LARP

US LHC Accelerator Research Program

BNL - FNAL- LBNL - SLAC

The LARP Collimation

in the context of

The LHC Collimation Program

with technical status of the LARP

Phase II Secondary Collimator Prototype for LHC

and an Introduction to

Crystal Collimation R&D: T980 & UA9

and

Hollow Electron Beam Scraping

1 June 2011

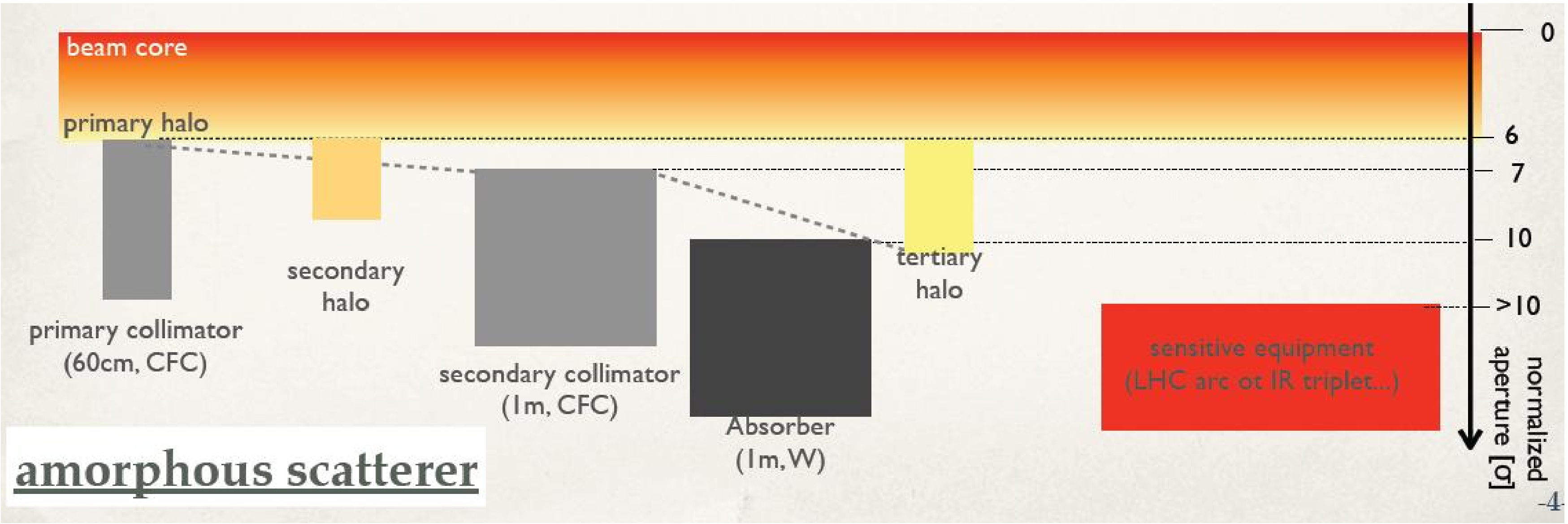
DOE Review of LARP, Fermilab

Tom Markiewicz/SLAC

LHC Collimation Today

"Phase I" system based on CARBON primary & secondary collimators in place and working very well

- Momentum Collimation in IR3
- Betatron Collimation in IR7
- 108 collimators and absorbers in the system



LHC Collimation Upgrade to Reach 1E34 Design Luminosity
Commitment by CERN to Fund Upgrade
Focus of LARP Collaboration on LHC Collimation

"Phased" approach to collimation system installation proposed in 2003 so that a "robust" system could be installed in time for LHC turn

- "Robust"=No damage from the impact of eight 7 TeV 1.1E11 bunches
  - Impedance of Carbon jaws would limit luminosity to ~30% nominal
  - System efficiency inadequate to reach 1E34
  - Radiation damage to CFC (carbon fiber composite)
  - Vacuum properties of CFC versus metals

A space behind each of the 30 Secondary Collimators has been prepared for plug-in "Phase II Secondary Collimators" to alleviate these issues

- LARP Rotatable Collimator (RC) was proposed as one design to consider

In 2003-2011 much work by a large talented group and the 2009-2011 operational experience with beam has augmented the list of what items to include in the upgrade

- June 14-15 Review at CERN to decide next steps

IR Collimation Work Package of HiLumi LHC FP7 Design Study

Pertains to collimation for the HL-LHC

For various 5E34 upgrade scenarios:

- Simulations of Beam Loss in the Experimental IRs
- Simulations of Energy Deposition in the Experimental Irs
- Design of Collimation in the Experimental IRs

LARP is not currently participating in this simulation effort

Hollow Electron Beam Lens as a "Scraper"

1st of three Areas of the LARP Collimation Program

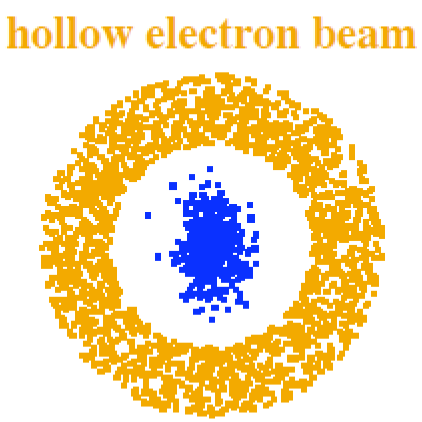
Details in talk by Alexander Valishev this afternoon

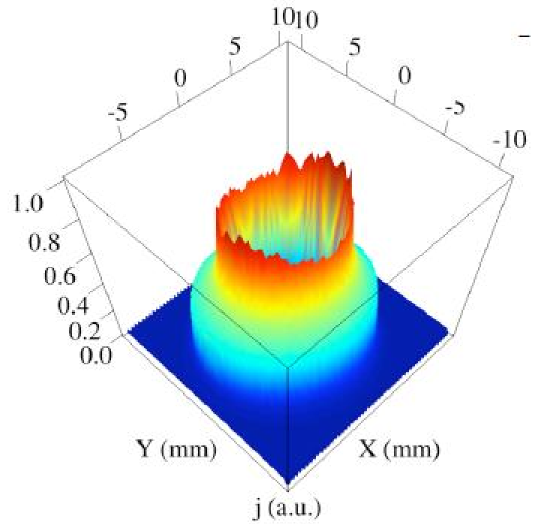
Purpose: Increase collimation efficiency by scraping halo very close to the beam core, driving halo into the main collimation system

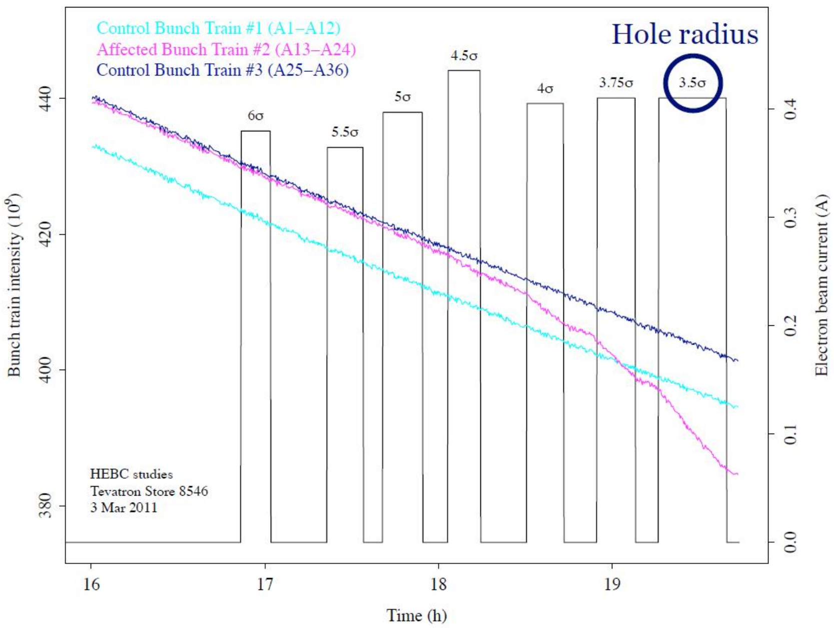
LARP support of analysis of Electron Lens as a Beam-Beam compensation device evolved into support of HEBC hardware/analysis in FY11 (~$268k)

Hollow e-beam scrapers are seen by CERN as an "inexpensive and safe way to reduce the magnitudes of peak beam loss."

Excellent results; discussions of how to transfer the hardware to CERN to continue the effort





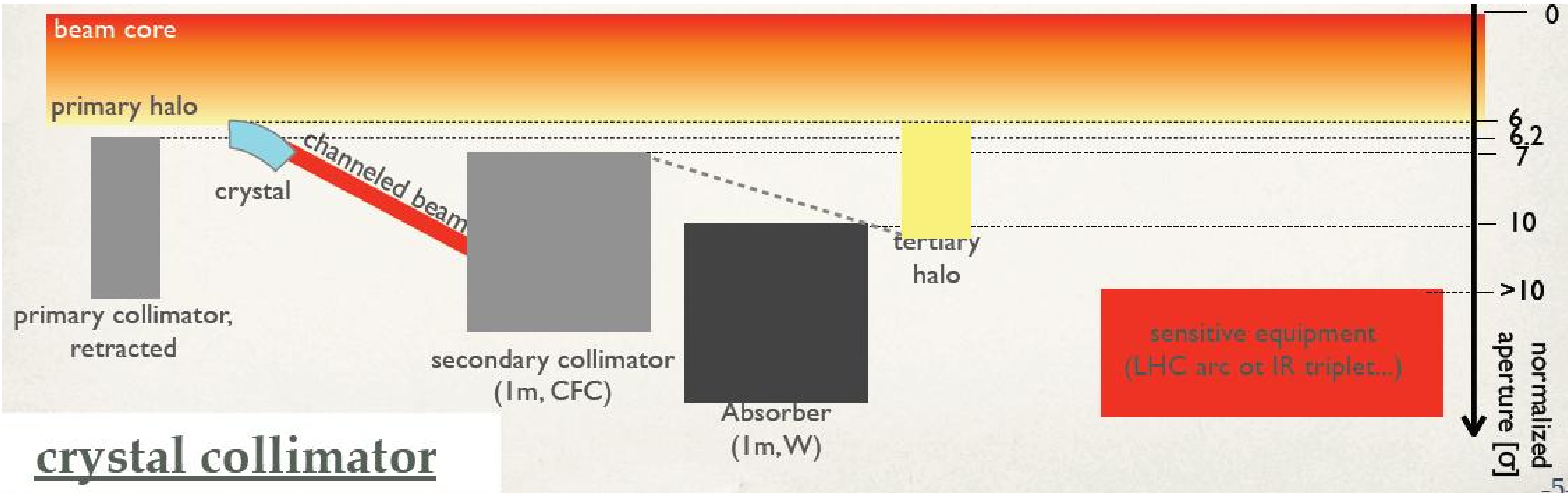


Bent Crystals as Primary Collimators

2nd of three Areas of the LARP Collimation Program

Details in talk by Nikolai Mokhov this afternoon

Purpose: Increase collimation efficiency driving halo directly into secondary collimators and absorbers rather than via multiple passes through amorphous solid



LARP support of T980 at the Tevatron ($500k FY09-11) and UA9 at SPS/H8 ($260k FY09-11)

LARP plans to participate in extension of these tests to the LHC

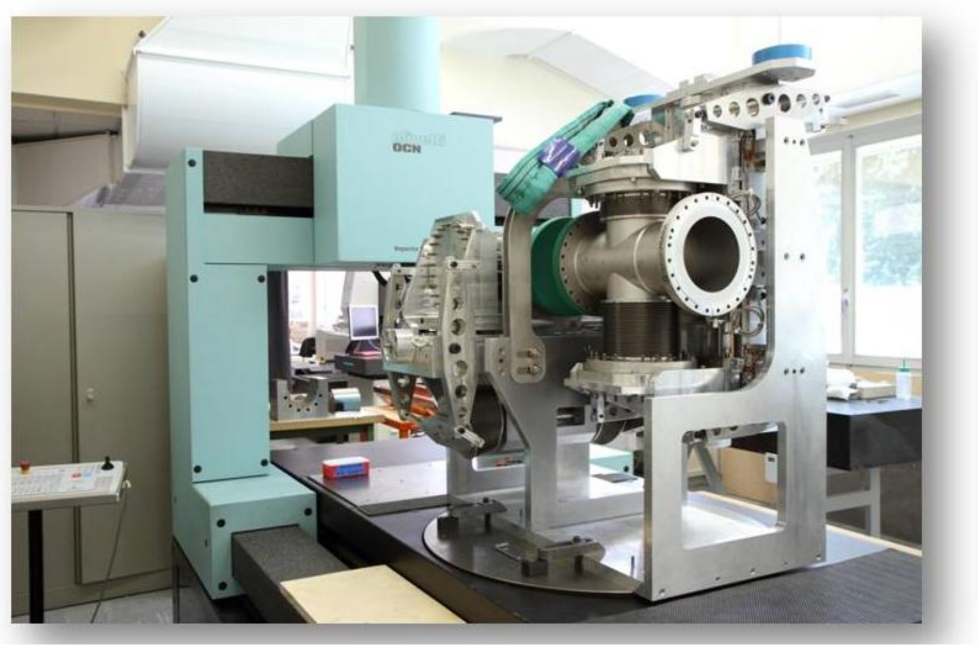
Despite excellent results from T980 and UA9 skeptical view is that, while more R&D is good, complications with alignment of the crystals may limit utility in LHC.

