Thermal Analysis of Beamline Components and Fatigue Design Criteria

presented by

S. Sharma

Contributors: V. Ravindranath, M. Givens, L. Zhang (ESRF)

Outline

- Background
- Analysis Method
- Results of thermal analyses of beamline components
- Progress on fatigue design criteria
- Summary

Background

- **All SR x-ray absorbers (right) were designed for 300 mA.**
- **Front-end and beamline components were designed for various current limits between 100 to 300 mA. Thermal analysis documentation is not readily available for many components.**
- **High current runs are on hold.**
- **Present design criteria are too conservative.**


C2


W2


Beam Dump


TR5


EA3


RF Taper


IEA6


Scraper

Background (contd.)

Advanced Photon Source

December 9, 2003

To:	R. E. Gerig E. Gluskin	Division Director, ASD Division Director, XFD
From:	W. G. Ruzicka	Division Director, AOD

Subject: **Request for Engineering Support**

AOD has been assigned the responsibility of the oversight of the compliance of critical components for safe operation of all the beamlines and front ends. Towards this end we would like to clearly define and document the operating envelop for all critical components of the beamlines and the front ends.

We would like to establish for every beamline and front end an envelope for safe operations based on the following criterion:

- Thermal limitations;
- Radiation limitations;
- Alignment requirements;
- Utility requirements; and
- Mechanical support requirements.

Of all the criteria listed above, we are currently focusing on the thermal limitations of critical components (shutters and masks). At this time we would like to start addressing the insertion device beamlines and front ends. Once we have a clear understanding on the insertion device beamline and front ends, we would subsequently address the bending magnet beamlines and front ends.

This memo was discussed in an Ops-Directorate meeting and it was decided to pursue two goals simultaneously.

Background (contd.)

- **Goal I: Perform linear elastic finite element (FE) analyses using existing (highly conservative) design criteria to obtain upper limit on beam current.**

  Design criteria:

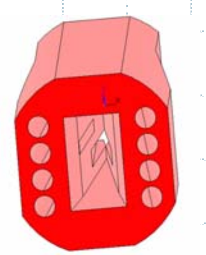
  - **Maximum temperature under the beam footprint should be less than 300 °C (for Glidcop).**
  - **Maximum stress is not to exceed yield stress (300-450 MPa for Glidcop)**
  - **Maximum temperature at the cooling channel wall should be less than the water boiling temperature (~ 145 °C).**

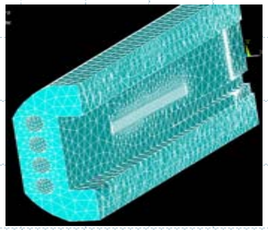
- **Goal II: Establish more realistic design criteria based on fatigue tests and nonlinear elastic-plastic finite element analyses.**

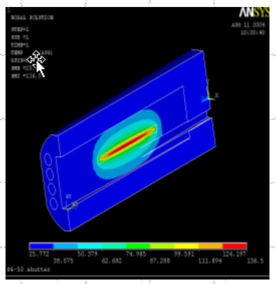
Analysis Method (Goal I)

- Beamline components were identified by M. Ramanathan.
- 2-D drawings were converted to Pro/E 3-D models by M. Givens (DD-ASD).
- 3-D models were transferred to Ansys in IGES format.
- Linear thermal and structural analyses were performed by V. Ravindranath (IIT) for beam power from Undulator A.
- Effects of assumptions (film coefficient, power distribution) were quantified.

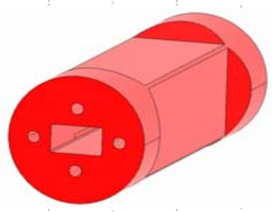
P4-40 Shutter

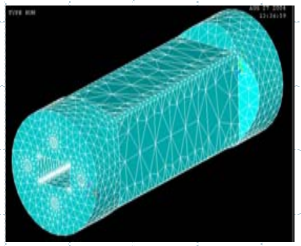


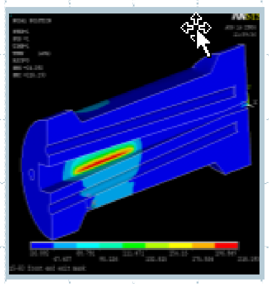




L5-83 Mask







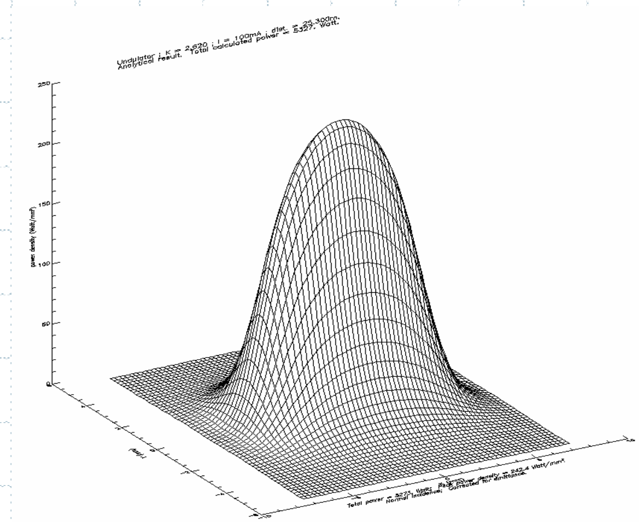
Beamline Components

NO.	Component	Distance from the Undulator Source
1	L5-83: front-end exit mask for all version 1.2 front ends	25.3 m
2	M4-40: front-end exit mask on version 1.5 front-ends	25.3 m
3	M7-20: front-end exit mask for 4ID	25.3 m
4	M4-30: front-end exit mask	26 m
5	M7-41: beam-line splitter mask for 4ID	26 m
6	M9-30: white beam stop and pink beam mask	30 m
7	P5 Integral Shutter	30 m
8	P4-20: shutter	30 m
9	P4-31: shutter for 4ID	30 m
10	P4-50: shutter	30 m
11	P4-41: shutter for 4ID	60 m
12	K5-50: white beam stop for 4ID	77 m

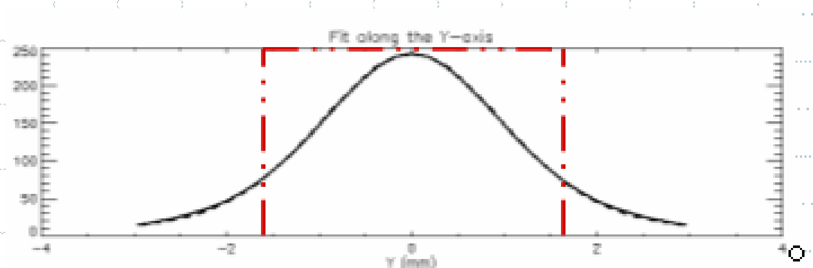
Analysis Method – Undulator Power

Undulator A

Parameter	Value
Beam current (mA)	100
Undulator period length λ (cm)	3.3
Length of undulator (m)	2.4
Minimum gap (mm)	11
Number of periods	72
Relativistic gamma	13700
Deflection parameter K	2.62
Horizontal beam size σ_x (mm)	0.352
Vertical beam size σ_y (mm)	0.018



SRUFF Program



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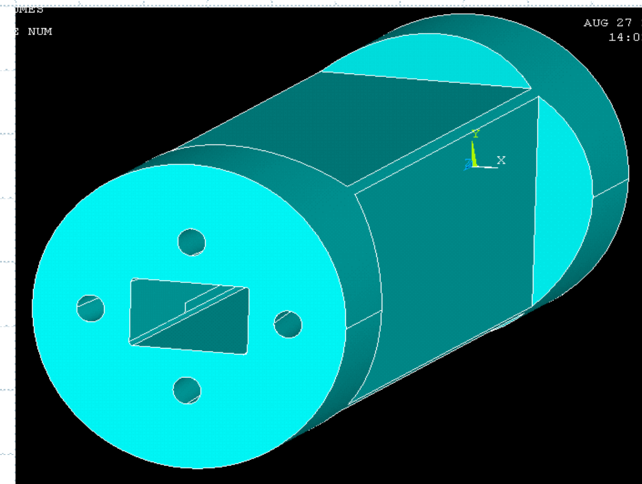
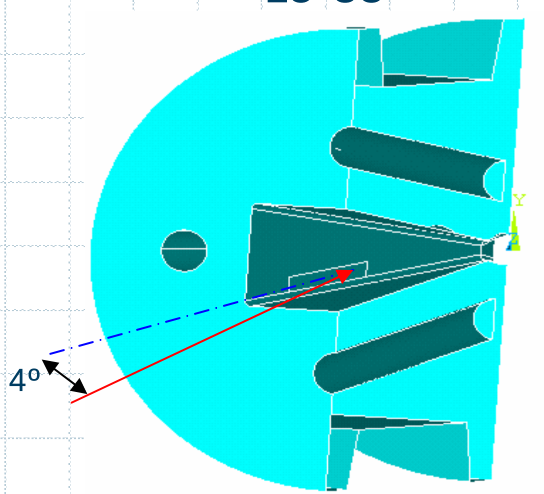
L5-83: Mask

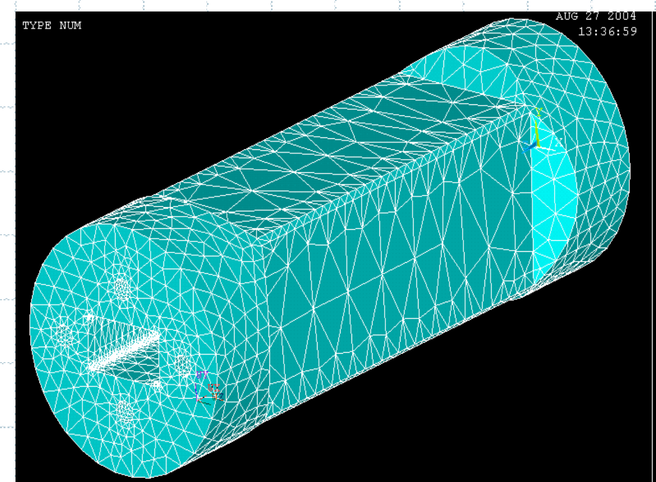
L5-83



L5-83 3-D model



L5-83 Beam orientation



L5-83 FEA mesh

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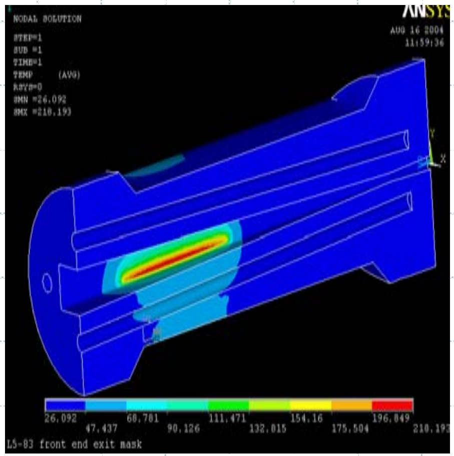
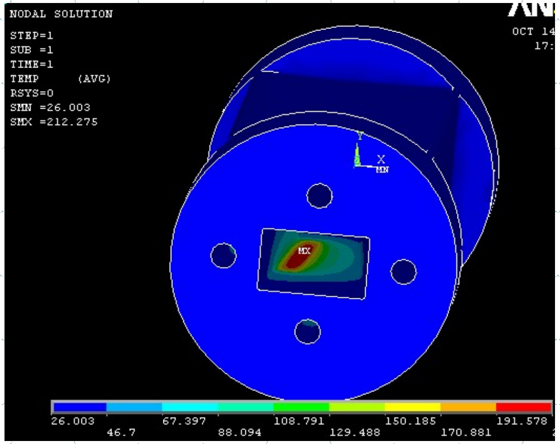
Results-Contour plots for L5-83

