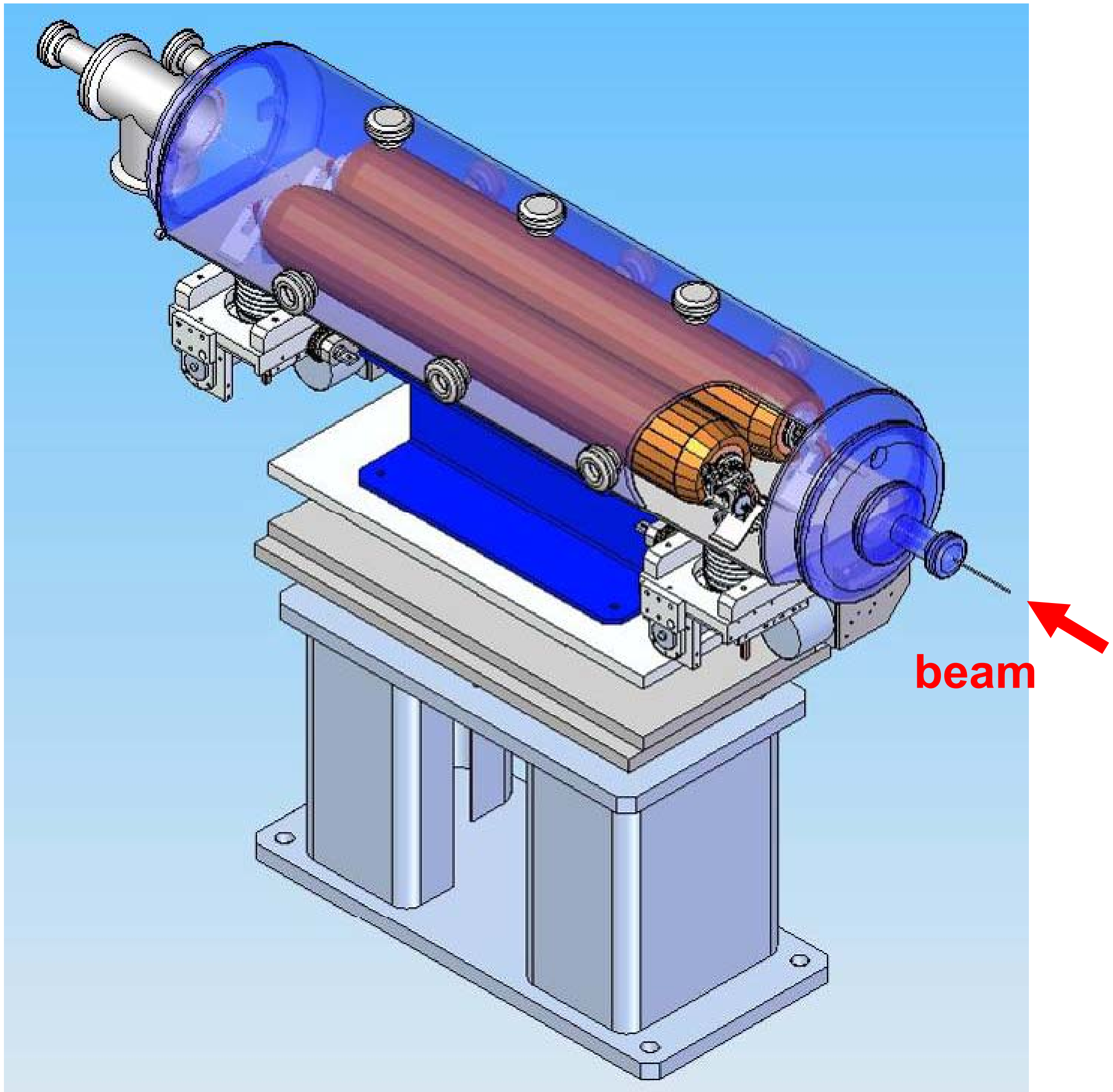


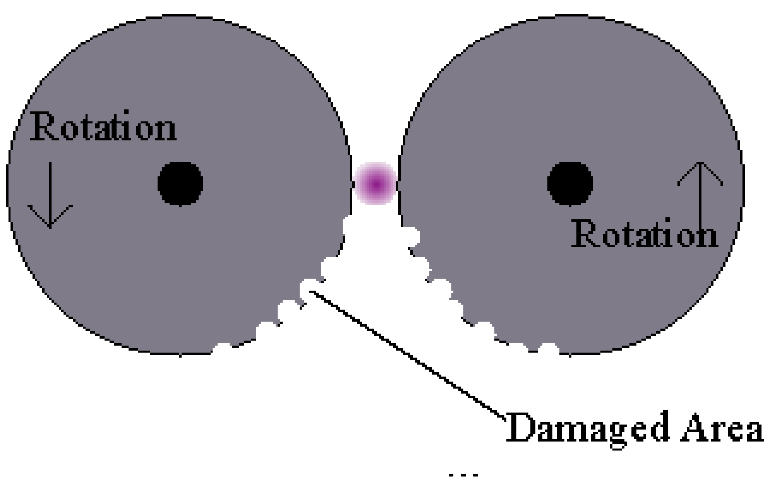
LARP Rotatable Collimator

02 April 2009

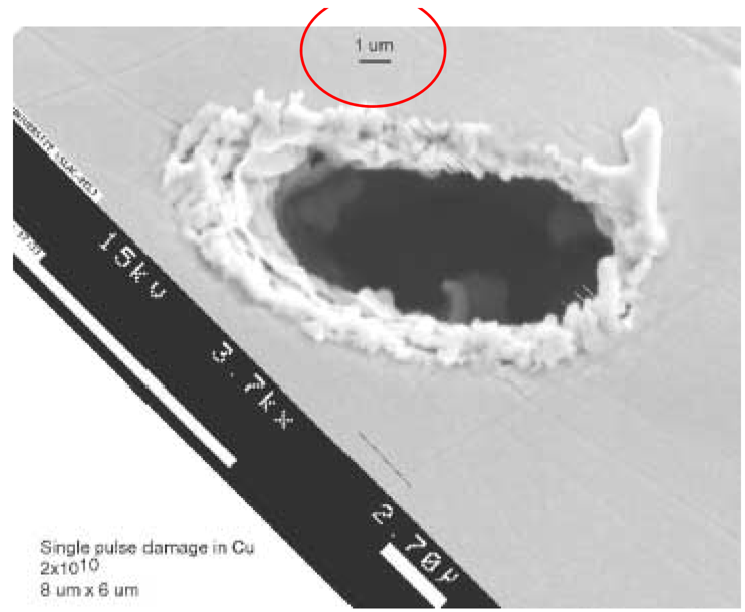
Phase II Collimation Conceptual Review - CERN

Tom Markiewicz/SLAC

SLAC Developed & Prototyped for NLC a "Consumable" Primary Collimator to Handle Infrequent e- Beam-Impact Events



Thin Cu with micron scale hole drilled by beam



Damage zone ~1mm

Only 6mm thick

NO COOLING!!

In 2003 SLAC suggested to CERN & LARP that this "Rotatable" concept might be the basis of an LHC Phase II Secondary Collimator

LARP

LHC Secondary Collimator Design Specifications

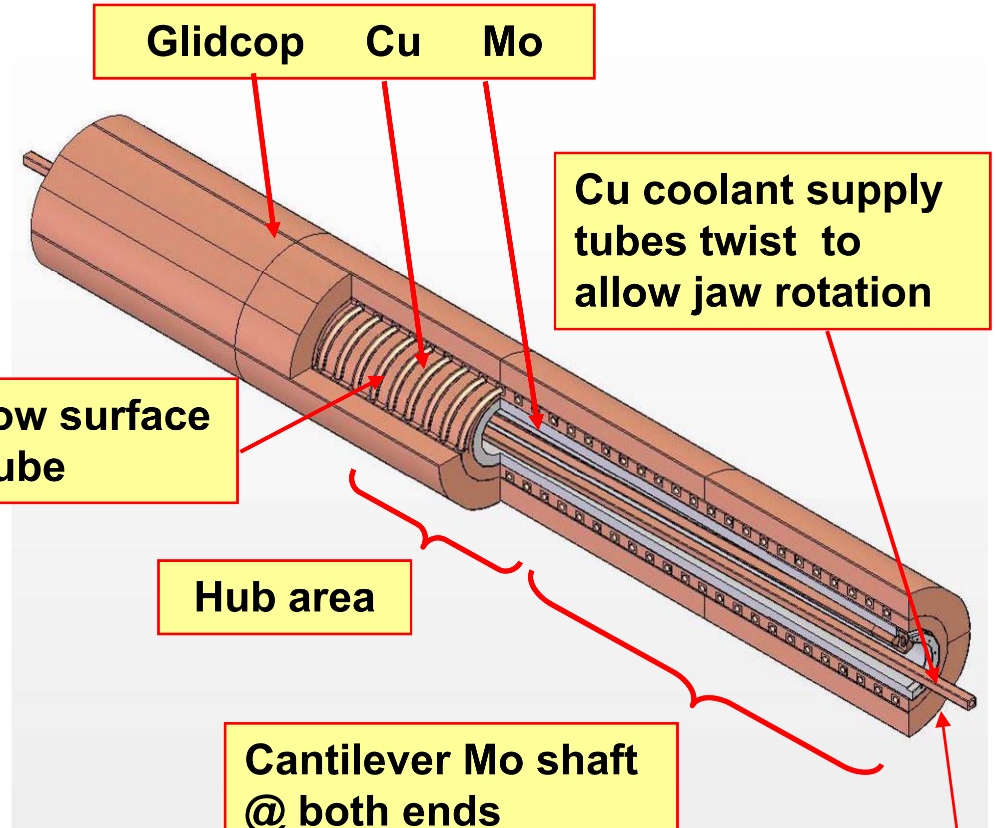
Space	Plug ready for 30 prepared Phase II locations & orientations Transverse dimensions to not interfere w/ other beampipe
Material	No Beryllium
Thermal performance	Thermal distortion under "Steady State" and "Transient" beam loss rates must not decrease collimation efficiency **Minimize thermal swelling & distortion from differential heating**
Vacuum	UHV, in situ bake-capable NO water-vacuum braze joints
Precision	25 μm jaw flatness, 5 μm step size
Robustness	Radiation Hard **Survive beam abort accident and still be useable**
Impedance	Metal, with low contact resistance in joint that permits rotation
Time Frame Needed	Originally, prototypes were to be required in 2008 → "Shovel Ready" materials & technology "Best Effort" extension of NLC design to LHC application

LHC Phase II Base Concept

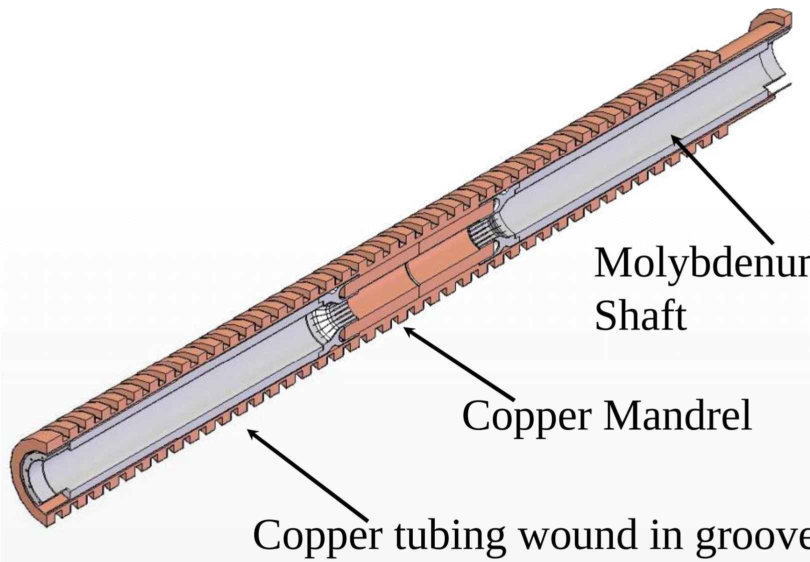
Glidcop Jaw - Cu Mandrel wrapped with CuNi coil – Hollow Glidcop Hub / Molybdenum Shaft with 2mm gap from Mandrel

- **Beam spacing: 136mm OD**
- **Length 1.47 m flange–flange:**
    - **930mm overall**
    - **2 x 38mm 15° tapers**
    - **854mm long facets**

20 facets



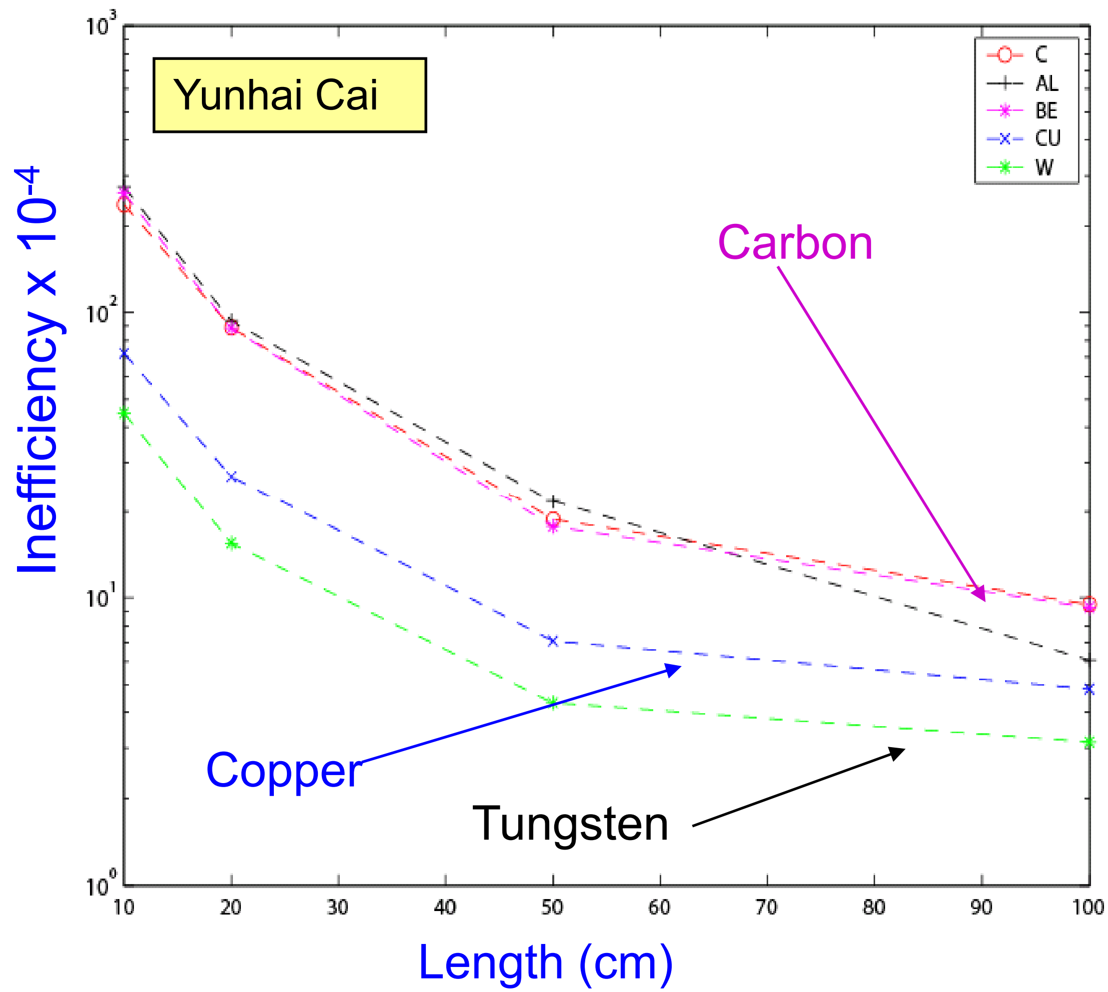
Helical cooling channels 23mm below surface with 16m long 10mm square CuNi tube



2mm gap between shaft OD and mandrel ID

MOTIVATION: HIGHER COLLIMATION EFFICIENCY

See Th. Weiler talk for thorough discussion



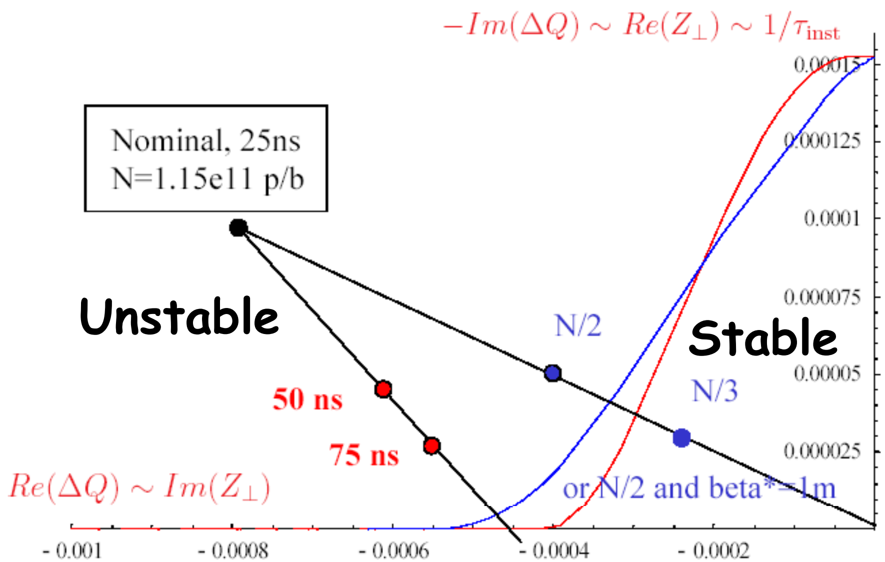
Similar SIXTRACK results by Aβmann, Bracco

- High Z materials improve system efficiency but generate more heat
- Copper eventually selected for SLAC Phase II design because of its high thermal conductivity and ease of fabrication
- Available length for jaws is about 1 meter, although gain after ~50cm is minimal
- Global inefficiency x3.6 better for Cu over C, but does nothing for Intensity Limit of particles lost in dispersion suppressor

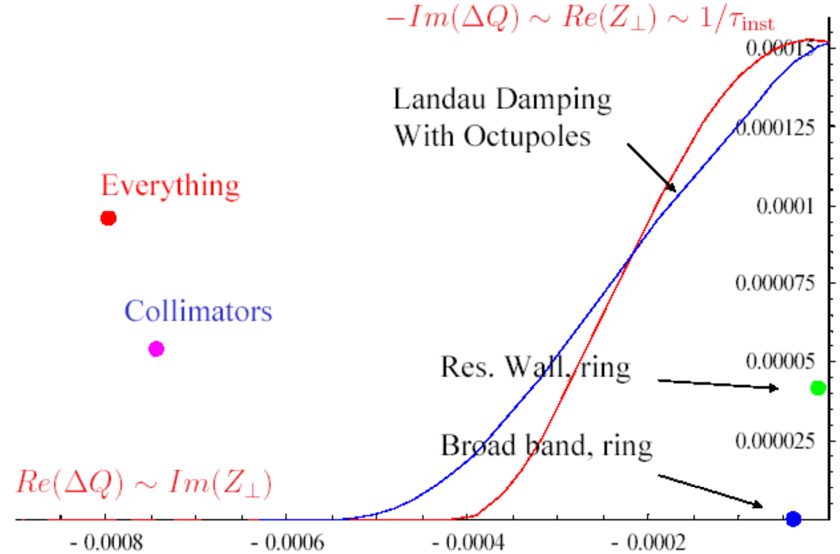
Motivation: Impedance Limits Luminosity
Carbon Collimators Dominate Impedance

