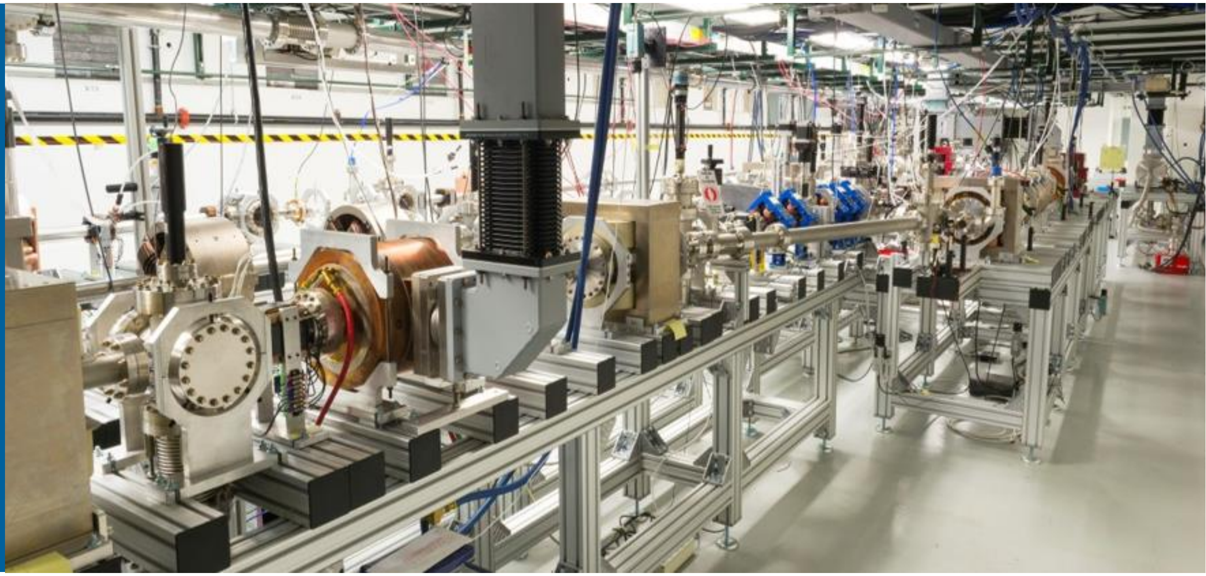
The short-pulse RF path to High Gradient

Argonne NATIONAL LABORATORY

HIGH GRADIENT RESEARCH ACTIVITIES AT AWA



JOHN POWER FOR ARGONNE WAKEFIELD ACCELERATOR (AWA)

https://www.anl.gov/awa

International Workshop on Breakdown Science and High Gradient Technology (HG2022) 16-19 May 2022

MY GOAL TODAY…

To help you understand the **High Gradient Research Program** at Argonne

- **Why?** → short-pulse RF
- **How?** → Structure Wakefield Acceleration
- **Where?** → Argonne Wakefield Accelerator Facility
- **What?** → Recent Progress in short-pulse RF

The Short Pulse RF Advantage

Breakdown Rate (BDR)

S. Doebert et al.,PAC'05
https://accelconf.web.cern.ch/p05/PAPERS/ROAC004.PDF

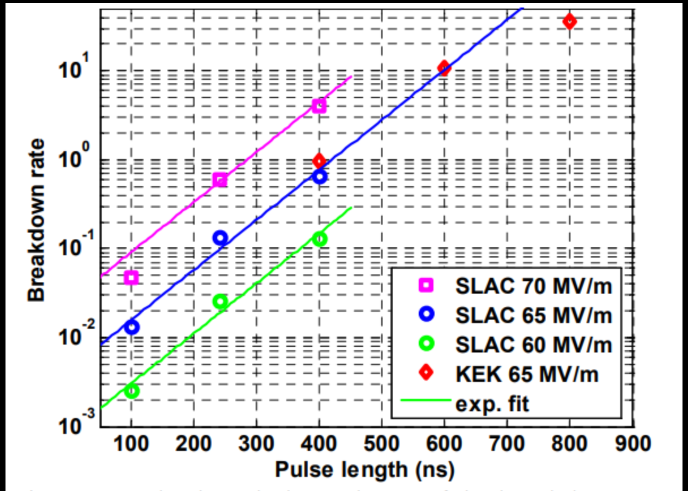
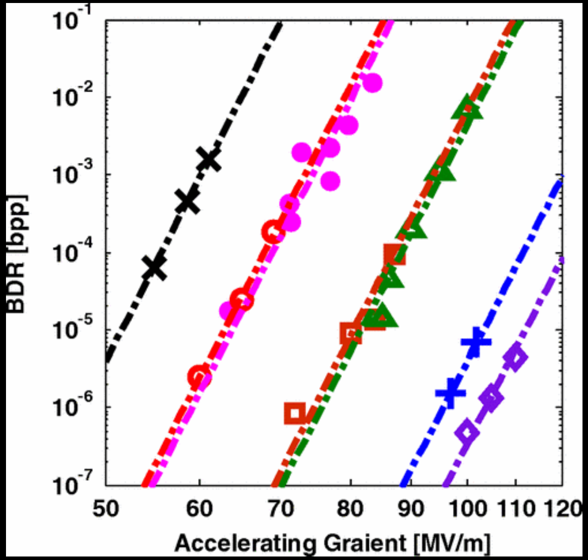


Figure 4: Pulse length dependence of the breakdown rate.

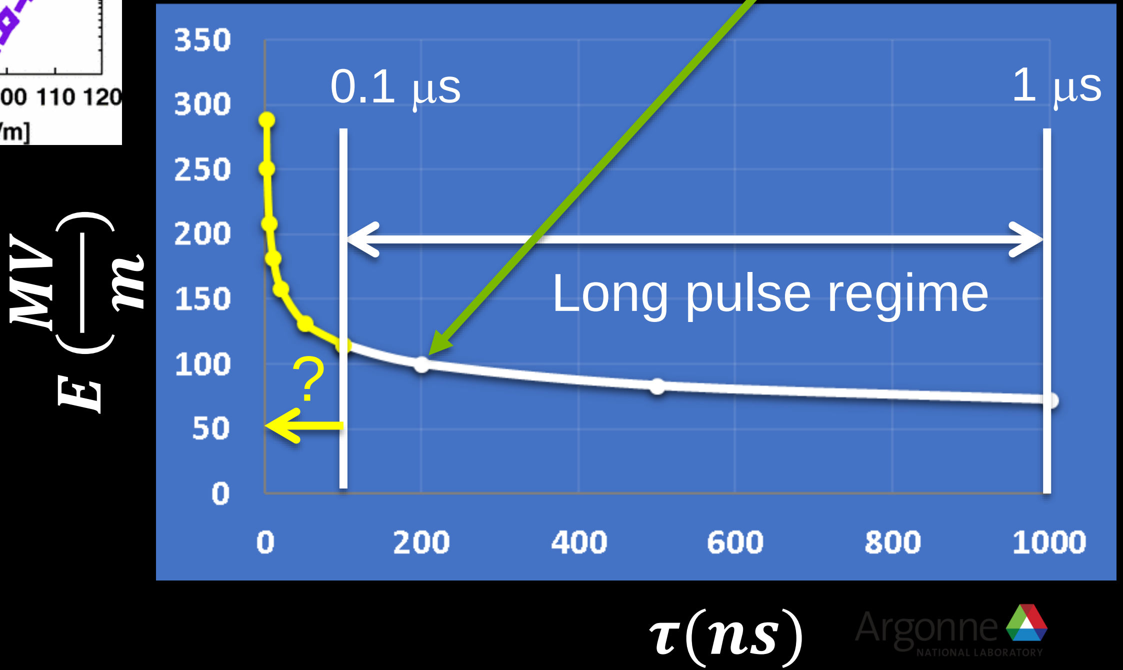
A. Grudiev, S. Calatroni, and W. Wuensch
Phys. Rev. ST Accel. Beams 12,102001 (2009)



SLAC/KEK/CLIC
Scaling Law

$$BDR \propto E^{30}\tau^{6}$$

3e−7, 100 MV/m, 200ns



ULTRA SHORT-PULSE REGIME

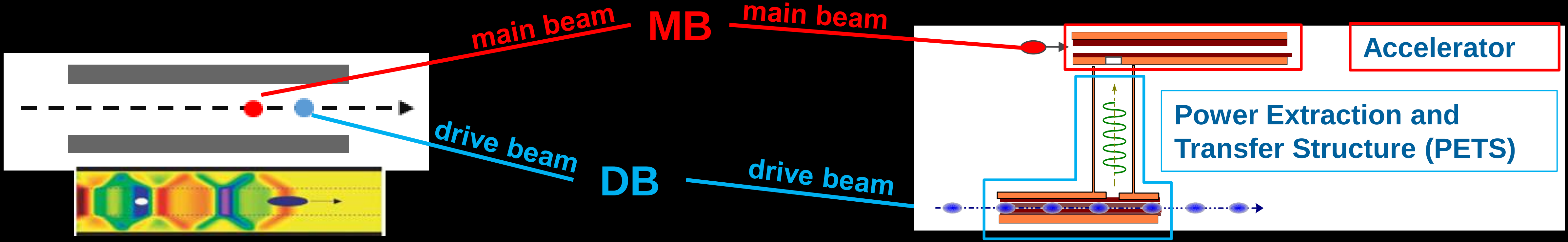
- **New physics:** Empirical scaling law, underlying mechanism may change
- **Challenges:** Challenges to operate in the short-pulse regime: broadband couplers, efficiency, stability, etc.

