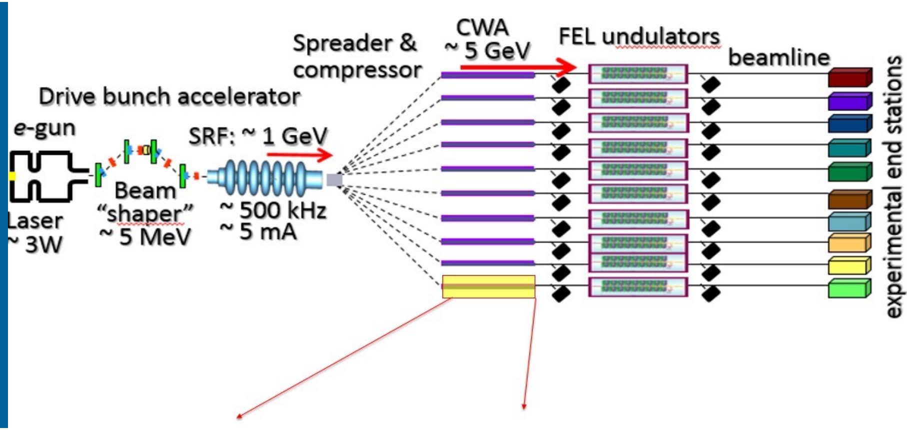
DETERMINATION OF MAXIMUM REPETITION RATE OF A CORRUGATED-WAVEGUIDE-BASED WAKEFIELD ACCELERATOR (A-STAR)



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July 29, 2021
MEDSI 2020

OUTLINE

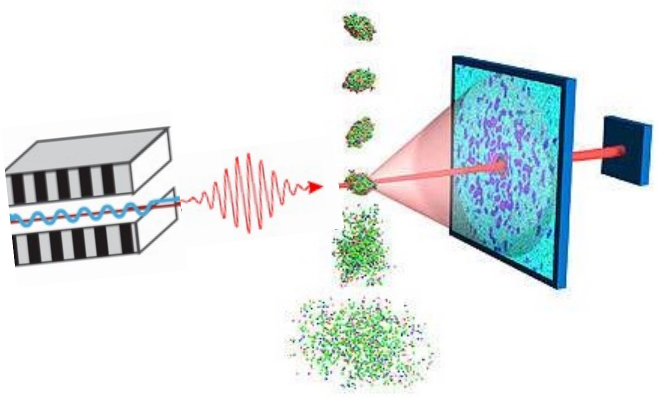
- Introduction to A-STAR device
  - What is a wakefield accelerator?
  - Power deposition and repetition rate
  - Specifics of physical design
    - CWA modules
    - Corrugated waveguide
    - Transition section
- Multiphysics FEA
  - FEA Formulation
  - Results
- Fabrication Challenges in designing A-STAR
- Existing state and future challenges.

APPLICATION - FEL

Enables diffraction imaging of aperiodic biological molecules

Optimal x-rays*)

- Photon energy 8–13 keV
- Pulse duration: a few fs or less
- Pulse rep. rate 50 kHz



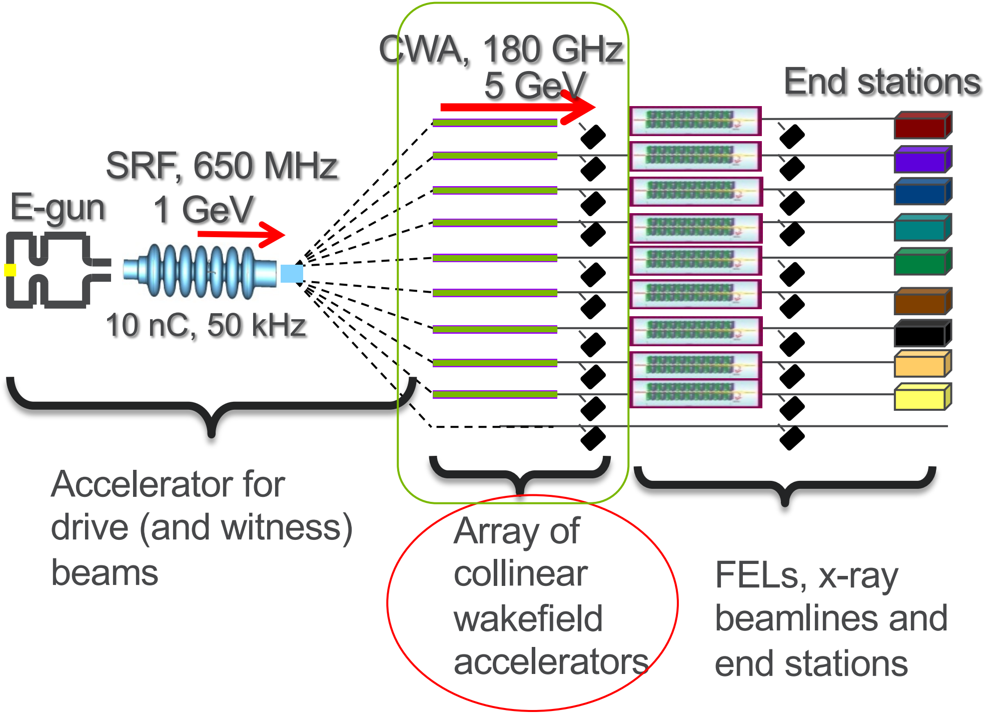
A protein exposed to an ultra-short X-ray pulse. Images show the molecule before, at and after interaction (see also Neutze, R. Wouts, D. van der Spoel, E. Weckert, and J. Hajdu, “Potential for biomolecular imaging with femtosecond X-ray pulses,” Nature 406 (2000) 752).

*) H. Chapman *et al*., Physical Review E 71, 061919 2005

A CONCEPT OF A- STAR DEVICE

High repetition rate operation is essential goal

- Multiple FELs maximize facility productivity.
- Each FEL uses its own accelerator.
- Single SRF gun and single SRF linac drive 10 collinear wakefield accelerators.
- Collinear wakefield accelerators increase witness beam energy from 1 GeV up to 5 GeV.
- Repetition rate up to 20 kHz per FEL minimizes data collection time.

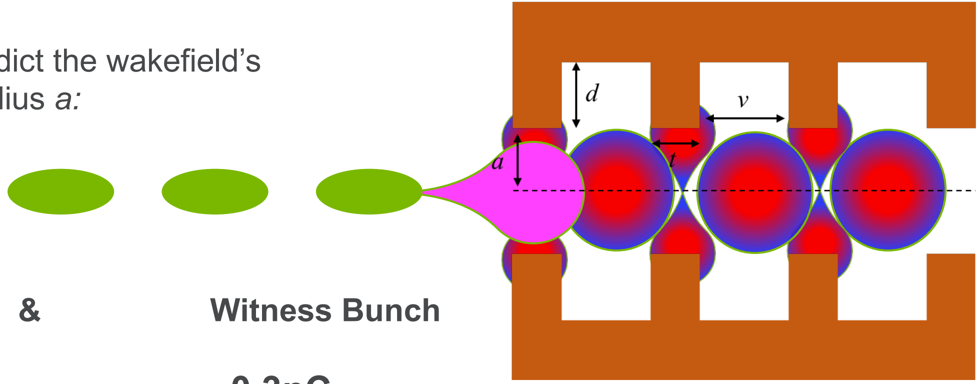


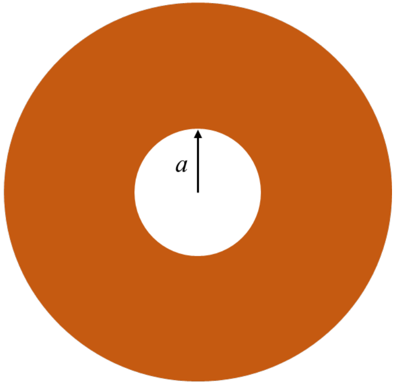
WAVEGUIDE WITH CORRUGATIONS

Inner radius largely defines loss and kick factors due to wakefield

Repetition rate and wakefield

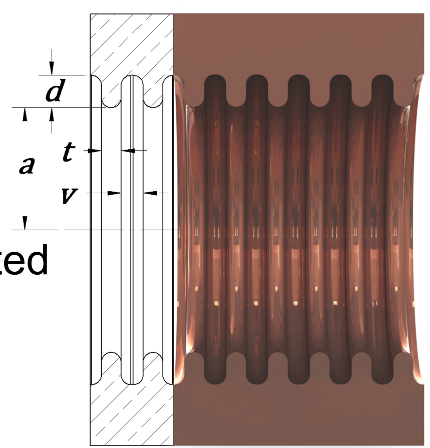
Theoretical models*) predict the wakefield's dependence on inner radius *a:*





Drive Bunch **&** **Witness Bunch**

Drive Bunch	Witness Bunch
10nC	**0.3nC**
~800MeV	**1GeV**
↓	↓
200MeV	**5GeV**



Value chosen: *a* =1mm

a: inner radius of cylinder.
d: depth of corrugations.
t: corrugation "tooth" width.
v: gap width between teeth.

RF power produced in 50 cm long corrugated waveguide:

- TM01 expected power is ~<u>1kW.</u>

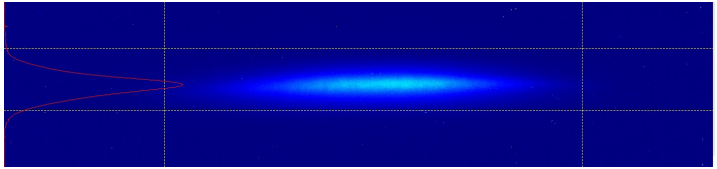
*) K. Bane and G. Stupakov, Nucl. Instrum. Meth. Phys. Res., Sect. A 677, 67 (2012).