See Th. Weiler & E. Metral talks for thorough discussion

7 TeV, vary beam parameters



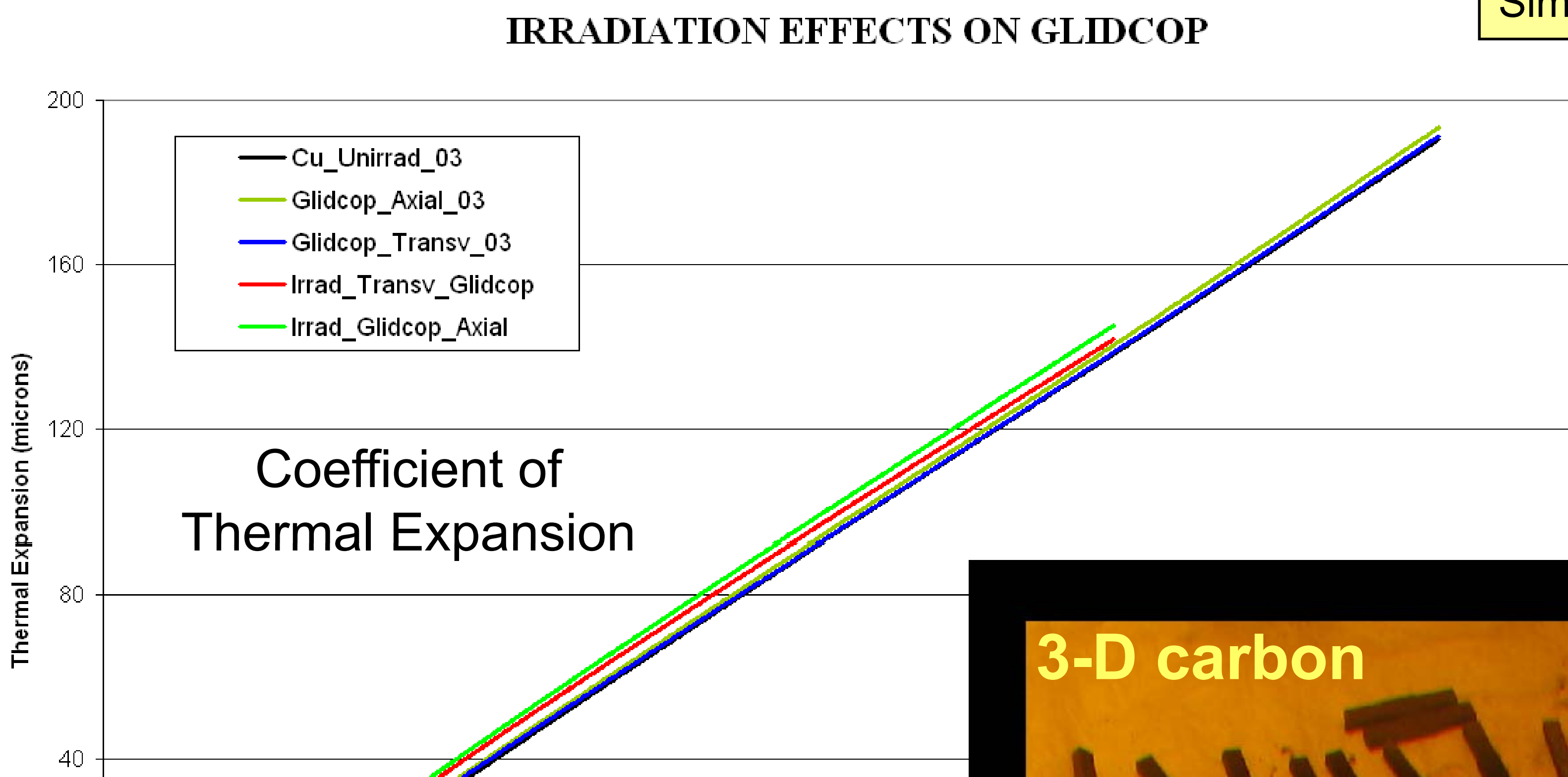
1.15e11 p/bunch , 25 ns spacing , 7 TeV

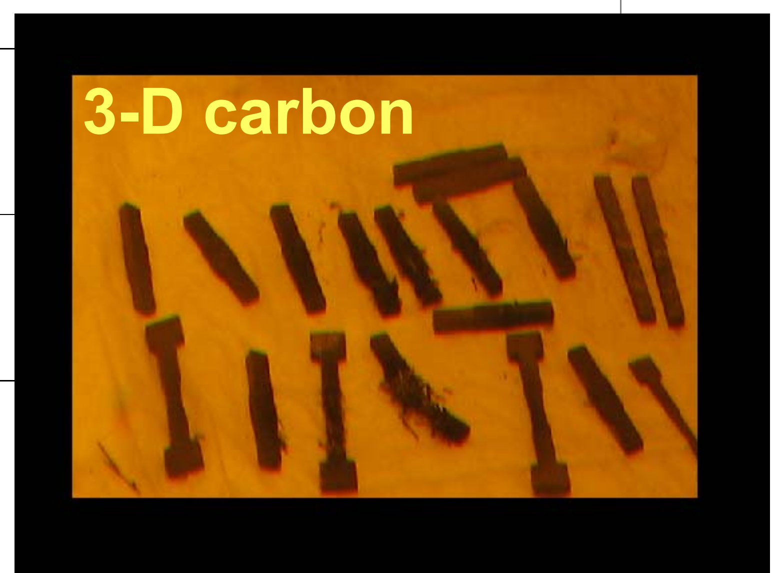


➔Limitation at about **40% of nominal intensity**… (nominal β*, full octupoles)
➔Contact resistance of RF transition piece to rotating jaw must be < ~ 1 mOhm

Motivation: Radiation Hardness of Metals

Simos





fluence ~ 10^{21} protons/cm^2

LHC Collimation Requirements

For performance metrics focus on:

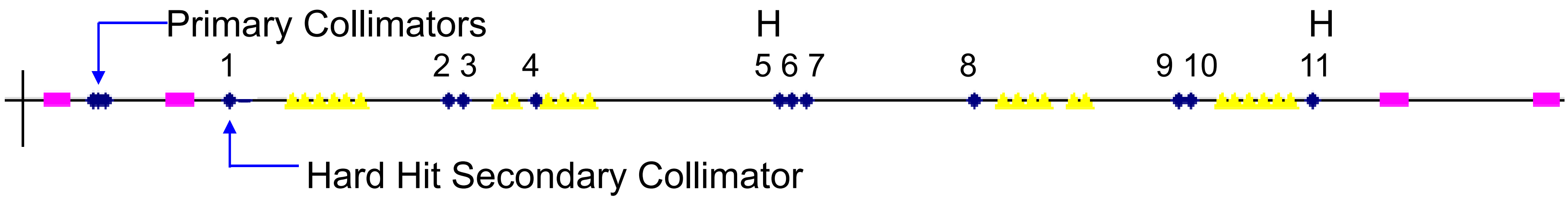
- "Transient" bursts corresponding to ~1.4% beam loss in 10 sec
  - beam lifetime τ = 12 min or
  - Particle loss rate =4E11 p/s
  - Energy loss rate =450kW
  - abort if lasts > 10 sec
- Note that "steady state" engineering loss rate is 5x less (1 hour beam lifetime)
- Long term beam loss rate another x10-20 less (10-20 hour beam lifetime)

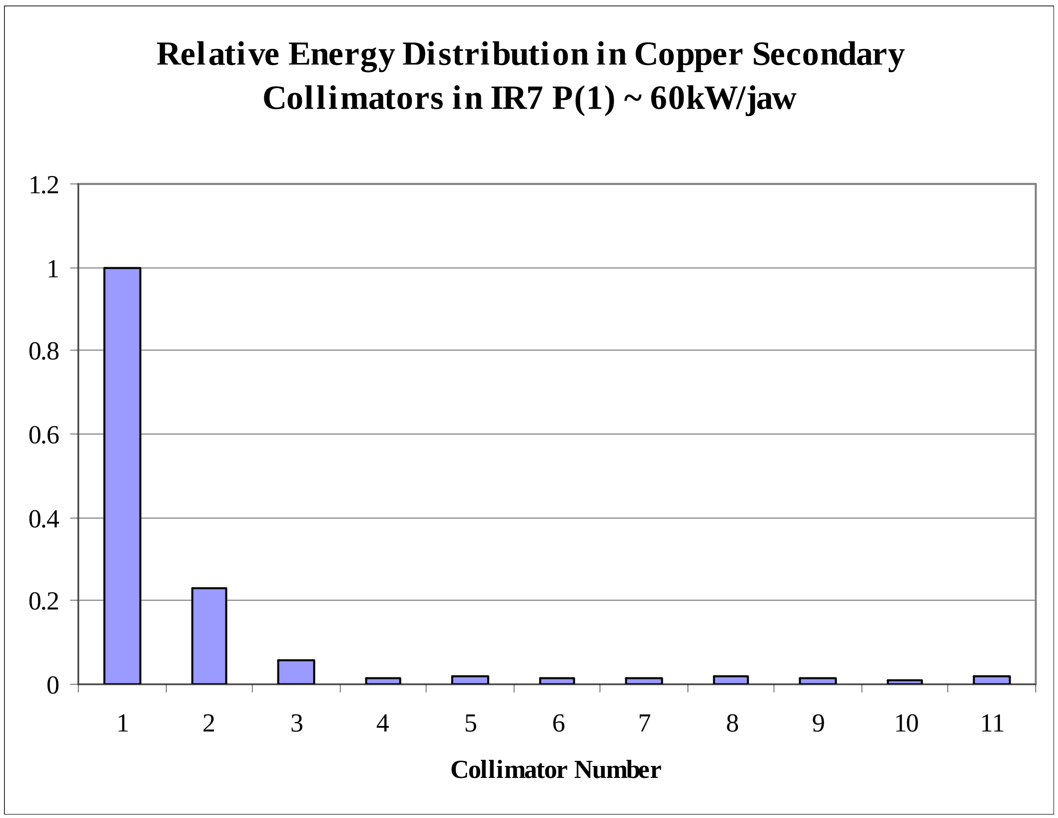
Recall that σ~200μm (collisions) and secondary collimators are at 7σ

Accident Scenario :

- Beam abort system fires asynchronously with respect to abort gap
- 8 full intensity bunches impact collimator jaws
- 1 MJoule incident energy

First Secondary in IR7 Sees Most Energy





- It is important to understand performance with “Cryo Collimators” in lattice
- Final configuration may have different designs, jaw materials or gaps

Not much difference

Inefficiency	**1C-10Cu**	**All Cu**
Horizontal	2.8×10^{-4}	3.7×10^{-4}
Vertical	3.6×10^{-4}	4.4×10^{-4}
Skew	4.6×10^{-4}	3.9×10^{-4}

SLAC Timeline for RC=Rotatable Collimator Prototype

J. Amann, **G. Anzalone**, Y. Cai, E. Doyle, L. Keller,
S. Lundgren, T. Markiewicz, H. Rogers, **J. Smith,** L. Xiao

2004: Introduction to project

2005: Conceptual Design Phase II RC using FLUKA, Sixtrack and ANSYS,
External Design Review: Basic Material Choice and cooling configuration

2006 Hire full time ME and designer, **Jaw-Hub-Shaft Design**, fabricate tooling, 2D/3D drawings of test and final parts, braze two short test pieces

2007: Examine test brazes, braze and examine 3rd short test piece, develop and build rotation mechanism, design RF shield, fab 1st full length jaw; hire postdoc

2008: **Thermal tests of 1st jaw**, begin to fabricate 3 more jaws, rework jaw fabrication process, redesign RF transitions, redesign vacuum tank, jaw support

2009: Fabricate & test full RC adequate for TT60 robustness tests; ship to CERN

2010: Fabricate & test 2nd full RC adequate for tests in SPS/LHC; ship to CERN

2011: TT60 and LHC tests (?); Collimator technology selection; final drawing package

2012: Production support, as needed

2013: Production & installation support

2014: Commissioning support

Main Deliverables

Thermal tests of single collimator jaw

Construct and mechanically test full RC prototype for TT60

Construct and mechanically test full RC prototype for LHC

FY	LARP (k$)
2004	110
2005	190
2006	350
2007	800
2008	950
2009	950
Total	3350

Evolution of Project from 2004-2009: More than Conceptual

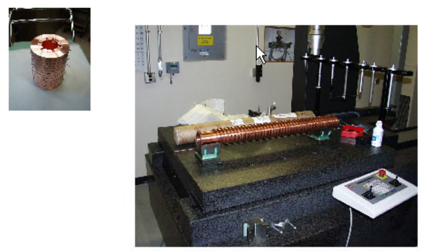
LARP

Too much for 20min talk: See web site and design report

- Materials: Copper, Glidcop, Molybdenum, CuNi
- Fabrication Process: Precision machining & brazing
- Mechanical Design: Ever evolving (how to stop it!):
  - >500 2-d drawing and 3-d solid models
- Test parts
- Tooling
- Metallurgy
- Vacuum tests
- Metrology
- Radiation testing
- Lab development
- Instrumentation
- DAQ
- ANSYS, FLUKA
- SixTrack, OMEGA3P

The Rotatable Collimator Program

The RC is one of several designs under consideration as a Phase II Secondary Collimators for the LHC



Management

Meetings

Status

- Drawing Tree with links to existing pdfs & jpegs and Summary of weekly status meetings
- Status of Mechanical Drawing Process

Photos

Talks

Files

Mechanical Design

Documentation

LHC Phase II Rotatable Collimator - RC1 Conceptual Design Report

J. Amann, G. Anzalone, R. Assmann, C. Bracco, Y. Cai, E. Doyle, L. Keller, L. Lari, S. Lundgren, T. Markiewicz, T. Raubenheimer, R. Rogers, J. Smith, Th. Weiler, L. Xiao,

1. Introduction
2. Beam Line Layout and Operating Scenarios
3. LHC Constraints and Specifications
4. Design Evolution and Rotatable Collimator Concept
5. Current Design
6. Prot ... nstr
7. Pro ... pe ... in

References

Appendix A. Efficiency Simulations
Appendix B. Energy Deposition Simulations
Appendix C. Accident Simulations
Appendix D. Impedance Calculations and Measurements
Appendix E. Evolution of ANSYS Simulations

DRAFT

http://www-project.slac.stanford.edu/ilc/larp/rc/

LARP

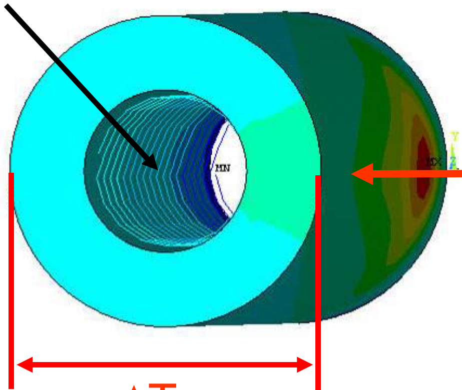
Rotatable Design: 1st Collimator: 4E11 p/s

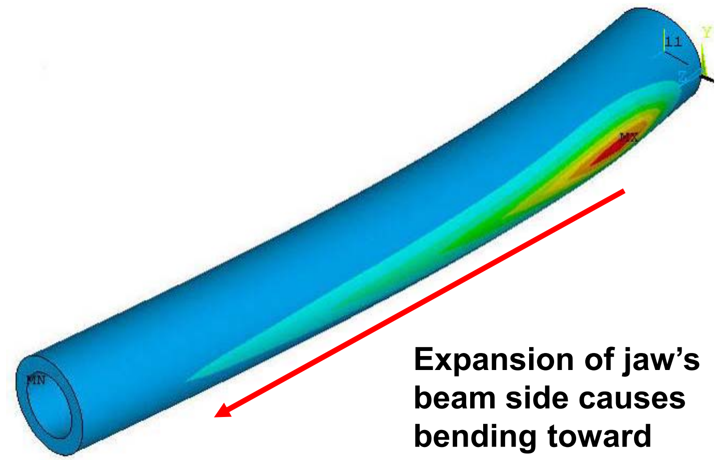
At τ=12 min, each jaw of Coll#1 in IR7 absorbs 3kW if C or 60kW if Copper

Temperature rise and differential heating cause jaw to distort

– Loss of efficiency as lose flatness

– Swell closer to beam core





Thermal distortion is a function of materials, jaw OD & ID, length, cooling & support design

Study energy deposition with FLUKA & mechanical response with ANSYS

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

Justification of Cu Choice

LARP

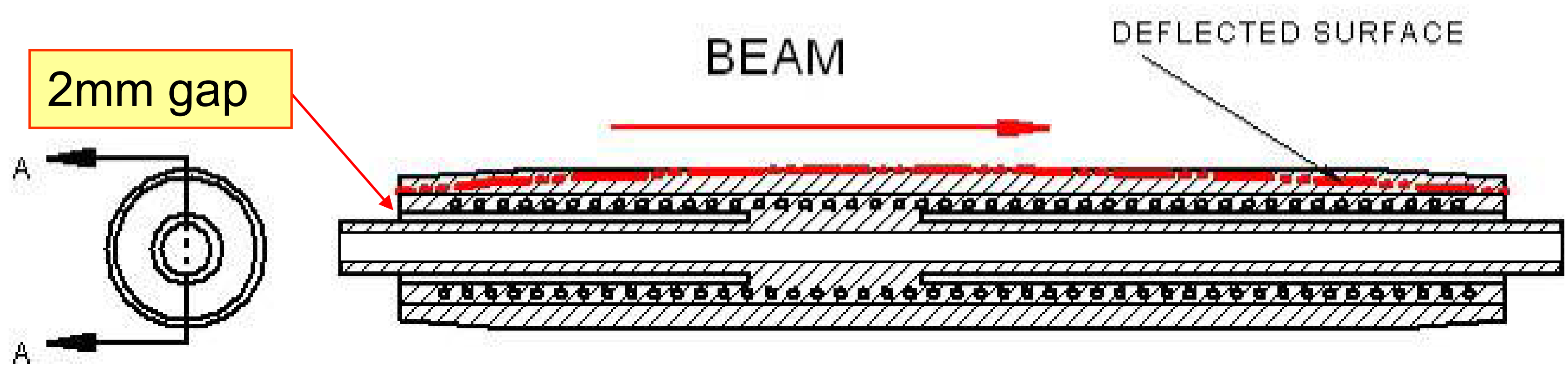
Cu chosen as best balance between collimation efficiency, thermal distortion & manufacturability

Material evaluations

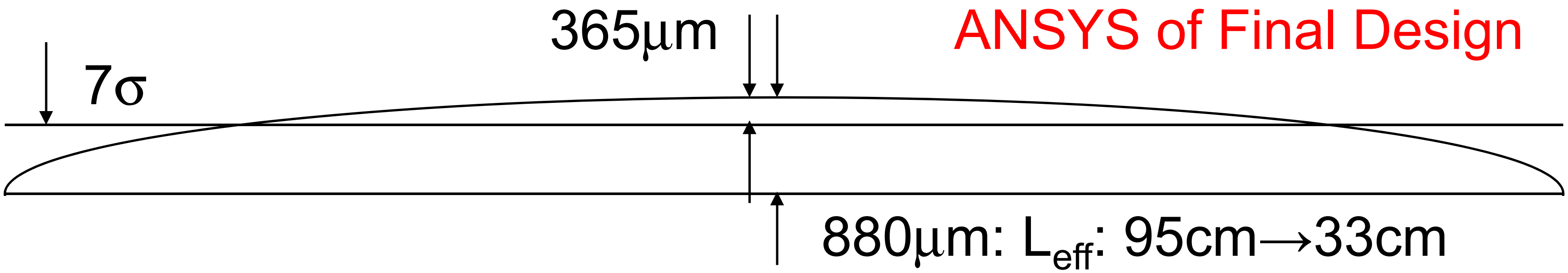
material	**reasons for rejection in favor of Cu**
Aluminum	relatively poor cleaning efficiency, water channel fabrication difficulty
BeCu (6% Cu-loaded Be)	(Note: an imaginary metal - unknown fabrication difficulties) Be is strongly discouraged by CERN policy; low cleaning efficiency.
Cu - 5mm wall	deflection only ~50% lower than 25mm Cu; loss of safety zone between the beam and water channels
Cu/Be (5mm/20mm bonded)	deflection only ~30% lower than 25mm Cu; Be prohibition; fabrication difficulty
Inconel 718	poor thermal conductivity => high temperature & very high deflection (1039um SS, 1509um transient)
Super Invar	poor thermal conductivity => high temperature 4X higher than temp at which low thermal expansion coefficient disappears.
Titanium	poor thermal conductivity => deflection 2.7 x Cu (591um, SS)
Tungsten	High temperature on water side (240C => ~30bar to suppress boiling); high power density - can't transfer heat without boiling; fab difficulty