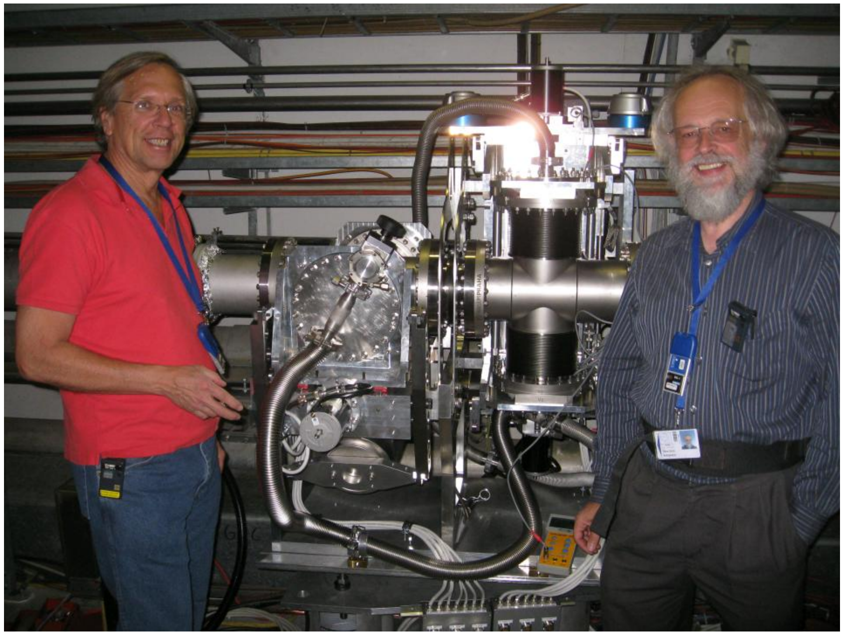
LARP Supported SLAC Built Roman Pot for UA9 Houses Tracking Detectors

LARP

4 June 2010 at CERN CMM

Installed in SPS 31 Aug 2010

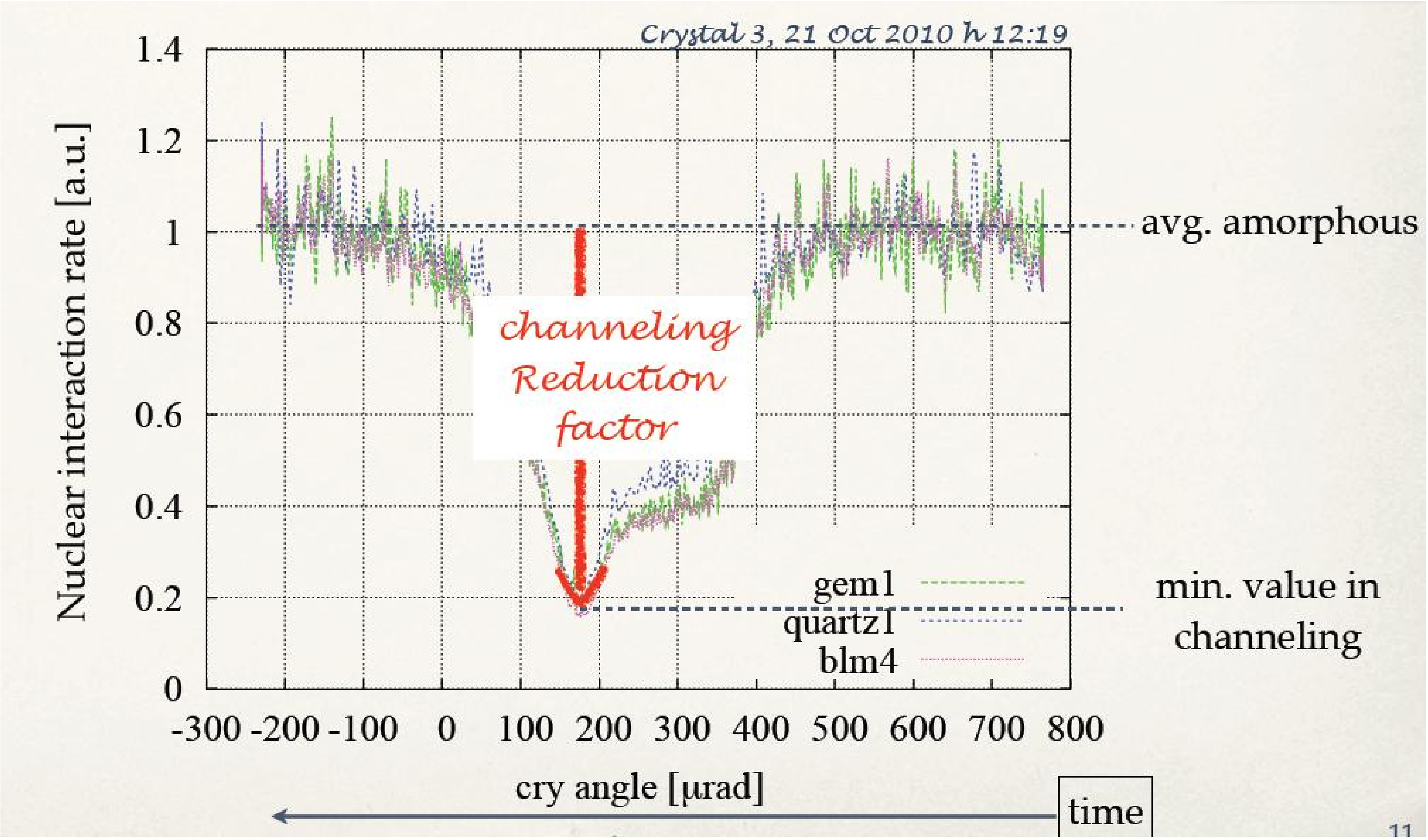




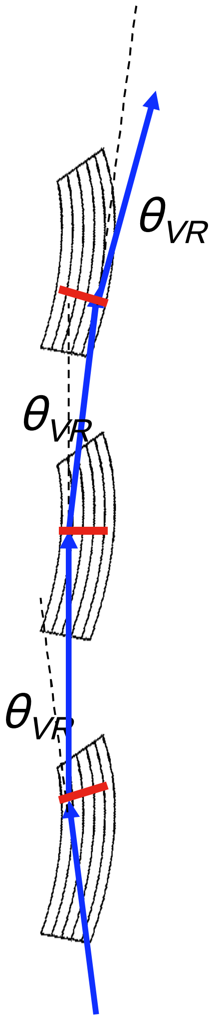
Future LARP financial support modest
Need to grow LARP analysis/scientific engagement

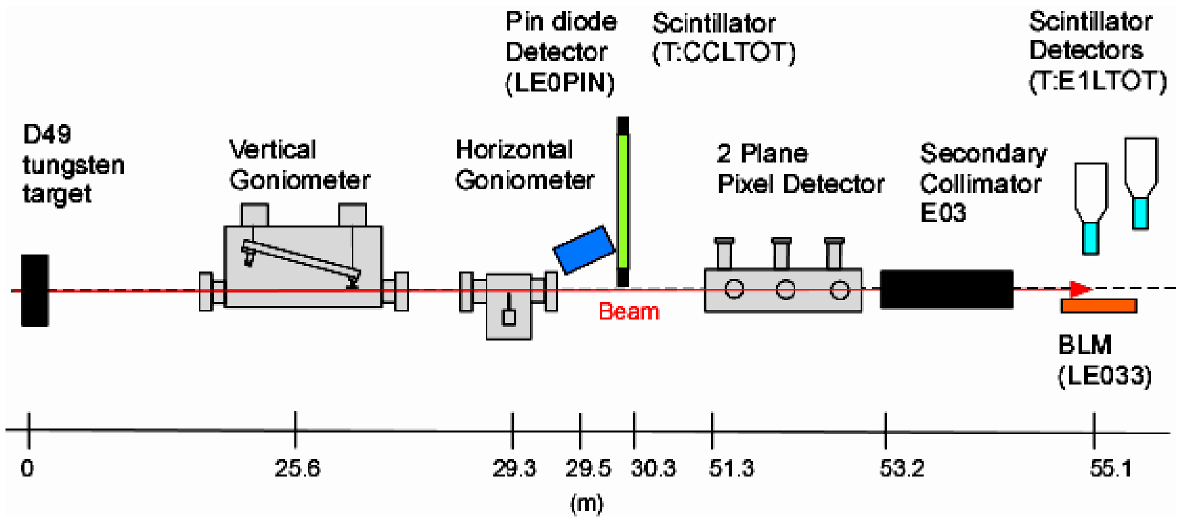
Example of Angular Scan of a Crystal in Channeling Mode at UA9

Showing Reduction of Halo Signal in 3 detectors as Crystal Sweeps Channeled Halo Away



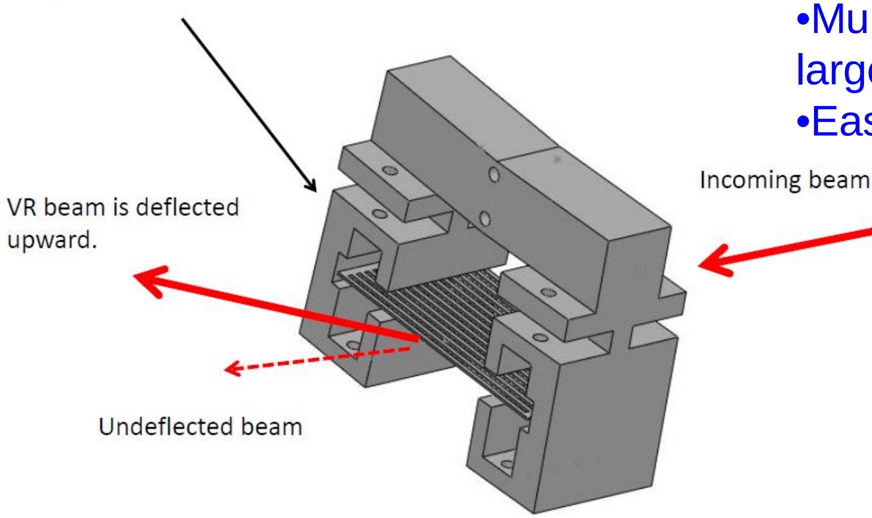
T980 at Tevatron





T-980 favors multi-strip crystals

- Large angular acceptance
- Multiple Volume Reflection gives large deflection
- Easy to work with



The LARP Rotatable Collimator Prototype
Candidate for a Phase II Secondary Collimator

LARP

3rd of three Areas of the LARP Collimation Program: $4565k FY07-11

Two jaw collimator made of Glidcop

- Rotate jaw after 1MJoule beam abort failure accident occurs

Each jaw is a cylinder with an embedded brazed cooling coil

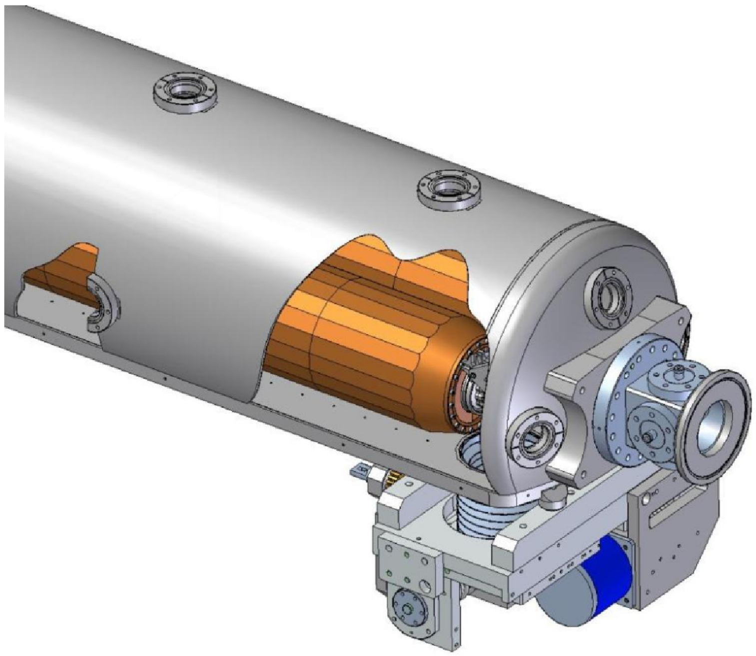
- No vacuum-water braze; 12kW/jaw cooling; minimal thermal distortion
- Maximum radius cylinder possible given beam pipe separation
  - 20 2cm wide facets provided for presumed rare beam abort accidents

Advantages:

- Not exotic material
- High Z for better collimation efficiency & more debris absorption
- Low resistance for better impedance
- Elemental for high radiation resistance

Disadvantages:

- Glidcop WILL be damaged in asynchronous beam abort



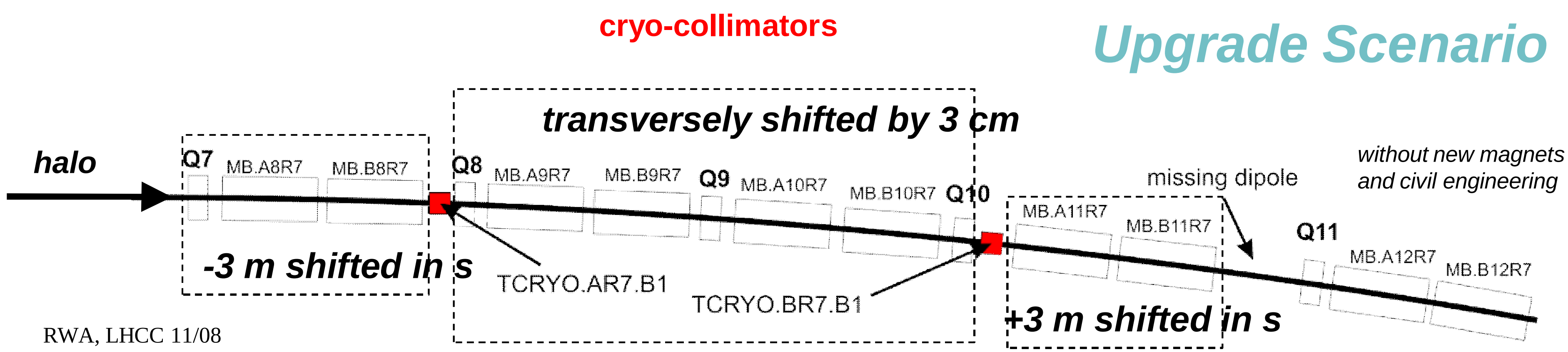
LHC "Cryo Collimator" Program

In 2009 it was shown that the beam intensity limit is dominated by "single diffractive interactions" in primary collimators which generate slightly off-energy protons lost in the "dispersion suppressor" SC magnets on either side of IR3, IR7. Proton-Proton interactions do the same in IR1, IR2, IR5. ….. → "Cryo-Collimator Program" starts

Move ~11 SC magnets per side per IR to make room for 2 "cryo" collimators

2010 Plan:

- Do this to IR3 during LS1 AND install enough collimators to do both Betatron & Momentum cleaning; modify IR 7,1,2,5 SC DS regions later

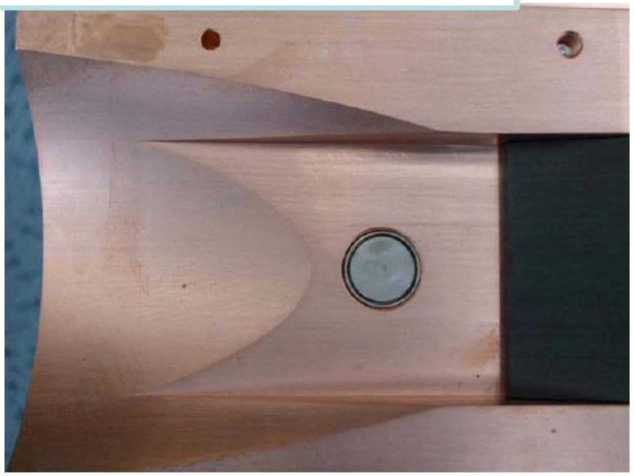


CERN designed Phase II Secondary Collimators

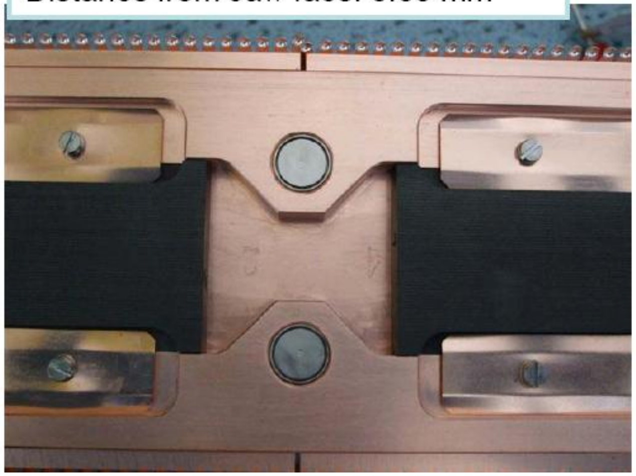
CERN mechanical design is extension of Phase I

- Operational experience has led to desire for INTEGRATED BPMs
  - Reduce setup time!
- Jaw material would depend on when devices needed and state of R&D
  - Same CFC as in Phase I (but with BPMs)
  - Ceramics
    - Frequency dependence of the real and imaginary parts of impedance and response of feedback system to control instabilities suggest these would work
  - Hi-tech (Diamond-Cu) for good robustness, low impedance, thermal stability and density

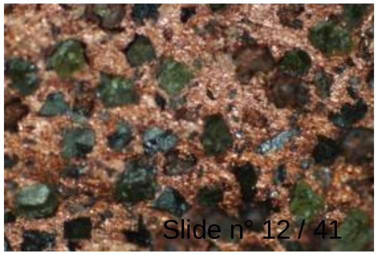
Button 1 at upstream port on D side
Distance from Jaw face: 10 mm



