# A-STAR

# A WAKEFIELD ACCELERATOR FOR HIGH-REPETITION RATE XFELS


Presenter: A. Zholents, **APS/ANL**

W. Jansma, S. Lee[1], M. Kasa, A. Nassiri, B. Popovic, M. Qian, S. Sorsher, N. Strelnikov[2], K. Suthar, E. Trakhtenberg, G. Waldschmidt (**APS/ANL**)
S. Doran (**HEP/ANL**)
M. Fedurin, K. Kusche (**ATF/BNL**)
A. Siy[3], N. Behdad, J. Booske (**University of Wisconsin**)
S. Baturin[4], P. Piot[5], W.-H. Tan[6] (**Northern Illinois University**);

1) now at LANL, 2) at Amazon, 3) at Quaise Energy, 4) at ITMO University, 5) at HEP/APS/ANL, 6) at SLAC



**AAC'2026 UCLA**

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# LCLS-II sets a new standard for the X-ray laser, delivering millions of X-ray pulses per second to scientific users to tackle questions that had previously been impossible to address

“The increase (*from 120 Hz to 1 MHz*) has already made an amazing change,” Dakovski said*). “Not only is the data coming in faster and with clarity we haven’t seen before, it actually helps us see how the materials are transforming over time. We can watch how energy flows through the material and how the atomic components interact. We can create frame-by-frame ‘movies’ of the dynamic processes.”

*) https://www6.slac.stanford.edu/news/2025-08-07-united-states-just-got-new-x-ray-laser-toolkit-study-natures-mysteries

Could we replace the SRF linac with more affordable compact accelerator?

1. Plasma-based wakefield accelerators driven by electron or laser beams

- The bunch length is not much smaller than the plasma wavelength ☹
- Operating at a high repetition rate is challenging ☹

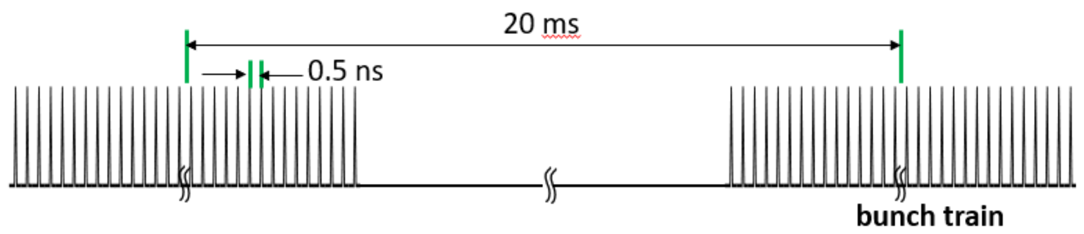
2. Structure-based accelerators driven by external RF sources

- $C^3$ - the cryogenically cooled copper C-band linac
- The *CompactLight* design study: leveraging the latest innovations in X-band linac and undulator technologies
- Long RF pulse -> low repetition rate ☹

3. EuPRAXIA: combines structure-based and plasma-based -> low repetition rate ☹

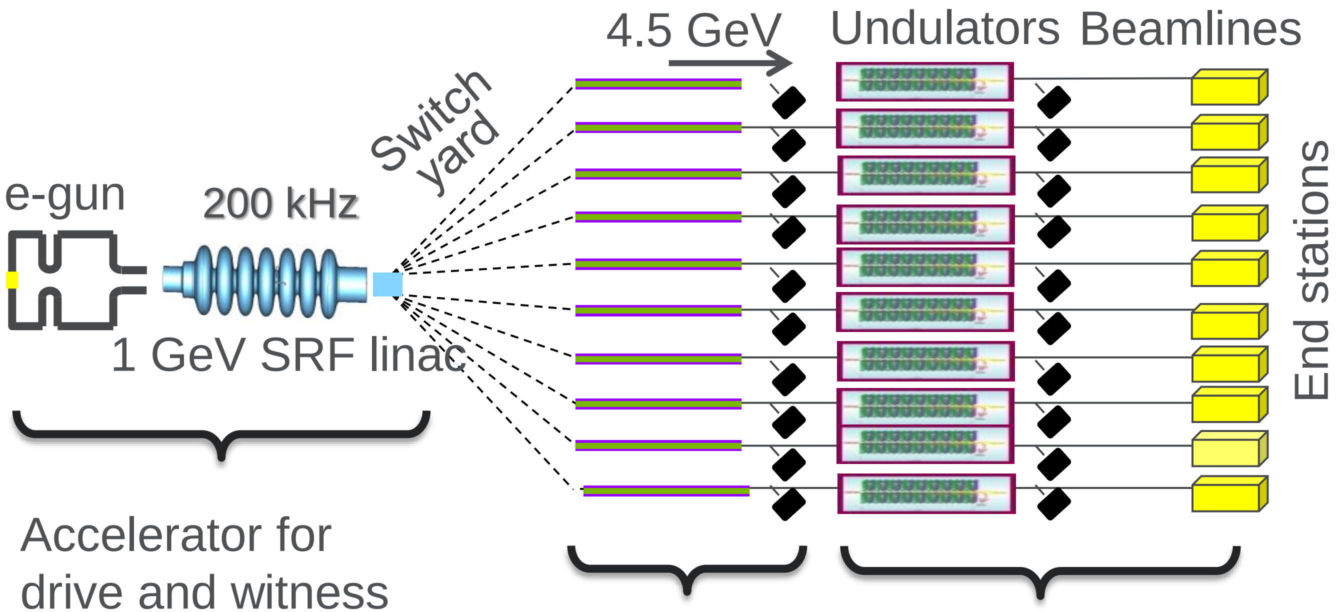
3. Two-beam wakefield accelerator -> CLIC (X-band 50 Hz, 312 bunches)

CLIC




☹

# Multi-user tender-to-hard X-ray free electron laser facility




Accelerator for drive and witness bunches
.

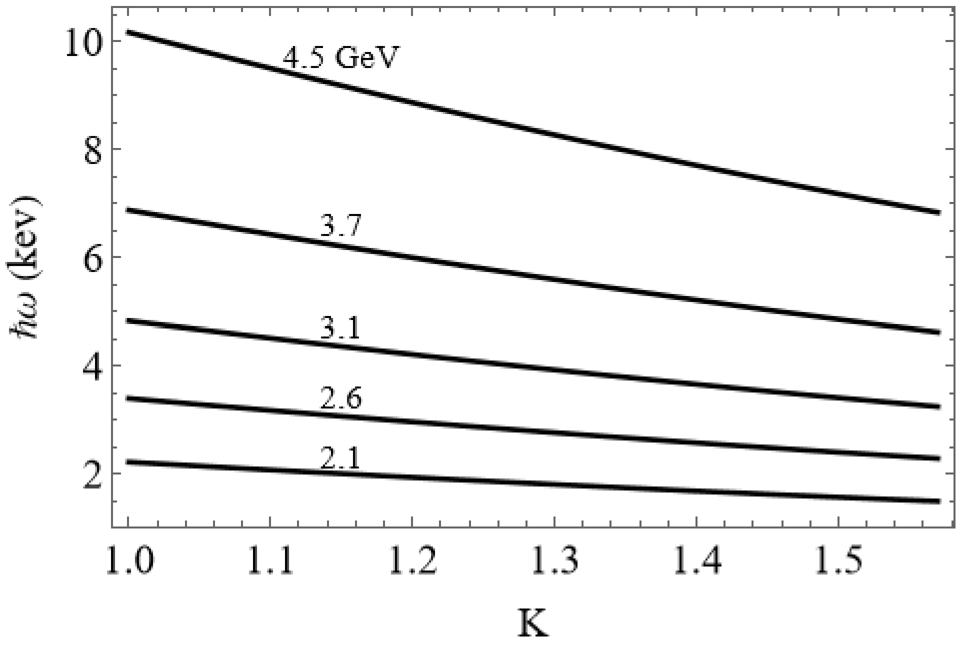
Array of collinear wakefield accelerators

XFEL undulators and beamlines

High wall plug power efficiency

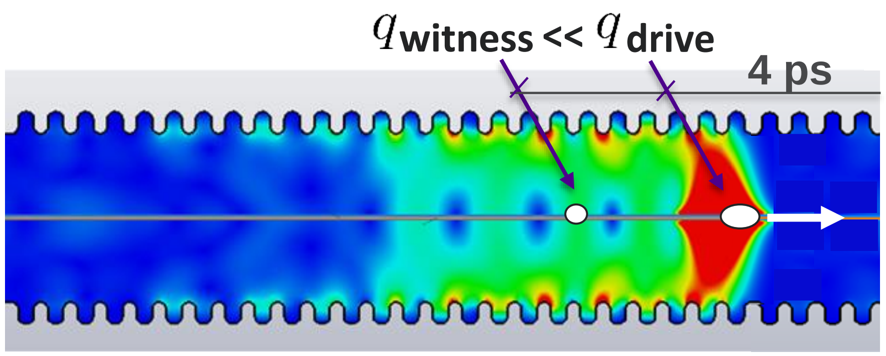
- CWAs do not need electrical power (almost)
- Undulators do not need electrical power (almost)

Wavelengths from 1.5 keV to 10 keV. This range includes $K$-edges of 18 atoms from silicon to zinc.



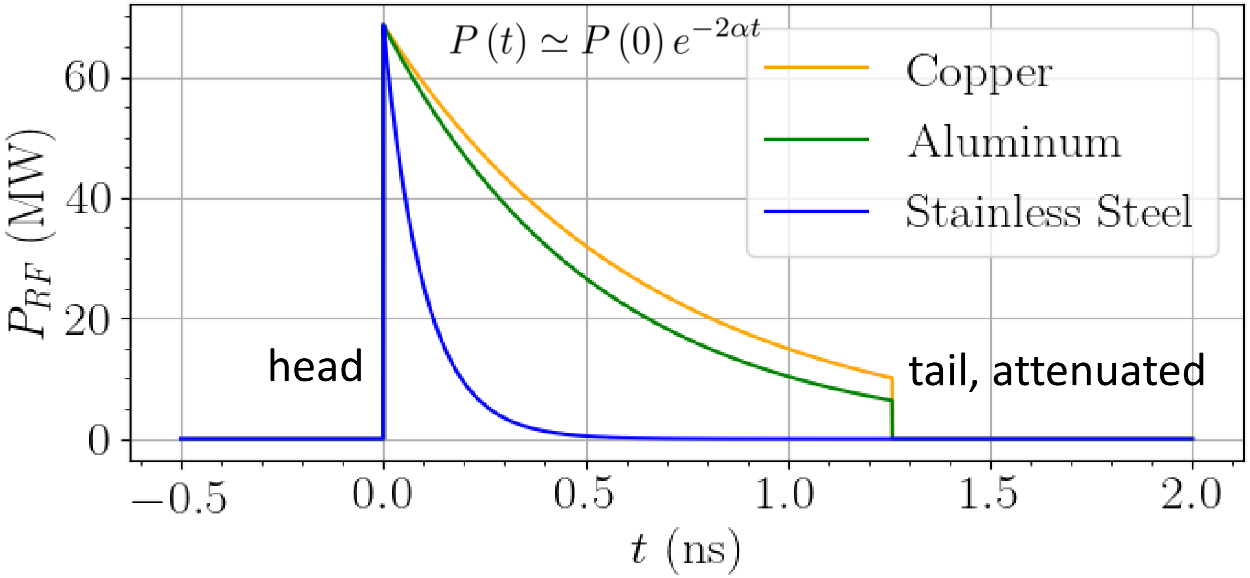

Photon energy $\hbar\omega$ versus undulator parameter $K$ calculated for FNAPU with a period of 12.6 mm.

