LHC Phase II Collimator R&D Plan

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SLAC

LAPAC Meeting Meeting

Fermilab

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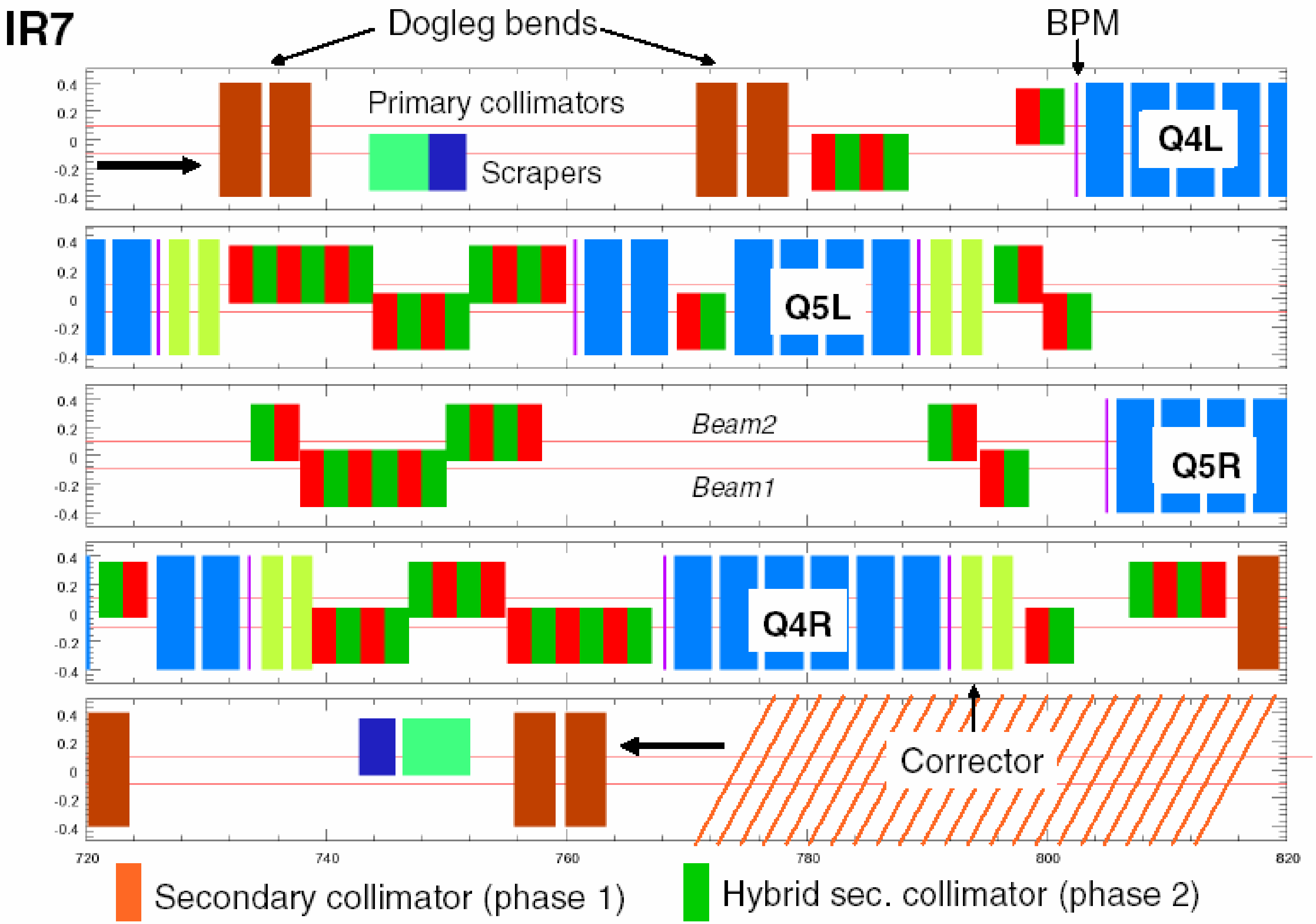
LHC Beam Parameters

#particles / bunch		1.15E+11
#Bunches		2808
Bunch spacing	ns	25
Total # protons		3.23E+14
Energy	TeV	7
Total Energy	MegaJoules	363.70
sig_x (rms)	um	200
sig_y (rms)	um	200
Energy Density	GigaJoule/mm^2	9.0926199

LHC Collimation System Design

- Phase I
  - Available at startup when beam parameters will be < nominal
    - Betatron cleaning in IR7
    - Momentum cleaning in IR3
  - Robust against anticipated abnormal conditions
    - Asynchronous beam abort in IR7
  - Adequate cooling and mechanical design for “normal” beam loss rates at nominal LHC parameters
  - Inadequate impedance and cleaning efficiency for nominal LHC beam
  - Large effort to complete design ongoing
    - Need energy deposition maps, absorber system, shielding design
- Phase II
  - Install presumably metal “secondary collimators” in the 2-m gaps left behind every Phase I collimator with better impedance & efficiency
    - Use only after injection and ramp
    - “Renewable” if surface damaged in asynchronous beam abort

IR7 Collimator Layout
2m gaps (32 in IR3 & 7) left for Phase II secondary collimators
Focus on the 2 SC behind primary collimators



Quad movements up to 1m, collimator movements up to 30 m! 40% of space for collimators!

Normal Proton Loss Rates

Handle heat load from normal proton loss rates:

- 487 kW for 10 sec
- 97 kW indefinitely

NB:

Power ABSORBED by any individual collimator << Power lost by beam

Maps of ENERGY DEPOSITION in the system are not yet available

Table 18.1: Specified minimum beam lifetimes τ, their duration T, the proton loss rate R_{loss}, and maximum power deposition P_{loss} in the cleaning insertion.

Mode	T [s]	τ [h]	R_{loss} [p/s]	P_{loss} [kW]
Injection	cont	1.0	0.8×10^{11}	6
	10	0.1	8.6×10^{11}	63
Ramp	≈ 1	0.006	1.6×10^{13}	1200
Top energy	cont	1.0	0.8×10^{11}	97
	10	0.2	4.3×10^{11}	487

Abnormal Proton Losses

Table 18.2: The beam deposited in the collimators for a few important one turn failures.

Abnormal condition	Beam energy [TeV]	Intensity deposit [protons]	Energy deposit [kJ]	Transverse dimensions [mm×mm]	Impact duration [ns]	Affected plane
Injection error	0.45	2.9×10^{13}	2073	1.0×1.0	6250	H/V/S
Asynchronous beam dump (all modules)	0.45	6.8×10^{11}	49	$\boldsymbol{5.0} \times 1.0$	150	H
	7.00	4.8×10^{11}	538	$\boldsymbol{1.0} \times 0.2$	100	H
Asynchronous beam dump (1 out of 15 modules)	0.45	10.2×10^{11}	74	$\boldsymbol{5.0} \times 1.0$	225	H
	7.00	9.1×10^{11}	1021	$\boldsymbol{1.0} \times 0.2$	200	H

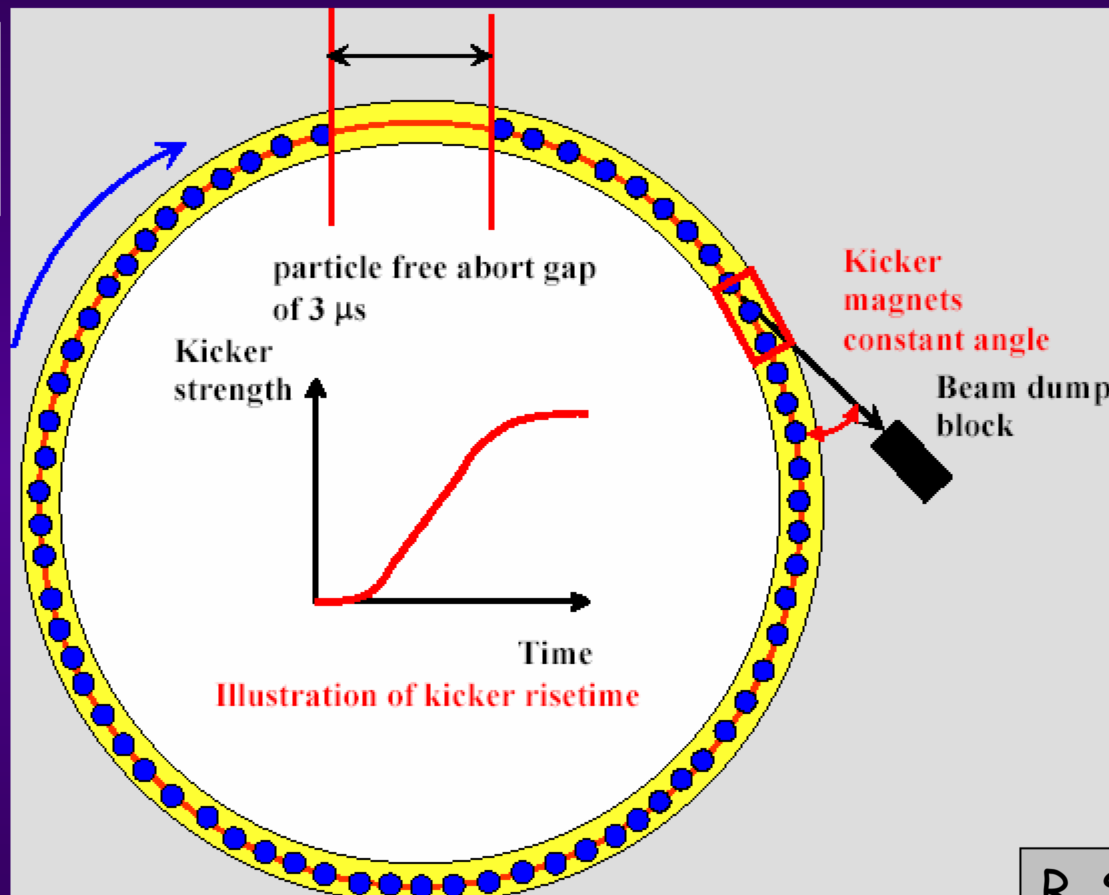
Beam Dump Abort System

Requirement for clean beam dump

Beam dump must be **synchronised** with particle free gap

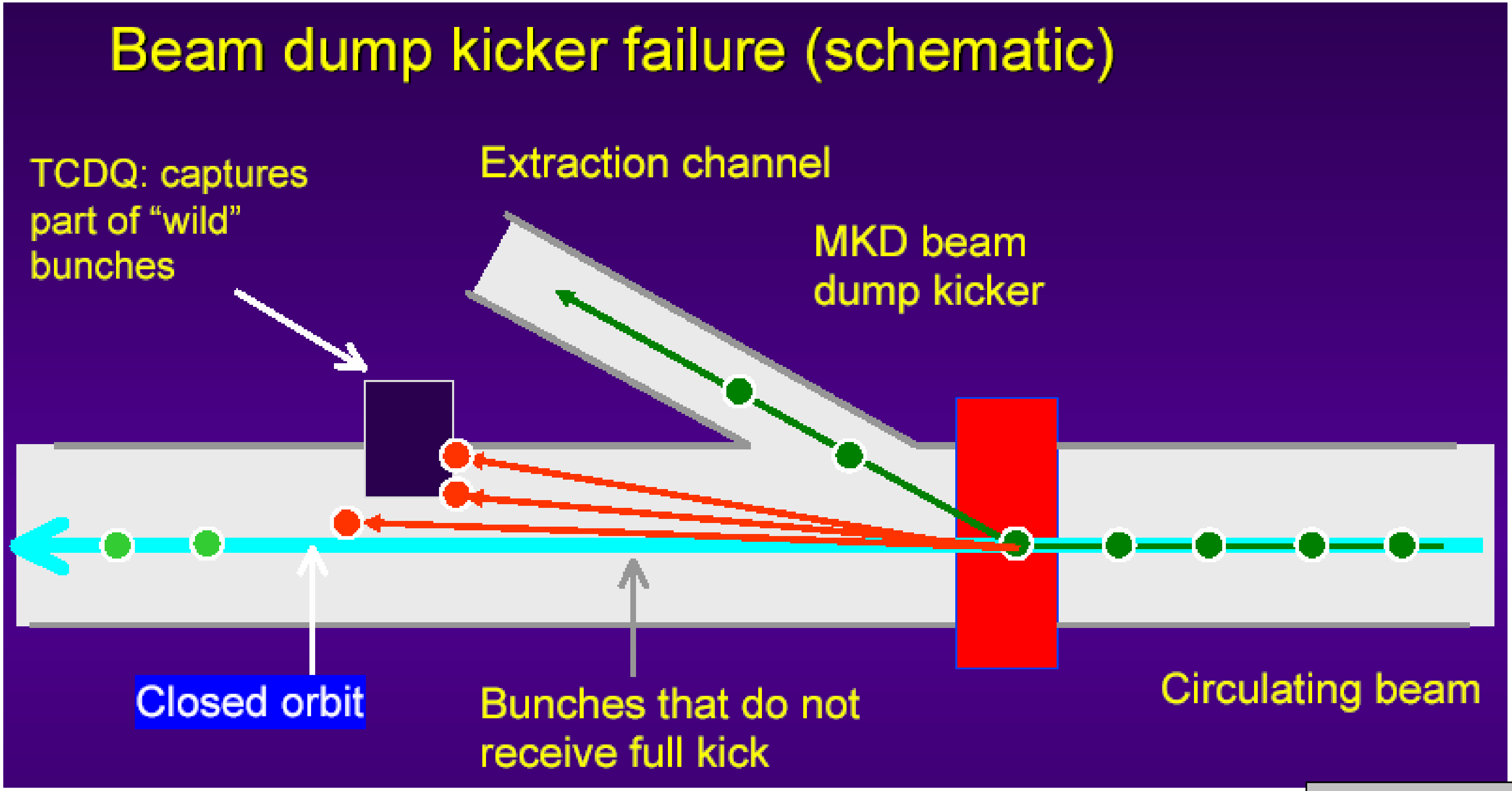
Strength of kicker and septum magnets must **match energy** of the beam

