AAC'22 Advanced Accelerator Concepts Workshop
November 6 - 11, 2022
Hyatt Regency Long Island, NY

WG3
Laser and High-Gradient Structure-Based Acceleration
Summary Presentation

Conveners: Sergey Belomestnykh (FNAL), Xueying Lu (Northern Illinois University)

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IEEE CSC
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WG3

The purpose of Working Group 3 is to **discuss recent advances in externally-powered structure-based accelerators, both laser and rf driven**. The capability to accelerate particles at higher accelerating gradients and efficiencies is essential for reduction of size and cost of future accelerators for science and industry. This includes the future multi-TeV e+e- collider for High Energy Physics, free-electron lasers (FELs) for Basic Energy Sciences and National Security, industrial accelerators for Energy and Environmental Applications, and accelerators for other applications (direct material investigation, medical field, nanotechnology, etc.).

The working group welcomes presentations on the following topics:

- **Recent developments in novel accelerating structures with new geometries**, new materials (dielectric, metamaterial, hybrid, etc.), new fabrication technologies (additive manufacturing, micromachining, etc.), frequencies from microwave to THz and optical spectrum, and operating conditions from normal conducting to cryogenic and superconducting.
- **Recent advances in understanding rf breakdown** and quench phenomena at different frequencies and materials, and other physics limitations to the accelerating gradient.
- **Recent advances in improving the accelerating efficiency**, such as understanding of sources of microwave dissipation and pathways, development of ultra-low rf loss material, heavy beam-loading compensation.
- **Demonstration of high accelerating gradients and efficiencies**.

The group will also try to address specific issues such as novel structure-beam interaction schemes (IFEL, undulator-mediated, etc.), high efficiency electromagnetic power source development, optimizing novel accelerating structures using advanced algorithms, beam dynamics and collective effects associated with reduced beam apertures, optimizing power coupling schemes to the structures, increasing wall-plug-to-beam efficiency, and integrated particle source designs.

WG3 submissions and summary outline

- 2 plenary talks
- 17 presentation in 6 WG sessions (one joint session with WG5)
- 2 student posters
- 5 contributed posters

Topics covered in WG3 sessions:

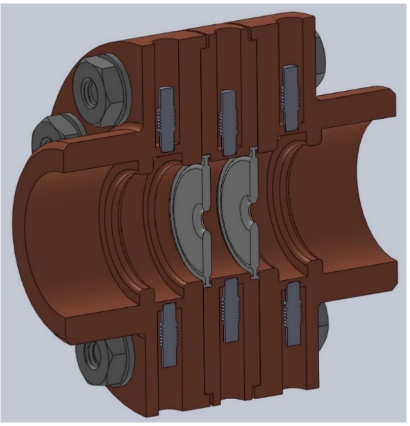
- High-gradient radio frequency structures & RF sources (10)
- Joint session with WG5 on injectors (2+1)
- Laser / THz structures (4)
- Plasmonic wakes in a semiconductor (1)

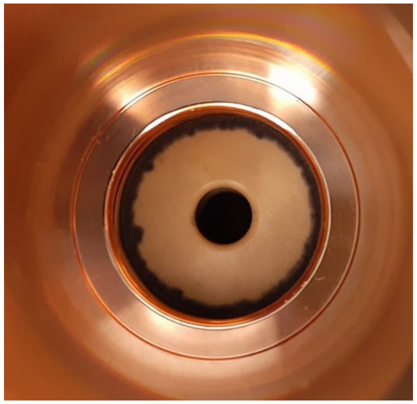
High-gradient radio frequency structures

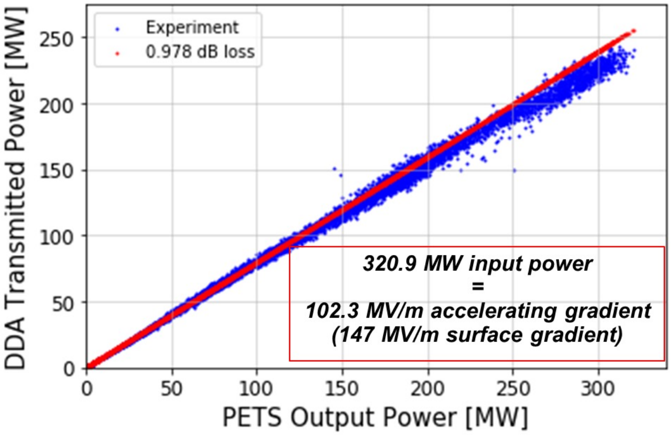
1. DDA structures and dielectric properties
2. High-gradient copper structures
3. Application of high-gradient structures to proton acceleration
4. RF cavity needs for future Muon Accelerators
5. High efficiency RF sources

High Power Test Results of X-Band Dielectric Accelerating Structures

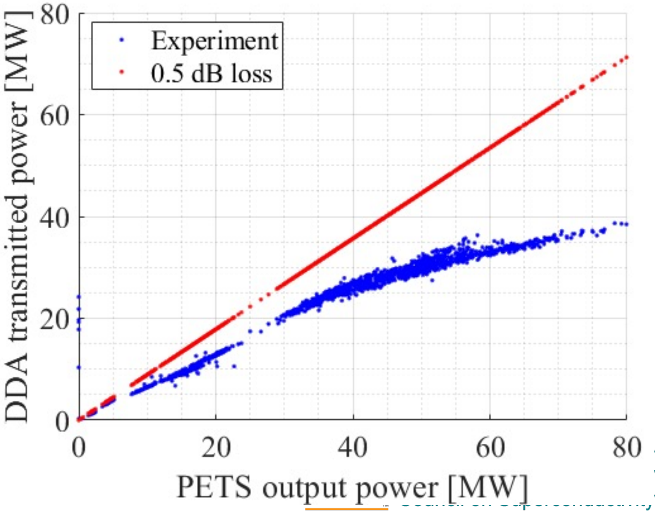
- Two single cell 11.7 GHz dielectric disk structures tested at high power
- Clamped structure reached >100 MV/m accel. grad. (input power limited)
  - No evidence of multipactor or breakdown
- Brazed structure limited by breakdown/multipactor at braze joint (triple junction) caused by field enhancement
- Multi-cell and additional brazed structures in production, to be tested







320.9 MW input power
=
102.3 MV/m accelerating gradient
(147 MV/m surface gradient)

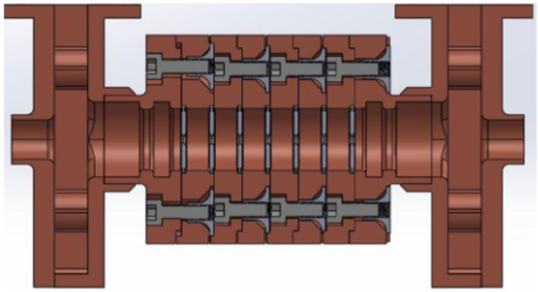


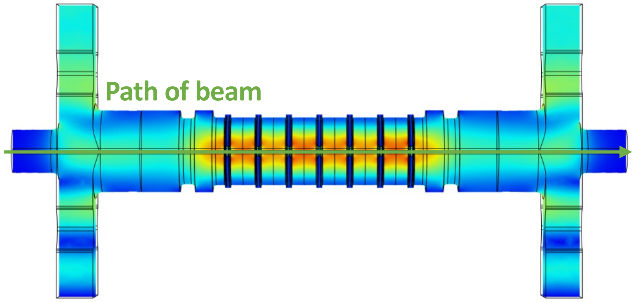
Simulation Results of Dielectric Disk Accelerating Structures