Glidcop Jaw – CuNi Coil- Cu Mandrel – Glidcop Hub - Molybdenum Shaft Design

LARP



ANSYS of Final Design

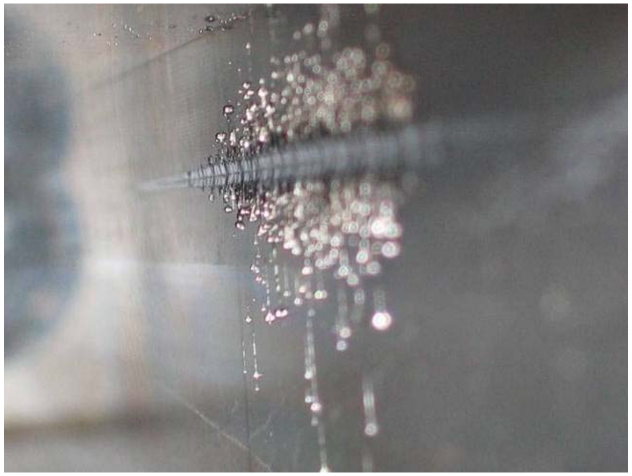


Proposal is to set 1st copper jaw at 8.5 σ (or to use C-C in this location)

Simulations show that remainder of system maintains efficiency

Rotatable Design: Asynchronous Beam Abort

FNAL Collimator with .5 MJ



In asynchronous beam abort onto any collimator:

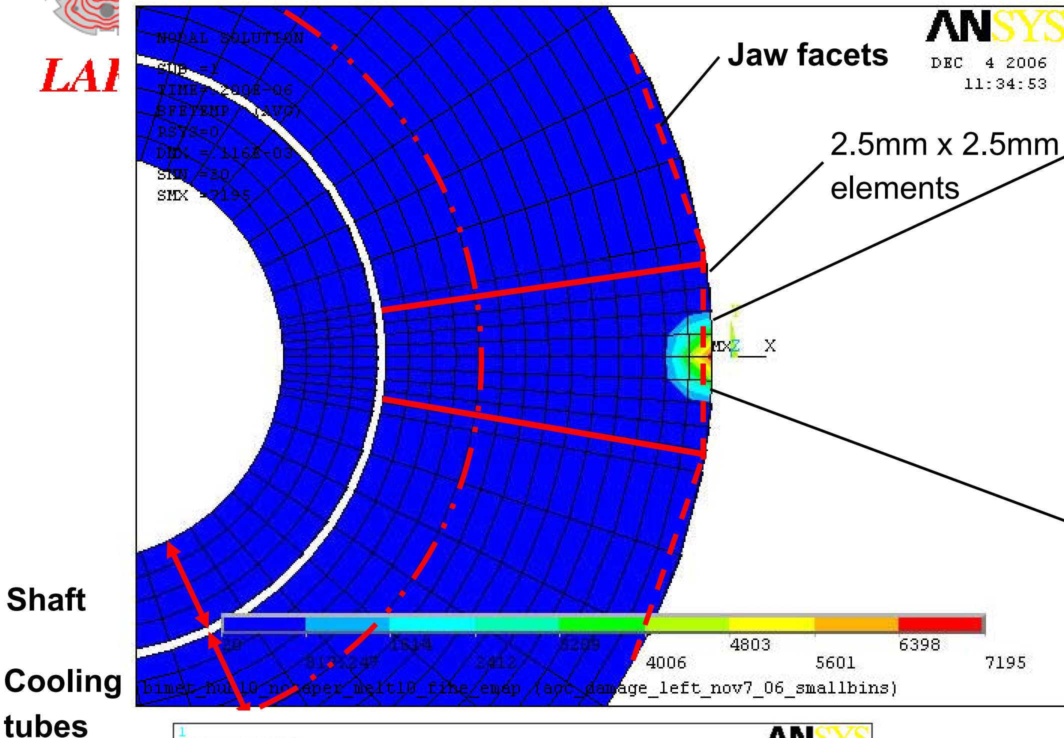
Cu absorbs 27% beam energy vs. 3.6% for C

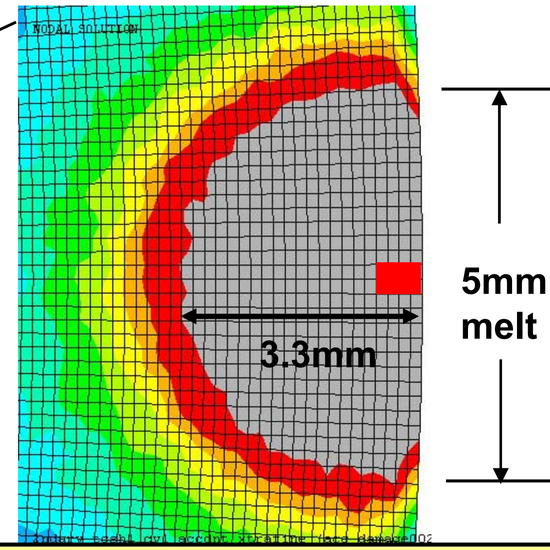
- Cu heated >> melting temperature
- Shock wave may permanently deform material

Relevant Considerations:

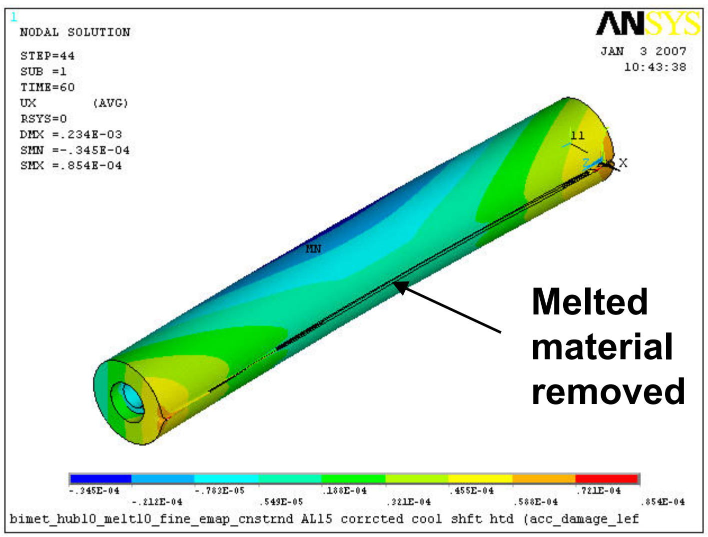
- Facet width of RC=20.25mm contains fracture
- Melt zone (T>1080°C) is 30cm long, centered on shower max ~ 20cm, with radius 3.3mm (~collimator gap)
- Fracture zone (T>200°C) is ~7mm radius, ~1/3 of distance to water coil
- Water ΔT~1.5°C with resultant ΔP~6 bar<< yield strength of copper
- Disposition of molten material problematic ←
  - Orientation dependent: vertical dripping, opposite jaw at risk as well
  - Horizontal collimators #5 & #11 predominately at risk
- Permanent deformation from shock ~50μm (away from beam)
- Opposite jaw ~3mm away has T_{max} ~840°C < T_{melt}
- If 60cm C primary at 6σ struck first (likely?), NO damage to secondary

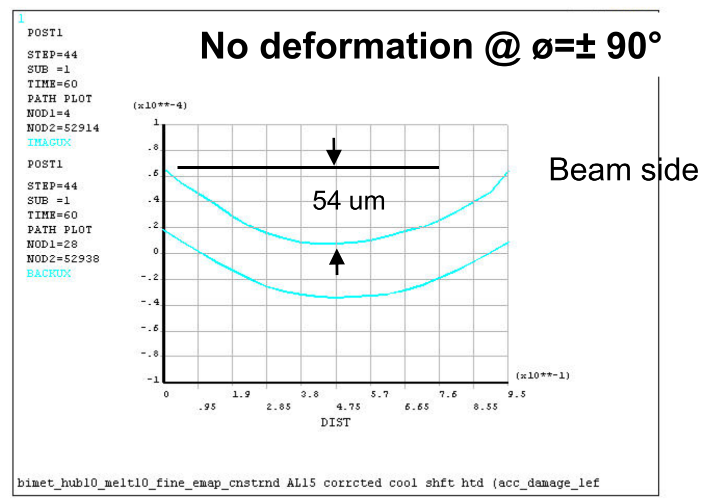
ANSYS: Beam Abort: 0.27MJ
Constrain jaw ends t<200ns, then quasi-static stress analysis





Shower max – extent of melted zone





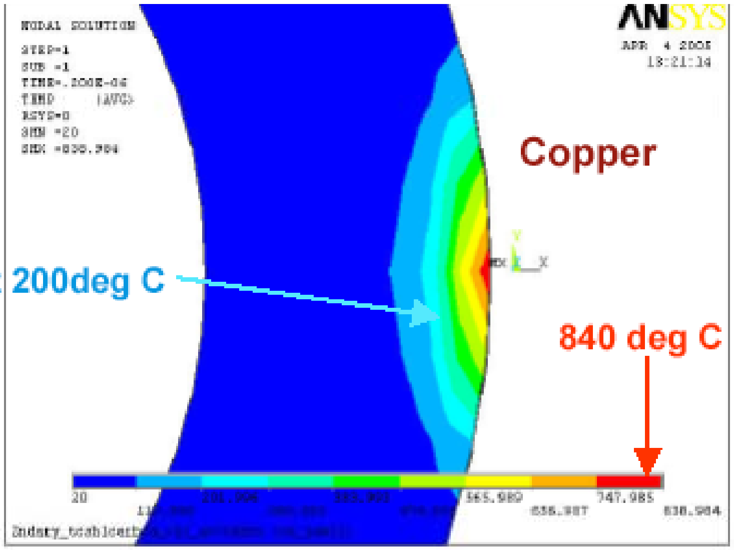
In-plane permanent deflection:

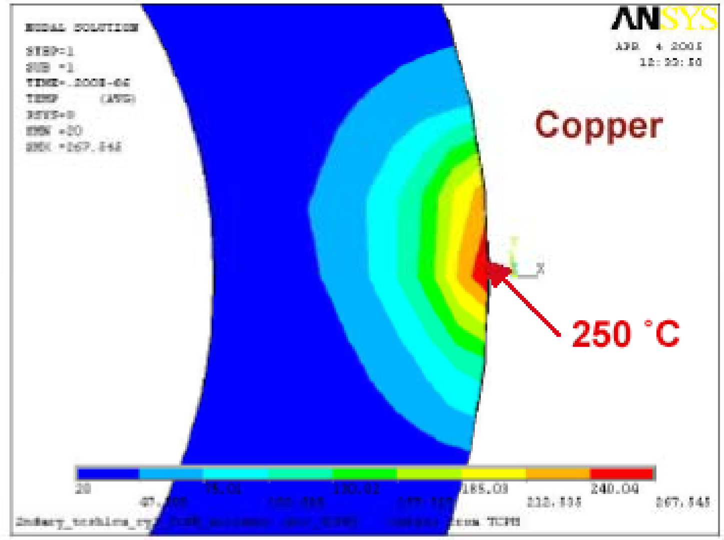
Accident Case

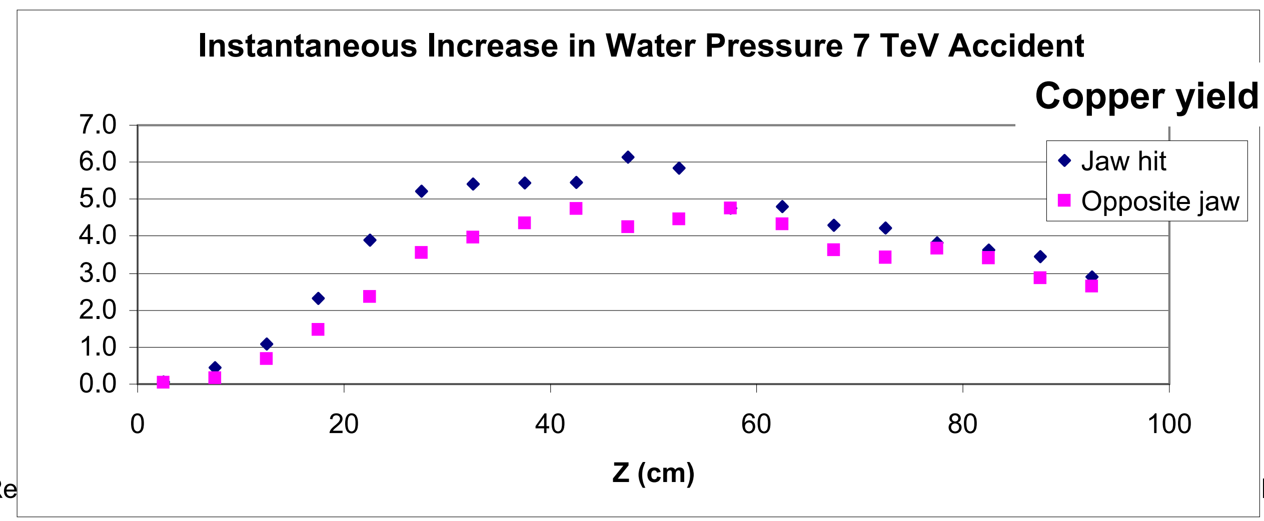
Adjacent Jaw:

At risk

Response if 60cm Primary Struck First: No melting





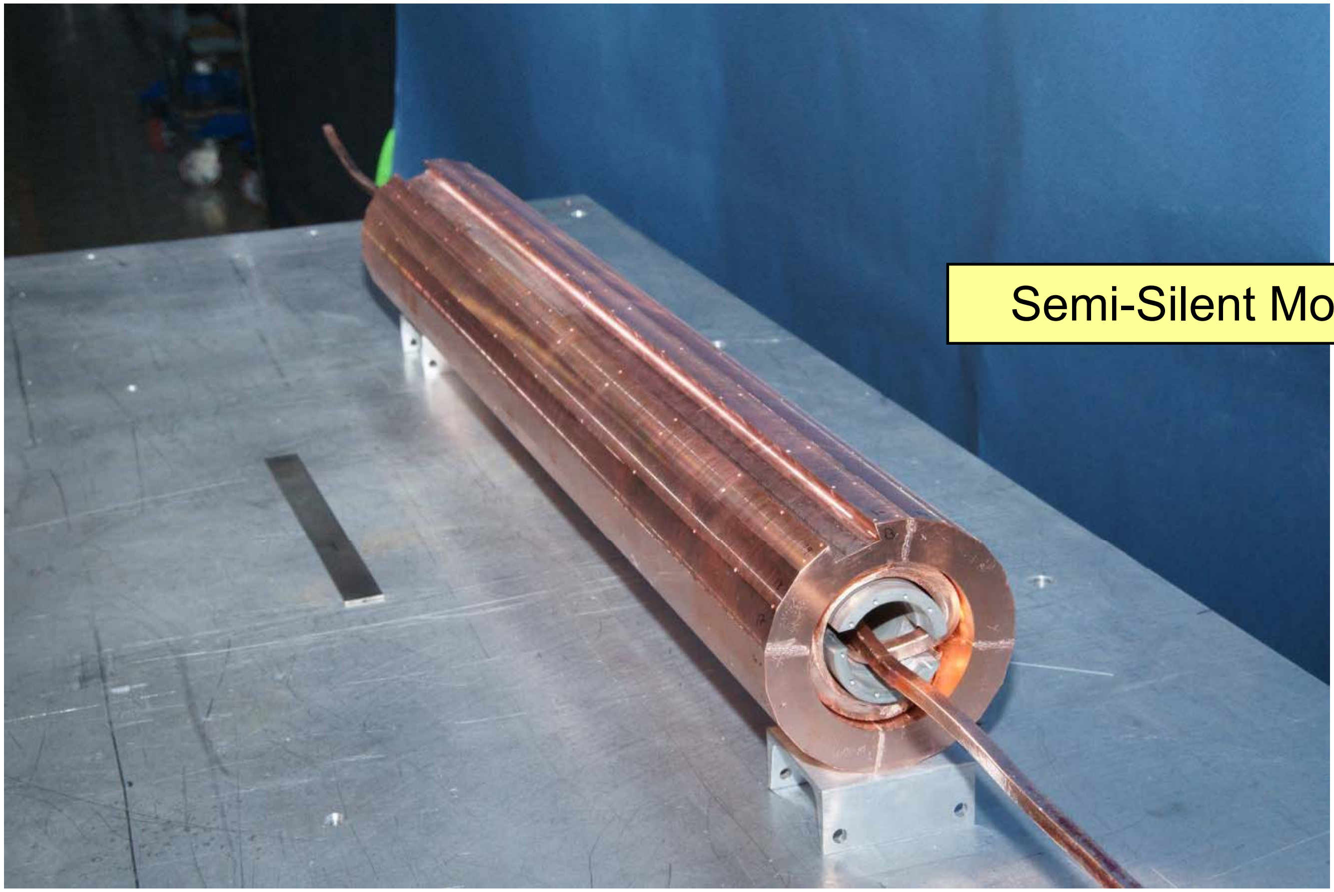


"RC0" First Full Length Jaw Finished May 2008

Thermal test with 10kW resistive heaters to verify ANSYS

Vacuum Bakeout

CMM Flatness measurement after bakeout

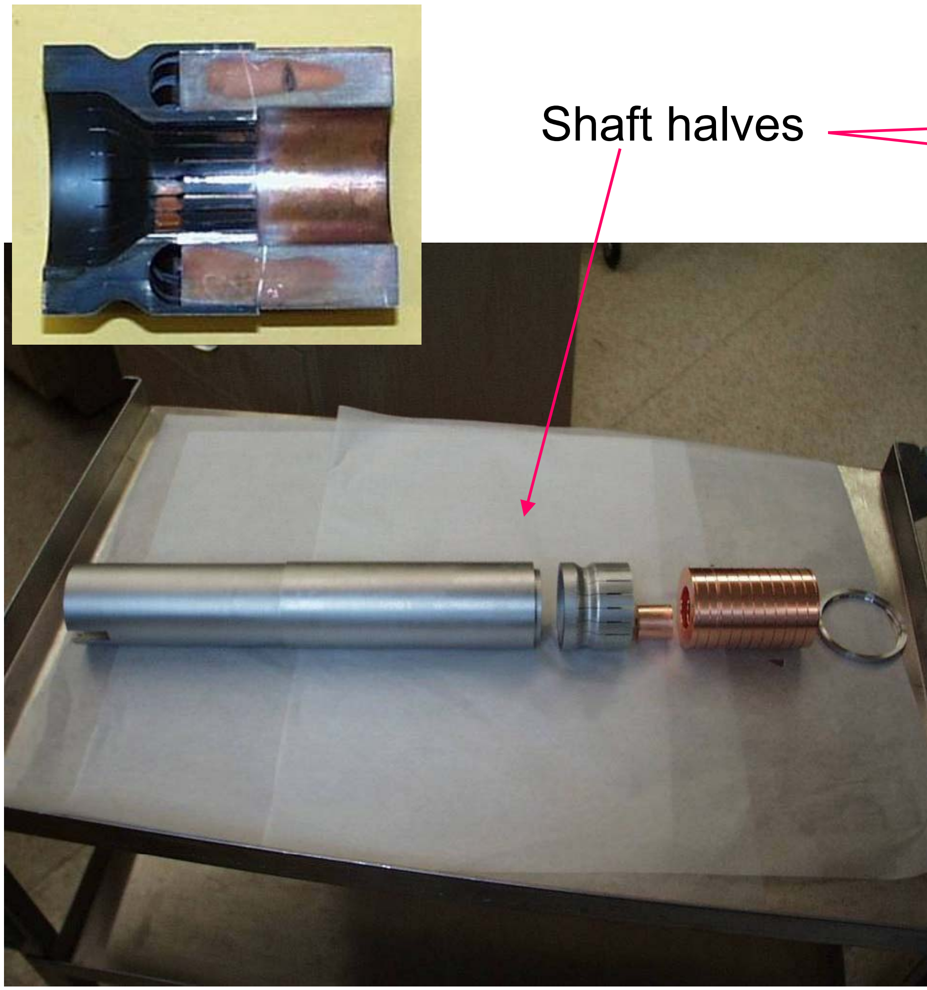


Semi-Silent Movie Follows

Brazing Each Moly Shaft End to a Central Copper Hub

LARP

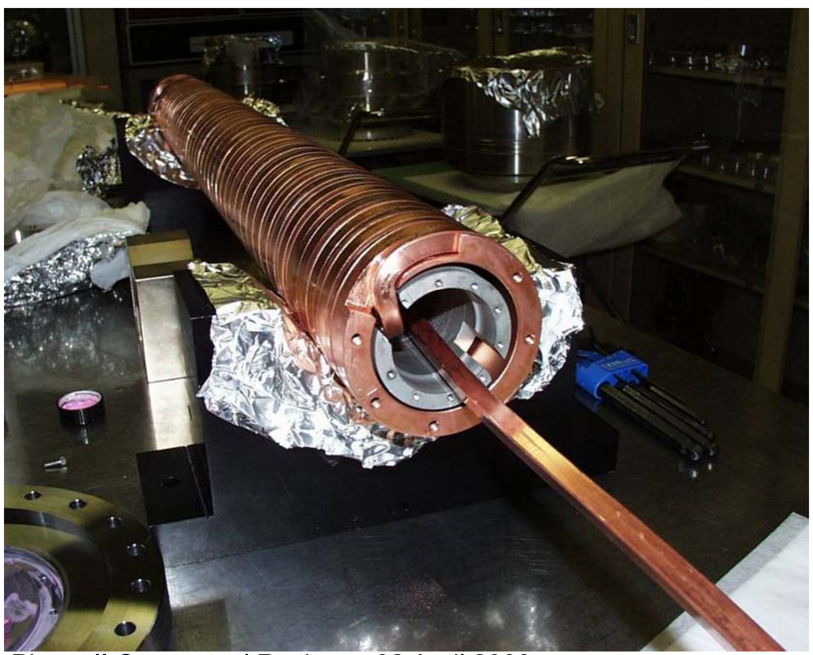
After **much** R&D, developed method to braze Molybdenum to Copper for inner shaft



