Advanced Accelerator R & D Activities at ANLHEP

Wei Gai

For Accelerator R&D Group, HEP, ANL
Feb 16, 2006
AARD Review

Argonne National Laboratory

Office of Science
U.S. Department of Energy

A U.S. Department of Energy
Office of Science Laboratory
Operated by The University of Chicago

Outline

I. Introduction/History

II. Argonne Wakefield Accelerator Facility Activities

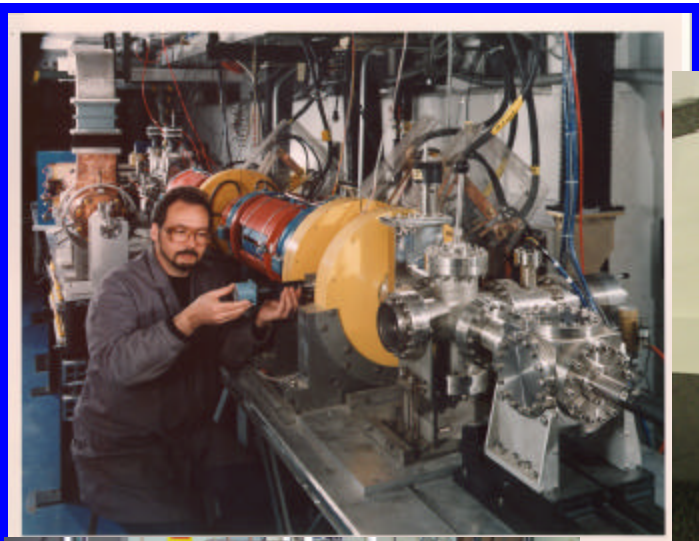
III. High Gradient Dielectric Experiments at NRL

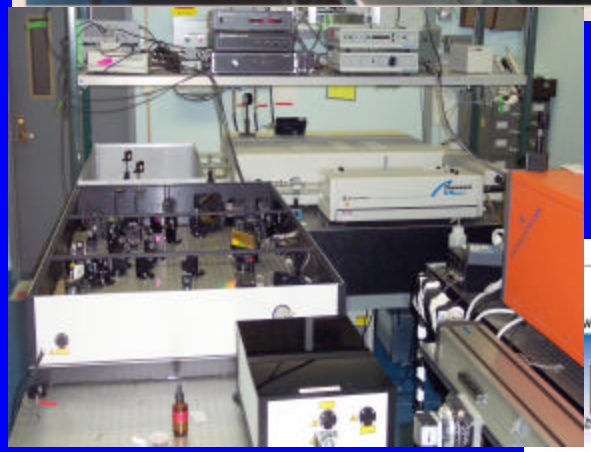
IV. Collaborate with other institutions / user program.

