

**LARP**

# Workshop on Materials for Collimators

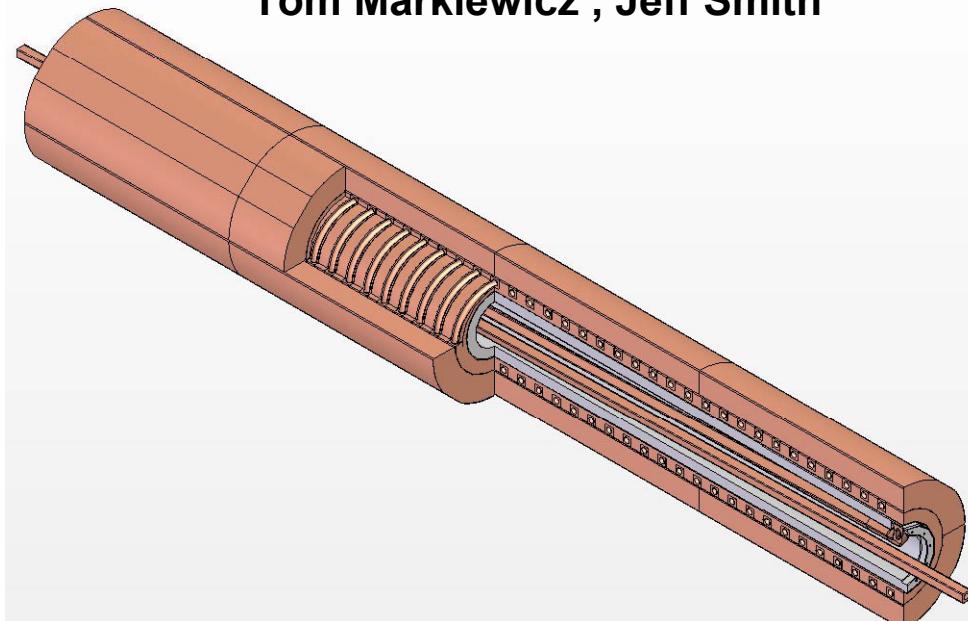
## CERN 2007/09/03

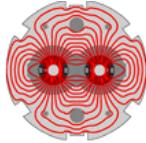


# Phase II Collimators for LHC Upgrade at SLAC - Material Issues

Presenter: Eric Doyle

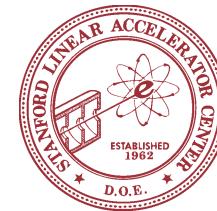
Workers @SLAC: Gene Anzalone, Yunhai Cai, Lew Keller, Steve Lundgren,  
Tom Markiewicz , Jeff Smith



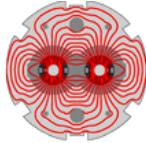


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# LHC Phase II Collimator Material Choice



- NLC collimator concept adapted to LHC
- FLUKA/ANSYS jaw thermal response simulations
  - Design cases (steady state, transient, accident)
  - Model/concept evolution
- Basic Jaw Material Choice
  - Cu => Glidcop
- Development of Final Design
  - Jaw-hub-shaft
- Accident damage
- Ongoing material issues



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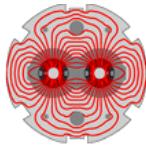
## Phase I and Phase II Collimation

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
  - 5x power for 10 sec when  $dE/dt=450$  kW handled as a transient
- Low, but adequate, collimation efficiency to protect against quenches at lower  $L$
- High, but adequate, machine impedance for stable operation at low  $L$

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

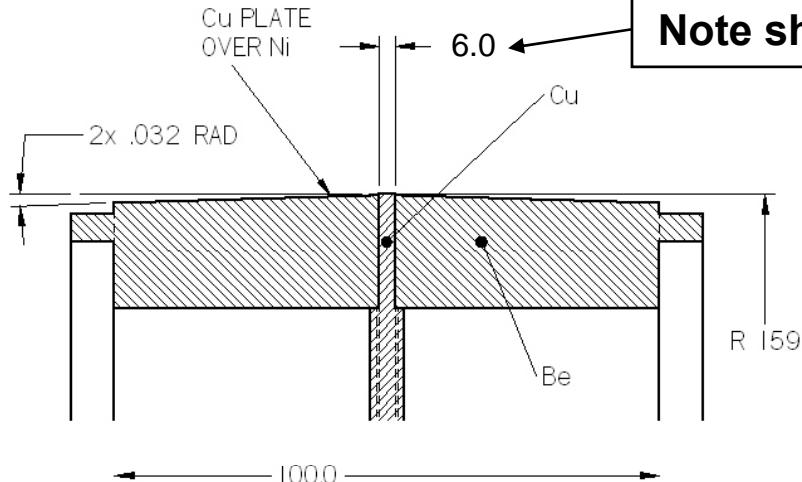
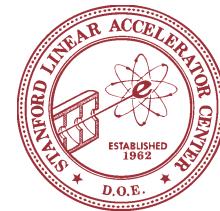
- Good impedance and efficiency allowing LHC to reach design  $L= 1E34$ 
  - After stable store open Carbon jaws and close Metal jaws
- Jaw will be damaged: what to do?
- More energy from primaries will be absorbed: cooling & deformation



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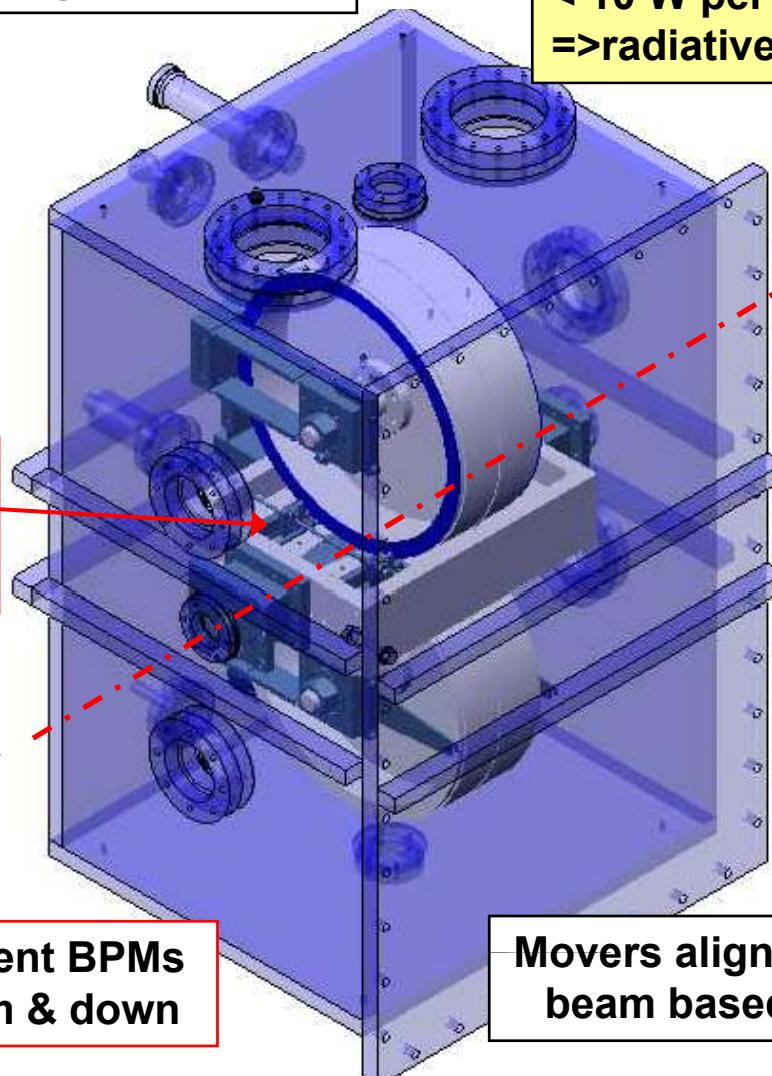
# NLC Consumable Collimator

## rotatable jaws – 500 to 1000 hits



Note short high-Z material.

< 10 W per jaw  
=>radiative cooling!

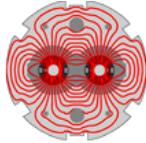


Aperture control  
mechanism – 5 $\mu$ m  
accuracy & stability

Alignment BPMs  
upbeam & down

Movers align chamber to  
beam based on BPMs





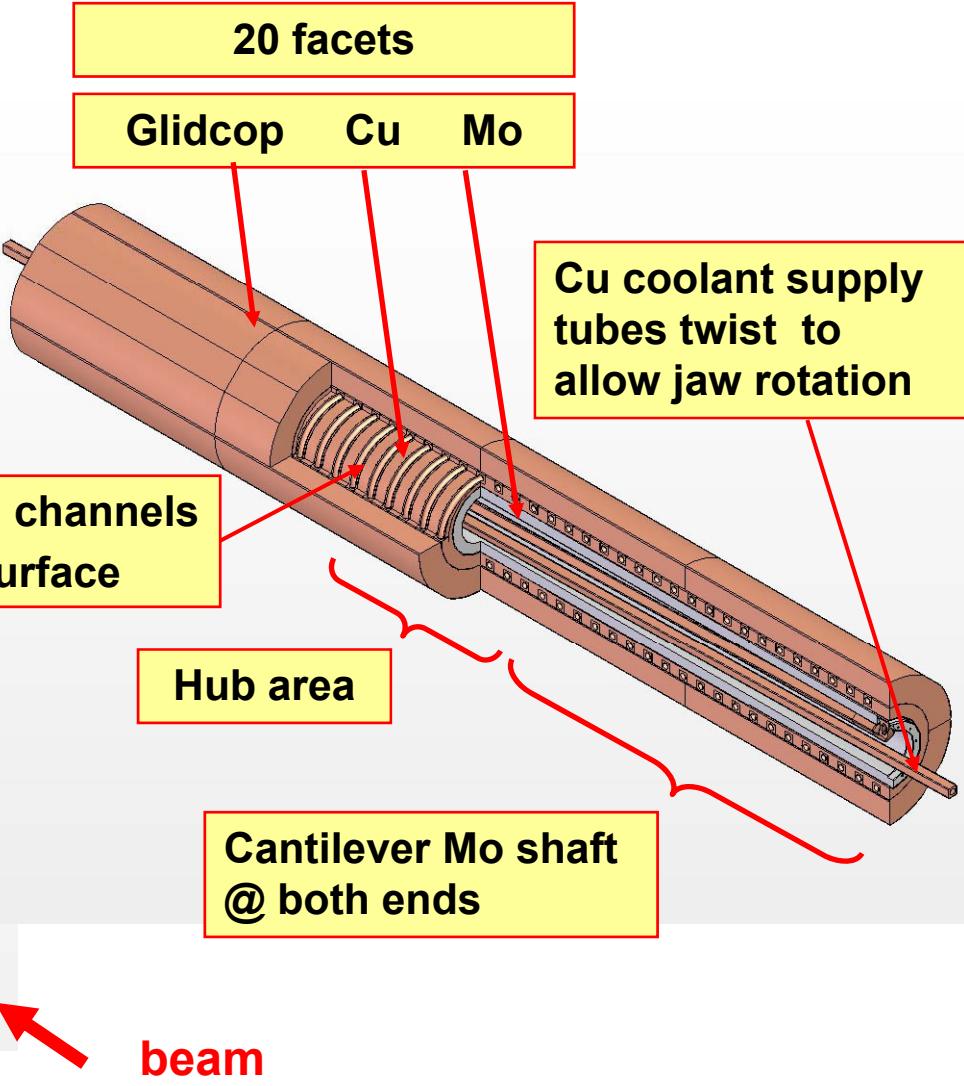
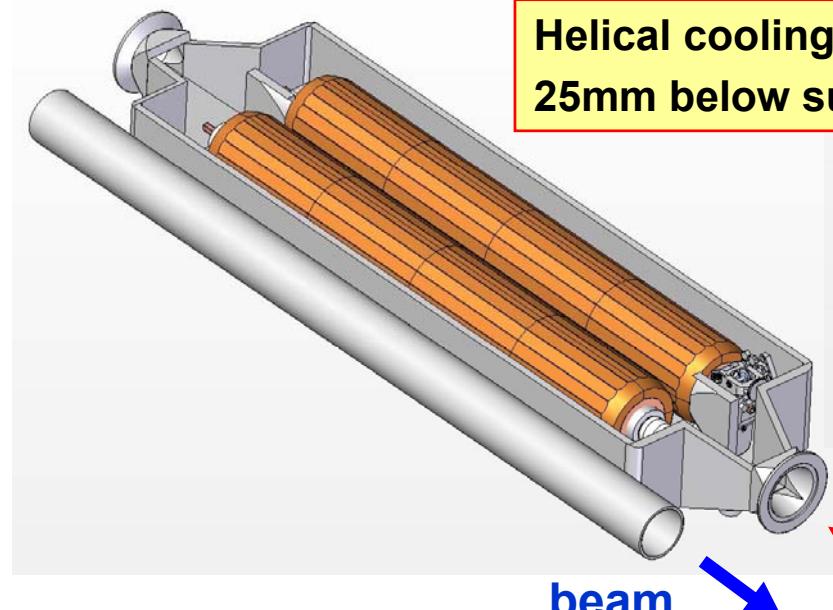
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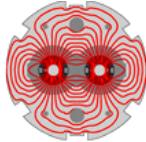
# LHC Phase II Base Concept

## physical constraints current jaw design



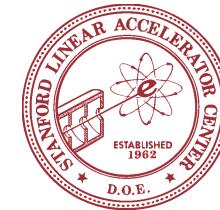
- beam spacing: geometrical constraint
- Length available 1.47 m flange - flange
- Jaw translation mechanism and collimator support base: LHC Phase I
- >10 kW per jaw Steady State heat dissipation (material dependent)





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# LHC Collimation Requirements

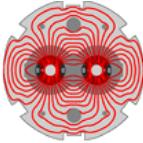


LHC Beam Parameters for nominal  $L=1E34\text{cm}^{-2}\text{s}^{-1}$ :

- 2808 bunches,  $1.15E11$  p/bunch, 7 TeV  $\rightarrow 350$  MJ
- $\Delta t=25\text{ns}$ ,  $\sigma \sim 200\mu\text{m}$  (collisions)

System Design Requirement:

- Protect against quenches as beam is lost
  - “Steady state” collimator cooling for  $\tau = 1$  hour or  $8E10$  p/s or 90kW
  - “Transient” bursts of  $\tau = 12$  min or  $4E11$  p/s or 450kW
    - abort if lasts > 10 sec
- Accident Scenario : Beam abort system fires asynchronously with respect to abort gap - **8 full intensity bunches** impact collimator jaws