# Collinear wakefield acceleration using one drive and one witness bunch is well suited for a high repetition rate operation

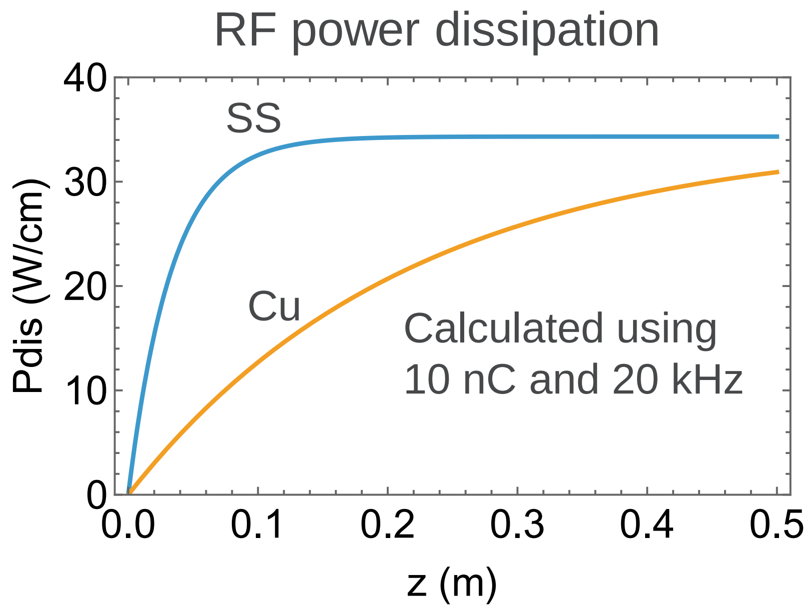



The corrugated waveguide is used to obtain a wakefield

… because the wakefield needs to exist only for a short time!



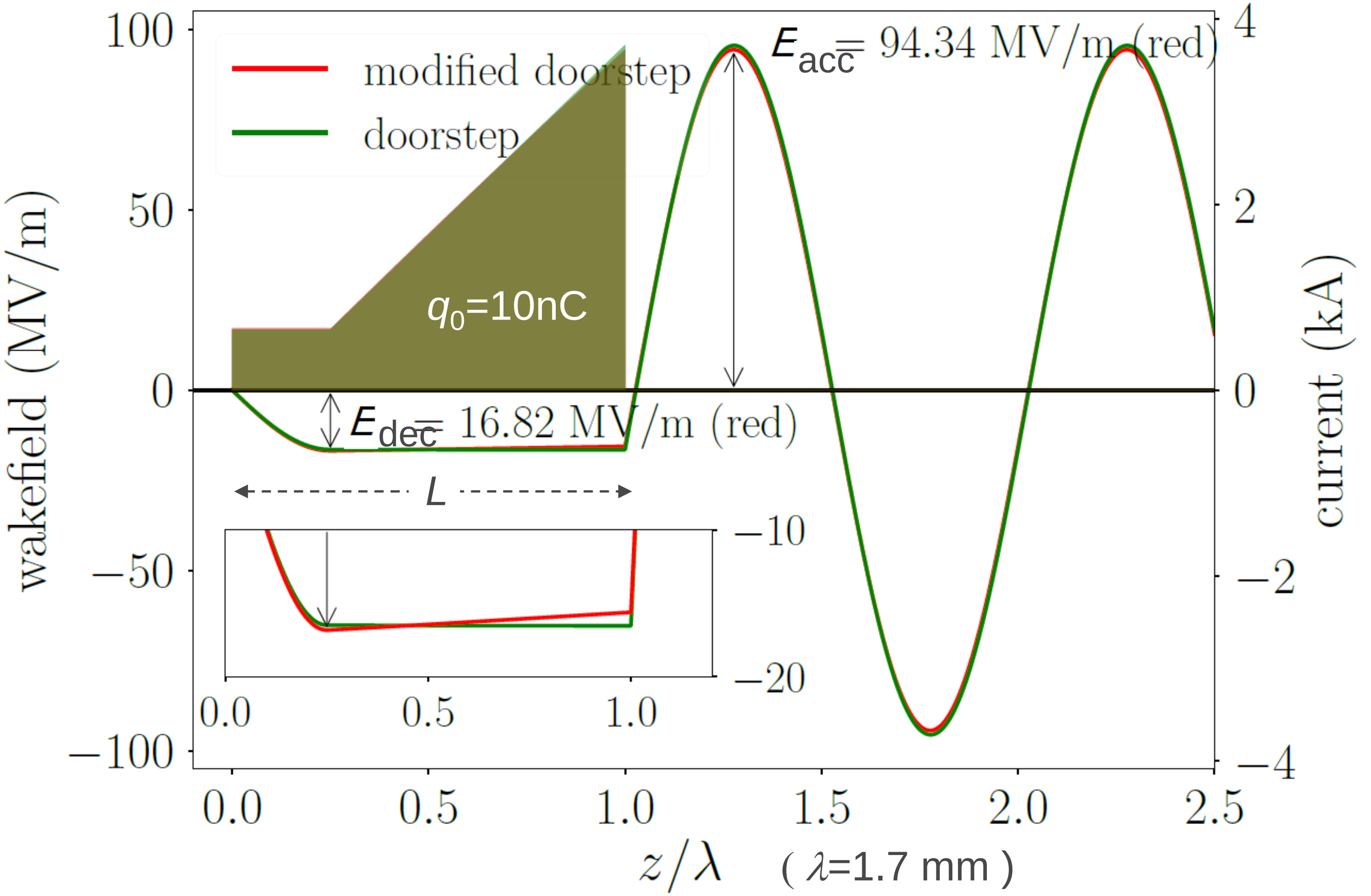

RF power envelope at the end of a 0.5 m long section of CWA operating at 180 GHz. The wakefield decays due to dissipation in the walls.




Using sub-THz frequency and lossy material is beneficial for obtaining short pulses, and possibly high breakdown fields

# Shaped drive bunch to obtain a high accelerating field for a witness bunch and an equal deceleration rate for almost all electrons in the drive bunch

A "doorstep" charge distribution[1]




Transformer ratio

$$\mathcal{R} \equiv |E_{acc}/E_{dec}|$$

$$\mathcal{R} \approx \sqrt{1+\left(2\pi\frac{L}{\lambda}\right)^2}$$

$$E_{acc} \leq 2\kappa_{\|}|q_0|\frac{2\mathcal{R}}{1+\mathcal{R}^2} \propto \frac{1}{\mathcal{R}}$$

loss factor

1) K. Bane, P. Chen, P. Wilson, Proc. of the Part. Acc. Conf. (PAC1985), Vancouver, Canada, p.3524–3526, 1985.

## maximum accelerating field

$$E_{\mathrm{acc}} \leq 2\kappa_{\|}|q_0|\frac{2\mathcal{R}}{1+\mathcal{R}^2} \propto \frac{1}{\mathcal{R}}$$

## loss factor in CGS units

$$\kappa_{\|} \leq \frac{2}{a^2}$$

## kick factor in CGS units

$$\kappa_{\perp} \leq \frac{8}{a^4}$$

## Lorentz force (cause of BBU)

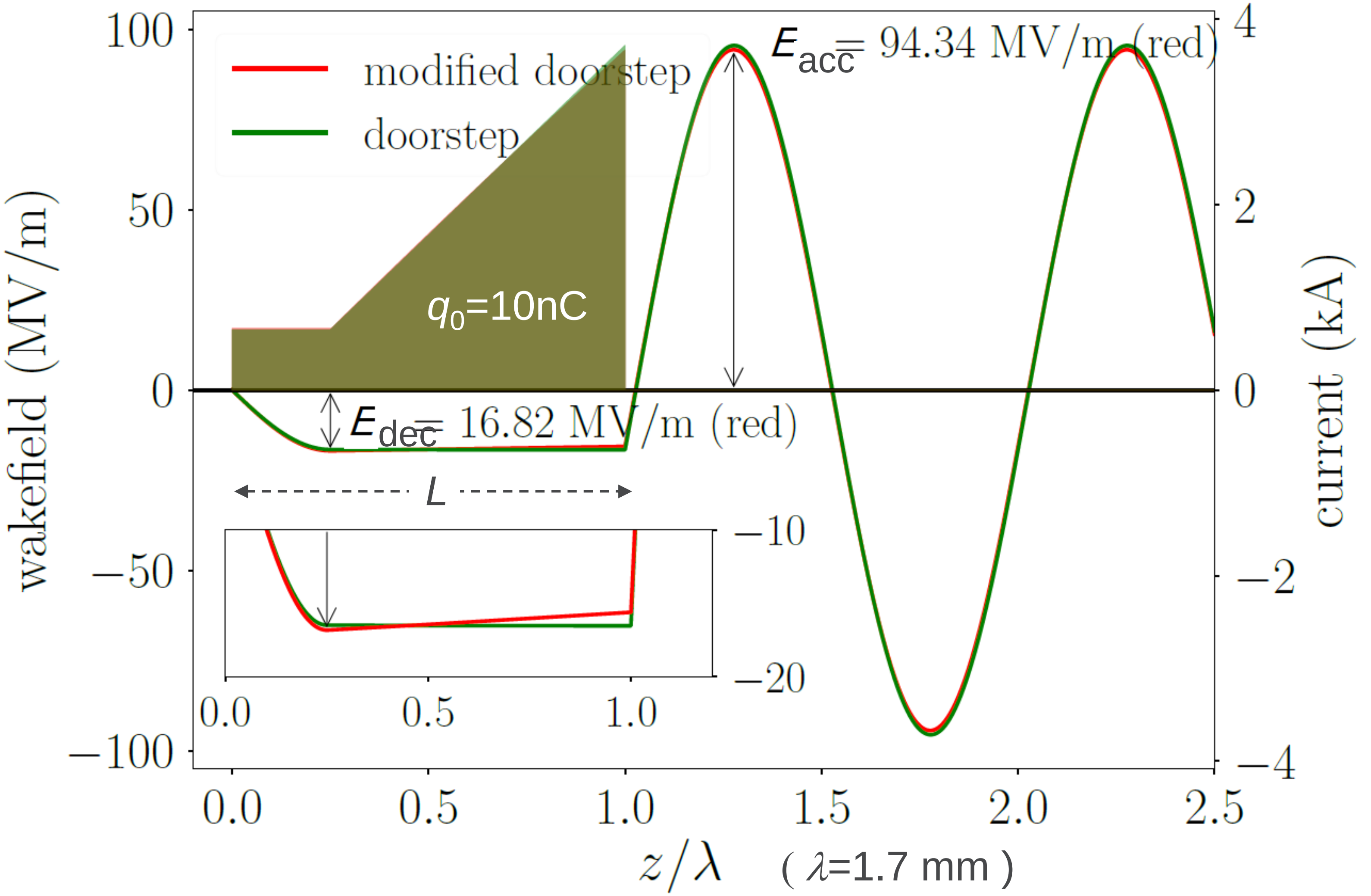

$$F_{\perp}(z,s) \propto \frac{\kappa_{\perp}}{k_1}\int_0^z \sin(k_1(z-z'))q(z')y(z',s)dz'$$ where $k_1 \propto \frac{2\pi}{a}$

Thus

$$E_{\mathrm{acc}} \propto 1/a^2$$
$$F_{\perp} \propto 1/a^3$$

# Adaptive energy chirp is used to facilitate BNS damping of BBU instability

A "doorstep" charge distribution[1]