EXPERIMENTAL RESULTS

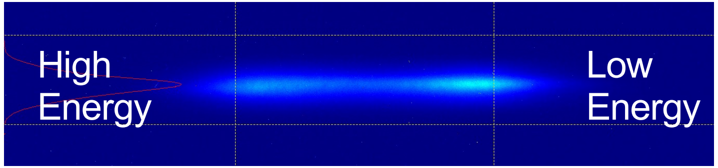
Evidence of 180GHz acceleration

Spectrometer Measurements

Tube with smooth wall

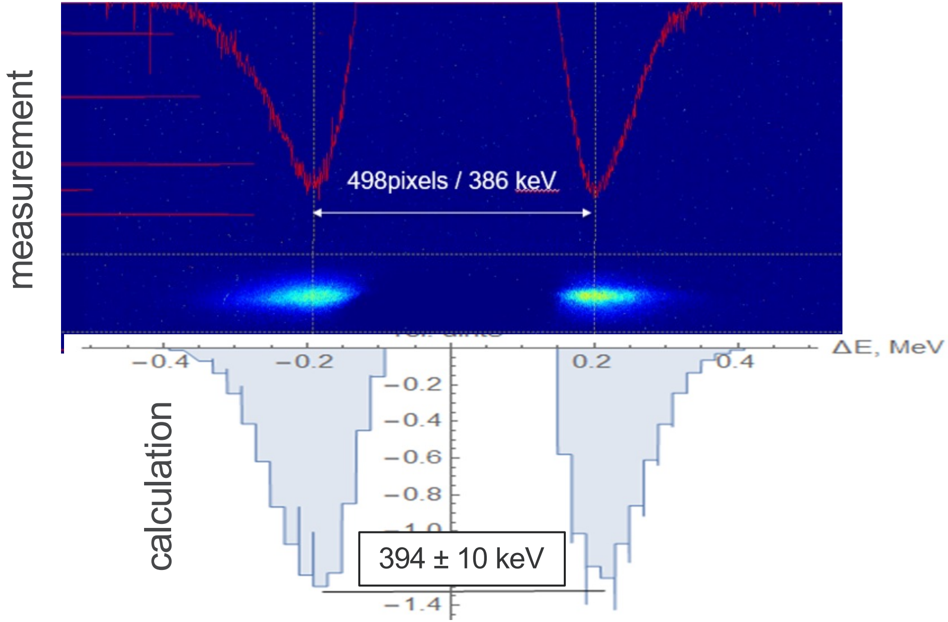


Corrugated Waveguide



Impact of the wakefield on slice medium energy

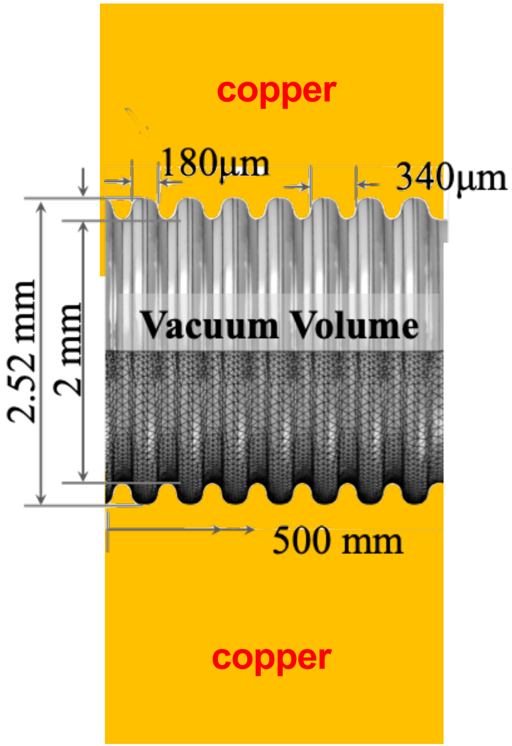
The measurement for the tube with smooth wall is subtracted from the corrugated waveguide measurement to show the effect of the corrugations.



Calculated difference in bunch energy distributions agrees with measured result

CORRUGATED RF DESIGN OPTIMIZATION

Corrugation Geometry



RF Calculation

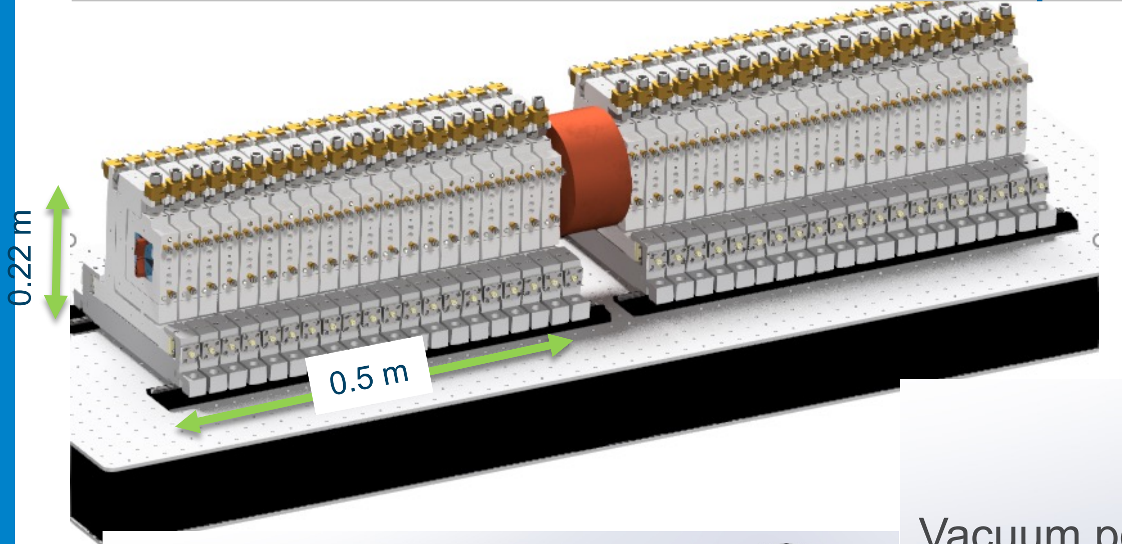
RF Simulation (CST)

Wakefield Simulation (ECHO)

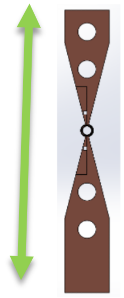
RF power produced in 50 cm long corrugated waveguide:
- TM01 expected power is ~1kW.
- TE11 expected power is ~1mW/μm^2.
- TM11 dipole mode power is weaker than TE11.

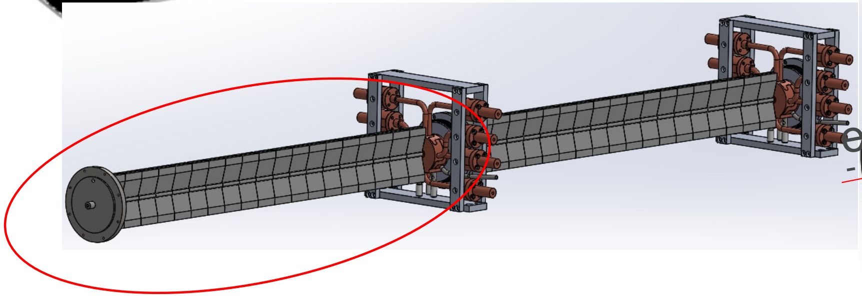
CWA MODULE

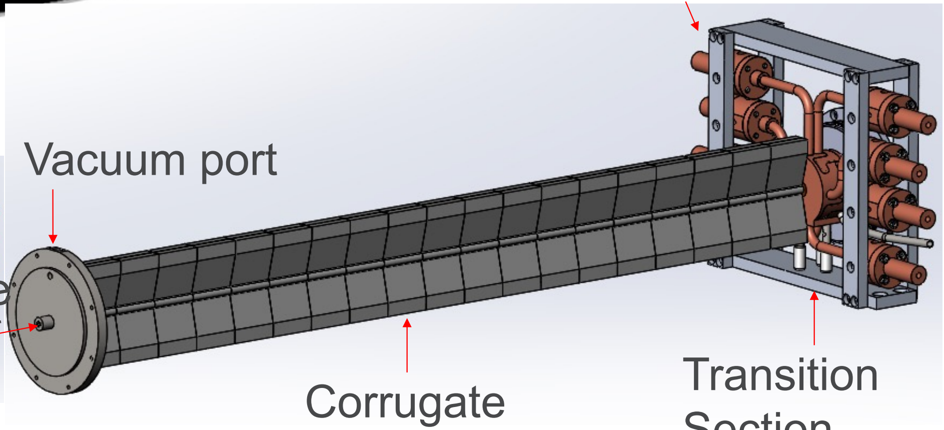
Two accelerator sections shown with and without quadrupoles



