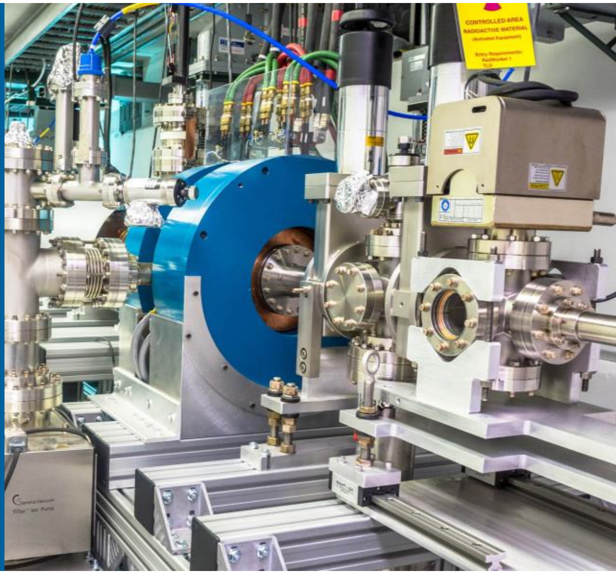
A METAMATERIAL STRUCTURE FOR WAKEFIELD ACCELERATION

at the

ARGONNE WAKEFIELD ACCELERATOR (AWA) FACILITY



JOHN POWER (for XUEYING LU now at SLAC)

jp@anl.gov

ALEGRO WORKSHOP
26-29 March 2019, CERN

OUTLINE

AWA FACILITY

John Power, Manoel Conde, Jiahang Shao, Eric E. Wisniewski
Argonne National Laboratory (ANL)

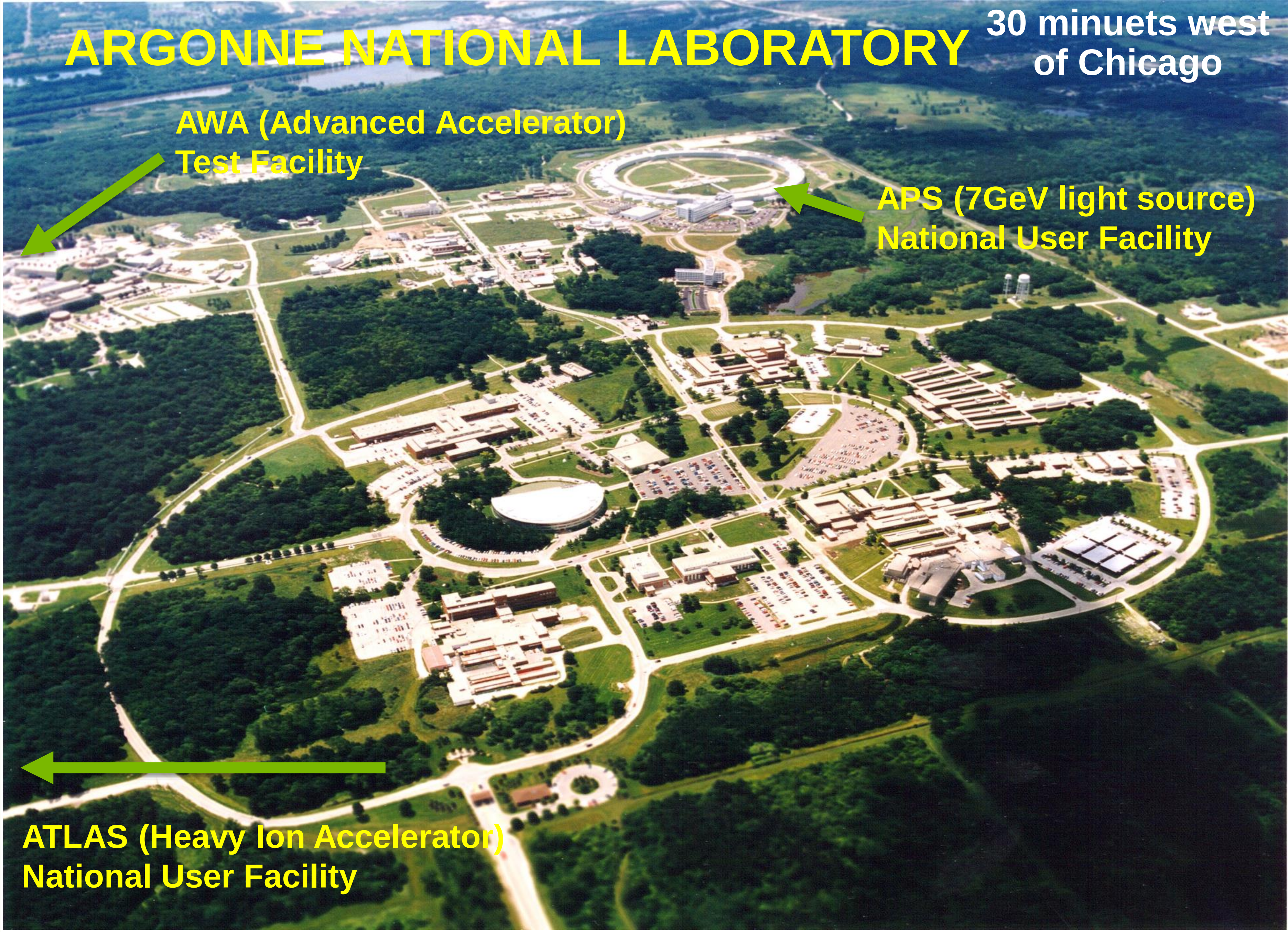
Chunguang Jing
Euclid Techlabs LLC

ALIC plans at AWA
(light version)

https://www.anl.gov/awa

METAMATERIAL EXPERIMENT

Xueying Lu, Michael A. Shapiro, Ivan Mastovsky, Richard J. Temkin
Massachusetts Institute of Technology (MIT)


ARGONNE NATIONAL LABORATORY
30 minuets west
of Chicago
AWA (Advanced Accelerator)
Test Facility
APS (7GeV light source)
National User Facility
ATLAS (Heavy Ion Accelerator)
National User Facility

https://www.anl.gov/awa

AWA MISSION

https://www.anl.gov/awa

Developing e^- Beam-driven Wakefield Acceleration

Advanced Acceleration Concepts

- **SWFA** (Two Beam Acceleration (TBA) and Collinear Wakefield Acceleration (CWA) and Novel structure R&D and RF breakdown study)
- **PWFA** (High Transformer Ratio)

Beam Physics

- **Longitudinal bunch shaping** (EEX and Laser controlled)
- **6D emittance repartitioning** (EEX + FBT)
- **Diagnostics**: Single shot & Non-destructive

Electron Sources

- **Novel cathodes**: field emission and photoemission
- **High brightness beam generation** (symmetrized)
- **Bunch Shaping** (both transversely and longitudinally)

Applications

- **TeV collider**
- **Compact X-ray source**
- **Tunable THz generation**
- **Electron cooling**
- **UED/UEM**

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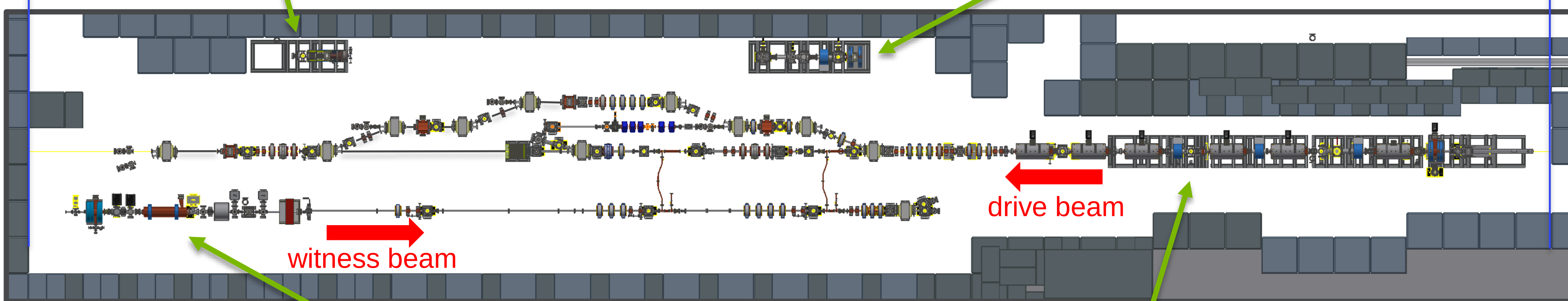
AWA BEAMLINES AND TEST-STANDS

~40 m

20 MW RF power station
RF gun studies and conditioning

ACT
Cathode studies
Breakdown studies



Witness beamline
4 – 15 MeV
0.001 – 20 nC

Drive beamline
8 – 70 MeV
0.001 – 100 nC (single bunch)
Bunch trains (up to 32 bunches with 600 nC total)

Unique capabilities of AWA:

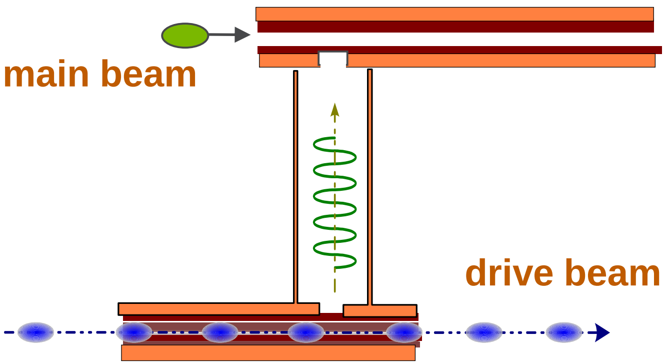
- Two independent linacs
- 6D: Emittance exchange and flat beam
- Wide range of bunch charge (highest)

→ Flexible Test facility for beam driven wakefield studies

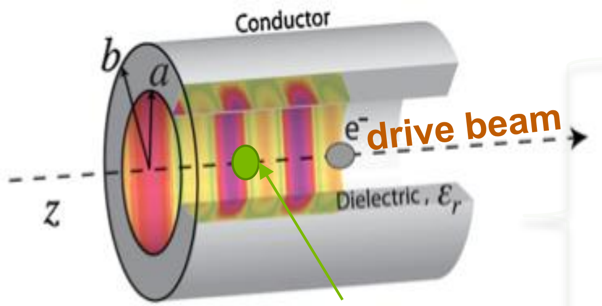
SWFA: STRUCTURE-BASED WAKEFIELD ACCELERATION

Several variations of scheme, geometry, frequency, material.

