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High Gradients and RF Power Generation at the Argonne Wakefield Accelerator Facility

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High Energy Physics Division

Argonne National Laboratory

APT Seminar – FNAL – 5/22/08

U.S. Department of Energy

UChicago Argonne LLC

Office of Science
U.S. DEPARTMENT OF ENERGY

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Outline

- AWA Group
- Wakefield acceleration concept
- Dielectric wakefield acceleration experiments
- High gradient excitation
- High RF power generation
- Next steps

Accelerator R&D at Argonne National Laboratory
High Energy Physics Division
AWA Group

- Wei Gai
- Sergey Antipov
- Manoel Conde
- Felipe Franchini
- Feng Gao
- Chunguang Jing
- Richard Konecny
- Wanming Liu
- Marwan Rihaoui
- John Power
- Zikri Yusof

Research at the AWA Facility

Advanced Accelerating Structures

Current effort has lead to comprehensive knowledge on construction and testing of dielectric based accelerating structures.

High Power Electron Beam (~ GW) and RF Power Generation

Operating a unique facility to study high current electron beam generation and propagation for efficient beam driven schemes, and high power RF generation.

Fundamental beam physics and advanced diagnostics

High brightness beam generation and propagation, phase space measurements, emittance exchange schemes.

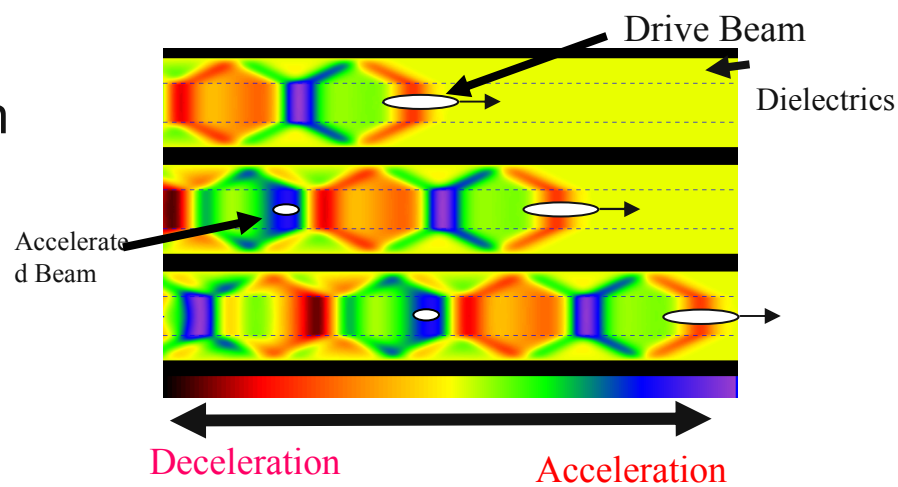
External Users / Collaborators:

- Euclid TechLabs
- U.Chicago
- NIU
- Fermilab
- U.Md.
- IIT
- APS
- Yale/Omega-P

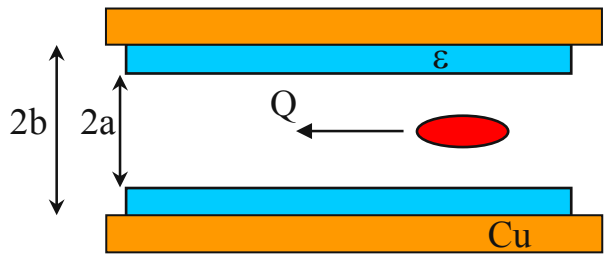
Experiments encompassing Advanced Acceleration Schemes, Fundamental Beam Physics, Astrophysics, Beam Diagnostics and Instrumentation.

Electron Beam Driven Dielectric Wakefield Accelerator

- A high current relativistic electron beam passing through a dielectric structure can generate high gradient field, high power microwaves instantaneously. A new way to power accelerating structures by transporting the power in the electron beam.
- Justifications for looking at dielectric structures:
  - Comparable accelerating properties as metal structures.
  - More material options; possibly higher gradients.
  - Simpler geometry, simpler construction and HOM damping.
- Applications:
  - Collinear wakefield acceleration
  - Two-beam acceleration



Wakefields in Dielectric Structures (a short Gaussian beam)



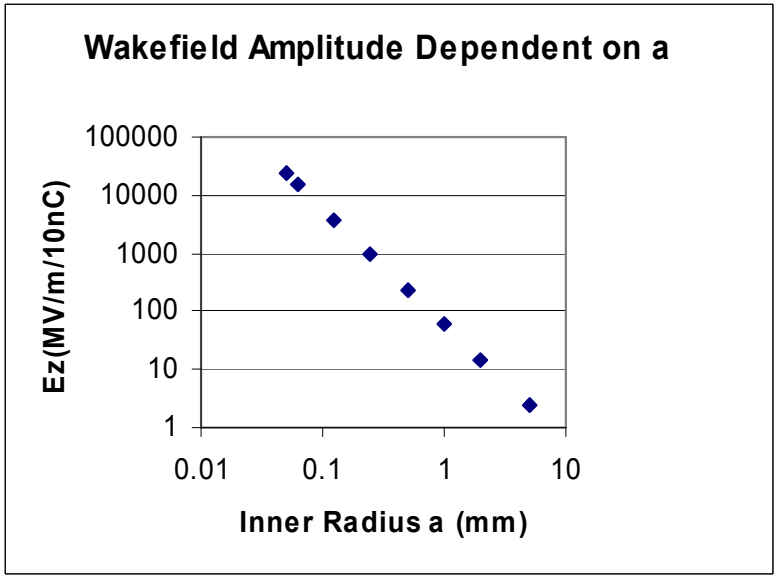
$$W_Z(z) \approx \frac{Q}{a^2} \exp\left[-2\left(\frac{\pi\,\sigma_z}{\lambda_n}\right)^2\right]\cos(kz)$$

$$\sigma_r = \left(\frac{\varepsilon_N}{\gamma}\beta\right)^{1/2}$$

Key to the success:

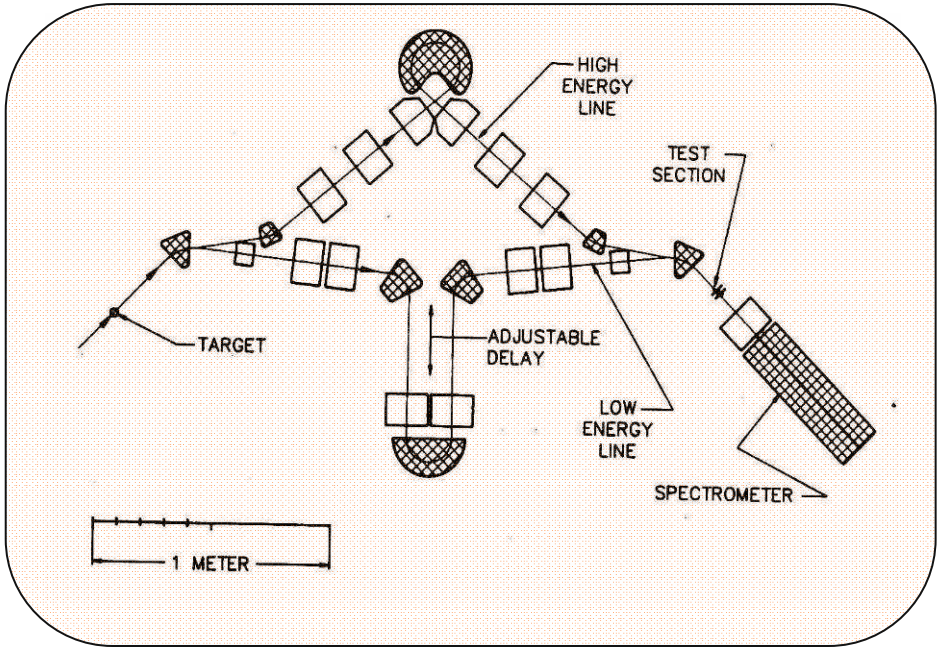
Drive beam, drive beam and drive beam!

- *Energy ↑*
- *Charge ↑*
- *Bunch length ↓*
- *Emittance ↓*



First Demonstration of Dielectric Wakefield Acceleration

- Argonne Accelerator Test Facility (AATF) in late 1980s



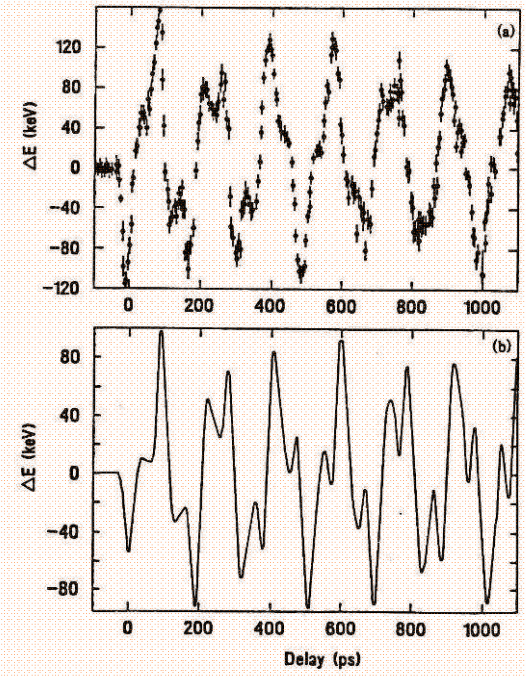
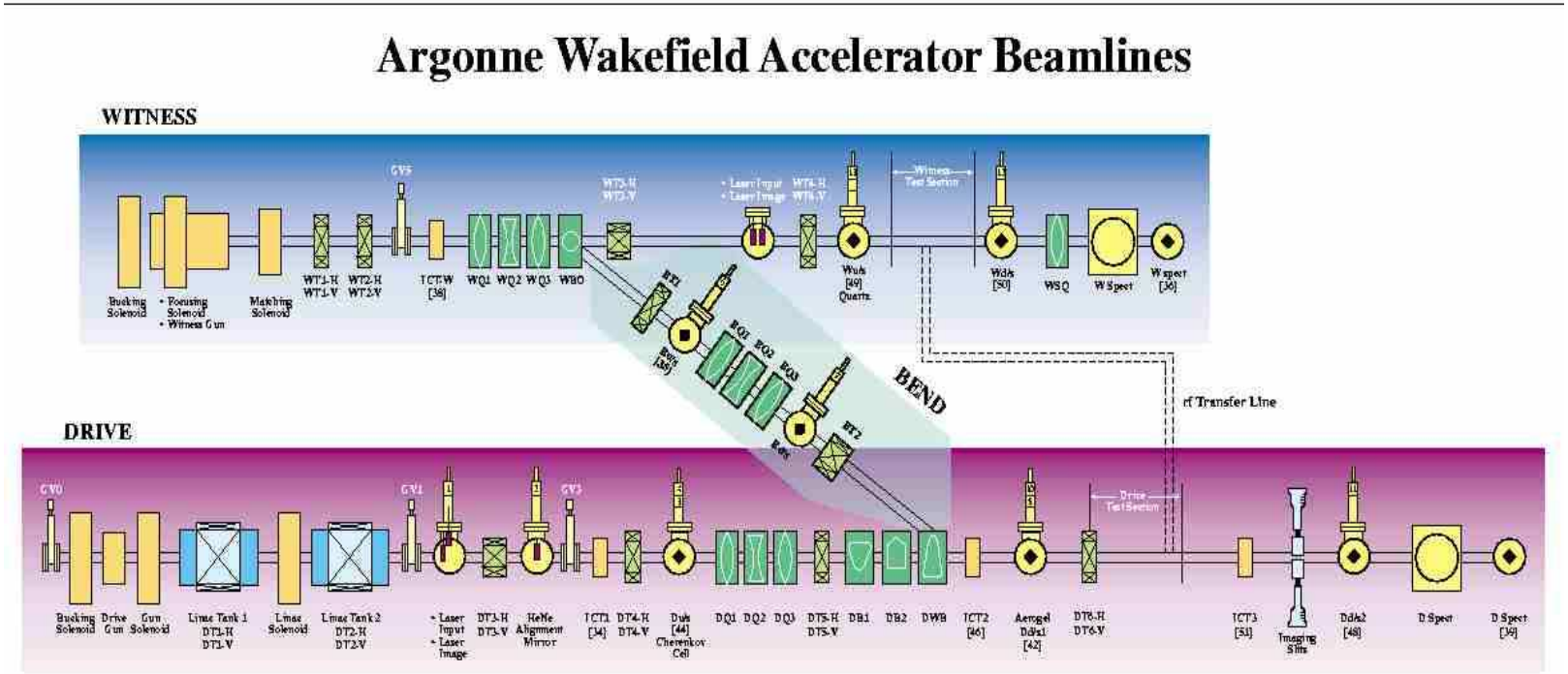


FIG. 3. Steatite scan: (a) measured and (b) calculated wake potential.

- 20 MeV drive beam (1 - 5 nC), and 16 MeV witness beam from the same thermionic RF gun
- Detailed mapping of wake potential (160 keV)
- Lesson: polymer based dielectrics charge up; ceramics are fine

Argonne Wakefield Accelerator – Original Configuration



- 14 MeV drive beam (10 – 100 nC), and 4 MeV witness beam from distinct photocathode RF guns
- Bunch train generation: four bunches of 10 nC

Wakefield Acceleration at AWA

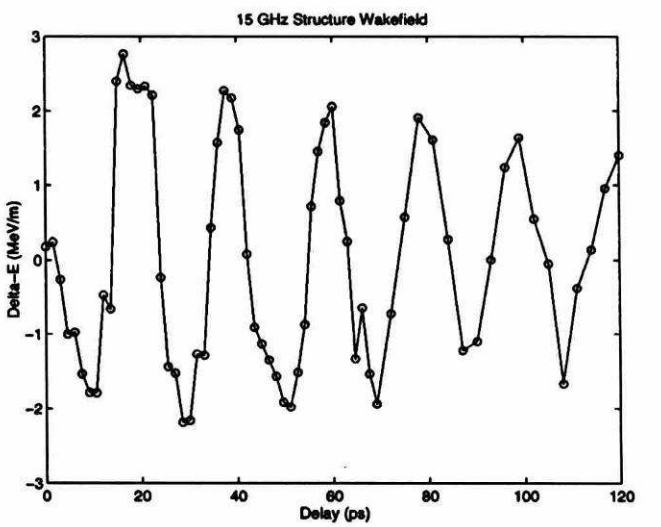
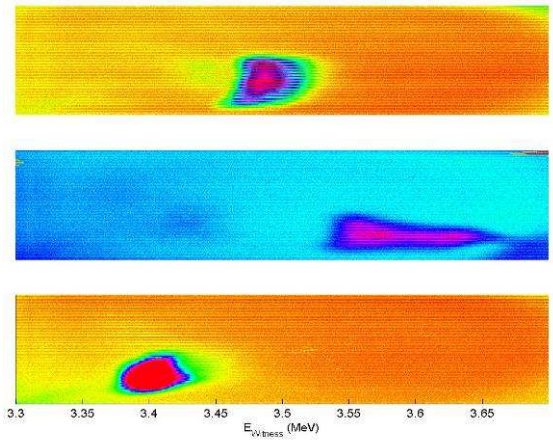
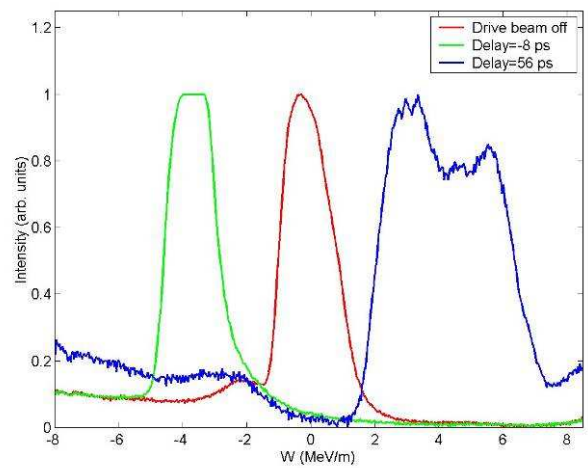


FIG. 3. Wake potential measurement for 15 GHz dielectric structure. Each data point is the change in the bend view centroid of the witness beam at the spectrometer 60° port.