Cross-section of the Vacuum chamber





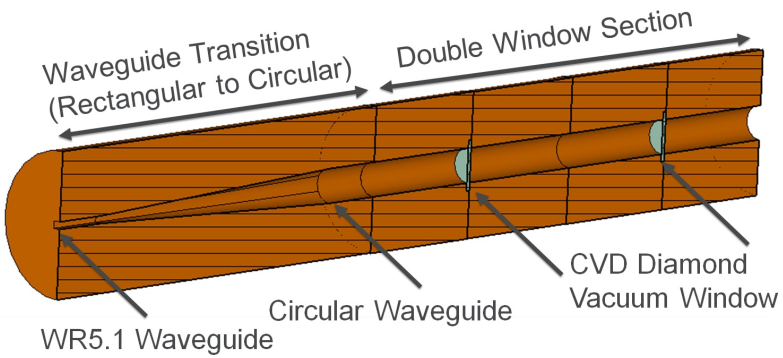


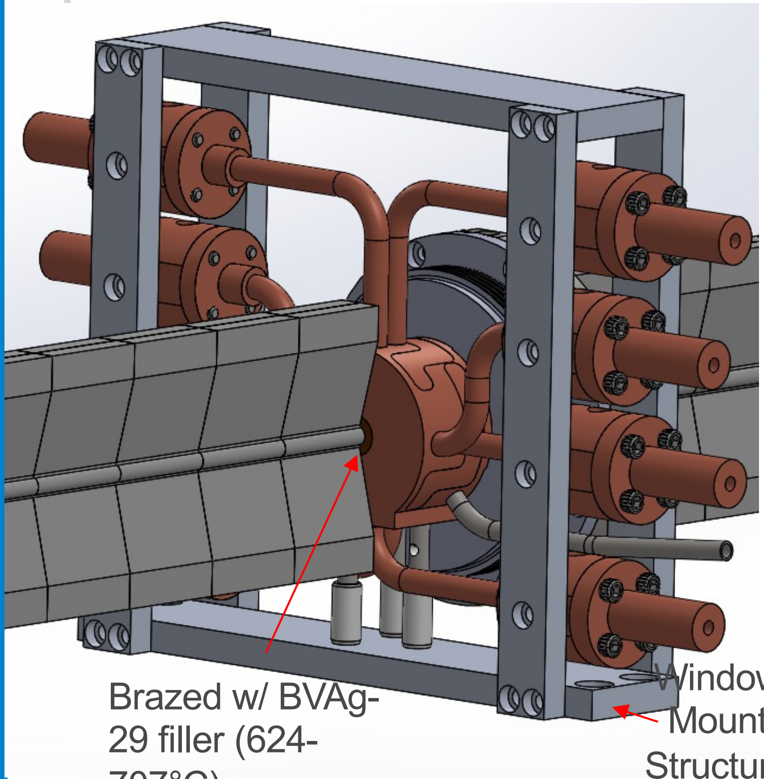
Vacuum chamber

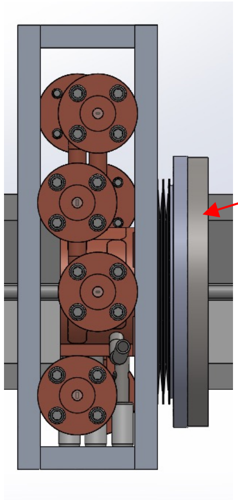
TRANSITION SECTION

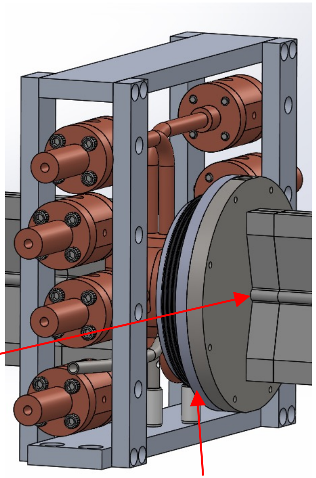
[TUPB06] Design of Miniature Waveguides and Diamond Window Assembly for RF Extraction and V…

This paper outlines the design of a diamond vacuum window and a millimeter wavelength (mmWave) wav…

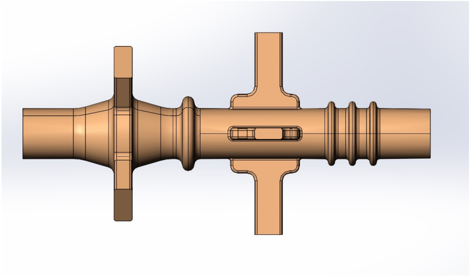


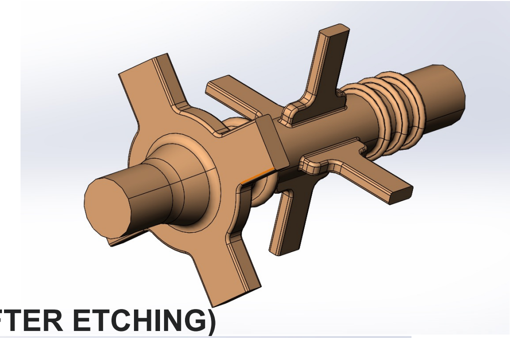




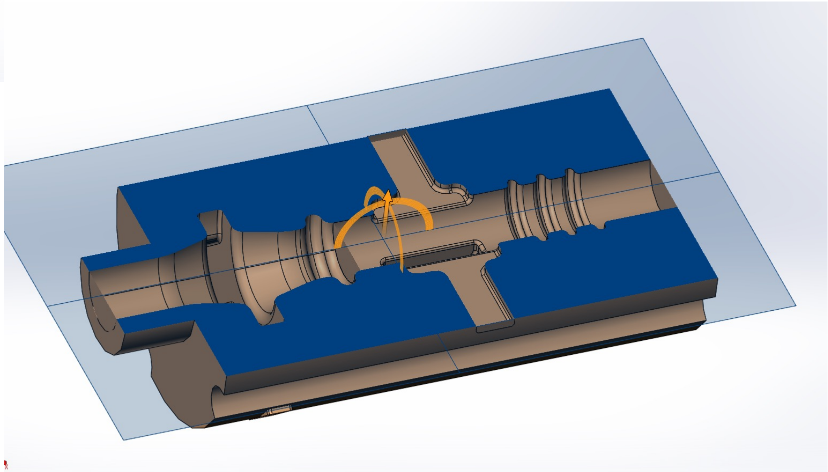


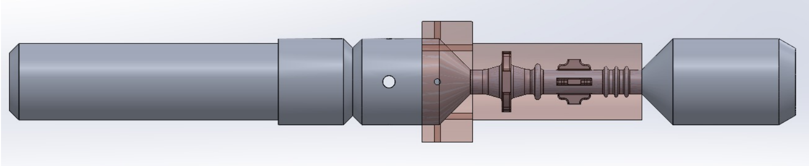
TRANSITION SECTION

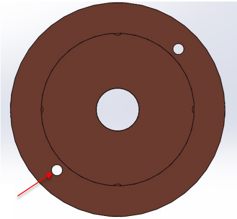




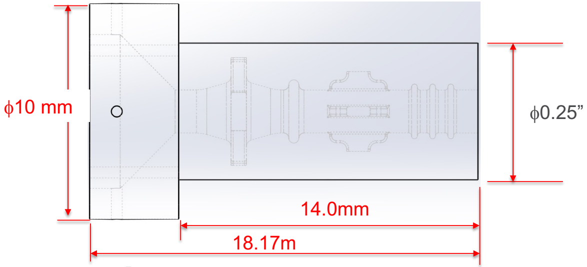
ELECTROFORMED COPPER (AFTER ETCHING)





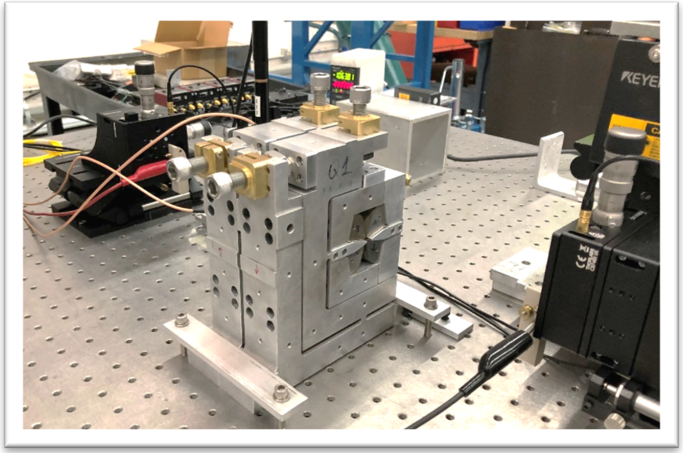


ϕ0.020”
thru-holes
(90°)

