LARP

US LHC Accelerator Research Program

BNL - FNAL- LBNL - SLAC

STANFORD LINEAR ACCELERATOR CENTER ESTABLISHED 1962 D.O.E.

LARP Rotatable Collimators for LHC Phase II Collimation

1) Adapt rotatable NLC design concept to LHC: “RC”
2) Build and test one collimator jaw with 10kW resistive heaters to verify thermo-mechanical performance
   - Minimize deflection when absorbs with 60kW for 10 sec
3) Build a full collimator & test it at CERN
   - 2009 Delivery

Gene Anzalone (CAD), Eric Doyle (ME-FEA, ret.), Lew Keller (FLUKA), Steve Lundgren (ME), Tom Markiewicz (Phys), Reggie Rogers (Mech Tech) & Jeff Smith (PD)

Status of RC Program

1. Jaw support & rotation mechanism **COMPLETE** (June 2007)
2. First full single jaw-hub-shaft unit **COMPLETE** (April 2008, CM10)
   - Jaw faces flat and parallel to axis to 0.001"=25um
3. Sagitta measurements of water cooled prototype jaw with 10kW resistive heaters indicate **performance in accord with FEA** to ~10% thus **validating predicted 236um sagitta** (~ 1 beam σ) in CERN's most demanding
   – 12 min beam lifetime for < 10 sec, 450kW beam loss rate
      - each jaw of 1st RC downstream of primary betatron collimator absorbs 12kW
4. Vacuum bakeout and RGA of test jaw in chamber results in 1.2E-09 torr and RGA clean of hydrocarbons

Final Prototype Construction: Details to follow

1. Material, fabrication & contracts for jaws in progress
   - Note: We are planning for enough parts for 3 jaws when 2 are needed
2. Design changes to jaw support and jaw fabrication procedure
3. RF impedance tests/calculations & continually evolving RF design

LHC Phase II Base Concept

physical constraints
current jaw design

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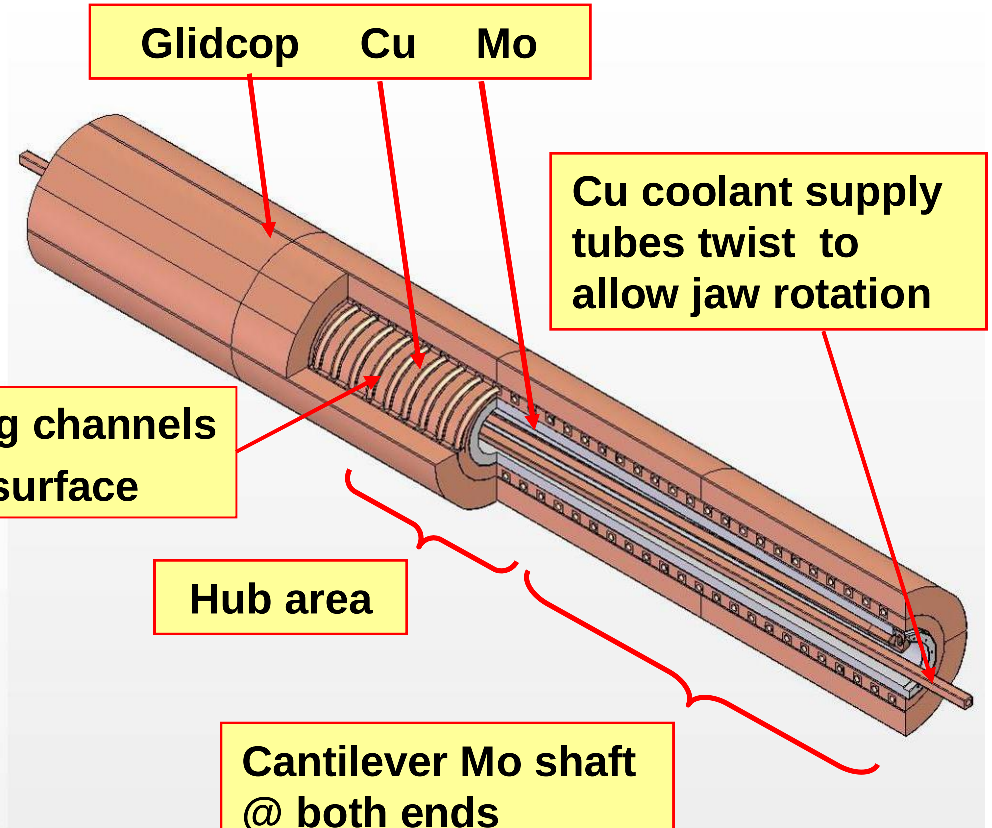
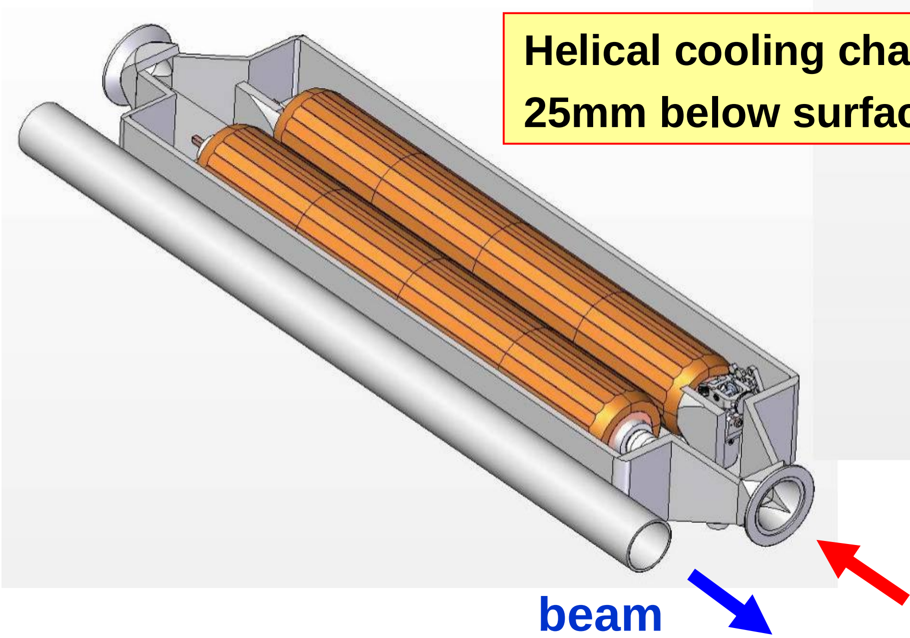
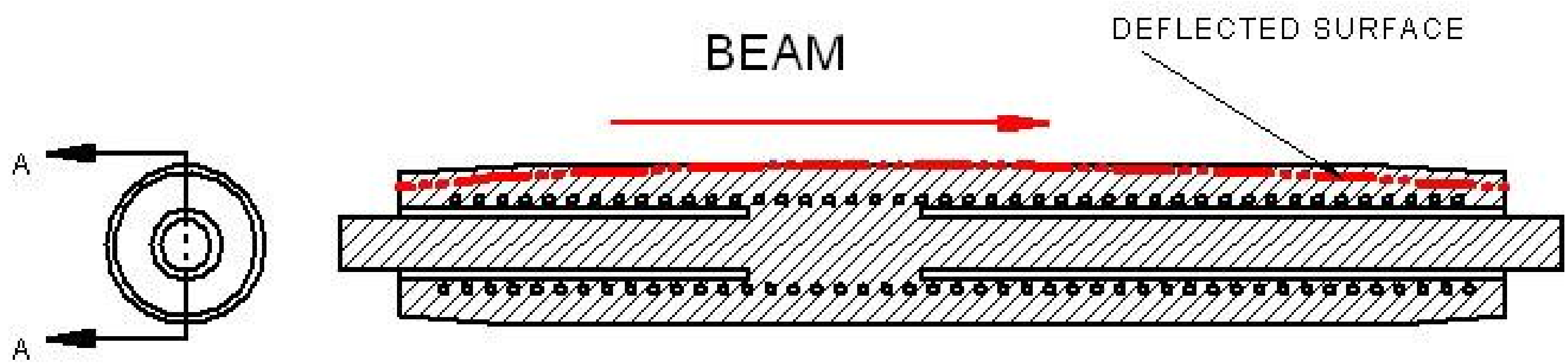
- **beam spacing: geometrical constraint**
- **Length available 1.47 m flange - flange**
- **Jaw translation mechanism and collimator support base: LHC Phase I**
- **>10 kW per jaw Steady State heat dissipation (material dependent)**



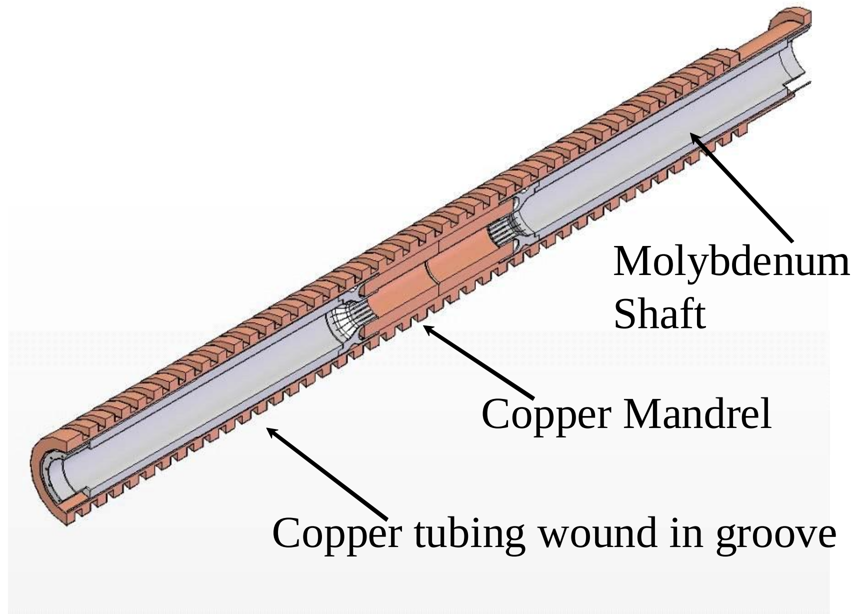


Cu Jaw-Cu Hub-Mo Shaft Design



2mm shaft-jaw gap gives x5 improvement in thermal deformation over solid shaft-jaw design
1260 um → 236 um (60kW/jaw, τ=12min)
426 um → 84 um (12kW/jaw, t=60min)

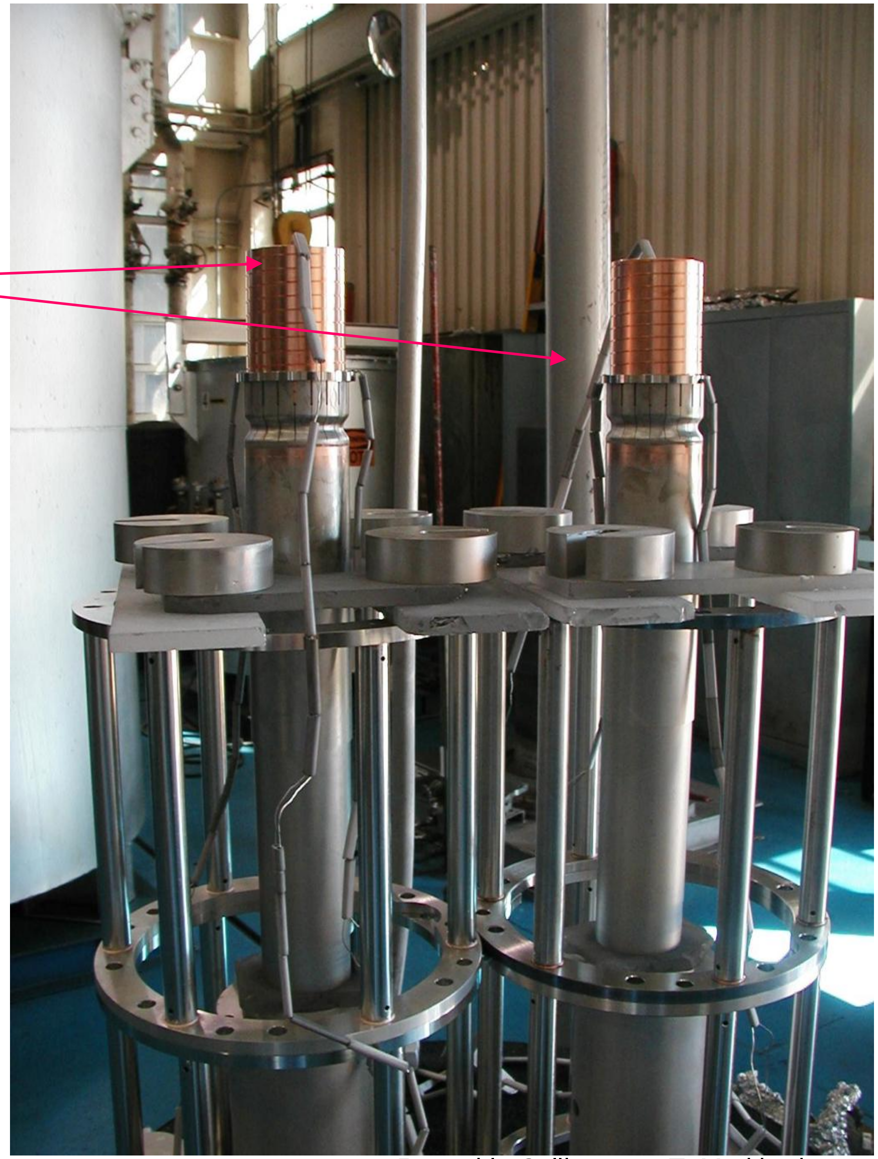
Rather than Cu, Moly shaft improves Gravity sag x3:
200 um → 67 um
Thermal bulge 30%:
339 um → 236 um



Brazing Each Moly Shaft End to a Central Copper Hub

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

Shaft halves



Three Braze Cycles

Three main brazing steps.

Brazing materials set to melt at gradually lower temperature.

1.) Braze each shaft end to a central half-hub

2.) In one go:

Braze shaft half-hubs to Mandrel

25% Gold, 75% Copper

Braze copper cooling coil to Mandrel

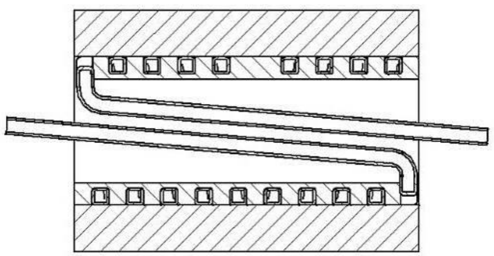
35% Gold, 65% Copper

3.) Braze jaw quadrants to mandrel surface after mating mandrel OD and jaw quadrant ID

50% Gold, 50% Copper

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

Original Grooved Mandrel destroyed by vendor when drilled out to accept shaft resulting in 2 month delay



Braze Step#1 Shaft Assembly & Coil to Mandrel

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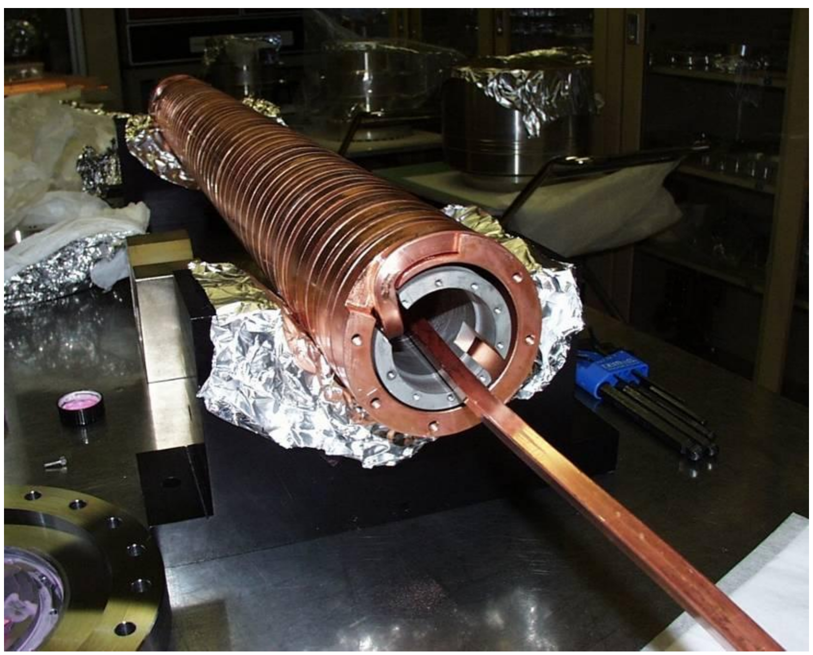
On support stand and ready for insertion in baking oven

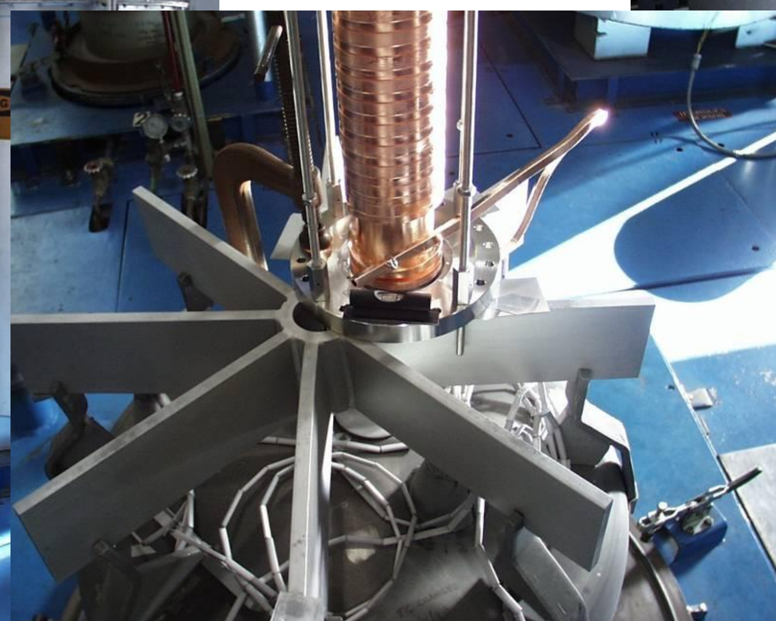
- Carbon block used to hold thermally expanding copper against central hub and shaft (moly and copper)
- Next time may use carbon block full length of mandrel



Filling Coil-Mandrel Keystone Gaps

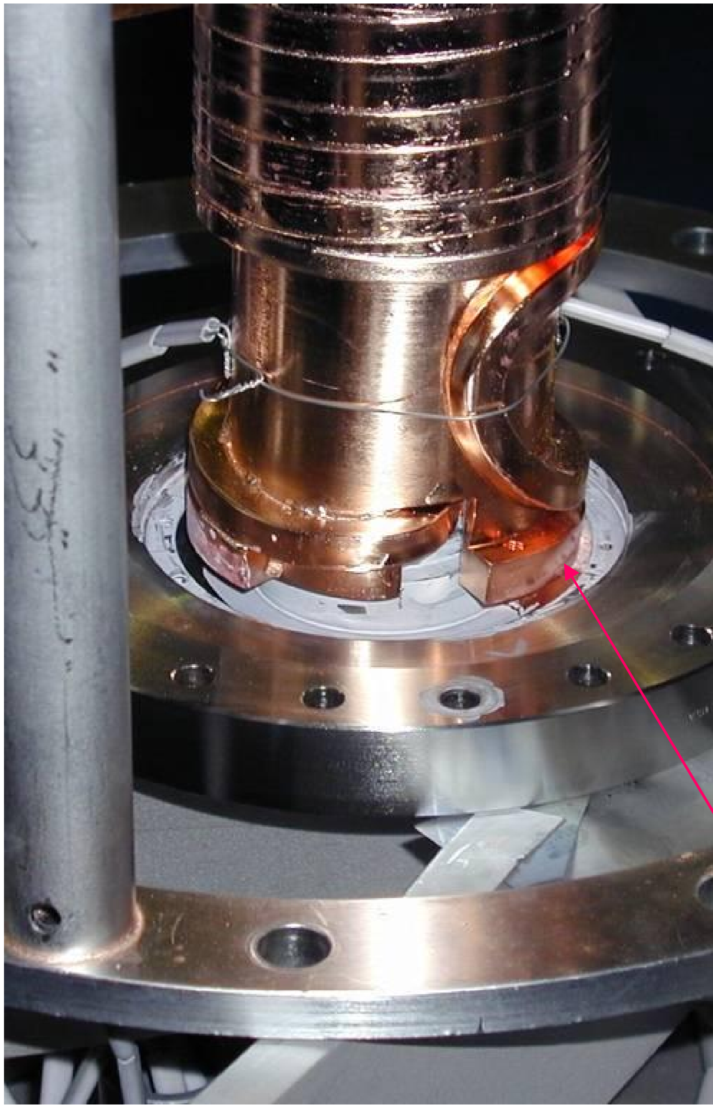
Three brazing cycles needed before coil-mandrel ‘keystone’ gaps filled adequately