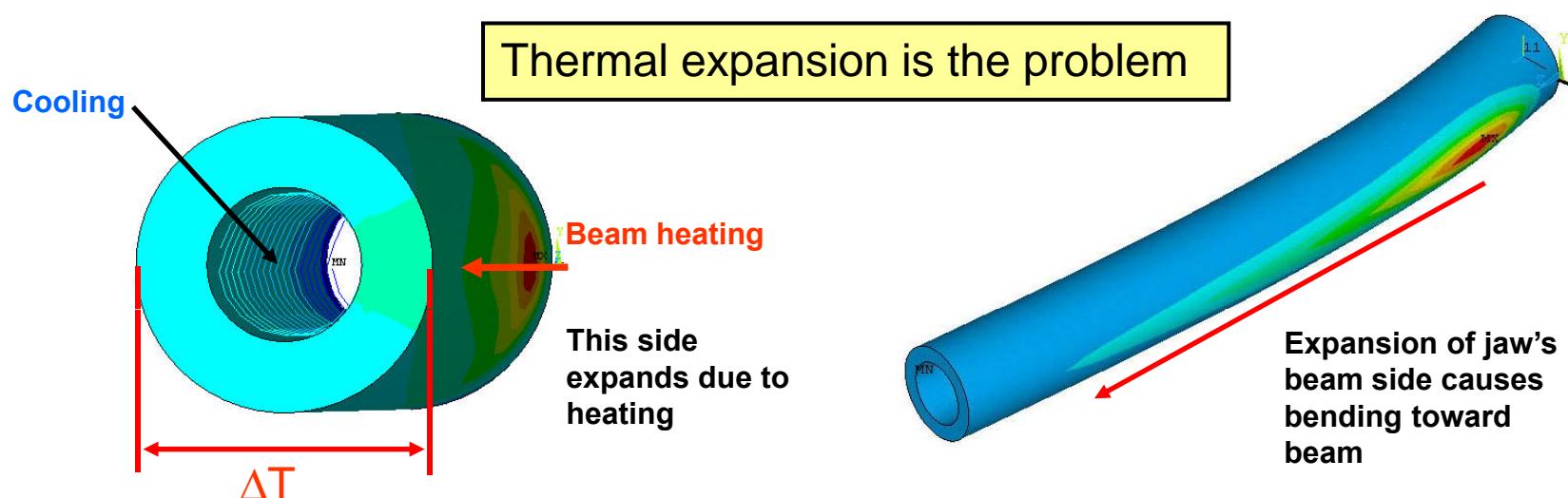


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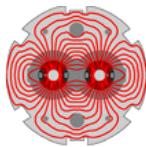
# Dominant collimator specifications



- $25\mu\text{m}$  maximum deformation toward beam
- $7\sigma$  nominal aperture
  - The first long secondary collimator may be set at  $8\sigma$  to ensure  $25\mu\text{m}$  intrusion with respect to  $7\sigma$
- 45 mm minimum aperture jaws fully retracted
- Beam spacing limits transverse dimensions
- Maximum length predetermined: 1.48 m flange-flange
- No water-vacuum joints



This effect is a function of material, jaw OD & ID, length, and cooling arrangement



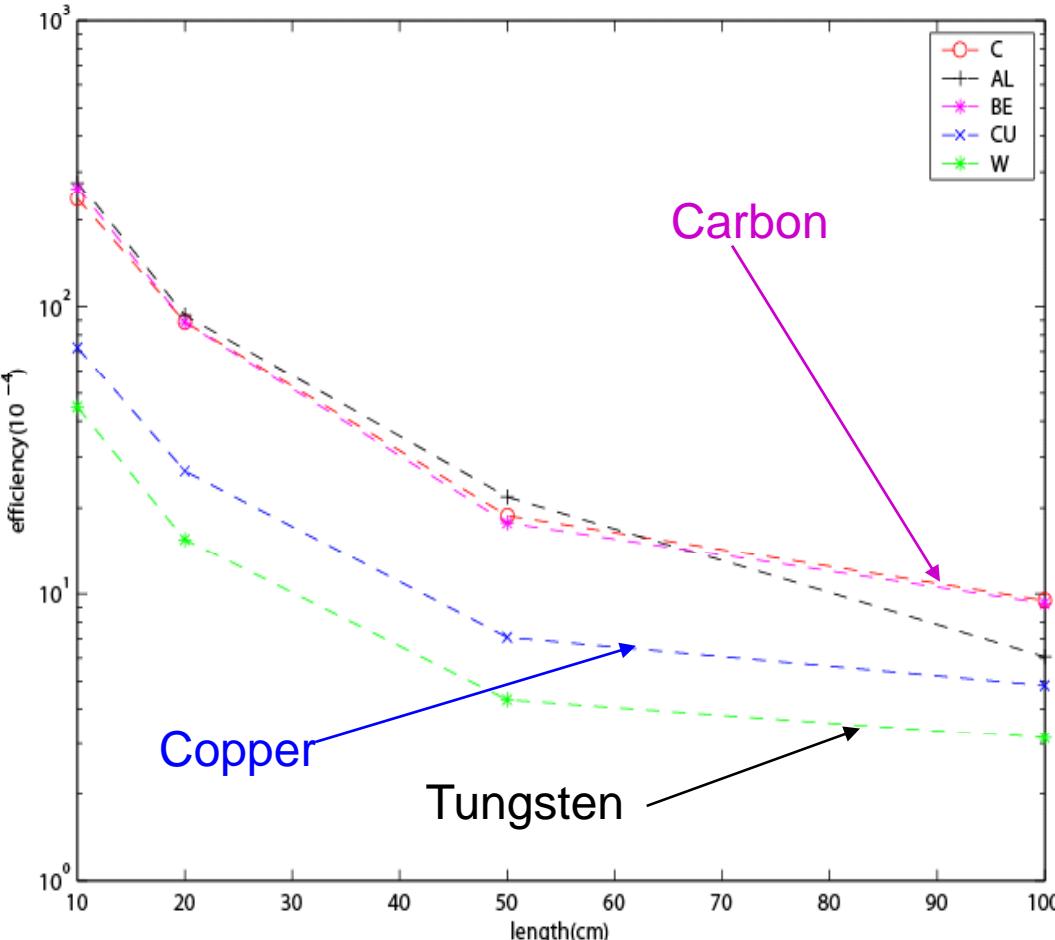
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# SIXTRACK simulation

## compare materials' collimation efficiency tradeoff with mechanical performance



Yunhai Cai



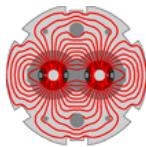
- High Z materials improve system efficiency but generate more heat
- Copper considered because its high thermal conductivity and ease of fabrication
- Available length for jaws is about 1 meter

Similar result was obtained by Ralph Aßmann

Phase II Collimators for LHC Upgrade at SLAC - Material Issues

E. Doyle 03 Sept. 2007

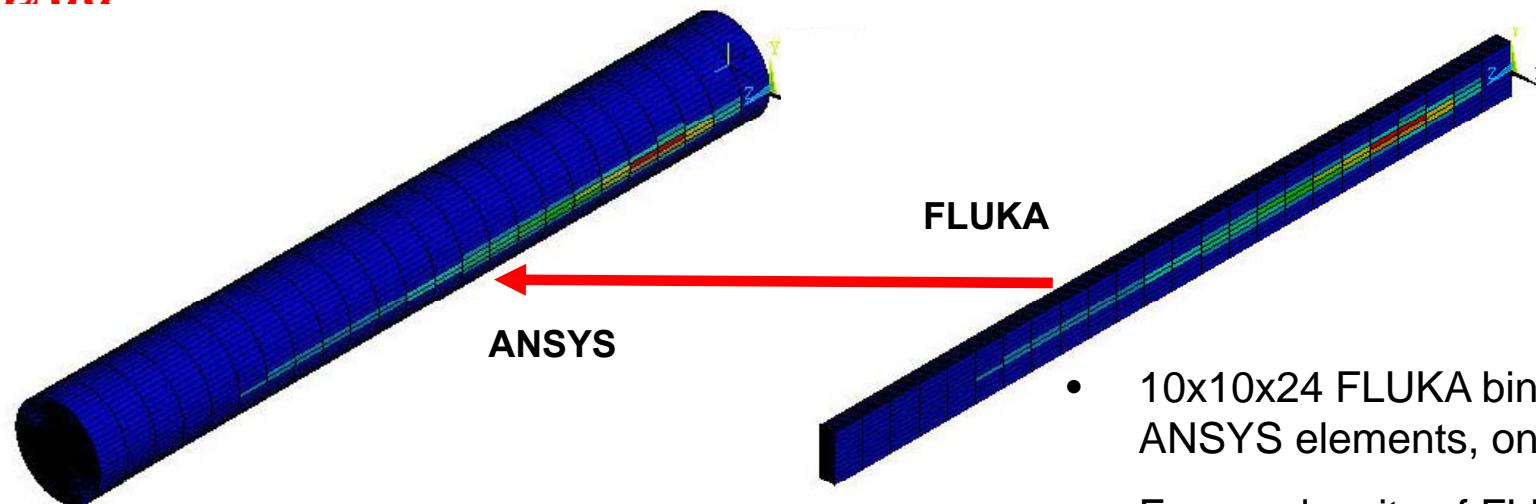
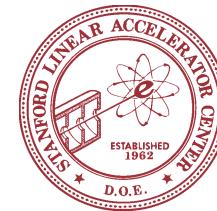
8/25



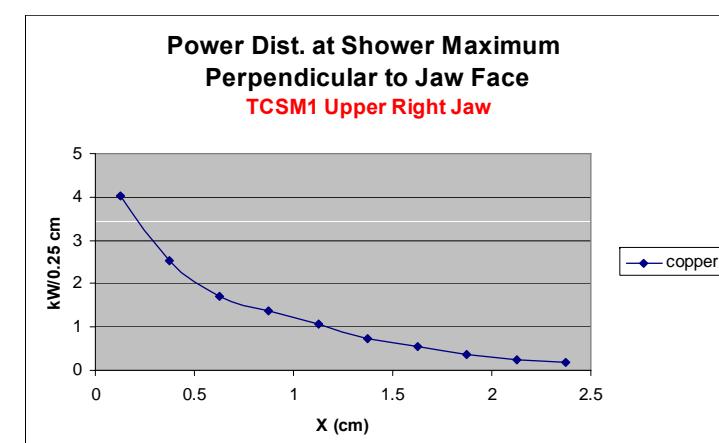
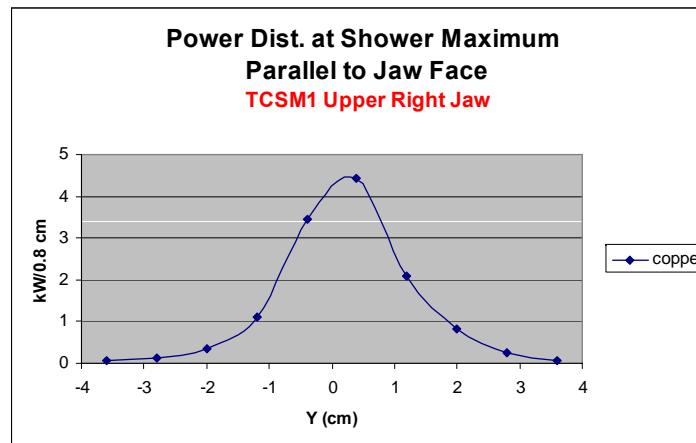
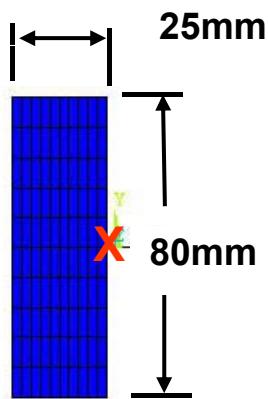
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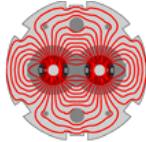
# Basis for Design Choices

## ANSYS Thermal/Mechanical simulations using FLUKA energy deposit



- 10x10x24 FLUKA bins mapped to ANSYS elements, one for one
- Energy density of FLUKA bin applied to ANSYS element





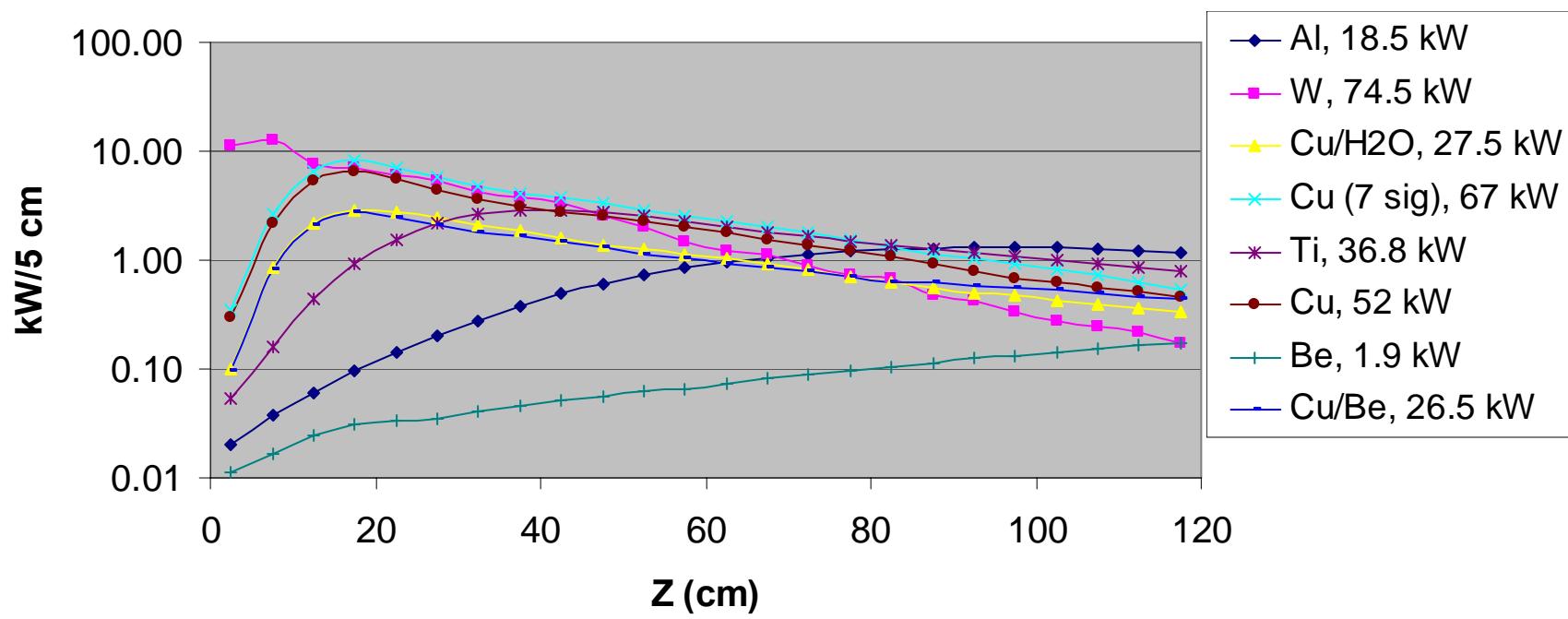
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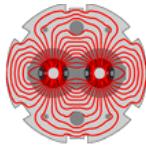
# FLUKA Results - Power Deposited vs. Length

- 1st secondary collimator
- Various materials



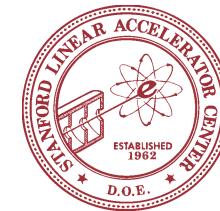
**kW Deposited in TCSM.A6L7 Upper Right Jaw vs. Length**  
80% halo on TCPV, 5% halo on TCSM.A6L7, 12 min. lifetime  
half-gaps =  $10\sigma$  unless noted