Case I : Uniform heat flux approximation



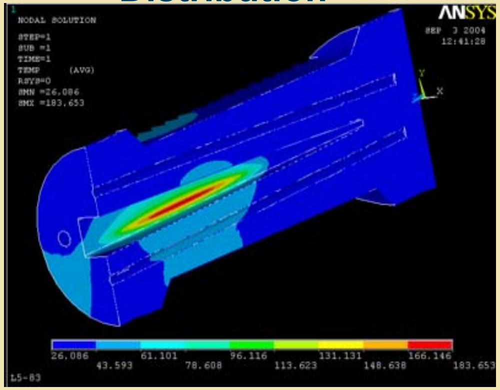
Temperature Contours
Horizontal Deviation



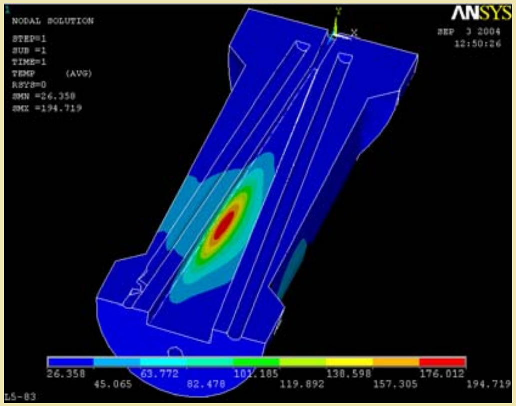
Temperature Contours
Vertical Deviation

Beam Deviation	Maximum temperature (°C)	Difference
Horizontal: Gaussian/Uniform	**184 /218**	**18 %**
Vertical: Gaussian/Uniform	**195 /212**	**9 %**

Case II & III : Gaussian Heat Flux Distribution



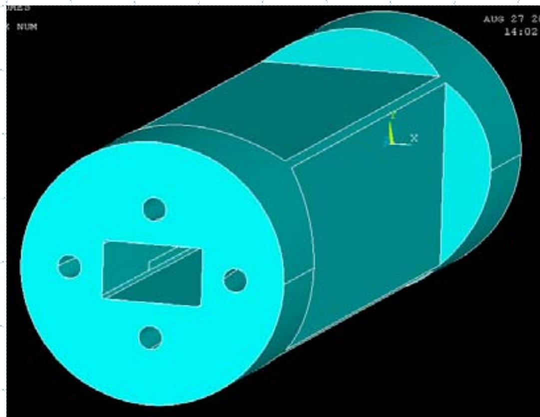
L5-83: Temperature Distribution for Horizontal Deviation

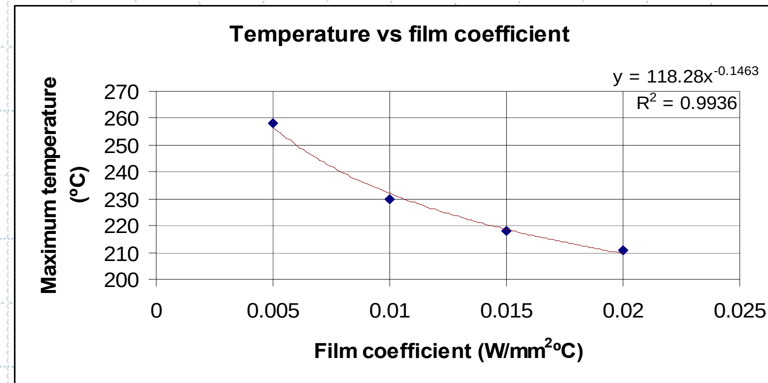


L5-83: Temperature Distribution for Vertical Deviation

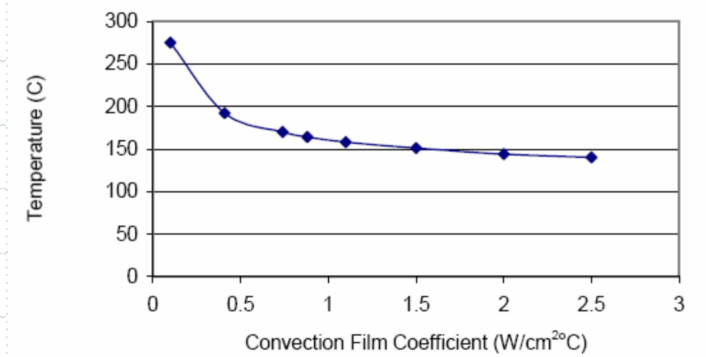
Analysis Method – Film Coefficient

L5-83 Mask





Crotch Absorber



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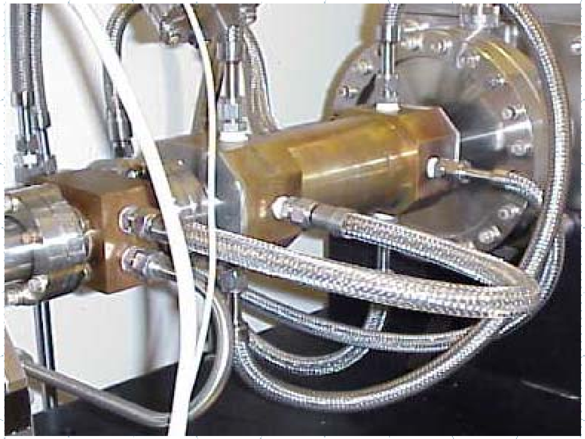
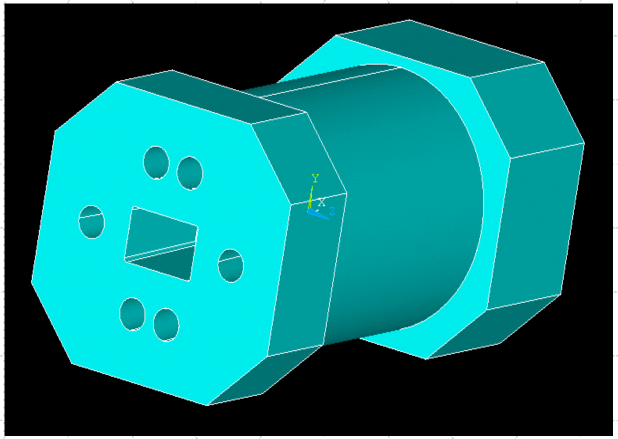
A nominal value of 0.015 W/mm².°C for the film coefficient was used for all thermal analyses. The effect of cooling efficiency (± 50%) on peak temperature is not significant.