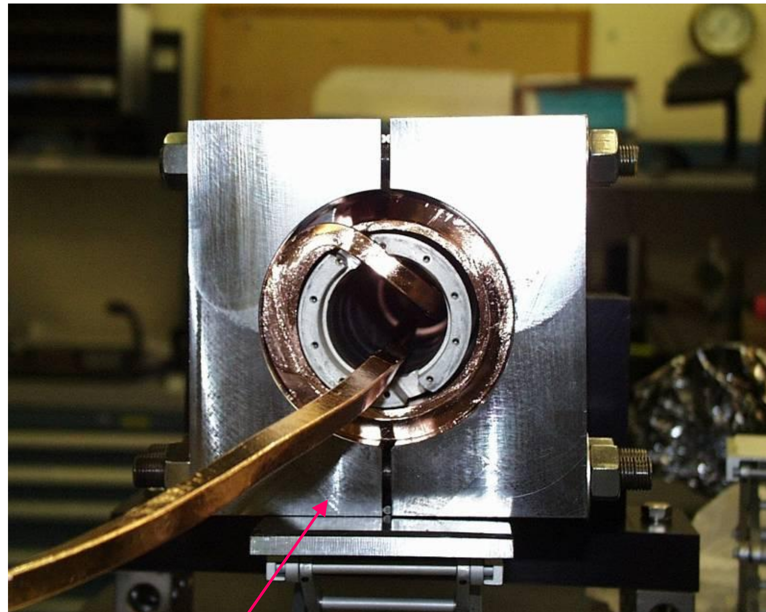
On 3rd cycle excess braze material attaches support stand to mandrel, which warps



Pix of 2nd braze cycle

Recovery after Excess Braze Material Attaches Mandrel & Shaft to INOX & Inconel Braze Supports

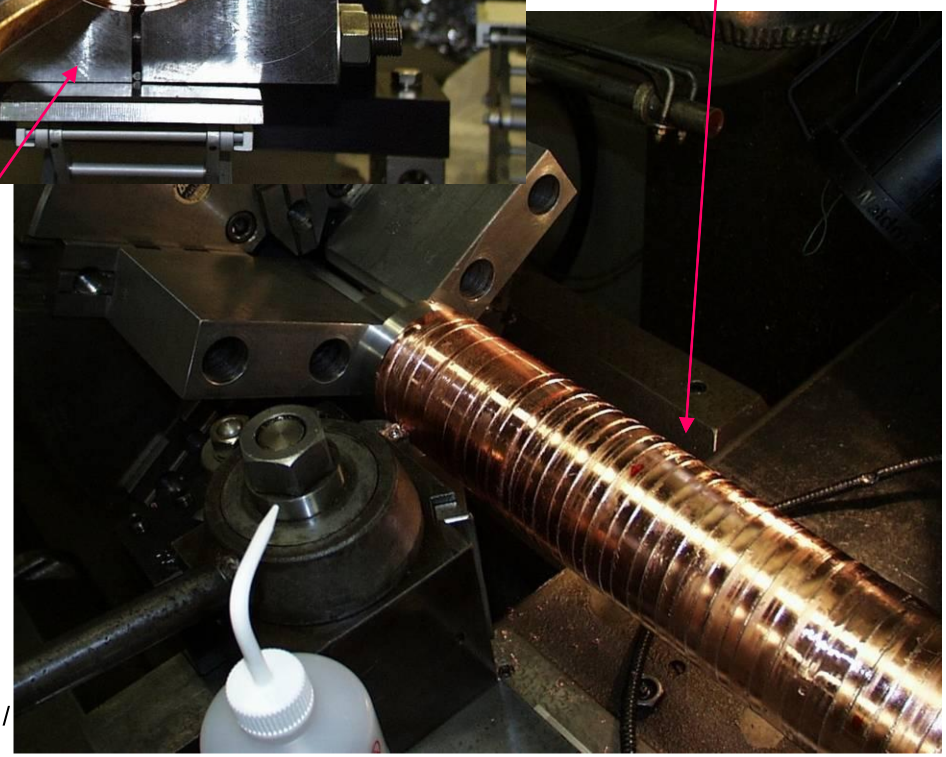




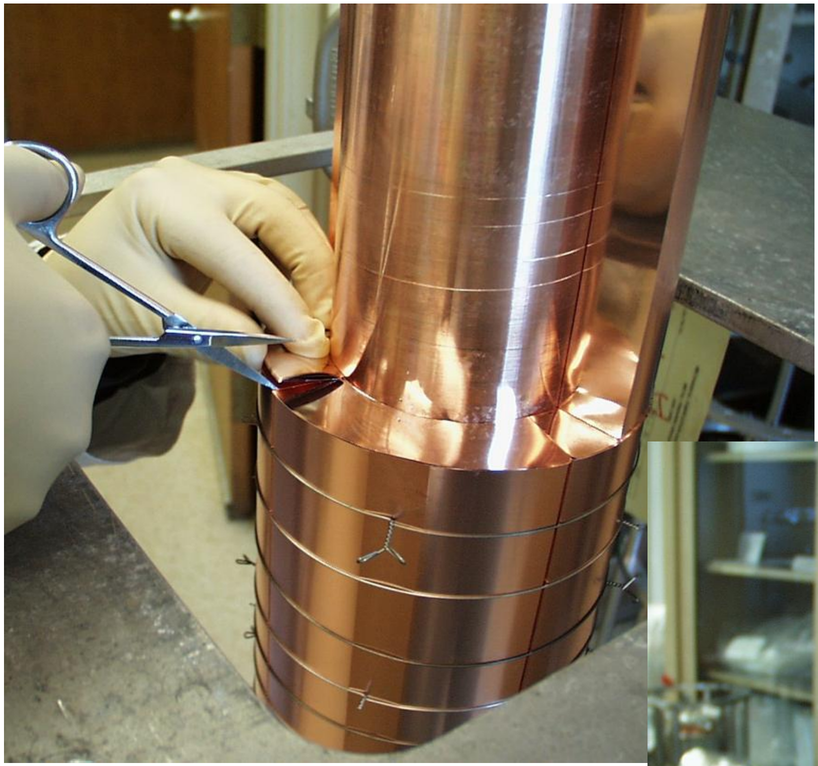
Machine to constant diameter

Bending fixture

Bent mandrel before hacksaw



Measure & Machine Quadrants to Mandrel. Assemble & Braze



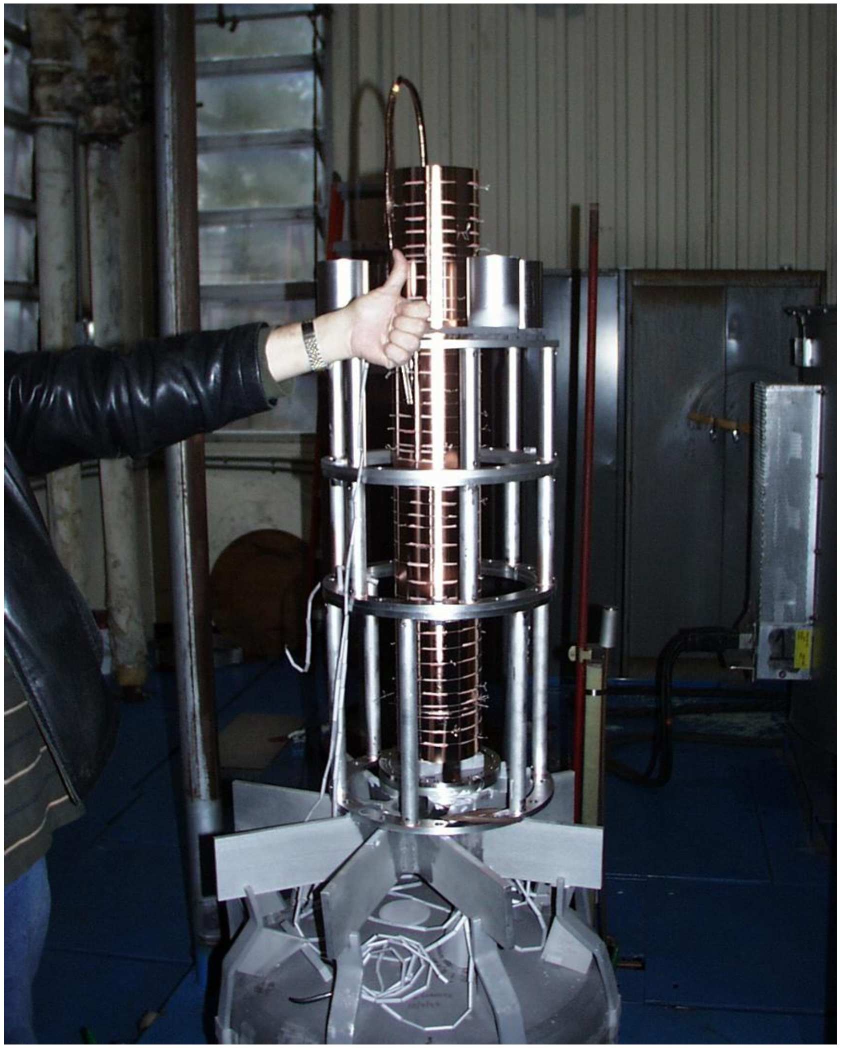
Using 50-50 Au-Cu brazing material ($$)

Results of Jaw Brazing 22 April 2008

Looks good!

Experience has made us consider:

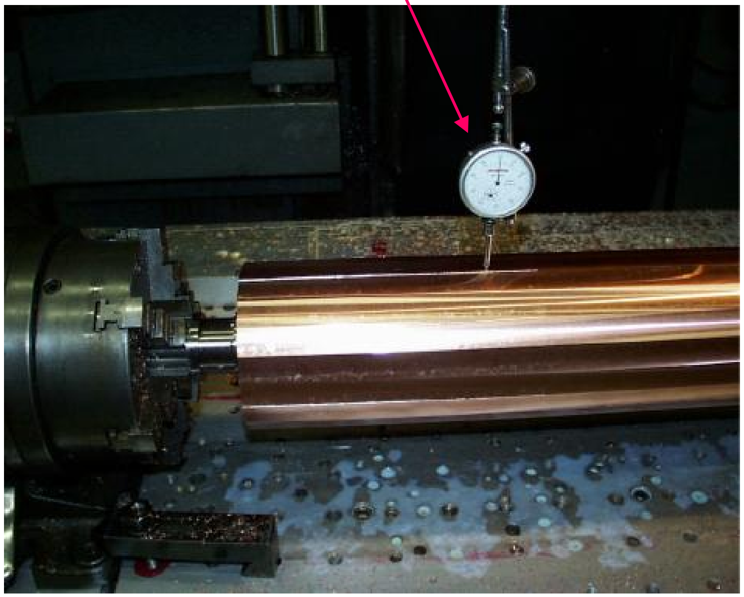
- Full round jaw segments
- Over-sizing parts & cutting down to proper radius
- Several ideas to minimize keystoning when coil wound on mandrel



Machine Flat Facets and Groove for Heater Test

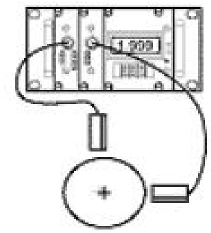
Final brazing was a success!

