Northern Illinois University

DESIGN AND MECHANICAL STABILITY ANALYSIS OF THE INTERACTION REGION FOR THE INVERSE COMPTON SCATTERING GAMMA-RAY SOURCE USING FINITE ELEMENT METHOD

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Thesis defense

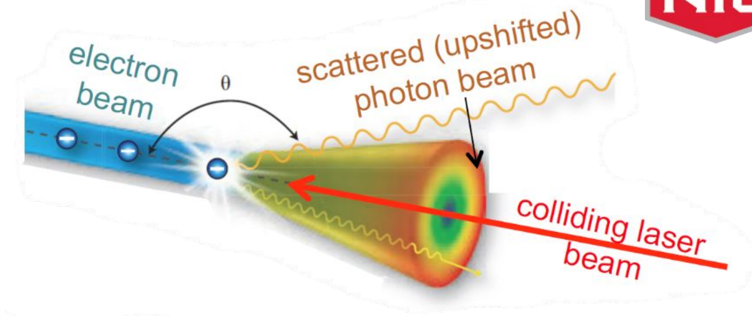
7/5/2017

Contents

- Introduction
- Design
- Static analysis
- Modal analysis
- Harmonic analysis
- Conclusion

Introduction - ICS

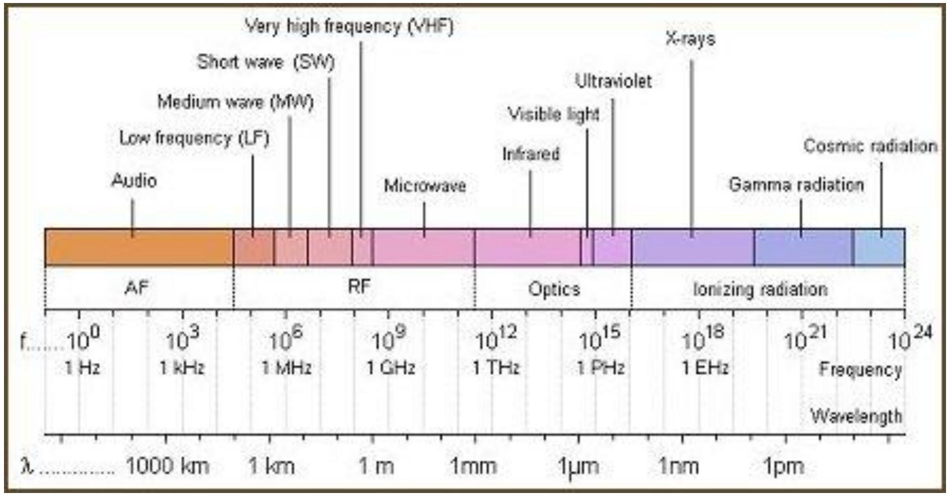
Inverse Compton Scattering – process of upshifting low frequency photons by colliding them with relativistic electron bunches. ICS is most effective in the head-on collision, when θ is close to 180°. Resulting radiation has a donut shape and 1/γ angle of propagation.



$$E_\gamma \approx 4\gamma^2 E_L$$

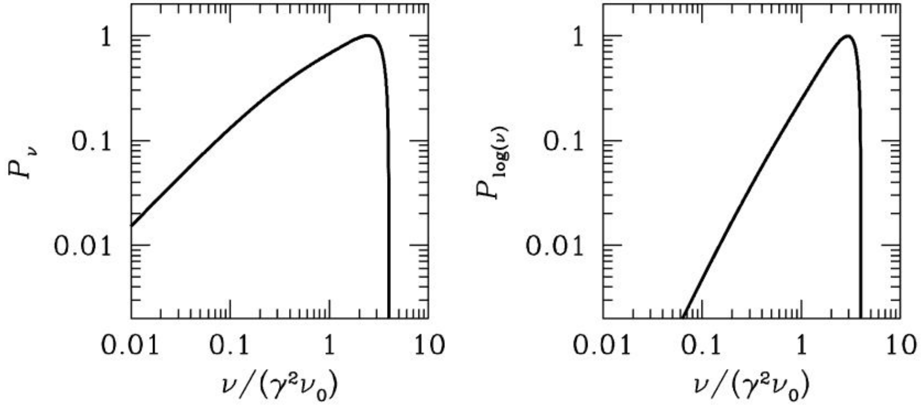
$$E_\gamma = h\nu$$

γ - Lorentz factor
h - Plank constant
E_γ - Energy of the upshifted photon
E_L - Initial energy of the photon
ν - Frequency of the upshifted photon



1 MeV = 2.42 x 10^{20} Hz

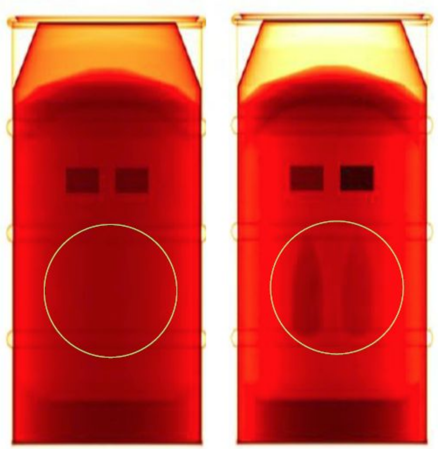
Introduction - ICS



The Inverse Compton spectrum of electrons with energy γ irradiated by photons of frequency ν_o. The log-log plot of power per logarithmic frequency range (right) more accurately shows how peaked the spectrum is. This explains why X and γ radiation generated by ICS has a relatively high *Brilliance*.

$$\text{brilliance} = \frac{\text{photons}}{\text{second} \cdot \text{mrad}^2 \cdot \text{mm}^2 \cdot 0.1\%\ \text{BW}}$$

Monte-Carlos simulation of γ-ray imaging using two different γ-ray sources



2 MeV Bremsstrahlung gamma rays

1.7 MeV Laser Compton gamma rays

Gamma rays produced by ICS are monoenergetic with small relative bandwidth (below 1 %) and offer high photon flux. Finally, they do not include the interaction with any solid target and therefore are in principle scalable to high repetition rate as no heat management is involved.

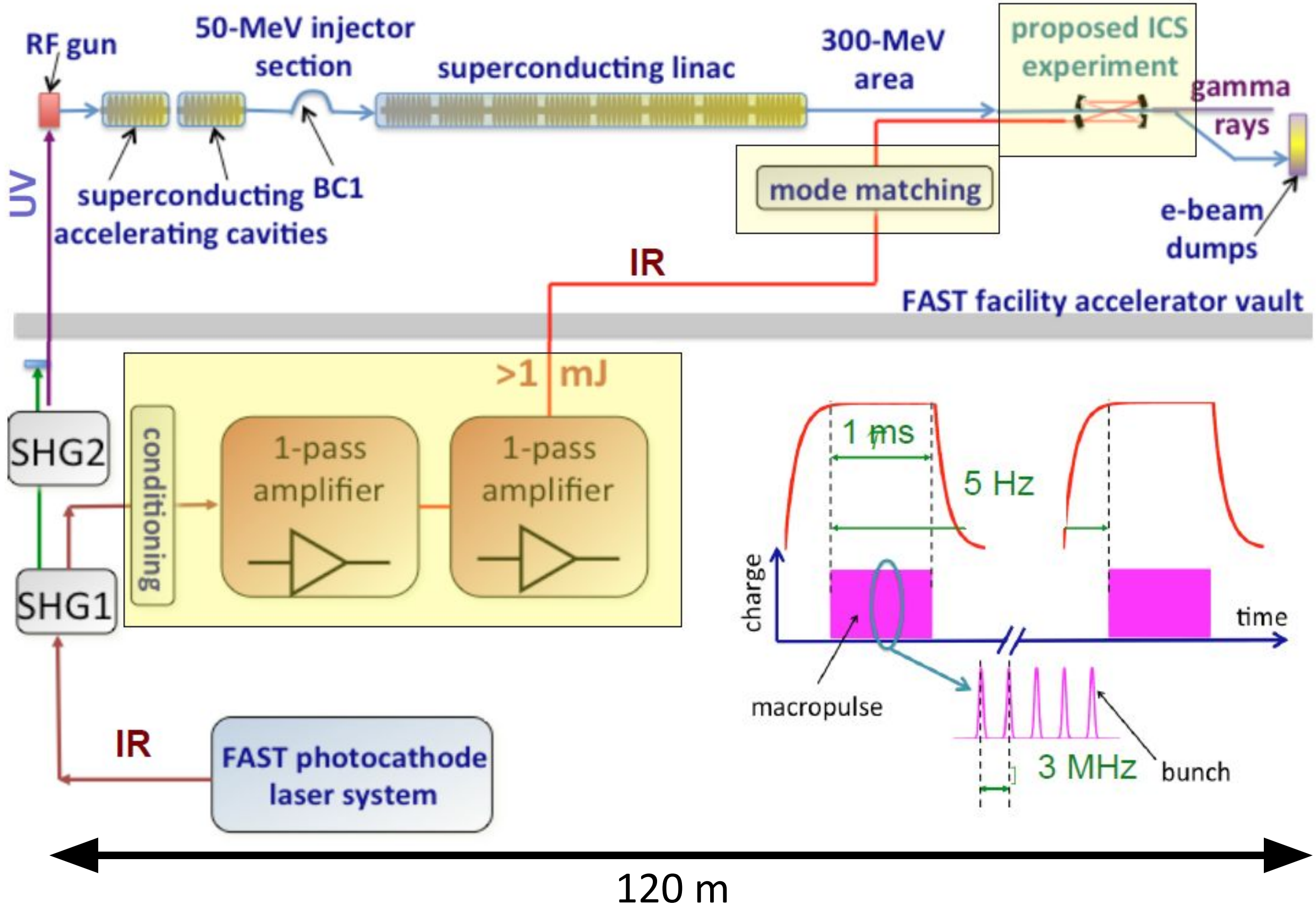
Image from C. Barty, LLNL, 2008

Introduction - Applications

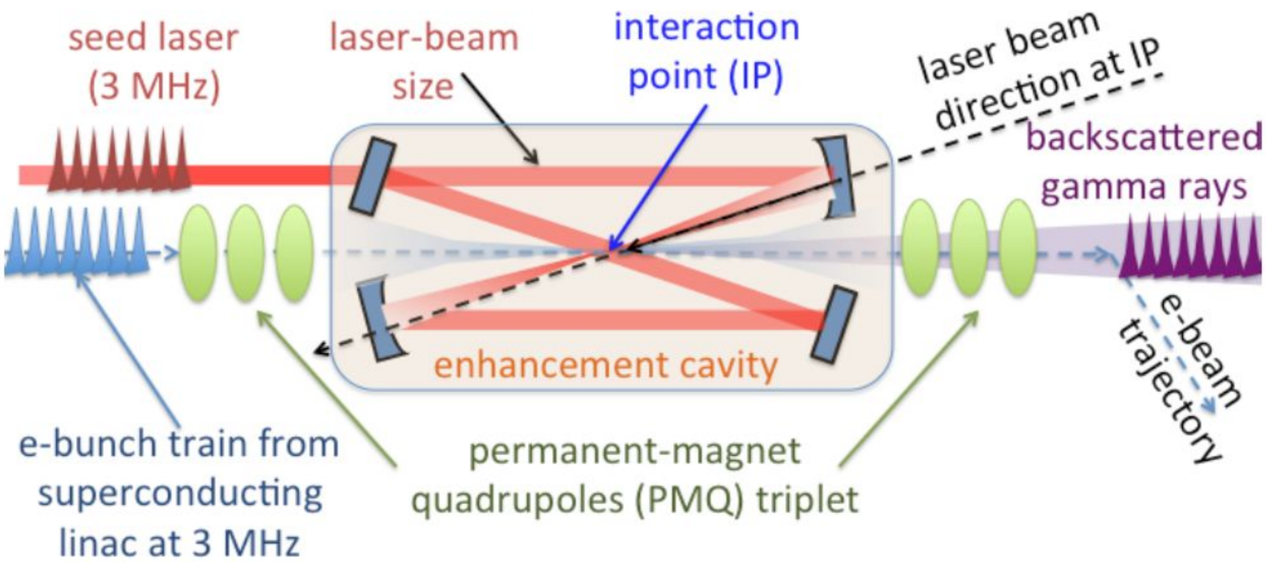
- Standoff inspection
- Nuclear element detection
- Oncology
- Nuclear astrophysics
- Nuclear medicine