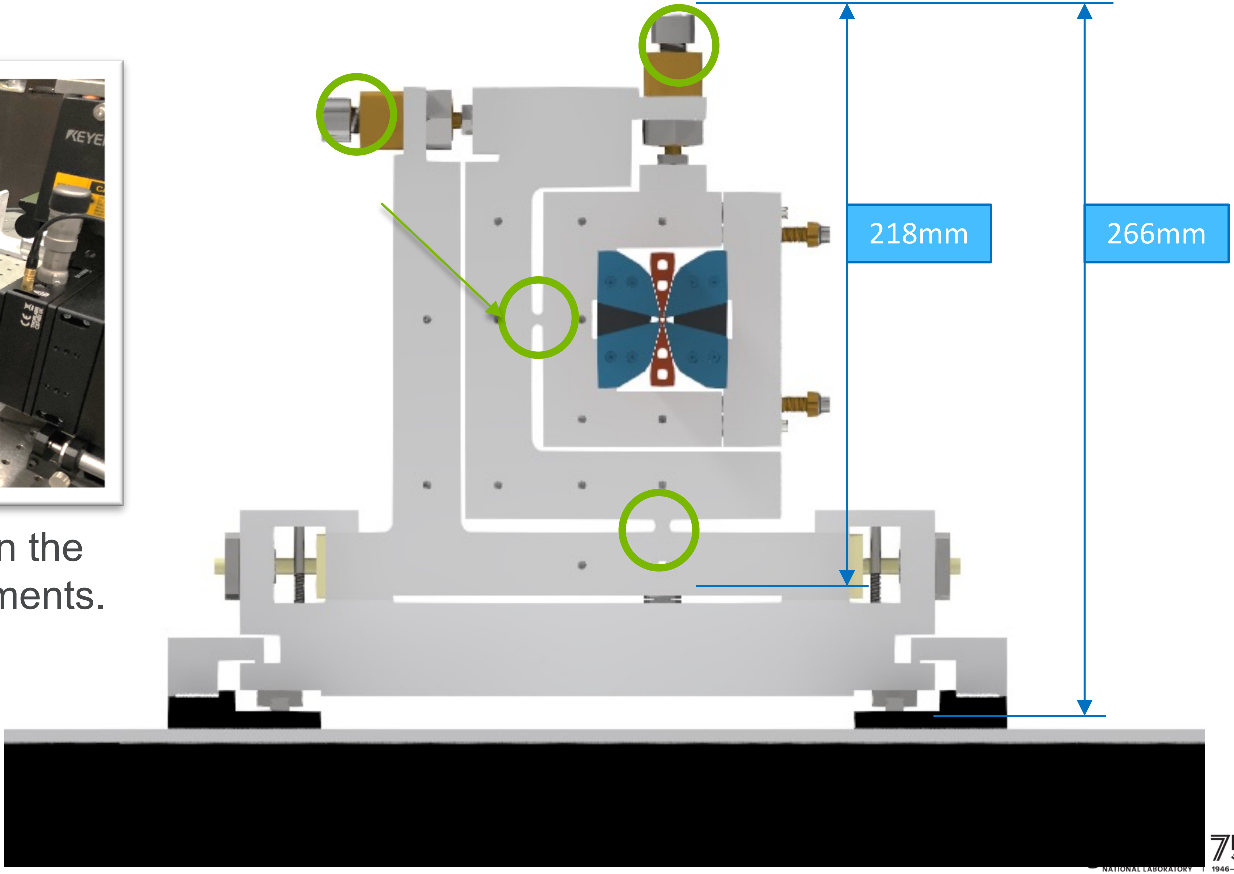


QUADRUPOLE WIGGLER

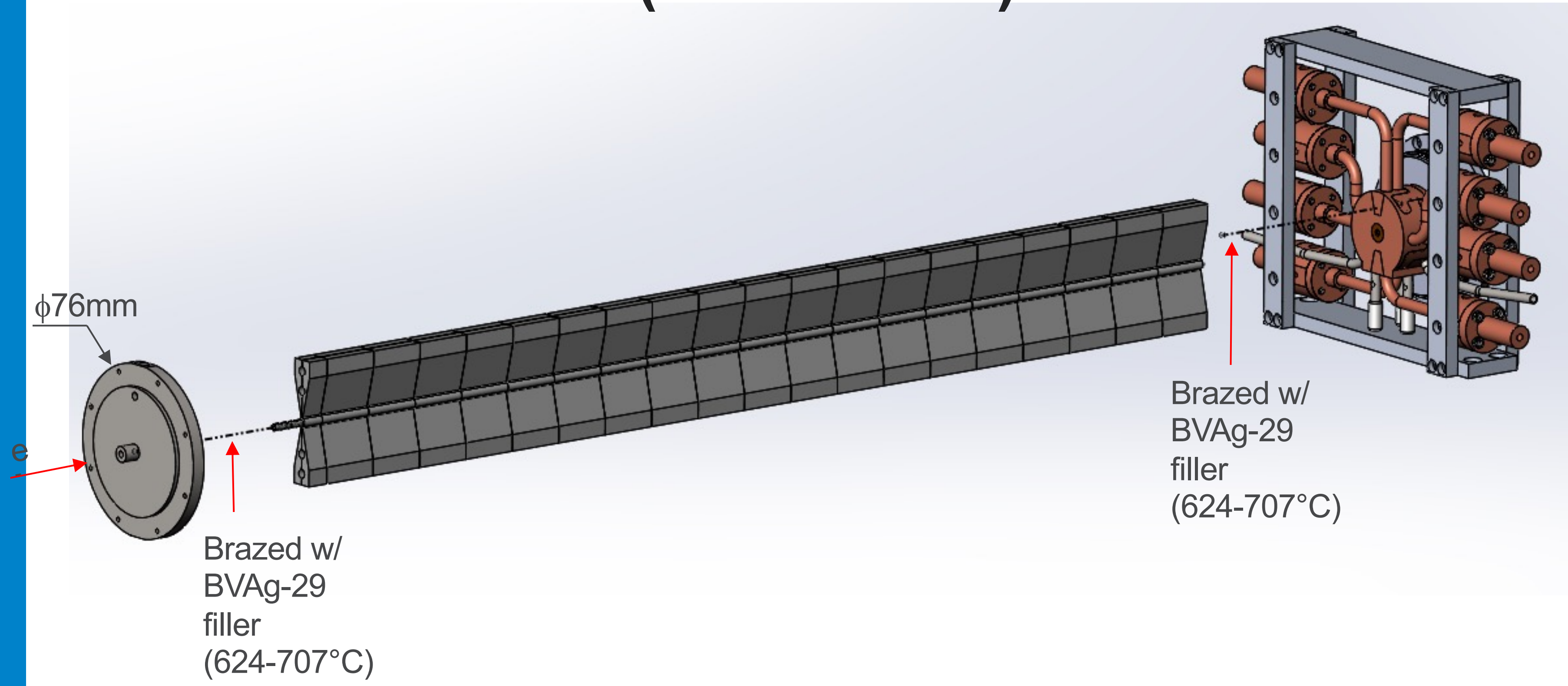
Requirement: quad-to-quad misalignment tolerance ≤ 1 μm



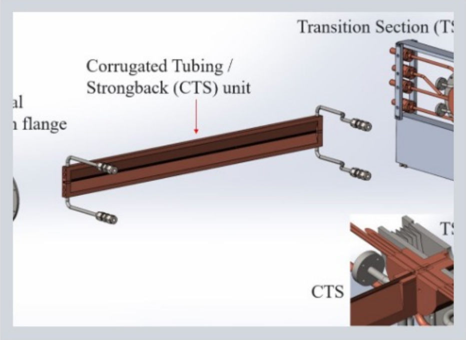
Two prototype quadrupoles on the bench for magnetic measurements.
Bore radius: 1.5 mm;
Gradient: 0.95 T/mm.



CWA ASSEMBLY (CONTINUE)



PUBLICATION – MEDSI2020



[WEPB04] Design and Fabrication Challenges of Transition Section for the CWA Module

An effort to build Argonne's Sub-THz AcceleRator (A-STAR) for a future multiuser x-ray free-electron laser ...

Live presentation starts on 07/28/2021

Presenters

Soonhong Lee
Principal Mechanical ...
Argonne National La...

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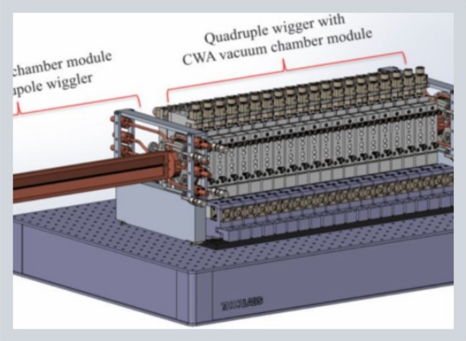

[WEPB05] Mechanical Design of a Compact Collinear Wakefield Accelerator

The Argonne National Laboratory is developing a compact collinear wakefield accelerator (CWA) based on...

Live presentation starts on 07/28/2021

Presenters

Soonhong Lee
Principal Mechanical ...
Argonne National La...

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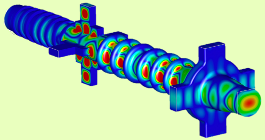
MULTIPHYSICS FEA

MULTIPHYSICS FORMULATION

CST® Microwave Studio



EM equation &
resistive Power loss

Surface Heat →

Fully Coupled Solution

Heat Transfer Module
Conduction and Convection
Temperature

Temperature →

Structure Mechanics Module
Displacement and Stress

↓ Heat Removal

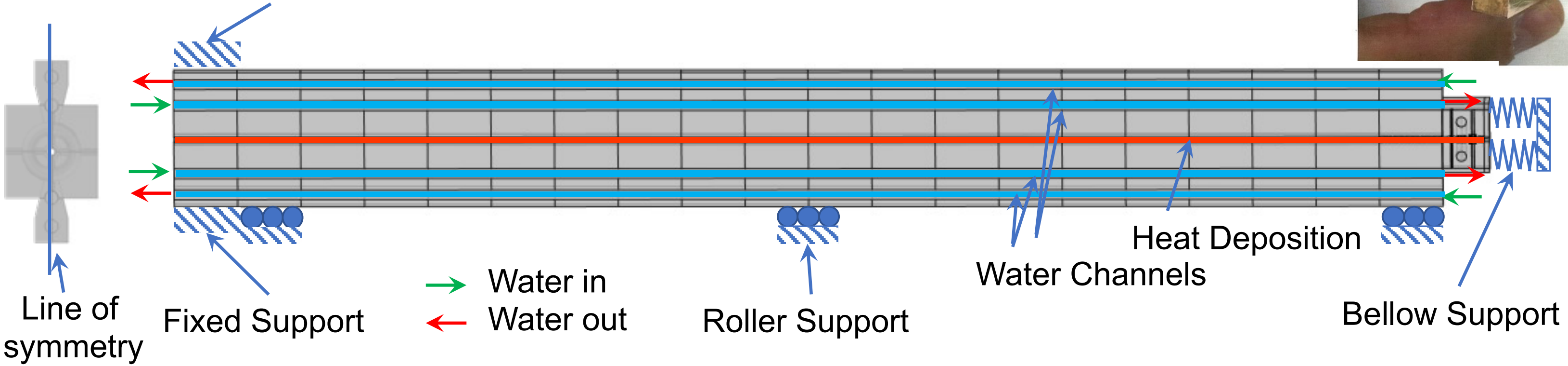
Computational Fluid Dynamics Module
Flow and Convection