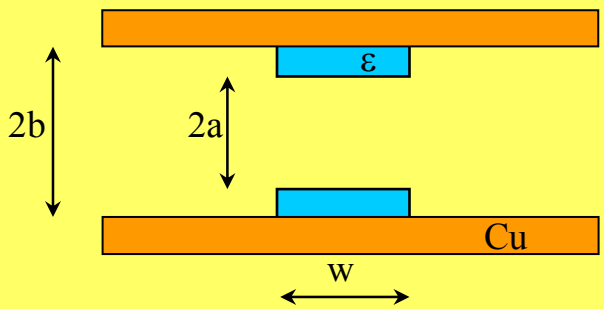




- Collinear wakefield acceleration: 15 MV/m
- First TBA with dielectric loaded structures: 3.5 MV/m deceleration in Stage I, 7 MV/m acceleration in Stage II

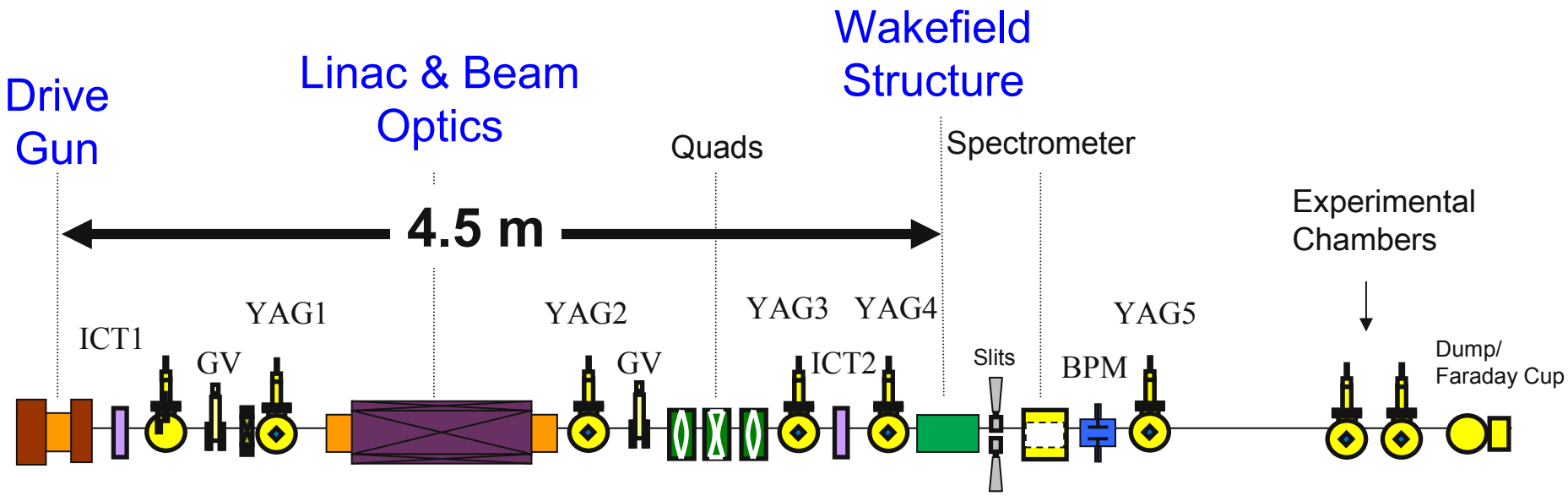
91 GHz Planar Dielectric Wakefield Accelerator at SLAC

M.E. Hill, C. Adolphsen, W. Baumgartner, R.S. Callin, X.E. Lin, M. Seidel, T. Slaton, D.H. Whittum, PRL **87**, 2001



- Planar dielectric structure in a ring resonator circuit.
- Dielectric slab: $0.3 \times 0.8 \times 25.4$ mm^3 alumina, $\varepsilon = 9.5$
- Structure: a = 360 μm, b = 660 μm, w = 800 μm
- Beam: 300 MeV, 100 ns, 0.5 A, 11.4 GHz (×8)
- Measurements: 20 MV/m, 200 kW, 42 MΩ/m

AWA Drive Beamline



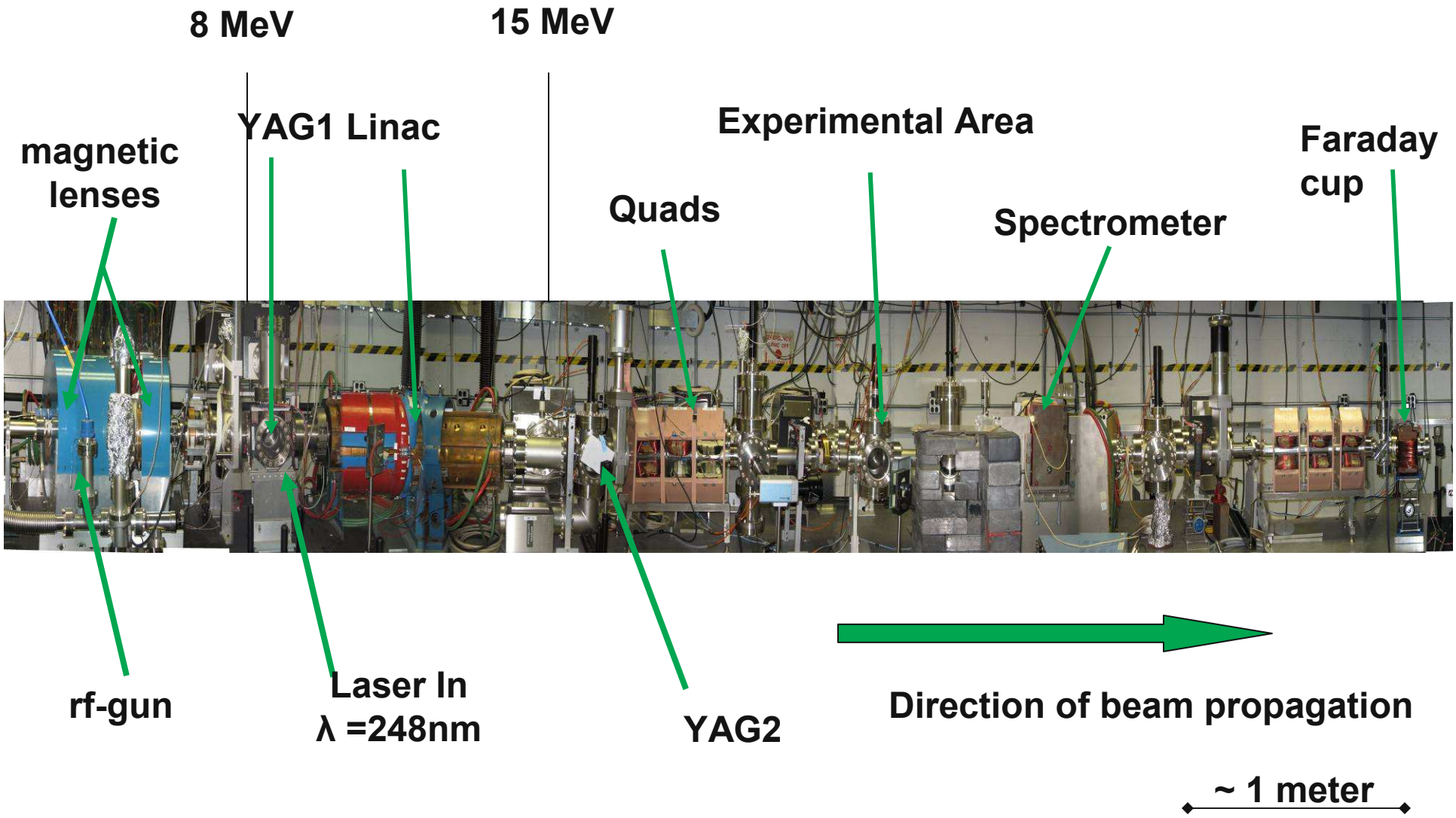
Single bunch operation

- Q = 1-100 nC (reached 150 nC)
- 15 MeV, 2 mm bunch length (rms), emittance < 200 mm mrad (at 100 nC)
- High Current: ~10 kA

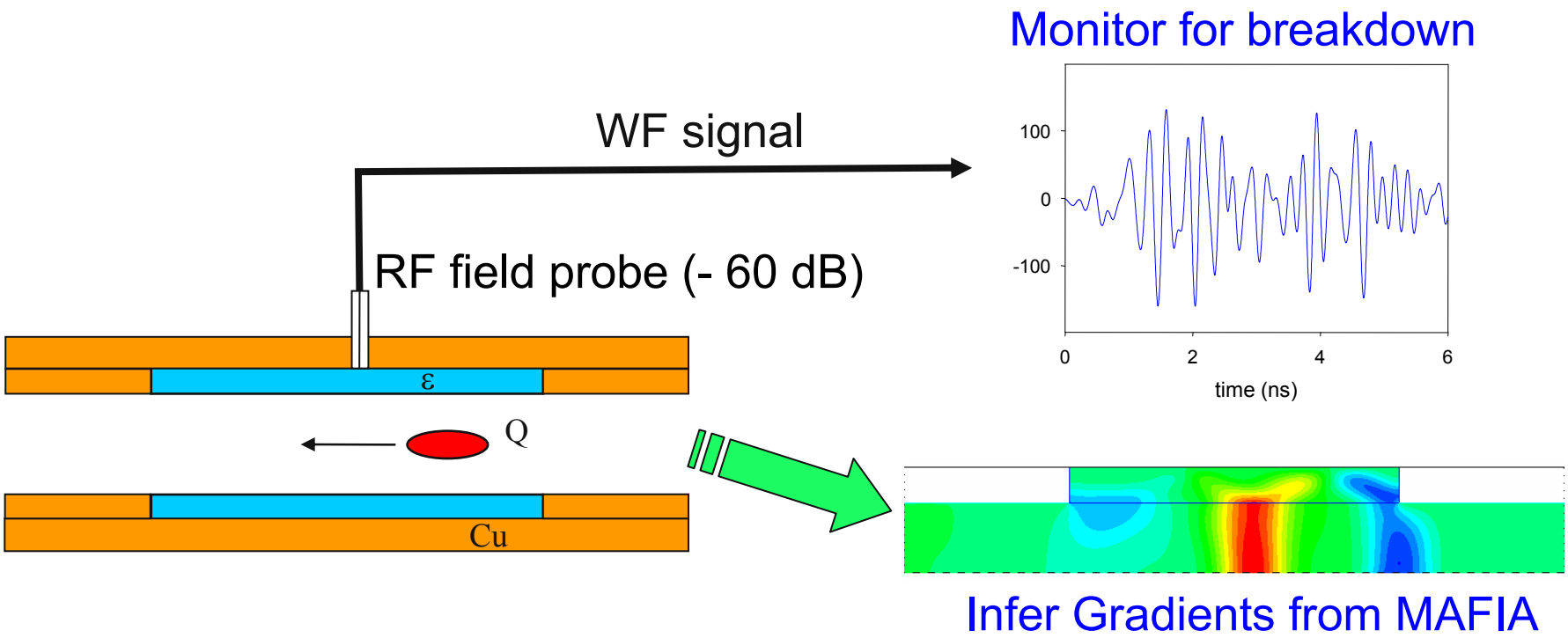
Bunch train operation

- 4 bunches x 10 nC (current)
- 16 - 64 bunches x 50 - 100 nC → 10 - 50 ns long (future)

The Argonne Wakefield Accelerator (AWA)

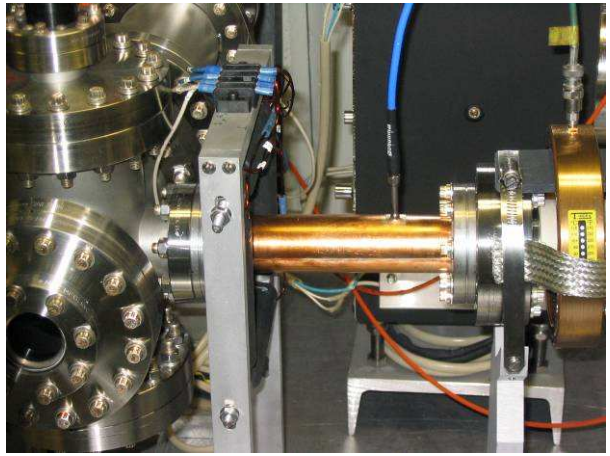


Experimental Setup for High Gradient Tests



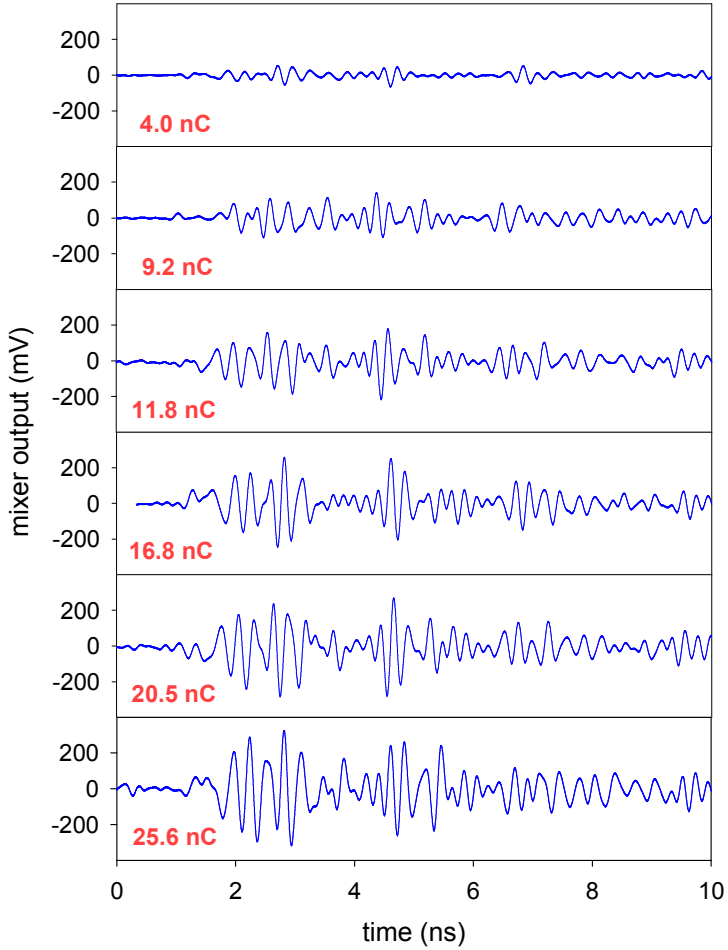
Goal:
Test breakdown thresholds of dielectric structures under short RF pulses.