Domestic Nuclear Detection Office

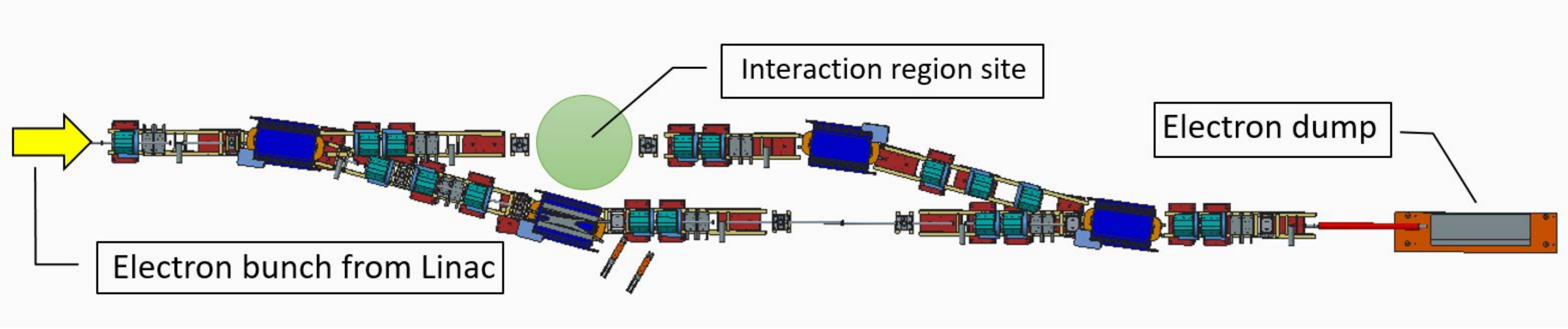
Introduction - FAST



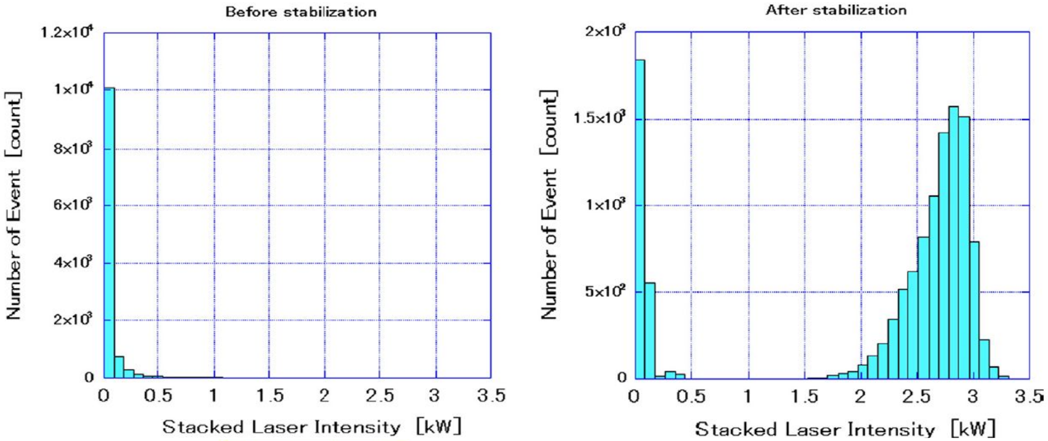
Introduction - Interaction region



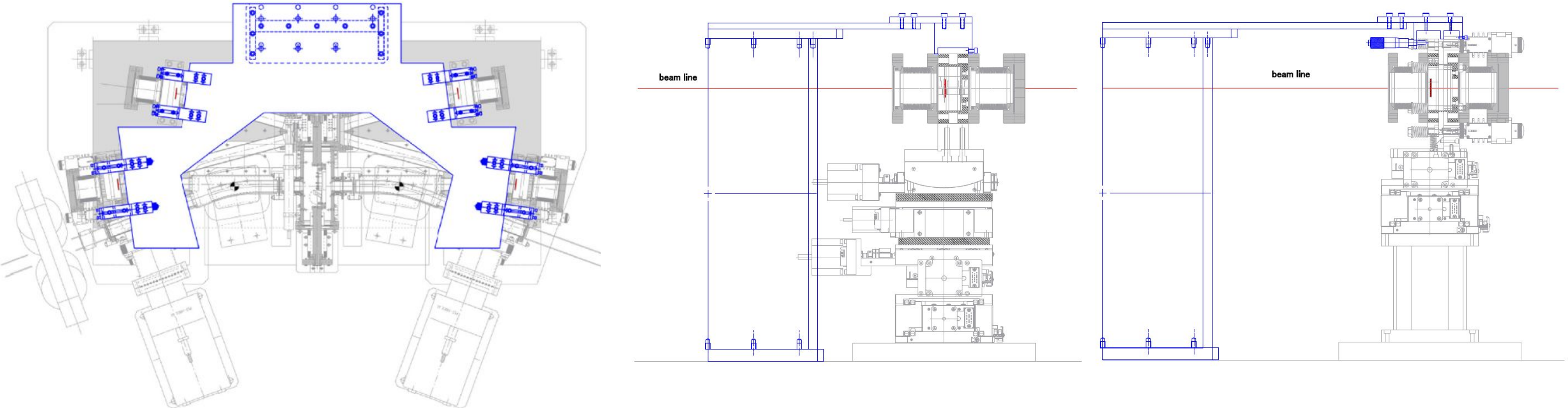
Concept of the interaction region



Introduction - Main challenge



Histograms of the stacked laser intensity. Left – prior to the improvement of the stability, right – after the improvement

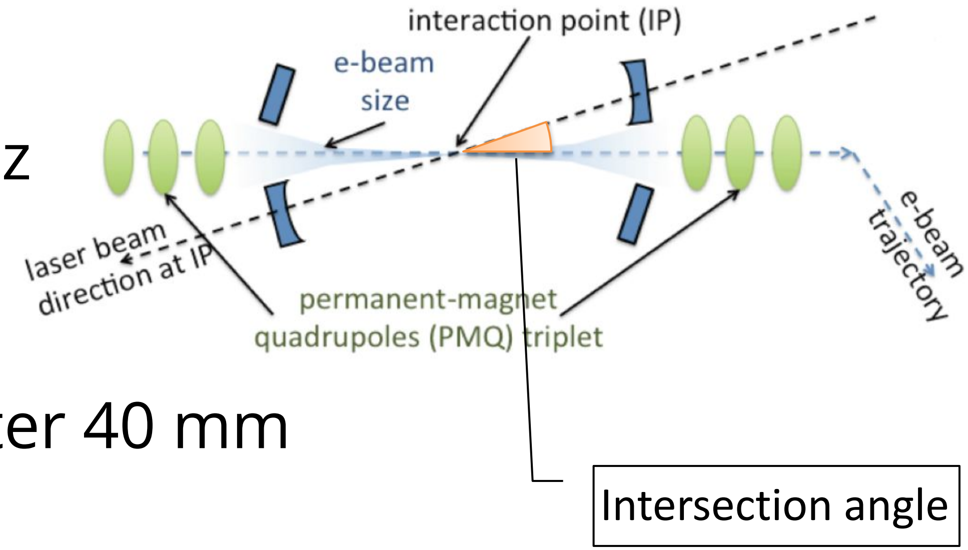


Hirotaka Shimizu - "Development of a 4-mirror optical cavity for an inverse Compton scattering experiment in the STF" KEK, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

Design - Objective

Cavity requirements:

- Recirculation cavity
- Target finesse > 1000
- Vacuum chamber
- Impulse frequency 3 MHz
- No bending magnets
- Intersection angle $\phi < 5°$
- Focusing magnet diameter 40 mm
- Setup length < 1.5 m
- Electron line height over the floor 1200 mm

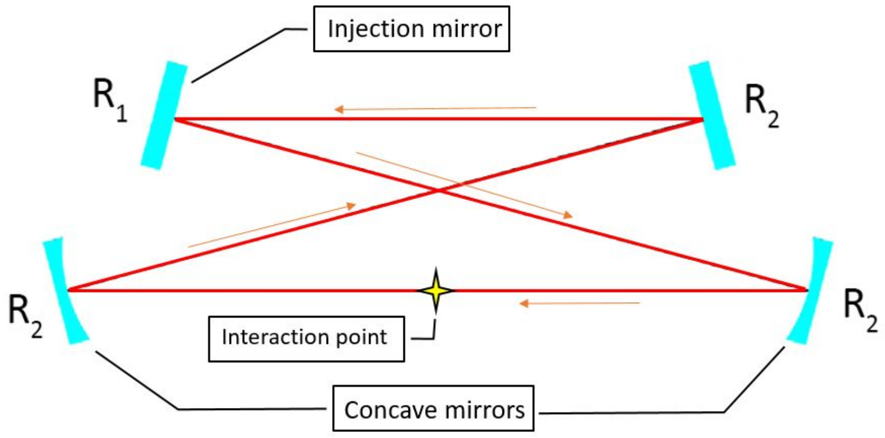


Design - Finesse

Finesse is a characteristic of oscillatory systems and resonators.

R_1 =99.9% (entrance mirror)

R_2 =99.995% (high reflectivity mirror)



Planar bow-tie optical setup (H. Shimizu)

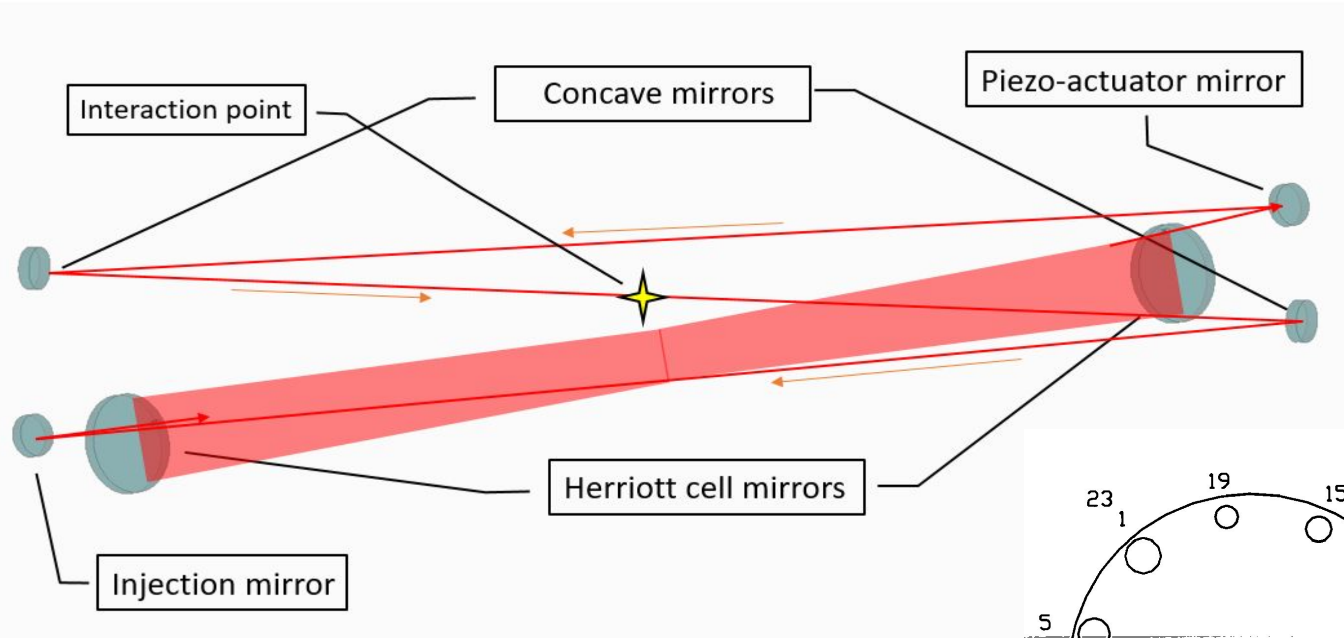
$$F = \frac{\pi \sqrt[4]{R_1 {R_2}^3}}{1 - \sqrt{R_1 {R_2}^3}}$$

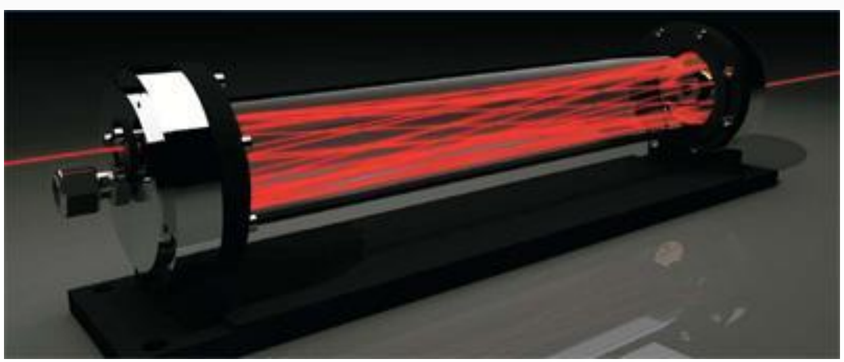
F ~ 5500 at ν matching the optical path length

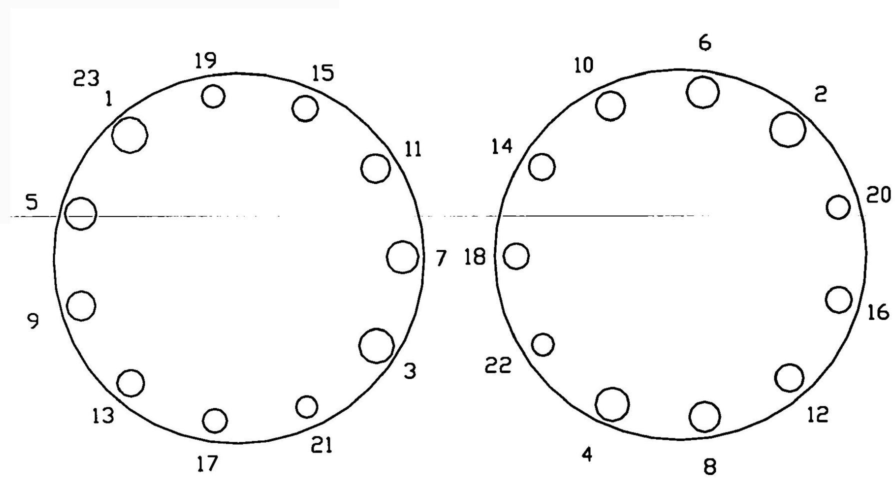
$$F = \frac{\pi \sqrt[4]{(R_1 {R_2}^3)^k}}{1 - \sqrt{(R_1 {R_2}^3)^k}}$$

F ~ 200 at *k*=27 (number of round trips)

