A 180 GHZ ACCELERATOR MADE FROM ELECTROFORMED COPPER

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1) now at LANL 2) at Quaise Energy

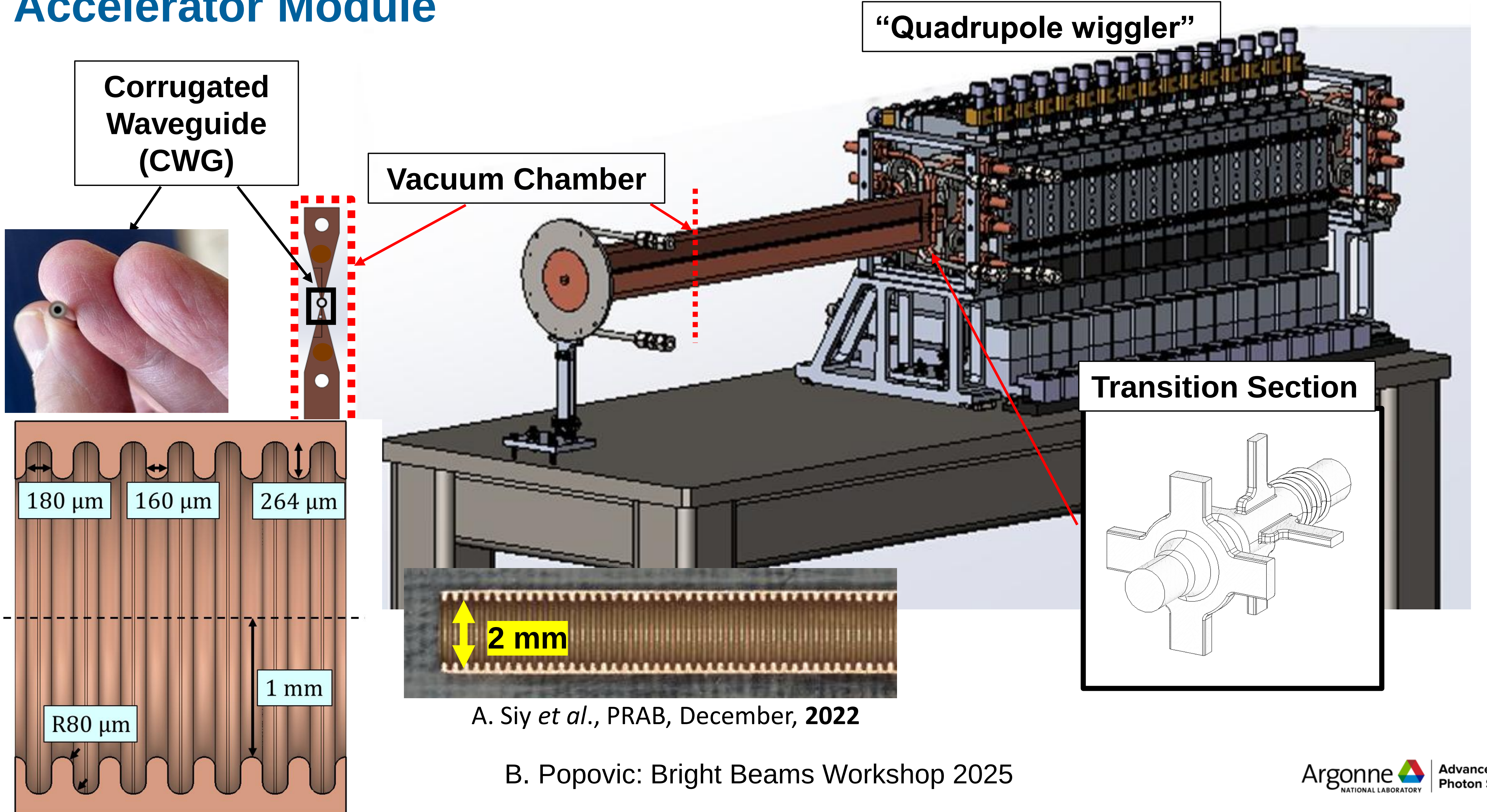
A. Zholents, S. Baturin, S. Doran, W. Jansma, et al., 18 coauthors, "*A high repetition rate millimeter wavelength accelerator for an X-ray free-electron laser*", Journal of Instrumentation, JINST 20 P01023 (2025), https://doi.org/10.1088/1748-0221/20/01/P01023

OVERVIEW

- Motivation
  - Components Beam Tested
- Corrugated Waveguide Interaction Structure
  - Fabrication Techniques Explored
  - Electroforming
- Transition Section Fabrication
  - Brazing Issues
- Future Work

ARGONNE SUB-TERAHERTZ ACCELERATOR: ASTAR

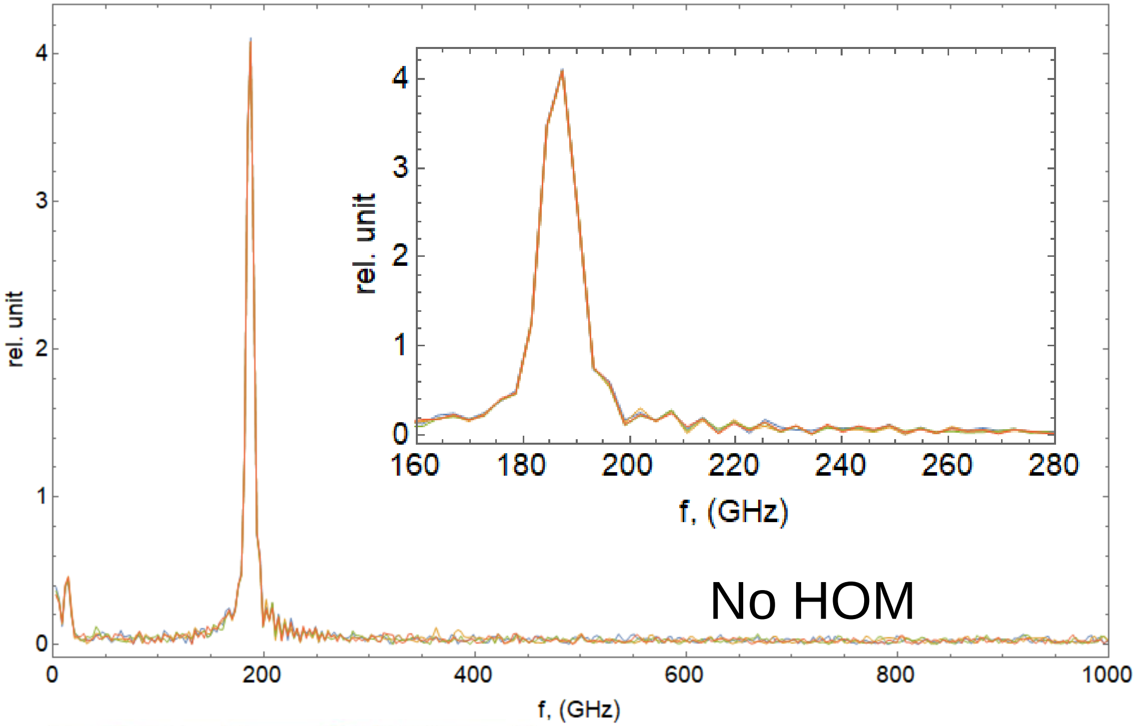
Accelerator Module

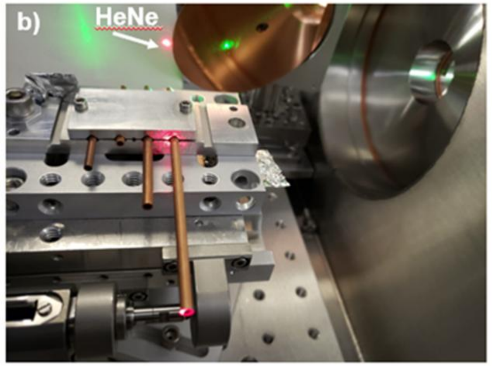


A. Siy *et al.*, PRAB, December, **2022**

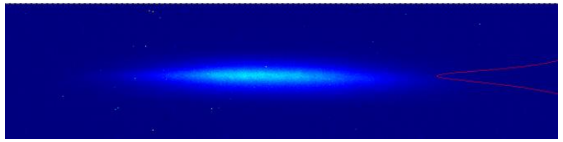
COMPONENTS TESTED AT BNL ATF

Corrugated Waveguide

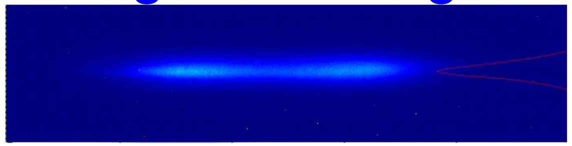




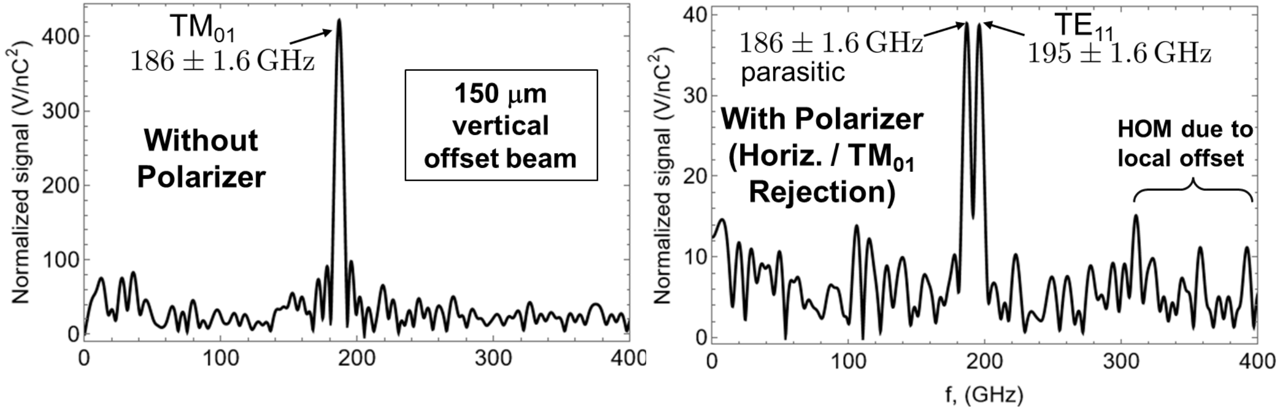
Tube with a smooth wall

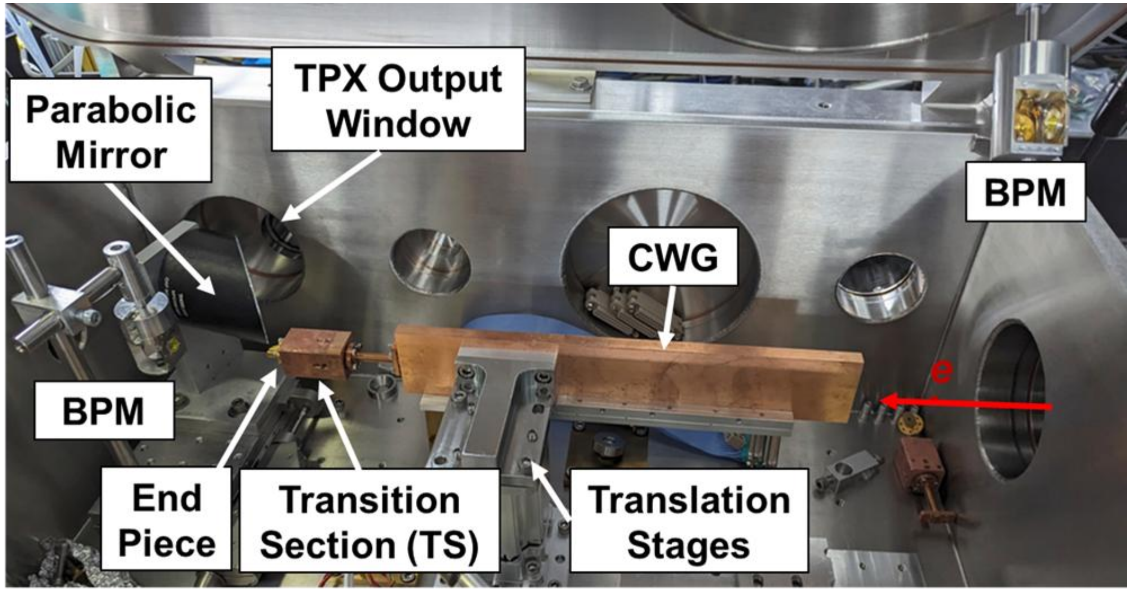


Corrugated Waveguide

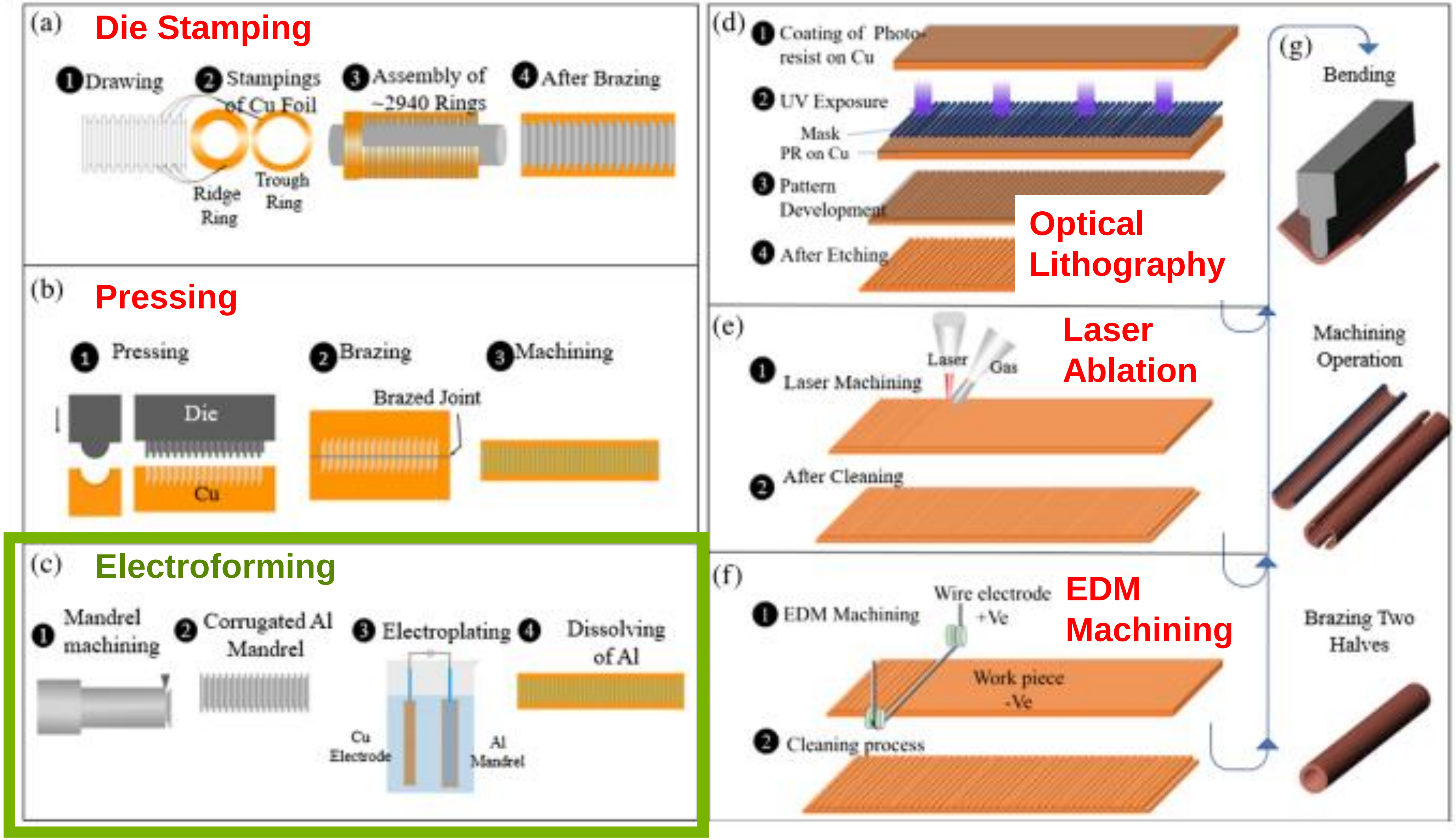


Transition Section

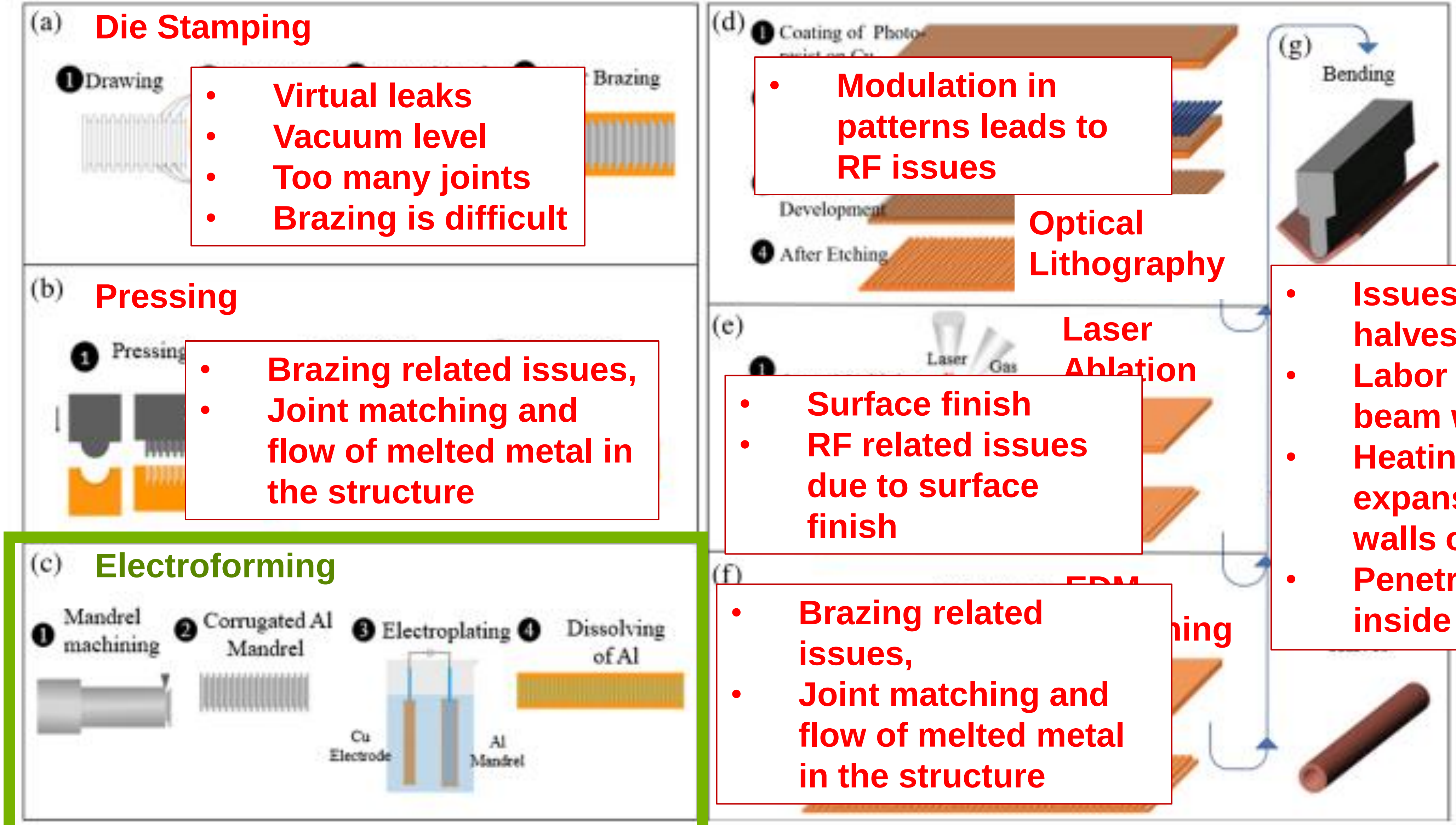




FABRICATION TECHNIQUES EXPLORED



TECHNIQUES EXPLORED



Die Stamping

- Virtual leaks
- Vacuum level
- Too many joints
- Brazing is difficult

Pressing

- Brazing related issues,
- Joint matching and flow of melted metal in the structure

Electroforming

Optical Lithography

- Modulation in patterns leads to RF issues

Laser Ablation

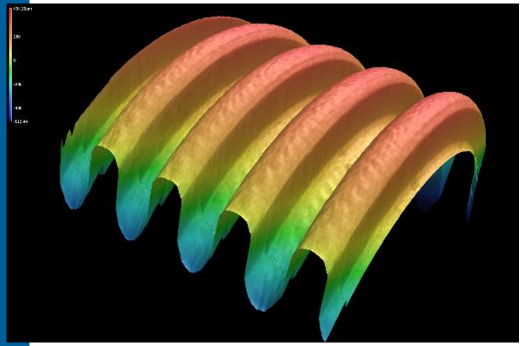
- Surface finish
- RF related issues due to surface finish

- Brazing related issues,
- Joint matching and flow of melted metal in the structure

- Issues joining two halves
- Labor intensive e-beam welding
- Heating and expansion of thin walls of tube
- Penetration of inside tube

Electroforming circular corrugated waveguide

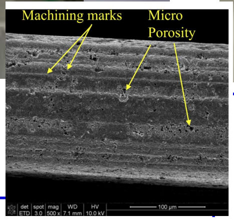
Aluminum mandrel production



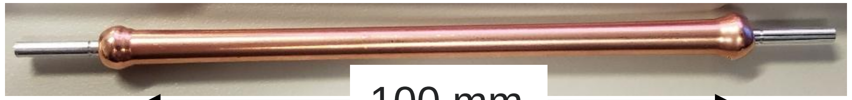
Proprietary micro-machining process
Tooth Height 252.7 μm; error 1.5 μm RMS
Tooth Width 175.9 μm; error 2.0 μm RMS

Mandrel inspection and straightening

using optical comparator



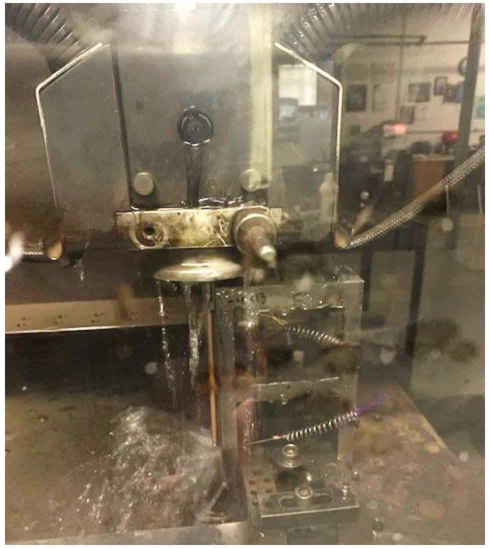
Electroforming



100 mm

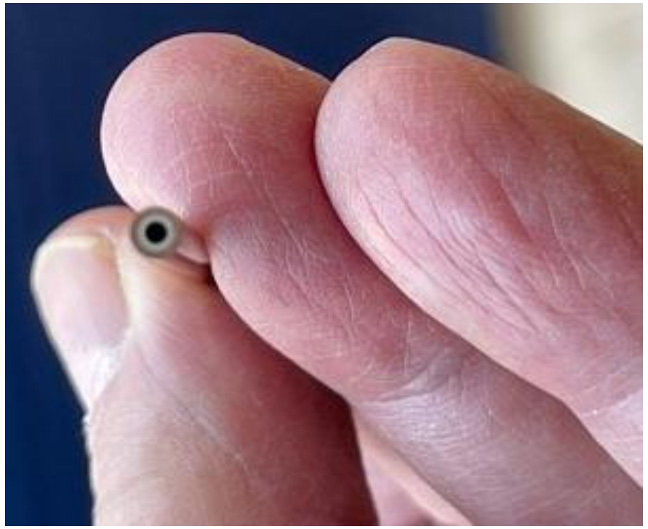
reference groove

EDM of outside diameter OD

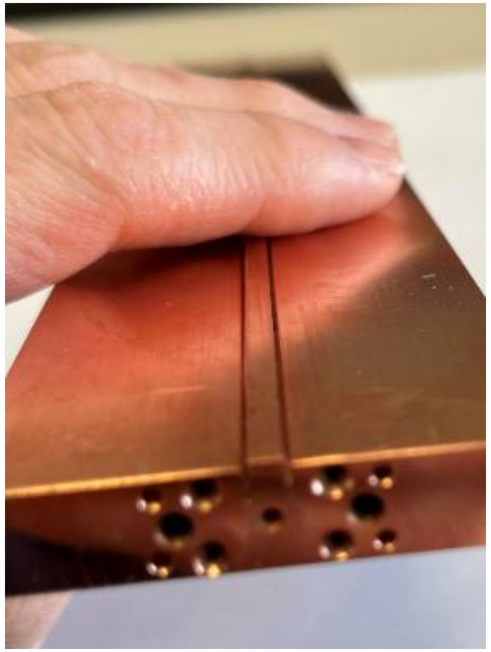


followed by second straightening

Precision cut of edges



followed by aluminum etching

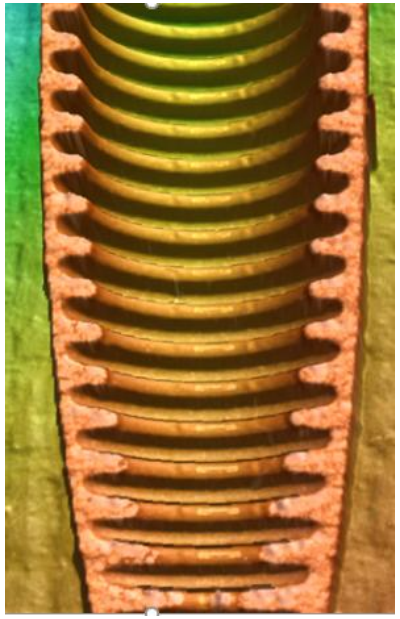


low temperature brazing at 365 ^{o}C
Braze alloy: 88% Au and 12% Ge

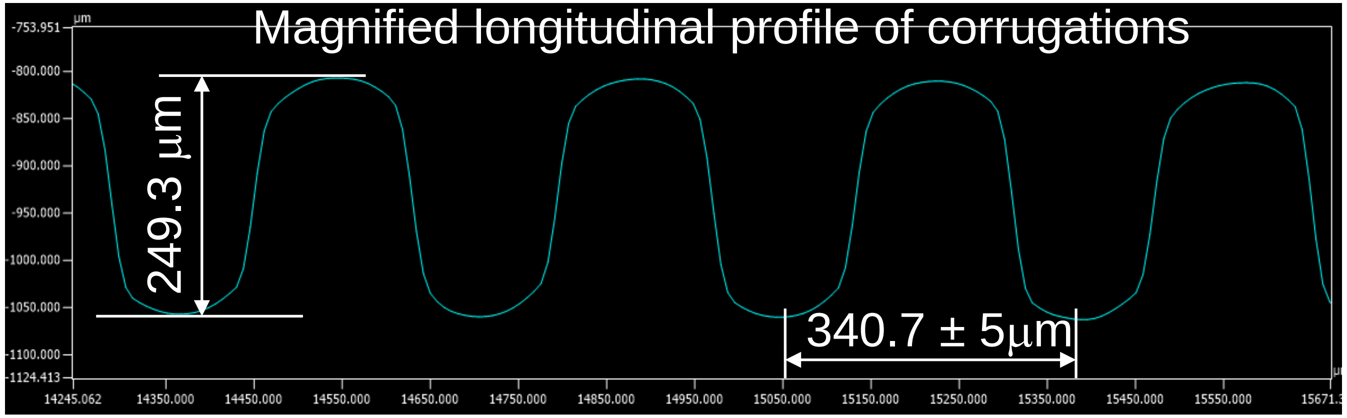
Measurements indicate excellent CWG fabrication quality

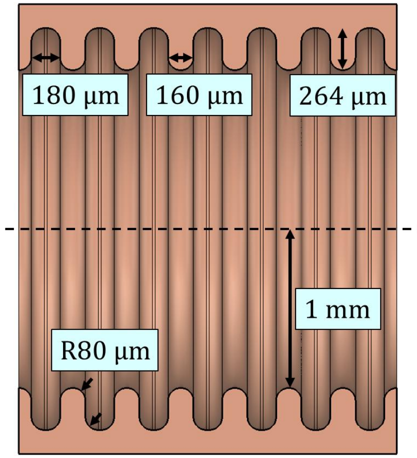
straight cut

Test samples are wire EDM cut to expose the internal corrugations for dimensional analysis