« Particle free gap » must be **free of particles**



R. Schmidt HALO '03

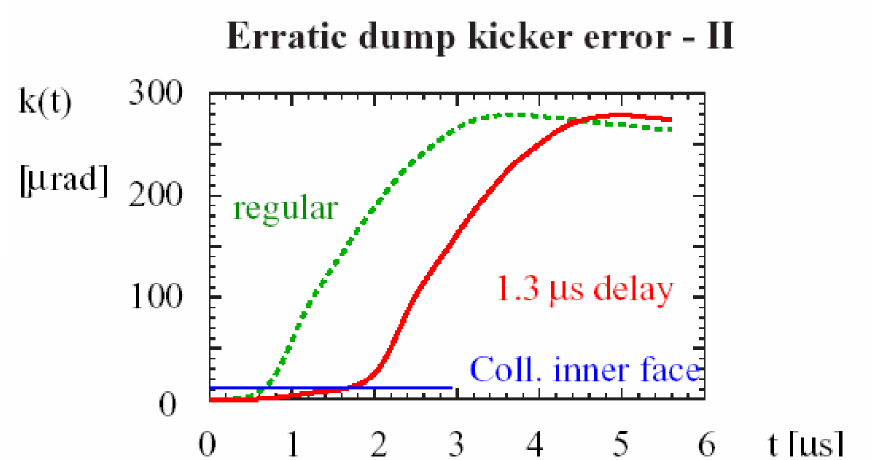
Beam Dump Kicker Failure

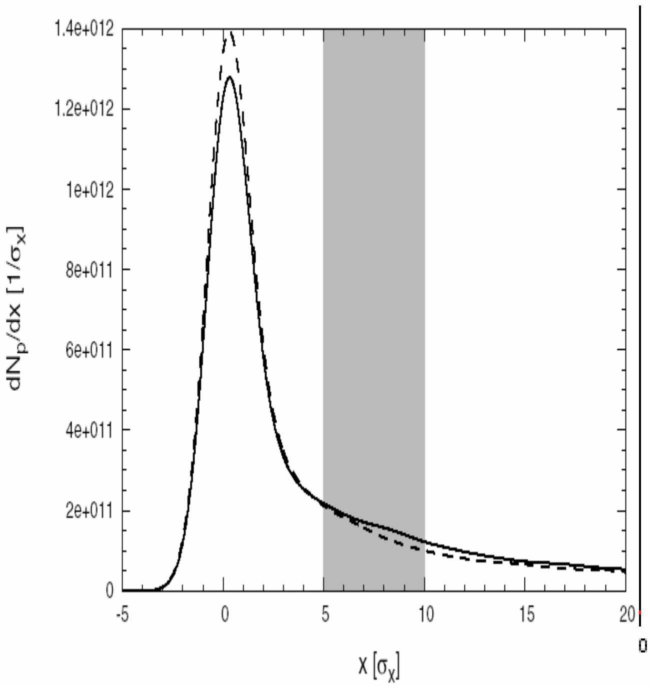


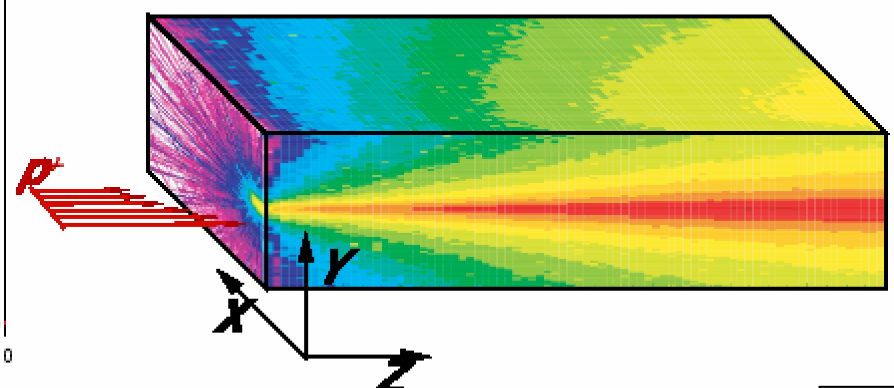
R. Schmidt HALO '03

Bunches on Collimators $\propto$ Delay in Retriggering Dump Kicker

Δt now < ~0.7 μs ⇒
8 bunches on colls





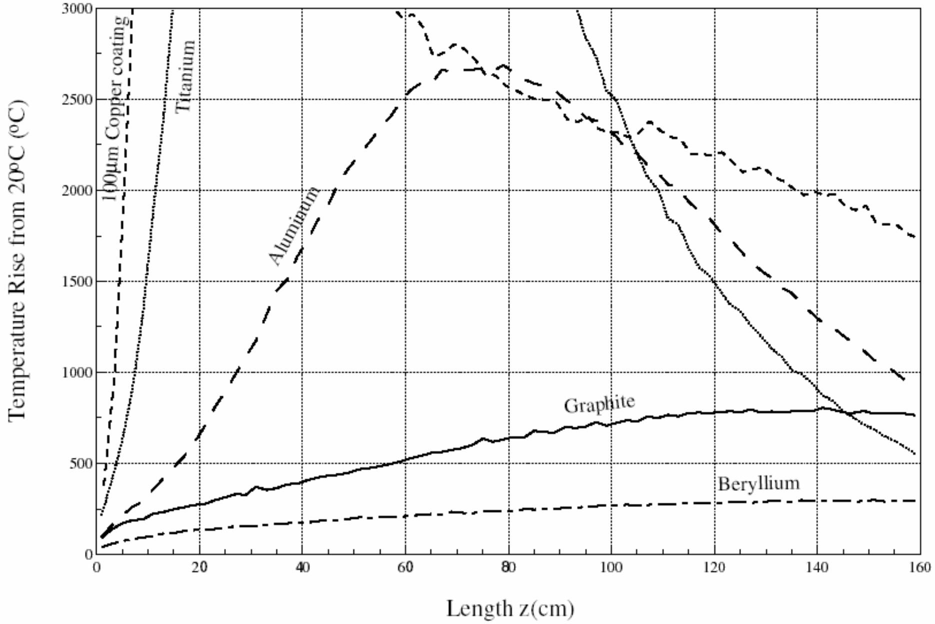


FLUKA → 3D-ANSYS → Peak stress

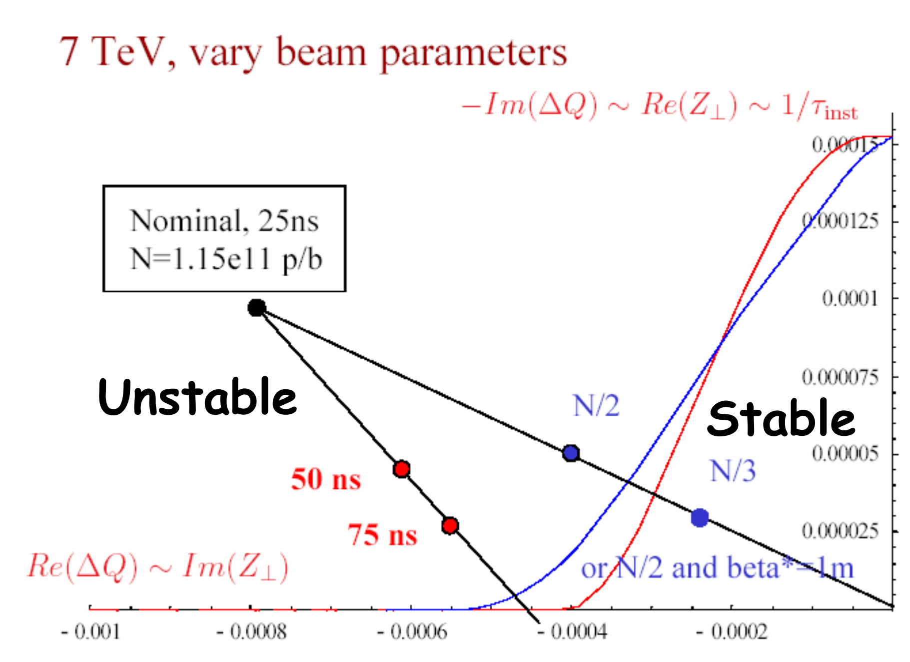
J.-B. Jeanneret
HALO '03

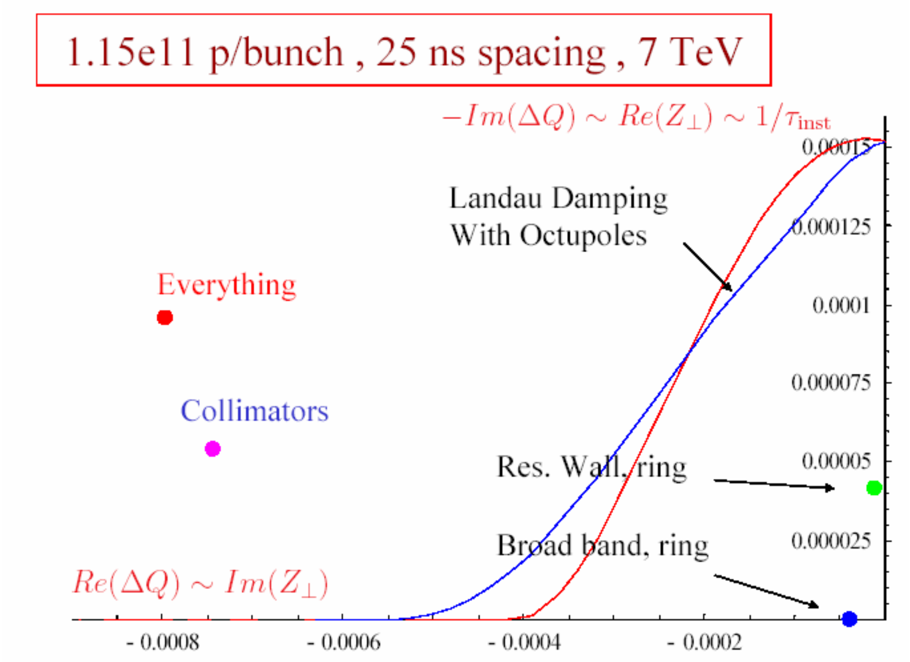
Graphite or Carbon-Carbon Chosen for Phase I