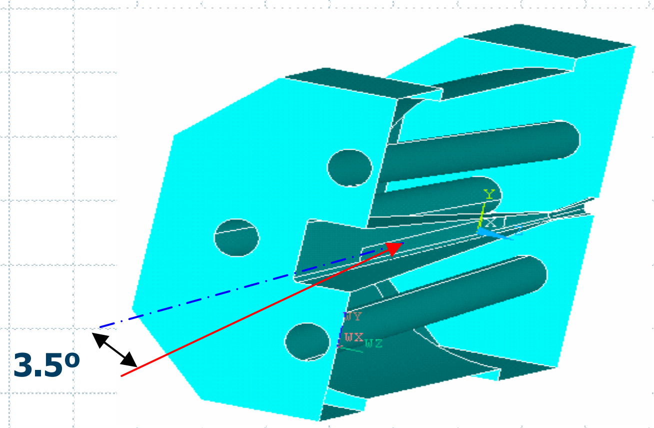
M4-40: Mask



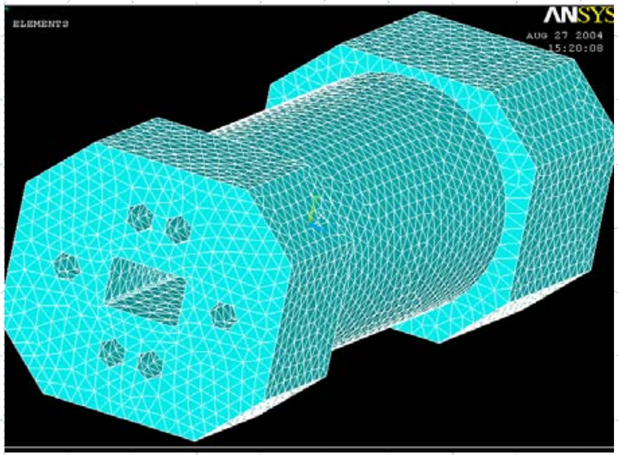
M4-40



M4-40 3-D model

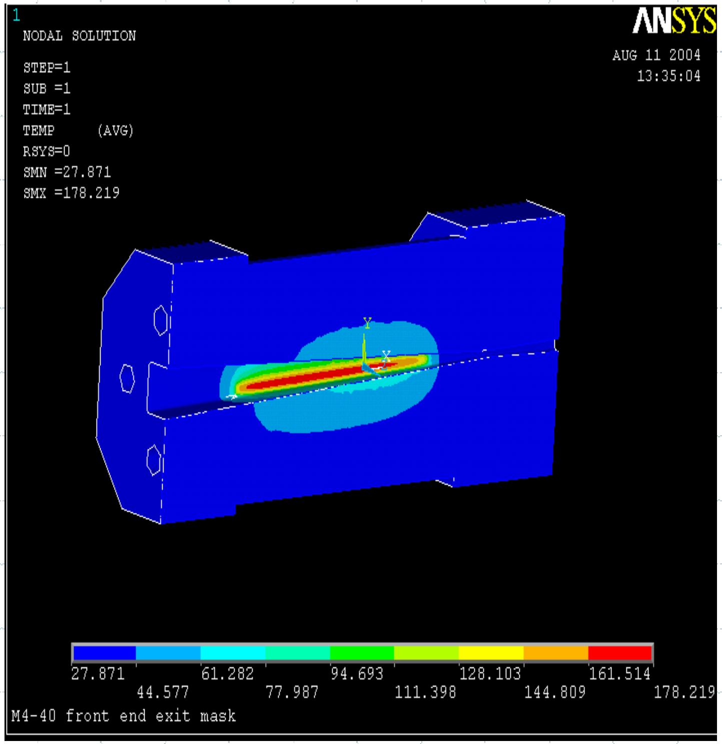


M4-40 Beam orientation

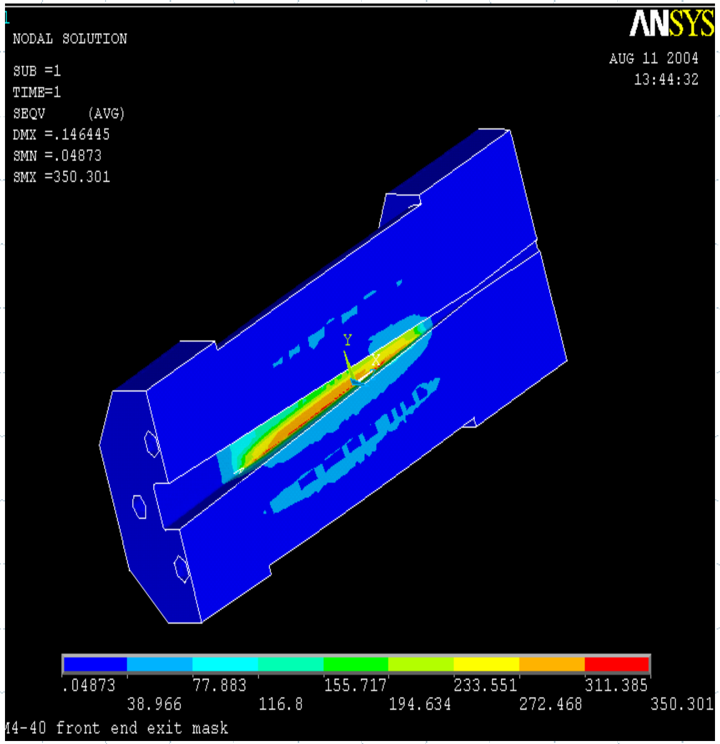


M4-40 FEA mesh

Results-contour plots for M4-40

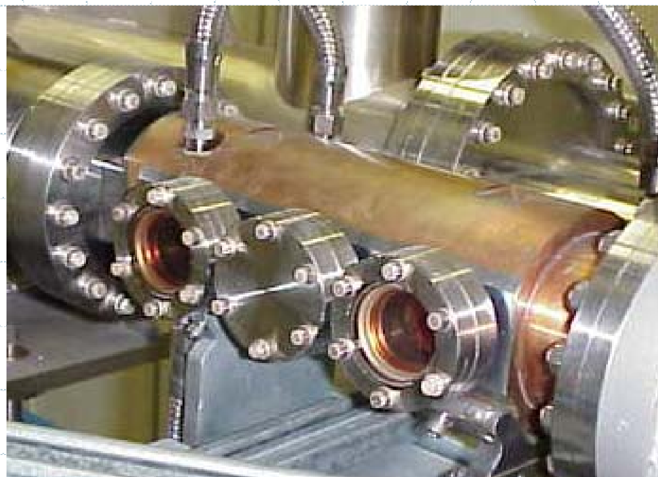


M4-40: Temperature Contours

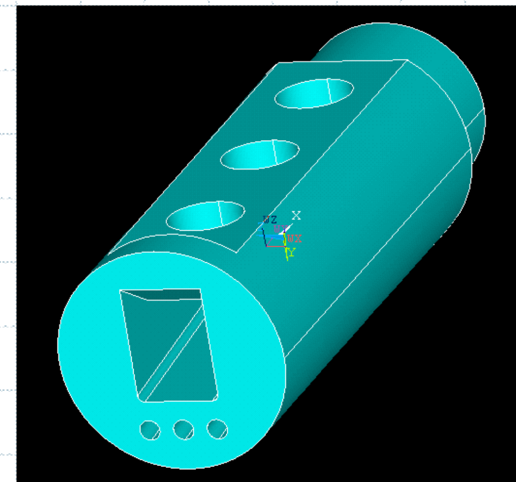


M4-40: von Mises Stress Contours

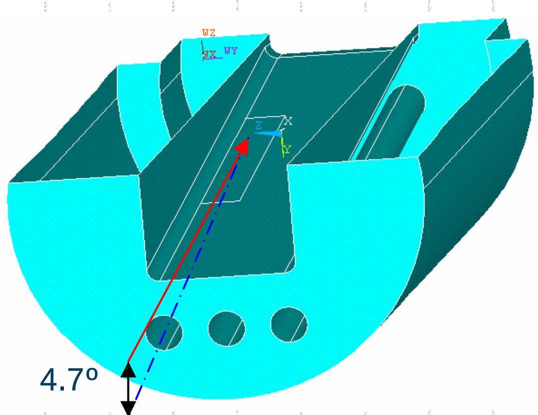
M9-30: Mask



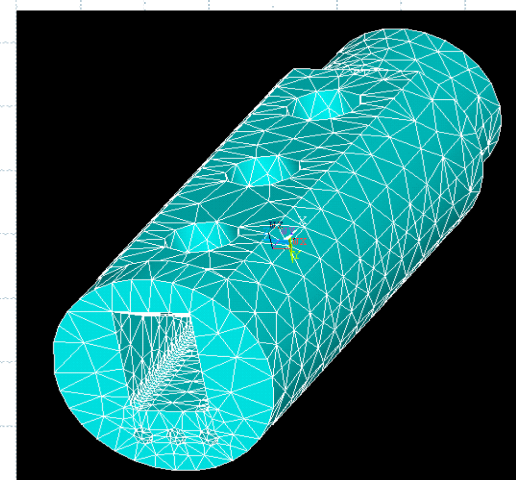
M9-30



M9-30 3-D model

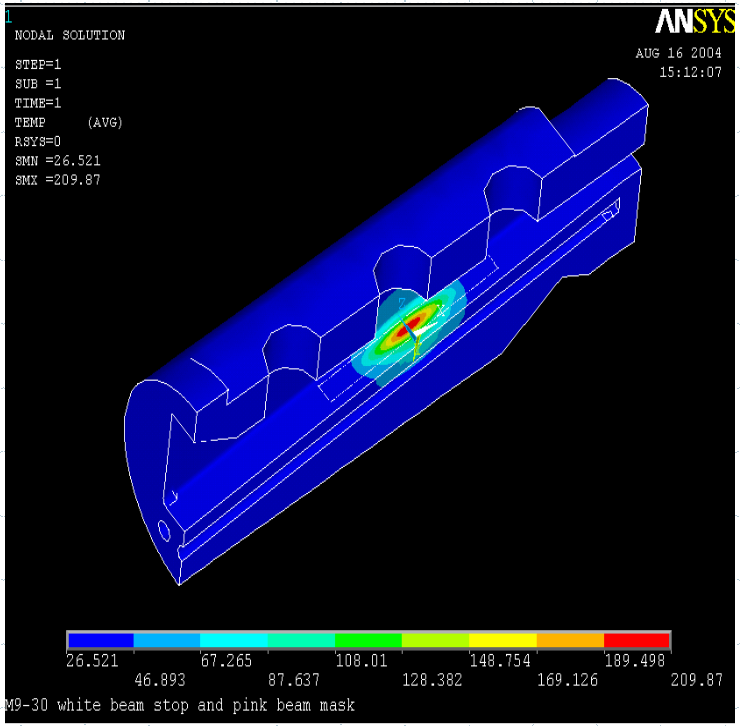


M9-30 Beam orientation

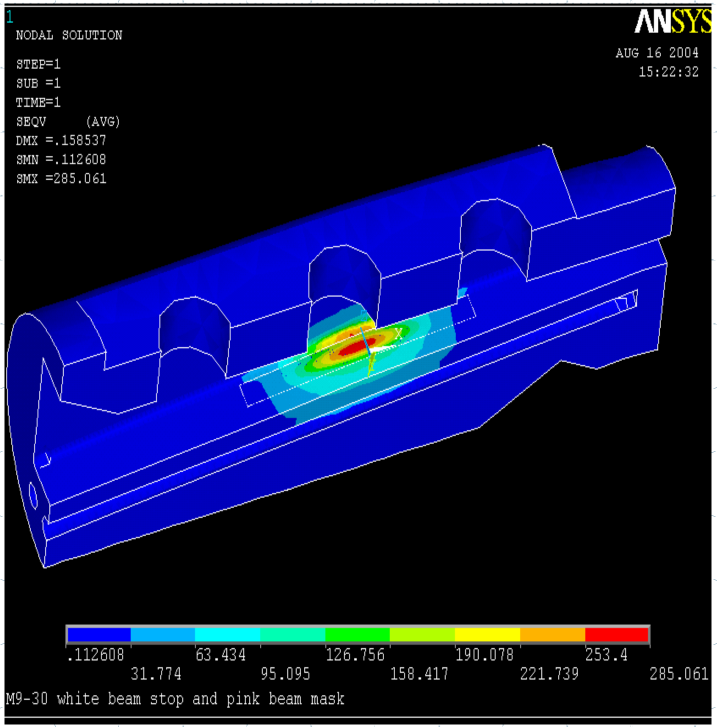


M9-30 FEA mesh

Results-contour plots for M9-30

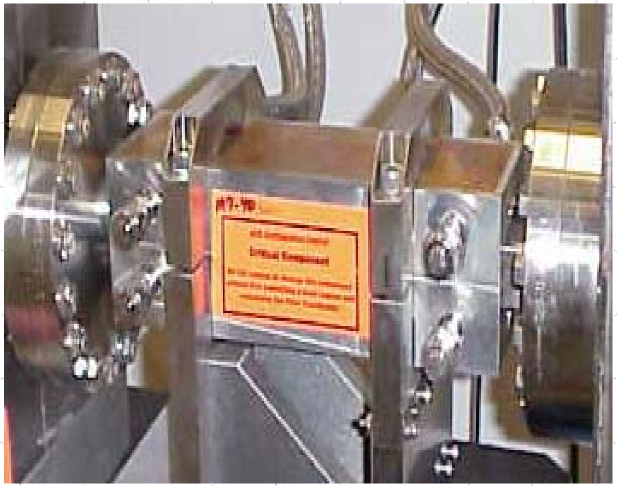


M9-30: Temperature distribution

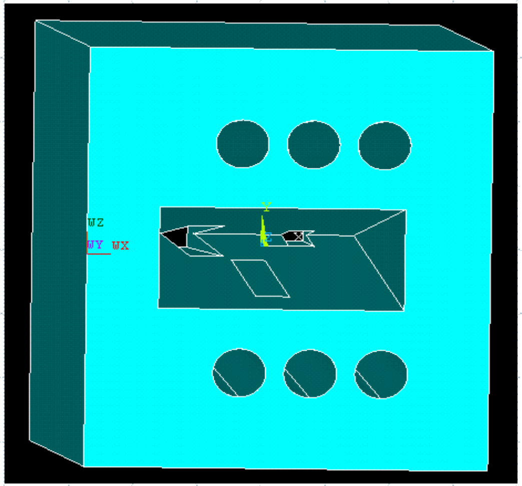


M9-30: von Mises stress distribution

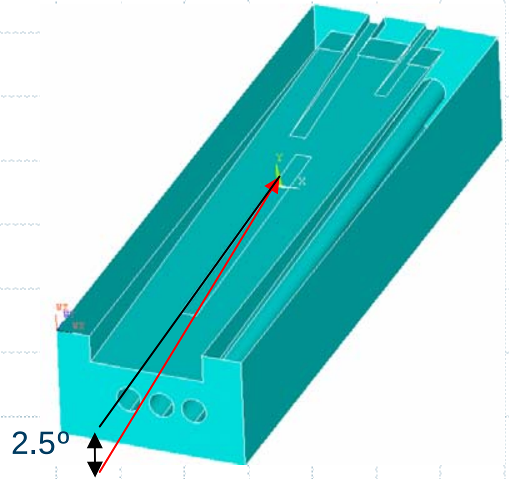
M7-40: Mask



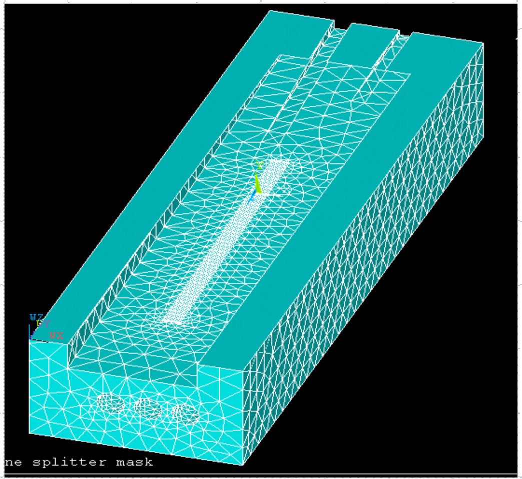