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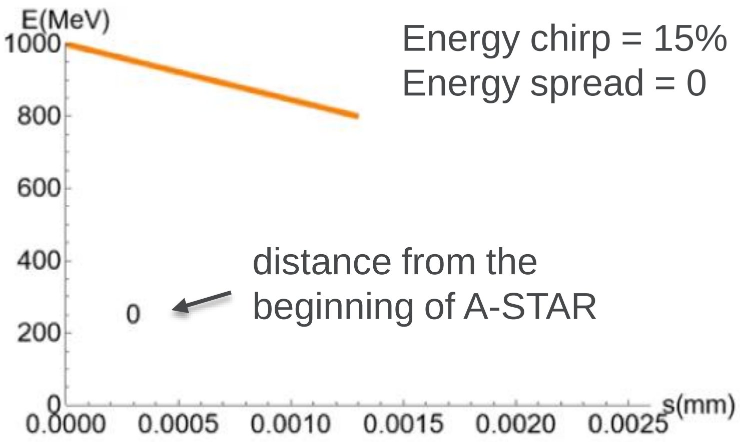
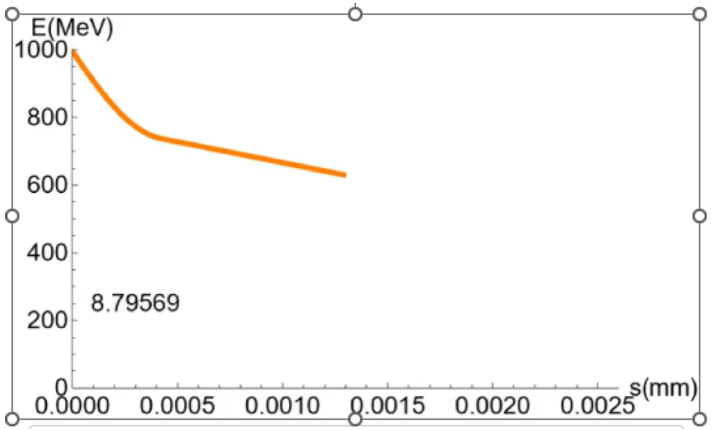
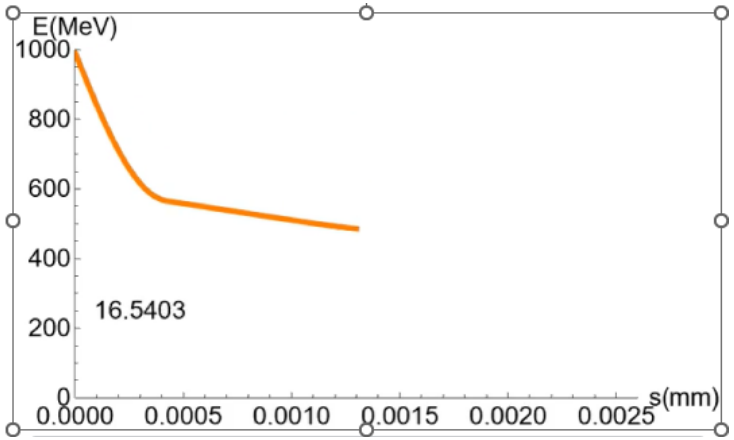
loss factor

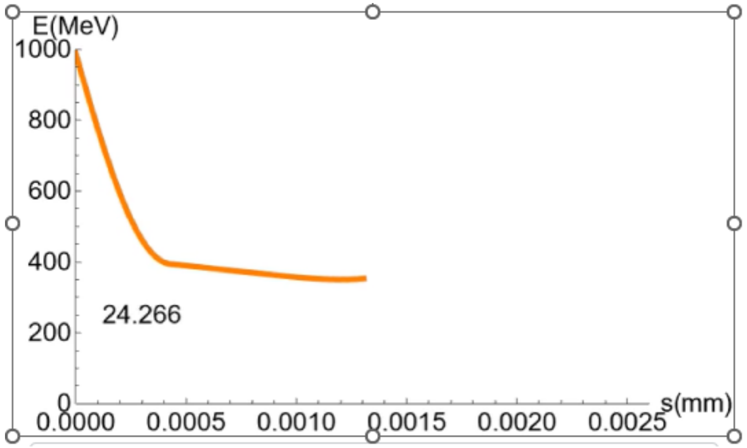
1) K. Bane, P. Chen, P. Wilson, Proc. of the Part. Acc. Conf. (PAC1985), Vancouver, Canada, p.3524–3526, 1985.

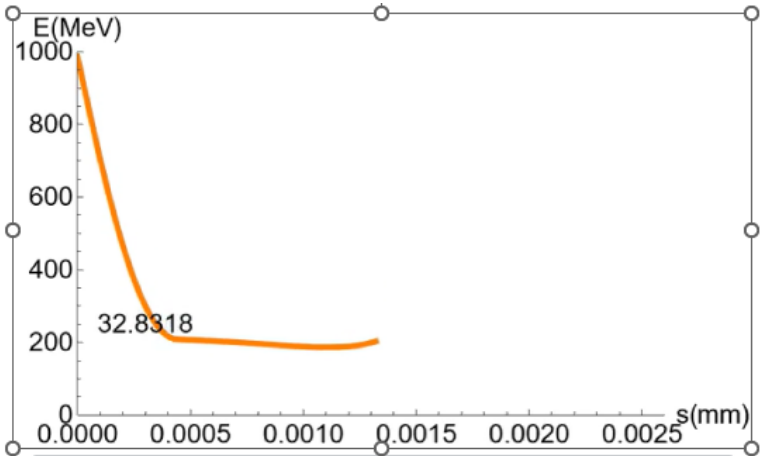
# Snapshots of the drive bunch longitudinal phase space taken at different locations along the A-STAR



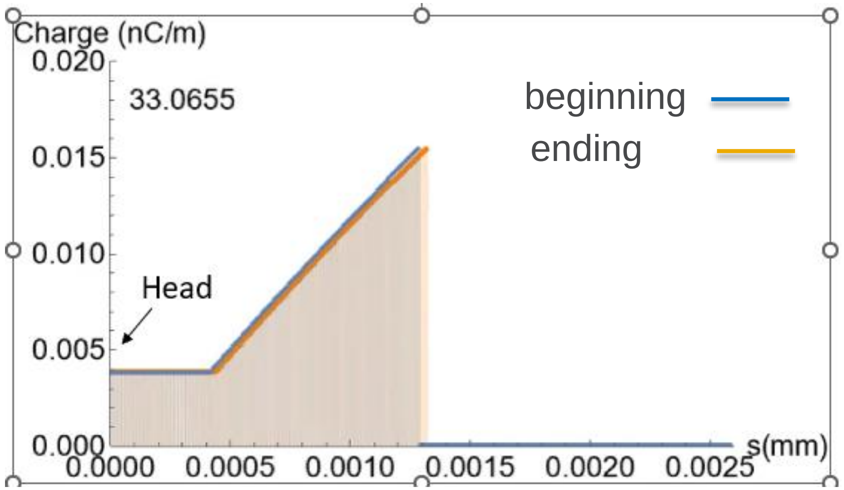



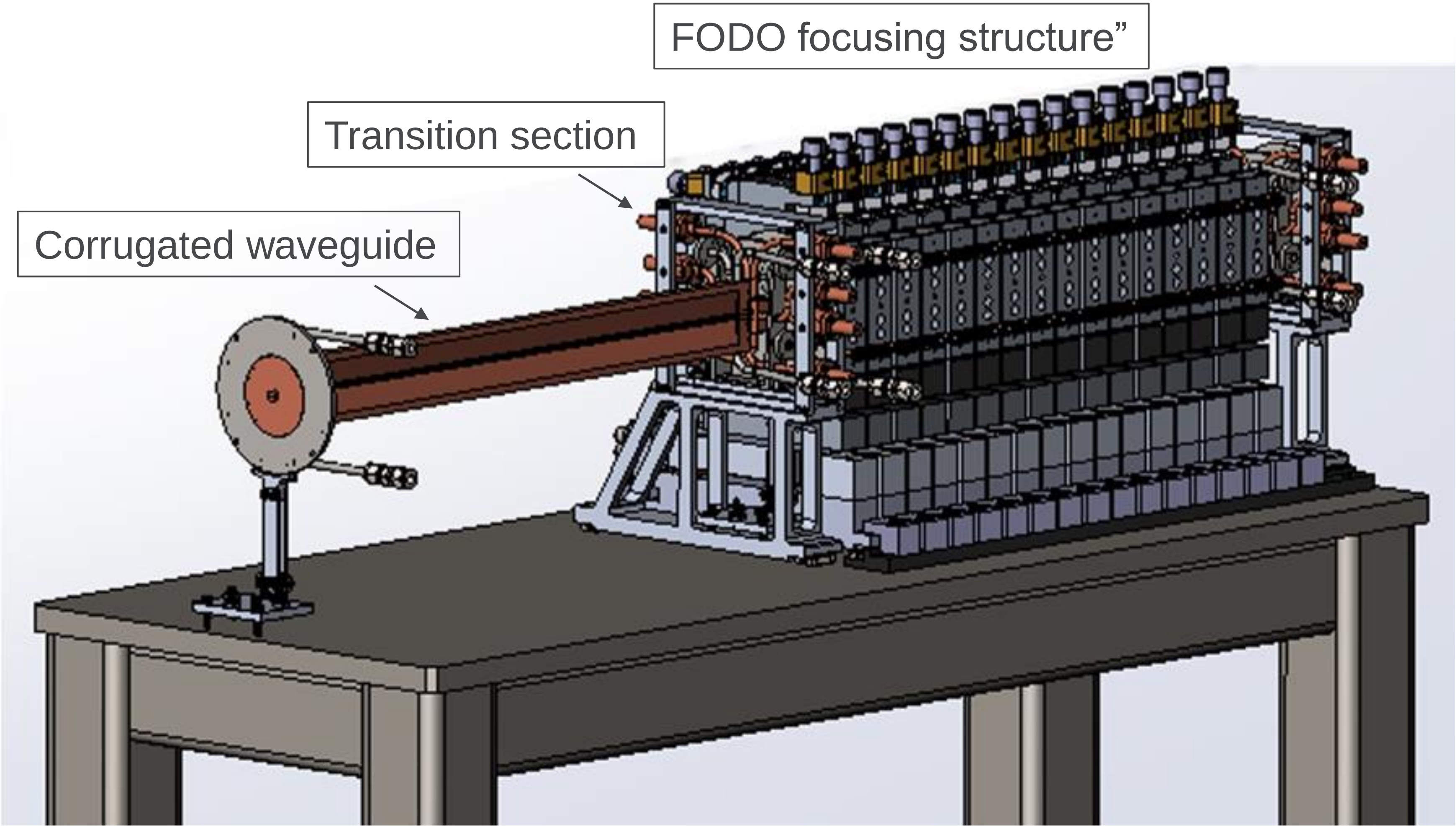



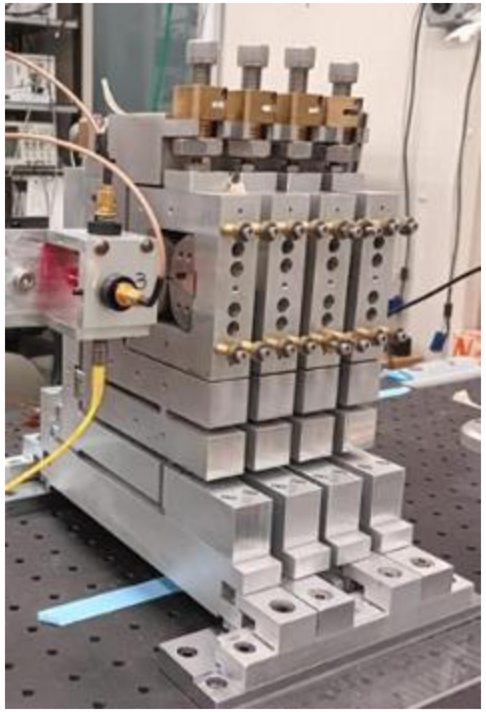




## Charge distribution



# Implementation of BNS damping



3-mm bore diameter quadrupoles play a decisive role in suppressing BBU instability

Two 0.5 m long modules of the collinear wakefield accelerator connected in series with the “quadrupole wiggler” removed on the left

# Upper bound for the maximum accelerating field in the structure-based collinear wakefield accelerator is defined by BBU

$$\max(E_{\mathrm{acc}}) \leq 1.25 \frac{\Delta\mathcal{E}}{\hat{\mathcal{E}}} c B_q \approx 90\,\mathrm{MV/m}$$

$B_q$: quadrupole's pole tip field at saturation (1.6 T is assumed )

$\Delta\mathcal{E}/\hat{\mathcal{E}} = 15\,\%$ is assumed

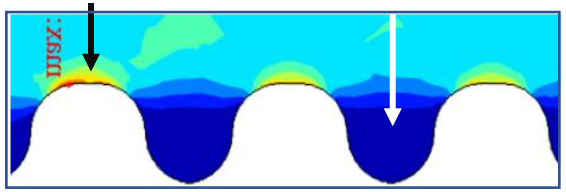
Using practical constraints

$a$ = 1 mm,
$q$0 = 10 nC,
R = 5,
we calculate $E_{\mathrm{acc}}$ ≈ 90 MV/m.