Material	Density [g/cm^{-3}]	Max. energy deposition [GeV/cm^{-3}]	Max. temperature [°K]	Energy escaping [%]
Graphite	1.77	1.3×10^{13}	800	96.4
Beryllium	1.85	0.9×10^{13}	310	97.0
Aluminium	2.70	5.3×10^{13}	2700	88.8
Titanium	4.54	1.7×10^{14}	> 5000	79.5
Copper coating (100μm)	8.96	7.0×10^{14}	> 5000	34.4

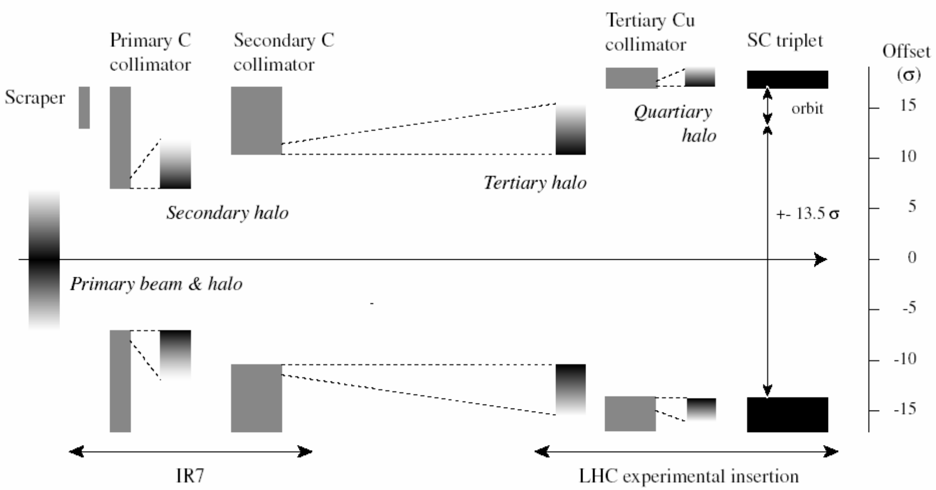


Impedance Limits Luminosity
Collimators Dominate Impedance

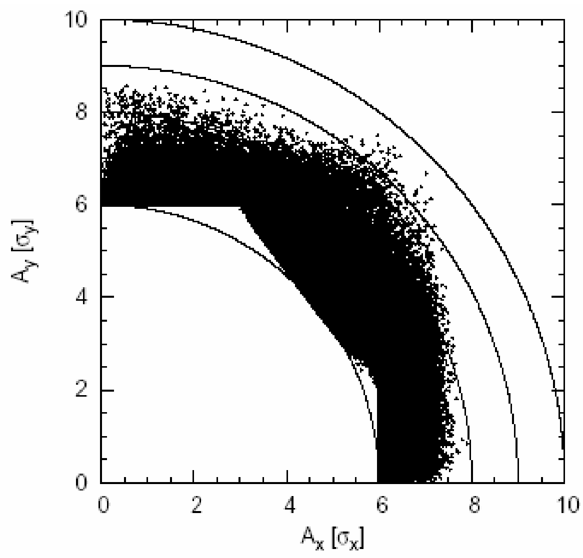


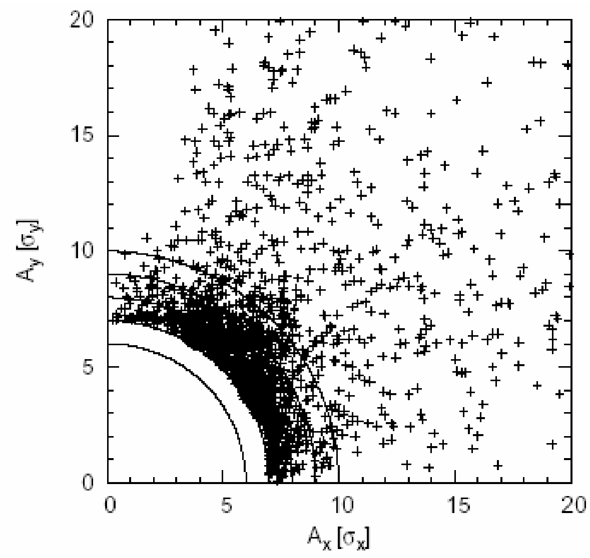


With Primary/Secondary C at 6σ/8.5σ
Phase I Inefficiency = 11E-4



Phase I Inj: PC @ 6σ /SC @ 7σ
Phase I 7 TeV: PC @ 6σ /SC @ 8.5σ
Phase II 7 TeV:PC @ 6σ /SC @ 7σ





Quench Protection Sets Maximum Current Given Collimator System Inefficiency

7.6E6 p/m/s @ 7 TeV

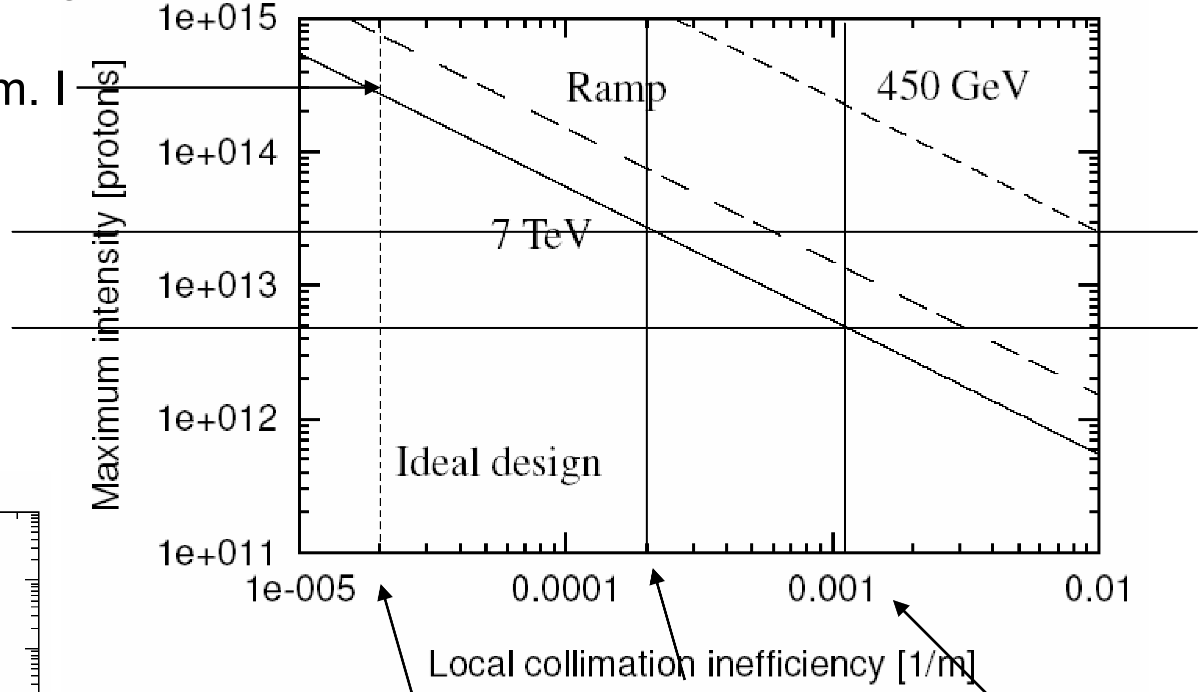
12min

$$N_{\rm tot}^{q} = \frac{\tau_{\min} \cdot R_q}{\tilde{\eta}_c}$$

Intensity

Inefficiency

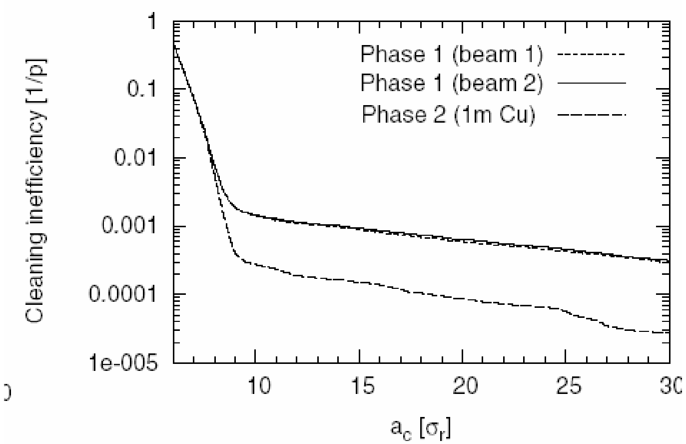
Nom. I



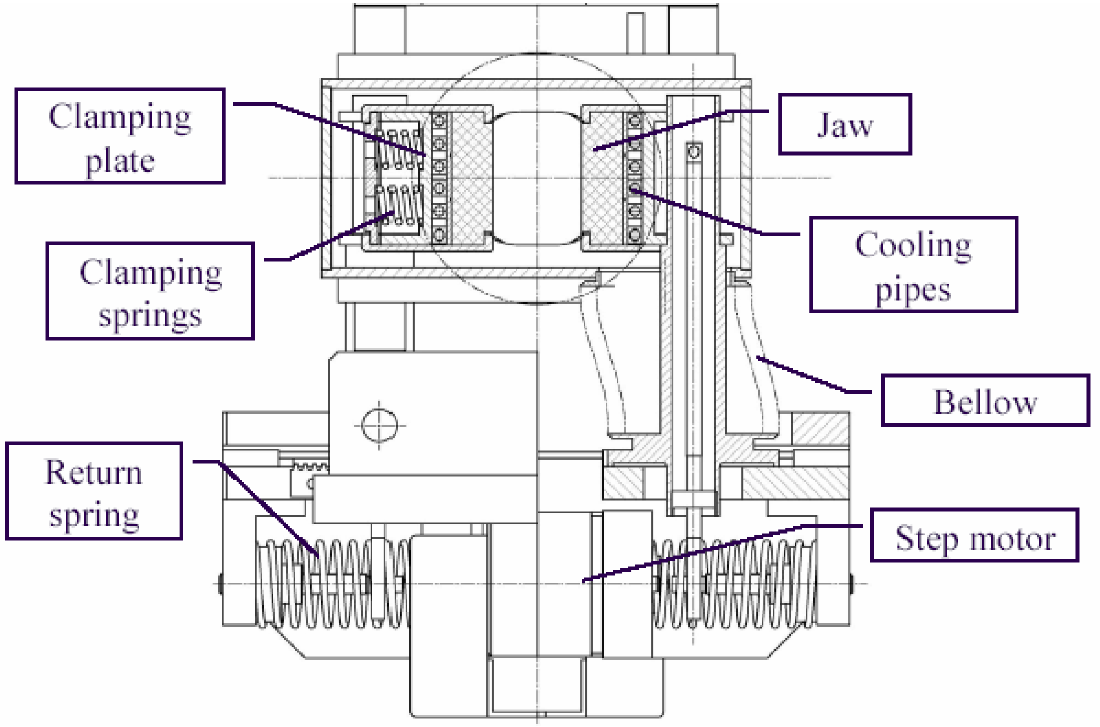
2E-5
Desired

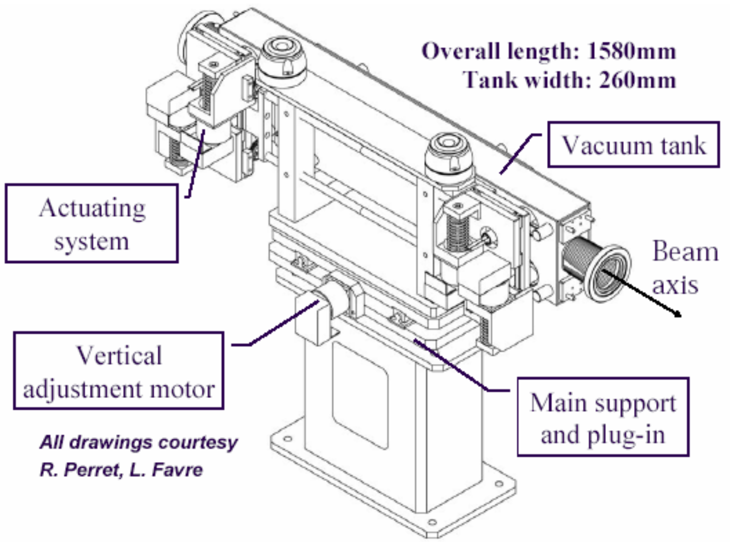
2E-4
Phase II
(assumes
1m Cu)