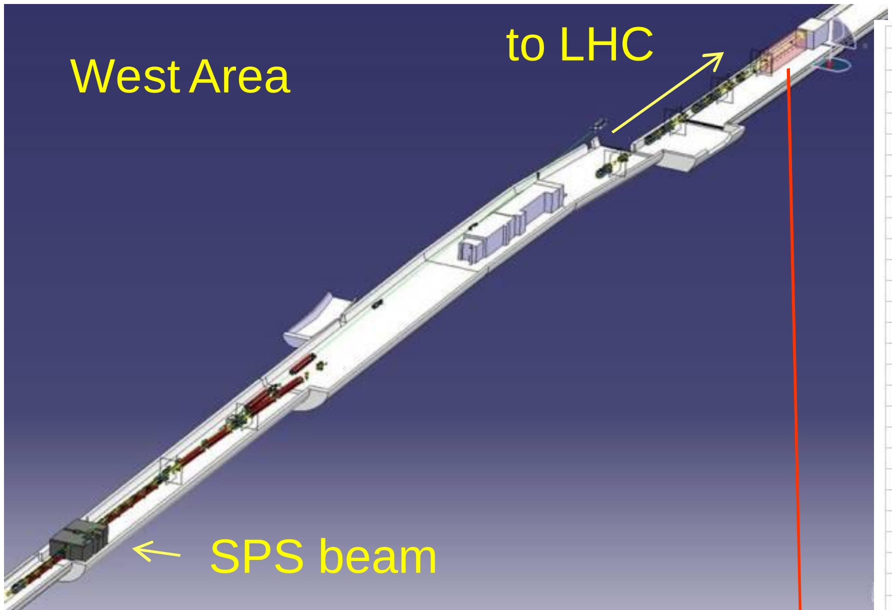
Button 10 at center of jaw on DB side
Distance from Jaw face: 0.05 mm

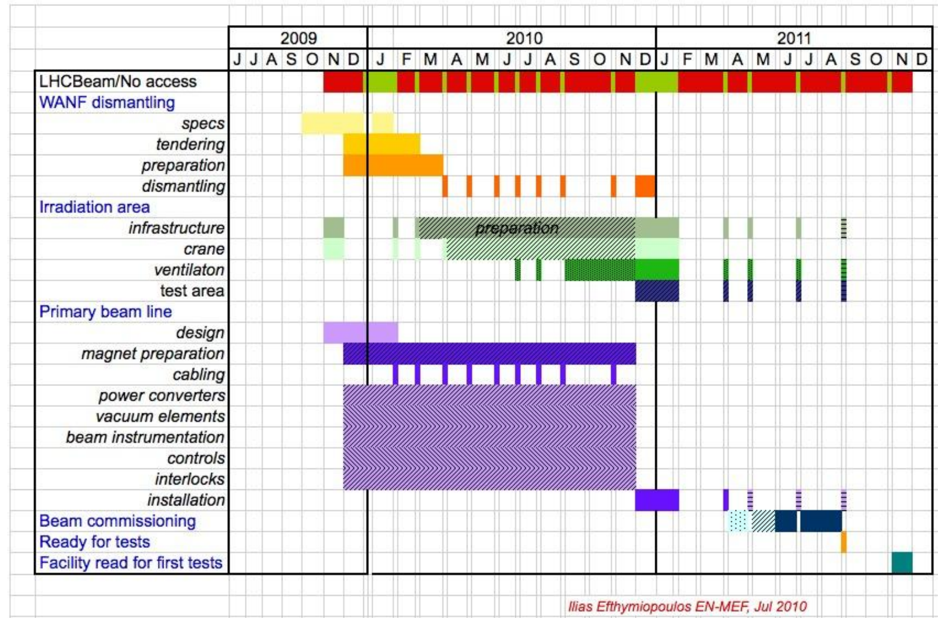


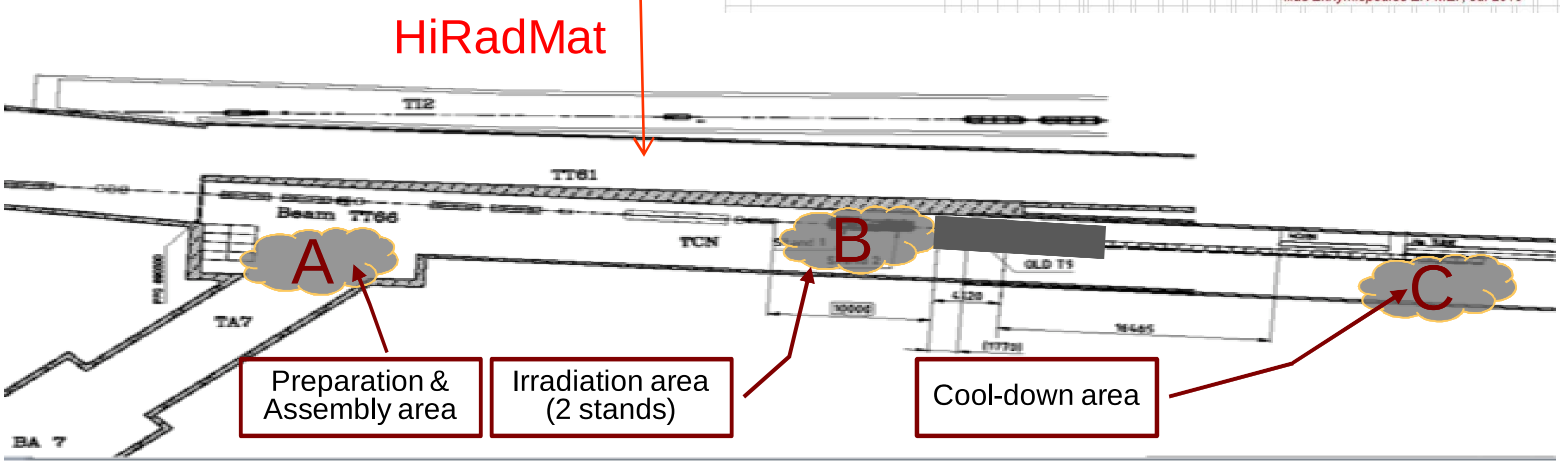
15cm sample



HiRadMat is New Beamline Required to Test Phase II Secondary Prototype Collimators Operational Winter 2011







Proposals for the June 14-15 Collimation Review

R. Assmann: CWG 2011-05-23

LARP

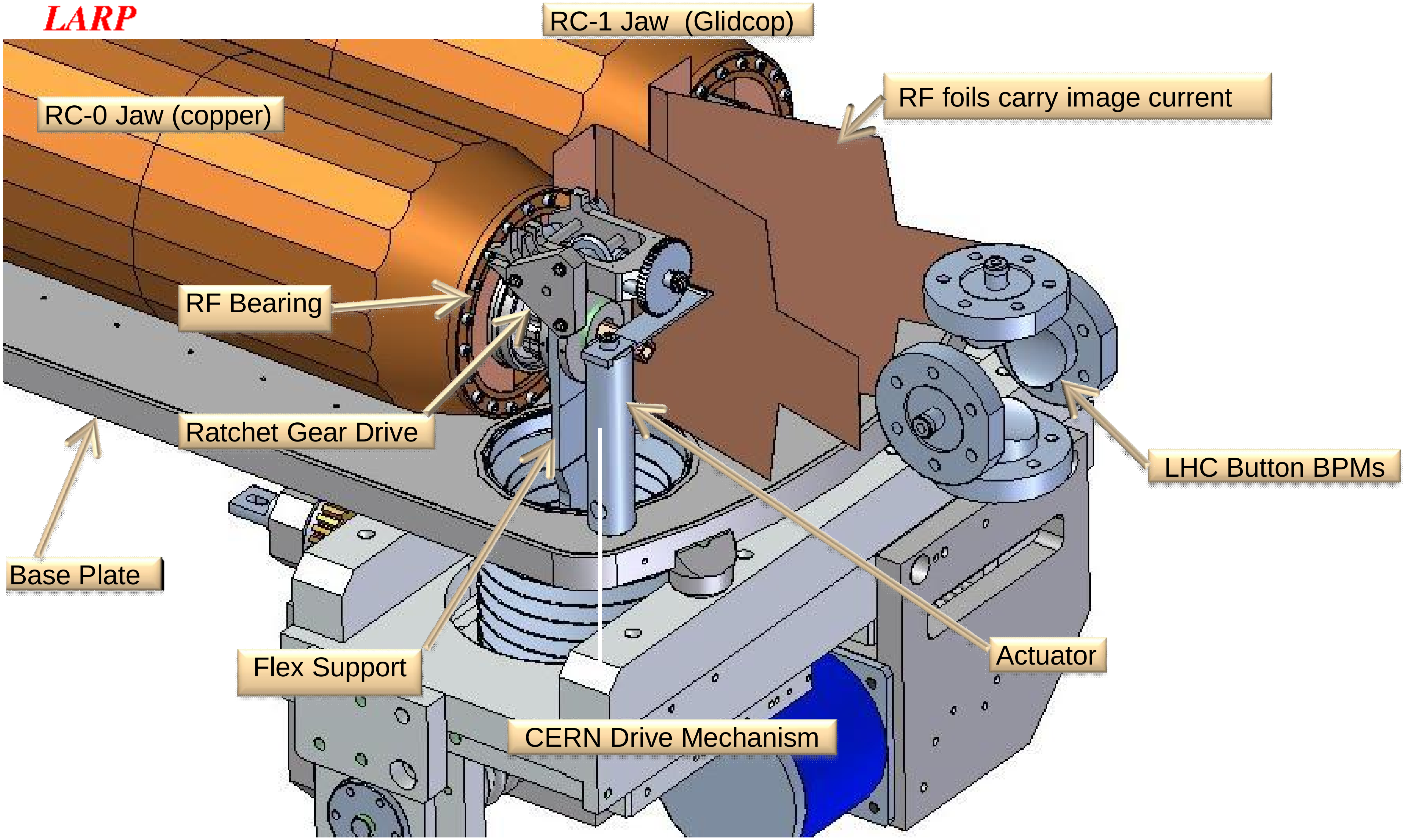
DRAFT

Given recent (May 2011) MD results:

- Higher than anticipated quench limits
- Longer than anticipated minimum beam lifetimes
- Higher than anticipated cleaning efficiency
- Subject to uncertainties in extrapolation to 7 TeV and higher intensities

- **Cancel the collimation upgrade for the IR3 dispersion suppressors** and the **temporary installation of vertical collimators into IR3** during the first long shutdown in 2014
- Start an overall study for the **upgrade of the LHC DS's with collimators** in IR1/2/3/5/7, developing a coherent approach.
    - Continue work on the collimator design and the high field Nb3Sn dipoles
- Reinforce the work towards **second generation collimators with beam position buttons** in their jaws, aiming for first installations in 2014.
- Reinforce the work towards **second generation collimators with robust collimator materials or damage handling concepts**, with EuCARD + LARP collaborators. Readiness goal is 2016.
- Start work on design and development of **hollow e-beam scrapers** for the LHC. Readiness goal is 2016.

SLAC RC Design Status



Summary of Work Since July 2010 Review

Lab tests **under load** post-review uncovered deficiencies in

- The primary support & rotation bearing
- The RF bearing (equivalent of "RF Fingers" in CERN design)
- The rotation drive unit and related hardware redesigned for x10 load

After successful tests with new ad-hoc bearings & housings, prototype moved from test lab (10/28/10) and into vacuum clean room for final welding, re-assembly with final W-S2 impregnated steel parts, vacuum testing and bake out

All mechanical tests successful

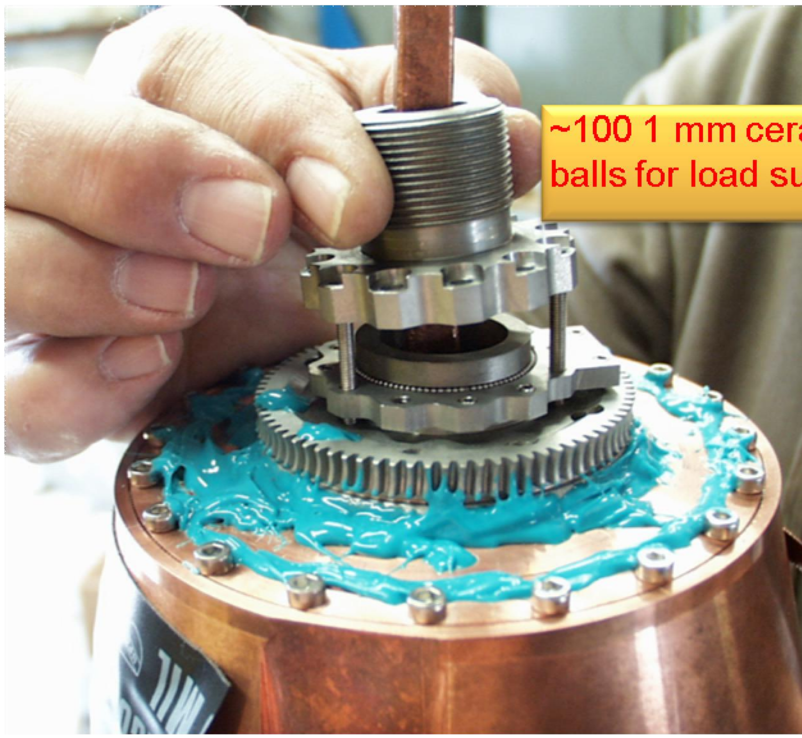
- Cooling tubes now twist, under vacuum, as jaws turn, with R~1 mΩ & align well

Discover that the cooling tube of each of the two jaws has been damaged (crack has developed) in a similar location

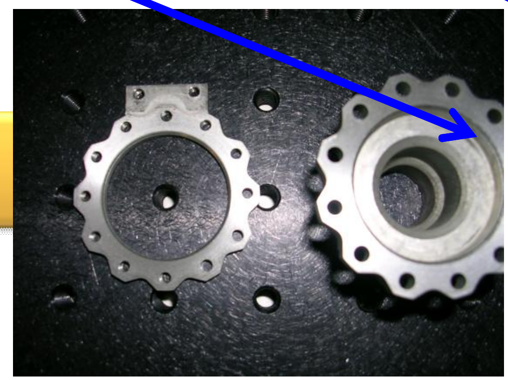
- Should have been caught earlier
- Not believed to be fundamental design issue

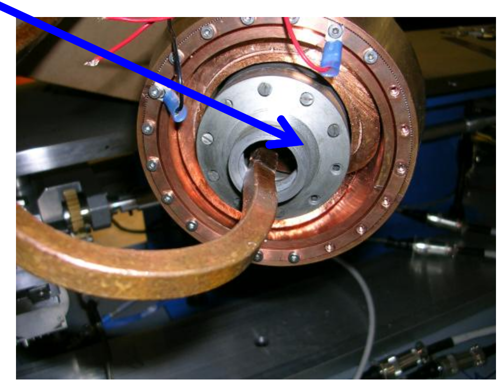
Switch Out Primary Ceramic Support Bearing for a 20mm/42mm “Classic” Steel Bearing