Inserting Molybdenum Shaft Ends into Mandrel then Wind Coil Around Mandrel with Ends of Coil Protruding Out Each End

Braze Step#1 Shaft Assembly & Coil to Mandrel

- 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

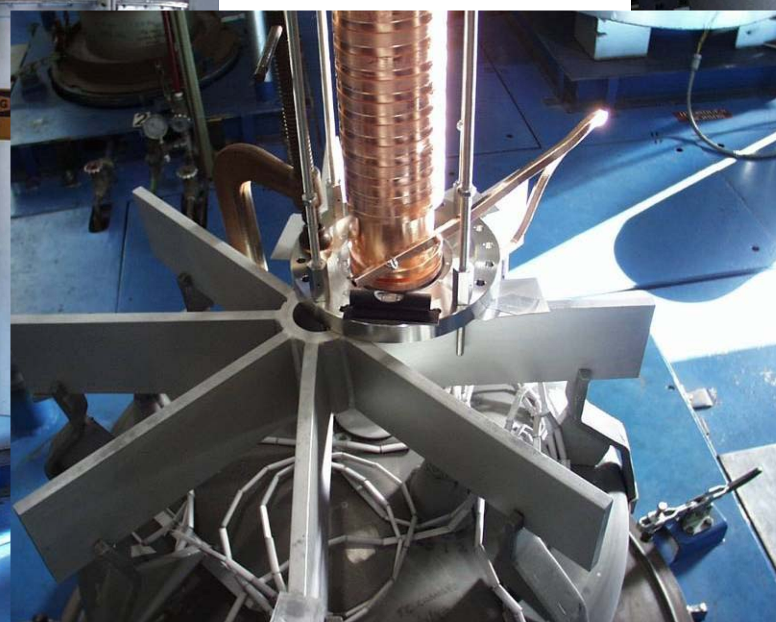


Filling Coil-Mandrel Keystone Gaps

LARP

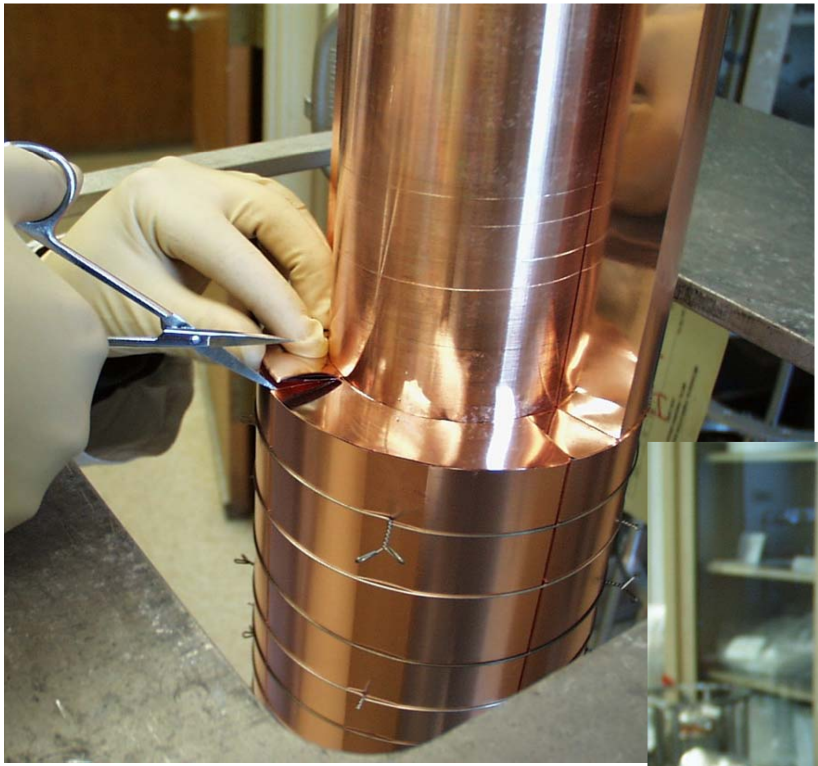
Three brazing cycles needed before coil-mandrel 'keystone' gaps filled adequately

Then machine mating surface to jaws



Pix of 2nd braze cycle

Measure & Machine Quadrants to Mandrel. Assemble & Braze



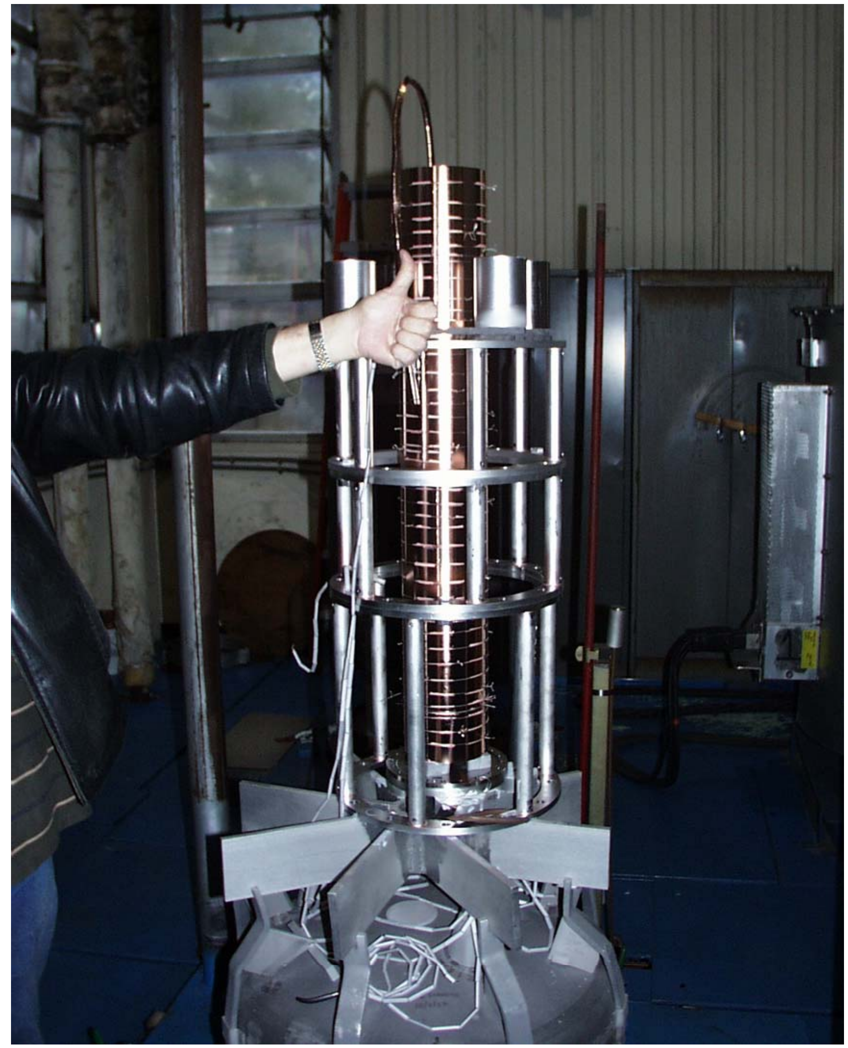
Using 50-50 Au-Cu
brazing material ($$)

Results of Jaw Brazing 22 April 2008

Looks good!

For next 3 jaws plan to:

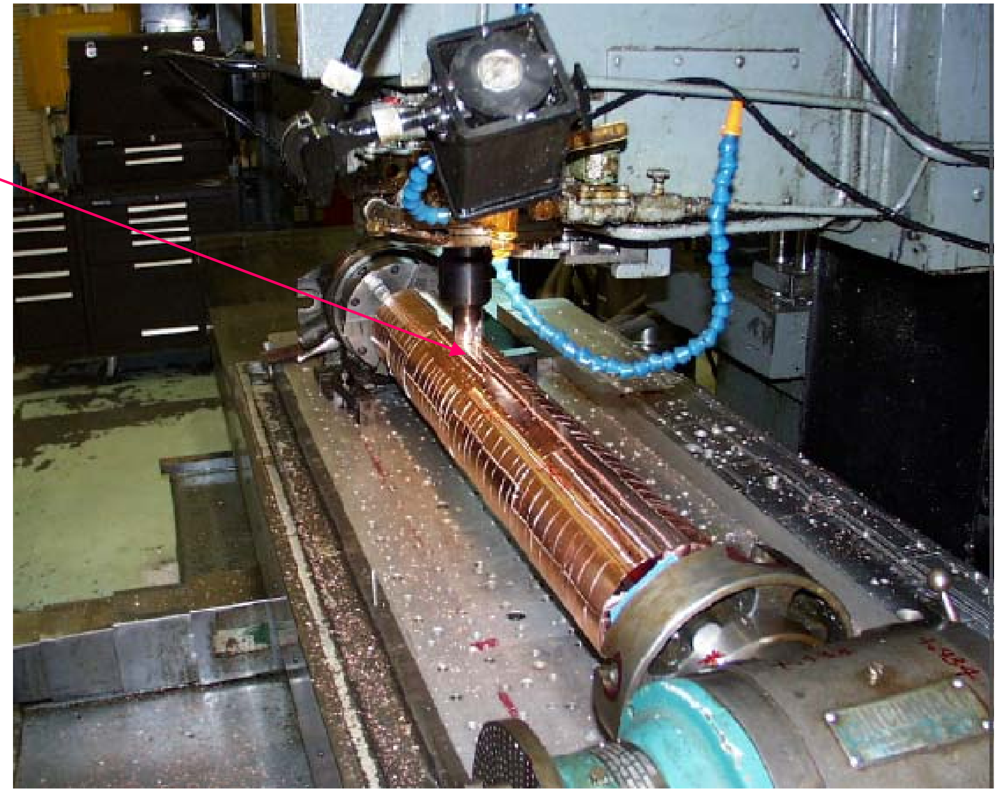
- Use full round jaw segments
- Over-size parts & cut down to proper radius

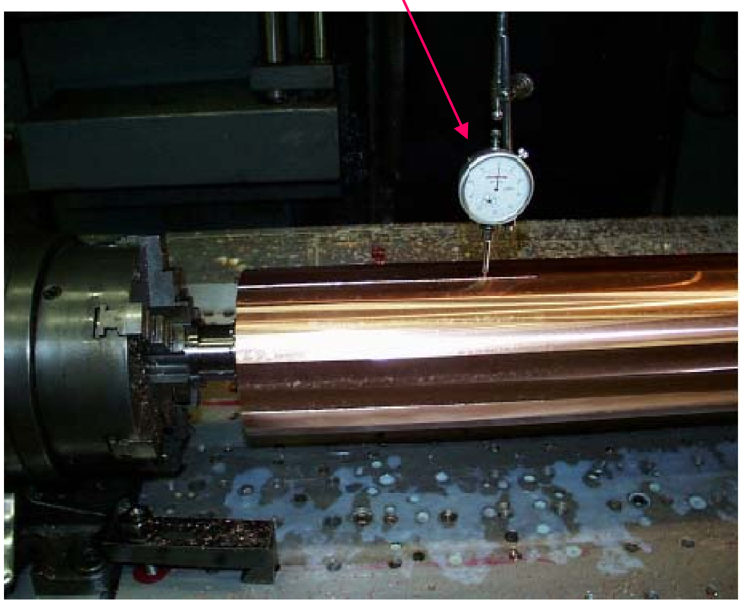


Machine Flat Facets and Groove for Heater Test

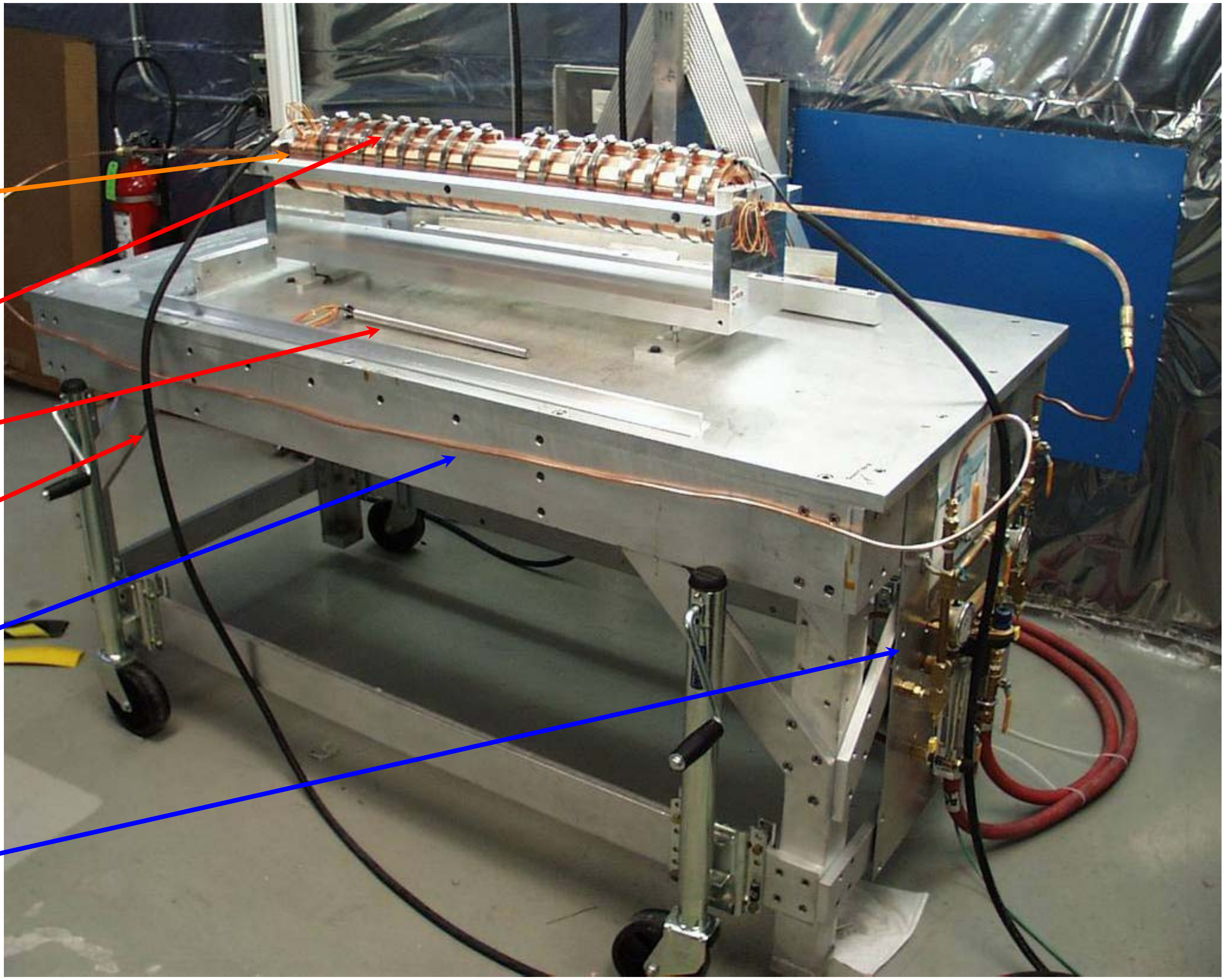
Final brazing was a success!

- Flat facets and grooves for heater tests and thermocouple holes have been machined.
- Within 25 micron tolerance along facet surface.