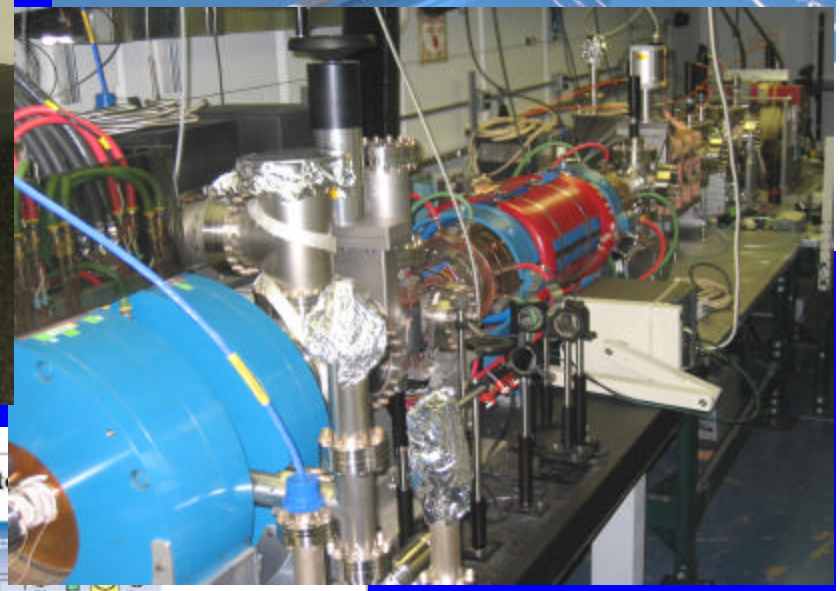
V. Summary

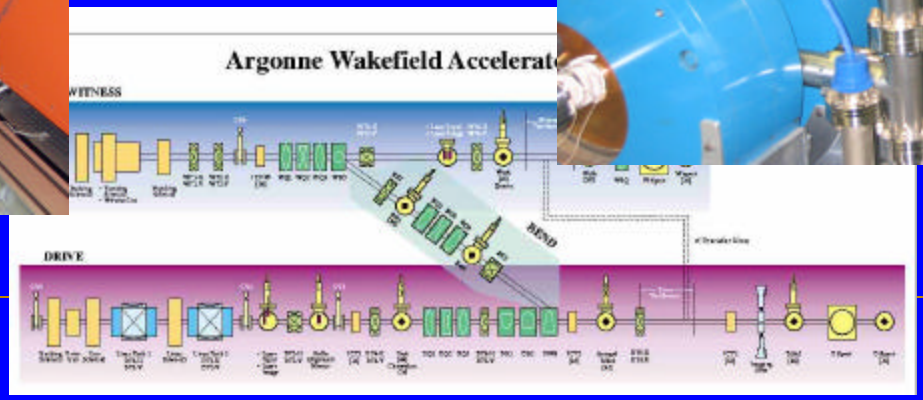
I. Introduction & History

Mission: Studying Physics and Inventing Technologies for Future HEP Accelerators.









Research Focus

1. Advanced Accelerating Structures

1. **Comprehensive dielectric structure program** → theory & simulation, construction & high-power testing.
2. **Novel structure investigation** → photonic band gap, left-handed meta-materials.

2. High-Power/High-Brightness Electron Beams

1. **Fundamental Beam Physics** → beam generation, propagation, & characterization.
2. **High-current beam production** → for beam-driven wakefield acceleration & RF generation schemes.
3. **Beam dynamics in wakefield structures** → BBU control

3. Support of existing HEP programs

1. **Positron source for ILC**
2. **Lab Astrophysics**
3. **Providing facilities for external user's research program.**

The Group

Staff/Engineer: (7)

W. Gai (group leader), M. Conde, R. Konecny, W. Liu (visiting scientist), J. Power and Z. Yusof, C. Jing (supported by Euclid).

Current Students: (3)

Graduates: F. Gao, Supported by Research fund, H. Wang, Supported by LDRD fund, S. Antipov, Supported by IIT Physics

Technician: (1)

F. Franchini

Support:

Strong Support from ANL Management (3 LDRDs)

Mechanical/Electrical/Laser: HEP, Chem and APS resources (0.5 FTE)

ES&H: HEP safety coordinator.

Previous Ph. D. Thesis Students: (7): Ph. D. students: C. Jing, 2005, Euclid ; P. Zou, 2002, Intel; N. Barov, 2000, Far-Tech; E. Colby, 1998, SLAC; J. Power, 1996, ANL; C. Ho, 1993, Siemens Medical; J. Rosenzweig, 1987, UCLA.

Recent Masters and Undergraduates: G. Beztel (NIU), MS, J. Hsin , J. Walsh, seniors, Physics (UChicago). T. Quan, EE senior , (Purdue). More this summer.

List of Accomplishments

Wakefield Acceleration Program

- Developed the direct wakefield (drive-witness) measurement technique
- Demonstrated many wakefield acceleration scheme
  - *collinear wakefield acceleration in dielectric & metallic structures, and plasmas*
  - *dielectric-based two-beam acceleration*
  - *multimode wakefield acceleration*
  - *enhanced transformer ratio with a ramped bunch train*
  - …
- First observation of plasma wakefield acceleration in underdense regime (non-linear) (with UCLA)

RF Photocathode Gun Development

- Operating a 100 nC RF photocathode gun and linac
- Generated and transported both flat and ramped high-current pulse trains
- Observed Schottky-enabled photoelectron emission in RF gun

Advanced Accelerating Structure Development

- First high-power test of dielectric traveling wave accelerators (at NRL);
- Discovered new multipactoring regime in dielectric structure.
- Invented ways to couple the RF into the structures.