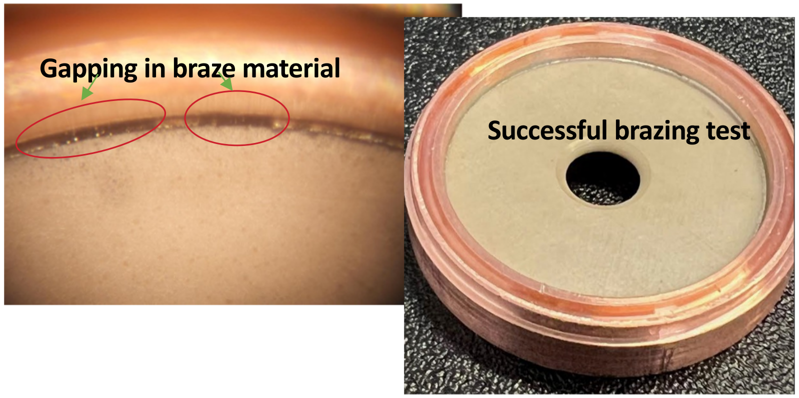
Sarah Weatherly, IIT

- **Dielectric Disk Accelerators** are high gradient accelerator structures with large shunt impedances
- Goals for research
  - Produce large accelerating gradient
  - Test thresholds of materials used in structure

- **New brazed single** cell structure being fabricated
  - Accelerating gradient 150 MV/m
  - Issues with brazing during fabrication
  - High power testing early next year







After successful high power test of single cell clamped structure, a **clamped multicell structure** has been designed, simulated and fabricated

- Accelerating gradient 108 MV/m
- New engineering design for better assembly to avoid damage
- High power testing later this year

Damage from previous high power clamped testing:

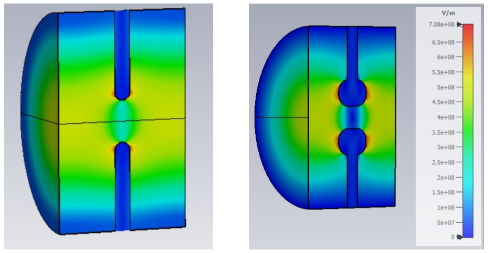
Dielectric Accelerators at Cryogenic Temperature

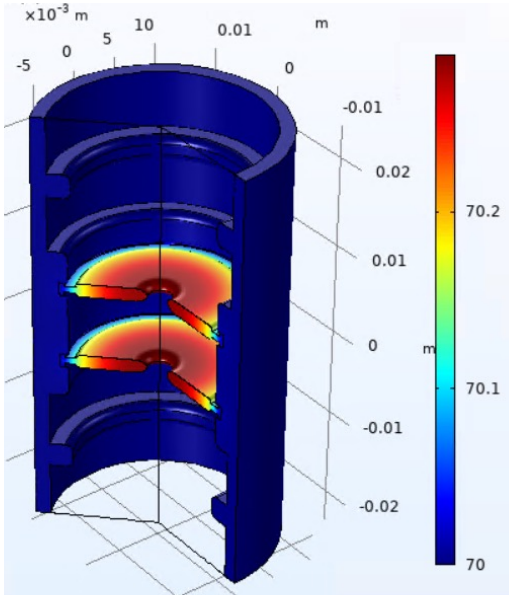
Chunguang Jing, Euclid Techlabs,LLC

- Dielectric accelerator shows surprisingly high shunt impedance at cryogenic temperatures.
- Challenges remain as in conventional dielectric accelerators, i.e., breakdowns due to variety of micro gaps.
- Worth to explore. The first step is to characterize different dielectric materials at low temperature.

Structure (X-band)	Temp, K	aperture	epsilon	R_{sh}, MΩ/m
DDA (dielectric disk accelerator)	300	2.6	50	181
DDA	77	2.6	50	463
DDA with 2 mm nose, $E_s/E_a = 2.5$	77	2.6	50	550

Note: Room temperature copper conductivity 5.8E7 S/m, cryogenic conductivity is 3e7 S/m; Dielectric loss at room temperature is 1e-4, at cryogenic temperatures is 3e-6.



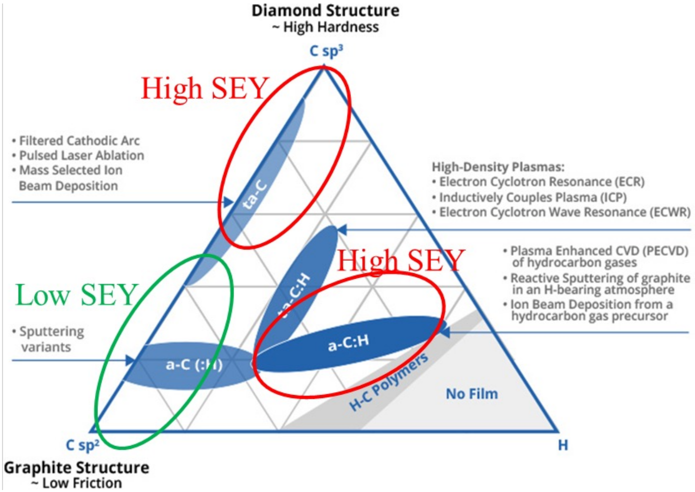


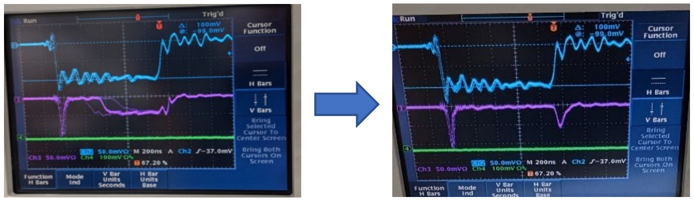
The thermal simulation of the X-band DCA prototype under 100 MV/m of gradient and 28 W of heat load.

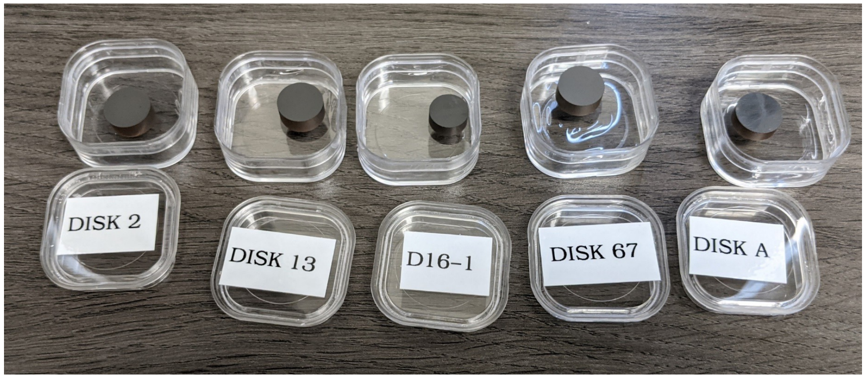
Evaluation of Multipactor Suppression in Dielectric Accelerators by DLC Coating

Chunguang Jing, Euclid Beamlabs, LLC

- Solving multipactor using the approach of Split DLA and DLC coating is promising. It reduces the SEY. And it has either no impact on or slightly improved loss tangent on the coated ceramics. This may be an ultimate solution.
- RF breakdowns currently limits the final demonstration.
- If success, it will be a game changer for ultracompact linac for industrial applications.







Short Pulse High Gradient Accelerating Structures

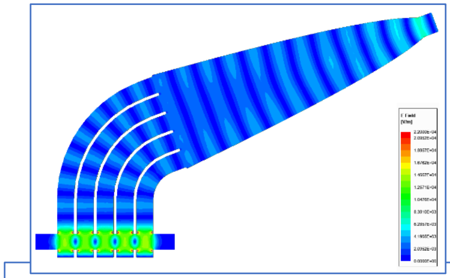
S. Kuzikov – Euclid Techlabs

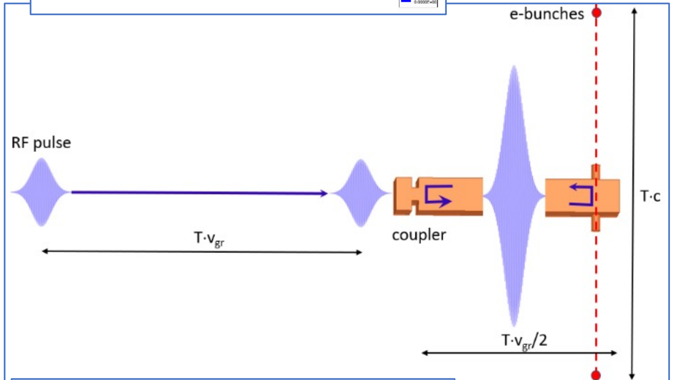
- Short-pulse structures show prospects to achieve ~GV/m gradients. Such structures can have high RF-to-beam efficiencies that are comparable with efficiencies of classical long pulse structures.