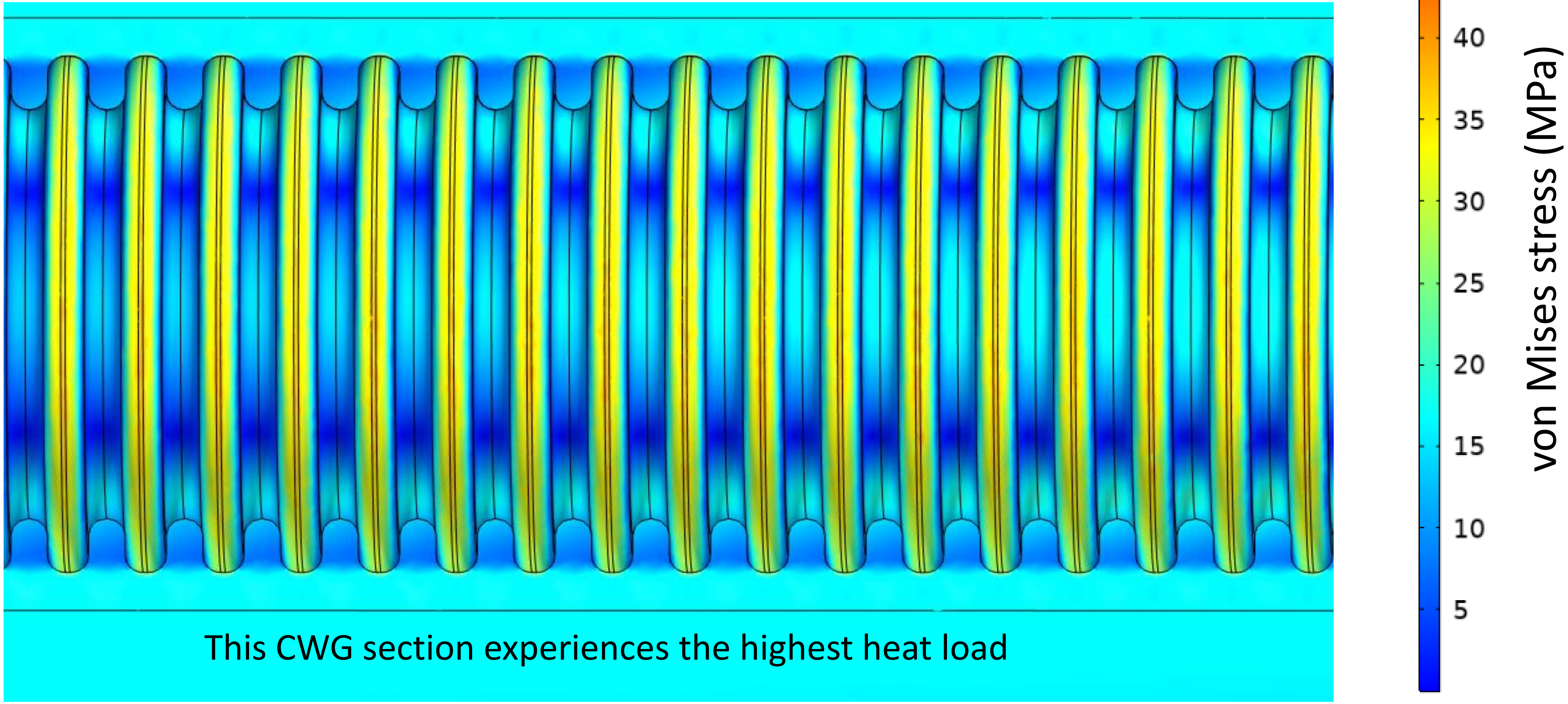
$$E_{\mathrm{acc}} \leq 2\kappa_{\parallel}|q_0|\frac{2\mathcal{R}}{1+\mathcal{R}^2}$$

# Bunch repetition rate is defined by the heat load and the tensile stress

Corrugation groove
41 MPa
Corrugation rib



10 kHz bunch rep. rate was used in this example

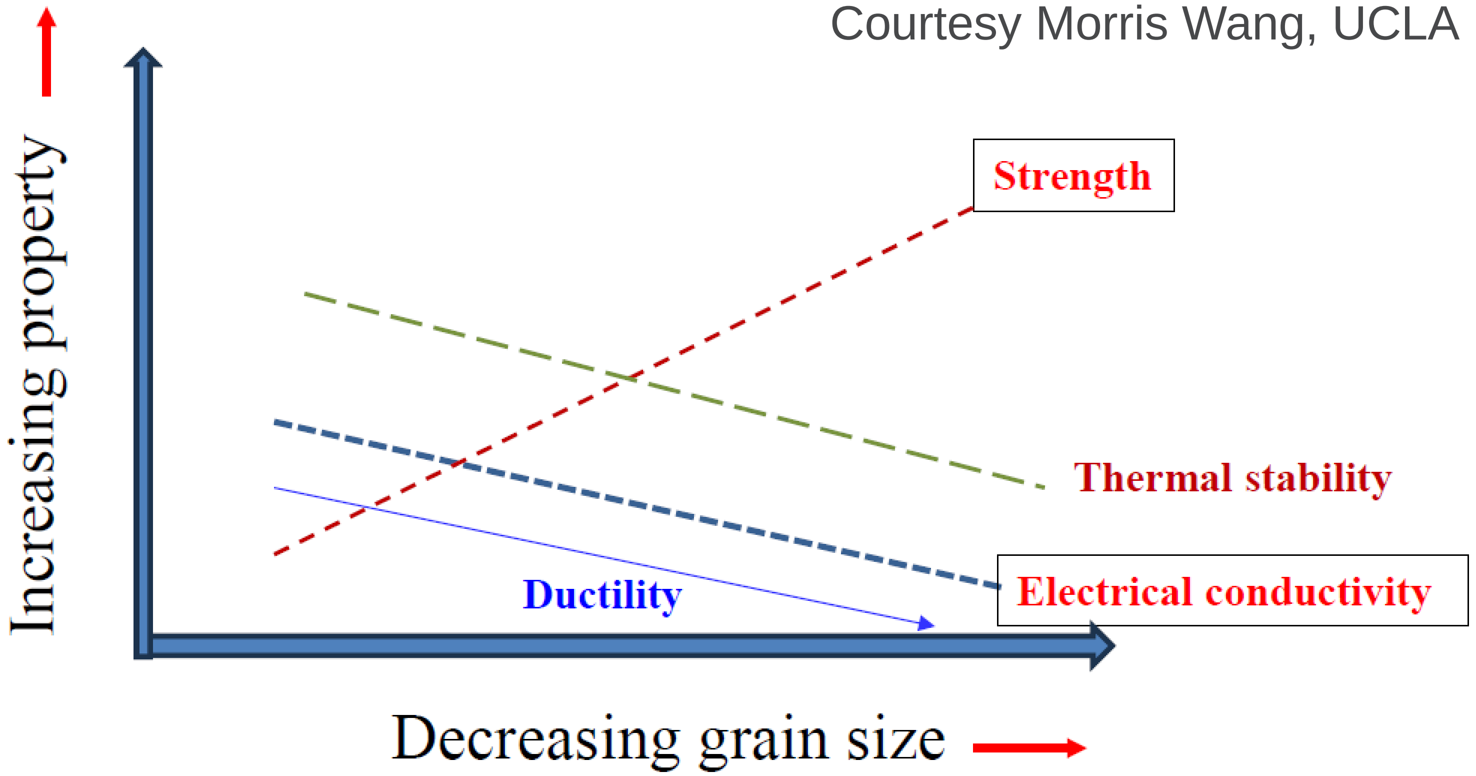


# Electroforming is used to make the corrugated waveguide

Electroformed copper can have much higher tensile stress threshold than ordinary copper (Hall-Petch effect) such as 100 kHz bunch repetition rate could be within the reach.

**Structure-property relationship of nanostructured copper**

Courtesy Morris Wang, UCLA

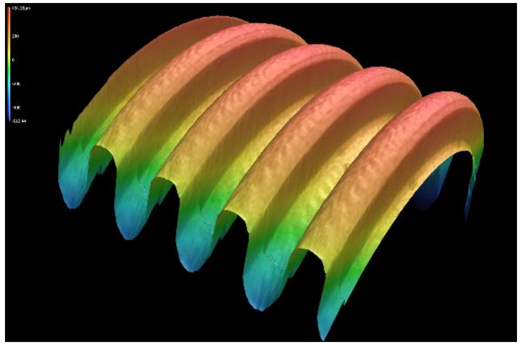



UCLA Samueli School of Engineering

M. Wang, et. al., Nat. Commun. 13, 5581 (2022).

# Electroforming of an axially symmetric corrugated waveguide

## Aluminum mandrel production



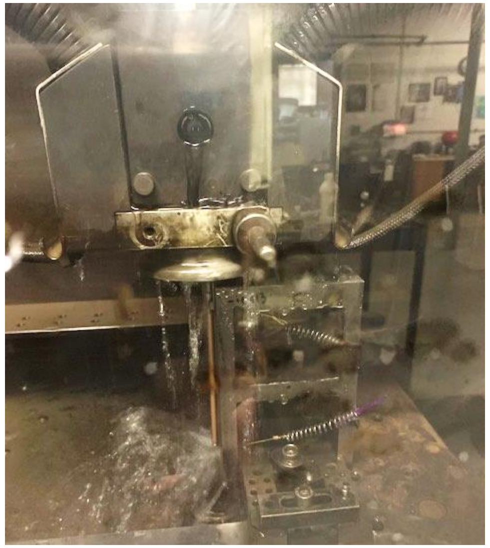

Proprietary micro-machining process
Tooth Height 252.7 μm; error 1.5 μm RMS
Tooth Width 175.9 μm; error 2.0 μm RMS