M7-40



M7-40 3-D model

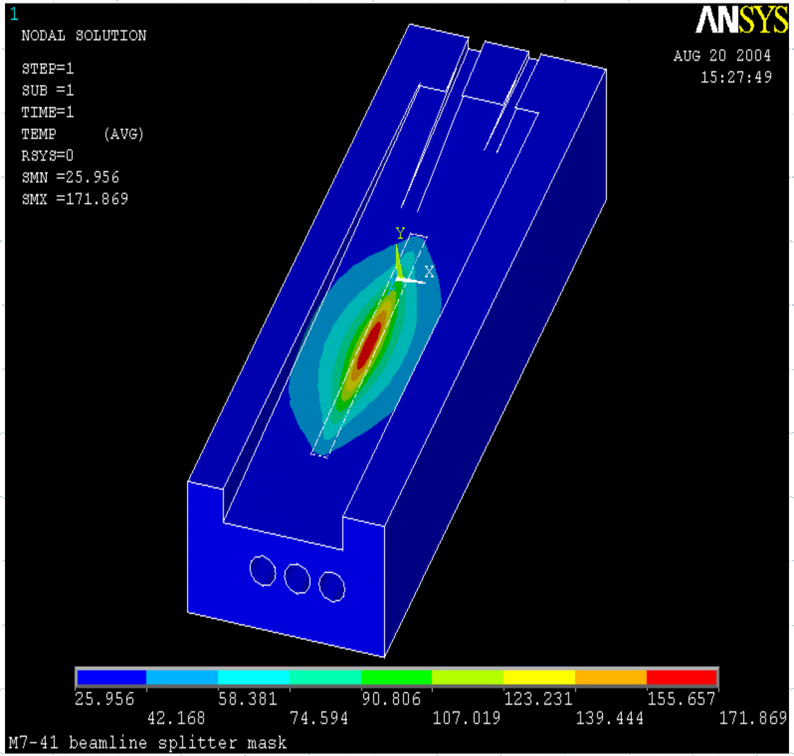


M7-40 Beam orientation

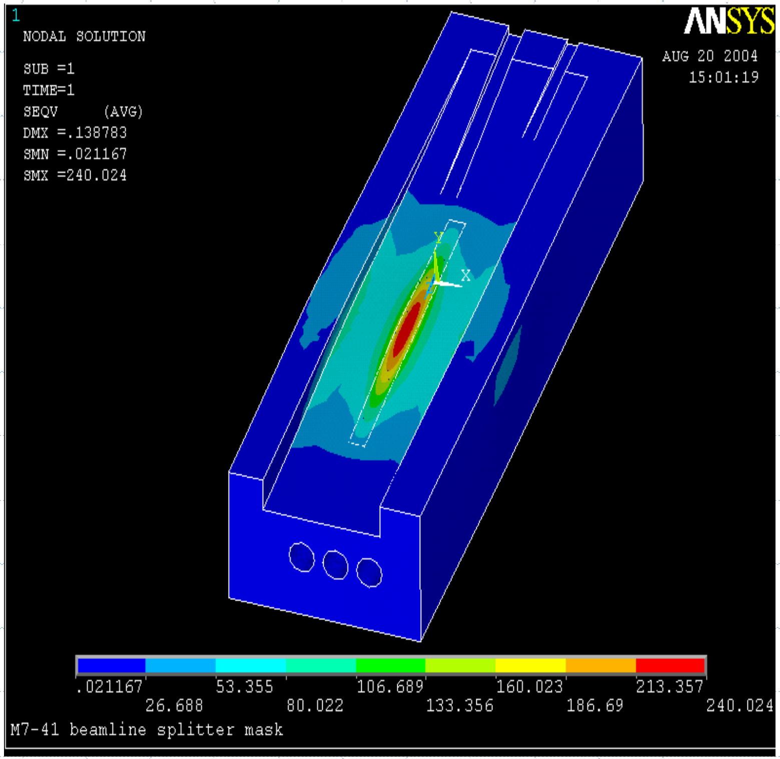


M7-40 FEA mesh

Results-contour plots for M7-40

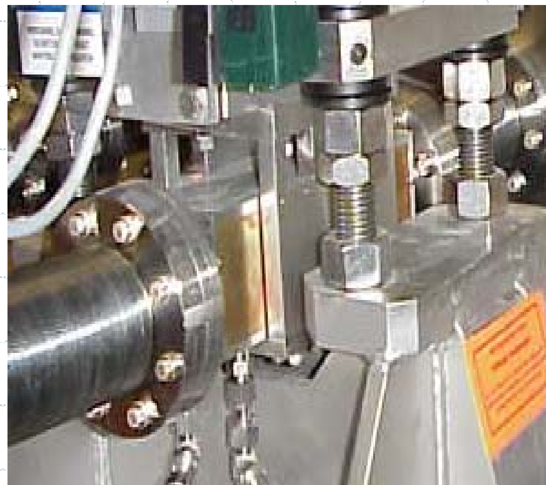


M7-40: Temperature Contours

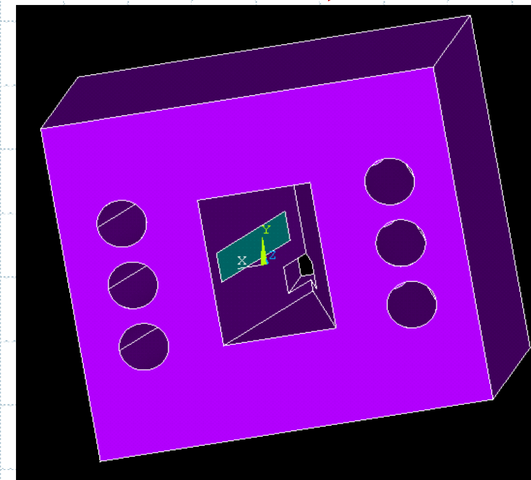


M7-40: von Mises stress Contours

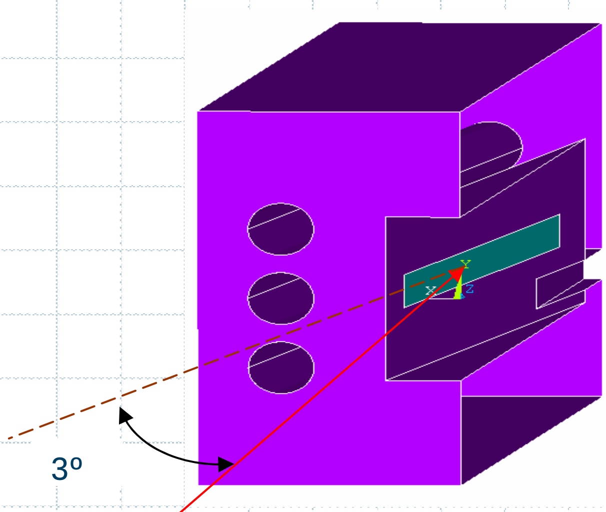
P4-30: Shutter



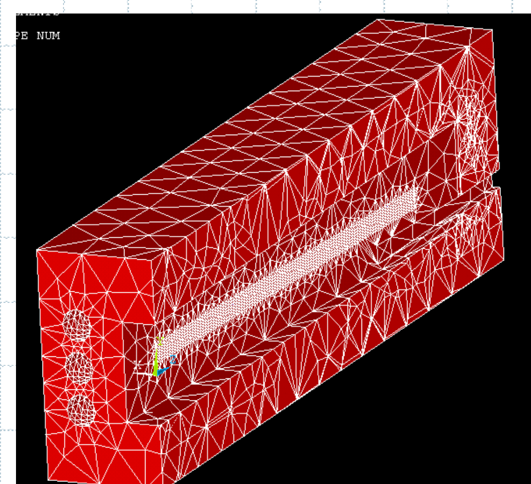
P4-30



P4-30 3-D model

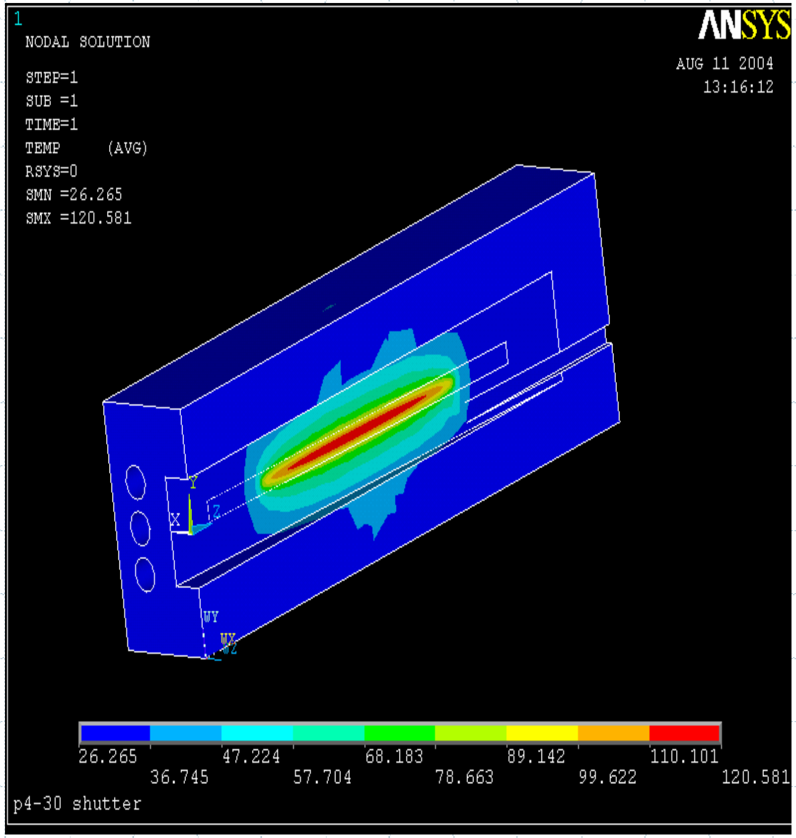


P4-30 Beam orientation

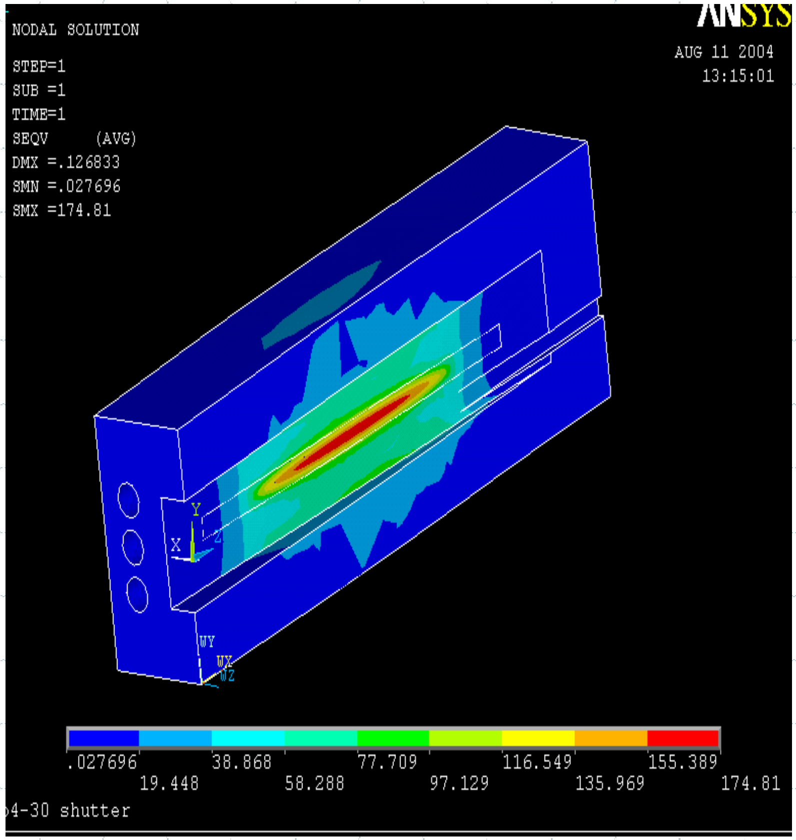


P4-30 FEA mesh

Results-contour plots for P4-30

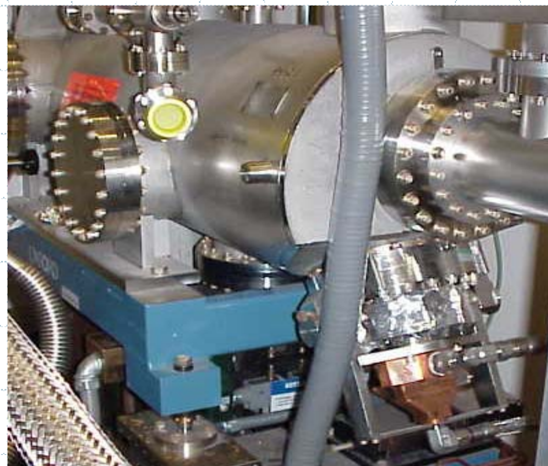


P4-30: Temperature Contours

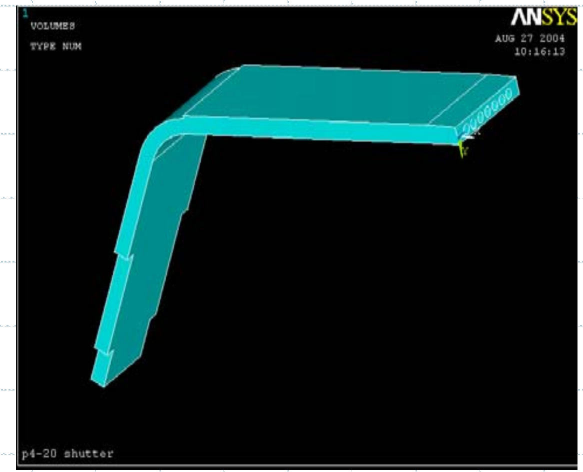


P4-30: von Mises Stress Contours

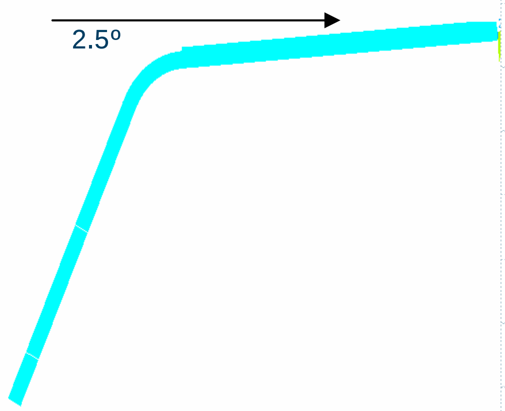
P4-20: Shutter



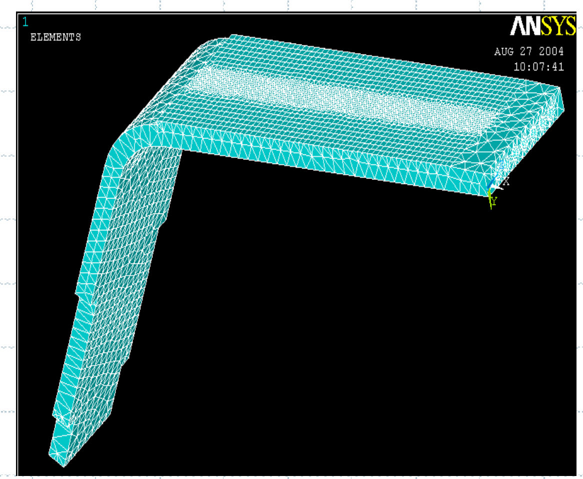
P4-20



P4-20 3-D model

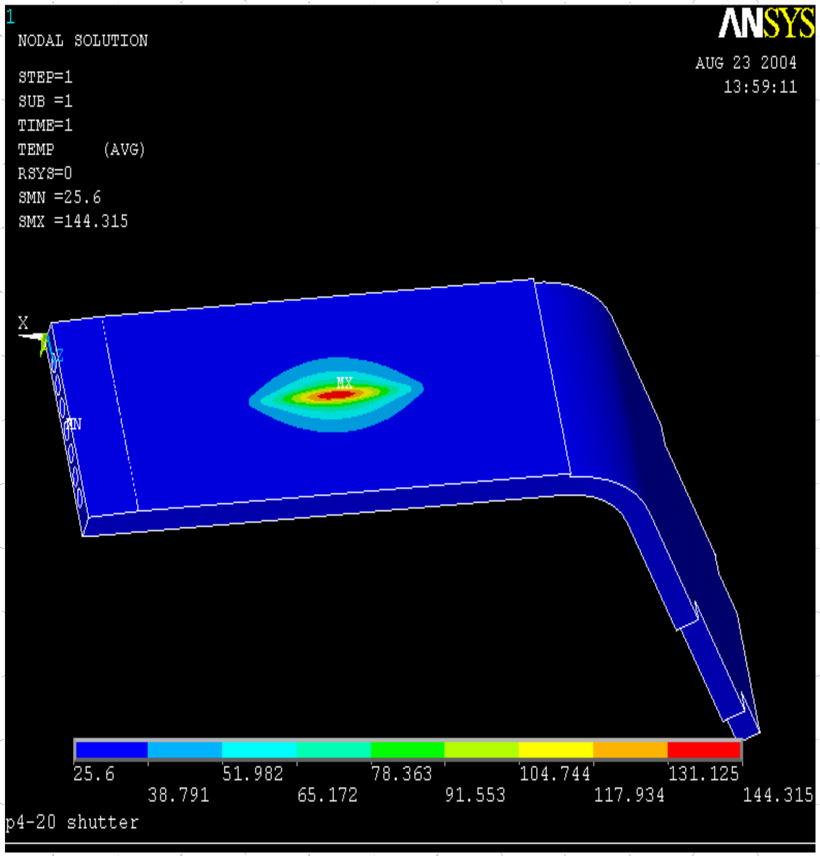


P4-20 Beam orientation