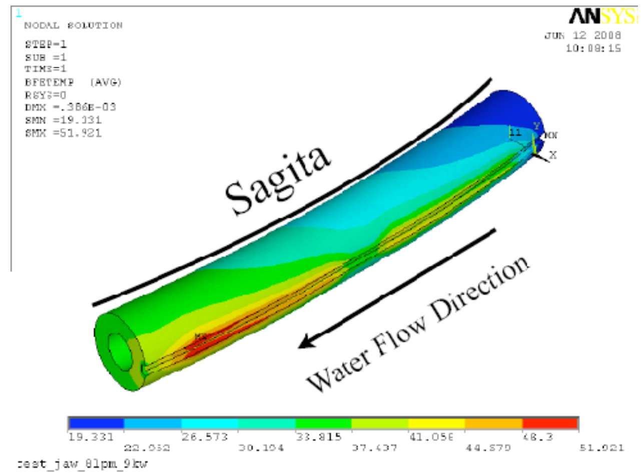


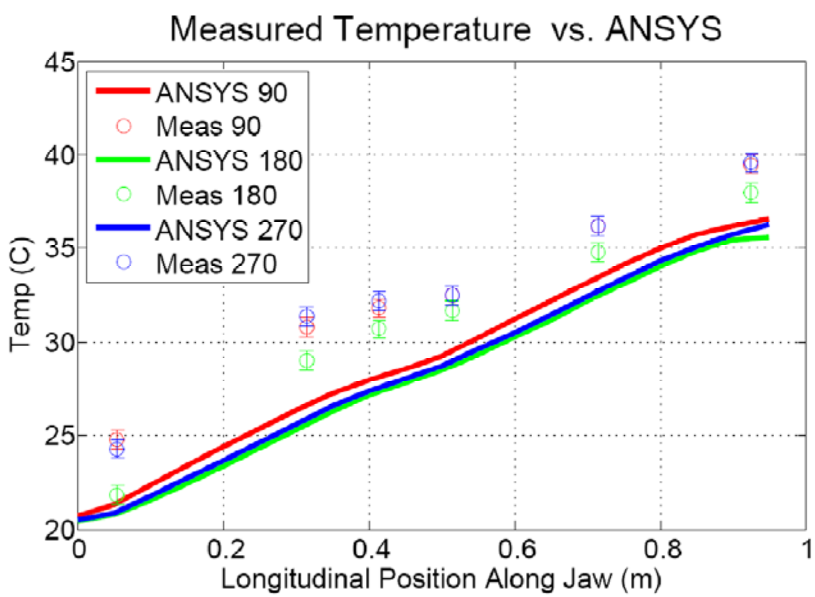
10kW Resistive Heater Thermal Test

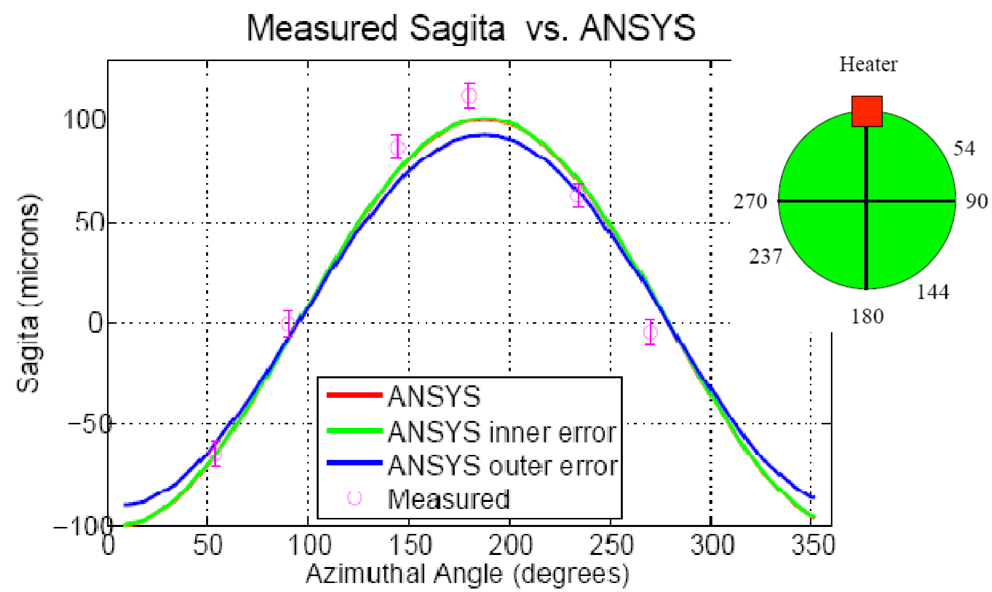


Comparison of Sagitta & Temperature with ANSYS as a function of angle with respect to heater

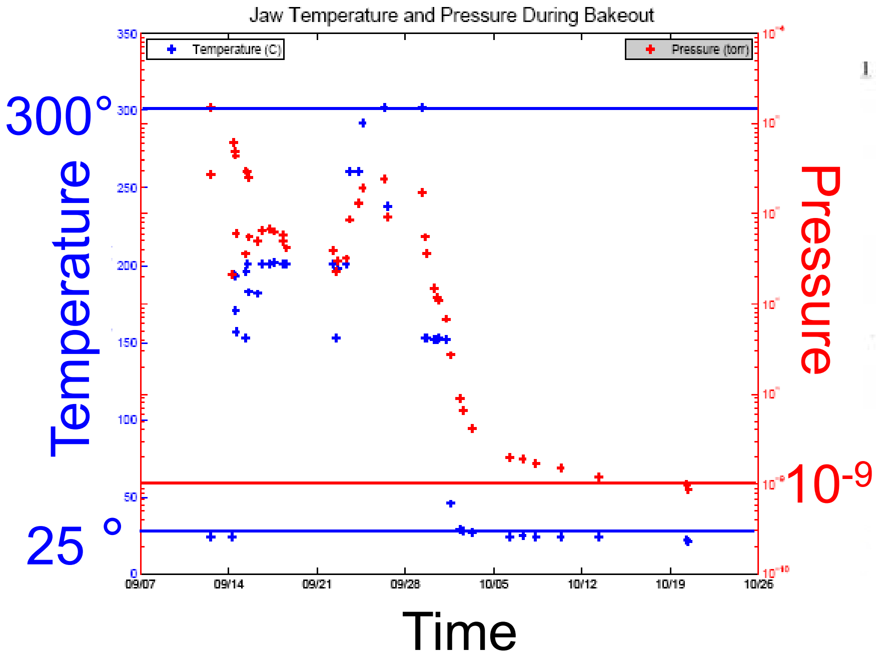
- Jaw with two 5 kW heaters modeled
- Includes accurate representation of
  - Water flow/temp change
  - Material properties
  - Thermal expansion
  - Heat flow / thermal conductivity
- Data ~10% larger than ANSYS

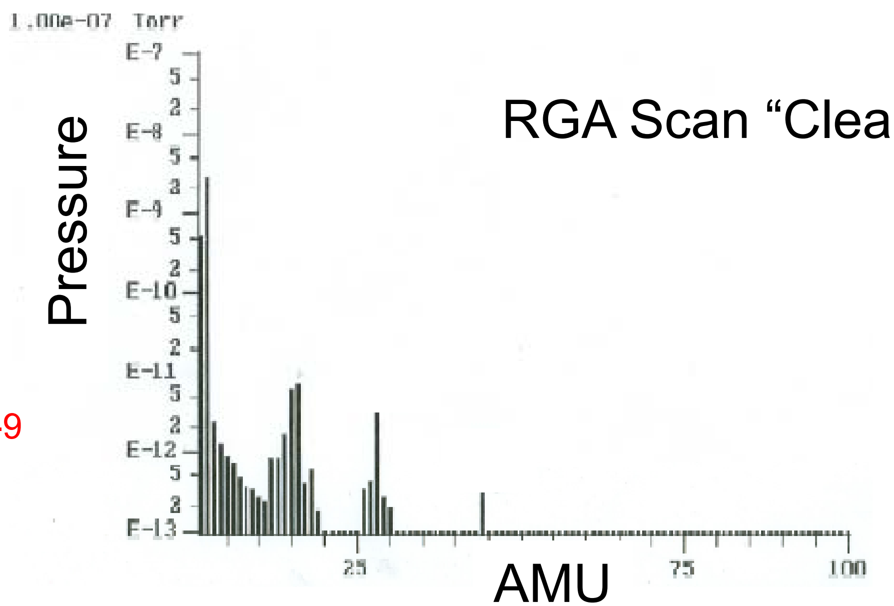






Results of RC0 Bake-Out test: 1.2E-09 torr for 1 jaw in a vacuum vessel



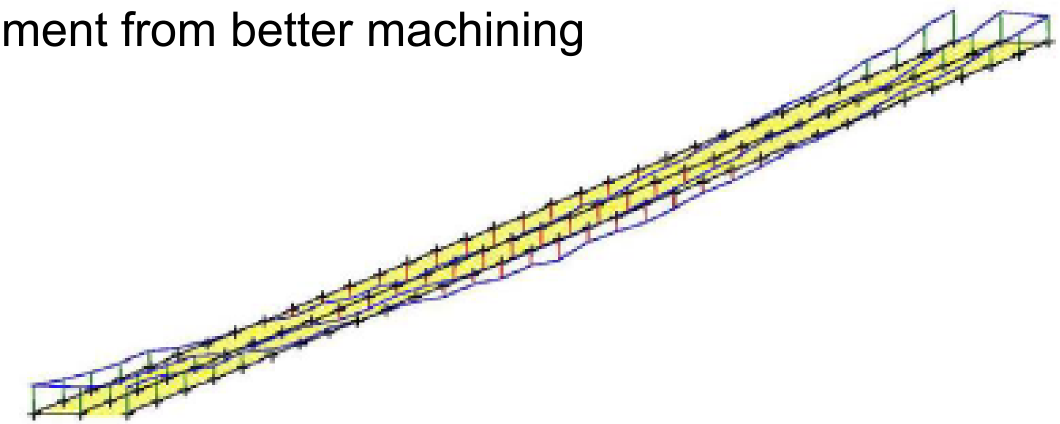


RGA Scan "Clean"

RC0 CMM Survey After Vacuum Bakeout

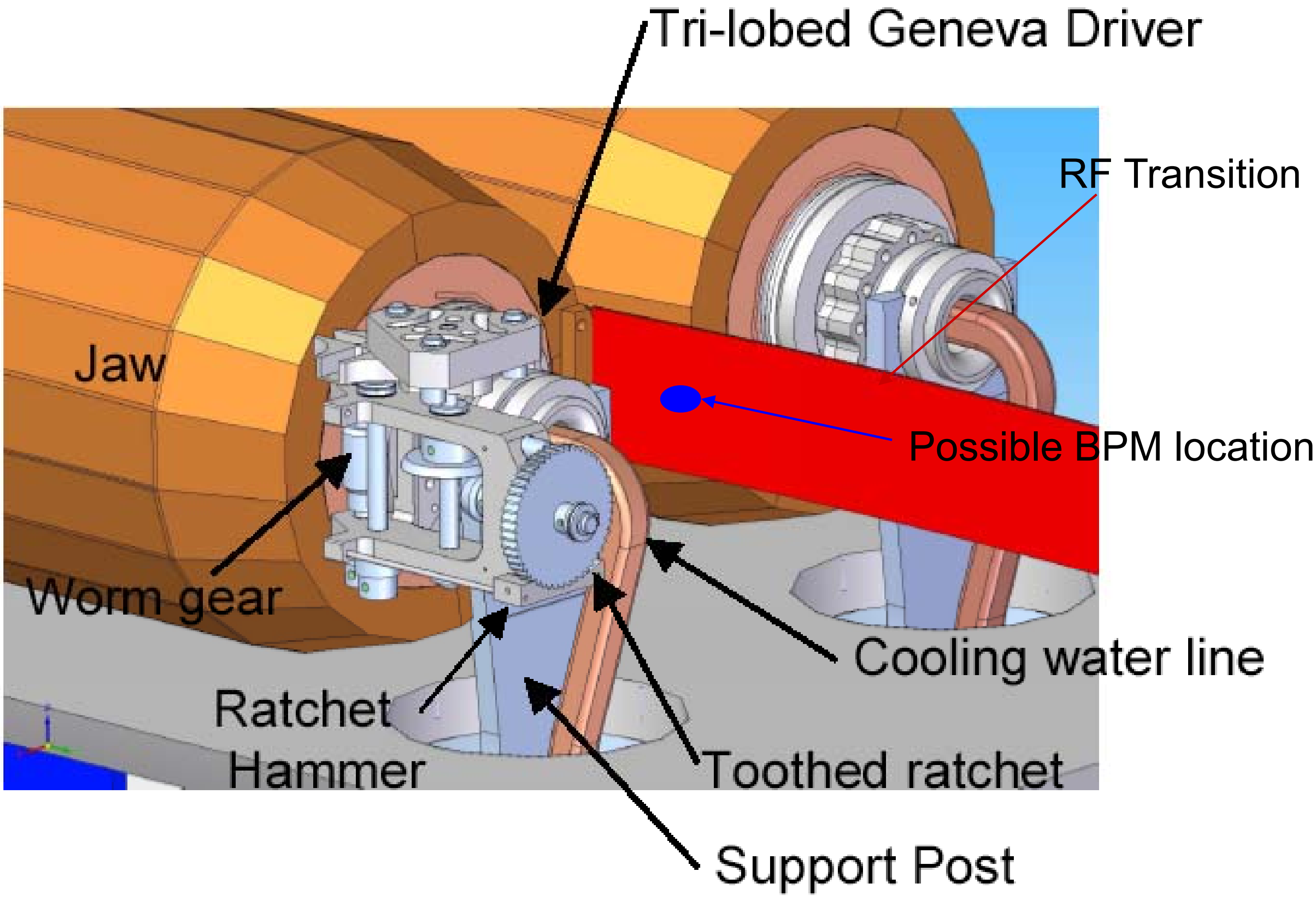
Maximum deviations < ~25 μm

- Pretty good given brazing problems in this piece
- Expect improvement from better machining techniques

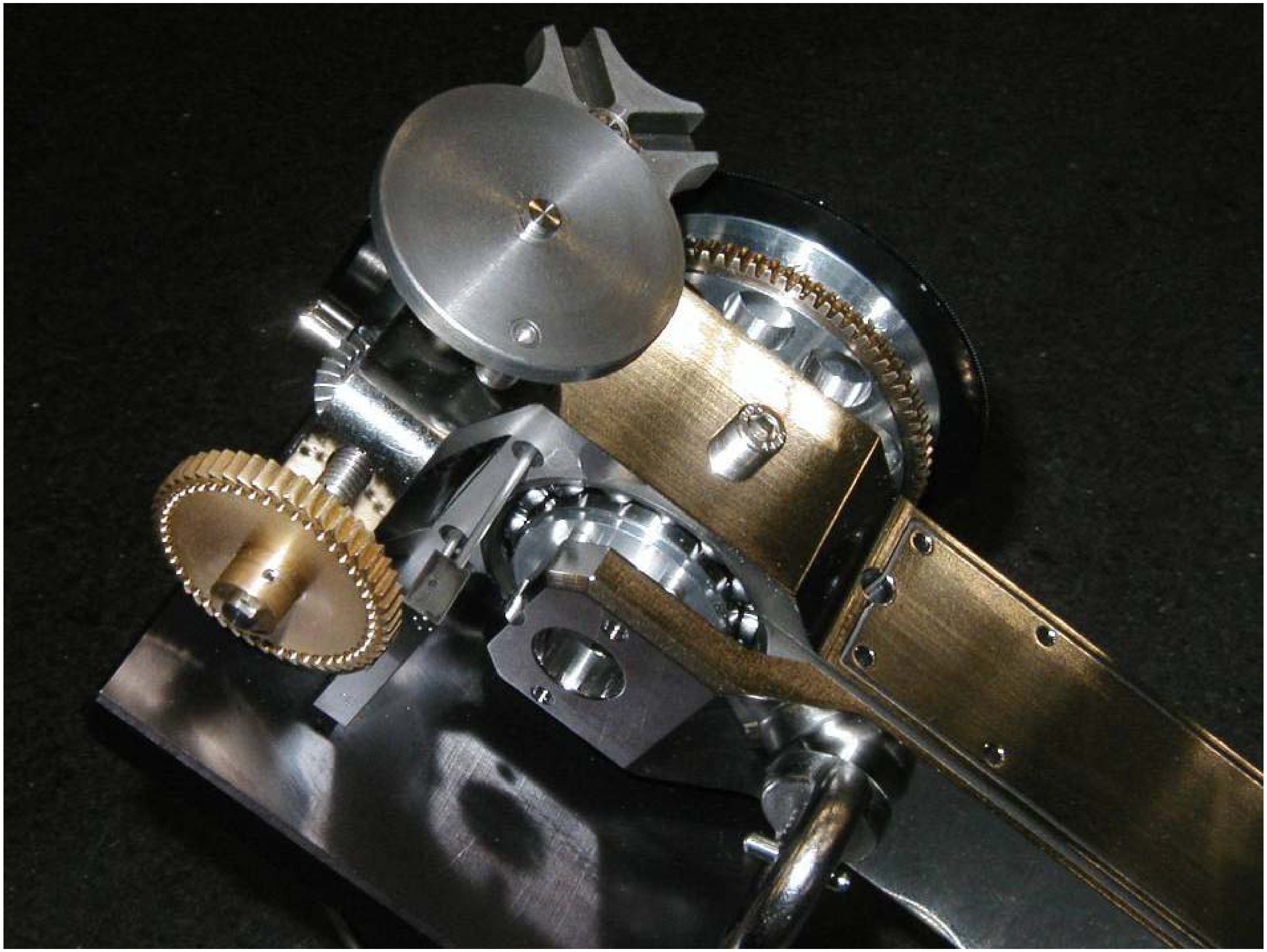


facet	max negative deviation (mil)	max positive deviation (mil)	total deviation (mil)
1	-0.6	1.0	1.7
5	-0.5	0.7	1.3
8	-0.5	0.5	1.0
13	-0.7	0.6	1.3
16	-0.5	0.8	1.3

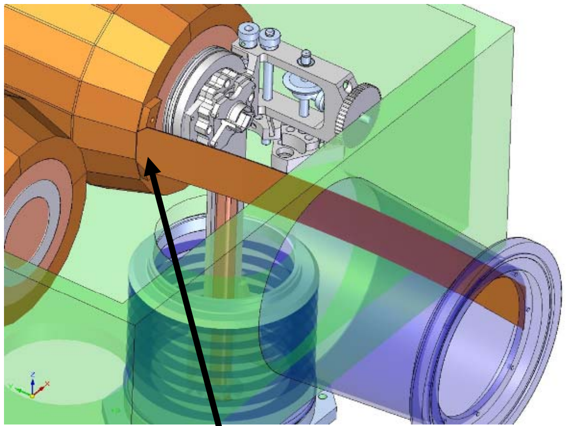
Second Generation Version of Collimator Assembly Support, Rotation Mechanism, and RF transition to Vacuum Tank



First Generation Fully Prototyped Up Beam Flex Mount Assembly showing Ratchet and Actuator