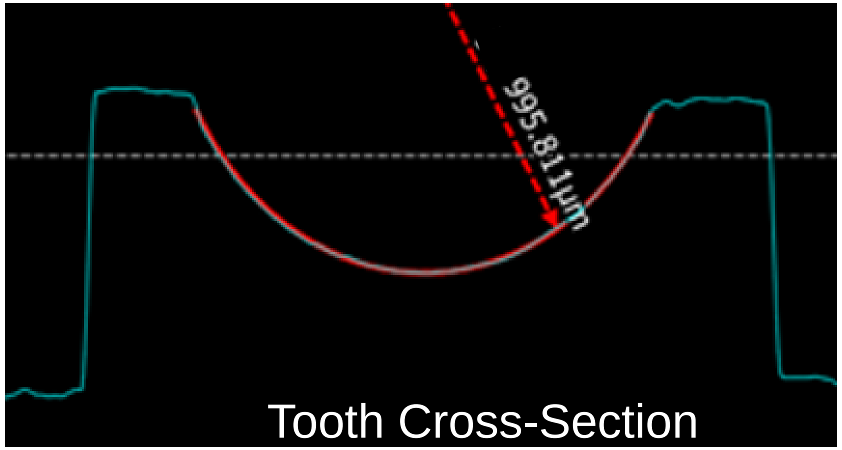


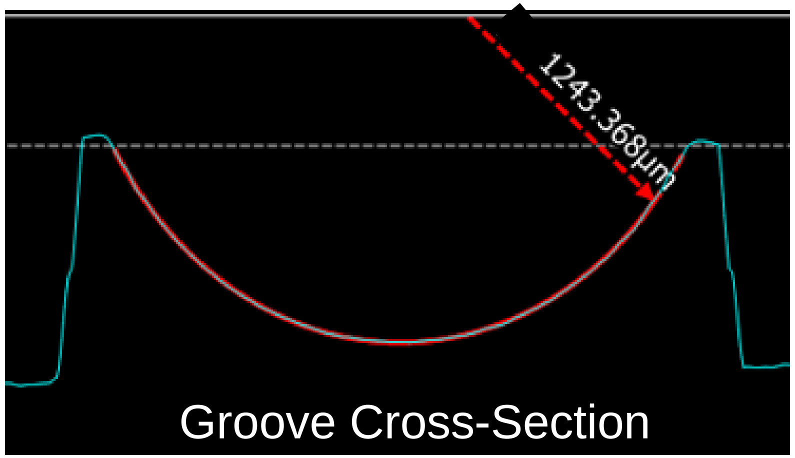
angular cut



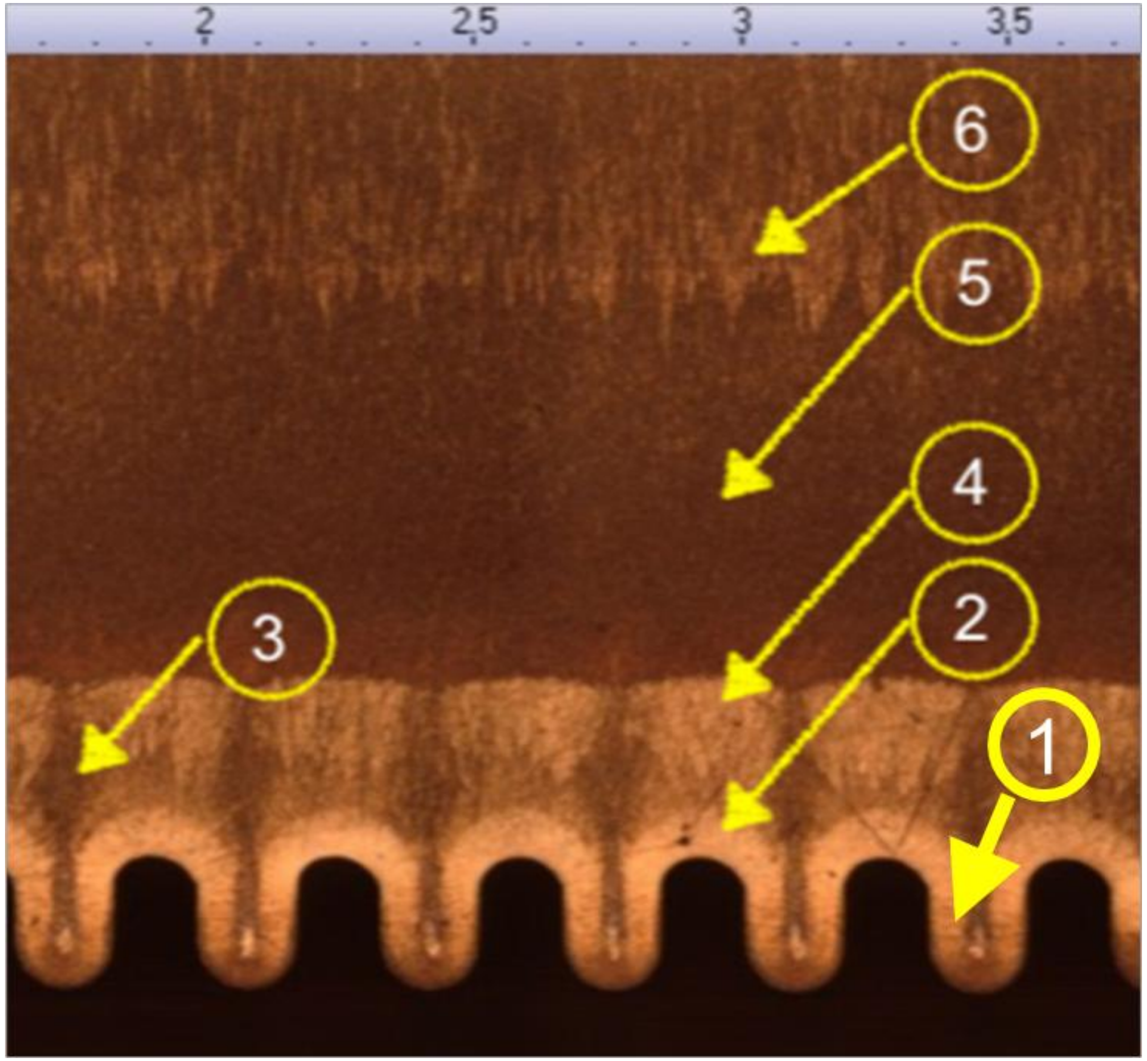


Average height of the corrugations of 249.7 µm was determined.

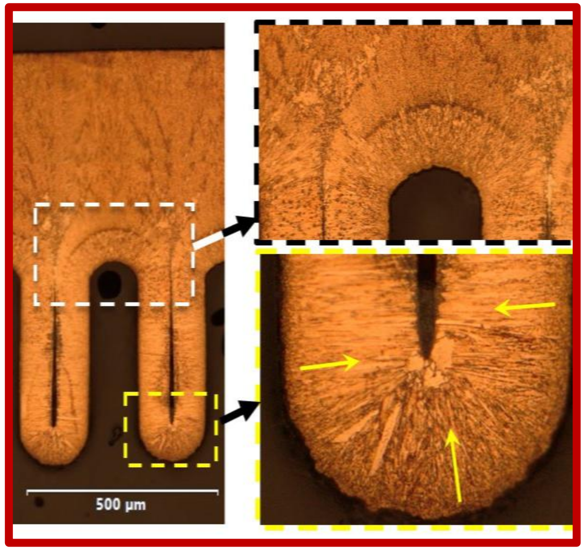




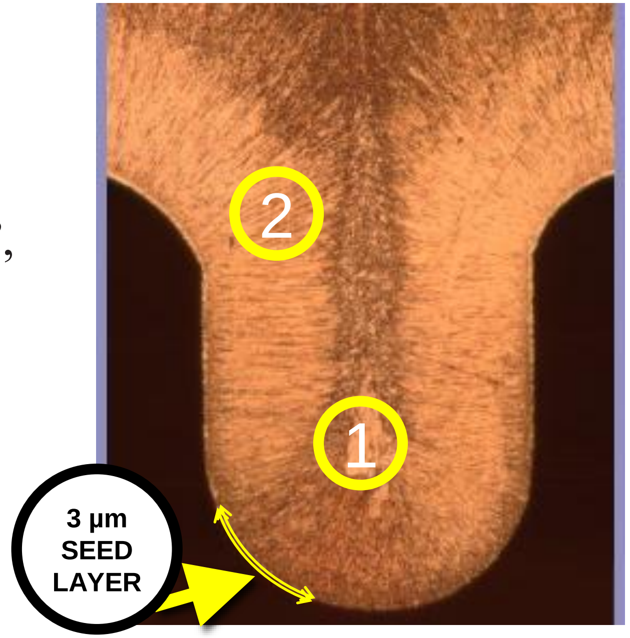
MICROSTRUCTURE OF CORRUGATIONS



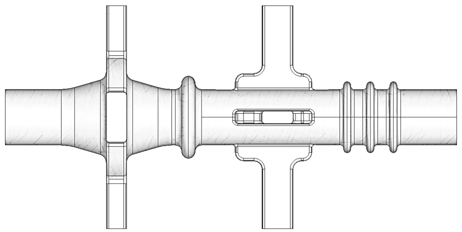
Sample from Servometer Drove Design Constraints



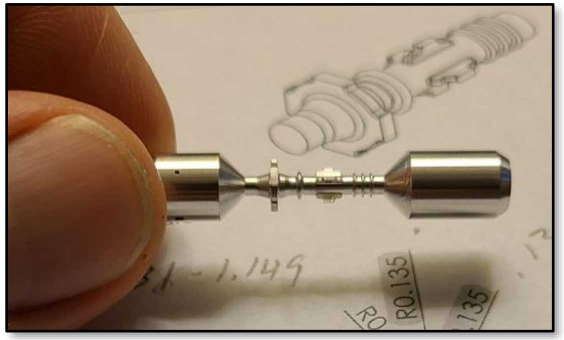
K. Suthar, G. Navrotski, P. Carriere, and A. Zholents, "*Study of copper microstructure produced by electroforming for the 180-GHz frequency corrugated waveguide*", Mech. Eng. Design of Synchrotron Radiat. Equip. and Instrum., MEDSI2020, Chicago,

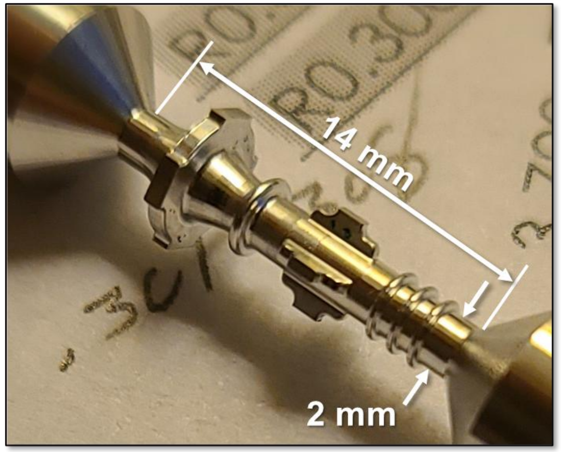


FABRICATION PROCESS: ALUMINUM MANDREL TO TS CORE

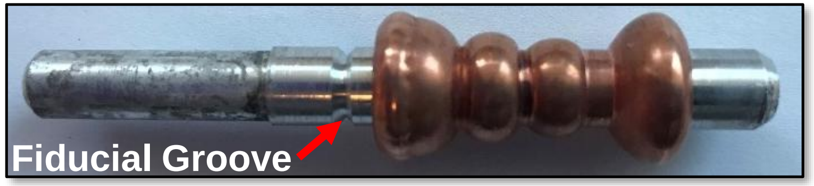


Aluminum Mandrel

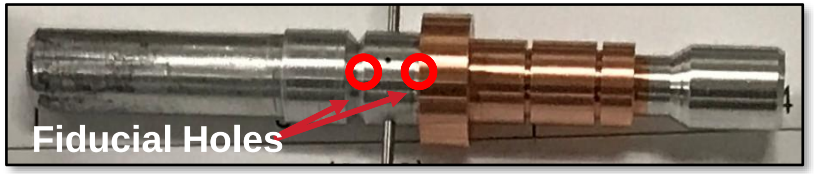




Electroformed Mandrel



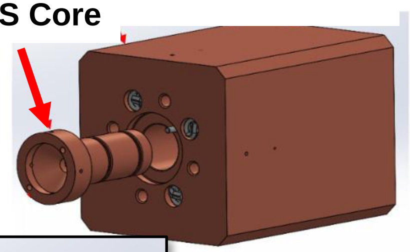
Machined Electroformed Mandrel

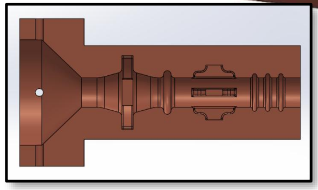


Leached out TS Core & Core Holder

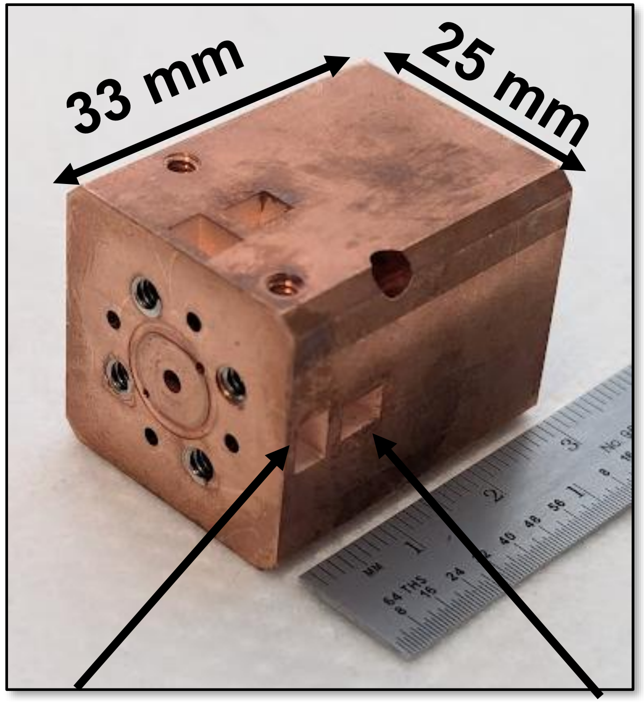
TS Core

TS Core Holder





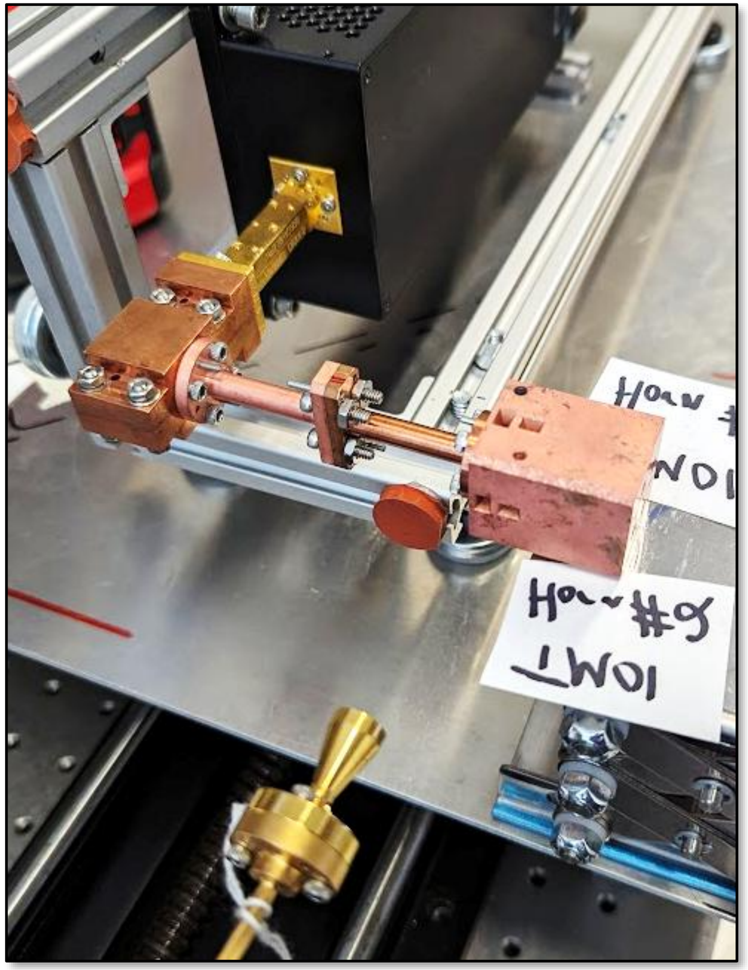
Final Machining and EDM of Horns

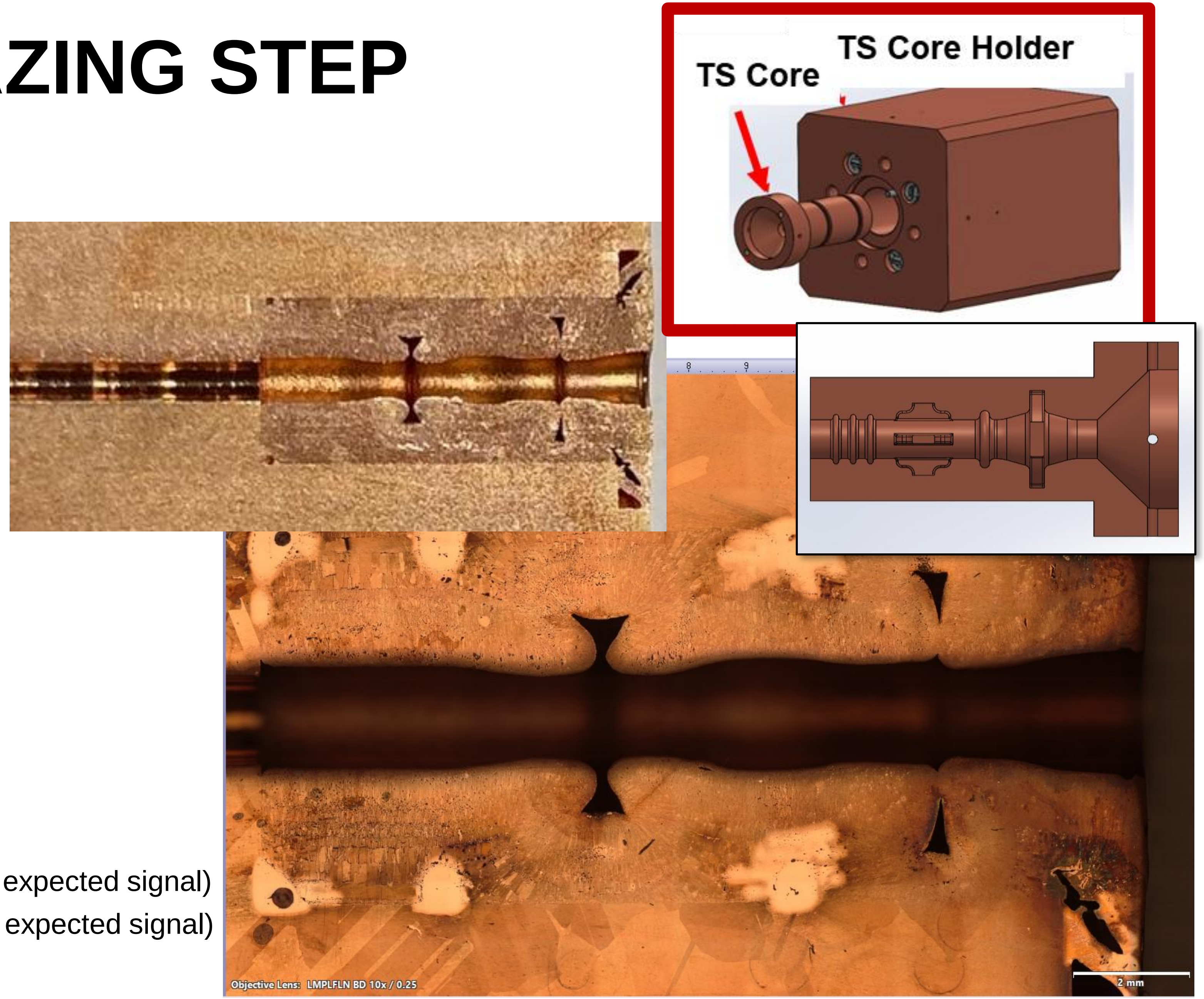


TM_{01} Coupler Horn Antenna, 0.72 mm × 1.78 mm

Integrated Offset Monitor (TE_{11}) Horn Antenna, 1.10 mm × 0.45 mm

ISSUES WITH BRAZING STEP

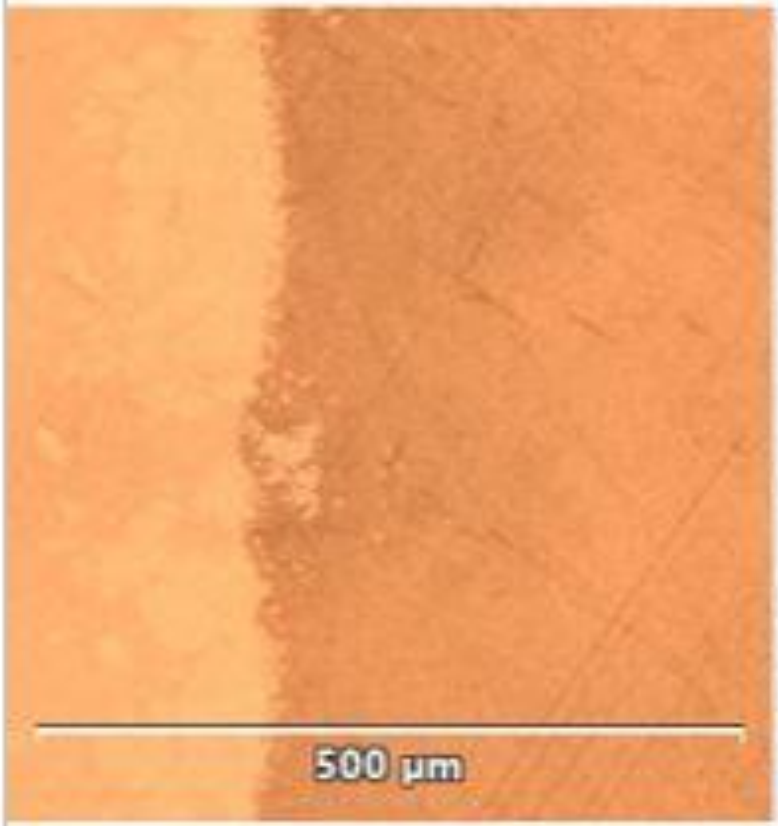




- TM$_{01}$ Coupler signal about -3 dB less (50% of expected signal)
- TE$_{11}$ Coupler signal about -20 dB less (1% of expected signal)

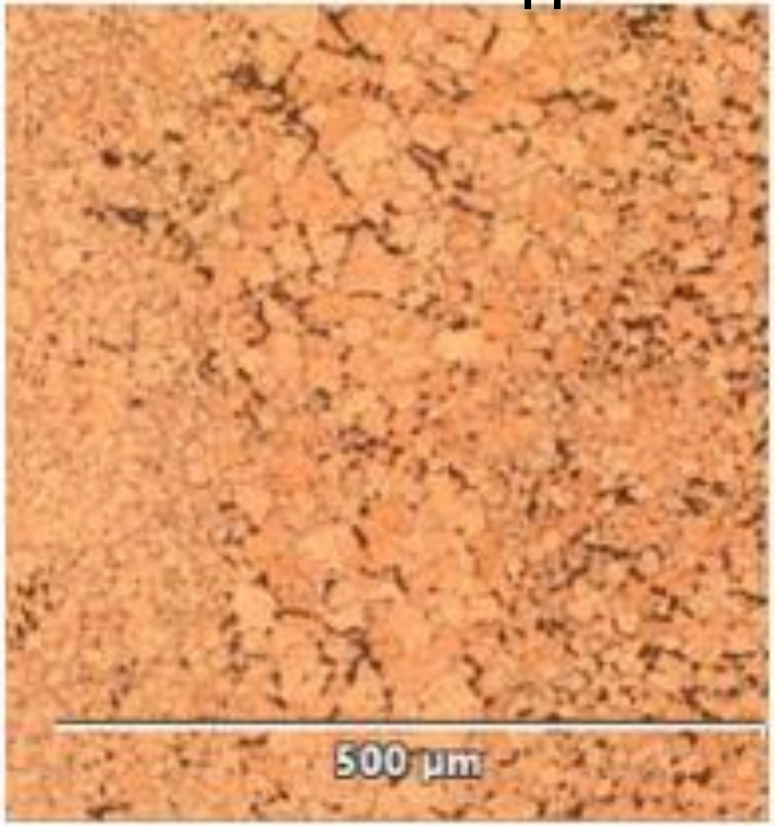
COMPARE MICROSTRUCTURES VS OFHC

Electroformed Copper



Remains uniform and featureless except for the distinct interface between dark and light regions that indicates a material change. Typical grain size is sub-µm.

Fully Annealed Electroformed Copper



Microstructure recrystallizes and, grains grow to roughly 8 µm in diameter with void coalescence at grain boundaries.

Oxygen-Free Copper (UNS C10100)

Note large grains.

FUTURE GOALS

- More closely control electroforming process
  - Understand what happens during brazing
  - Increase yield strength
    - Increasing repetition rate
  - Smaller Grain size
- Measure breakdown field of electroformed copper
  - Physics poorly understood
    - Short pulses
- Simplify mode couplers (transition section) geometry
  - Fundamental mode coupler may not be necessary
  - Simplified diagnostic port geometry
    - Demonstrated good extraction efficiency experimentally
- Other materials? Stainless steel?
  - Stainless steel layer for corrugated waveguide
    - Few factors more than skin depth deposited on copper
      - Avoid different thermal expansion coeff.
        - Steel Alloys?
  - How to deposit this layer?

CONCLUSION

- Design of complex ASTAR elements
- Fabrication of corrugated waveguides and transition section
- Tested at Brookhaven ATF
- Looking to the future for improved design and fabrication
  - Lots of lessons learned!

Thank you

Supporters

S. Baturin[4], P. Piot[5], W.-H. Tan[6] (**Northern Illinois University**);
J. Byrd, D. Mills, G. Navrotski, G. Pile, S. Streiffer **(APS/ANL)**
J. Power **(HEP/ANL)**
C. Jing, A. Kanareykin **(Euclid Technology)**
M. Palmer **(ATF/BNL)**
P. Carriere **(RadiaBeam)**
G. Mouravieff, S. Oliphant **(Precision Manufacturing)**
B. Bentley, D. Leitner, K. Pearson, C. Redding **(LBNL/Engineering/Central Shop)**
J. Conway, N. Kuzmanovic, W. Toter **(ANL/Central Shop)**

4) at ITMO University, 5) at HEP/APS/ANL, 6) at SLAC

Selected Publications

Regarding Fabrication

1. A. Zholents, S. Lee, B. Popovic, M. Fedurin, K. Kusche, W. Li, A. Nassiri, A. Siy, S. Sorsher, K. Suthar, E. Trakhtenberg, and G. Waldschmidt, "*Fabrication and testing of the transition section between modules of a wakefield accelerator*", Phys. Rev. Accel. Beams 27, 081303 (2024), https://journals.aps.org/prab/pdf/10.1103/PhysRevAccelBeams.27.081303
2. A. Siy, N. Behdad, J. Booske, M. Fedurin, W. Jansma, K. Kusche, S. Lee, G. Mouravieff, A. Nassiri, S. Oliphant, S. Sorsher, K. Suthar, E. Trakhtenberg, G. Waldschmidt, and A. Zholents, "*Fabrication and testing of corrugated waveguides for a collinear wakefield accelerator*", Phys. Rev. Accel. Beams 25, 021302 (2022), https://link.aps.org/doi/10.1103/PhysRevAccelBeams.25.021302

Regarding Quadrupole Wiggler

1. M. Qian, M. Kasa, J. Xu, S. Doran, S. Lee, S. Sorsher, N. Strelnikov, E. Trakhtenberg, and A. Zholents, "*Quadrupole wiggler for a collinear wakefield accelerator*", Phys. Rev. Accel. Beams 28, 012401 (2025), https://doi.org/10.1103/PhysRevAccelBeams.28.012401

Publications

Overview

1. A. Zholents, S. Baturin, S. Doran, W. Jansma, et al., 18 coauthors, "*A high repetition rate millimeter wavelength accelerator for an X-ray free-electron laser*", Journal of Instrumentation, JINST 20 P01023 (2025), https://doi.org/10.1088/1748-0221/20/01/P01023

Theory

1. S. Baturin, A. Zholents. "*Upper Limit for the Acceleration Gradient in the Collinear Wake Field Accelerator as a Function of the Transformer Ratio*", Phys. Rev. Acc. and Beams 20, no. 6, June 19, 061302 (2017).
2. S. Baturin, A. Zholents. "*Stability condition for the drive bunch in a collinear wakefield accelerator*", Phys. Rev. Acc. and Beams 21, 031301, (2018).