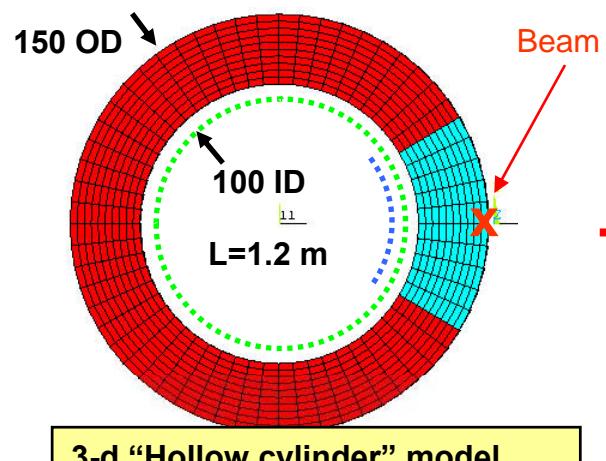


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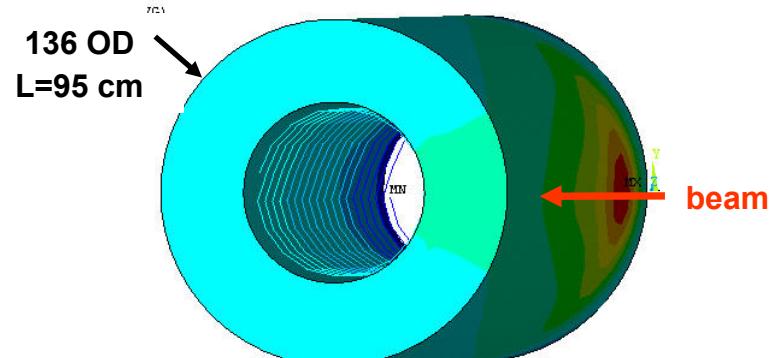
# ANSYS models – Material Choice and CDR



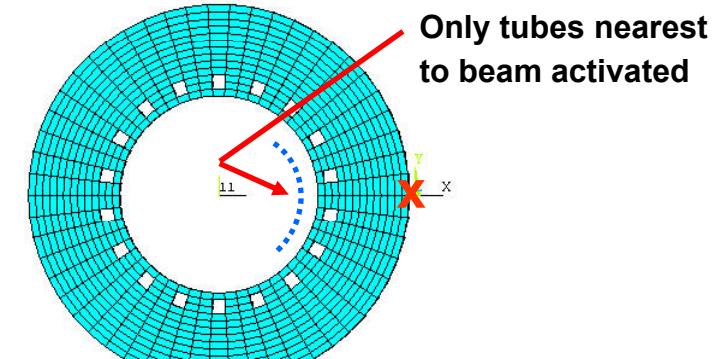
## Basis for Jaw Material Choice “abstract” water simulation



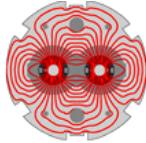
## Conceptual Design Review realistic water simulation



“RC1 Baseline” Model: helical H<sub>2</sub>O channels, 5cm pitch



Alternative CDR Model: Axial H<sub>2</sub>O channels, channels nearest beam activated. **Rejected – not practical.**

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# Material thermal performance

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

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 <sup>1</sup>	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 <sup>2</sup>	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

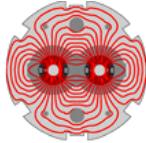


1. deflection not valid, super invar loses its low c.t.e. at 200C

2. pressure > 30 bar needed to suppress boiling

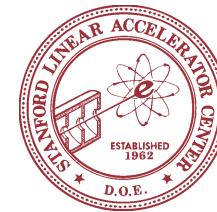
\* **Promising but no practical implementation**

**Cu chosen – balance of efficiency, deflection and manufacturability**



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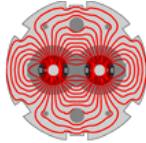
# Justification of Cu Choice



## 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

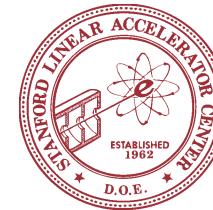
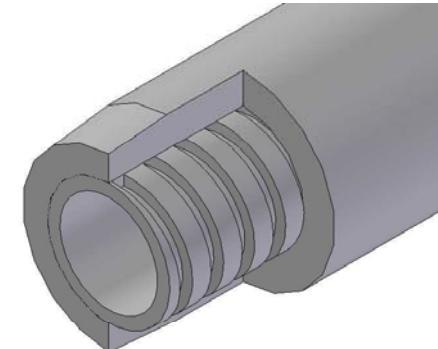
**Cu chosen as best balance between collimation efficiency, thermal distortion & manufacturability**



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## RC1 Baseline Jaw

- CDR review 12/05
- Helical cooling channels
- O.D. = 136 mm, I.D. = 71 mm, L = .95 m
- NLC-type edge supports
- 7 $\sigma$ , new ray file
- SST core no benefit



material	cooling arc (deg)	power (kW) per jaw, nominal	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)
CERN ray file, 7 s, 83.8% 60cm TCPV, 4.8% direct hits											
Cu, 136x71x950-, 750 heated, (helical), fluid pipes	-	11.7	86.5	394	68.3	5.7E+05	58.5	231.3	1216	153.5	1.6E+06



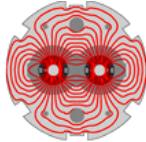
### Cu/SST & solid Cu - 5cm pitch helical cooling

Cu solid, helical cooling	-	11.7	75.5	209			58.5	208.9	919		
25mm Cu on SST core	-	11.7	85.2	402			58.5	231	1135		
10mm Cu on SST core, Cu cooled	-	11.7	95.3	448			58.5	256	1111		
10mm Cu on SST core, SST cooled	-	11.7	97.7	475			58.5	265	1158		

baseline concept

RC1 review committee suggestion

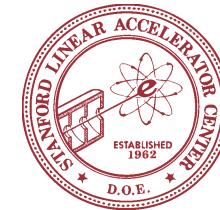
Cu SST core evaluated on recommendation of RC1 CDR committee – not successful



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# Glidcop Improves on Cu Performance

## Prevents Permanent Deformation in SS Operation

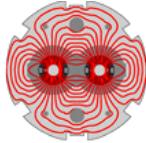


### Cu jaw deforms permanently in 12 min beam lifetime transient

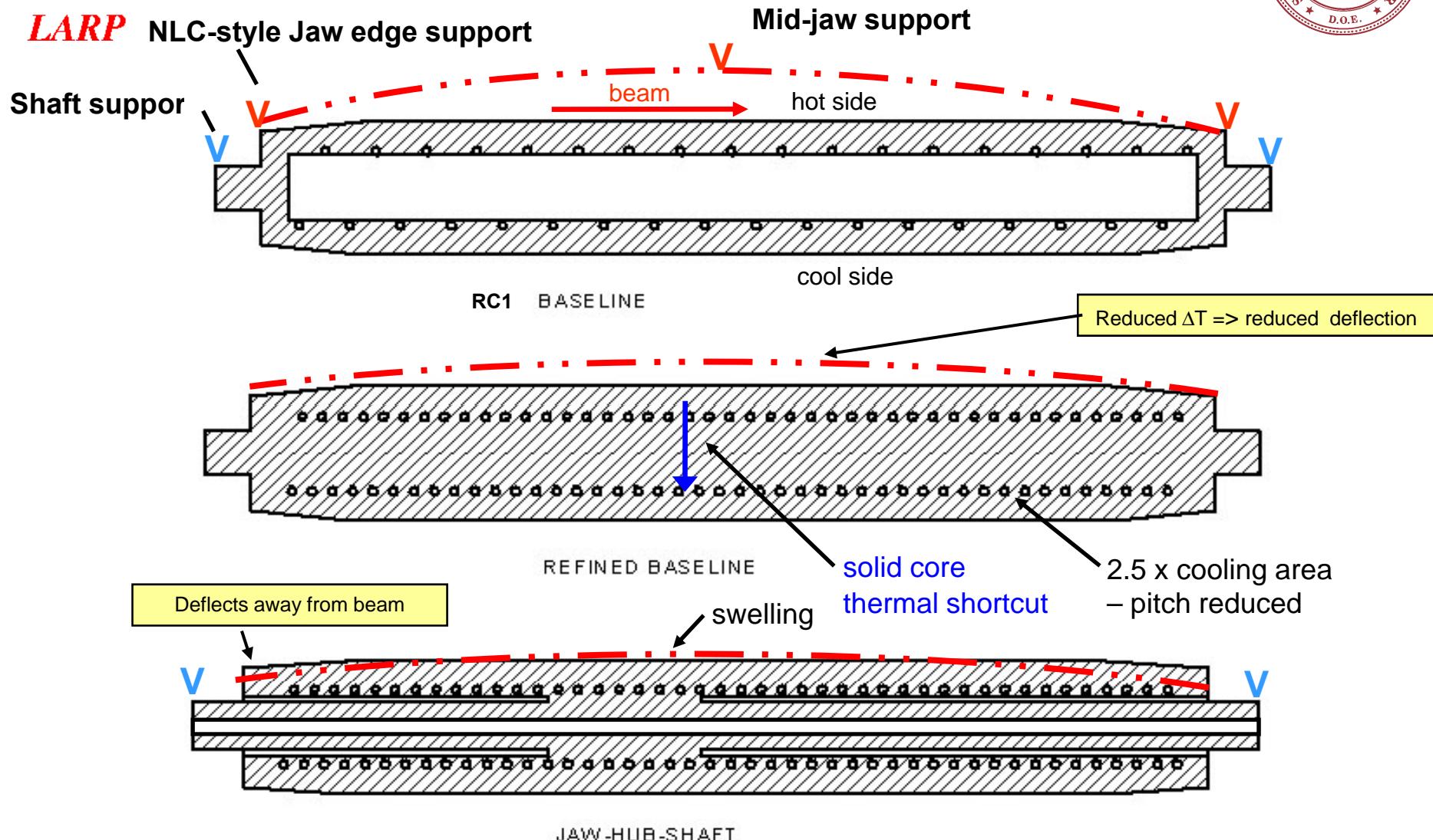
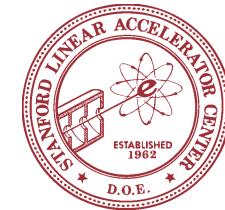
- jaw-hub-shaft model
- temperature history
  - steady at 1hr beam lifetime
  - 10 sec at 12 min beam lifetime
  - cool to ambient temperature
- ~60  $\mu\text{m}$  permanent curvature concave with respect to beam

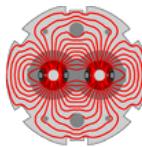
### Glidcop (AL15) jaw

- no permanent deformation in 10 sec transient
- slightly reduced thermal properties
- Accident case problematic – see later slides



# Development Since RC1 Baseline

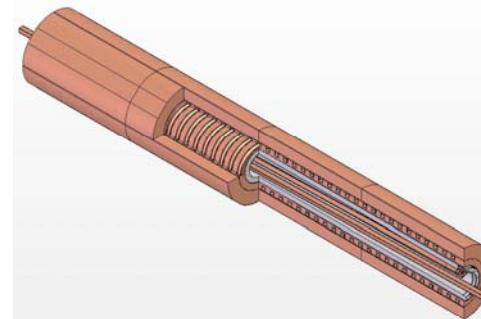




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# Current Configuration

- Jaw – Hub – Shaft Model
- Mo chosen for shaft
- Glidcop or Cu as alternatives



## Current design vs RC1

- Glidcop outer jaw
- more cooling (2cm pitch)
- Reduced jaw end taper
- Mo shaft (low cte, high E)
- \* fabrication issues

## SS 1 hr beam lifetime

steady state 1 hr beam lifetime								
jaw		upbeam		midjaw		downbeam		effective L
power <sup>5</sup> (kW)	temp (C)	ux (um)	uz (um)	ux (um)	ux (um)	uz (um)	(m)	(um)
jaw-hub-shaft all Cu	11.7	66.3			100			0.51
Mo shft, no taper	12.9	66.0	-176	-226	83.6	-40.9	437	0.74
Glidcop jaw, Mo shft	12.9	70.6	-186	59	105	-40.6	737	0.67
Glid jaw + sst shaft	12.9	70.6	57.3	6388	351	193	6998	0.67
Glid jaw, thk glid shft	12.9	70.6	-175	28	111	-29	966	0.68
Glid, thk Cu shf, .3m hub	12.9	70.7	-98	139	156	-14	830	0.67
								218

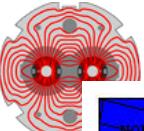
## Shaft response ss & transient

gravity loading	ss	trans
simple supports	shaft	shaft
	downbm	downbm
ux (um)	slope (rad)	uz (um)
-200. <sup>4</sup>	-	
-67.5	2.60E-04	215
-68.1	2.38E-04	779
-	-	865
-120.3	4.59E-04	13478
-88.3	3.11E-04	13623
		1377
		1266

## 10 sec transient 12 min beam lifetime

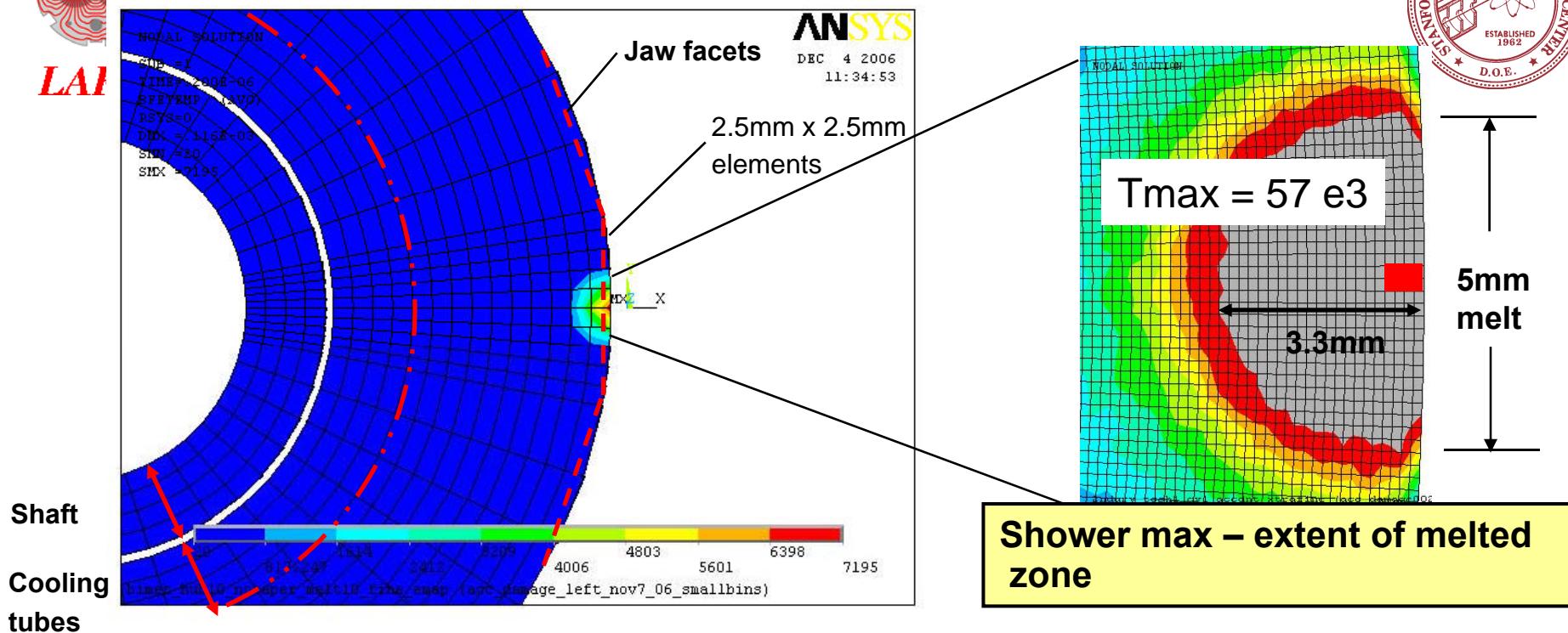
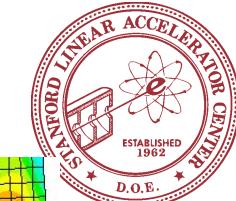
transient 12 min beam lifetime, 10 sec duration								
jaw		upbeam		midjaw		downbeam		effective L
power <sup>5</sup> (kW)	temp (C)	ux (um)	uz (um)	ux (um)	ux (um)	uz (um)	(m)	(um)
jaw-hub-shaft all Cu	58.5	197			339			0.25
Mo shft, no taper	64.5	198	-753	-550	236	-278	603	0.39
Glidcop jaw, Mo shft	64.5	224	-735	-229	365	-229	957	0.33
Glid jaw + sst shaft	64.5	224	-338	6127	766	148	7325	0.34
Glid jaw, thk glid shft	64.5	224	-618	18	467	-141	1215	0.33
Glid, thk Cu shf, .3m hub	64.5	224	-347	-68	641	-51	1124	0.34
								846