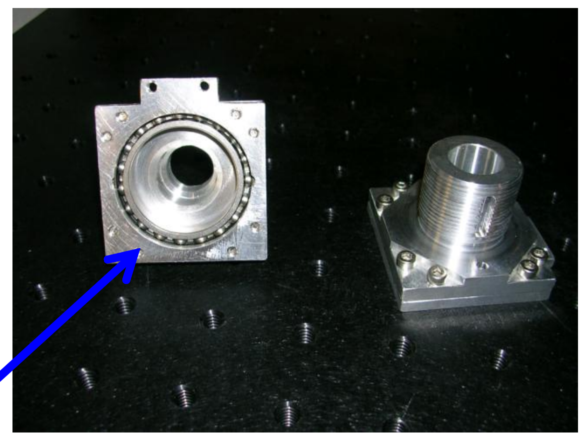
Find that 1mm ceramic balls have crawled on top of each other & have frozen the bearing (note scuff marks in housing and on axle butt)



~100 1 mm ceramic balls for load support







New Bearings: Friction torque →0

RF Continuity Hardware

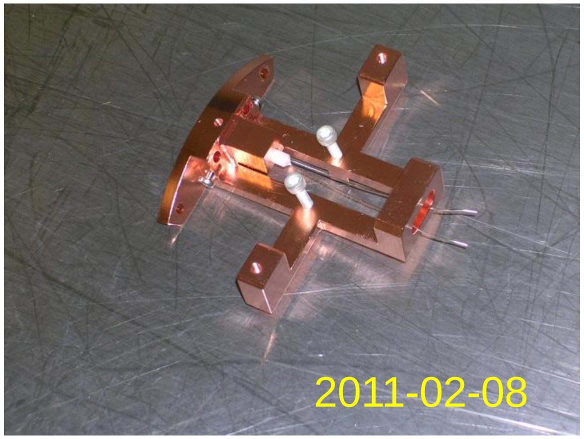
Now "Wiper" provides RF Continuity between Jaws and BeCu Foil
Previously relied on tuning contact resistance versus rotational friction in bearing (300 Rhodium coated SS balls)

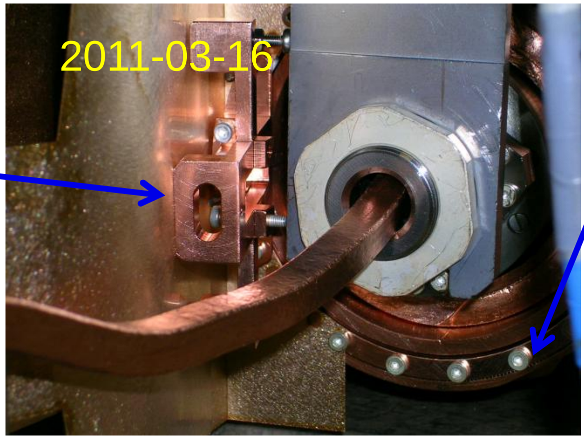
Rhodium Coated RF "Wiper"

BeCu Foil

Wiper/Foil Held to Stationary RF Bearing by Thermistor Holder as Jaw Rotates

Thermistor Holder

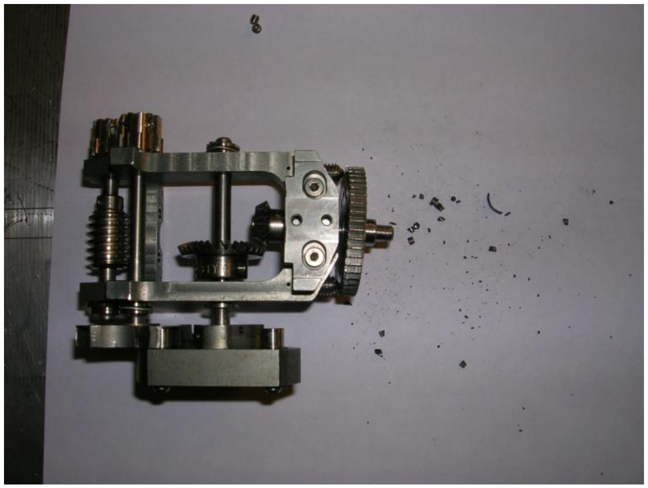




RF Continuity: 4-wire R~1-2 mOhm
Checked for each facet of each side of both jaws

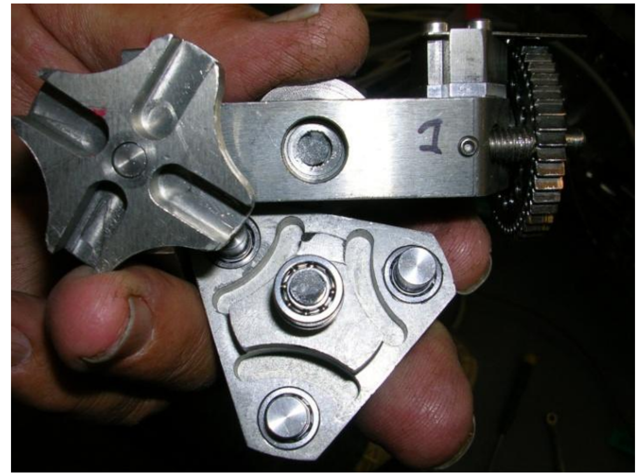
Examples of Rotation Drive Failures & Test System

LARP

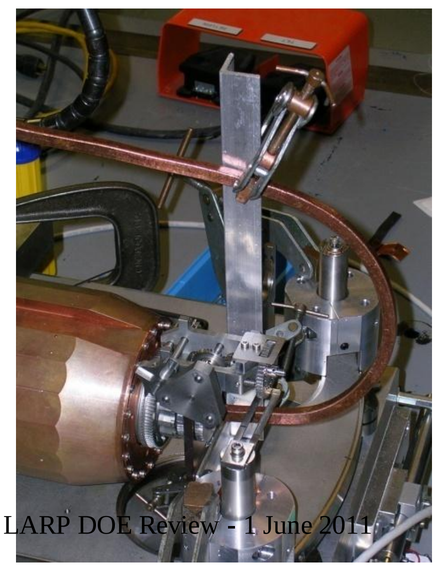


21-July-10: Ceramic race on one of the two bearings on actuator fails under load

22-Oct-10: Flattened 1mm balls on worm thrust bearing

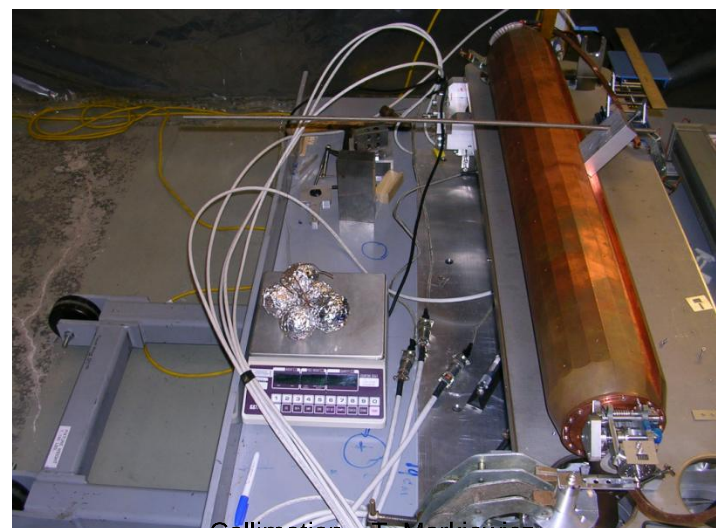


01-Sept-10: Geneva Drive Axle Breaks at ~300 inch-pounds of torque



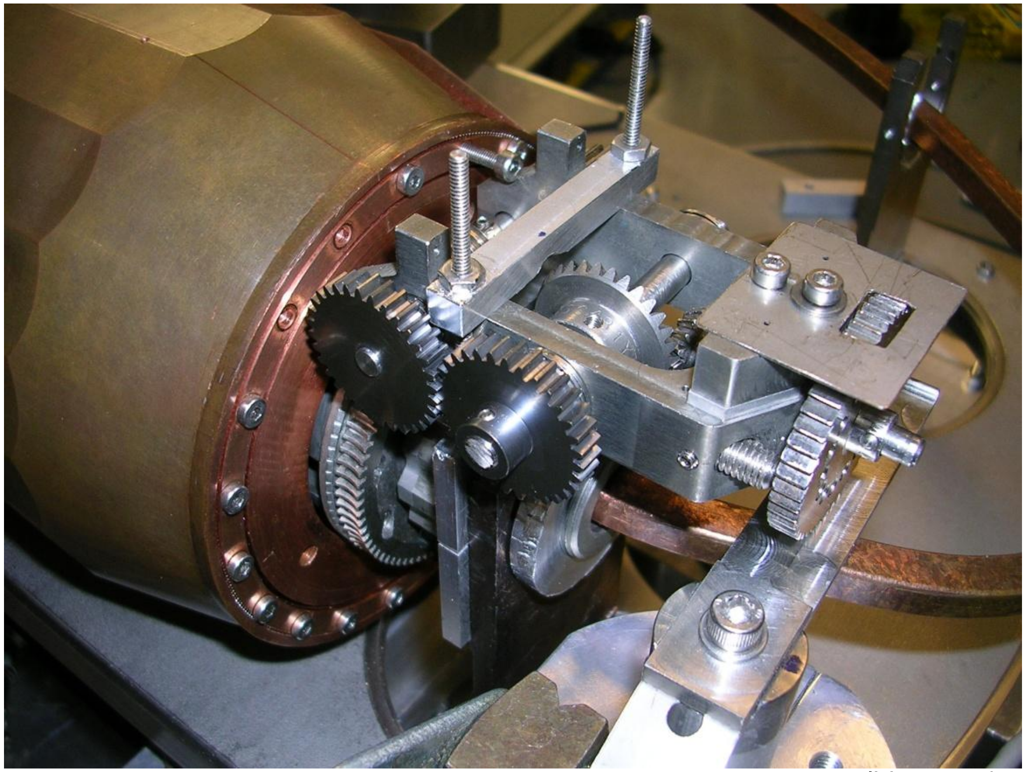
Problems only apparent when we start load-tests of rotation drive

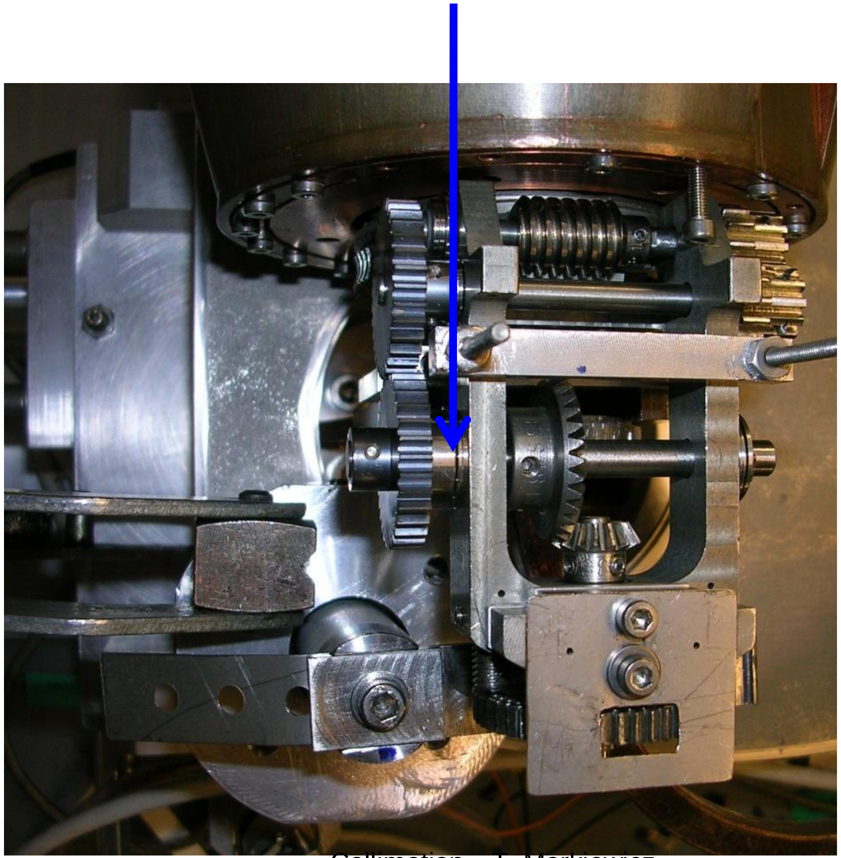
Eventually go to systematic system to work drive against applied torque



Prototype Drive Rebuilt
Tested to 10x Anticipated Load
Required to Rotate Jaw & Twist Cooling Tube:
300 inch-pounds

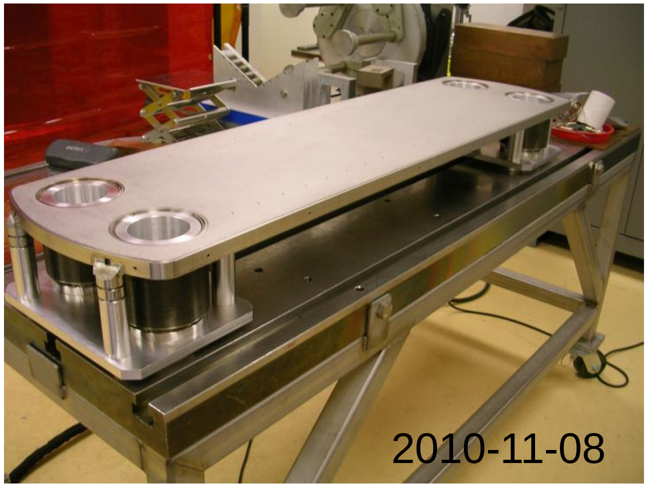
- Add Large Thrust Bearing at end of Axle to prevent bending
- Exchange Geneva Drive for Pair of 1:1 Gears (load reduced x3)
- 5mm Moly shaft (& two bearing sets) -> 6mm Steel (& larger bearing sets)





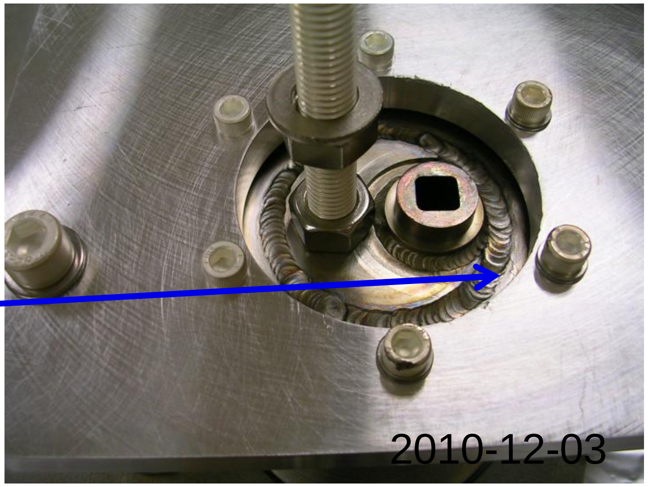
Baseplate, Bellows & Jaw Support Welds

Bellows Fixtured, Protected and Welded to Vacuum Side of Baseplate



Cooling Tube Feedthrough Welded to A286 SS Jaw Support

Bellows Plug Held by Fixture and Welded to Bottom of Bellows



Rebuilding and Reassembly of Rotation Drives and Main Rotation Bearings

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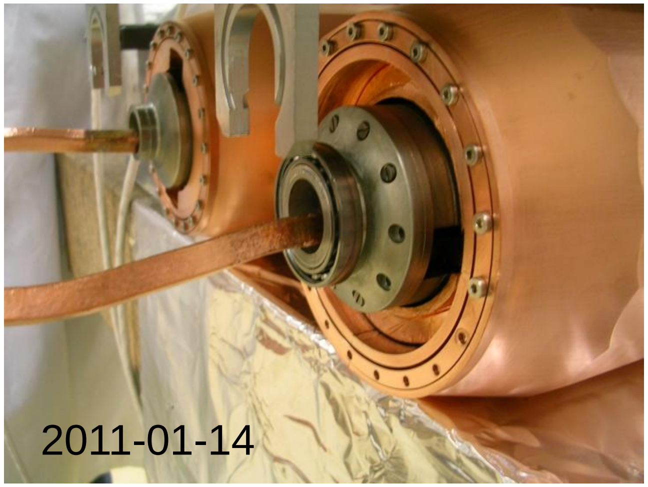
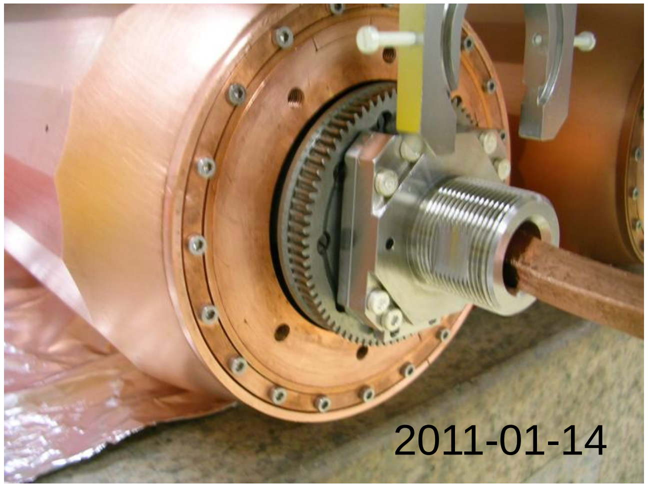
Rotation Drives