Design - Herriott cell



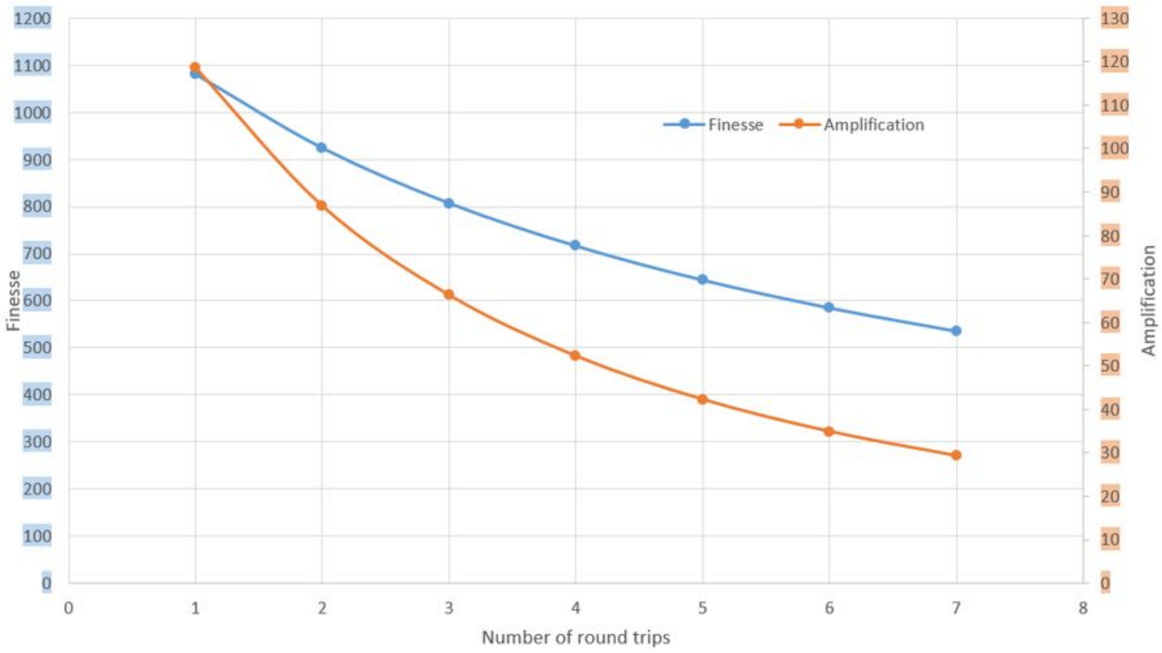




Francesco D'amato - "Variable length Herriott-type multipass cell", EP 1972922 A1

Design - Finesse and amplification estimates

Optical path length of one trip	100	50.0	33.3	25.0	20.0	16.7	14.3
k (number of round trips)	1	2	3	4	5	6	7
n (total reflection number)	93.3	45.0	28.9	20.8	16.0	12.8	10.5
a (optical amplitude loss)	0.99710	0.99661	0.99611	0.99562	0.99513	0.99464	0.99415
Finesse	1080	924	807	716	644	585	536
Finesse decrease %	0%	14%	25%	34%	40%	46%	50%
Amplification	119	87	66	52	42	35	29
Amplification decrease %	0%	27%	44%	56%	64%	71%	75%

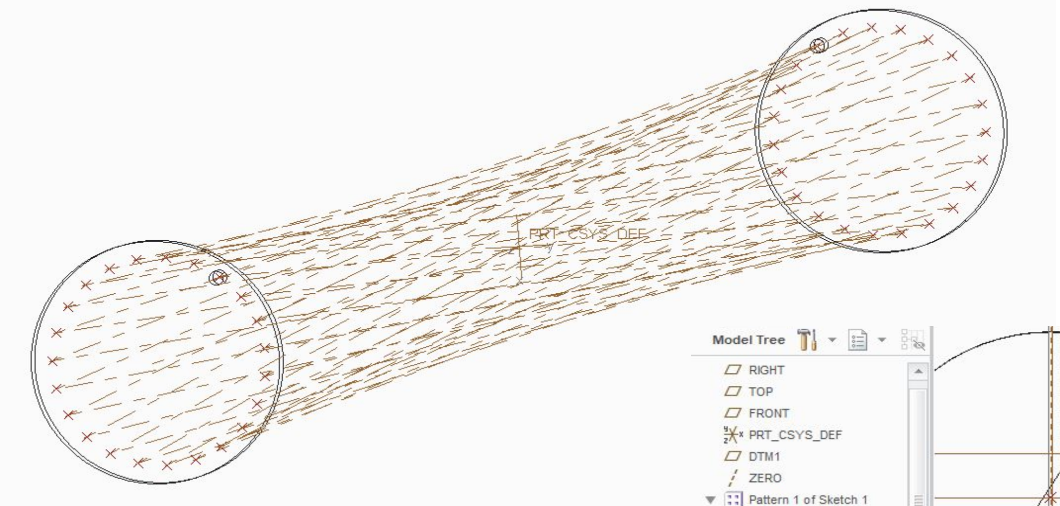


$$a = \sqrt{{R_1}^k {R_2}^{k(n+3)}}$$

$$F = \frac{\pi\sqrt{a}}{1-a}$$

$$A = \frac{1-R_1}{(1-a)^2}$$

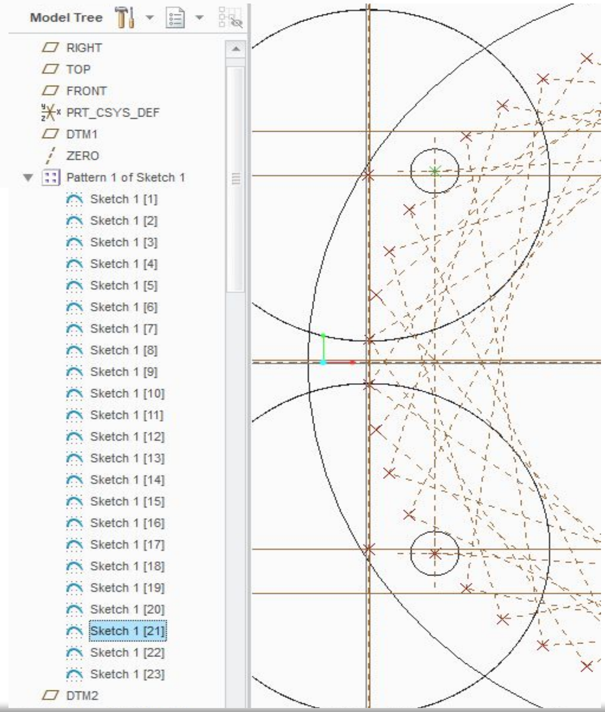
Design - Herriott cell



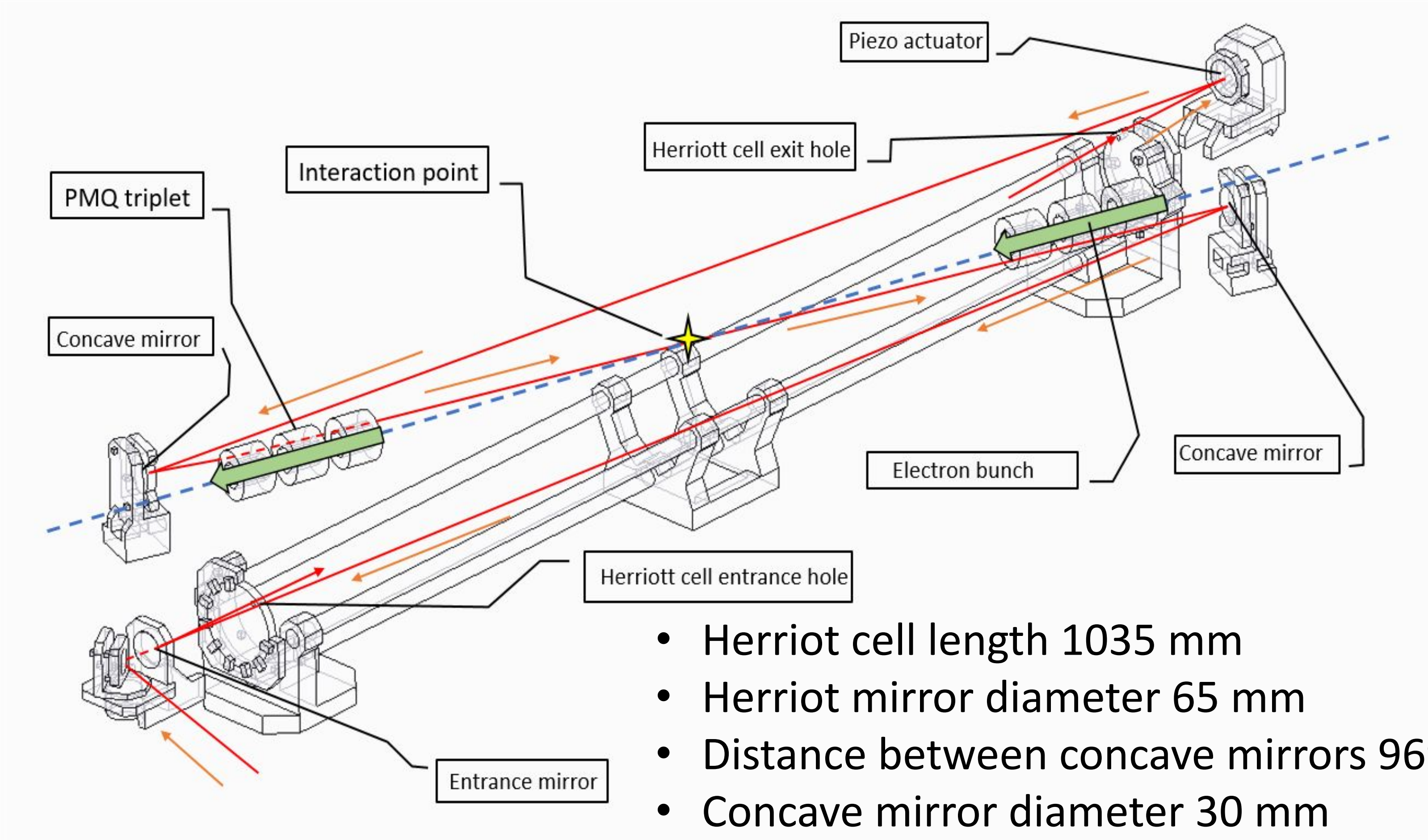
$$\alpha = 360°/23 = 15.65°$$

$$f_H = \frac{L}{2(1-\cos\alpha)} = 13.4\ \text{m}$$

	Length	Multiplier
Herriott cell (mm)	1035.05	45
Herriot-reflector (mm)	122.396	2
Reflector-concave (mm)	1104.48	2
Concave-concave (mm)	969	1
Herriott path (m)	46.57725	
Outside path (mm)	3423	
Total path (mm)	50000.002	
Difference (mm)	**0.00**	

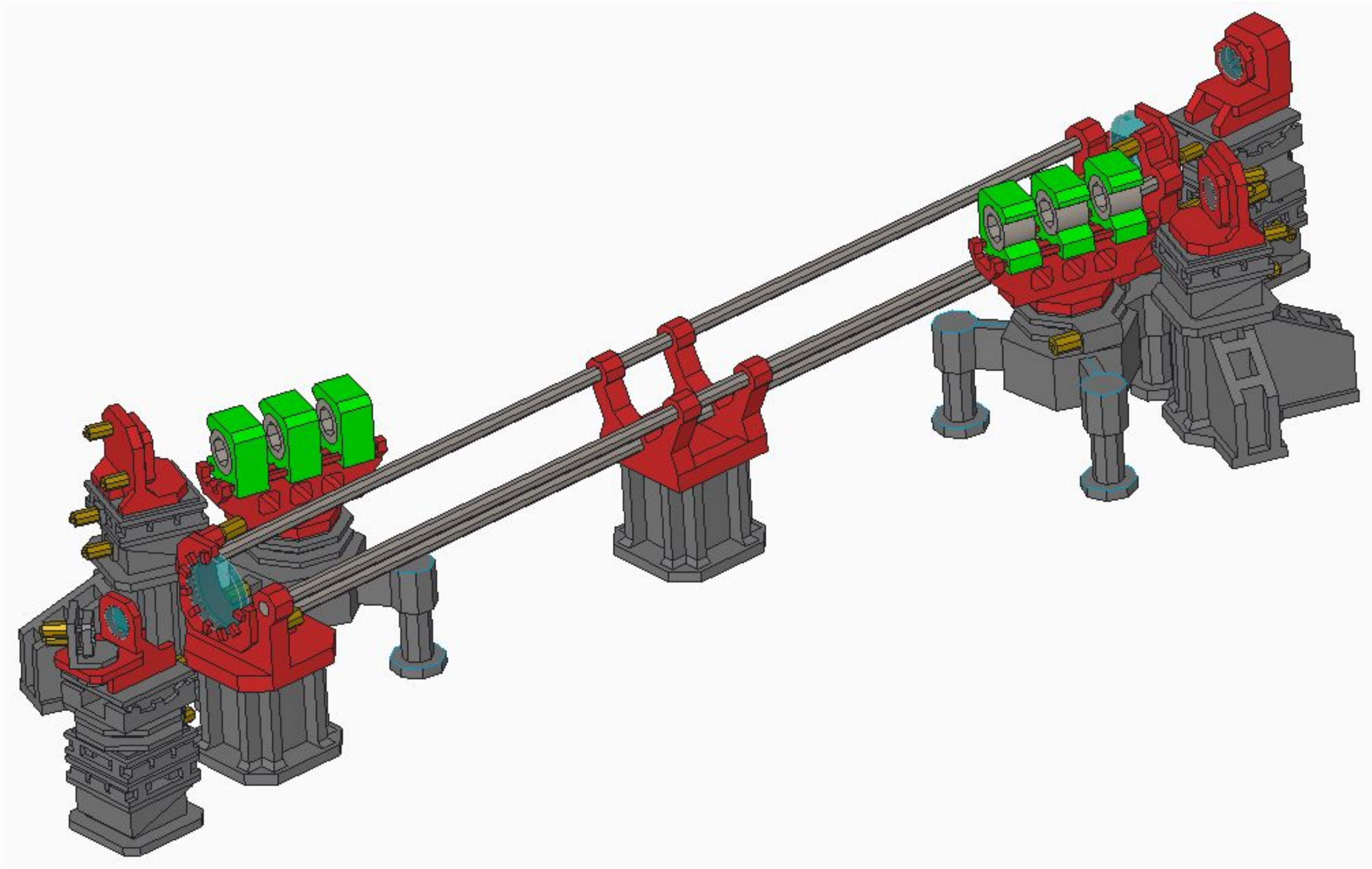


Designing - Dimensions



- Herriot cell length 1035 mm
- Herriot mirror diameter 65 mm
- Distance between concave mirrors 969 mm
- Concave mirror diameter 30 mm
- Electron and laser beam intersection angle 5°

