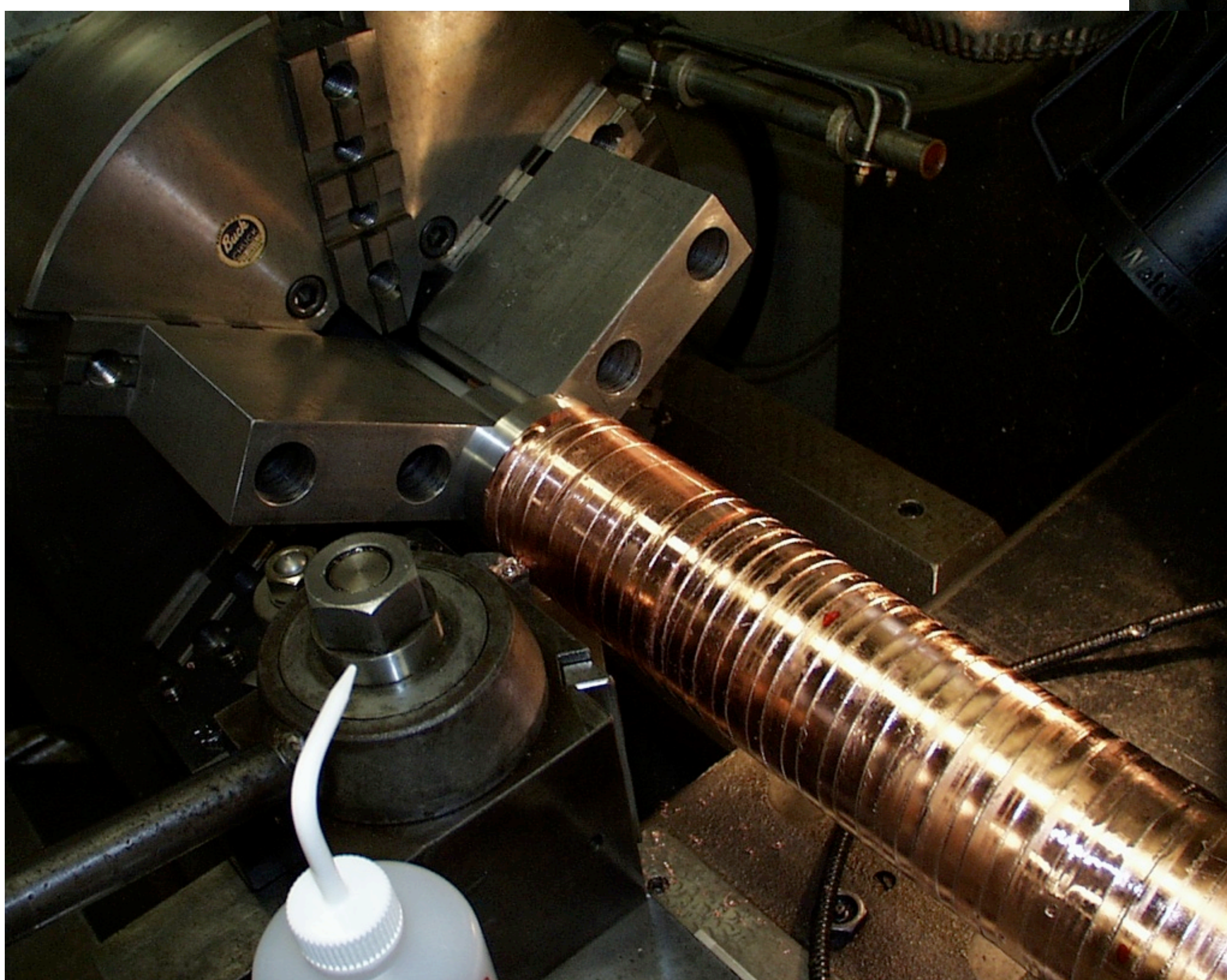


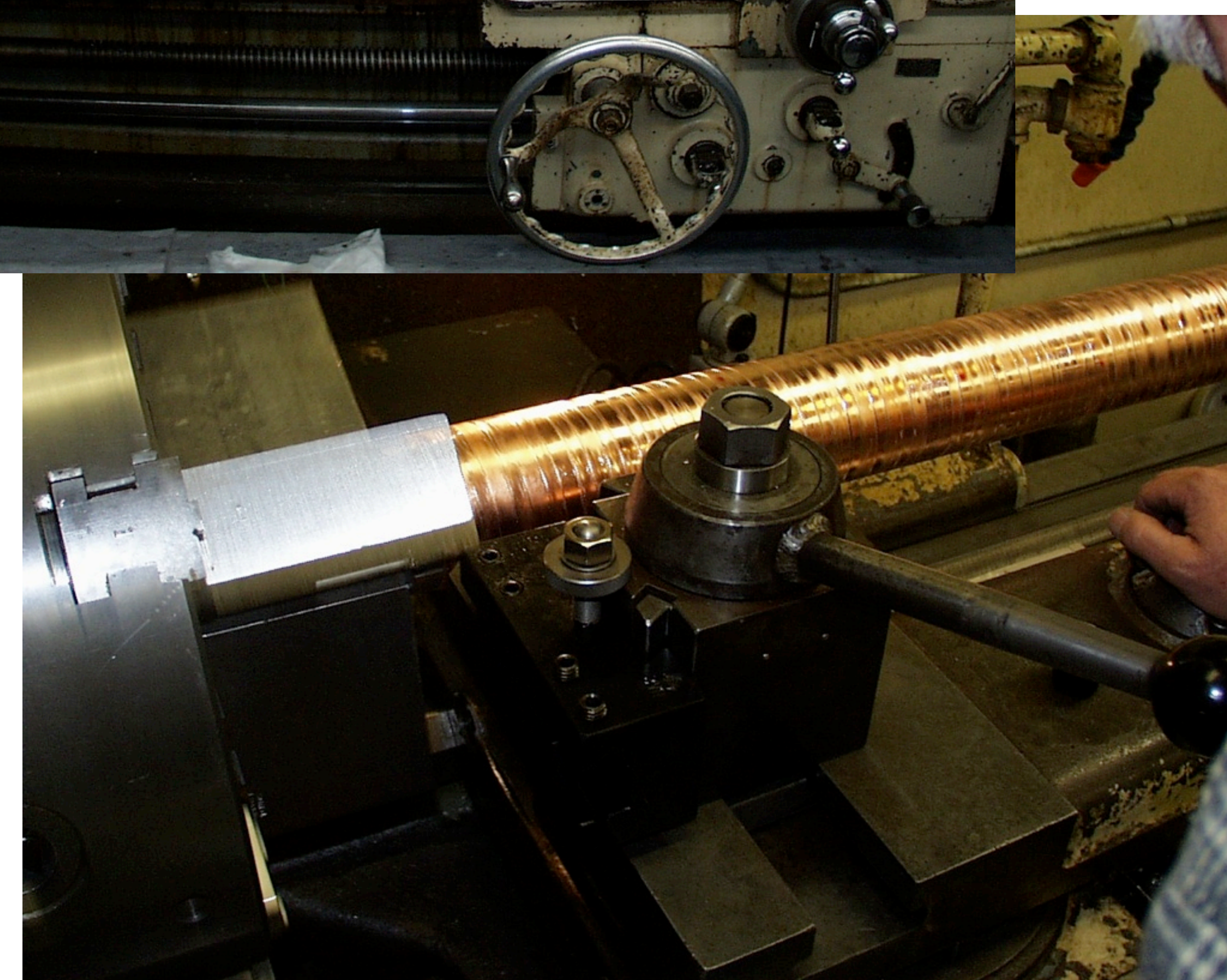


Machining of mandrel surface

- Mandrel concentricity looks OK now after repairs
- Surface must be machined flat for reception of Jaws quadrants
- Slight kink in mandrel had to also be bent out