Bearing on Naked Shaft





Main Bearing in Threaded Housing on Shaft About to be Captured by Jaw Support

Final Version “Pawls” to Prevent Backlash

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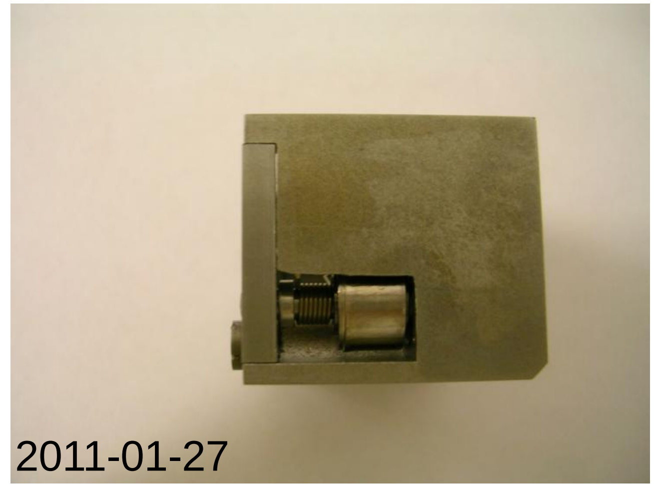
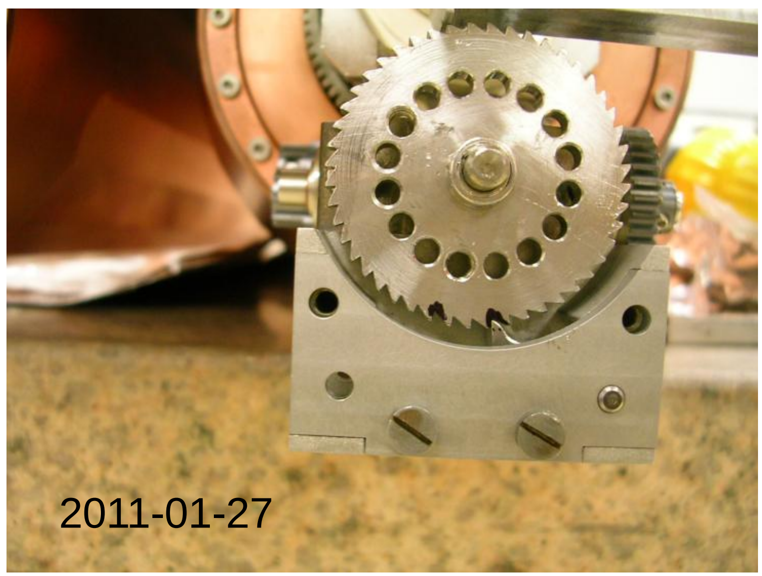
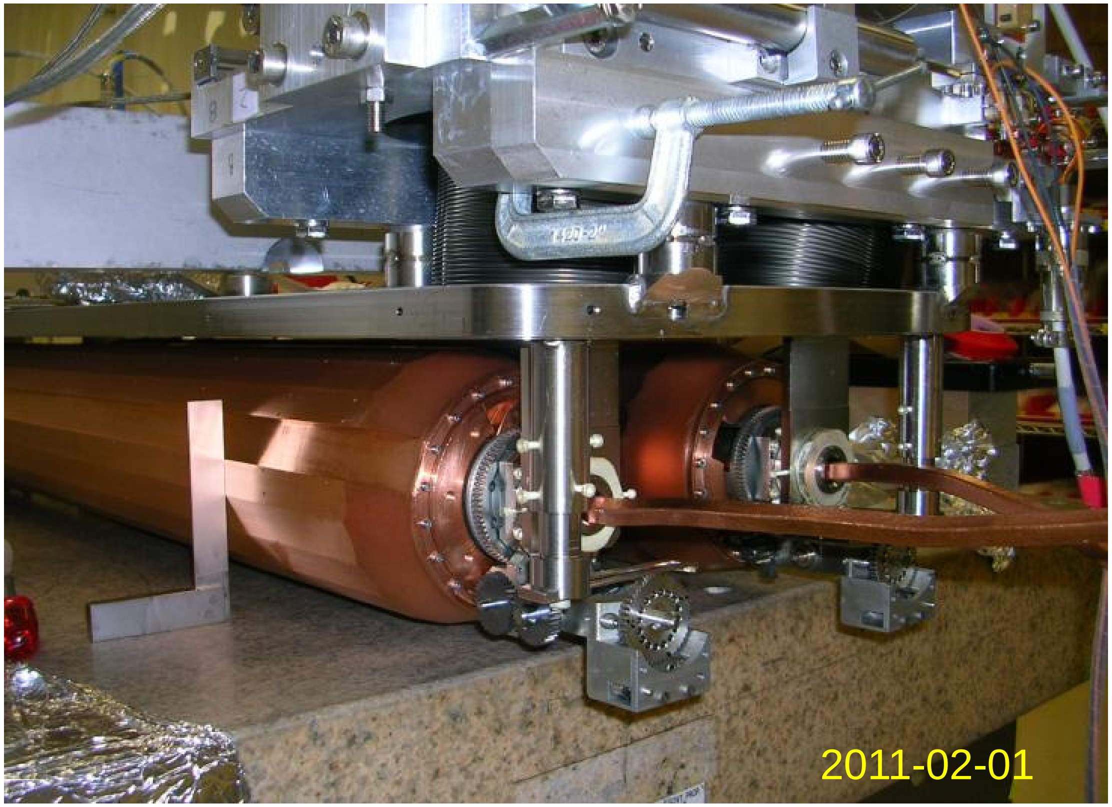
L/R Symmetric Mo Housing

Underside w/Spring Visible



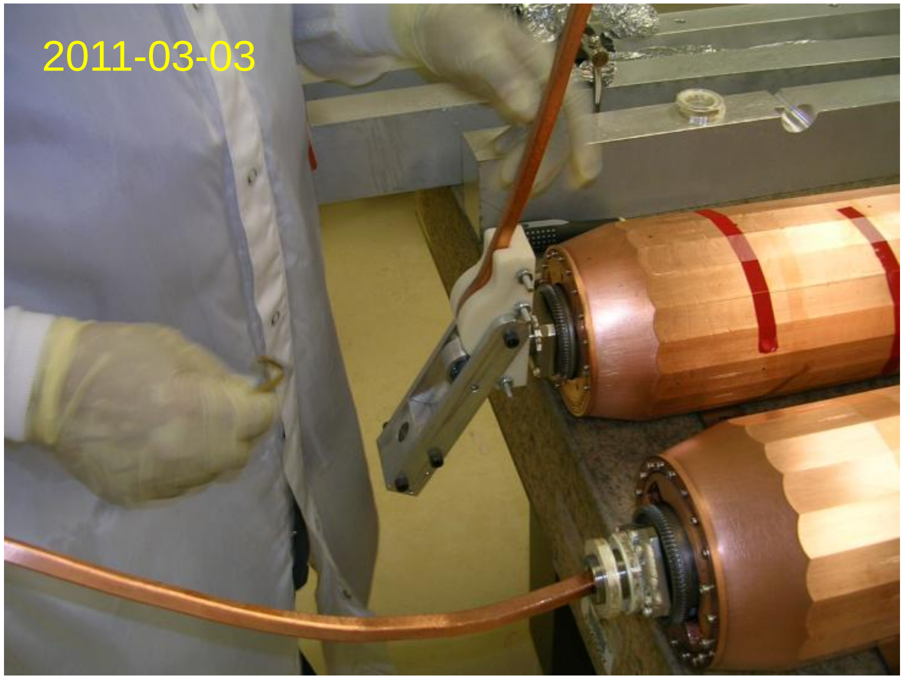


Remounting All Hardware onto Jaw Shafts for Last Tests Where We Are Free to Rotate Jaw as Much as Needed

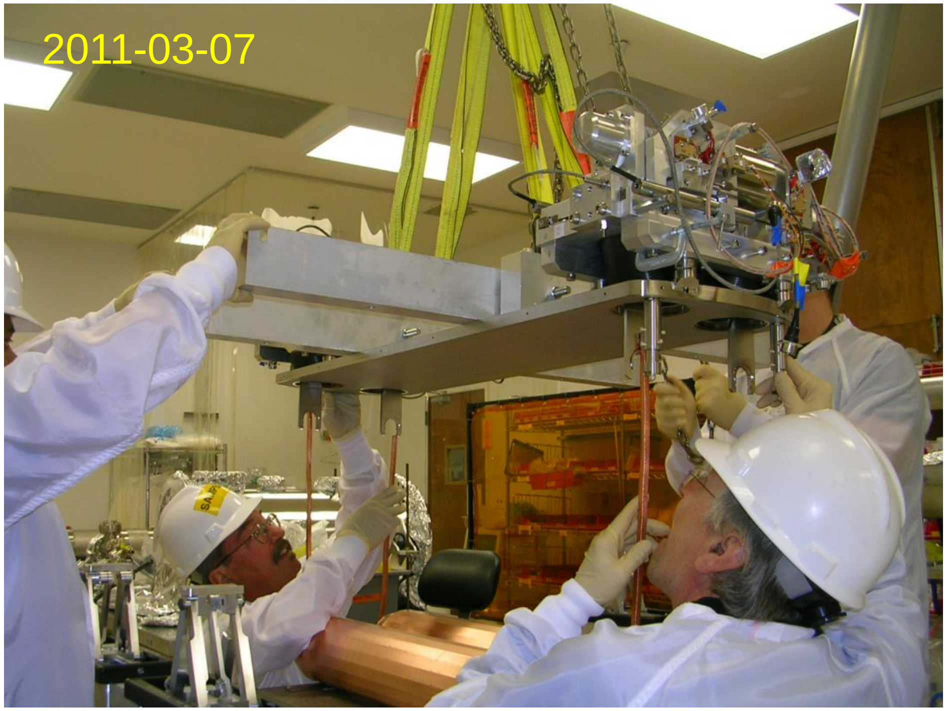


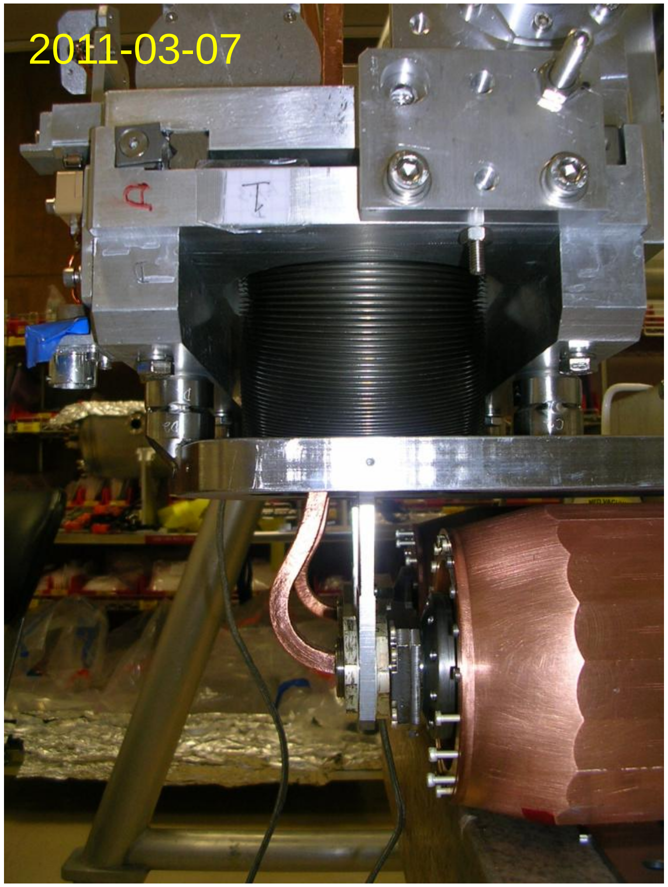
Each Jaw Rotated 360 degrees (several times, facet by facet) to check that drive unit does not slip and that each of the 20 facets is perpendicular to beam gap after required number (8 x 48 = 384) of pushes against actuator

Bending the Cooling Tubes

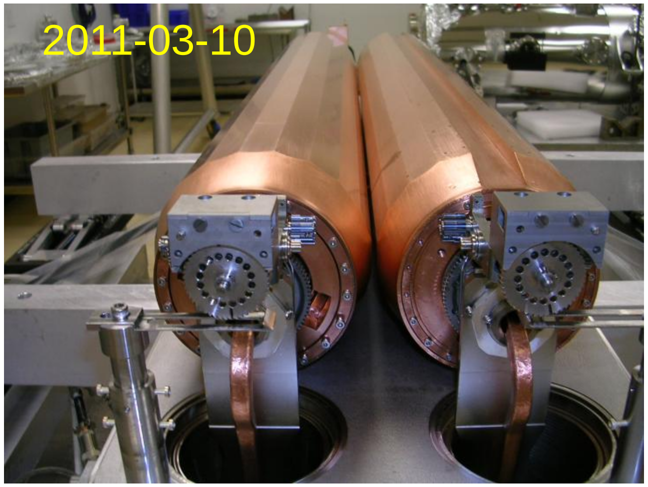


Cooling Tubes Threaded through Feedthroughs in Plates Holding Jaw Supports at Bottom of Bellows