~ 500 W shaft heat on Mo



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# Accident Case



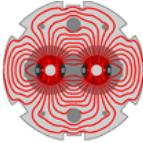
**Case:** beam abort system fires asynchronously, **8 full intensity bunches into jaw**

**Model:**

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

**Result:**

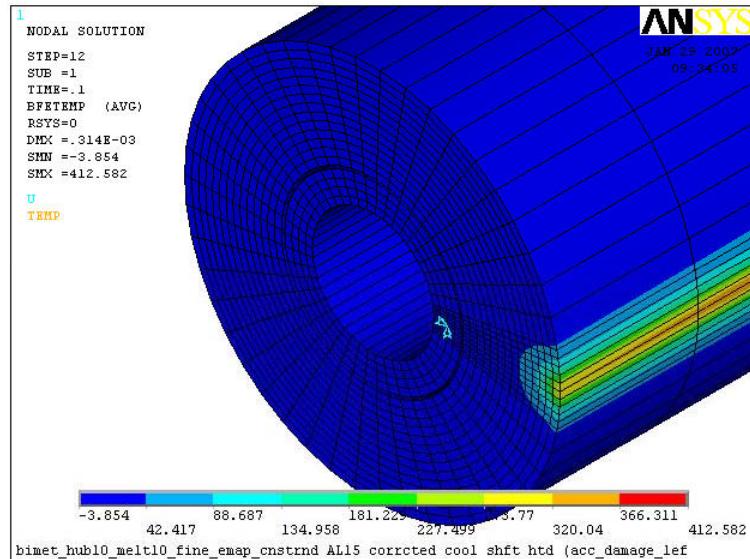
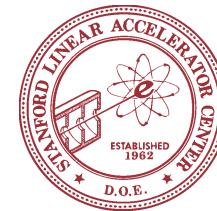
- 57e3 peak temperature (ultra fine model)
- **54  $\mu$ m permanent deformation** (concave)



**LARP**

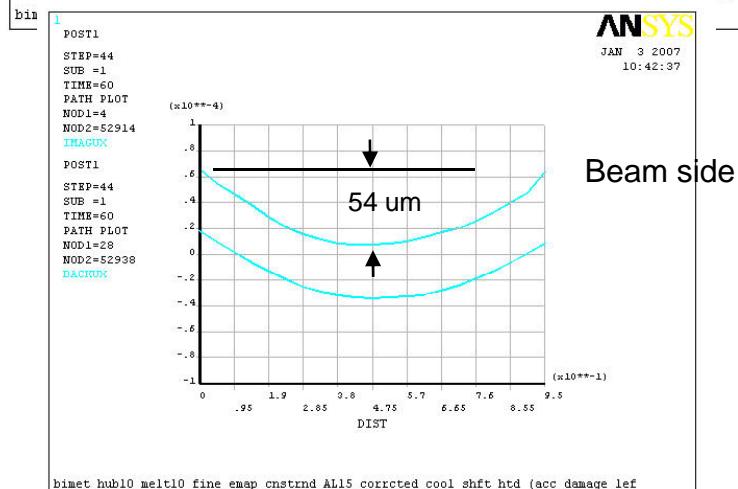
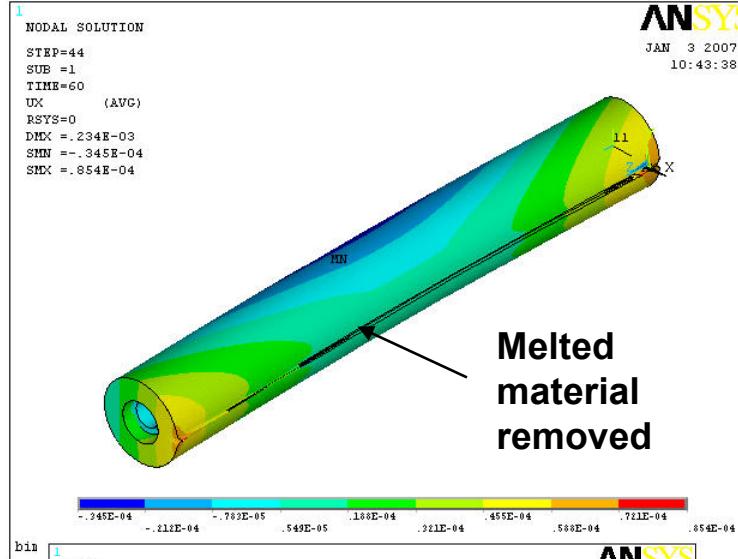
## Accident Case

### Permanent Jaw deflection, ux, after 60 sec cool-down

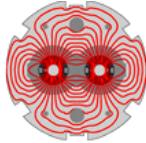


After energy deposit (200ns – 60 sec),  
z-constraints released. Original analysis used this constraint at all times.

- What happens to vaporized/melted material?
- How to use deformed jaw?



In-plane permanent deflection



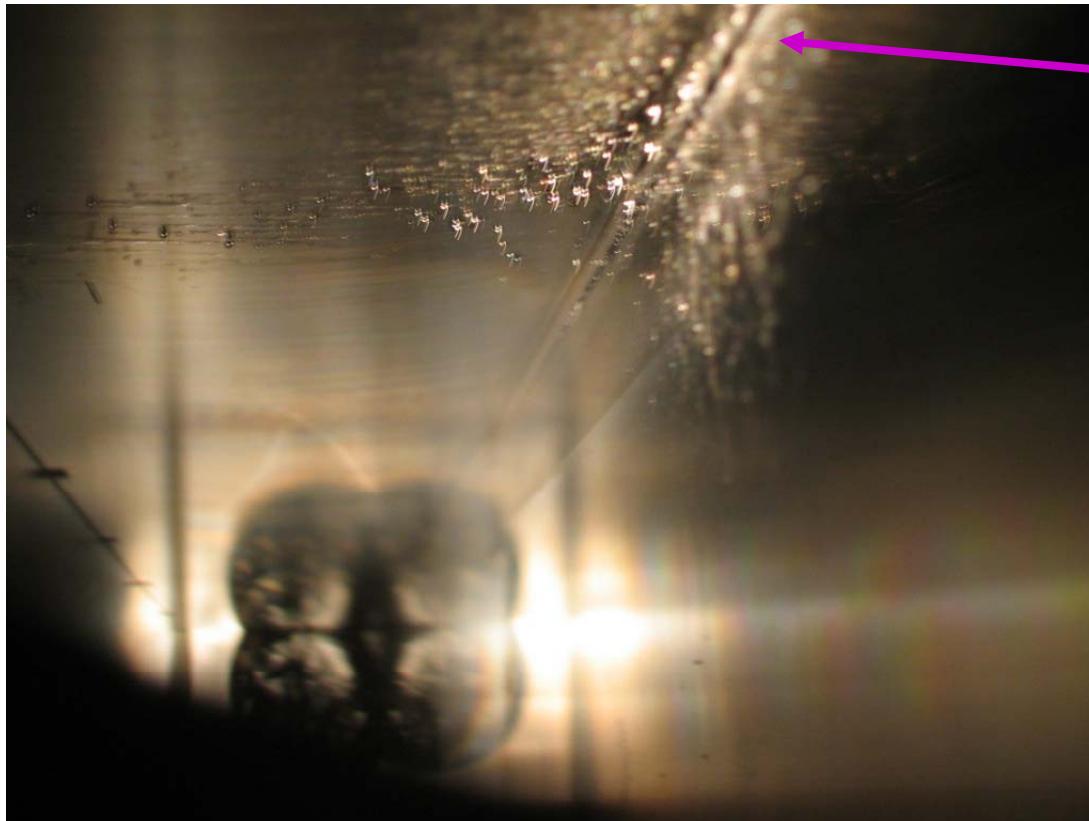
**LARP**

# Tevatron Accident – 2003

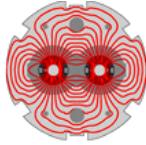


## Beam Lost on Stainless Steel Collimator

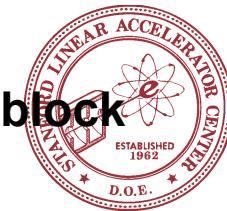
**Energy deposition ~0.5 MJ**



**groove is 25 cm long,  
1.5 mm deep**

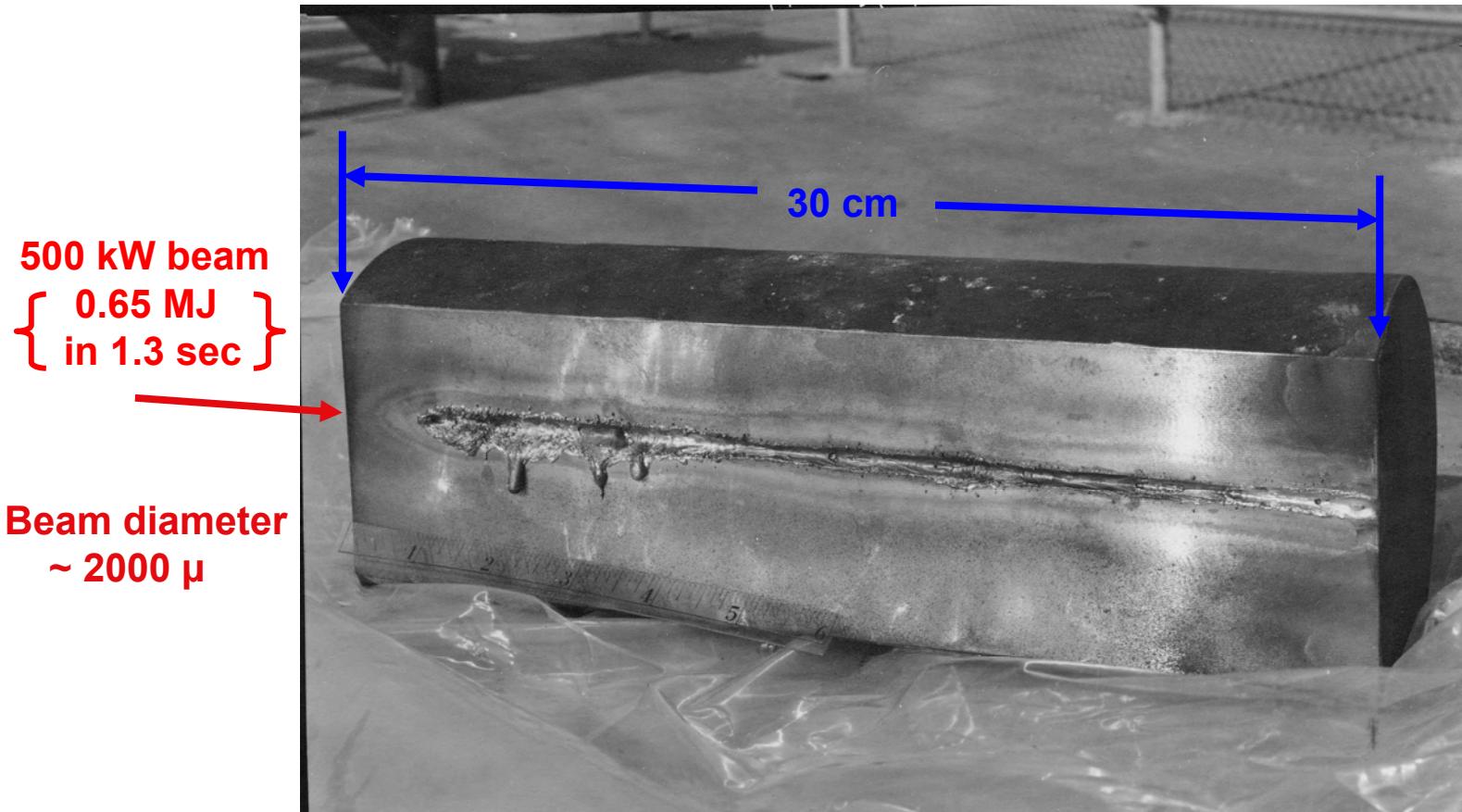


## SLAC Damage Test - 1971

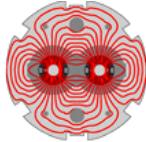


**LARP**

Beam entering a few mm from the edge of a 30 cm long copper block  
The length and depth of this melted region is comparable to the ANSYS simulation for the LHC accident.



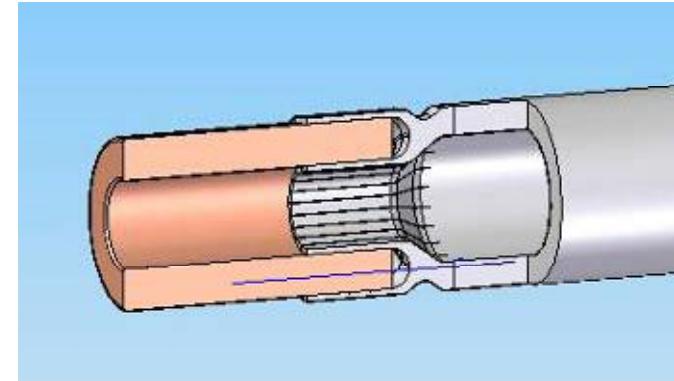
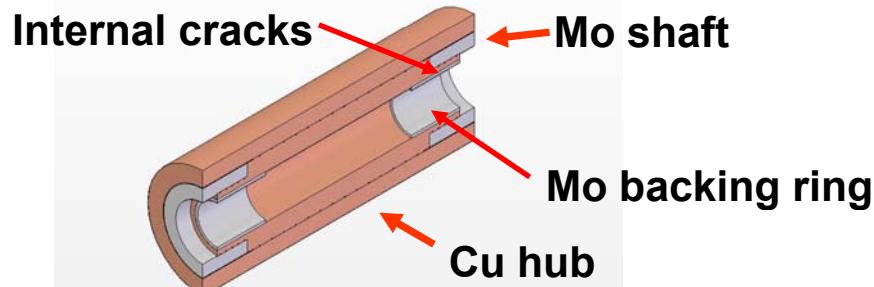
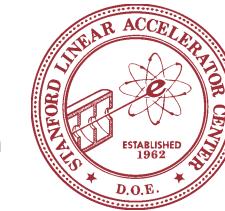
It took about 1.3 sec to melt thru the 30 cm block, but for this relatively large beam, the front two radiation lengths remain intact.