Design - mounts and supports

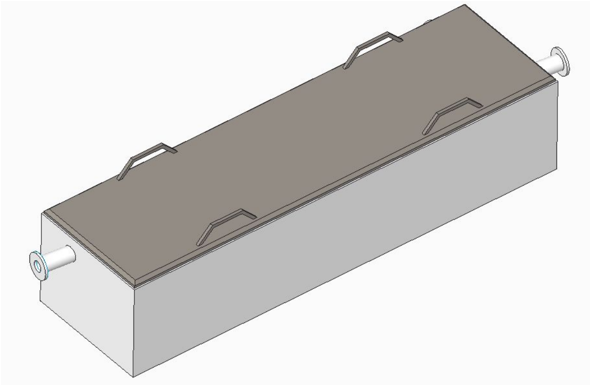


Number of individual models - 33

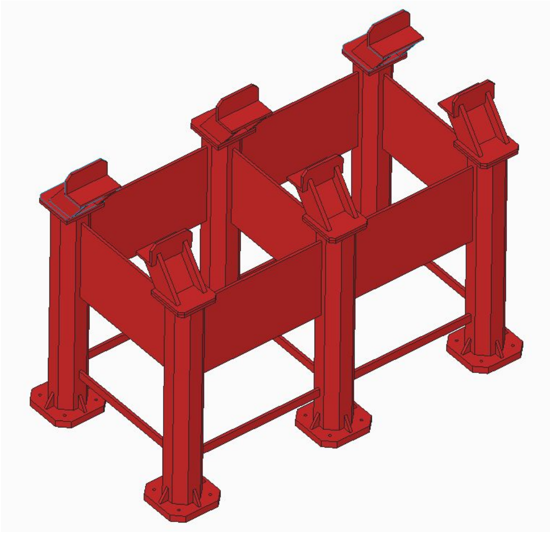
Number of assembly elements - 108

Build version - 3.12

Design - Vacuum chamber and frame

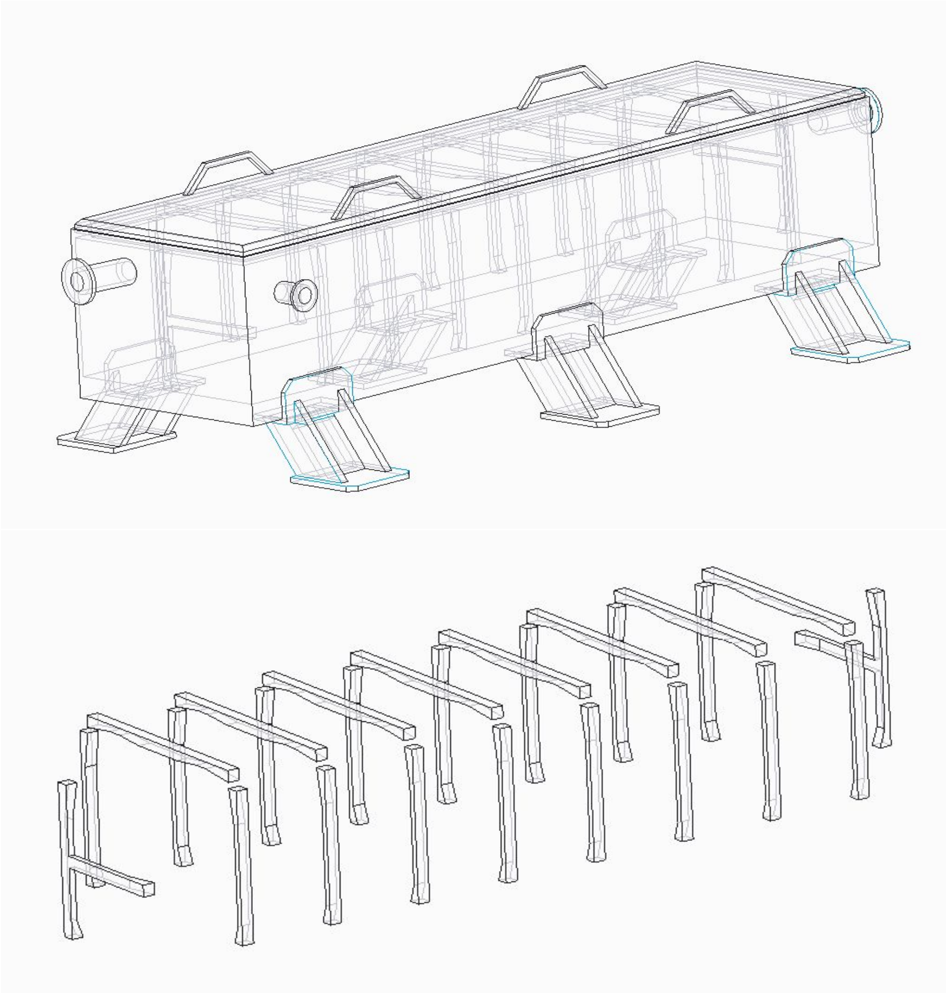


Dimensions: 1500x420x336 mm
Weight: 280 kg



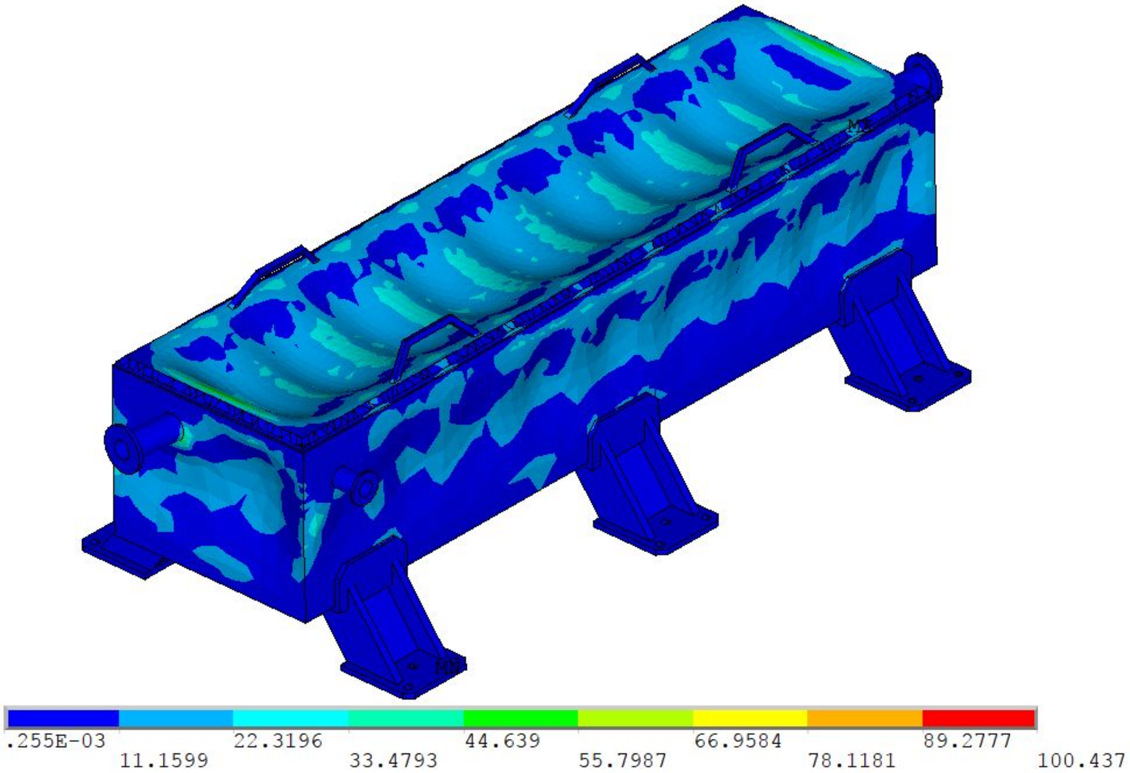
Dimensions: 1400x1015x780 mm
Weight: 321 kg

Static analysis - Implosion test



The von Mises yield criterion
The von Mises stress is often used in determining whether an isotropic and ductile metal will yield when subjected to a complex loading condition. This is accomplished by calculating the von Mises stress and comparing it to the material's yield stress, which constitutes the von Mises Yield Criterion.

Static analysis - Implosion test



ANSYS stress units - MPa

A36 steel properties:

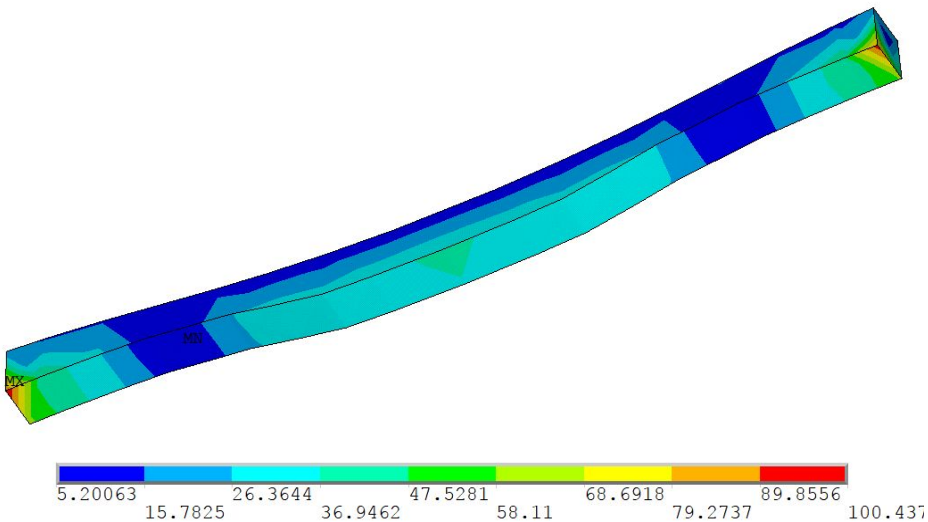
Density of 7,800 kg/m3

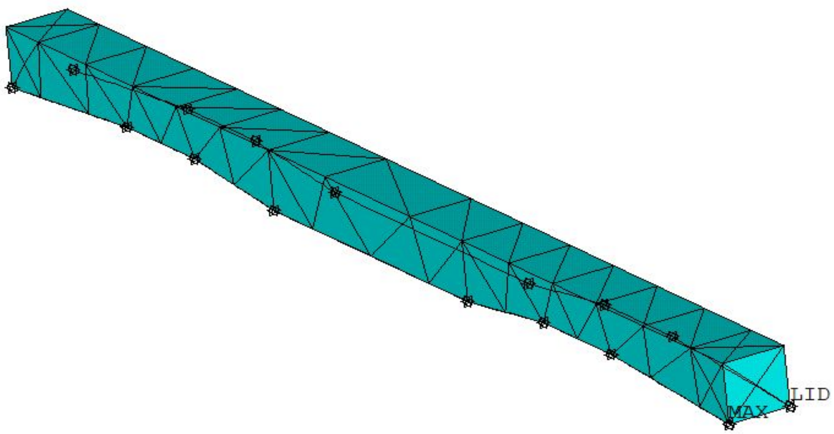
Young's modulus 200 GPa

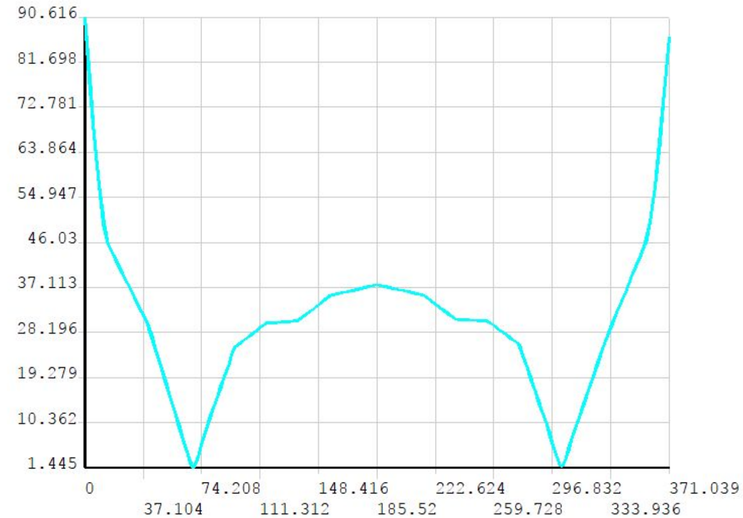
Poisson's ratio of 0.26

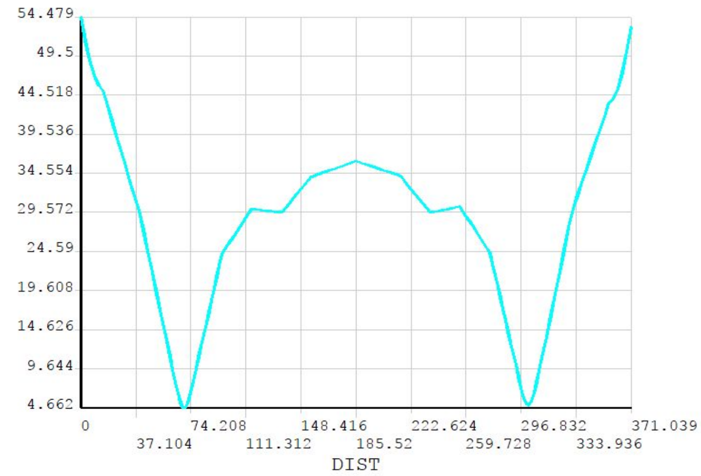
A36 steel in plates, bars, and shapes with a thickness of less than 8 in (203 mm) has a minimum yield strength of 36,000 psi (250 MPa)