Result ↓

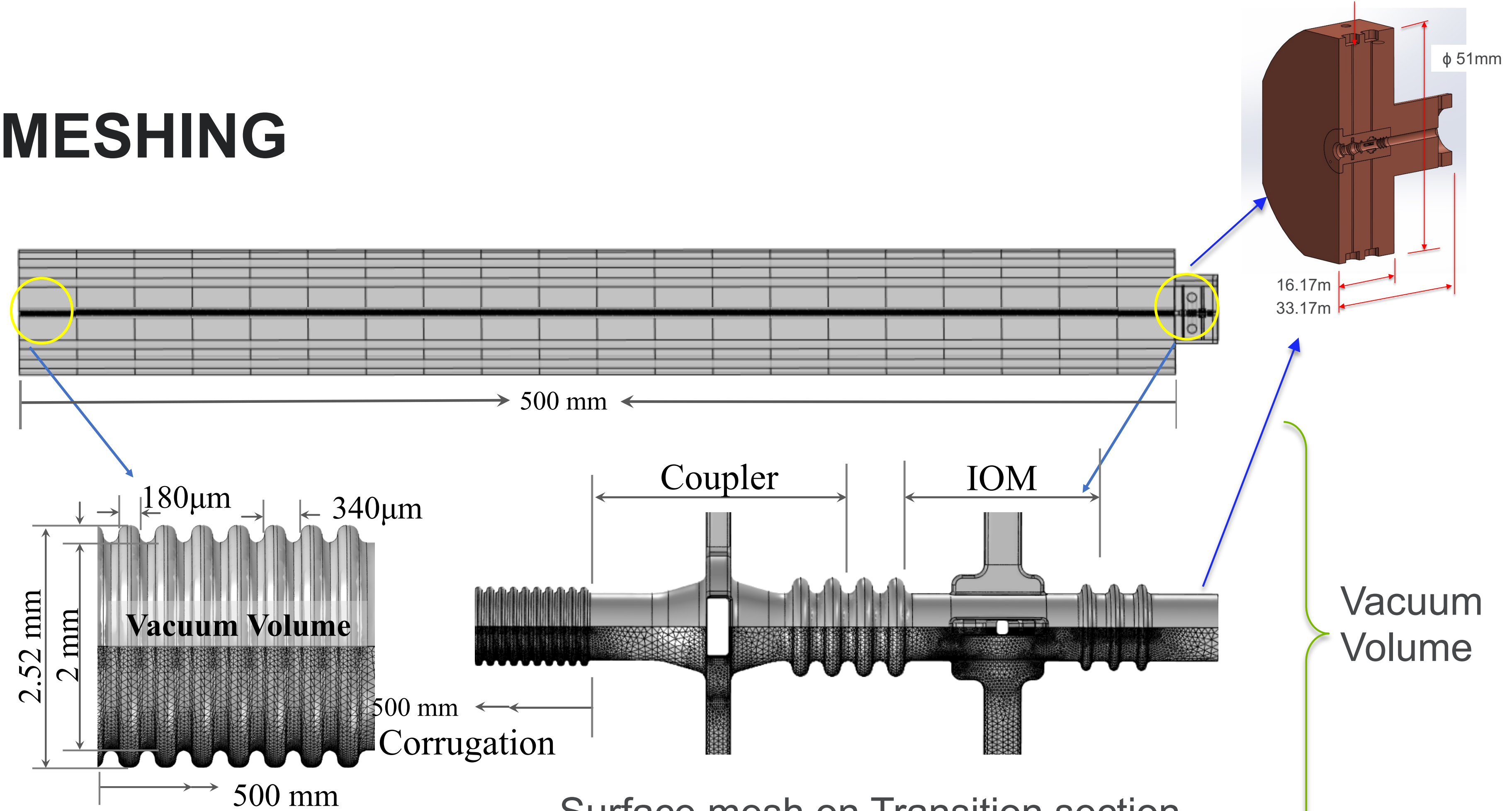
Deformation and thermal stress

COMPUTATIONAL MODEL

Boundary Conditions



MESHING



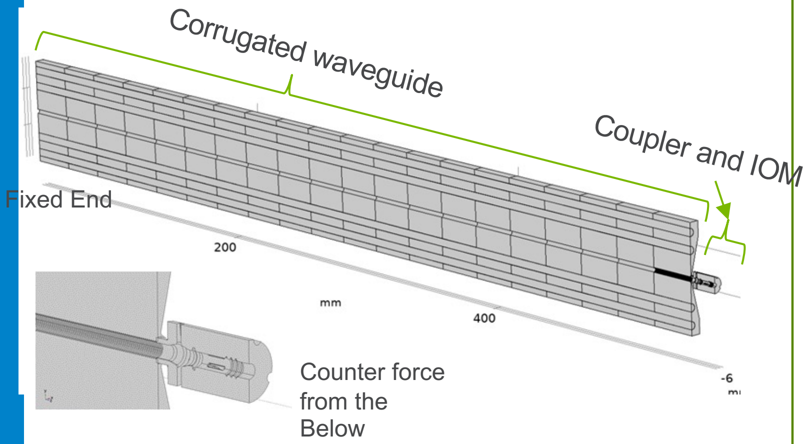
Surface mesh on Transition section

PARAMETERS

- Rep rate vs heat load

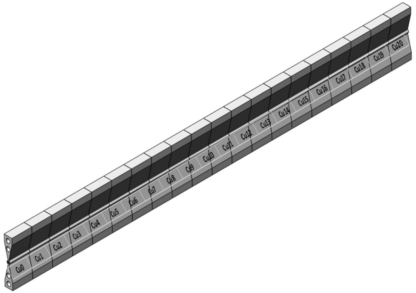
Parameters	Rep. Rate (kHz)	Heat Load (W)
1	10	590
2	20	1181
3	30	1771
4	40	2362

HEAT LOAD -10KHZ



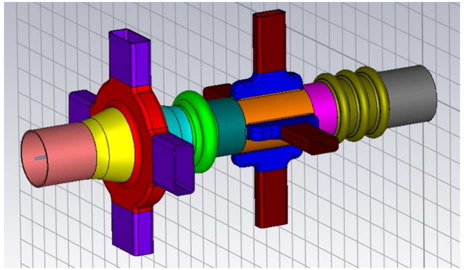
- Bunch charge: 10 nC (180GHz Modified Bane function)
- Repetition rate: 50 kHz
- Copper reduced conductivity: 2.3e7 S/m
- Total power in Cu: 21.81W (after ~4ns)
- Bunch loss factor: 46.76W

Corrugated Waveguide



Location	MWS result	Losses (W) (10nC / 10kHz)
Bp In	2745	0.03
Bp Out	1.11E+05	1.11
Cu 1	3.94E+05	3.94
Cu 2	9.90E+05	9.90
Cu 3	1.48E+06	14.80
Cu 4	1.91E+06	19.06
Cu 5	2.24E+06	22.40
Cu 6	2.54E+06	25.45
Cu 7	2.77E+06	27.71
Cu 8	2.99E+06	29.90
Cu 9	3.14E+06	31.40
Cu 10	3.30E+06	33.00
Cu 11	3.40E+06	34.00
Cu 12	3.52E+06	35.20
Cu 13	3.58E+06	35.80
Cu 14	3.67E+06	36.70
Cu 15	3.70E+06	37.00
Cu 16	3.77E+06	37.70
Cu 17	3.79E+06	37.88
Cu 18	3.84E+06	38.44
Cu 19	3.85E+06	38.49
Cu 20	3.96E+06	39.57
Total	58947445	589.47

Transition Section



Part Name	Color	Power [W]	Area [mm^2]	[W/cm^2]
Cyl_WG_In		156mW	12.56	1.24
Taper_In		267mW	10.20	2.62
TM01_Cavity		16.93W	32.35	52.3
TM01_WR_Out		2.39W	31.45	7.60
Taper_Out		284mW	10.20	2.78
TM01_Convolution		366mW	12.40	2.95
TM01_IOM_Spacer		130mW	7.23	1.80
IOM_Cylinder_Wall		209mW	11.54	1.81
IOM_Step		138mW	20.56	0.67
IOM_WR_Out		47mW	25.01	0.19
IOM_Notch_Spacer		97mW	5.93	1.64
IOM_Notch_Filter		651mW	22.48	2.90
Cyl_WG_Out		143mW	12.56	1.14

TM01_Cavity has high Q ringing at 110GHz. Simulation results are extrapolated to estimate total power loss.

THERMAL STRESS

Thermal Stress and Strain

CTE: $\alpha = 17.7{\times}10^{-6}\ m/m/C^o$
Volume average temperature rise:

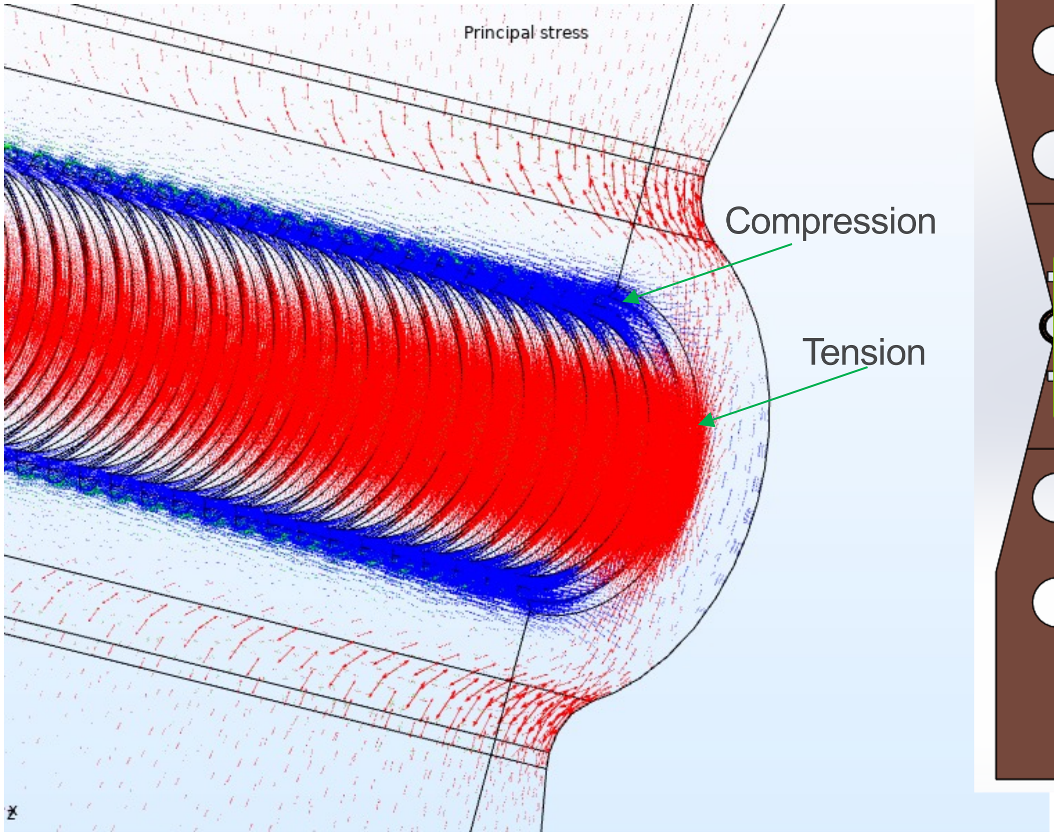
$$T = 5.5℃$$

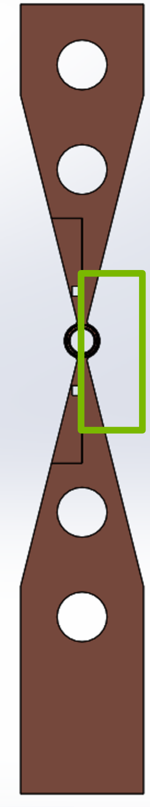
Length: $L = 0.5m$
Thermal Strain :$\frac{\varepsilon_T}{L} = \alpha T$
Thermal Expansion :$\Delta L = 48.675\mu m$
Thermal Stress: $\sigma_T = \varepsilon_T E$
Mod. Of elasticity: $E = 110GPa$