11E-4
Phase I



LHC Phase I Carbon/Carbon Secondary Collimators





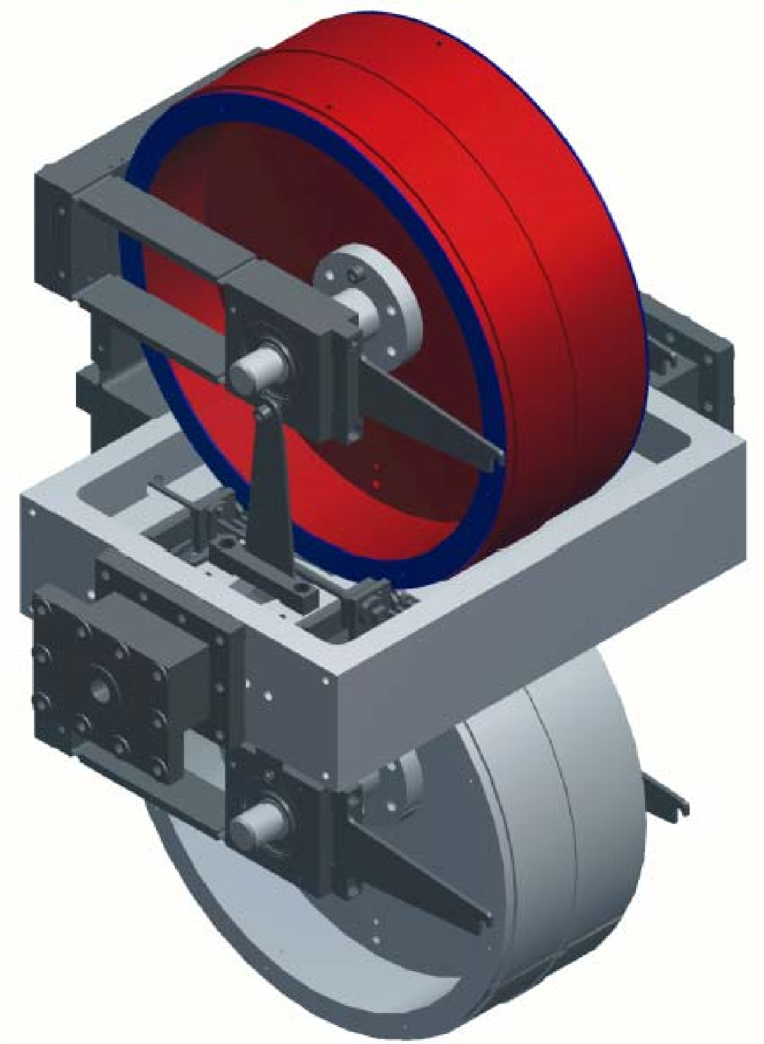
All drawings courtesy R. Perret, L. Favre

LHC Phase I Secondary Collimators
Mechanical Requirements

Length: 10+100+10 cm in 2m space
Width: 65mm (H) x 25mm (W)
Min. Gap: 0.5 mm
Max. Gap: 60 + 10 mm
Gap tolerance: 50 μm
Flatness tolerance: 25 μm
Angular tolerance: 15 μrad
Jaw position (Motor step size): 10μm
Jaw setting reproducibility: 20 μm
Roughness: 1 μm
Coating: 1 μm
Vertical adjustment: 10mm
Jaws fully adjustable (same mechanism used for H, V & 45° collimators)
Jaw max operating temperature: 50°C
- limited by outgassing outgassing rates of graphite
Bakeout temperature: 250-300°C
Radiation Hardness: 10^8-10^{10} Rad/year
Transverse Space constraints: 192-224 mm between beamlines

Flatness required to keep inefficiency low
Difficult to achieve when power deposition is high

NLC Rotating Collimator
Two 30cm ϕ x 10cm wheels



NLC Consumable Spoiler Requirements

Max.# Damaging Hits	1000
Length @ Min. Gap	0.6 rl
Radius of curvature	.5 m
Overall width	10 cm
Aperture	200-2000 μm
Edge Placement Accuracy	10-20 μm
Edge Stability under rotation	5 μm
Beam Pipe ID	10 mm
% Beam Intercepted per side	.05%
Beam Halo Heating	~0.2 W
Image Current Heating	~0.5 W
Radiation Environment	10^5-10^6 rad/hour
Vacuum (tbd)	$<10^{-7}$ torr

~30cm diameter

7mm Cu + Be wings

Radiative Cooling

First Suggestion ~15 months ago

If LHC collimator problem is risk of damage by failure of beam abort system, maybe they should consider “consumable” or “allowed to be damaged” concept of NLC design

R&D Plan Based on Extension of SLAC Design

DRAFT_PROPOSAL_ver1.1
15 January 2004

Rotating "Consumable" Collimators for LHC Phase II Operation

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Abstract

SLAC has developed a prototype collimator for the NLC based on two 30-cm diameter, 10-cm wide wheels referenced to a common base plate with bearing to set the collimator gap. The device operates in vacuum and is not externally cooled. A ratcheting mechanism moves the wheels ~1mm azimuthally while maintaining the gap position and gap width. If the collimator surface is damaged by a high power density errant beam it can be rotated to a fresh position approximately 1000x.

The LHC beam abort system is expected to accidentally fire at a very low but non-zero rate; at design luminosity the beam will damage the collimators. The LHC collimators are 50cm thick and must have 1kW of average cooling. We propose to adapt the NLC collimator design to the LHC situation, fabricate prototypes, perform vacuum and beam tests, and deliver a drawing package that CERN can use to industrially fabricate the required number (between 5-10) of collimators.

The collimator design, prototyping and testing would is planned for 2004-2007; collimator production would occur in 2008, and installation and commissioning in 2009. The non-production total estimated cost is $2.3M$.

30cm ϕ x 50cm wide

1kW DC cooling

Does the LHC want what we can build? Can we build what the LHC wants?

Work at CERN has been focused on:
- the Phase I Carbon secondary collimators
- the most ‘at-risk’ location behind the 20cm primary collimators in IR7

When Phase II SCs are considered, the CERN base model is 1m of Cu

Problems with 1m Cu secondary collimators
- It is not clear the SLAC mechanical design can be extended to 1m length or to the mass implied by two 30cm diameter Cu cylinders
- A priori, there is not enough space between beam lines for two 30cm disks
- It is not clear how much of the surface or volume of the collimator will be damaged in an asynchronous beam abort failure nor is the design number of damage incidents clearly specified yet
- Most importantly, the limited amount of work that has been done to date implies DC power levels more usually associated with beam dumps than with collimators

HOWEVER:

It is likely that many of the 32 collimators in less demanding locations can be well served by some variant of the SLAC design

Important questions for Phase II Secondary Collimators

Given lattice & space allotted how to optimize collimator efficiency while minimizing length, thickness, energy absorbed?

Is there a better overall configuration?

For metals under consideration what exactly happens when an asynchronous abort occurs?

- Melt radius, fracture radius, molten metal jets, grooves, holes, grooves…

What are the DC cooling requirements?

- Inelastic interactions from protons kicked by primary spoilers after one or many orbits of LHC
- Absorption of showers begun in other beamline components
- Spatial distributions, energy deposition maps, requirements by location for relevant variants of machine tune, etc.

Can we specify engineering interface so it can be installed before region is radioactive?

The Ideal Phase II Secondary Collimator

Large elastic scattering cross section (high efficiency)

Zero inelastic scattering cross section (low power absorbed)

High heat capacity (low temperature per unit power absorbed)

High melting and fracture temperature (survivability)

Large thermal conductivity (dissipate heat rapidly)

Weakly bound atoms (beam can blow a hole in it when abort fails)

Low temperature expansion coefficient (mechanical tolerances in beam))

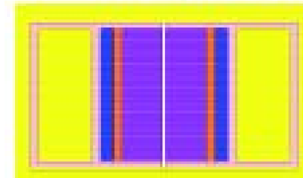
Low density and stiff (mechanical support, alignment, gap adjust)

High electric conductivity (impedance)

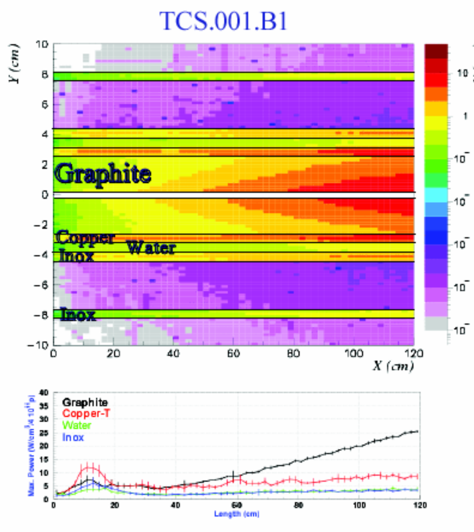
Heating of Phase I Secondary Collimators

CERN FLUKA group w/ Particle loss maps from Assmann

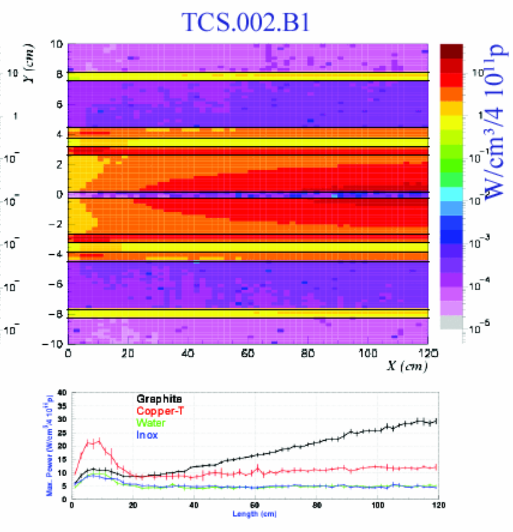
12 sec – 450 kW – 4E11 p/s case (10 sec)	
Pencil beam on secondary collimator	3kW
RF heating	1 kW
Pencil beam on primary collimator	30kW
Total	34 kW