Static analysis - Implosion test

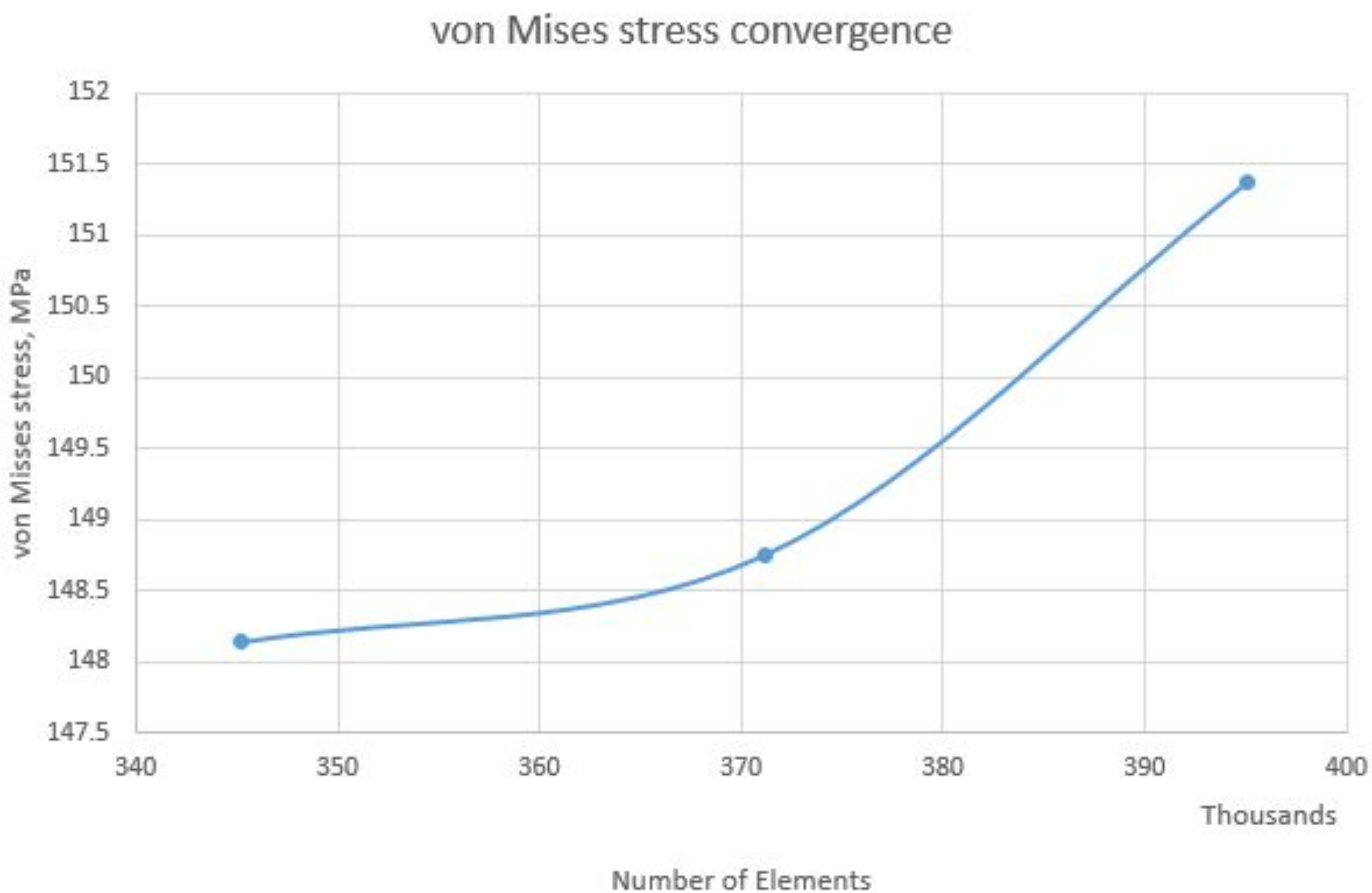






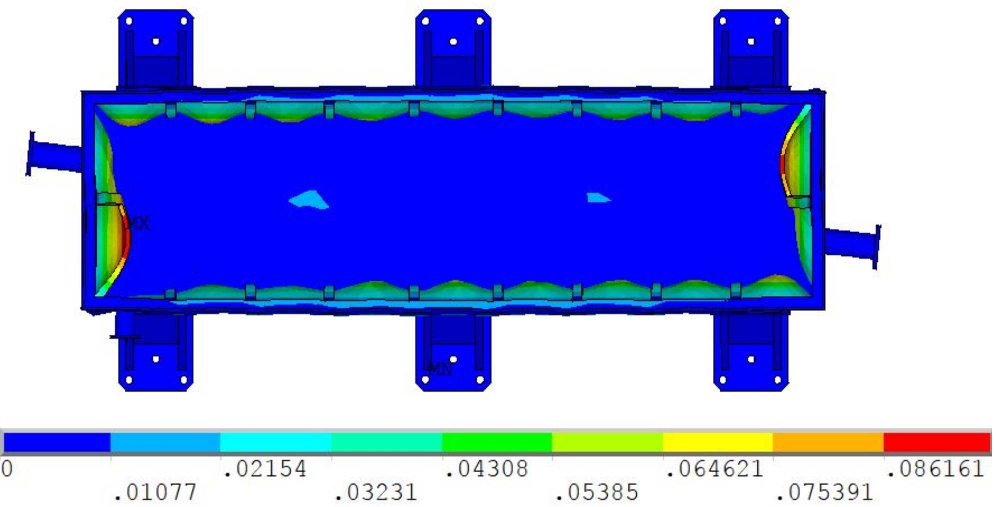


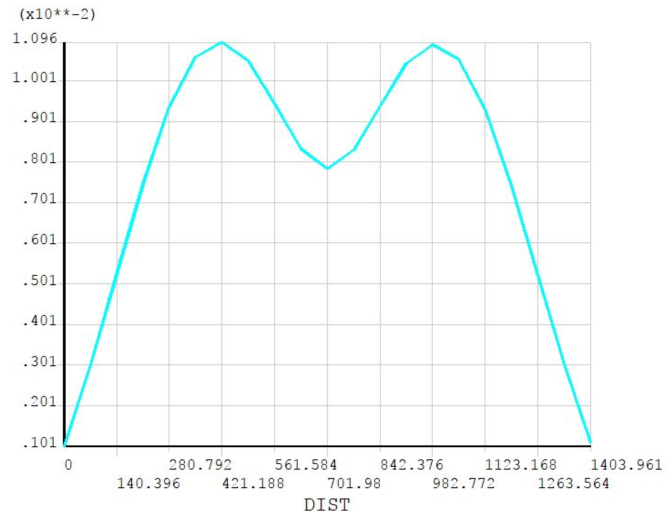
Static analysis - Convergence

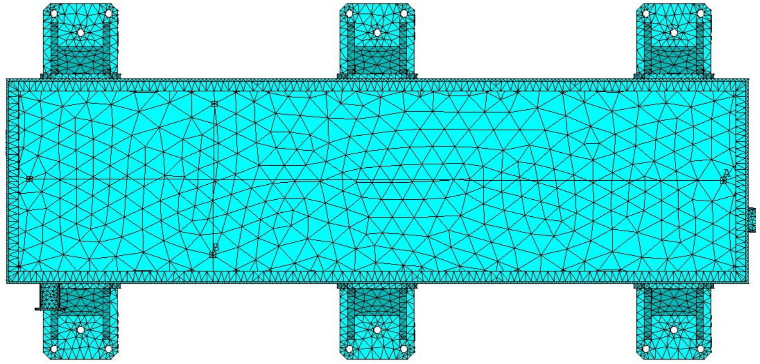


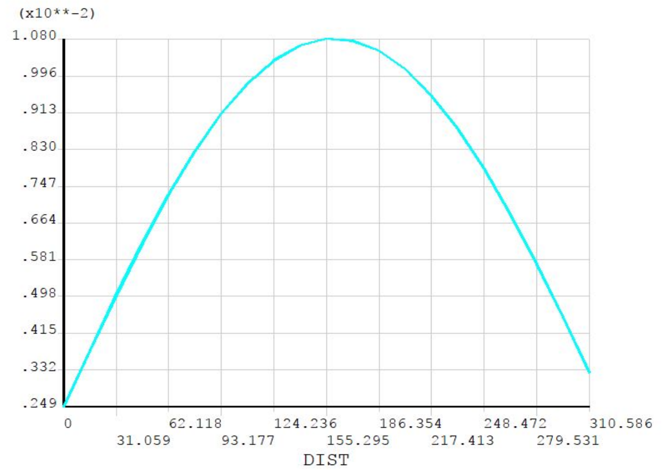
Von Mises stress at singularity points does not converge and grows with higher mesh resolutions

Static analysis - Displacement

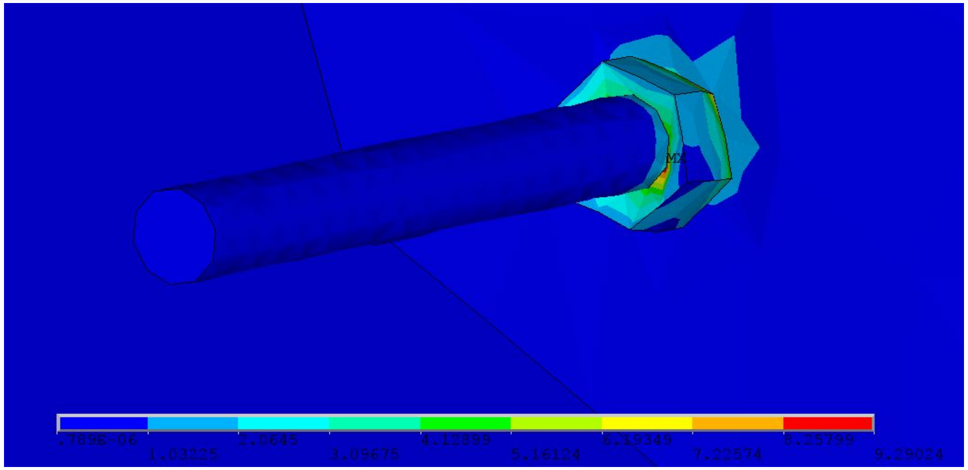


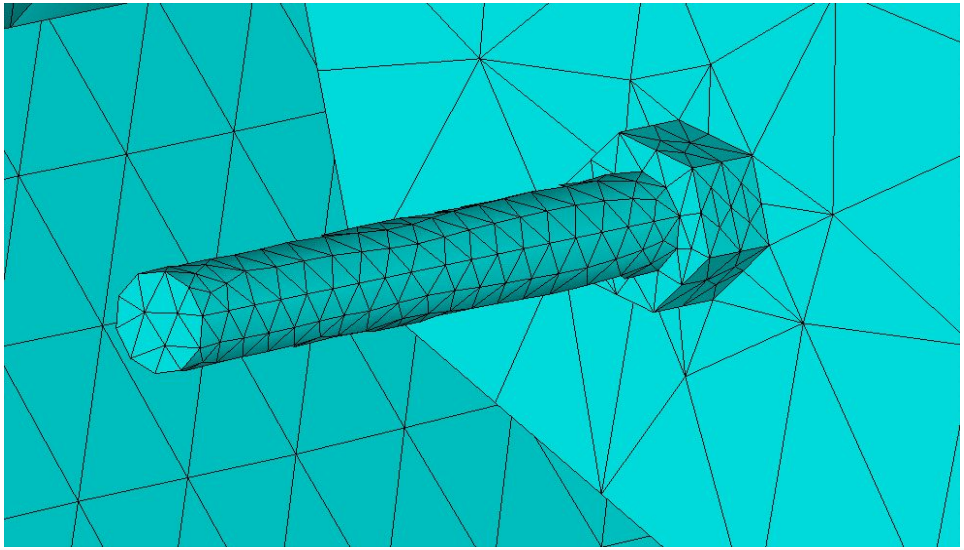






Static analysis - Gravity compression

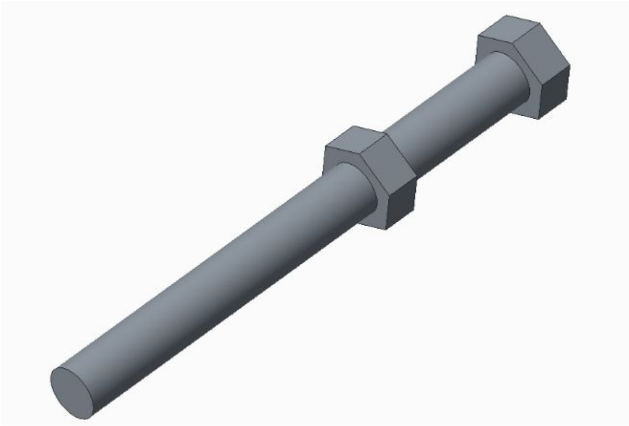




Von Mises stress - 9.29 MPa

Generally, the stands are fastened hard to the floor with 3/8” bolts into drop-in inserts. Main frame is mounted to the floor by 24 hexagonal bolts (4 per each of six legs)

	Body Diameter Basic	Width Across Flats Basic	Head Height Basic
inches	3/8	9/16	1/4
mm	9.53	14.28	6.35