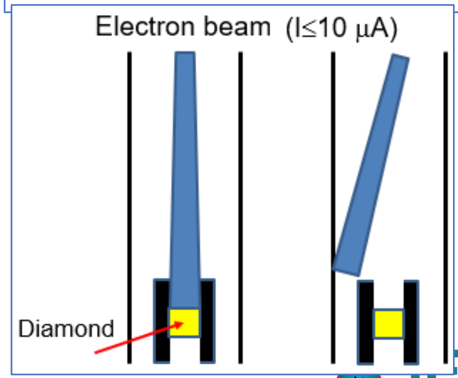
- Estimations show that the lifetime of short pulse structures in presence of occasional breakdown events is scaled as
$$N_{LT} \sim \frac{1}{\tau^{11/15}}$$

- High repetition rate (MHz or sub-GHz), short pulse RF sources are necessary. For sources based on Q-switching effect we propose RF switches based on electron induced conductivity in diamond.

- The synergistic effect of short pulse technology and cryogenic technology would allow reaching world record gradients.





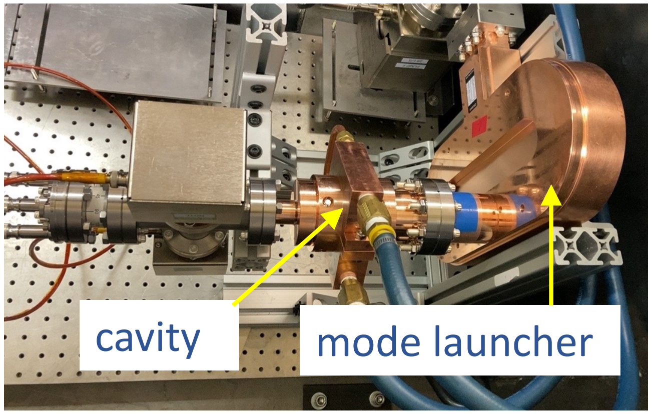


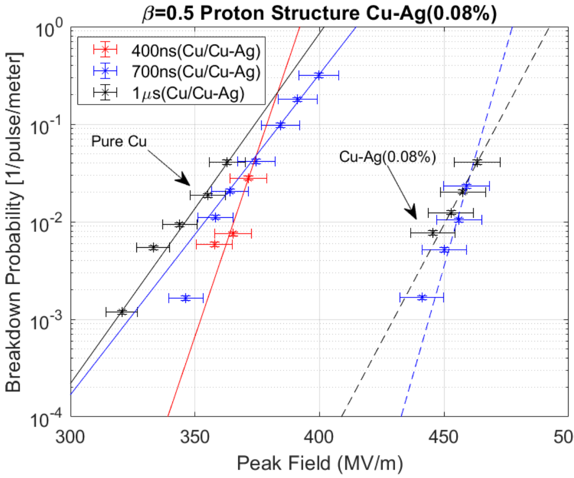
LANL C-band Engineering Research Facility (CERF-NM)

E. Simakov – LANL

CERF-NM was built with $3M of LANL's internal infrastructure investment.

- Powered with a C-band Canon klystron
- Conditioned to 50 MW
- Frequency 5.712 GHz
- 300 ns – 1 µs pulse length
- Rep rate up to 200 Hz (typical 100 Hz)
- Nominal bandwidth 5.707-5.717 GHz





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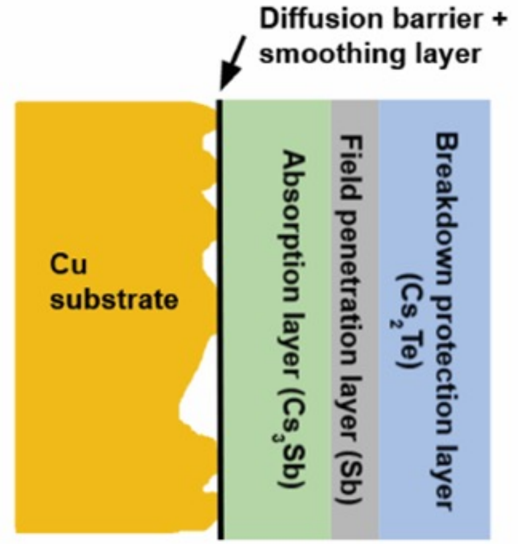
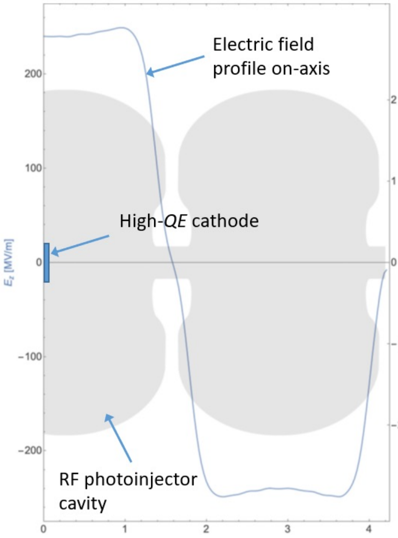
CARIE: Cathodes And Rf Interactions In Extremes

E. Simakov – LANL

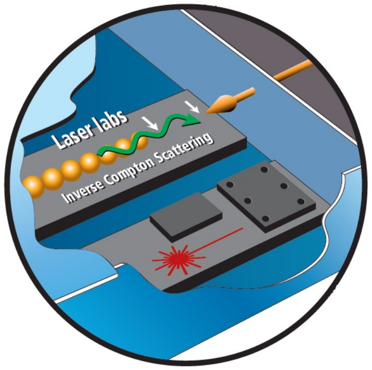
A new three-year project was funded at LANL to demonstrate operation of high-quantum-efficiency cathodes in a high-gradient RF injector.

- Project builds upon LANL's expertise in high-gradient C-band and high-QE photocathodes.
- The proposed heterostructured cathode will include multiple layers to ensure atomic flatness of the surface, high QE, and the ability to withstand high electric fields with no breakdown.





- Target beam parameters: 250 pC, 0.1 μm*rad, $B_{5D} = 10^{16}$ A/m^2.