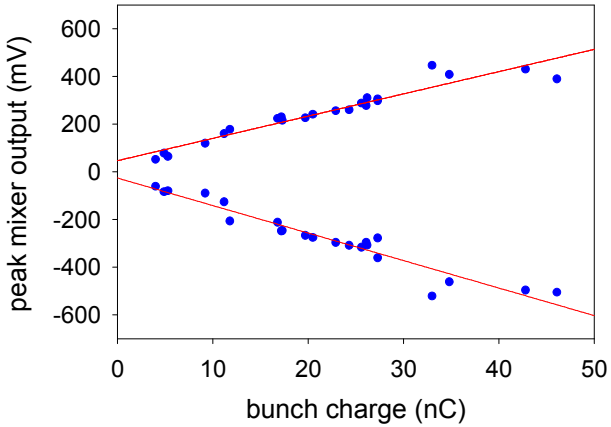
Dielectric Loaded Structures Tested

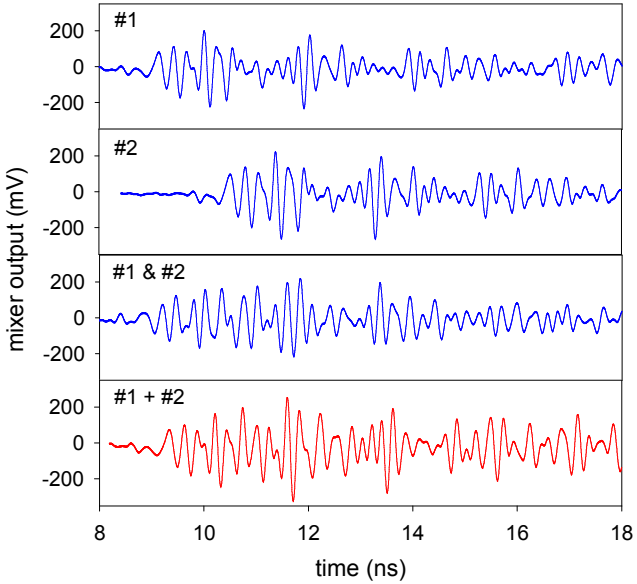


SW Structure	#1 C10-102	#2 C10-23	#3 C5.5-28	#4 Q3.8-25.4
Material	Cordierite	Cordierite	Cordierite	Quartz
Dielectric constant	4.76	4.76	4.76	3.75
Freq. of TM01n	14.1 GHz	14.1 GHz	9.4 GHz	8.6 GHz
Inner radius	5 mm	5 mm	2.75 mm	1.9 mm
Outer radius	7.49 mm	7.49 mm	7.49 mm	7.49 mm
Length	102 mm	23 mm	28 mm	25.4 mm
Wakefield Gradient	0.45 MV/m/nC	0.5 MV/m/nC	0.91 MV/m/nC	1.33 MV/m/nC

Wakefield Measurements: Structure #1 (C10-102)



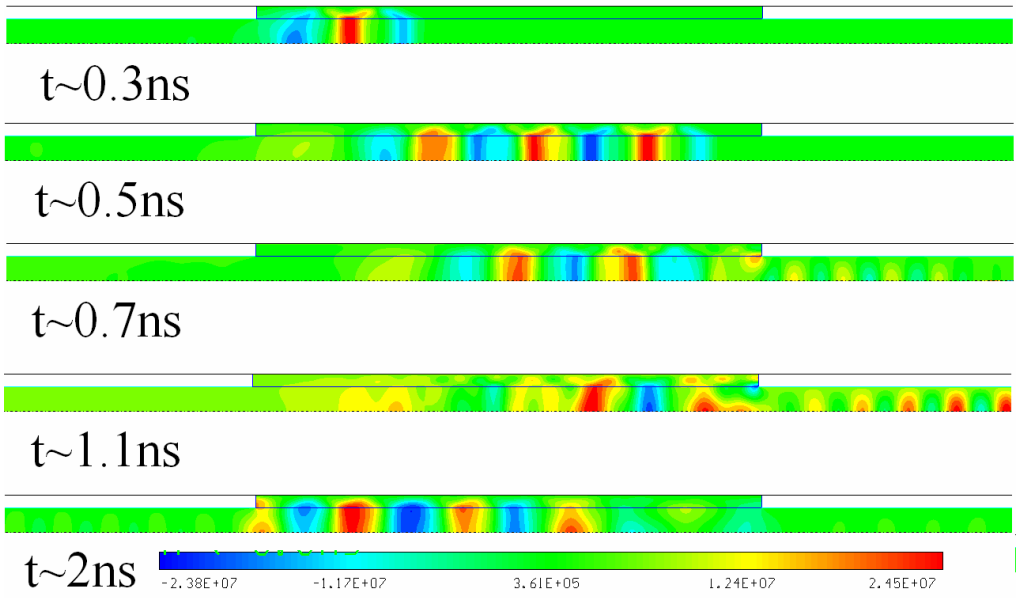




46 nC → 21 MV/m

☺

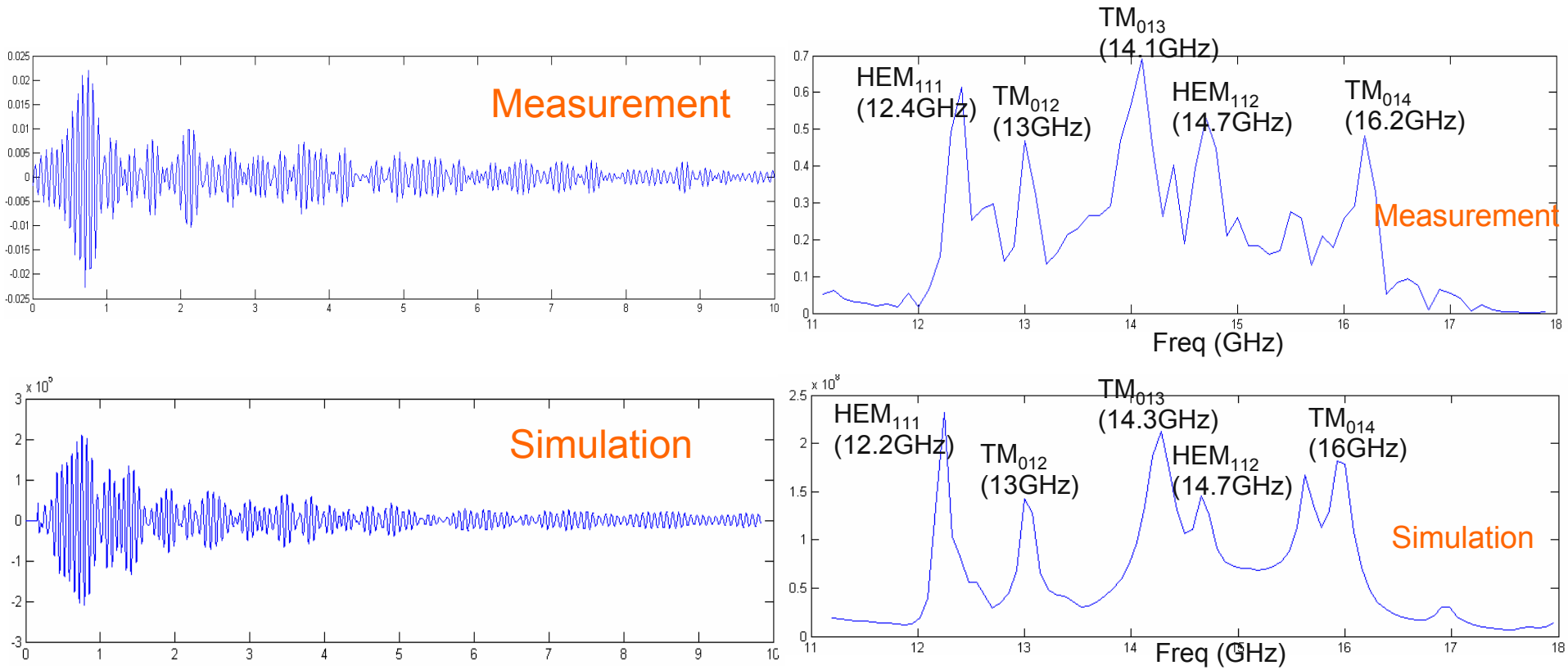
MAFIA Simulation of Structure #1 (C10-102)



Snapshots of wakefield amplitude

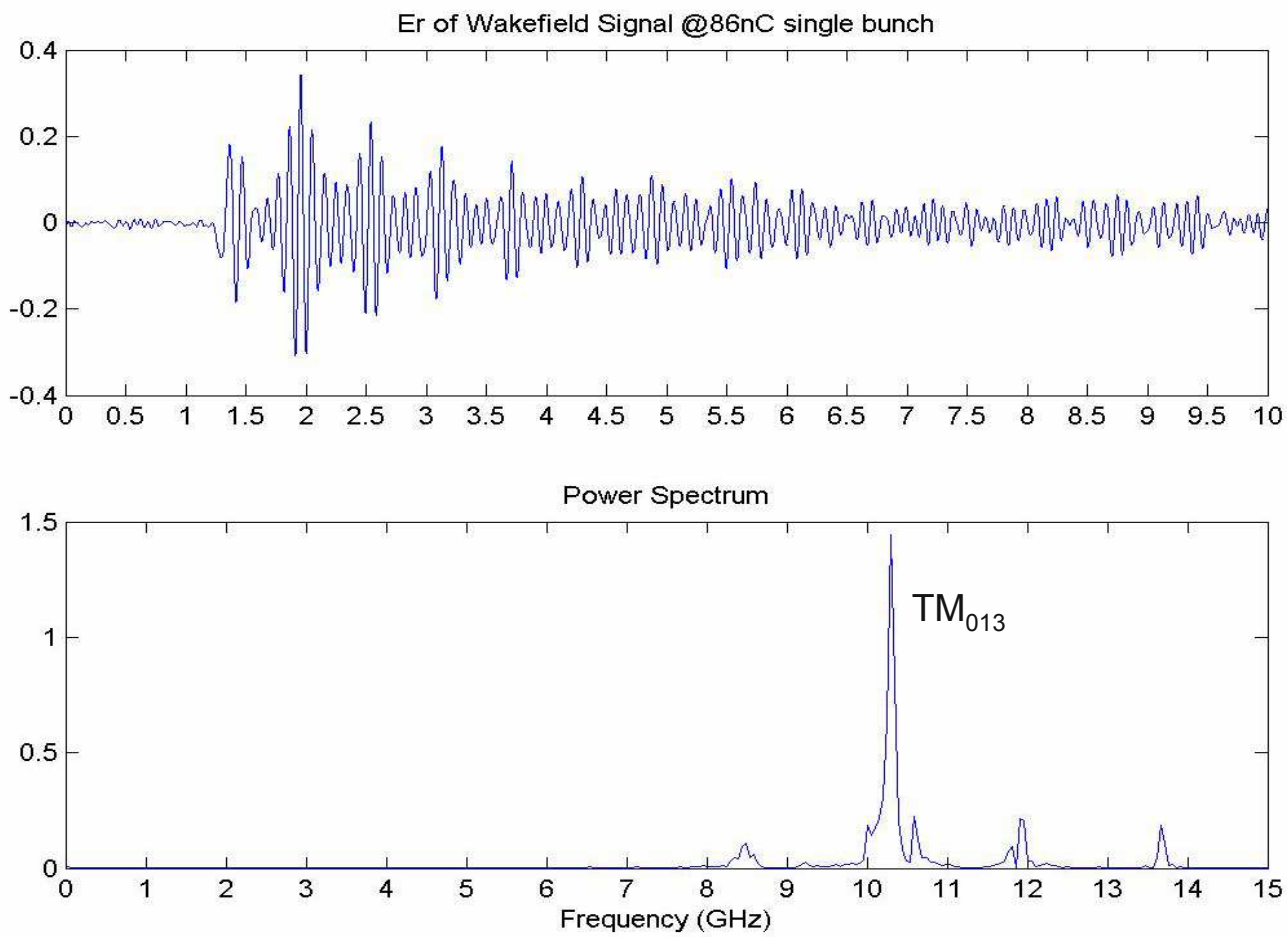
Wakefield Measurements: Structure #2 (C10-23)

Measured and simulated E_r probe signals



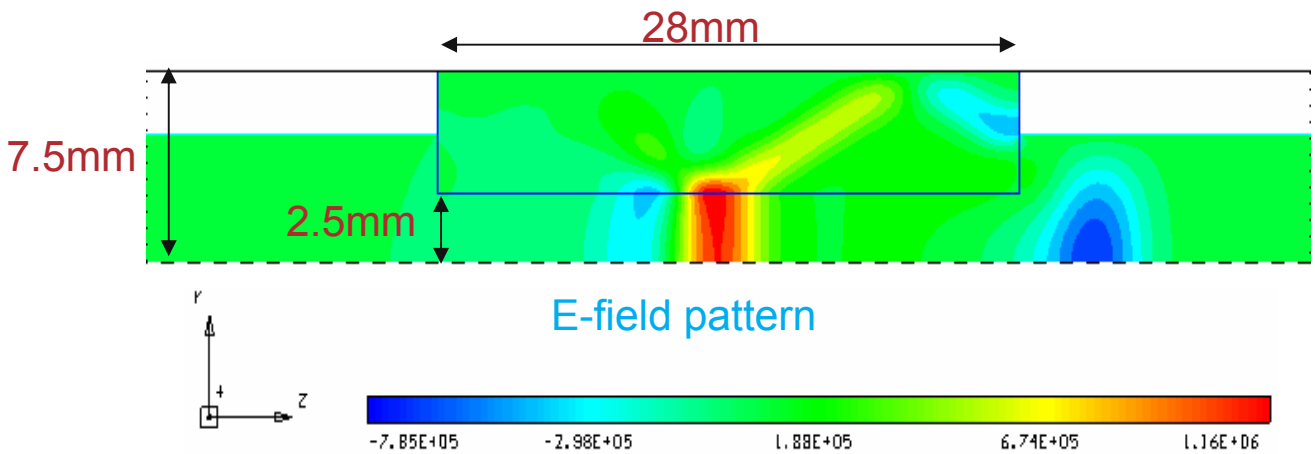
86 nC → 43 MV/m ☺

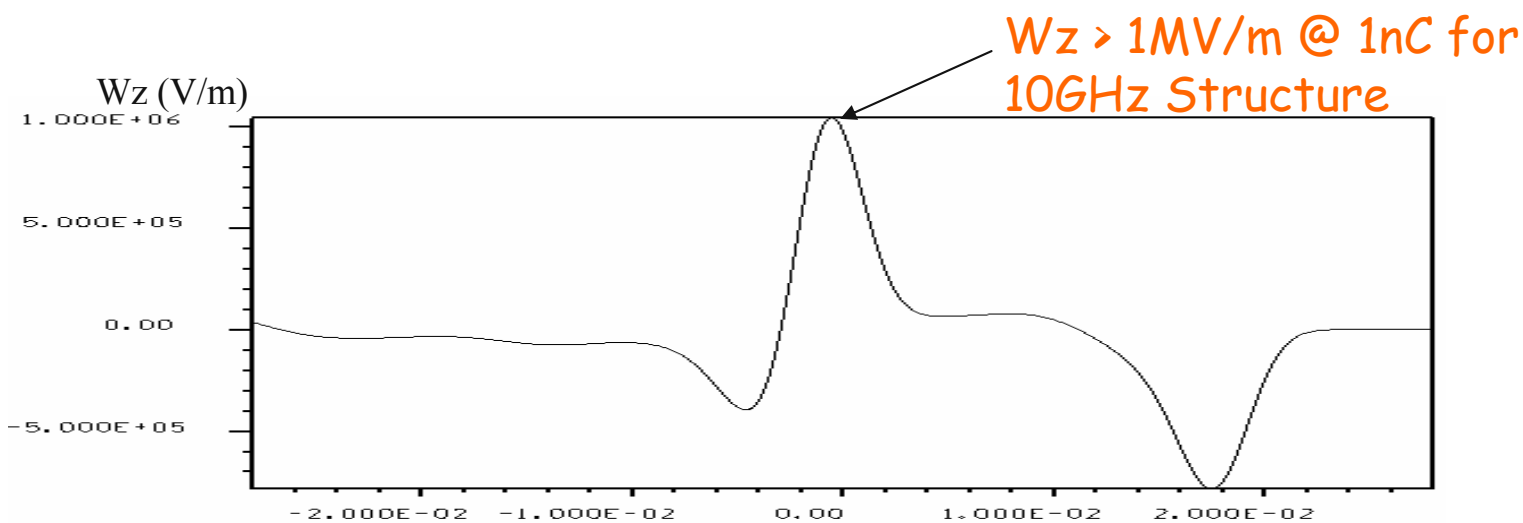
Wakefield Measurements: Structure #3 (C5.5-28)



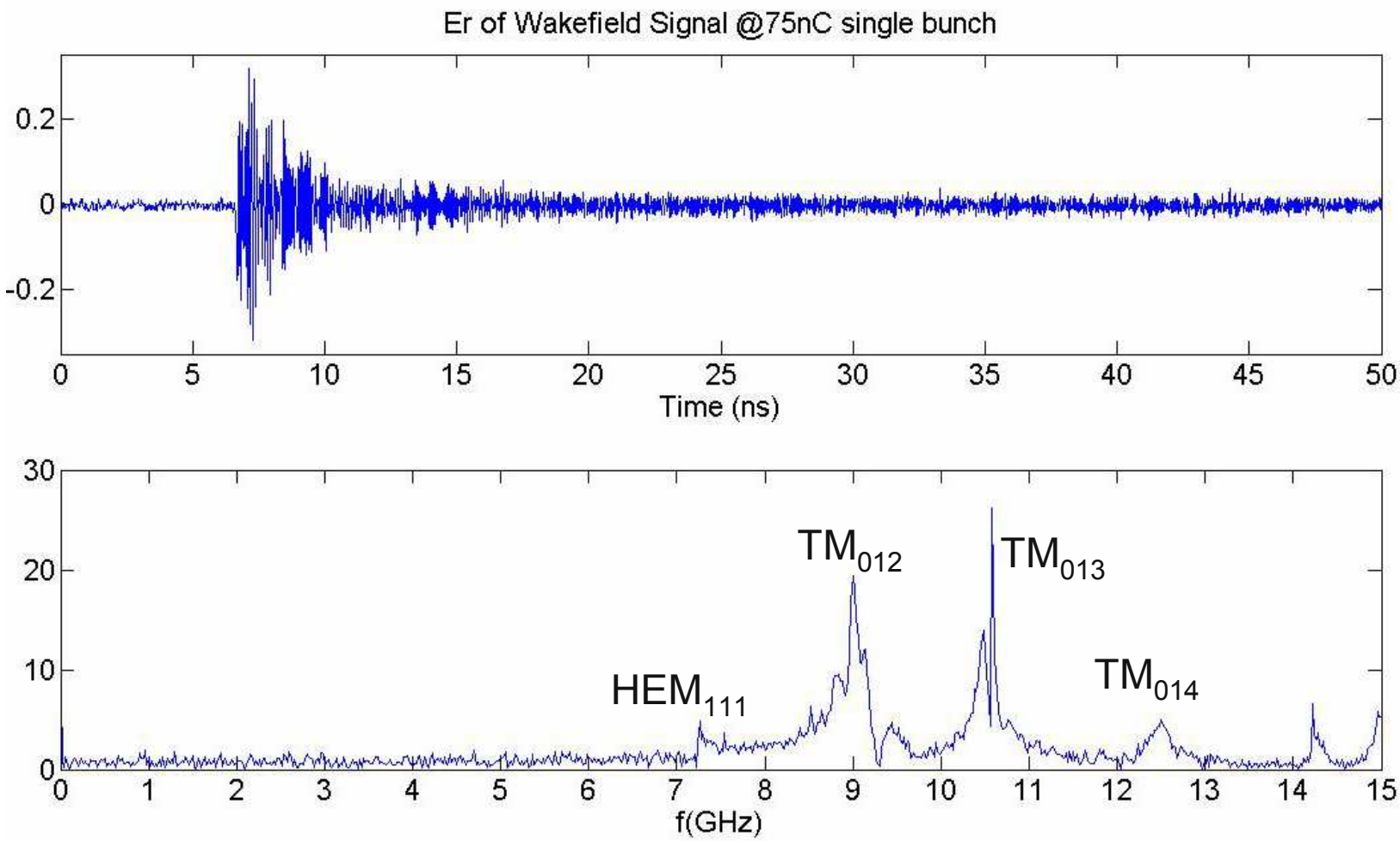
86 nC → 78 MV/m ☺

MAFIA Simulation of Structure #3 (C5.5-28)