Design

1. W. Jansma, S. Sorsher, K. Suthar, E. Trakhtenberg, A. Zholents, "*Metrology in the R&D for the high repetition rate multi-user x-ray free-electron laser*", The Journal of CMSC (Autumn 2019).
2. Wei Hou Tan, P. Piot, A. Zholents, "*Formation of temporally shaped electron bunches for beam-driven collinear wakefield accelerators*", Phys. Rev. Accel. Beams, 24, 051303(2021).
3. K. Suthar, E. Trakhtenberg, S. Sorsher, and A. Zholents, "*Vacuum analysis of a corrugated waveguide wakefield accelerator*", Mech. Eng. Design of Synchrotron Radiat. Equip. and Instrum., MEDSI2020, Chicago, IL, p.160, 2021, doi:10.18429/JACoW-MEDSI2020-TUPB07 .
4. K. Suthar, A. Siy, G. Waldschmidt, S. Lee, E. Trakhtenberg, S. Sorsher, and A. Zholents, "*Determination of maximum repetition rate of a corrugated-waveguide-based wakefield accelerator*", Mech. Eng. Design of Synchrotron Radiat. Equip. and Instrum., MEDSI2020, Chicago, IL, p.336, 2021, doi:10.18429/JACoW-MEDSI2020-THIO02 .

Design

1. S. Lee, S. Doran, W. Jansma, A. Siy, S. Sorsher, K. Suthar, E. Trakhtenberg, G. Waldschmidt, and A. Zholents, "*Mechanical design of a compact collinear wakefield accelerator*", Mech. Eng. Design of Synchrotron Radiat. Equip. and Instrum., MEDSI2020, Chicago, IL, p.276, 2021, doi:10.18429/JACoW-MEDSI2020-WEPB05.
2. S. Lee, W. Jansma, A. Siy, S. Sorsher, K. Suthar, E. Trakhtenberg, G. Waldschmidt, A. Zholents, "*Design and fabrication challenges of transition section for the CWA module*", Mech. Eng. Design of Synchrotron Radiat. Equip. and Instrum., MEDSI2020, Chicago, IL, p.273, 2021, doi:10.18429/JACoW-MEDSI2020-WEPB04.
7. K. Suthar, G. Navrotski, P. Carriere, and A. Zholents, "*Study of copper microstructure produced by electroforming for the 180-GHz frequency corrugated waveguide*", Mech. Eng. Design of Synchrotron Radiat. Equip. and Instrum., MEDSI2020, Chicago, IL, p.178, 2021, doi:10.18429/JACoW-MEDSI2020-TUPC01.
8. B. Popovic, S. Lee, E. Trakhtenberg, K. Suthar, A. Siy, G. Waldschmidt, S. Sorsher, A. Zholents, "*Design of miniature waveguides and diamond window assembly for rf extraction and vacuum isolation for the CWA*", Mech. Eng. Design of Synchrotron Radiat. Equip. and Instrum., MEDSI2020, Chicago, IL, p.156, 2021, doi:10.18429/JACoW-MEDSI2020-TUPB06.
9. A. Siy, N. Behdad, J. Booske, G. Waldschmidt, and A. Zholents, "*Design of a cylindrical corrugated waveguide for a collinear wakefield accelerator*", Phys. Rev. Accel. Beams 25, 121601(2022).
10. A. Siy, N. Behdad, J. Booske, G. Waldschmidt, and A. Zholents, "*Electromagnetic design of the transition section between modules of a wakefield accelerator*", Phys. Rev. Accel. Beams 26, 012802(2023).
11. J. Xu, M. Qian, and A. Zholents, "*A force-neutral adjustable phase undulator for a compact x-ray FEL* ", in: Proceedings of the IPAC 2023, Venice, Italy, p.1754, (2023); Pending patent application.

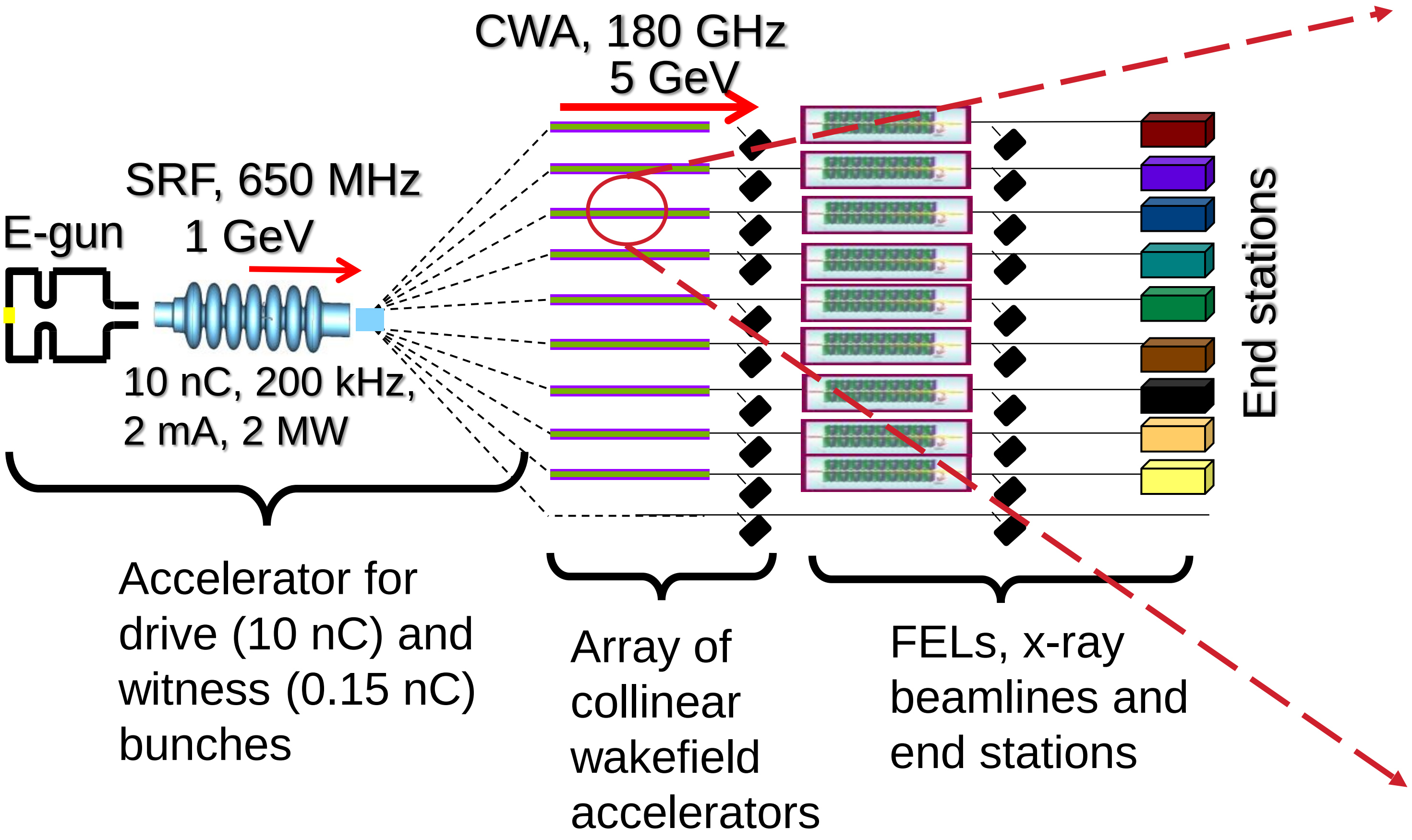
Publications

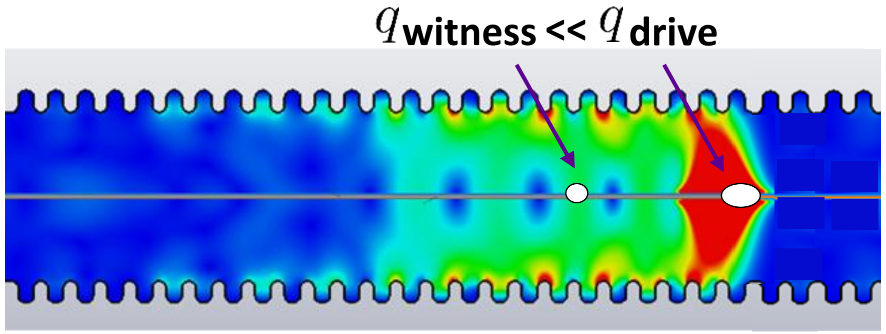
Testing

1. A. Zholents, S. Lee, B. Popovic, M. Fedurin, K. Kusche, W. Li, A. Nassiri, A. Siy, S. Sorsher, K. Suthar, E. Trakhtenberg, and G. Waldschmidt, "*Fabrication and testing of the transition section between modules of a wakefield accelerator*", Phys. Rev. Accel. Beams 27, 081303 (2024), https://link.aps.org/doi/10.1103/PhysRevAccelBeams.27.081303
2. A. Siy, N. Behdad, J. Booske, M. Fedurin, W. Jansma, K. Kusche, S. Lee, G. Mouravieff, A. Nassiri, S. Oliphant, S. Sorsher, K. Suthar, E. Trakhtenberg, G. Waldschmidt, and A. Zholents, "*Fabrication and testing of corrugated waveguides for a collinear wakefield accelerator*", Phys. Rev. Accel. Beams 25, 021302 (2022), https://link.aps.org/doi/10.1103/PhysRevAccelBeams.25.021302
3. M. Qian, M. Kasa, J. Xu, S. Doran, S. Lee, S. Sorsher, N. Strelnikov, E. Trakhtenberg, and A. Zholents, "*Quadrupole wiggler for a collinear wakefield accelerator*", Phys. Rev. Accel. Beams 28, 012401 (2025), https://doi.org/10.1103/PhysRevAccelBeams.28.012401

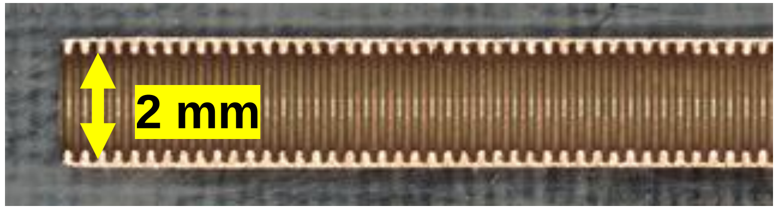
MOTIVATION

A multi-user FEL facility based on the array of Collinear Wakefield Accelerators

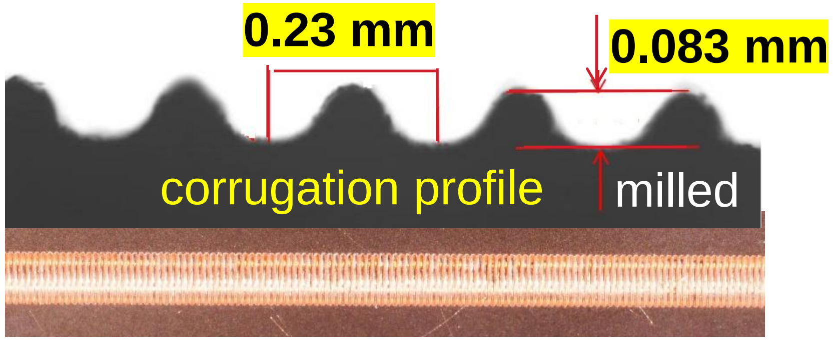




G. A. Voss and T. Weiland, DESY M-82-10, **1982**



A. Siy *et al.*, PRAB, December, **2022**

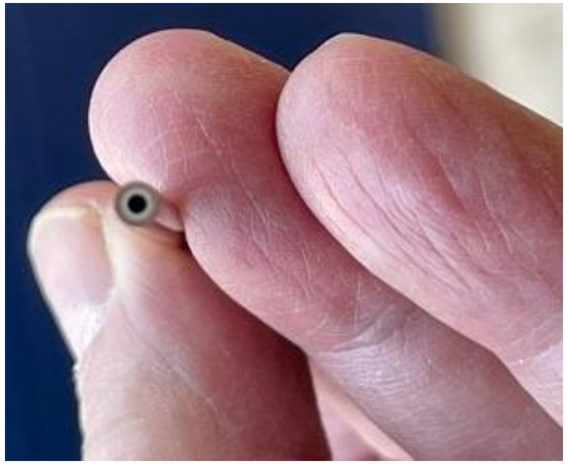


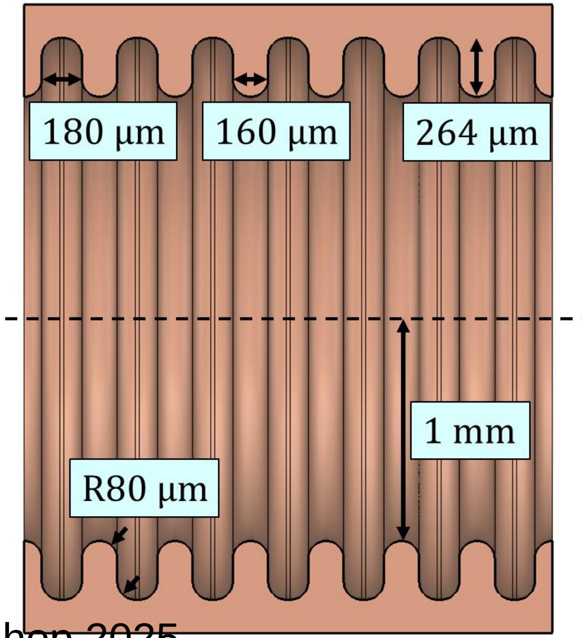
K. Bane *et al.*, NIM A, **2017**
(photo: courtesy G. Bowden)

- High bunch repetition rate operation is the essential goal
- High wall plug power efficiency
  - CWAs do not need electrical power
  - Undulators do not need electrical power

CORRUGATED WAVEGUIDE DESIGN

- **Maximize**
  - Loss factor
  - Group velocity
- **Minimize**
  - Peak surface fields
  - Power dissipation on the walls
  - Transient temperature rise of surface
  - High order modes
- Simplify fabrication

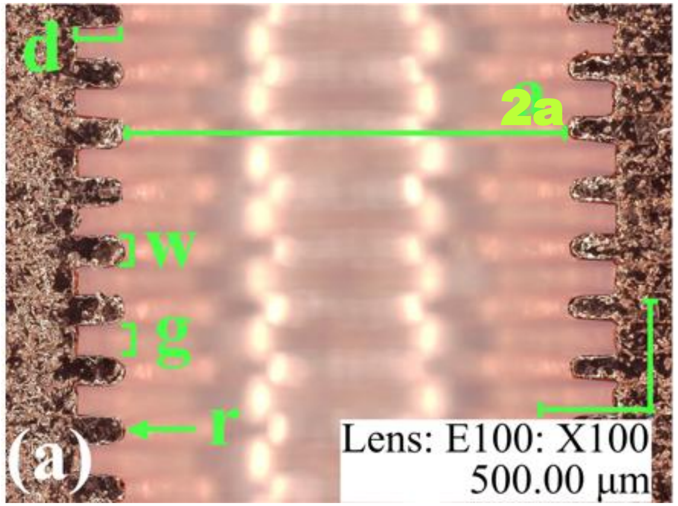




DIE STAMPING

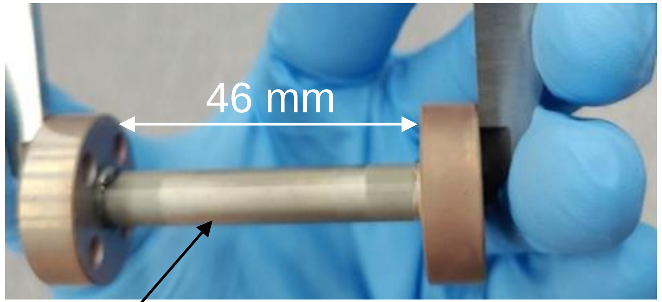
(This slide is based on recent publication H. Kong *et al*., Scientific Reports, **2023)**

Made in Pohang Accelerator Laboratory



a=1.02 mm
w = 130 μm
g= 130 μm
d=200 μm
r =65 μm

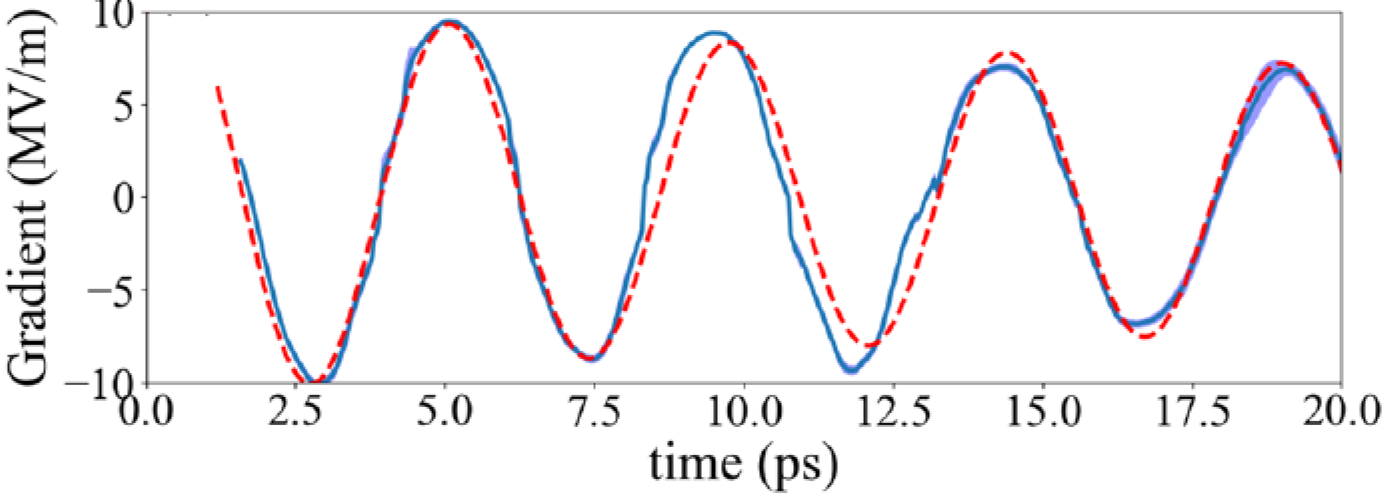
Diffusion bonding of stamped discs



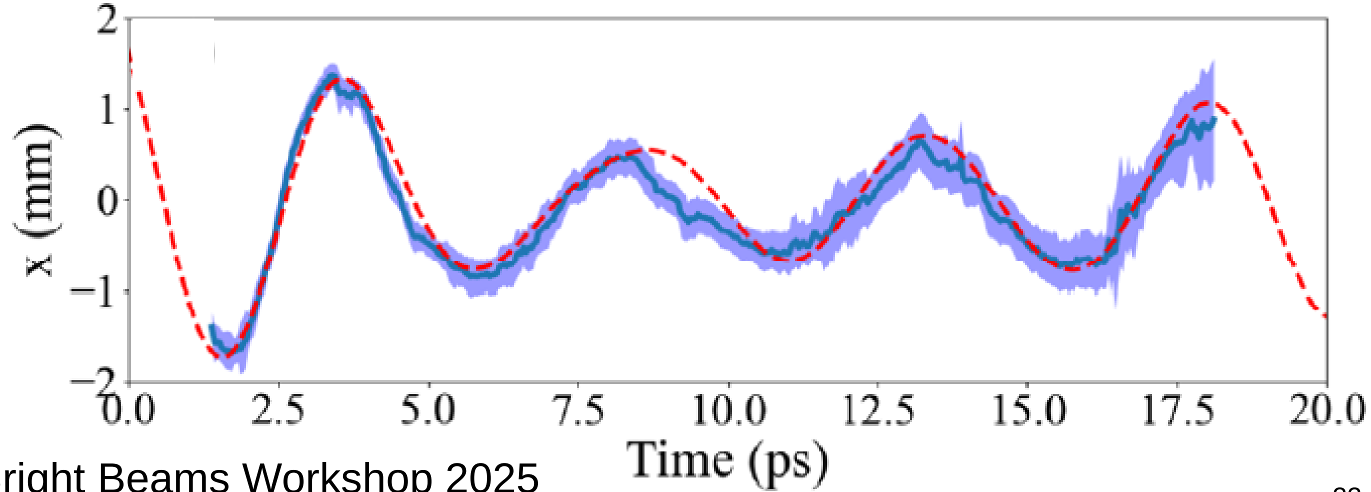
SS jacket, 8 mm OD

(photos, courtesy H. Kong)

Measurement of longitudinal wakefield at AWA/ANL



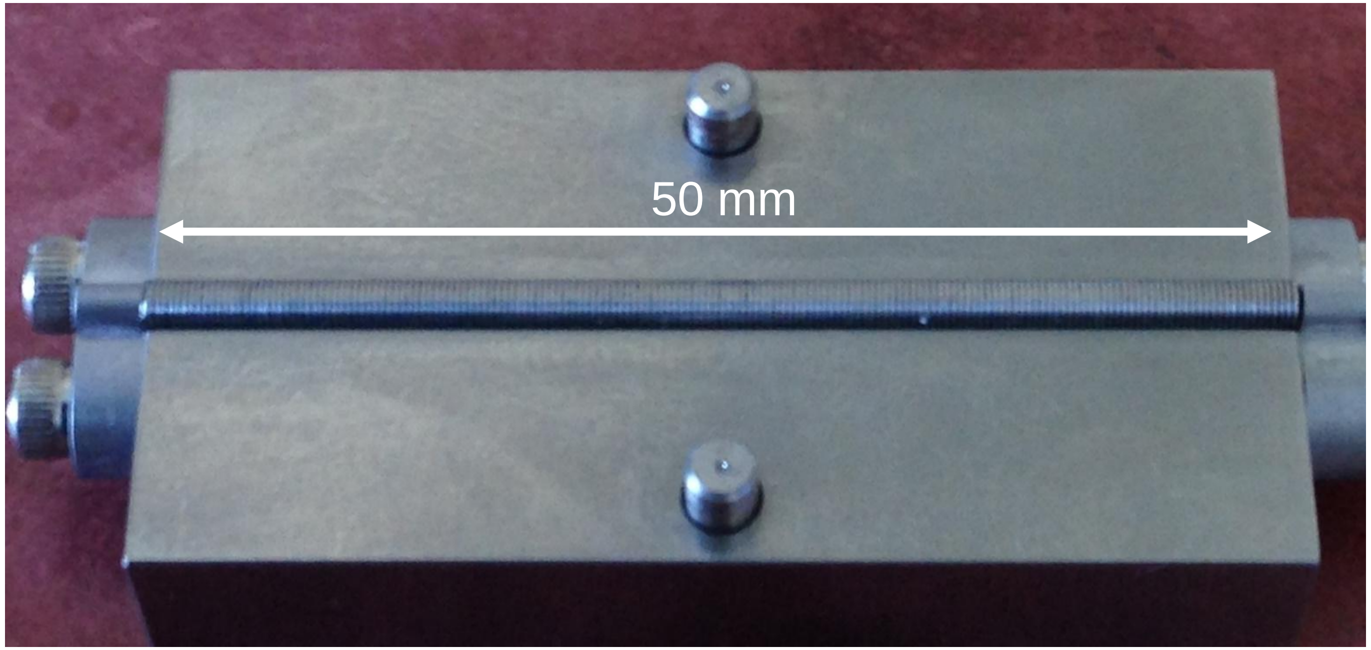
Measurement of transverse wakefield at AWA/ANL



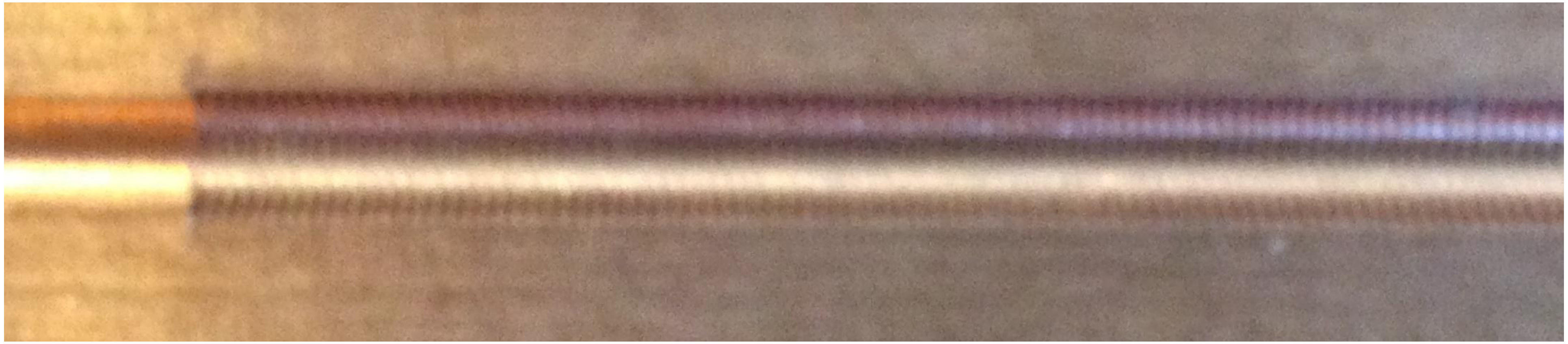
IMPRESSION (COLD FORMING)

Impression of a stainless steel die into a machined, semi-circular groove in a copper plate

Stainless steel die



Copper sample after pressing

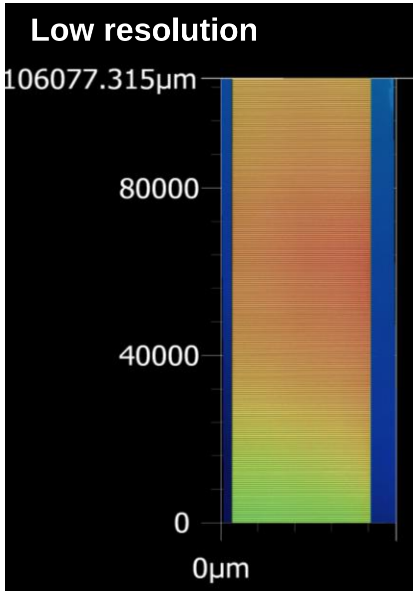


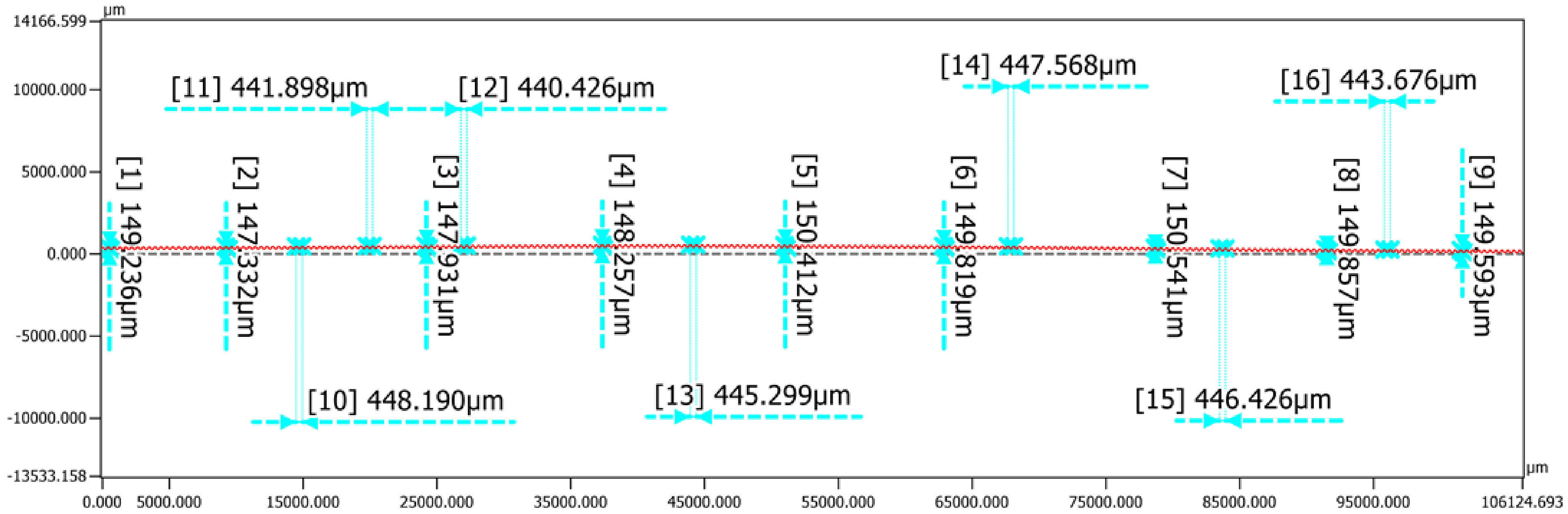
Can be used for shallow grooves

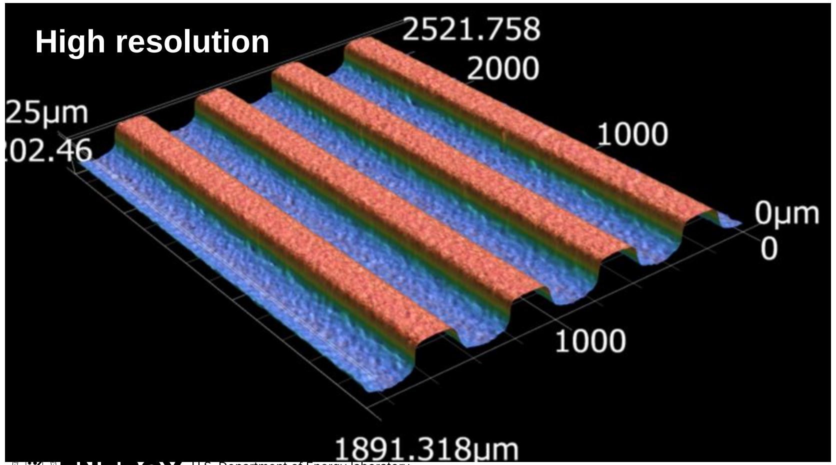
also tried by S. Antipov from Euclid Techlabs