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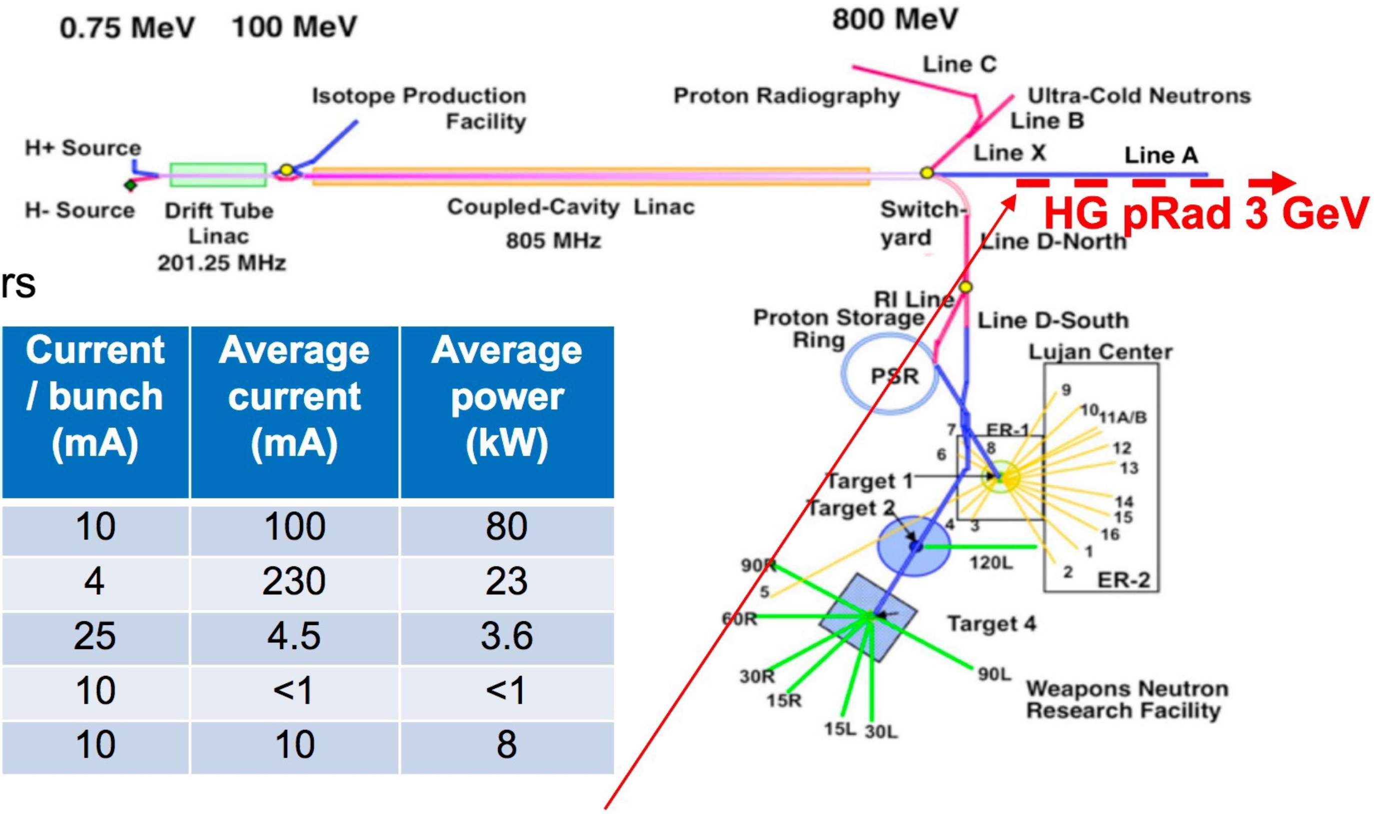
High-Gradient 3-GeV Booster for Enhanced Proton Radiography at LANSCE

Yuri Batygin and Sergey Kurennoy, Los Alamos National Laboratory, NM 87545, USA



LANSCE Beam Parameters

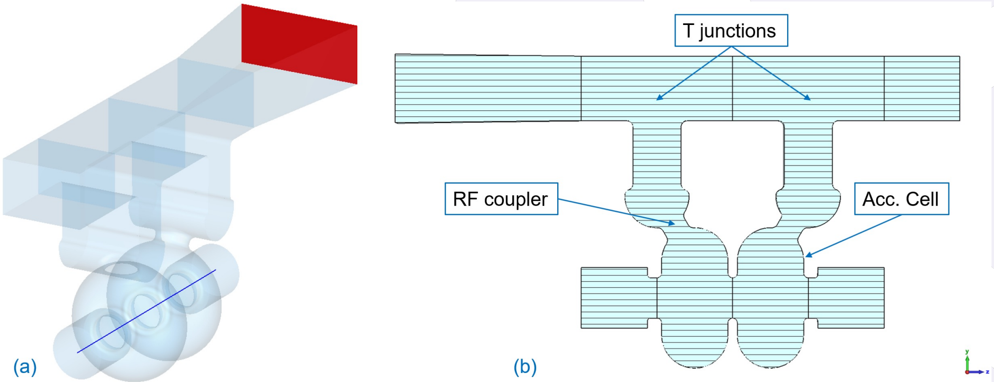
Area	Rep. Rate (Hz)	Pulse Length (ms)	Current / bunch (mA)	Average current (mA)	Average power (kW)
Lujan	20	625	10	100	80
IPF	100	625	4	230	23
WNR	100	625	25	4.5	3.6
pRad	1	625	10	<1	<1
UCN	20	625	10	10	8

Potential Location of High-Gradient pRad booster to 3 GeV at LANSCE

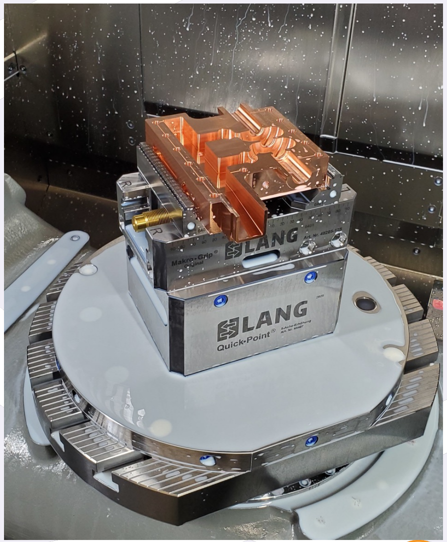
HG Structures for 3-GeV Proton Radiography Booster

S. Kurennoy, Y. Batygin, and E. Olivas, LANL

- High-gradient (HG) booster linac for proton radiography (pRad) is designed to increase the beam energy from 800 MeV to 3 GeV. HG normal-conducting cavities will work since pRad needs very short beam pulses at low duty.
- We are developing standing-wave π-mode S- and C-band structures with distributed RF coupling for protons with β = 0.84-0.97 (800 MeV to 3 GeV).
- Short 2-cell C-band test cavity for β = 0.93 was designed for 5.712 GHz. It is delivered to LANL and will be tested soon at the C-band RF test stand.



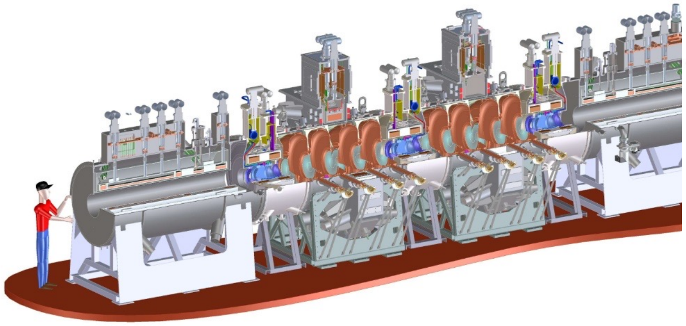
2-cell π-mode test cavity for β = 0.93 (1.6-GeV protons): inner vacuum volume with standard WG187 port (red).

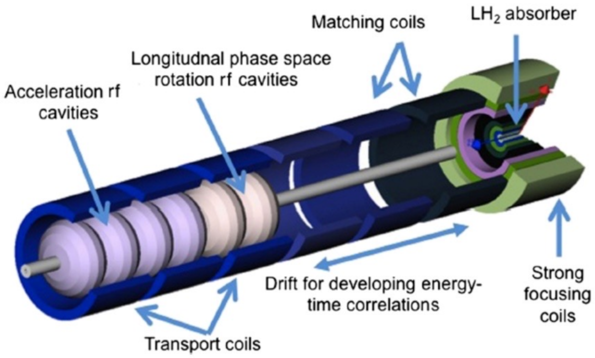


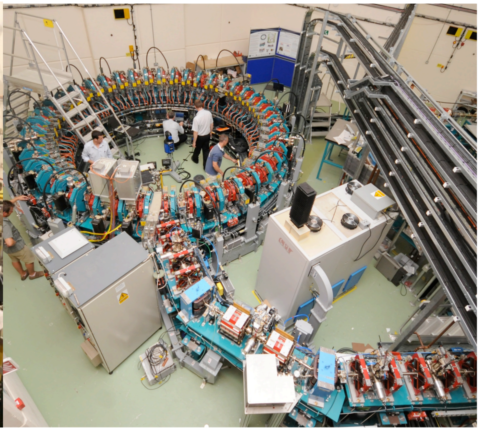
RF Cavity Needs for Future Muon Accelerators

B. Freemire – Euclid Beamlabs

- Significant R&D has been done for many critical systems:
  - Proton driver, target system, beam cooling & acceleration, collider ring
- Technology largely demonstrated for Neutrino or Higgs Factories
- Cooling channel & acceleration designs for multi-TeV collider need additional development
  - Experimental demonstration is critical
- Benefits of cold copper cavities, short RF pulses, travelling wave SRF cavities, unconventional cavity materials… could significantly advance feasibility







CCR Calabazas Creek Research, Inc.