LARP

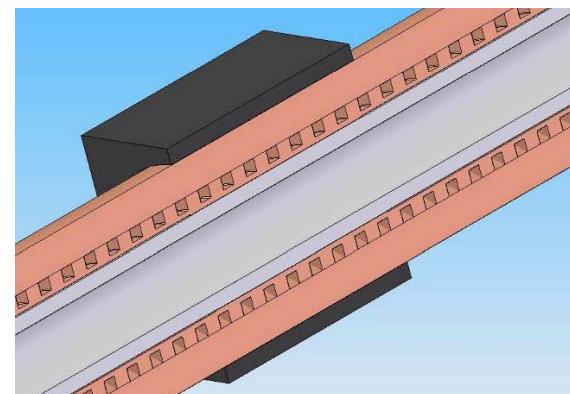
# Ongoing Material Issues

## Jaw Fabrication – Cu–Mo thermal expansion mismatch

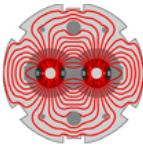


First try: braze cycle =>cracks at critical load point

Mo can flex radially to follow Cu at braze temp



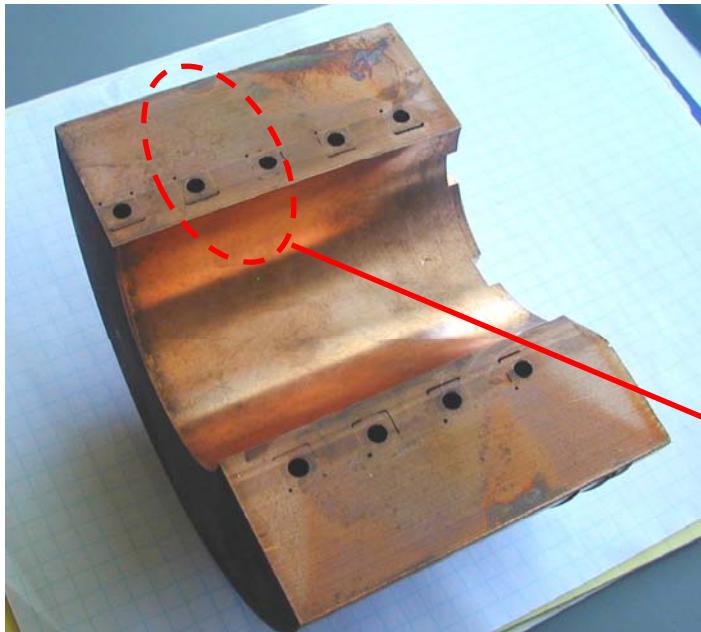
Thru Mo shaft, interference fit using carbon constraining collar



LARP

# Ongoing Material Issues

## Cu grain boundary cracking during brazing

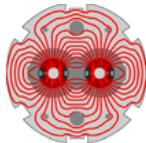


Specimen 140mm OD x 60mm ID x 200mm L ( $\frac{1}{4}$  section shown)

- 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?

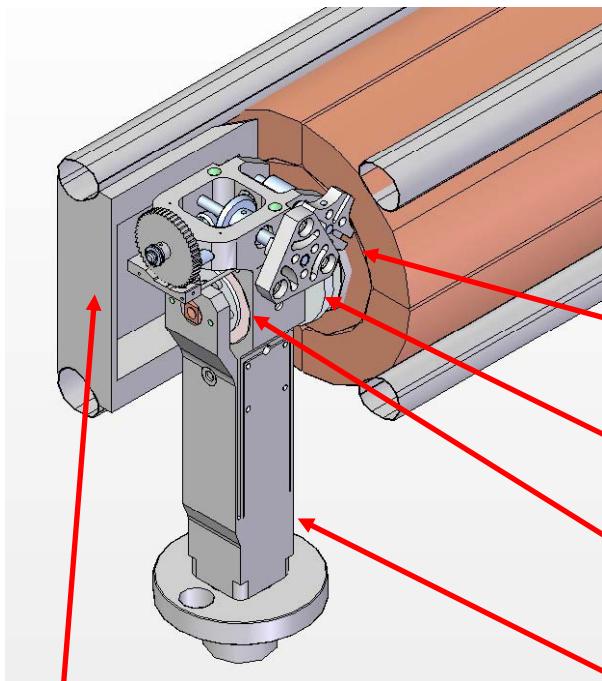
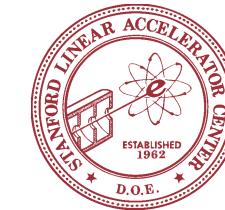
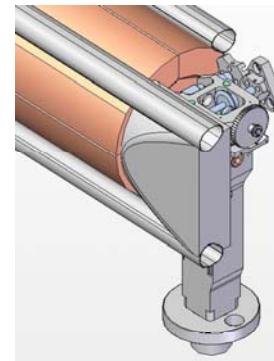


**LARP**

# Ongoing Material Issues

## Cooling Support & RF parts

- minimize heat generation
- maximize heat removal



Beam Transition – Al, 15+ W

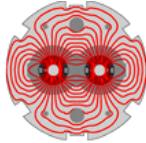
**Jaw Support:**  
**One revolution of jaw**  
**Shaft thermal expansion**  
**Shaft thermal & gravity bending**

Mo shaft ~ 500 W

Mo Stub shaft ~ 11 W

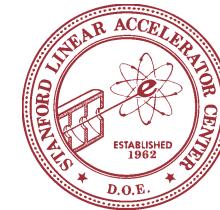
Ball bearings –  $\text{Si}_3\text{N}_4$ , ~ 1 W

SST supporting post, water cooled ~ 12 W

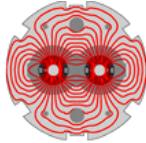


**LARP**

# Conclusions

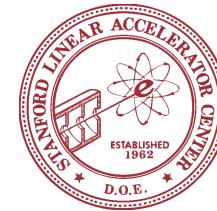


- To dissipate ~ 10kW of heat with < 25 $\mu\text{m}$  deflection is extremely challenging
- Material choice, interaction with beam, cooling configuration, support mechanism and fabrication process are inter-related
- Cu chosen for high collimation efficiency, good thermal conductivity, well known fabrication characteristics
  - Glidcop trades high strength (6x) for slight reduction in other properties
- 25mm Cu thickness chosen as buffer between beam and water
- Exotic jaw metals rejected for various performance and production reasons
- Behavior of Cu/Glidcop jaw in accident case is a major risk factor
  - Destination of displaced material
  - Deflection of jaw
  - Interaction of RF systems with damaged jaw surface
  - Testing to answer these questions
- Other internal systems present major heat survival issues to be solved

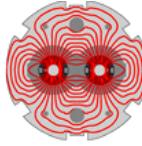


**LARP**

# LHC Phase II Collimation



# EXTRA SLIDES



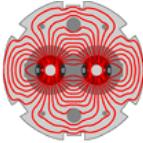
**LARP**



# Material Properties

material	dens	ex	nuxy	kxx	c	alpx						
	density	elastic modulus	Poisson's ratio	thermal conductivity	specific heat	thermal diffusivity	coeff therm expansion	melting temperature	yield strength	tensile strength	fracture temp.	Comment
	kg/m^3	Pa		W/m/C	J/kg/C	m^2/sec	m/m/C	C	MPa	MPa	C	
Cu	8960	1.29E+11	0.355	390	391	1.11E-04	1.70E-05	1083	45-450	255	116	zdr fract temp 180C; anneal 45min @ 450C
Glidcop AL-60	8810	1.30E+11		322			1.66E-05		413-517	469	217	yp:300C - 20C, annealed
GlidCop AL-25		1.30E+11		344			1.65E-05		296-372	250-410		yp:300C-20C, annealed
GlidCop AL-15	8900	1.30E+11		365			1.55E-05		255-331	241-366		yp:260C-20C, annealed
316 SST ann	8000	1.93E+11	0.33	15	502	3.74E-06	1.70E-05		207-379	496-793	#####	annealed
316 SST cw									517-965	758-1276		cold worked
Be	1848	2.80E+11	0.34	180	1827	5.33E-05	1.62E-05	1285		379	84	
Ti	4500	1.20E+11	0.32	21.9	523	9.31E-06	8.80E-06	1725	345	448	424	zdr fract temp 770C
W	19600	4.06E+11	0.33	167	142	6.00E-05	4.50E-06	3400		1380	755	
Mg	1827	4.50E+10		137	1025	7.32E-05	3.92E-05					
Al	2823	7.00E+10	0.33	200	960	7.38E-05	2.30E-05	600	55	124	77	
Al 2219-0	2840	7.30E+10	0.33	172	864	7.01E-05	2.23E-05	543	75.8	172	106	
Inconel 718	8100	2.15E+11		12.4	435	3.52E-06	7.00E-06	1400		1240	824	
Super invar	8110	1.50E+11		11	515	2.63E-06	9.00E-07	1450	352	482	3570	properties valid to 200C
Invar (36)	8050	1.50E+11		11	515	2.65E-06	2.40E-06	1427	276	482	1339	properties valid to 200C
Alloy 52	8300	1.60E+11		12.8	515	2.99E-06	1.03E-05	1427	166	552	335	properties valid to 600C
Kovar	8360	1.40E+11	0.317	17.3	440 - 650		5.20E-06	1450	345	517	710	
molybdenum	10140	3.07E+11	0.32	142	260	5.39E-05	5.30E-06	2610	379-620	414-759		
C R4550	1830	1.15E+10	0.33	100	710	7.70E-05	4.00E-06			60	1304	
C R7500	1770	1.05E+10		80	710	6.37E-05	3.90E-06			33	806	
SiC	3100	4.10E+11	0.14	120	750	5.16E-05	4.00E-06			550	335	comp str 3900
Si <sub>3</sub> N <sub>4</sub> pressed	3290	3.10E+11	0.27	30			3.30E-06			830	811	hot pressed
Si <sub>3</sub> N <sub>4</sub> sintered	3270	3.10E+11	0.24	29			3.30E-06			689	674	sintered

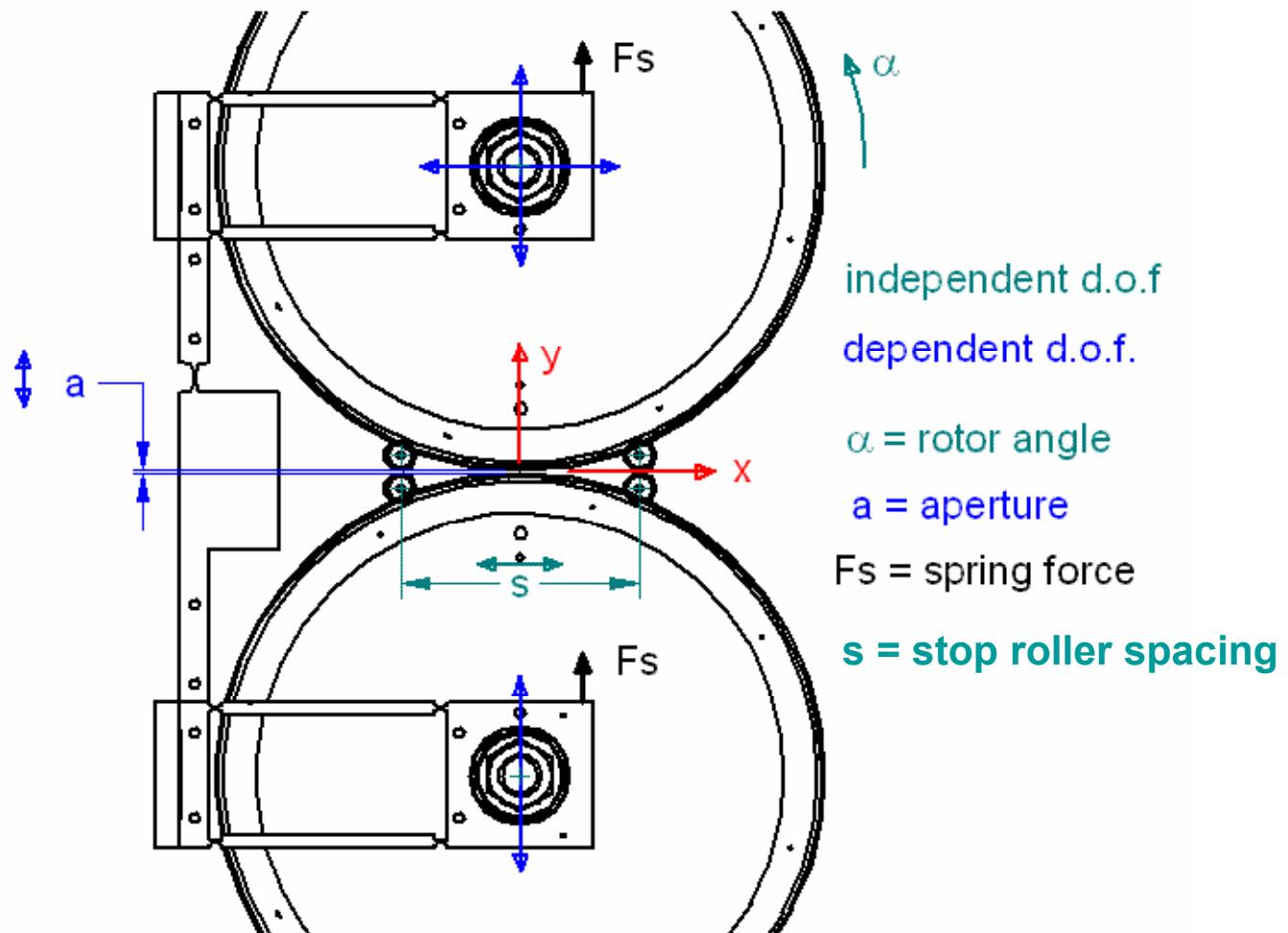
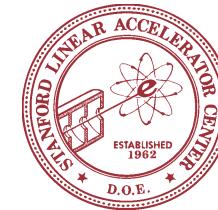
Notes: 1. fracture temperature = uts/(elast mod \* cte)



LARP

# NLC Aperture-Defining Geometry

One independent variable (stop roller spacing,  $s$ ) defines aperture.



independent d.o.f.

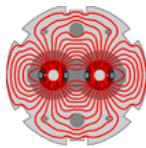
dependent d.o.f.