$$\sigma_T = \frac{48.675\mu m \cdot 110\ GPa}{0.5m}$$

$$Average\ stress:\ \sigma_T = 10.7\ MPa$$

Principal Stress

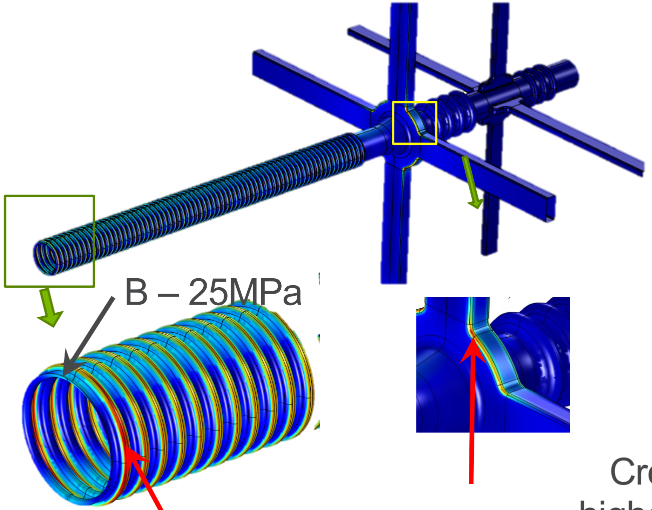


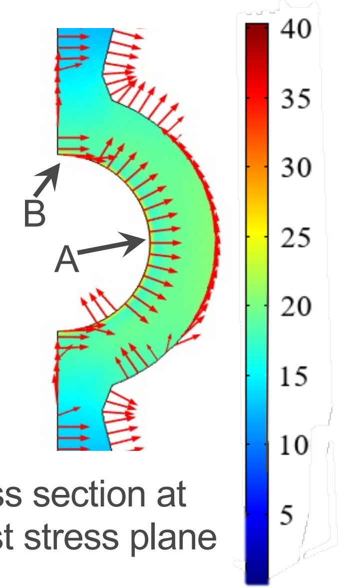


Principal Stress in Tension

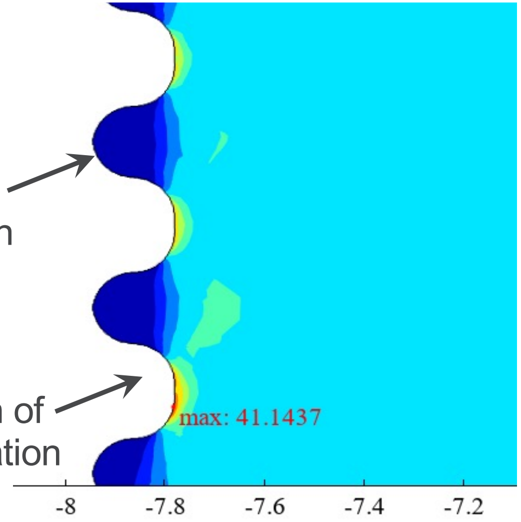
Principal Stress in compression

SURFACE STRESS





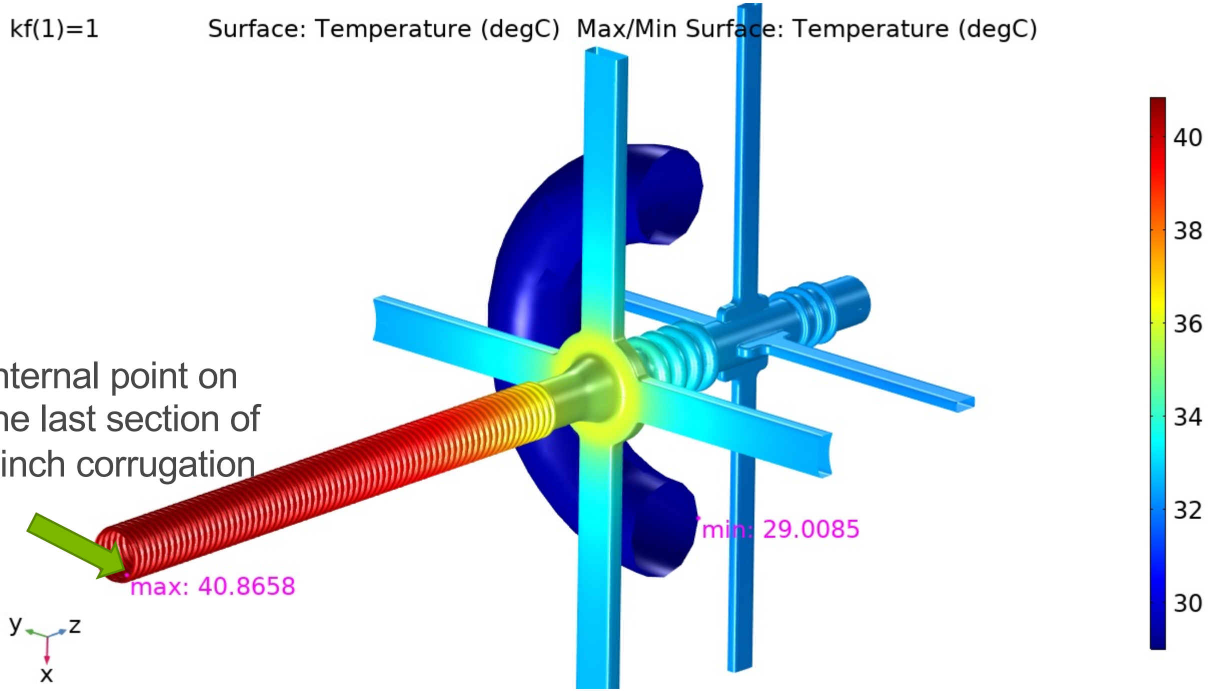
Von Mises Stress Profile



Stress in Corrugation

TEMPERATURE PROFILE FOR CASE # 1 (HEAT LOAD 590W)