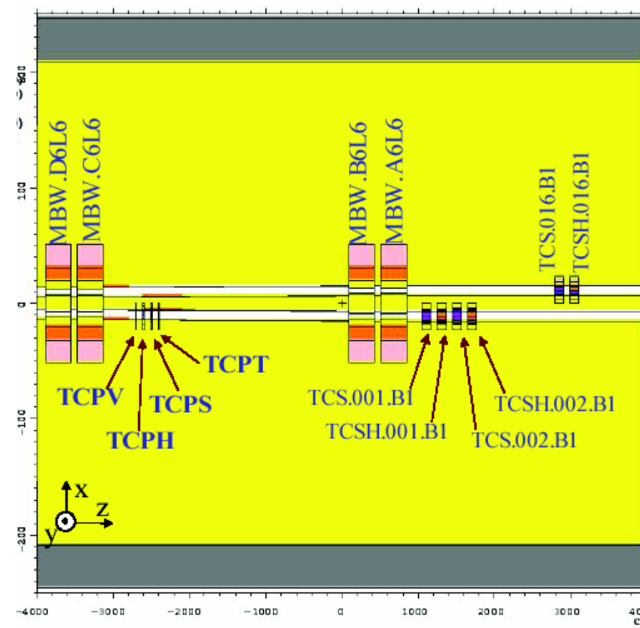


12kW



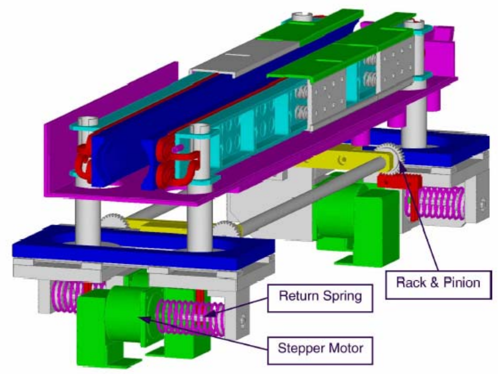
30kW

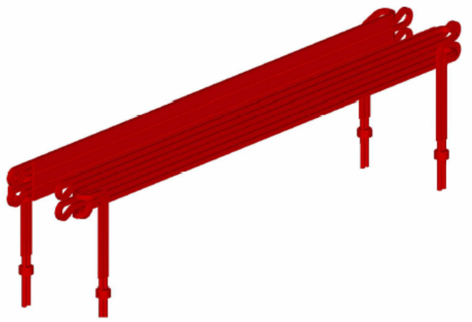




Total Power	450 kW
Power IR7	233 kW
Power absorbed	116 kW

Estimate of Phase I Collimator Cooling

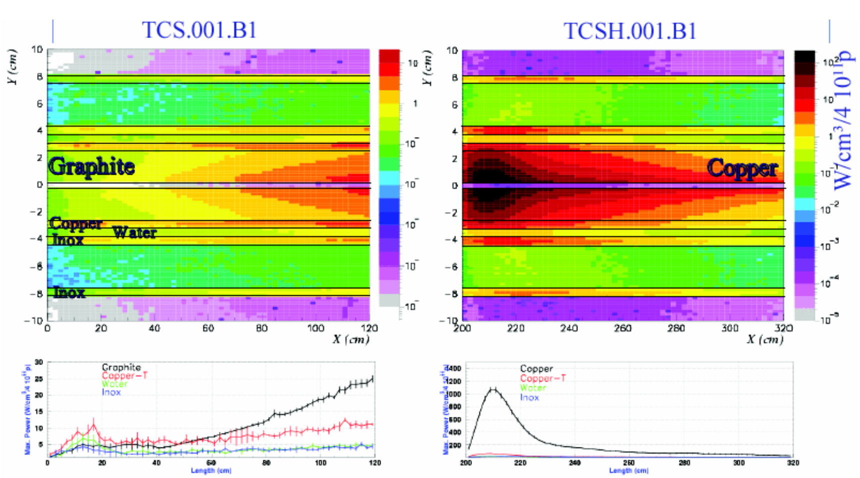


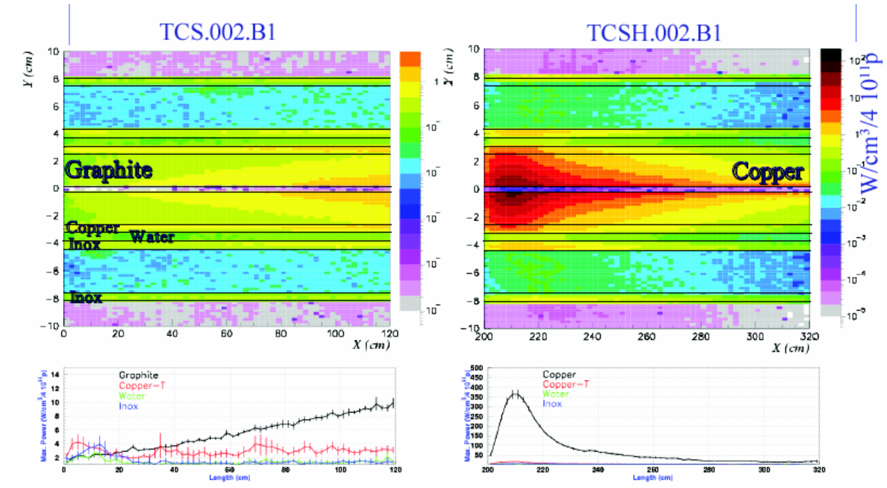


# Jaws		2
# pipes/jaw		2
Flow rate / pipe	l/min	5.0
Water input temperature	°C	27.0
Max jaw temperature	°C	50.0
Water output temperature	°C	50.0
Pipe inner diameter	mm	6.0
Heat Capacity of water	Joules/(gm-°C)	4.184
Phase I Cooling Capacity	kW	32.08

Heating of 1m Cu Secondary Collimators
Phase I Carbon design – In-Line with Same Aperture

14kW | 130kW | 5kW | 30kW



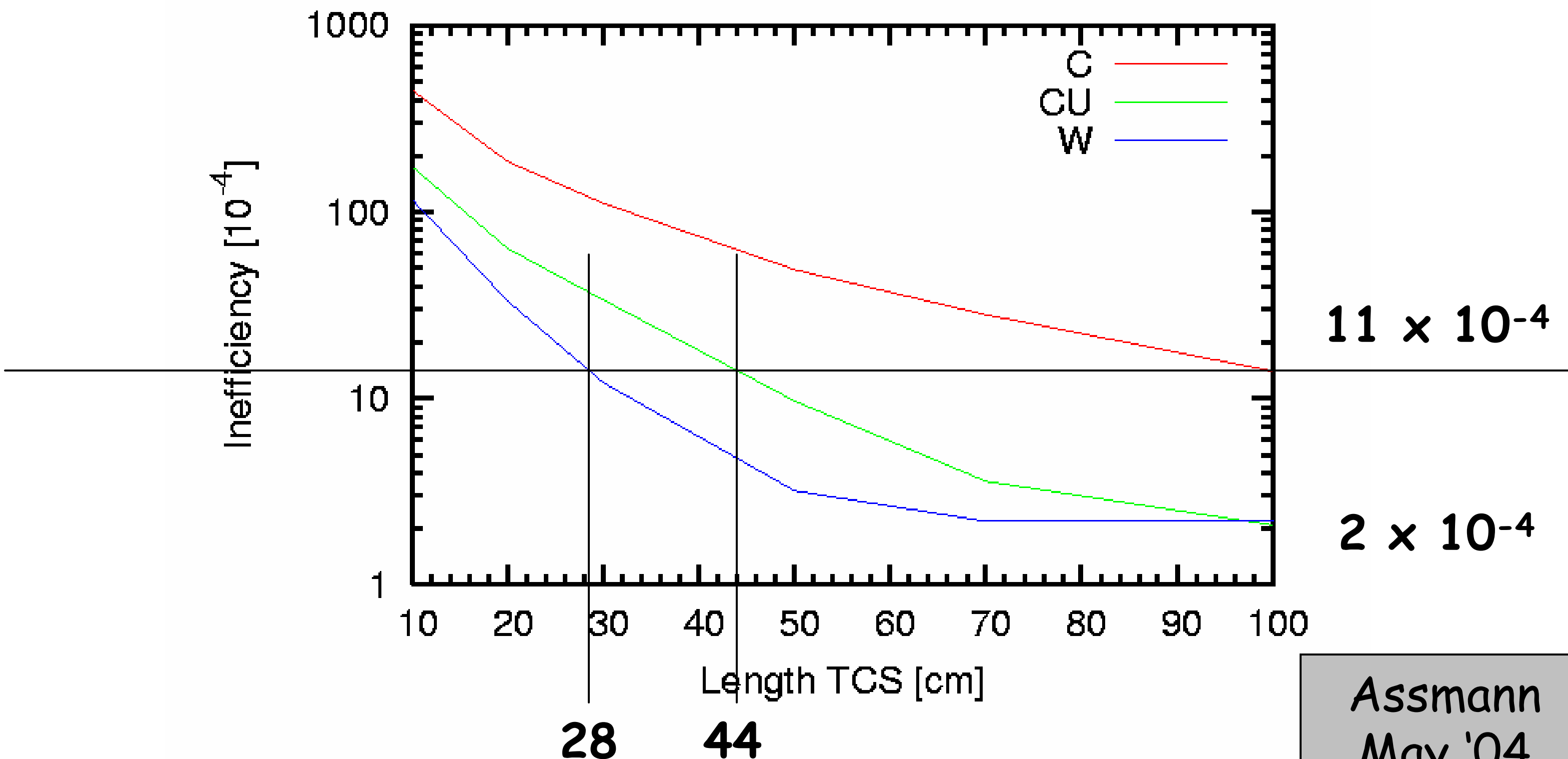


Largest heat load for a conventional collimator, using chilled water & turbulent flow, ~40 kW

130 kW would require beam dump style techniques

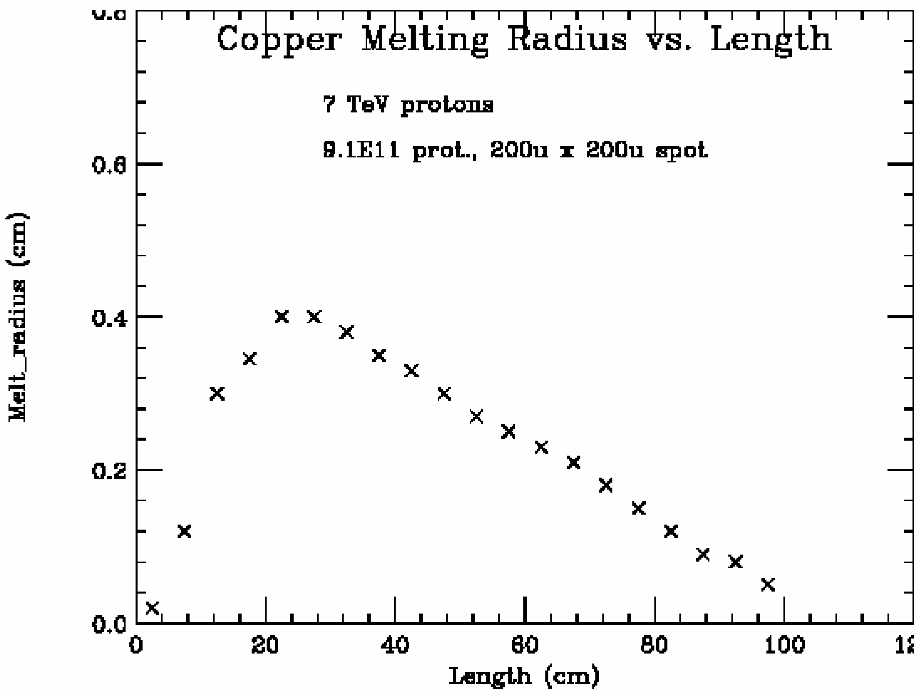
Initial Design Paradigm

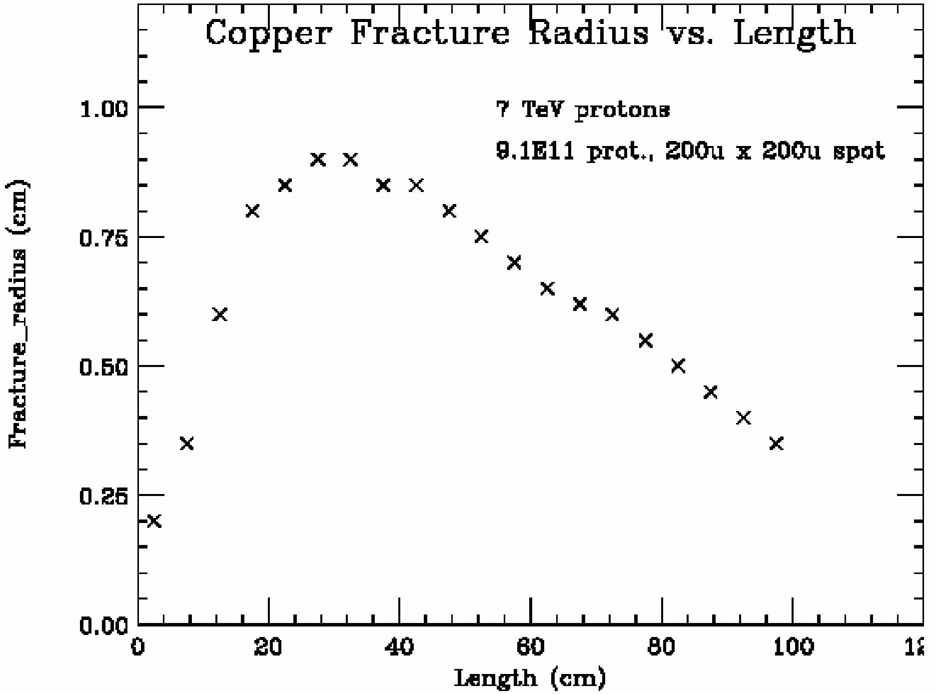
Replace C Phase I SC with Cu so than Collimation System Efficiency is the identical but Collimation System Impedance is Improved to allow Design Parameters