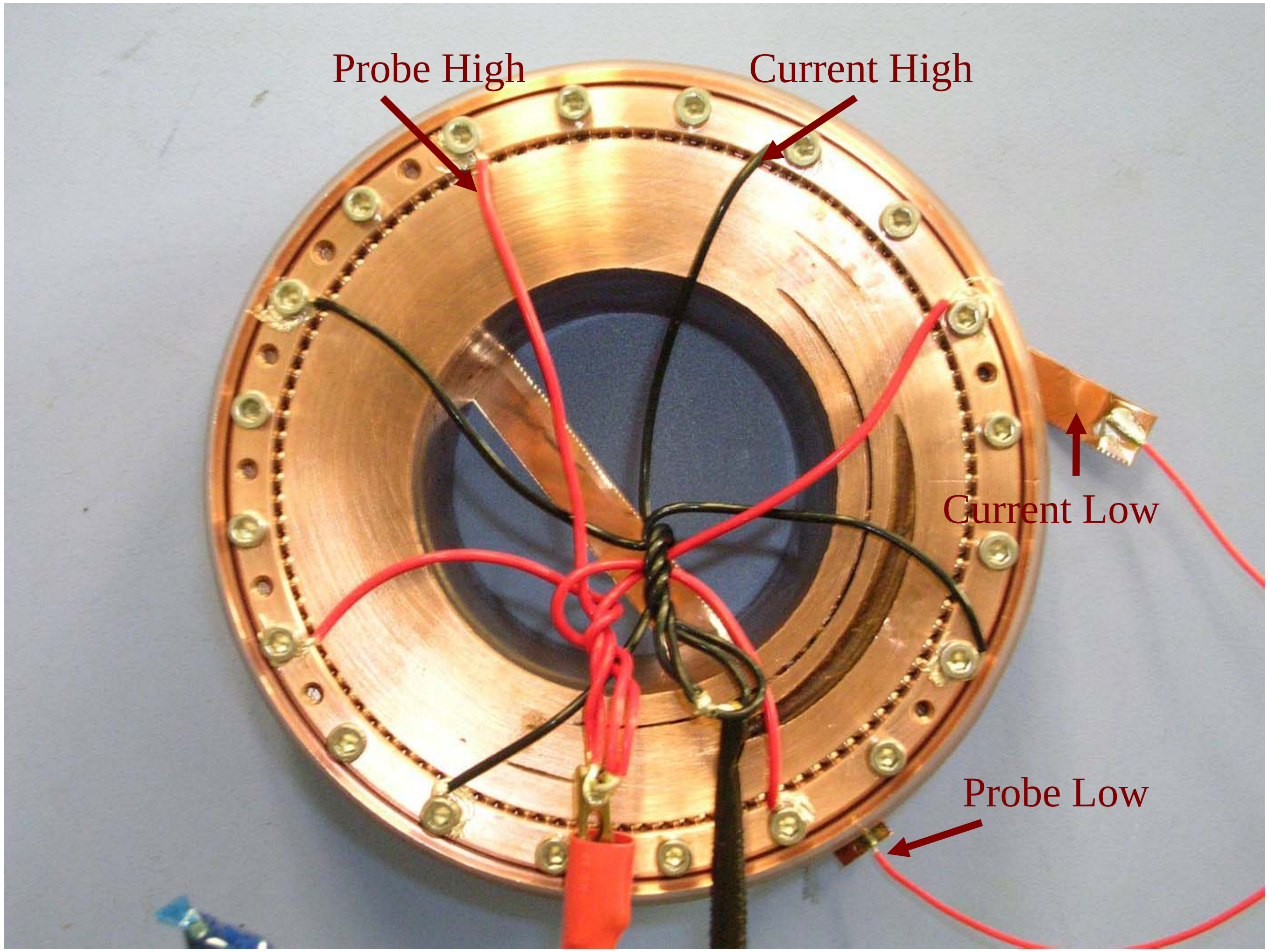


RF Image Current Foil Assembly



•This surface mounts to bearing race

•Foil only needs to shadow beam from rotation drive



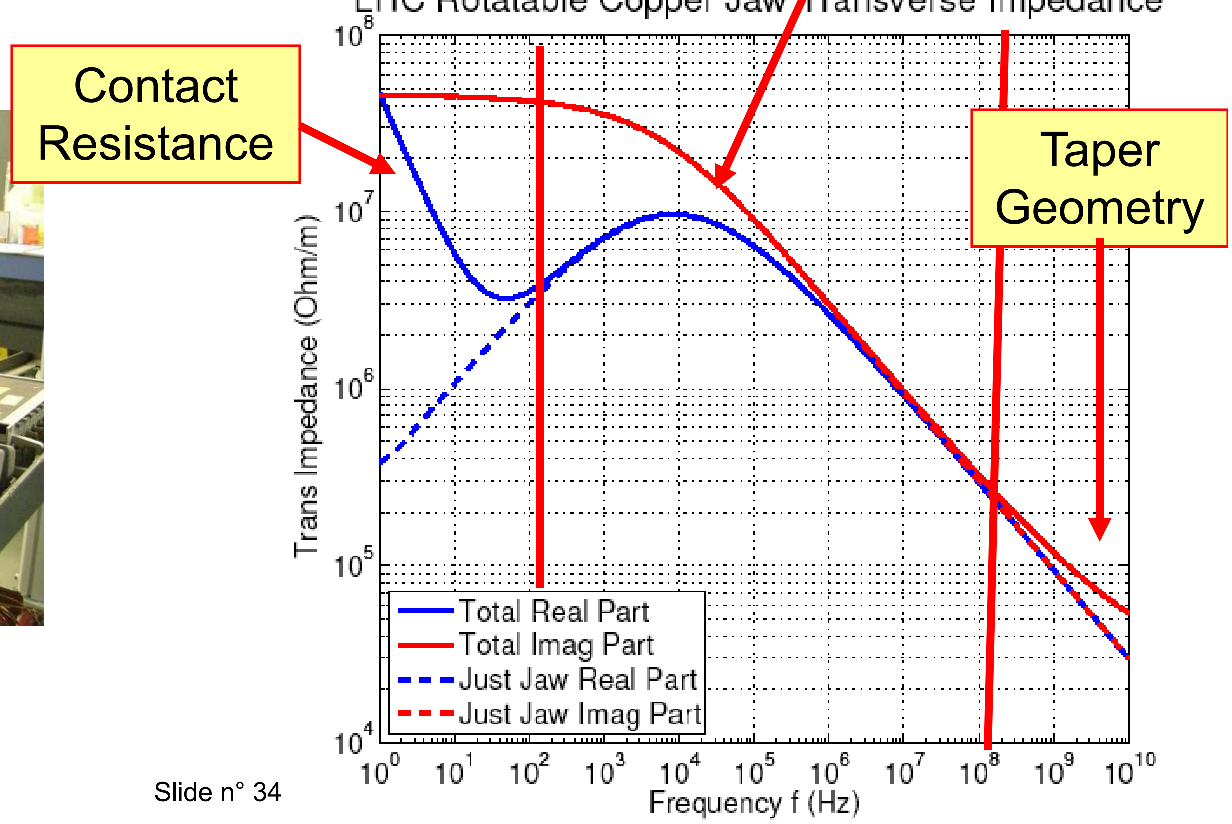
Axial load on Rhodium coated 1mm diameter Stainless ball bearing provides desired contact resistance of less than 1 milliohm

Resistive and Geometric Impedance

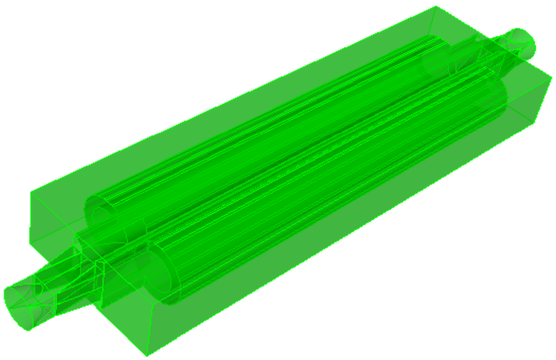
Impedance measured with coil and LCR meter for C-C jaws with & without Copper RF transition pieces:

Resistive wall component dominates at relevant frequencies

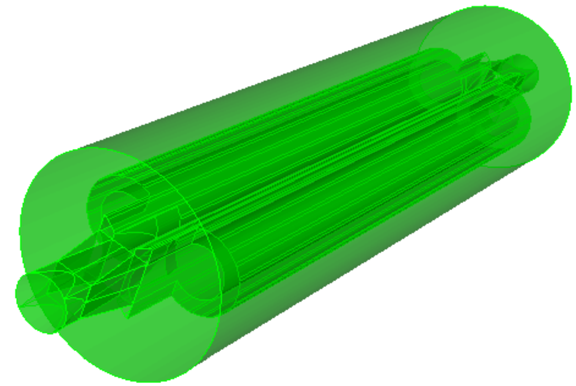
Although transition pieces are required to carry the image current, their geometry are of little consequence



Study of Longitudinal & Transverse Trapped Modes in Rectangular & Cylinder Vacuum Tanks Using Omega3P Code



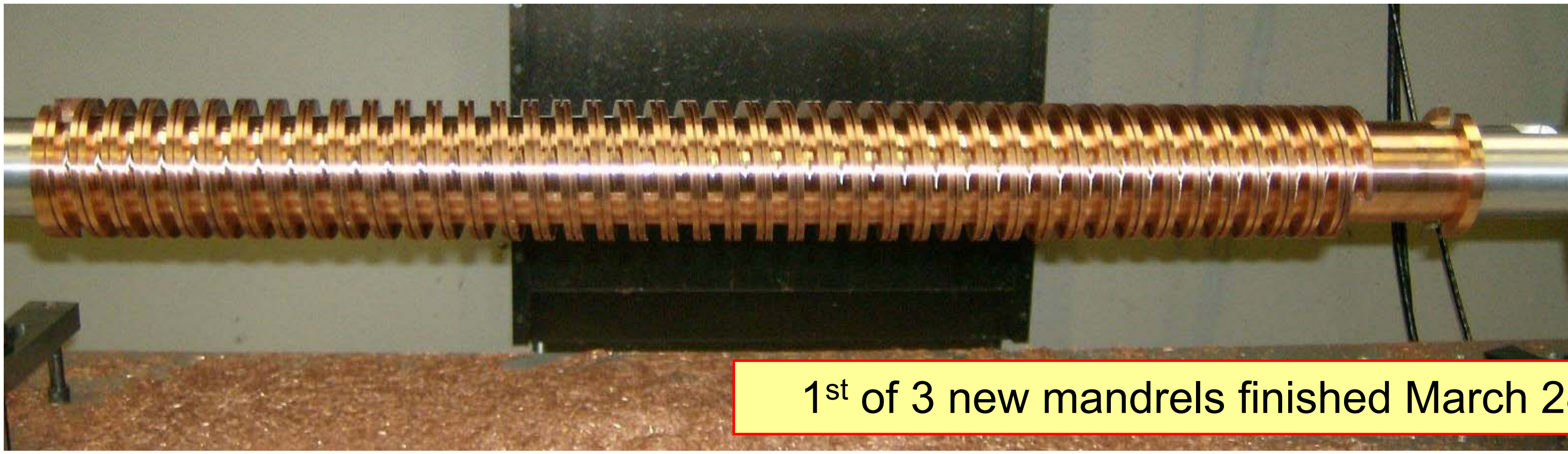
- R/Q
- Q Factor
- Power Dissipation
- Ferrite Loading
- Use as BPM



	Beam offset y0 / $P_{dissipation\text{-}wall}$	0.100mm	Max. offset 0.075mm	0.050mm
Rectangular Vacuum Tank	Transverse Modes (<2GHz) gap=2mm	**11W**	**6W**	**2.7W**
	Longitudinal Modes (<2GHz) gap=42mm		**15W**	
Round Vacuum Tank	Transverse Modes (<2GHz) gap=2mm	**26.6W**	**15.2W**	**6.7W**
	Longitudinal Modes (<2GHz) gap=42mm		**515W**	Use Ferrites

LARP

Plan to Make 3 More Cylinder Jaws for total of 4→Two Full Collimators



1st of 3 new mandrels finished March 28

6 Moly Half-shafts at SLAC

Plan:

RC1-TT60 end of 2009

RC2-SPS/LHC in 2010

The Rotating Collimator Design

LARP

Improves global efficiency and protects sensitive components by absorbing more beam power than Phase I collimators

Provides a path to LHC impedance limited beam stability that does not rely on unproven RF feedback

Is composed of radiation hard, vacuum bake-able, non-porous, non-exotic metals that can be easily machined and brazed

Can be manufactured immediately

Estimates of jaw deformation under high load transient beam loss are limited to < ~ beam sigma on the first secondary collimator

- Other collimators in the system maintain system collimation efficiency

Maintains water-to-vacuum integrity under accident conditions, providing a clean, flat surface, geometrically protected from spraying molten metal & mild shock wave induced permanent deformation, without the need for change out

- This needs to be studied in TT60 beam tests

Bonus Slides

Design and Performance Summary

Grooved Copper Mandrel with center bore is wound with 16m 10mm x 10mm x 1.5mm wall CuNi tube provides cooling

Glidcop Jaws with 20 facets, brazed to OD of mandrel, provide collimation surface

Hollow Molybdenum half-shafts, brazed to a central hub, in turn brazed to ID of mandrel, supports mandrel & jaw assembly at center, providing a 2mm gap so that when hot beam-side of collimator expands, assembly bends away from beam

Ends of CuNi tube reverse wound back through center of hollow shaft and twist to permit rotation

Simple Molybdenum vane supports shaft and Geneva-Gear rotation drive and permits jaw expansion

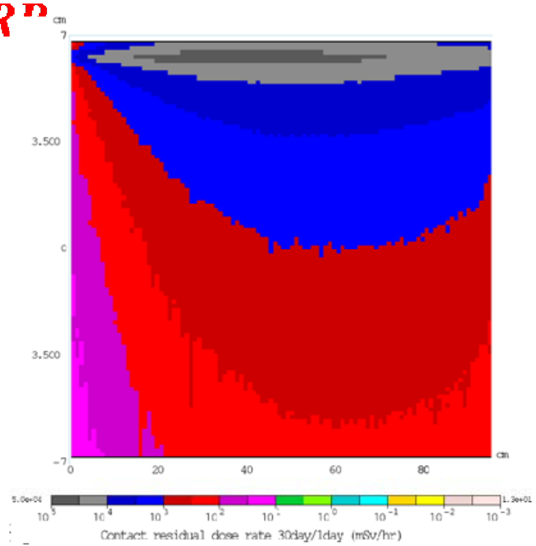
RF transition piece to vacuum tank ends runs on jaw end on 1mm Rhodium plated ball bearings & permits jaw to open for injection

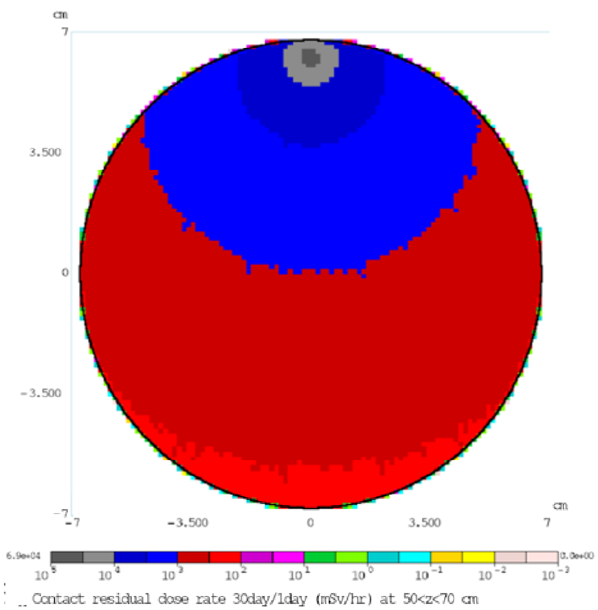
Bench-marked ANSYS calculations predict 105µm, 336µm swelling towards beam for t = 1hr, 12min beam lifetimes

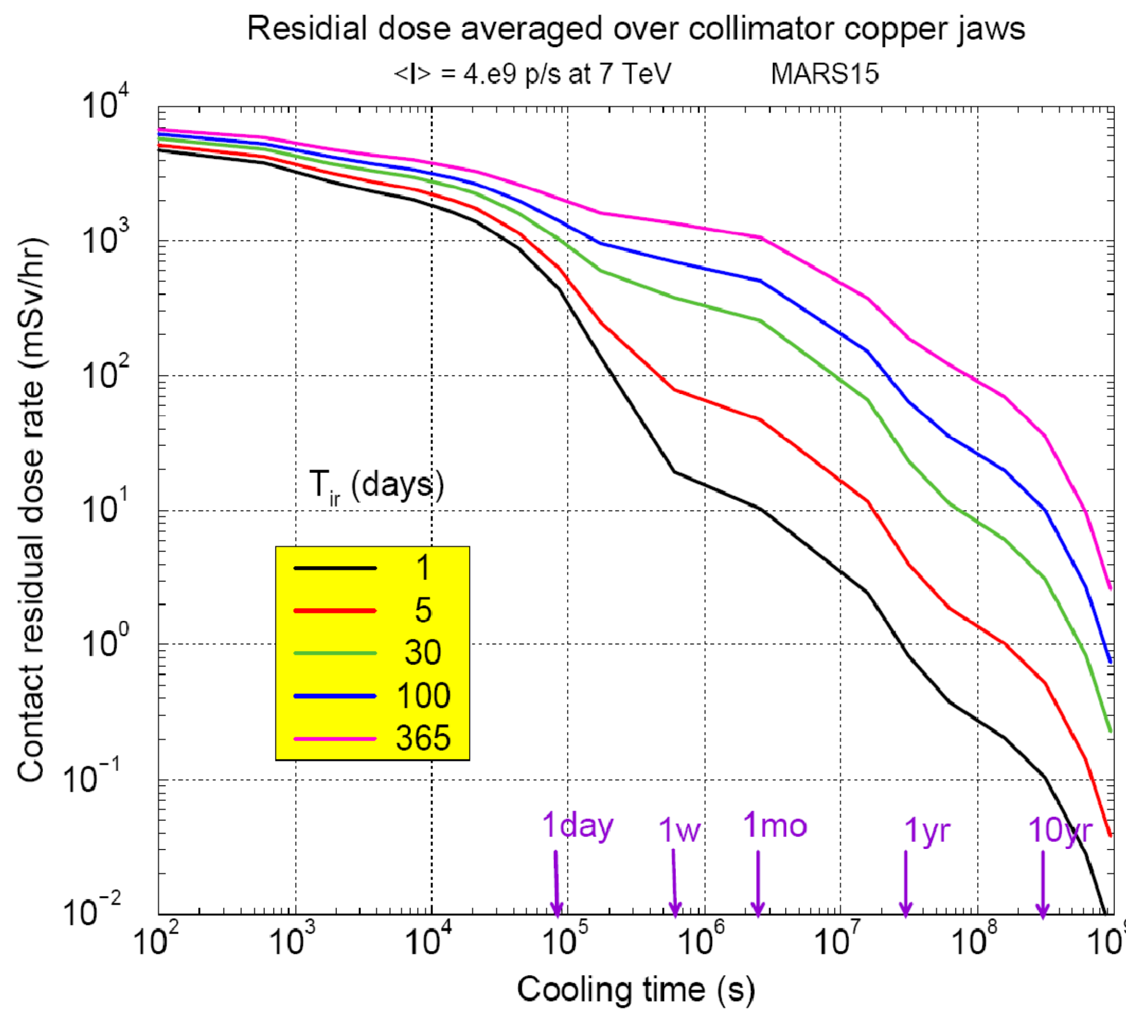
For 1 MJ beam abort accident ANSYS calculations predict 50µm permanent deformation and 1.5°C temperature rise in cooling water (6 bar). Risks to be tested in TT60 include:

- Damage to Glidcop surface that extends over “too much” of circumference
- Cu vapor gumming rotation mechanism
- Welding opposite jaws together

Rotatable Collimator Activation & Handling







Need dose rate at ~1m; Mokhov et al

Heat deposited in major components (W/m^3) in 1 hr beam lifetime operation

Component	Units	Upbeam	Downbeam
Stub shaft, aluminum	W/m^3	6.5e3	52e3
Bearing, Si3N4	W/m^3	8.3e3	66.4e3
Image current bridge, aluminum	W/m^3	150e3	400e3
Mo shaft (~const in z, concentrated in $\phi=120^o$)	W	520	
Jaw, Glidcop AL-15 (heat highly variable in z and ϕ)	kW	12.8	

Major jaw dimensions and calculated cooling performance

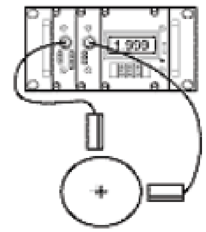
Component	dimension	units
Jaw OD tangent to 20-faceted surface	136	mm
Jaw OD to facet vertices	137.7	mm
Jaw ID	66	mm
Jaw length, including 10mm (in z) x 15^{o} taper on each end	930	mm
Mo Shaft OD	64	mm
Mo Shaft ID	44	mm
Hub length (centered)	150	mm
Cooling tube OD x ID (square x square)	10 x 7	mm
Embedded helix – center radius	80	mm
Helix – number of turns	~47	-
Cooling tube length – helix + entry + exit from vac tank	~16	m
Flow per jaw	9	l/min
Velocity	3	m/s
Water temperature rise (SS 12.8 kW per jaw)	20.3	C
Pressure drop	2.4	bar

Cu-Mo Hub Braze Test parts

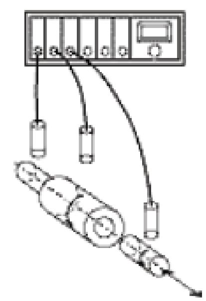
#1 - Mandrel Dummy (not shown)
#2 - Mo Shaft Dummy
#3 - Mo Backing Ring
#4 - Cu Hub with braze wire grooves