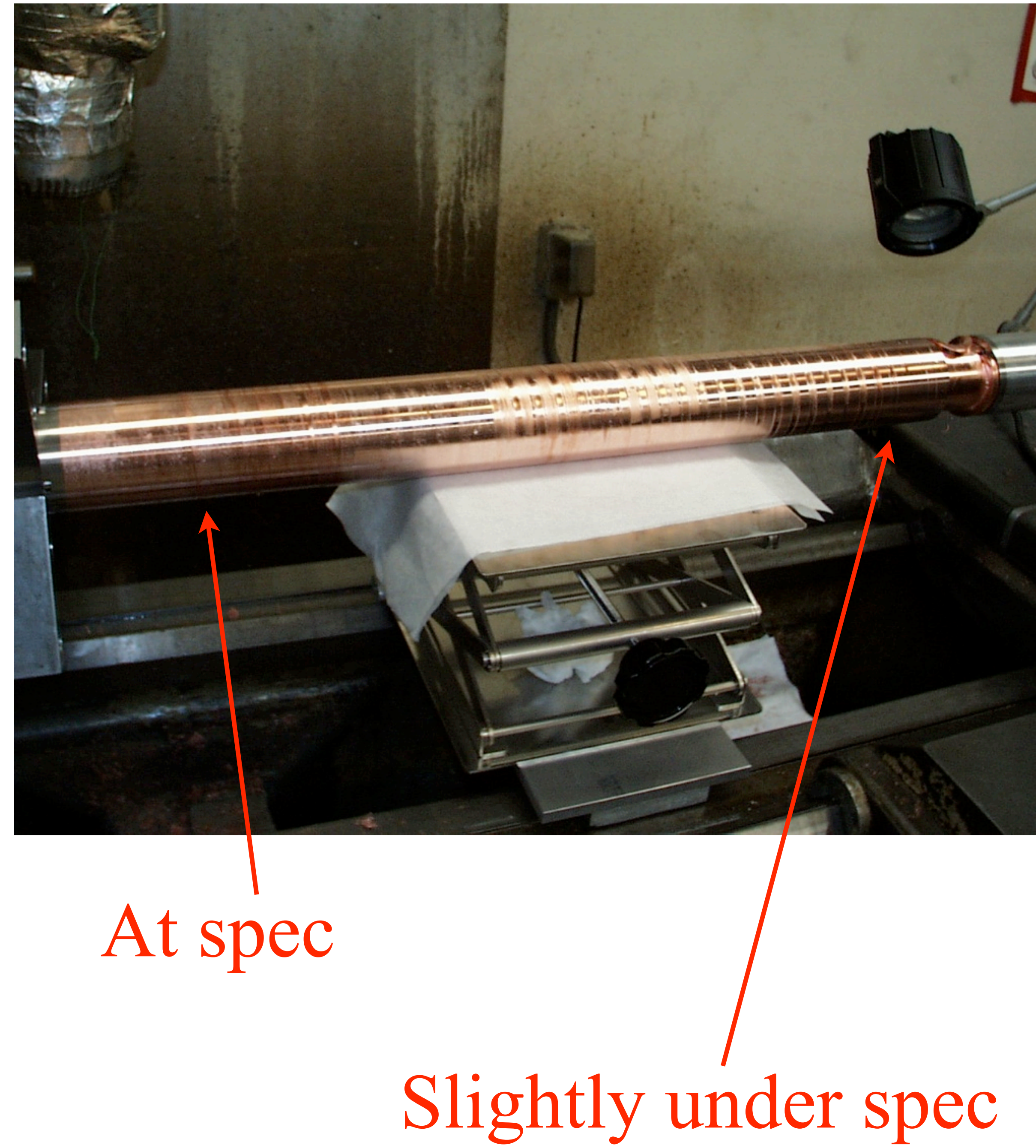






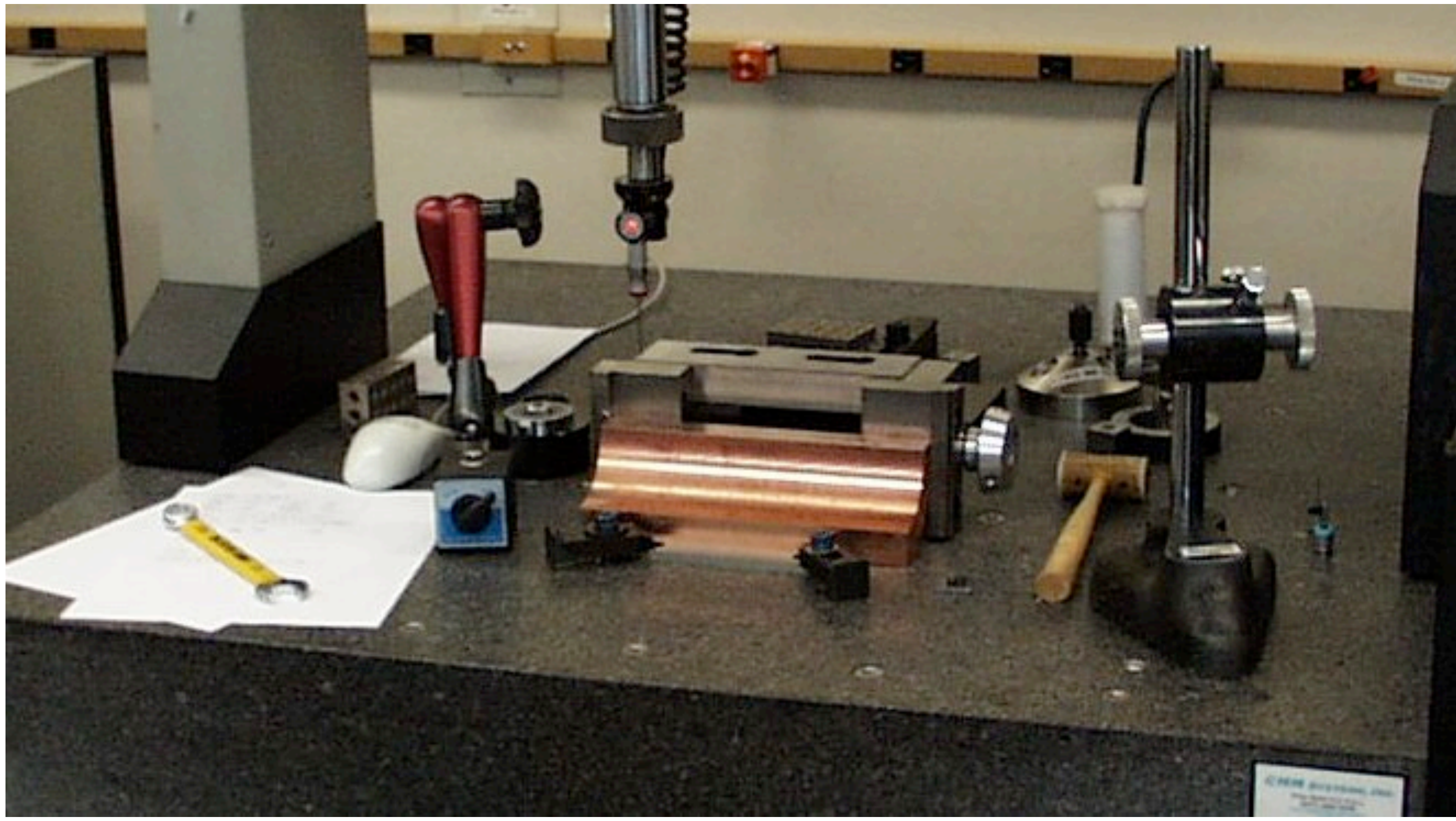
Jaw Quadrants

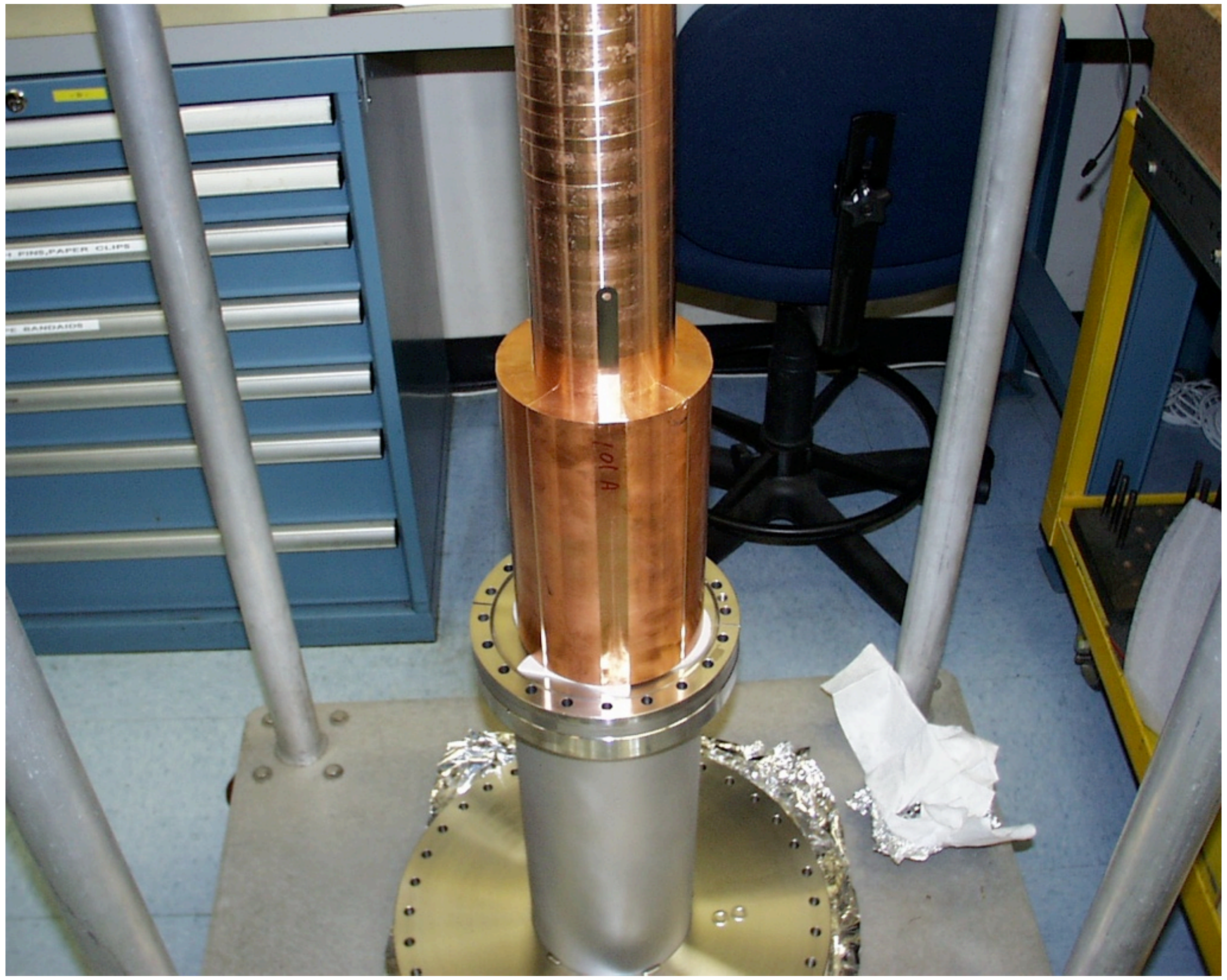
- Surface machined and ready for reception of jaw quadrants
- Slightly different outer diameters.
- left side in picture at o.d. spec. Right side will require slightly modified jaws to fit on diameter. Add material to fill gap.
- Want very good thermal contact between jaws and cooling coil around mandrel.



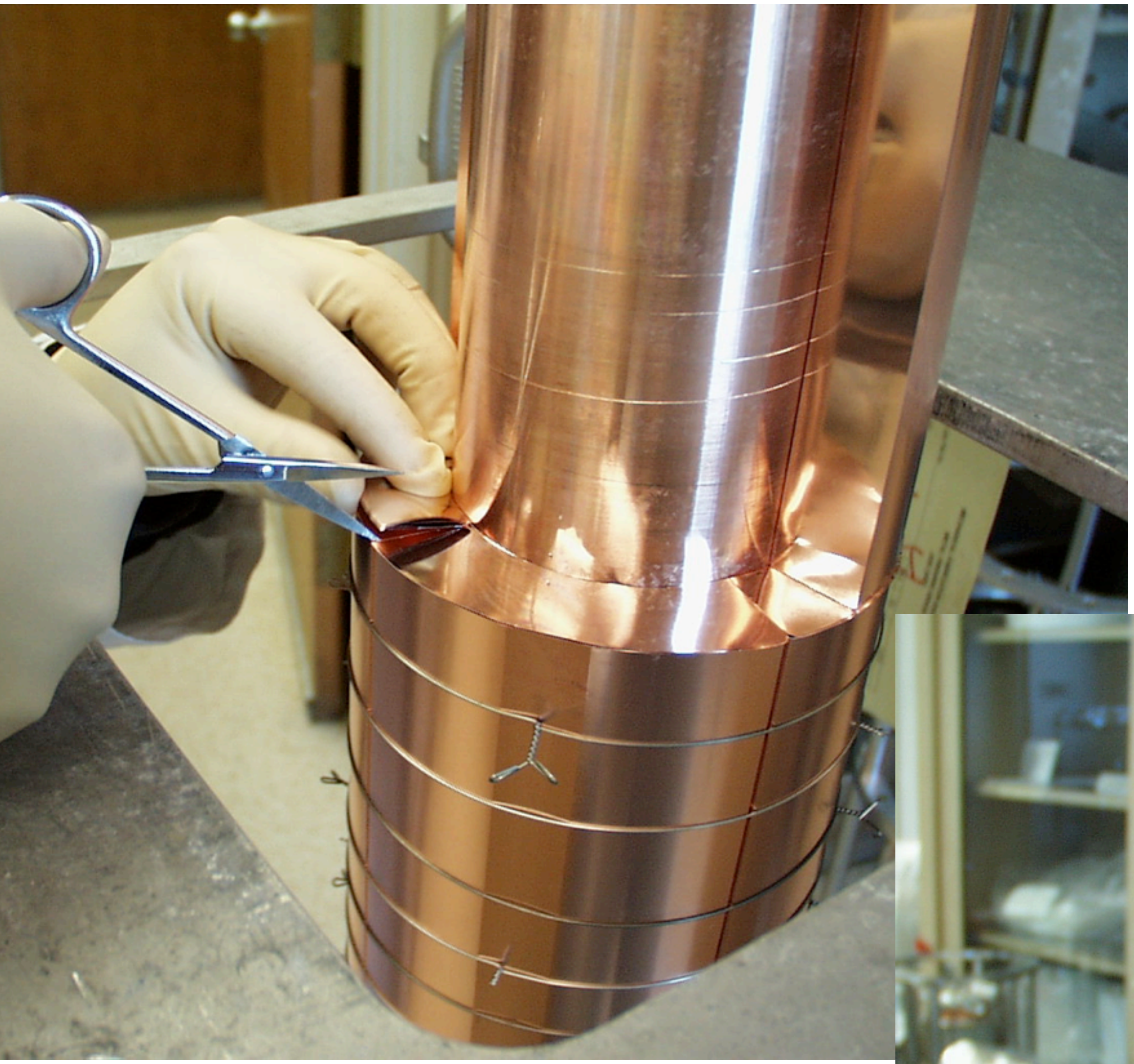
jaw Quadrant modifications

- Jaw Quadrants measured and machined to cleanly fit Mandrel o.d.
- Assembled around Mandrel





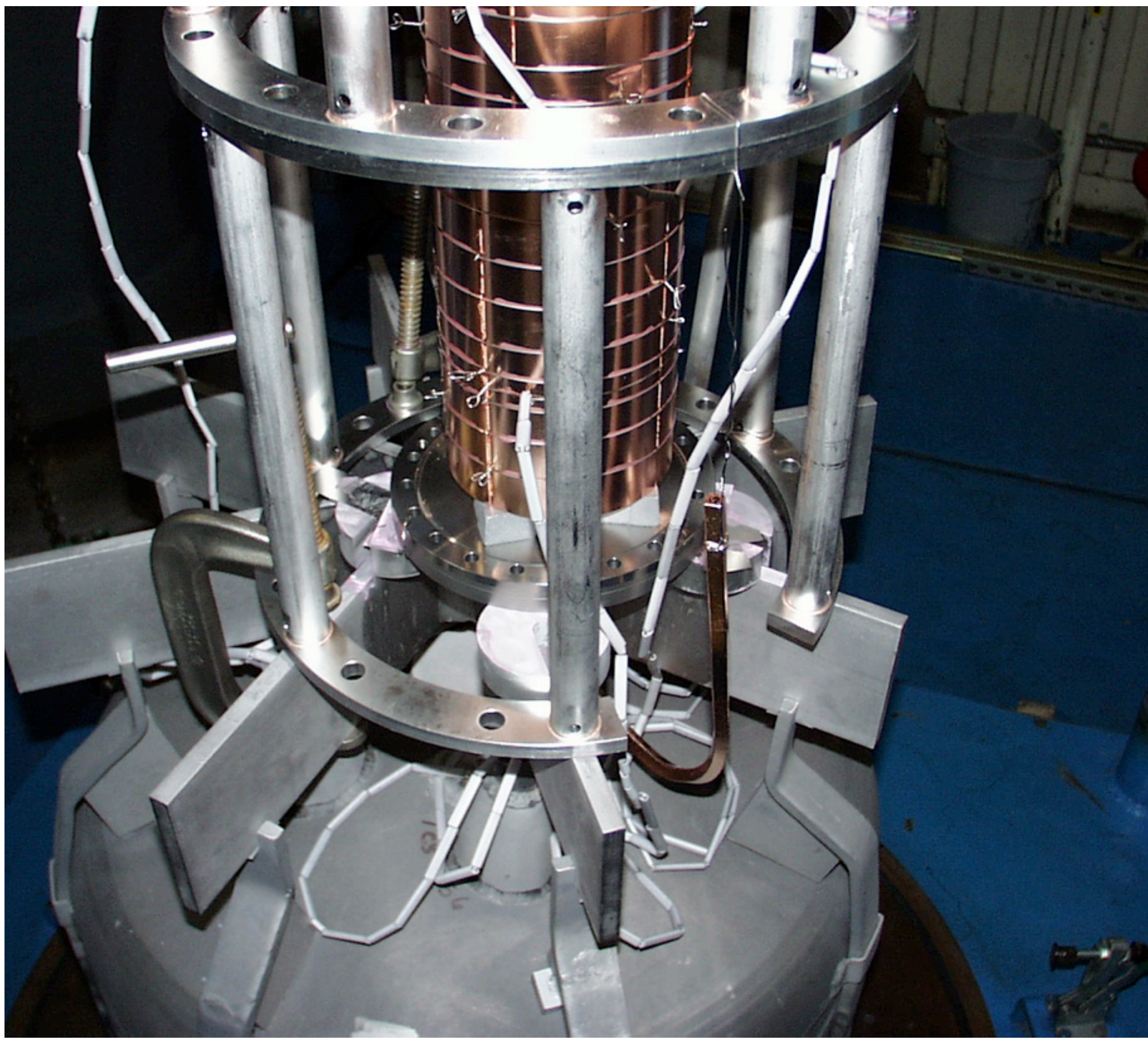
Quadrants around Mandrel



- Using 50-50 Au-Cu brazing material ($$)