Wakefield Measurements: Structure #4 (Q3.8-25.4)



75 nC → 100 MV/m ☺☺

Dielectric Loaded Structures at AWA: Steadily Increasing Accelerating Gradients

- The 1990s: ~10 MV/m
- Structure #1 (Summer 2005): 21 MV/m
- Structure #2 (Winter 05/06): 43 MV/m
- Structure #3 (Summer 2006): 78 MV/m
- Structure #4 (Spring 2007): 100 MV/m

Next Steps:

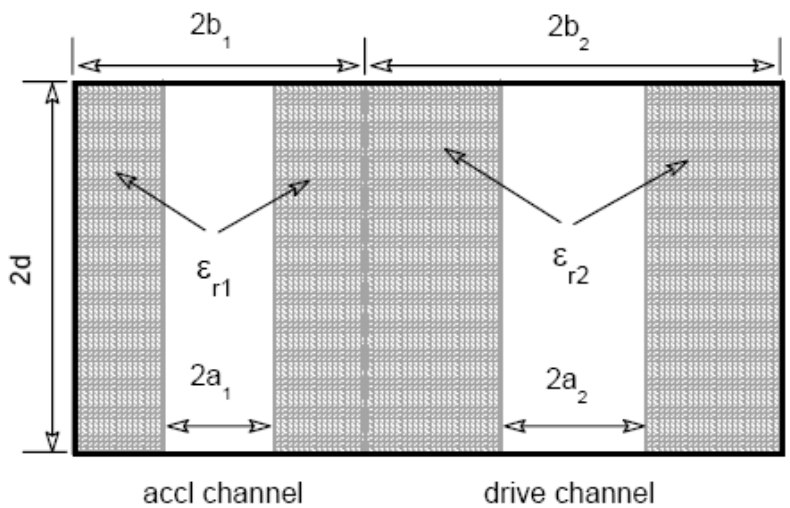
- Test more structures
- Additional klystron (thanks to B. Carlsten, S. Russell, and DOE !!)
- Complete new RF gun
- Cesium telluride photocathodes (long, high charge bunch trains)
- Restore two-beam-accelerator capability

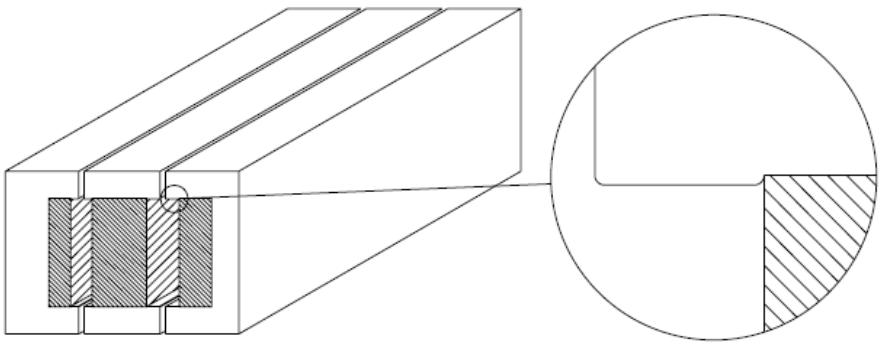
HG two-beam wake field accelerator using a two-channel rectangular dielectric structure*

J.L. Hirshfield[1,2], T.C. Marshall[2,3], V.P. Yakovlev[2], G.V. Sotnikov[2,4], C.B. Wang

[1] *Yale University Beam Physics Laboratory*
[2] *Omega-P, Inc.*
[3] *Columbia University*
[4] *Kharkov Institute of Physics and Technology*

* *Research sponsored by US DoE, DHEP*





Features of a two-beam dielectric wake field accelerator (DWFA):

- High adjustable transformer ratio *T* >> 2*;*
- Wall slots and bunch location that may help suppress HOM's;
- Simple but precise fabrication of planar dielectric elements;
- Continuous coupling of energy from drive to accelerated bunch;
- No need for coupling/transfer structures;
- Continuous pumpout of narrow channels through wall slots;
- High accelerating fields in the single bunch mode.

E-169: Wakefield Acceleration in Dielectric Structures

A proposal for experiments at the SABER facility

H. Badakov[α], M. Berry[β], I. Blumenfeld[β], A. Cook[α], F.-J. Decker[β], M. Hogan[β], R. Ischebeck[β], R. Iverson[β], A. Kanareykin[ε], N. Kirby[β], P. Muggli[γ], J.B. Rosenzweig[α], R. Siemann[β], M.C. Thompson[δ], R. Tikhoplav[α], G. Travish[α], D. Walz[β]

[α] *Department of Physics and Astronomy, University of California, Los Angeles*

[β] *Stanford Linear Accelerator Center*

[γ] *University of Southern California*

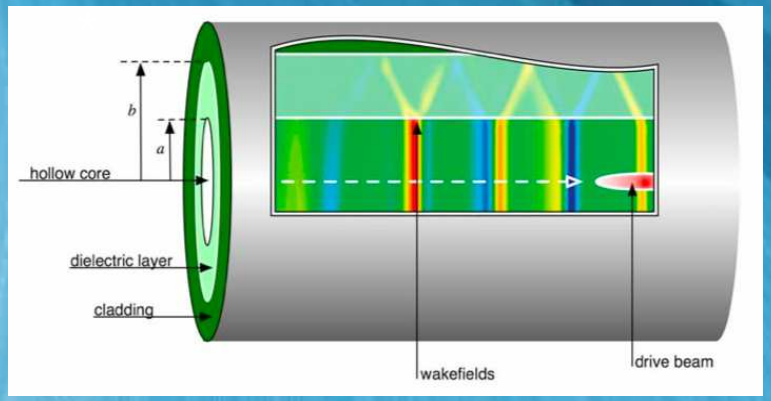
[δ] *Lawrence Livermore National Laboratory*

[ε] *Euclid TechLabs, LLC*

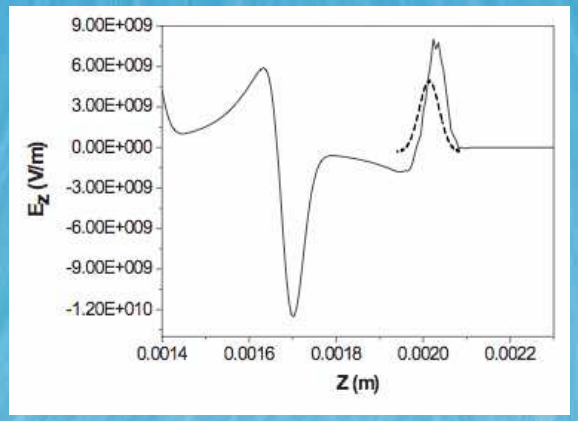
Collaboration spokespersons

Dielectric Wakefield Accelerator

Overview



- Design Parameters $a,\ b,\ L_d,\ \varepsilon\ \ N_b,\ \sigma_z$



Ez on-axis, OOPIC

- Electron bunch (β ≈ 1) drives ***Cerenkov wake*** in cylindrical dielectric structure
  - Variations on structure features
  - Multimode excitation
- Wakefields accelerate trailing bunch
  - Mode wavelengths

$$\lambda_n \approx \frac{4(b-a)}{n}\sqrt{\varepsilon-1}$$

  - Peak decelerating field

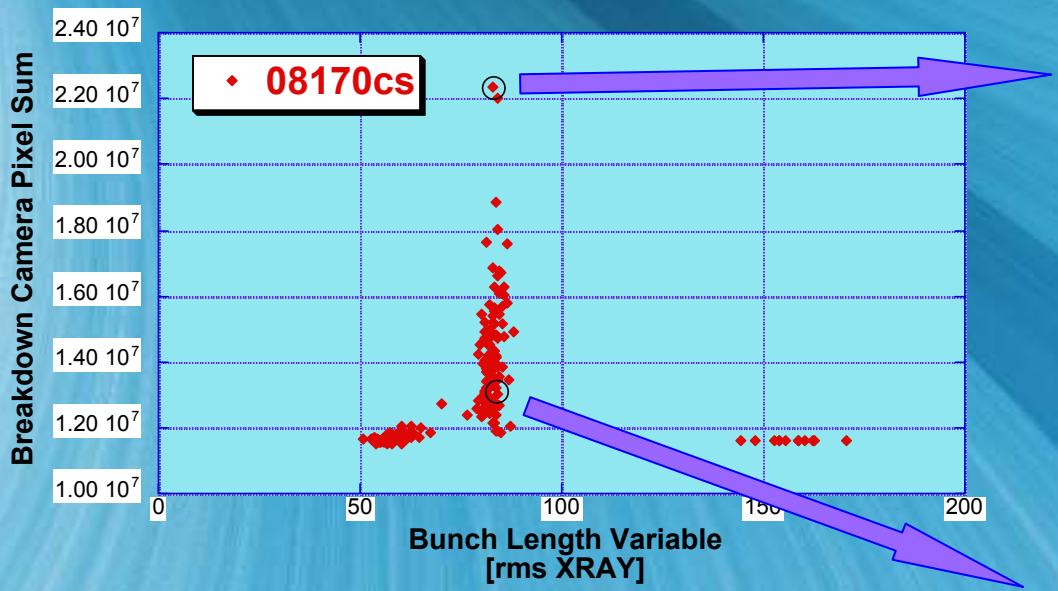
$$eE_{z,dec} \approx \frac{-4N_b r_e m_e c^2}{a\left[\sqrt{\frac{8\pi}{\varepsilon-1}}\varepsilon\sigma_z + a\right]}$$

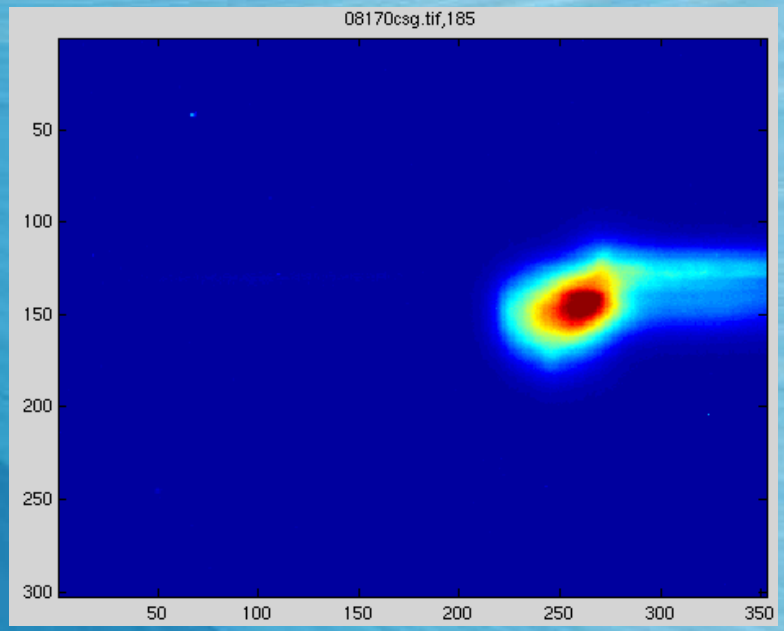
Extremely good beam needed

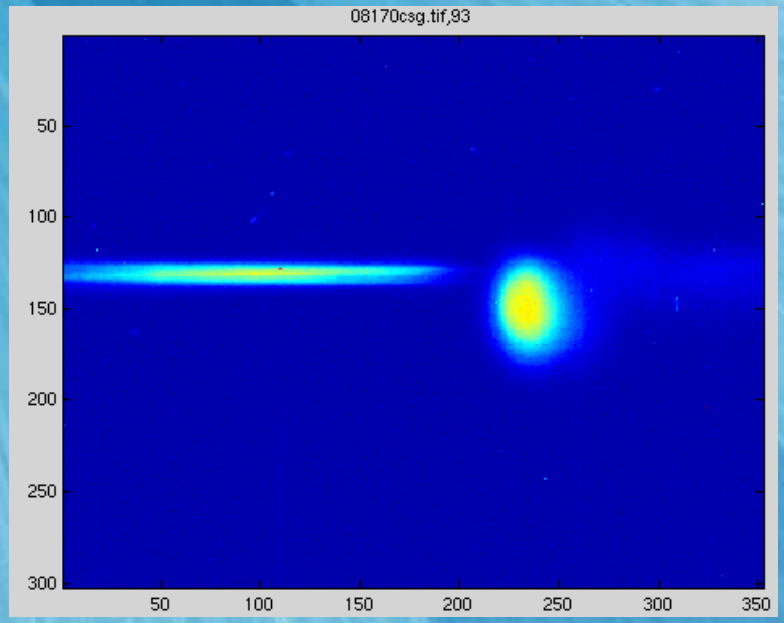
  - Transformer ratio

$$R = \frac{E_{z,acc}}{E_{z,dec}} \leq 2$$

Breakdown Threshold Observation





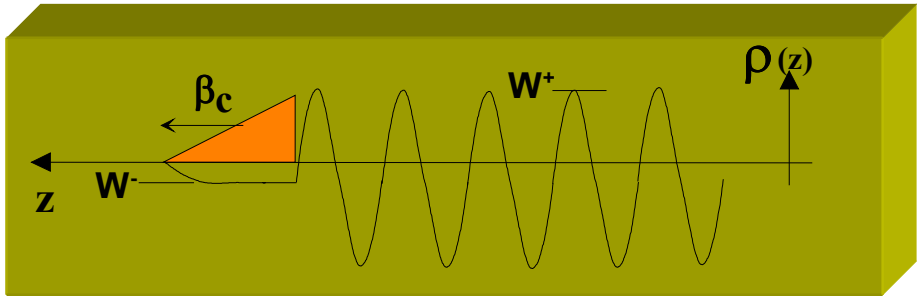


- Goal: breakdown studies
  - Al-clad fused silica fibers
    - ID 100/200 μm, OD 325 μm, L=1 cm
  - Avalanche v. tunneling ionization
  - Beam parameters indicate ≤12 GV/m longitudinal wakes
    - 30 GeV, 3 nC, $\sigma_z \geq 20$ μm

*Wakefield Transformer Ratio Enhancement Experiment at AWA**

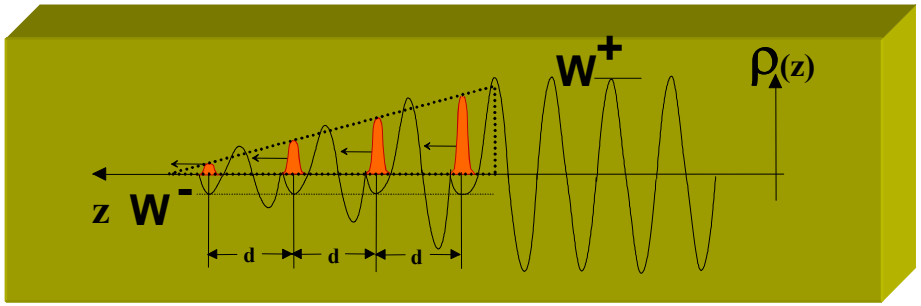
- Transformer ratio limited: Wakefield theorem says: A trailing beam can not gain more than twice of the drive beam peak energy loss in a collinear wakefield scheme if the drive beam is longitudinal symmetric distributed, which results in the accelerated beam can not gain much due to the limited drive beam energy
- The asymmetric bunch distribution will beat R<2 limit---the principal goal of this experiment is to demonstrate this idea.