H. H. Braun, et al., "*High-power testing of 30 ghz accelerating Structures at CTF II*", CLIC Note 475
W. Wuensch, et al., "*A demonstration of high-gradient acceleration*", PAC'03

ELECTRON BEAM DRIVEN SFWA

Collinear Wakefield Acceleration

Two Beam Acceleration



PWFA-like

CWA uses single beamline

- Pros
  - One structure & no couplers
- Cons
  - Challenges associated with combined beam dynamics of drive and witness bunches.

Klystron-like

TBA uses two parallel beamlines

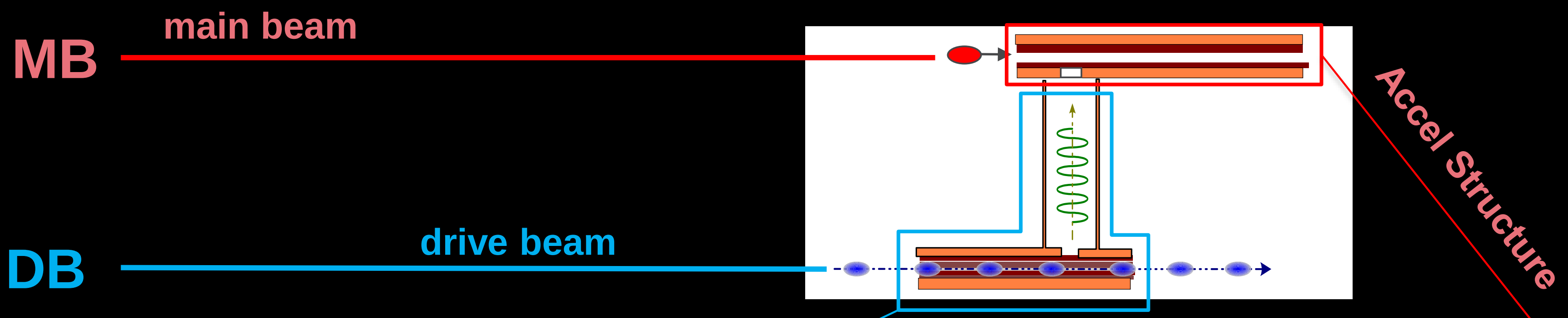
- Pros
  - Decoupled drive/main beam optics design
  - Structures optimized for drive and witness beam
- Cons
  - Two structures with complex waveguide & couplers,

A. Zholents, et al, *NIMA* **829**, 190-193 (2016)
A. Zholents, et al, *Proceedings of IPAC2018*

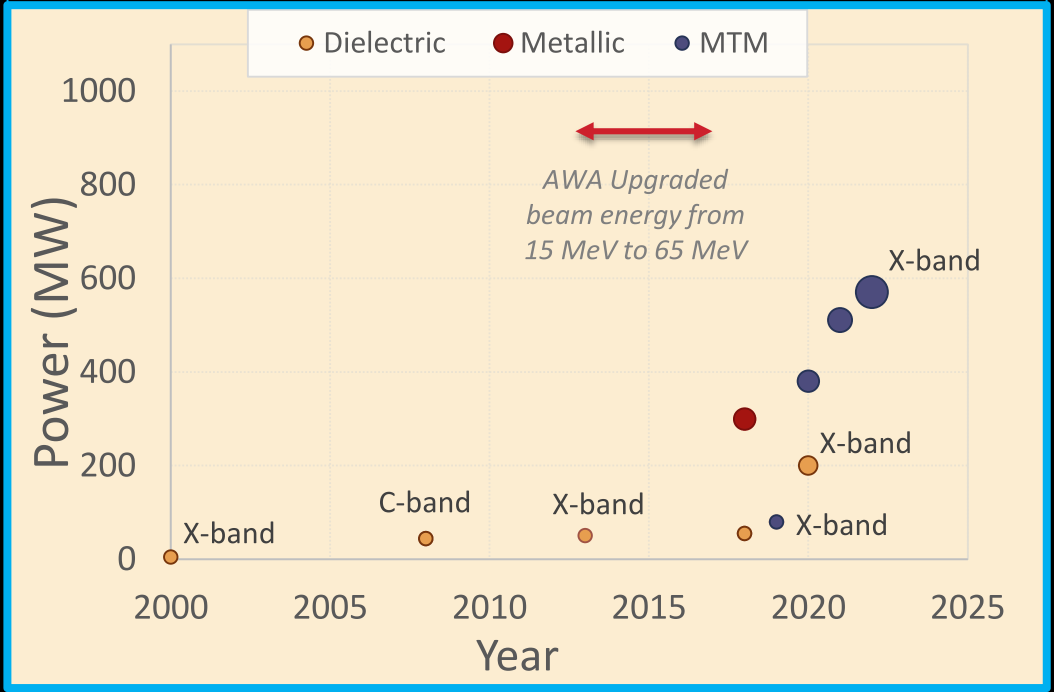
CLIC CDR: https://project-clic-cdr.web.cern.ch/CDR_Volume1.pdf
W. Gai, C. Jing, J.G. Power, *JPP* **78**, 339-345 (2012)

ELECTRON BEAM DRIVEN SFWA – TBA

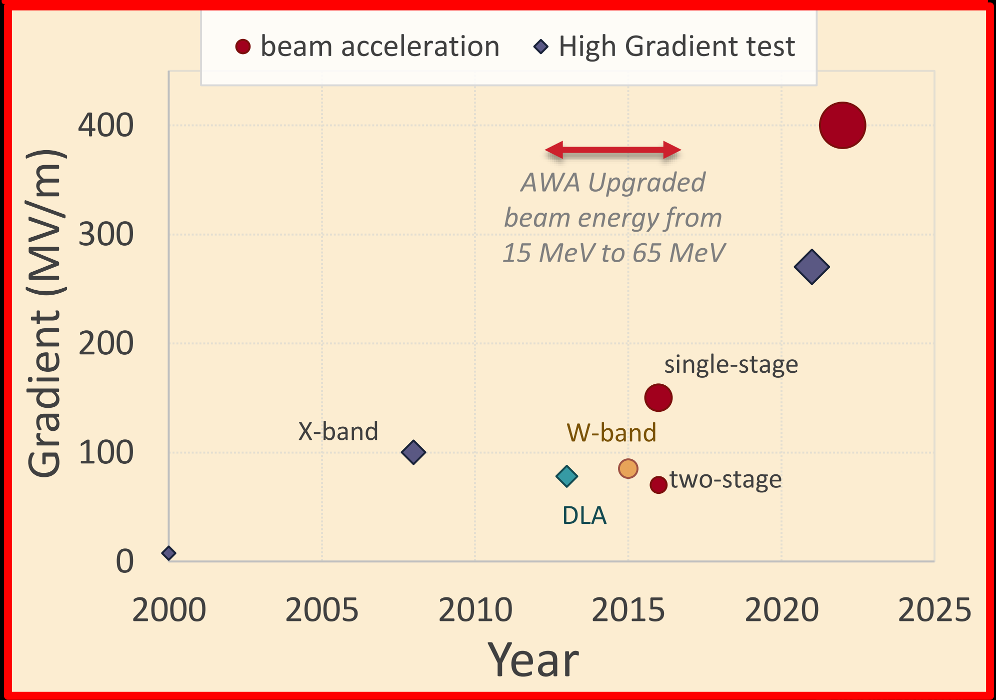
Structure Wakefield Acceleration – Two Beam Acceleration