Parameters 10kHz

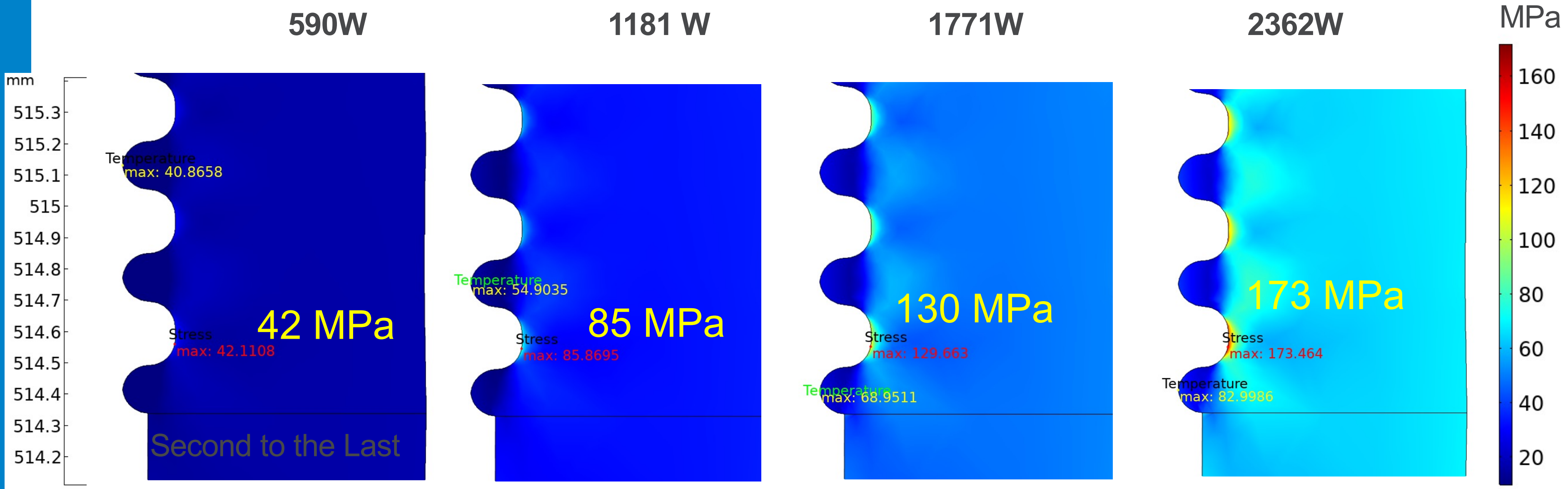


Internal point on the last section of 1inch corrugation

STRESS PROFILE WITH MAXIMUM TEMPERATURE MARKED ON THE THINNEST SECTION OF THE CORRUGATION

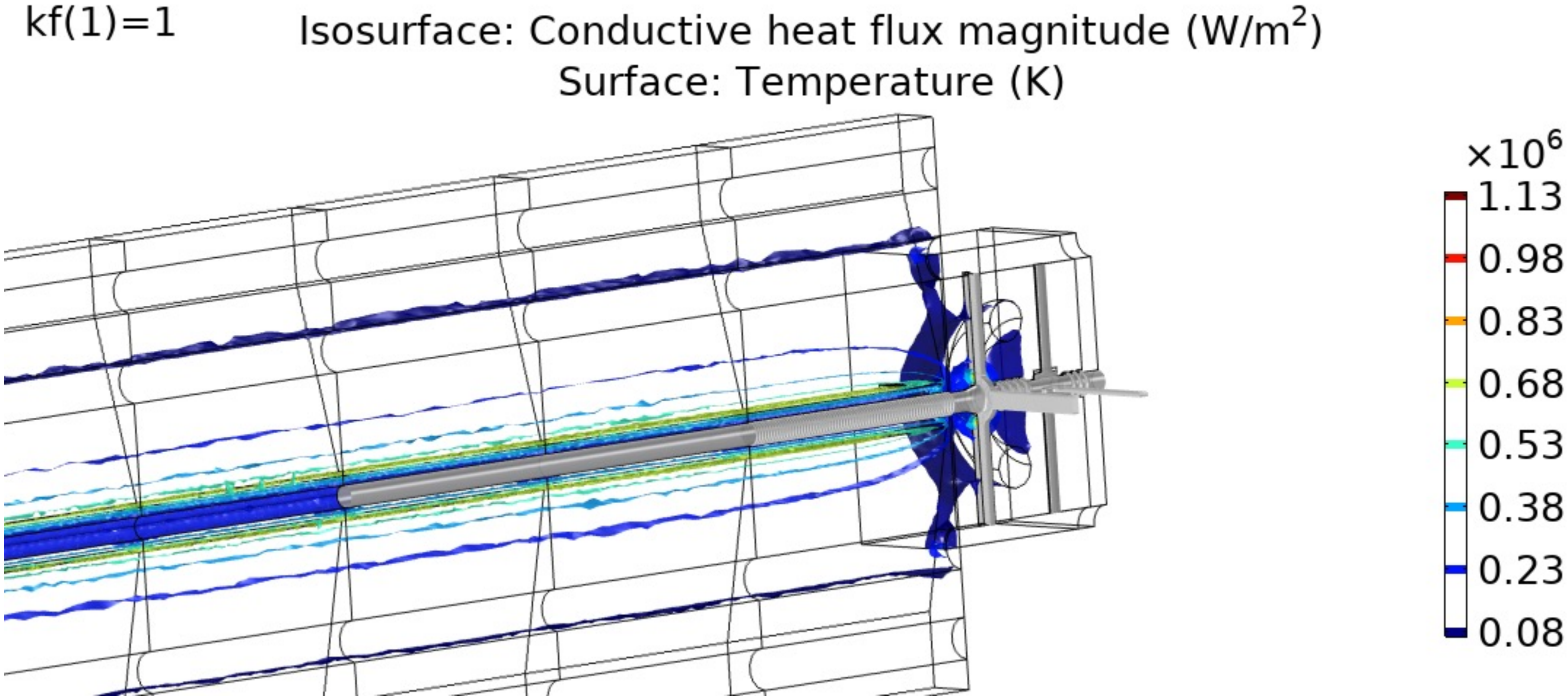
Last few Corrugation Sections

10 kHz	20 kHz	30 kHz	40 kHz
590W	1181 W	1771W	2362W

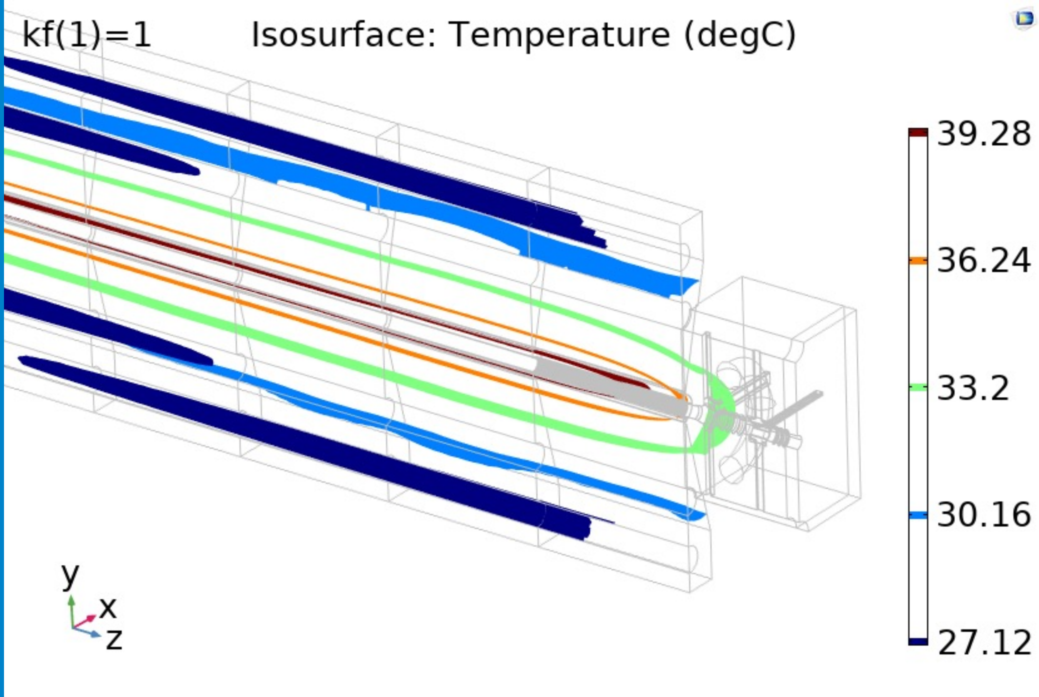


40.86 C	54.9 C	68.9 C	82.9 C

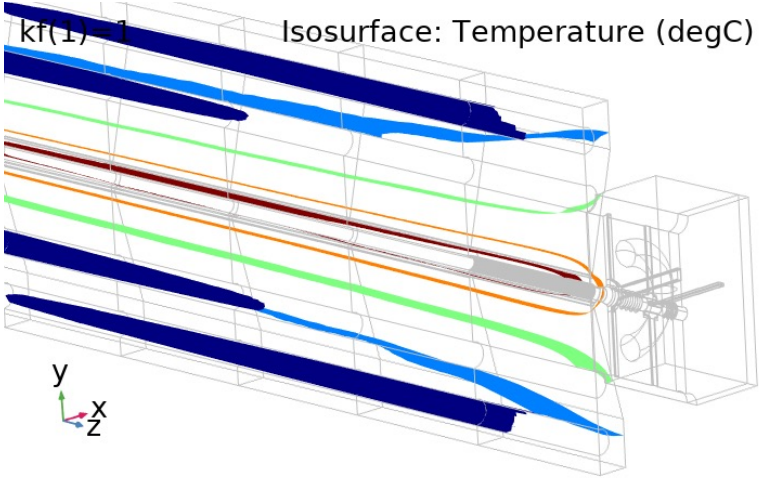
ISOSURFACE OF TEMPERATURE AND HEAT FLUX



TEMPERATURE COMPARISON

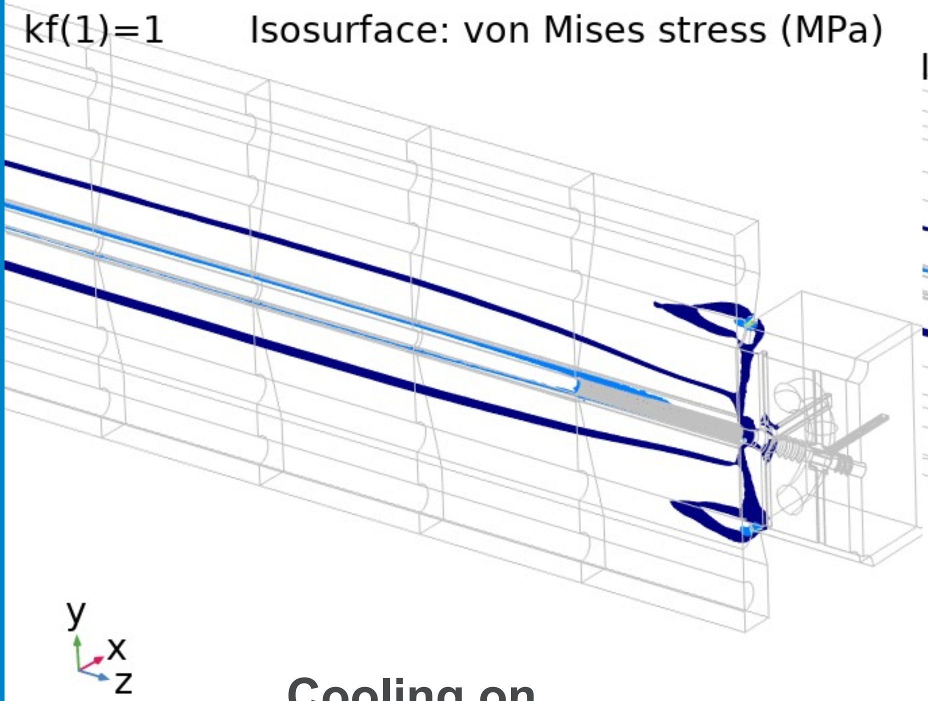


Cooling on

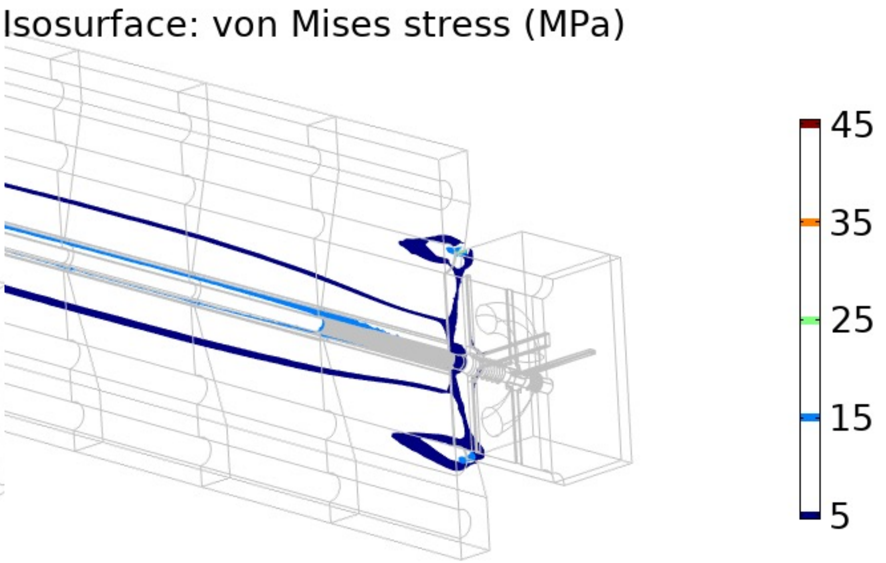


Cooling Off

STRESS COMPARISON

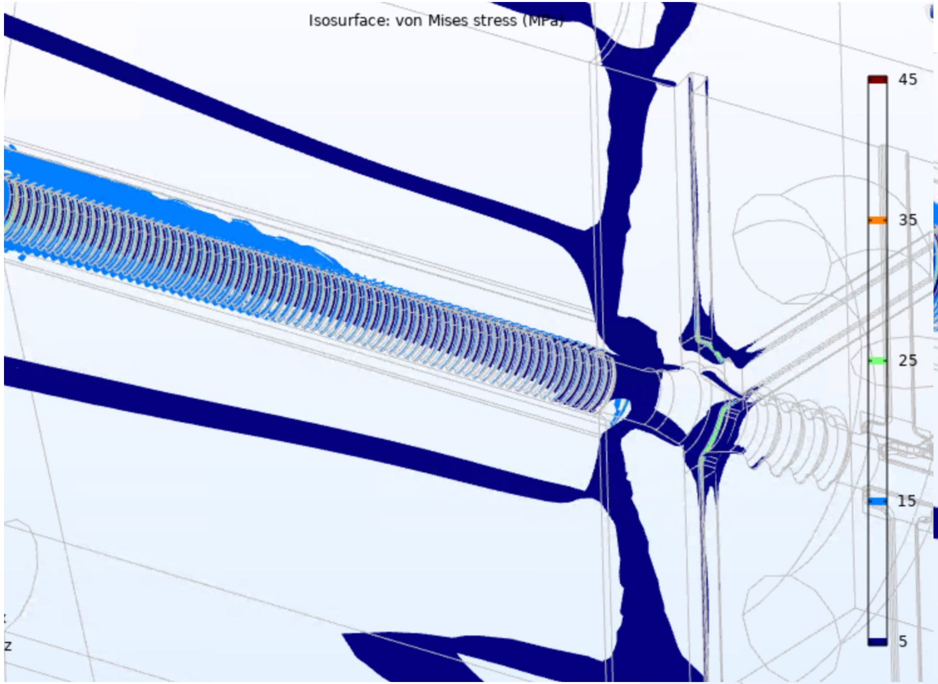


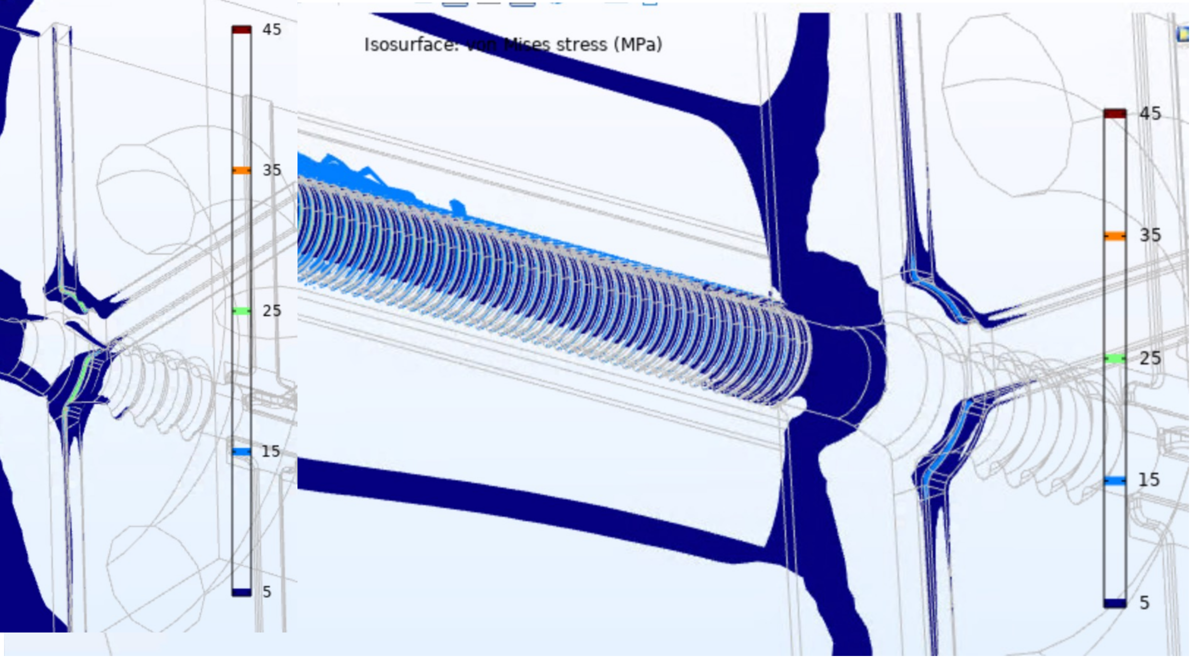
Cooling on



Cooling Off

STRESS COMPARISON





Cooling on

Cooling Off

CONCLUDING SLIDE

- The accelerator design is primarily controlled by thermal stress at the trough region
- Thermal load is linearly increasing along the length.
- The maximum temperature doesn't occur at the extreme end rather it is occurring 5-10 mm away from the end towards the upstream
- Therefore, the trough area near this end of the corrugation showed higher stress
- In order to reduce the thermal stress and equalize the heat distribution we decided not to cool transition section, which has improved the thermal stress by expansion.
- We were able to optimize the rep-rate to **15 kHz** level as compared to an excessive cooling design which showed 11 kHz of heat load as maximum possible limit.

FABRICATION

PROTOTYPING BY ELECTROFORMING

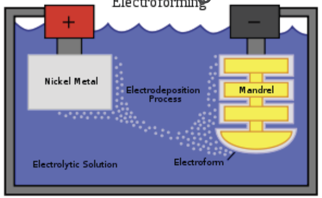
Step 1: Mandrel Design

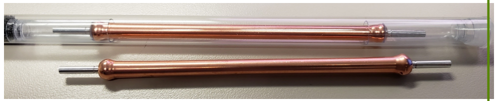
The mandrel is the base machined component, typically made from Aluminum 6061T which defines the internal geometry of an electroform.

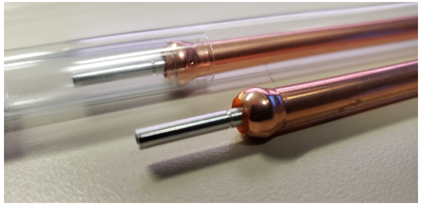
Step 2: Machining

Electroforms can be manufactured to