## Mandrel inspection and straightening

using optical comparator

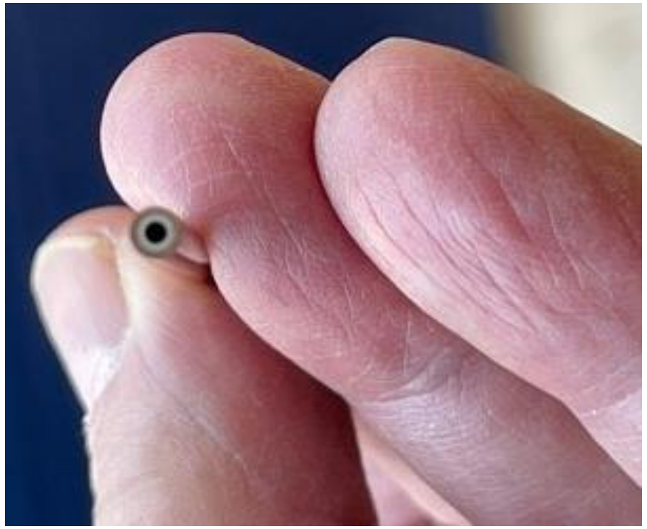
## Electroforming


## EDM of outside diameter

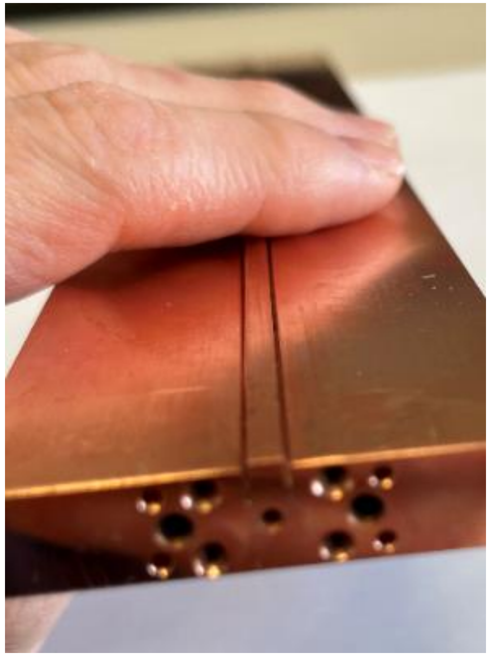


followed by second straightening

## Precision cut of edges



followed by aluminum etching

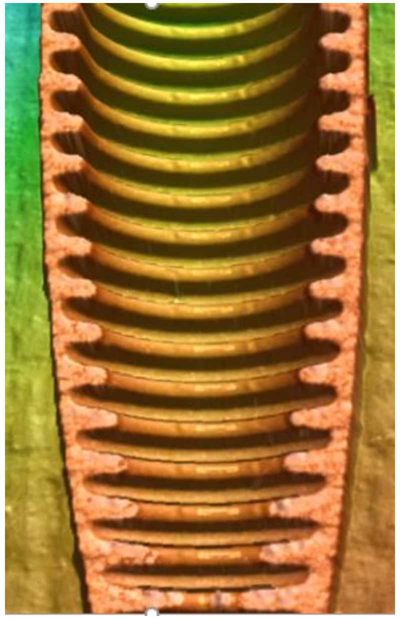


chamber with five 10-cm long tubes after brazing (currently use three);
low temperature brazing at 360 $^{o}$C

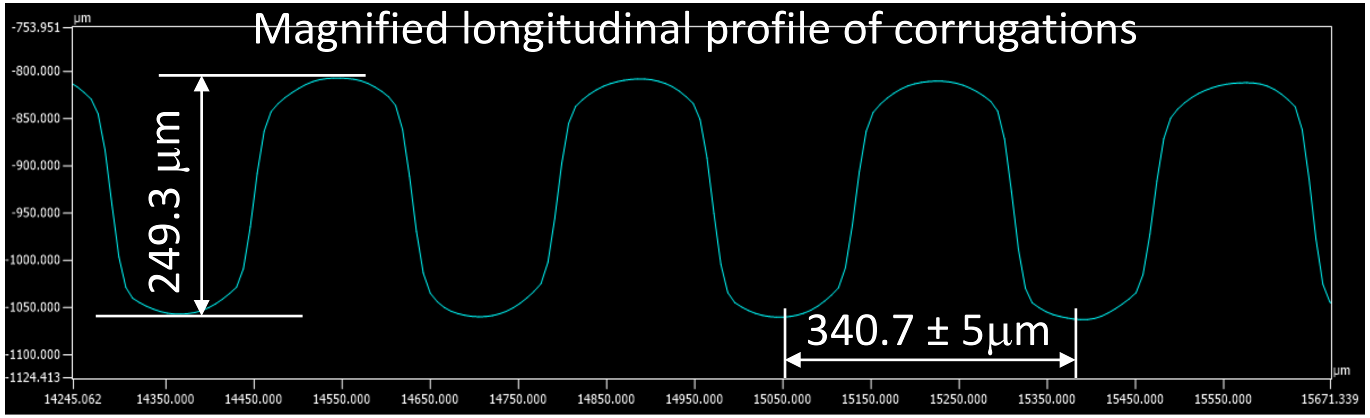
# Example of a fabricated corrugated waveguide

straight cut

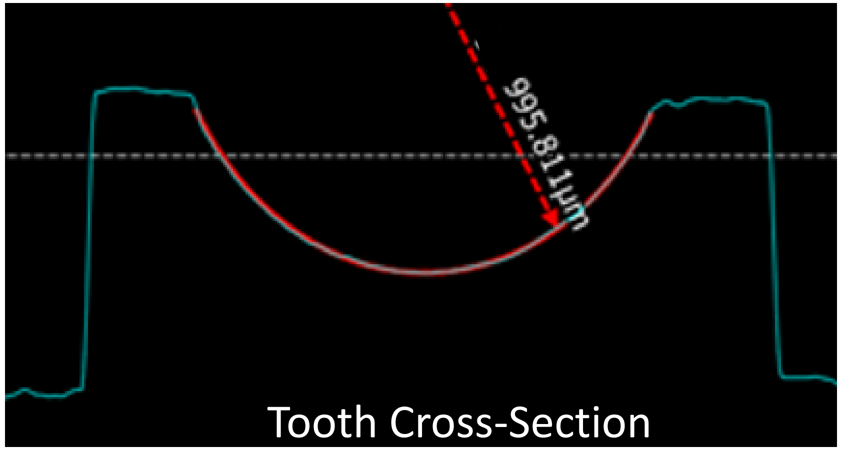
Test samples are wire EDM cut to expose the internal corrugations for dimensional analysis

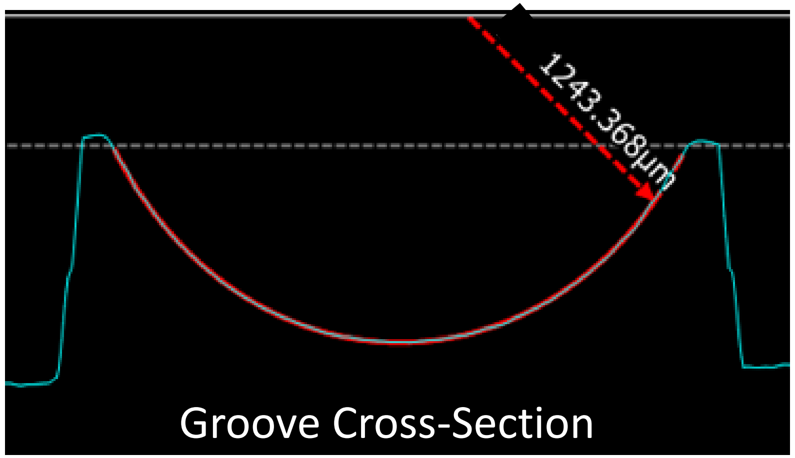


angular cut



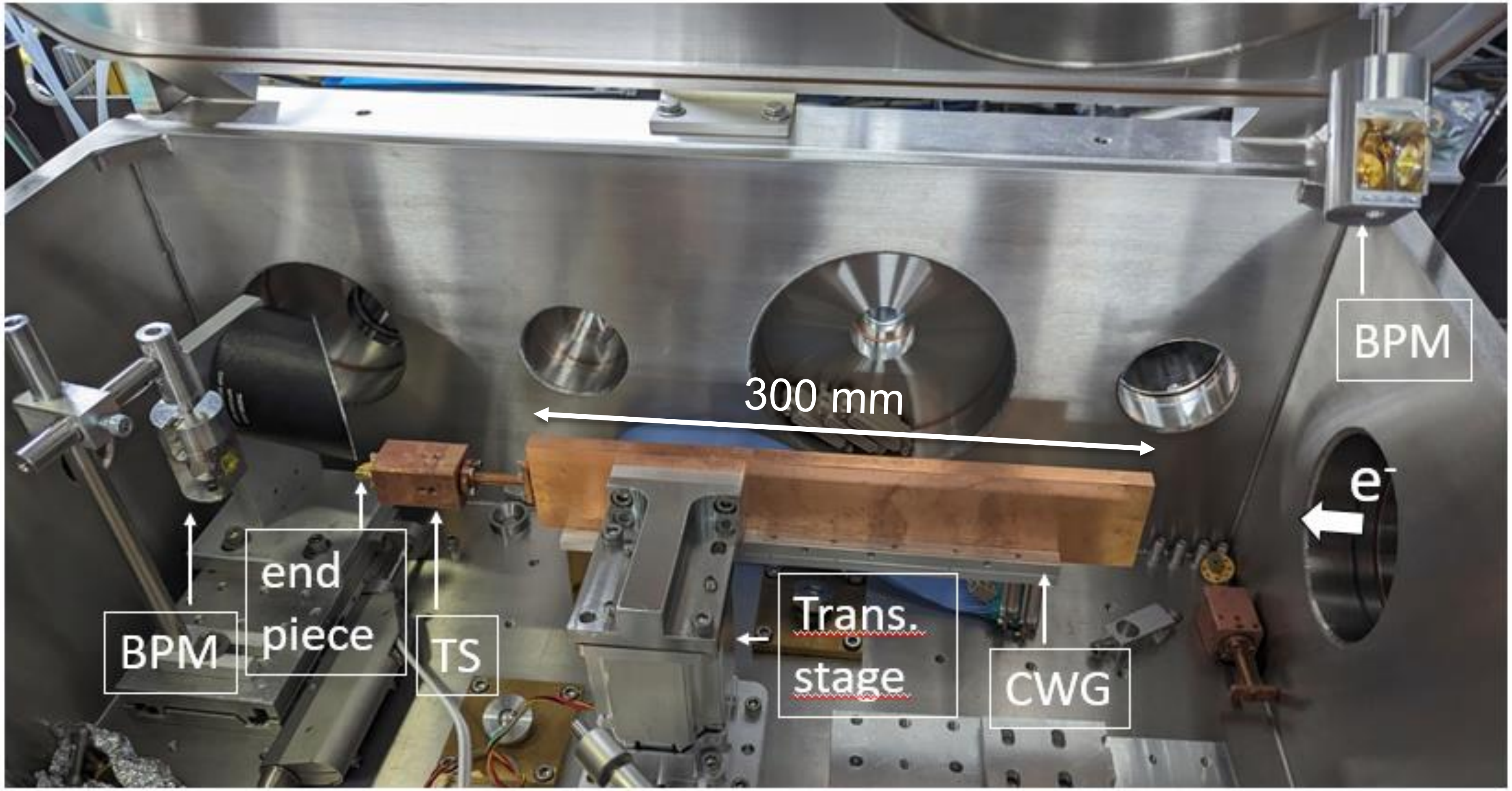

Average height of the corrugations of 249.7 µm was determined.