RF Power Generation



Accelerating Gradient

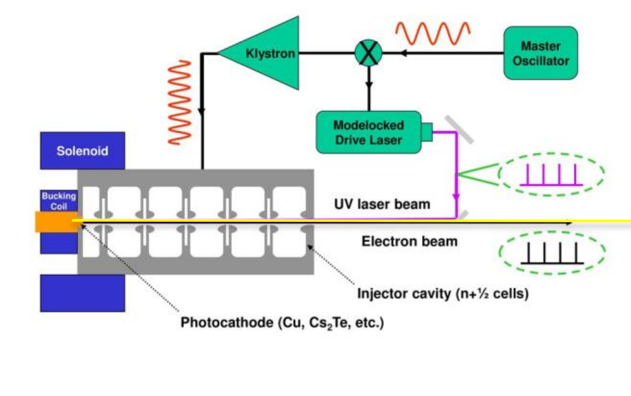


THE
ARGONNE WAKEFIELD ACCELERATOR
TEST FACILITY

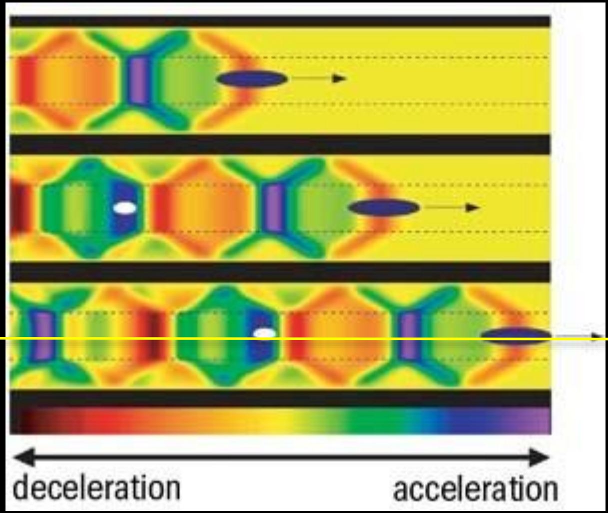
AWA R&D PROGRAM

Beam Production → Advanced Acceleration → Beam Manipulation → APPLICATION

RF Photoinjector

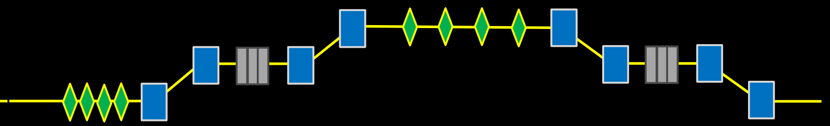


High brightness electron source, novel cathodes



- High-gradient & high-efficiency
- SWFA & PWFA acceleration

Double EEX beamline



- Bunch Shaping
- Beam Diagnostics

THE ARGONNE WAKEFIELD ACCELERATOR FACILITY

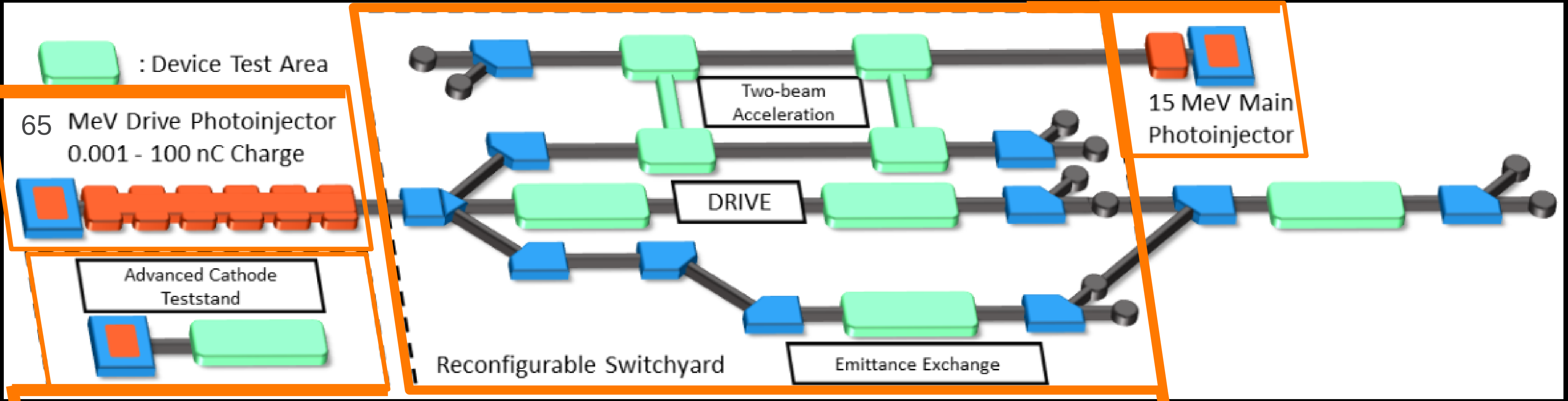
3x 1300 MHz RF photocathode guns

DRIVE

- 65-MeV Drive photoinjector (Cs_2Te) linac
  - World's highest-charge (e.g. 100 nC) photoinjector
    - High brightness low-Q beam

WITNESS

- 15 MeV photoinjector linac
  - Produces bright beam acceleration
    - Supports low-energy experiments



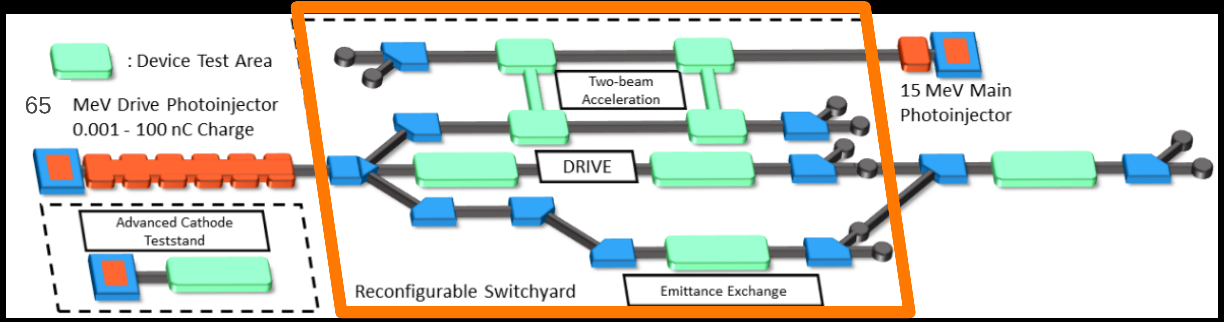
ACT (Argonne Cathode Test)

- 1-5 MeV RF gun
  - Cathode research (photocathode and field emission)
    - Breakdown Physics

Reconfigurable Experimental Switchyard

THE ARGONNE WAKEFIELD ACCELERATOR FACILITY

THE AWA FACILITY



RESEARCH AREAS

Beam-driven wakefield acceleration

- Structure Wakefield Acceleration (SWFA)
  - Collinear Wakefield Acceleration (CWA)
  - Two-Beam Acceleration (TBA)
- Plasma Wakefield Acceleration (PWFA)

RF Acceleration Technology

- 100's MV/m NCRF short-pulse structures
- 100's MW NCRF short-pulse power source

Accelerator and Beam Physics

- 6D phase space manipulation
- Electron cooling
- Novel diagnostics (Single-shot, AI/ML Virtual, etc.)

Electron sources

- Photo and field emission. High brightness beams.