Two-**B**eam **A**cceleration (**TBA**)



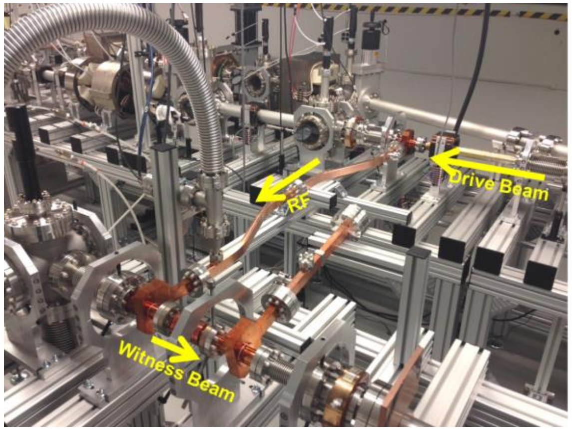
Collinear Wakefield **A**cceleration (**CWA**)



- Geometry: cylindrical, planar, or novel (PBG, metamaterial, etc)
- Frequency: typically from 10 GHz to 1 THz
- Material: metallic, dielectric, hybrid

Goals:
- high efficiency
- high gradient
- beam quality

TBA: METALLIC STRUCTURES



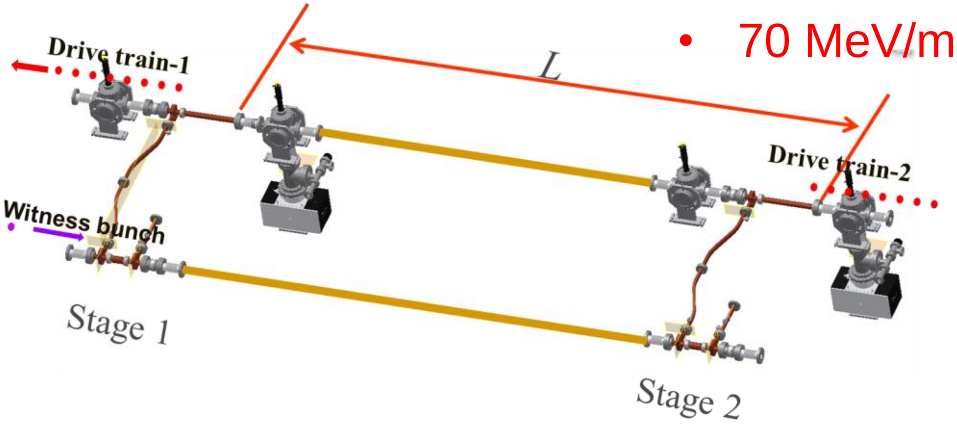
Demonstrated: High Gradient in a Single Stage

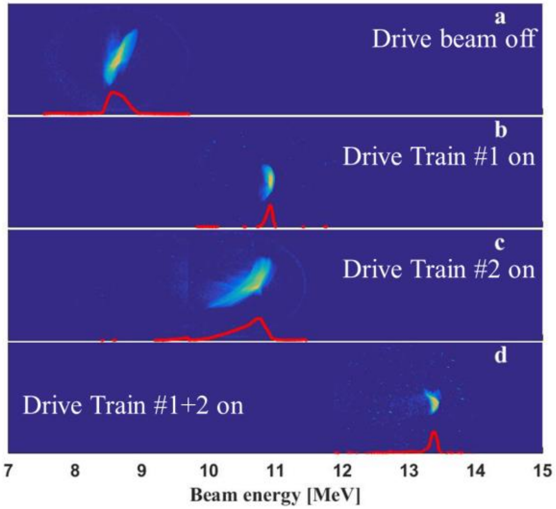
- 11.7 GHz metallic iris loaded structure
- 300 MW
- 150 MeV/m

New Dielectric TBA results
(See Alexei Kanareykin next talk)

Demonstrated: Staging

- 70 MeV/m



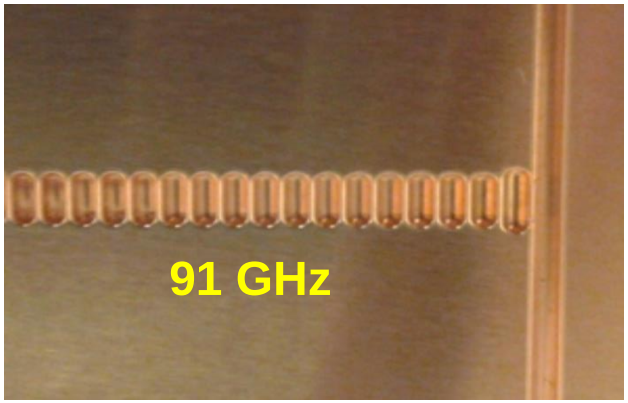


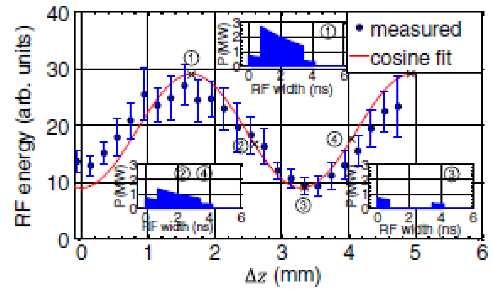
C. Jing et al., Nucl. Instr. Meth. in Phy. Res. A 898, 72-76 (2018)

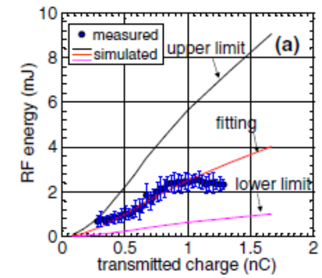
CWA: METALLIC STRUCTURES

- **High power, high gradient at 91 GHz with two halves structure**

D. Wang, *et al, Phys. Rev. Lett.*, 116, 054801 (2016)



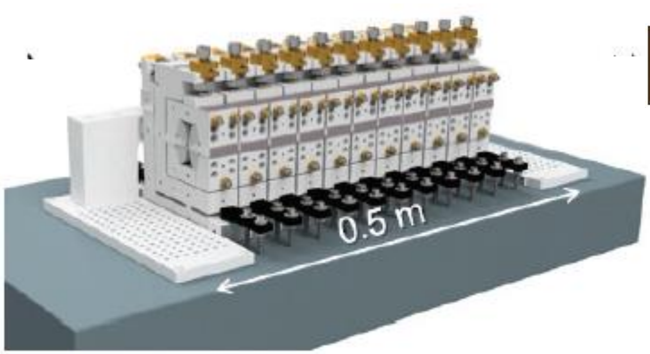


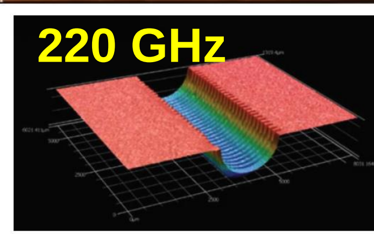


Peak power ~5 MW peak gradient 85 MeV/m

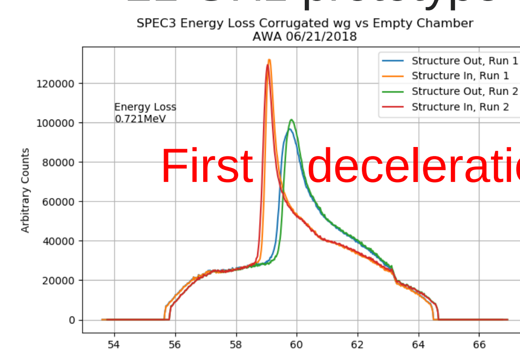
- **Corrugated waveguide structure for multi-beamline XFEL**