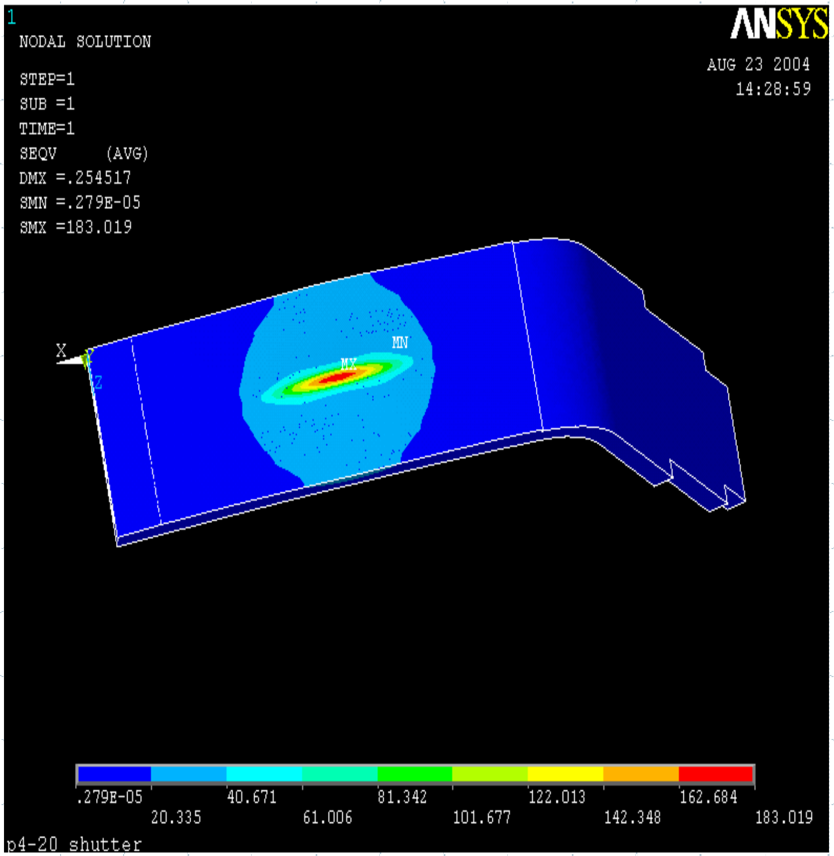


P4-20 FEA mesh

Results-contour plots for P4-20

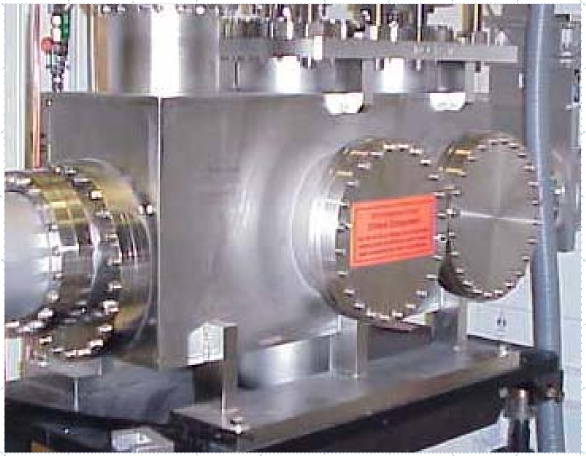


P4-20: Temperature Contours

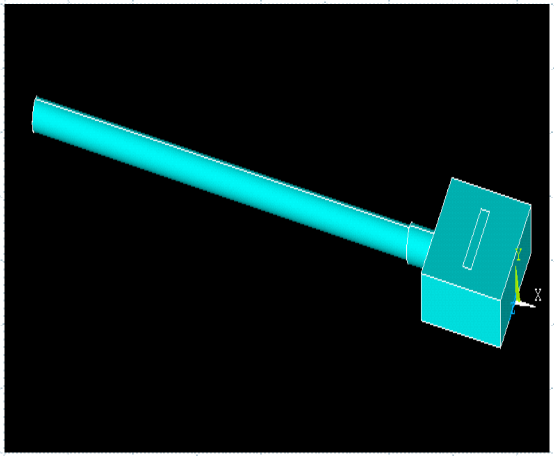


P4-20: von Mises Stress Contours

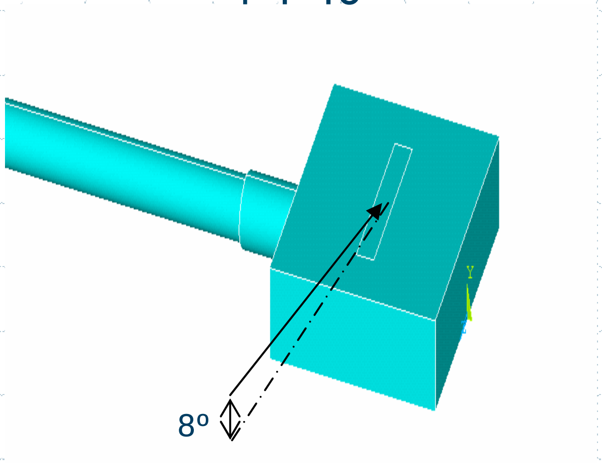
P4-40: Shutter



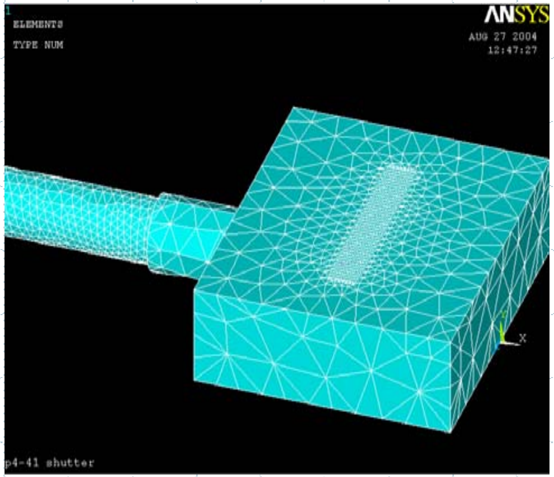
P4-40



P4-40 3-D model

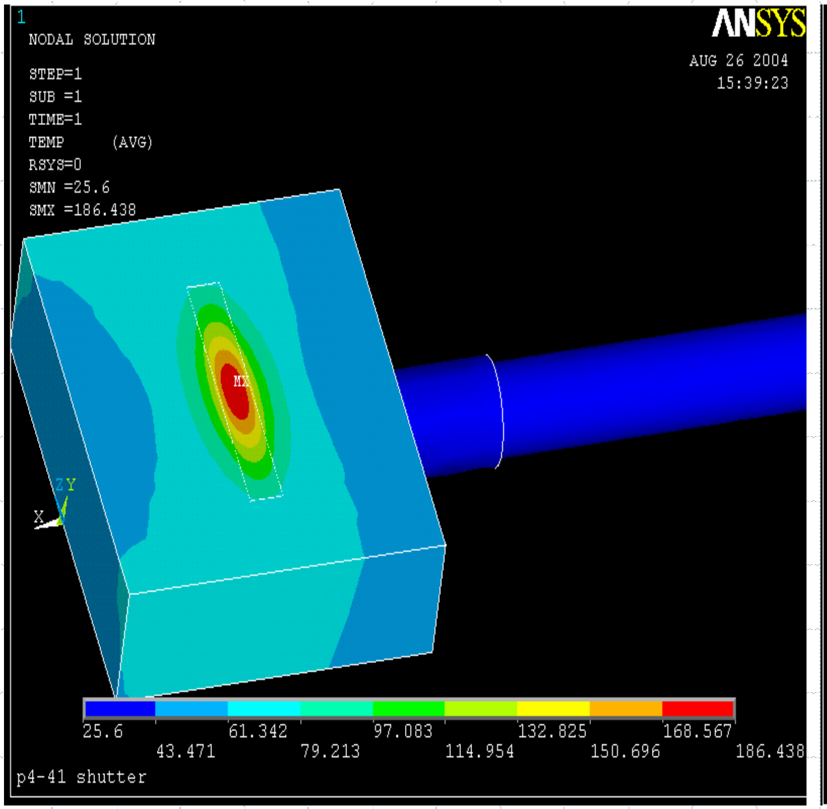


P4-40 Beam orientation

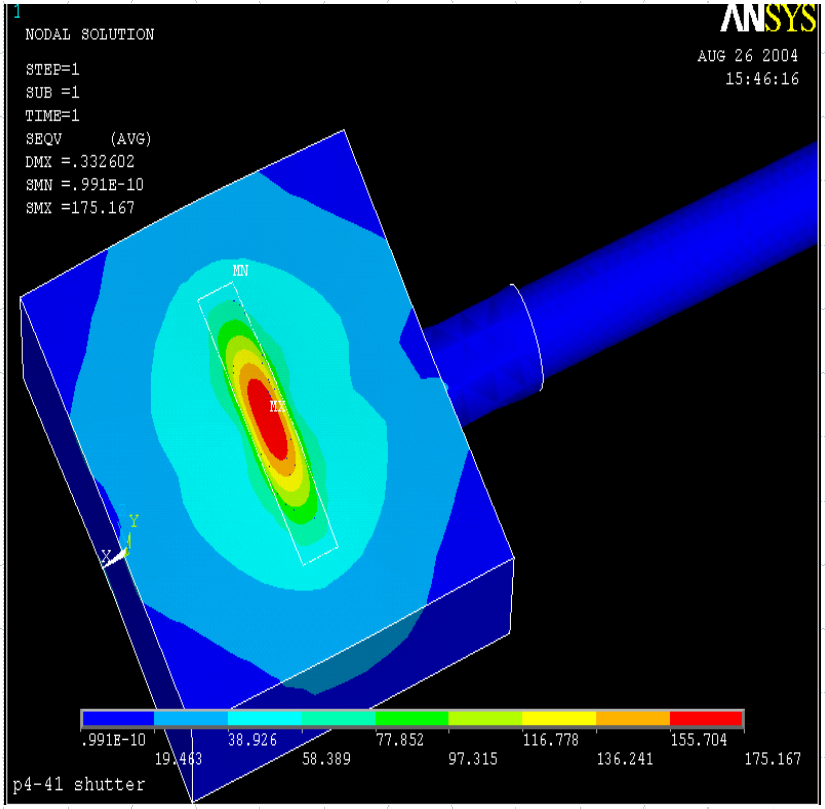


P4-40 FEA mesh

Results-contour plots for P4-40

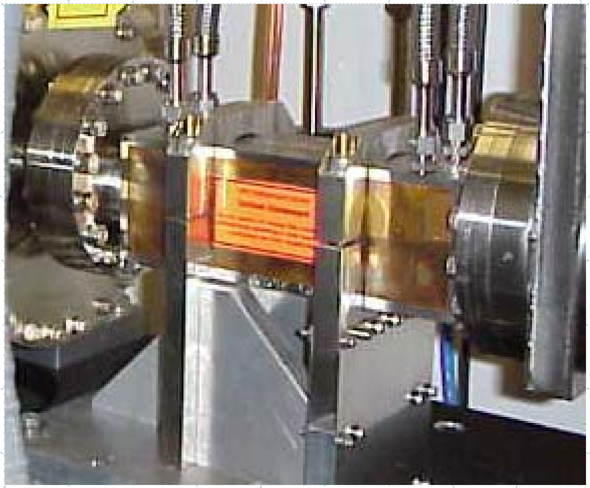


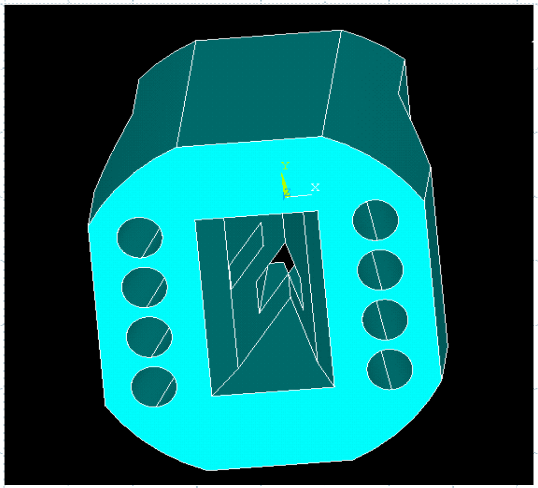
P4-40: Temperature Contours

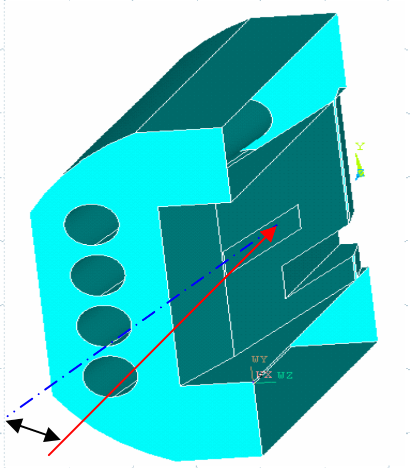


P4-40: von Mises stress Contours

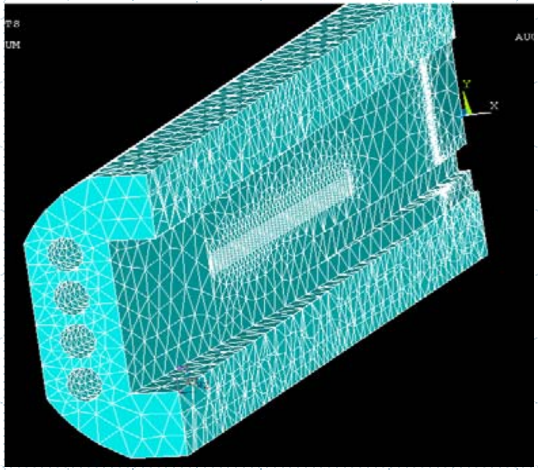
P4-50 Shutter


P4-50

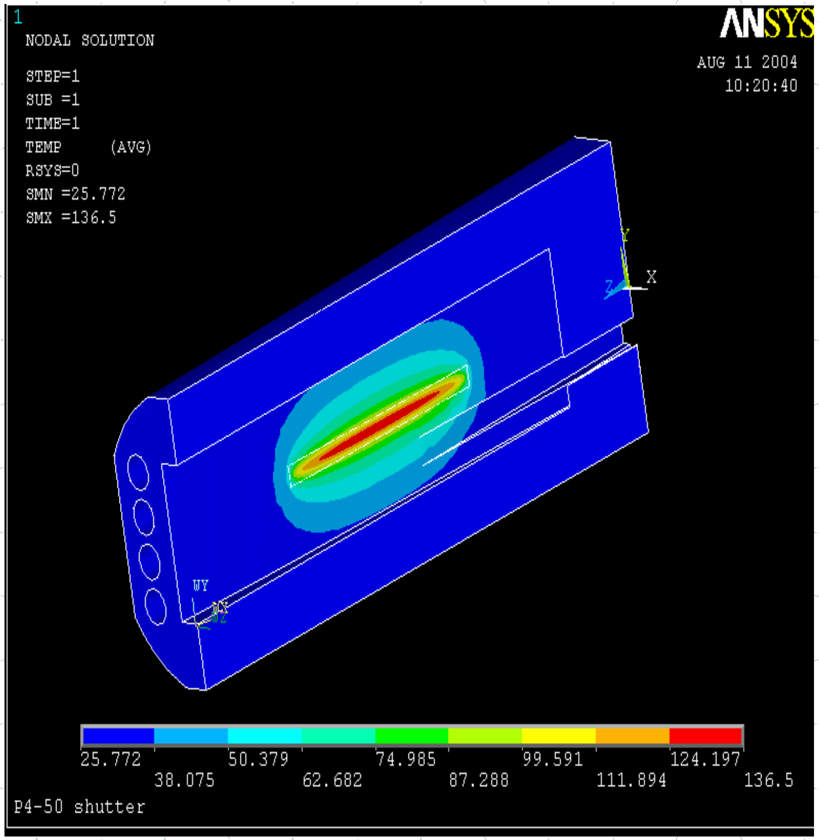

P4-50 3-D model



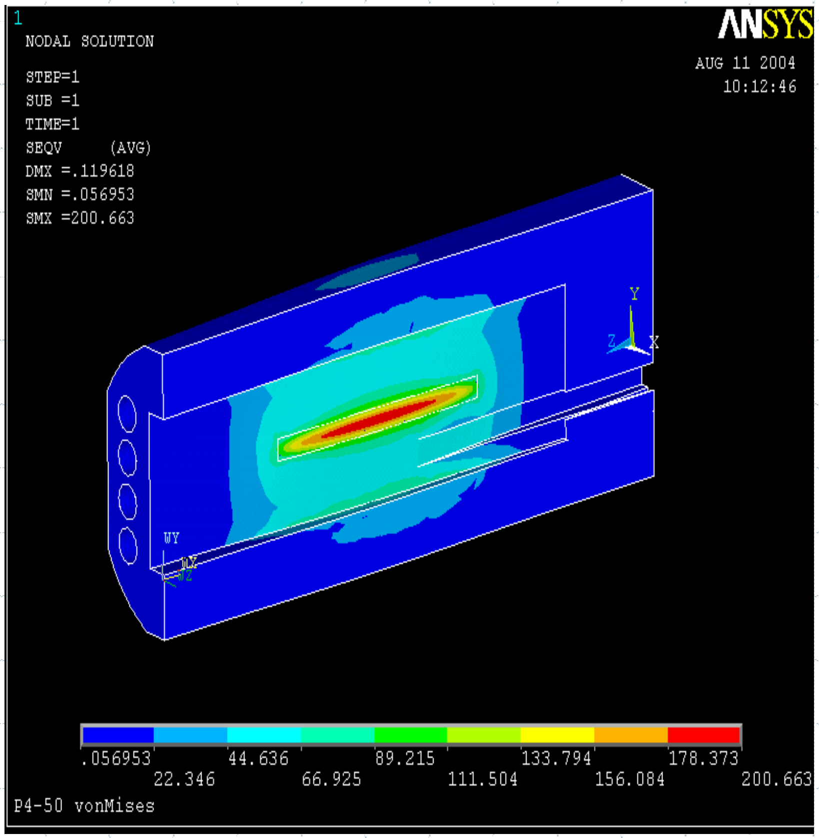
P4-50 Beam orientation


P4-50 FEA mesh

Results-contour plots for P4-50



P4-50: Temperature Contours