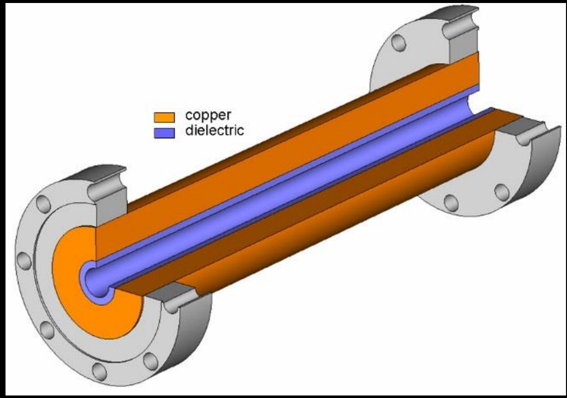
Machine Learning

- ML for machine control, virtual diagnostics and physics

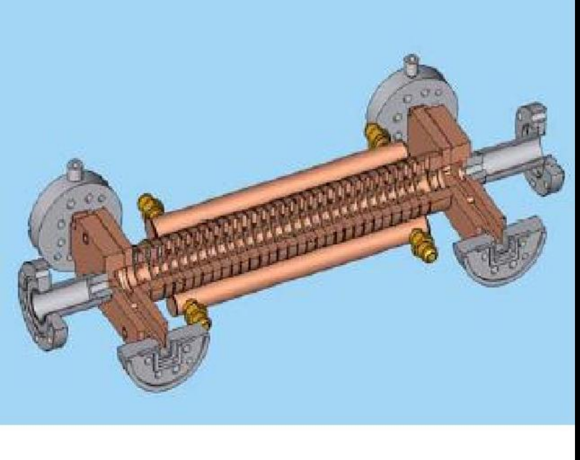
THE ARGONNE WAKEFIELD ACCELERATOR FACILITY

Novel Structure Development

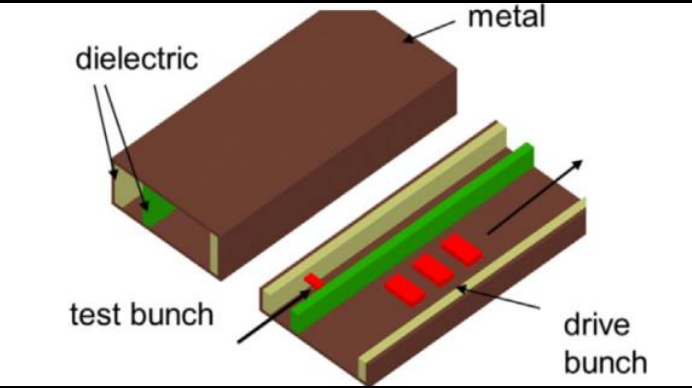
Dielectric loaded structures



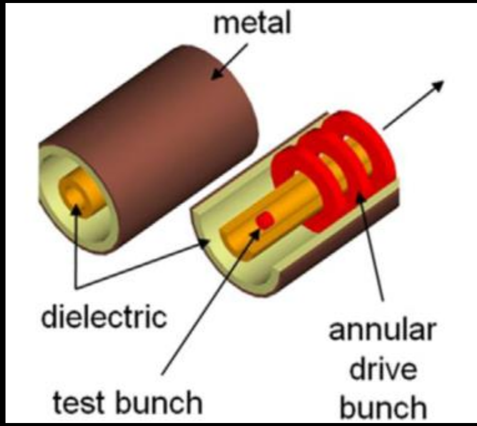
Iris loaded structures



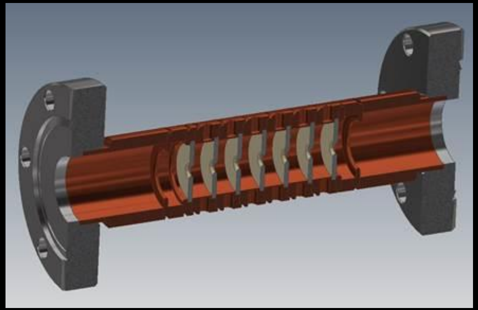
Rectangular dielectric



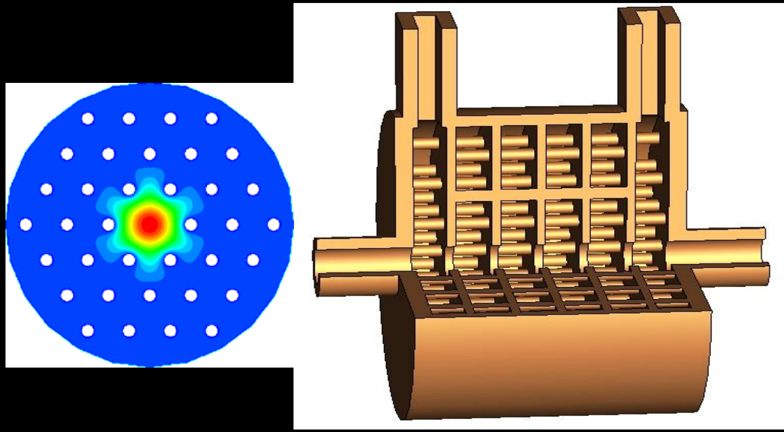
Coaxial dielectric



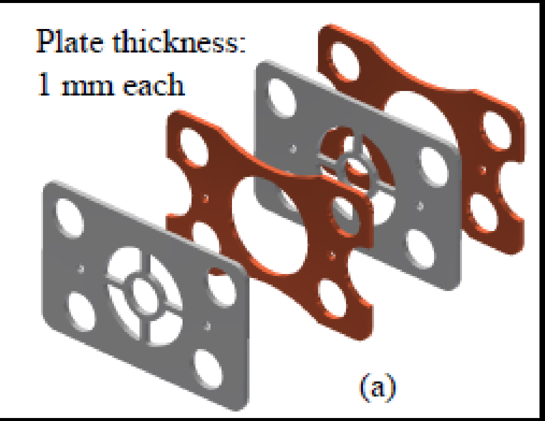
Dielectric disk accelerator



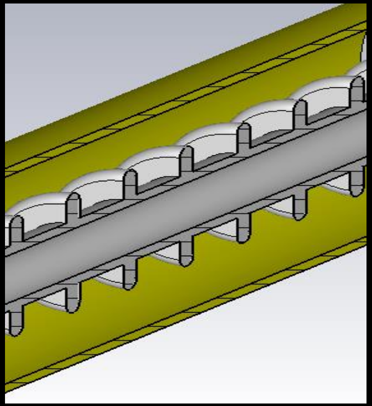
Photonic band gap structures



Meta/left-handed structures



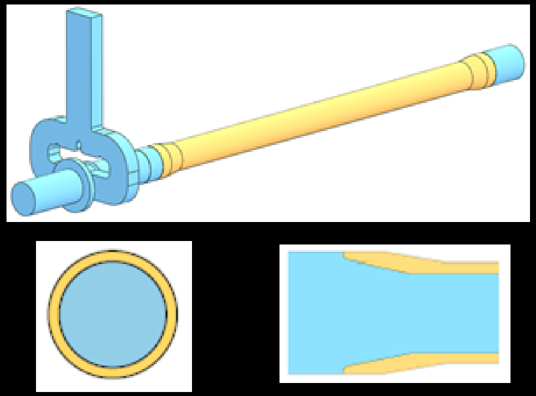
Cryogenic Dielectric Corrugated accelerator



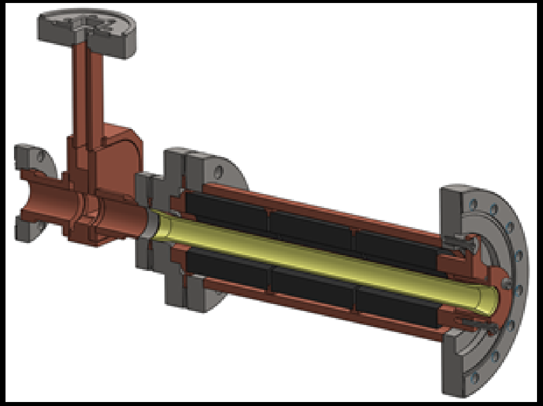
THE ARGONNE WAKEFIELD ACCELERATOR FACILITY