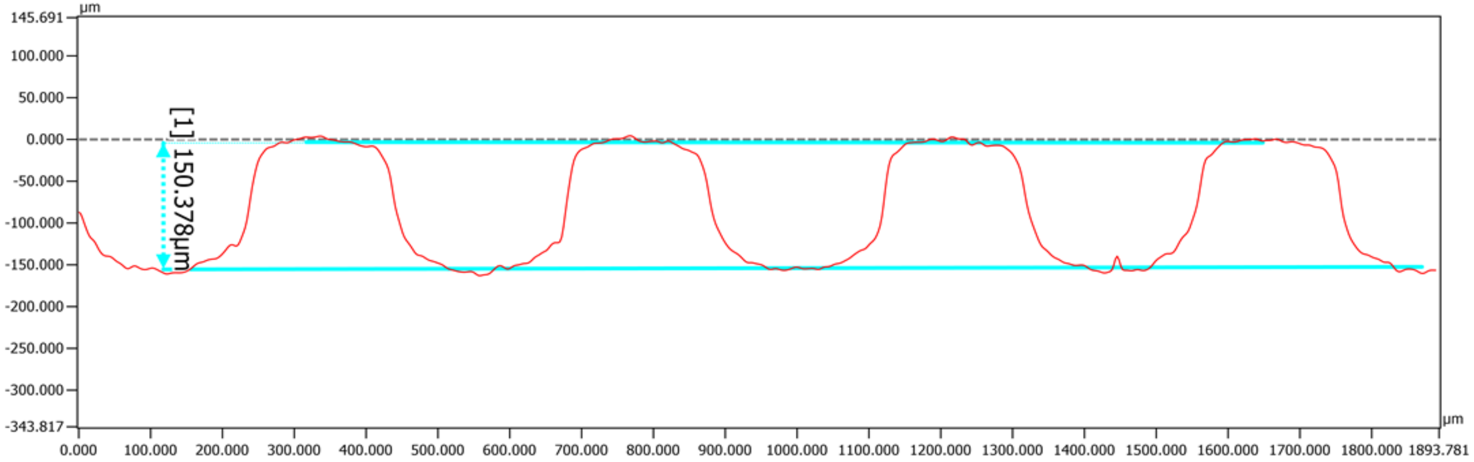
23

FLAT PLATE


Low resolution
106077.315µm
80000
40000
0
0µm

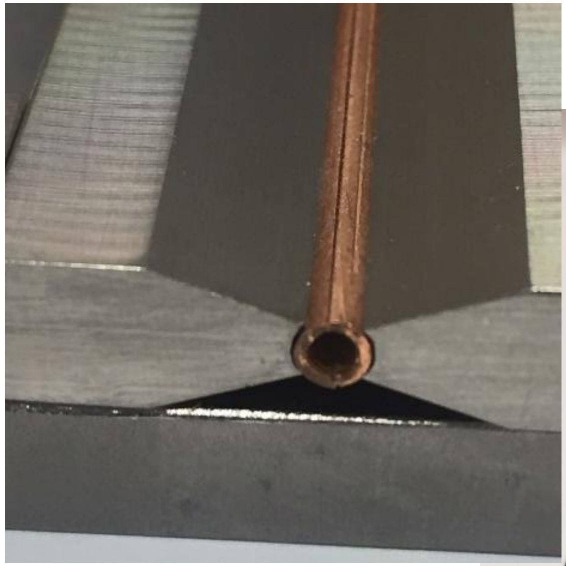

[1] 149.236µm
[2] 147.332µm
[3] 147.931µm
[4] 148.257µm
[5] 150.412µm
[6] 149.819µm
[7] 150.541µm
[8] 149.857µm
[9] 149.593µm
[10] 448.190µm
[11] 441.898µm
[12] 440.426µm
[13] 445.299µm
[14] 447.568µm
[15] 446.426µm
[16] 443.676µm


High resolution
2521.758
2000
1000
0µm
0
1000
1891.318µm

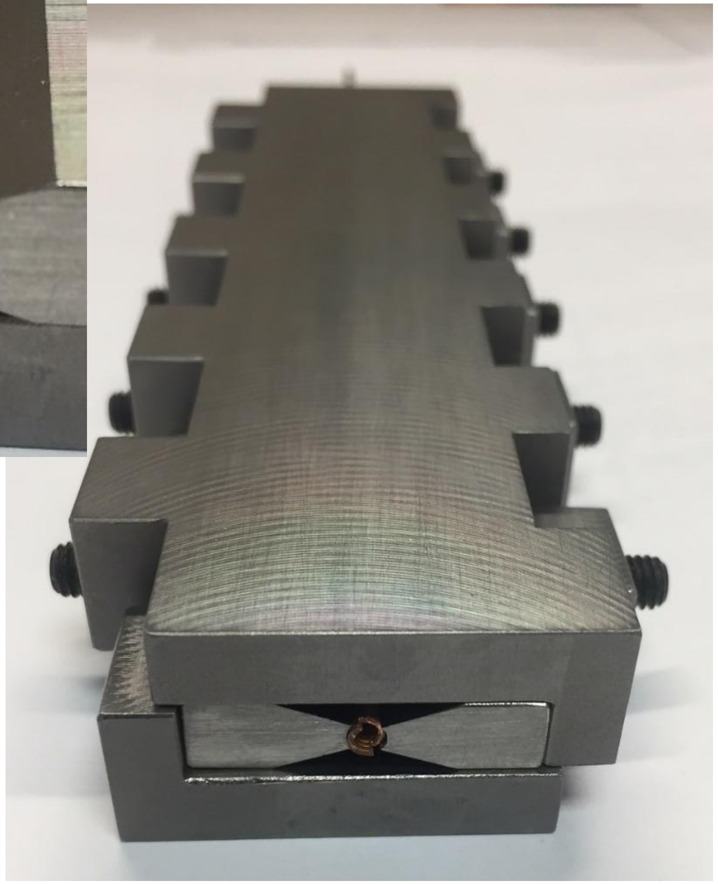

[1] 150.378µm

FORMING ROUND CORRUGATED STRUCTURE

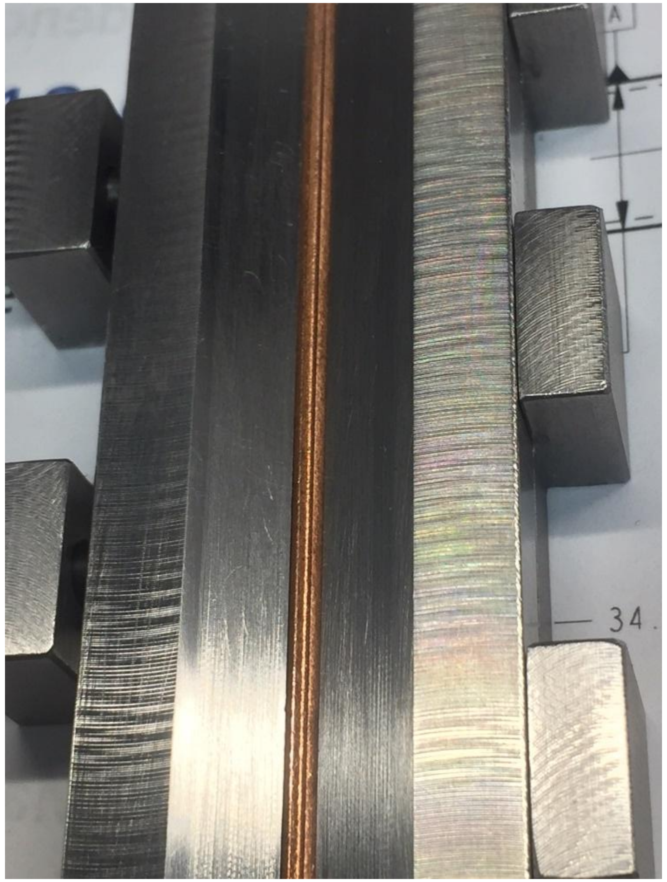
Bending



Joining

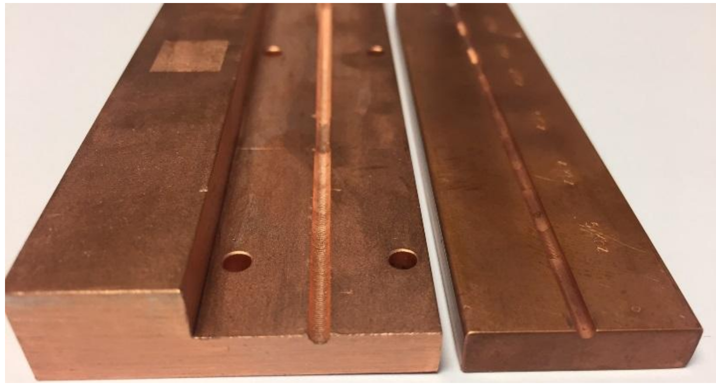


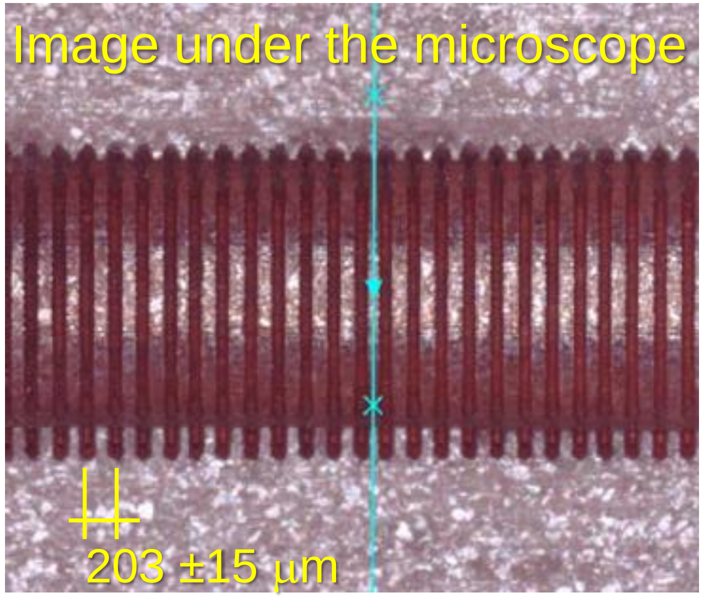
Holding

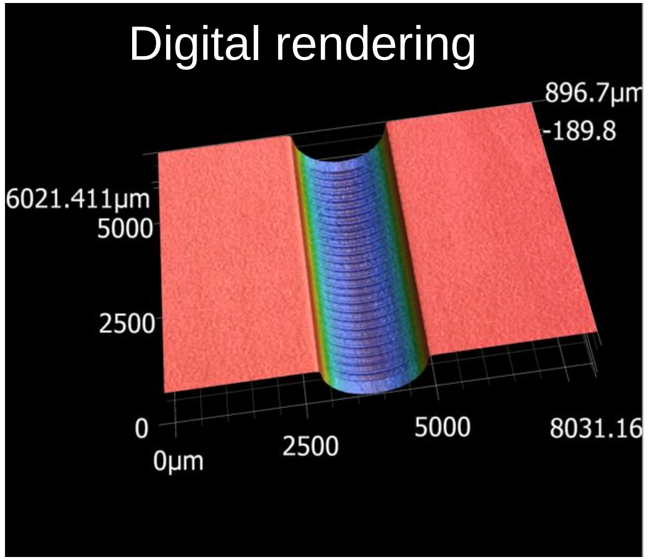


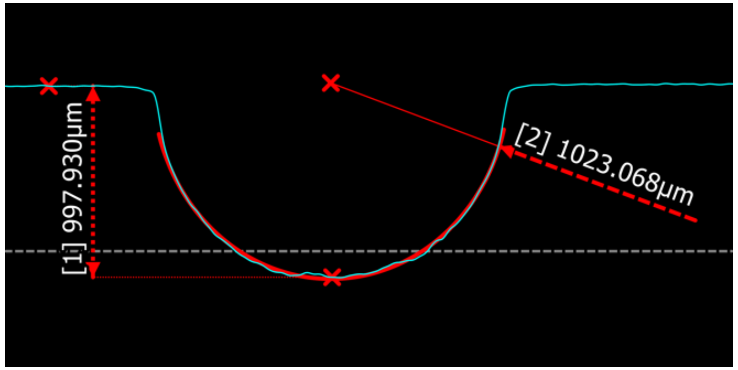
Welding
laser/e-beam

GROOVE

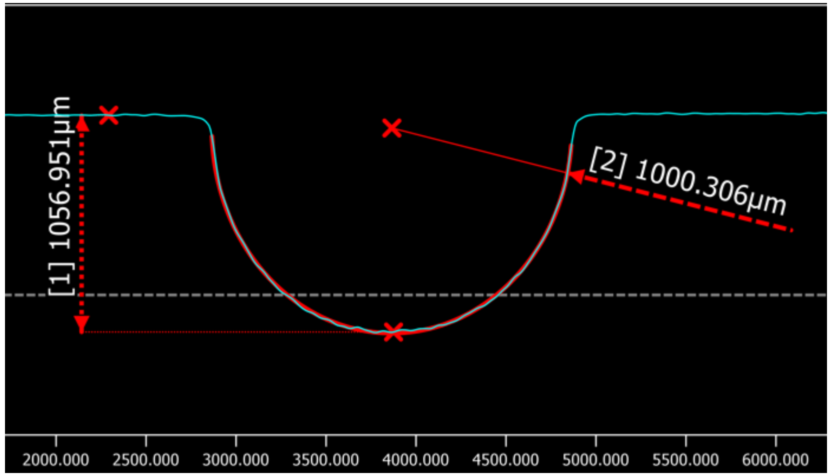








Cross-sectional profile through a raised tooth

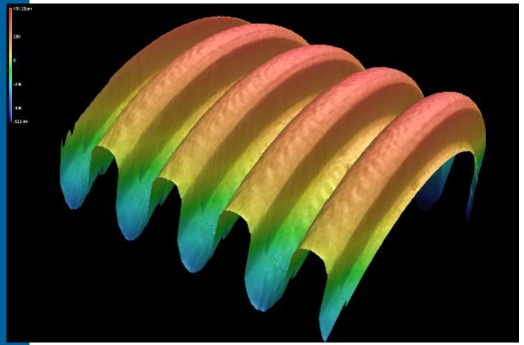


Cross-sectional profile through a groove

also tried by S. Antipov from Euclid Techlabs

ELECTROFORMING CIRCULAR CORRUGATED WAVEGUIDE

Aluminum mandrel production

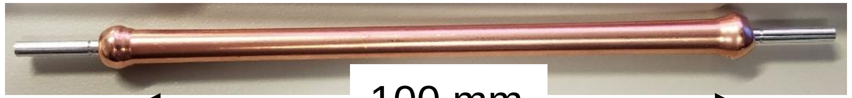


Proprietary micro-machining process
Tooth Height 252.7 μm; error 1.5 μm RMS
Tooth Width 175.9 μm; error 2.0 μm RMS

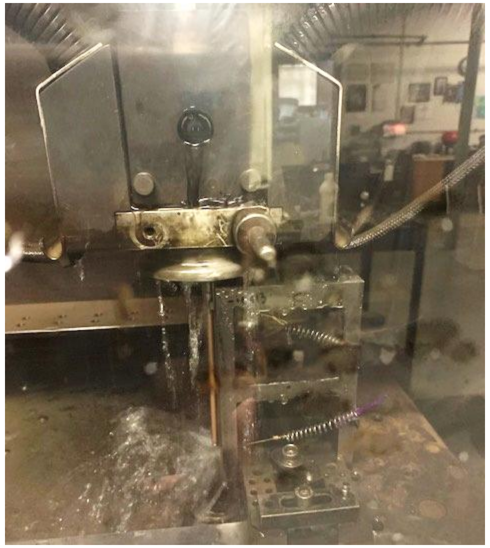
Mandrel inspection and straightening

using optical comparator

Electroforming

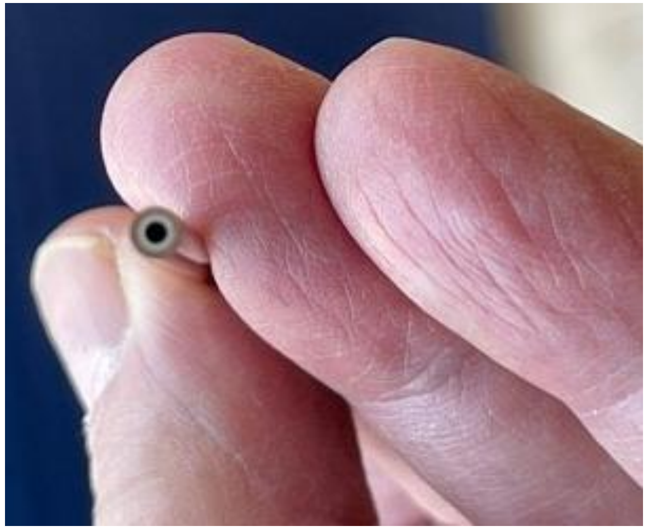


EDM of outside diameter OD

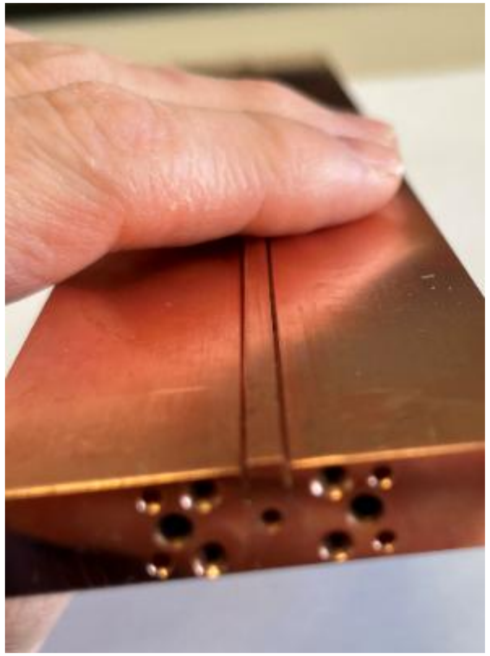


followed by second straightening

Precision cut of edges



followed by aluminum etching



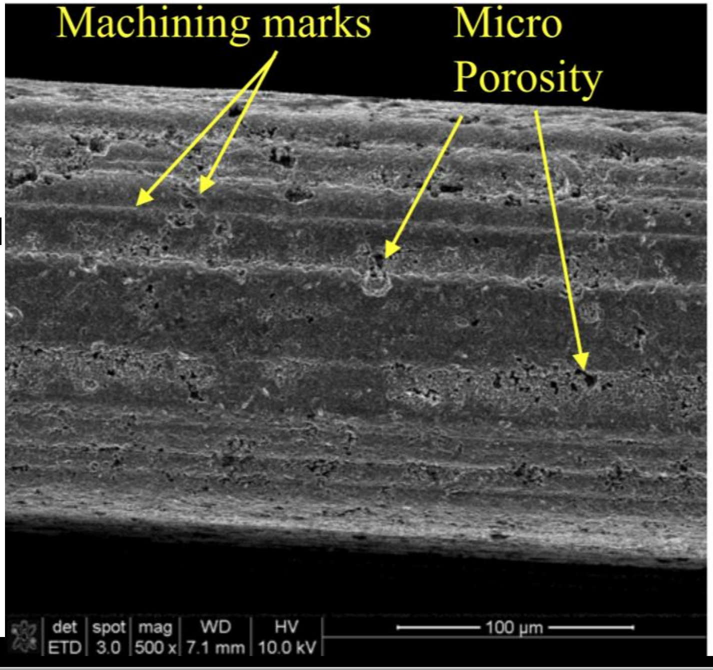
chamber with five 10-cm long tubes after brazing (currently use three)

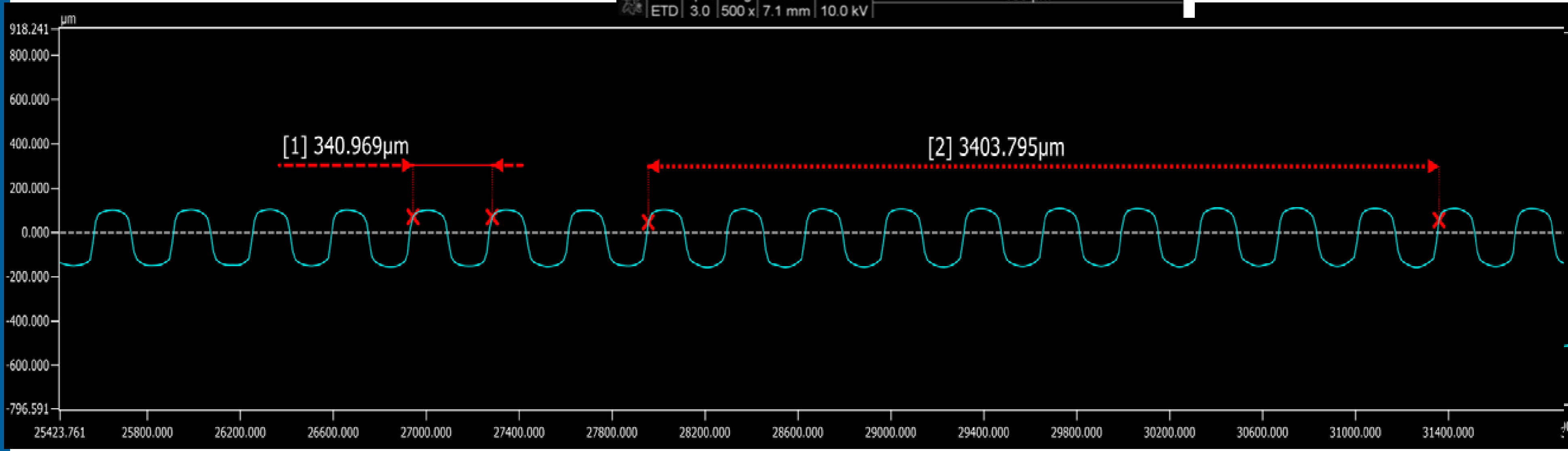
Mandrel inspection and straightening

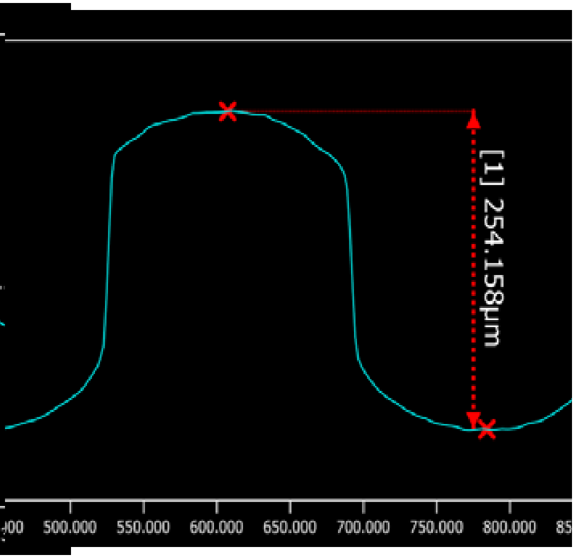
Inspect for mandrel defects.

Mandrel defects will imprint onto the electroformed structure inner surface. Machining marks on the aluminum mandrel inadvertent scratches from handling or shallow pits created during cleaning form the template that is duplicated during the electroforming process.