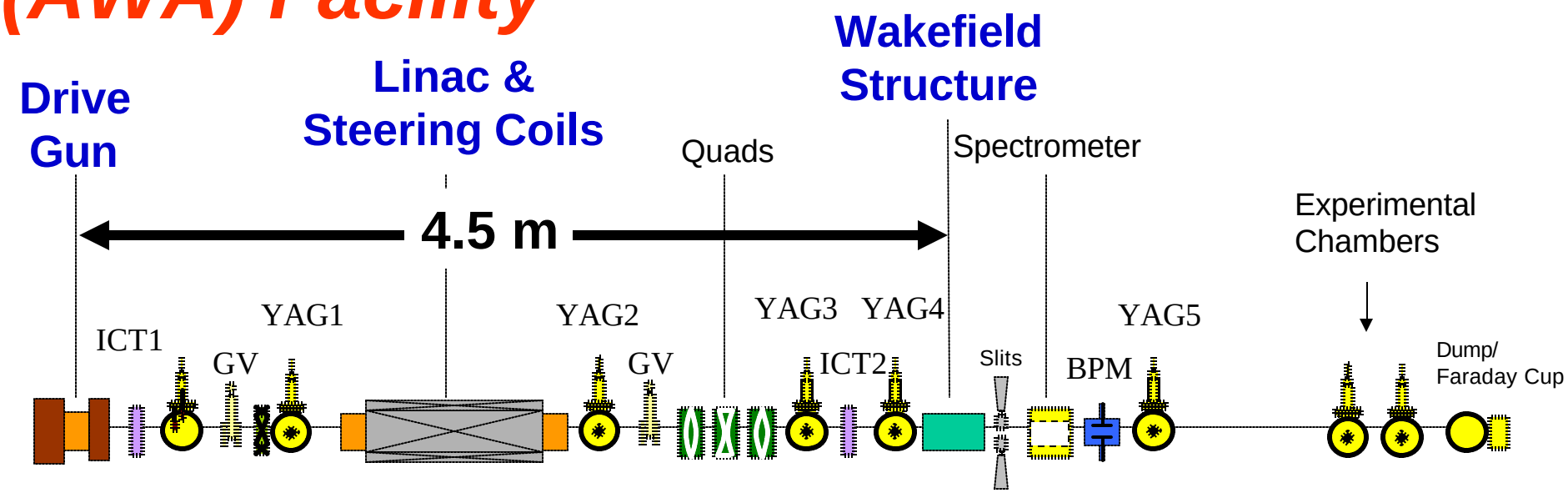
Other notable contributions:

- TESLA Test Facility photoinjector.
- First wakefield measurement of a detuned SLAC/NLC structure
- Laboratory astro-physics experiment.
- Beam dynamics modeling of the ILC positron beam.

Collaborations

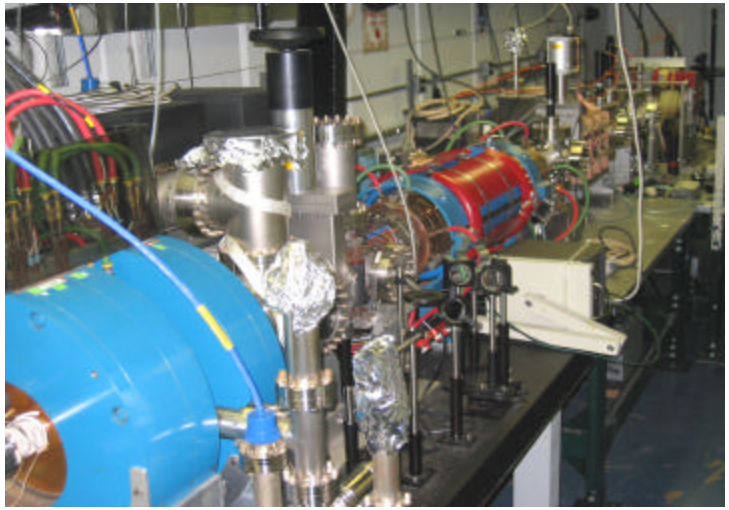
- **Naval Research Lab/SLAC/Tsinghua Univ.**
  - A dedicated X-band facility to test X-band dielectric structures established with SLAC's help. Advanced structure development.
- **ANL APS and ES Division**
  - High quality electron FEL applications and positron beam generation studies for LC and BES research. ILC accelerator issues.
- **CERN and DULY Research Inc.**
  - High power generation using dielectric as decelerator. (SBIR funded)
- **Euclid Concepts**
  - High dielectric constant material development and engineering processing. Tunable dielectric materials. Ramped bunch train experiment (SBIR funded).
- **Univ. of Chicago, Hawaii/UCLA**
  - Laboratory astrophysics, Radio and fluorescence astrophysics.
- **Illinois Institute of Technologies and UT Austin**
  - Advanced structure studies.
- **Maryland and NIU**
  - Diagnostics on high intensity and high brightness beam.