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

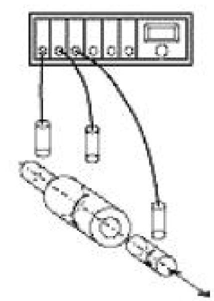


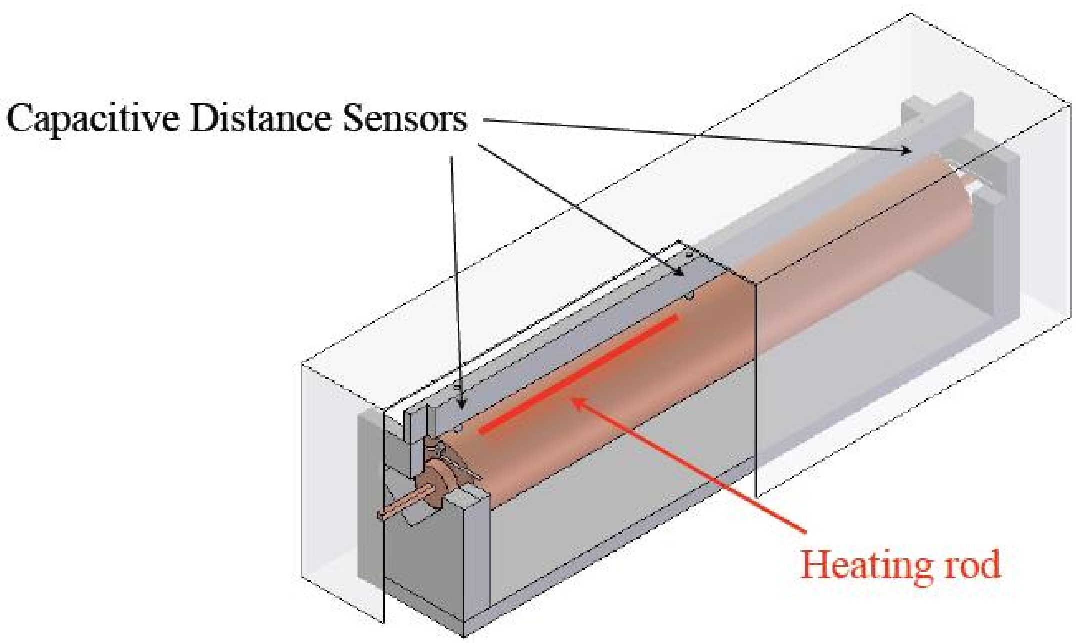
First Full Length Jaw Thermal Tests

- 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





Thermal test setup

Jaw in support stand

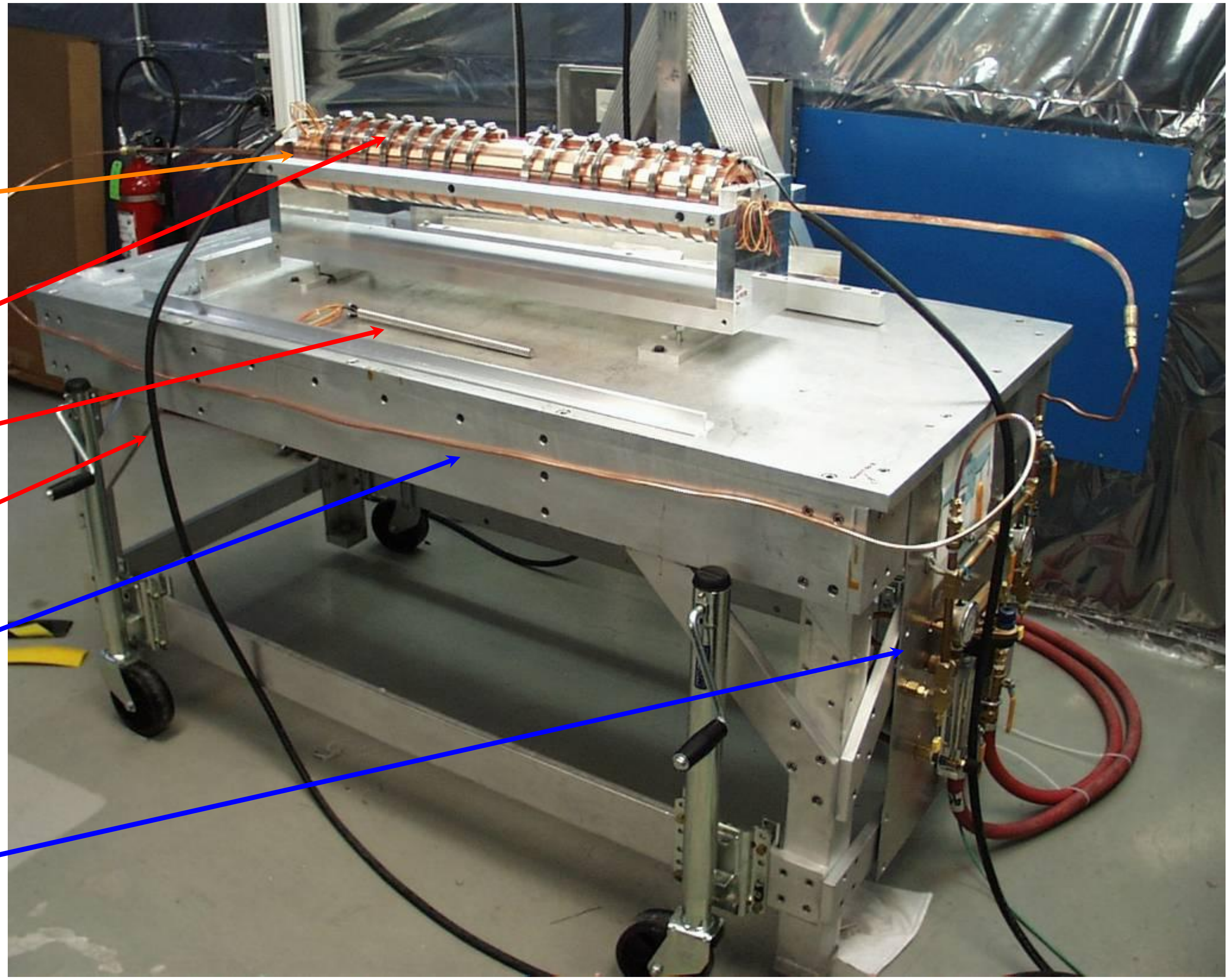
Heaters strapped on jaw

Extra heater

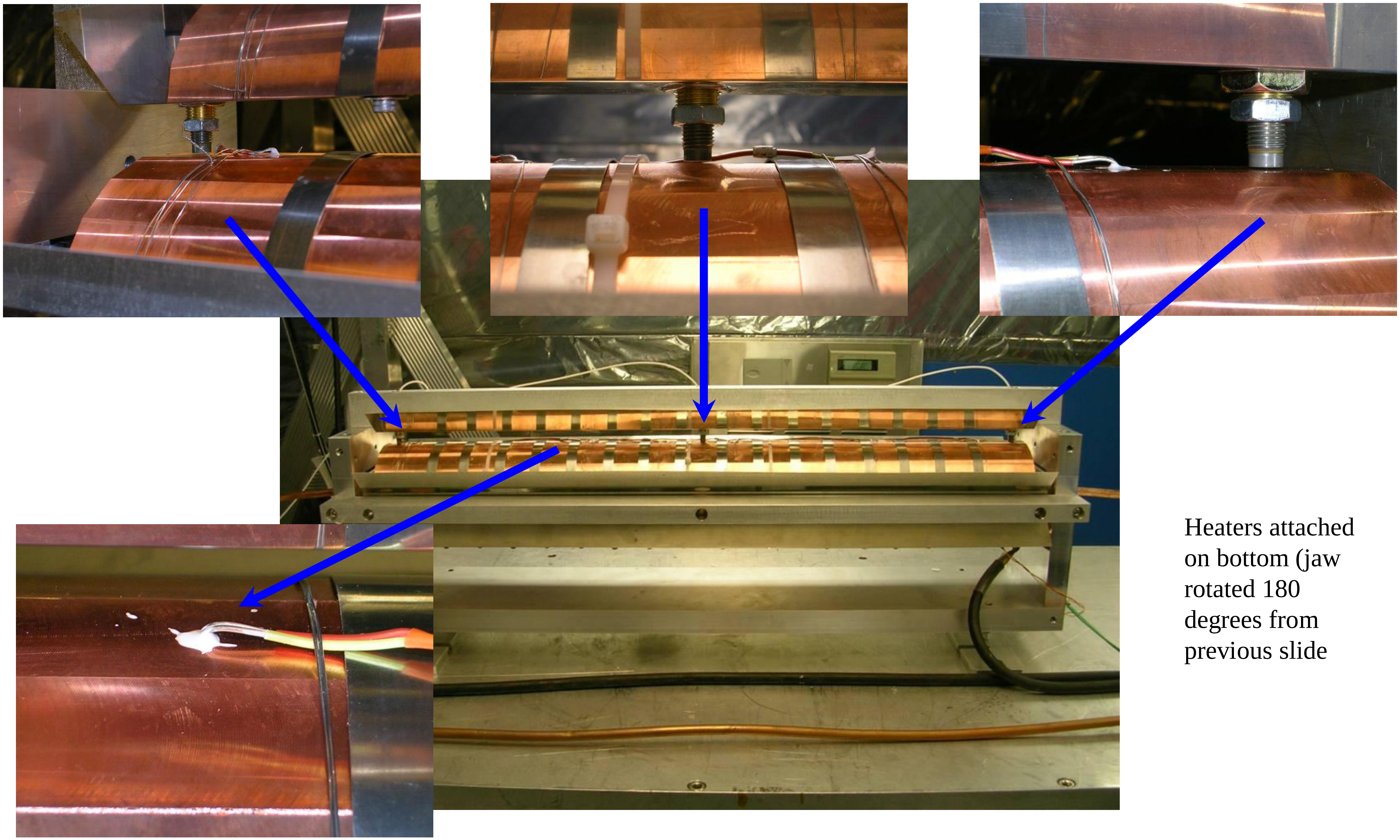
Heater cable

Water flow tube

Water flow control



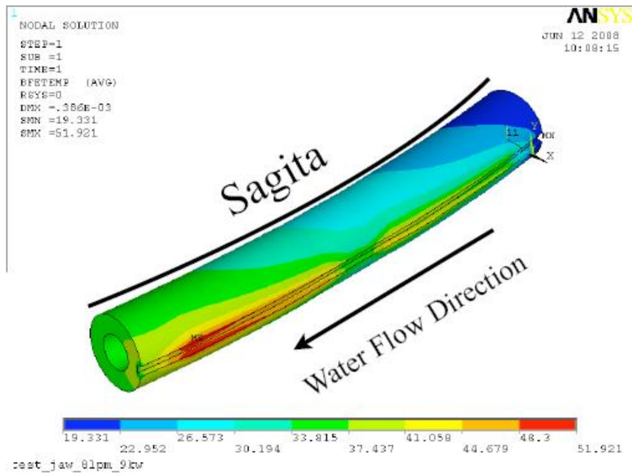
Measure jaw thermal expansion

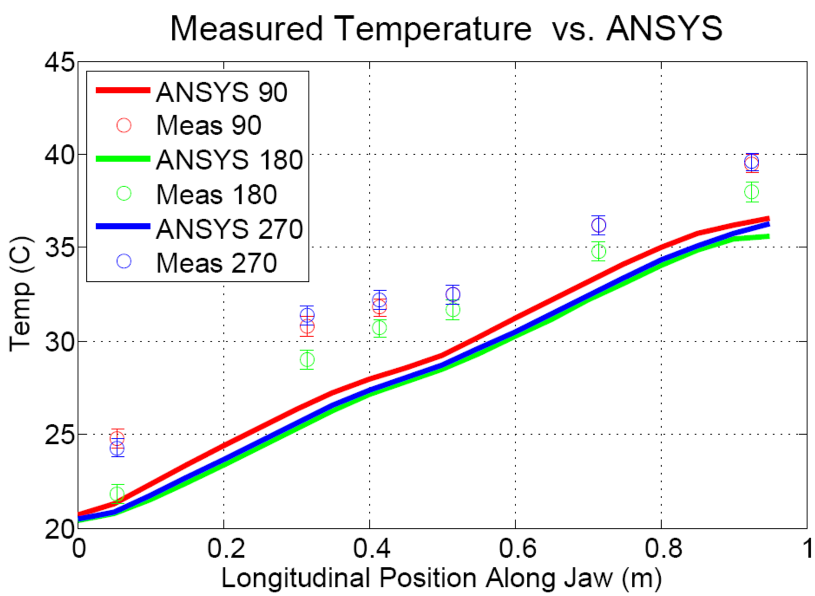


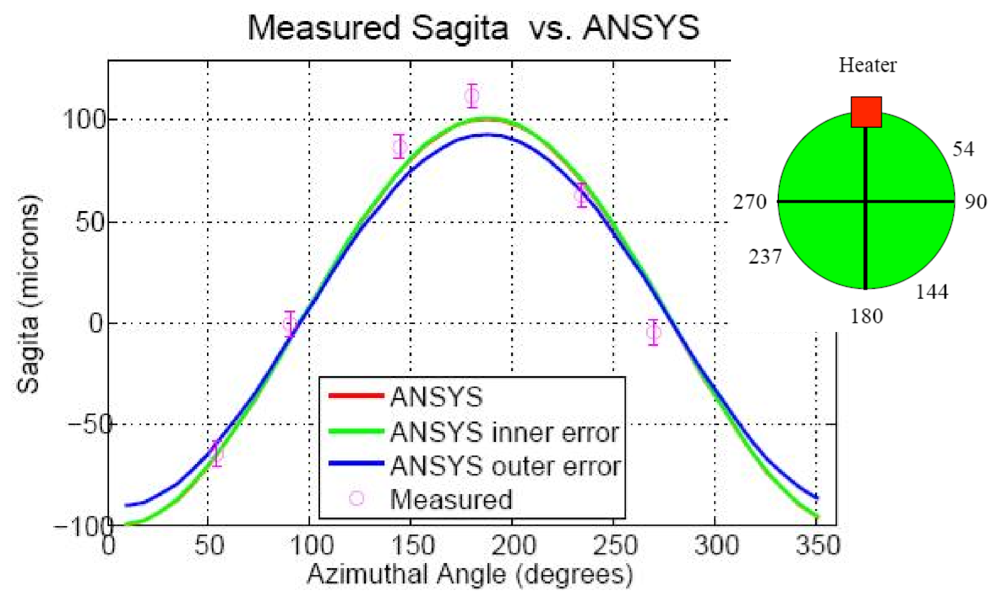
Heaters attached on bottom (jaw rotated 180 degrees from previous slide

Comparison of Sagitta & Temperature with ANSYS as a function of angle wit 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



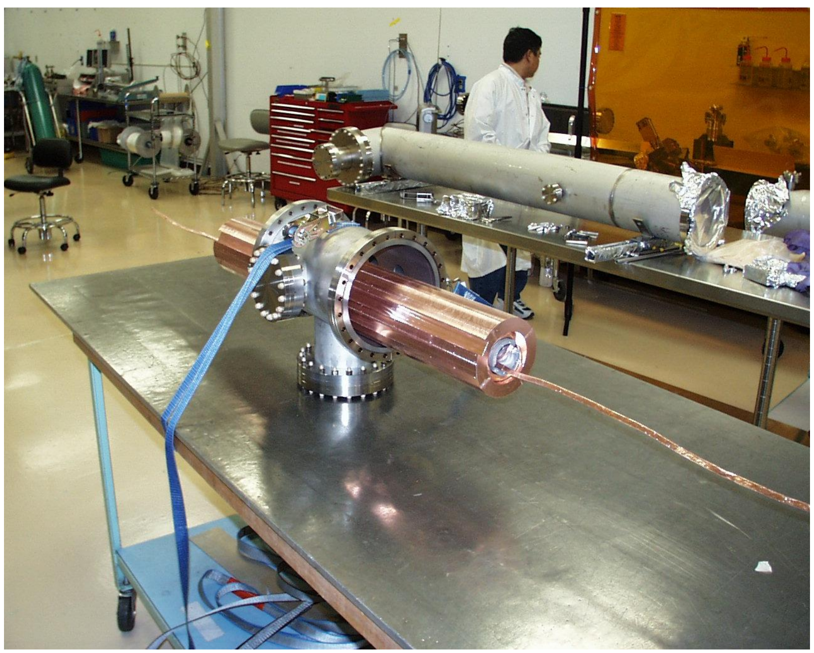


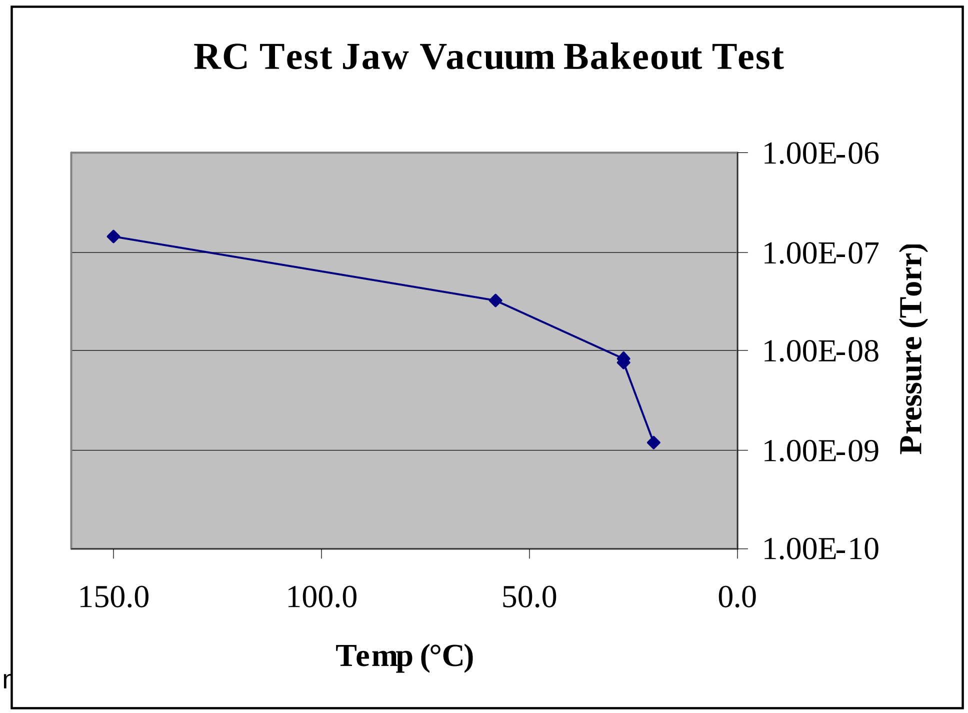


Results of Bake-Out test: 1.2E-09 torr for 1 jaw in a vacuum vessel

Process:

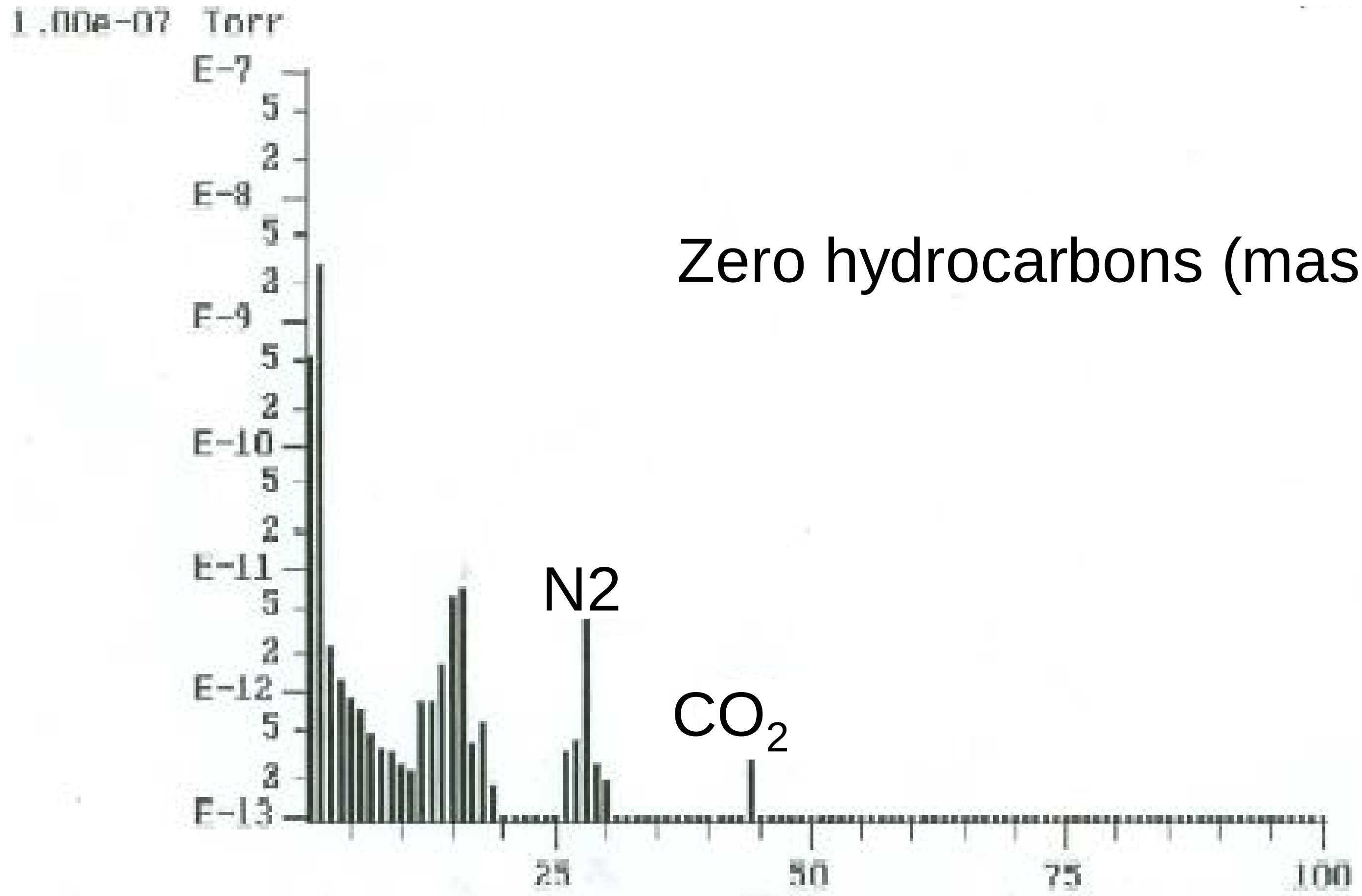
- "Standard" PEP-II Beamline bake-out sequence:
- Vacuum vessel separately baked 200°C for several days
  - 3.7E-9 torr
- Jaw H fired at 850°C before bake to accelerate bake-out process
- Bake 200°C several days with 24 hour excursion to 300°C
  - paranoia





Slide r

RGA Scan



Zero hydrocarbons (mass >40)

Final Prototype Construction
Moly Half Shafts

Order for 6 half shafts ($3k/ea.) placed 17 July 08

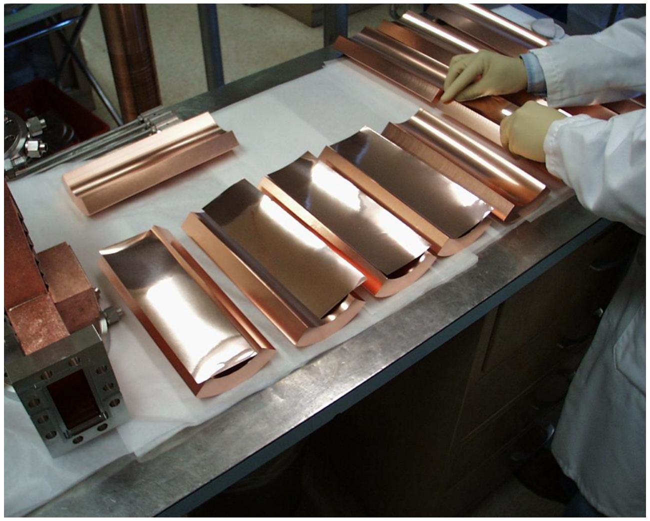
- 3 arrive 13 October with shipping damage
  - 2 have two broken teeth but pass metrology QC
    - Plan to use, perhaps brazing teeth back on
  - 1 has 3 broken teeth & is sent back
- 3 did not pass vendor inspection

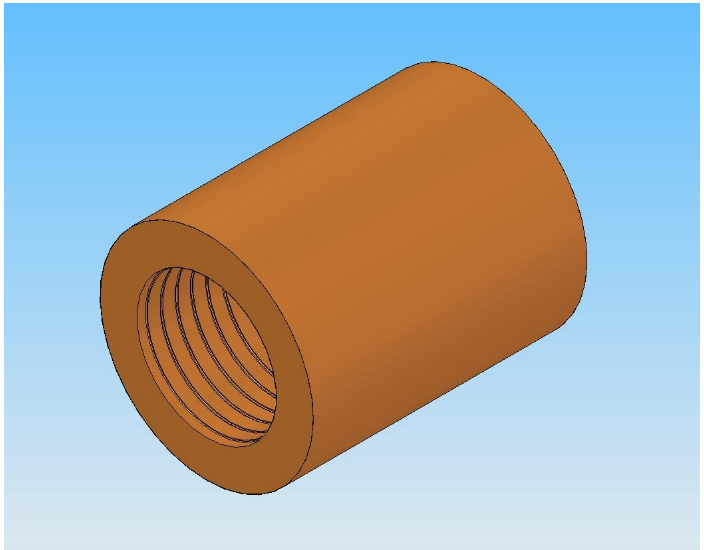
As of 10/23 no word on discussion between SLAC purchasing & vendor regarding new delivery date & costs

Final Prototype Construction

Jaws

16 ¼-Jaws → 5 rounds w/ braze wire grooves

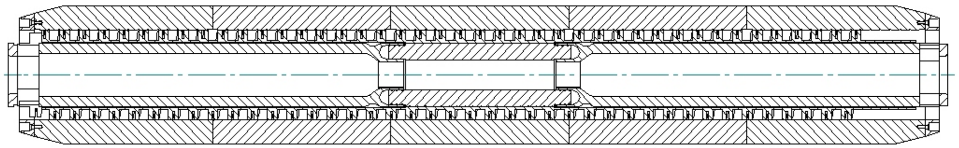




Glidcop for Jaws and Shaft-Hubs

- $56k order for material placed 2 October & promised 6-8 week delivery
  - December 9 (?)
- Material for one 2 half-hubs being expedited for 2 moly half shafts