G. Waldschmidt, *et al, in Proceedings of IPAC2018* (2018)



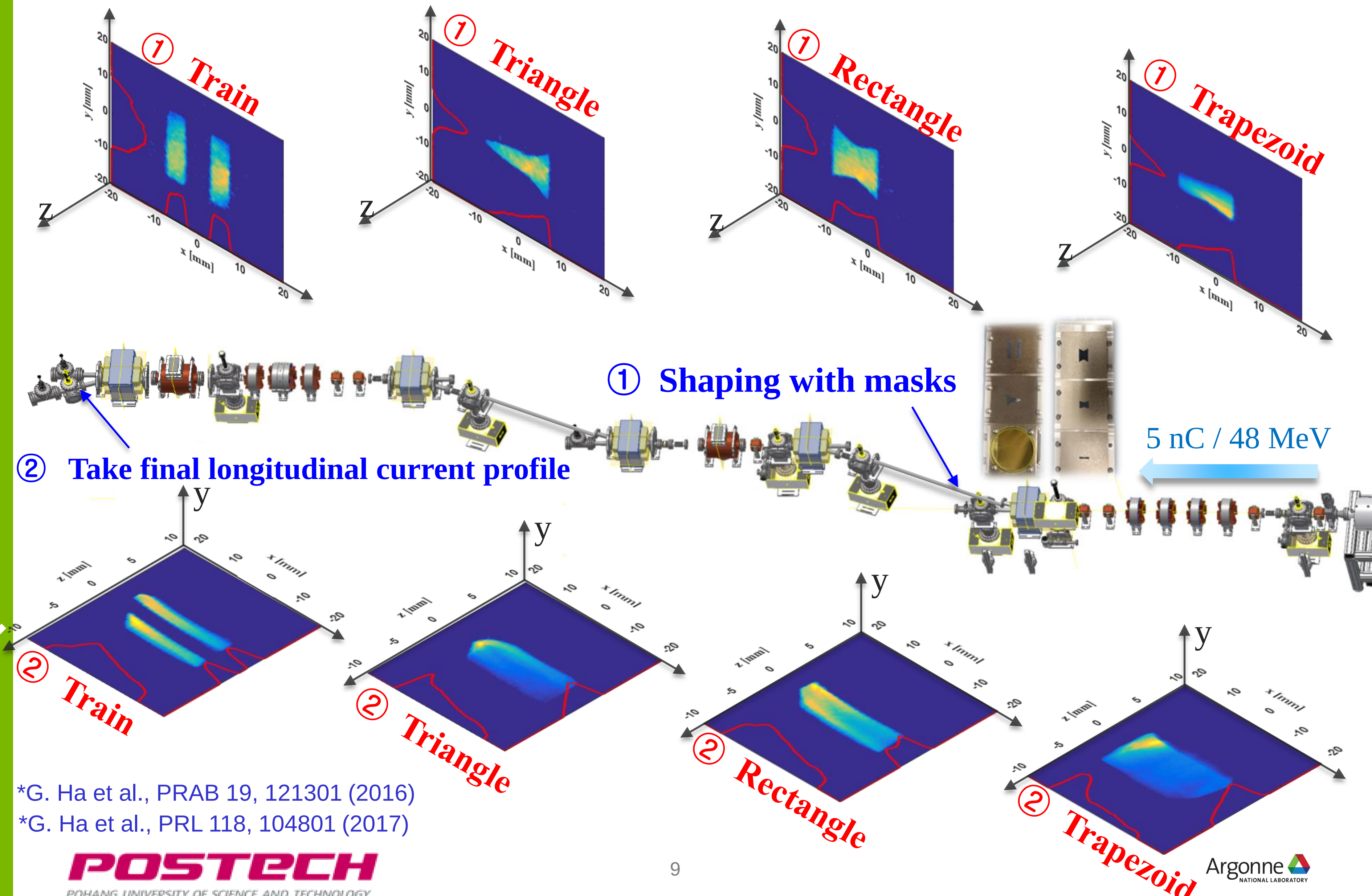


21 GHz prototype



Beam Physics

LONGITUDINAL SHAPING WITH EEX



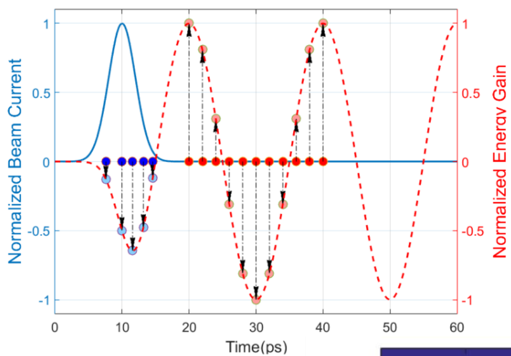
*G. Ha et al., PRAB 19, 121301 (2016)
*G. Ha et al., PRL 118, 104801 (2017)

POSTECH
POHANG UNIVERSITY OF SCIENCE AND TECHNOLOGY

Argonne NATIONAL LABORATORY

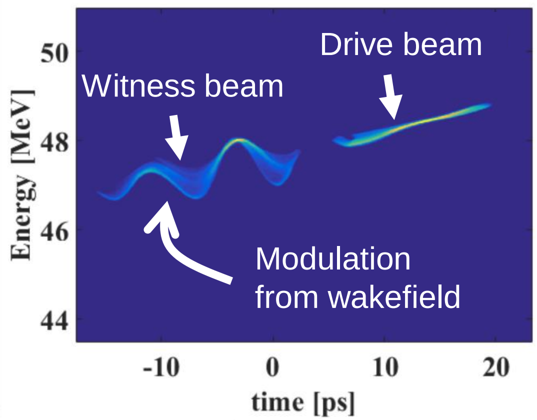
BEAM DIAGNOSTICS DEVELOPMENT

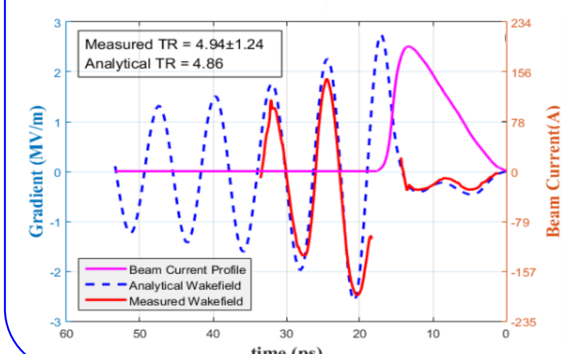
Single shot wakefield measurement



Energy change follows wakefield

Comparison between with and without wake provides actual shape of the wake



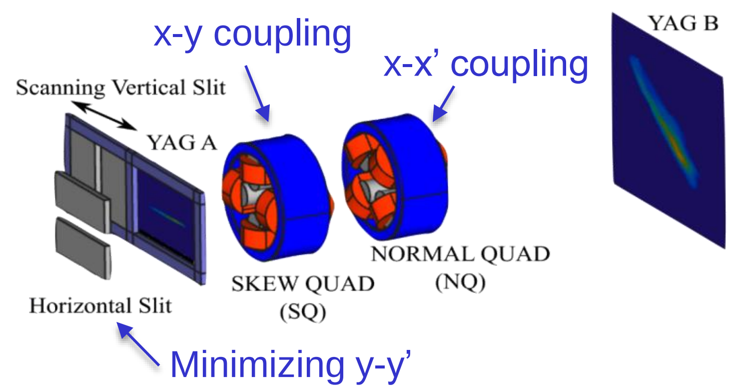


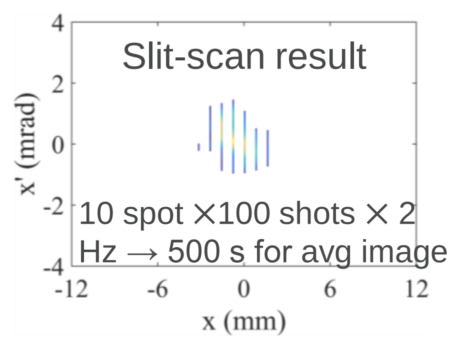
The second new method since AWA made witness scan method in 80's

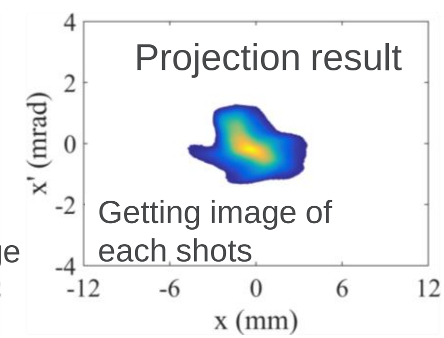
*Q. Gao et al., PRAB 21, 062801 (2018)

Transverse phase space measurement

- This is new method introduced since 90's
- (x,x') or (y,y') can be projected in to (x,y) screen
- A fast way to characterize the beam and beamline







*G. Ha et al., submitted (2019)

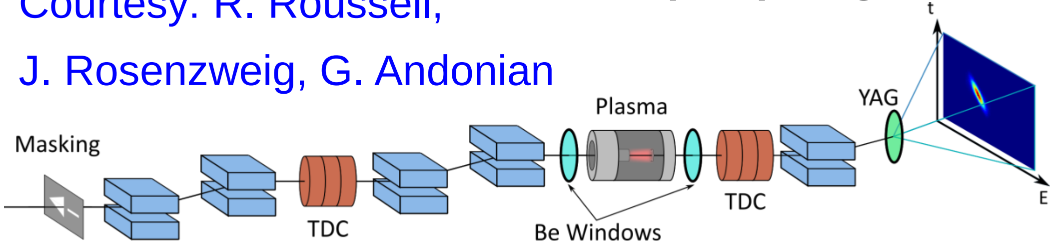
Argonne NATIONAL LABORATORY

PWFA:
PLASMA WAKEFIELD ACCELERATION

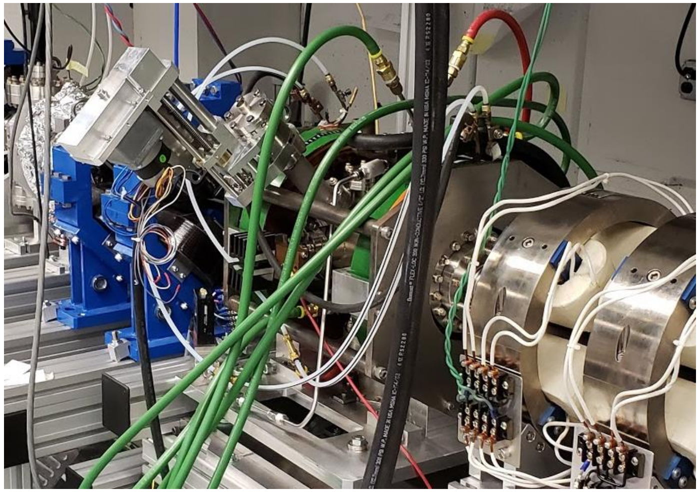
High R with EEX

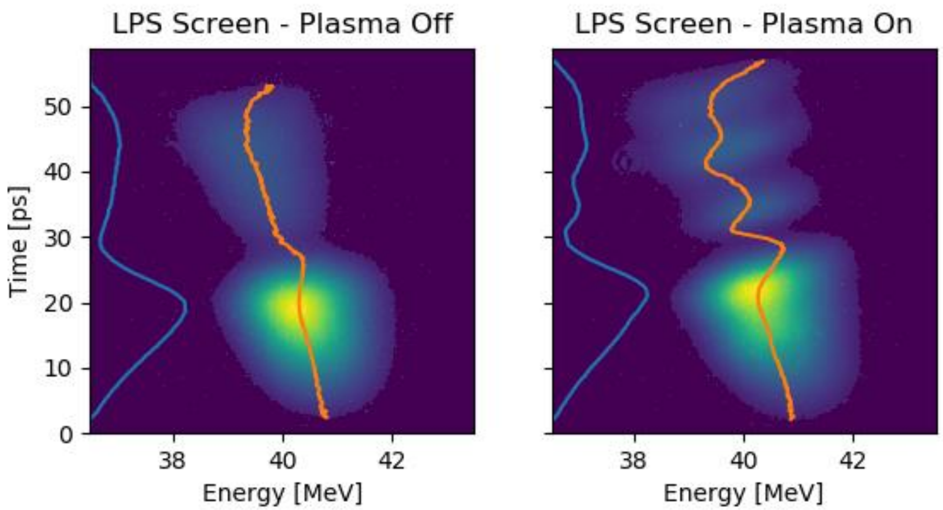
Courtesy: R. Roussell,
J. Rosenzweig, G. Andonian