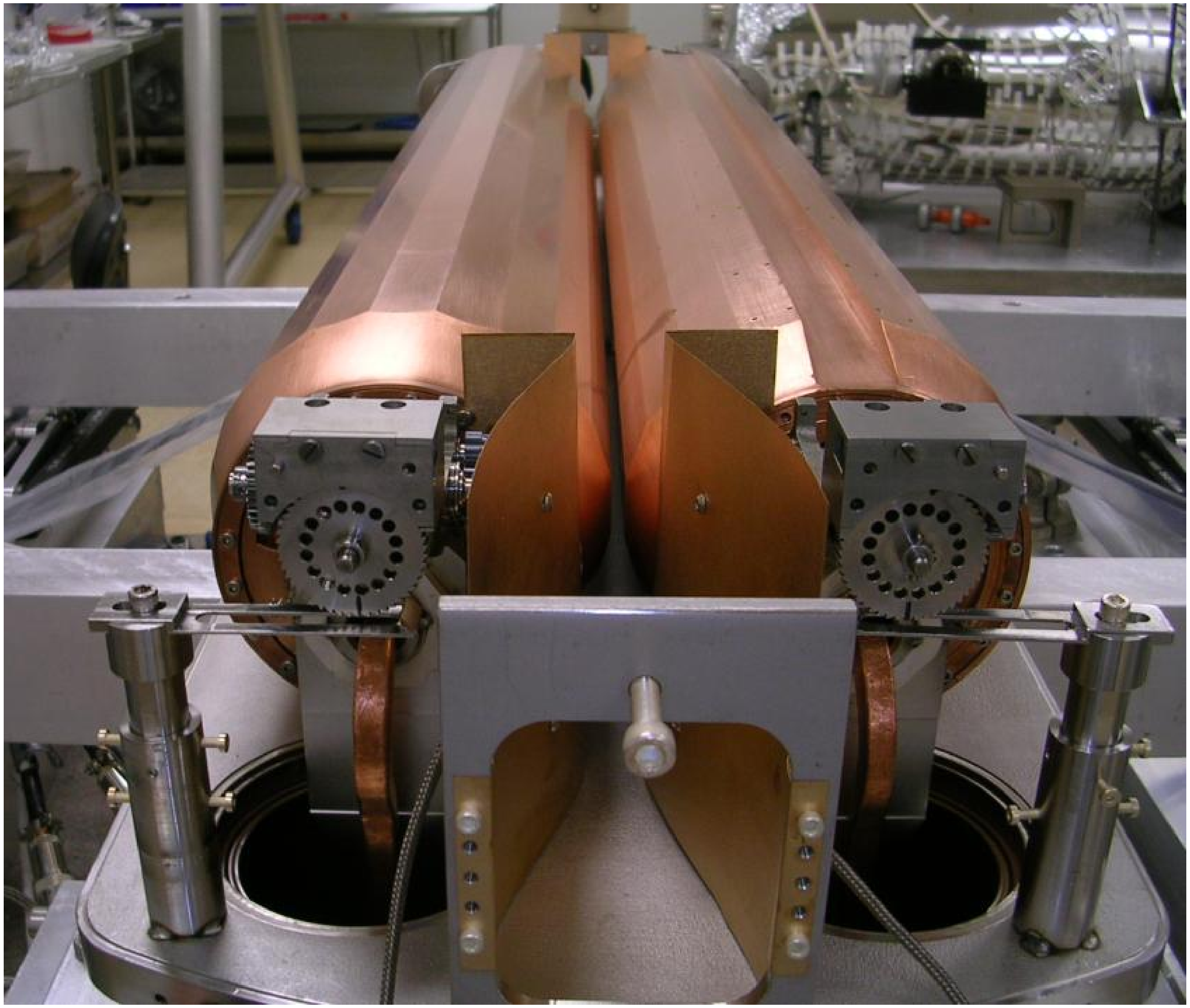




Actuator Positioning Critical



Collimator Assembled 13-Mar-11

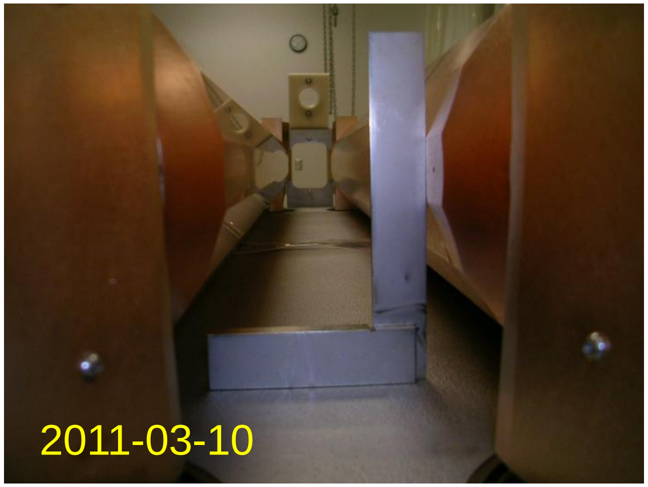


Rotation Test 1 Successful

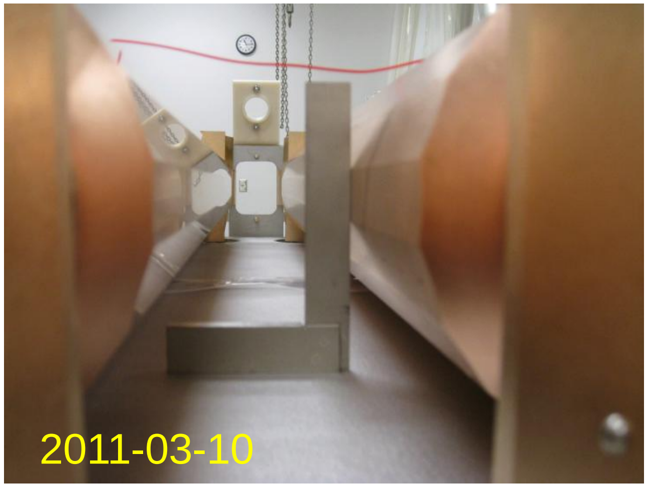
Tubes captured, Pre-weld of Internal Parts (13-Mar-2011)

First Permanent "Twist" of Long Straight Length of Cooling Tubes

Before

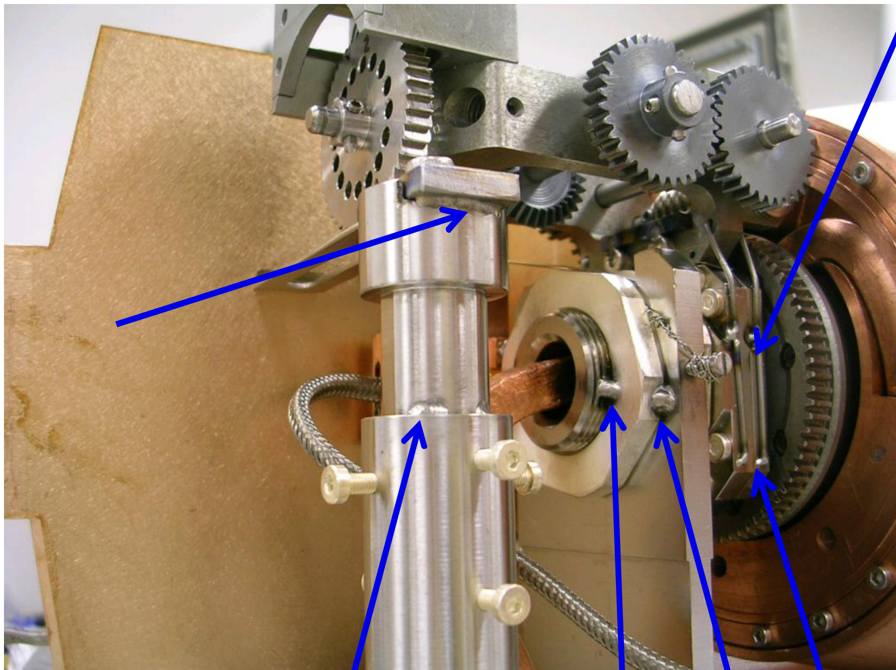


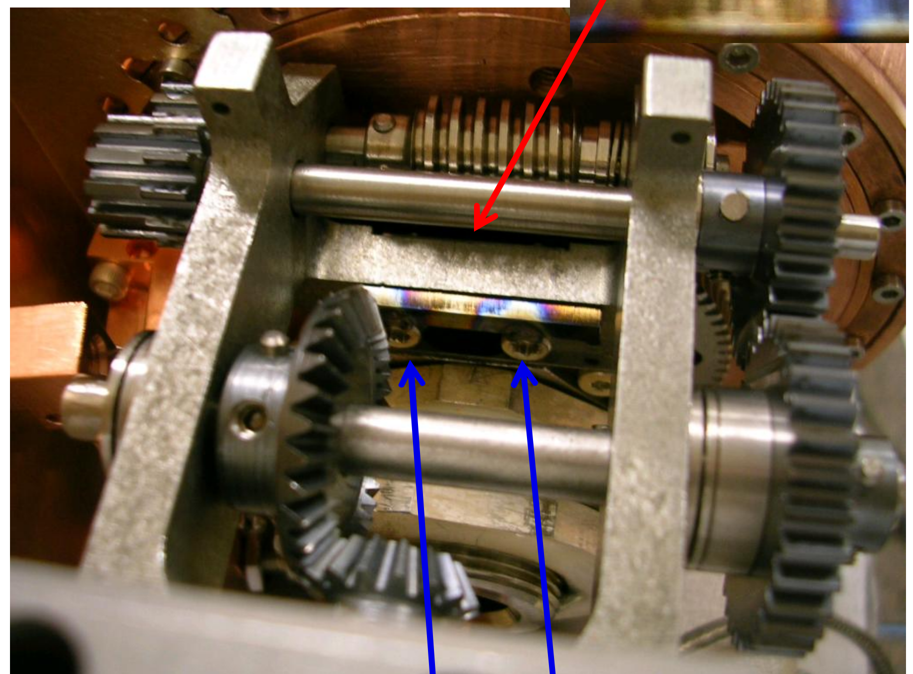
After



Rotation Test 2 Successful

After Internal Parts Welded (16 Mar-2011)



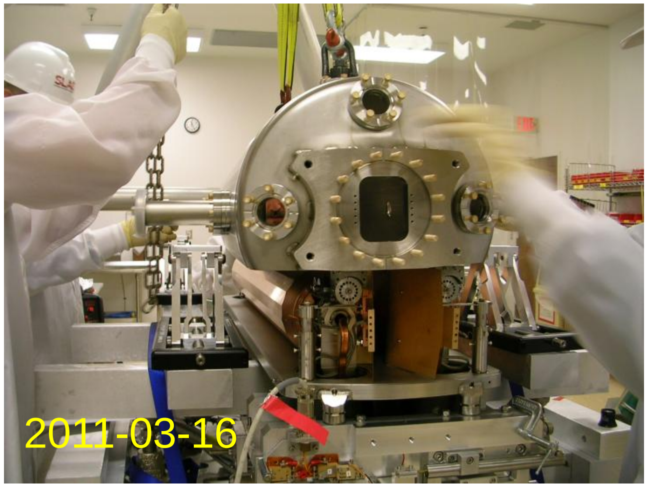


Welds

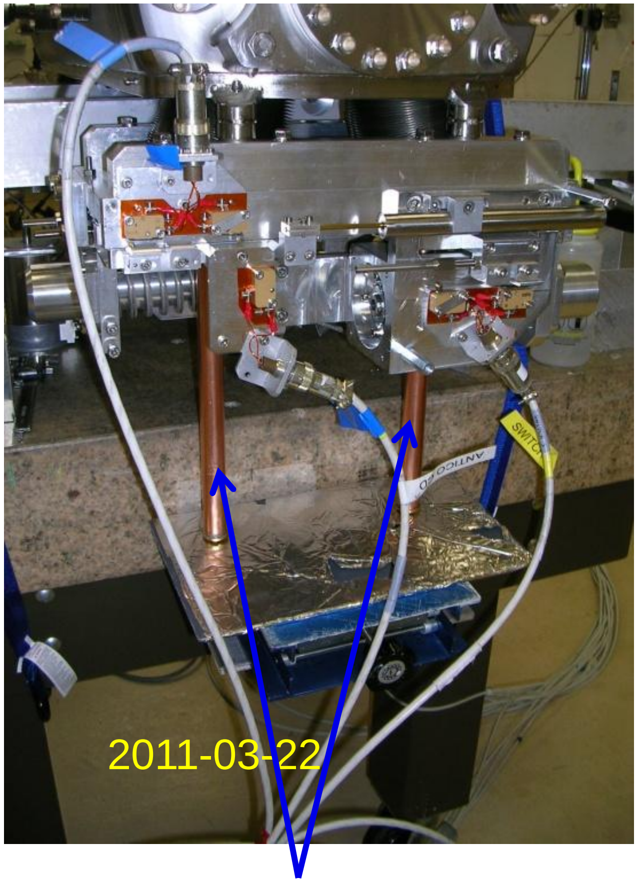
Post Alignment Check as Before: Collimating Facets ⊥ to beam

(required adjustment of switches as actuator moved in weld)

Tank Installed, Aligned & Welded

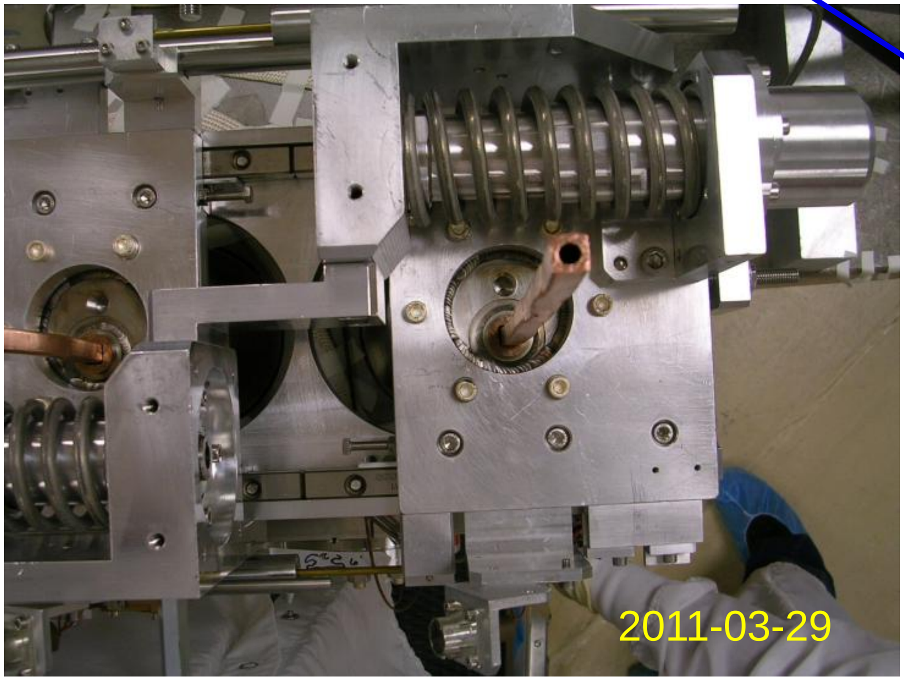


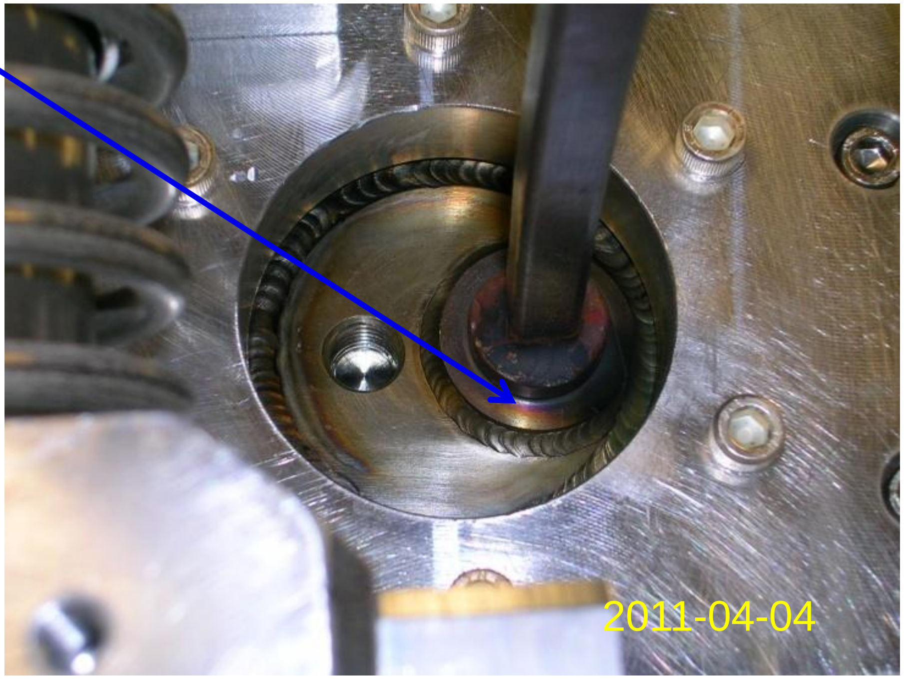
FARO arm Alignment



Tubes sealing cooling tube feedthroughs to check vacuum quality of tank weld
Leak Rate = 4.7E-10 mbar-l/s