Modal analysis

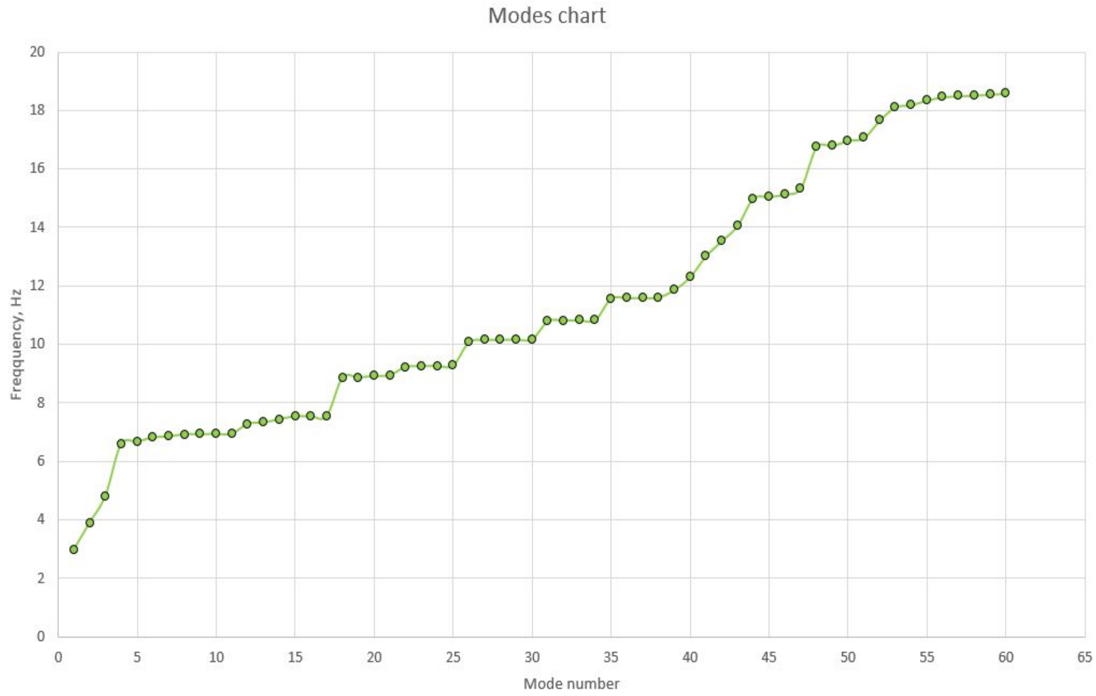
The purpose of performing a modal analysis is to find the natural frequencies and mode shapes of a structure. If a structure is going to be subjected to vibrations, then it is important to analyze where the natural frequencies occur so that the structure can be designed appropriately

$$[M]\{\ddot{u}\} + [K]\{u\} = 0$$

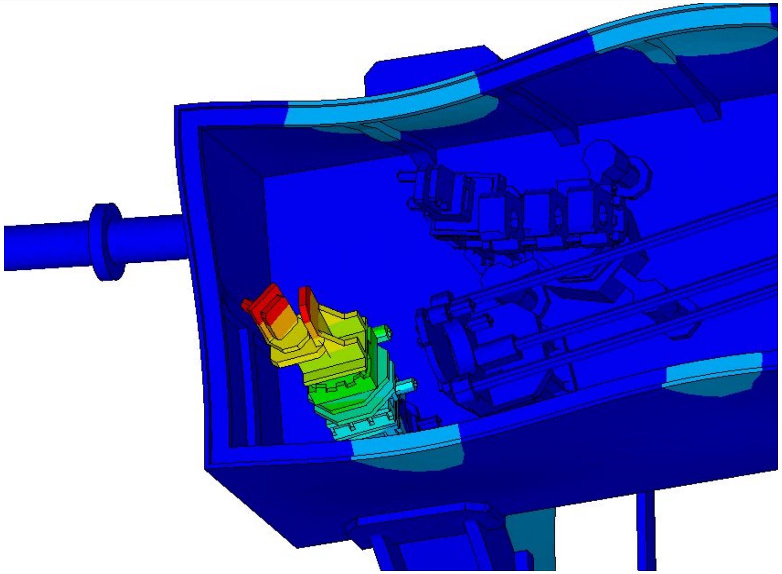
$$\{u\} = \{\varphi\}_i \cos(\omega_i t)$$

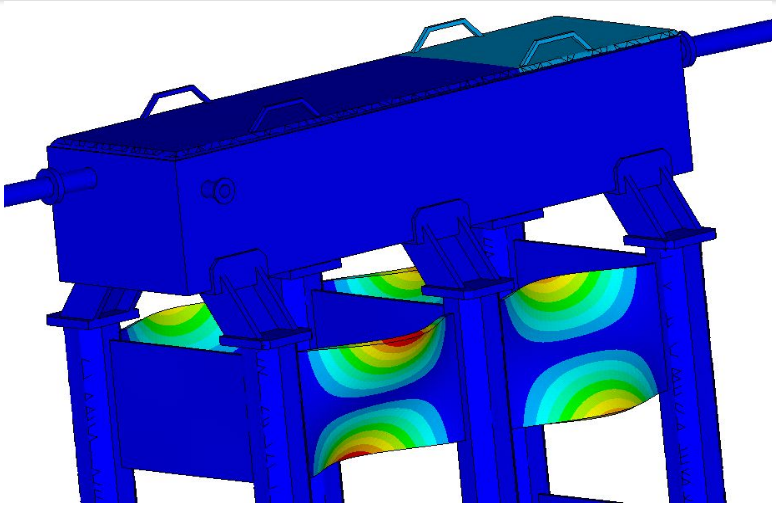
$$|[K] - \omega^2[M]| = 0$$

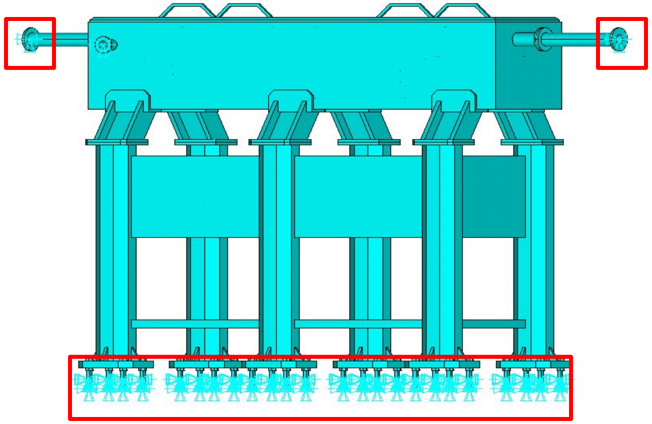
$$f_i = \frac{\omega_i}{2\pi}$$

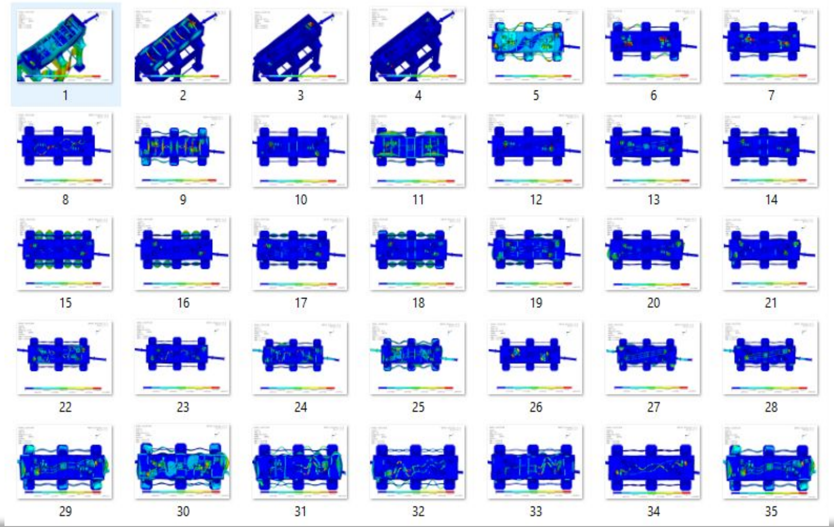


Modal analysis - Modal maps

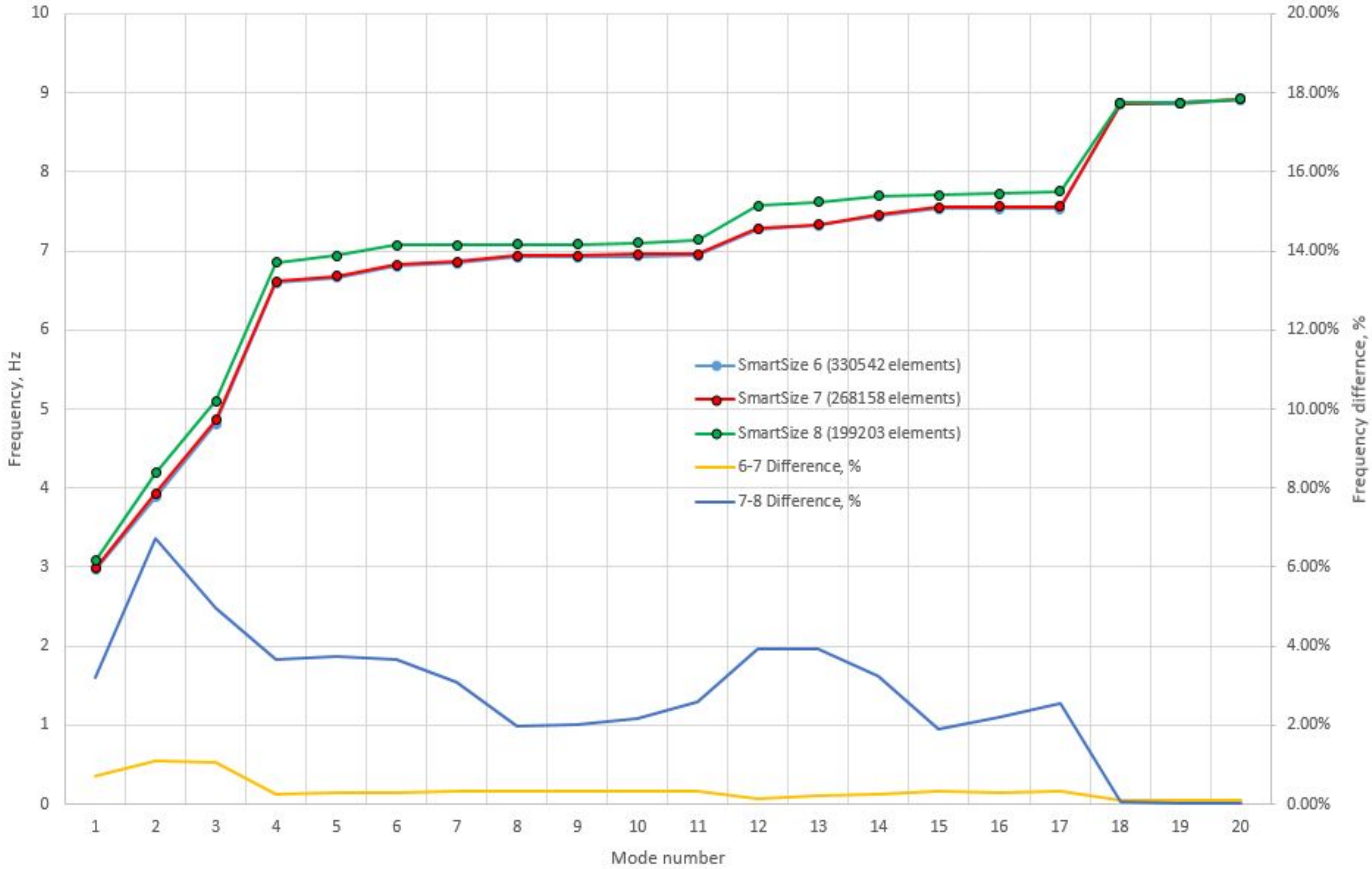








Modal analysis - Convergence



Harmonic analysis - Full

A harmonic analysis finds the steady state response of a structure under sinusoidal loading conditions. A harmonic, or frequency-response, analysis considers loading at one frequency only. Loads may be out-of-phase with one another, but the excitation is at a known frequency. This procedure is not used for an arbitrary transient load.