$\alpha$  = rotor angle

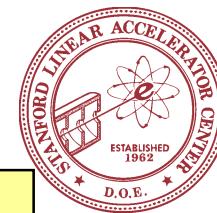
$a$  = aperture

$F_s$  = spring force

**$s$  = stop roller spacing**

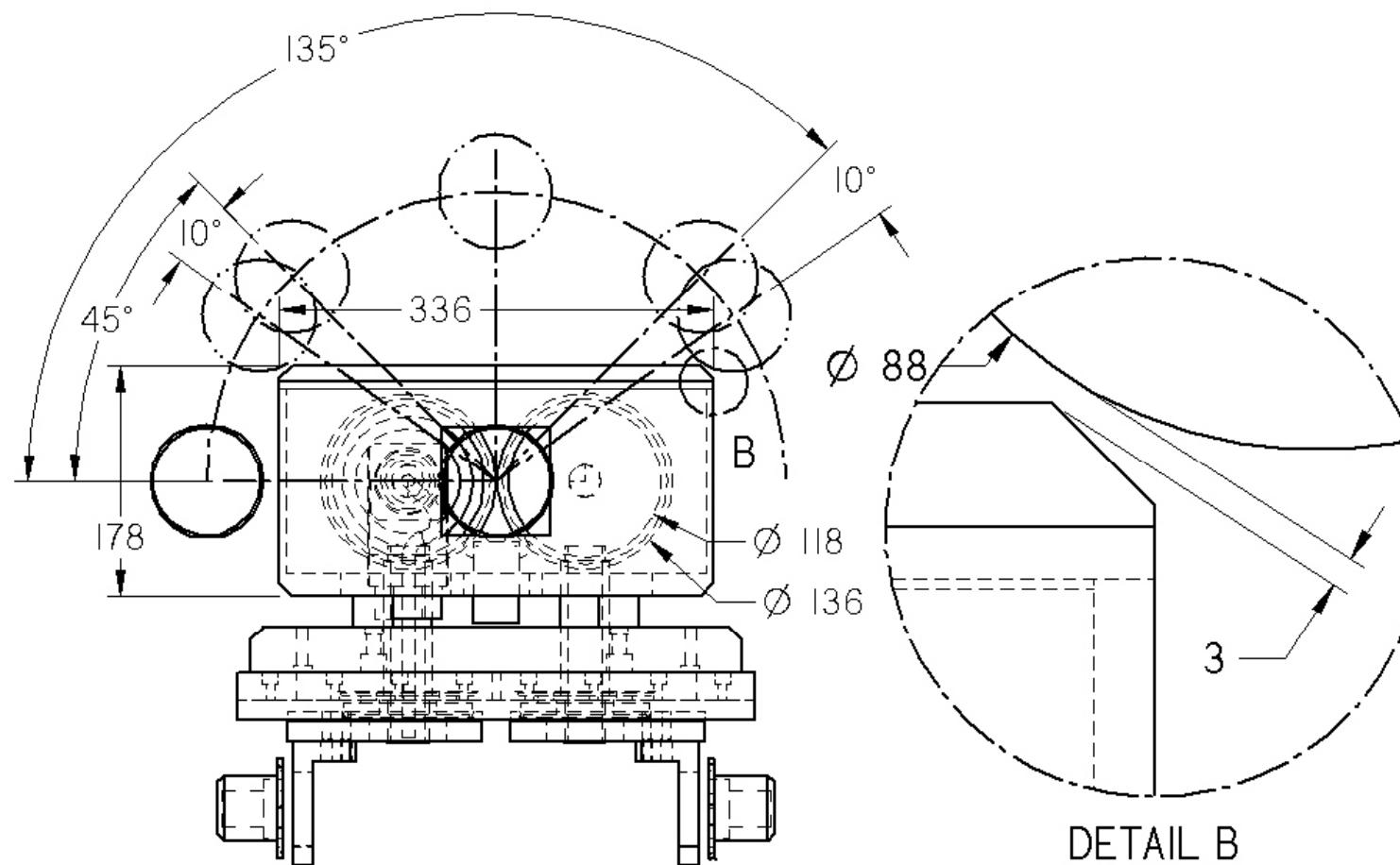


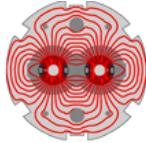
# LHC Ph II Jaw Diameter Constraints



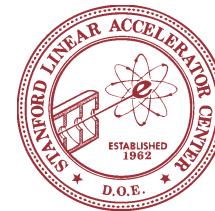
**LARP**

**Jaw diameter – limited by vacuum tank size and required range of motion. Vacuum tank size limited by proximity of opposing beam pipe in all collimator orientations.**





**LARP**



# Specifications for baseline Phase II collimator

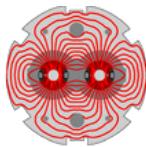
\*

	<b>spec</b>	<b>value</b>
Beam	sigma	200um
	location	Centered in pipe +/- 5mm
Beam pipe	Spacing	224mm c-c opposing beampipes
	diameter	88mm OD
	clearance	8mm vacuum tank to opposing beampipe
Jaw	Length	95cm including 10cm tapers on ends
	Diameter	136mm
	Material	Copper
	cooling	Embedded helical channel
	cooling	No water-vacuum joints if possible
Special features		Circumferential slots to reduce thermal-induced bending, if no RF problems
	deformation	<25um toward beam; <325mm away, steady state; <750um away, 10 sec transient
	Peak temp.	200C operating, 250C bakeout
	Range of motion	25mm per jaw, including +/- 5mm beam location drift
	Damage extent	15mm
Aperture stop	Range of motion	Positively controls aperture from 5-15 sigma (2-6mm full aperture), must float +/- 5mm as jaws are moved to follow beam drift
Heat load	Steady state	11.7 kW
	Transient	58.5 kW
Vacuum	pressure	<1e-7 Pa (7.5e-10 Torr)
Vac. tank	length	1.48m flange-flange
	flanges	CERN quick disconnect
Cooling	Clearance	Clears opposing beampipe with +/- 10° adjustment in all orientations
	Supply	27C
RF contacts	return	42C max
	configuration	Sheet metal parts per Figures 7-9 subject to CERN approval

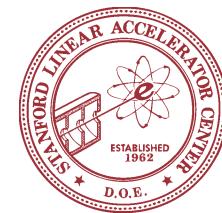


baseline design deviates

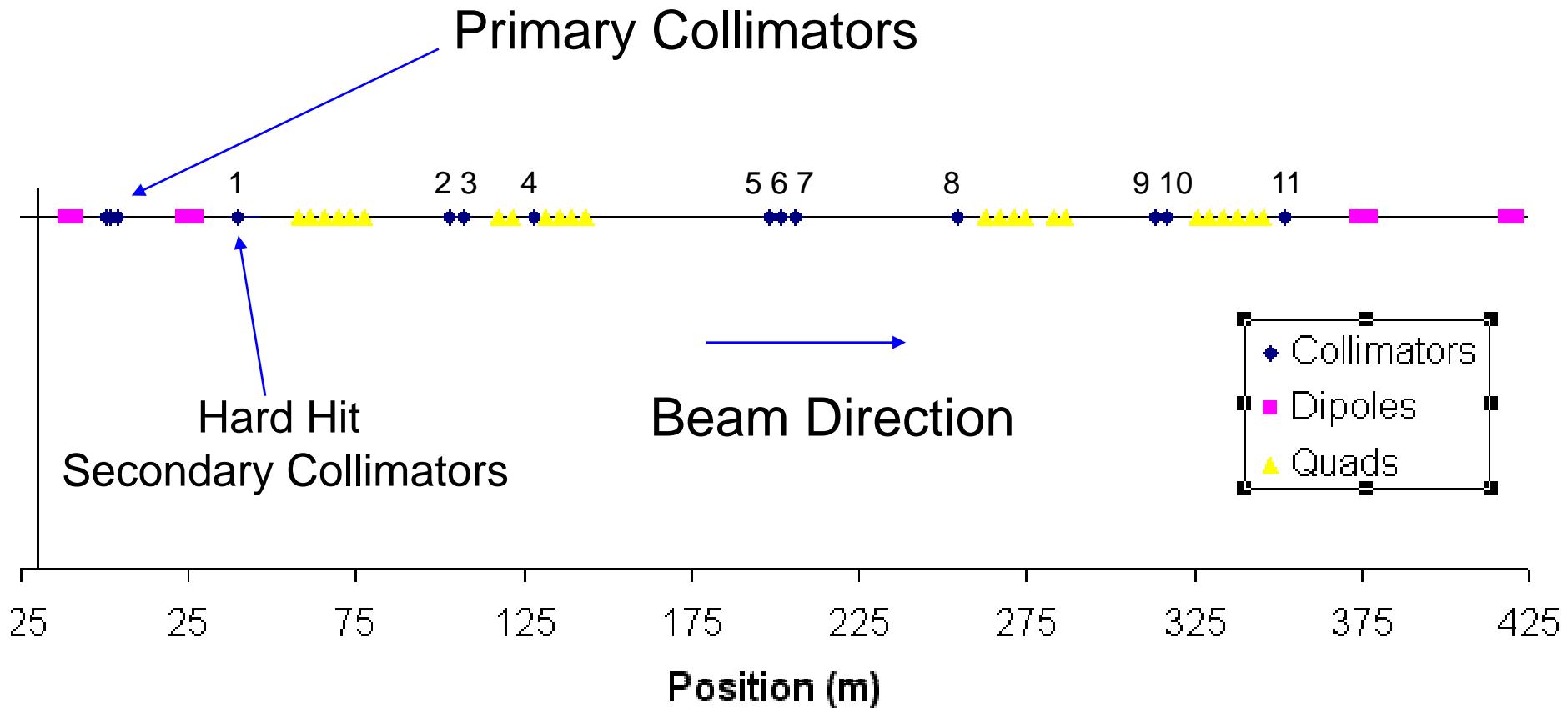
\* Relaxed from original spec

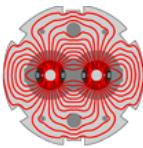


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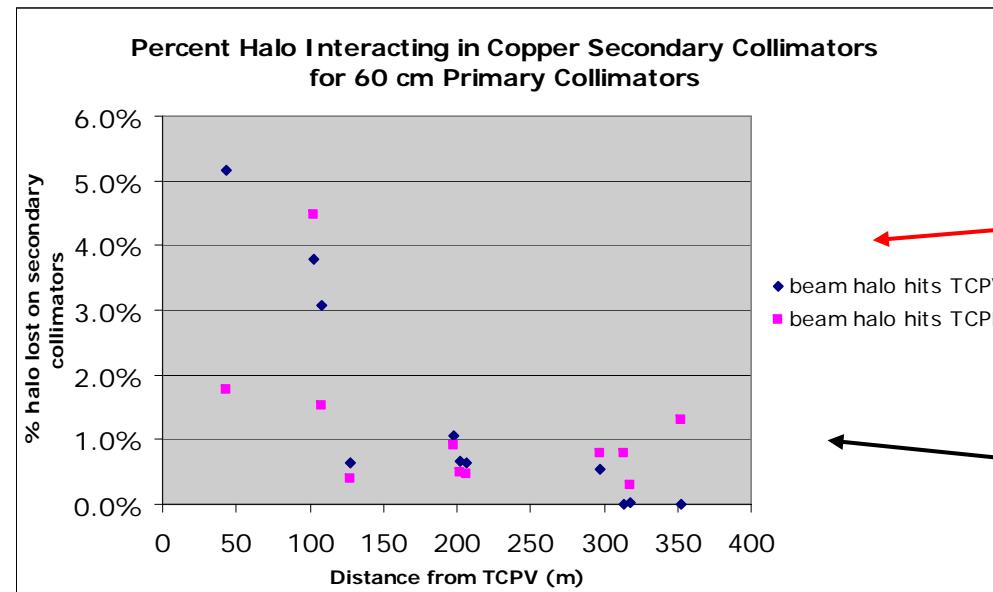
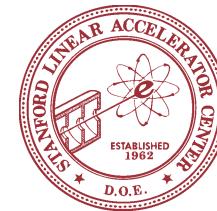
## IR7 Collimator Layout





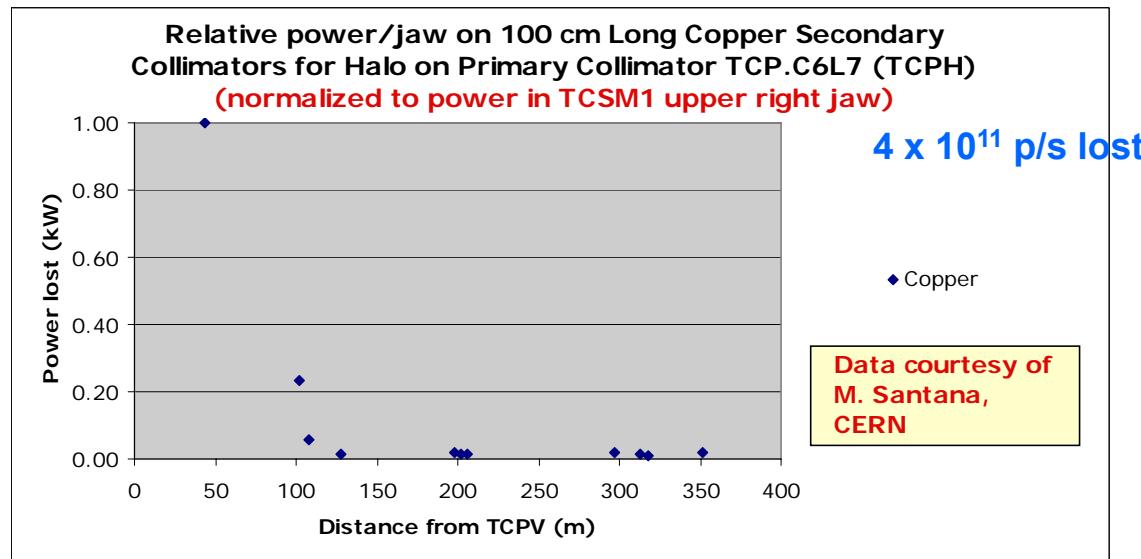
LARP

# First Secondary Collimator Takes the Heat

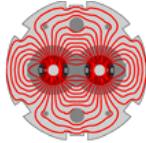


Comparing TCPV with TCPH,  
the main differences occur in  
the 1<sup>st</sup> three secondary colls.