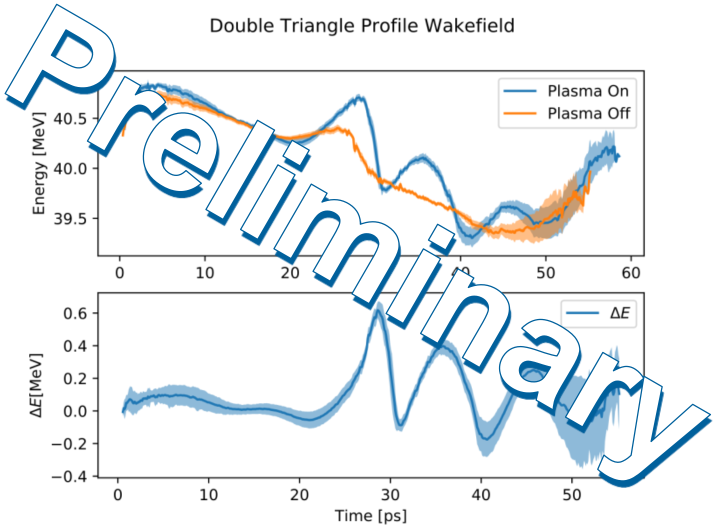
Longitudinal Phase Space (LPS) Diagnostic



Emittance Exchange







AWA MISSION

Develop Science & Technology of e^- Beam-driven Wakefield Acceleration

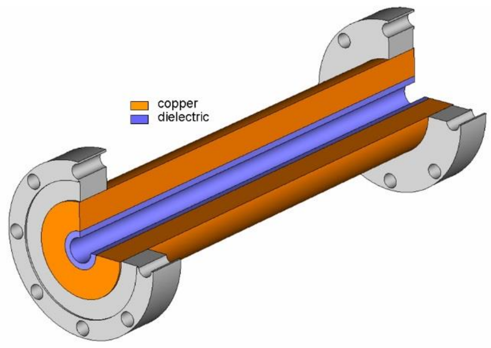
- SWFA: Two Beam Acceleration (TBA) and Collinear Wakefield Acceleration (CWA)
- **Novel structure R&D**
- Fundamental field emission and RF breakdown study
- BBU control in wakefield accelerators
- PWFA

Advanced Acceleration Concepts

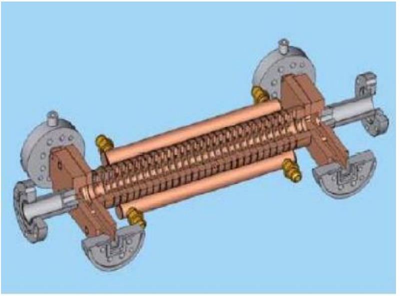
NOVEL STRUCTURE R&D AT THE AWA

Some of the structures that have been tested at the AWA facility

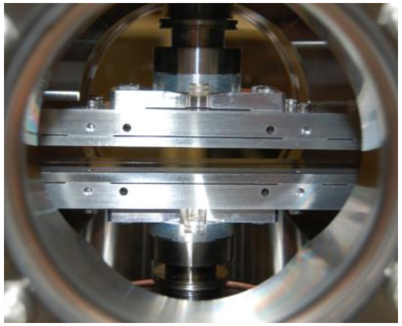
Cylindrical dielectric (AWA)



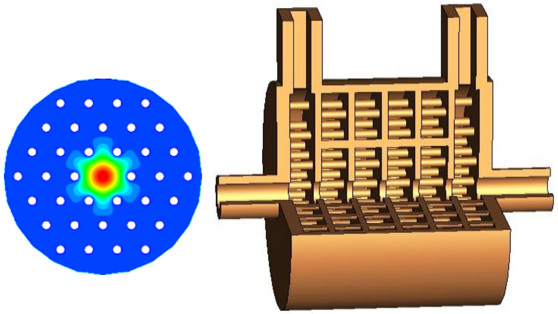
Iris loaded Metallic (AWA)



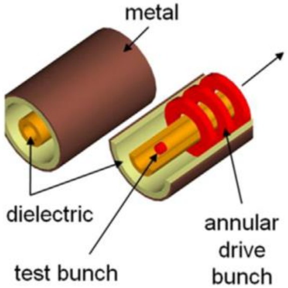
Planar dielectric (Euclid)



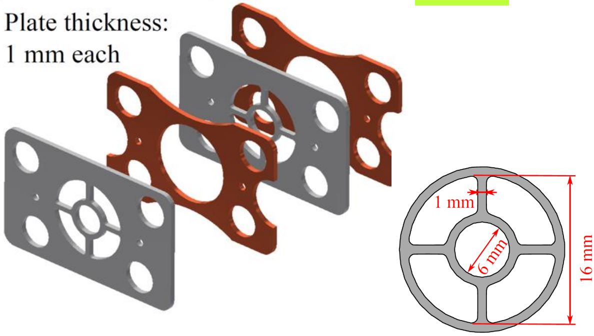
Photonic band gap (LANL)



Coaxial dielectric (Omega-P)



Meta/left-handed (MIT)



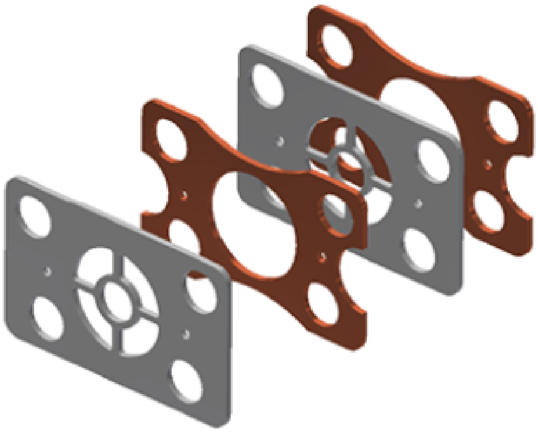
Recent Publication

PHYSICAL REVIEW LETTERS **122,** 014801 (2019)

Editors' Suggestion   Featured in Physics

Generation of High-Power, Reversed-Cherenkov Wakefield Radiation in a Metamaterial Structure

Physics VIEWPOINT



A Metamaterial for Next Generation Particle Accelerators

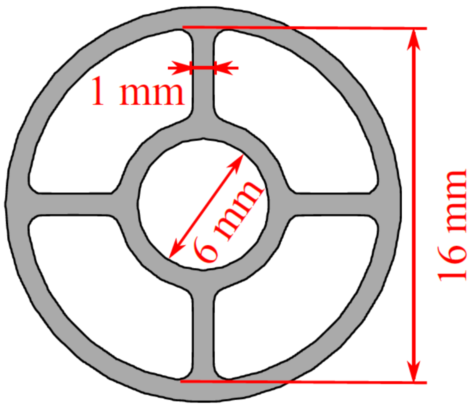
Published 7 January 2019

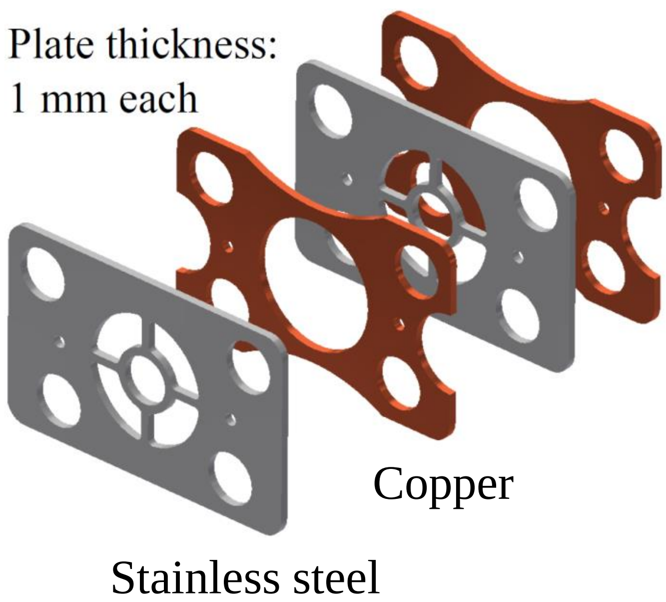
An experiment reveals the potential of custom-engineered metamaterials to yield higher accelerating gradients than current particle accelerator technology allows.