Final Prototype Construction
Mandrel: Critical Path Item

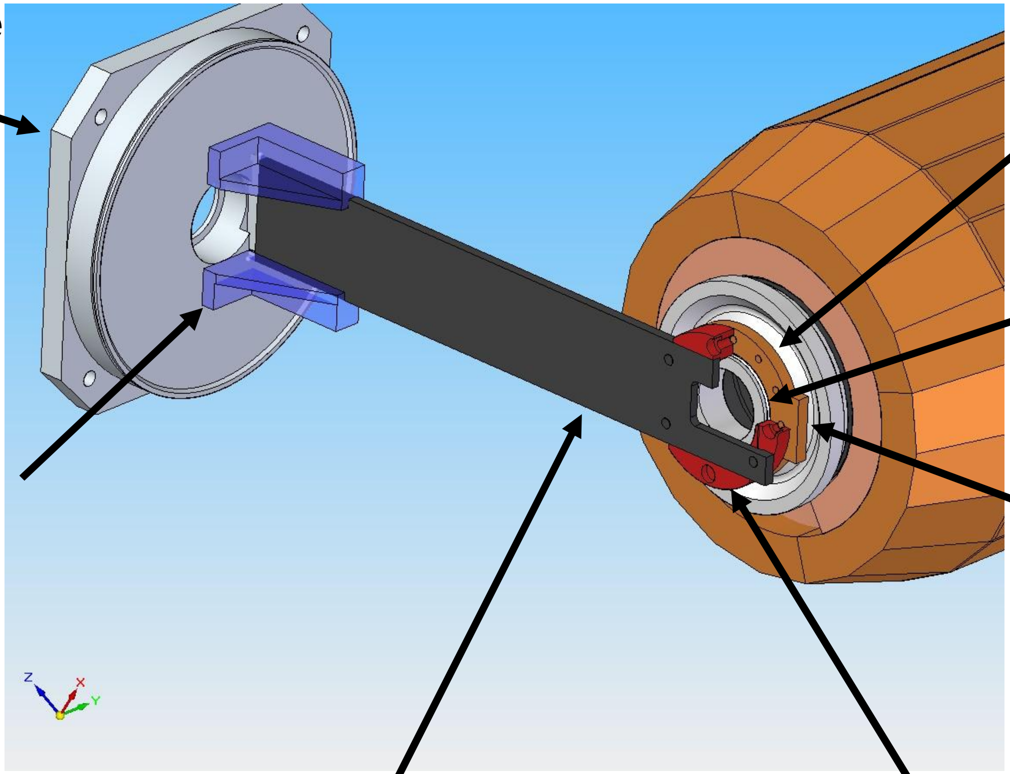


- Copper blanks in house
- Had been delaying action pending results of vacuum test
  - Alternate designs to limit possible "virtual leaks" available but given good result will pursue as a "back burner" project
  - Plan is to use square OFE copper tubing available in house
    - Have recently re-opened question of water velocity induced corrosion with CERN and possible need to use stiffer Cu-Ni alloy: parallel activity
- Contract signed for "gun drilling" 2" diameter starter bore
- MultiStep contract being bid for all remaining machining operations interleaved with SLAC brazing runs
  - 2 willing vendors given preliminary documentation package
  - Final "released" mechanical drawings expected from SLAC 31 Oct
  - Hope for bid by 17 November
- NB: First test jaw mandrel had grooves and bore cut by vendor then the many mating machining operations done by SLAC shops
  - Expensive (45% Overhead charge) and time consuming

Simplified Jaw End Support Design

Proof of concept tests complete

Will incorporate the same "Geneva" rotation drive



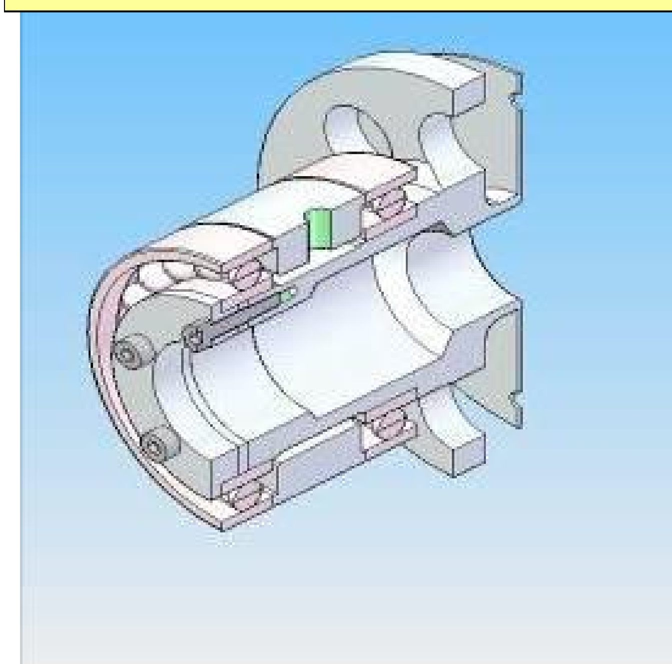
REPLACES

Internally actuated drive and jaw mount for rotating after beam abort damages surface

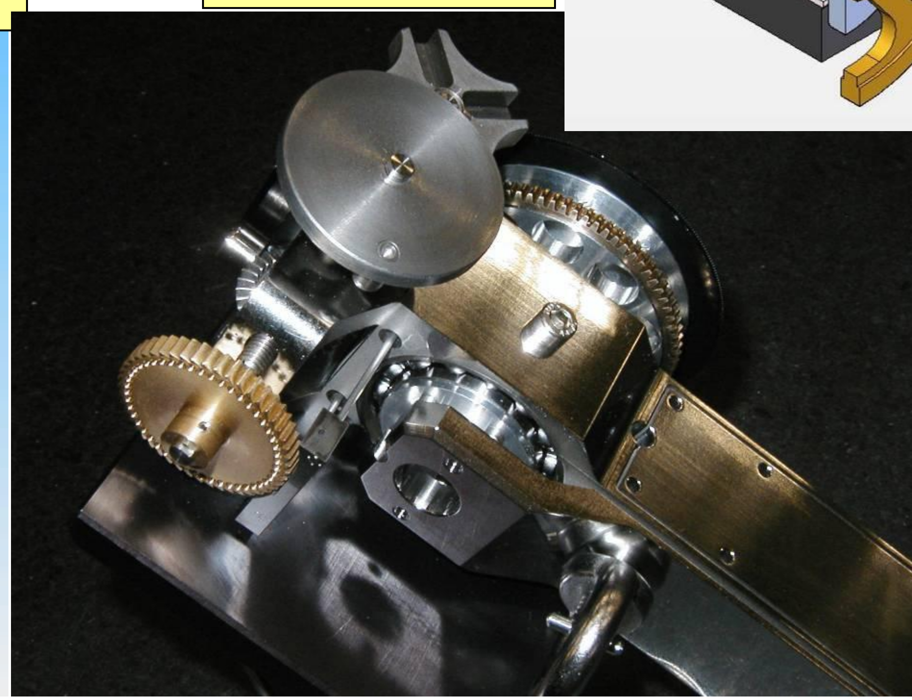
Completed 27 May 2007

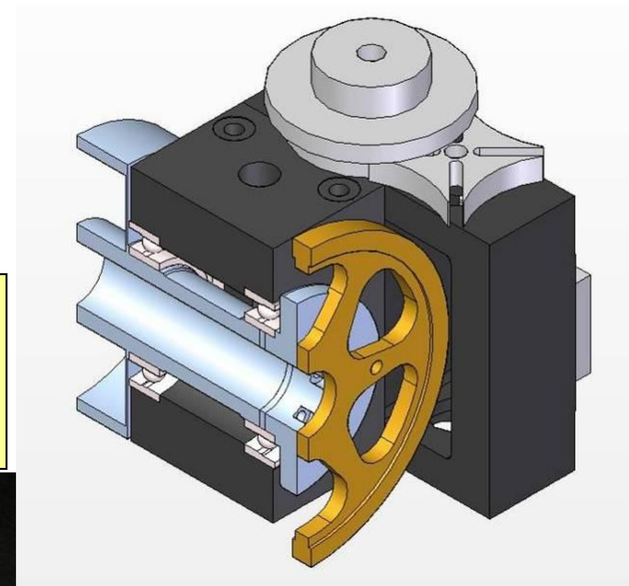
Universal Joint Drive Axle Assembly

- Thermal expansion
- Gravity sag
- Differential transverse displacement



Rotation drive with “Geneva Mechanism”





Simulated Shaft mounted to End Supports

Calculations and full scale mock-up show required motions due to Jaw and Shaft thermal expansions are easily met

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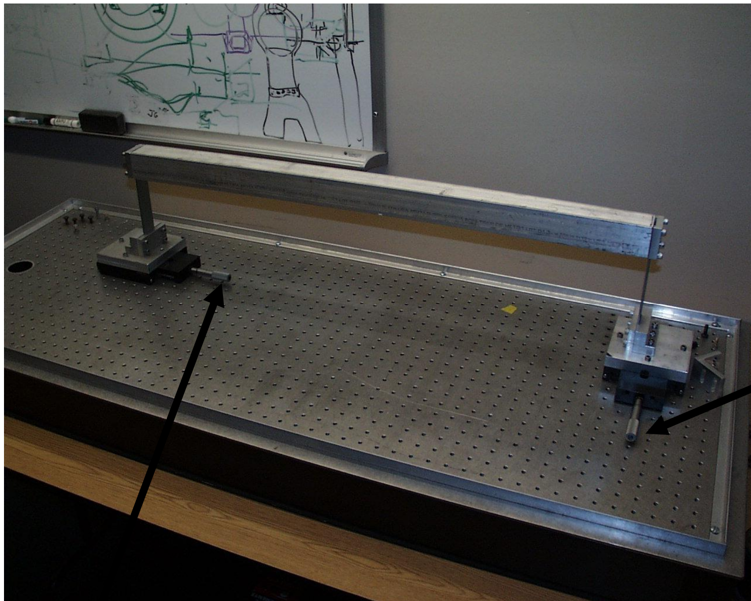
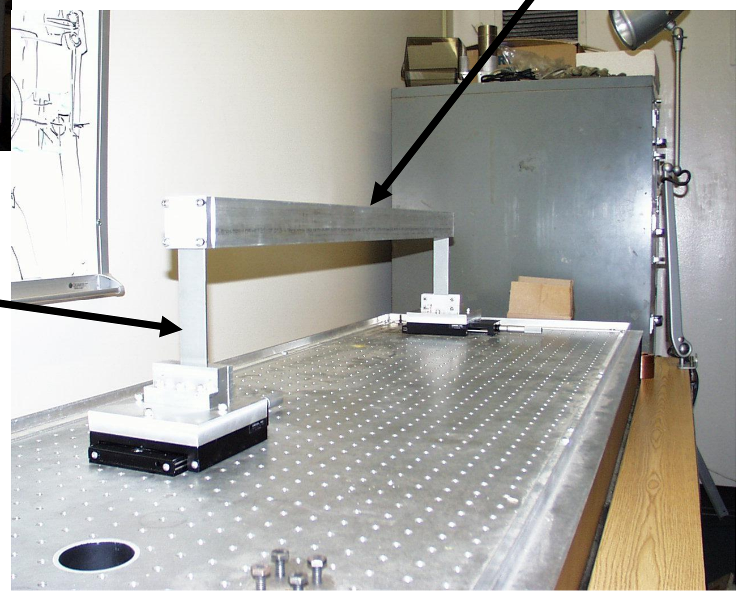


Mass was added (in proper ratio) to mid-point of "shaft" to mimic end rotation of Moly Shaft

Aluminum "Shaft"

"Mic" is used for adjusting in relative transverse offset of ends



Appropriately flexible End Support

"Mic" is used to adjust in the thermal expansion amount expected in accident case.

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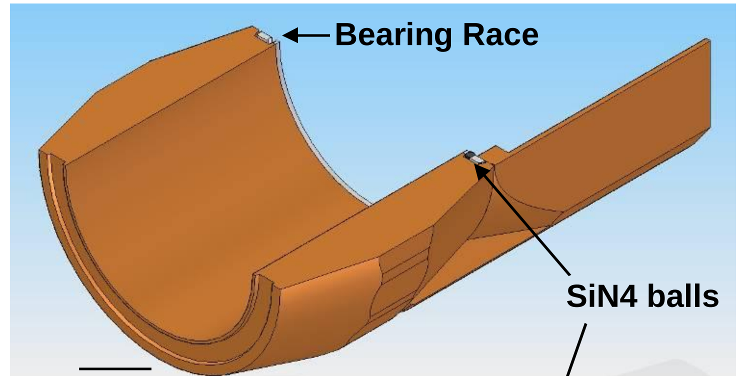
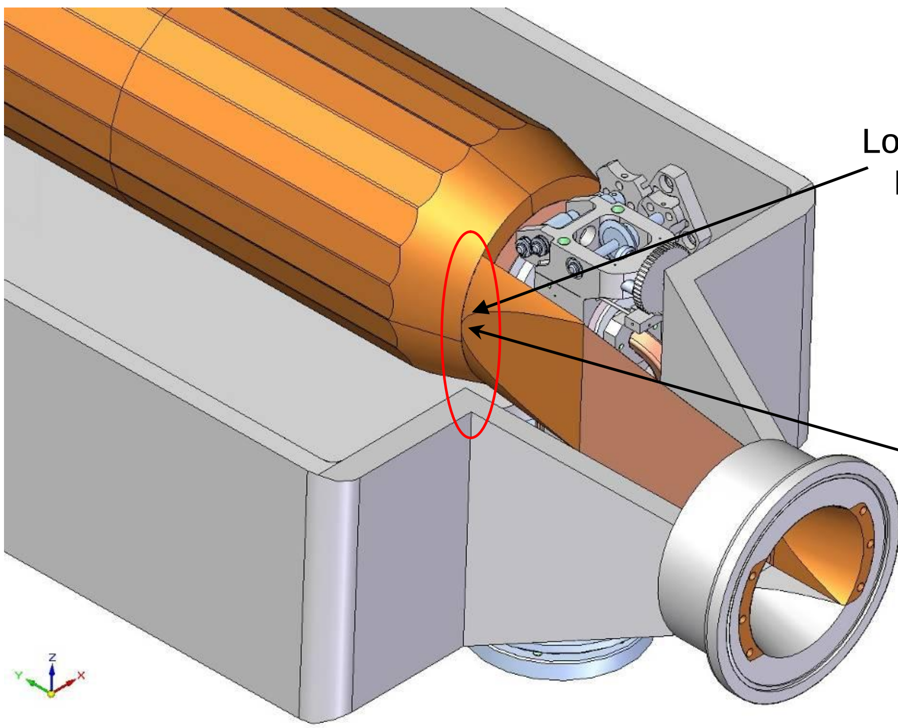
RF Design

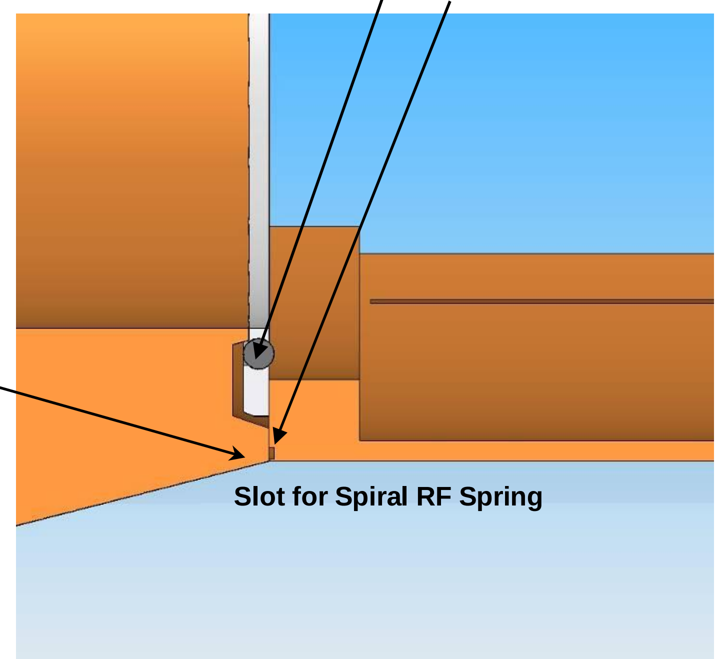
UNDER STUDY

- Contact Resistance Measurements
- Stretched Wire Impedance Measurements
- Trapped mode study using Omega3P

Short RF Test Jaw with End Socket mounted

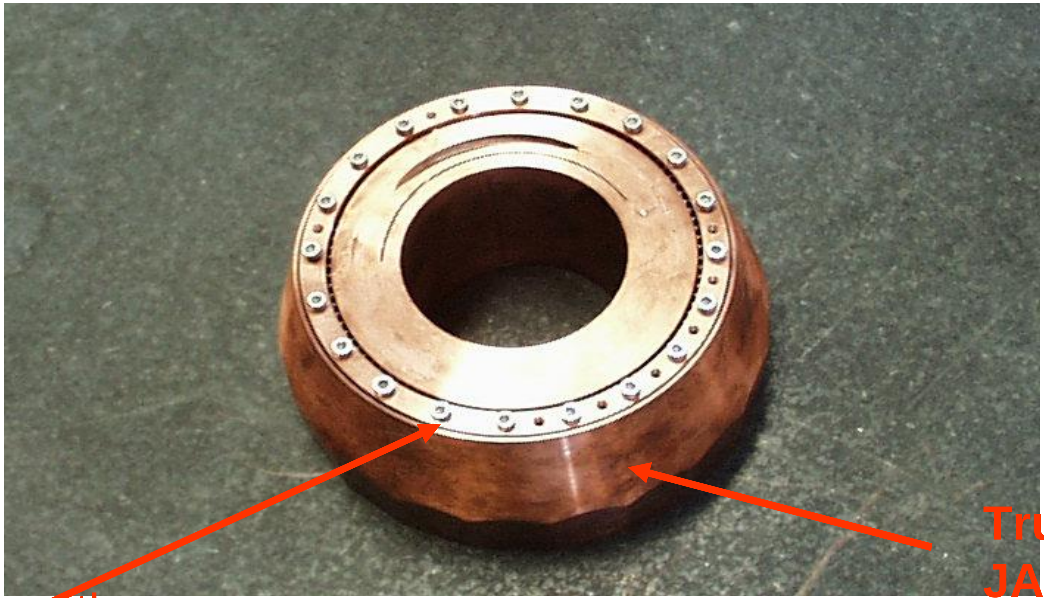






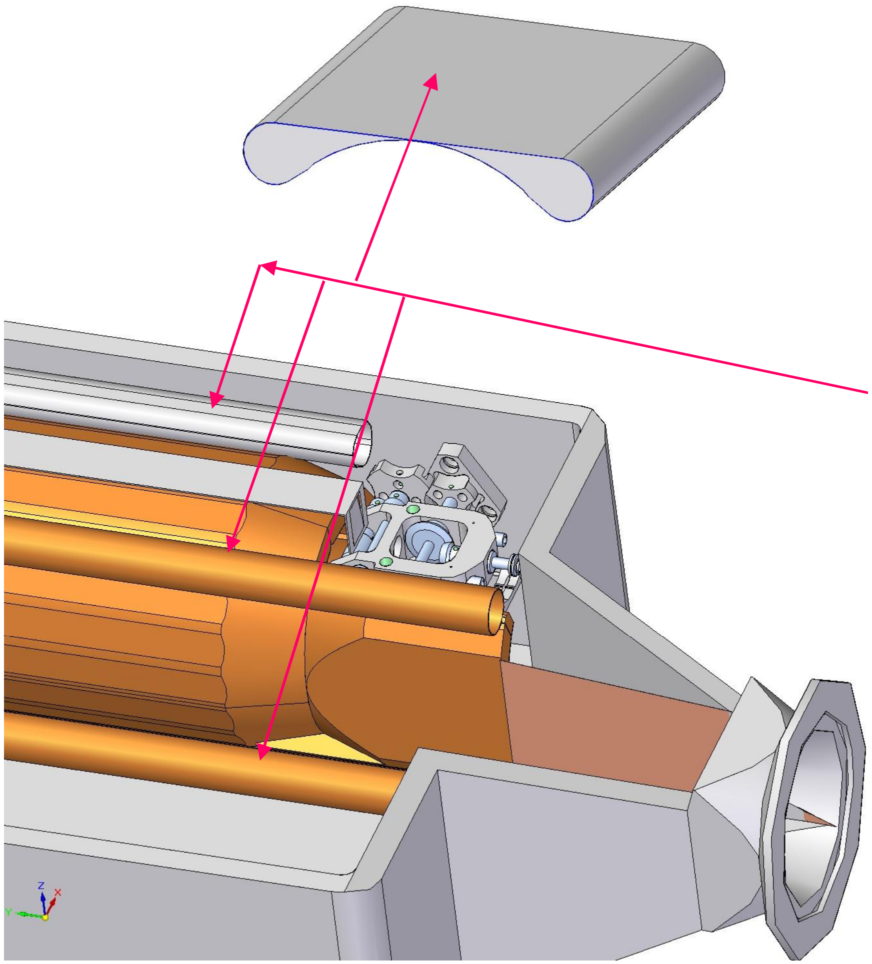
Jaw Transition Resistance Test

- **4 wire resistance test planned**
- **Awaiting reconfiguration of Spring Mounting Ring for new style spring and Rhodium plating on the Spring groove surface**



Spiral Spring Mounting ring not shown

Summary of Impedance Tests and HOM Calculations



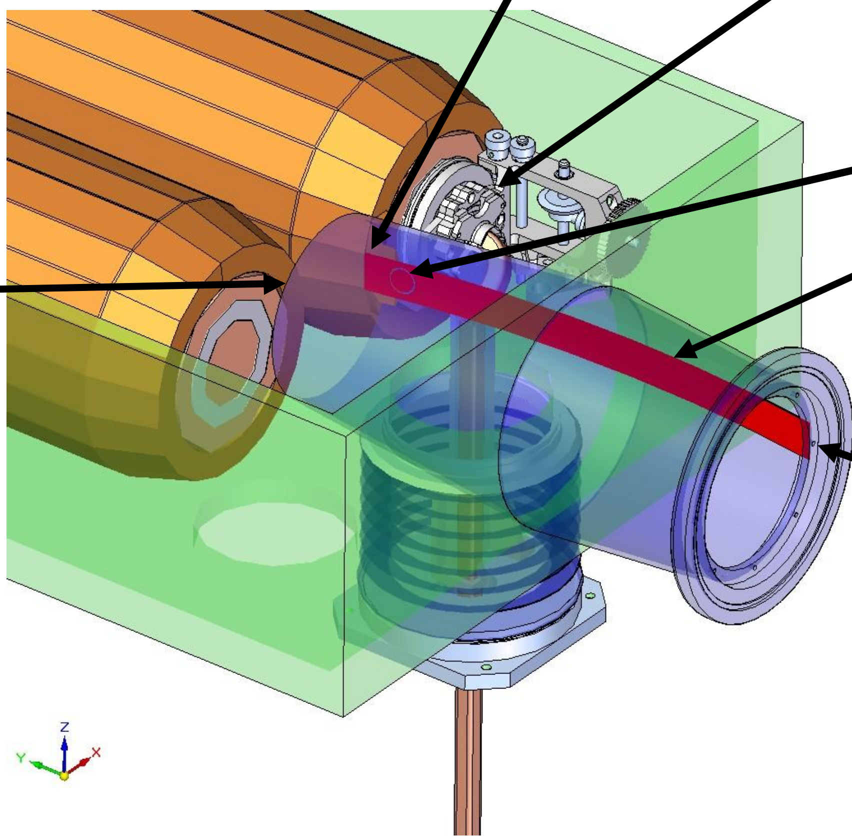
Apologies to Jeff for shortchanging this work in this presentation

Suggest that interested parties discuss details of this part of project with him when he arrives tomorrow

My summary:

1. Do not need contact between tops of jaws and vacuum tank
2. Resistive component of impedance dominates questions of exact shape of transition piece
3. Excellent contact resistance between rotating pieces is required

Design Concept to Incorporate BPM into RF Transition



Rotatable Collimator Task Summary

RC Design essentially complete

First jaw constructed and test results agree with calculation.