$$[M]\{\ddot{u}\} + [C][\dot{u}] + [K]\{u\} = \{F^a\}$$

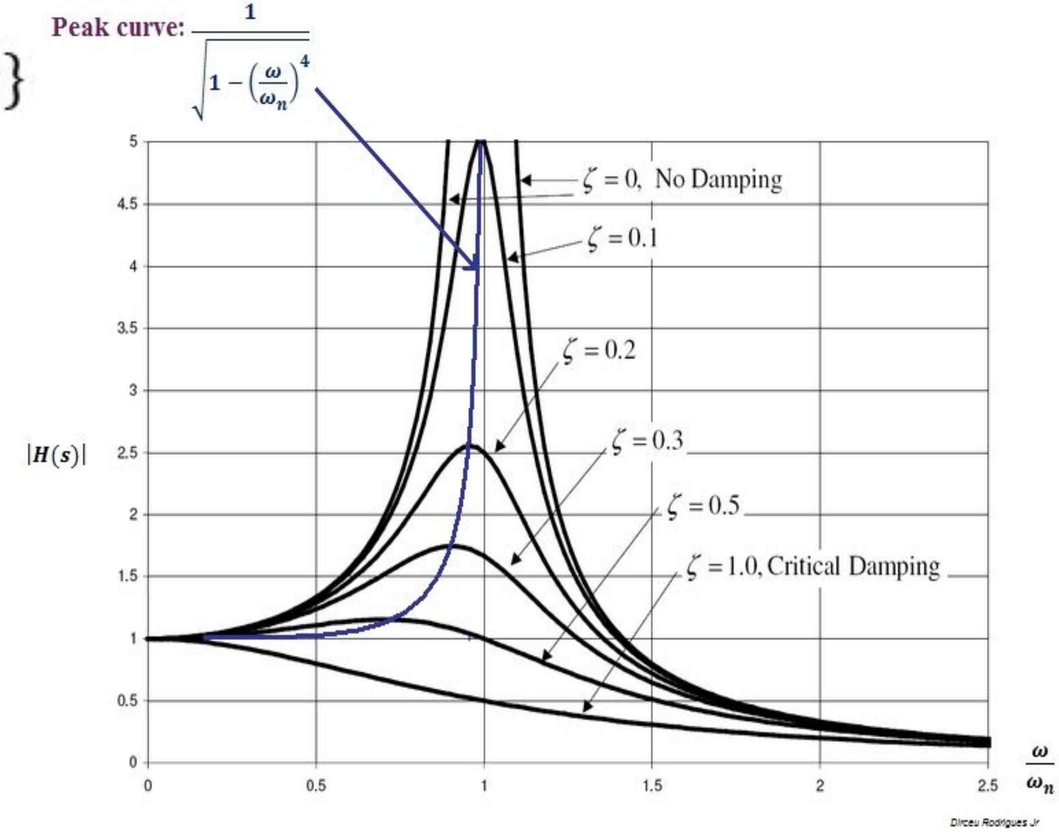
$$[C] = \alpha[M] + \beta[K]$$

$$\xi_j = \frac{\alpha}{2\omega_j} + \frac{\beta\omega_j}{2}$$

$$\xi_j = \frac{c}{c_{cr}}$$

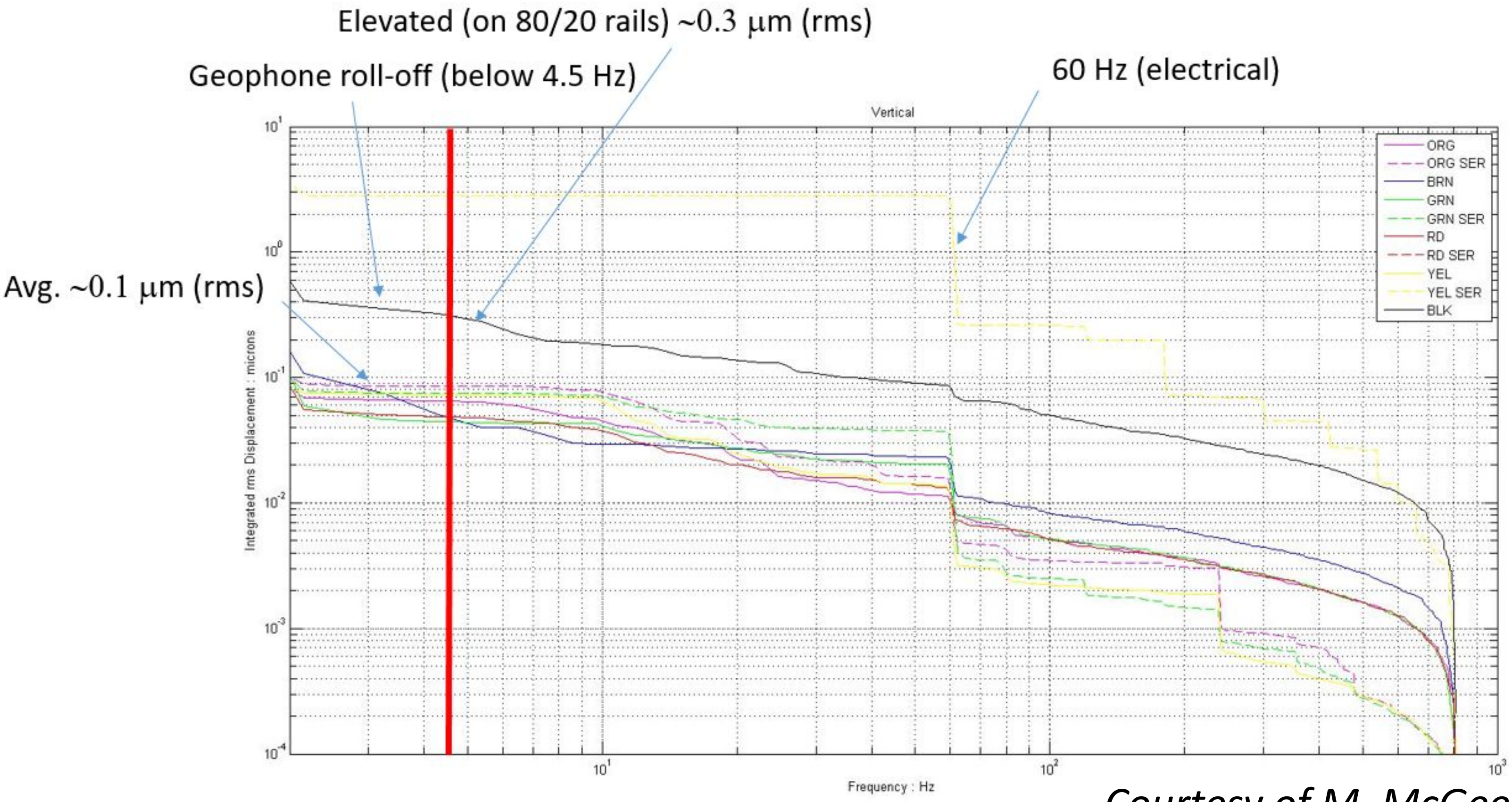
Types of damping available in Full harmonic analysis:

- Alpha damping
- Betha damping
- Constant damping ratio



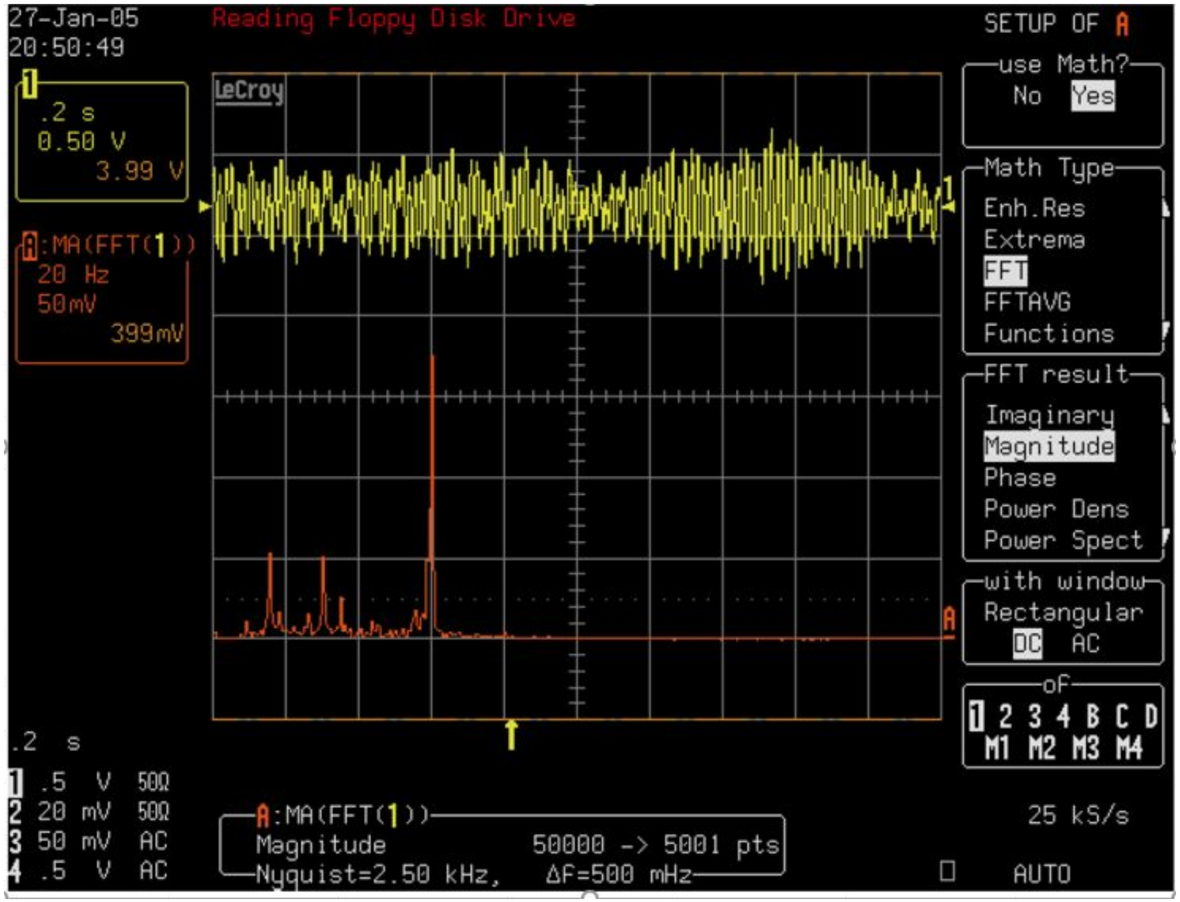
Harmonic analysis - Loading data

Vertical Integrated Displacement (rms) Results 8 June 2017 (12:00 – 13:00) FAST



Courtesy of M. McGee (Fermilab)

Harmonic analysis - Seismograph readings



Rodion Tikhoplav - Vibration measurements at the A0 laser room

Fourier transform is used to convert signal from time domain to frequency domain. Calculating a Fourier transform requires understanding of integration and imaginary numbers.

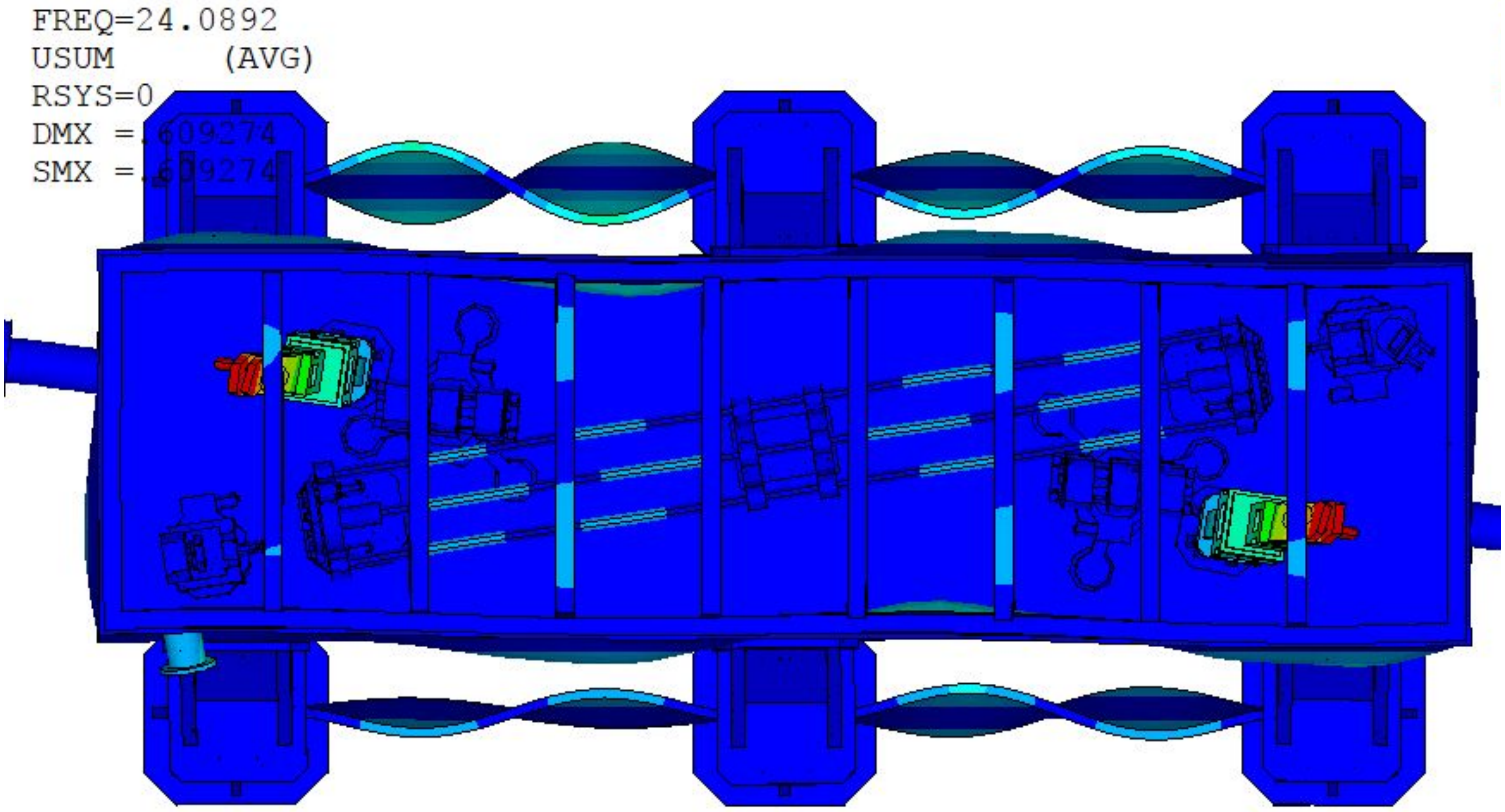
$$F(\omega) = \int_{-\infty}^{\infty} f(t) e^{-j\omega t} dt$$

$|F(\omega)|$ is called the amplitude spectrum of f

$$F(\omega) = \int_{-\infty}^{\infty} f(t) \cos \omega t \, dt$$

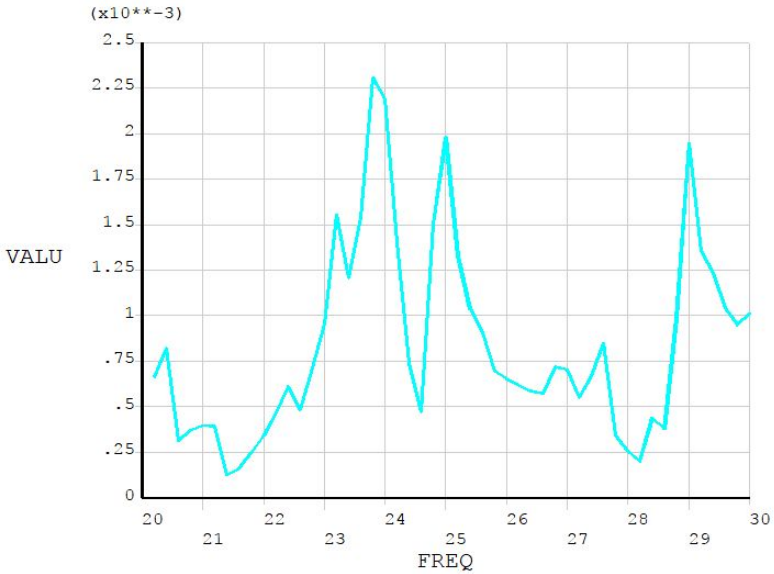
$$- j \int_{-\infty}^{\infty} f(t) \sin \omega t \, dt$$

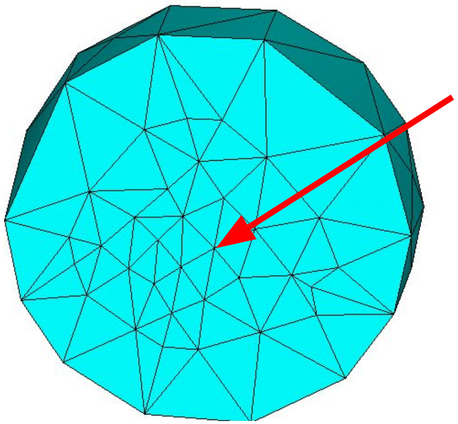
Harmonic analysis - Postprocessing



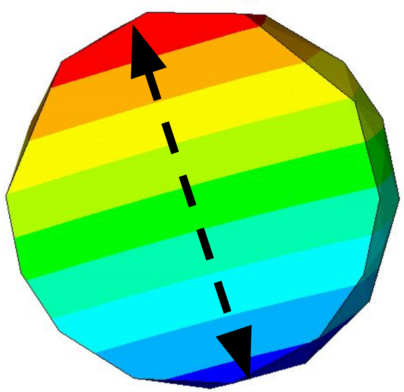
Dangerous mode to be examined - concave mirror supports