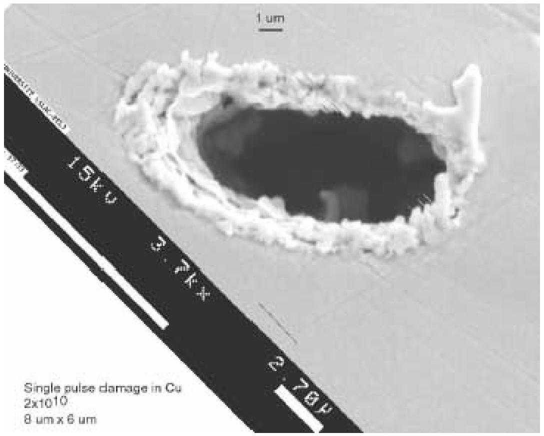
Assmann
May '04

SLAC FLUKA Abort Failure Analysis
Damage Region in Cu ~ 9 mm

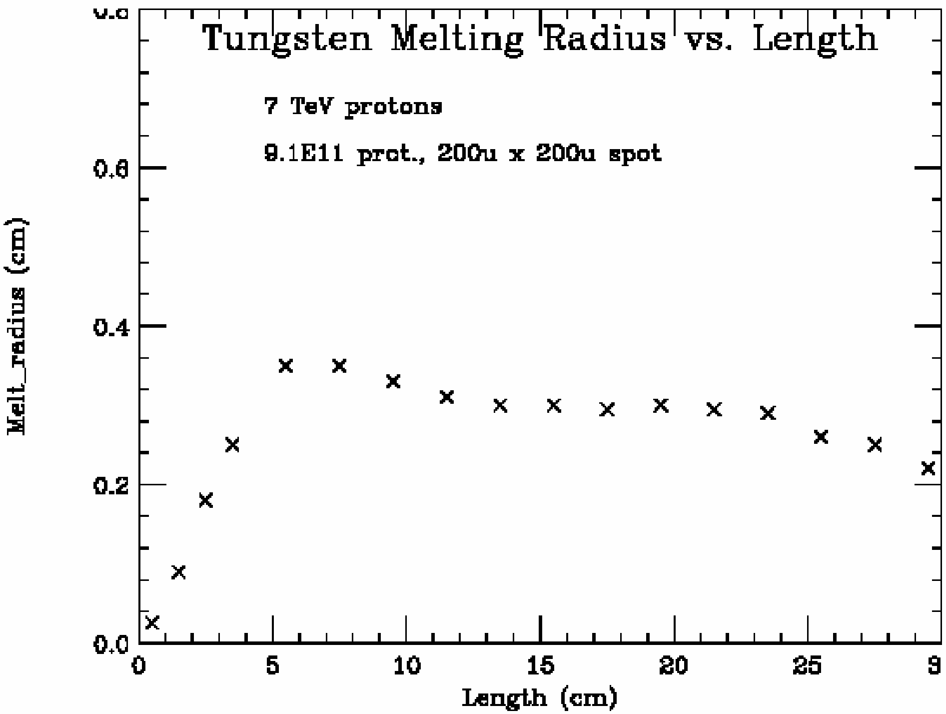


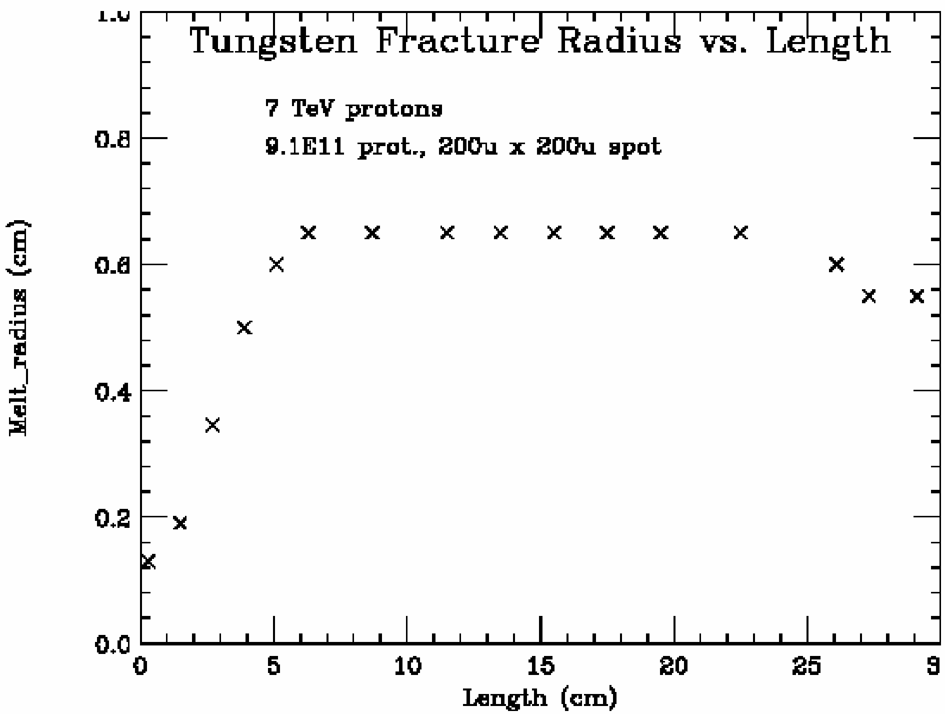


Thin Cu sample in FFTB electron beam at SLAC
Hole = Beam Size



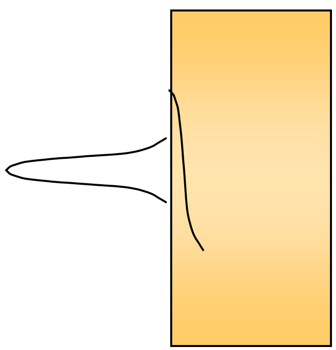
SLAC FLUKA Abort Failure Analysis
Damage Region in W ~ 7 mm





SLAC FLUKA Calculations
Pencil beam on Collimator Edge
4×10^{11} p/sec, 0.2 hr beam lifetime over 10sec, 450kW

Lew's FLUKA calculations for peak slow losses		**Carbon**	**Copper**	**Tungsten**
Length	cm	100	45	30
Total Power Absorbed	kW	4	44	76
Maximum Energy deposition per proton in a 0.02 x 0.02 x 2cm volume	GeV/cm^3	35	1560	10000
z of maximum	cm	100	12	5
Energy escaping		99.17%	90.91%	84.31%
# incident protons in 5 msec		2.15E+09		
Temperature rise in 5 msec	°C	3.05	156.62	1337.62
Melting Temperature	°C	3600.00	1080.00	3300.00

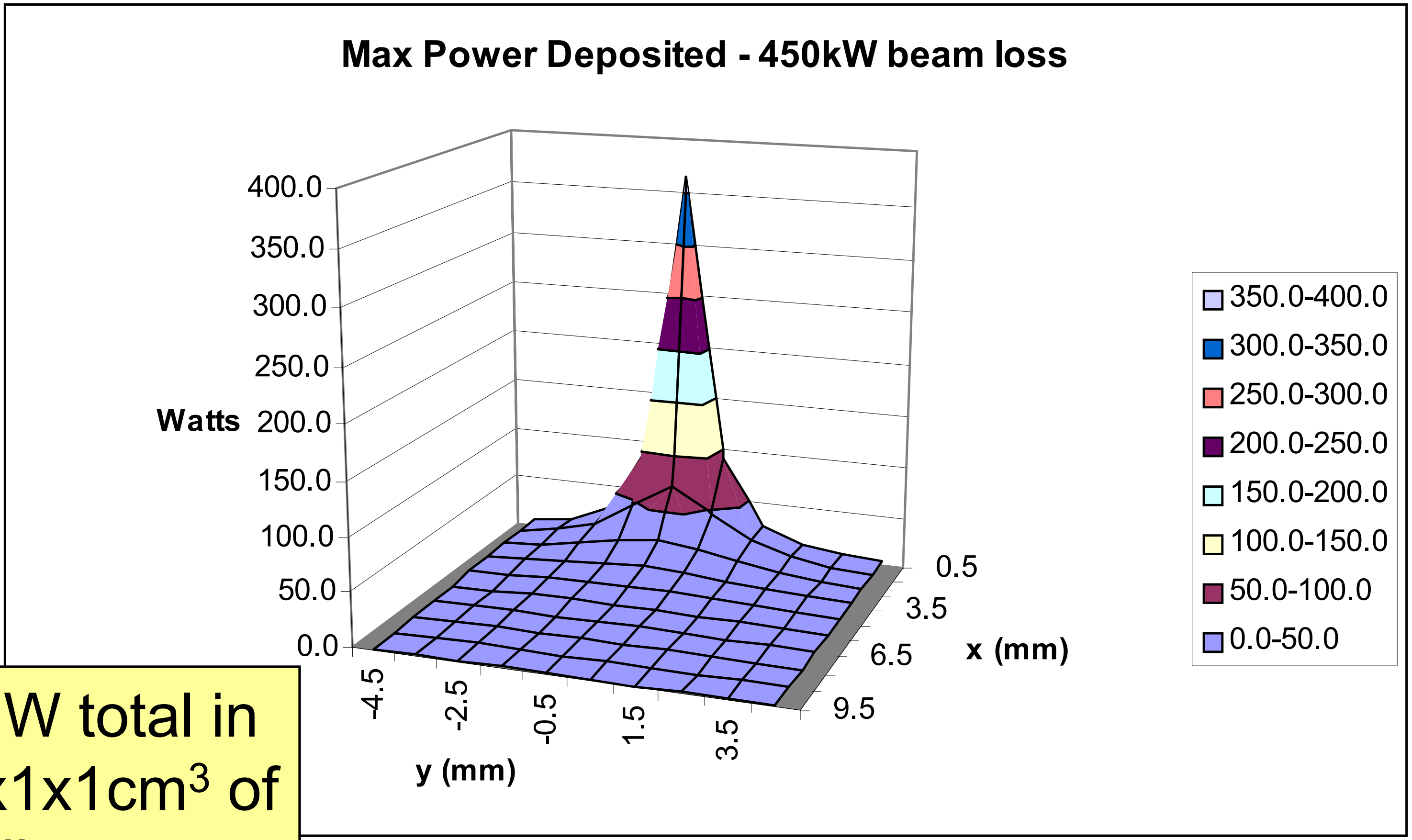


Geometry:
σ_x = 200 μm Gaussian inward from jaw edge
σ_y = 200 μm Gaussian

Transparency of C due to high ratio of L_rad / L_int

Material	EM energy Deposited per proton (GeV)	Total Energy Deposited per proton (GeV)	EM/Total (%)	Beam Energy Deposited (%)
C -- 100 cm	48.4	62.0	78	0.88
Cu -- 45 cm	636.	688.	92	9.8
W -- 30 cm	1,116.	1204.	93	17.2