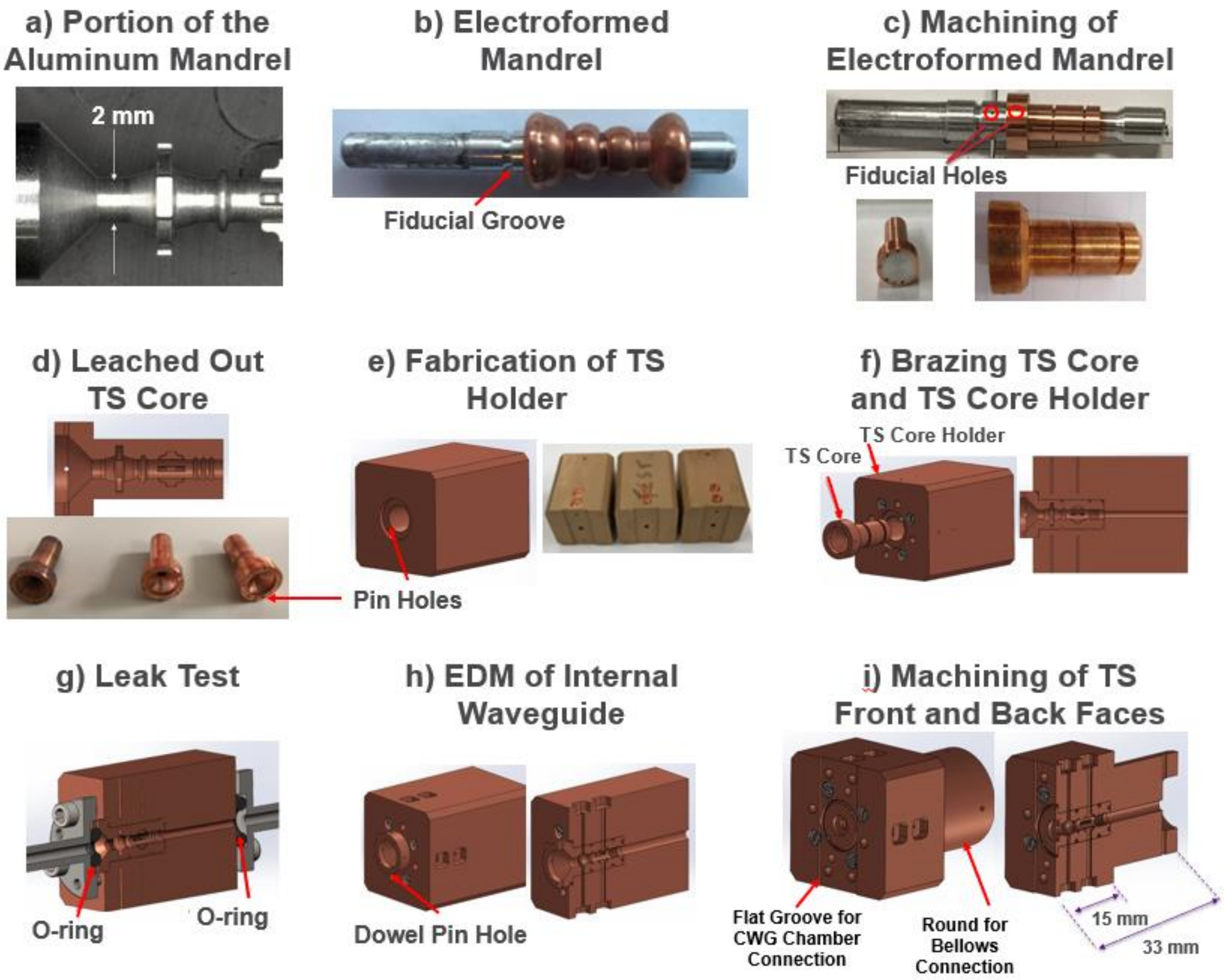




Measurements indicate excellent fabrication quality

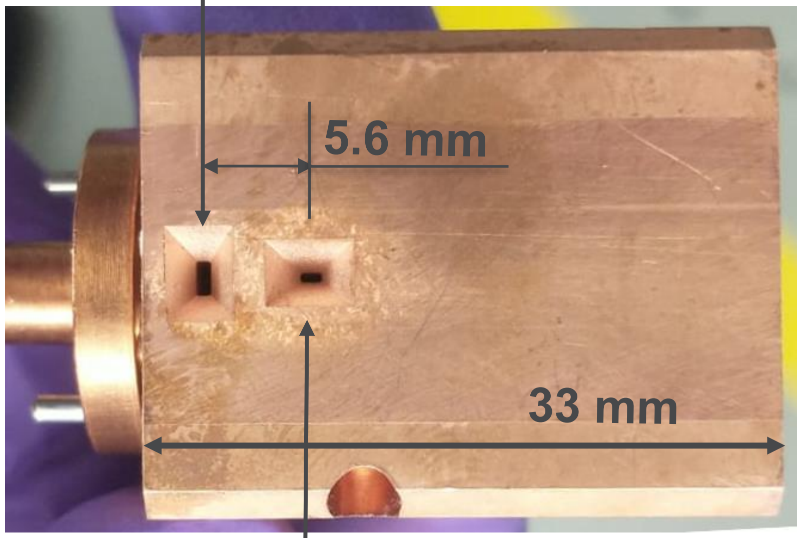
# Setup of the experiment at ATF



# Fabrication of transition section between accelerator modules



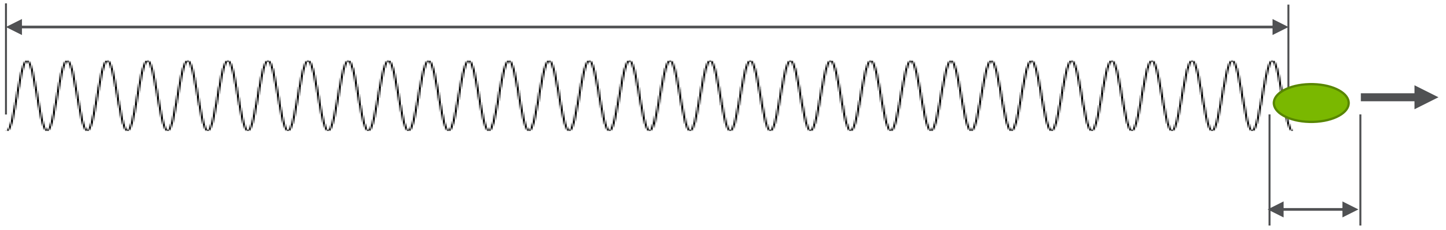

$TM_{01}$ coupler horn antenna, 0.72 mm × 1.78 mm

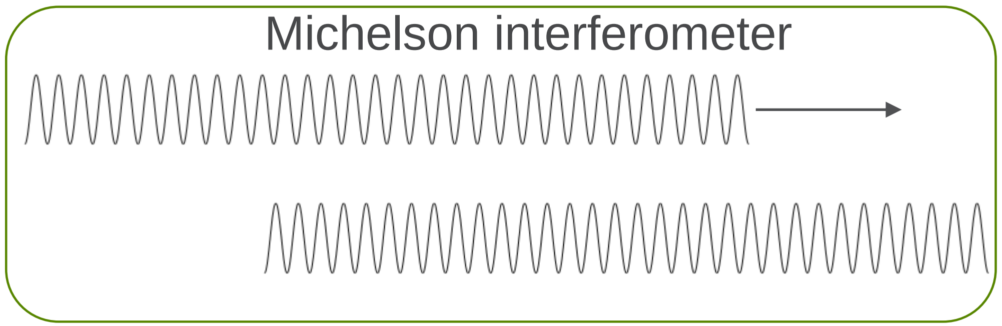



Integrated offset monitor horn antenna, 1.10 mm × 0.45 mm

# MEASUREMENT OF CWG: FREQUENCY & GROUP VELOCITY

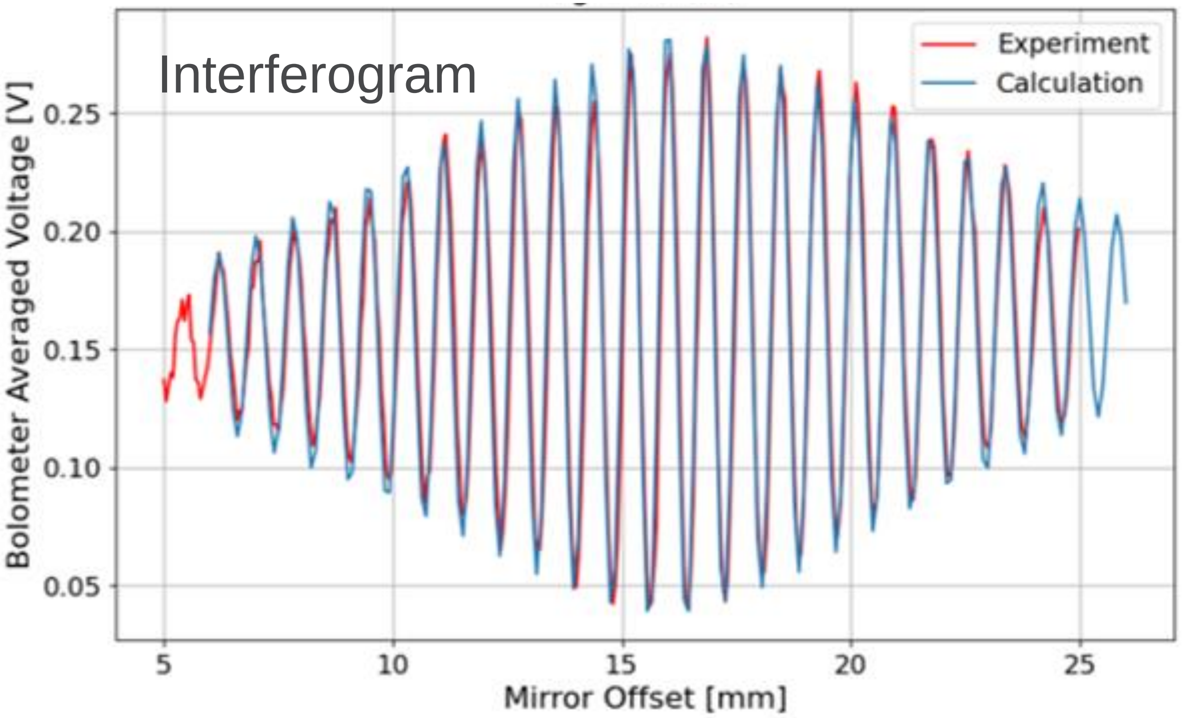
$$\Delta t = L\left(\frac{1}{v_g} - \frac{1}{v}\right)$$ ($L$=34 mm)