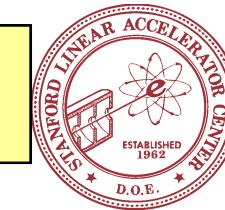
Data from COLLTRK  
Y. Cai



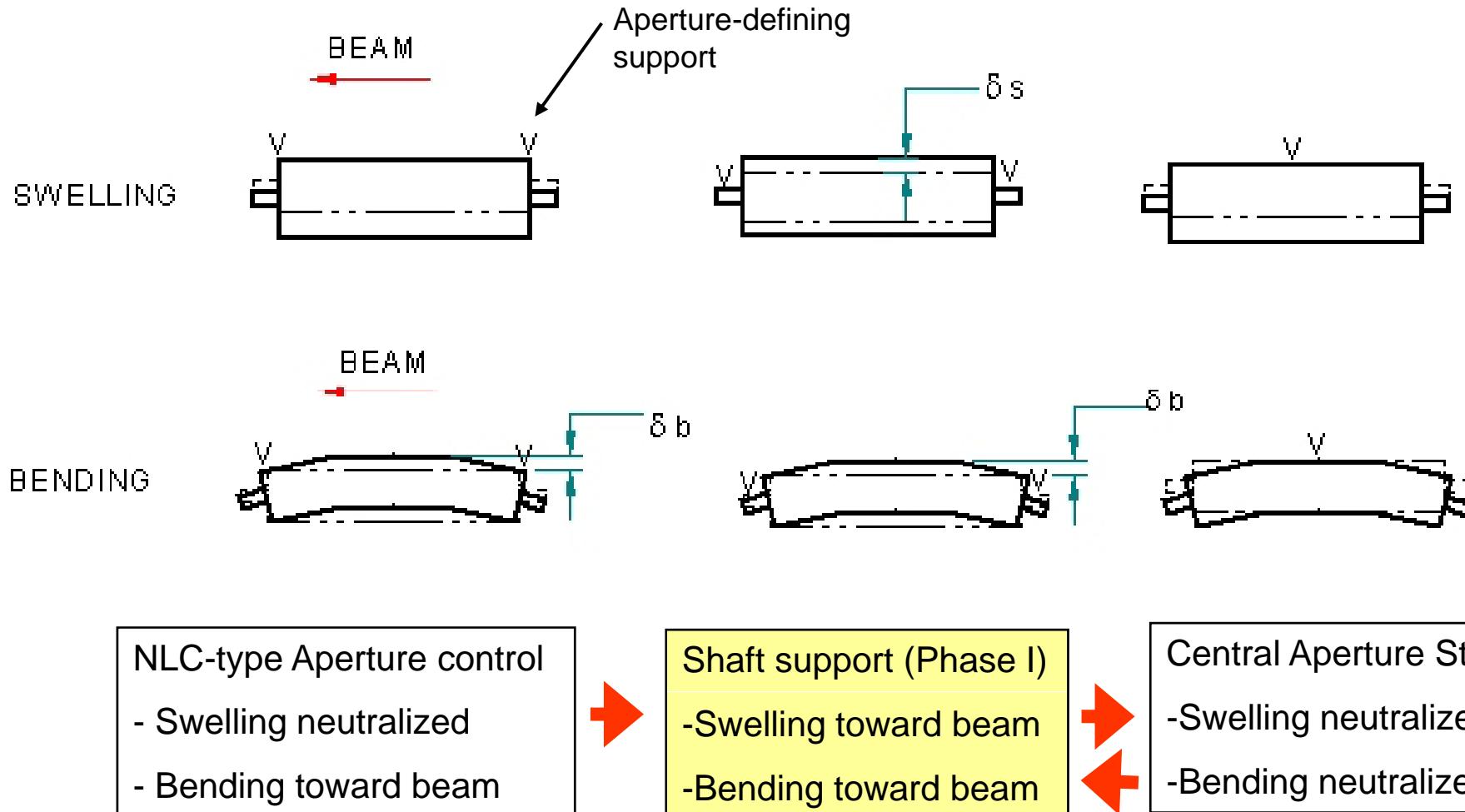
~ 4X the power of  
succeeding colls

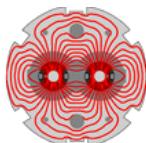


## Aperture-Defining Scheme - Effect on Bending and Swelling Deformation toward Beam



LARP

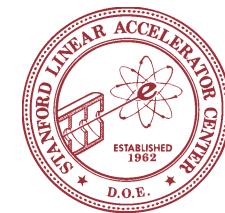




**LARP**

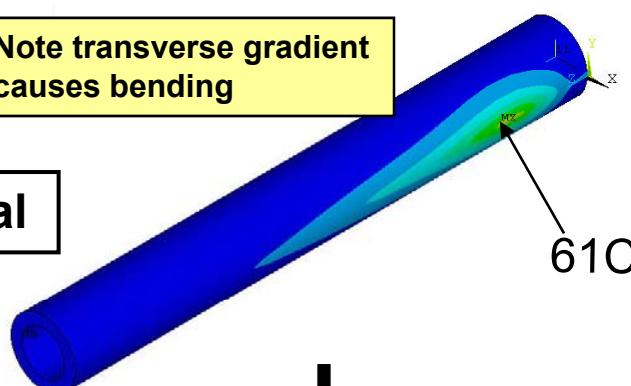
## Limited Cooling Arc

- Hollow Cylinder model
- 360° and 36° cooling arcs



### 360° full I.D. cooling

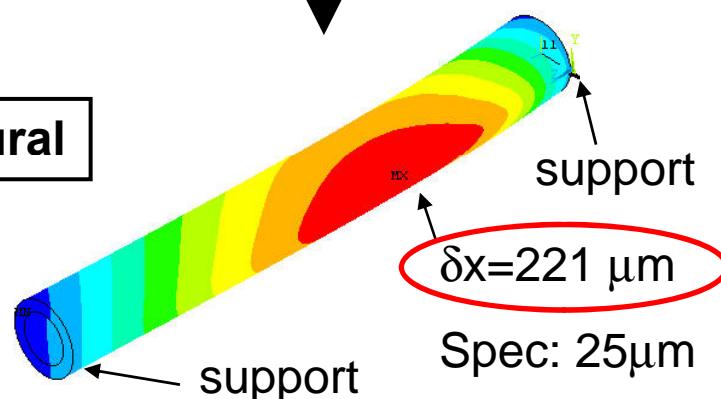
Note transverse gradient causes bending



**Thermal**

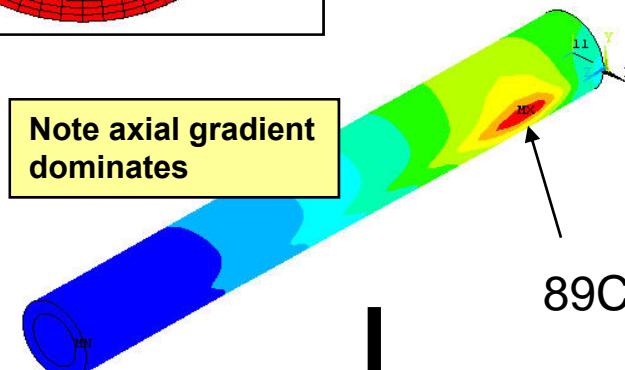


**Structural**



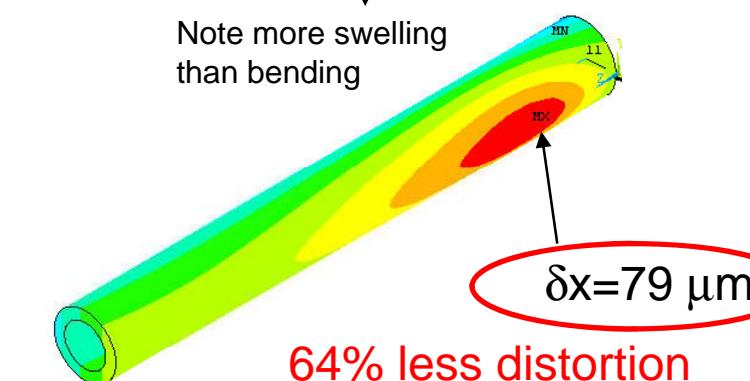
### 36° arc cooling

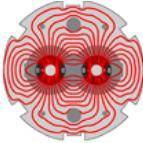
Note axial gradient dominates



89C

Note more swelling than bending

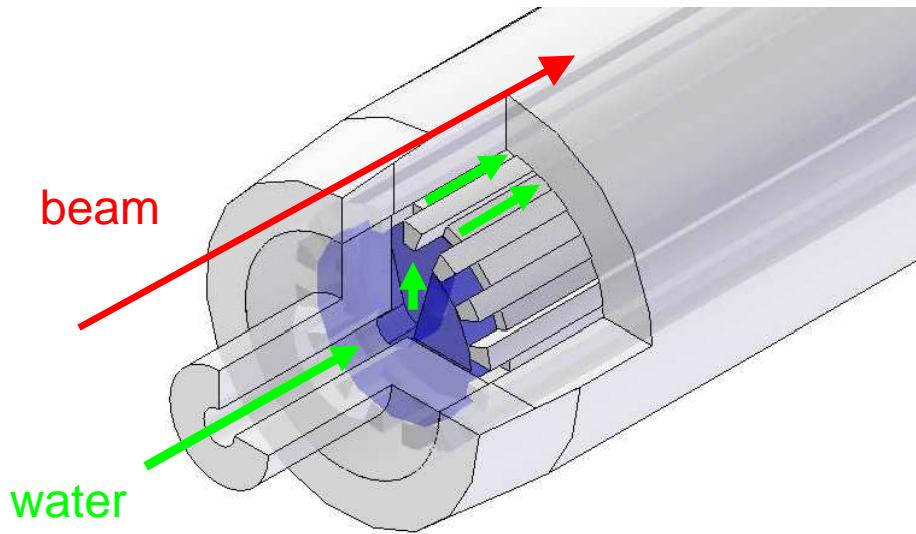




LARP



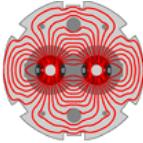
## Limited Cooling Arc - Implementation



**Limited cooling arc:** free wheeling distributor – orientation controlled by gravity (or other means?) – directs flow to beam-side axial channels.

**Pro:** Causes far side of jaw to heat up, reducing thru-jaw  $\Delta T$  and thermal distortion.

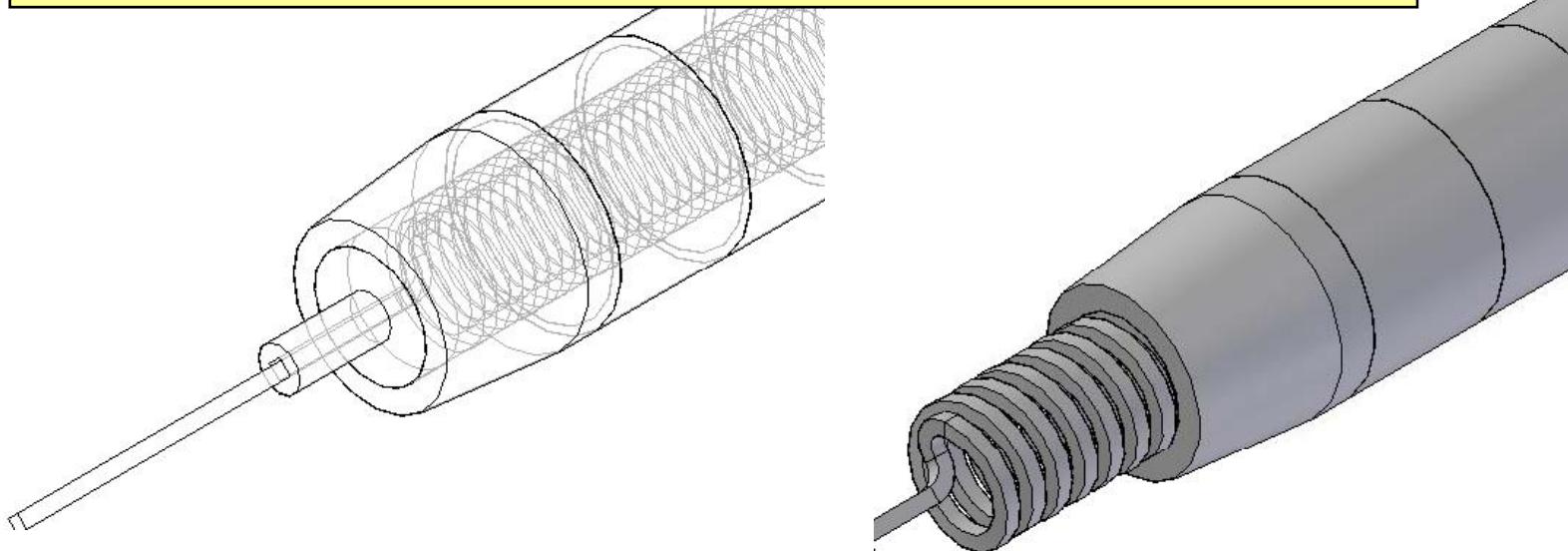
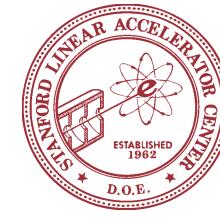
**Con:** peak temperature higher; no positive control over flow distributor (could jam); difficult fabrication.



**LARP**

## Helical cooling passages chosen for manufacturability and beamline vacuum safety

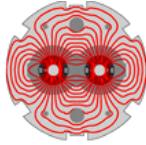
Per CERN's Policy – no water-vacuum weld or braze



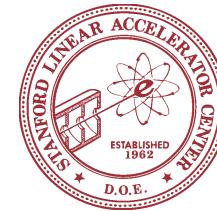
- Tube formed as helix, slightly smaller O.D. than jaw I.D.
- O.D. of helix wrapped with braze metal shim
- Helix inserted into bore, two ends twisted wrt each other to expand, ensure contact
- Fixture (not shown) holds twist during heat cycle

Variations:

1. Pitch may vary with length to concentrate cooling
2. Two parallel helices to double flow
3. Spacer between coils adds thermal mass, strength
4. Electroform jaw body onto coil

**LARP**

## RC1 Baseline Jaw Performance

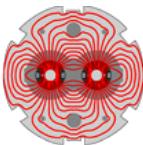


**Exceeds spec, or other possible problem as noted**

Collimator		TCSM.A6L7	
Cooling scheme		Helical	Axial (36°)
Cooling	# channels	1	2
	Diam (m)	.008	.006
	Velocity (m/s)	3	3
	Total flow (l/min)	9	10
Beam heat	SS	Power (kW)	11.7
	Trans	Power (kW)	58.5
Temp (C)	SS	Jaw peak	86.5
		Cooling chan. peak	68.3
		Water out	36.0
	Trans	Jaw peak	231
		Cooling chan. peak	154
		Water out	43.6
Deflection (um) <sup>4</sup>	SS		394
	Trans		1216
Eff. length (cm) <sup>5</sup>	SS		43
	Trans		24
			75
			31

Max Cu temp 200  
 Possible boiling  
 Max water return temp  
 } Deflection 325 & 750 (SS & trans)

All temperature simulations based on 20C supply. For CERN 27C supply add 7 to all temperature results. CERN max water return temp 42C