Copper Cooling Tubes Before and After TIG Braze to Copper Feedthrough (Last Operation)

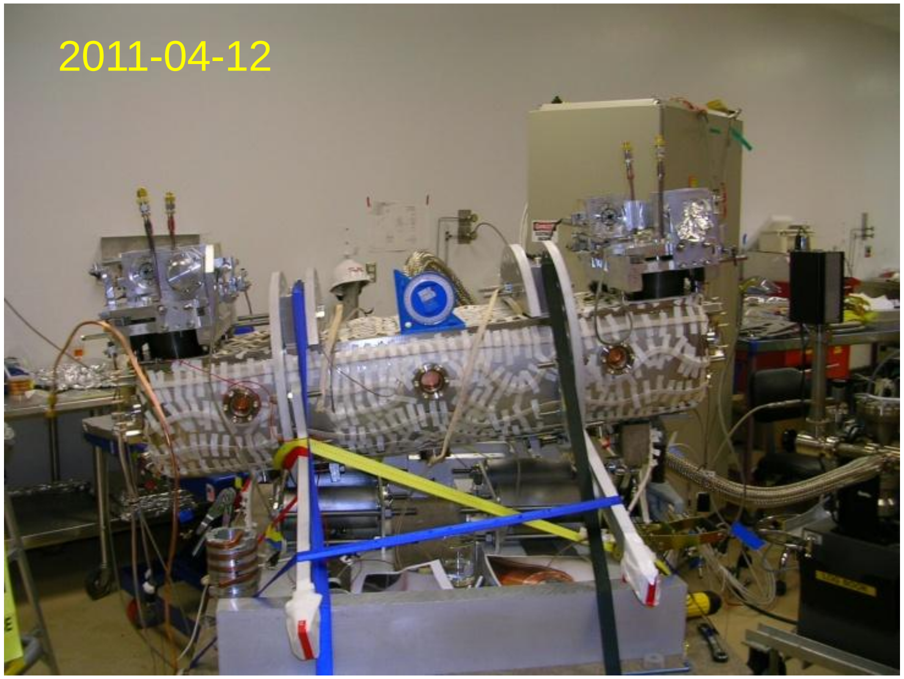




In principle, tank is now vacuum tight ….

However, to make a long story short, we find …

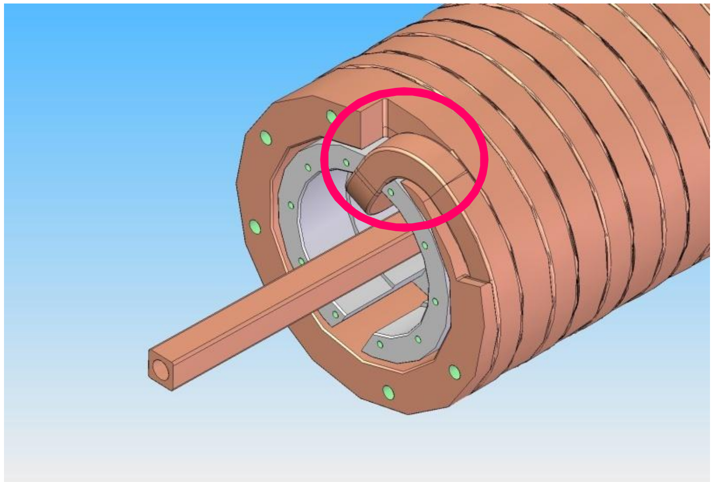
Each Jaw Is Damaged Very Near the End of the Jaw



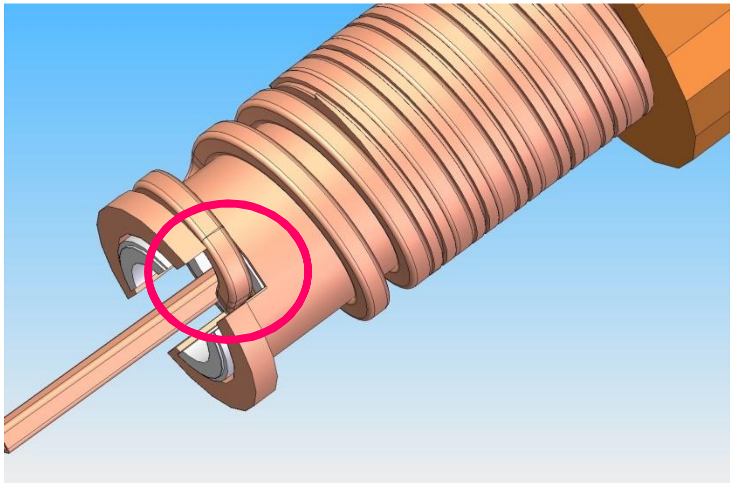
Pour 60mL Alcohol Into Each Cooling Tube
Find that it Drains Out Cracks at the Very End of Each Jaw

Possible Leak Locations

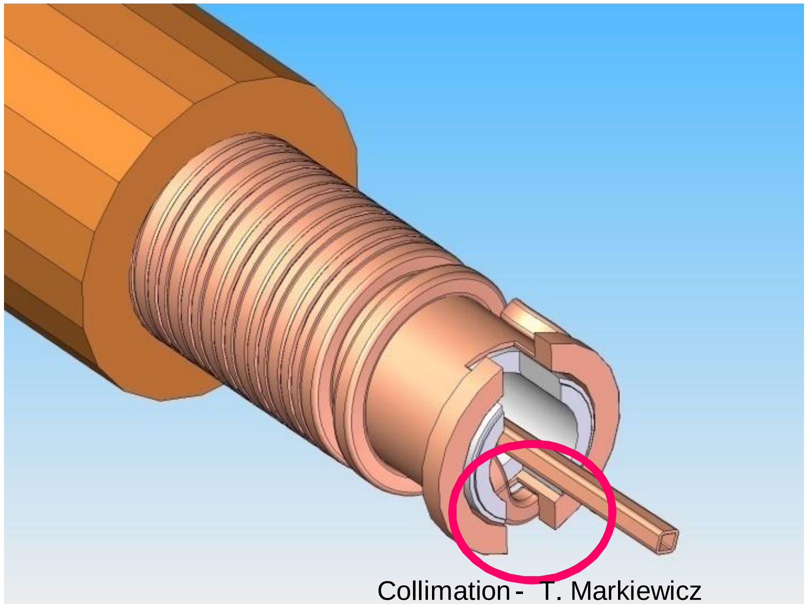
Upbeam Side of RC0 Jaw



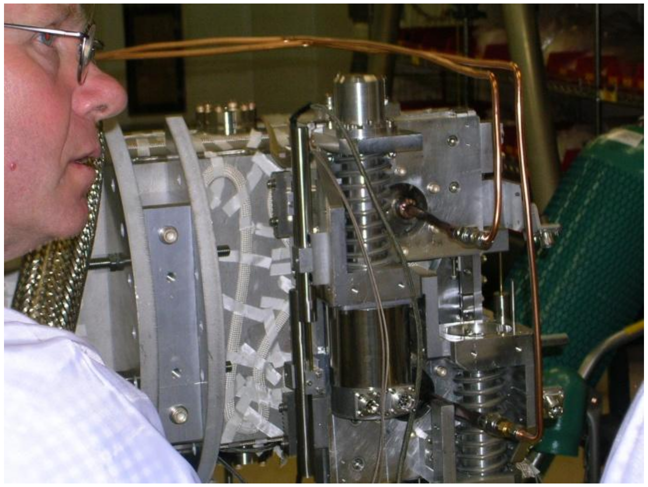
Downbeam Side of RC1 Jaw



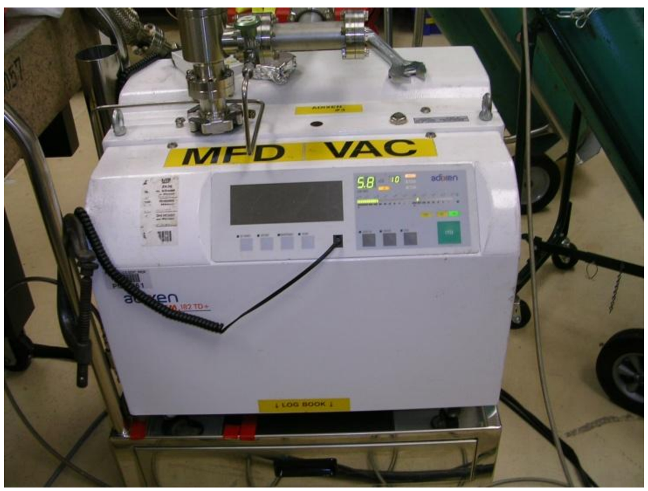
Recall that Cooling Tube Enters from Opposite Side of Jaw then Begins its Spiral around the Mandrel

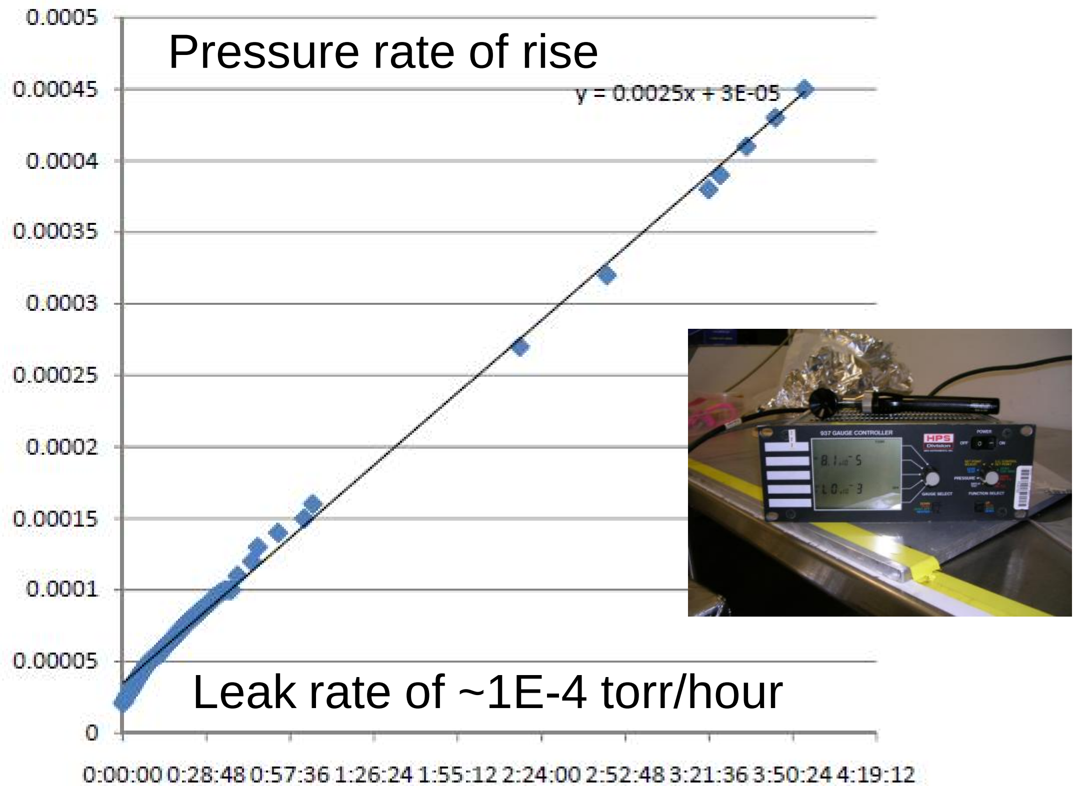


When Cooling Tubes Capped and Tank Pumped Vacuum IS Good



Pressure: 1.9E-5 Torr (Cold Cathode Gauge on tank)
Leak rate: 5.9E-10 mbar-l/sec (on the Adixen input)



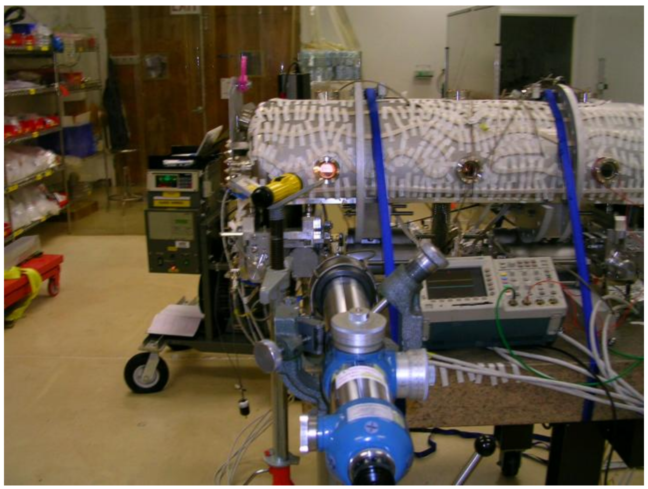


Rotation Test 3 Successful

First Test Under Vacuum (18 Apr-2011)

LARP

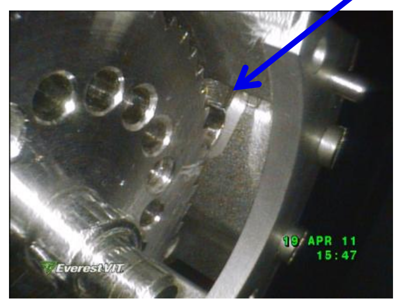
Alignment Via Telescope and Scribed Lines



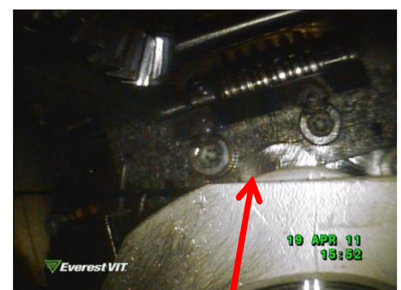
Scribed Lines

Pawl Alignment Post Rotation Checked Via Boroscope (no slippage)