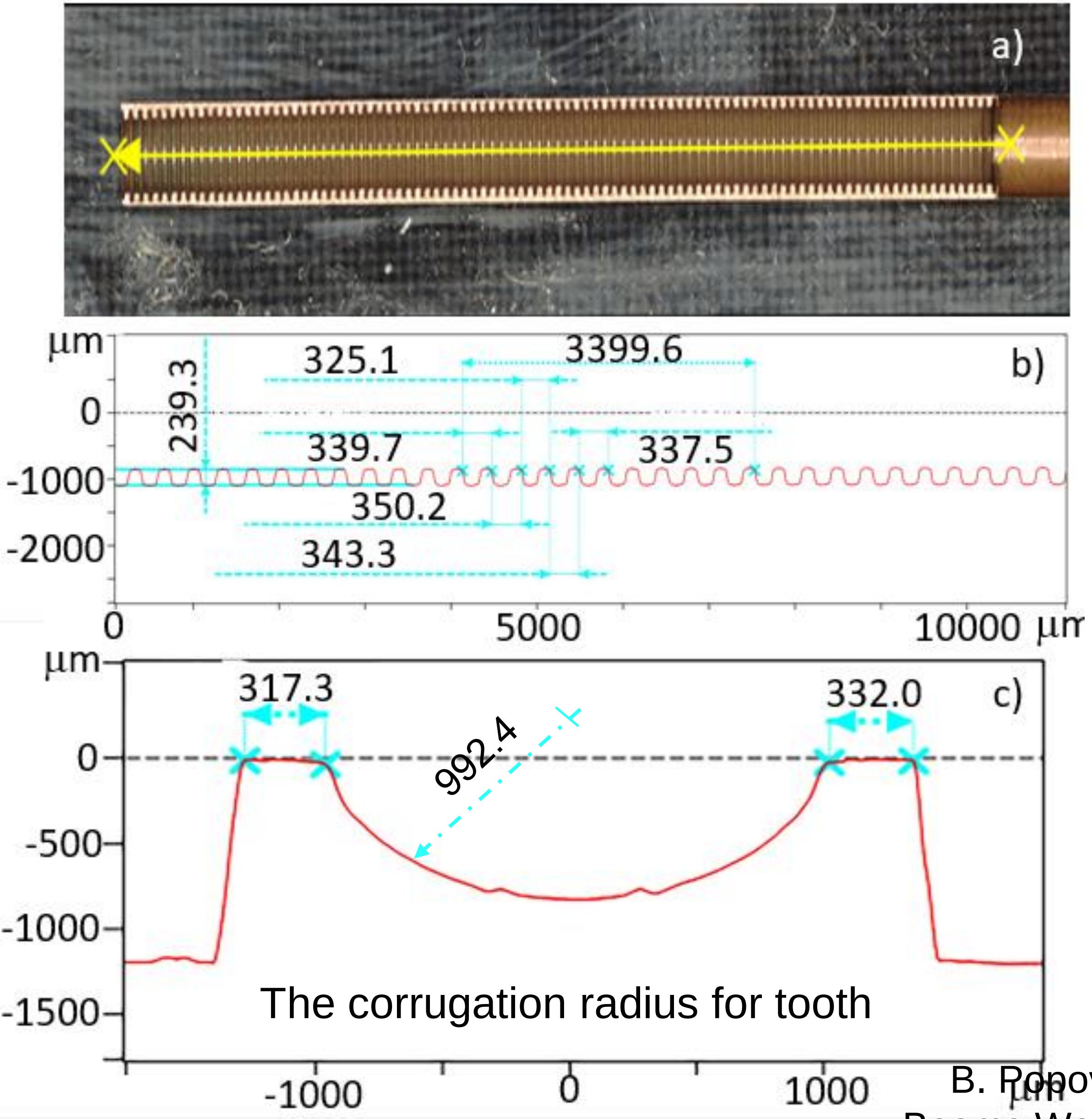
Mandrel measurements indicate excellent fabrication quality

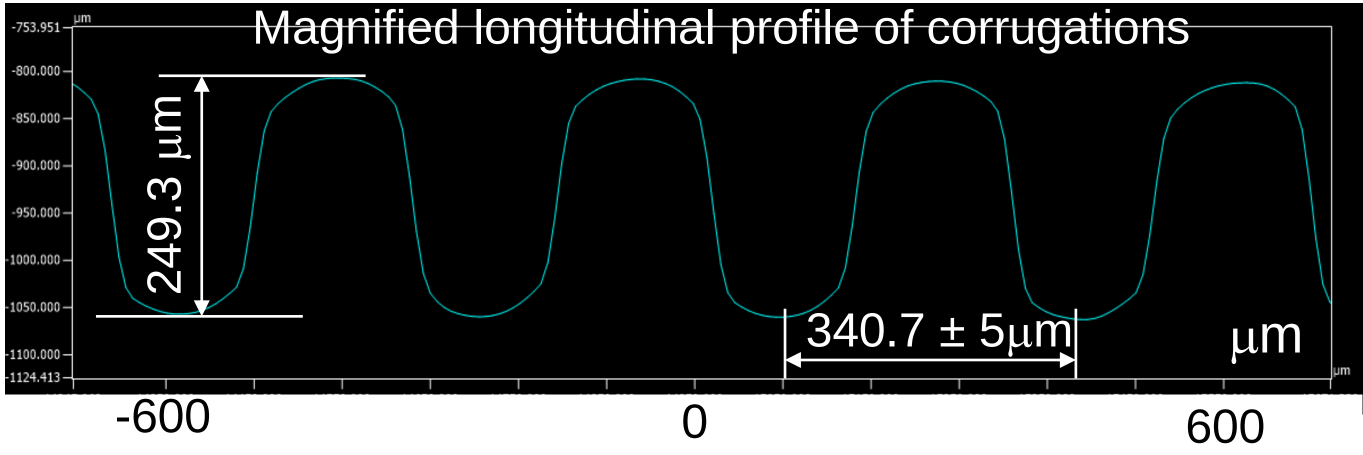


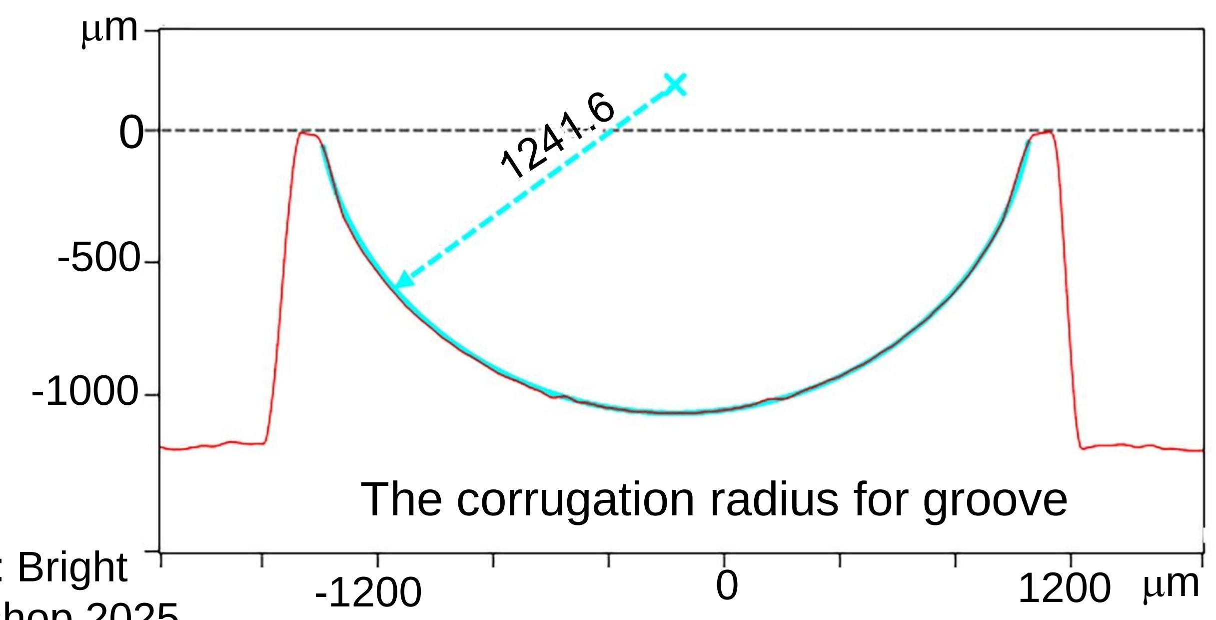




ELECTROFORMING CIRCULAR CORRUGATED WAVEGUIDE (2)

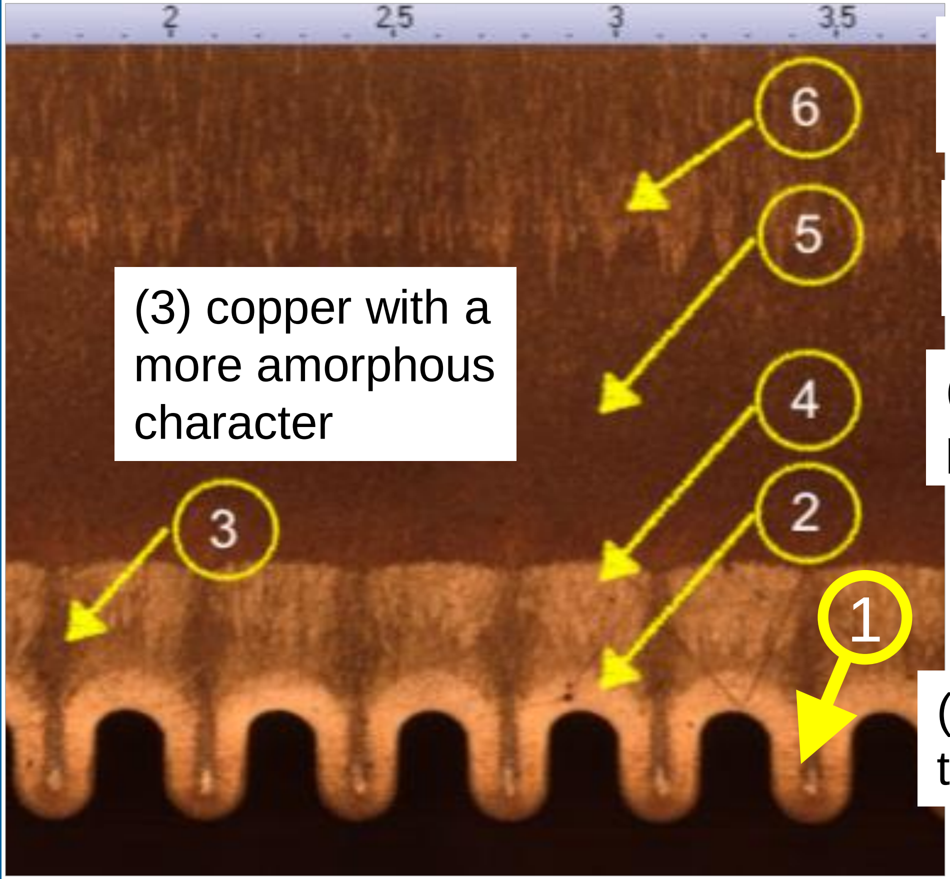






MICROSTRUCTURE OF CORRUGATIONS

- Improved prototype microstructure



(3) copper with a more amorphous character

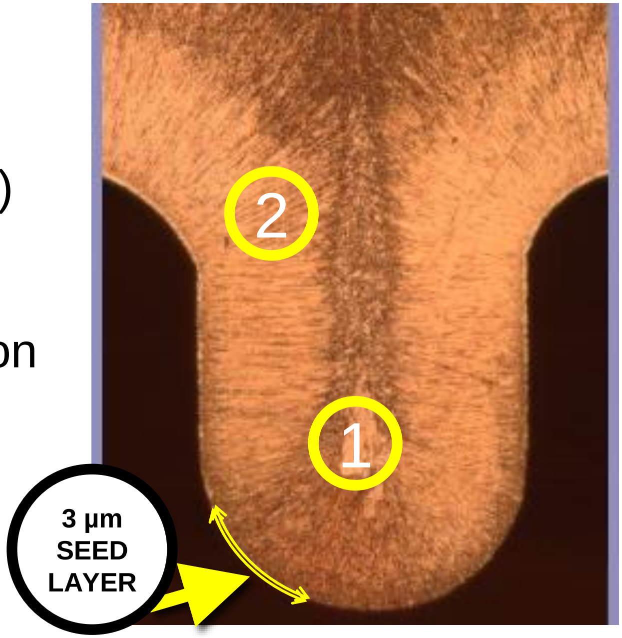
(6) layer with the same nascent recrystallization characteristics as region (4)

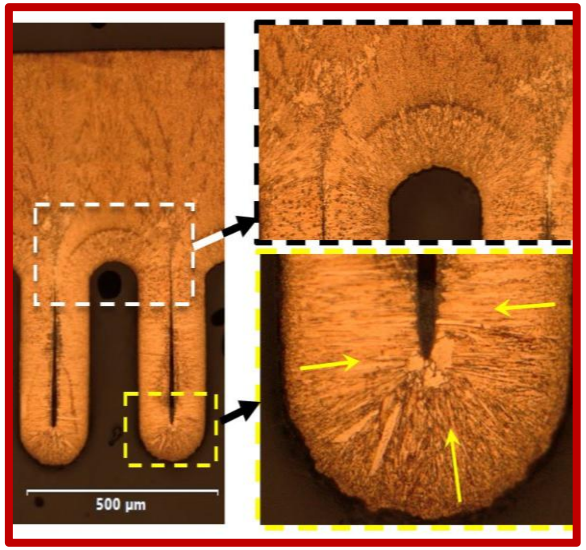
(5) the darkest, smallest grain, most amorphous, and the highest hardness region

(4) layer with a degree of recrystallization preferentially oriented away from (2)

(2) layer highly elongated layer of single crystal follow the seed layer contour

(1) small cluster of large equiaxed grains at the apex of each corrugation.

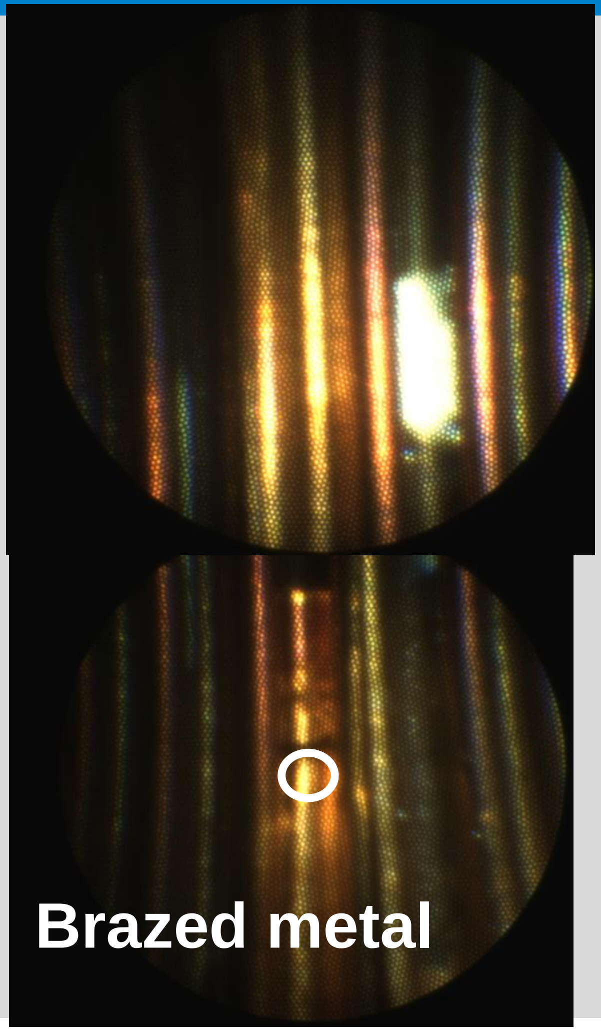




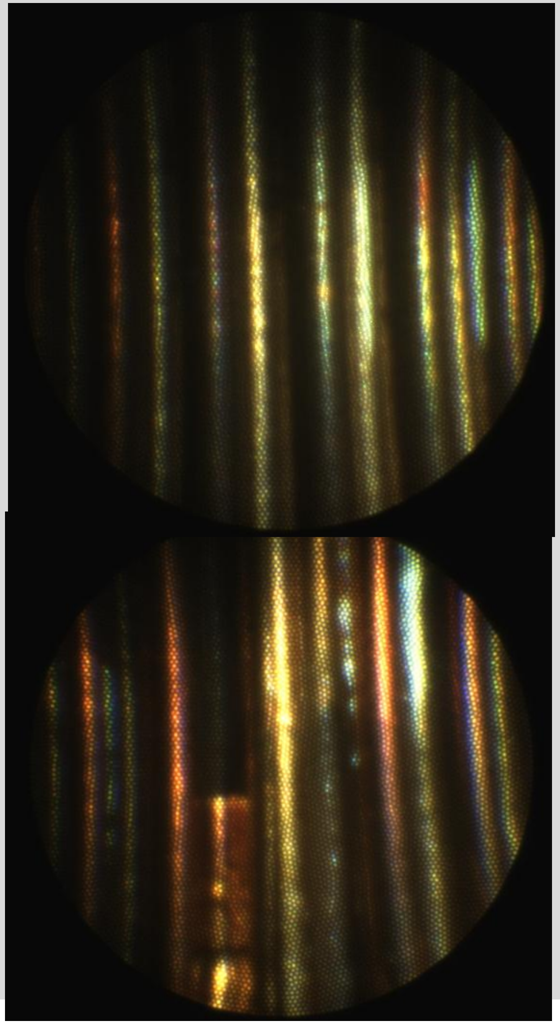
Test Sample

BORESCOPE INSPECTION OF CORRUGATIONS

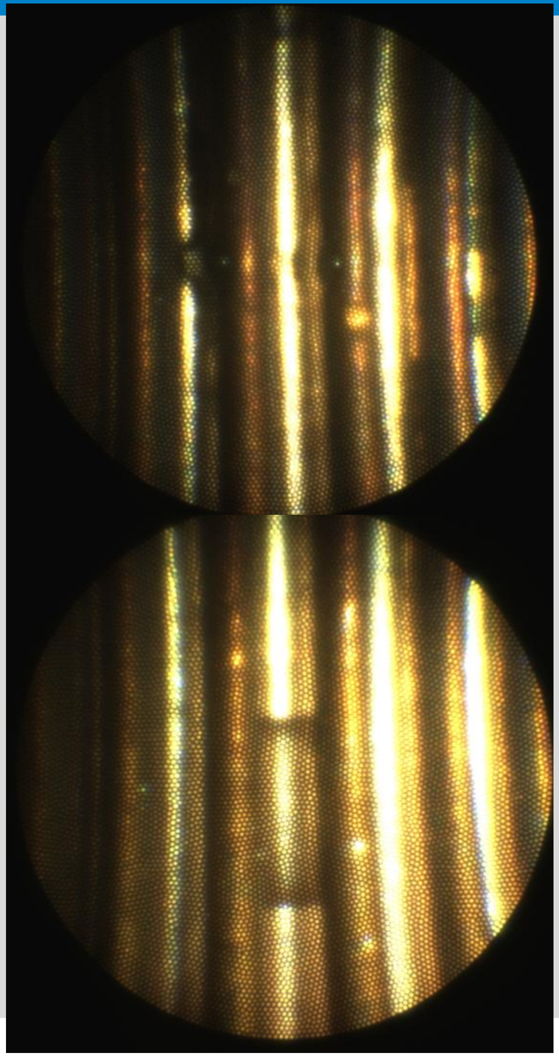
Joint



Discoloration



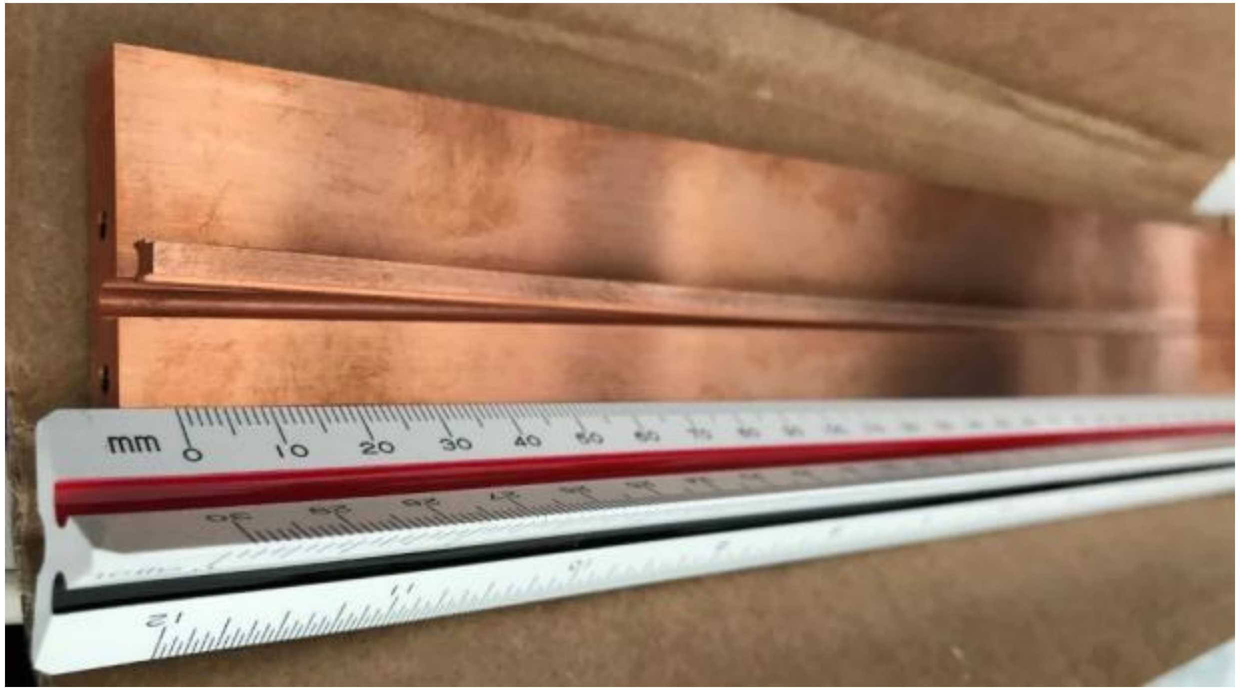
Some Features



SELECTION OF WAVEGUIDES FOR BRAZING

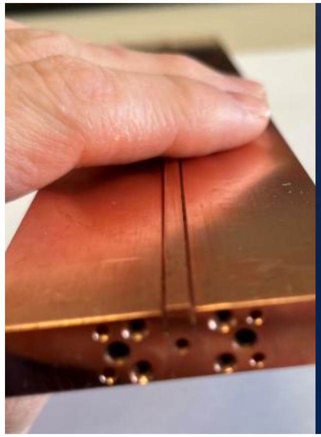
- Check Diameters
- Cleaning before brazing

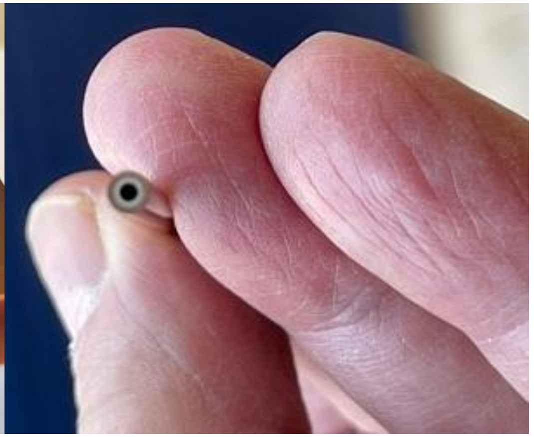
Figure 1: Twelve(12) waveguides in transport tubes, as received from Servometer.

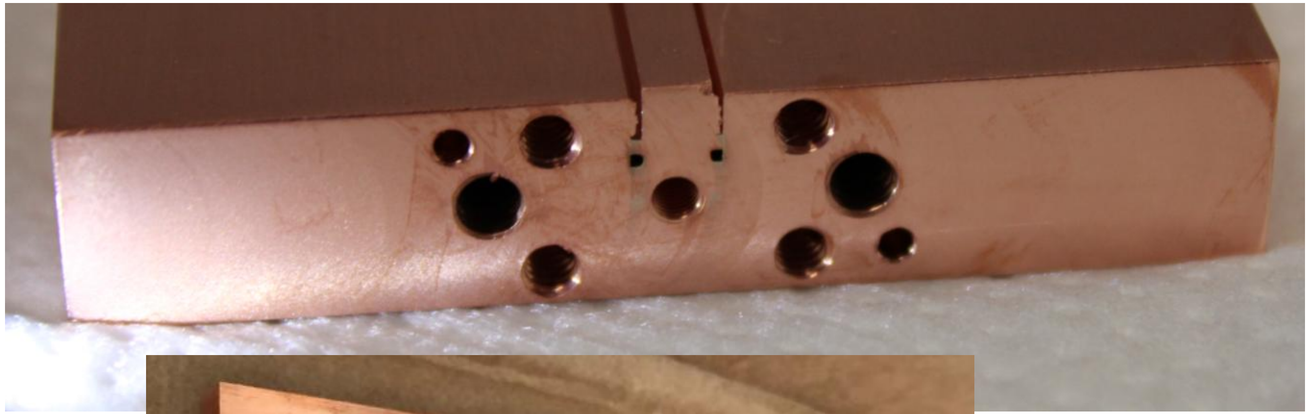


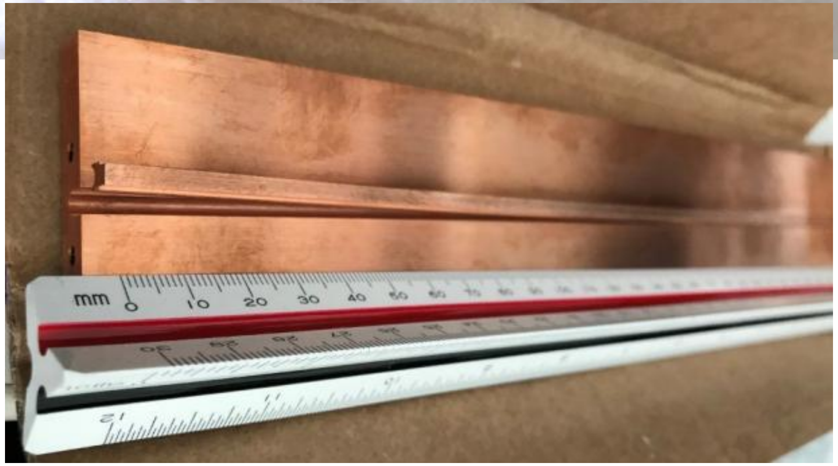
CHAMBER (300 MILLIMETERS)

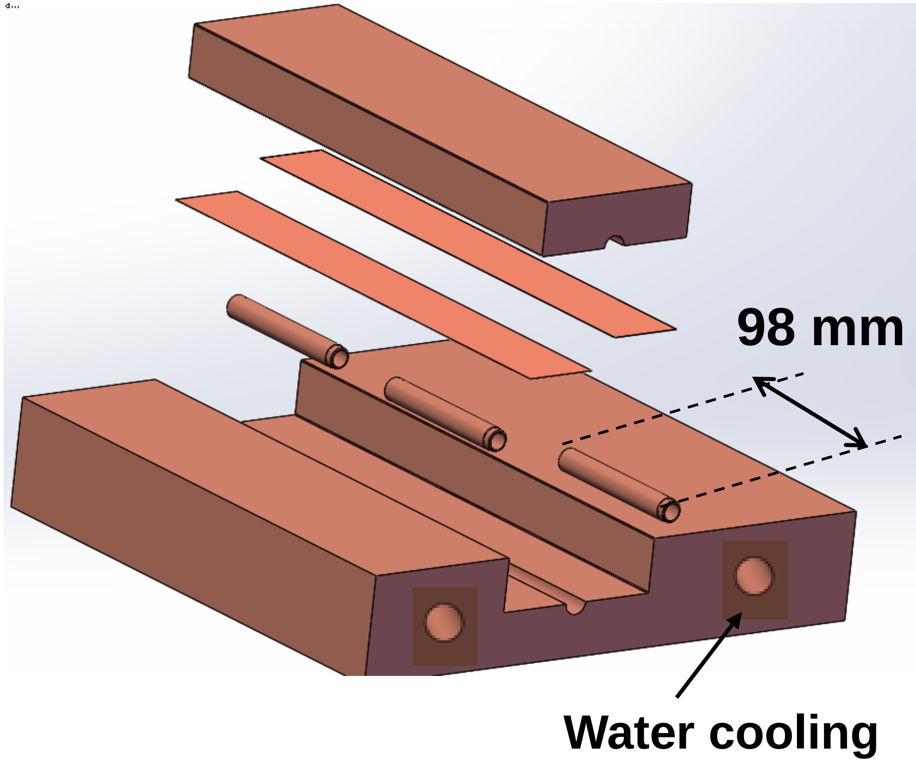
Three 10-cm long tubes after brazing:
low temperature brazing at 360 ^{o}C