RF Structure R&D → end to end capabilities

Physics design

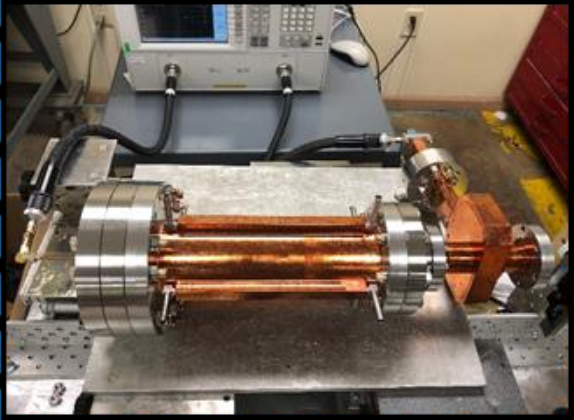


Mechanical design



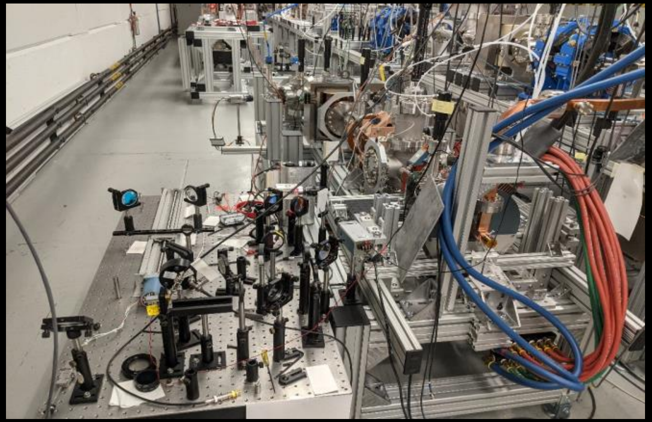
Fabrication*

Bench test

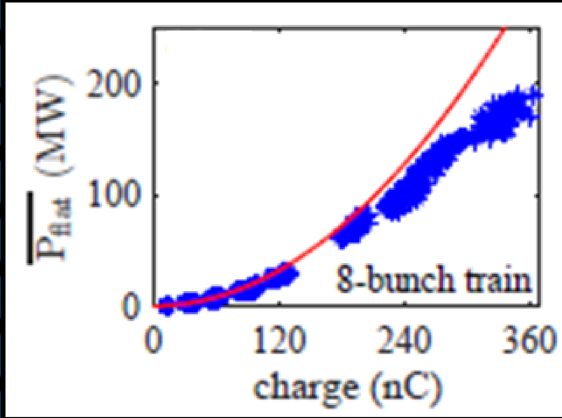


High power test

Beam acceleration test



Data analysis



RECENT PROGRESS IN THE *SHORT-PULSE REGIME*

1. **RF Power Generation – demonstrated**
   - 565 MW Metamaterial PETS – Xueying Lu (Talk Tuesday)
2. **High Gradient Acceleration – demonstrated**
   - 300 MV/m Single-cell – Jiahang Shao (Talk Tuesday)
   - 400 MV/m & low-dark current RF TW photocathode gun (publication submitted)
   - 100 MV/m Dielectric Disk Accelerator – Ben Freemire (Talk Thursday) & Sarah Weatherly (Poster Thursday)
3. **Short-pulse – New directions**
   - X-band deflector – Chunguang Jing (Poster Tuesday)
   - Single Cycle Structures – Sergey Kuzikov (Poster Wednesday)

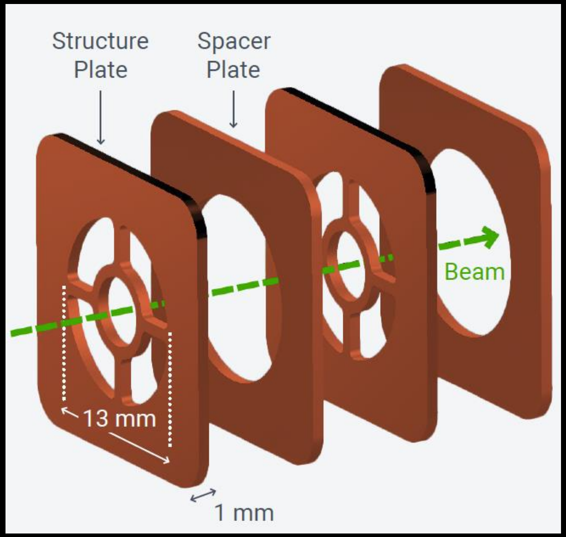
565 MW with MTM PETS – RF Power Generation

Metamaterial (MTM) structures for SWFA

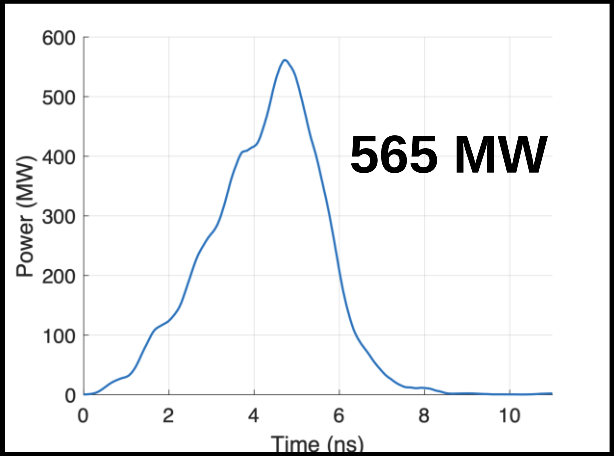
Talk: Xueying Lu (Tuesday)

- A new type of structure designed for efficient wakefield generation and acceleration
- Highest power generated using a 11.7 GHz MTM power extractor
  - Stage-3 experiment in 2021*
  - 565 MW RF power generated by a structure-based PETS
  - 355 nC train of eight bunches used to drive the MTM PETS
- Ongoing research:
  - MTM structures as accelerators for two-beam acceleration

Wagon wheel MTM structure



RF Power Measured from MTM Power Extractor



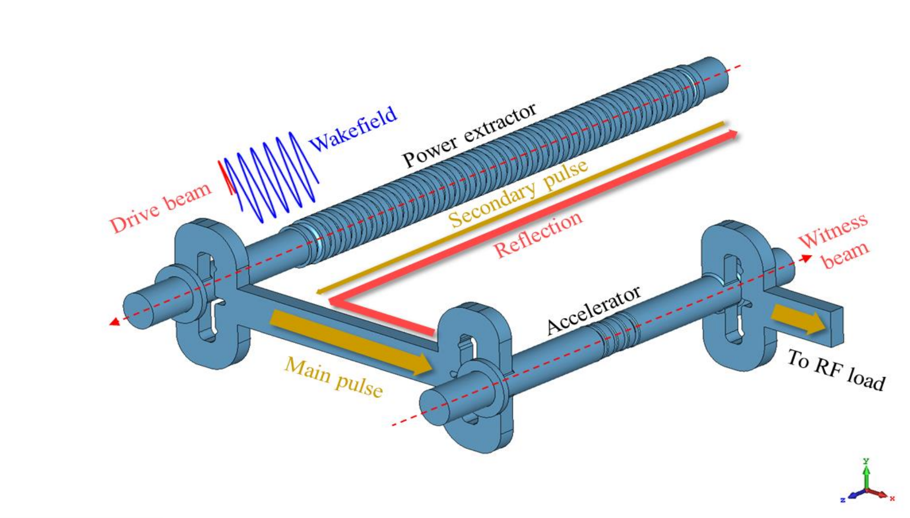
*J. Picard, *et al.*, "Generation of 565 MW of X -band power using a metamaterial power extractor for structure-based wakefield acceleration", *Physical Review Accelerators and Beams*, **accepted**

270 MV/m Single-cell – High Gradient Acceleration

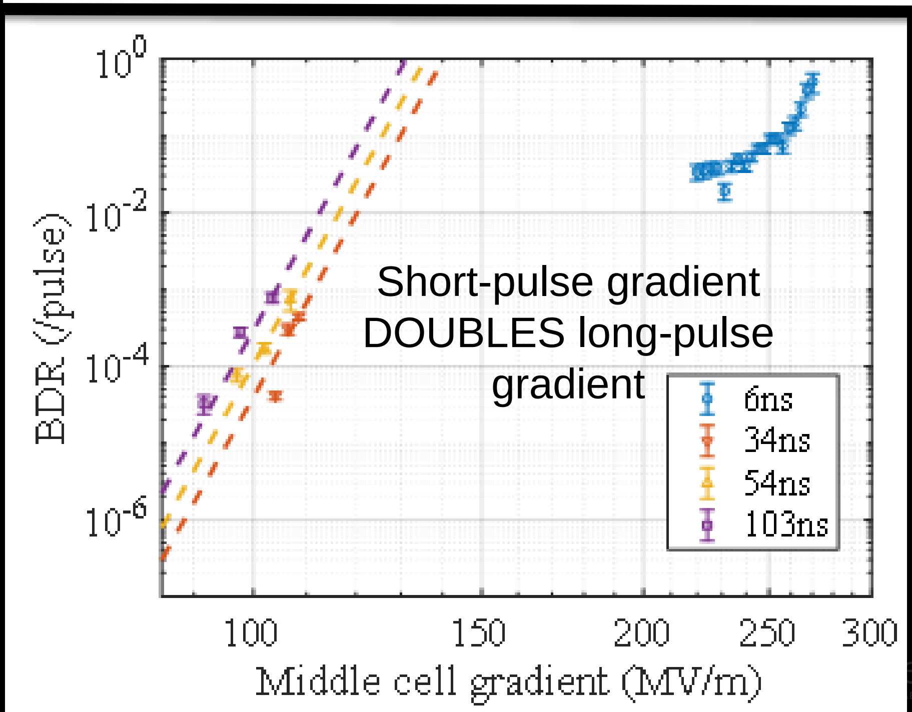
Talk: Jiahang Shao (Tuesday)

BDR tests, "*6 ns, 34 ns, 54 ns, 103 ns*"