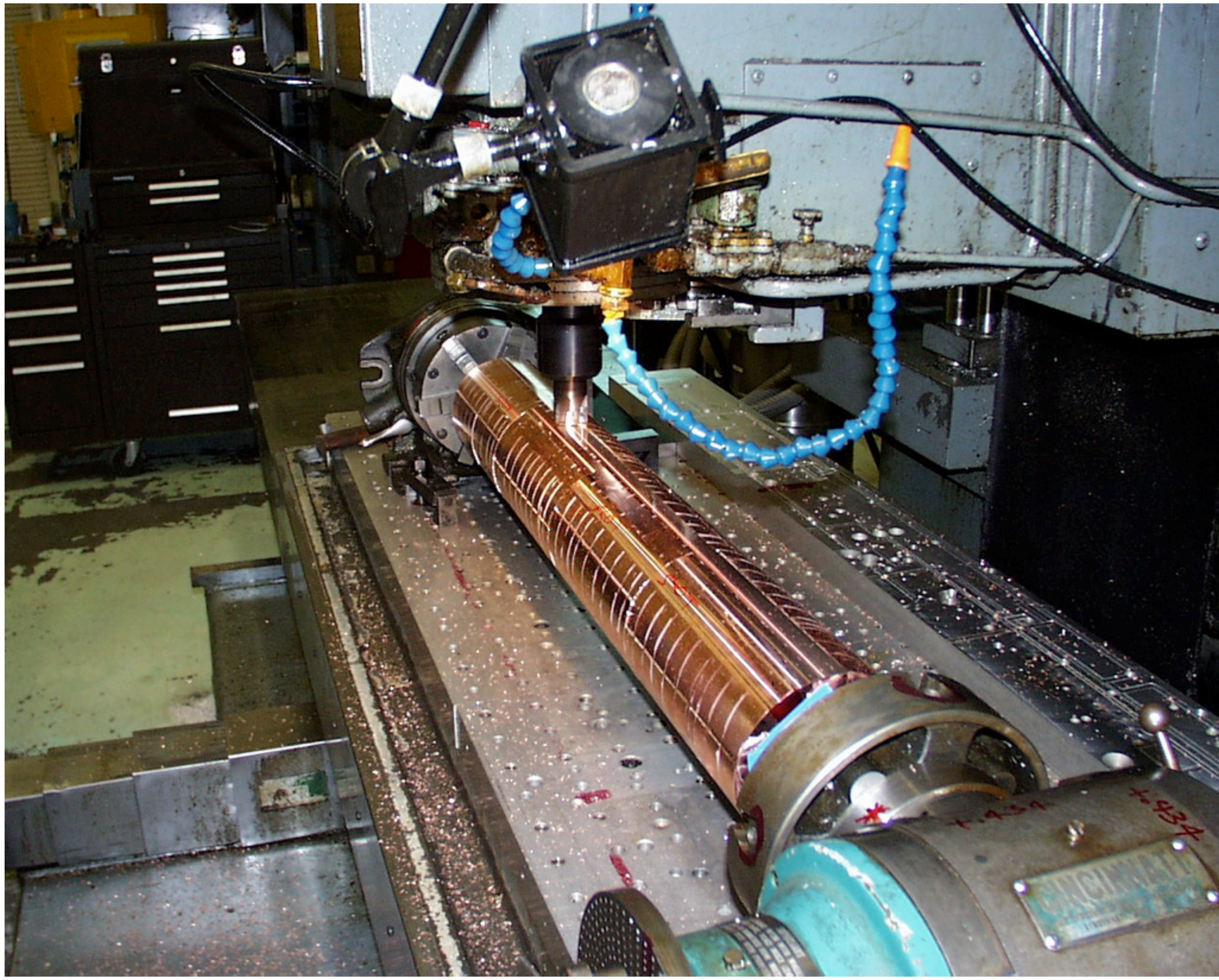
Brazing Jaws

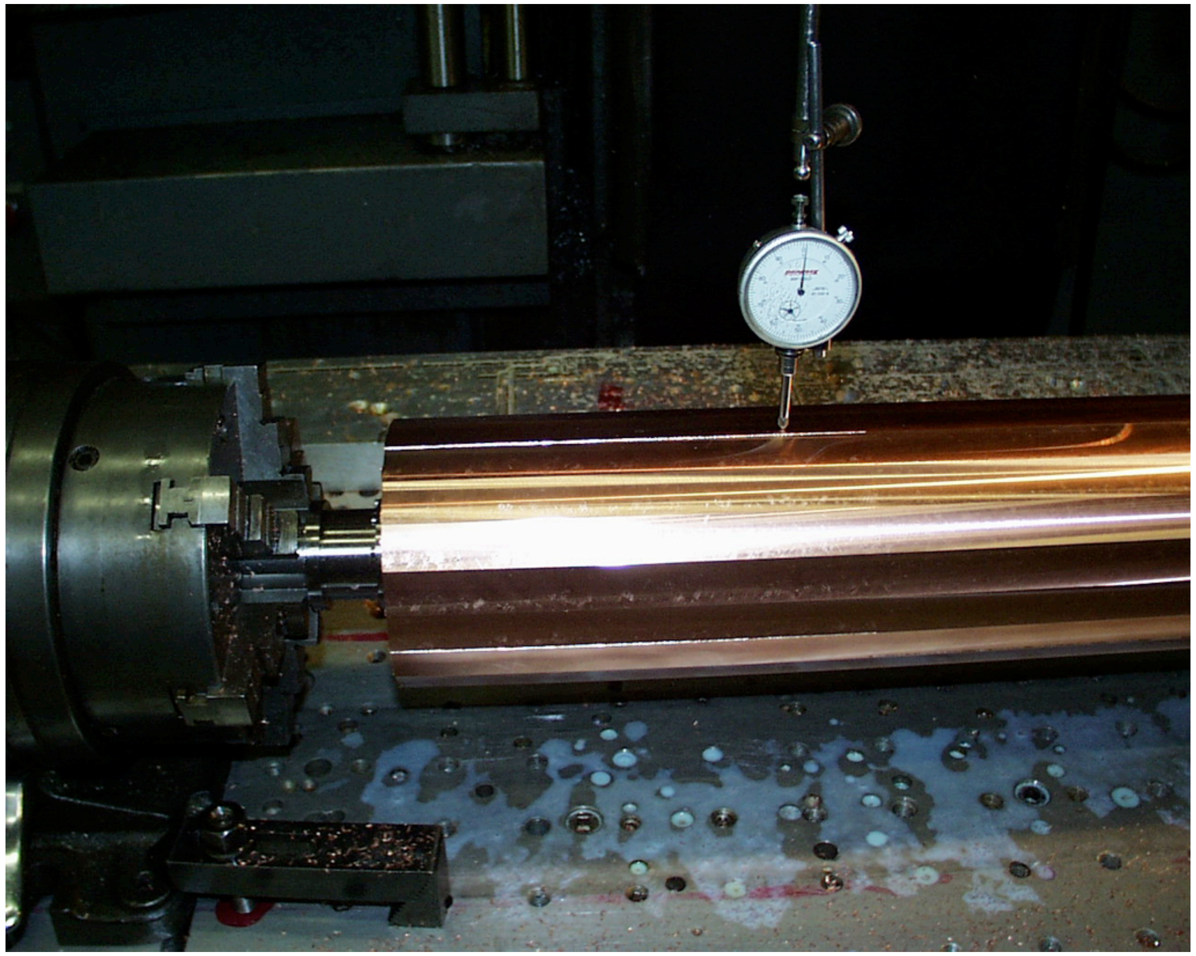
- Brazing Jaw Quadrants



Machine flat facets and grooves for heater test

- Final brazing was a success!
- Flat facets and grooves for heater tests and thermocouple holes have been machined.
- Within 25 micron tolerance along facet surface.



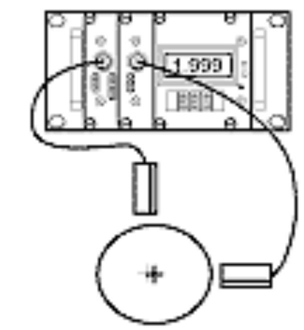


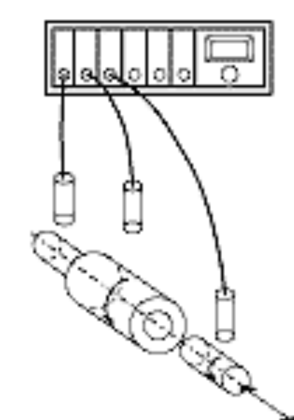
Considerations for Jaw Construction

- Discovered several complications in machining/assembling/brazing first full length jaw.
- Gained much experience in brazing techniques. Lots of small hurdles have been overcome with limited number of people.
- Reconsidering how much braze alloy we apply
  - We needed a lot to fill up cavities and crevices due to coil winding
  - Coil “keystones” as it’s wound, creating large gaps to fill
- Considering alternative winding techniques or methods to fill gaps without using braze
  - Maybe use a round tube (not square), will have less keystone and less gap, test being performed now.
  - Maybe we can expand the tube to fill the gap
    - Pressurized air or water
    - freeze water in tube

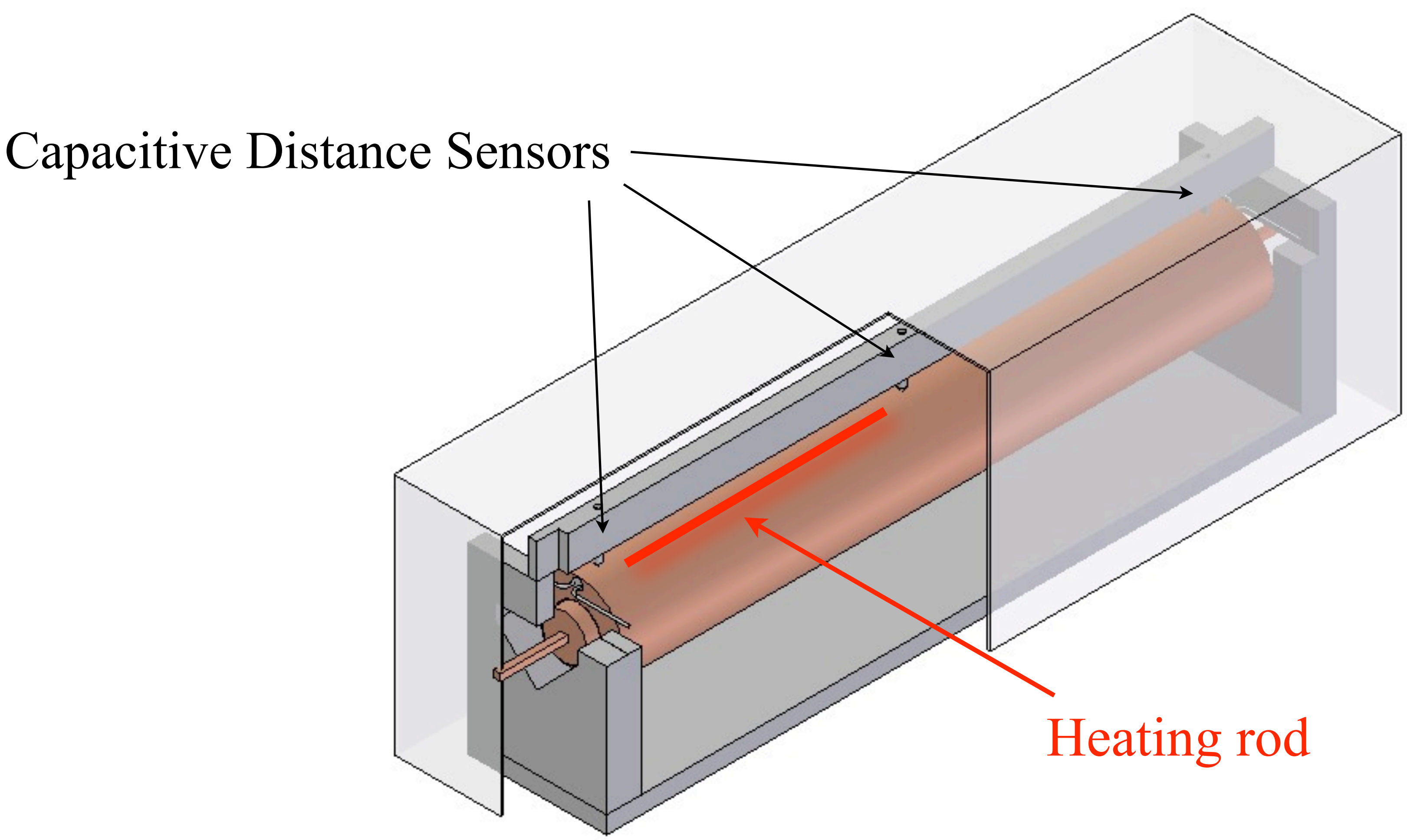
First Full Length Jaw Thermal Tests

- This jaw will undergo thermal tests using two 5 kW heaters placed along jaw surface (simulating steady state beam heating)
- Sensors will then measure thermal deflection to confirm ANSYS simulations.
- Deflection toward beam during beam heating must be minimized.