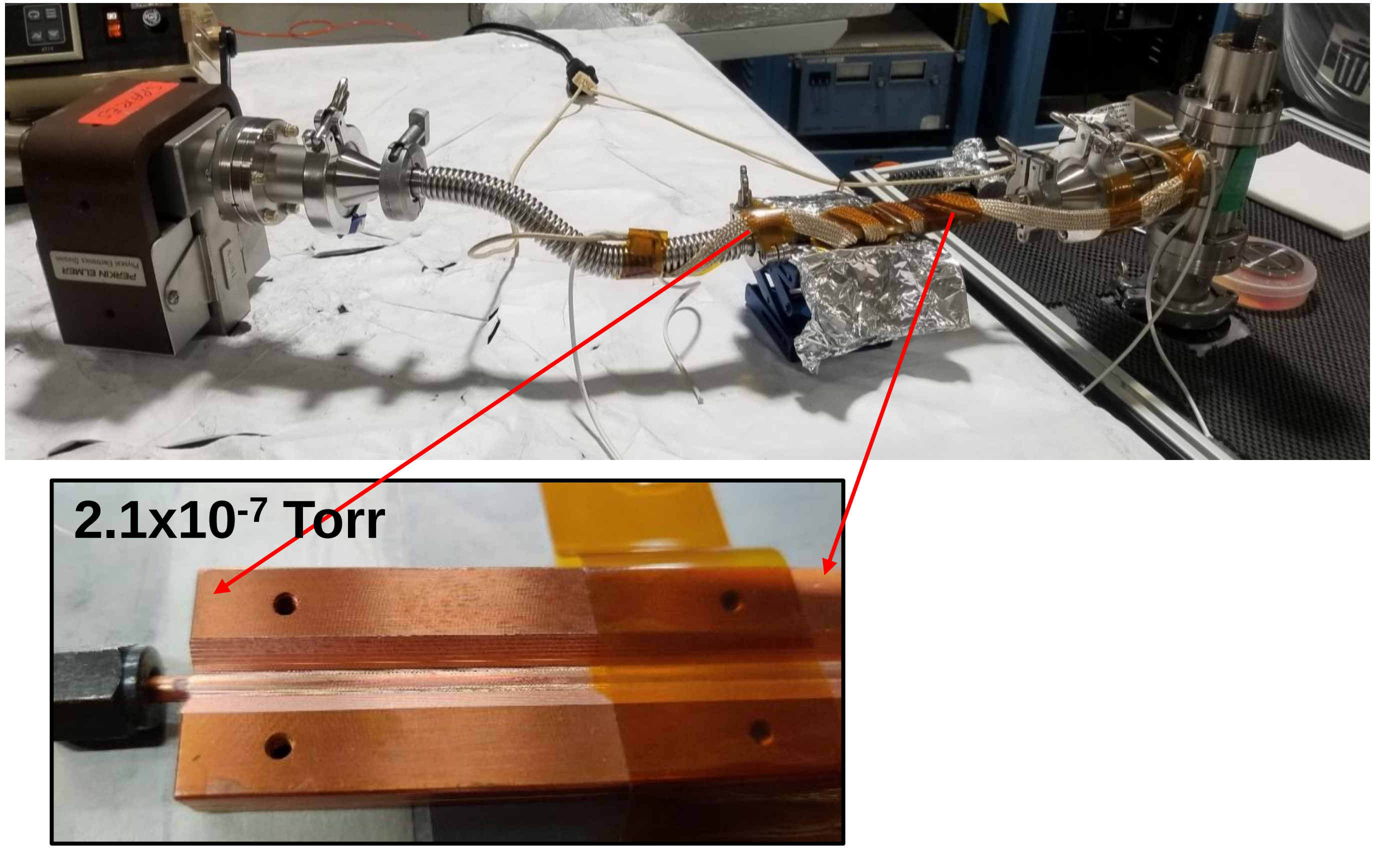




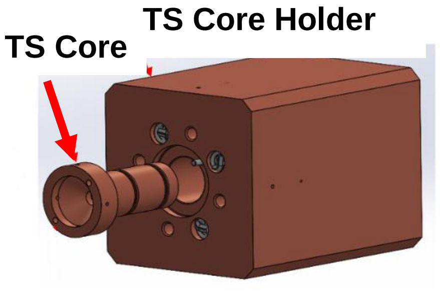


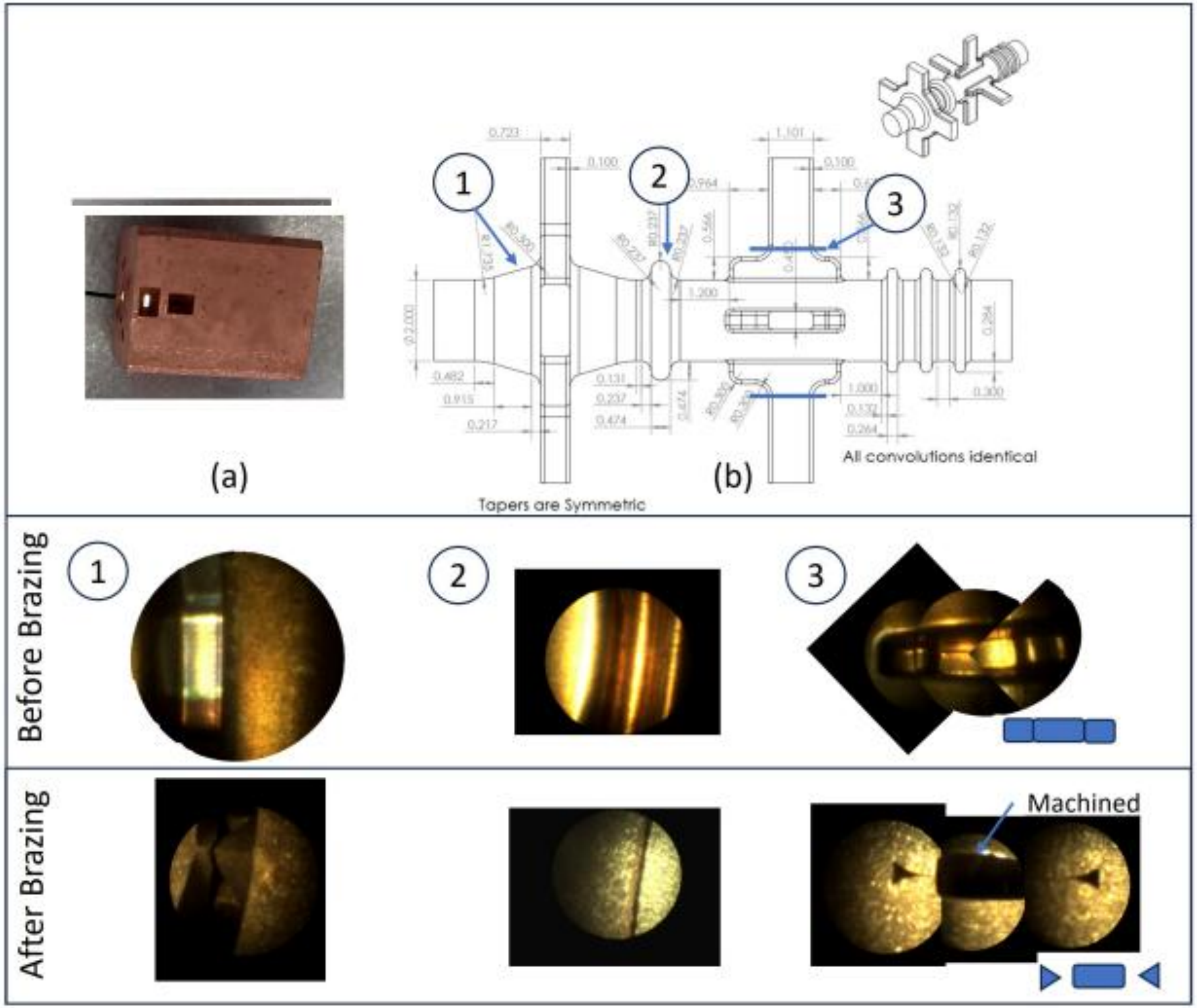
VACUUM TESTING OF 152MM TEST PIECE

- Smooth Tube
  - 8.5E-8 Torr after bakeout
- Emittance beam grow due to multiple Columb scatter of electrons is negligible at 4E-7 Torr
  - 10^-7 mm*mrad
  - This vacuum is acceptable if permitted by electrical breakdown

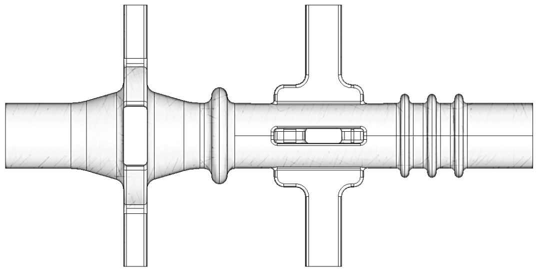


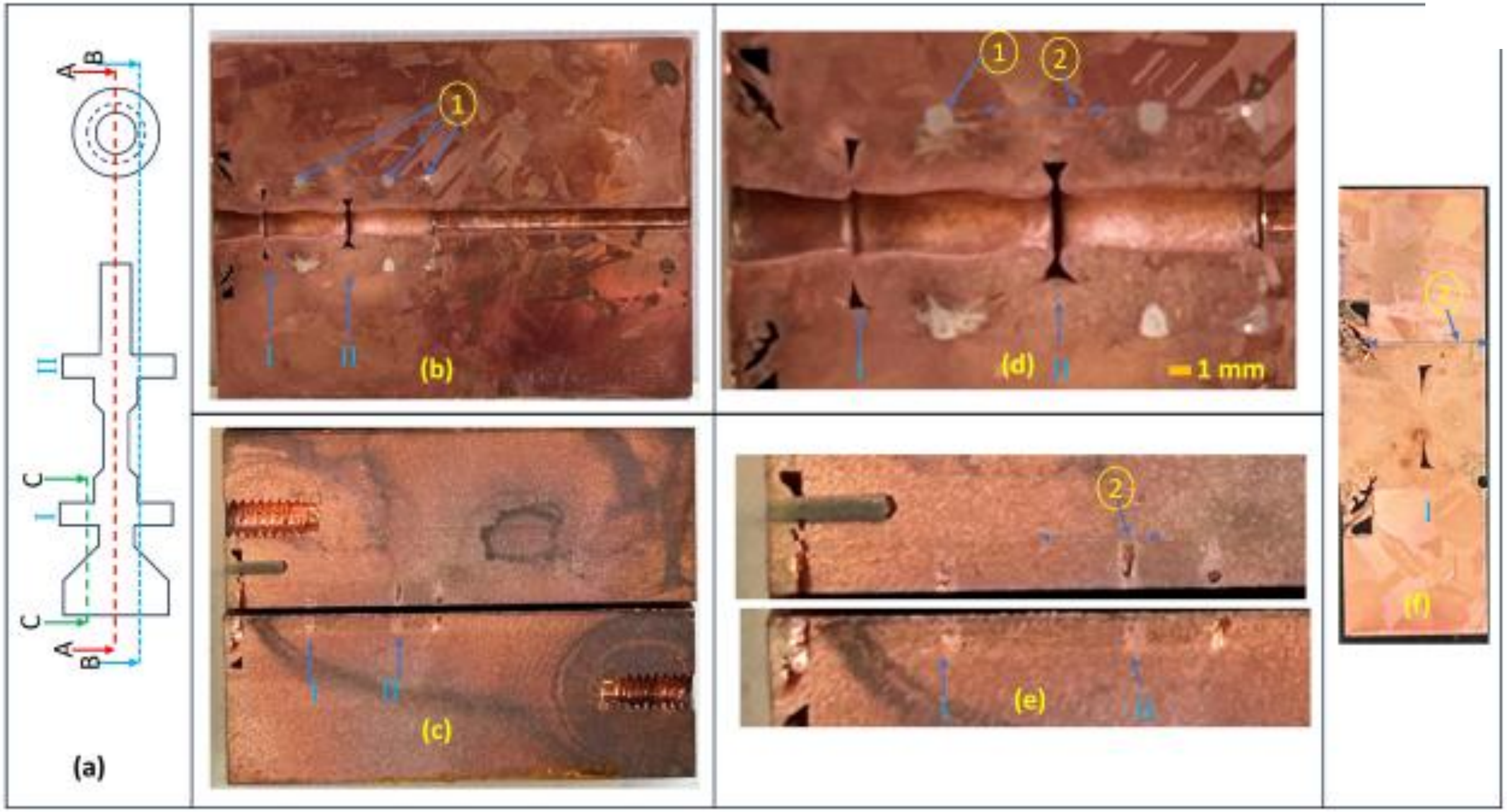
ISSUES WITH BRAZING STEP….



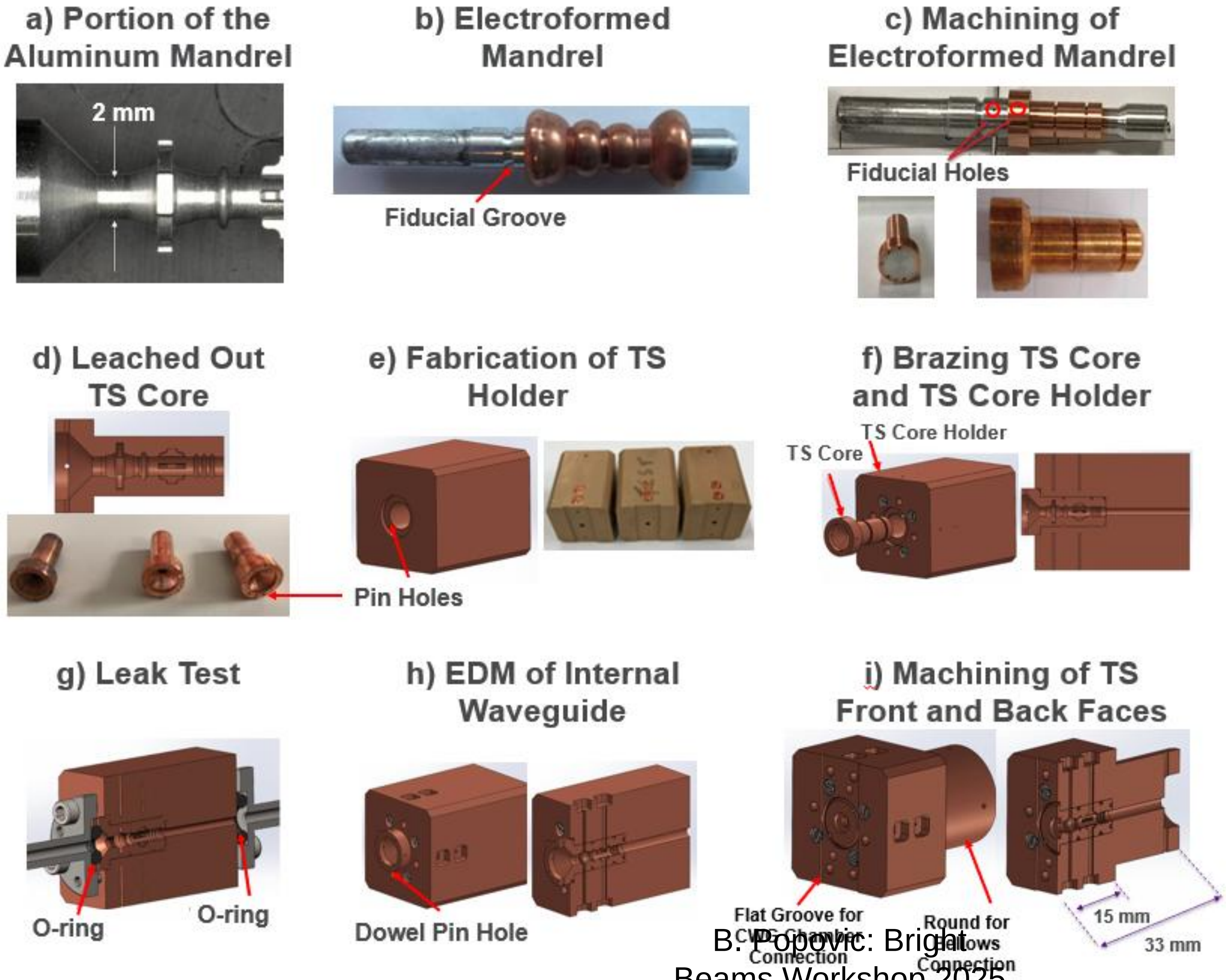


ISSUES WITH BRAZING STEP….

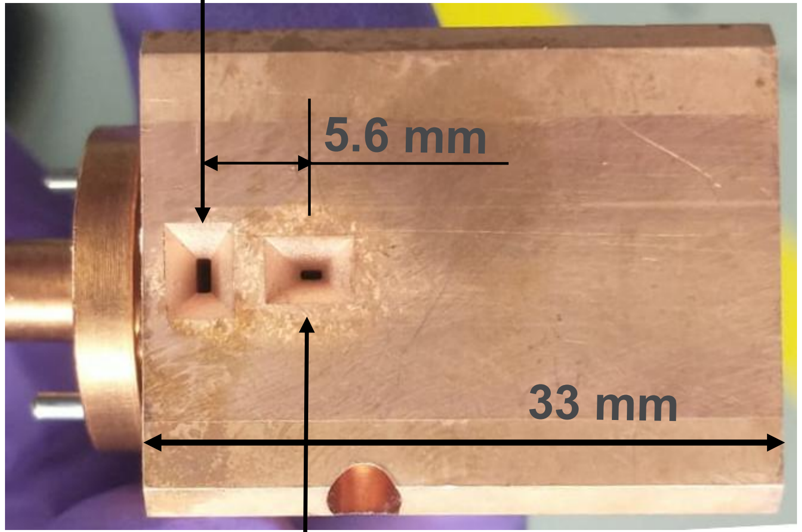




Fabrication of transition section between accelerator modules



TM$_{01}$ coupler horn antenna, 0.72 mm × 1.78 mm



Integrated offset monitor horn antenna, 1.10 mm × 0.45 mm

MEASUREMENT OF CORRUGATED WAVEGUIDES

- Beam measurement of individual tubes at BNL ATF
- Initial cold testing of assembled 300 mm section?
  - Qualitative measurement
    - Poor performance of the mode convertors
  - Show general transmission
  - Attenuation factor in range of expected
- Beam measurement of assembled 300 mm section at BNL ATF

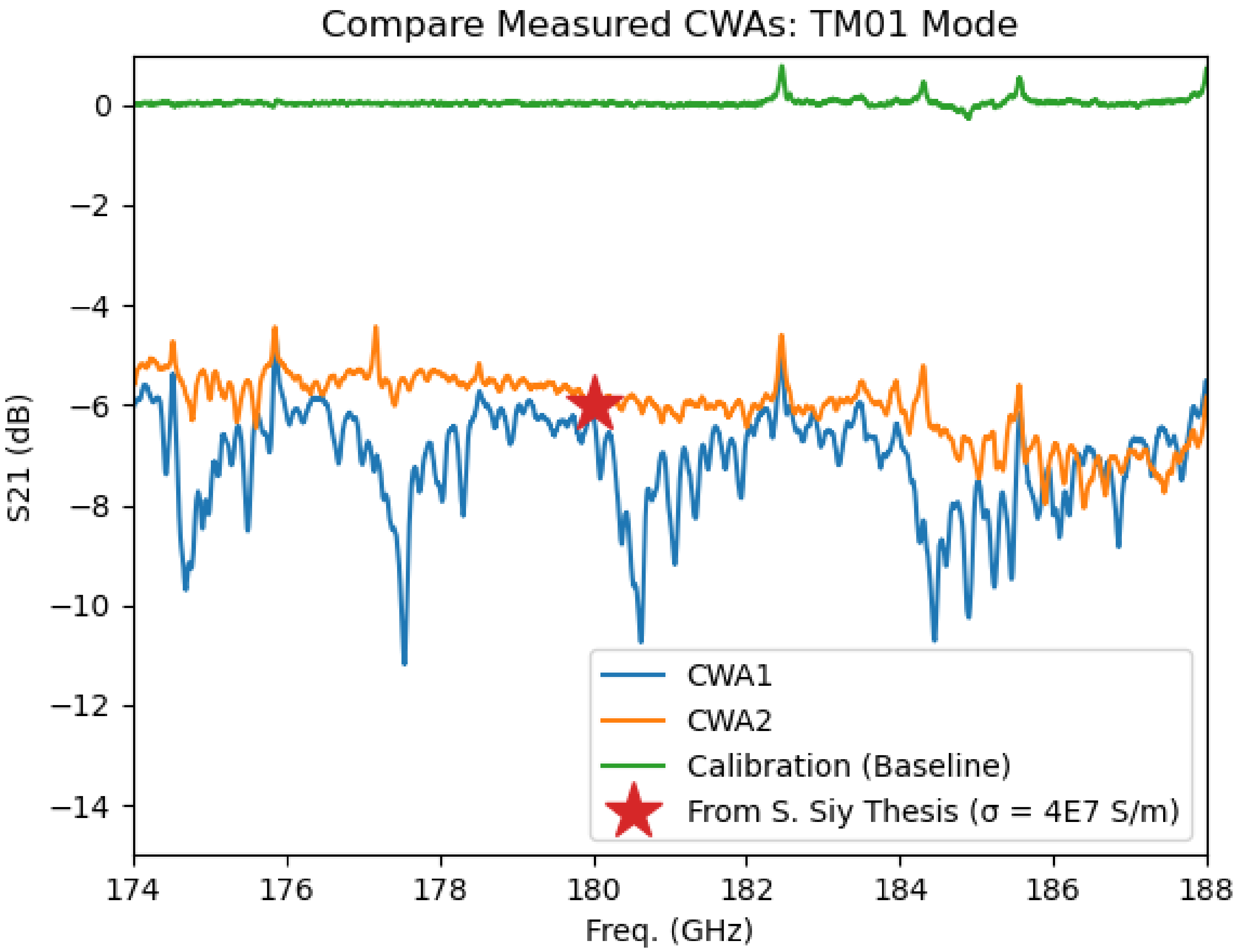
COLD TESTING OF CORRUGATED WAVEGUIDES

Attenuation Factor (From S. Siy Thesis)

	TM_{01}	HEM_{11}	Units
f	180	190	GHz
κ	1.18e16	2.19e10/µm^2	$V\,C^{-1}\,m^{-1}$
β_g	0.57	0.62	None
α	2.31	1.96	$Np\,m^{-1}$

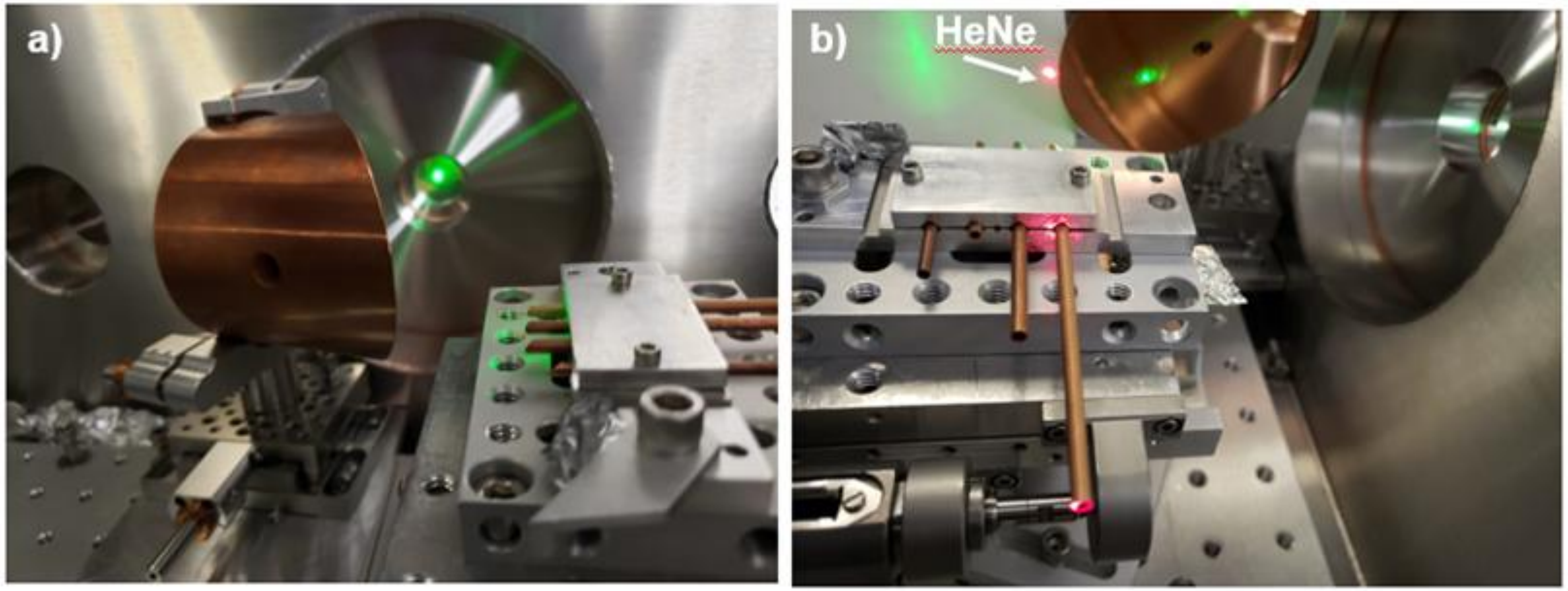
TABLE III. A-STAR synchronous electromagnetic mode characteristics. The loss factor κ for the HEM_{11} mode scales with the square of the beam offset and the attenuation coefficient α is given for a structure with conductivity of $4 \times 10^7\,S\,m^{-1}$.

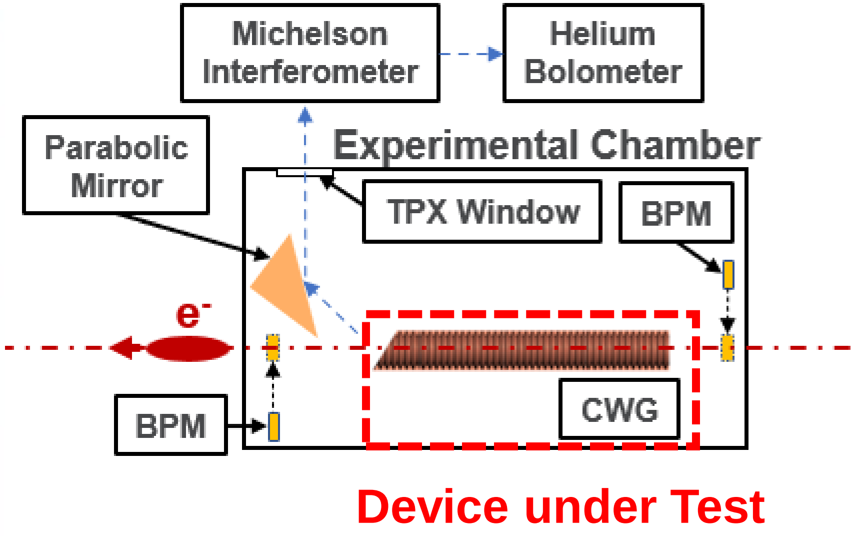
- For TM01 mode, 300 mm CWA
  - 6 dB loss expected



BEAM TESTING AT BNL ATF

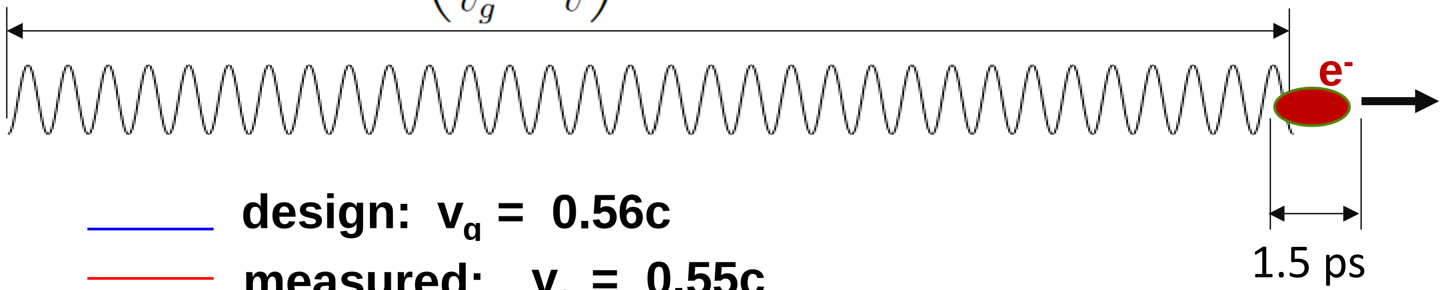
Experimental Setup: Chamber with CWG





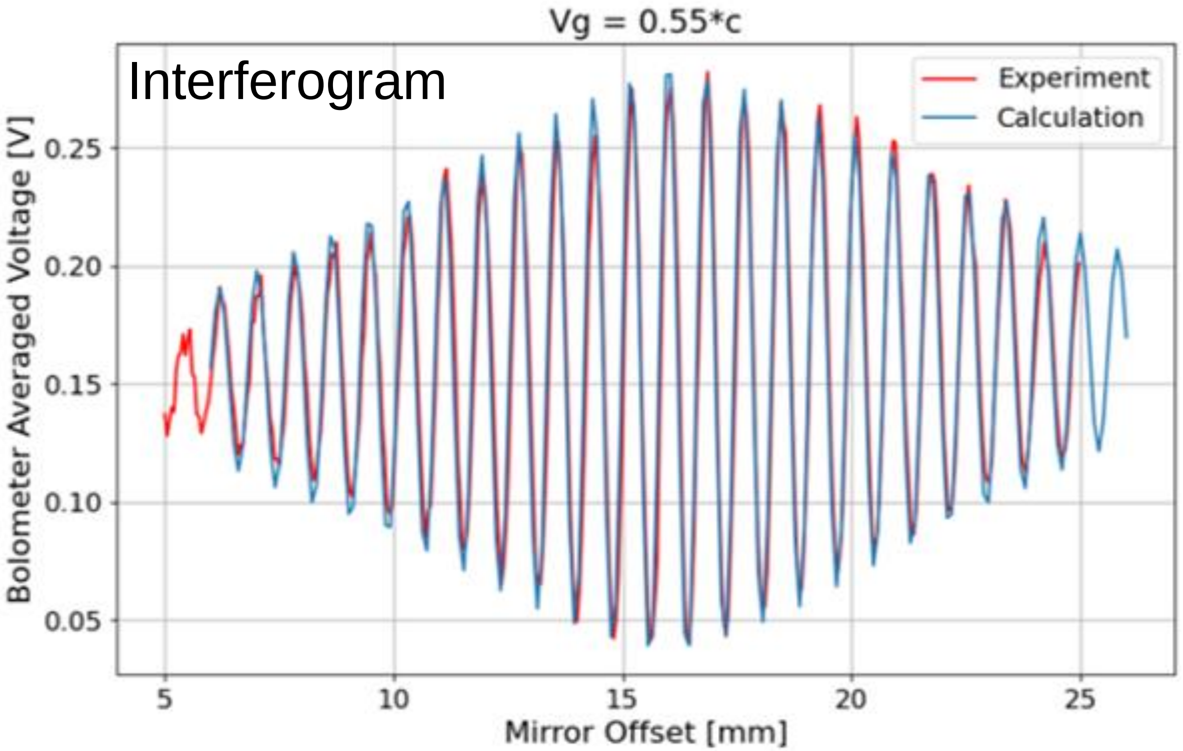
MEASUREMENT OF CWG: FREQUENCY & GROUP VELOCITY