- X-band TW single-cell accelerating structure
  - 1 normal cell + 2 matching cells
  - Longer pulse (34, 54,103 ns) tested at Tsinghua: klystron + pulse compressor
  - Short pulse (6 ns) tested at AWA: metallic PETS



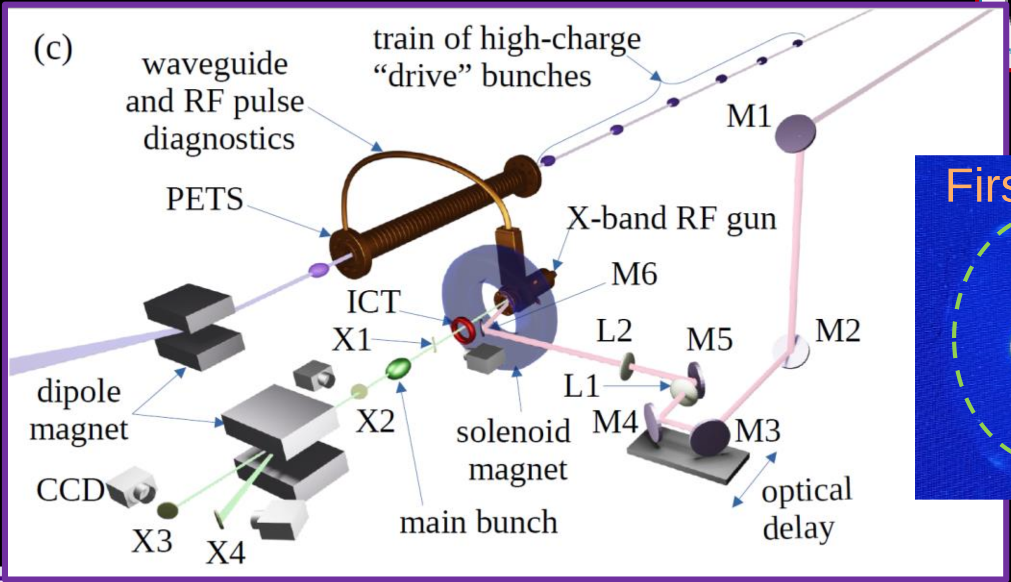
- Record gradient in X-band normal conducting structures
  - 270 MV/m accelerating gradient in the normal cell
  - 300 MV/m field in the first matching cell
  - 500 MV/m surface gradient in the first matching cell

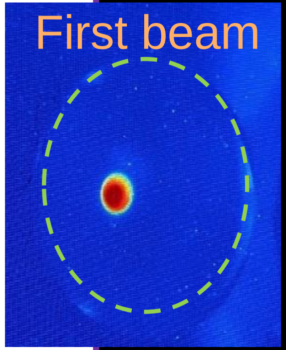


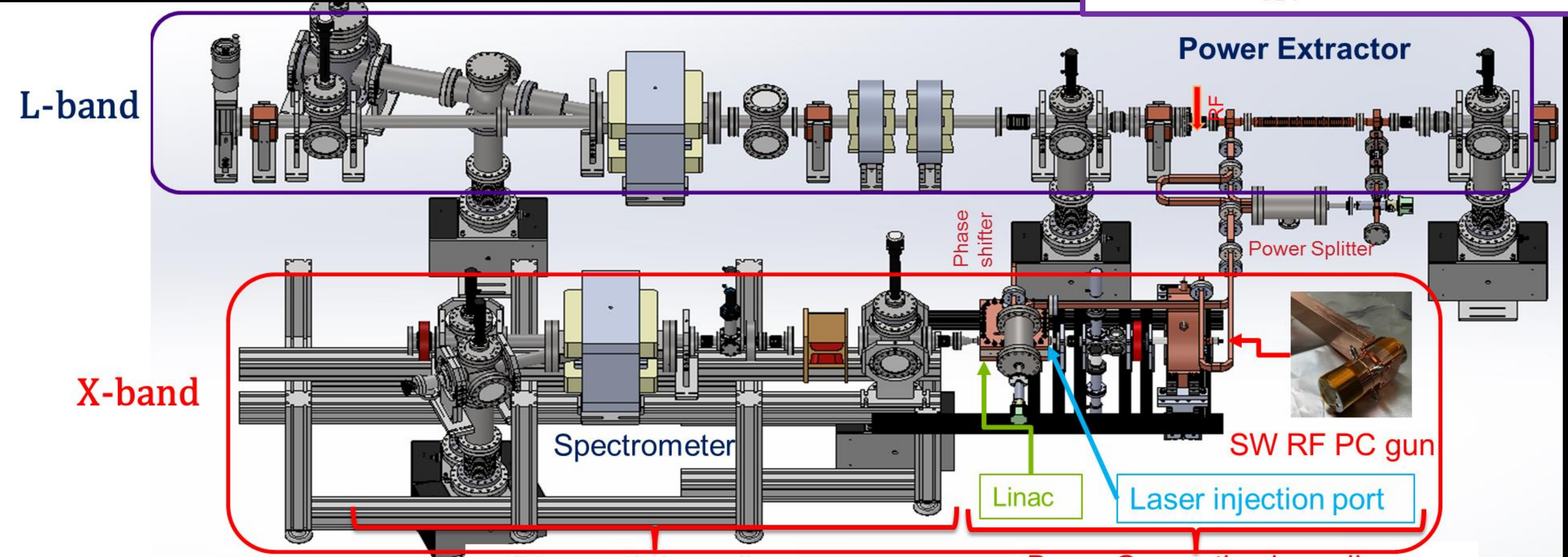
400 MV/m Photocathode Gun – High Gradient Acceleration

High-Gradient X-band PC gun accelerate photoelectrons

- Gun performance
  - 387 MV/m on the photocathode
  - BDR ~4e-6 (estimated)
  - Ultra low dark current (<1pC per RF pulse)
- First beam! (initial characterization)
  - 100 pC @ 3 MeV







- Next Step

Building complete X-band beamlines operating in short-pulse regime

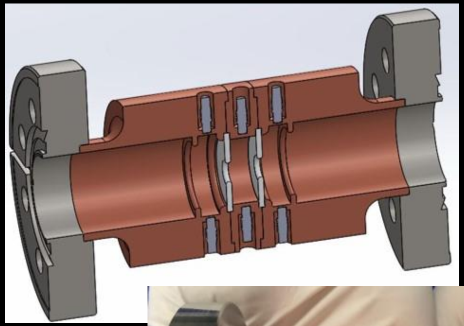
100 MV/m Dielectric Disk Accelerator

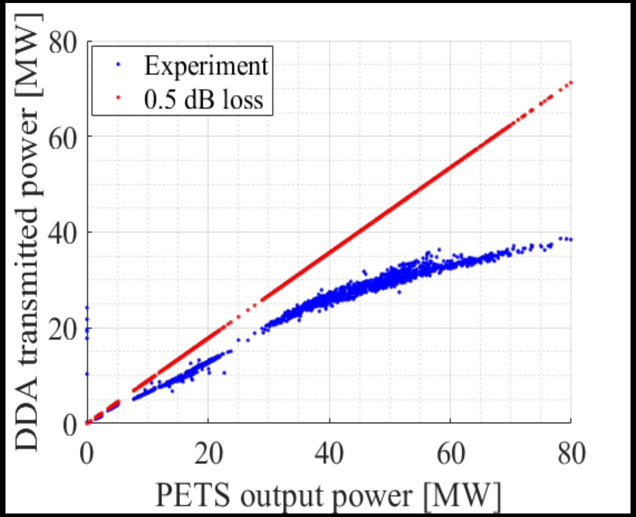
High Gradient Acceleration

Talk: Ben Freemire (Thursday)

Brazed Single-Cell DDA

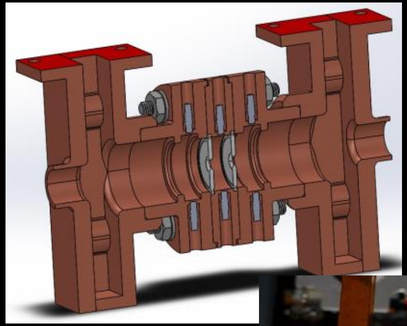
- High Power Test
  - Significant multipacting observed
  - Significant breakdown observed
  - 80 MW achieved (400 MW goal)
- Post-mortem inspection revealed field enhancement problem at triple junction