In principle all procedures, methods, parts finalized and need only "push the button" to fabricate first full prototype.

However, precision UHV high power devices intrinsically difficult. First jaw had many important construction failures at vendors and at SLAC.

In June 2006 DOE was told

"Expect thermal tests and completely tested RC1 device by end of FY06 and mid-FY07, respectively"

In June 2007 DOE was told:

"Expect thermal tests to begin and completely tested RC1 device by end of FY07 and end-FY08, respectively"

In June 08 DOE was told:

"Expect RC1 device mid-CY09"

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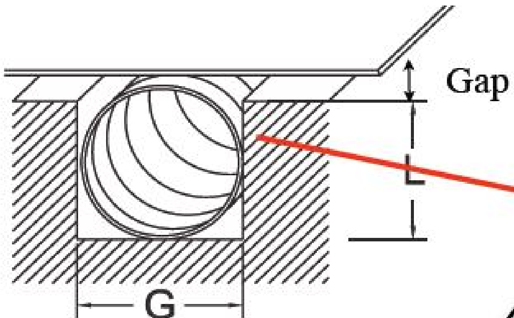
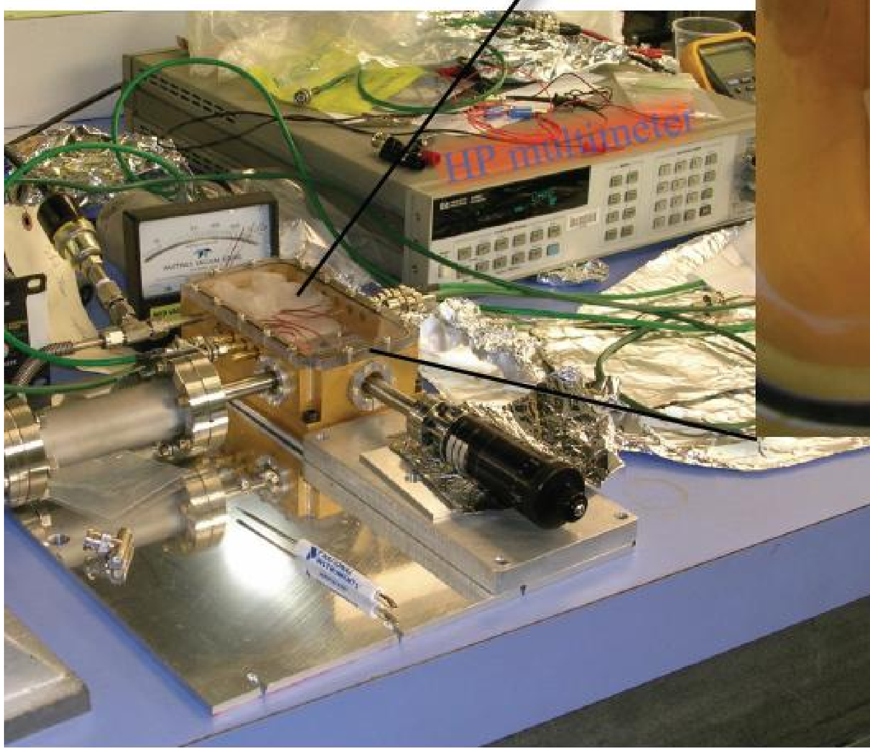
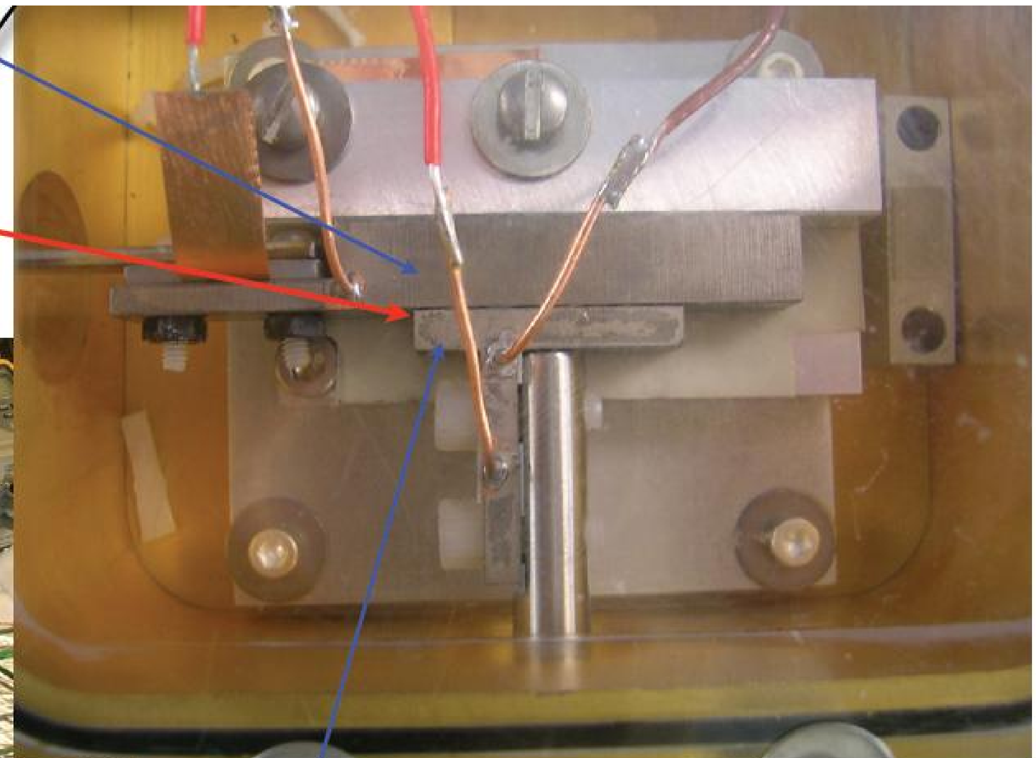
Contact Resistance Experimental Setup for Spira™ Spring



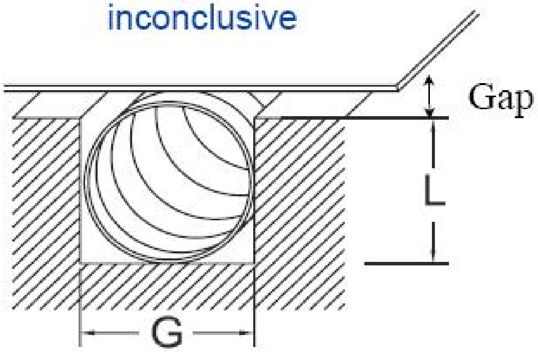




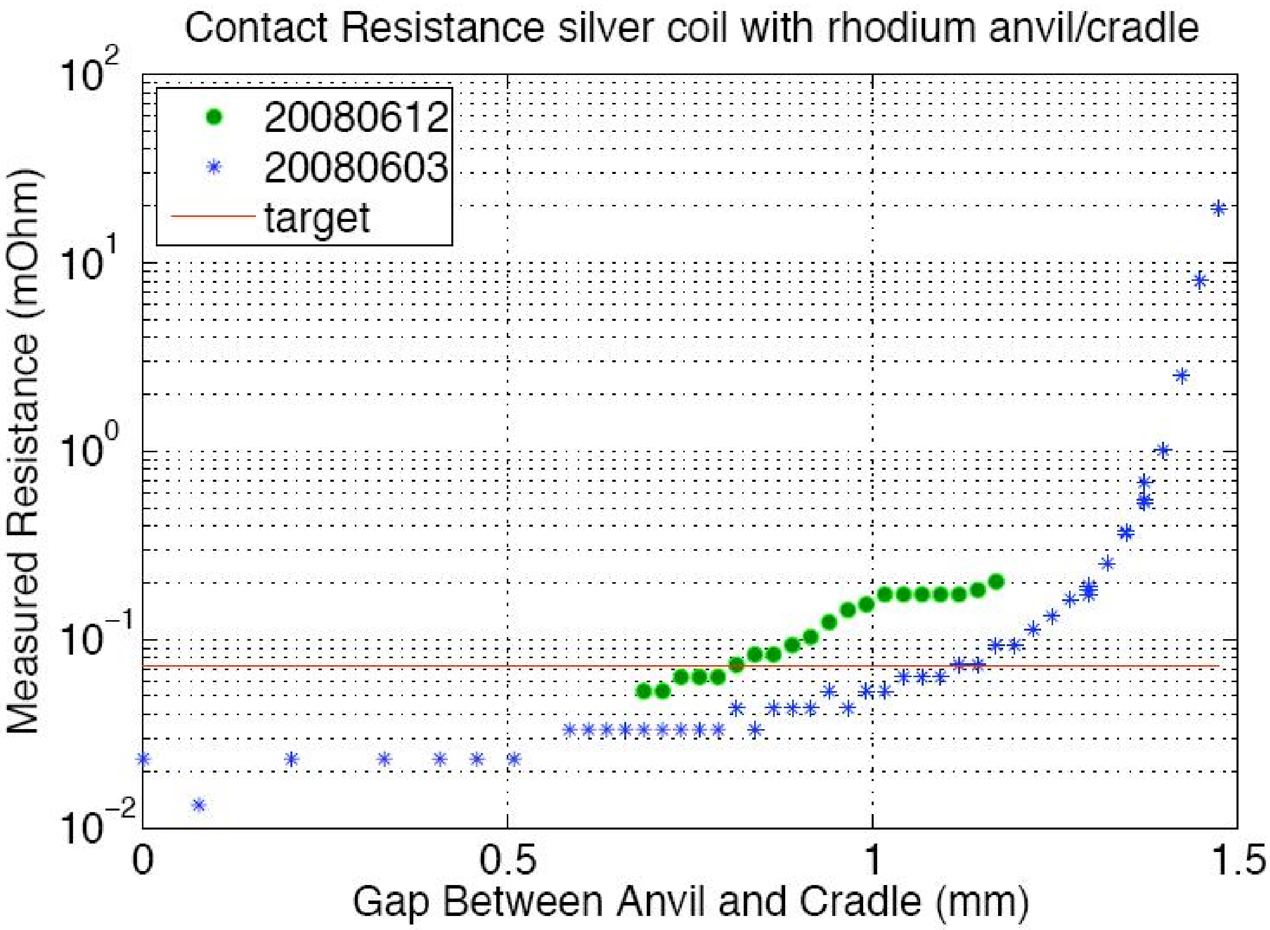
Rhodium plated glidcop anvil and cradle
Silver plated BeCu spiral spring

First 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.
- Still need to look into degradation due to wear and tear with rubbing surfaces
  - Rubbing results so far inconclusive



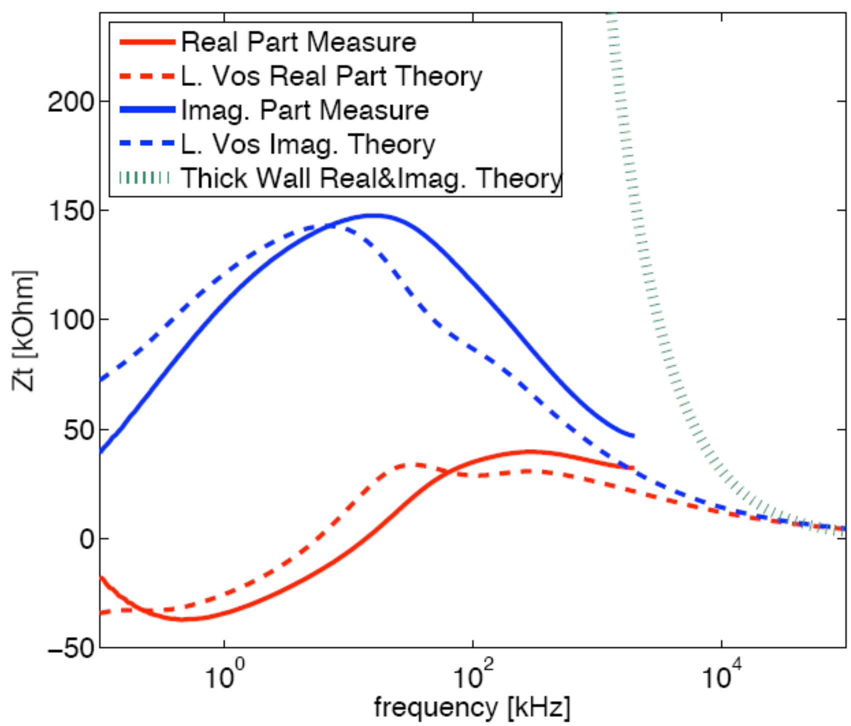
Spira Manufacturing Corporation

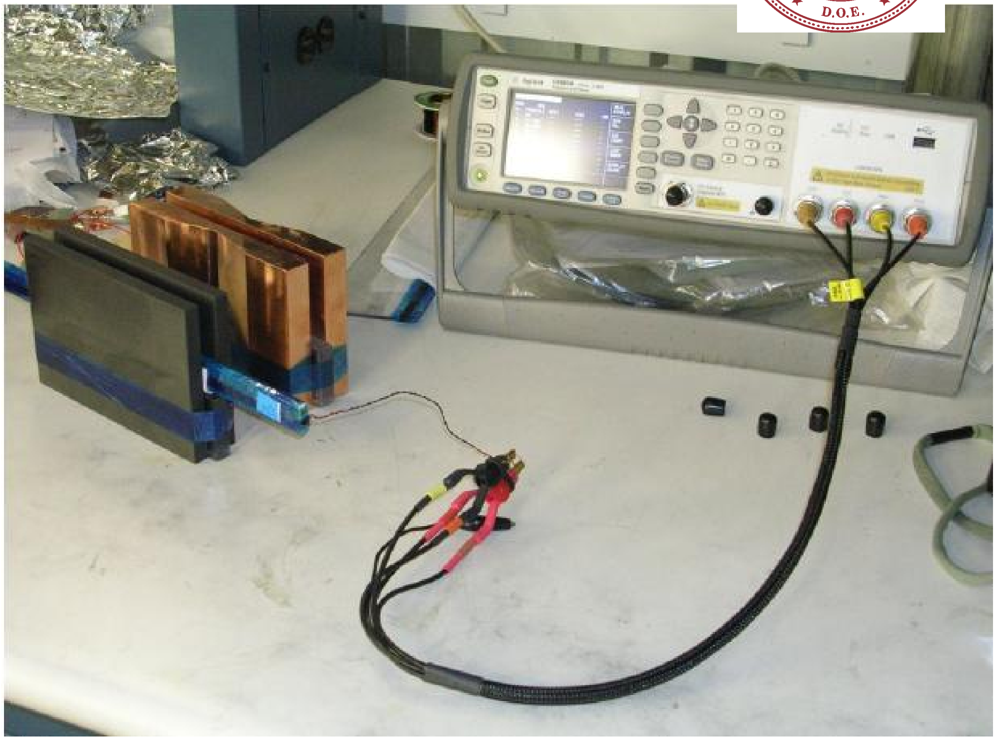


Stretched Coil Impedance Measurements

•LCR meter obtained (better than Network Analyzer for low frequency impedance)
•First step just to measure inductive by-pass in graphite and copper and confirm CERN results