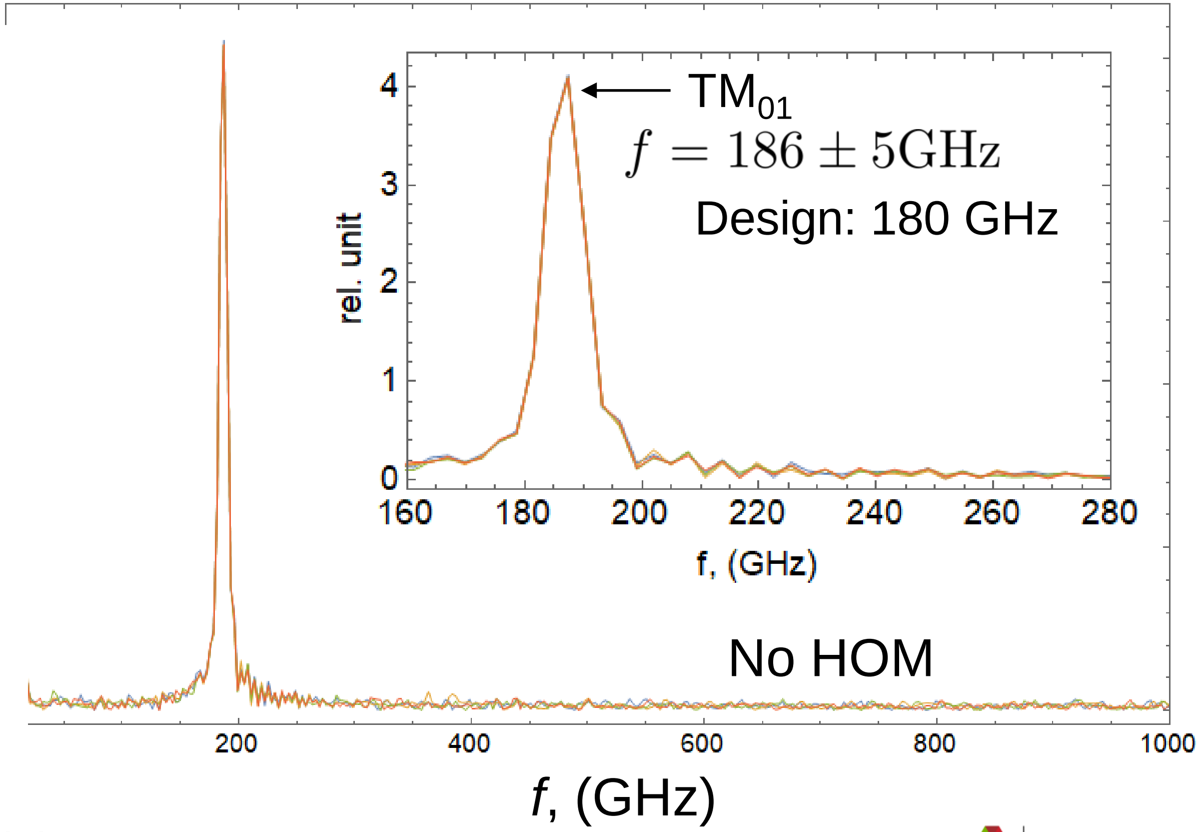
$$\Delta t = L\left(\frac{1}{v_g} - \frac{1}{v}\right)$$ (L=34 mm)



design: v_g = 0.56c

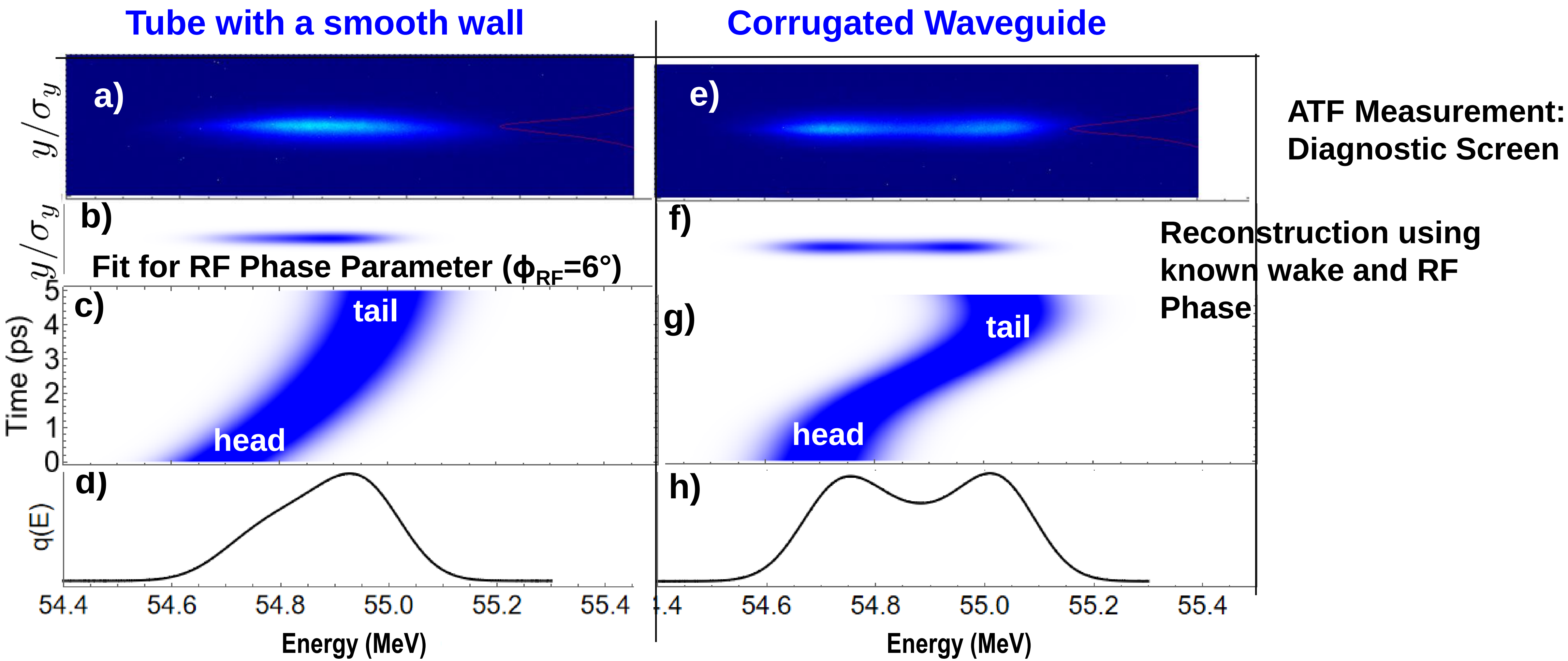
measured: v_g = 0.55c





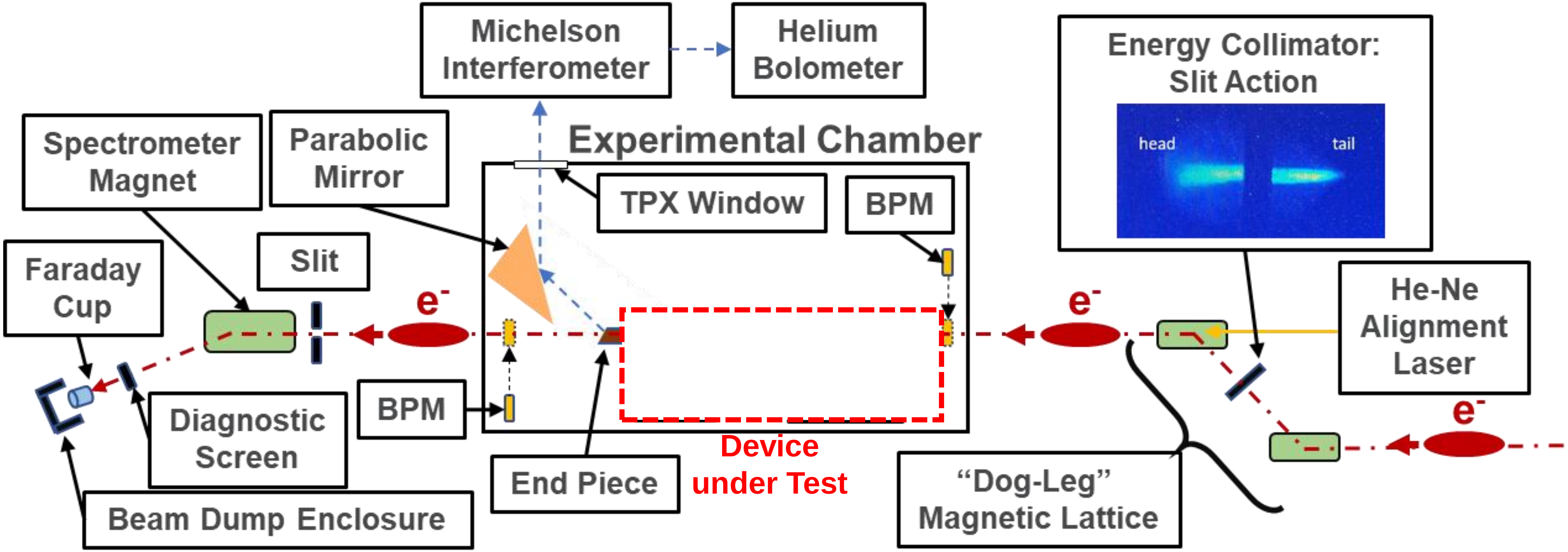
Electron beam self energy modulation by the wakefield

Calculated results for a 5 ps (~λ TM_{01} mode), 130 pc bunch with a flattop peak current distribution and 65 keV slice energy spread. Off crest acceleration by 6.0 degree. Tube length=74 mm



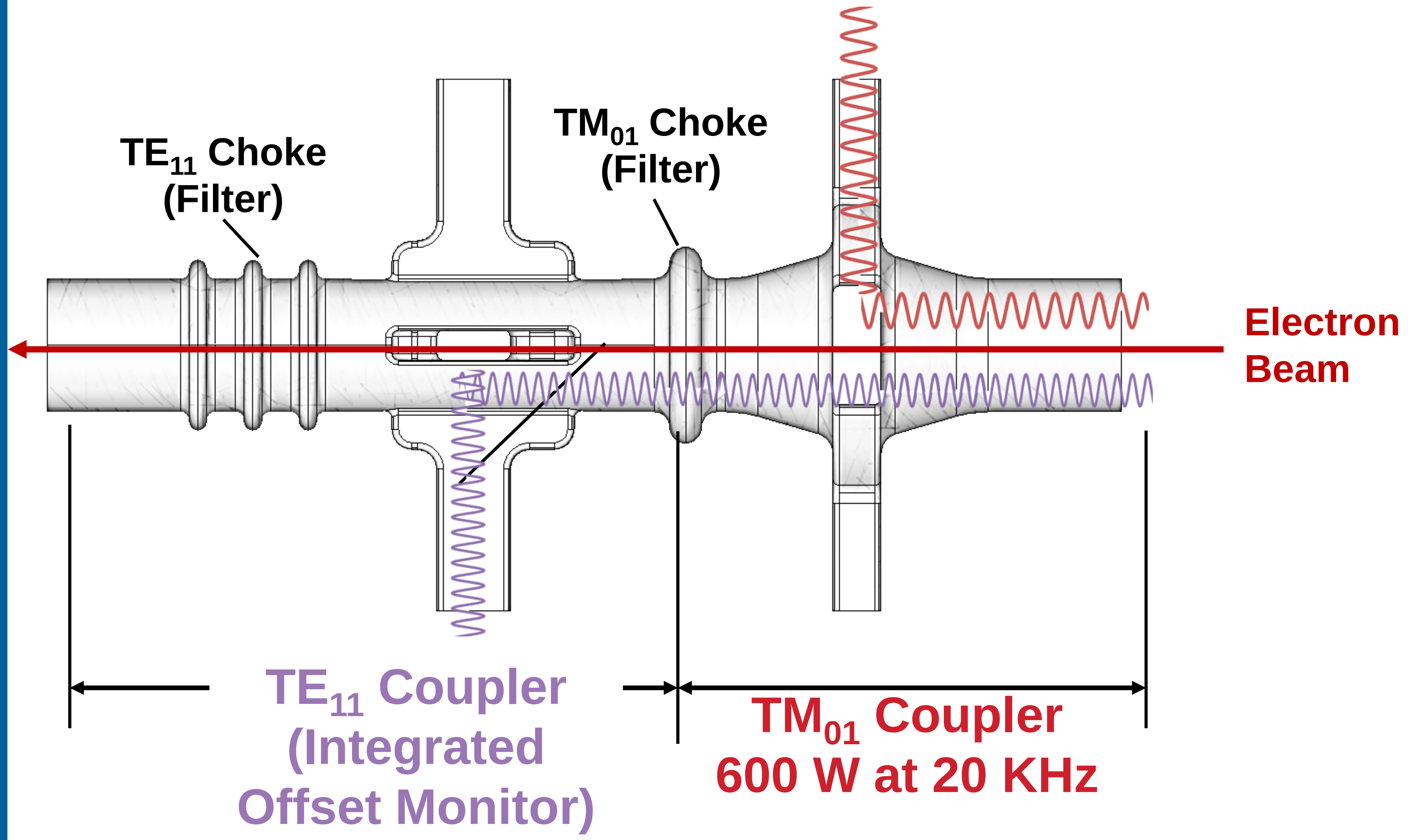
EXPERIMENTAL SETUP AT BNL ATF

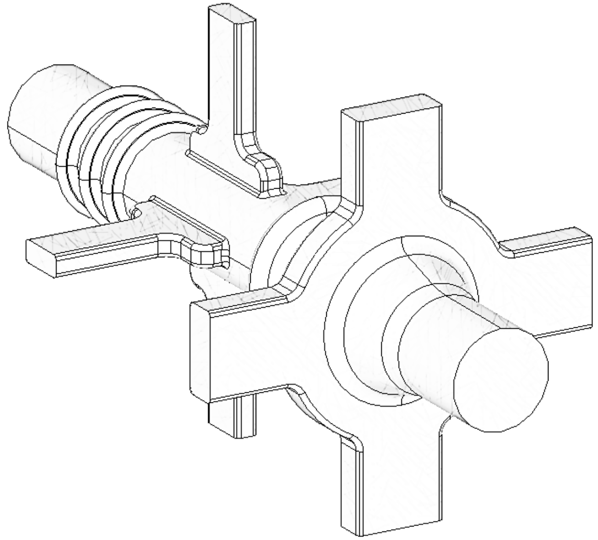
Beam Parameters	Value
Beam Energy	55 MeV
Bunch Charge	10-40 pC
Charge Distribution	flat top
Bunch Length, l_b/c	~ 1-2 ps



TRANSITION SECTION DESIGN

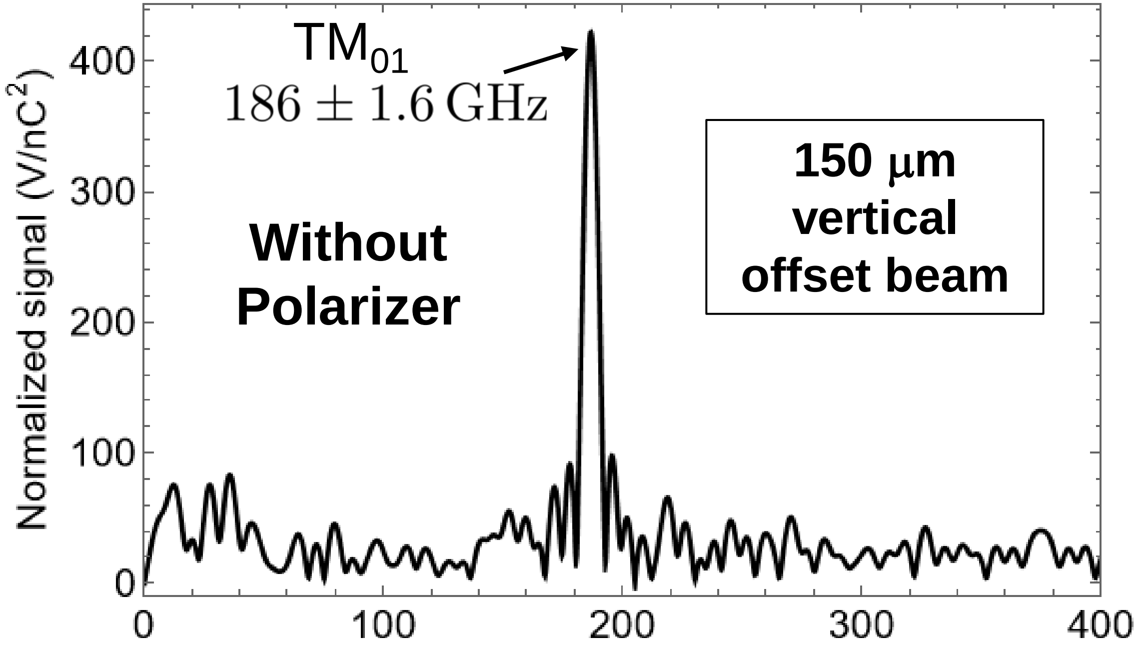
- Multiple CWG connected via Transition Sections (TS)

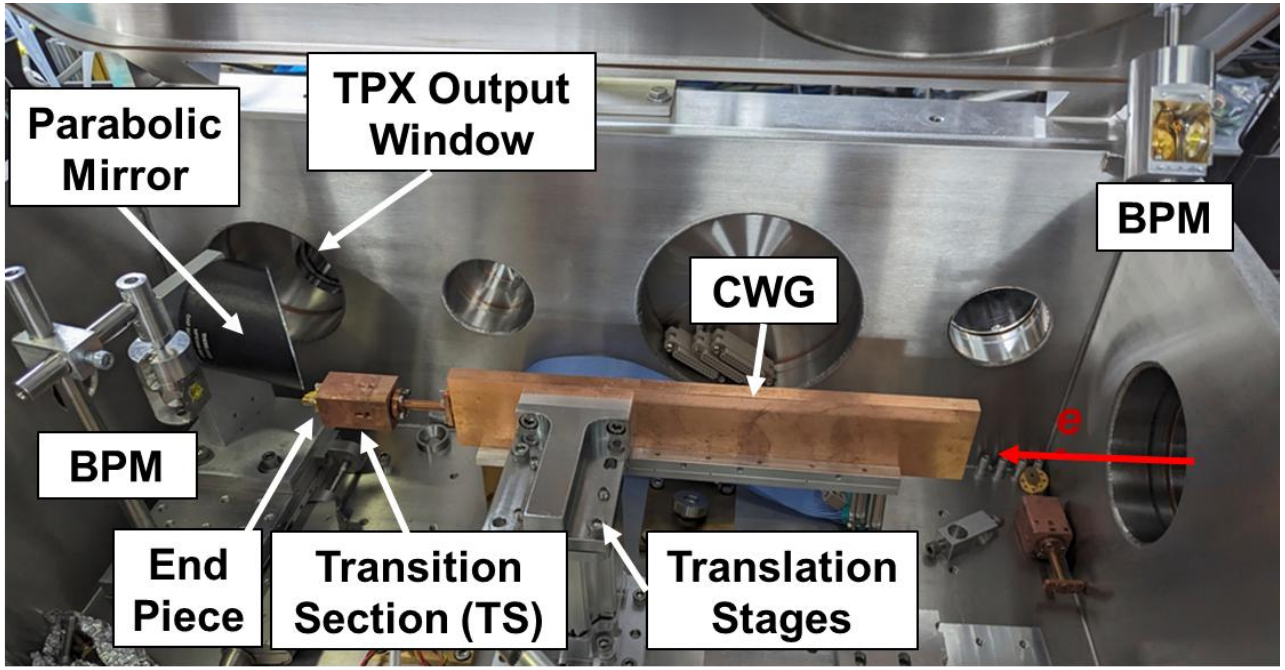


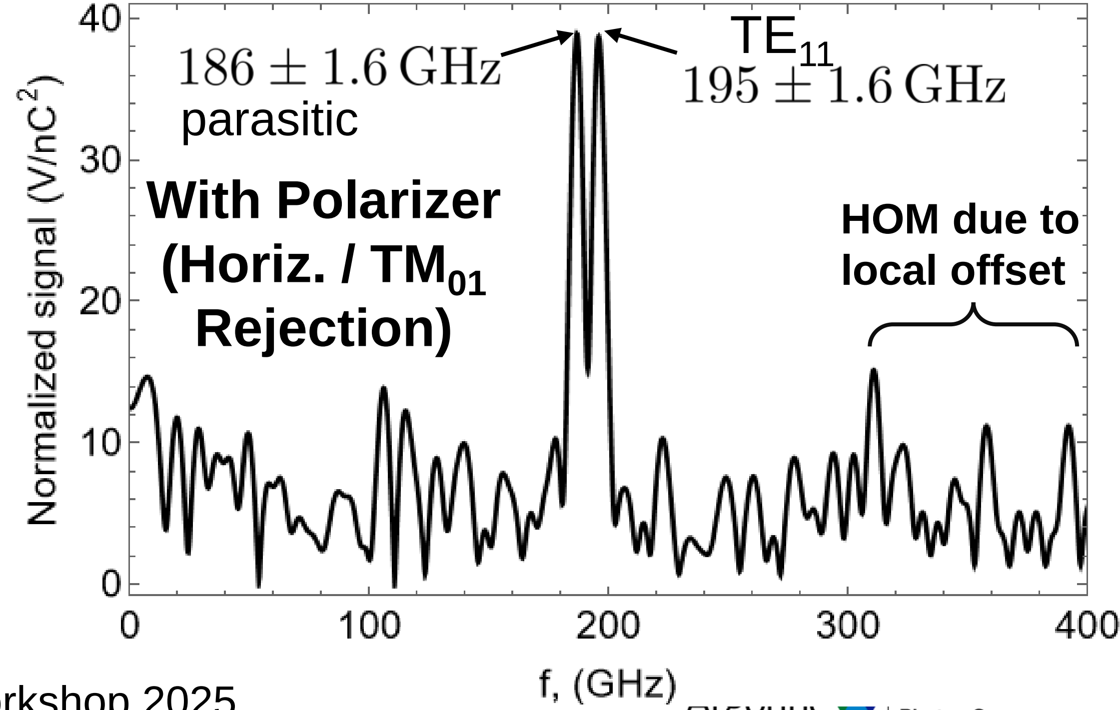


TRANSITION SECTION BEAM TESTING AT BNL ATF

Capture Rate	Mode Coupler	
	TM_{01}	TE_{11}
Polarization	**Horizontal**	**Vertical**
CWG 1	97.9±0.5%	97.1±1.1%
CWG 2	95.9±1.6%	95.8±3.0%



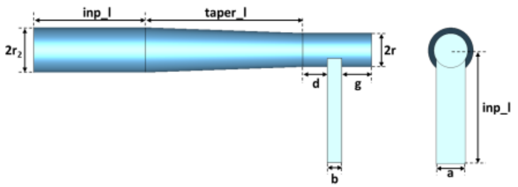


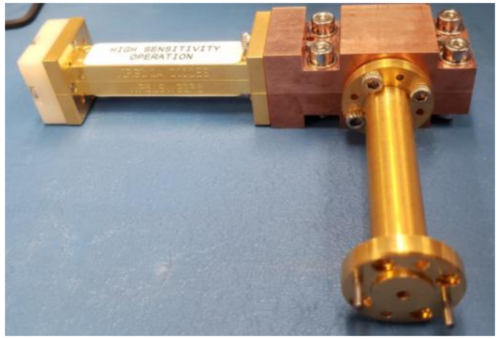


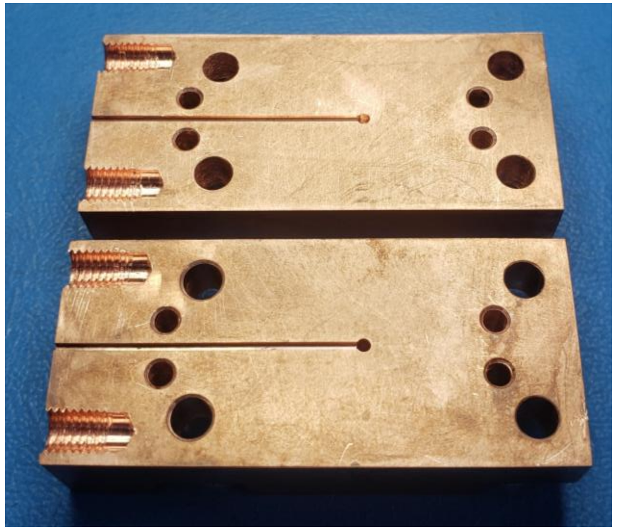
MODE CONVERTORS

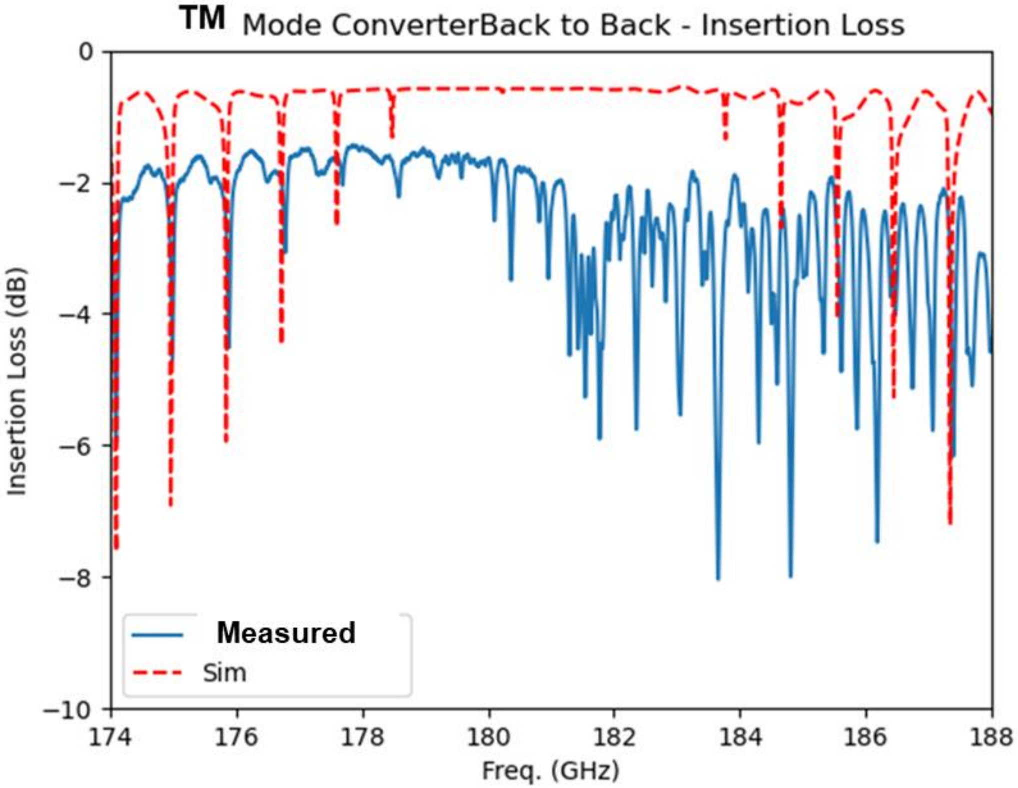
WR5 to Circular (TM_{01} & TE_{11})