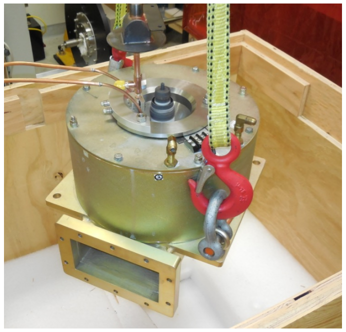
High efficiency RF source development

L. Ives – Calabazas Creek Research

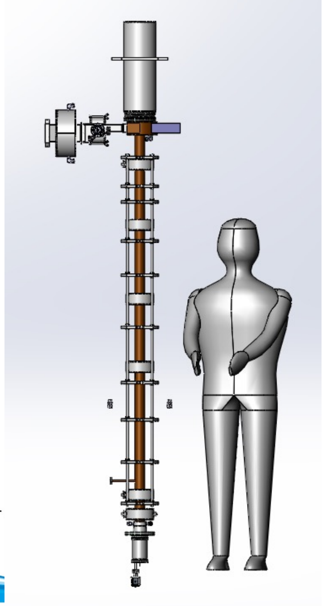
RF system is one of the major cost drivers (both capital and operations) for accelerator projects – **developing high-efficiency, low-cost RF sources becomes more and more important**. The company is developing several new RF sources:

- **Magnetron** System: 100 kW (10 kW ave.), 1.3 GHz Amp/Phase Control, 80+% efficiency, $1/Watt – Completed
- **High Efficiency Klystron**: 100 kW CW, 1.3 GHz, 78% (Core Oscillation method), Freq/Pwr Scalable – Test in January 2023
- **Triode**-base RF sources: 200 kW CW, 350–700 MHz, $0.5/Watt, compact – MB Triode in test
- **Multiple Beam IOT**: 700 MHz, 200 CW kW, 80% – Drawings and fabrication in progress, Test in spring 2023

Magnetron

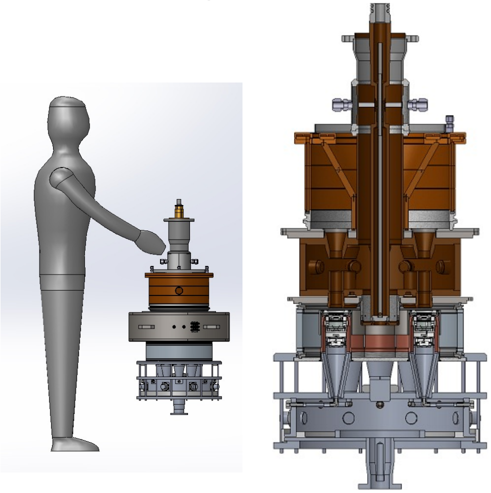


Klystron



Multi-Beam triode

MB IOT



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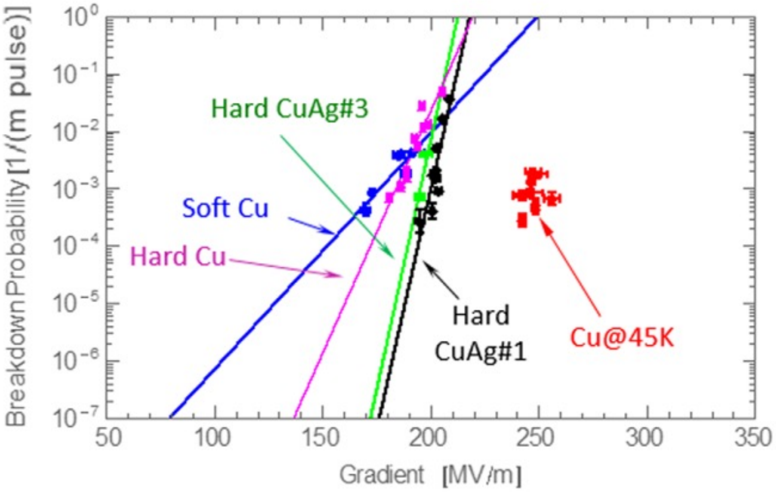
Joint session with WG5 on injectors

Development of High Brightness Photoinjector for AWA

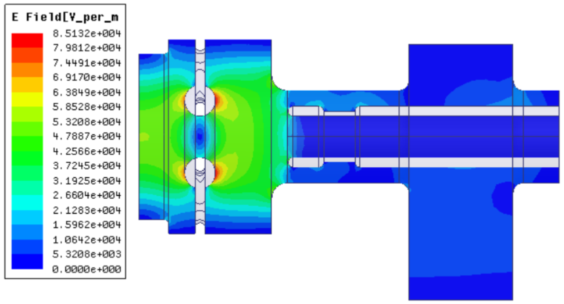
S. Kuzikov – Euclid Techlabs

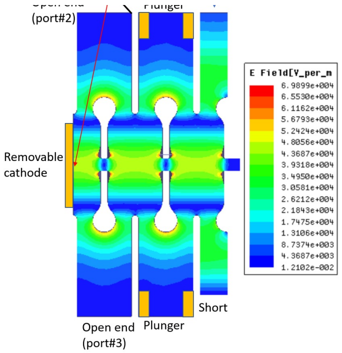
We have plans to modify RF design of the short pulse 11.7 GHz photoinjector at AWA to increase gradient and energy gain and to improve compatibility with the solenoid.

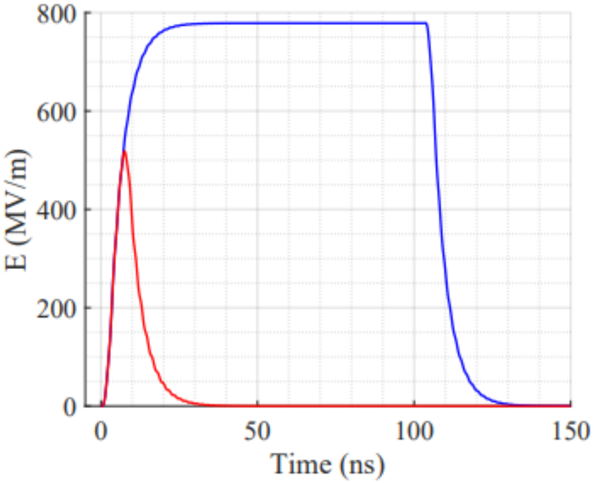
Breakdown rate vs gradient [1]



[1] A. D. Cahill et al. High gradient experiments with X-band cryogenic copper accelerating cavities, 2018.







Cathode gradient when driven by long (blue) and short (red) pulses. The power is 300 MW and the rising/falling is fixed at 3 ns.

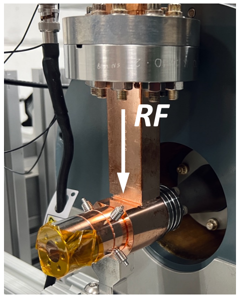
At 45 K for the 11.7 GHz gun the cathode gradient could be as high as more than **500 MV/m**, maximum surface electric field might be as high as **750 MV/m**. The BDR ~10^{-6} is expected.

X-Band high-gradient Photoinjector

Gongxiaohui Chen, ANL

Highlights

Xgun RF Conditioning

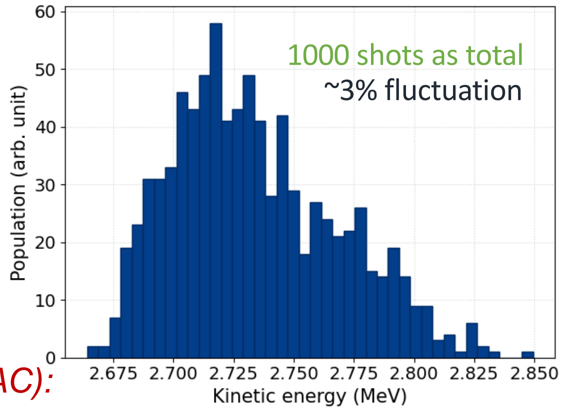


- Short rf pulse operation (9 ns).
- Xgun fully conditioned within **70k pulses.**
- Gradient reached **388 MV/m**.
- After fully conditioned, no dark current observed.