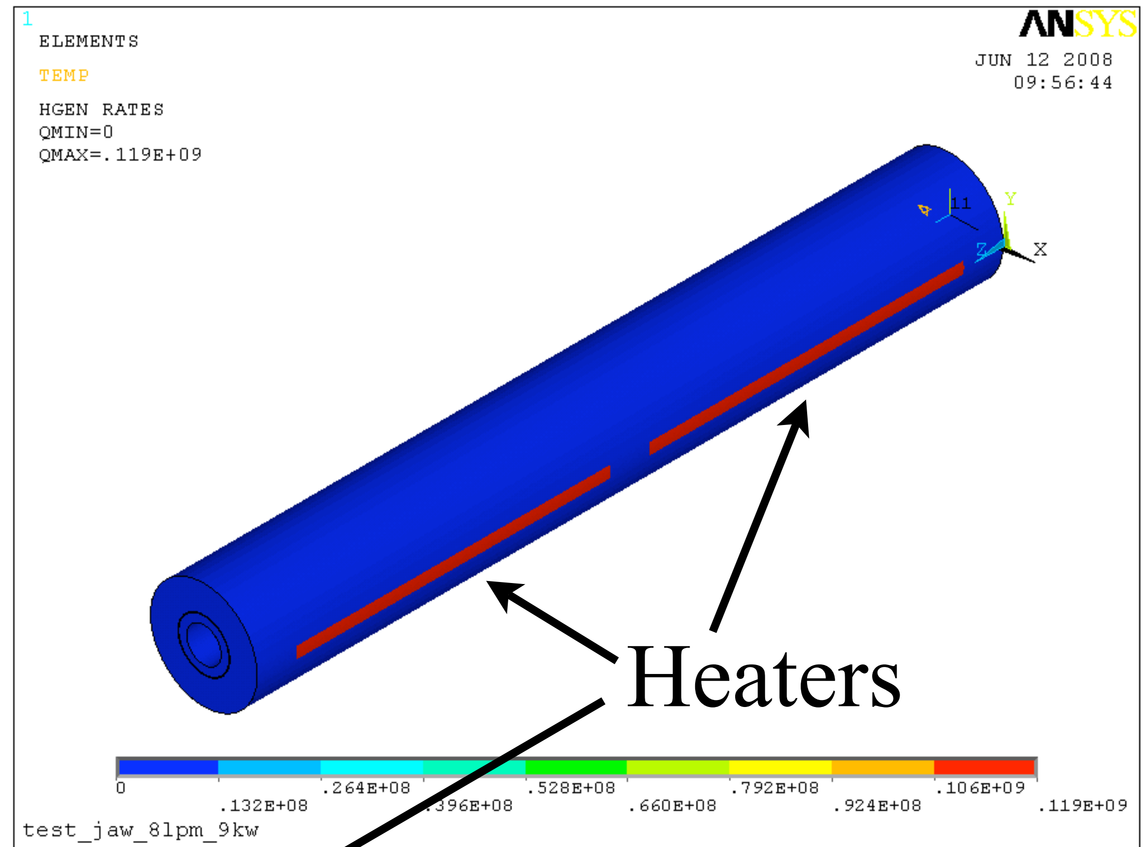


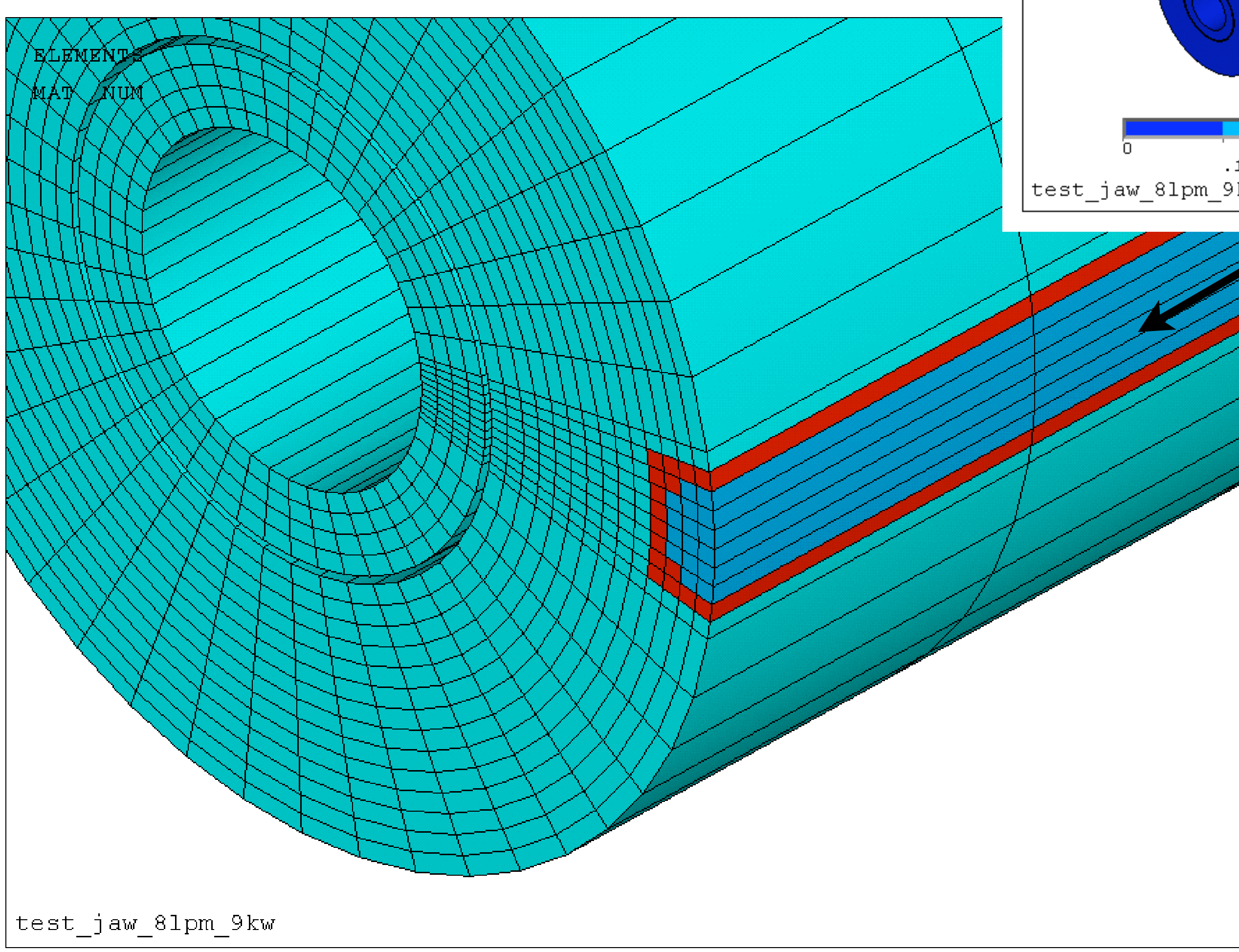
Images from www.capacitec.com

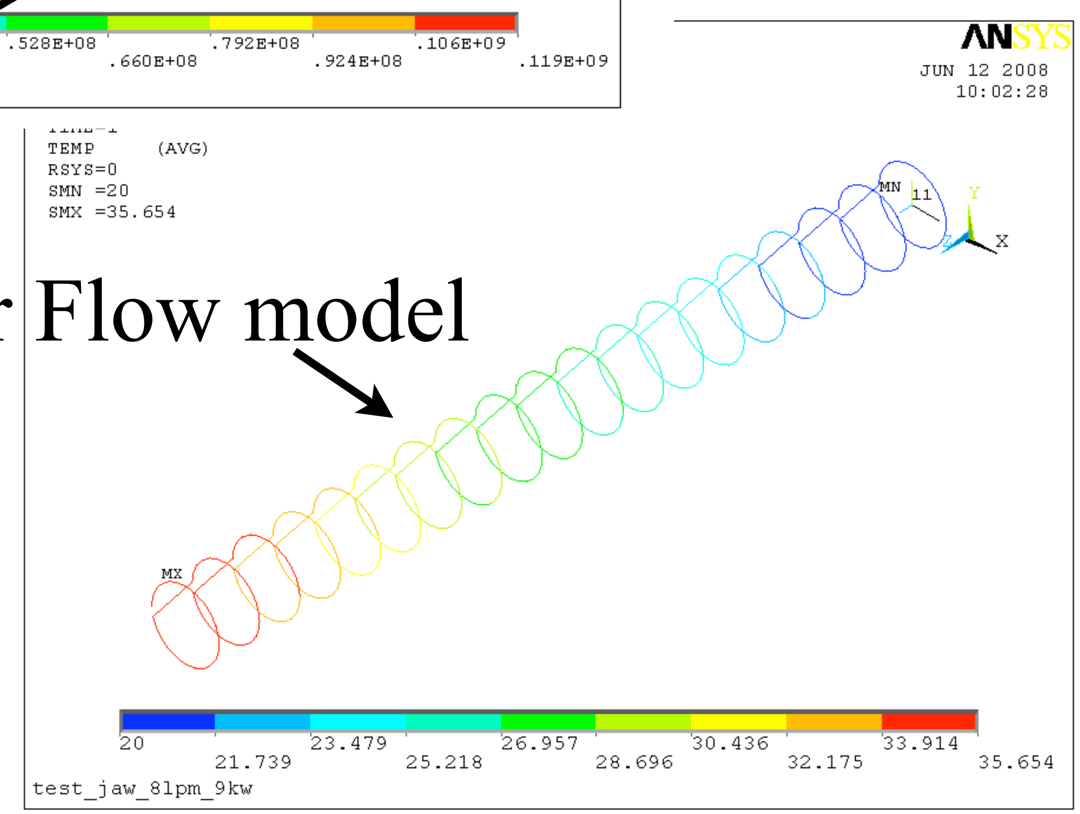


ANSYS Simulations

- Jaw with two 5 kW heaters modeled in ANSYS
- Includes accurate representation of
  - Water flow/temp change
  - Material properties
  - Thermal expansion
  - Heat flow / thermal conductivity

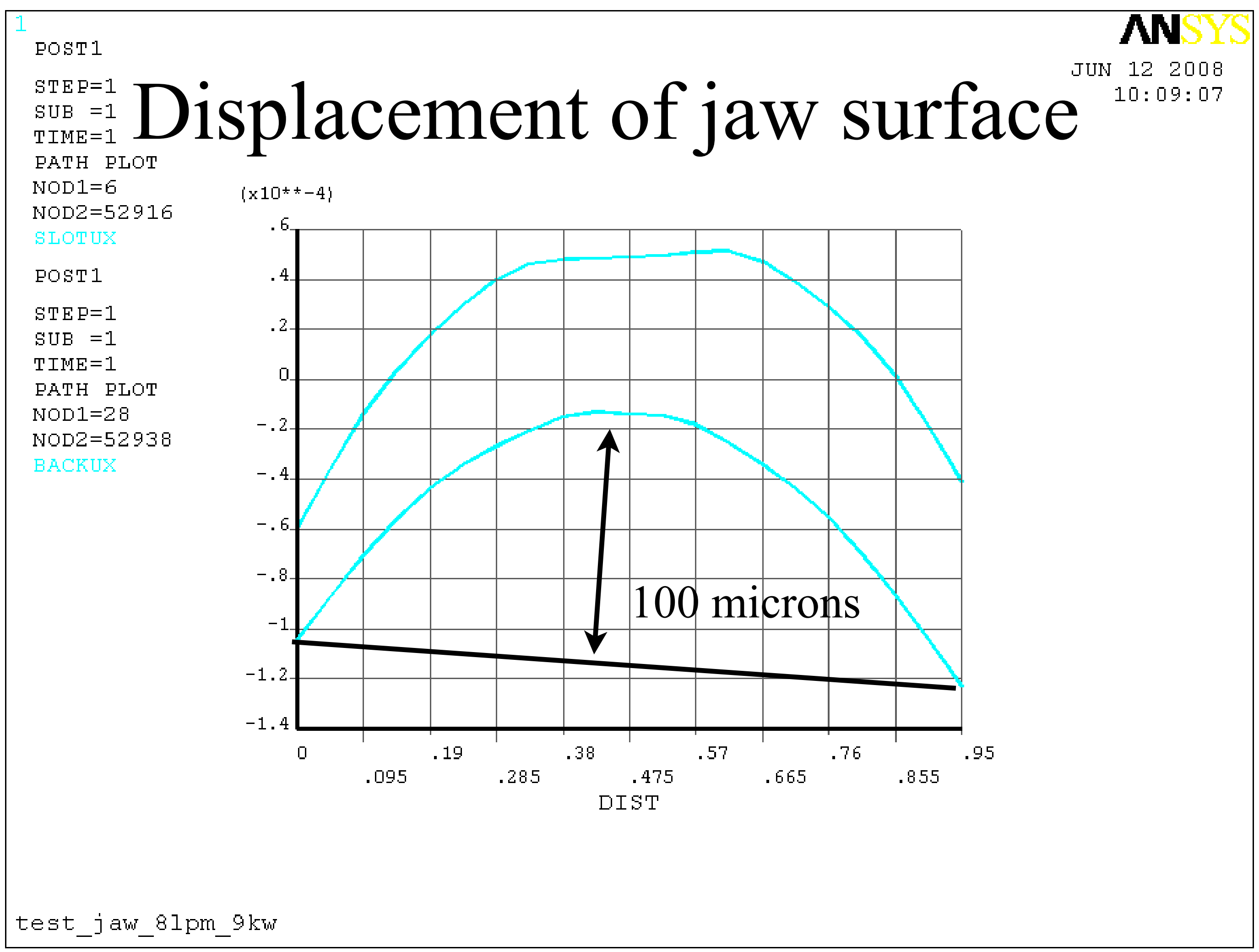


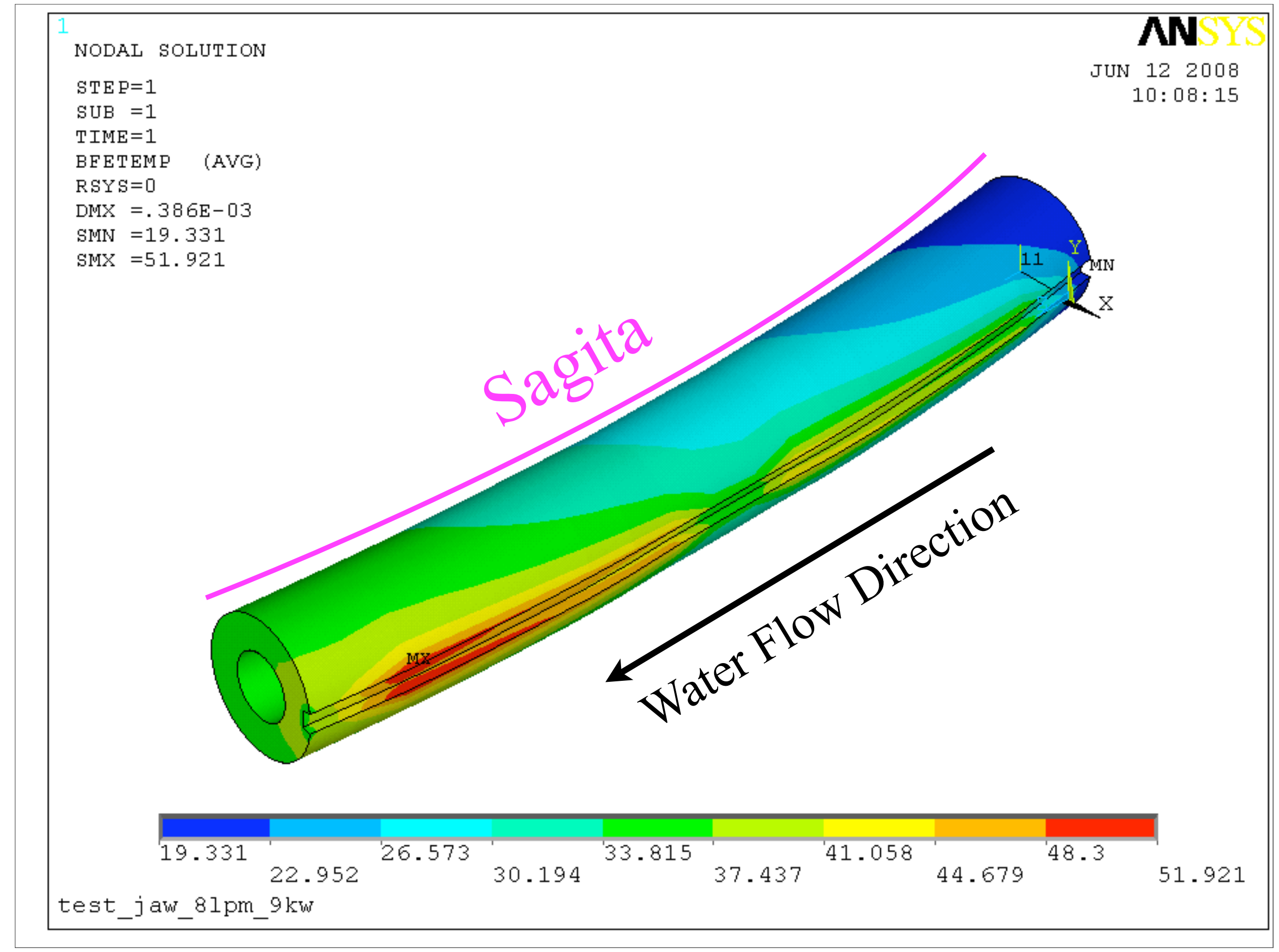




ANSYS Predictions

- ANSYS predicts 100 microns sagita on side opposite heaters (where capacitec sensors are mounted)
- (Note: this is different than the sagita due to realistic beam heating.)