Graphite – Copper Plate Impedance Measurement



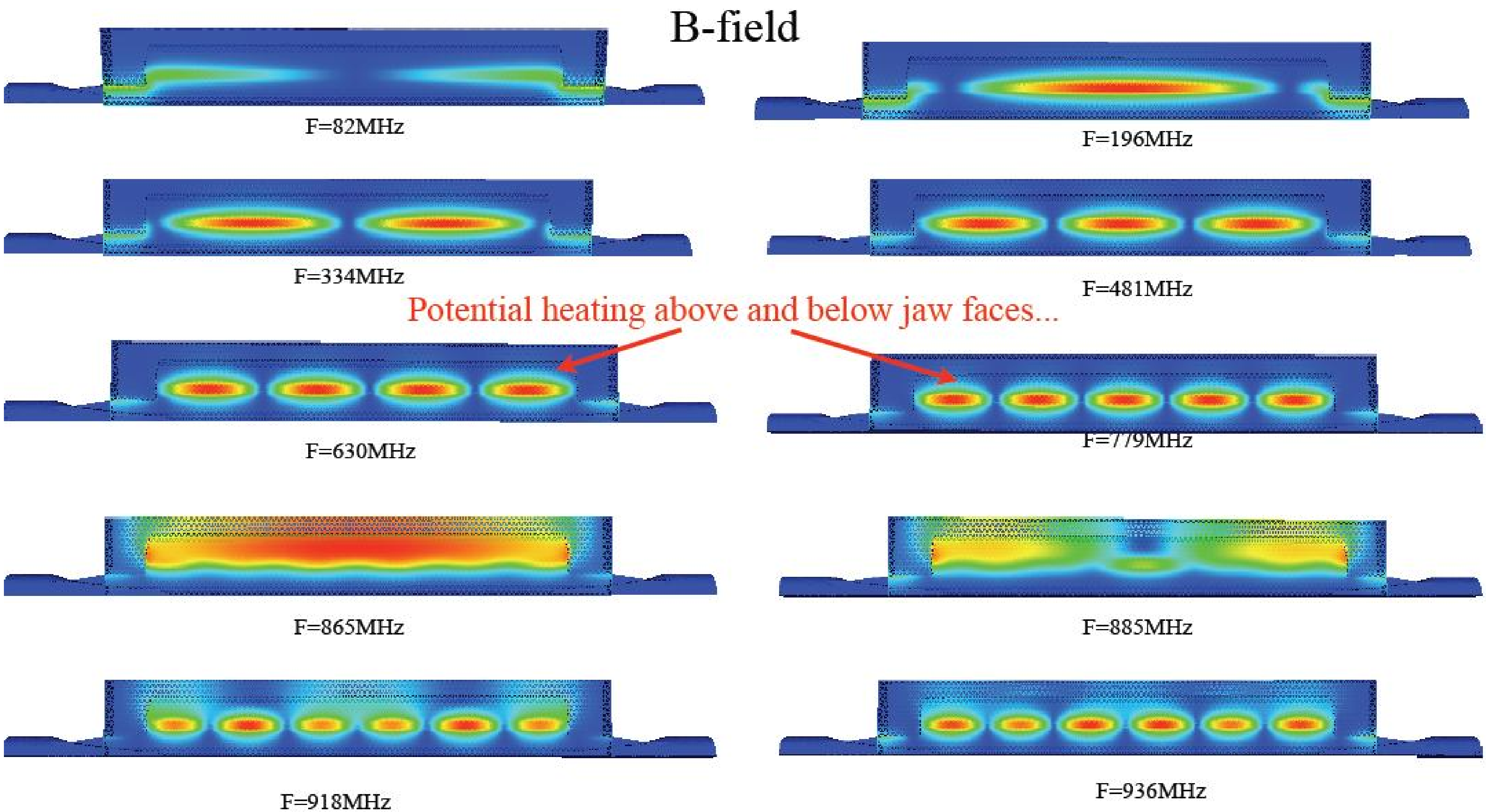


•Agreement between measurement and theory not as good as CERN

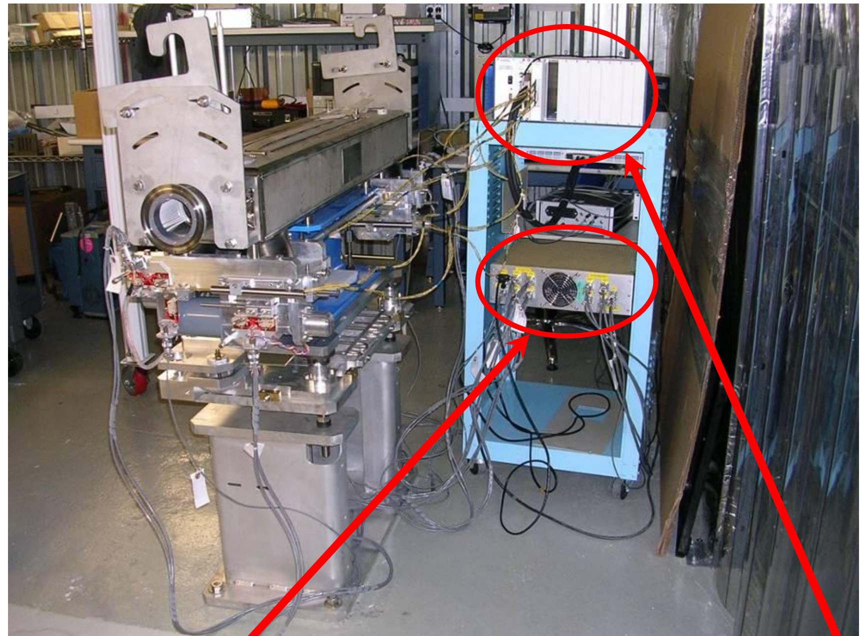
•Much more planned for these measurements!

Preliminary results on TM monopole modes-Omega3p run

Beam pipe R=42mm, Fc(TE11)=2.1GHz, Fc(TM01)=2.73GHz

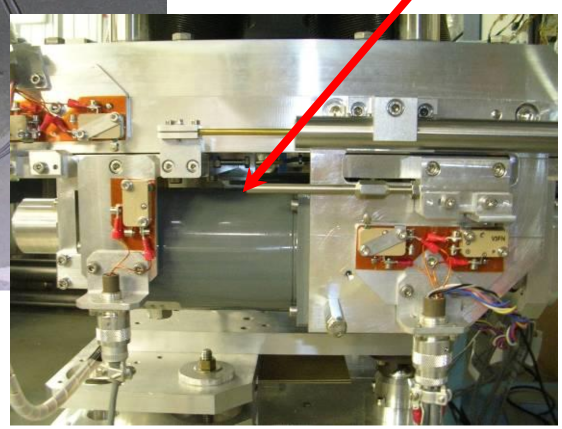


Phase I Graphite Collimator Bought from CERN & mounted and set up in our lab



Stepper Controller

LVDT Controller



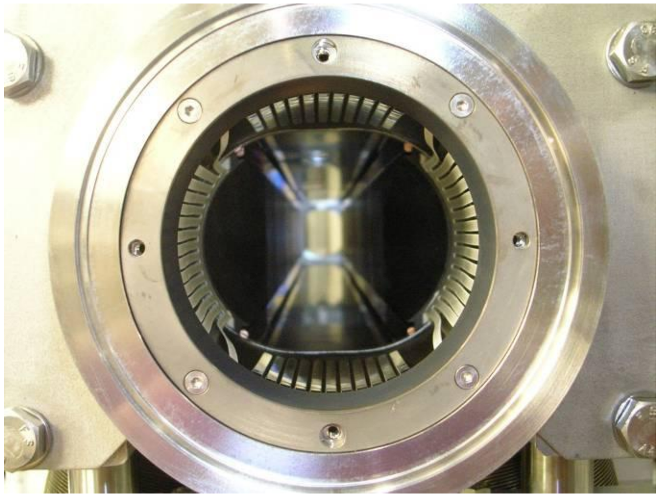
Motion Control

CERN LabView control software modified and working with our controllers.

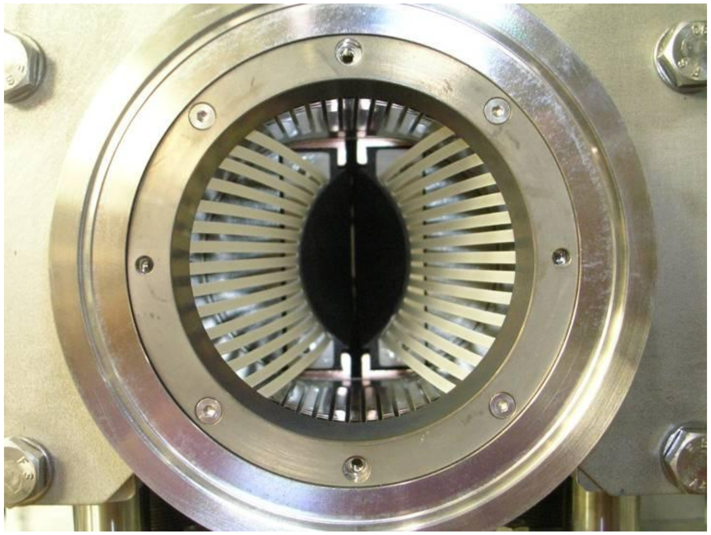
Verified full motion of Phase I jaws as test of SLAC steppers & controllers

Will test steppers for increased weight of copper jaws and be sure LAR{ jaws can be controlled by CERN software before shipping

Open



Closed



Bonus Slides

LHC Collimation Requirements

LHC Beam Parameters for nominal *L*=1E34cm^{-2}s^{-1}:

- 2808 bunches, 1.15E11 p/bunch, 7 TeV → 350 MJ
- Δt=25ns, σ~200μm (collisions)

System Design Requirement: Protect against quenches as beam is lost

- Design shielding for expected <τ>~30hr or 3E9 p/s or 3.4kW
- Design collimator cooling for τ = 1 hour or 8E10 p/s or 90kW
- Plan for occasional bursts of τ = 12 min or 4E11 p/s or 450kW
  - abort if lasts > 10 sec

Collimation system inefficiency:

- Inefficiency · Max Loss Rate < Quench Loss Rate
- dQ/dV ~ 1.5mW/gm in SC coil causes quench
- Estimate inefficiency of collimation system via SIXTRACK program
- Determine minimum required inefficiency via FLUKA/MARS
  - 8E6 p/s on TC will quench Q3 in triplet → 2E-5 inefficiency @ 4E11 p/s loss

The LHC Collimation System

Betatron Collimation in IR7

- 3 short (60cm) “Primary” collimators (H,V,S) at 6σ per beam
- 11 long (1m) “Secondary” Collimators (various angles) at 7σ per beam

Momentum Collimation in IR3

- 4 long (1m) “Secondary” collimators per beam

Other

- 1m H&V Tungsten Tertiary Collimators at Experimental IRs at 8.4σ
- 1m Cu or W Absorbers at 10σ
- Warm Magnets, tunnel and shielding absorb remainder of lost beam energy

Accident Scenario

When beam abort system fires asynchronously with respect to abort gap (armed HV trips accidentally) **8 full intensity bunches 1 MJ** will impact collimator jaws

Non-Accident Engineering Challenge

- The first long secondary collimator downstream of the primary system must absorb much more energy than any other secondary in the system since 80-85% of list particles interact inelastically in the 6σ primaries
- The deformation specification of the collimator jaw is set at 25μm in order to maintain system efficiency

Phase I and Phase II Collimation

Phase I: Use Carbon-Carbon composite as jaw material

- 60cm/1m Carbon undamaged in Asynchronous Beam Abort
- Low energy absorption of secondary debris eases cooling & tolerances
  - 6-7 kW in first 1m C secondary behind of primaries when dE/dt=90 kW
    - 10 sec 450 kW load handled as a transient
- Low, but adequate collimation efficiency to protect against quenches at lower *L* expected at startup
- High, but adequate machine impedance for stable operation at low *L* expected at startup

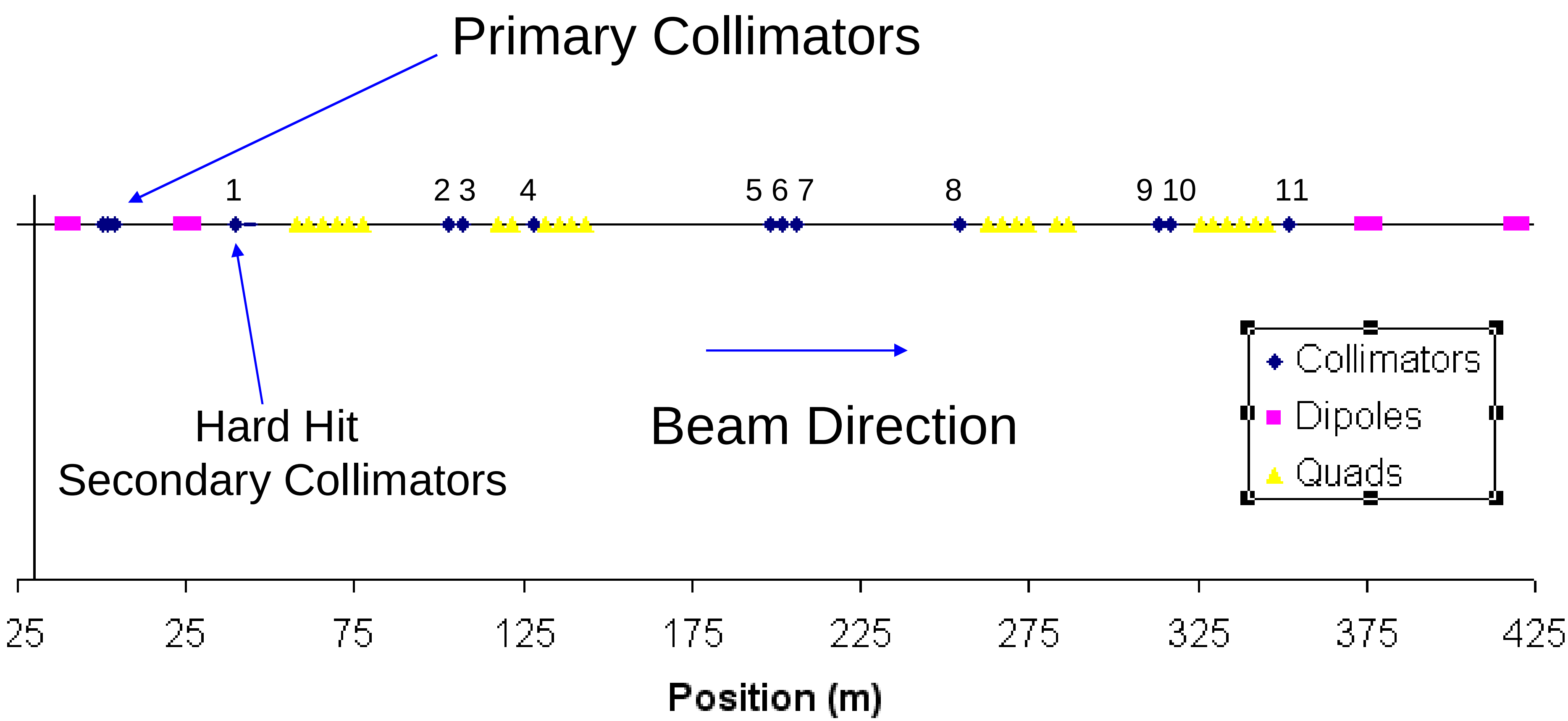
Phase II: Metal collimators into vacant slots behind each Phase I secondary

- Good impedance and efficiency allowing LHC to reach design L= 1E34
  - After stable store open Carbon jaws and close Metal jaws
- Jaw will be damaged: **how badly?** what to do?
- More energy from primaries will be absorbed: cooling & **deformation**
  - only pertains to **first** collimator per beam in betatron cleaning insertion!

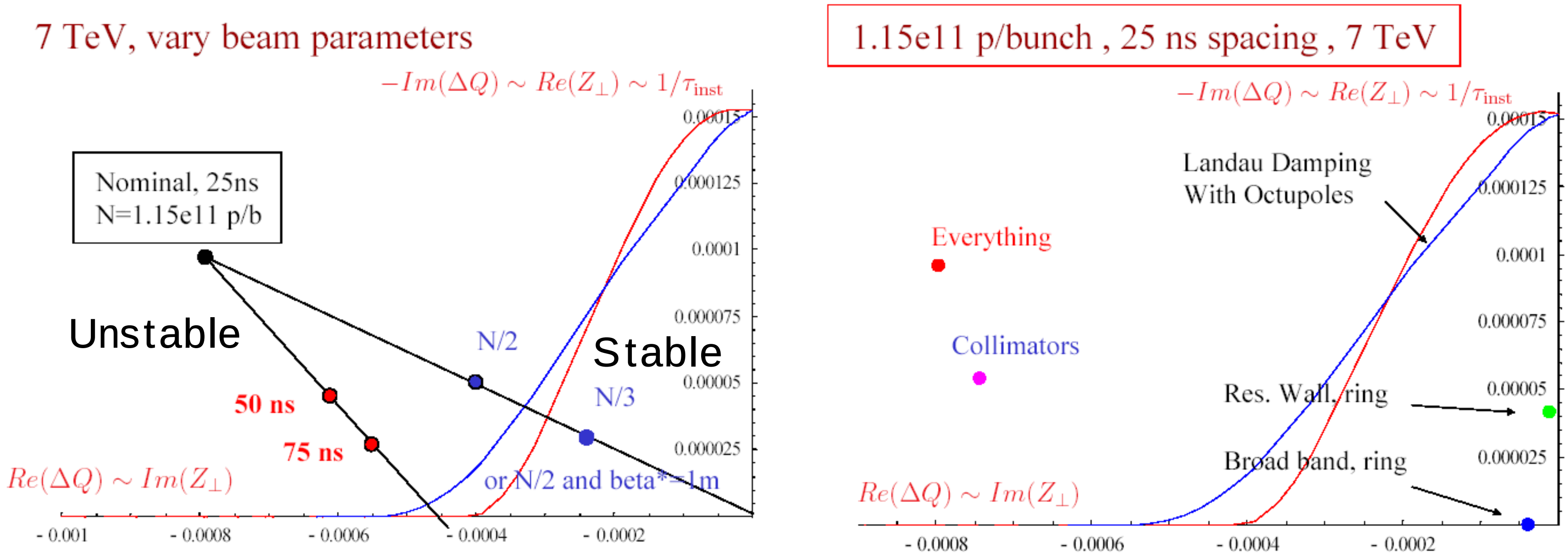
IR7 Collimator Layout

11 Carbon Phase I and 11 Metal Phase II

Secondary Collimators per beam in IR7



Impedance Limits Luminosity
Carbon Collimators Dominate Impedance

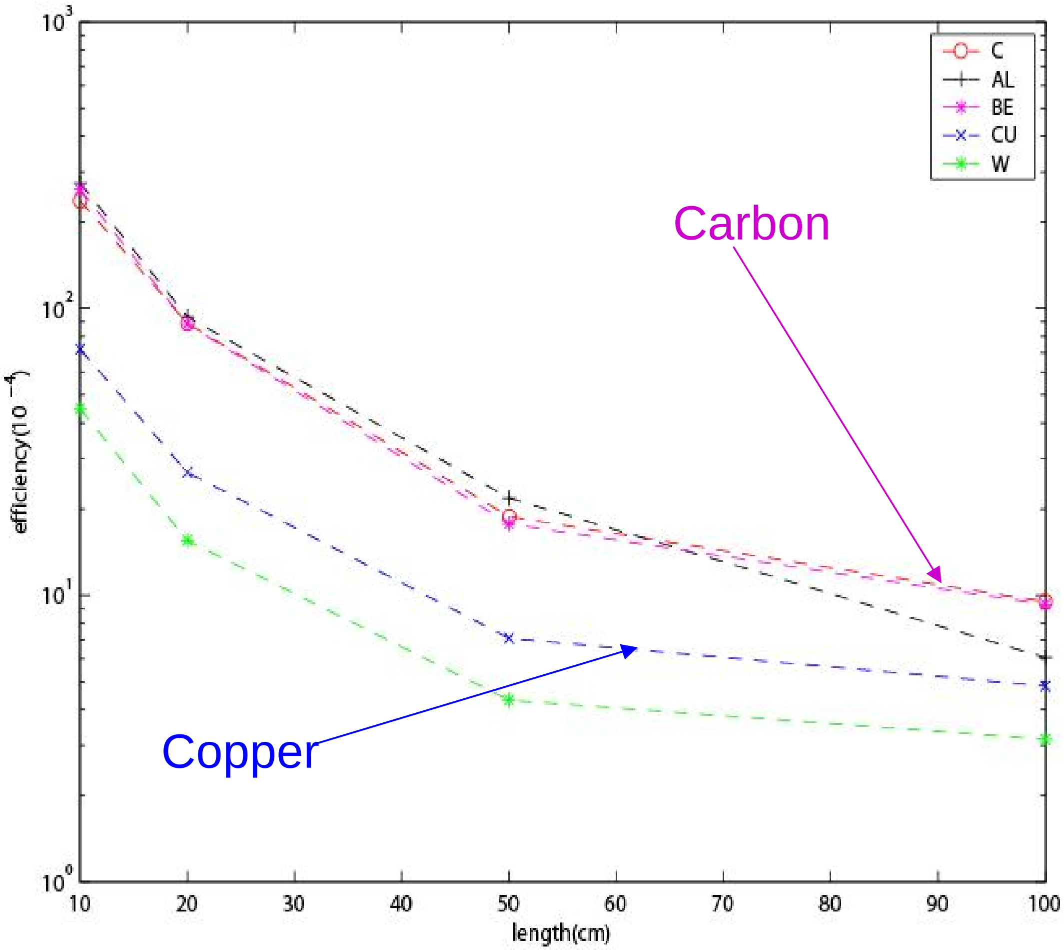


➔ Limitation at about **40% of nominal intensity**… (nominal β*, full octupoles)