Scheme I---Single Triangular Bunch



Reference: Bane et. al., IEEE Trans. Nucl. Sci. NS-32, 3524 (1985)

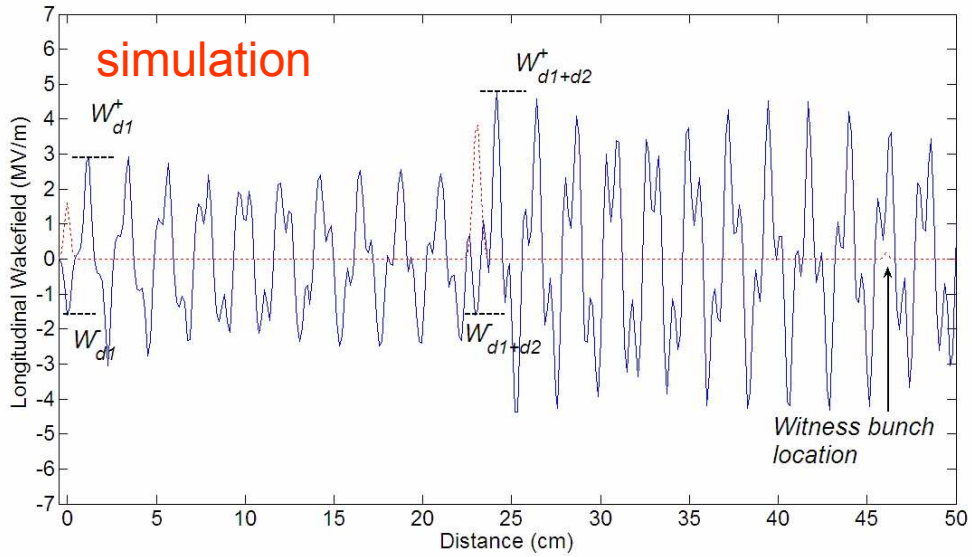
Scheme II---Ramped Bunch Train



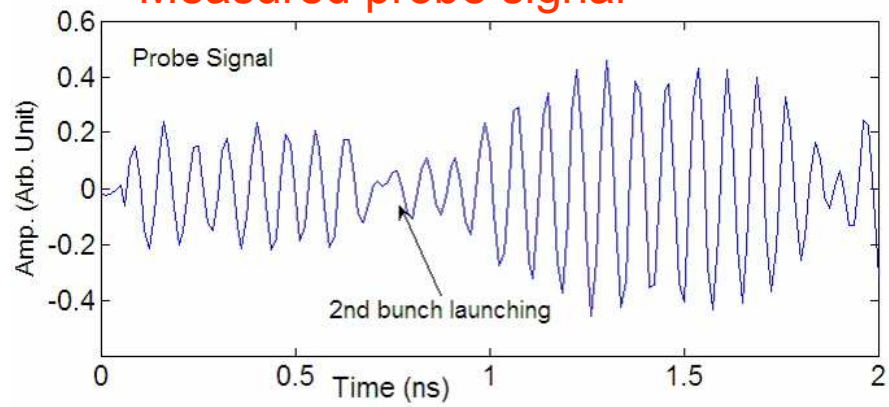
Reference: Schutt et. al., Nor Ambred, Armenia, (1989)

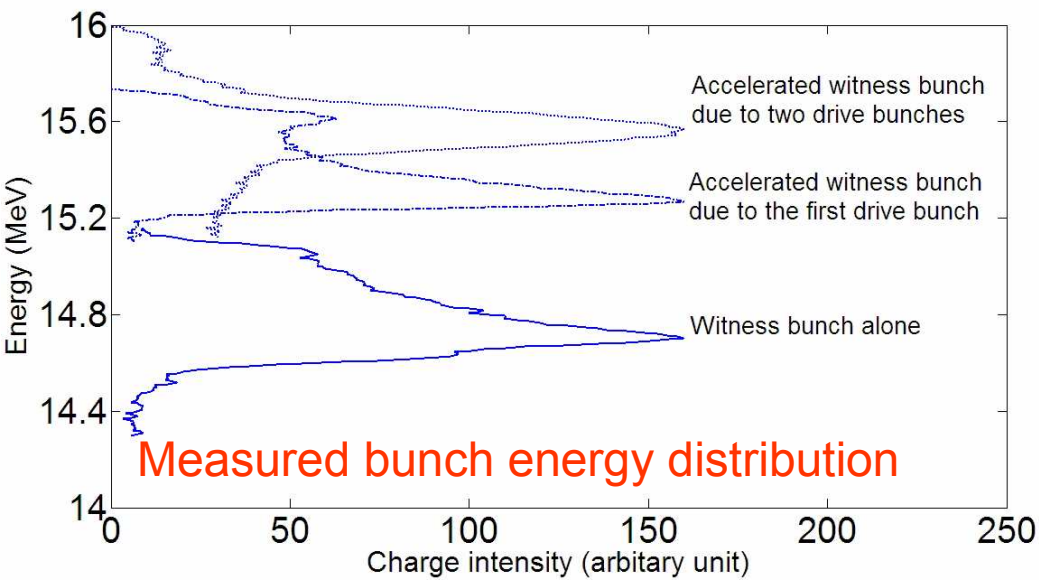
** This work is a collaboration with Euclid Techlabs, LLC. The results were published in Phys. Rev. Lett. 98 (2007) 144801. This work was supported by DoE SBIR funding.*

Measurements



Measured probe signal





measurement $\Longrightarrow$ $\dfrac{W^-_{d1+d2}}{W^-_{d1}} = 1$

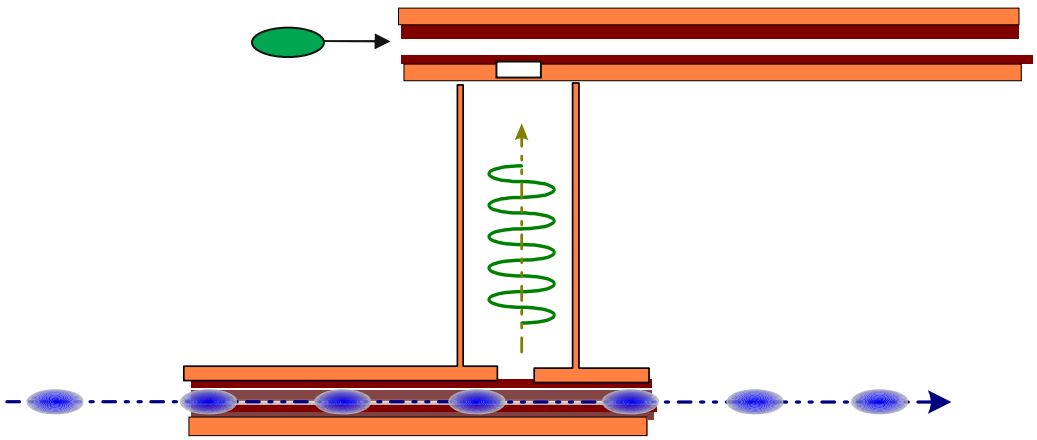
measurement $\Longrightarrow$ $\dfrac{W^+_{d1+d2}}{W^+_{d1}} = 1.31 \pm 0.13$

This is measured wakefield transformer ratio enhancement! Transform Ratio R was enhanced for two ramped bunches is 3 in theory and 2.3 in measurement.

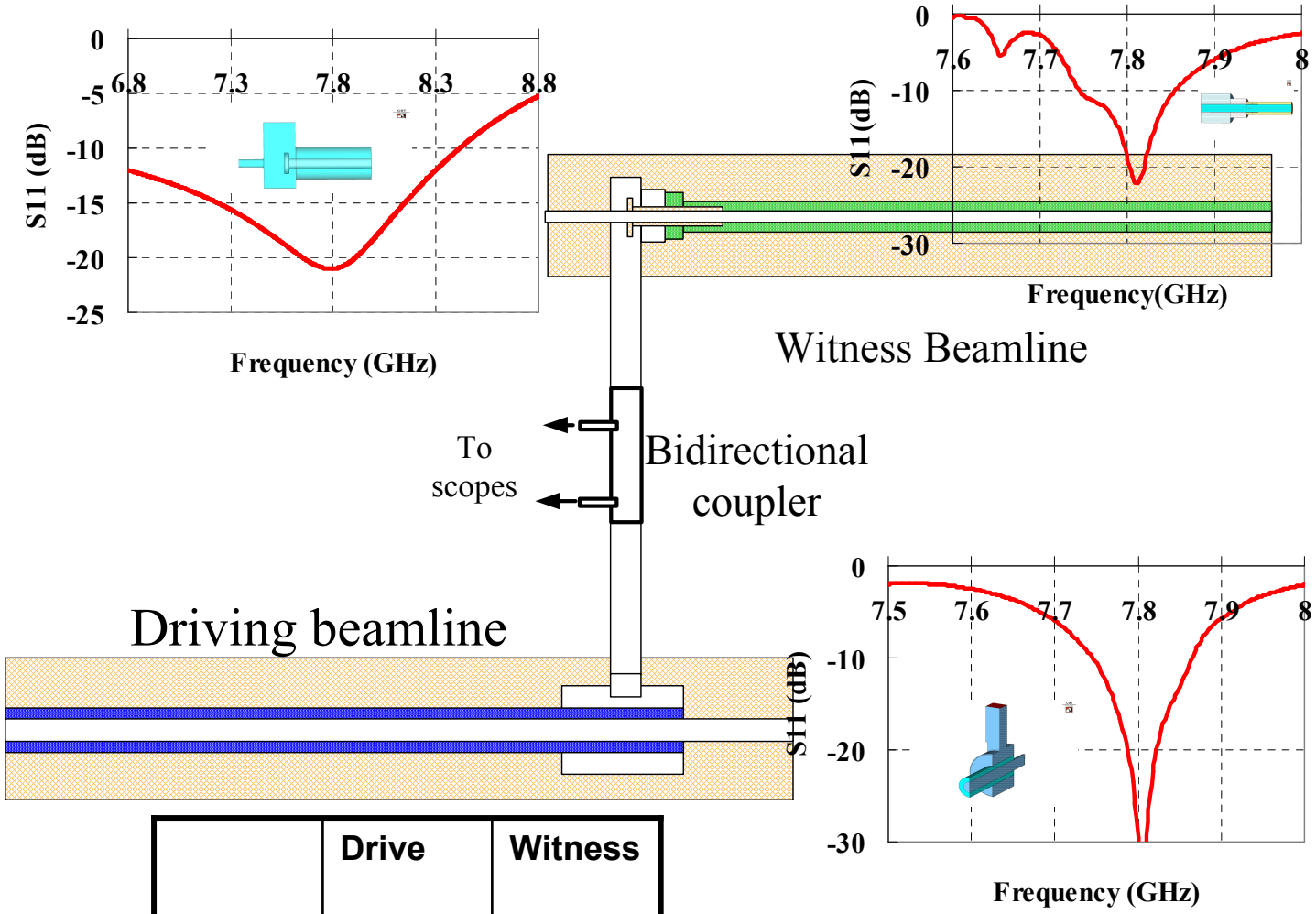
High Power Generation for Two Beam Acceleration

An Example of Two-Beam Accelerator (Future Goal)

- Drive beam: 64 bunches of 50 nC, each separated by one RF period, generating a 50 ns long RF pulse.
- Stage I (28 cm long): 2a=11 mm, 2b=22 mm, ε = 4.6, 45 MV/m deceleration field, generating 500 MW (flat top).
- Stage II (85 cm long): 2a= 6mm, 2b= 11 mm, ε = 20, 112 MV/m acceleration field, yielding a total acceleration of 95 MeV.

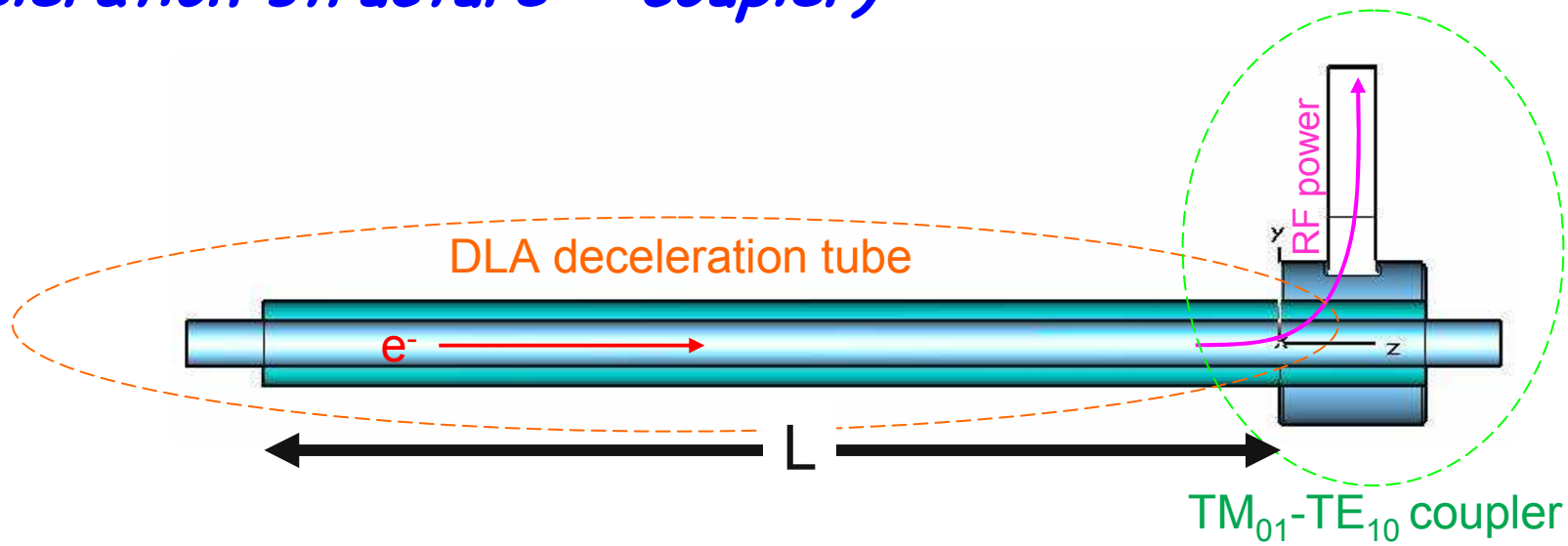


Two Beam Accelerator Design



	Drive	Witness
a (mm)	6.02	3.00
b (mm)	11.17	5.406
ε_r	4.6	20

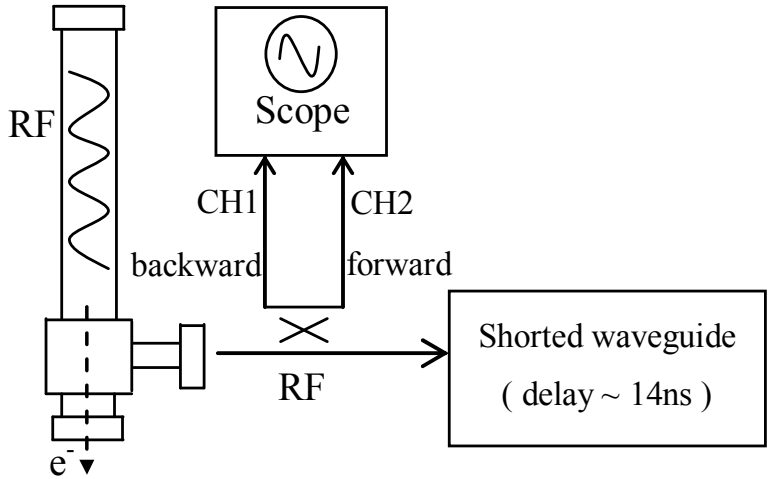
Development of a 7.8 GHz Power Extractor (deceleration structure + coupler)