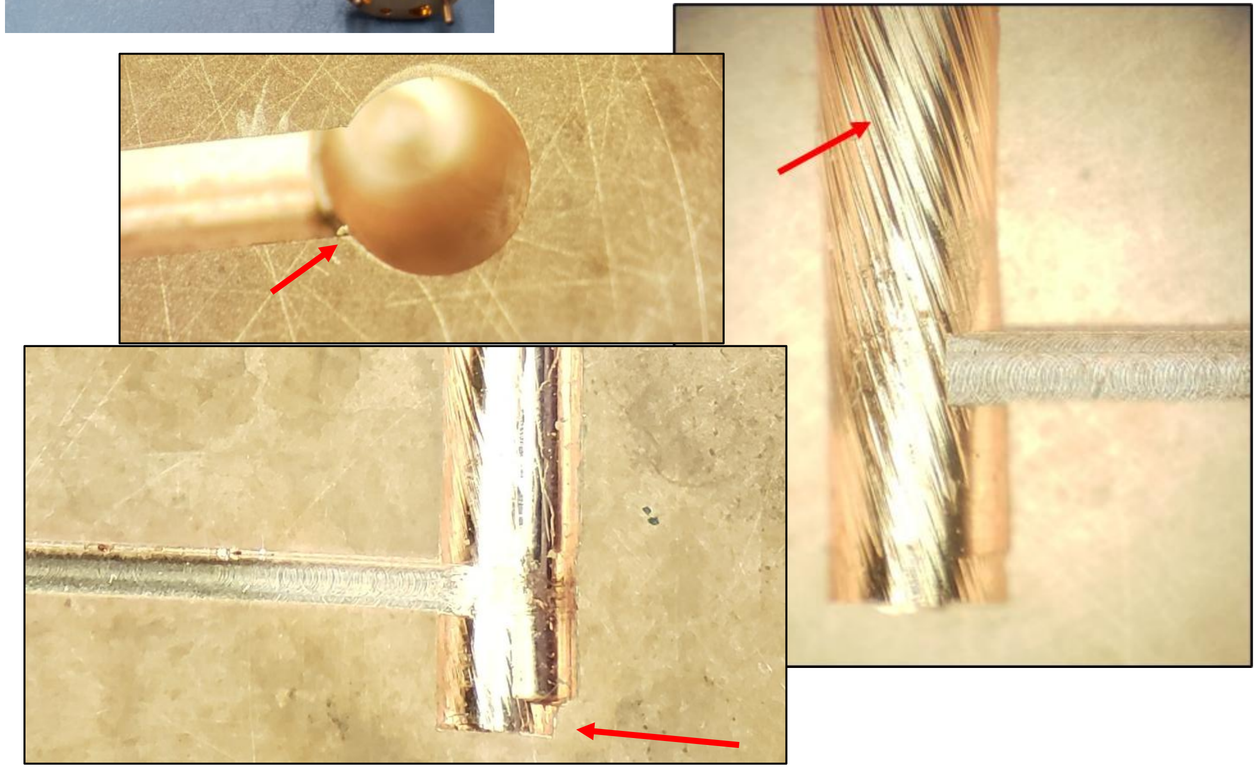
- Traditional Machining



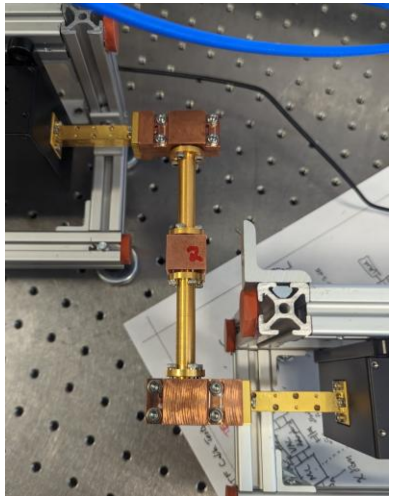


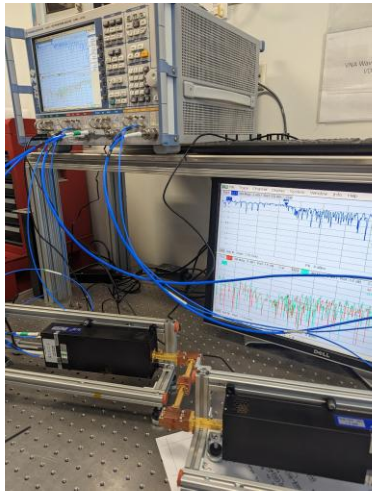


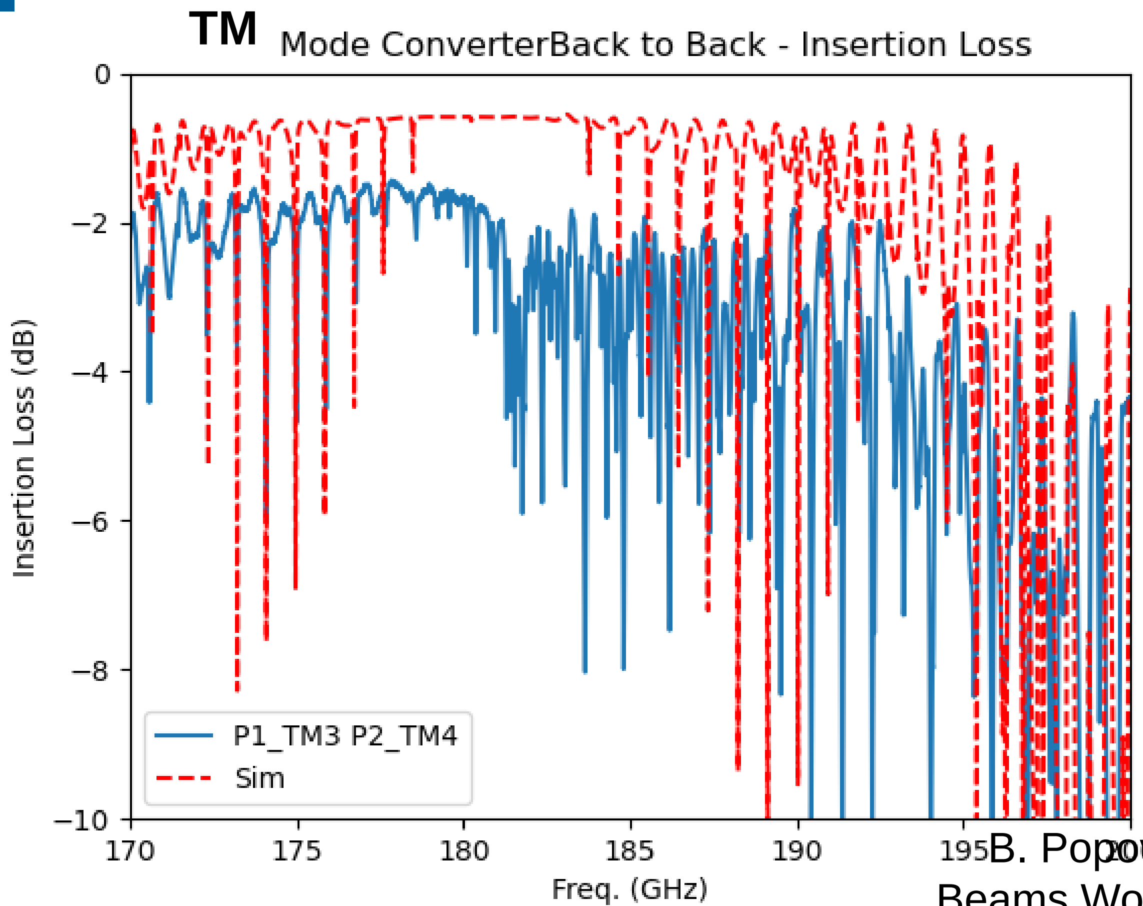


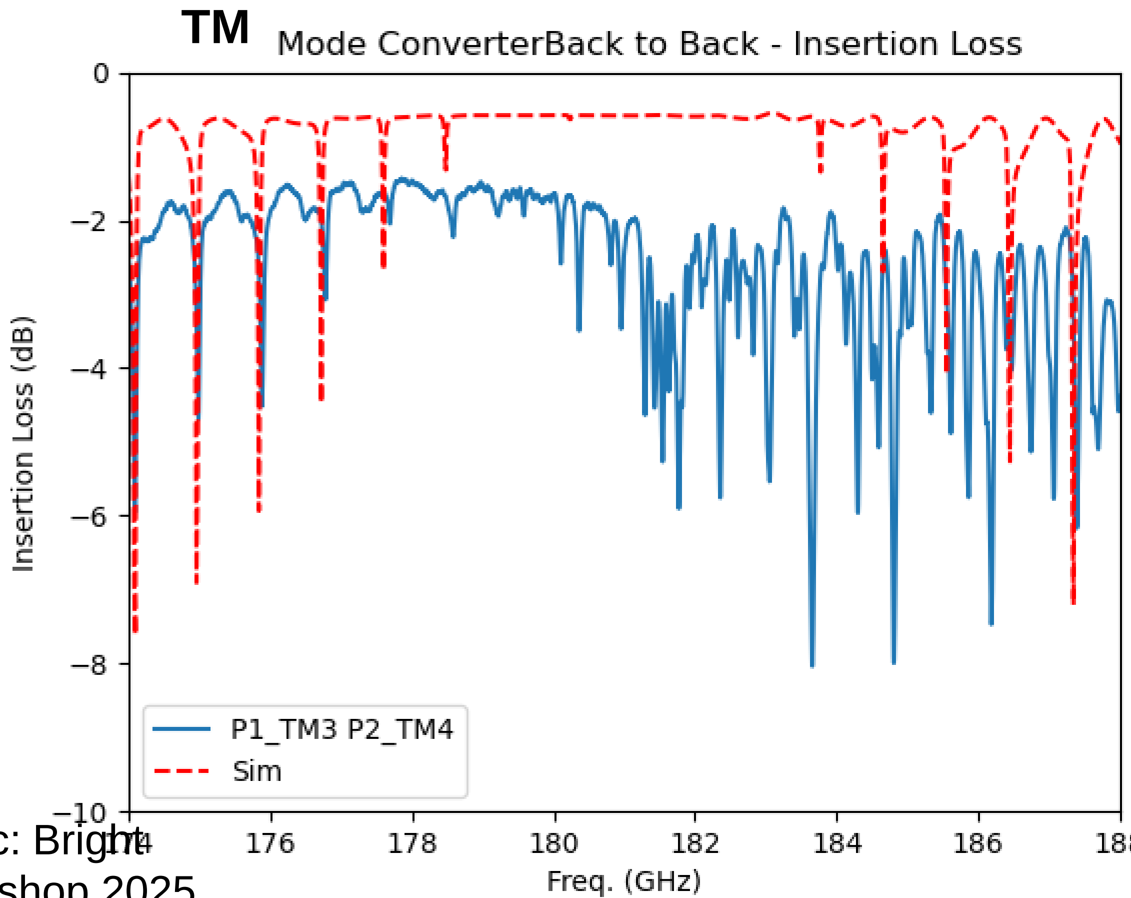


BEST PERFORMING MODE CONVERTORS (TM3 & TM4) : BACK TO BACK

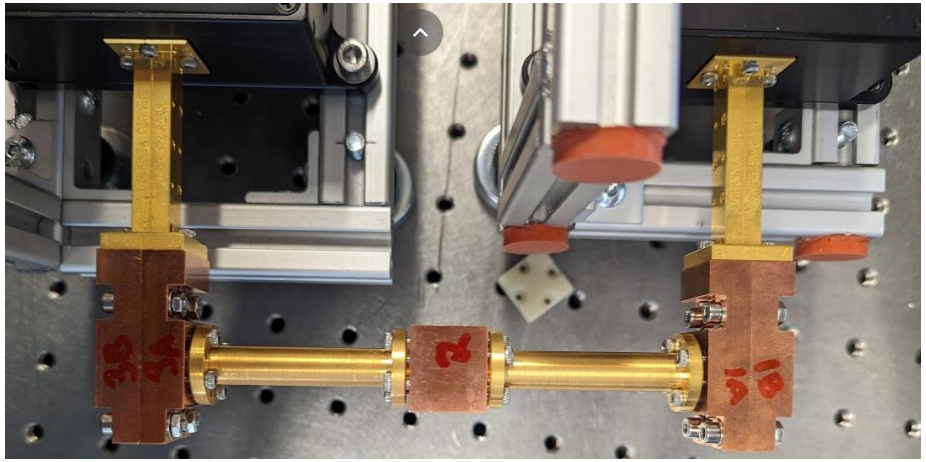


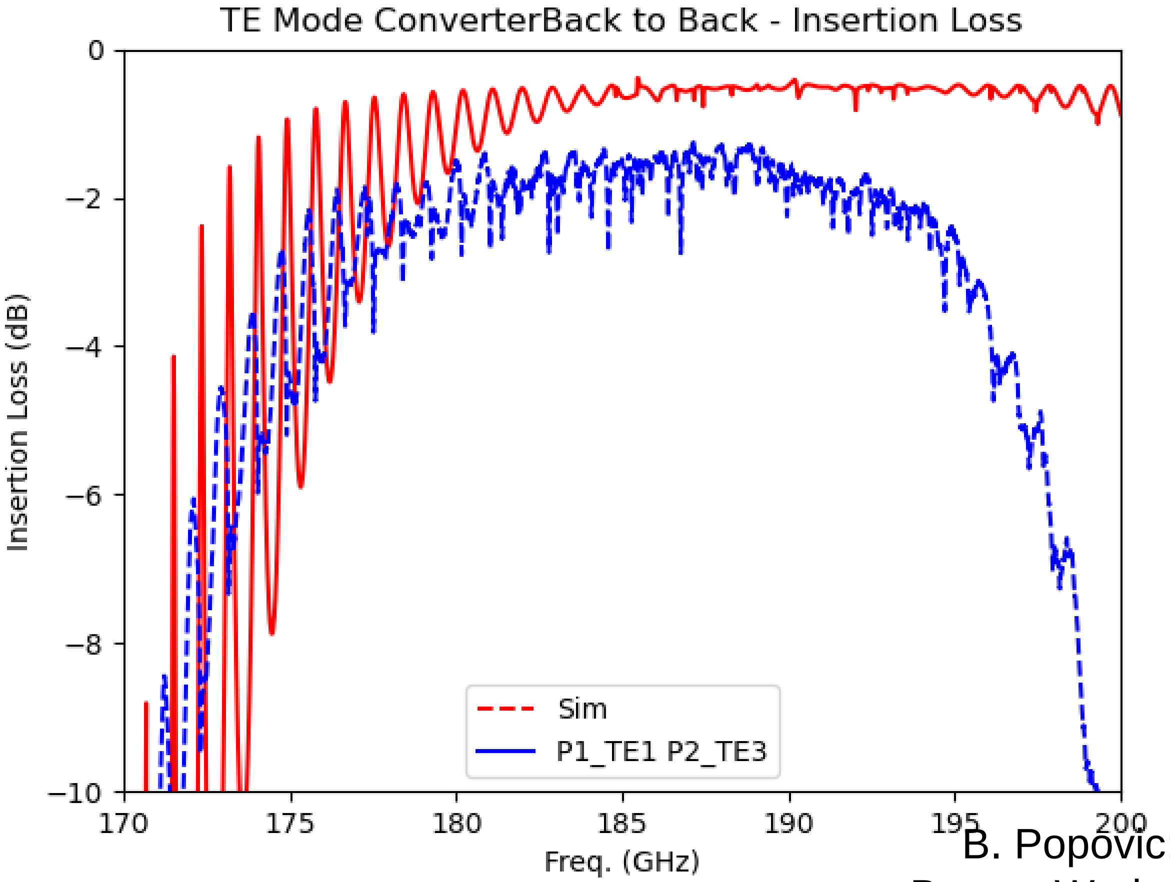


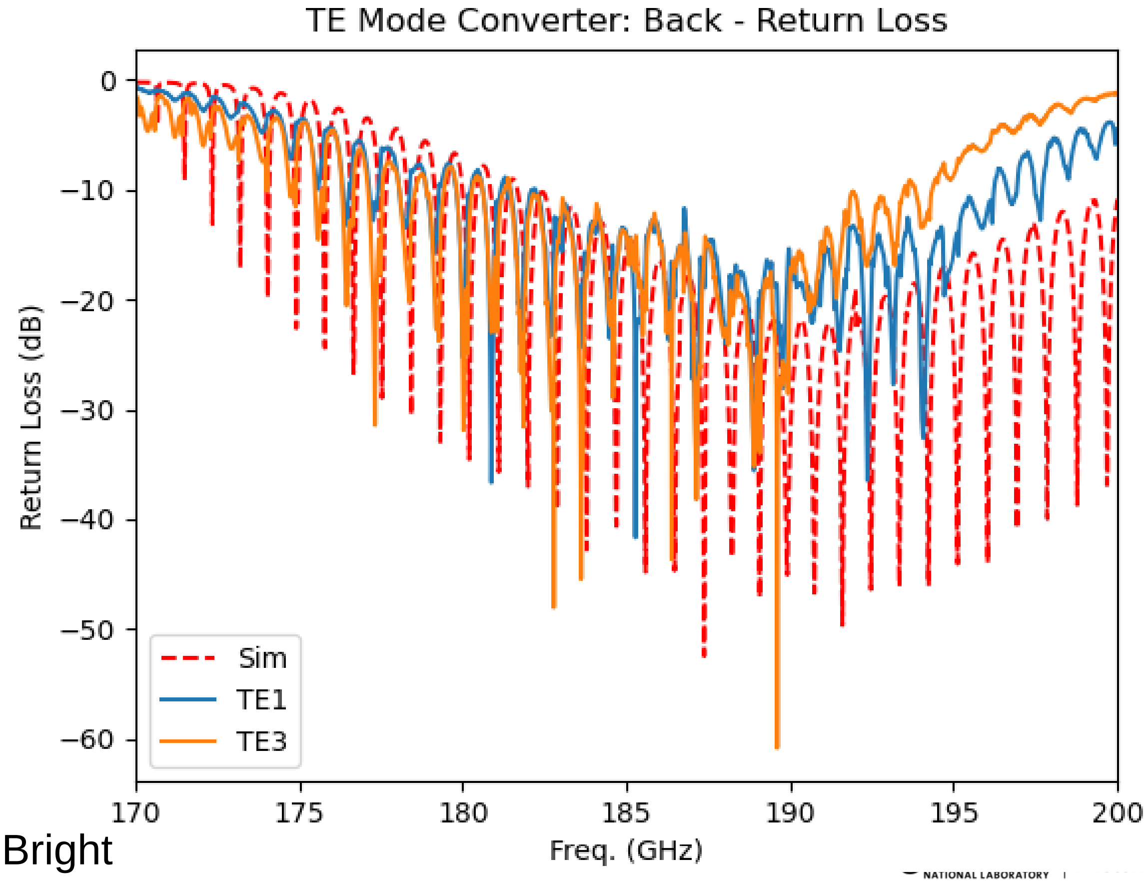




TE11 MODE CONVERTOR: COMPARE TO SIMULATION



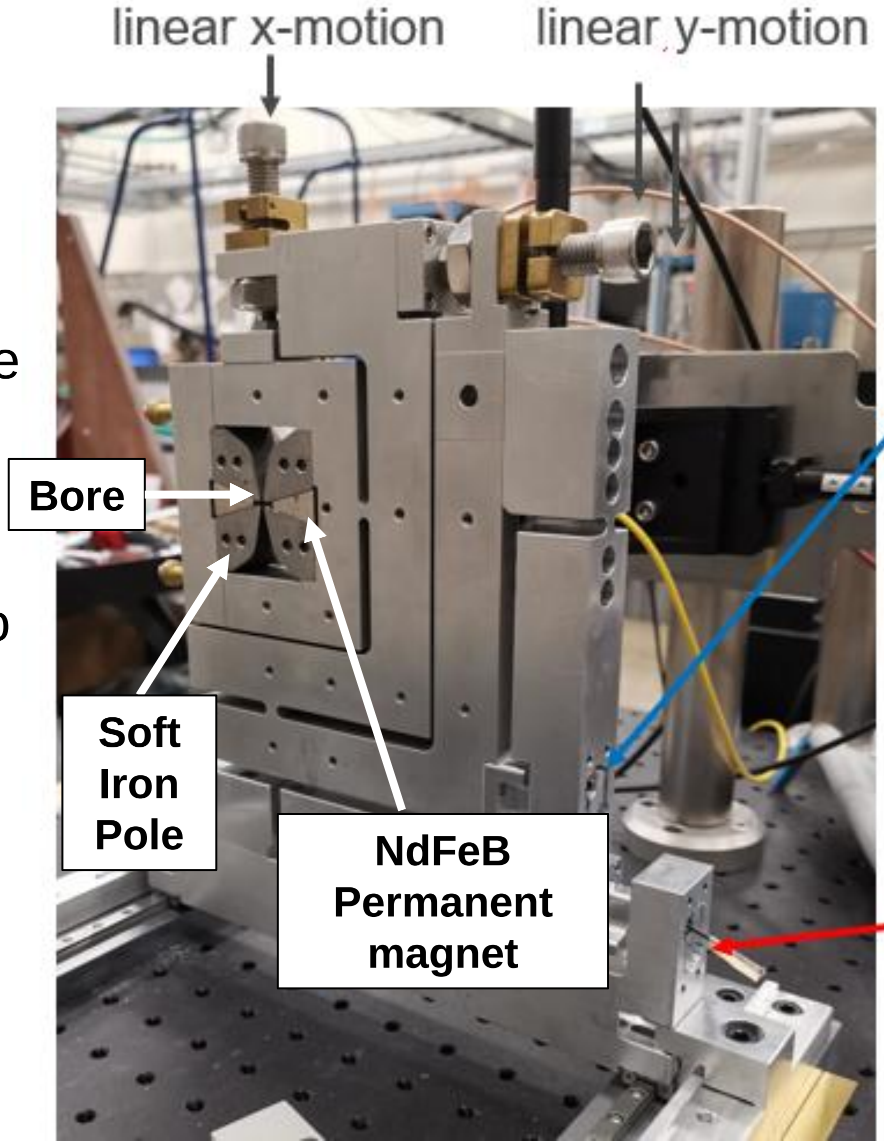


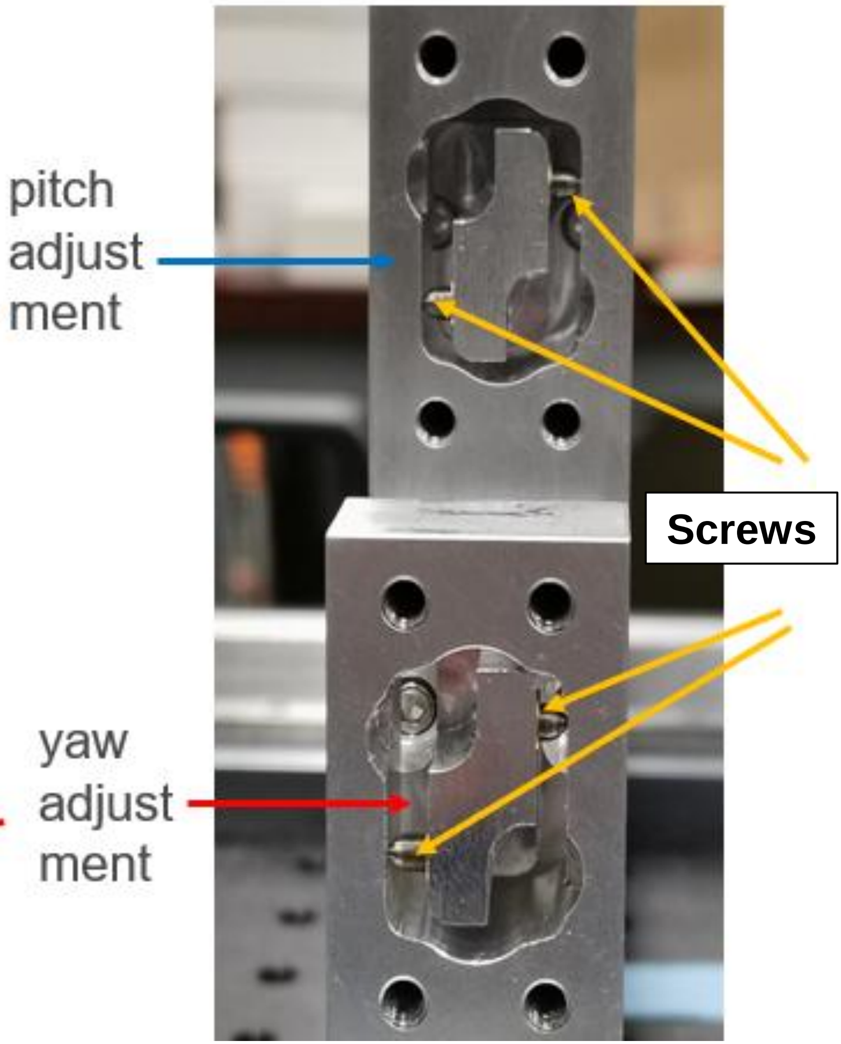


DESIGN AND MAGNETIC MEASUREMENTS OF THE QUADRUPOLE WIGGLER

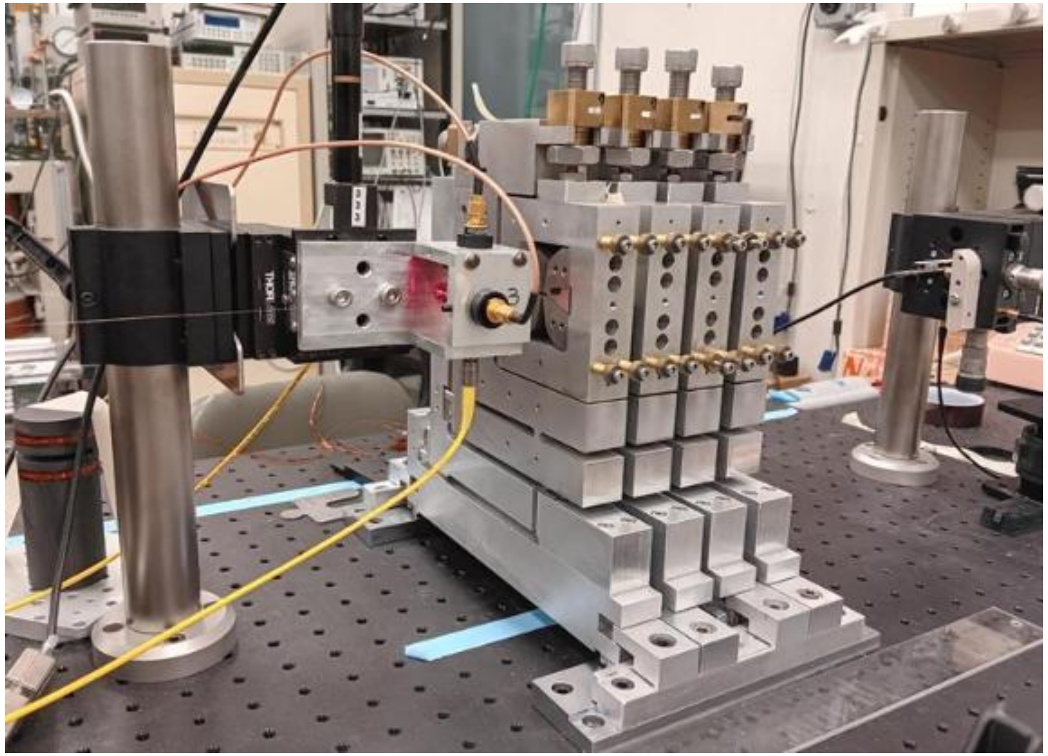
Requirements: (Defined by BBU Suppression)

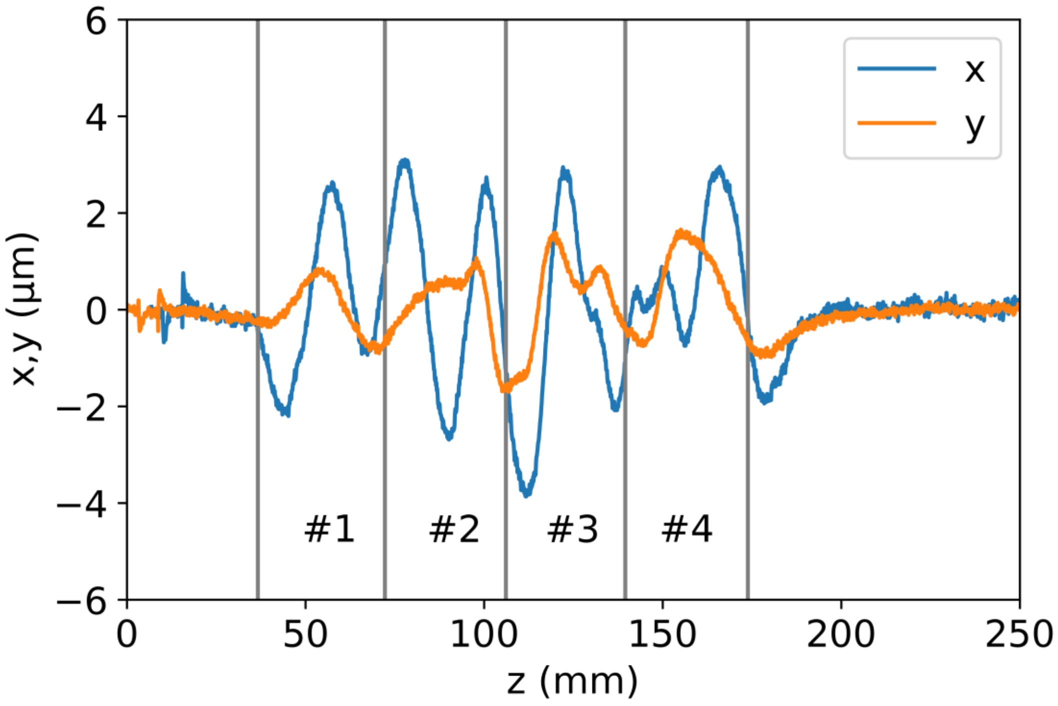
- Ultimate gradient of the magnetic field
  - Maximum Gradient in the Middle of Quad: 0.95 T
- Smaller than 1 micron misalignment of magnetic centers of all quadrupoles to a common central line
- Smaller than 200 microradians yaw and pitch angle misalignment of individual quadrupoles





Measurement of prototype quadrupole wiggler





Temperature dependent drift of the magnetic center was measured as 4.4 µm/°C

Alignment of four quadrupoles.
The final quadrupole magnetic axis offset from the wire derived from the first field integral measurement: less than 0.5 microns
The oscillations of the offsets are due to small wavering in the longitudinal profile of the quadrupole poles.