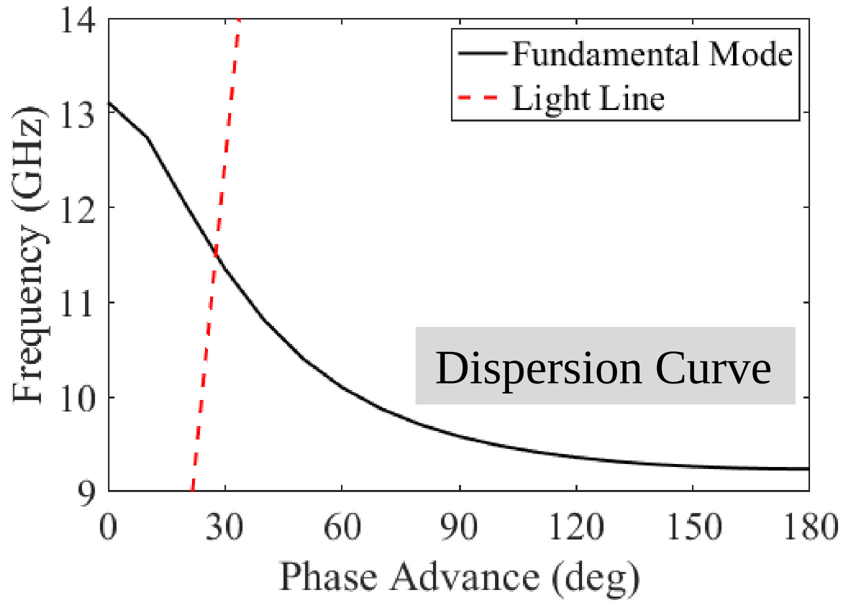
See more in *Physics*

Wagon Wheel Structure Unit Cell

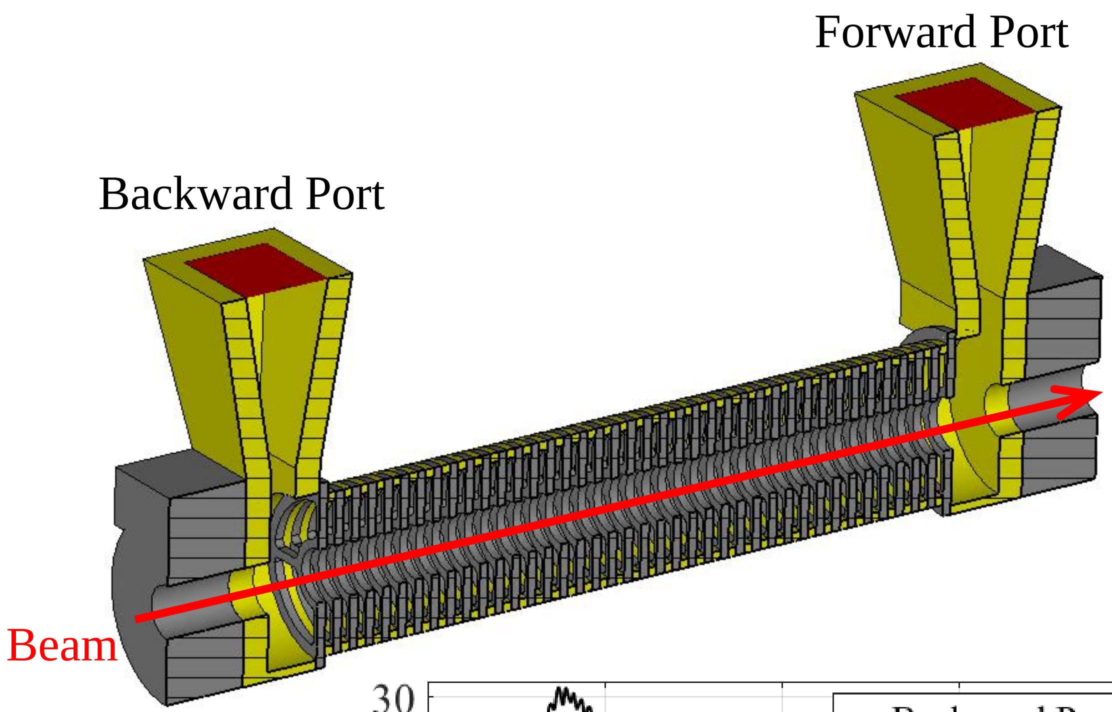
- Wagon wheel structure
  - Periodic subwavelength structure
    - Period: 2 mm
    - Free wavelength at 11.42 GHz: 26 mm
  - Negative group velocity
  - Fundamental mode: TM mode
  - Interaction frequency: 11.42 GHz
    - Cutoff frequency of an empty waveguide: 14.2 GHz

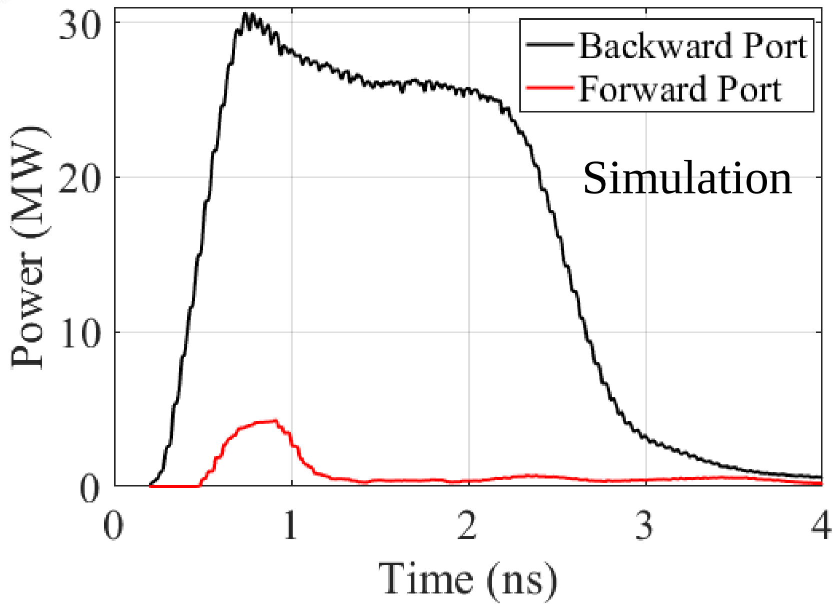






CST Simulation



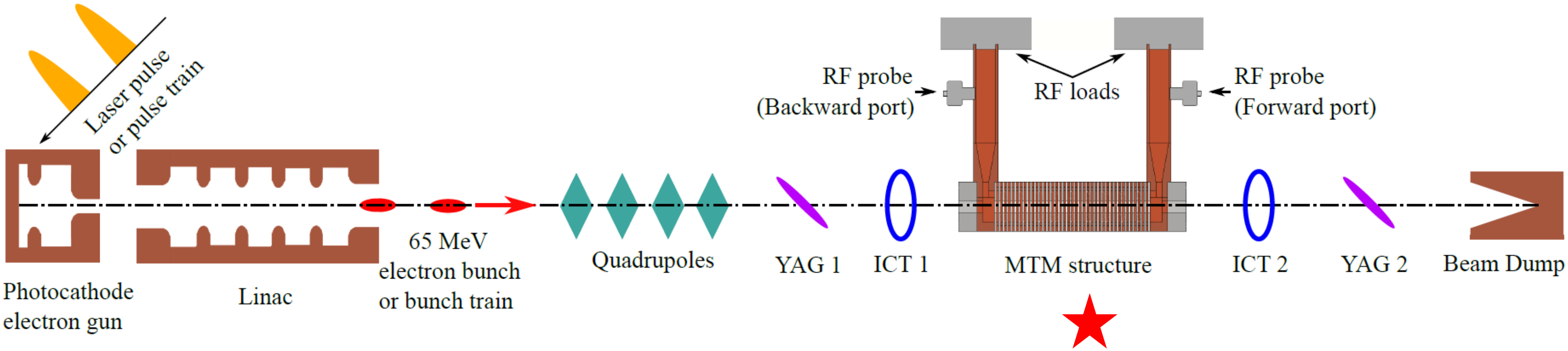


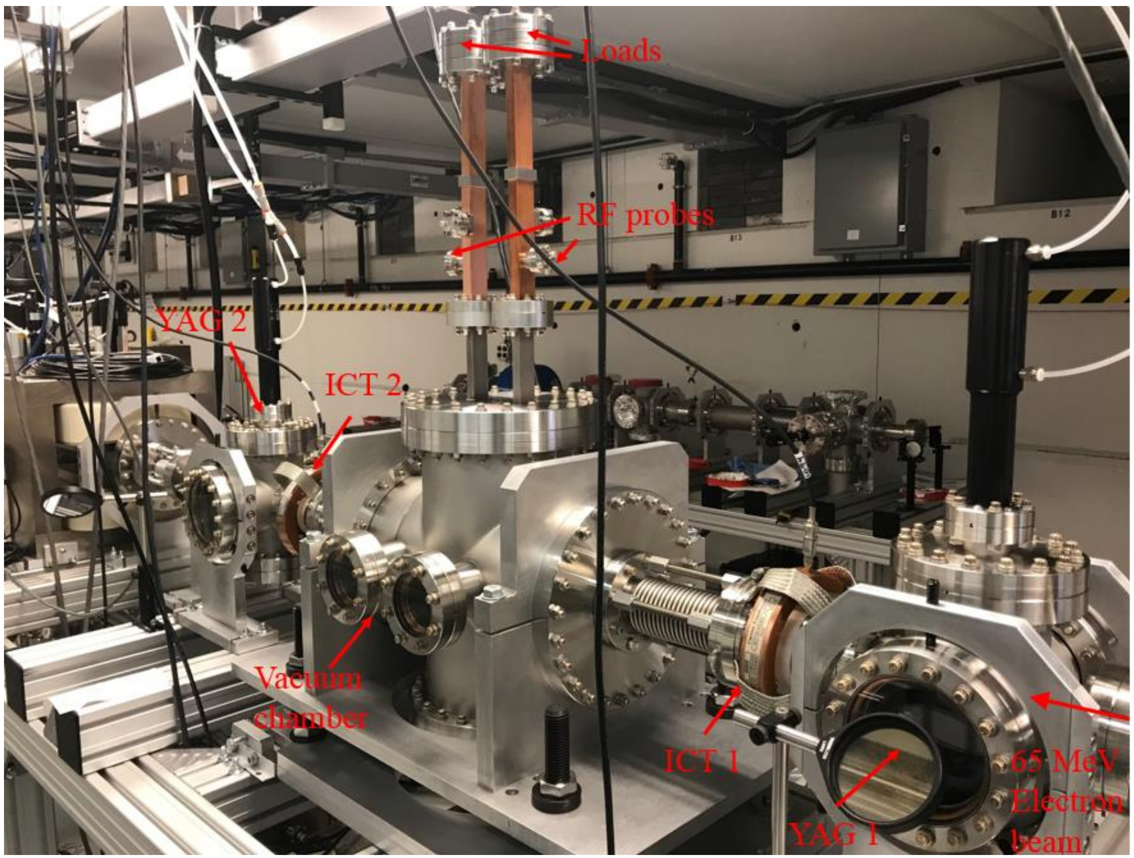
- CST Wakefield solver, single bunch
  - 45 nC, σ_z = 1.2 mm
- **26 MW** steady state in the backward port
- Much lower power in the forward port
  - Reversed Cherenkov radiation
- Analytical theory:

$$P = q^2 k_L |v_g| \left(\frac{1}{1 - v_g/c} \right)^2 \Phi^2$$

= 25 MW

Experimental Setup at AWA





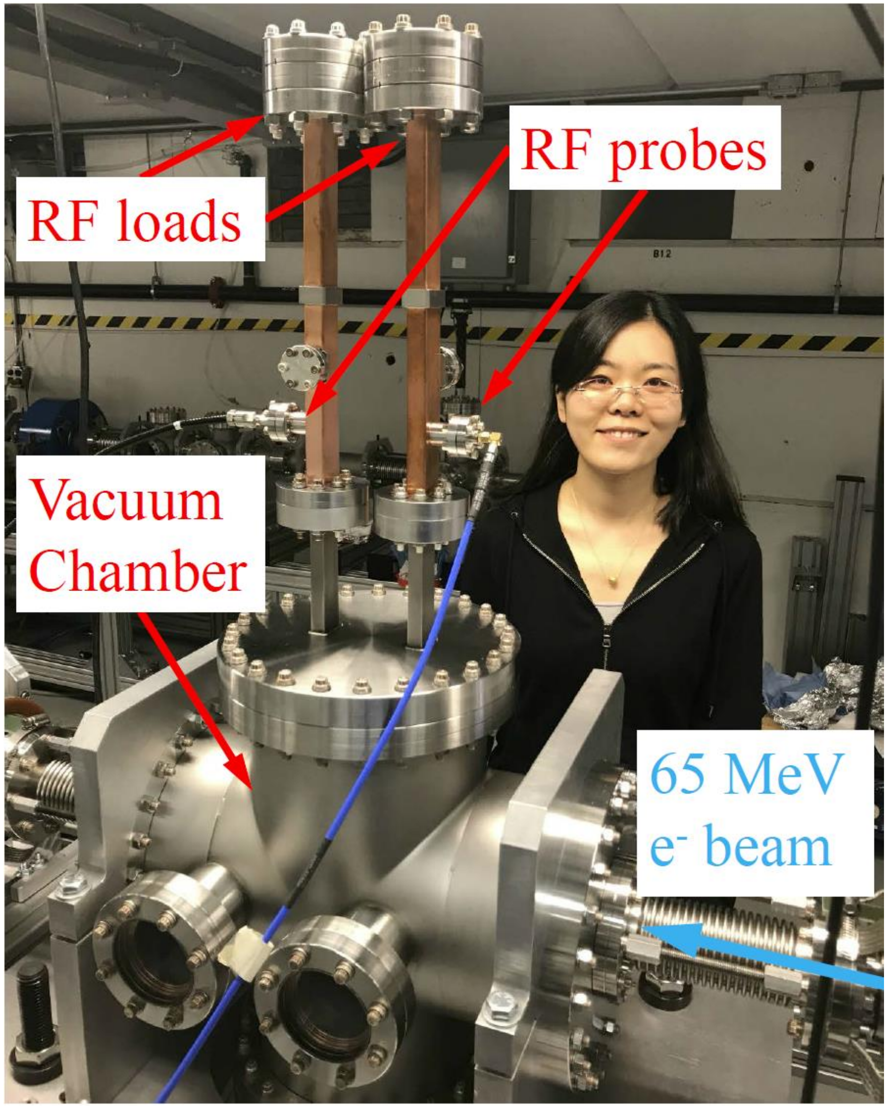
Diagnostics:

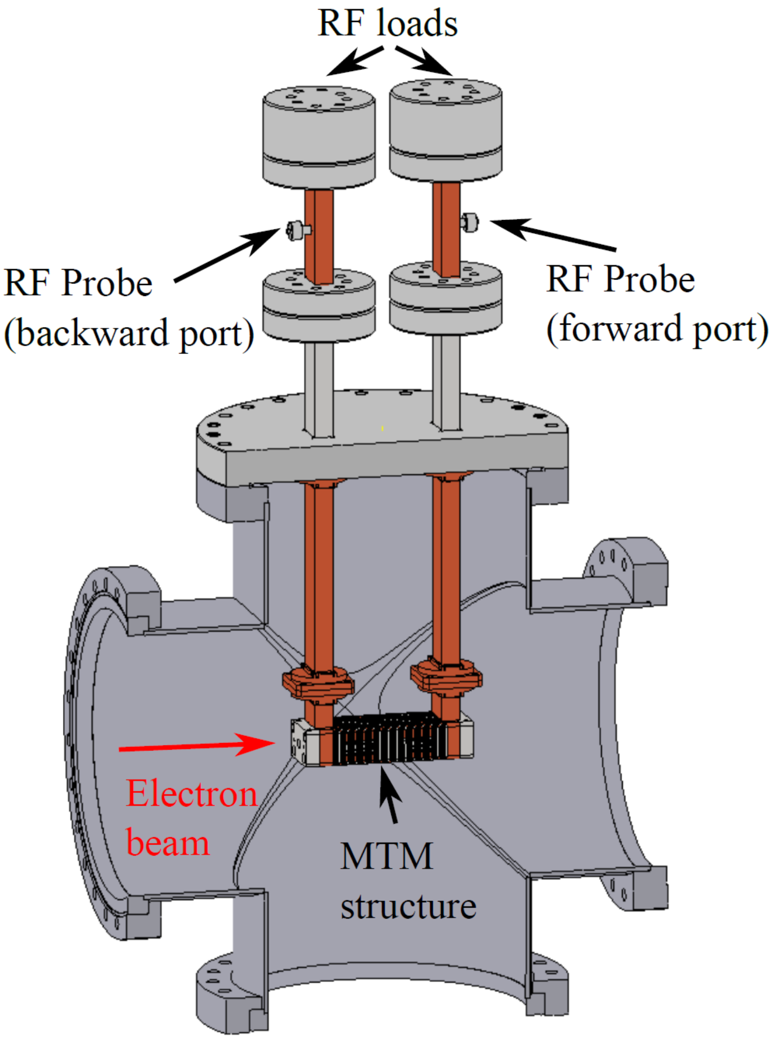
ICT (Integrating current transformer): Bunch charge