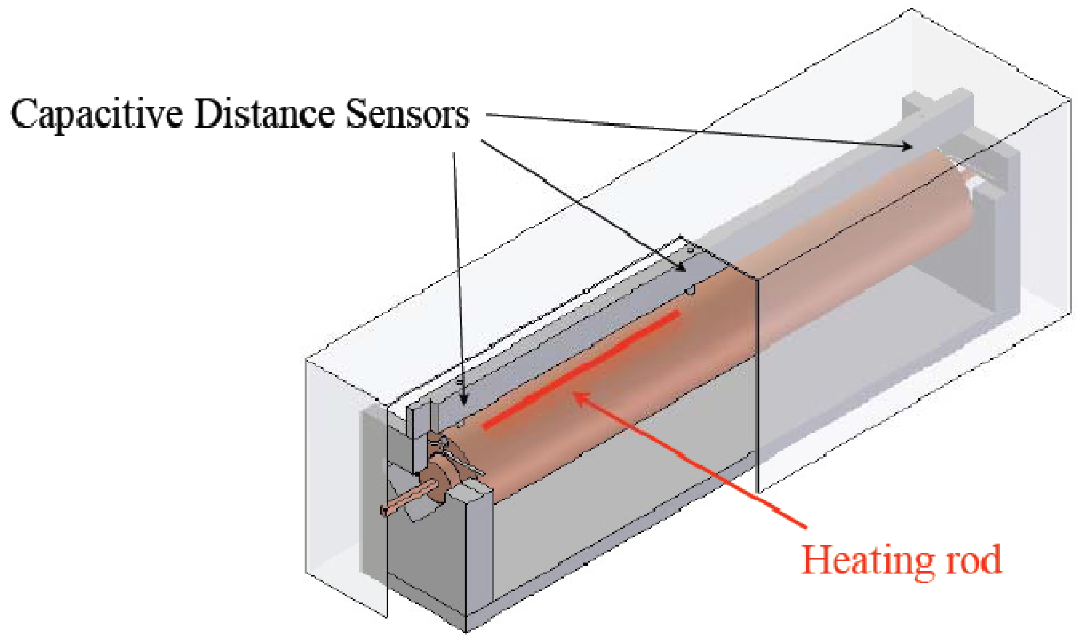
First Full Length Jaw Thermal Tests

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

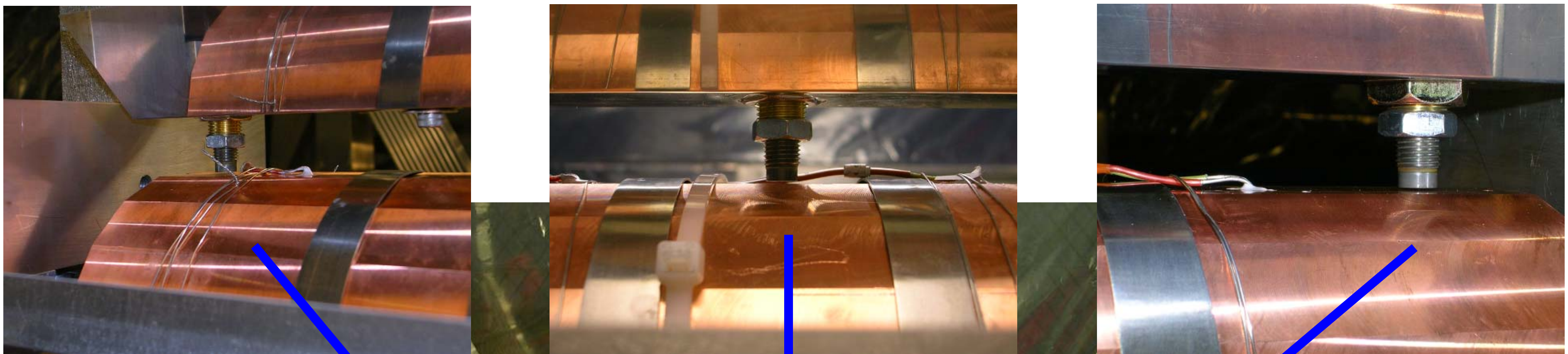


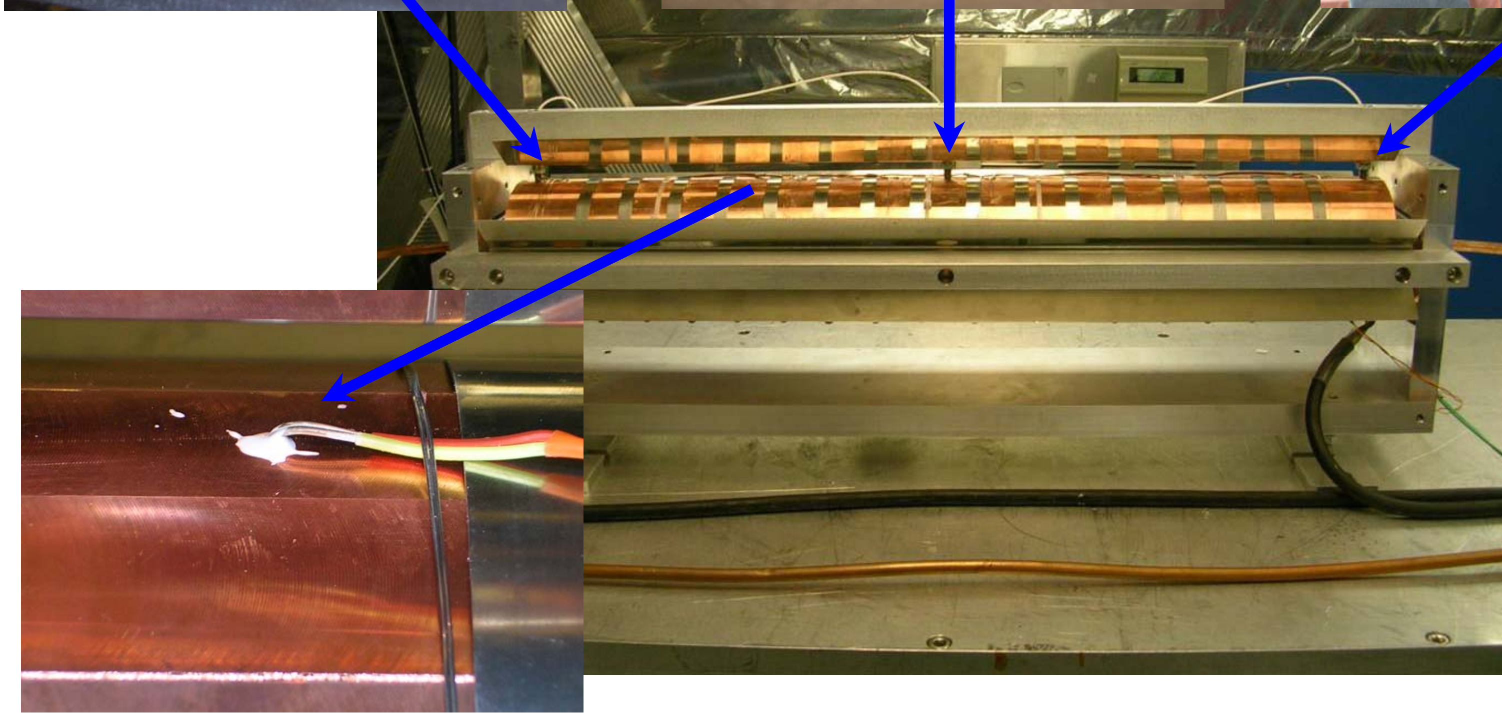
Images from www.capacitec.com





Measure jaw thermal expansion

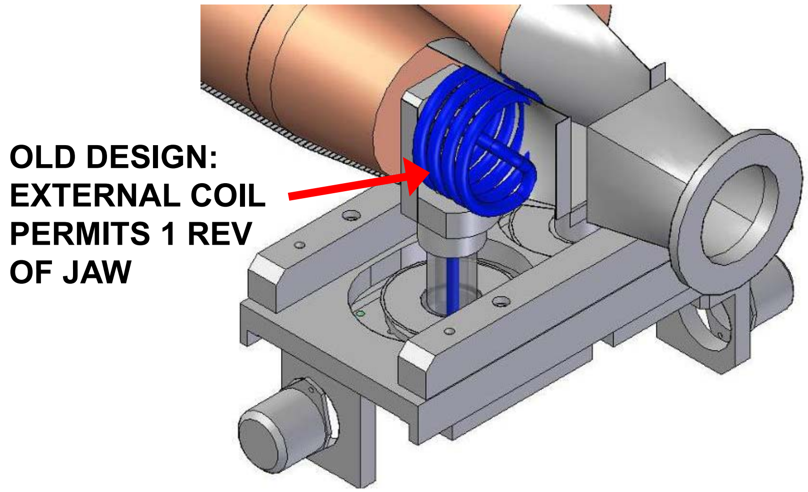




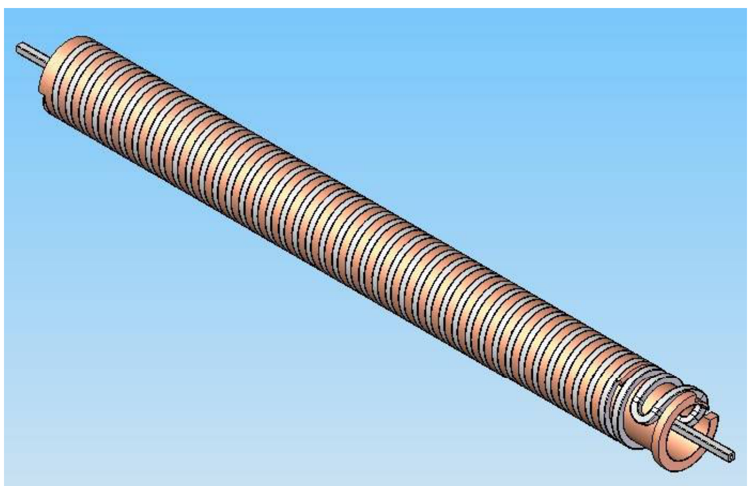
Heaters attached on bottom (jaw rotated 180 degrees from previous slide

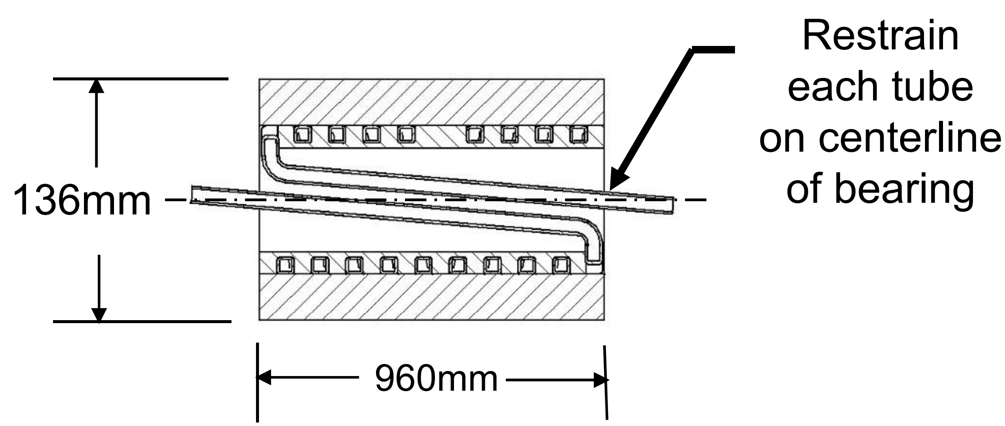
Reverse-bend and Twisted Cooling Coil

permits longer jaws and frees up length for jaw supports, rotation mechanism and RF-features



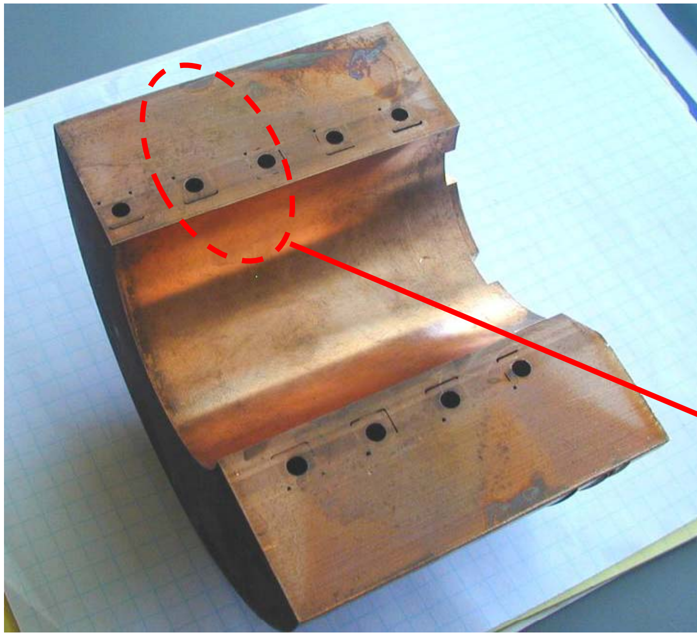
4-1/2 Turns without failure

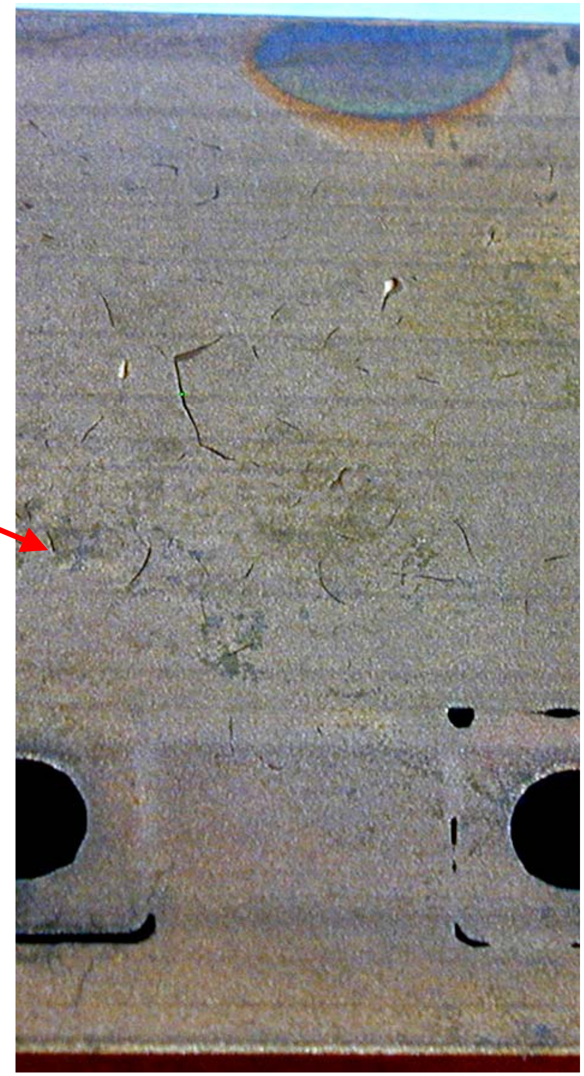




Braze Test #3: Sectioning & Examination

Cu grain boundary cracking during brazing





Specimen 140mm OD x 60mm ID x 200mm L (¼ section shown)

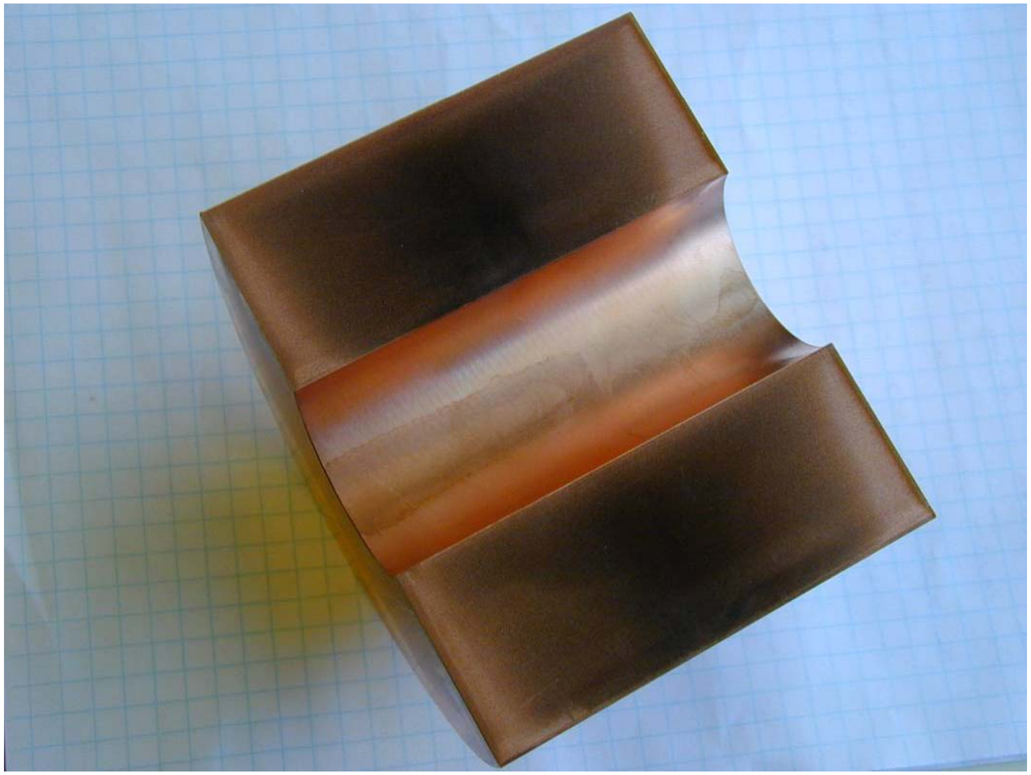
- **one braze cycle in the 900 C range**
- **grain boundary cracks located in interior regions**
- **believed due to excessive heating rate**
- **Glidcop to be tested**

Concerns

- **Effect on performance**
- **What happens in accident case?**

Glidcop Al-15 Heat sample

While 1st jaw used to test thermal mechanical issues is Copper, first full 2 jaw prototype will use Glidcop

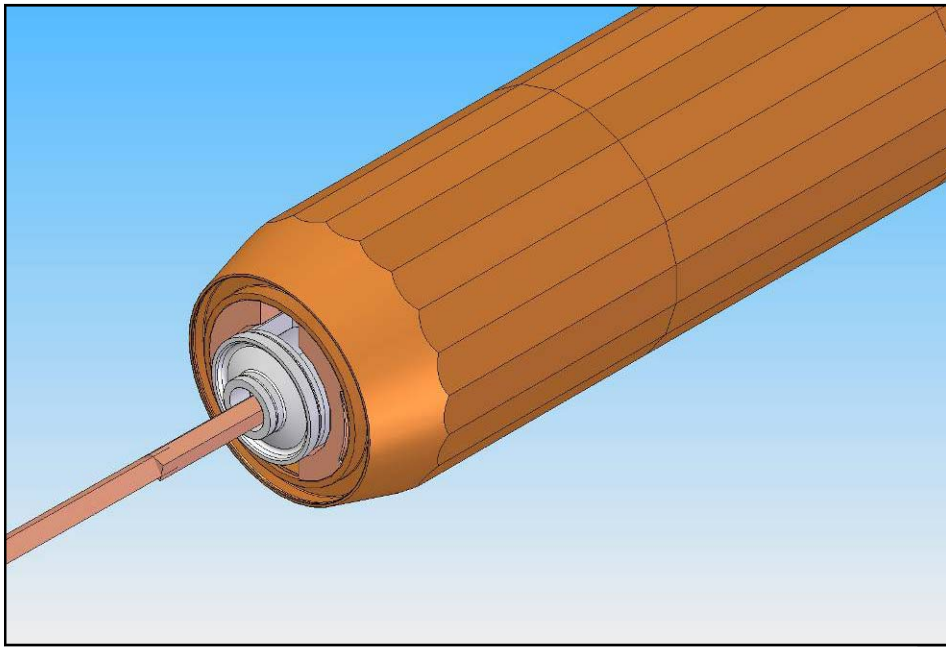


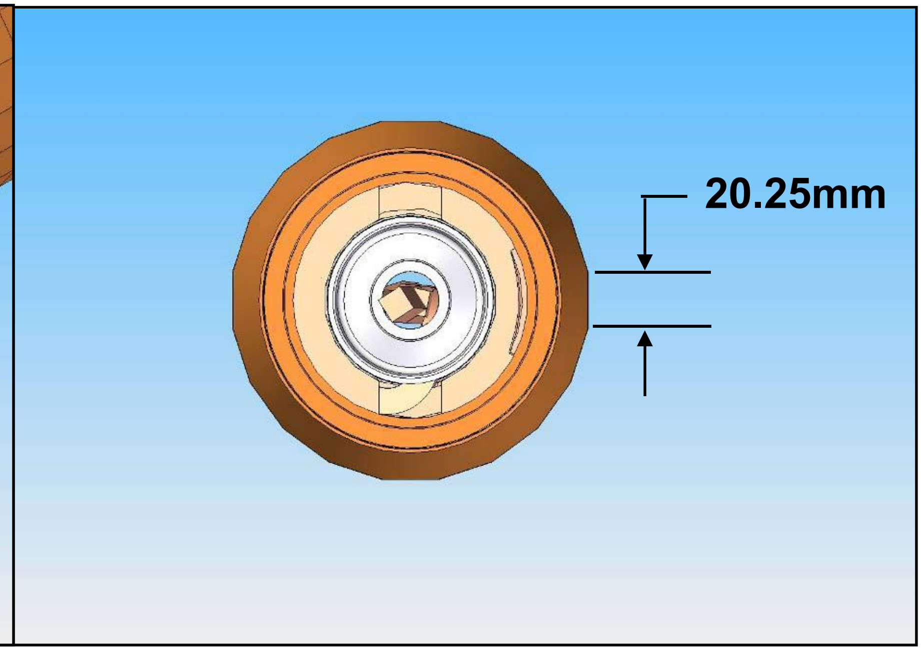
2 Heats (at Jaw brazing temperature)