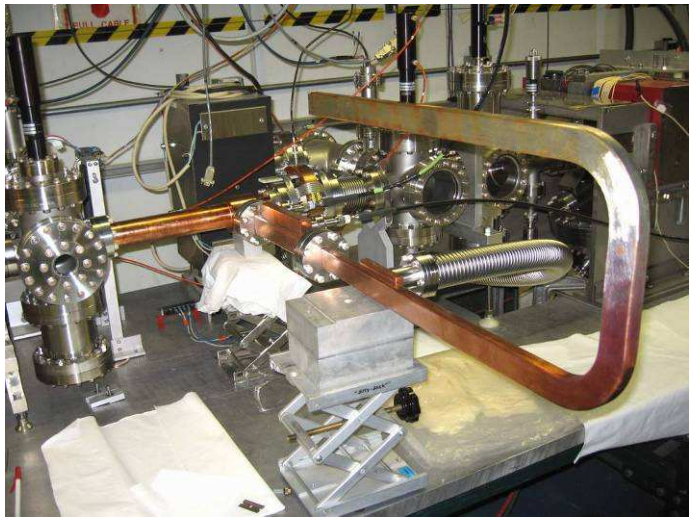


f_{RF} GHz	ID mm	OD mm	L mm	ε_r	β_g	t_d ns	δ_d 10^{-4}	Q_w	Q	$[r/Q]$ kΩ/m	r_{sh} MΩ/m
7.8	12.04	22.34	266	4.6	0.23	2.9	5	8777	2745	6.09	16.7

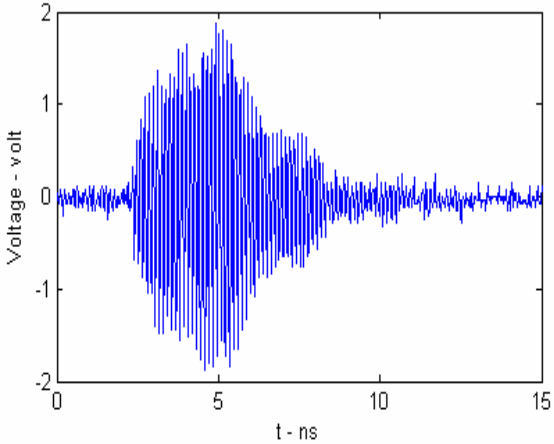
dielectric = cordierite

7.8 GHz Power Extractor

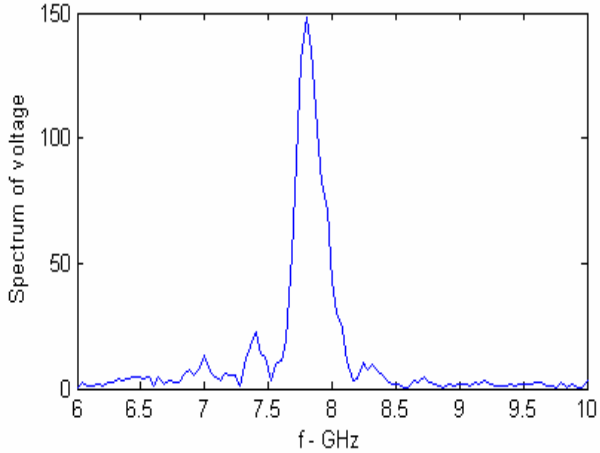




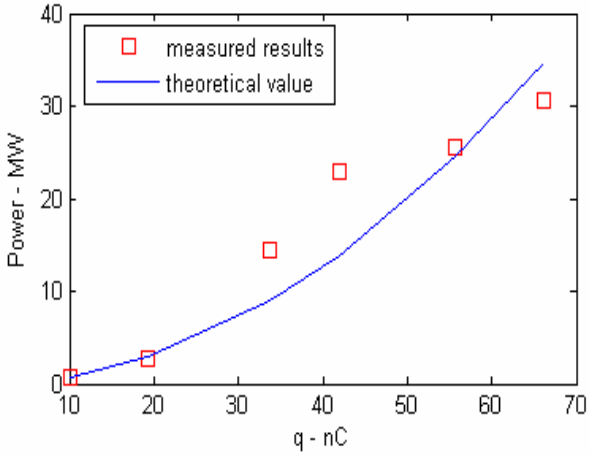
Detected voltage signal
(q = 66nC, σ_z=2mm)



Spectrum of the signal
(q = 66nC, σ_z=2mm)

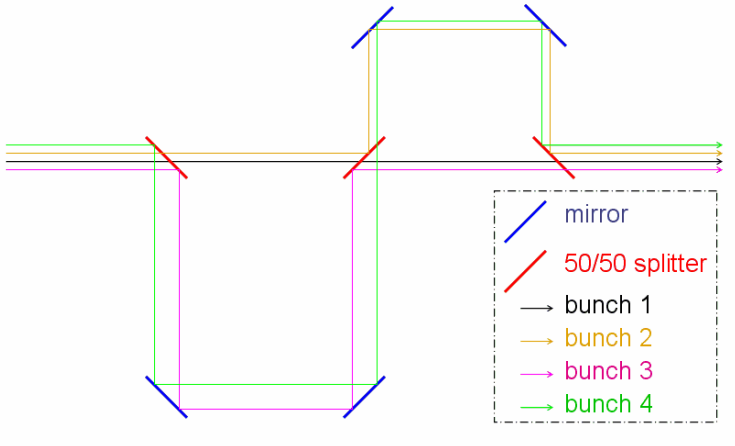


Generated power vs. charge
(single bunch test)

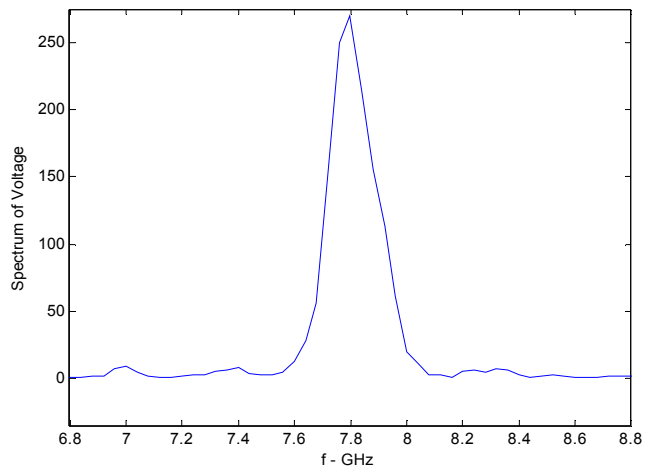


Bunch Train through Power Extractor

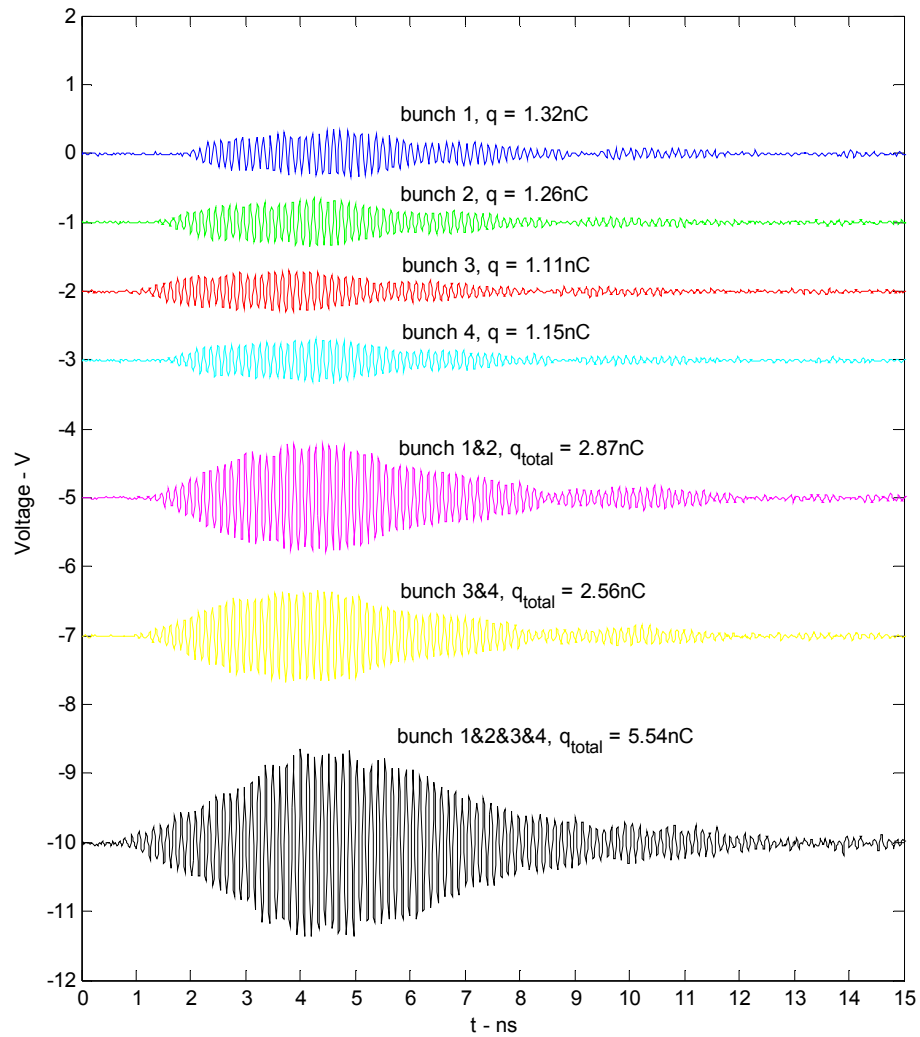
Laser beam splitter



Spectrum of voltage signal



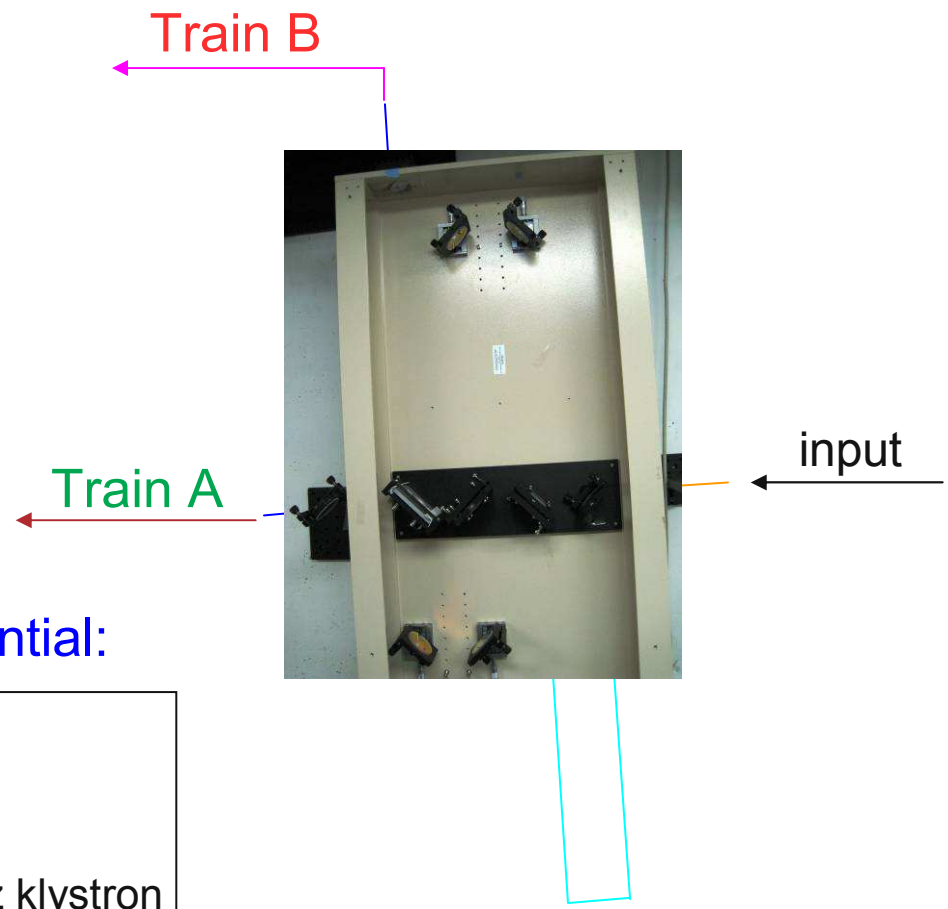
Wakefield superposition observed (200 kW)



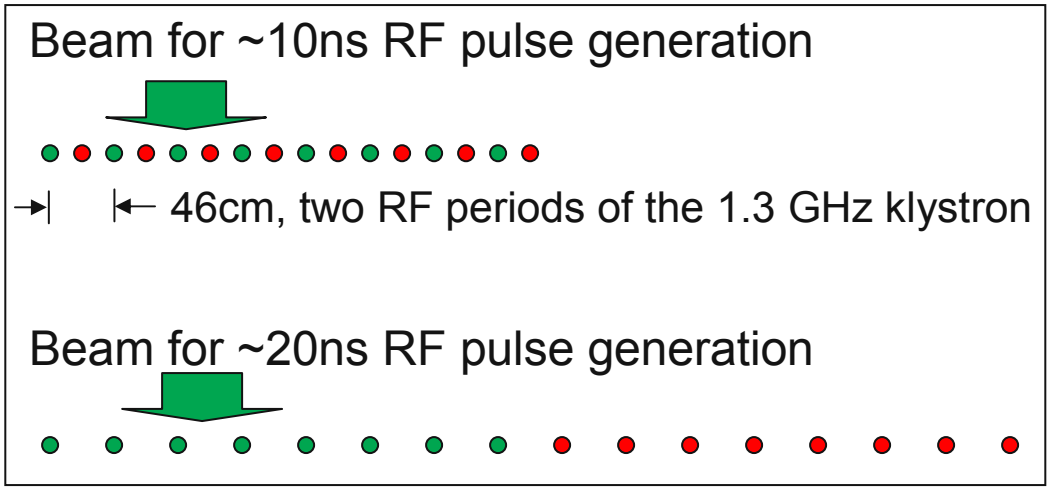
Longer Laser Pulse Train

16 laser pulses (12 ns):

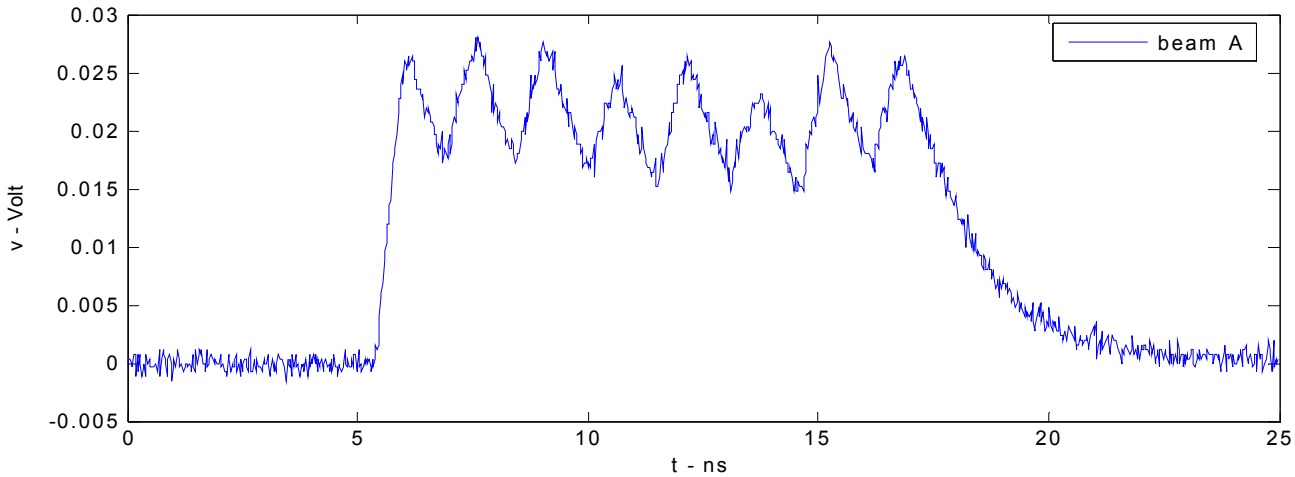
- one group of 8 pulses (spaced by two RF periods) from each port.
- each group uses a different mirror to reach the photocathode.