*The Argonne Wakefield Accelerator (AWA) Facility**



Single bunch operation

- Q=1-100 nC
- Energy=14 MeV
- High Current = 10 kAmp



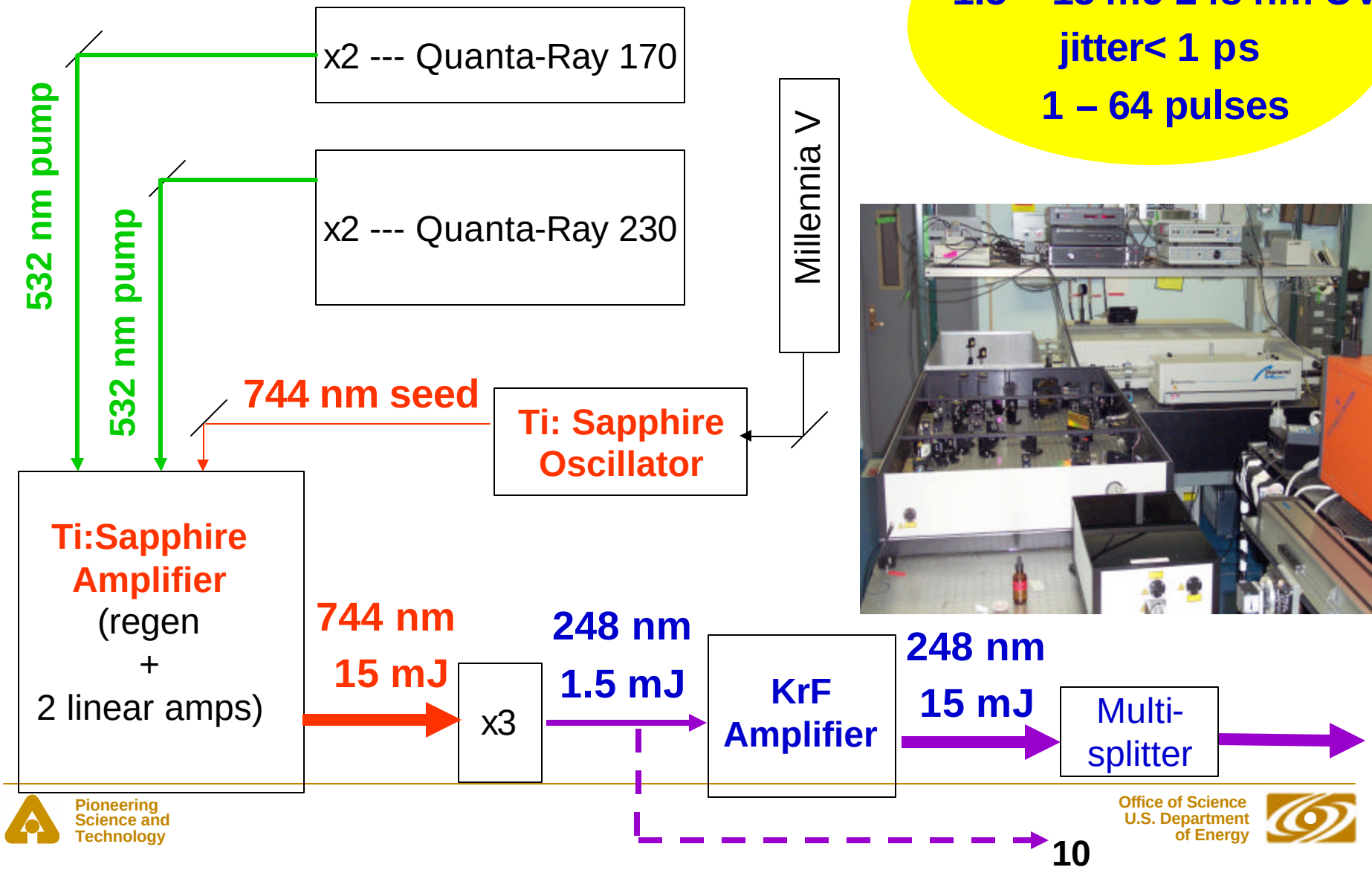
Bunch train operation

- 64 bunches x 50 nC → 50 ns long

***World's Highest Q RF Photoinjector**

AWA Photocathode Laser System

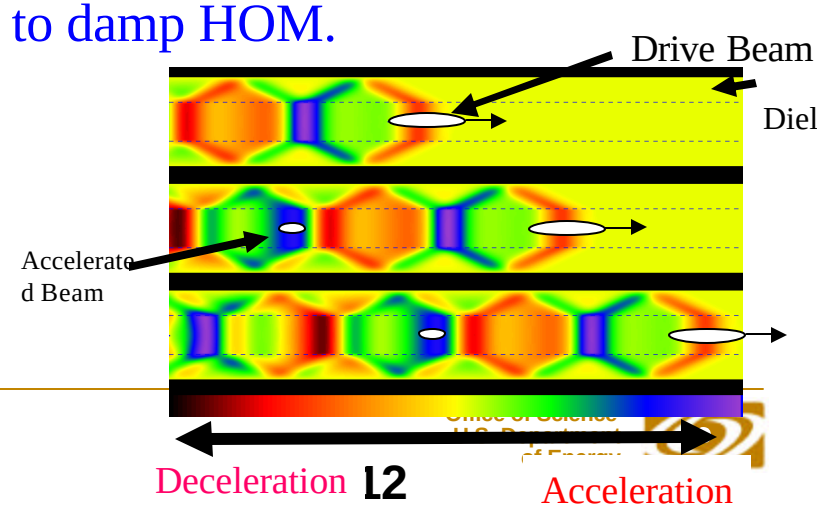
8 ps FWHM
1.5 – 15 mJ 248 nm UV
jitter< 1 ps
1 – 64 pulses



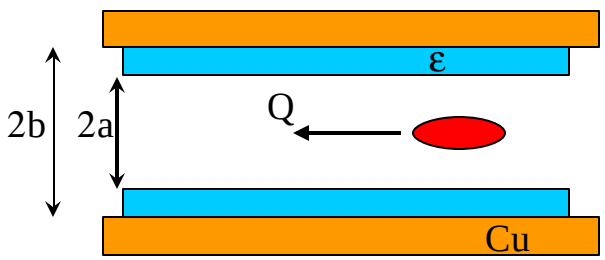
II.
Argonne Wakefield Accelerator Facility Activities

Electron Beam Driven Wakefields

- **A new way to power the accelerating structure by transporting the power in the electron beam.**
- **Advantages over RF powered structures**