No grain boundary cracking is apparent

Metallographic samples are being prepared for microscopic inspection

20 Facets 20 years?





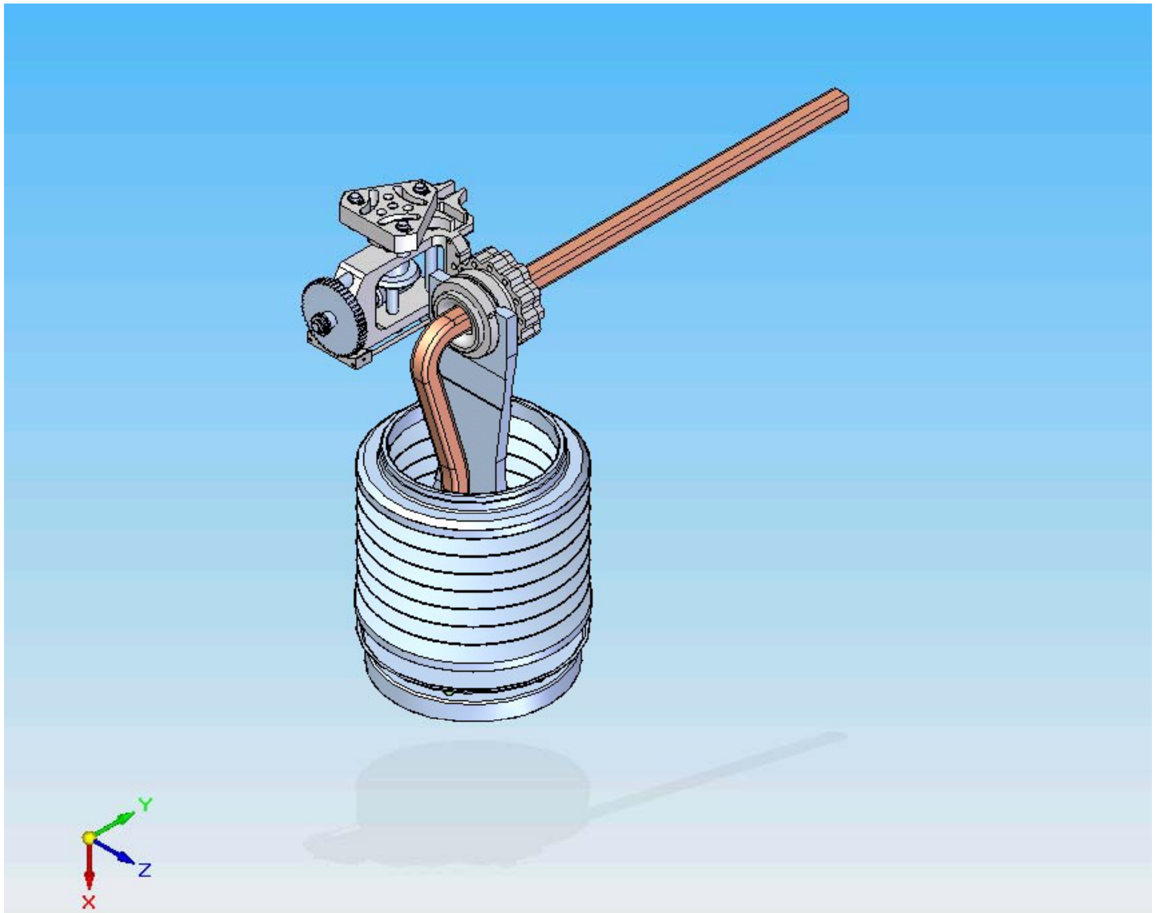
~15 degree taper at each end places RF contact bearings ~10mm away from facet.

Facet length = 930mm (oal) – 2x38mm (taper) = 854mm

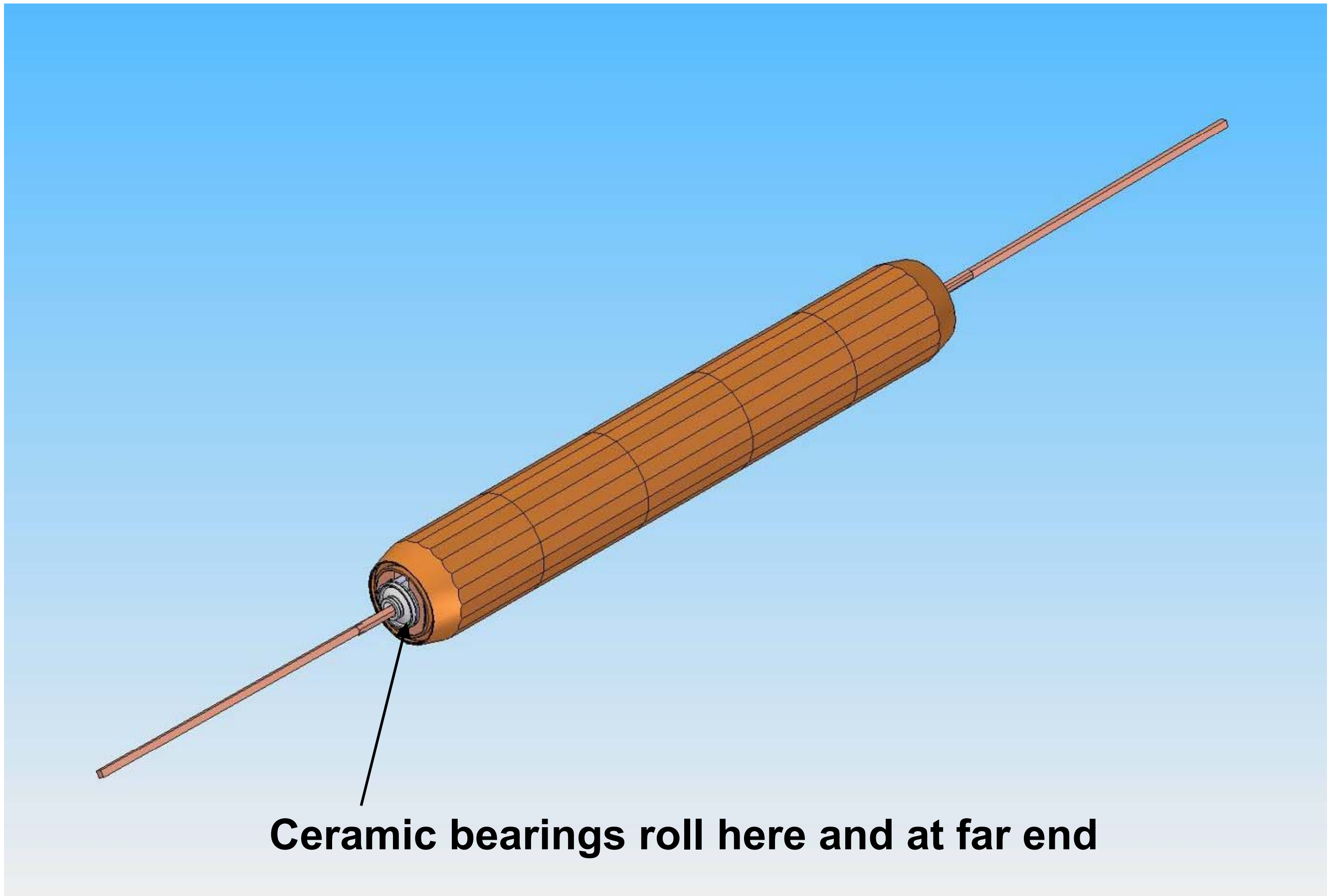
Taper may be too generous and could be shortened for a longer facet.

Thickness of Glidcop Jaw (facet to water) is 24.5mm.

Up Beam Jaw Support Current Version



Shaft Ends are grooved for ceramic ball bearings

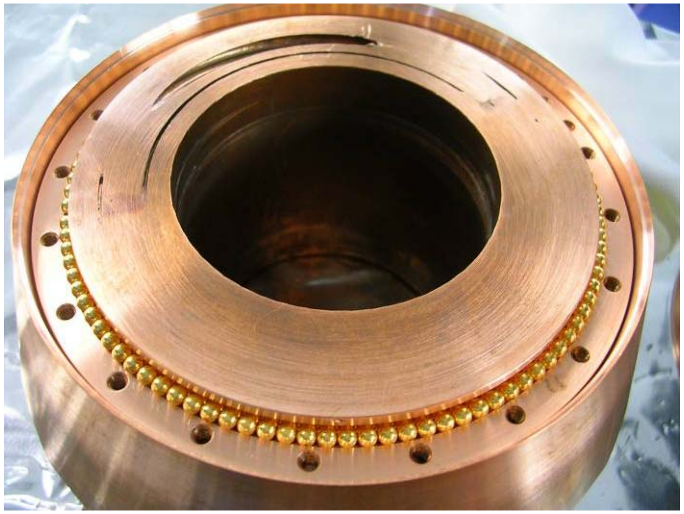


Balls

Bare Stainless Steel

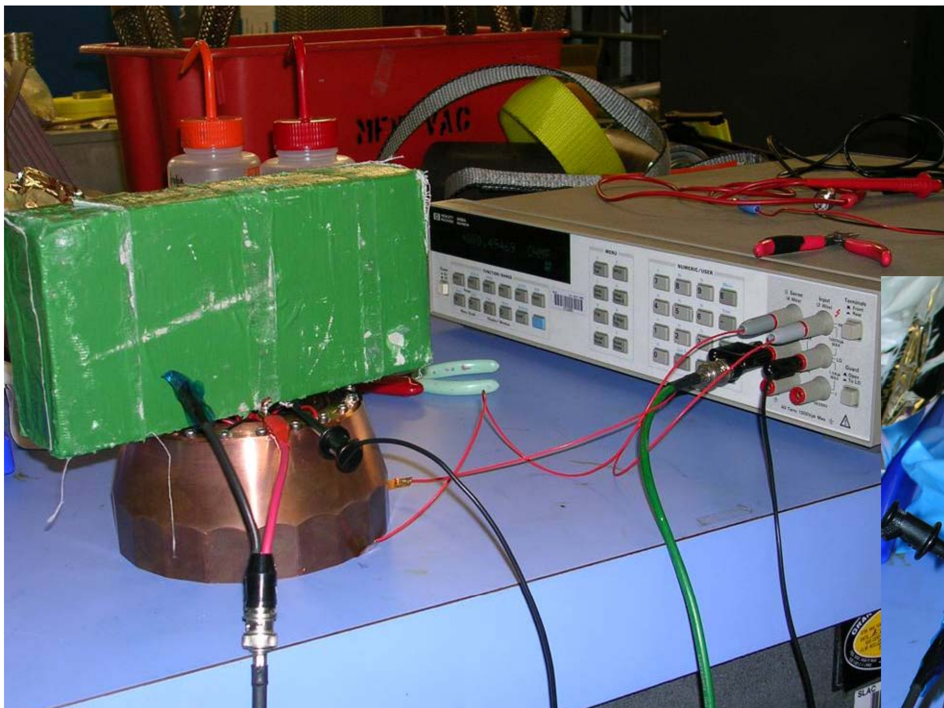
Rhodium Plated, 2 micron

Gold Plated, 4 micron



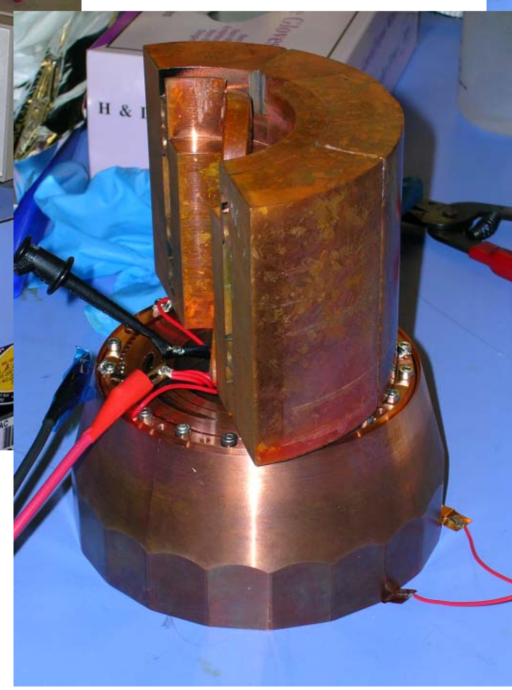
Try Different Loads

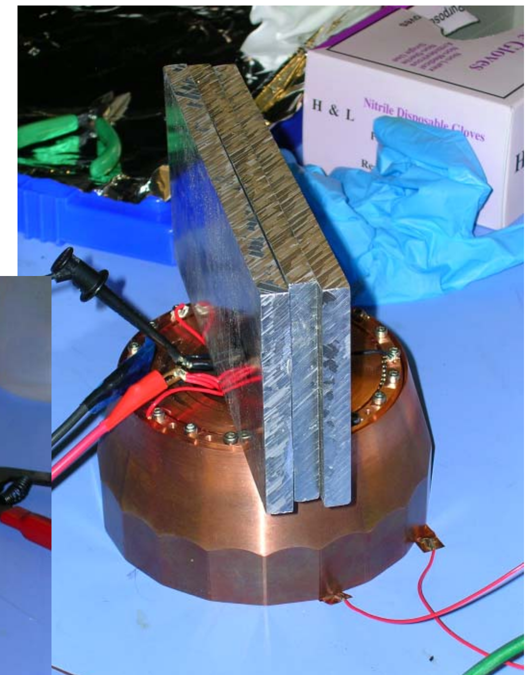
- We want to determine the amount of load needed to bearings to get desired resistance of less than 1 milliohm.



26 pounds (lb)

10 pounds





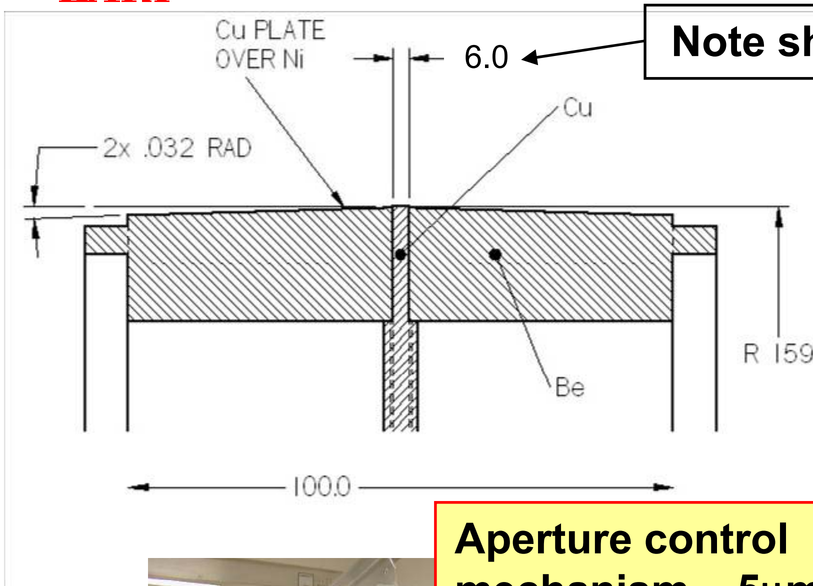
3 pounds

Sorry for the British Imperial Crown units!

LARP

NLC Consumable Collimator Prototype

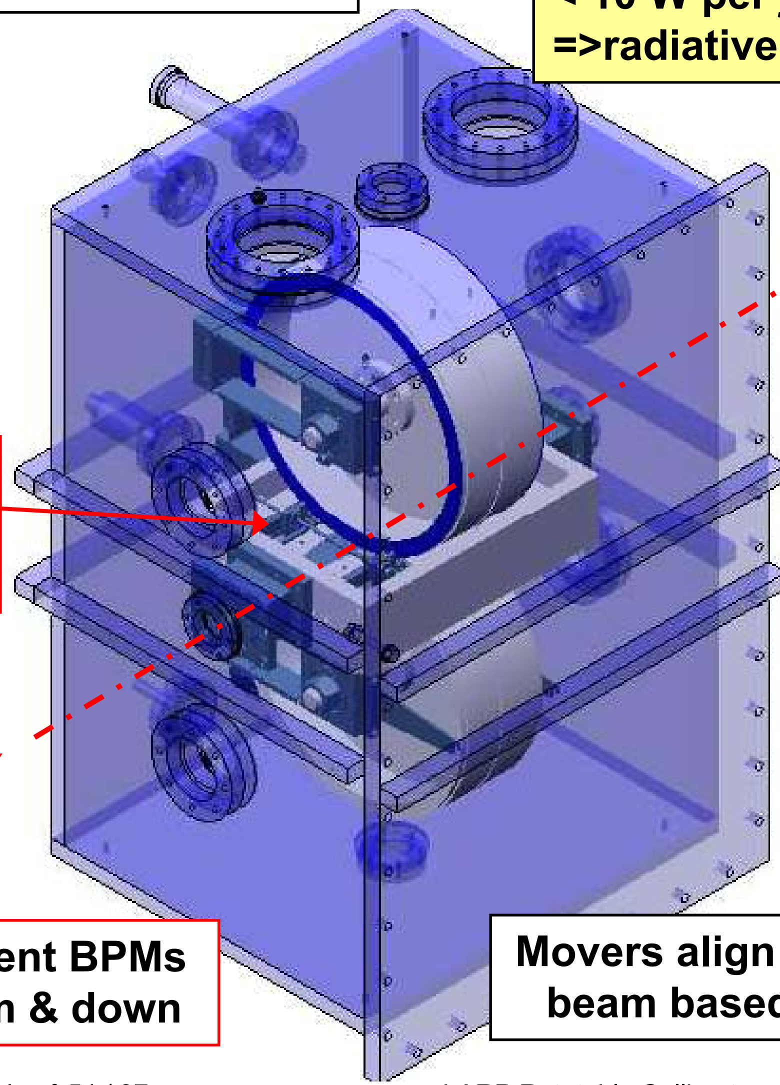
32cm Ø rotatable jaws → 500 to 1000 hits;
6mm thin; no water cooling, no space restrictions



Note short high-Z material.

< 10 W per jaw
=>radiative cooling!

Aperture control mechanism – 5µm accuracy & stability



Alignment BPMs upbeam & down

Movers align chamber to beam based on BPMs