SIXTRACK simulation

compare materials' collimation efficiency tradeoff with mechanical performance

Yunhai Cai



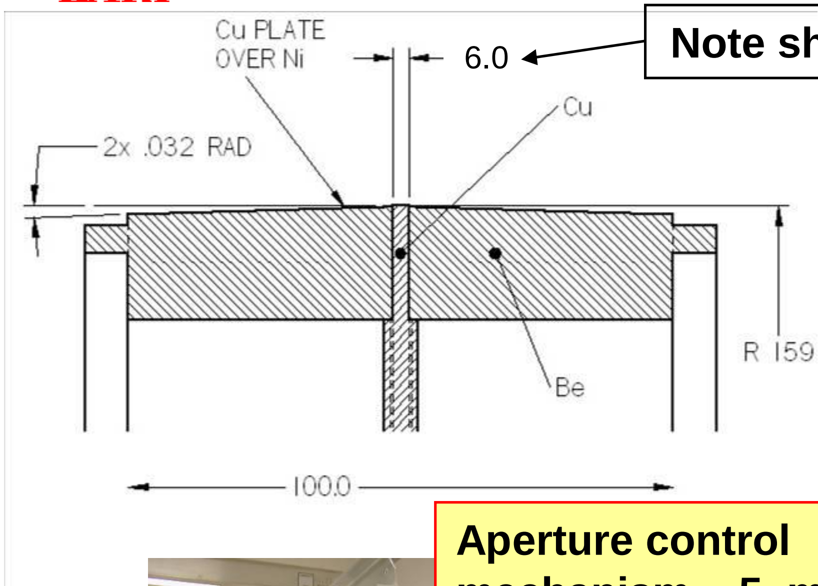
- High Z materials improve system efficiency but generate more heat
- Copper eventually selected for SLAC Phase II design because of its high thermal conductivity and ease of fabrication
- Available length for jaws is about 1 meter, although gain after ~50cm is minimal

Similar result was obtained by Ralph Aβmann

NLC Consumable Collimator:

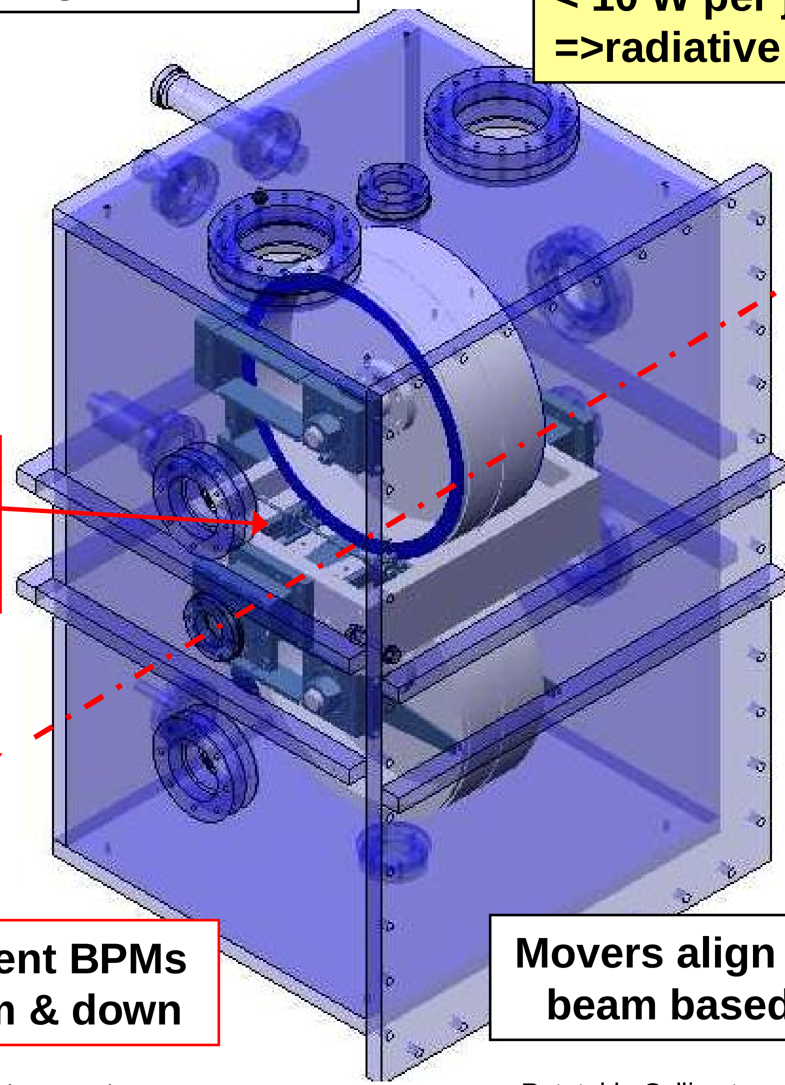
32cm diameter, thin, rotatable jaws – 500 to 1000 hits with no cooling

LARP



Note short high-Z material.

Aperture control mechanism – 5μm accuracy & stability



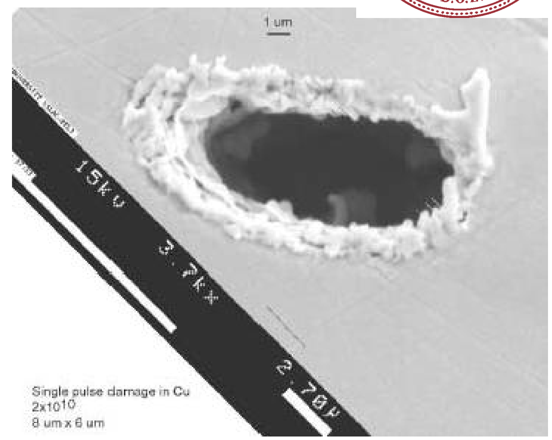
< 10 W per jaw =>radiative cooling!

Alignment BPMs upbeam & down

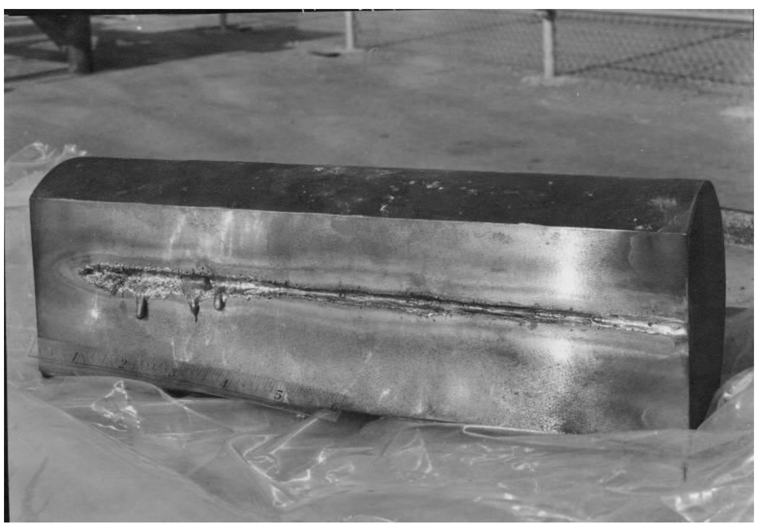
Movers align chamber to beam based on BPMs

Exact Nature & Extent of Damaged Region
Biggest DESIGN RISK to RC

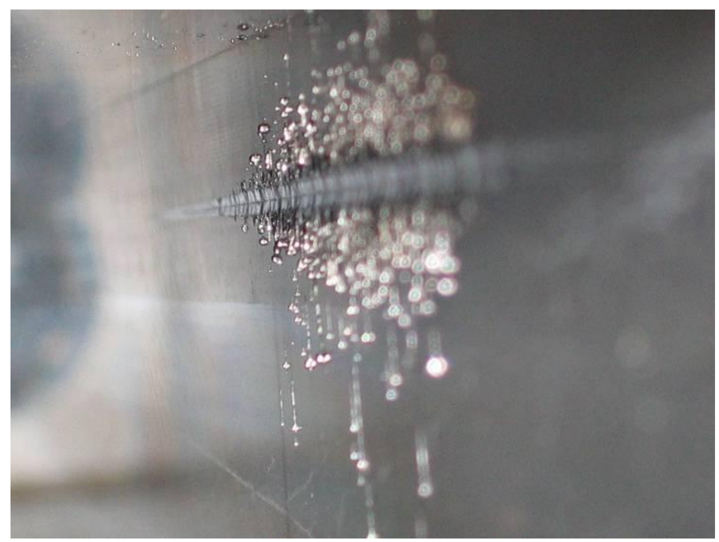
Thin Cu sample in FFTB electron beam at SLAC
Hole = Beam Size



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



SLAC Timeline for RC=Rotatable Collimator Prototype
Pre-APL Plan

LARP

2004: Introduction to project

2005: Conceptual Design Phase II RC using FLUKA, SIXTRACK and ANSYS; External Design Review: changes recommended

2006 Hire full time ME and designer: Improved Conceptual Design; fabricate winding tooling, 2D/3D drawings of test and final parts, braze two 20cm test pieces; collimator test lab set up begins

2007: Vacuum test & section test parts, braze and test 3rd 20cm unit, develop and build rotation mechanism, complete Cu/Mo shaft-hub assembly; hire first postdoc; preliminary design RF shield design; acquire CERN Phase I collimator

2008 Fab 1st full length jaw; equip CERN collimator with steppers and LVDTs; thermal tests of single jaw; more tests to improve braze process, begin to fabricate two more mandrels, jaws, shafts, rotation devices, …for RC

2009: Finish all parts and assemble into a vacuum tank compatible with Phase I adjustment mechanism = RC; Mechanically test RC, ship and install in SPS/LHC

2010: Collimator tests at LHC & Final drawing package for CERN

2011: Await production & installation of chosen design(s) by CERN

2012: Commissioning support

Main Deliverables

Thermal tests of single collimator jaw

Construct and mechanically test full RC prototype to be sent to CERN

CERN Collimation Plan & Schedule

0) Assume SLAC LARP develops Rotatable Collimator
1) Develop TWO other complementary designs
2) Develop a test stand for the three designs
3) Fabricate 30 Phase II collimators of chosen design & 6 spares

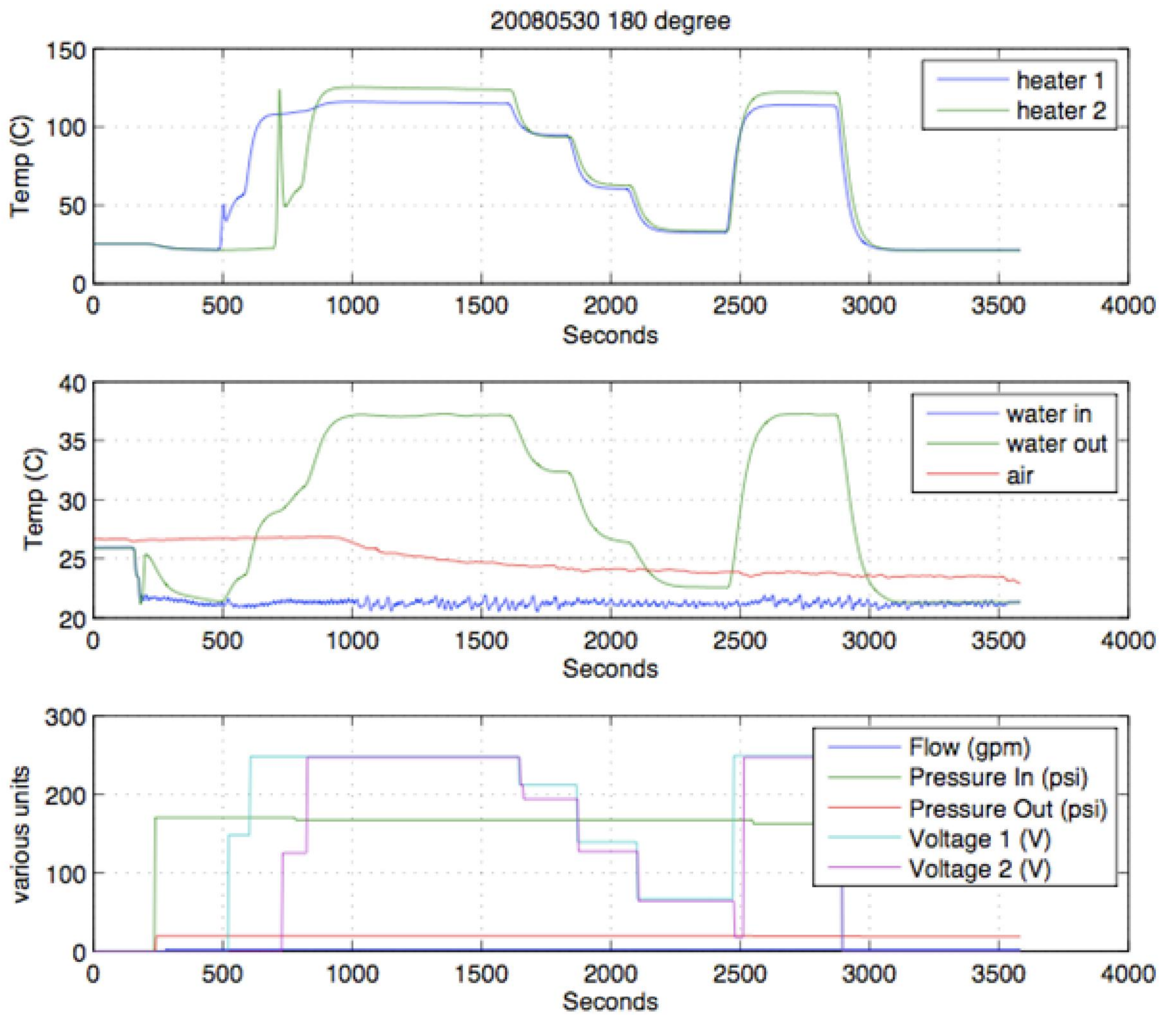
The target schedule for phase 2 of LHC collimation:

2005	Start of phase 2 collimator R&D at SLAC (LARP) with CERN support.
2006/7	Start of phase 2 collimator R&D at CERN.
2009	Completion of three full phase 2 collimator prototypes at CERN and SLAC. Prototype qualification in a 450 GeV beam test stand at CERN.
2010	Installation of prototypes into the LHC and tests with LHC beam at 7 TeV. Decision on phase 2 design and production at end of year
2011	Production of 36 phase 2 collimators.
2012	Installation of 30 phase 2 collimators during the 2010/11 shutdown. Commissioning of the phase 2 collimation system. LHC ready for nominal and higher intensities.
RED	One year slip from recent white paper, “Second Phase LHC Collimators”

Measurements

Measure:

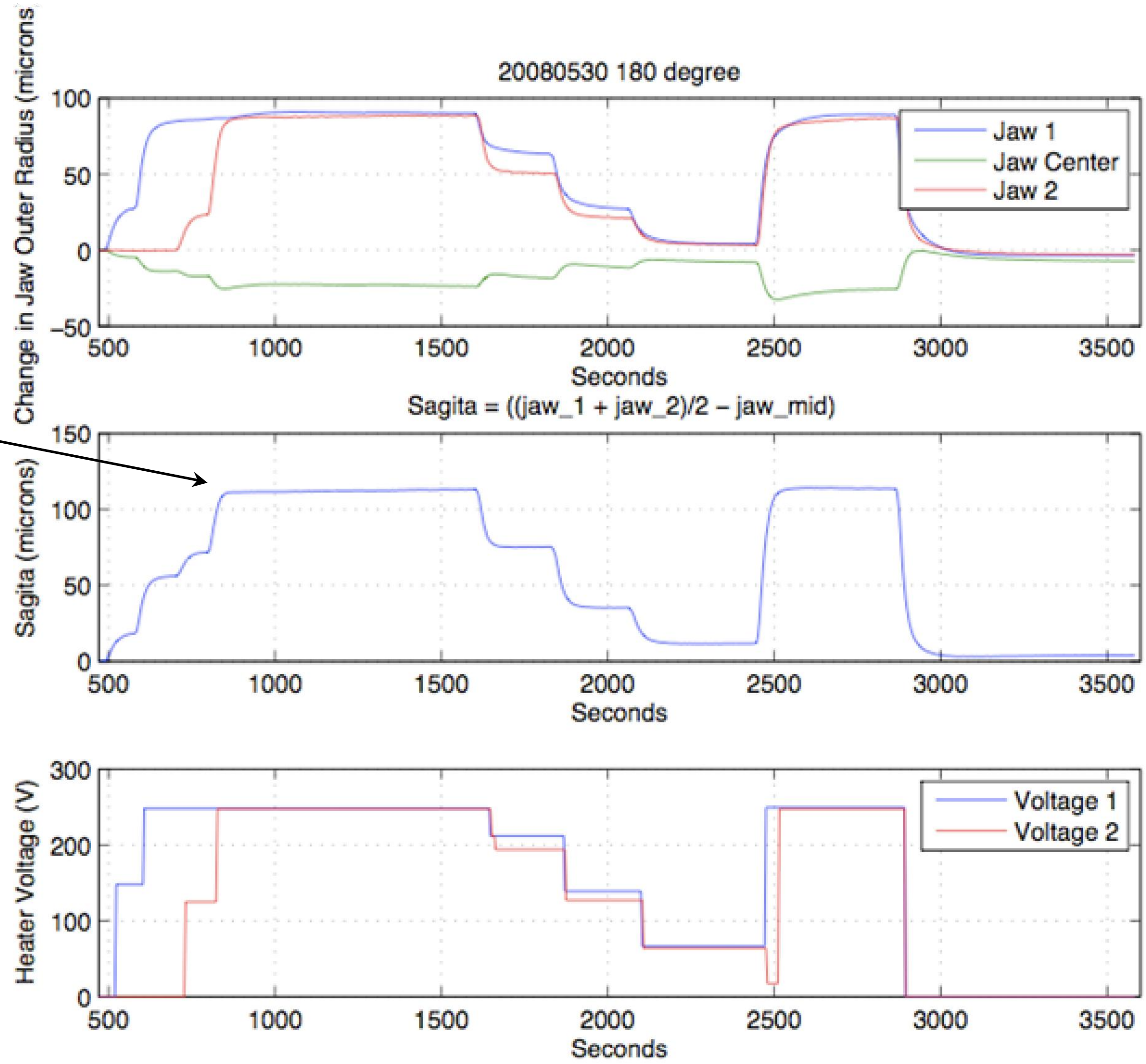
- time
- water flow
- water pressure in
- water pressure out
- water temp in
- water temp out
- power supply voltage x2
- power supply current x2
- capacitive distance sensors x3
- thermocouples x22
- 37 parameters in total