YAG screen: Bunch transverse size

RF probes: Output microwave

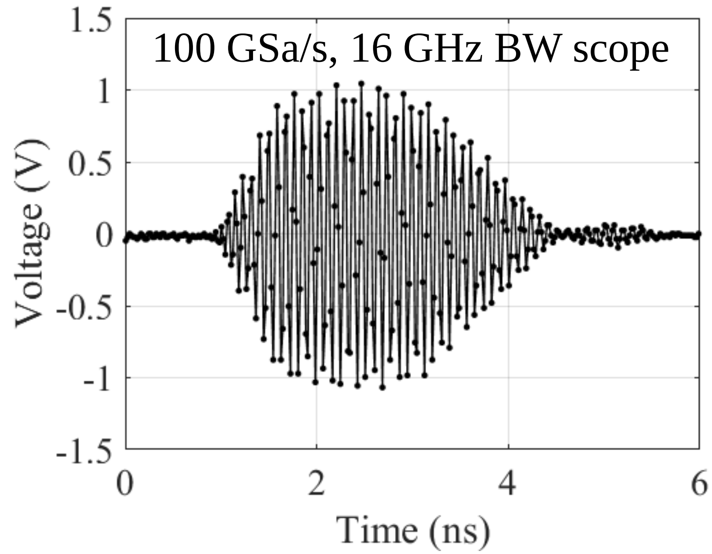
Installed Experiment at AWA

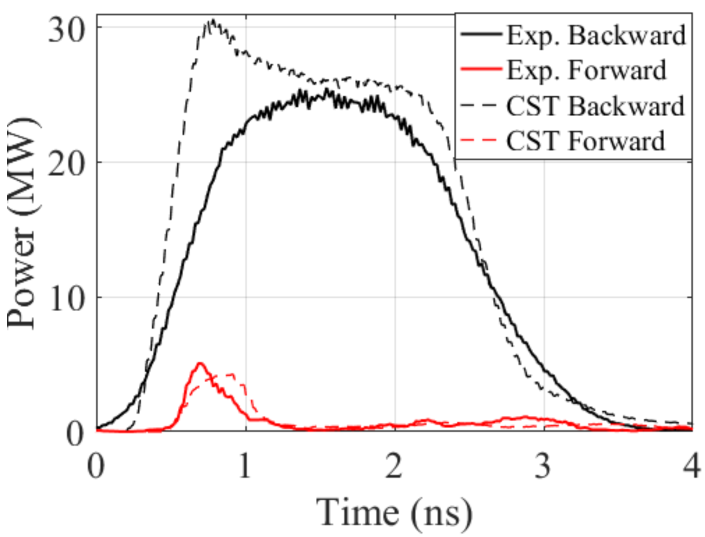


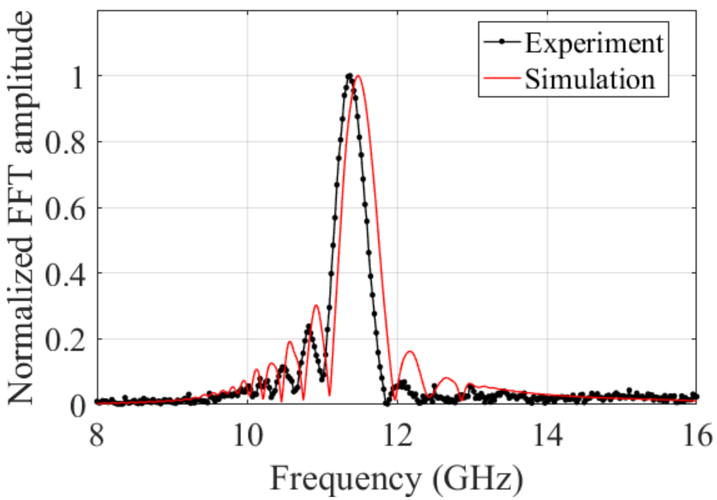


Single Bunch Experiment

- High RF power from a single 45 nC bunch
  - Experiment: 25 MW
  - Simulation: 26 MW (steady state)
  - Analytical theory: 25 MW
- Reversed Cherenkov radiation verified
  - Coherent radiation at 11.4 GHz
  - Backward port has much more power

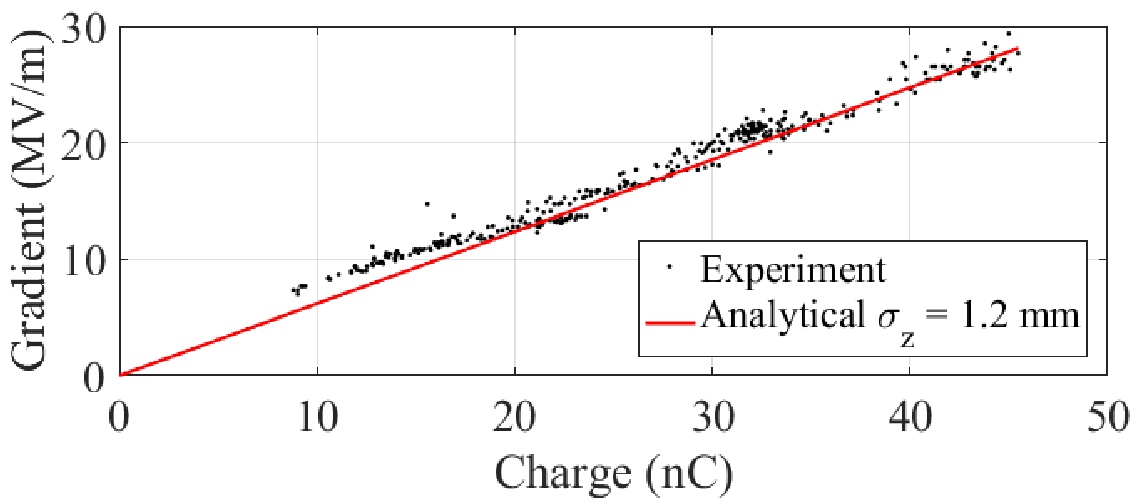


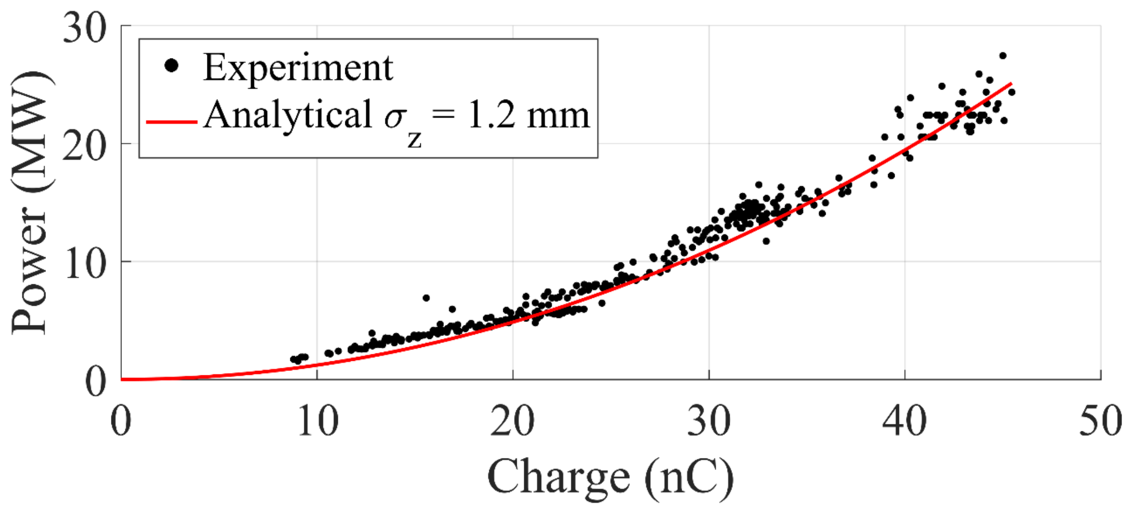




Scaling with Charge

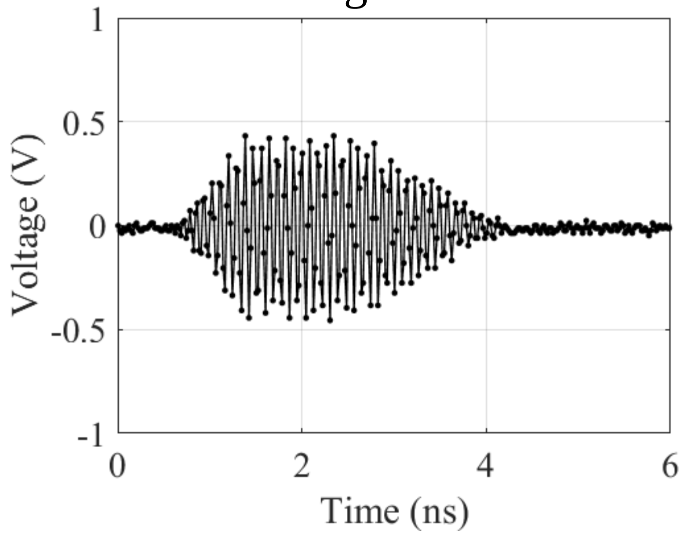
- Good linear scaling of gradient vs. charge, good agreement with theory
  - No breakdown events