  - Short pulse operation can increase the breakdown threshold.
  - More material options:
    - *Low Q and high Q structures produce the same wakefield. More material options.*
    - *Low and high group velocity structures can both be used for wakefield acceleration.*
  - Simpler geometry, easy to construct, easy to damp HOM.
- **Applications**
  - ***Collinear wakefield acceleration***
  - ***Two-beam acceleration***



(#1) Wakefield Scaling in Structures



$$W_Z(z) \approx \frac{Q}{a^2} \exp\left[-2\left(\frac{p\ s_z}{l_n}\right)^2\right]\cos(kz)$$

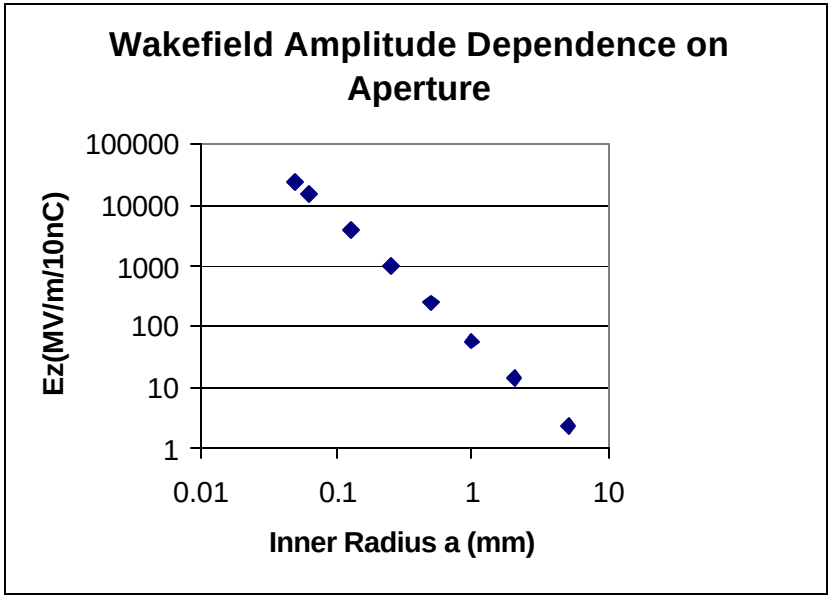
$$s_r = \left(\frac{e_N}{g} b\right)^{1/2}$$