Beam Characterization

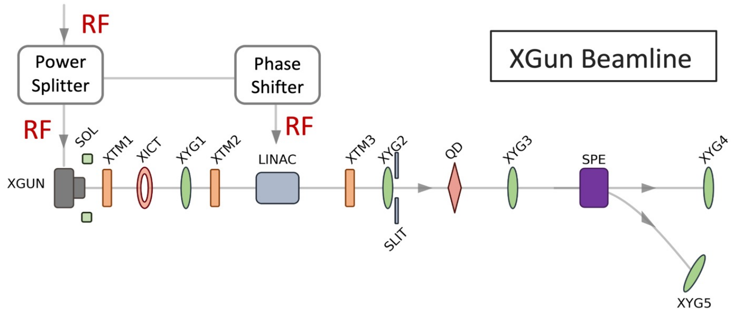
1st beam test (Xgun only):

- Energy was measured by the spectrometer dipole at 340 MV/m.
- Beam energy stability was characterized ~3% fluctuation.



2nd beam test (Xgun and LINAC):

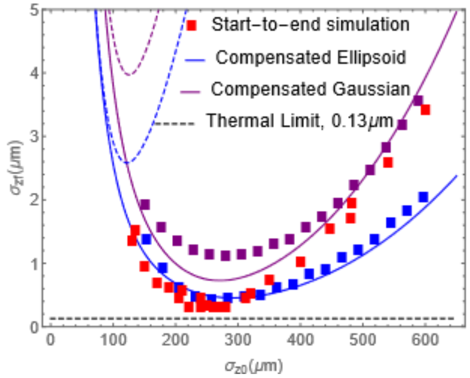
- A LINAC was installed in the beamline
- Total power splits between the Xgun and the LINAC.
- Optimized emittance can achieve **~$0.2\ \mu m$** from the simulation.
- Preliminary emittance was measured by quad scan at relatively low gradient and non-optimized beam conditions:
    - $\varepsilon_{n,x} = 5.58\ \mu m$
    - Kinetic energy: 5.9 MeV
- **Future work:** more studies are planned under LDRD.

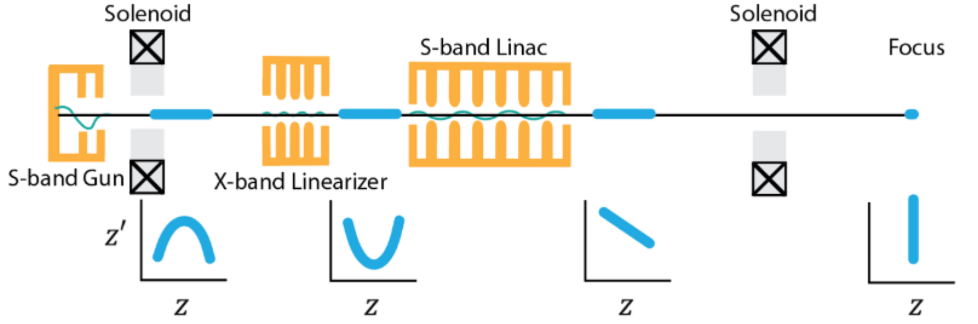


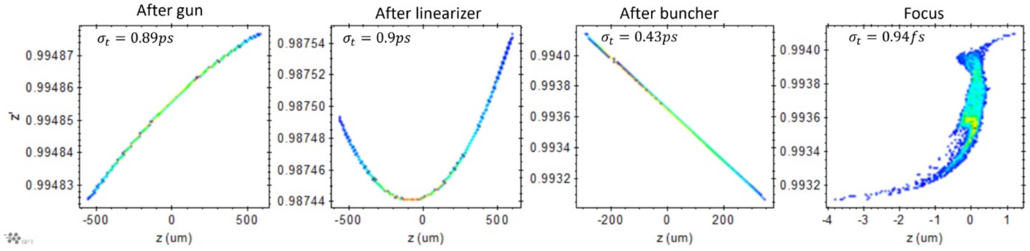
Summary: Ultrashort Beam generation at PEGASUS.

P. Denham, P. Musumeci, UCLA Department of Physics and Astronomy

- Single shot UED temporal resolution determined by the bunch length at ballistic focus.
- Competing non-linear effects limiting the shortest achievable bunch length.
- Overcome non-linearities with laser shaping of electron beam and higher harmonic compensation.
- Bunch lengths in attosecond to sub-fs regime (for 10-100 fC charge) achievable.
- Implemented X-band and took measurements of LPS linearization—reduced energy spread.
- Seeking novel bunch length diagnostic to measure sub-fs bunches. Developments underway.







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Laser / THz structures

THz Generation Summary

Pavle Juranic, PSI

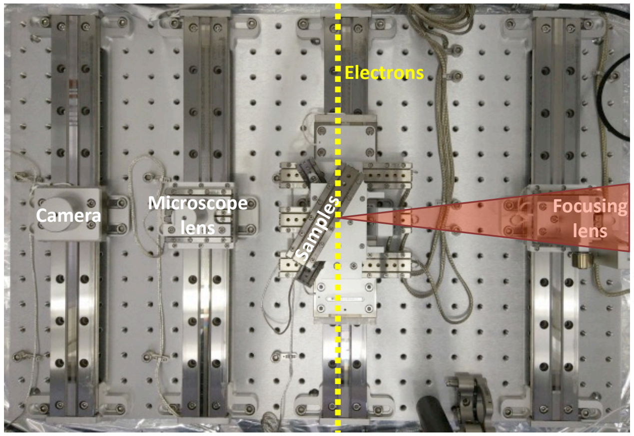
2D results from 3-D printed structure are promising, and we are looking to move the structure to 3D and collect and collimate the THz beam. Observed coherence effect in 2D case.

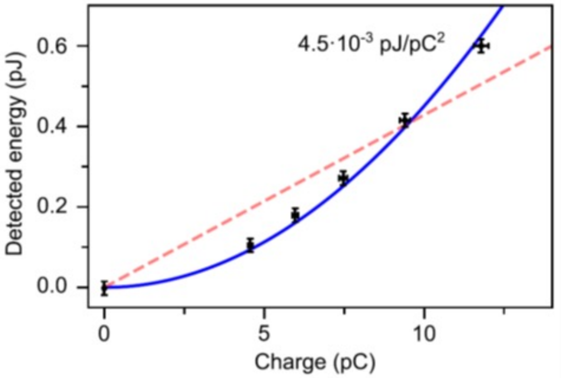
$$\alpha = arc\tan\frac{R}{L} = arc\tan\frac{1}{\beta n}$$

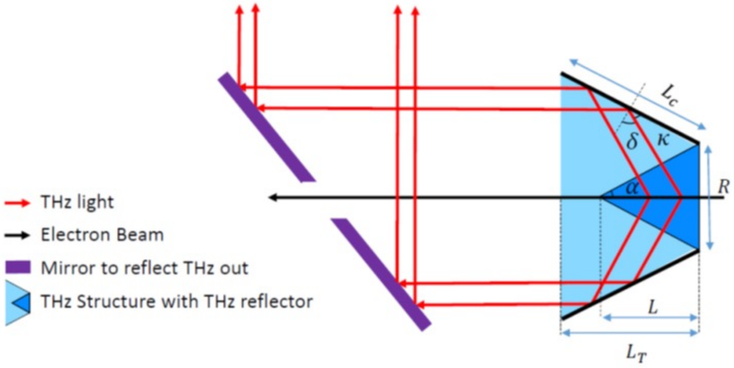
$$\sin\kappa = \frac{\sqrt{R^2 + L^2}}{L_C}$$

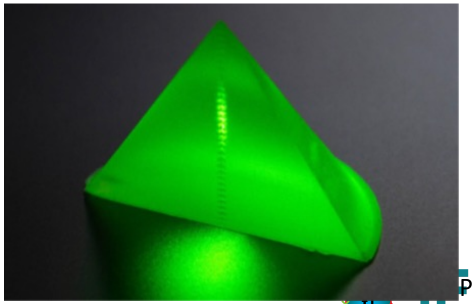
$$L_T = L_C\cos\kappa = \sqrt{R^2 + L^2}\cot\kappa$$