Results consistent with ANSYS Simulations

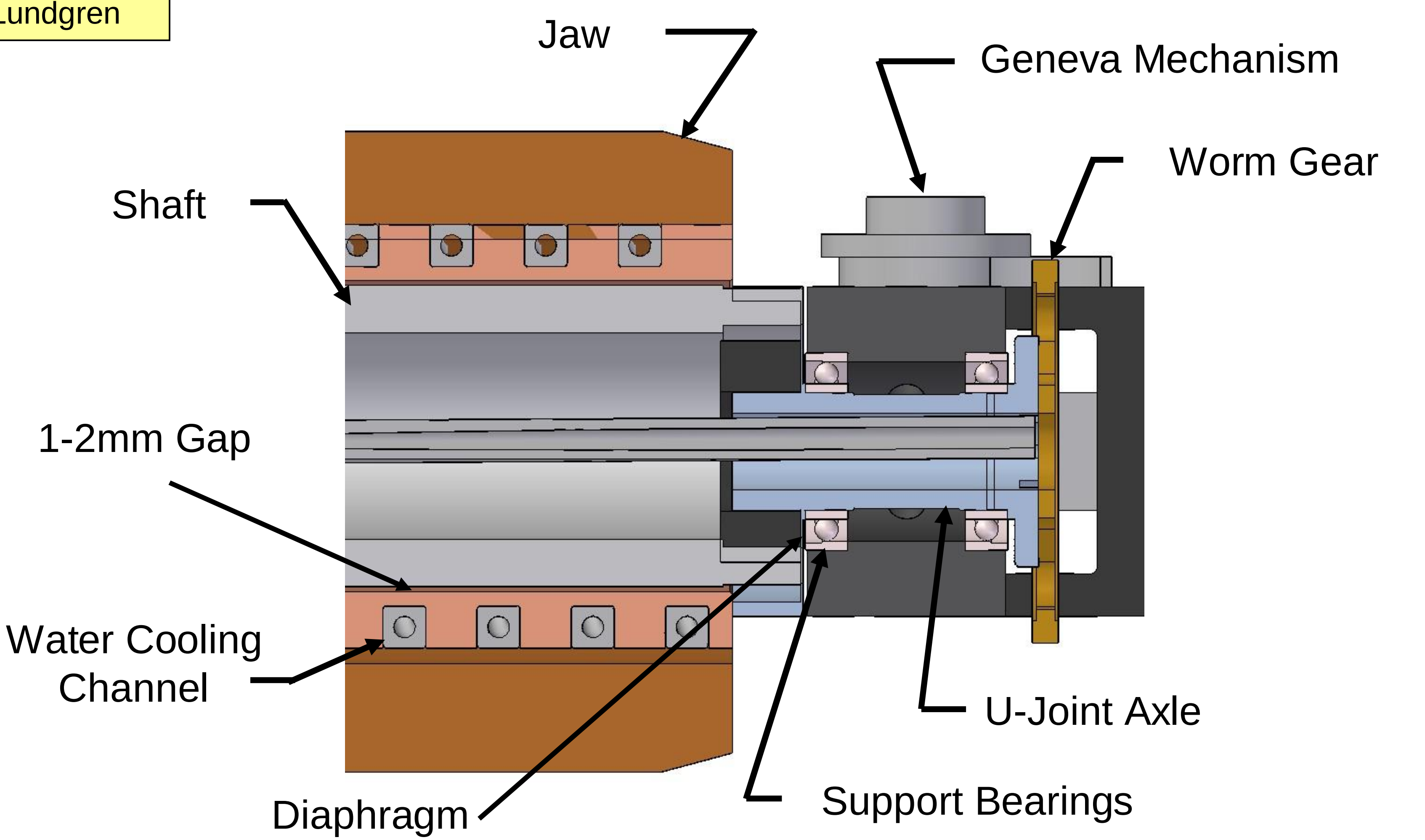
Total Sagita: 112 microns

ANSYS Simulation predicts 100 microns

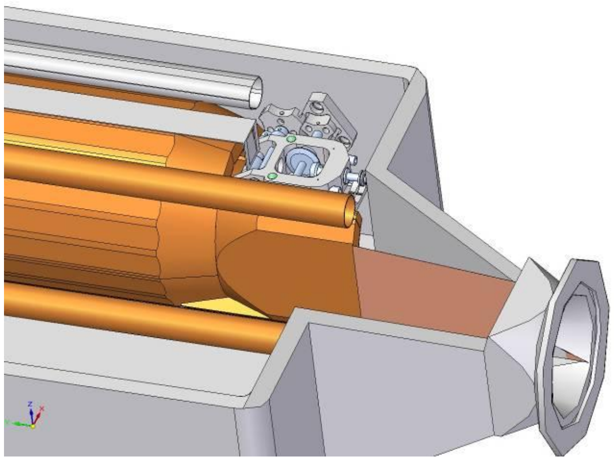


Upstream end vertical section

Lundgren



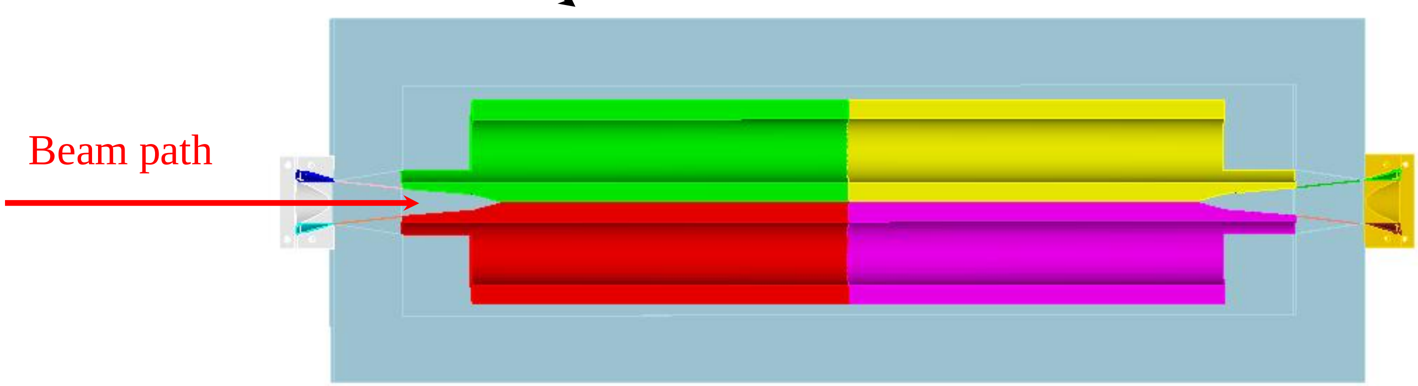
RF Trapped Modes studies



- Studies have begun on looking into trapped modes in our collimator design
- Many cavities and crevices, hour-glass shape
- Will RF leak out into chamber behind jaws?
- Cause wakefields effecting beam?
- Chamber heating? Melt RF contacts?
- Studies being carried out by Cho Ng and Liling Xiao with help by Karl Bane.

Model of collimator in Omega3P with jaws fully inserted

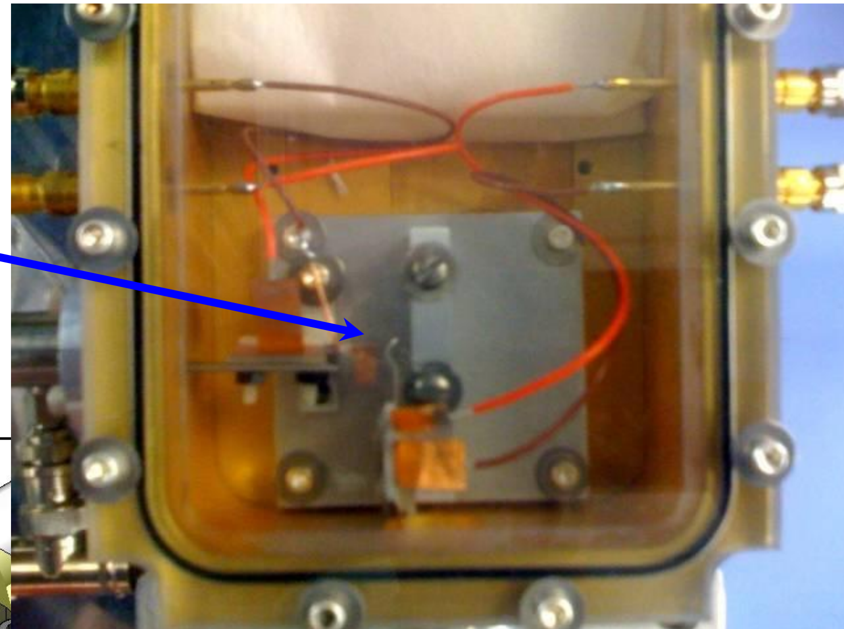
Omega3P uses the finite-element method and parallel processing. The finite-element method allows high-fidelity representation of complex ...ate calculations can ...cessing helps tackle ... shorten

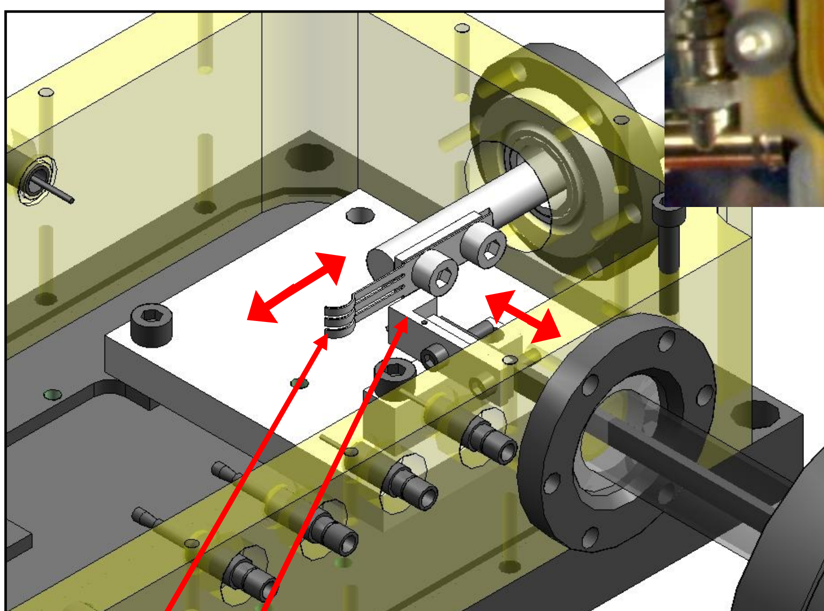


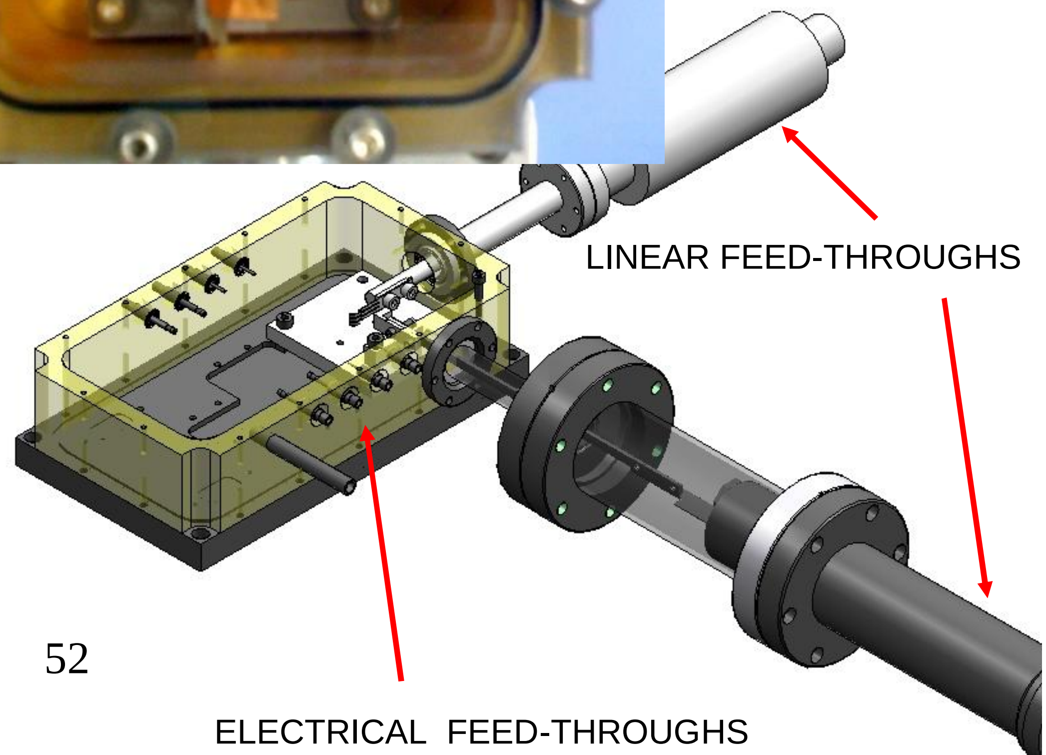
RF Contact Measurements Setup

LARP

Test critical RF contact resistance.
First results with silver coated fingers ~0.6 mOhm.



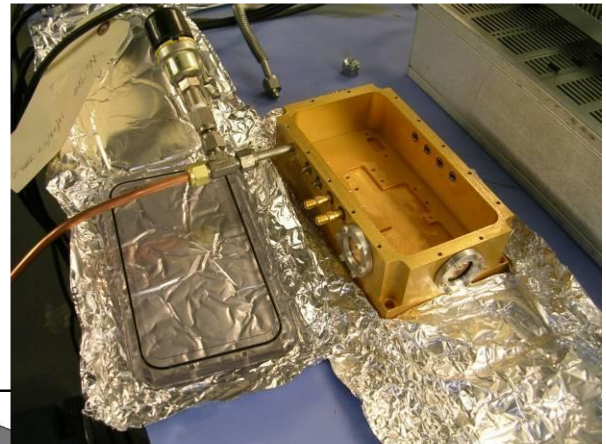


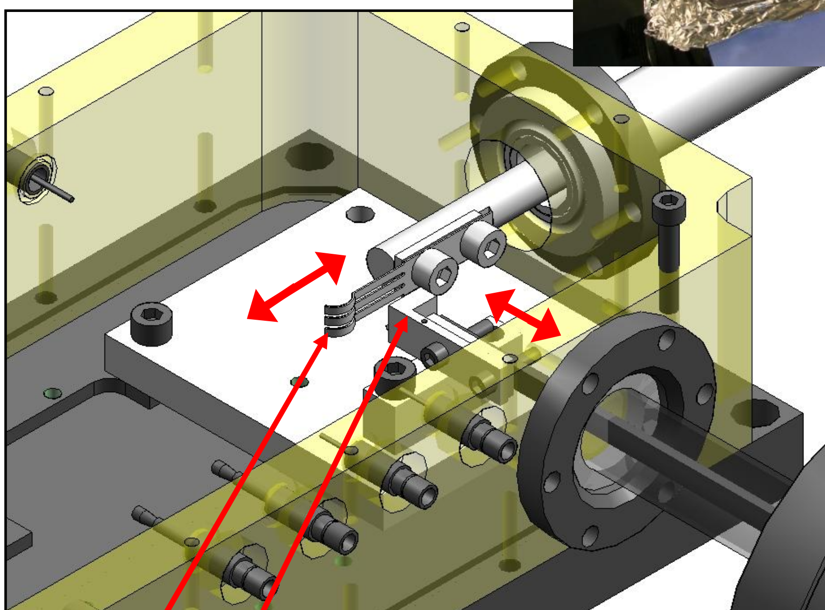


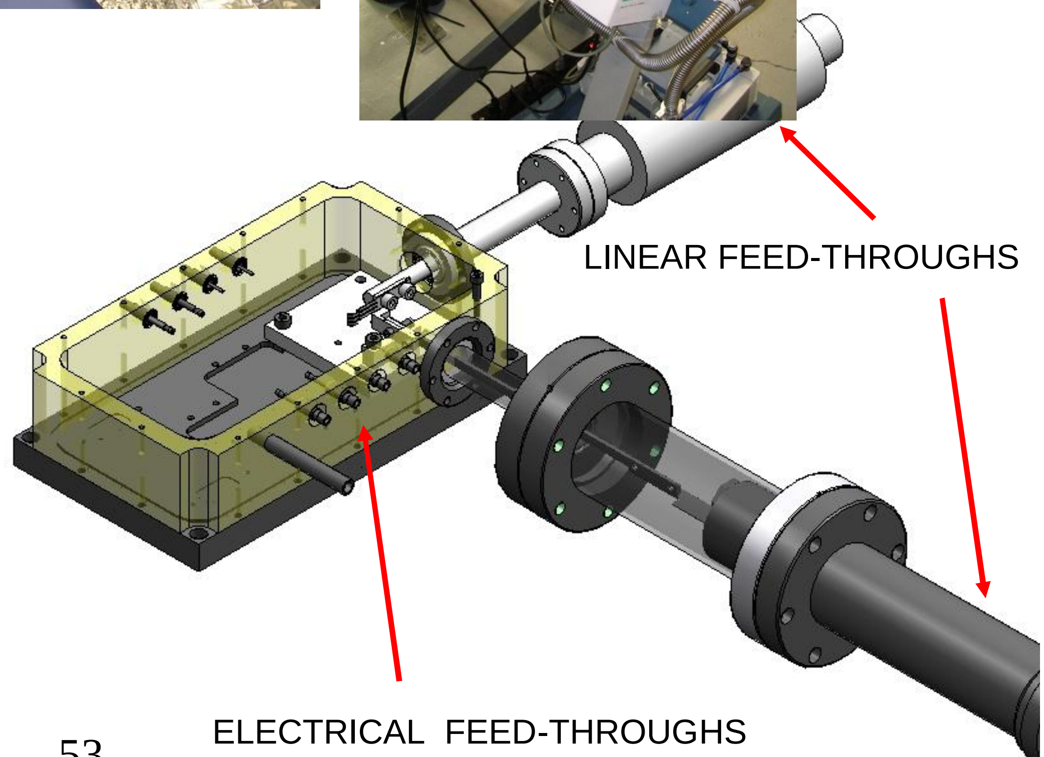
RF Contact Measurements Setup

LARP

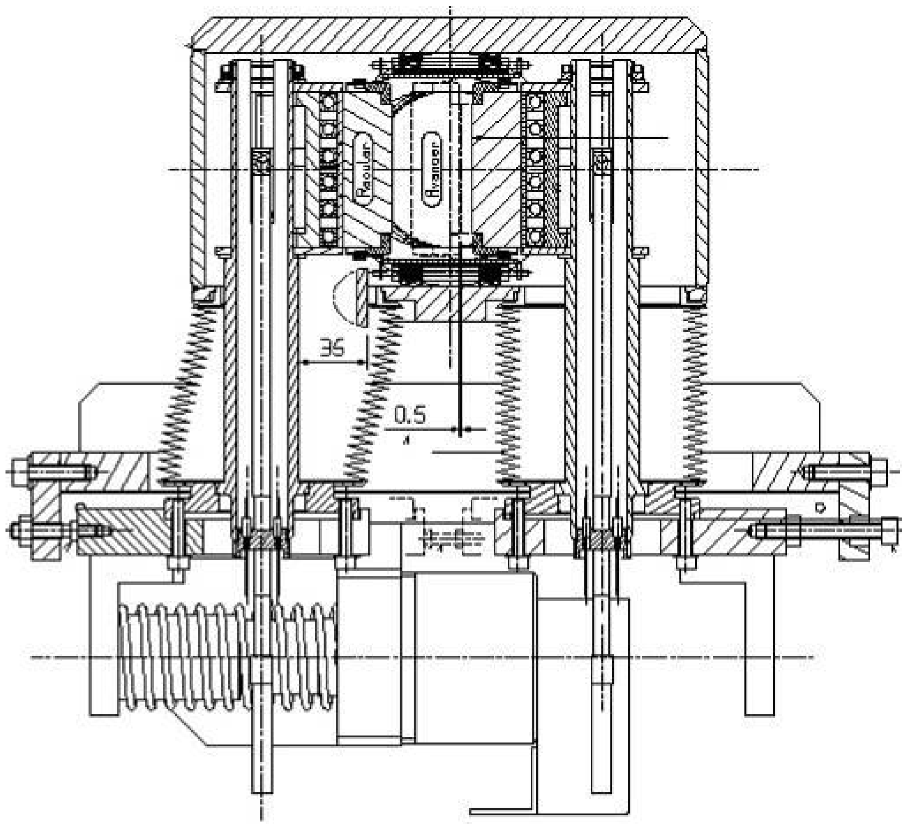
Test critical RF contacts.
work proceeding...
Results by EPAC08

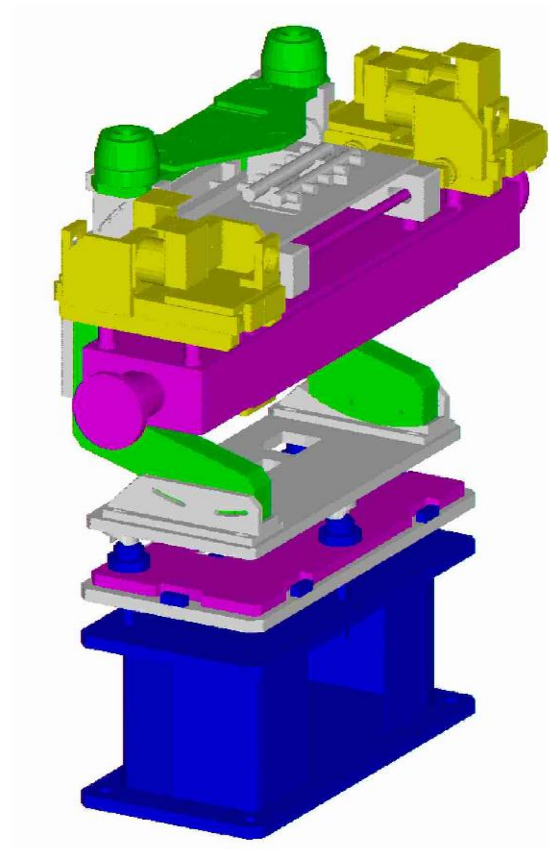






Vacuum tank, jaw positioning mechanism and support base derived from CERN Phase I





Contact Resistance Experimental Setup