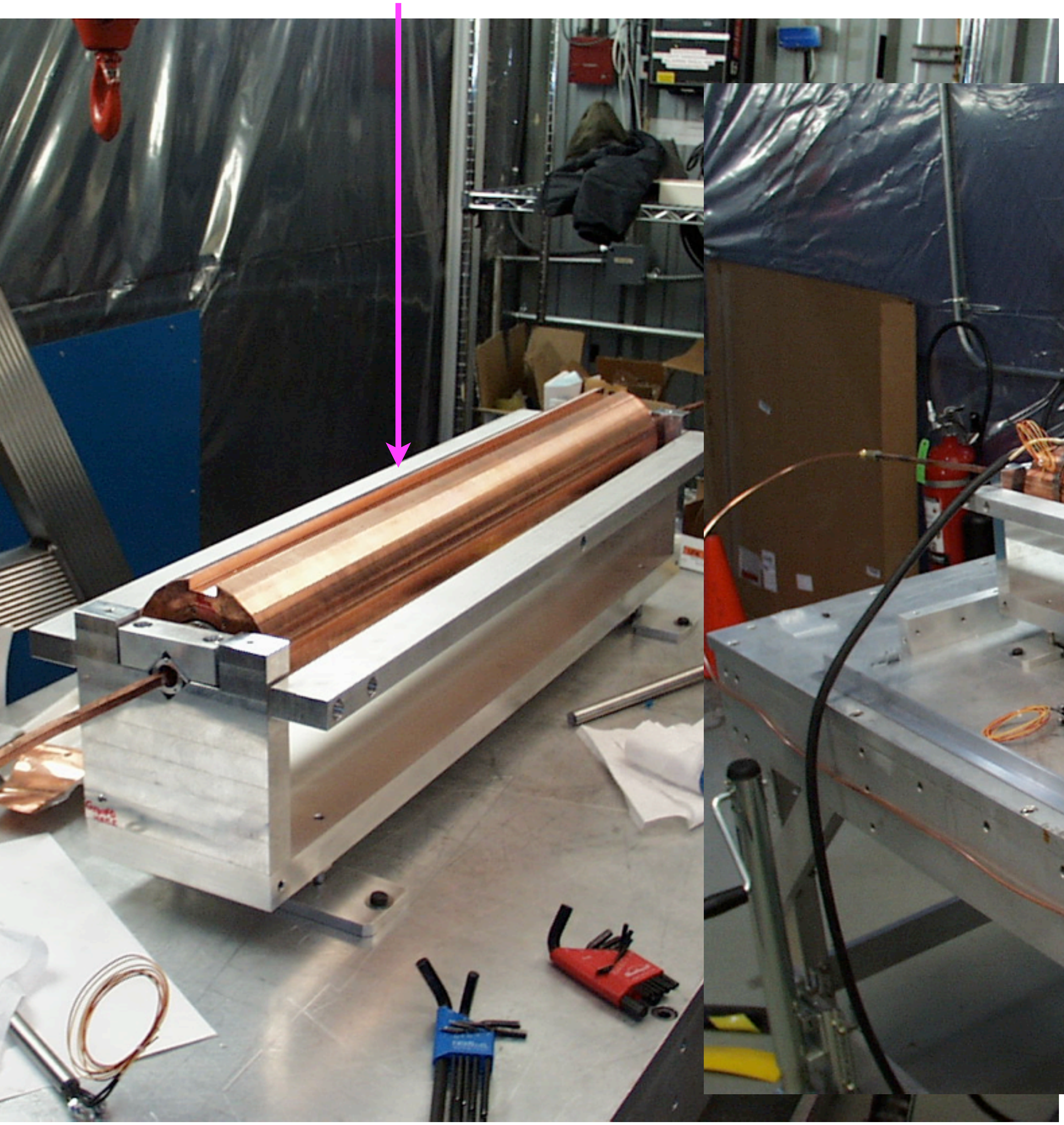


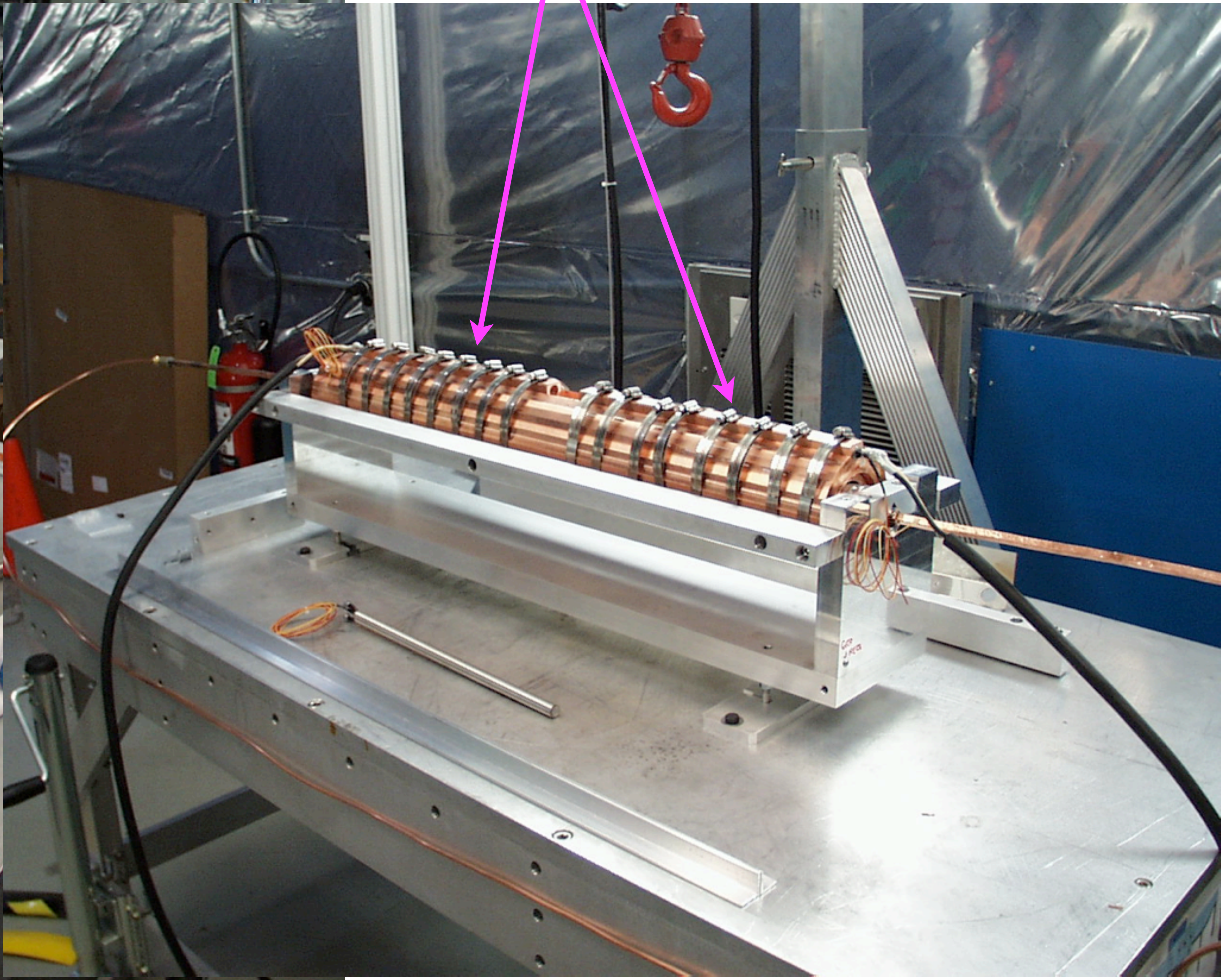


Mounting jaw and heaters

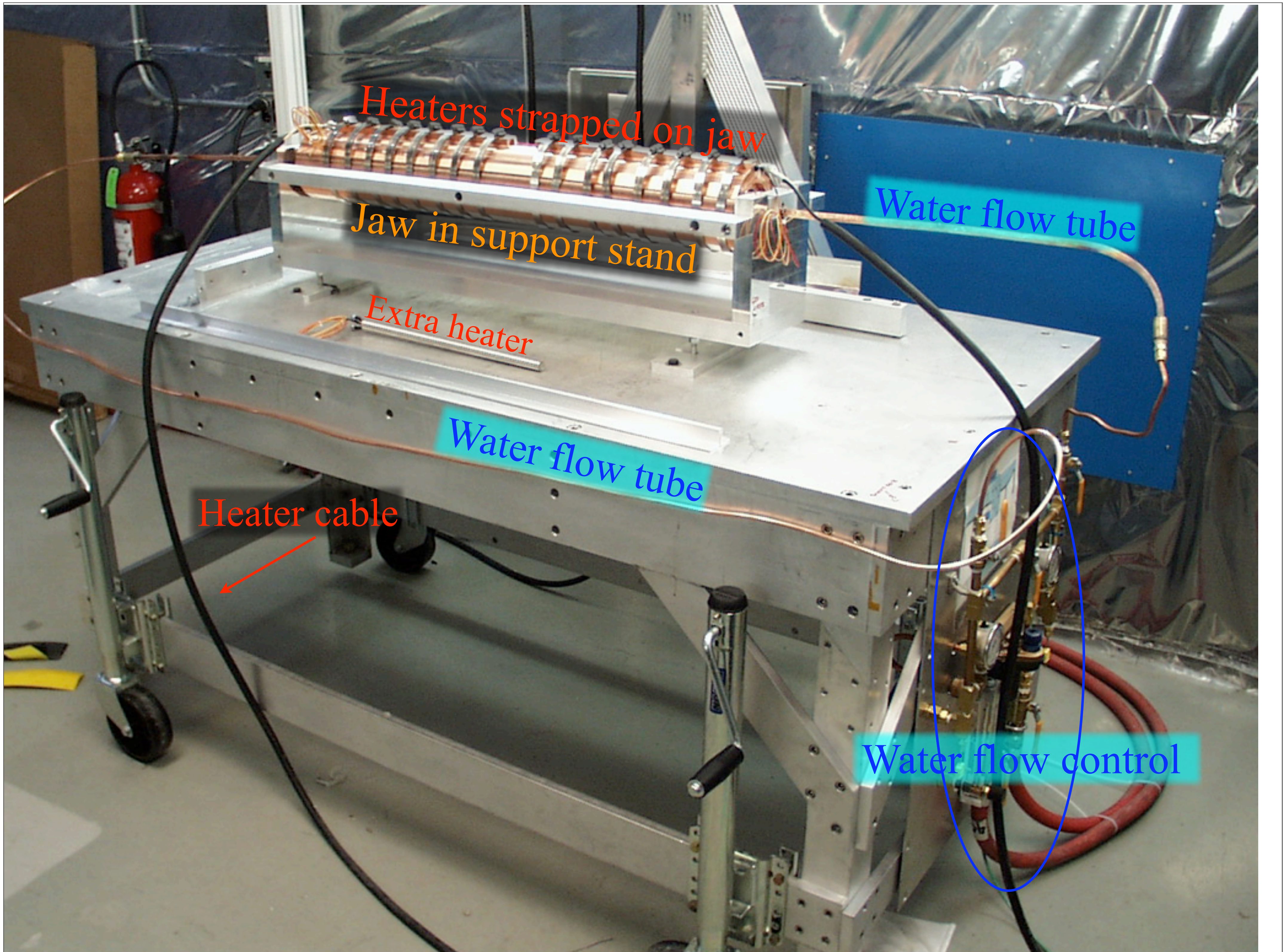
Heater slot

Heaters mounted and strapped in

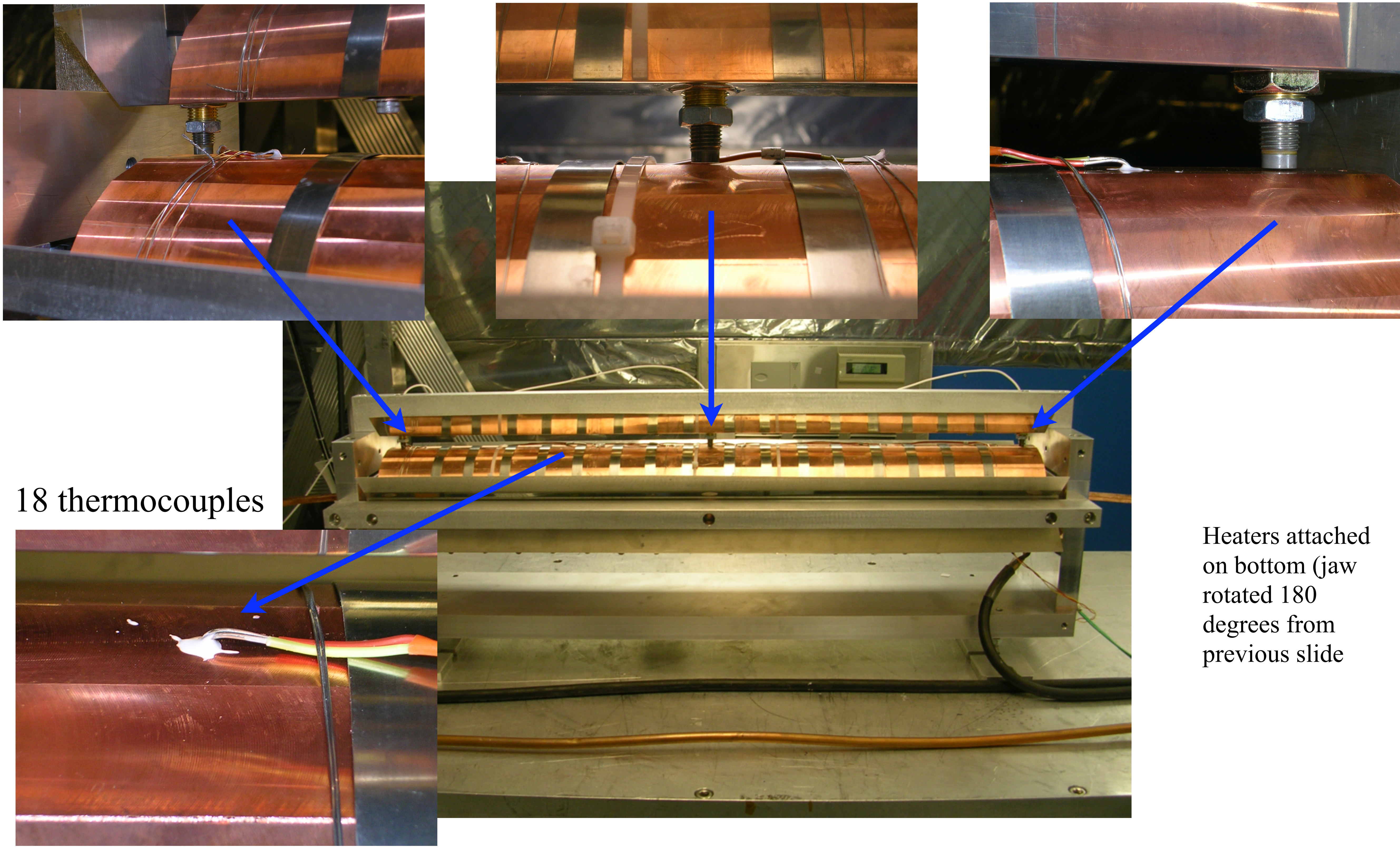




Thermal test setup



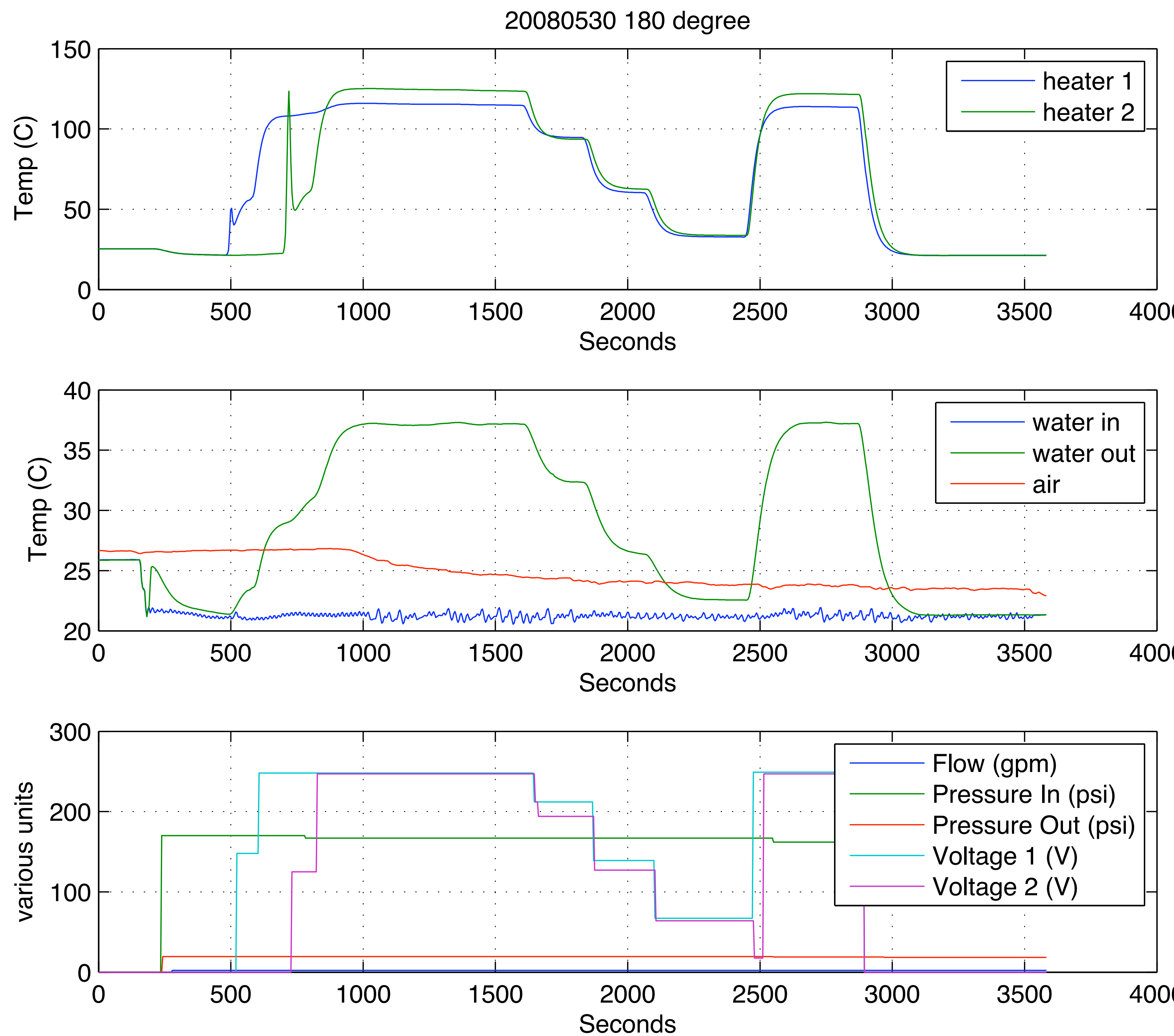
Measure jaw thermal expansion with capacitive distance sensors



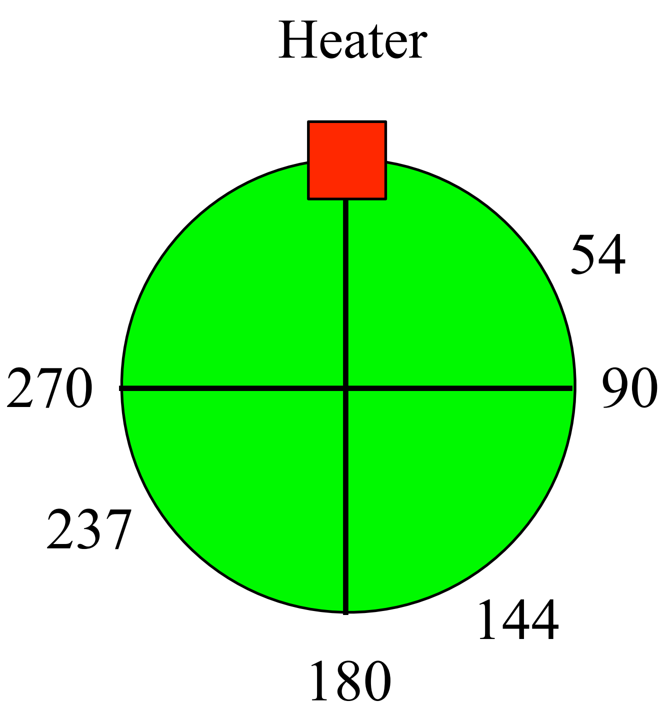
Heaters attached on bottom (jaw rotated 180 degrees from previous slide