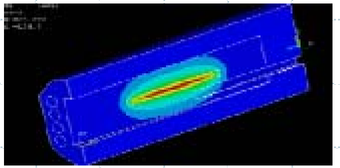
P4-50: von Mises Stress Contours

Results

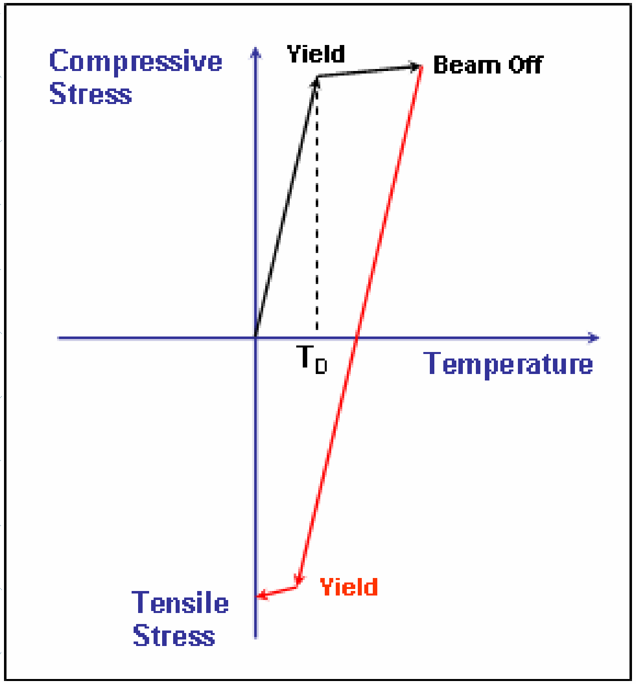
Components	Temperature (°C)	von Mises Stess (MPa)	Channel Wall Temperature (°C)
Masks			
L5-83 front end exit mask	195	378	98
*M4-30 front end exit mask	96	151	55
*M4-40 front end exit mask	178	350	68
*M7-20 front end exit mask	156	274	68
M7-41 beamline splitter mask	172	240	73
M9-30 white beam stop and pink beam mask	210	285	80
Shutters			
P5 Integral Shutter	238	280	95
P4-20 shutter	144	183	84
P4-30 shutter	121	175	57
P4-41 white beam stop	186	175	94
P4-50 shutter	137	201	62
K5-50 white beam stop	175	312	135

Goal II: Fatigue Design Criteria

Linear elastic Analyses are not useful in determining beam current limit or for predicting fatigue life.



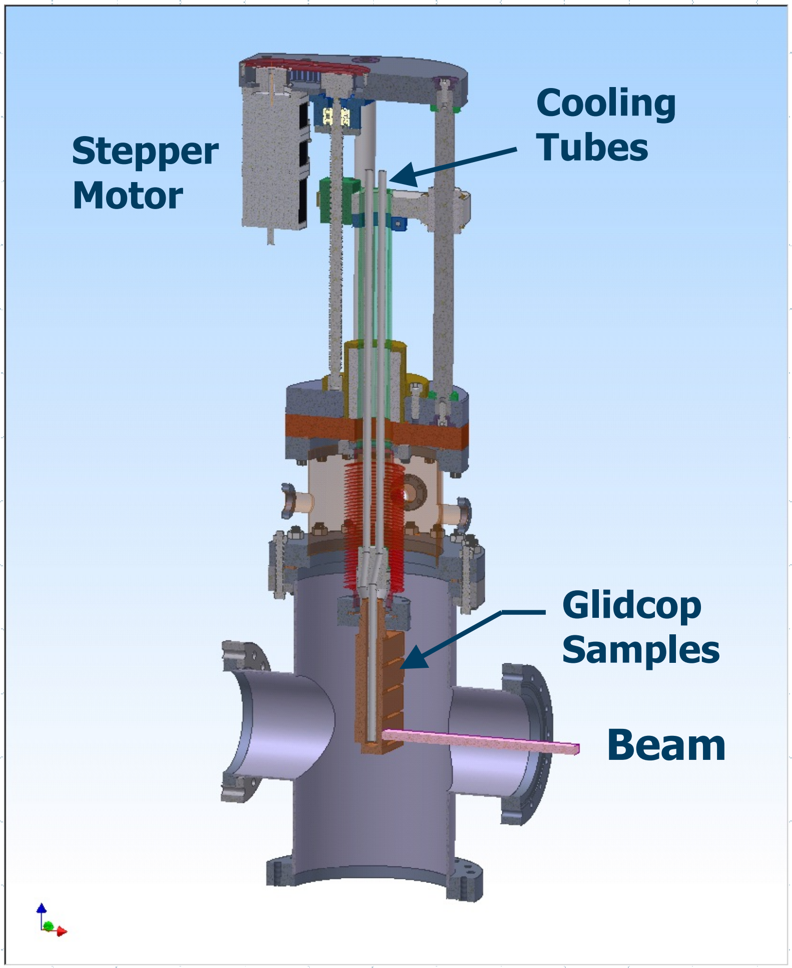
- **Thermal stresses are generally compressive.**
- **Tensile stresses cause cracks and fatigue failure.**