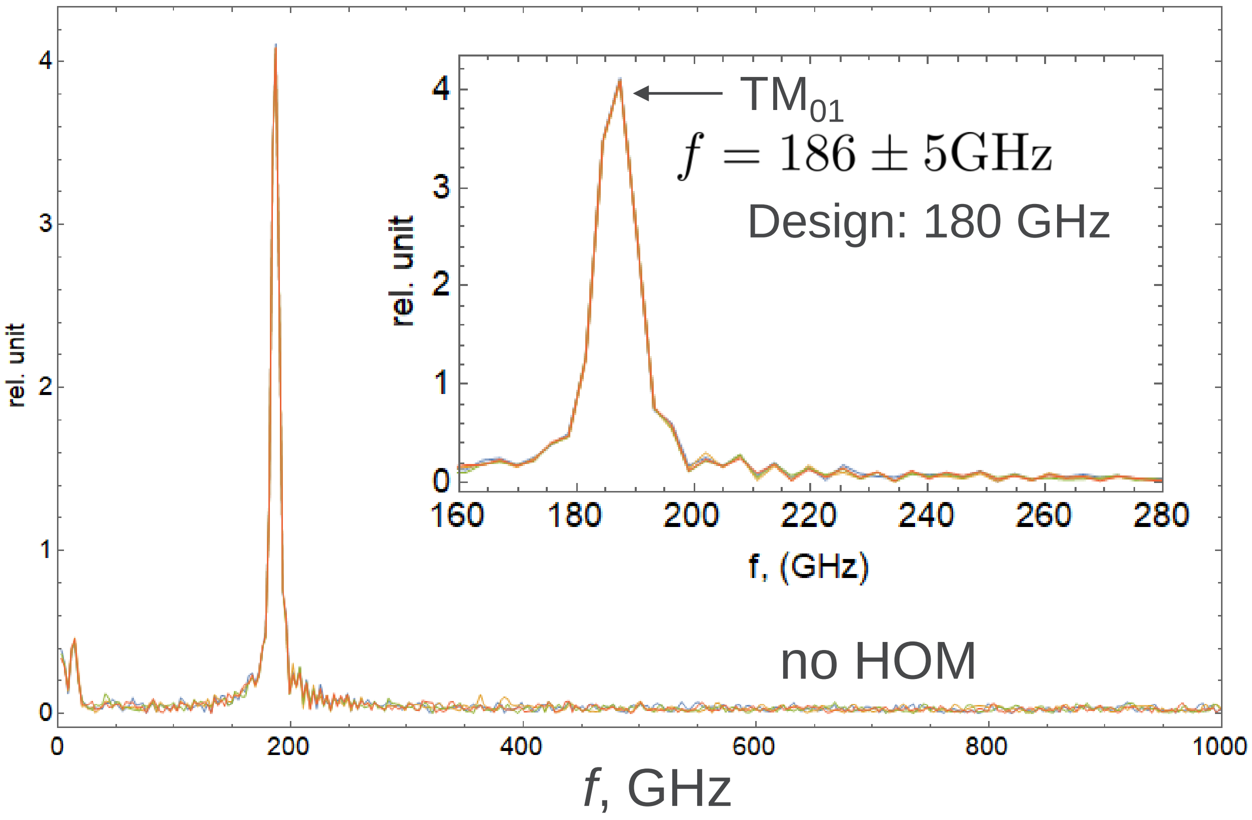



design: $v_g$ = 0.57c

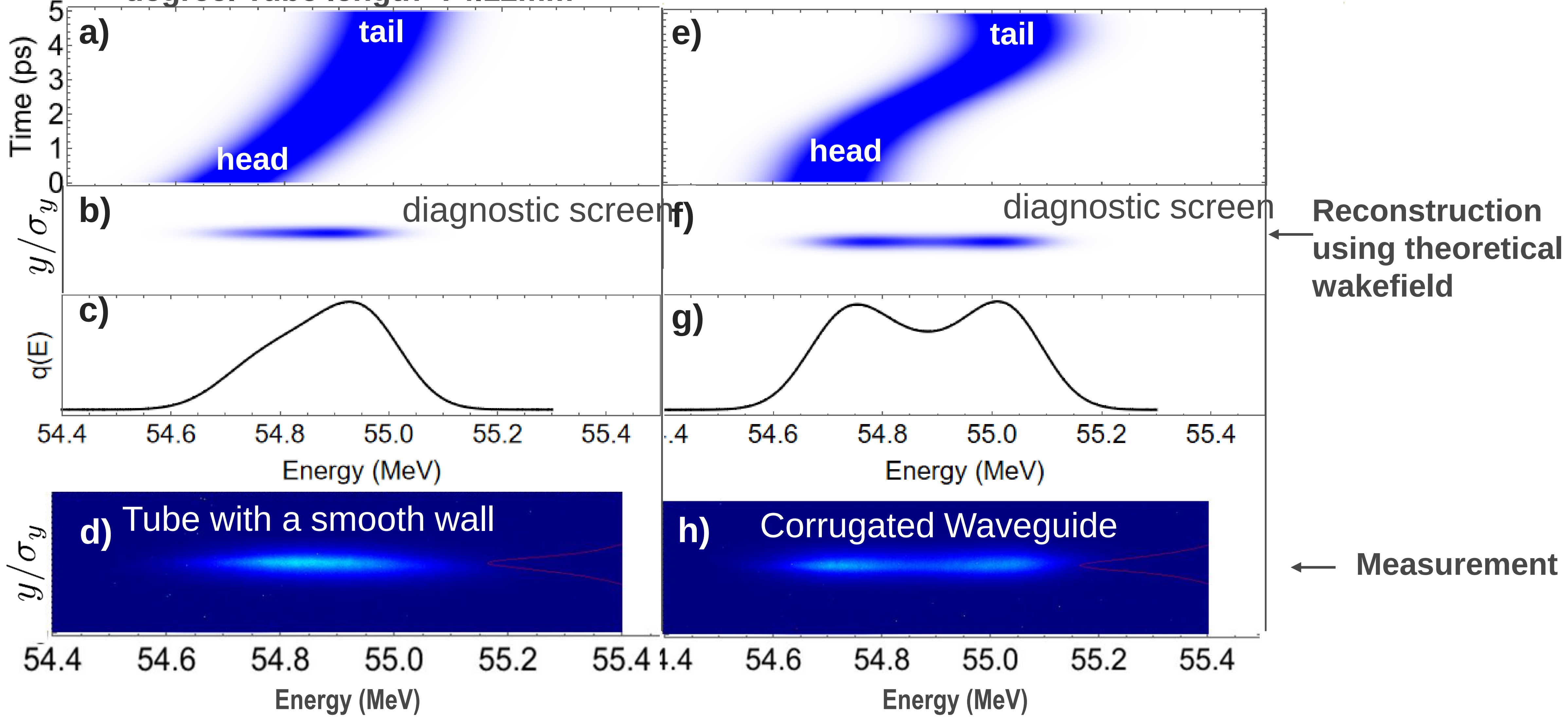
measured: $v_g$ = 0.55c



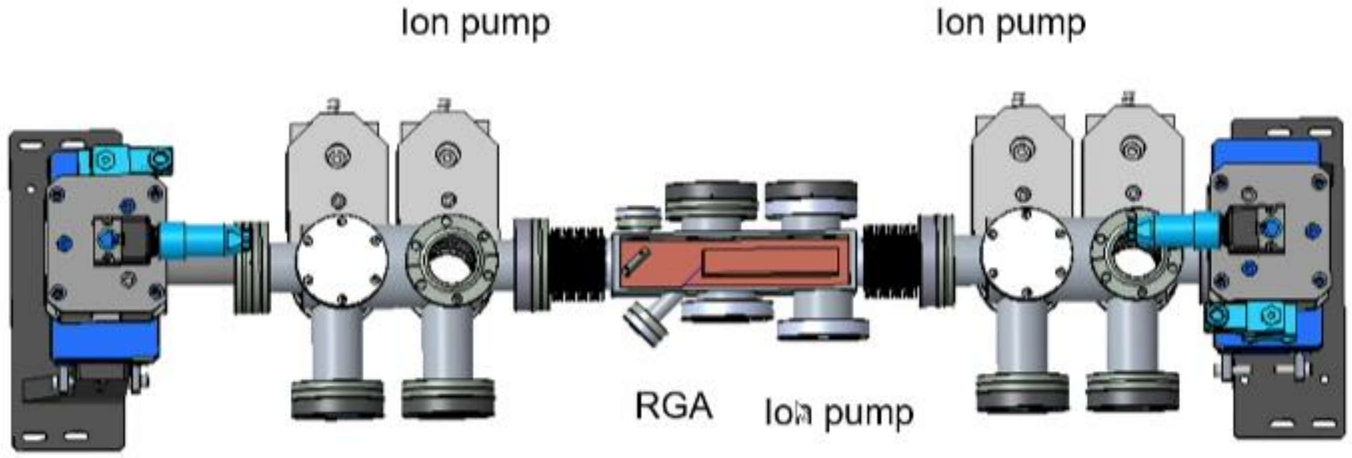
# Measurement of the electron beam self energy modulation

**Calculated results for a 5 ps, 130 pc bunch with a flattop peak current distribution and 65 keV slice energy spread. Off crest acceleration by 6.0 degree. Tube length=74.12mm**



# Future work:

- measurement of the electrical breakdown threshold and the rate of the breakdown events




- development of the electroformed copper with a high tensile stress threshold

# Conclusion

BBU instability constrains the accelerating gradient in A-STAR to 90 MV/m.

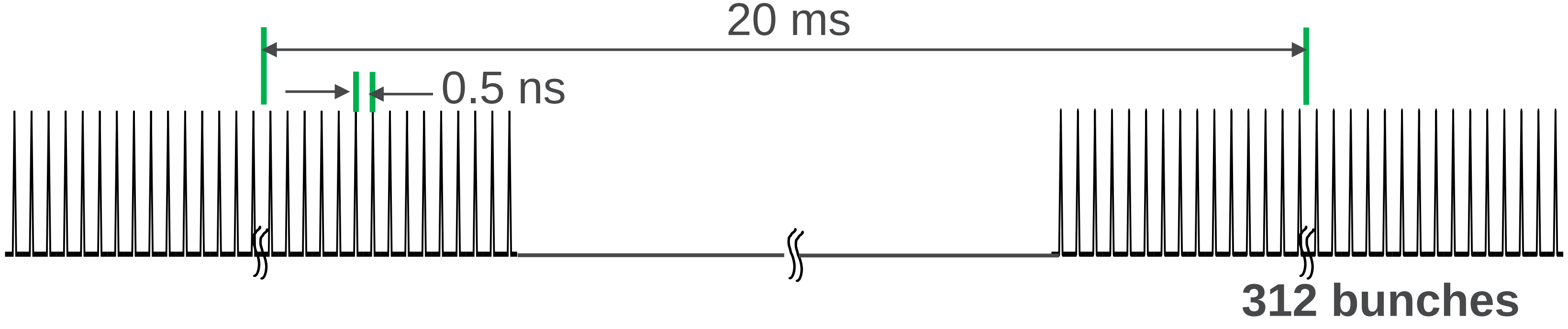
All principal A-STAR components were fabricated and tested on the bench and with the electron beam. Work as designed.

As is, the A-STAR is expected to operate with the bunch repetition rate of 20 kHz. With more R&D, achieving 100 kHz could be feasible.

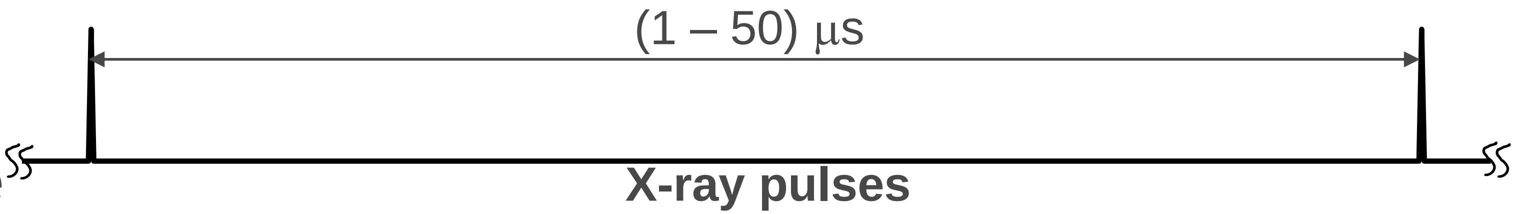
In the A-STAR project, we prioritize a full utilization of the drive-bunch energy in one stage and achieving a high bunch repetition rate, rather than a high accelerating field. Even so, A-STAR is designed for a real-estate acceleration rate of 90 MeV/m using 10 nC drive bunches.