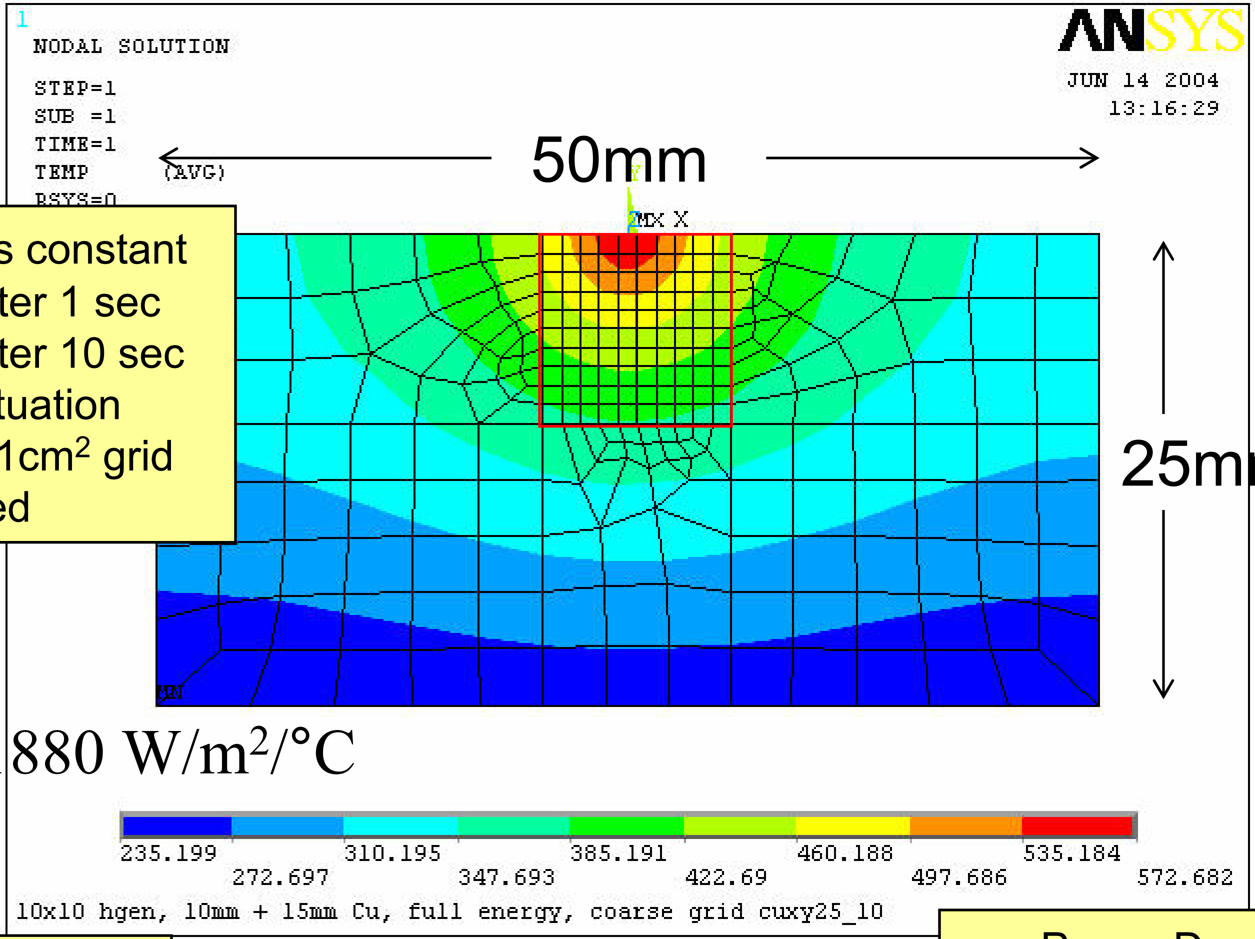
Power per mm^2 in 1cm at peak (z=12 of 45cm) @ 4E11 p/s loss



1325 W total in this 1x1x1cm^3 of collimator

Temperature of a 25mm Solid Cu Jaw in thermal contact w/20 °C water with 450kW beam loss at z of maximum power absorption: 1325 W

- C_V Cu taken as constant
- T_{max}=250 °C after 1 sec
- T_{max}=450 °C after 10 sec
- 50mm < real situation
- Power outside 1cm^2 grid (~450W) ignored

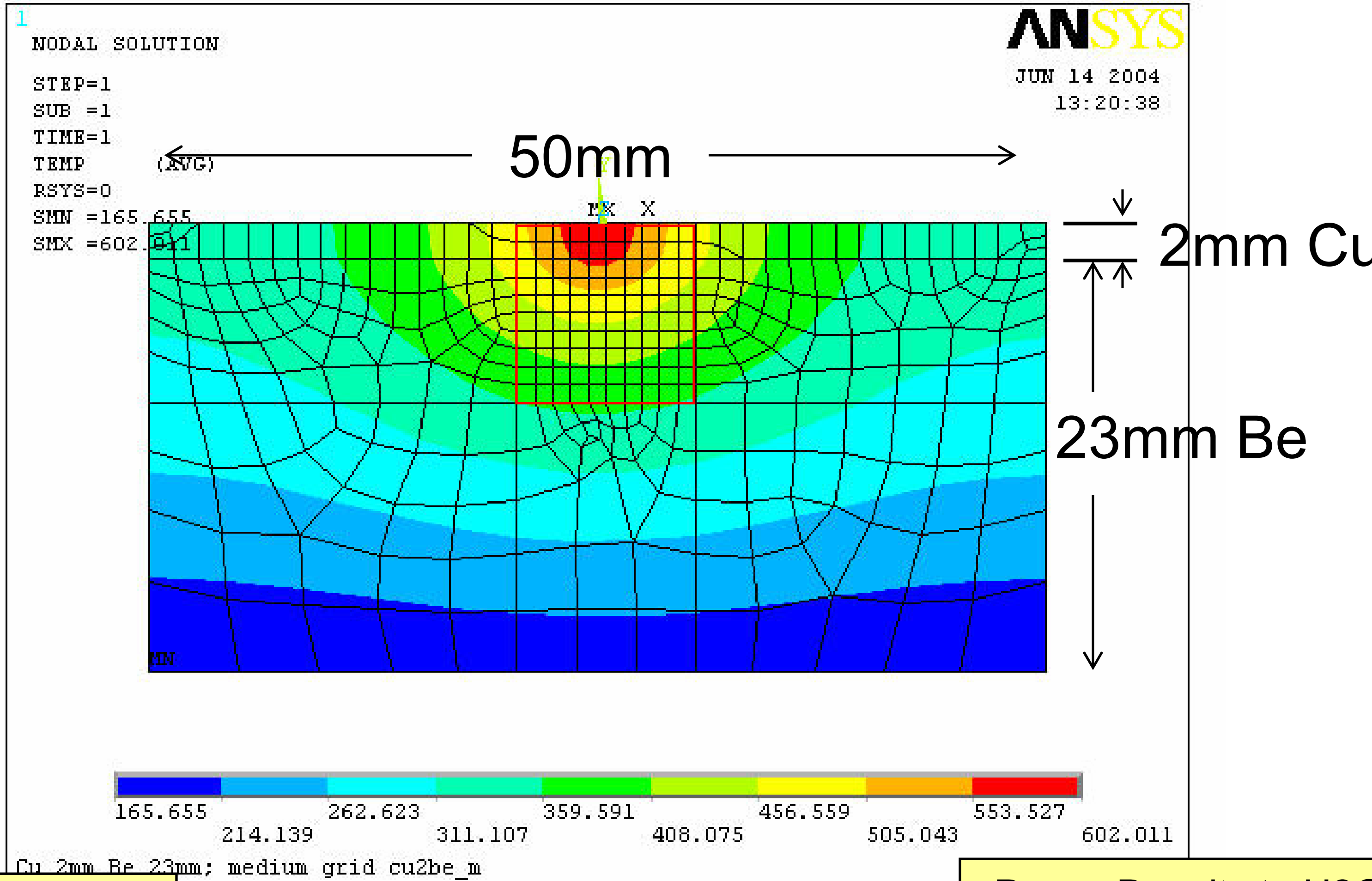


HC_{H20}=11880 W/m^2/°C

Boundary Condition:
Convection Coefficient
HC_{H20}=11880 W/m^2/°C

Power Density to H2O
2.6 MW/m^2
(H2O boils at 1 atm @ 1.3E6)

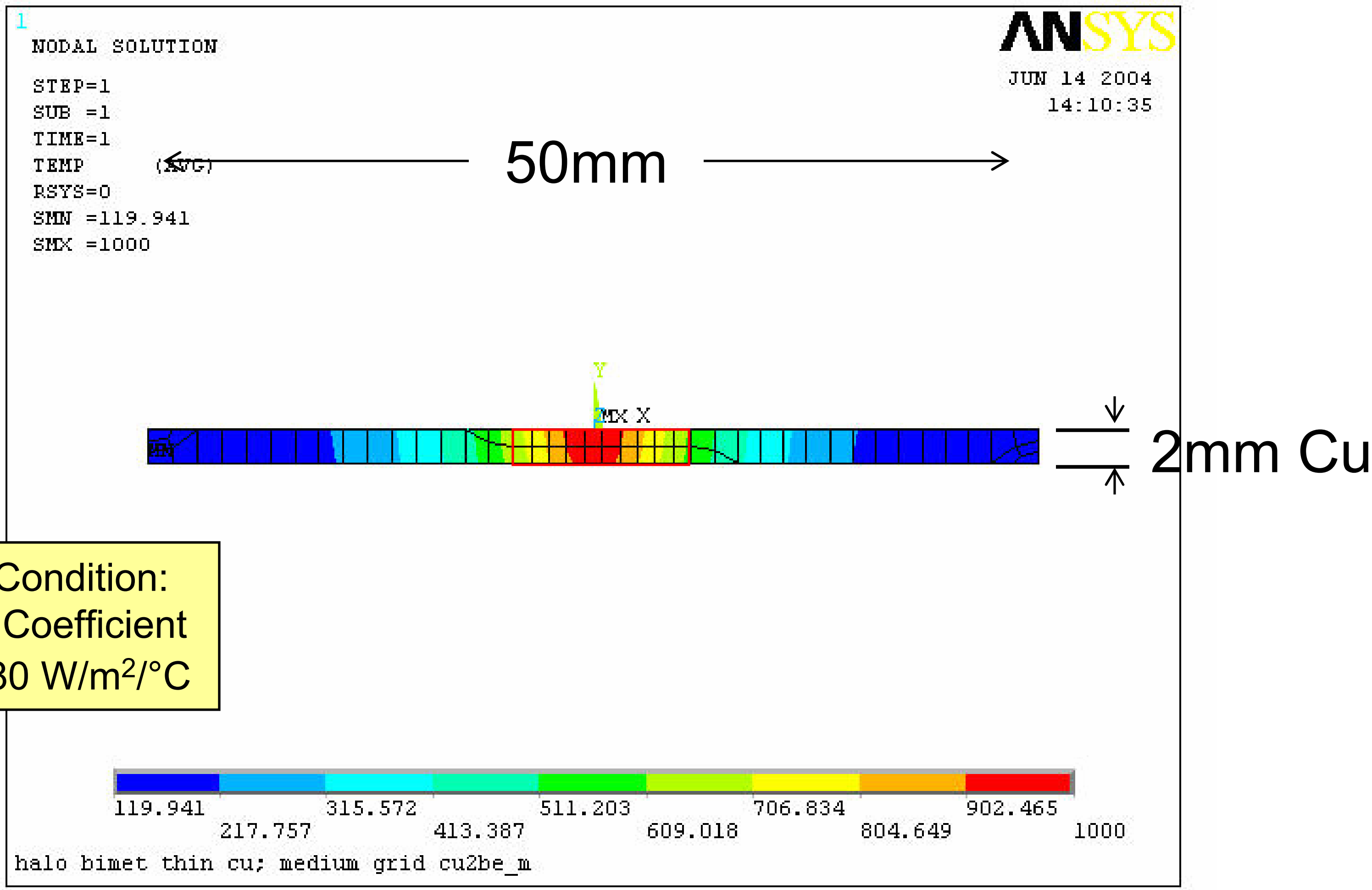
Temperature of a 2/23mm Cu/Be Jaw in thermal contact w/20 °C water with 450kW beam loss at z of maximum power absorption: 900 W