- **Temperatures higher than T_D will cause yielding.**
- **Compressive plastic deformation will cause tensile stresses on unloading (beam off).**



- **A fatigue design committee was appointed:**

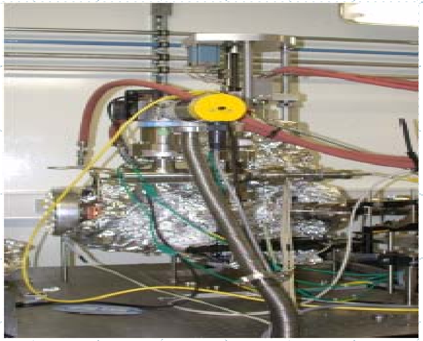
Professor Michael Gosz (IIT), Yifei Jaski (XFD), Dr. Saurin Majumdar (ET-ANL)
Sushil Sharma (ASD, Chair), Dr. Lin Zhang (ESRF)
(new members, Carlos Segre, Dean Haeffner ?)

Fatigue Tests at ESRF



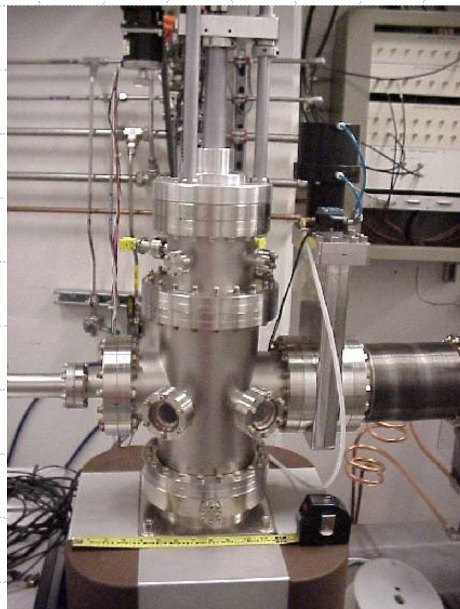
Test Setup (ME-ASD)

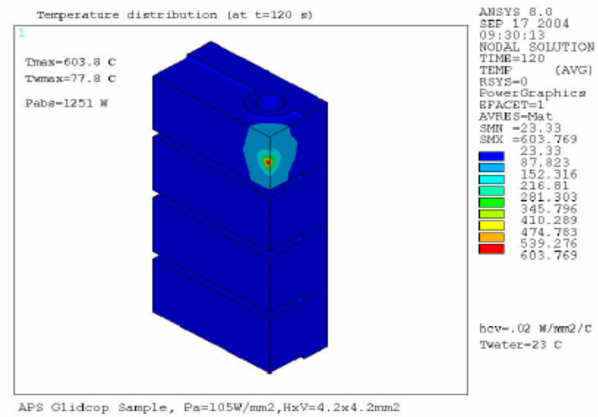
Beamline Hutch



- Two U42 and one U34 undulators
- P = 105 W/mm² (200 mA, 73 % absorption)
- Beam size = 4.2mm x 4.2mm
- Total absorbed power = 1251 W
- Max. Temperature = 604 ⁰C

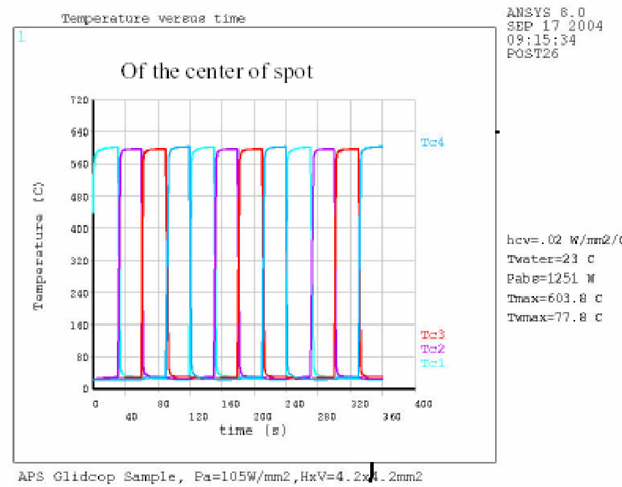
Fatigue Tests at ESRF – **Temperature Cycles**





APS Glidcop Sample, Pa=105W/mm2,HxV=4.2x4.2mm2

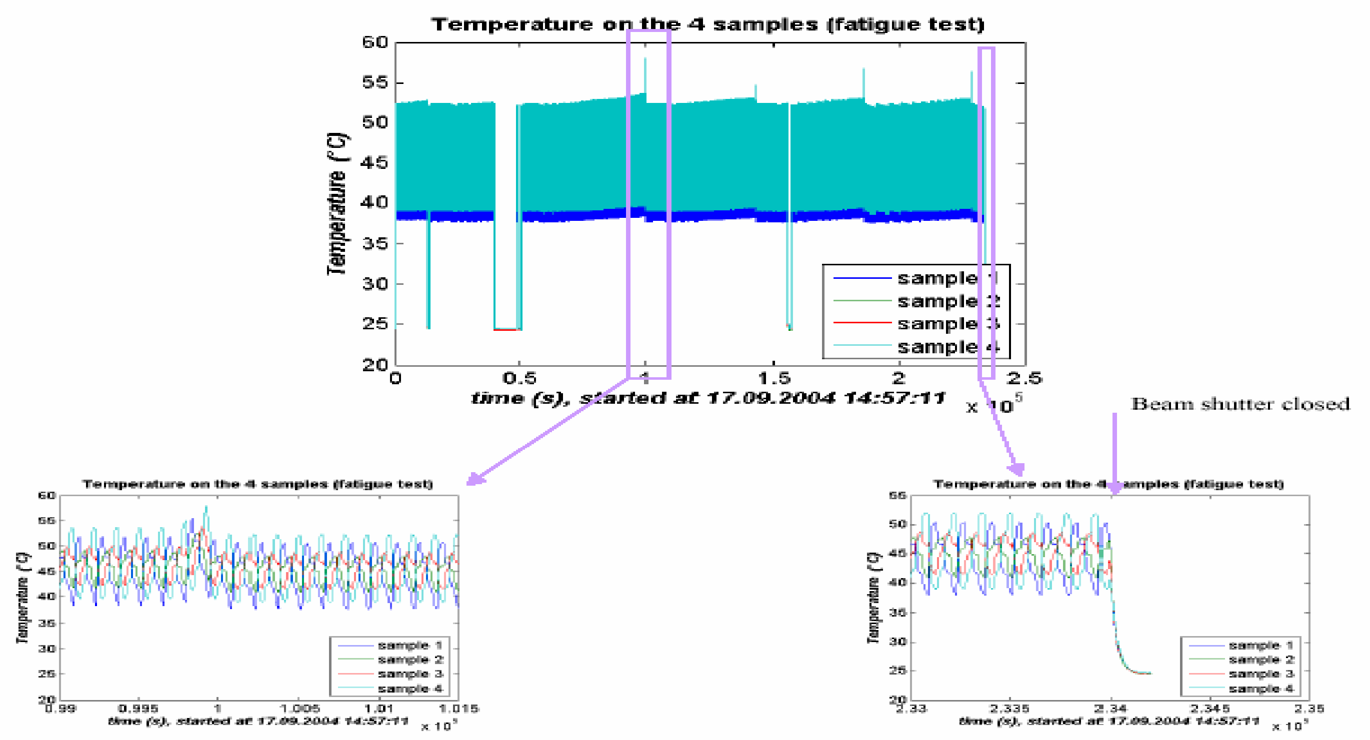
Thermal Analysis



A sapphire window will allow IR imaging of the beam footprint.