# Bunch "train" structure

Linear collider CLIC




XFEL user's preference

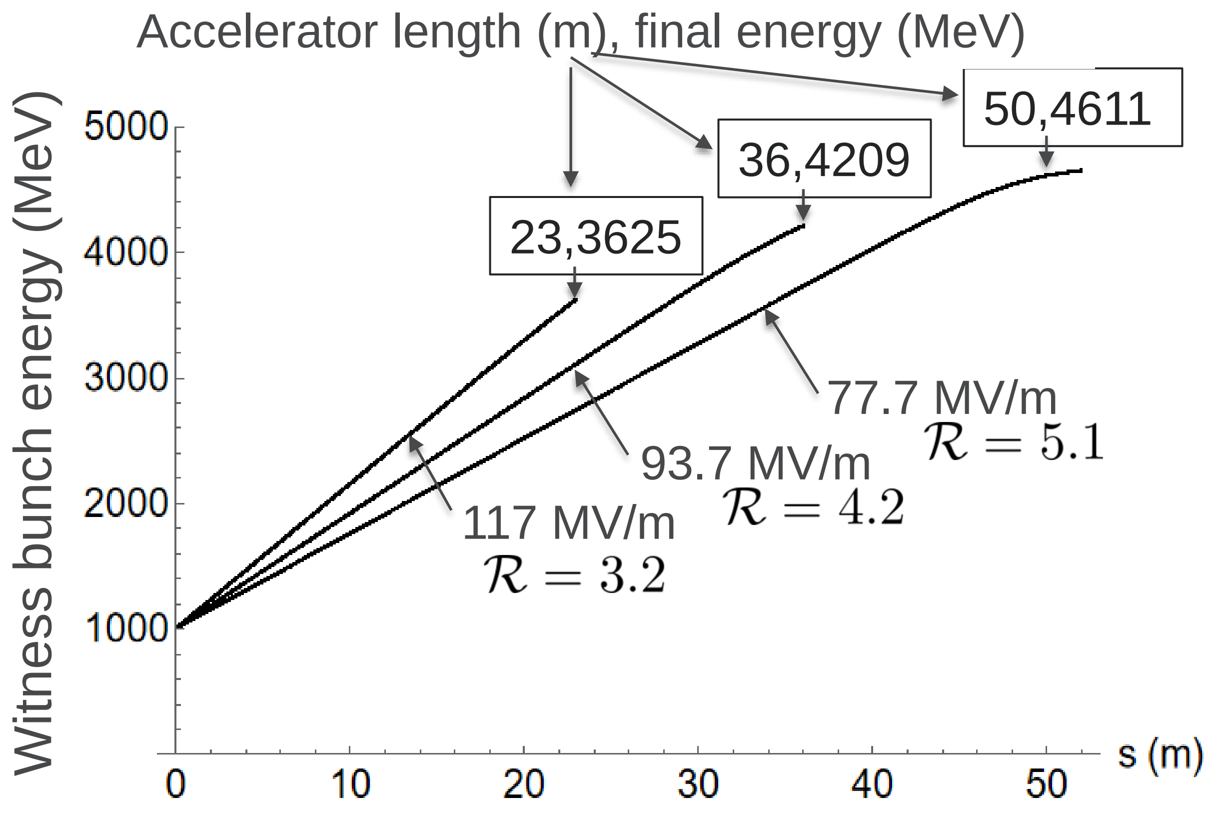



collect data pulse-by-pulse

# Comparison of options for obtaining high energy witness bunch

**Drive bunch:**
Charge = 10 nC
Initial energy = 1 GeV
Final energy = 0.1 GeV

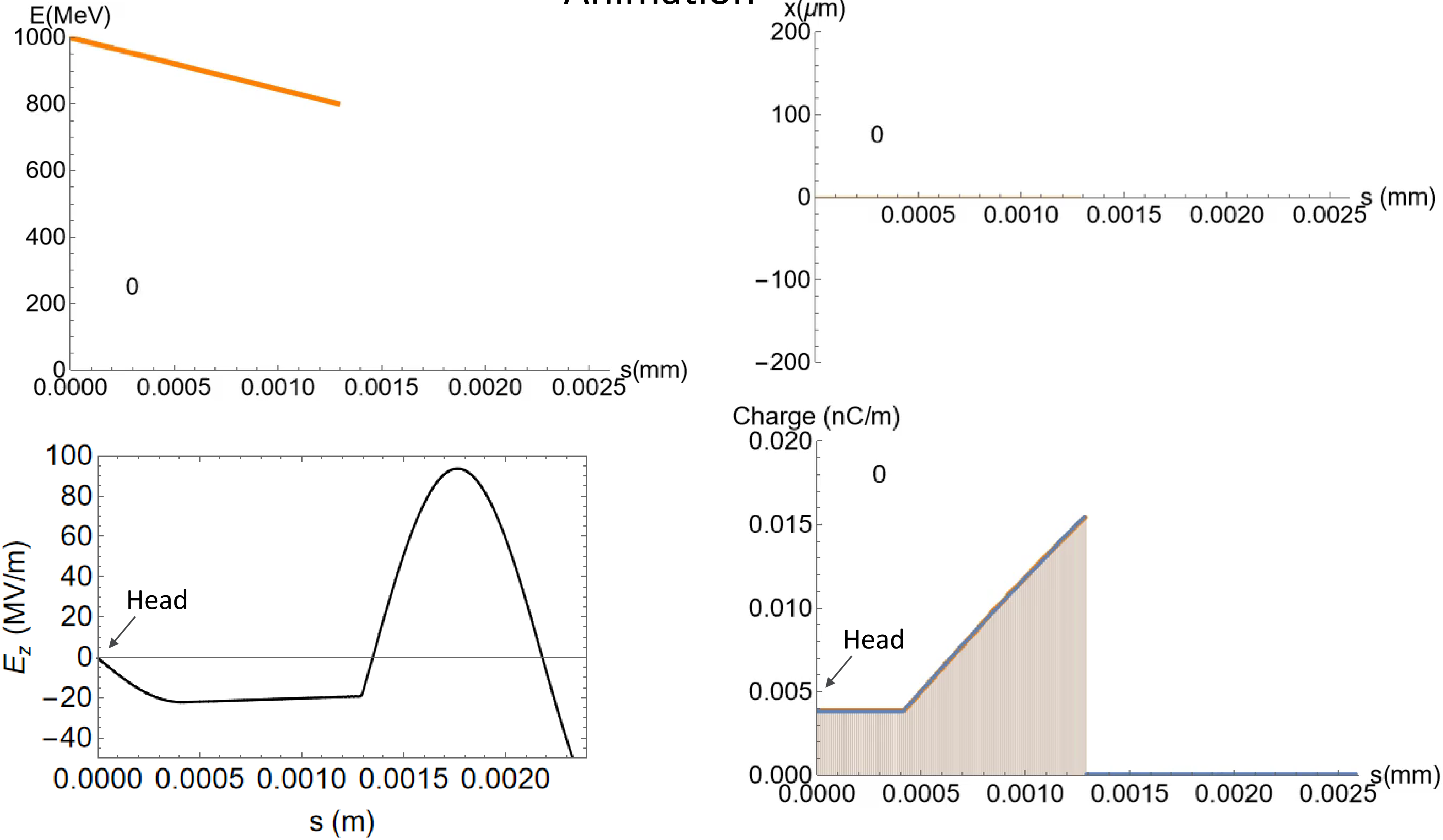
**Witness bunch:**
Charge = 0.15 nC
Initial energy = 1 GeV
Final energy, see Table




| Option | Transformer Ratio | $E_{acc}$ (MV/m) | Maximum Energy (MeV) | Acc. Length (m) | Bunch rep. rate (kHz) | Efficiency % |
|---|---|---|---|---|---|---|
| 1 | 3.2 | 117 | 3625 | 23 | 10 | 57 |
| 2 | 4.2 | 93.7 | 4209 | 36 | 15 | 100 |
| 3 | 5.1 | 77.7 | 4611 | 50 | 22 | 161 |

reference option (Option 2)

# Animation

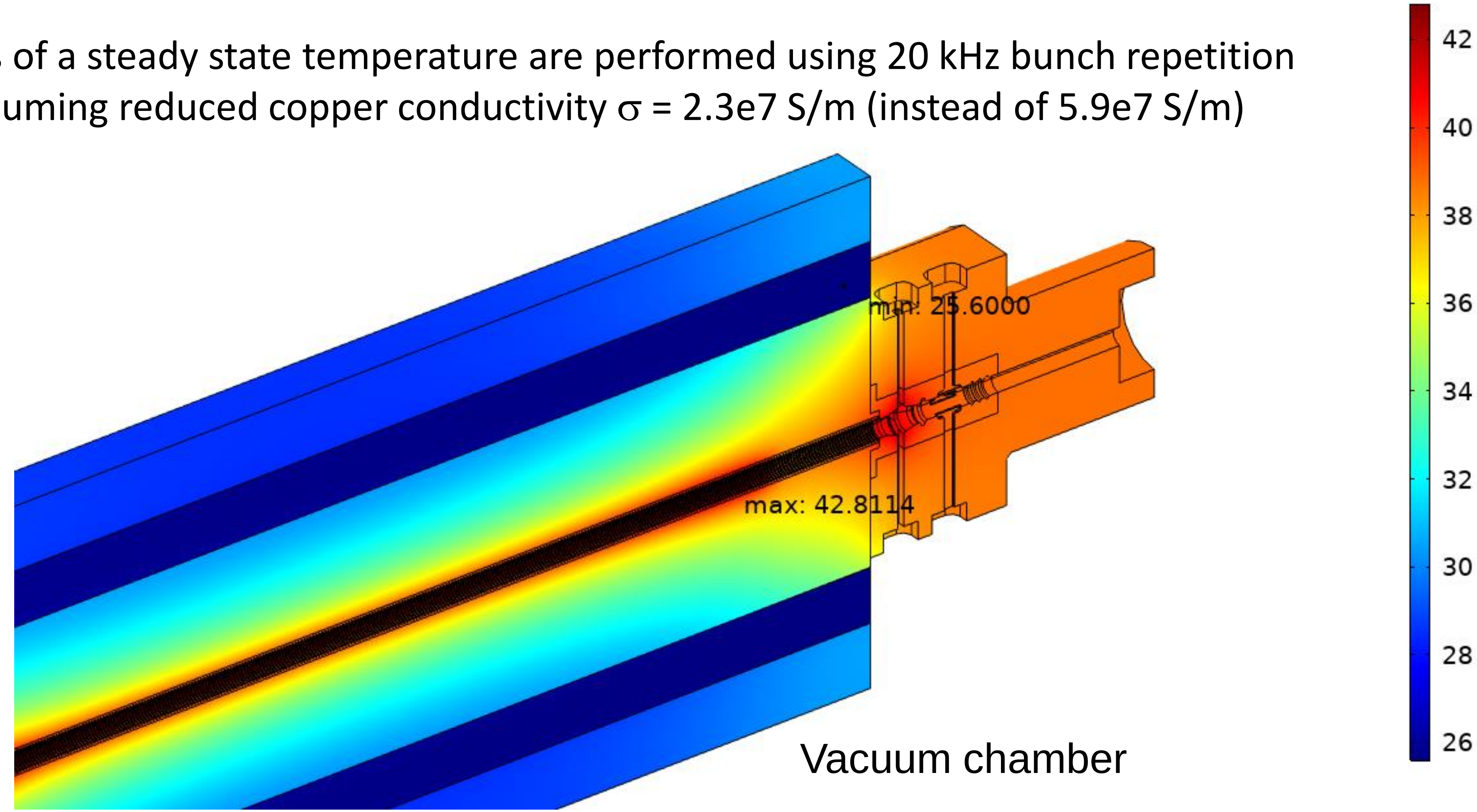


E(MeV)
1000
800
600
400
200
0
0.0000
0.0005
0.0010
0.0015
0.0020
0.0025
s(mm)
x(μm)
200
100
0
−100
−200
0.0005
0.0010
0.0015
0.0020
0.0025
s (mm)
100
80
60
40
20
0
−20
−40
$E_z$ (MV/m)
Head
0.0000 0.0005 0.0010 0.0015 0.0020
s (m)
Charge (nC/m)
0.020
0.015
0.010
0.005
0.000
Head
0.0000
0.0005
0.0010
0.0015
0.0020
0.0025
s(mm)

# Heat load

Calculations of a steady state temperature are performed using 20 kHz bunch repetition rate and assuming reduced copper conductivity $\sigma$ = 2.3e7 S/m (instead of 5.9e7 S/m)

Water temperature 25.6 $^{o}$C




Vacuum chamber

Average power dissipation on 0.5 m long CWG at 20 kHz bunch repetition rate is 1050 W