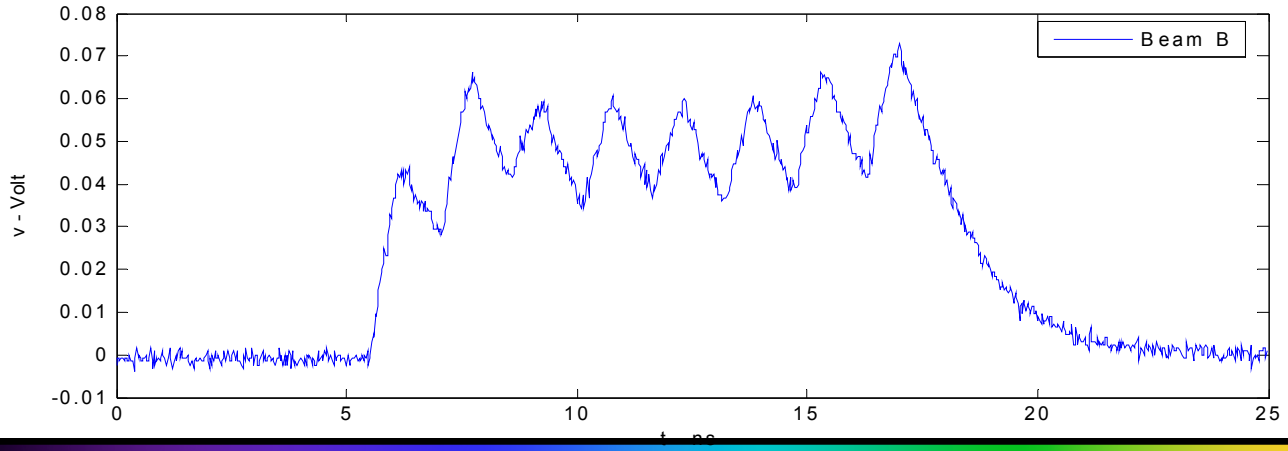


Trains A and B interleaved or sequential:

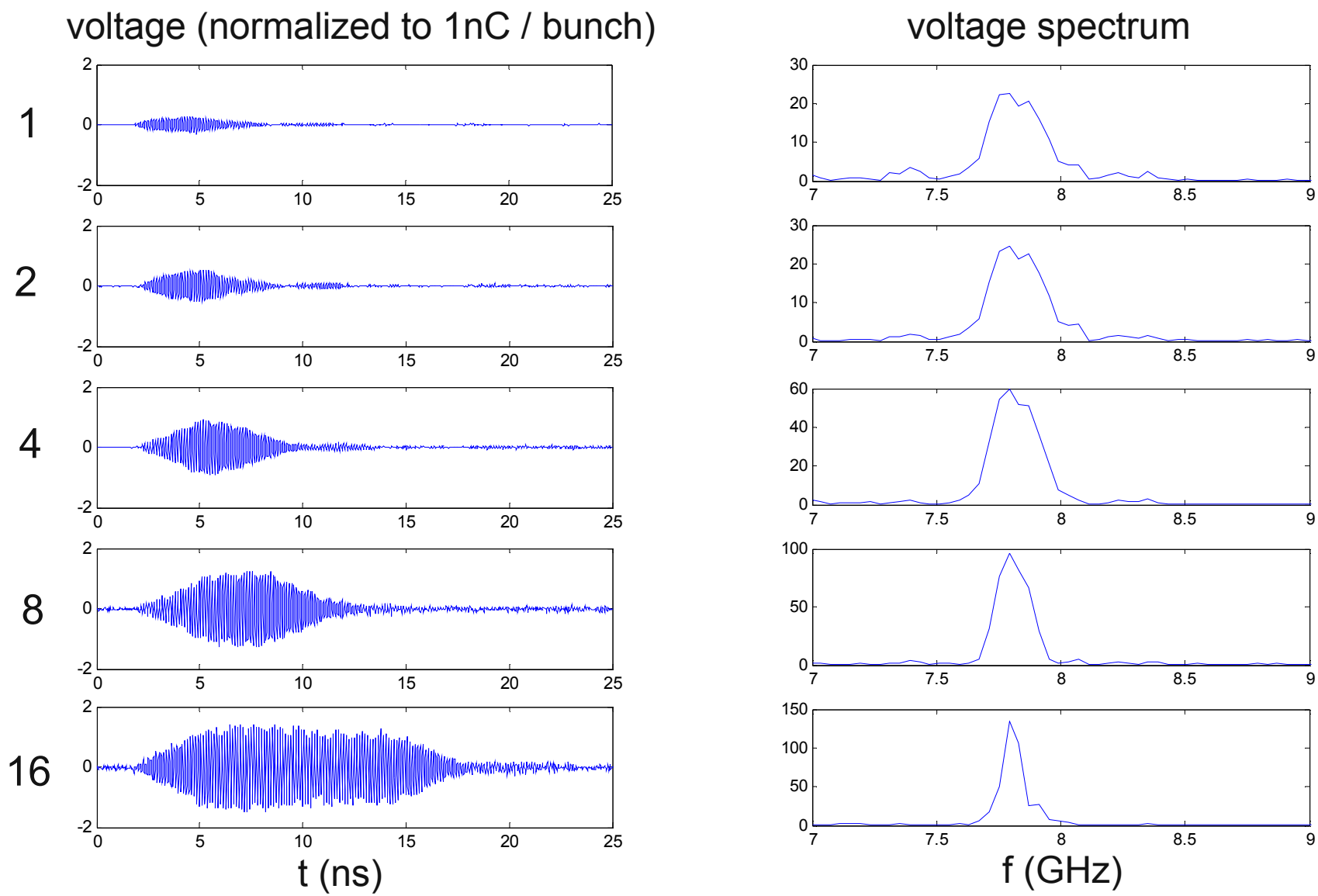


Time Spacing Measurement with Photodiode

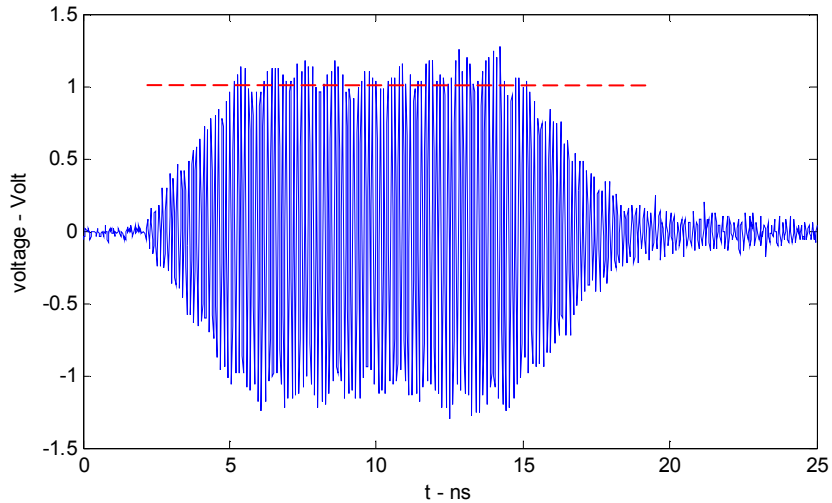




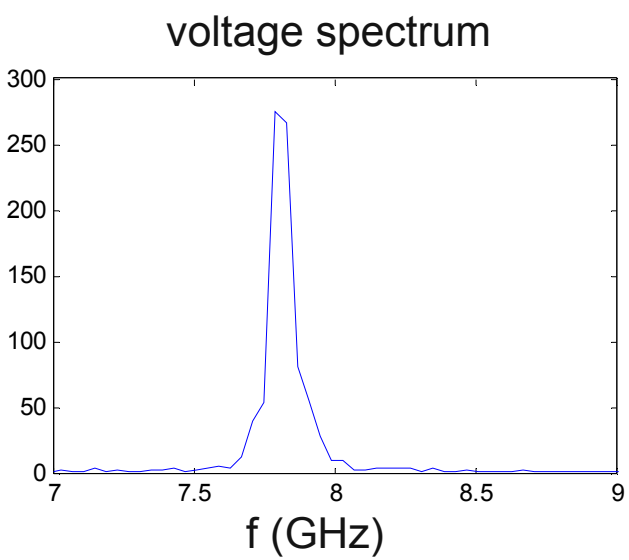
RF Power Generated by Interleaved Bunch Trains

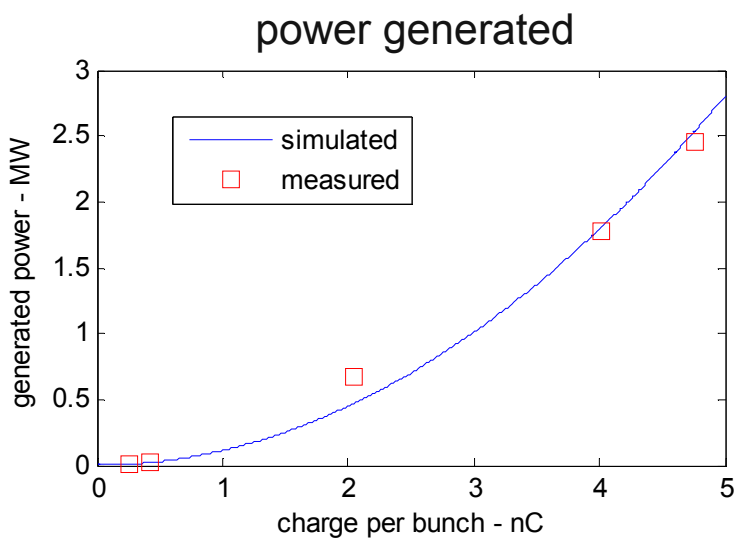


RF Power Generated by 16 Interleaved Electron Bunches



2.4 MW generated
2.2 MW extracted



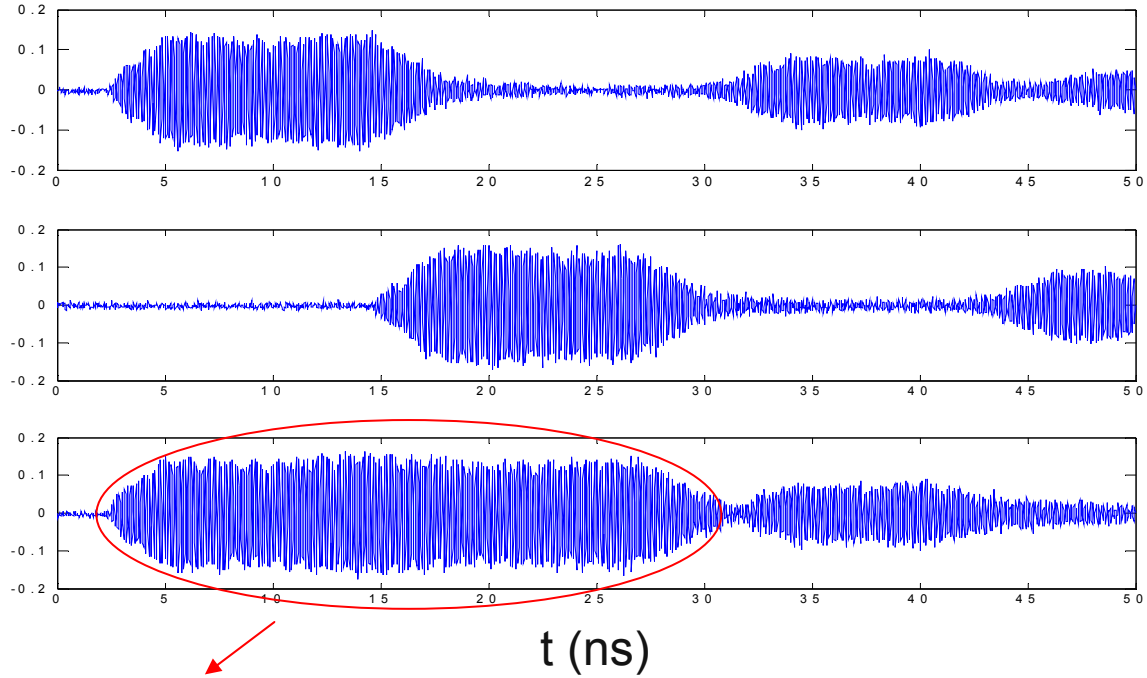


RF Power Generated by Sequential Bunch Trains

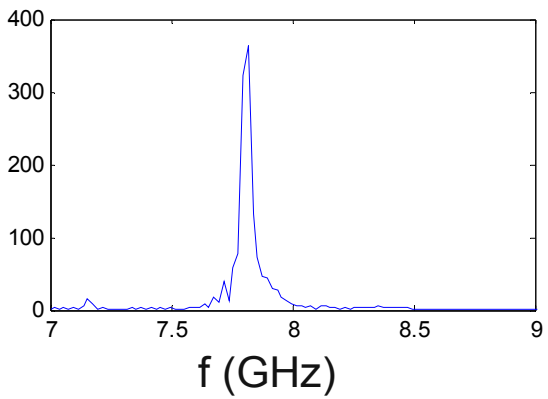
Train A

Train B

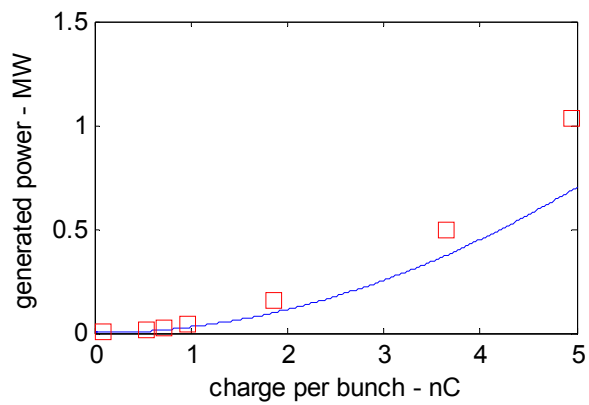
A & B



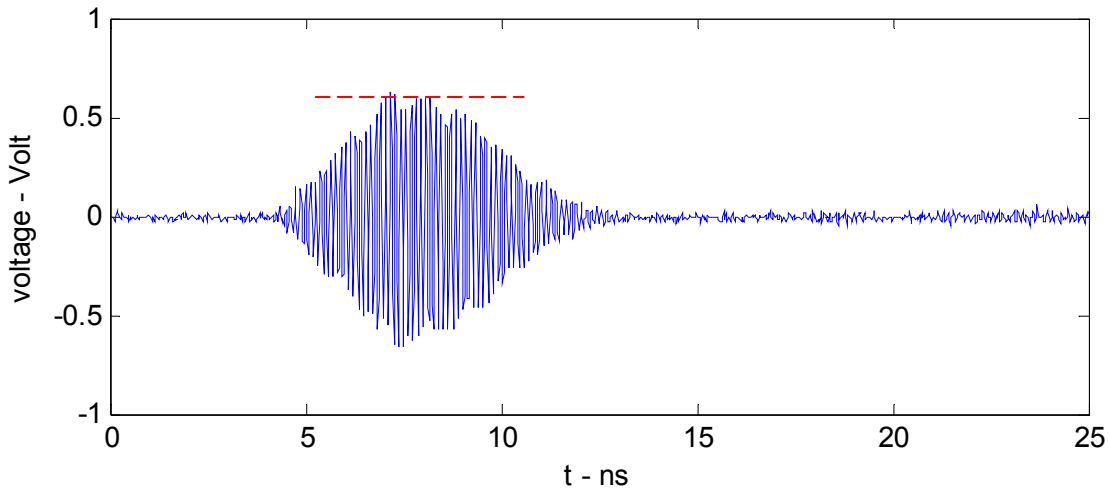
voltage spectrum



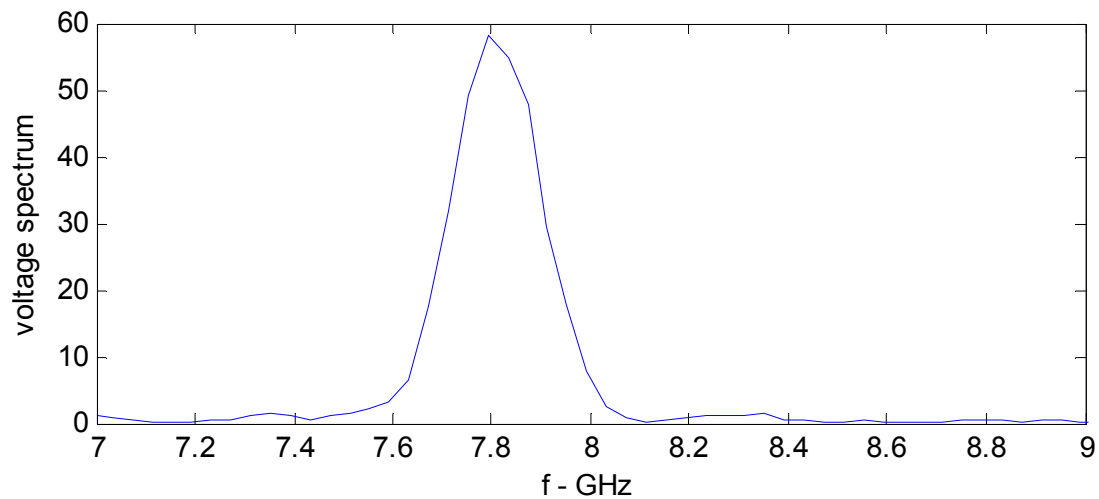
power generated



RF Power Generated by Four Bunches (107 nC total charge)