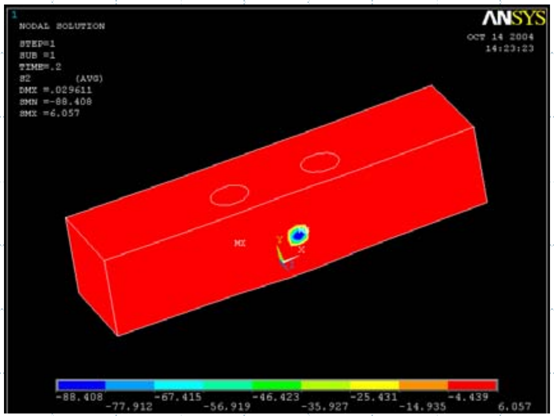
Temperatures were monitored with thermocouples attached at the sides of the samples.

Fatigue Tests at ESRF – **Temperature Cycles**

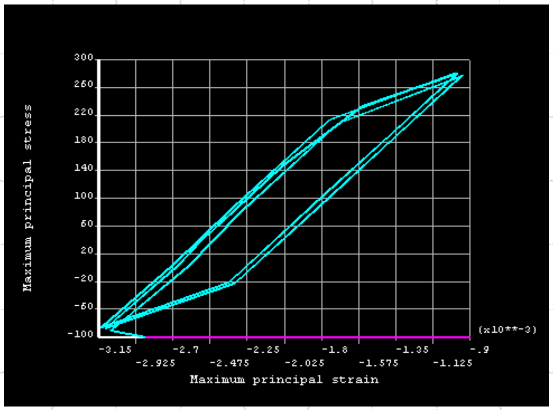


- **No change in vacuum pressure after 3,755 cycles.**
- **Peak temperature of ~ 600 ºC at the center of beam footprint.**
- **Testing will continue in November for up to 10,000 cycles.**
- **An IR camera will be used for imaging thermal contours.**
- **Surface analysis of the samples will be performed.**

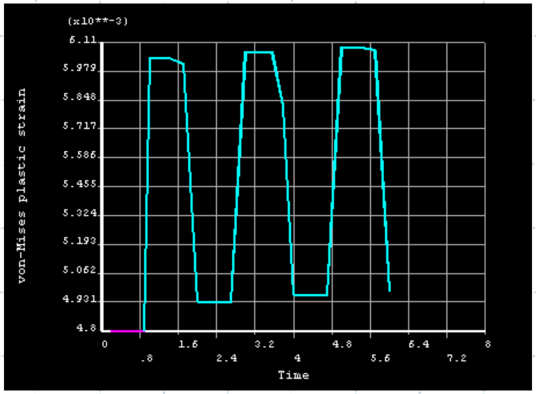
Fatigue Tests: Preliminary Thermal, Elastic-Plastic Analyses



Temperature Contours



Stress – Strain Cycles



Plastic Strain vs Time

- **Thermal and Elastic-Plastic analyses are being performed both at APS and ESRF.**
- **Strain amplitude can be obtained from strain vs time graph.**
- **Fatigue life can be estimated by a simplified Coffin-Manson approach:**

$$\Delta\varepsilon / 2 = \varepsilon_f' (2N_f)^c$$

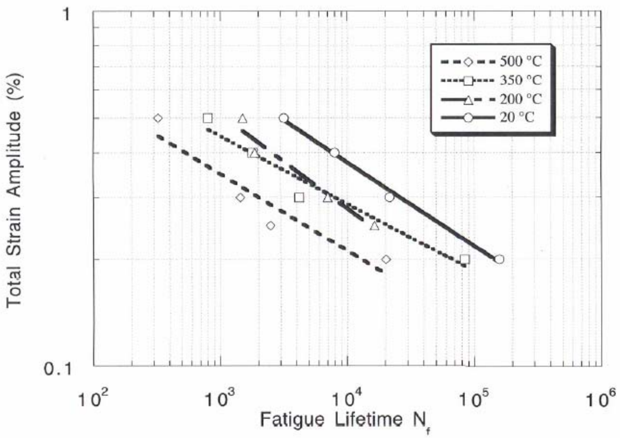
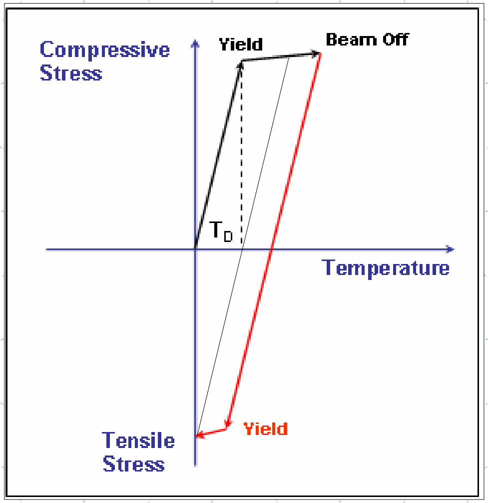


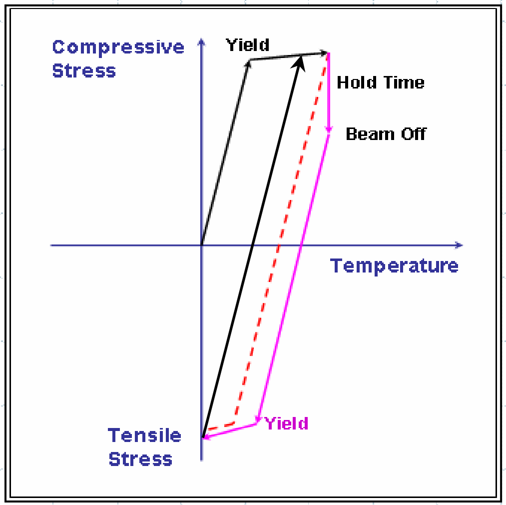
Fig. 8(a)

Li et al. , Metallurgical and Materials Trans. Vol. 31A (10), 2000

Fatigue Tests – Hold-Time (Stress Relaxation) Effect



Fatigue Test Cycles



Operational Cycles

- **Hold-time (creep) effect may lead to higher tensile stresses.**
- **Further testing and analysis will be undertaken to determine this effect.**

Fatigue Tests – Effect of Initial Yield Strength

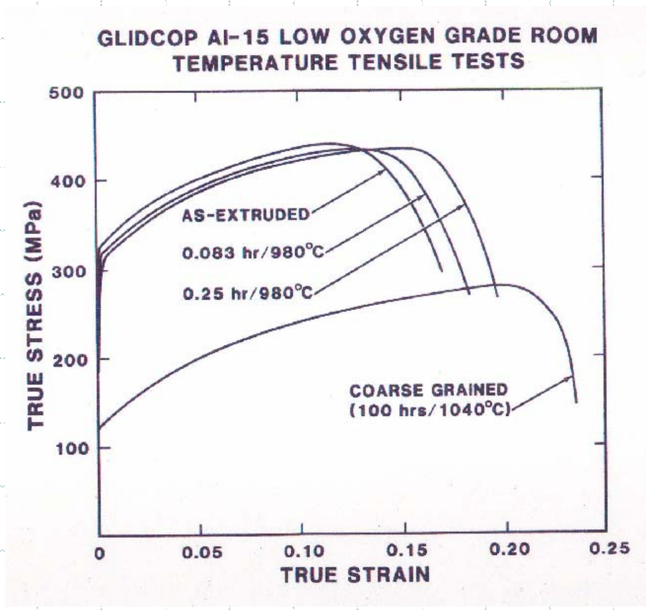


Fig. 5

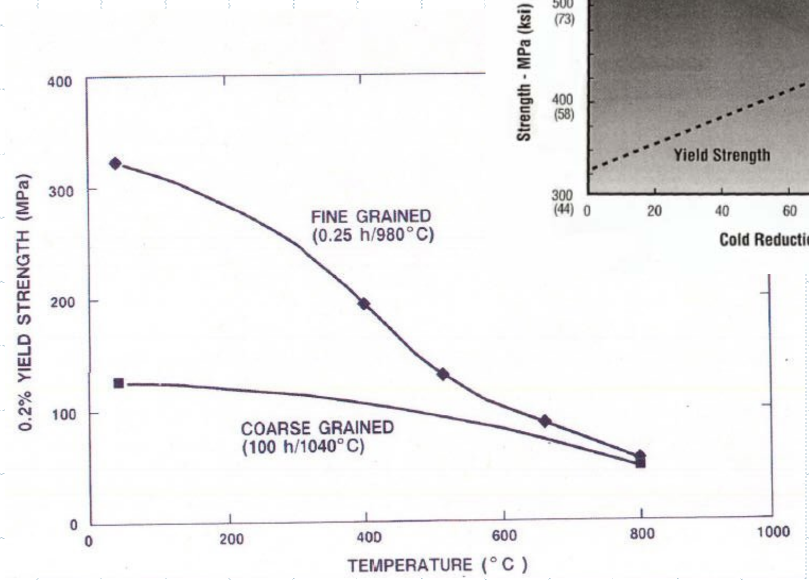
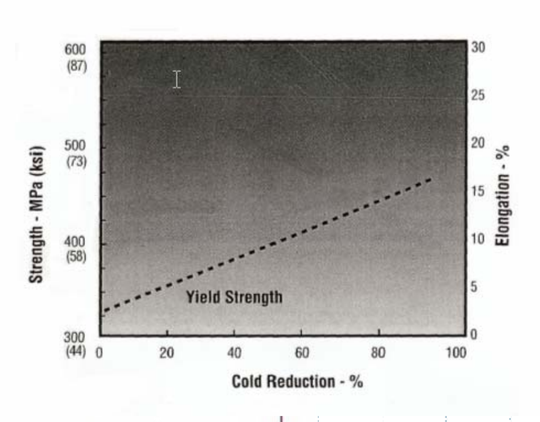


Fig. 20



"Comparison of strain rate: flow stress at 800 °C for the fine-grained, braze cycled material with coarse-grained, long term (100 hr. at 1040 °C) material, Figure 23, indicates that the coarse grained material is significantly stronger than the fine grained material. "

J. J. Stephens et al. SAND88 – 1351 (1988), pp. 15

Summary

- **Thermal analyses of beamline components identified by M. Ramanathan have been completed.**
- **Results show that conservative design criteria are met (with some exceptions, e.g. K5-50) for a beam current of ~ 140 mA.**
- **Fatigue tests (ongoing at ESRF) show that a maximum temperature limit of ~ 600 °C may be acceptable for a few thousand temperature cycles.**
- **High current runs of short durations appear to pose little risk (assuming no damage to Glidcop samples under fatigue testing at ESRF).**
- **Further fatigue tests and elastic-plastic analyses are planned to:**

  (1) Correlate experimental and analytical data at different maximum temperatures.

  (2) Evaluate the effects of other factors such as stress relaxation and initial yield stress.