RC1 Pawl



RC0 Pawl

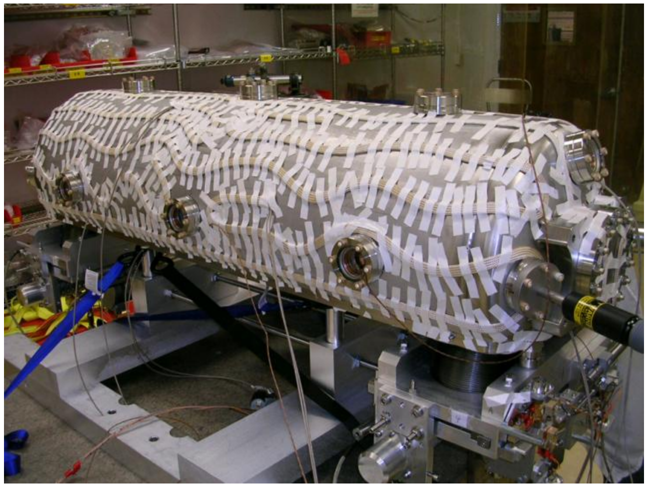


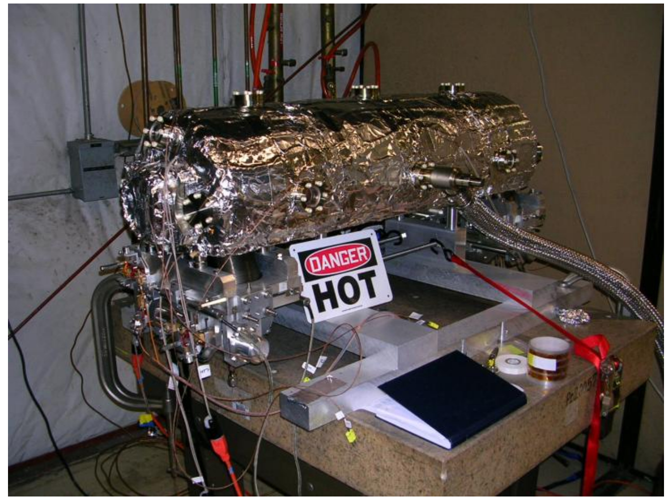
Crack in Mo Stable

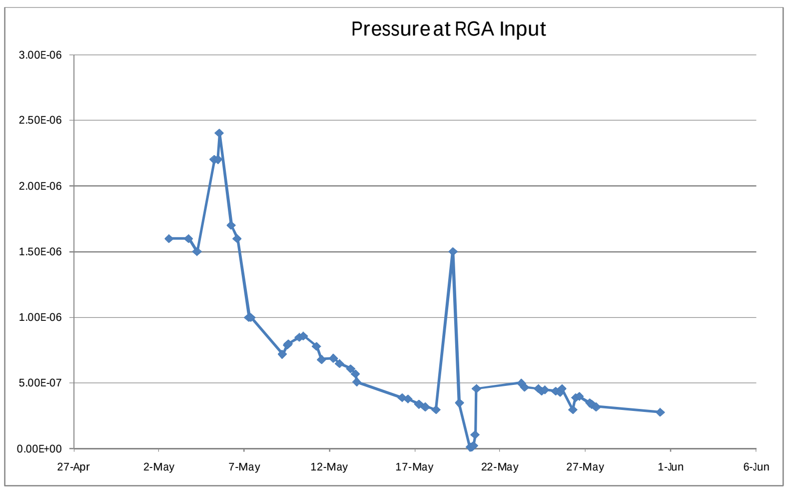
LARP

Pressure and Leak Rate Good Enough to Begin Vacuum Bakeout of Vessel with Capped Cooling Coils 2011-04-29

T~240˚C







P~2.8E-7 torr (Hot) on 2011-05-31

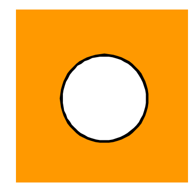
RGA (Hot) on 2011-05-31

Post Mortem has Begun, but No Conclusion

We did not anticipate that the cooling tubes might be subject to damage and we believe that, with the knowledge that they might be vulnerable, this problem will not happen again.

Speculation as to cause:

- Copper grain boundary growth coupled with stress on material could result in cracks at boundaries
- Work hardening from bending
- Damage from TIG welds/brazes



RC0 Jaw Material: SLAC in-stock magnet conductor

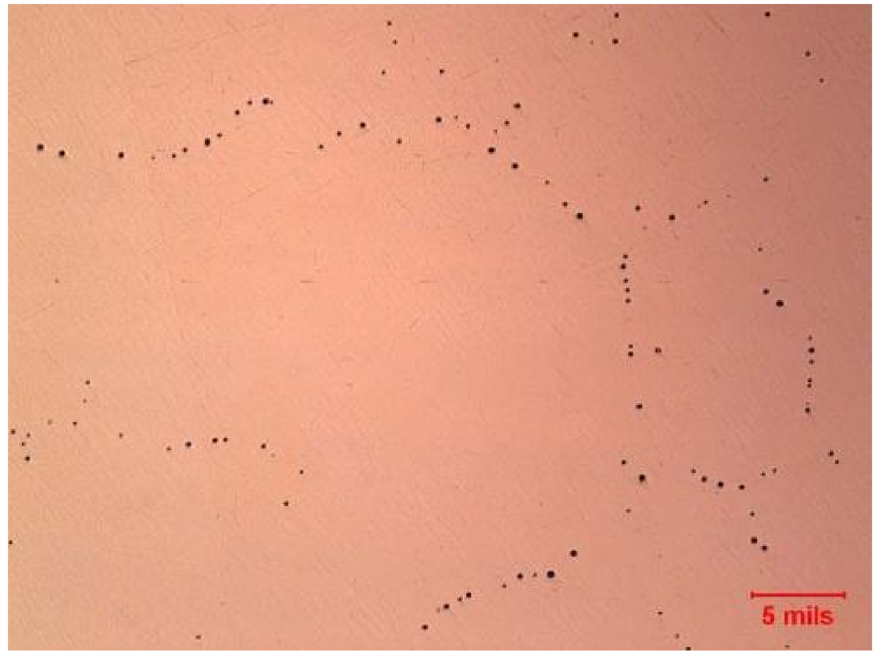
- OFE 102 copper: 3/8” square with 3/16” hole w/ 6 braze cycles

RC1 Jaw Material: New order from Luvata, 101 OFE COPPER F68 Class 1, w/documentation

- 10mm square w/ 7mm square hole; 3 braze cycles

Metallurgy: Samples to IMR Labs

"Large non-equiaxed grains consistent with hydrogen annealed OFE copper. Porosity was rated per ASTM F 68 Plate 1. Porosity was observed within and across grains.



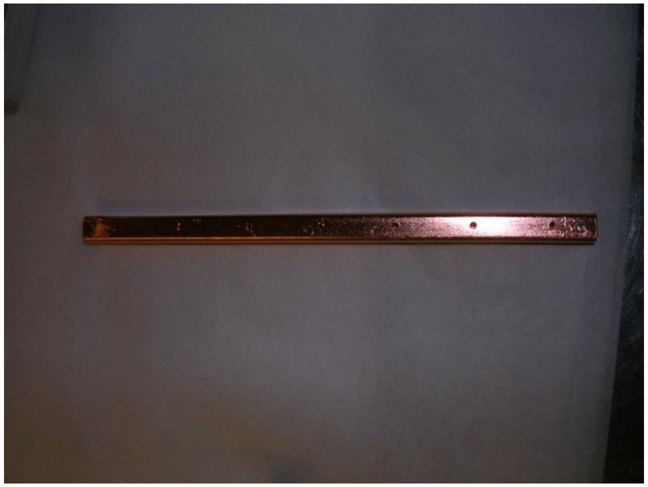
"The samples **conform to ASTM F68 Metallographic Class 4 for porosity** resulting from oxygen contamination."

- Material purchased as Grade 1 OFE with test data sent by manufacturer
- We have sent samples of virgin material to be tested as well

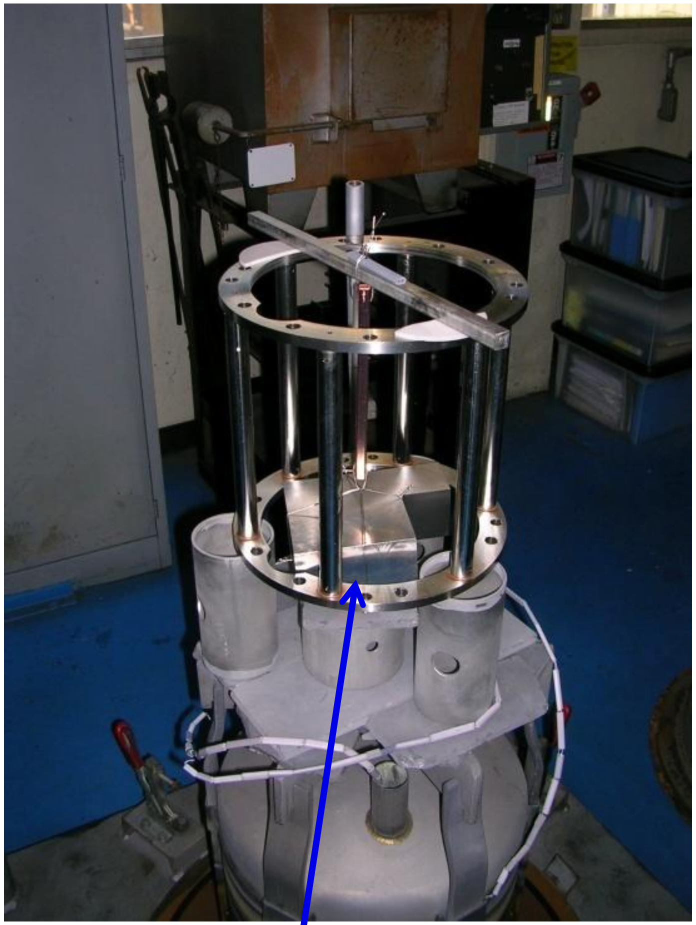
Furnace Runs to try to Duplicate Problems (in progress)

LARP

Bent & Straight Samples



Straight Sample on Braze Oven Stand



Tungsten Block to Provide Stress

RC Status & Plan Going Forward

Prototype RC finished

We believe that the fundamental design is robust and working to find problems

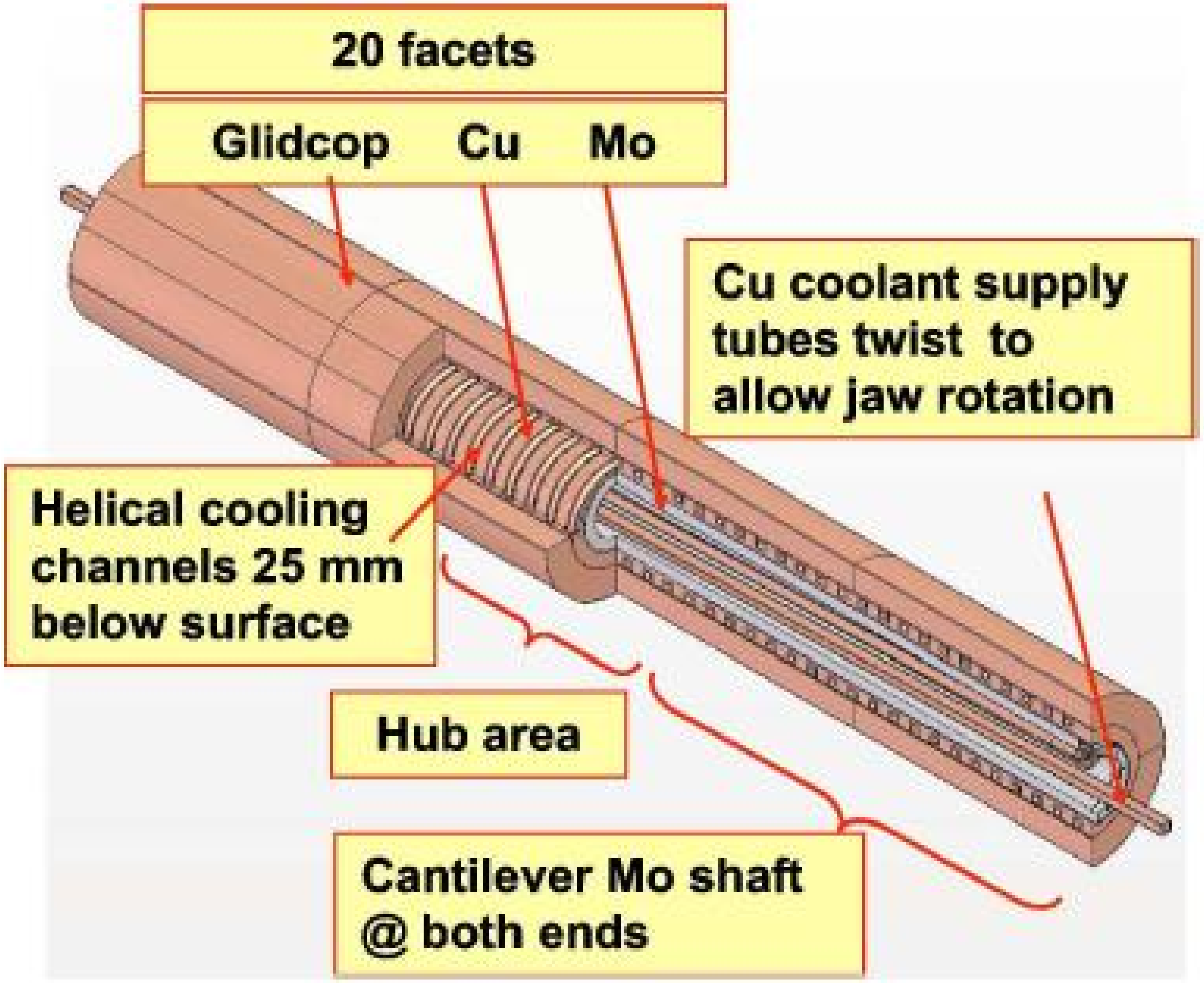
- Jaws cannot be cooled
- Expect vacuum to be good (LCLS/SPS)
- All mechanical tests look good
  - Will still need to do a last test rotation in vacuum after the bake

Plan: Active discussion with CERN colleagues in progress

- Preferred
  - Ship to CERN asap
  - Lab tests at CERN: Impedance, mechanical, vacuum, metrology
  - Install without cooling in SPS for operation & impedance tests
  - Install in HiRadMat test beam for destructive tests
    - But integrity of water circuit under shock untestable
  - Understand cooling tube problem with small samples at SLAC
- Other choice: dissect & destroy at SLAC
- More HW?: 2nd prototype, 2nd HiRadMat test device,…

Thank You for Your Attention

Jaw Designed to Minimize Thermal Distortion



Summary of Work Since July 2010 Review

Lab tests **under load** post-review uncovered deficiencies in

- The primary rotation bearing
  - 1mm diameter ceramic bearings in V-race grind into moly shaft & jam
  - Change to classic captured $W\text{-}S_2$ coated stainless balls in race
- The RF bearing
  - Add Rhodium coated crenulated “RF Wiper” to make contact between jaw & RF Foil & loosen screws in bearing housing
- The rotation drive unit and related hardware
  - Switch out Geneva Drive for standard gears (gain x3 on load)
  - Switch out ceramic bearings for $W\text{-}S_2$ coated stainless
  - Larger diameter shafts (5mm→6mm)
  - Use of thrust bearings to compensate unbalanced drive gears
  - Worm gear restraint and associated thrust bearings

After successful tests with new ad-hoc bearings & housings, prototype moved from test lab (10/28/10) and into vacuum clean room for final welding, assembly with final coated steel parts, bake out and testing

Clean Room Work from 1-Nov-2010 to Present

- ✓ Weld bellows to base plate and jaw supports to bellows
- ✓ Install final version of all parts
  - ✓ Rotation drives with new larger diameter W-S_2 impregnated bearings and shafts
  - ✓ Rebuilt primary jaw-support bearings and their housings
  - ✓ Final version of “pawls” to prevent gear backlash under load
  - ✓ Parts which hold thermistors & prevent “oil-canning” of RF shields
- ✓ Weld cooling tubes into their feed throughs so that all rotation tests from this point on cause tubes to twist
- ✓ Rotation, resistance, & alignment tests
- ✓ Tests under vacuum after vessel cover welded: no more access
- ➢ Vacuum bake out & RGA scan: 4-weeks into 240°C bake
- Still need one post-bake out rotation tests under vacuum