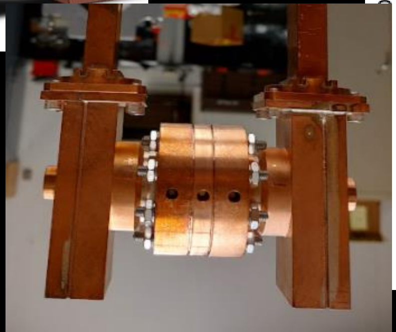


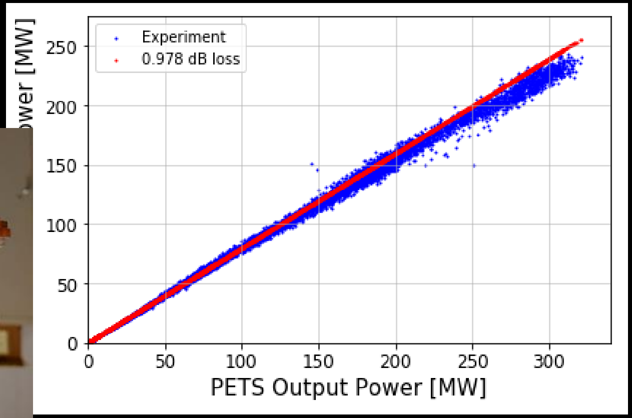


Clamped Single-Cell DDA

- Special attention to triple junction design
- Not brazed to simplify physics & engineering
- High Power Test
  - 100 MV/m DDA (beam limited)
  - First dielectric structure not limited by multipactor at high-gradient







100 MV/m Dielectric Disk Accelerator

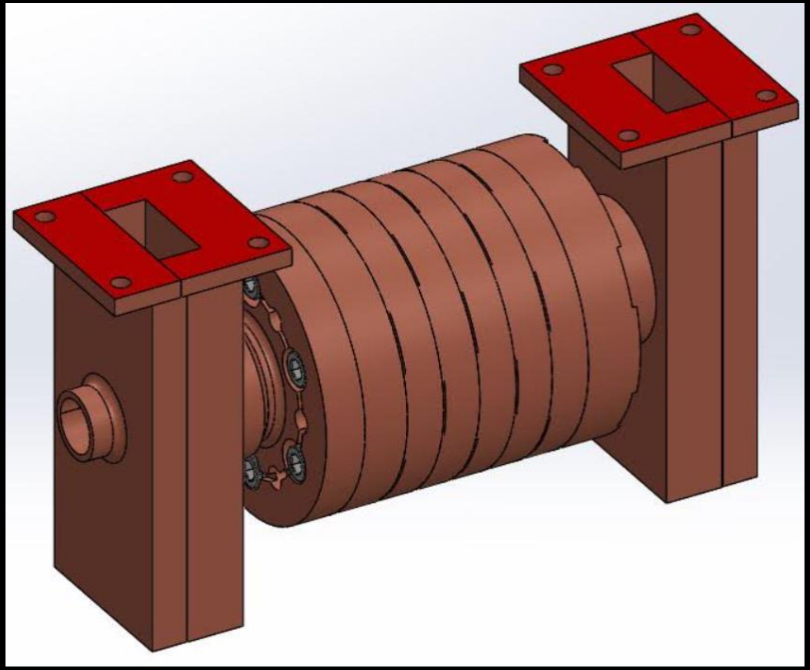
High Gradient Acceleration

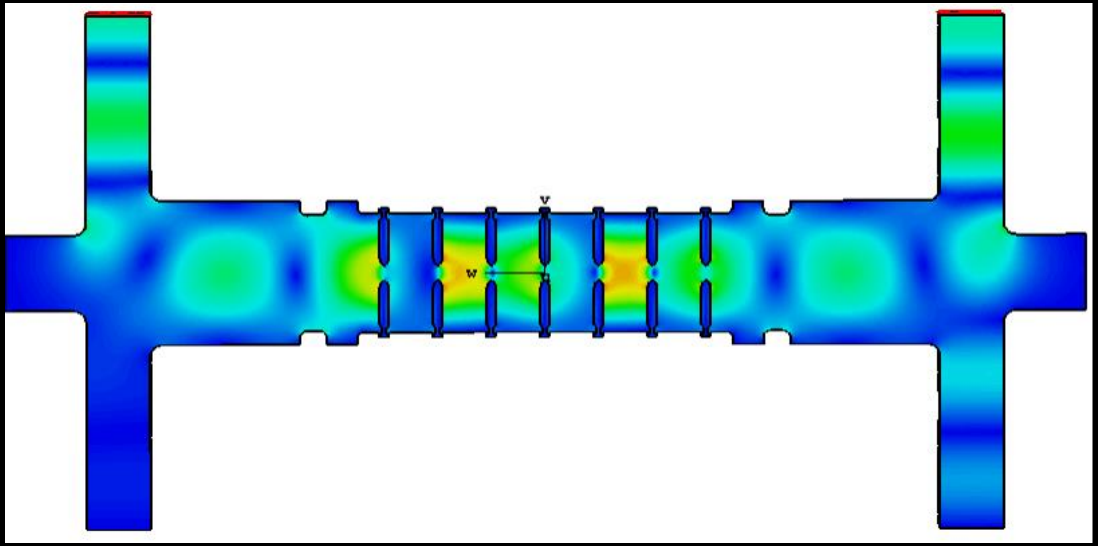
Euclid TechLabs · Illinois Tech

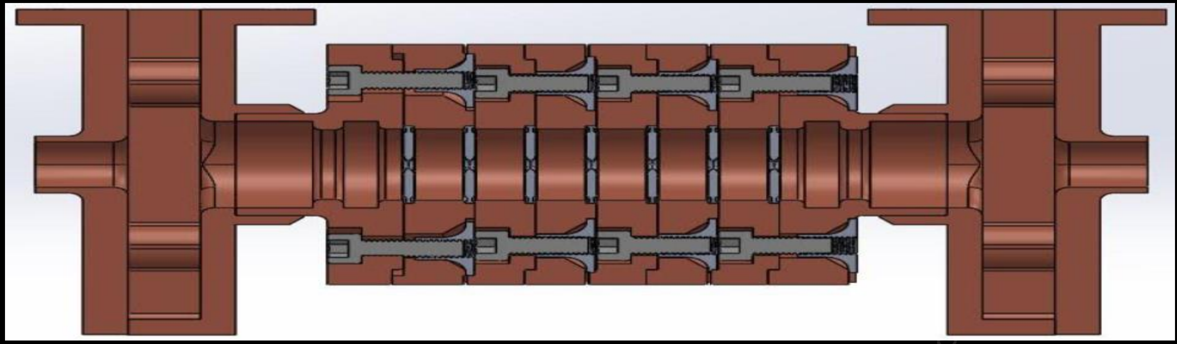
Next step: Multicell DDA

- Clamped model, like single cell prototype.
- RF geometry is complete; fabrication will begin soon.

Poster: Sarah Weatherly (Thursday)