less than a 0.5mm diameter with a wall thickness
of less than 0.008mm.

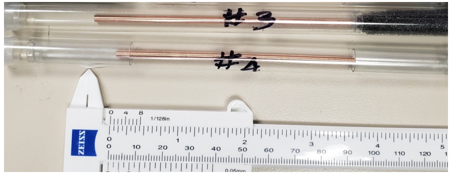
Step 3: Electroforming



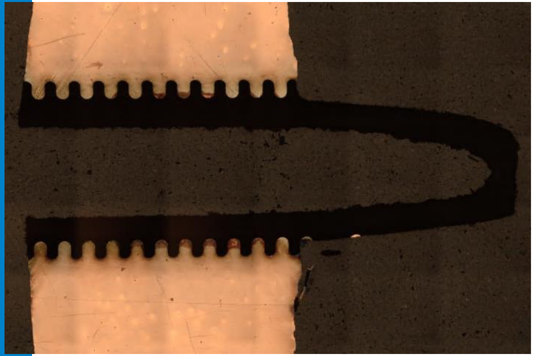


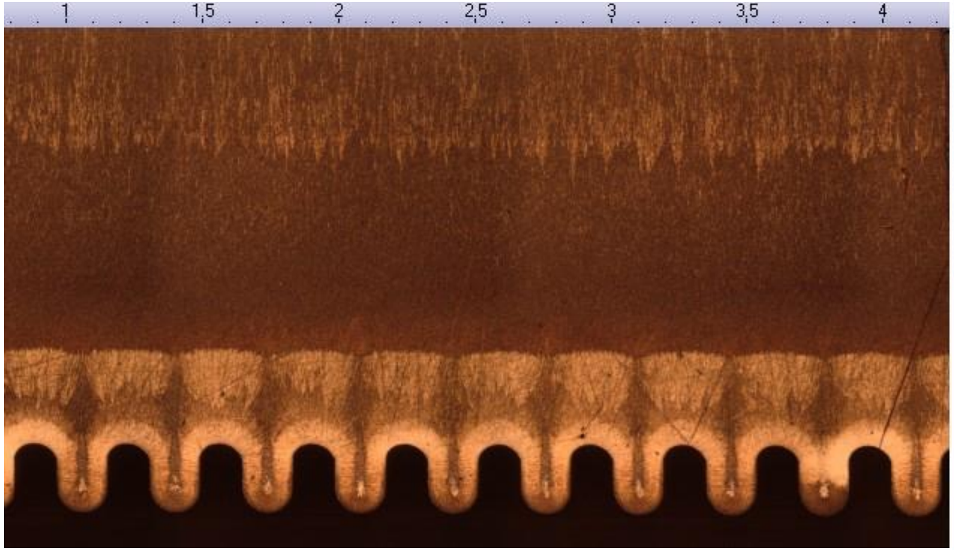


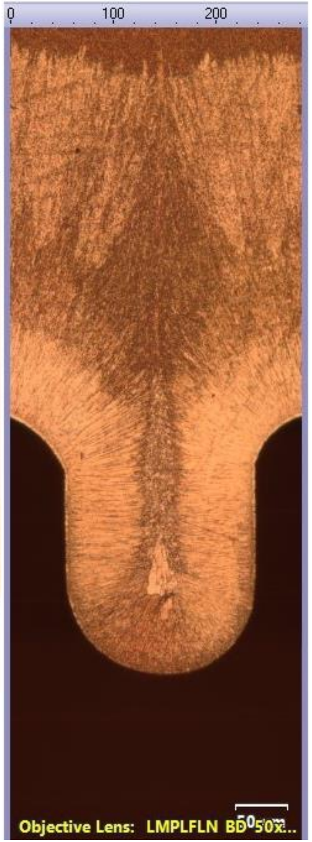
Step 4: Removing the Mandrel



AFTER IMPROVED DESIGN



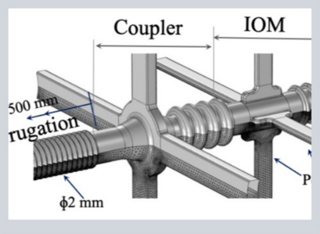




[TUPC01] Study of Copper Micro Structure Produced by Electroforming for the 180 GHz Frequency ...

Fabrication of the corrugated structure that generates a field gradient 100 m^-1 at 180 GHz is challenging...

A-STAR DEVICE GROUP PUBLICATION



[TUPB06] Design of Miniature Waveguides and Diamond Window Assembly for RF Extraction and V…

This paper outlines the design of a diamond vacuum window and a millimeter wavelength (mmWave) wav…

Live presentation starts on 07/27/2021

Presenters

Kamlesh Suthar
Principal Mechanical …
Argonne National La…

Alexander Zholents
Scientist
ANL

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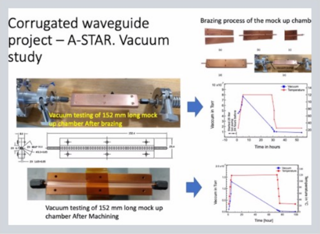

[TUPB07] Vacuum Analysis of a Corrugated Waveguide Wakefield Accelerator

The vacuum level in a 2 mm diameter,0.5 m-long copper corrugated waveguide tube proposed* for a com…

Live presentation starts on 07/27/2021

Presenters

Kamlesh Suthar
Principal Mechanical …
Argonne National La…

Alexander Zholents
Scientist
ANL

54 1 0

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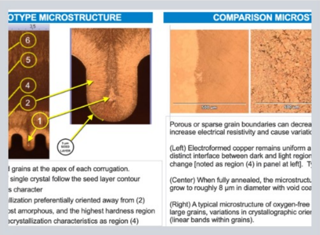

[TUPC01] Study of Copper Micro Structure Produced by Electroforming for the 180 GHz Frequency …

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Presenters

Kamlesh Suthar
Principal Mechanical …
Argonne National La…

Gary Navrotski
Research Engineer
Argonne National La…

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Thank you

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