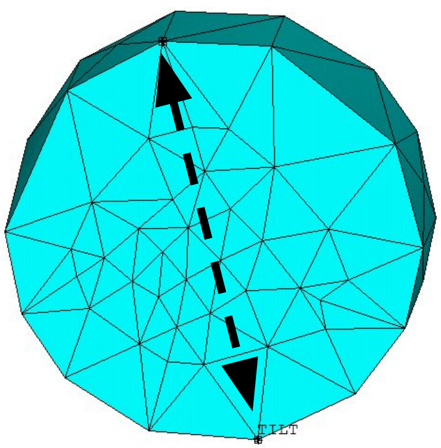
Harmonic analysis - Postprocessing





Tracking displacement of a single node over the whole frequency region in order to find the peak response



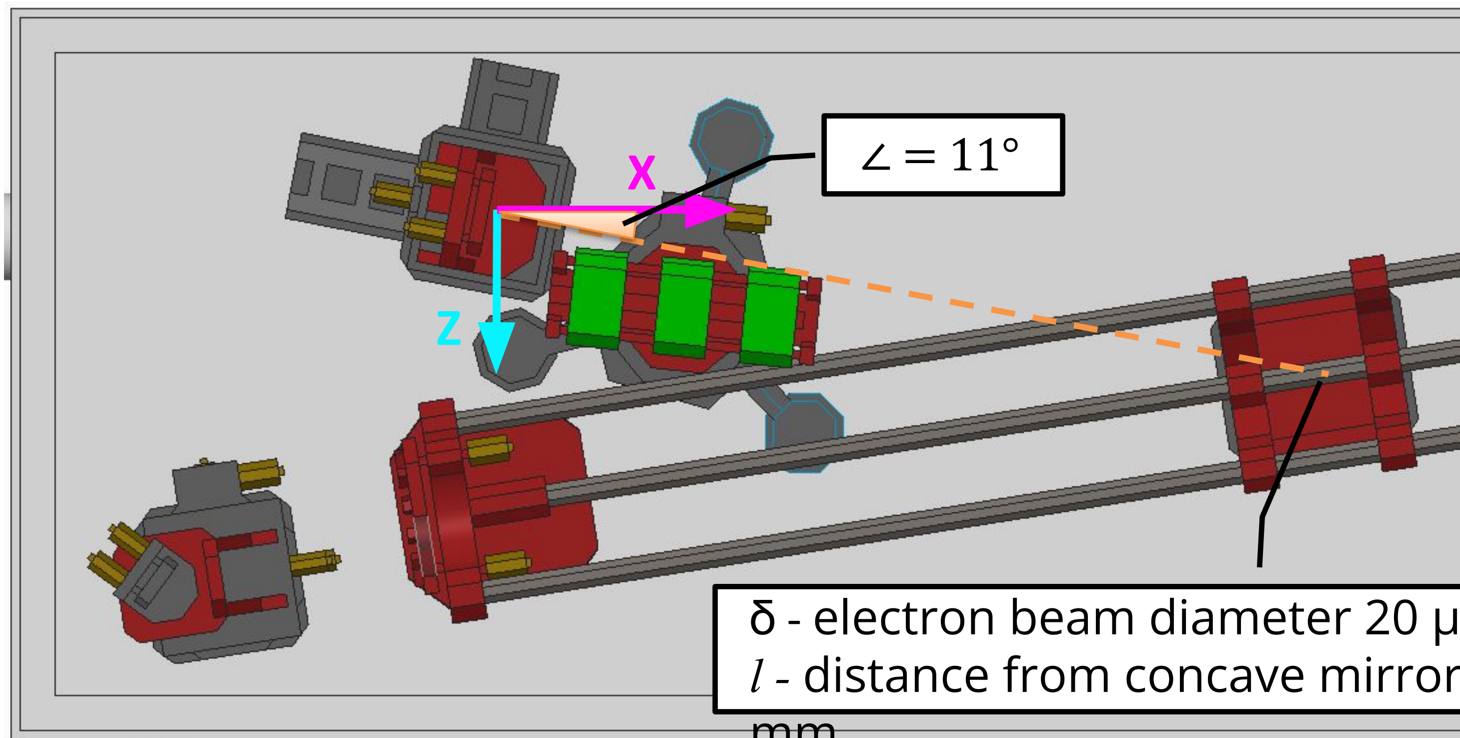


On a chosen frequency map the displacement on the path on the surface of the mirror. Linear approximation will give the tilt angle of the mirror.

Harmonic analysis - Critical displacement

Design success criterions:

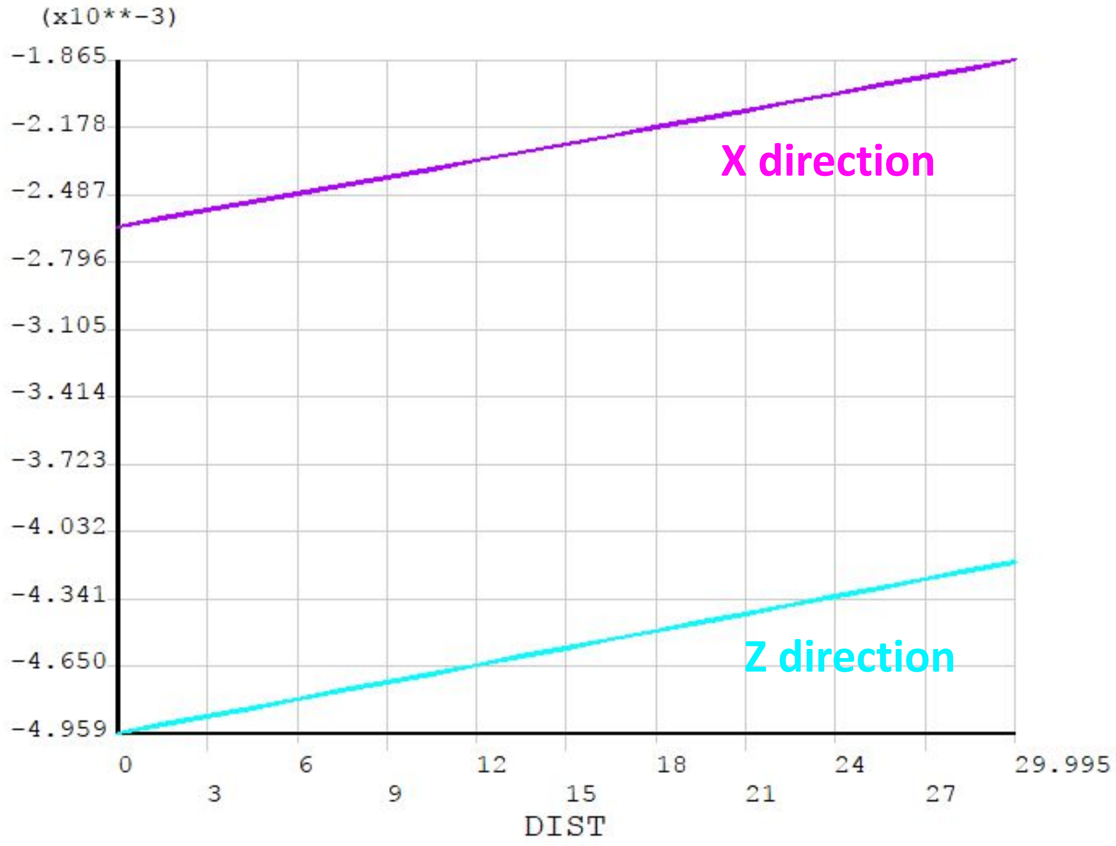
- Mirror displacement should not exceed wavelength of 1.054 µm
- Concave mirror tilt angle should not exceed α = $4.13 * 10^{-5}$ rad



$$\alpha = \frac{\delta}{l}$$

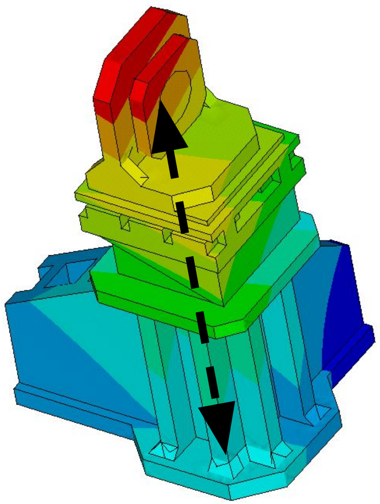
δ - electron beam diameter 20 µm
l - distance from concave mirror to IP 484.5 mm

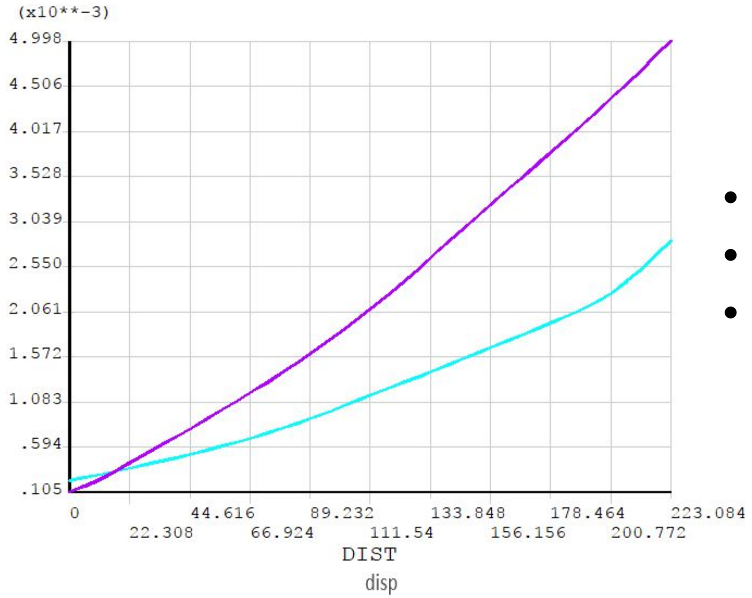
Harmonic analysis - Postprocessing



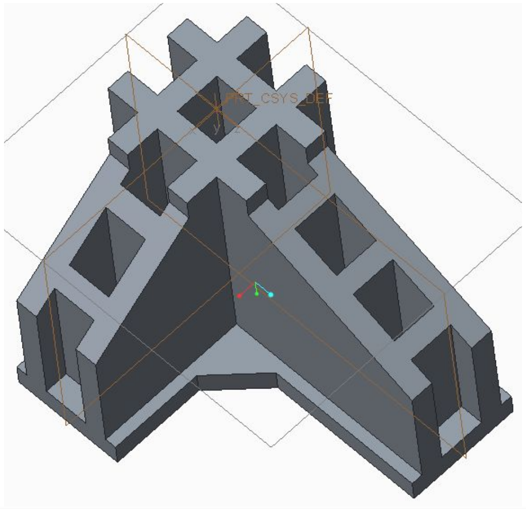
	A	B	C	D	E	F
1	S	X	Z	angle	disp	
2	0	-2.63E-03	-4.96E-03	0.191986218	3.53E-03	
3	1.4997	-2.59E-03	-4.92E-03		3.49E-03	
4	2.9995	-2.56E-03	-4.88E-03		3.44E-03	
5	4.4992	-2.52E-03	-4.84E-03		3.40E-03	
6	5.999	-2.48E-03	-4.80E-03		3.35E-03	
7	7.4987	-2.44E-03	-4.76E-03		3.31E-03	
8	8.9984	-2.41E-03	-4.73E-03		3.26E-03	
9	10.498	-2.37E-03	-4.69E-03		3.22E-03	
10	11.998	-2.33E-03	-4.65E-03		3.17E-03	
11	13.498	-2.29E-03	-4.61E-03		3.13E-03	
12	14.997	-2.25E-03	-4.57E-03		3.08E-03	
13	16.497	-2.21E-03	-4.53E-03		3.04E-03	
14	17.997	-2.18E-03	-4.49E-03		2.99E-03	
15	19.497	-2.14E-03	-4.45E-03		2.95E-03	
16	20.996	-2.10E-03	-4.41E-03		2.90E-03	
17	22.496	-2.06E-03	-4.37E-03		2.86E-03	
18	23.996	-2.02E-03	-4.33E-03		2.81E-03	
19	25.496	-1.98E-03	-4.29E-03		2.77E-03	
20	26.995	-1.94E-03	-4.25E-03		2.72E-03	
21	28.495	-1.90E-03	-4.21E-03		2.67E-03	
22	29.995	-1.87E-03	-4.17E-03		2.63E-03	
23						
24	3.00E+01	max-min			9.03E-04	max-min
25						
26	l	4.845E-01	**4.128E-05**	rad	**3.01029E-05**	rad
27	delta	2.000E-05				
28			**1.054E+00**	µm	**3.530606178**	µm

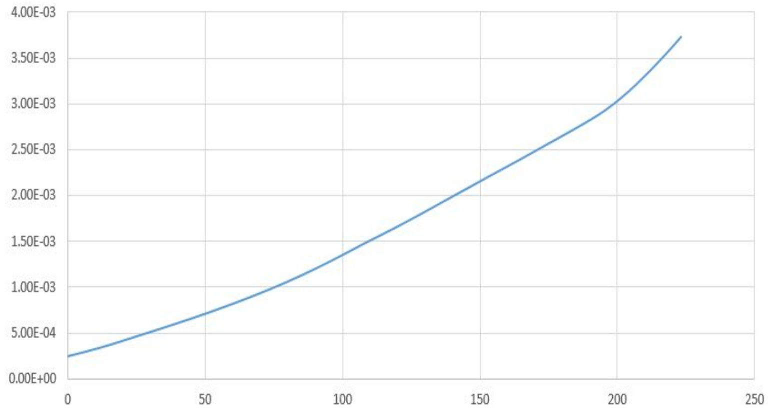
Harmonic analysis - Solutions





- Geometry modifications
- Extra supports
- Make shorter mounts





Height support modification has mitigated maximum response in the mirror from 7 μm to 3 μm

Conclusion

- ICS is an exceptional method of generating γ radiation of high brilliance, its development is important for National security and a number of other applications.
- Designing of ICS interaction region is a complicated process that comes in several interconnected stages.
- Present design is a trade-off between technical requirements of finesse, size, mechanical stability and overall complexity. It has its limitations.

Thank you for your attention