44 MW generated
40 MW extracted



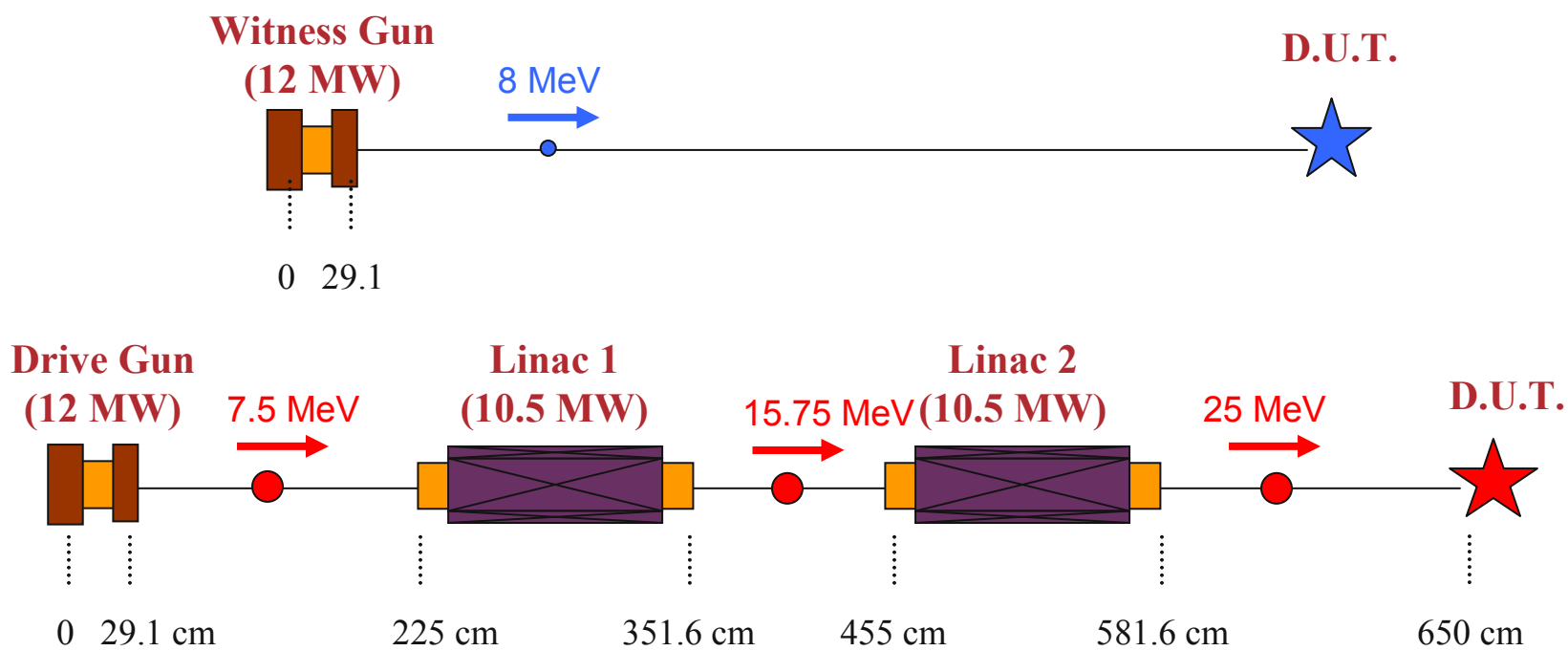
How long should the RF pulses be?

- We have shown that dielectric structures (even not brazed) can withstand 100 MV/m for a few nanoseconds.
- It has been seen (at CTF2) that metallic structures may not have breakdown problems at time scales of 10 ns (a few 100 MV/m).
- It may be worth reexamining the attractiveness of short RF pulses and short structures, if the gradients are high enough. (Considering that civil construction is a very large part of the total cost of a large accelerator.)
- Needs high gradients (> 200 MV/m) with not-high-precision structures (cheaper), with enough bandwidth. High repetition rate would be necessary for high luminosity.

Where we go from here

- Remember that the dominating factor in enabling progress in electron beam driven wakefield schemes is the drive beam.
- To improve the drive beam, we are currently upgrading the AWA facility:
  - A new L-band 1.3 GHz RF station to increase the drive beam energy from 15 to 25 MeV.
  - Fabrication of Cesium Telluride high quantum efficient photocathodes to produce long, high charge bunch trains.
- Once the upgrade is complete, the goal is to achieve:
  - Higher gradient excitation: ~ 0.5 GV/m in structures (3 mm apertures)
  - Higher RF power extraction: ~ 1 GW (10 ns)

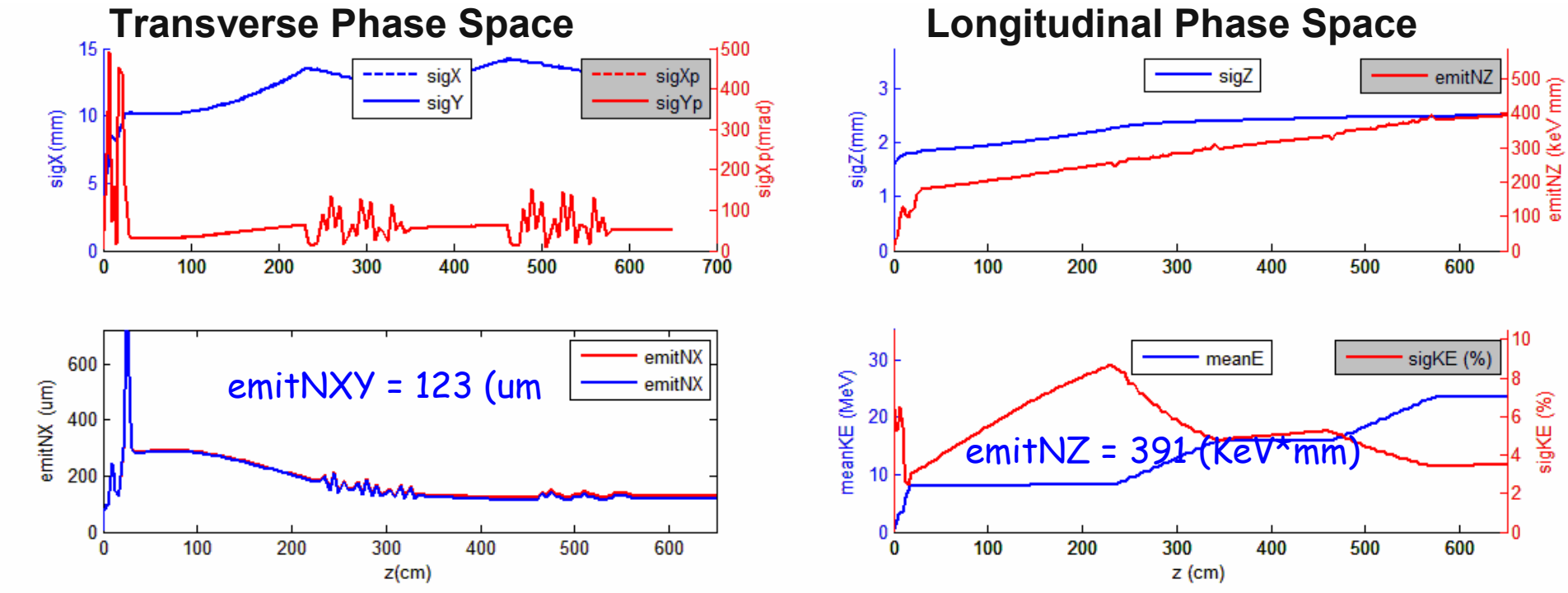
Future AWA Facility (25 MW + 25 MW = 50 MW)



Single Bunch: 50 - 100 nC
Bunch Train: 16 – 64, total charge 1 – 2.5 μC

*all distances in cm

Future Drive Beam Capabilities



<u>Long Phase Space at End</u>

σ_Z = 2.497 (mm)
σ_{KE} = 3.499 (%)
σ_{NZ} = 391.919 (keV*mm)
<E> = 23.504 (MeV)
Zloc = 650.000 (cm)

Q = 100 nC

Laser = Gaussian
FWHM = 8 psec

New 30 MW RF Station (1.3 GHz)

Klystron, solenoid and HV Transformer

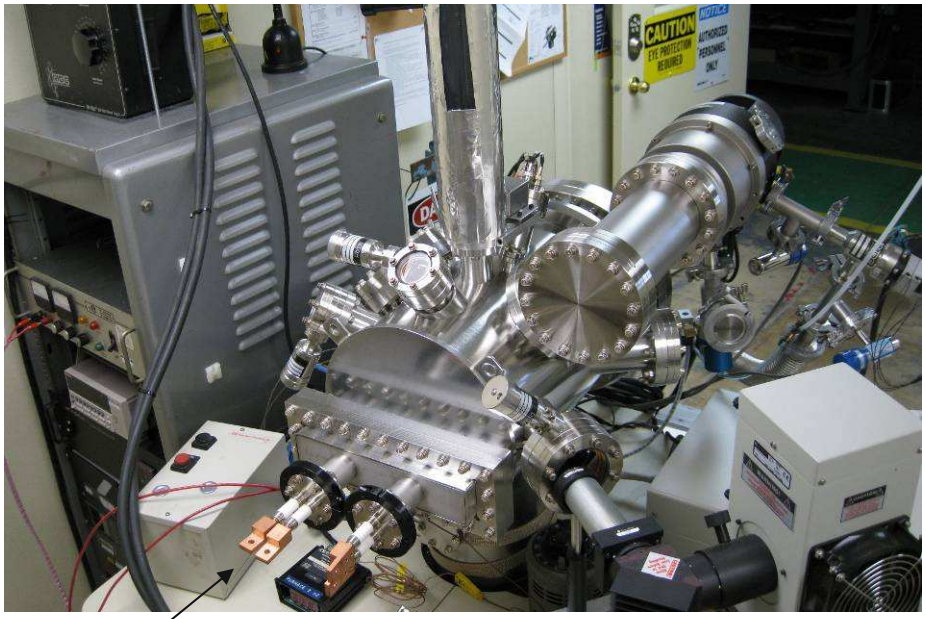
HV cabinet, thyratron, capacitors

constant current charging supply

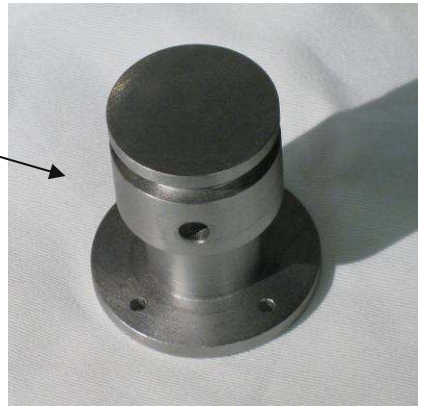
Not shown:

- RF circulator, waveguides

Cesium Telluride Photocathode Fabrication



Molybdenum substrate



arc discharge lamp

magnetic actuator

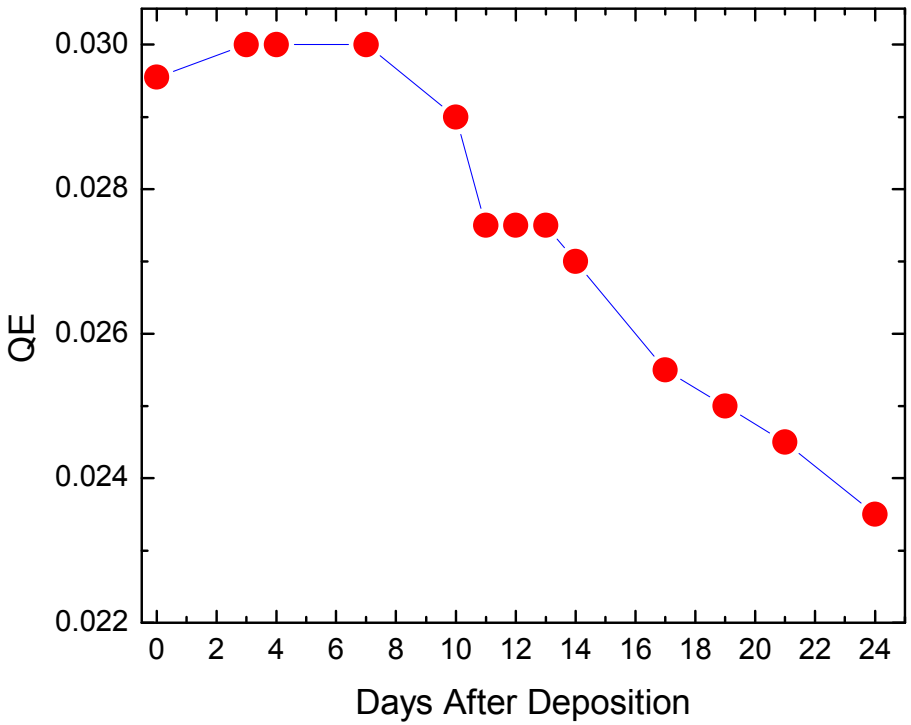
Cs dispenser

gate valve

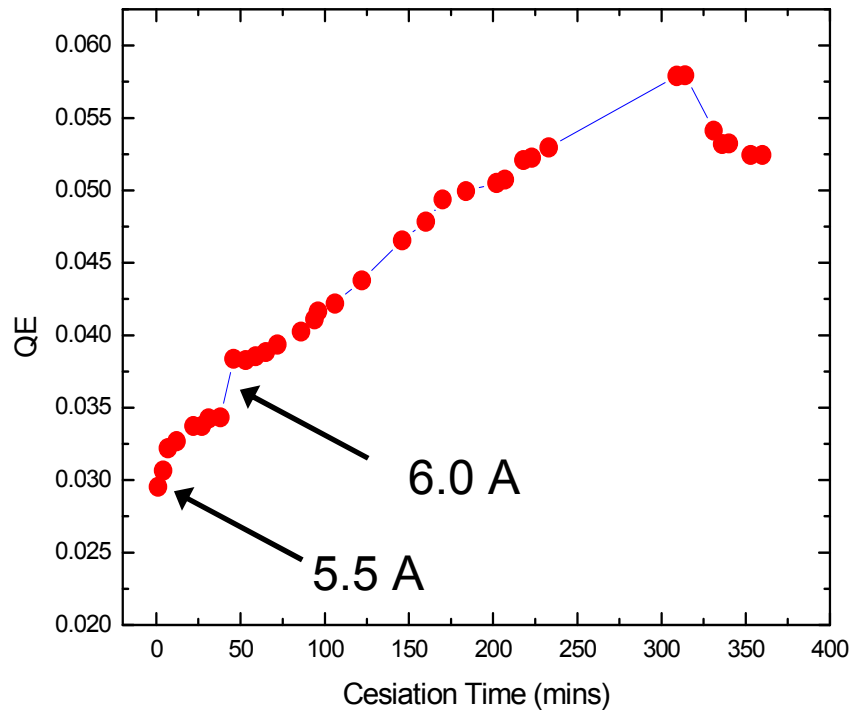
Te dispenser

Quantum Efficiency Measurements

Cs_2Te Deposition on 06/29/07



Re-Cesiation on 7/25/07



Goal is to have operation with QE ≥ 1%

Concluding remarks:

- High gradient (100 MV/m) in dielectrics has been achieved. Generation of RF power using beam driven dielectric structures is progressing well.
- AWA is undergoing upgrades that will enhance its capabilities:
  - Construction of new RF station.
  - High QE photocathode (Cs_2Te) fabrication, for high charge bunch train generation.
- In addition to high gradient experiments, outside users have been using the facility for advanced accelerator, high brightness beam diagnostics, beam instrumentations and laboratory astro-physics experiments.
- R&D at AWA is relevant to future HEP accelerators.

Significant and steady progress being made in the development of Dielectric Wakefield Accelerators!

Some goals of the AWA program:

- Verify that structures can withstand gradients higher than 100 MV/m.
- Generation of ~ GW level RF power (25 MeV, 130 Amps, 10 ns, 3 GW beam power).
- Demonstrate high gradient, broad bandwidth, low cost structures (power extractors and accelerators).
- Typical parameters:
  - f = 10 – 30 GHz, Vg = 5 – 20%
  - Required power: 0.5 – 5 GW peak
  - Example (for dielectric based structure):
    - 21 GHz, a = 3 mm, b = 4 mm, ε=12, Vg=0.112
    - For Ez=200 MV/m, it requires P= 1 GW
    - 16 ns RF pulse, structure length : 30 cm, fill time = 8.4 ns
    - Beam loading (fundamental mode):0.75 MV/m/nC