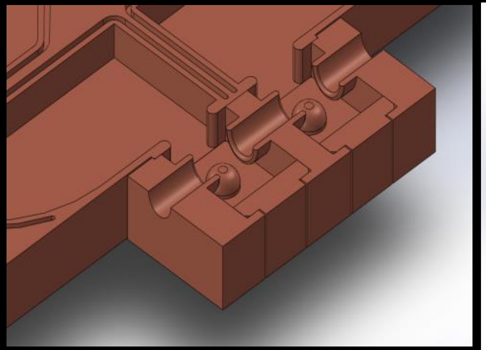


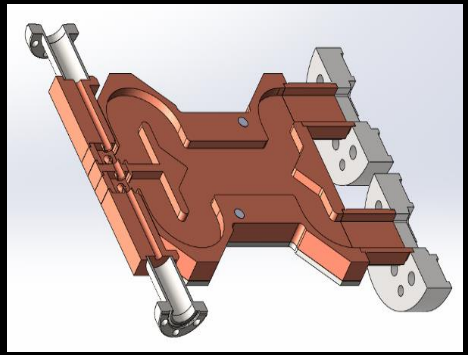
X-band Deflector – New Directions

Deflector based Bunch-Shaping

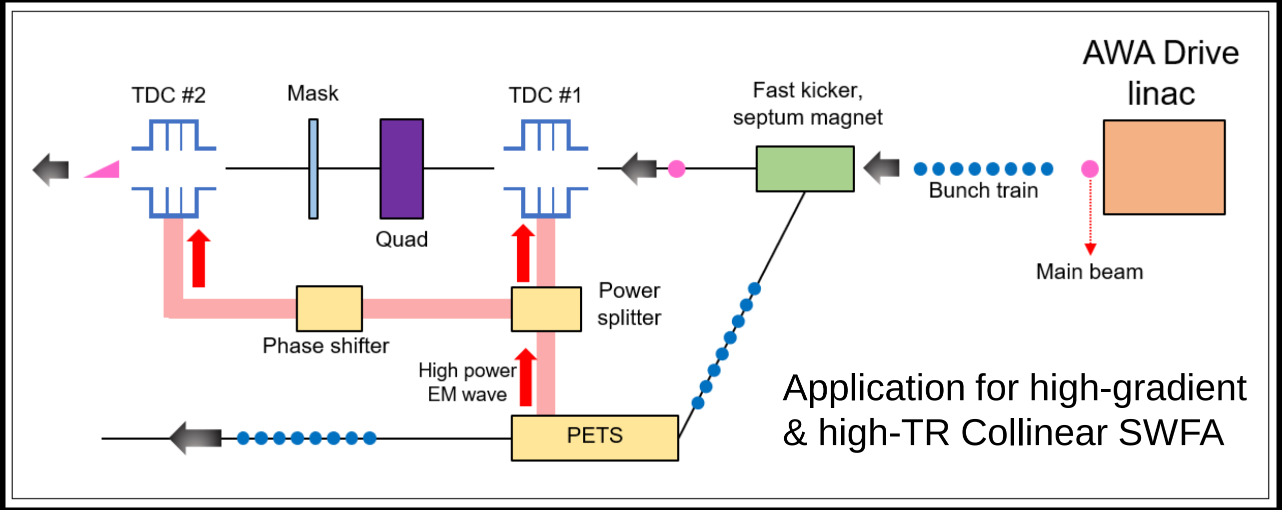
Poster: Chunguang Jing (Tuesday)

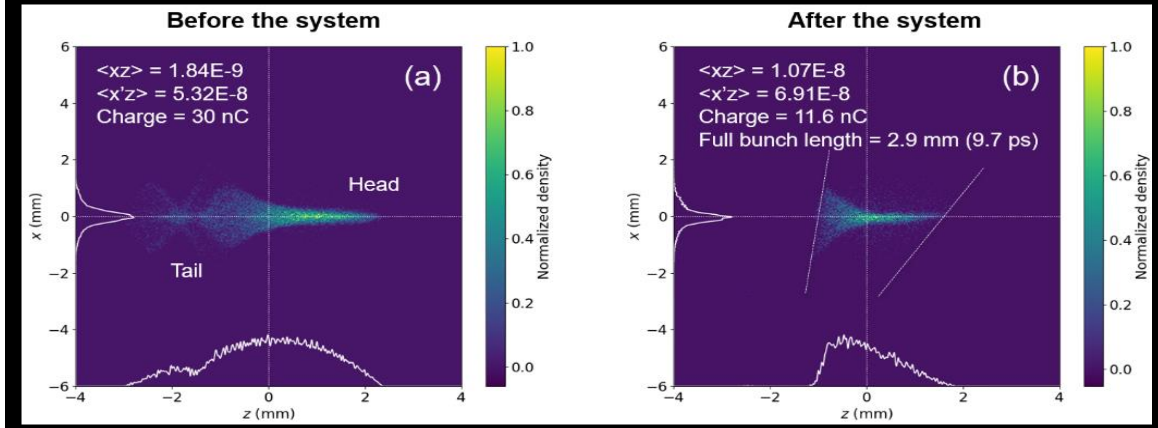
- **100MV/m** → RF conditioned the first high-gradient, short-pulse deflector





- Deflector-based bunch shaping beamline (CSR free)

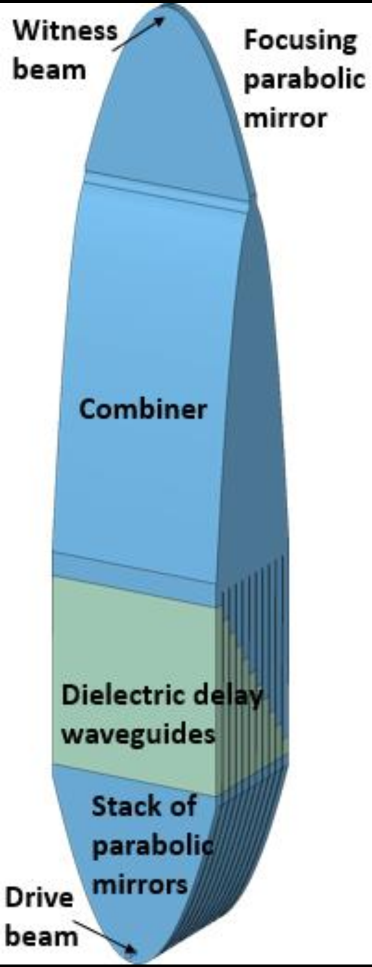




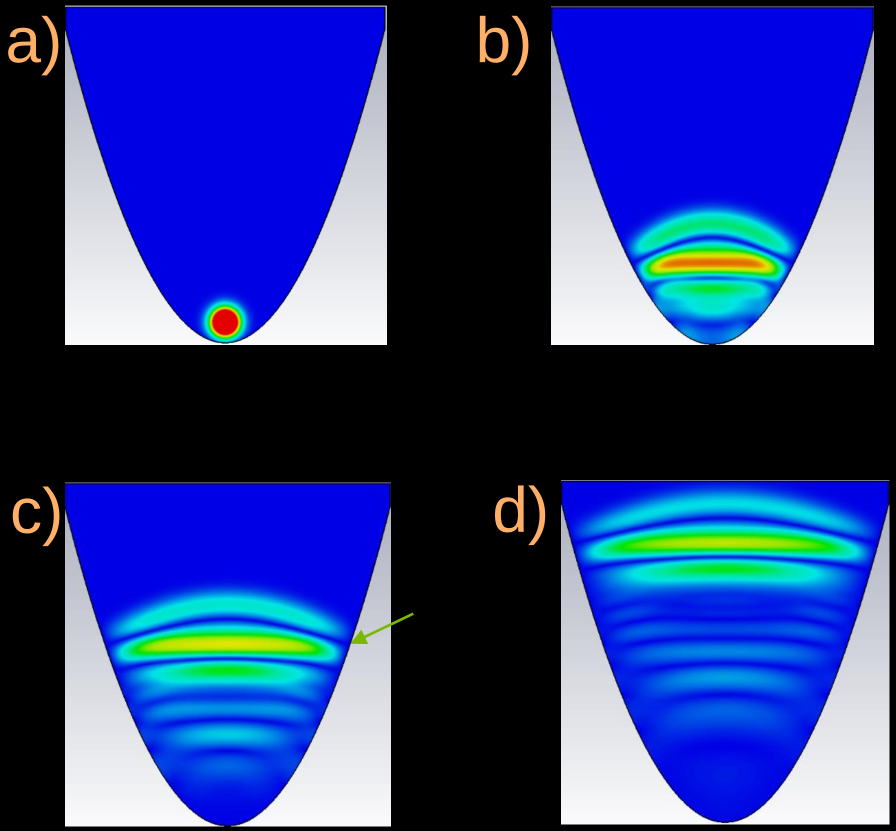
Single-Cycle Structure – New Directions

Single-Cycle Accelerating Structure

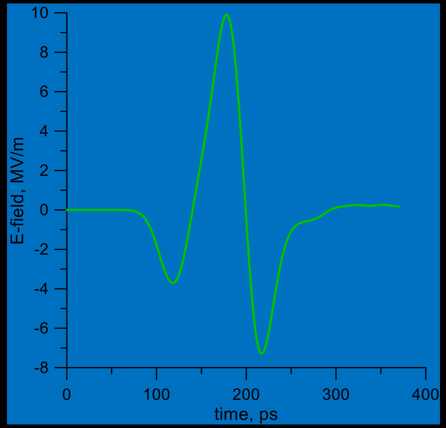
Poster: Sergey Kuzikov (Wednesday)



Single-cycle acceleration cell.



Excitation of a single-cycle wake in a gap with a parabolic shape. Time flows evenly as a-b-c-d.



Shape of the single-cycle wake

SUMMARY

SHORT-PULSE REGIME

- Exploring breakdown physics on short time scales (1-100ns)
- Progress
  - 565 MW metamaterial power extractor
  - 300 MV/m X-band TW accelerating structure
  - 400 MV/m X-band SW photocathode gun
  - 100 MV/m dielectric disk accelerator
  - 100 MV/m X-band transverse deflector
- Next Steps
  - Single cycle accelerators, higher frequency,
  - Integration → short pulse accelerating beamlines

STRENGTHEN COLLABORATION BETWEEN *SWFA* AND *HG* COMMUNITIES

- short-pulse RF offers a promising path to high-gradient acceleration

THANKS TO SWFA GLOBAL COMMUNITY