Boundary Condition:
Convection Coefficient
HC_{H20}=11880 W/m^2/°C

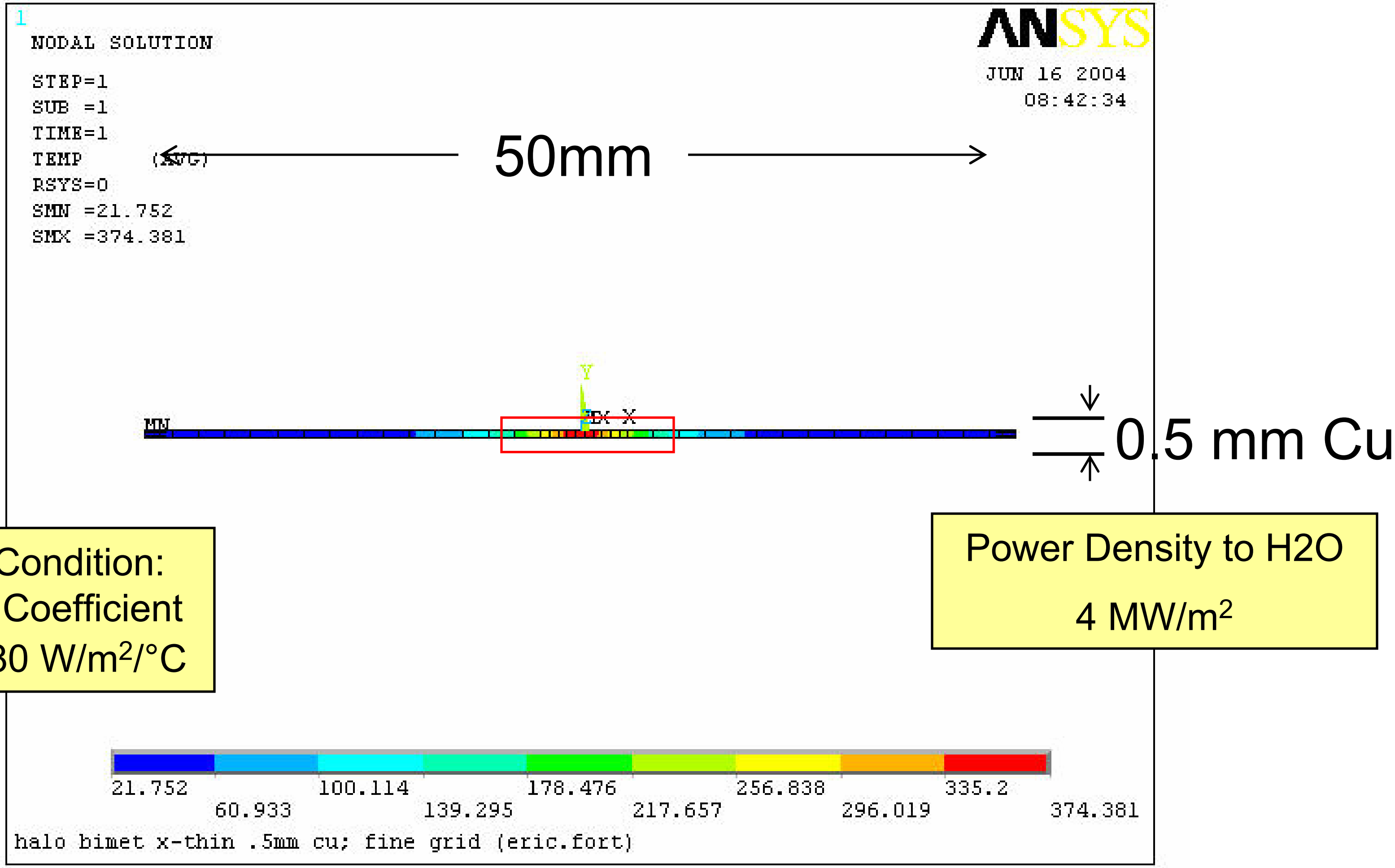
Power Density to H2O
1.8 MW/m^2

Temperature of a 2mm Cu Jaw in thermal contact w/20 °C water with 450kW beam loss at z of maximum power absorption: 800 W



Boundary Condition:
Convection Coefficient
HC_{H20}=11880 W/m^2/°C

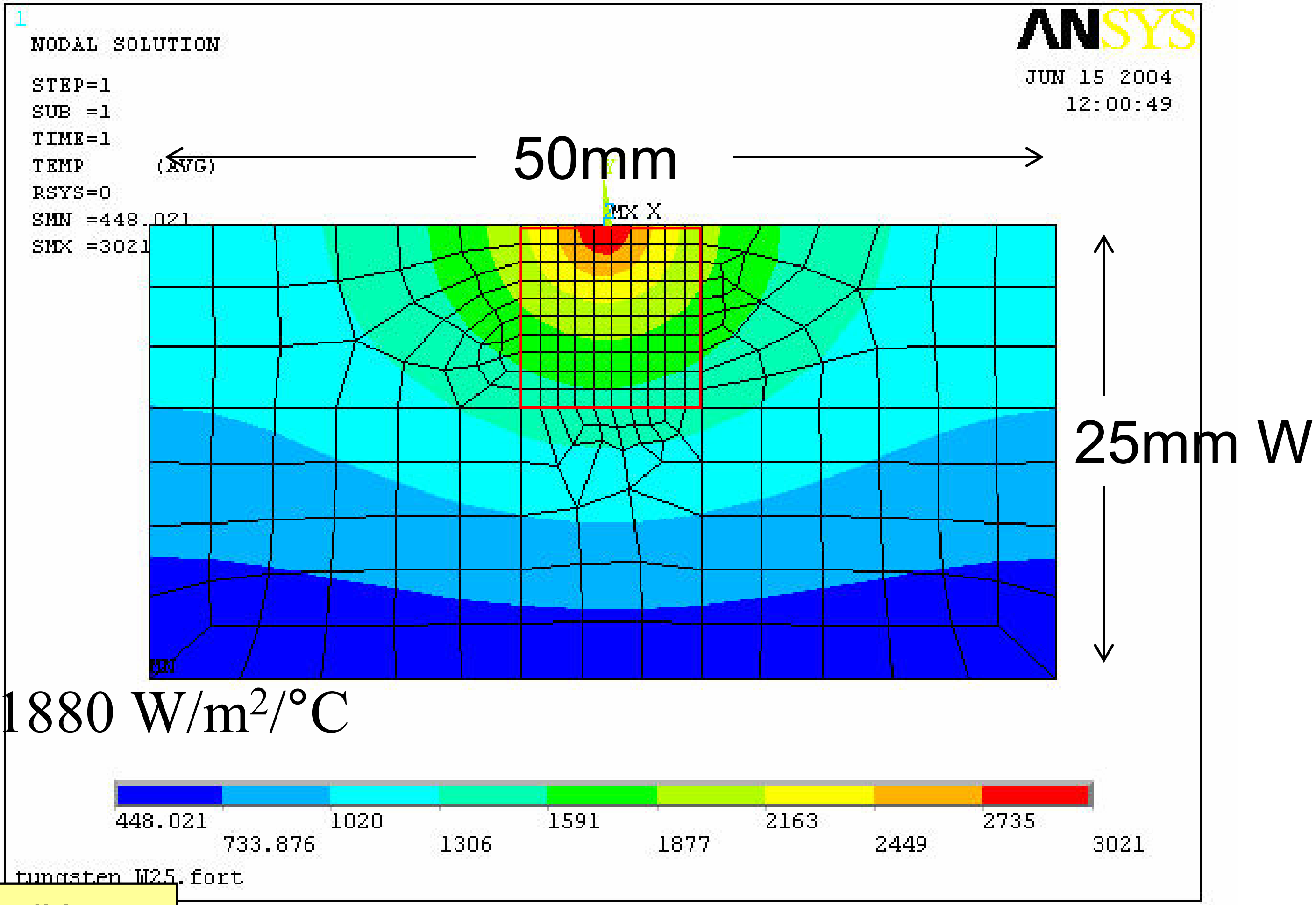
Temperature of a 2mm Cu Jaw in thermal contact w/20 °C water with 450kW beam loss at z of maximum power absorption: 388 W



Boundary Condition:
Convection Coefficient
HC_{H20}=11880 W/m^2/°C

Power Density to H2O
4 MW/m^2

Temperature of a 25mm Solid W Jaw in thermal contact w/20 °C water with 450kW beam loss at z of maximum power absorption: ~2500 W



HC_{H20}=11880 W/m^2/°C

Boundary Condition:
Convection Coefficient
HC_{H20}=11880 W/m^2/°C

Questions on Phase II Collimator Heat Load

For 45cm Cu in 450kW loss scenario:

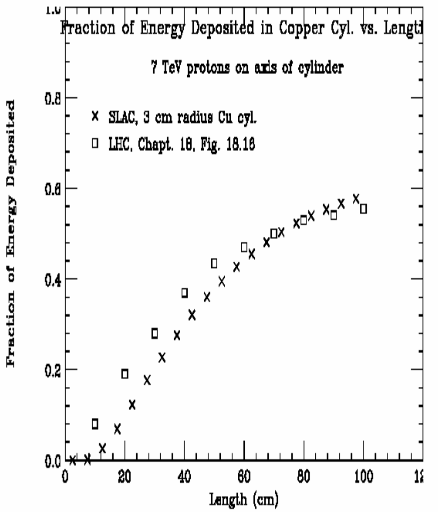
- Is 44 kW from direct beam interactions required
  - Don't all protons pass through primary collimators first
- What is heat load that corresponds to phase I estimate of 30kW?
  - When Phase I jaws are open so we are not collecting shower debris
- Can we survive 10 sec transient and cool only for 1 hour beam lifetime?
- Are any of the beam loss requirements reviewable?

BUT:

Do not yet understand why 45cm Cu = 100 cm C:

- 10cm Cu would have ~ power absorption as 100cm C
- why doesn't inefficiency scale with P (or A, Z^2, L_{rad}, etc.)

%E vs L



Doyle ANSYS Calculations
Deformation vs. Power Absorbed

collimator	power kW	Twater C	convect. Coeff J/m^2/C	Tmax C	Tmin C	uy um	seq MPa	sy MPa	seq psi
Ph 1 secondary (graphite)	7	20	11880	66	24.4	317			
Ph 2 secondary (Cu)	7	20	11880	35.6	20	26			
Ph 2 secondary (W)	7	20	11880	73.3	20	14	72		10
Ph 2 secondary (Cu)	97	20	11880	236	20	294	347	69 - 500	50
Ph 2 secondary (W)	97	20	11880	759	20	200	1000	1500	145

notes:
conective heat transfer coefficient calculated based on lhc Phase 1 collimator cooling system
uy = max displacement of collimator surface in section through beam path
seq = von Mises equivalent stress
sy = yield strength

Proposal

A joint SLAC/LARP/CERN study (Accelerator Physics, FLUKA/MARS, ANSYS) that would answer outstanding questions and lead to a set of design requirements and conceptual engineering solutions for each of the Phase II secondary collimators

If a decision is made by CERN that a “reasonable” extension of the NLC “rotating collimator” concept can satisfy all or a sufficient number of Phase II collimators, SLAC/LARP would provide

- Vacuum compatible mechanical prototype
- Fully instrumented prototype that would be beam tested

If device cannot be supported by SLAC’s rotating collimator expertise:

- Support of technology transfer / design to appropriate lab

After Phase I running experience CERN would decide whether or not to proceed with unmodified or modified production versions of the prototype. Assuming project goes forward, SLAC/LARP would provide

- Drawing package for series production

CERN would be responsible for

- Fabrication
- Installation

SLAC/LARP would provide

- Support for commissioning

Additionally, if desired & appropriate, SLAC would provide support for Phase I collimators:

- Short and long-range wakefield measurements using the COLWAKE facility
- Material damage studies in SLAC FFTB coupon test facility

Phase II Collimator Plan Summary

FY 2004:	Introduction to project
FY 2005:	Phase II CDR and Set Up of collimator lab at SLAC
FY 2006:	Tests of RC0, Design and construction of RC1
FY 2007:	Tests of RC1 (two rounds), design and construction of RC2
FY 2008:	Non-Beam Tests of RC2
FY 2009:	RC2 beam tests & final drawing package for CERN
FY 2010:	Await production & installation by CERN
FY 2011:	Commissioning support

Glossary:

RC: Rotating Collimator

RC0: Existing NLC prototype

RC1: Prototype with horizontal jaws, made of non-exotic UHV compatible materials

RC2: Beam-test capable prototype with exotic materials

Phase II Collimator Labor Summary

FY	Labor
2004	
2005	2
2006	3
2007	2.75
2008	3.5
2009	3.5
2010	1.5
2011	2
Grand Total	18.25

FY05 Labor Detail

Postdoc	FNAL	0.50	FTE
Postdoc	SLAC	1.00	FTE
Physicist	SLAC	0.25	FTE
ME	SLAC	0.25	FTE

FY06 Labor Detail

ME	SLAC	1.00	FTE
Postdoc	FNAL	0.50	FTE
Postdoc	SLAC	1.00	FTE
Physicist	SLAC	0.25	FTE
Designer	SLAC	0.25	FTE

Phase II Collimator Budget Summary

FY	Labor	M&S	Shop	Grand Total
2004		11000		11000
2005	265000	89000	7000	361000
2006	471000	124000	153000	748000
2007	462000	204000	321000	987000
2008	603000	50000	95000	748000
2009	621000	65000	32000	718000
2010	245000	26000		271000
2011	381000	81000		462000
Grand Total	3048000	650000	608000	4306000