# Glidcop Jaw

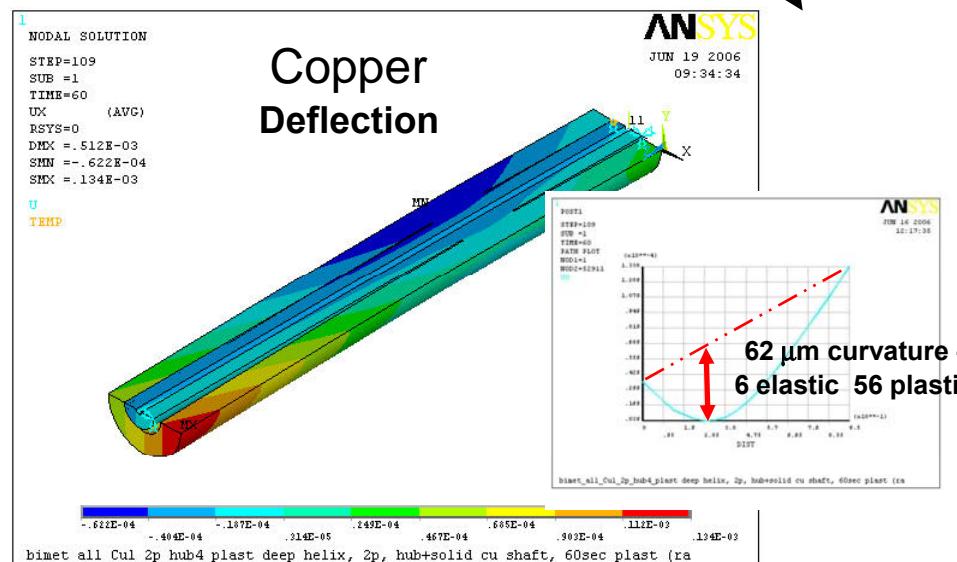
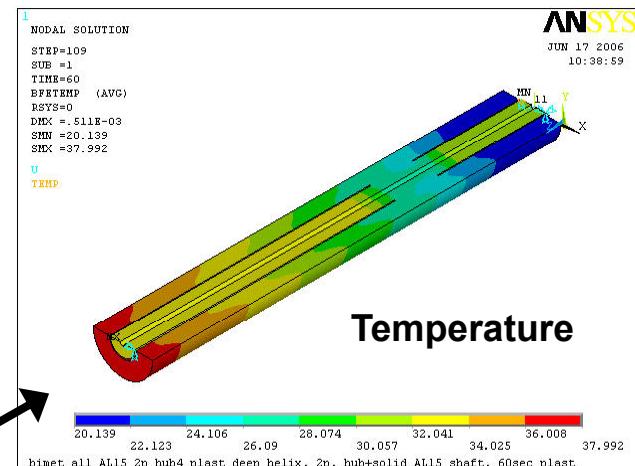
## Prevents Permanent Deformation in SS Operation

**Initial condition: SS @ 1 hr beam lifetime heating rate**

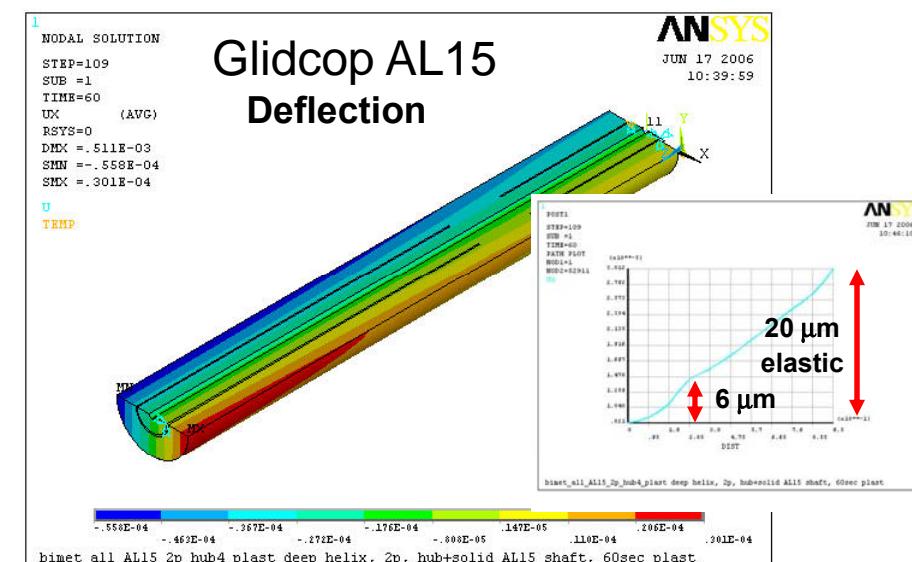
**Transient:**

**10 seconds heating at 12min beam lifetime rate**

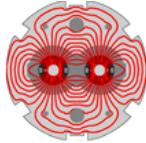
**50 seconds cooling => residual  $\sim 17^\circ \Delta T$ , axial**



- 56  $\mu\text{m}$  plastic strain (corrected for 6  $\mu\text{m}$  elastic due to residual  $\Delta T$ )



Elastic swelling due to residual  $\Delta T$ .  
**Glidcop prevents plastic deformation**



**LARP**

# Refined Baseline & Jaw-hub Shaft Model

- No shaft heating
- Shaft Material Comparisons
- Effect of shallow cooling tubes



**RC1 baseline**

**RC1 baseline  
Refined baseline**

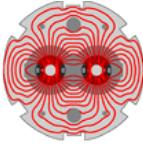
**Shallow  
Jaw-hub-shaft  
cooling**



	deflections referred to jaw edge	SS @ 1 hour beam life			transient 10 sec @ 12 min beam		
		power (kW) per jaw	Tmax (C)	defl (um)	power (kW)	Tmax (C)	defl (um)
Simple support, deflections referred to jaw edge or shaft							
RC1 baseline	Cu, 136x71x950-, cooling 25mm deep, 5cm pitch	11.7	86.5	394	58.5	231	1216
RC1 baseline Refined baseline	Simple support, deflections referred to shaft						
Shallow	Cu, 136x71x950-, cooling 25mm deep, 5cm pitch	11.7	86.5	426	58.5	231	1260
Jaw-hub-shaft cooling	Cu, 136x11x950-, solid, cooling 25mm deep, 2cm pitch	11.7	65.7	238	58.5	195	853
	Cu, 136x11x950-, solid, cooling 10mm deep, 2cm pitch	11.7	54.3	171	58.5	159	646
	Cu, solid shaft, 25mm, 2cm pitch	11.7	66.3	100	58.5	197	339
	Cu, solid shaft, 10mm, 2cm pitch	11.7	54.7	78	58.5	160	280
	Cu, super invar shaft, 25mm, 2cm pitch	11.7	67.4	90	58.5	199	266
	Cu, tungsten shaft, 25mm, 2cm pitch	11.7	66.8	88	58.5	198	270
	Cu, sst shaft, 25mm, 2cm pitch	11.7	67.3	132	58.5	199	368
	Cu, Be shaft, 25mm, 2cm pitch	11.7	66.7	112	58.5	198	368
	Cu, Mo shaft, 25mm, 2cm pitch	11.7	66.5	96	58.5	200	286
	Glidcop AL15, solid, cooling 25mm dp, 2cm pitch	11.7	68.6	103	58.5	205	348

Various hub geometries, through shaft, no shaft heating, no gravity.

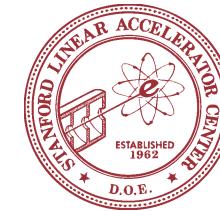
Mo selected - stiffness, thermal conductivity, cte, **production problems due to cte mismatch**



**LARP**

# Jaw-Hub-Shaft Model (with shaft heating)

## Short (.5 m) Glidcop jaws



**Half-length version of current design**

**SS  
1 hr beam lifetime**

**jaw-hub-shaft all Cu**

Mo small shft

Mo shft, no taper

htd Mo shaft

**Glidcop jaw, Mo shft**

**Glidcop jaw - .5 m**

Glid jaw + sst shaft

Glid jaw, thk glid shft

Glid, thk Cu shf, .3m hu

**steady state 1 hr beam lifetime**

jaw		upbeam		midjaw		downbeam		effective L	curvature
power <sup>5</sup> (kW)	temp (C)	ux (um)	uz (um)	ux (um)	ux (um)	uz (um)	(m)	(um)	
11.7	66.3				100			0.51	221
11.7	66.1	-183	-187	95.6	-57.3	425			
12.9	66.0	-176	-226	83.6	-40.9	437	0.74	197	
12.9	66.0	-166	0	96.1	-30.1	750	0.76	170	
12.9	70.6	-186	59	105	-40.6	737	0.67	226	
8.3	70.7	-35	-68	79	0	293	0.5	96	
12.9	70.6	57.3	6388	351	193	6998	0.67	234	
12.9	70.6	-175	28	111	-29	966	0.68	223	
12.9	70.7	-98	139	156	-14	830	0.67	218	

**Shaft response, ss & trans**

gravity loading	ss	trans
simple supports	shaft	shaft
	downbm	downbm
ux (um)	slope (rad)	uz (um)
-200.	<sup>4</sup> -	uz (um)
-67.5	2.60E-04	210
-67.5	2.60E-04	215
"	"	777
-68.1	2.38E-04	865
-5.7	4.60E-05	186
-	-	13478
-120.3	4.59E-04	1377
-88.3	3.11E-04	1061
		1266

**10 sec transient  
12 min beam lifetime**

**jaw-hub-shaft all Cu**

Mo small shft

Mo shft, no taper

htd Mo shaft

**Glidcop jaw, Mo shft**

**Glidcop jaw - .5 m**

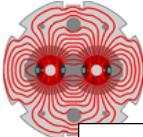
Glid jaw + sst shaft

Glid jaw, thk glid shft

Glid, thk Cu shf, .3m hu

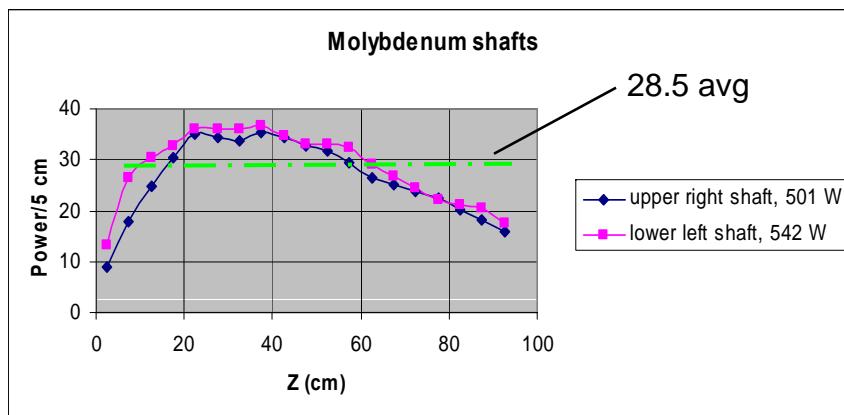
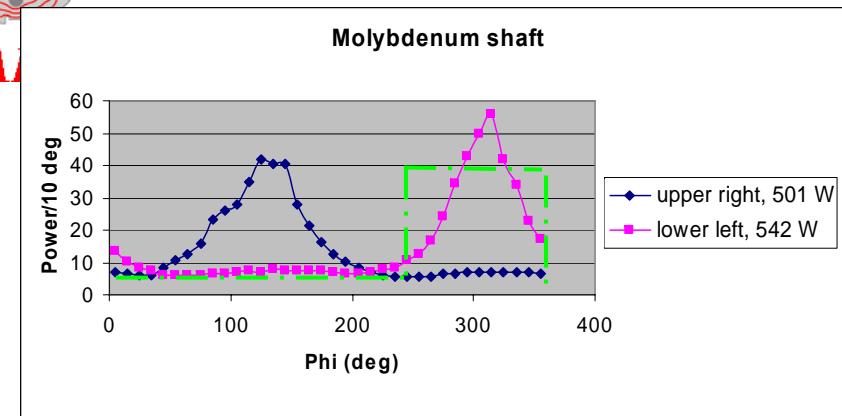
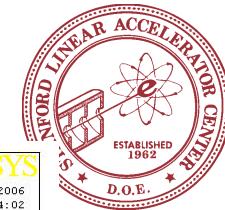
**transient 12 min beam lifetime, 10 sec duration**

jaw		upbeam		midjaw		downbeam		effective L	curvature
power <sup>5</sup> (kW)	temp (C)	ux (um)	uz (um)	ux (um)	ux (um)	uz (um)	(m)	(um)	
58.5	197				339			0.25	881
58.5	198	-780	-434	285	-354	600			
64.5	198	-753	-550	236	-278	603	0.39	781	
64.5	198	-663	0	333	-200	915	0.36	798	
64.5	224	-735	-229	365	-229	957	0.33	880	
41.5	222	-190	205	248	-395	528	0.23	395	
64.5	224	-338	6127	766	148	7325	0.34	880	
64.5	224	-618	18	467	-141	1215	0.33	868	
64.5	224	-347	-68	641	-51	1124	0.34	846	



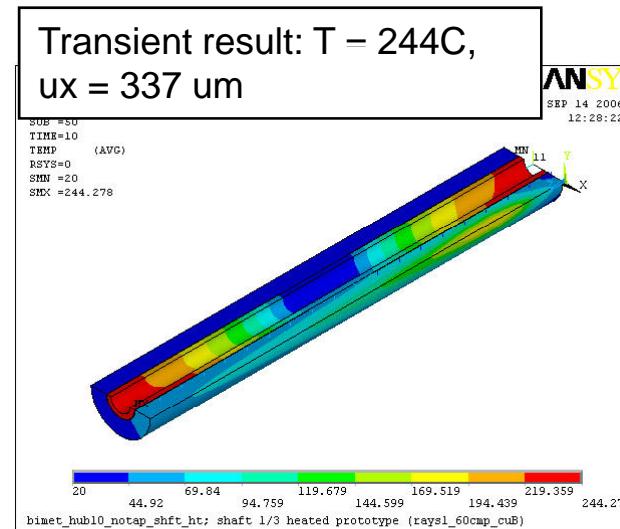
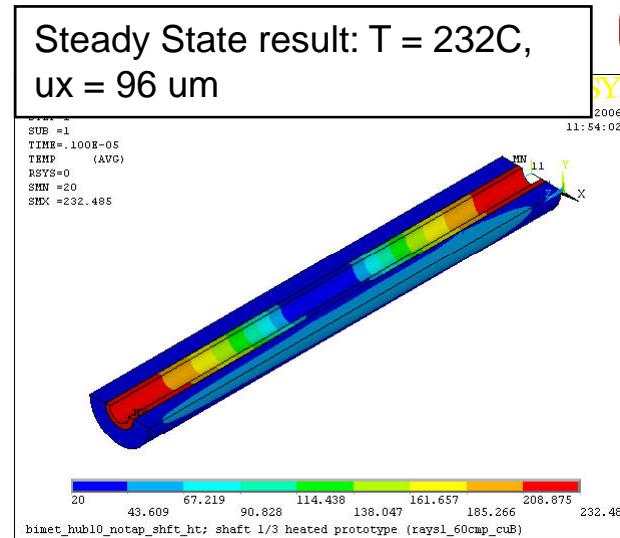
LAC

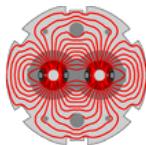
# Mo Shaft Heating SS & Transient



Modeling assumptions:

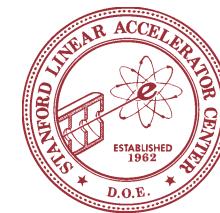
- Power concentrated in  $120^\circ$  of circumference
- Power constant in length
- No heat transfer at shaft ends
- No radiative heat transfer





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## Power Absorbtion in Both Copper Jaws of First Secondary Collimator, TCSM.A6L7



95 cm long, solid cylinders, 100 % of halo on primary collimator