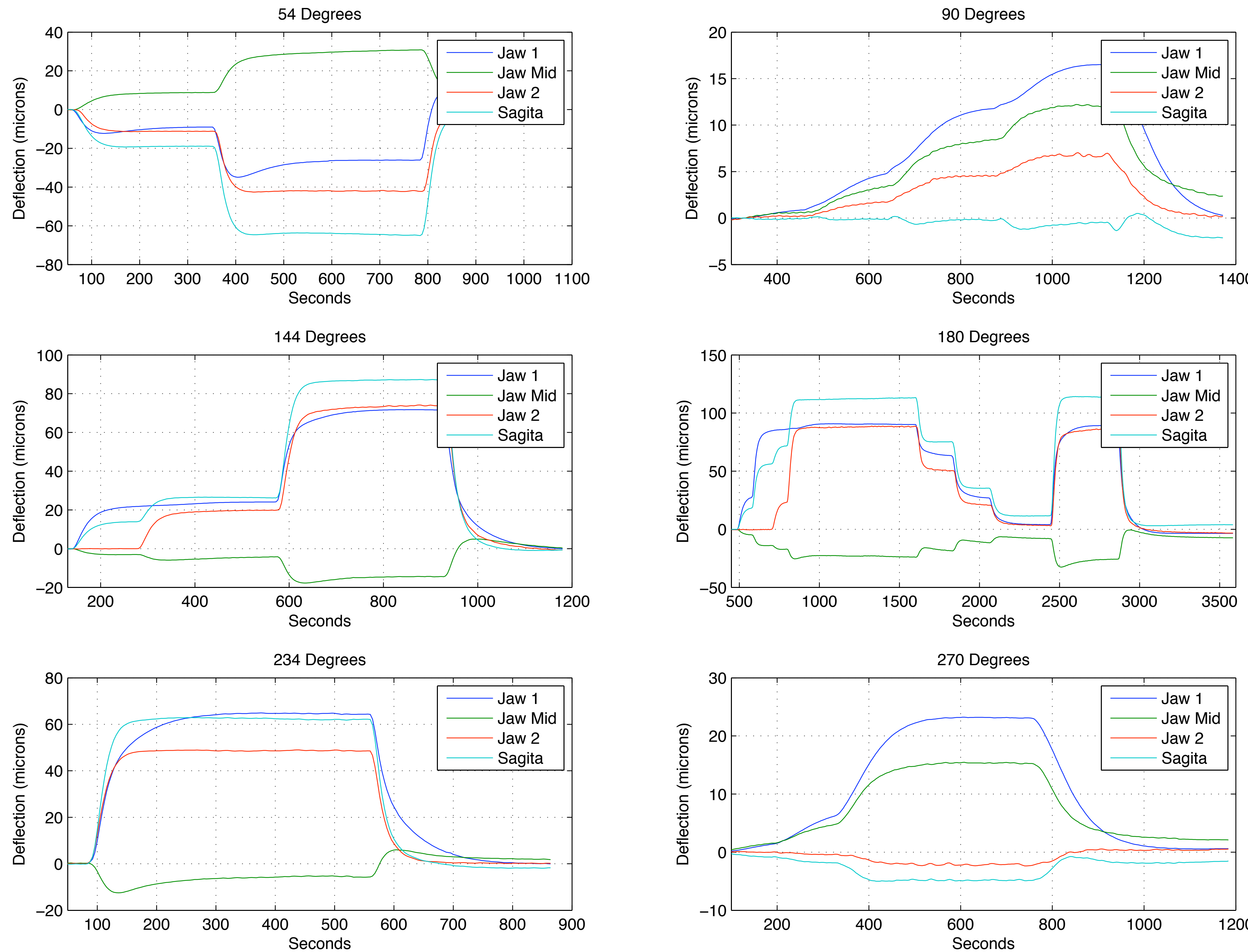
Measurements

- Measure:
  - time
  - water flow
  - water pressure in
  - water pressure out
  - water temp in
  - water temp out
  - power supply voltage x2
  - power supply current x2
  - capacitive distance sensors x3
  - thermocouples x22
  - 37 parameters in total
- From data at right can show 9kW from heaters = 9 kW absorbed in water
  - Very little escapes radiatively or conduction/convection through air



Measured Sagita at 6 Locations Around Jaw

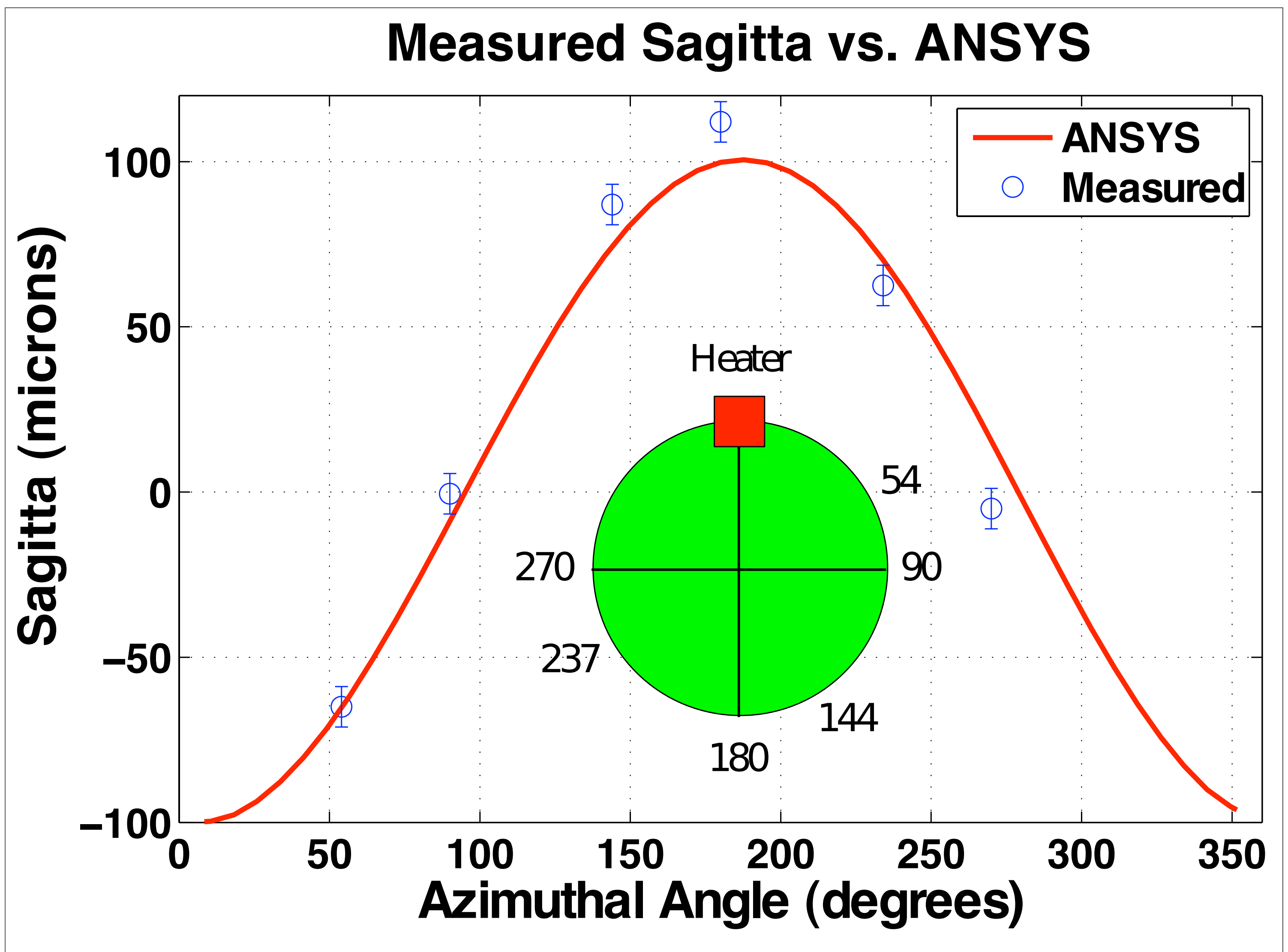


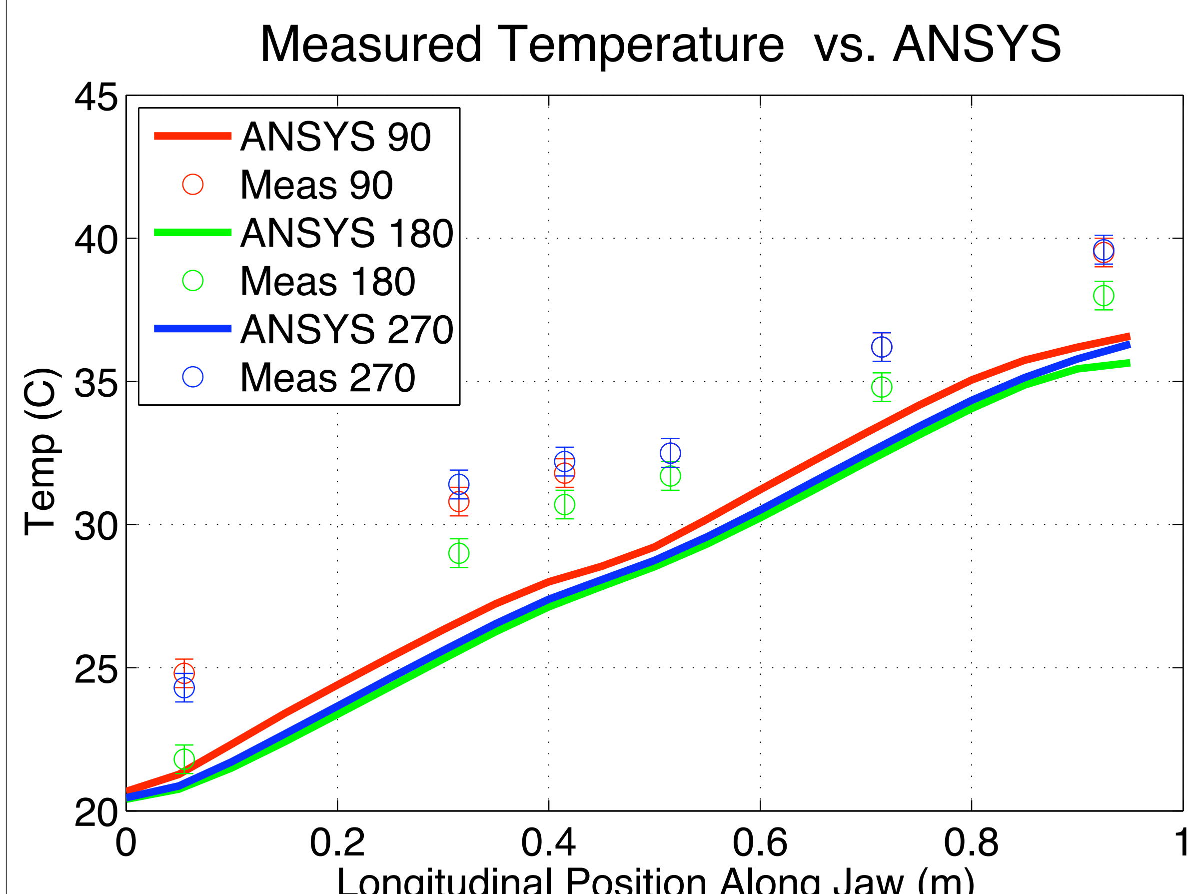


(different runs so time not consistent between runs)

To summarize the results

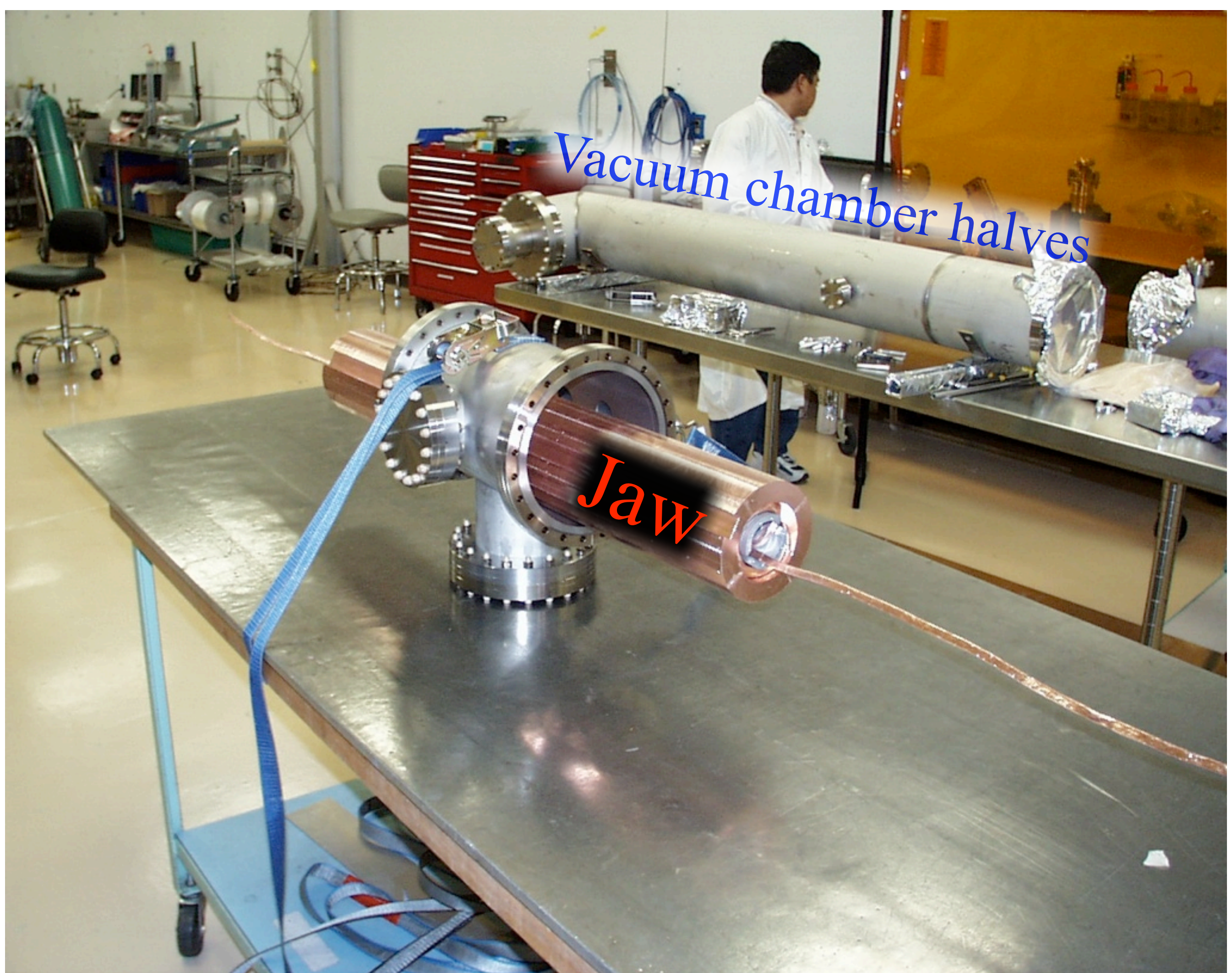
- The deformation of the jaw is in good agreement with ANSYS predictions along the entire azimuthal angle
- Temperature change along jaw is also in good agreement