For relativistic electrons in PMMA: $\alpha = 31.56°$, $\kappa = 29.22°$





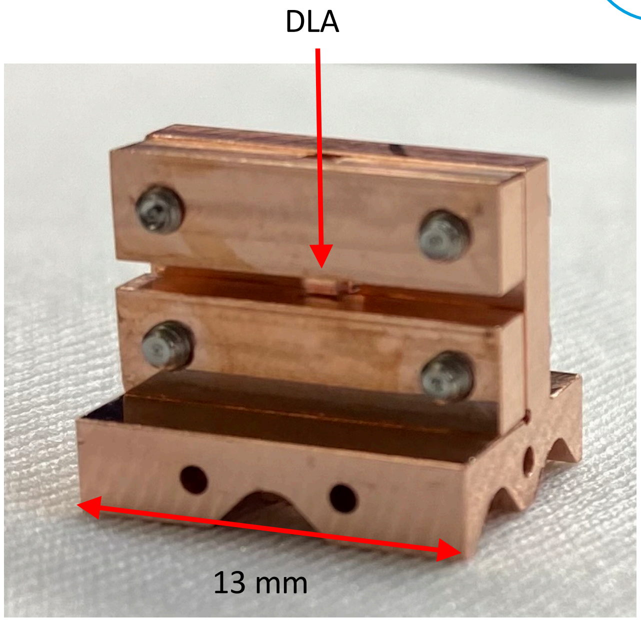




ACHIP@ARES

Willi Kuropka, DESY

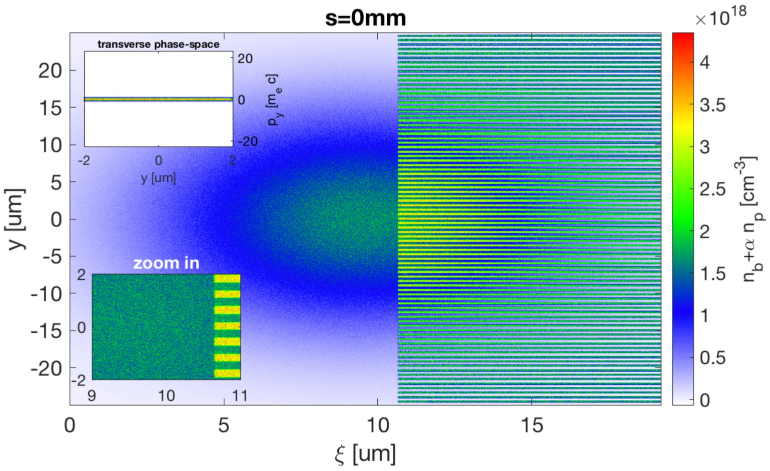
- ARES normal conducting S-band linac commissioning has been successful and continues towards sub-fs bunches
  - Almost all design electron beam parameters demonstrated
  - Comprehensive accelerator R&D program, including external users
  - PolariX transverse deflecting structure commissioning starting Q1 2023
- Dielectric laser acceleration experiment
  - Spatial and temporal overlap of laser and electron beam has been established on dielectric laser accelerator
  - Will be continued in coming months



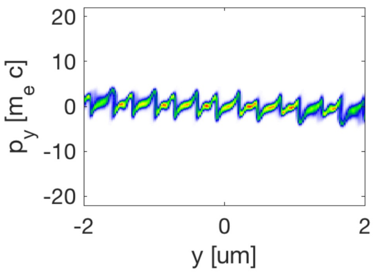
Modulation of dense electron beams in nanostructures: A simulation study in preparation of the FACET-II E-336 experiment

A. Knetsch, Laboratoire d'Optique Appliquée

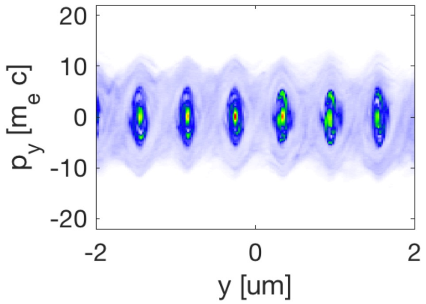
Transverse beamlet formation for beam overfilling nanotube target



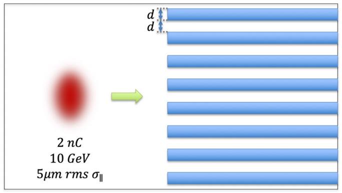
s = 0.5 mm

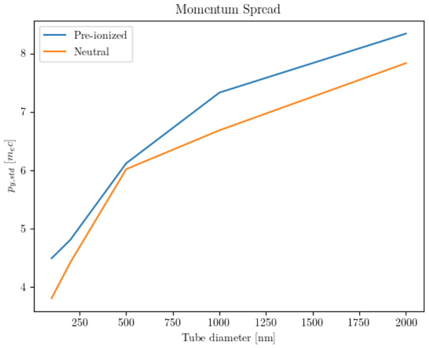


s = 2 mm

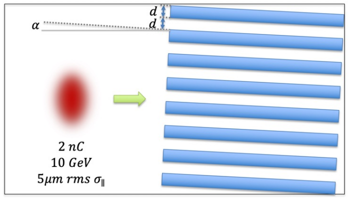


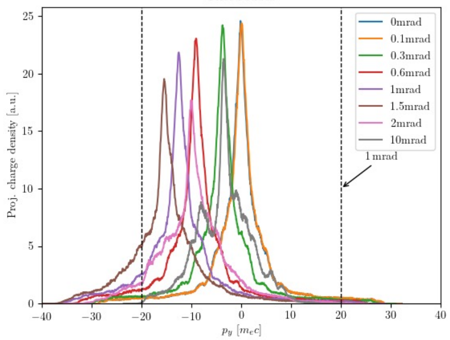
Dependence divergence on nanotube size





Dependence kick on target tilt





See also WG4 presentation
by Robert Ariniello "Wakefield Acceleration in Nanostructures: The E336 Experiment at FACET-II"

Energy Modulation in a Commercial Grating Structure

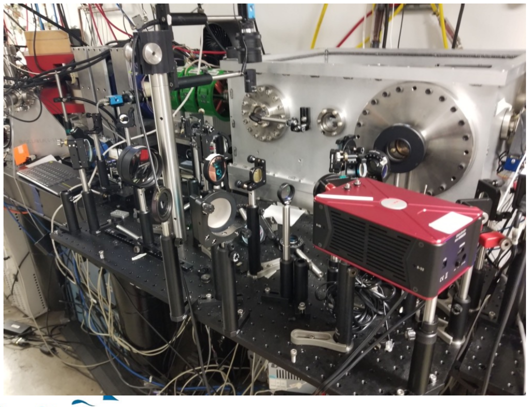
S. Crisp, UCLA

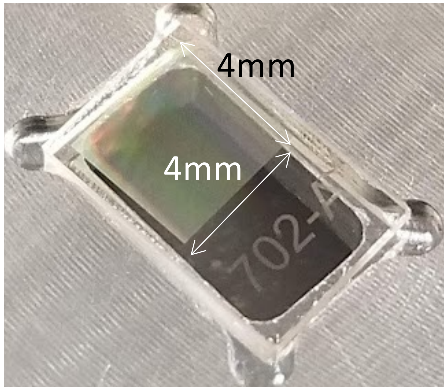
- Commissioned a new optical system combining pulse front tilt with Spatial Light Modulator
- Built and characterized new commercially based structures
- Demonstrated modulation using these commercial structures