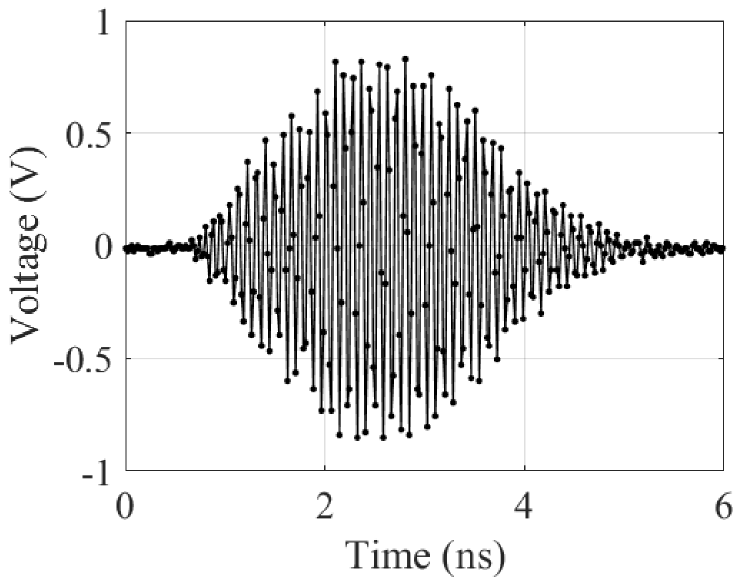


Two-Bunch Experiment

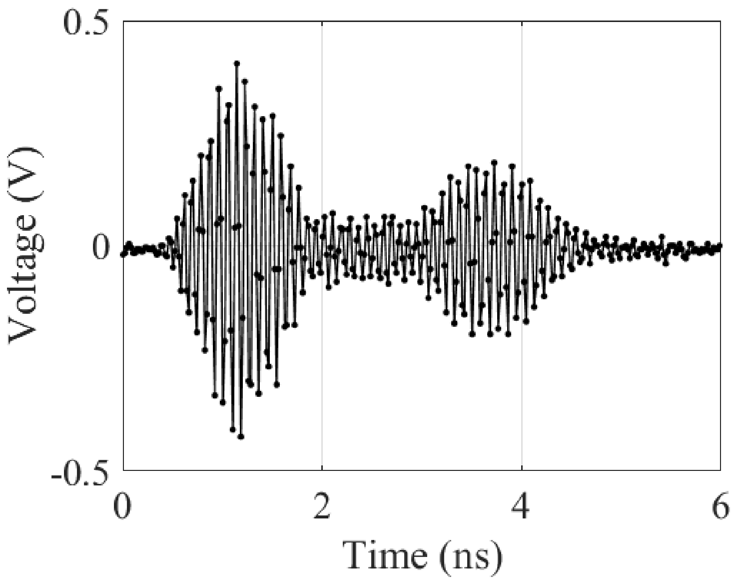
Single bunch



Two bunches with 0 deg phase difference

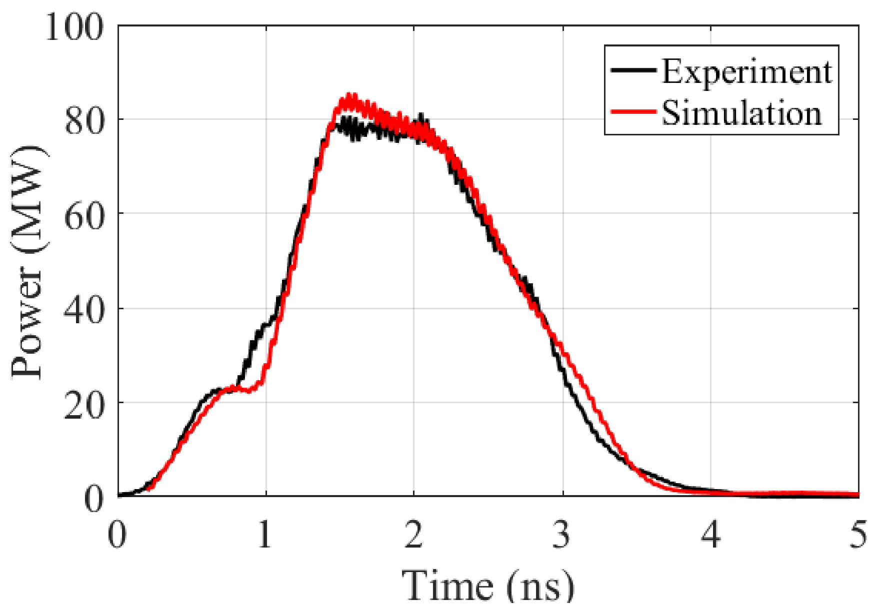


Two bunches with 180 deg phase difference



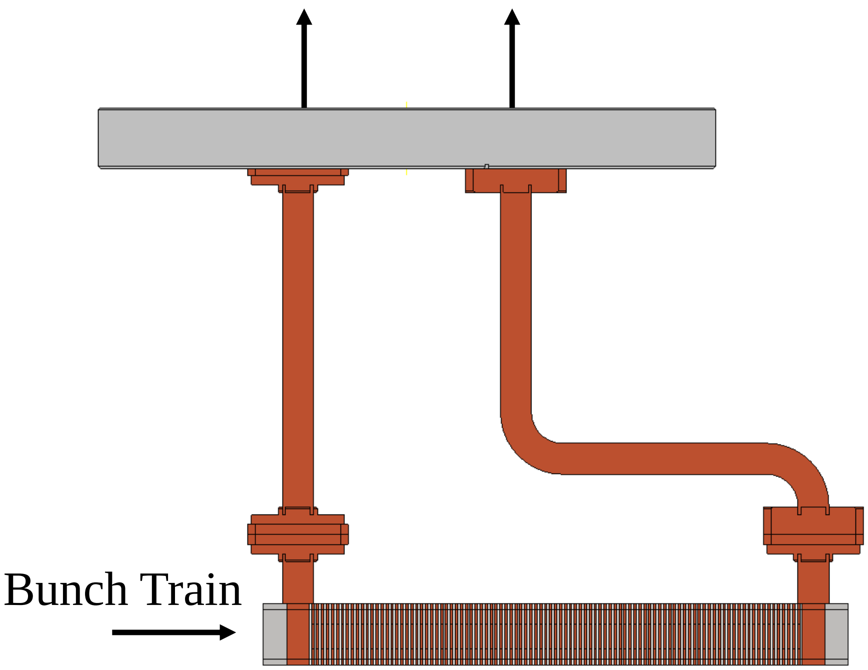
Highest power shot

- Two bunches with a total charge of 85 nC
- **80 MW** extracted RF power
- 50 MV/m decelerating electric field
  - 75 MV/m available accelerating gradient for a possible witness bunch
- ~130 MV/m maximum surface field

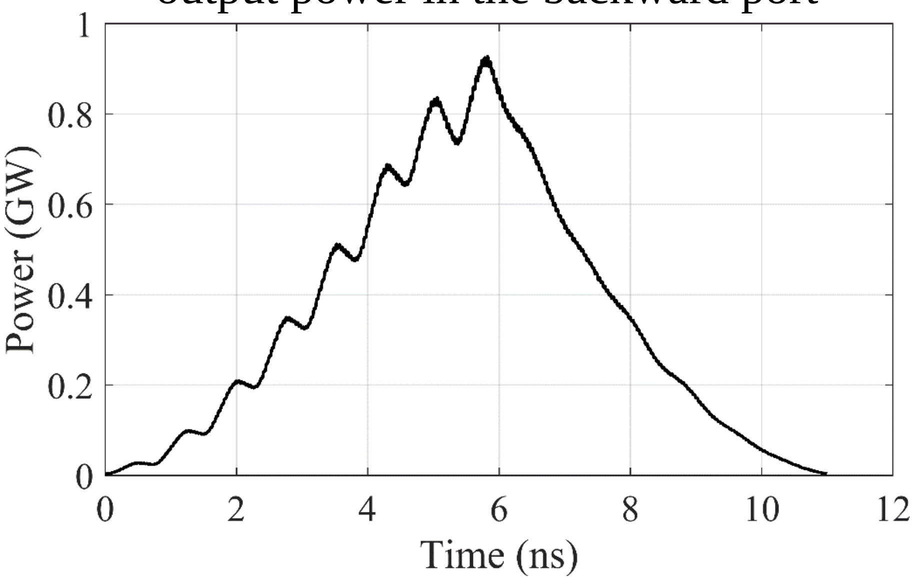


Next Experiment: Longer Structure

- 100-cell structure (20 cm long), 8 bunches, 40 nC/bunch
  - 0.9 GW peak power
  - 170 MV/m decelerating gradient
  - 250 MV/m available accelerating gradient for a witness bunch

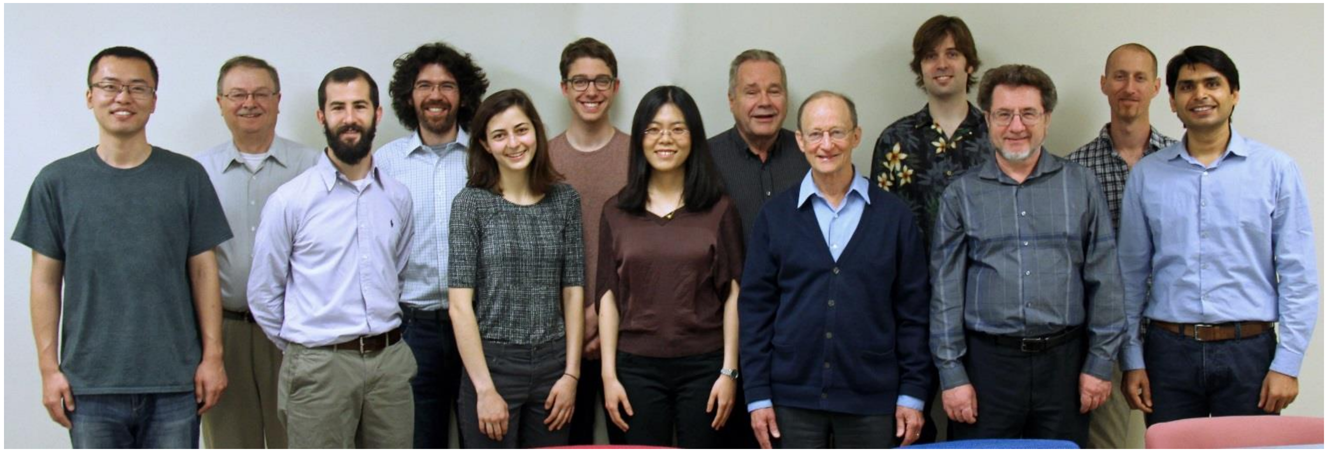


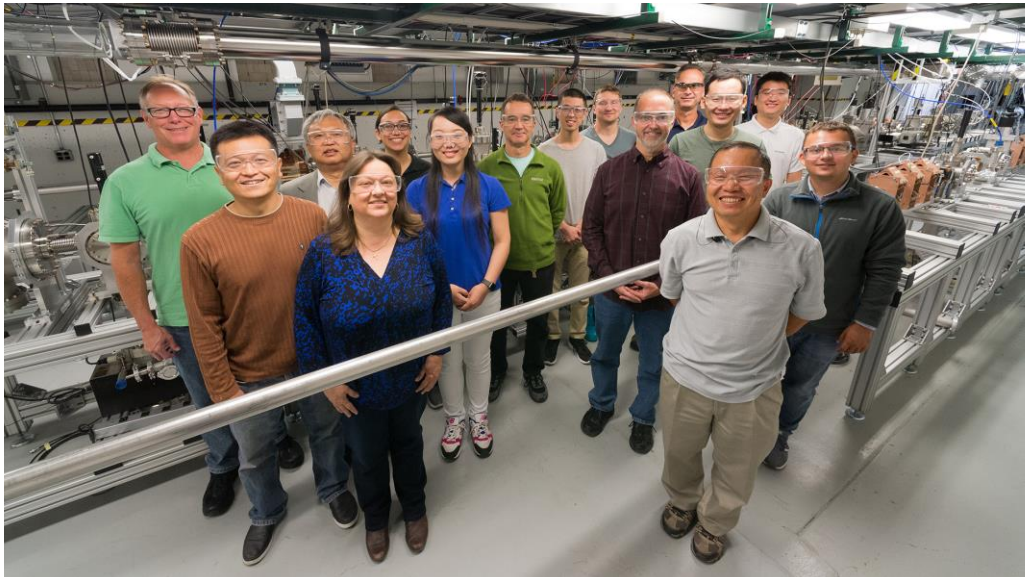
CST simulation of
output power in the backward port



Acknowledgement

MIT





ANL-AWA

Funding agency:

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ANL: U.S. Department of Energy, Office of Science under Contract No. DE-AC02-06CH11357.