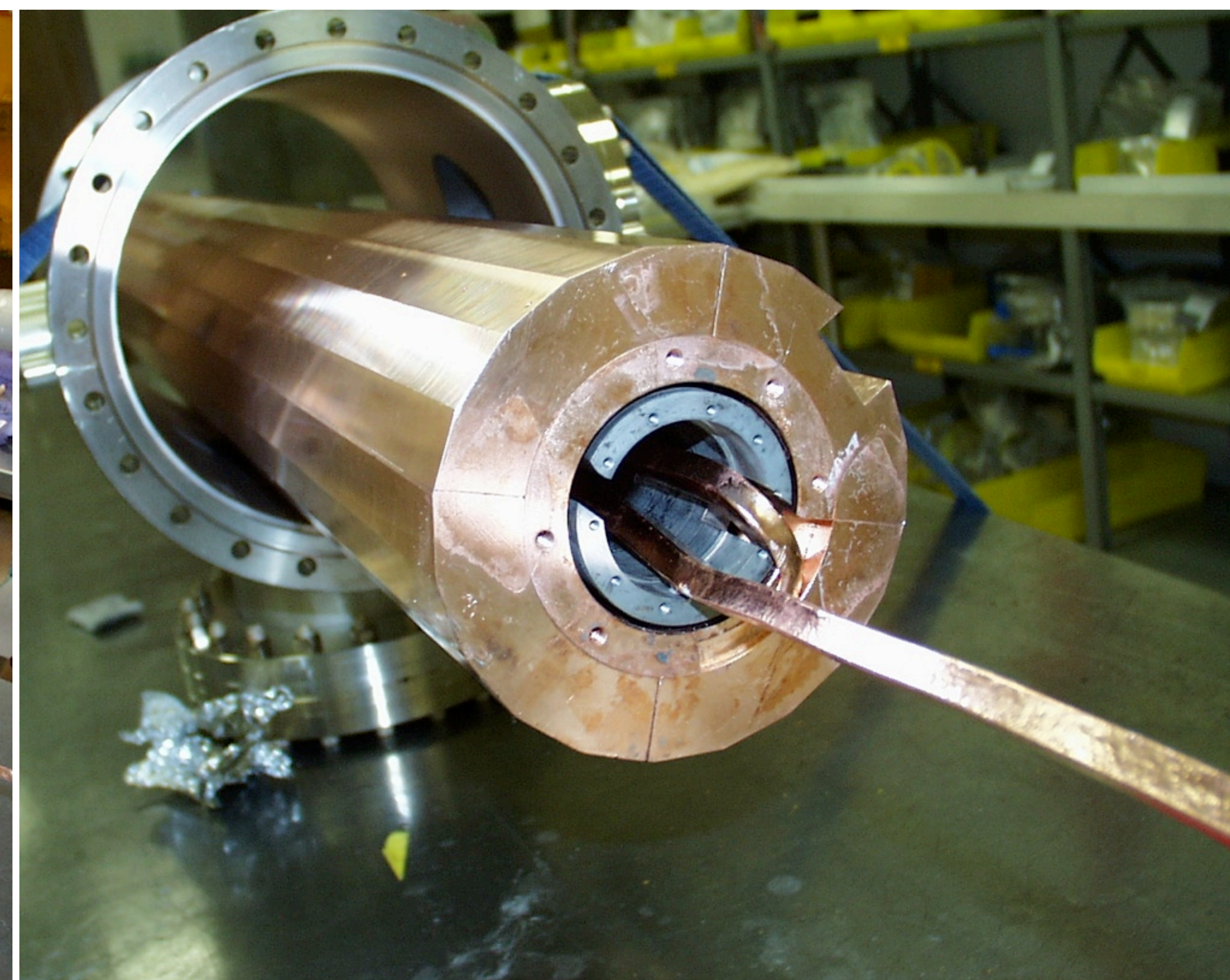




Vacuum Testing

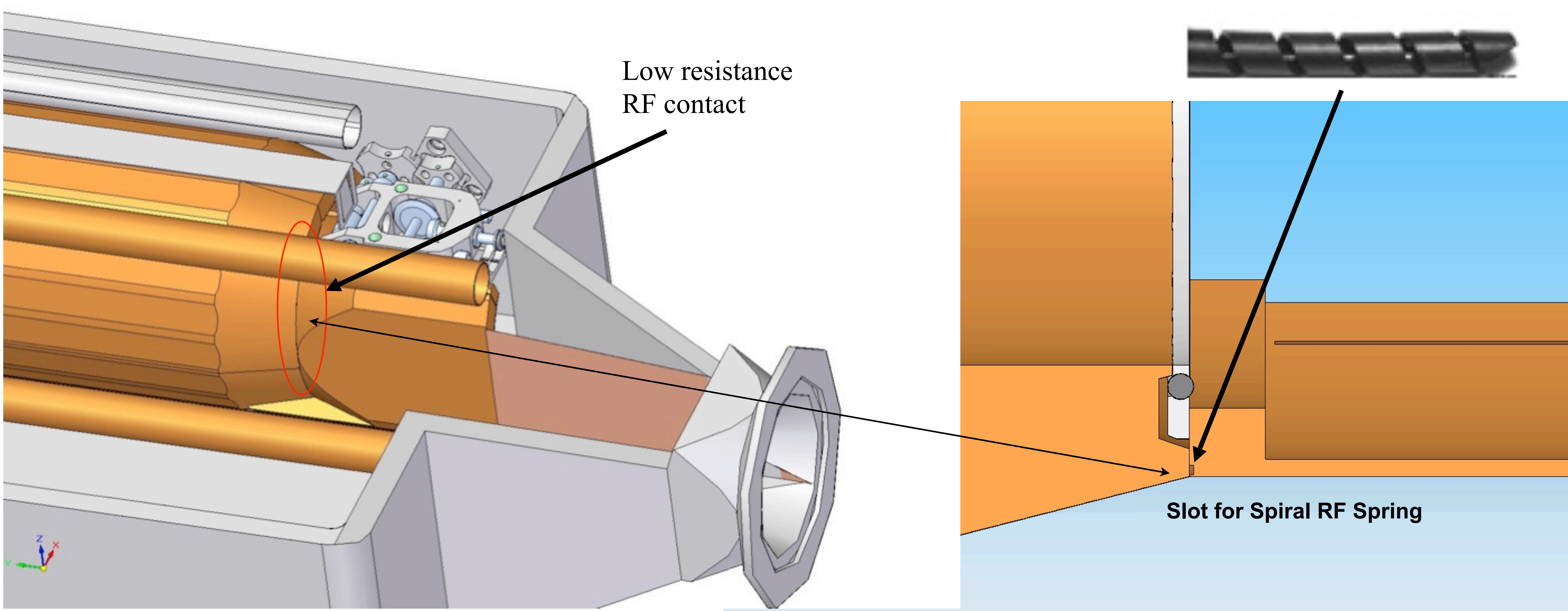
- Last year some vacuum bake-out tests on short jaws were completed with varying degrees of success.
- With our thermal tests completed, jaw is now undergoing bake-out tests.
  - Results should come soon!



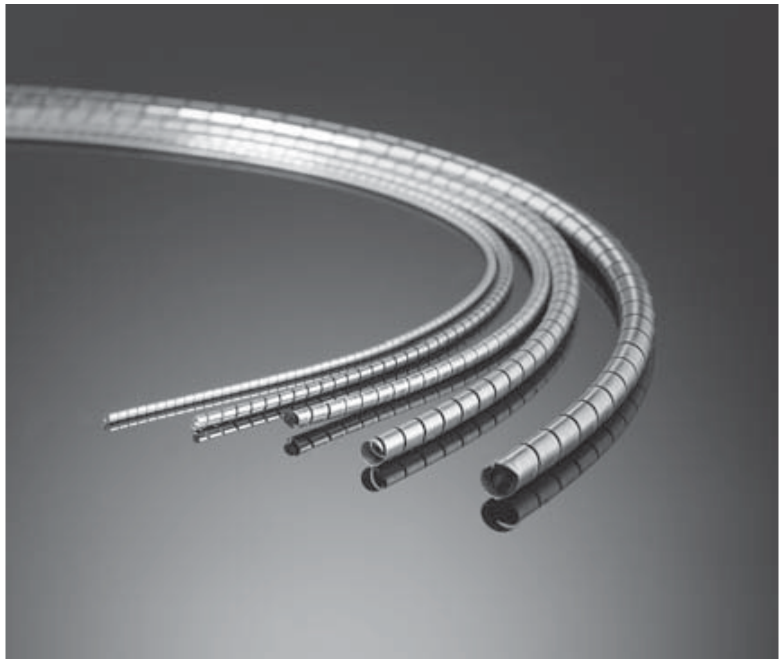


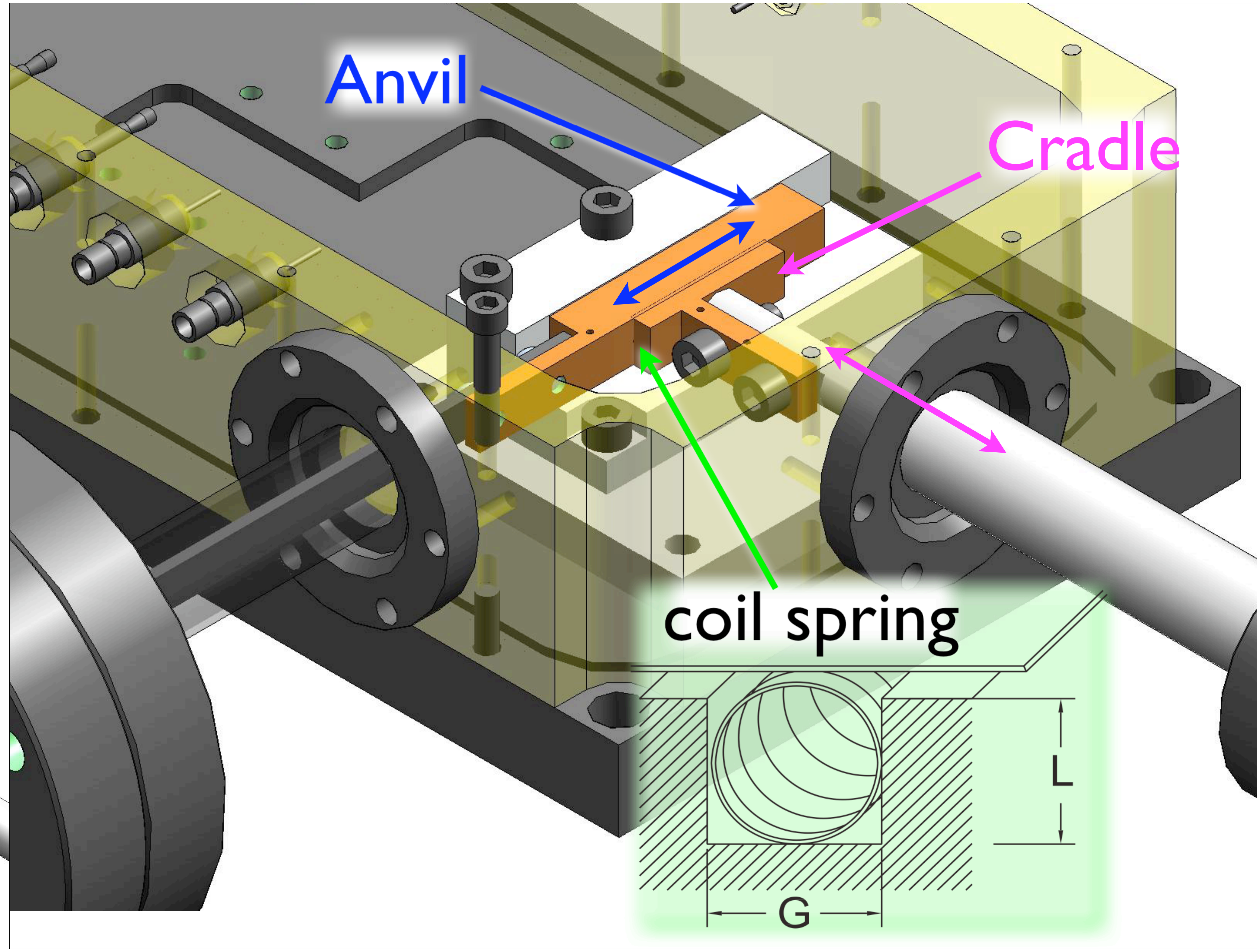
RF Contact Measurements

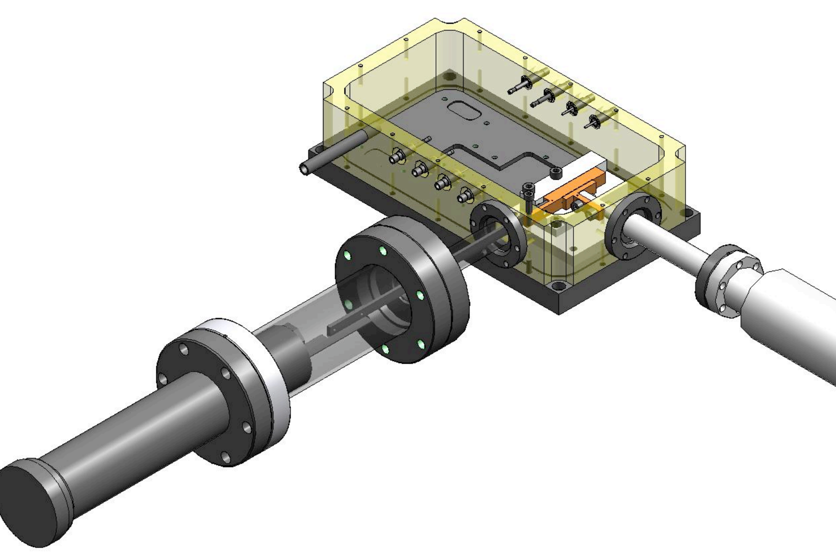
- Must have low resistance for RF contacts, especially Jaw/transition piece interface
  - This interface is ~11 mm from beam and must have ~<0.02 mOhm total low frequency resistance
  - What kind of electric contacts should be used here?
    - Silver plated? Rhodium? Is copper good enough? (probably not) Cold welding copper?
    - Considering results from Sergio Calatroni et al.
    - How much force needed for good contact?
    - How will resistance increase with wear and tear?
- Performing RF contact resistance measurements with HP microOhm multimeter.