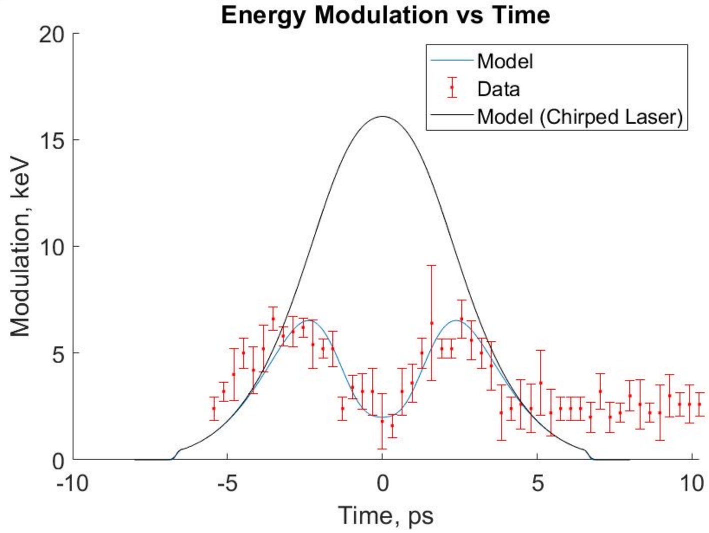
WG3 Student poster award winner

On the way:

  - MeV energy gains via longer interactions lengths
  - Soft tuning utilizing Alternating Phase Focusing







AAC'22 Advanced Accelerator Concepts Workshop
November 6 - 11, 2022
Hyatt Regency Long Island, NY

ACHIP

UCLA

IEEE CSC
Council on Superconductivity

Plasmonic Wakes in a Semiconductor

Tom Katsouleas, Maxime Pindrys

University of Connecticut

Aakash Sahai

University of Colorado, Denver

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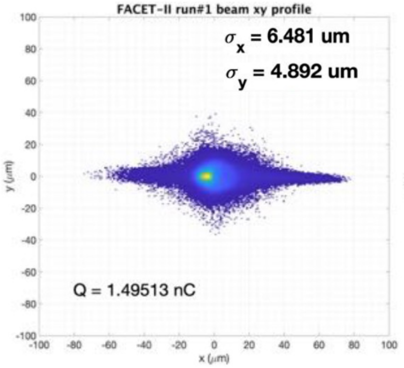
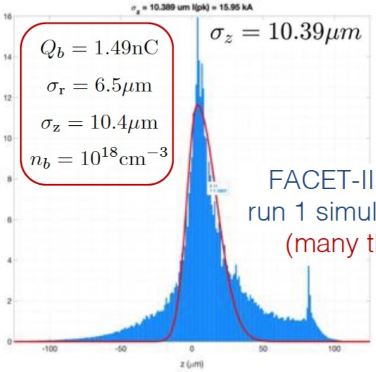
Can the carrier electrons of a doped semiconductor support a plasma-like wakefield?

University of Colorado Denver

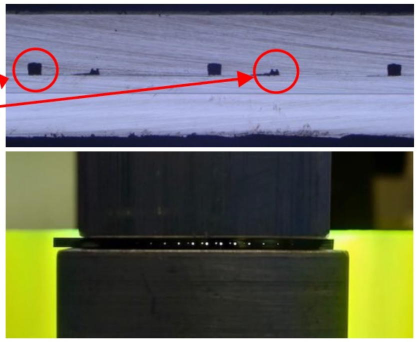
Match with FACET-II





$Q_b = 1.49\mathrm{nC}$
$\sigma_\mathrm{r} = 6.5\mu\mathrm{m}$
$\sigma_\mathrm{z} = 10.4\mu\mathrm{m}$
$n_b = 10^{18}\mathrm{cm}^{-3}$

FACET-II beam phase-space for run 1 simulated using Lucretia code (many thanks to Dr. G. White)



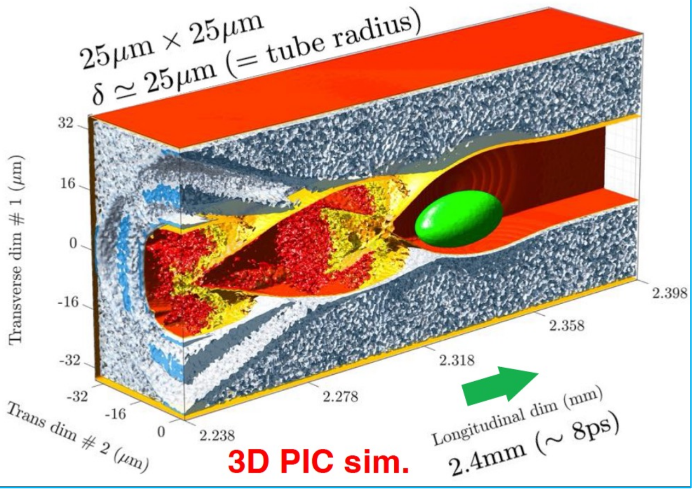
100 and 30 μm rectangular tubes fabricated in Si

MATCH: Plasmon ≈ Beam properties

n-type **P-doped** Silicon
free e⁻ Fermi gas density ~ $10^{18}\mathrm{cm}^{-3}$ **(~ n_b)**

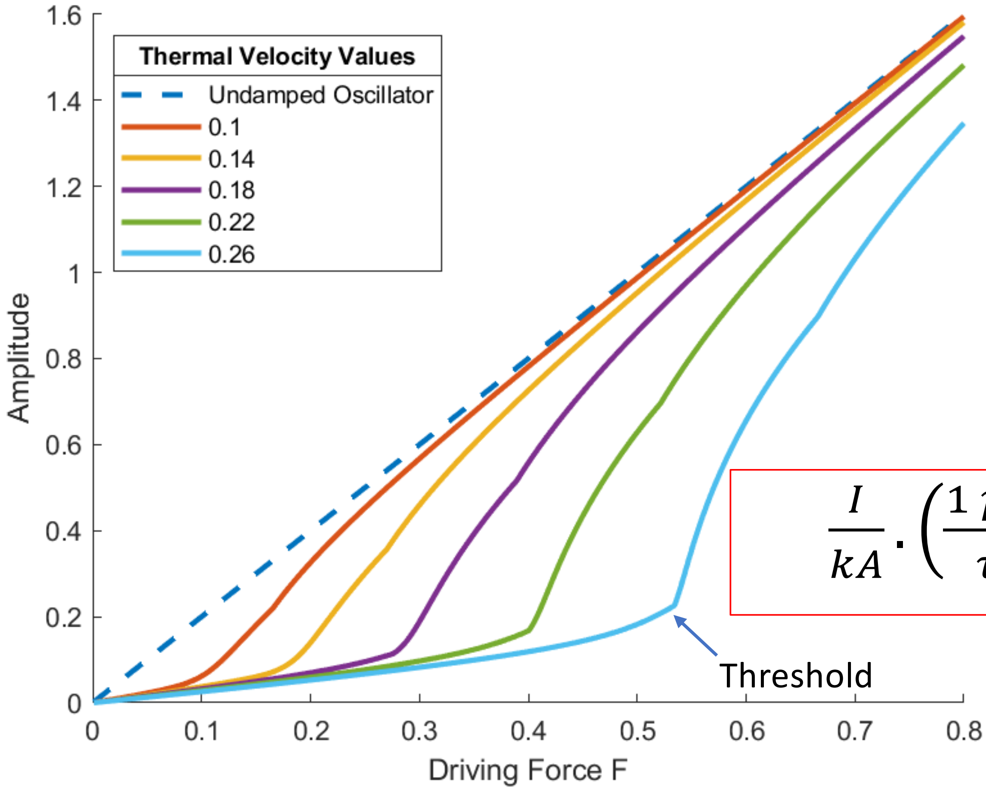
Plasmon wavelength: $\lambda_\mathrm{plasmon}[10^{18}\mathrm{cm}^{-3}] = 33\mu\mathrm{m}$
λ_plasmon ~ **tube dim. ~ 10s of μm**

maximize: beam-plasmon energy exchange



3D PIC sim.

Carrier electrons act like a free plasma if driven above a threshold to overcome Coulomb collisions:



$$\frac{I}{kA} \cdot \left(\frac{1\,ps}{\tau}\right)^{1/3} \cdot \left(\frac{\lambda_{mfp}}{10\,nm}\right)^{1/6} \gtrsim 2$$

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Thank you!