Experimental setup

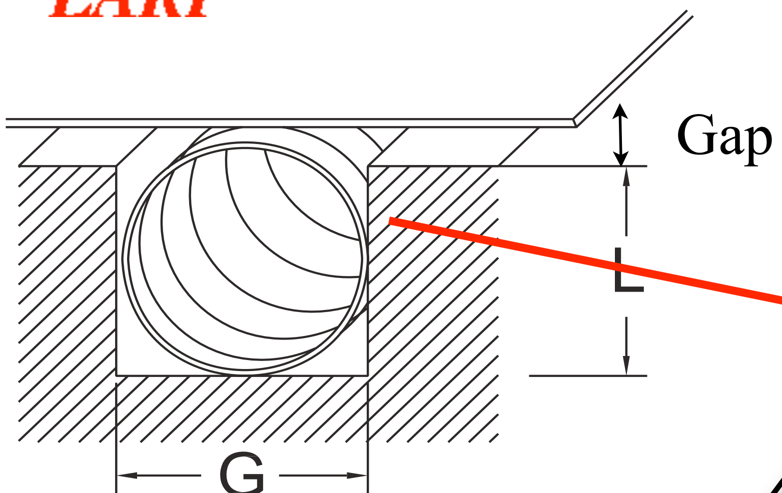


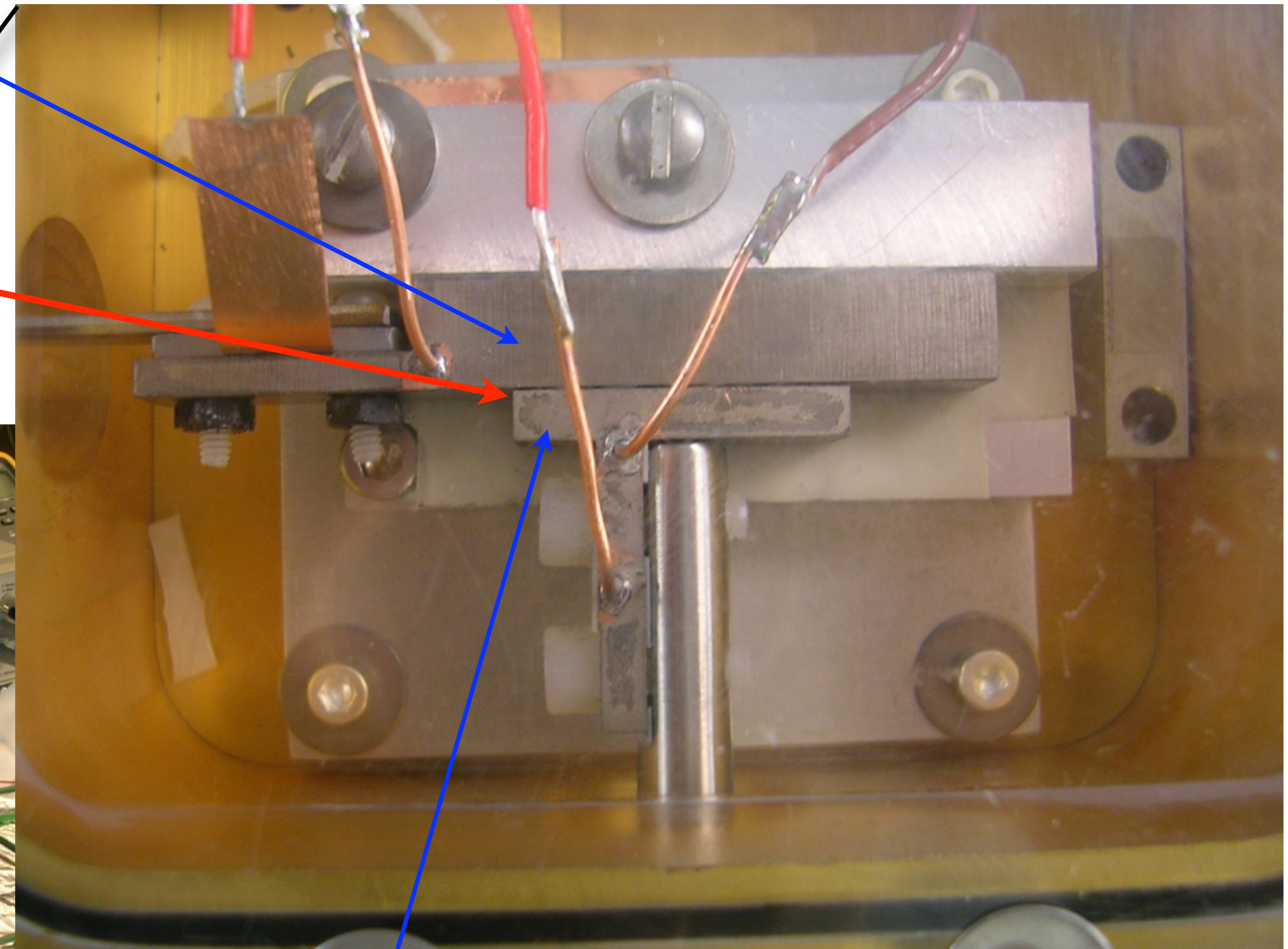


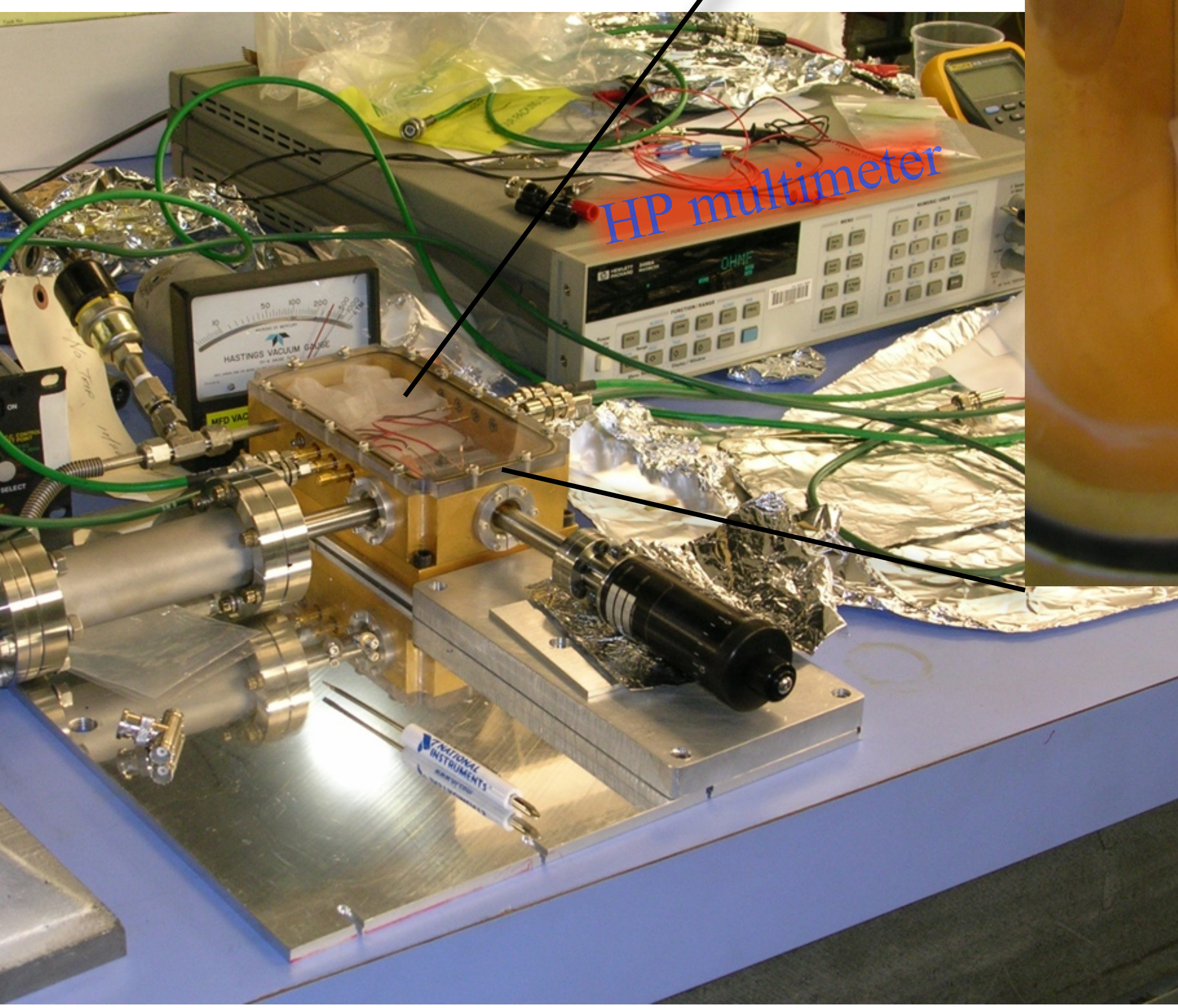


LARP

Spira™-Shield Setup

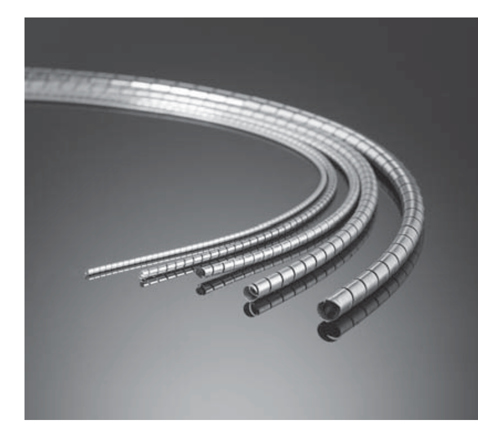






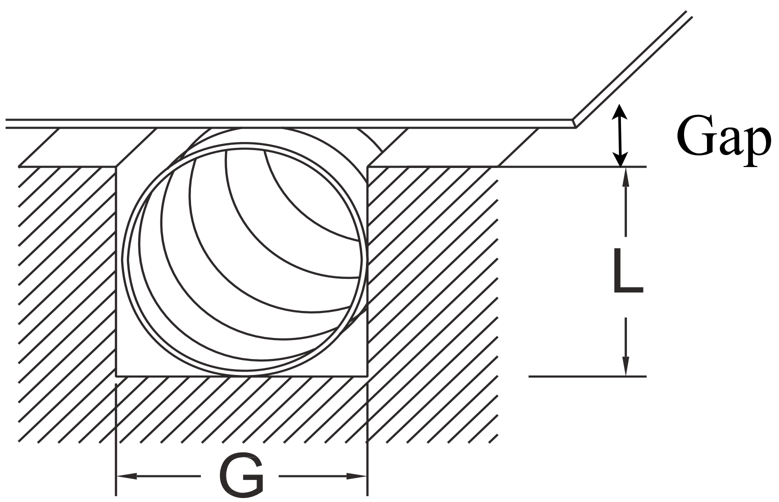
Rhodium plated glidcop anvil and cradle

Silver plated BeCu spiral spring

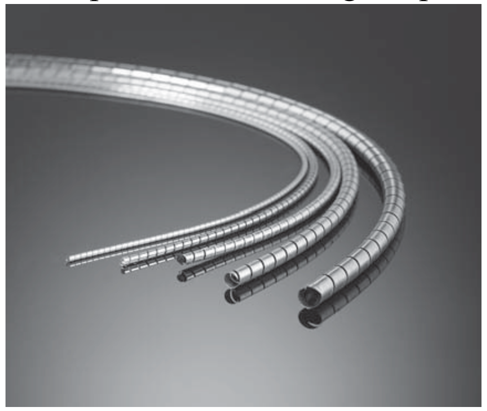


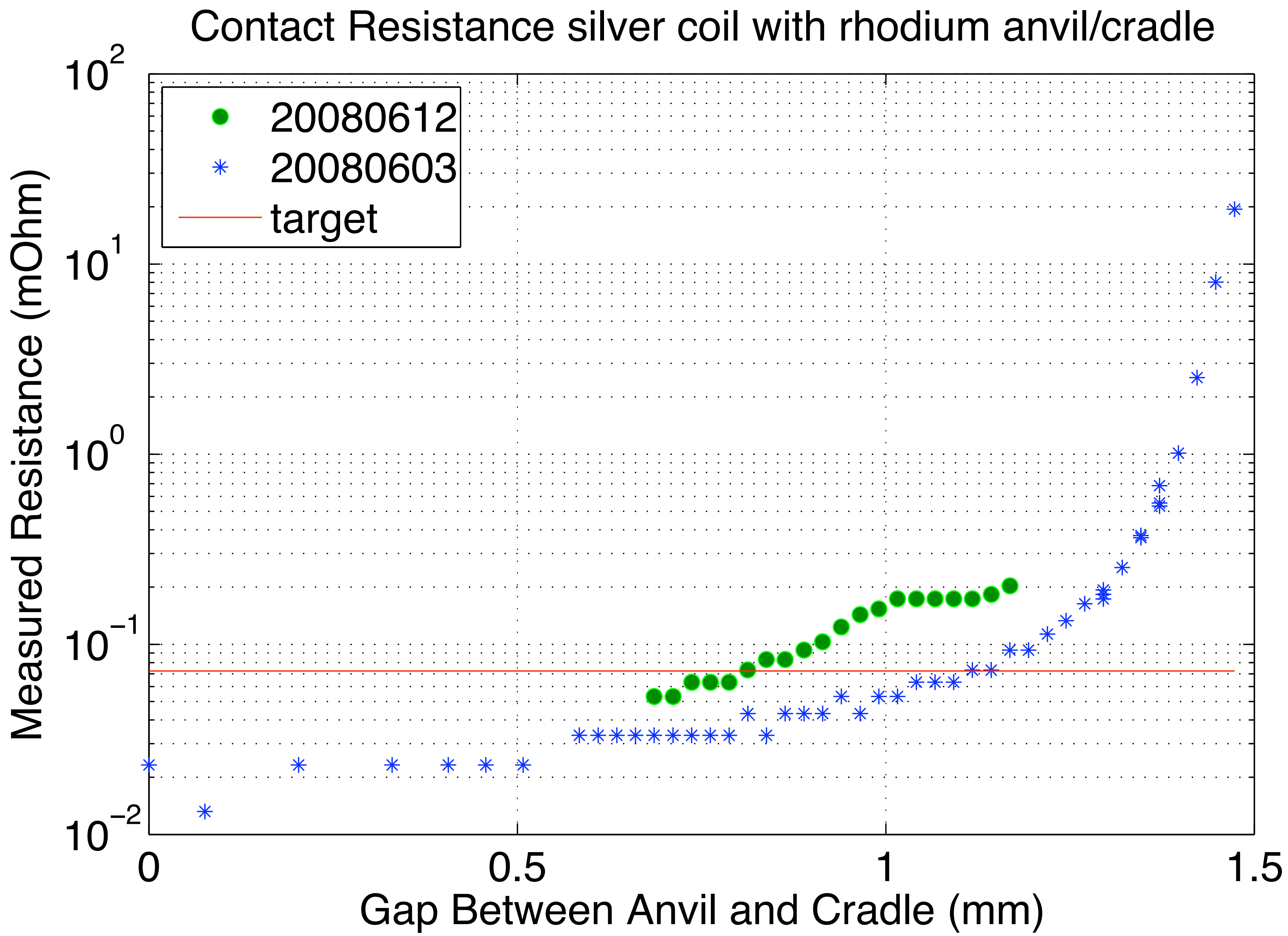
Results with Spira™-Shield Spring

- Results with Spira™-Shield spring as a function of compression.
  - Bulk resistance of anvil/cradle (0.02 mOhm) removed
- Desire <0.08 mOhm.
  - No observed degradation with rubbing



Spira Manufacturing Corporation





Next step

- Test contact resistance in real geometry
- Manufacture “end cap” for jaw and transition piece.
- Work underway, should have results within the month.

Impedance considerations and RF Trapped Modes

- I wasn't going to get into this for this talk.
- But we can discuss it if you like...

For Further Information

- SLAC Rotatable Collimator website:
  - http://www-project.slac.stanford.edu/ilc/larp/rc/default.htm
- Here you can find:
  - Documentation
  - A lot of photographs
  - Mechanical Design Drawings

Thanks to many people who have helped along the way:

- LARP Rotatable Collimator Group:
  Gene Anzalone, Eric Doyle, Lew Keller, Steve Lundgren, Tom Markiewicz, Jeff Smith
- SLAC ARD
  Karl Bane, Cho Ng, Liling Xiao, Dan Van Winkle, Jim Lewandowski, Yunhai Kai, Sasha Novakaski, Arden Kulikov
- SLAC Klystron department (brazing):
  John Ward, Michael Benes, Lou Garcia, Jim Fenske, Robert Jusinski, Andy Nguyen, Arnie Massoletti, Rafael Miranda, Giovanni Nguyen
- SLAC Engineering and MFD:
  Reggie Rogers, Kim Cook, Pete Franco
- CERN:
  Ralph Assman, Elias Metral, Fritz Caspers, Benoit Salvant, Federico Roncarolo, Alexej Grudiev, A. Ferrari, Chiara Bracco, Luisella Lari, Sergio Calatroni, Oliver Aberle, Alessandro Bertarelli