Keys to the success:

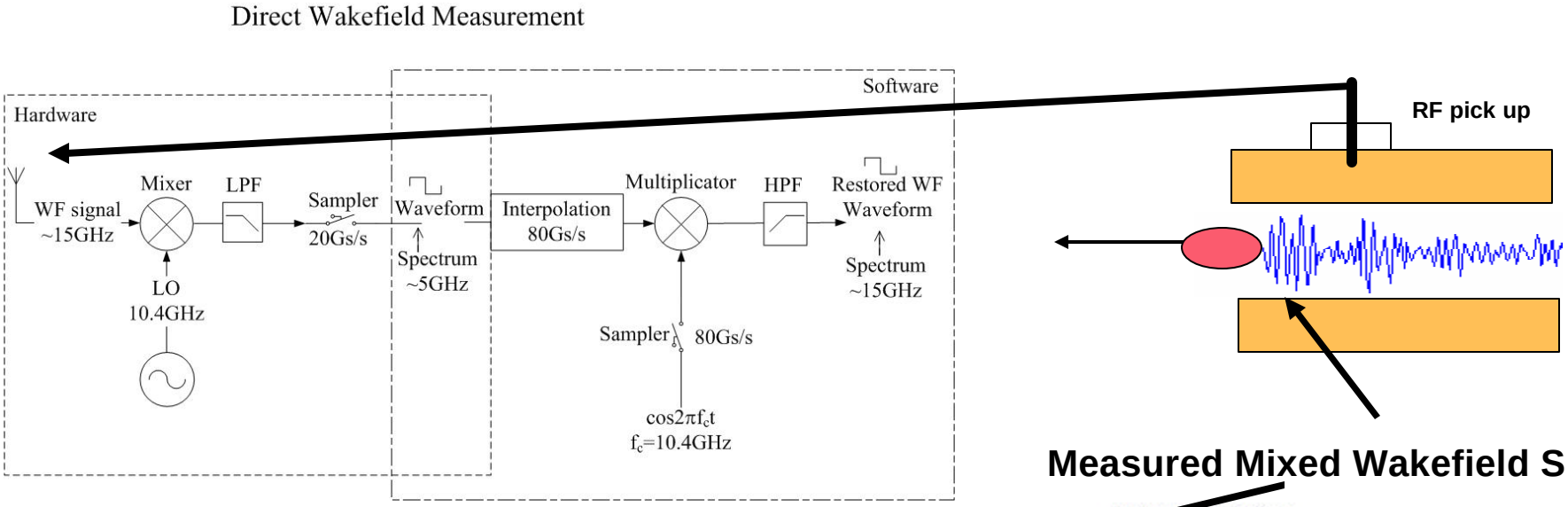
Drive beam, drive beam and drive beam!

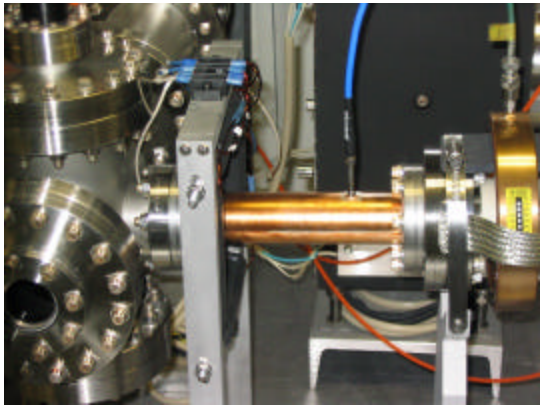
- *Energy* -
- *Charge* -
- *Bunch length* –
- *Emittance* –

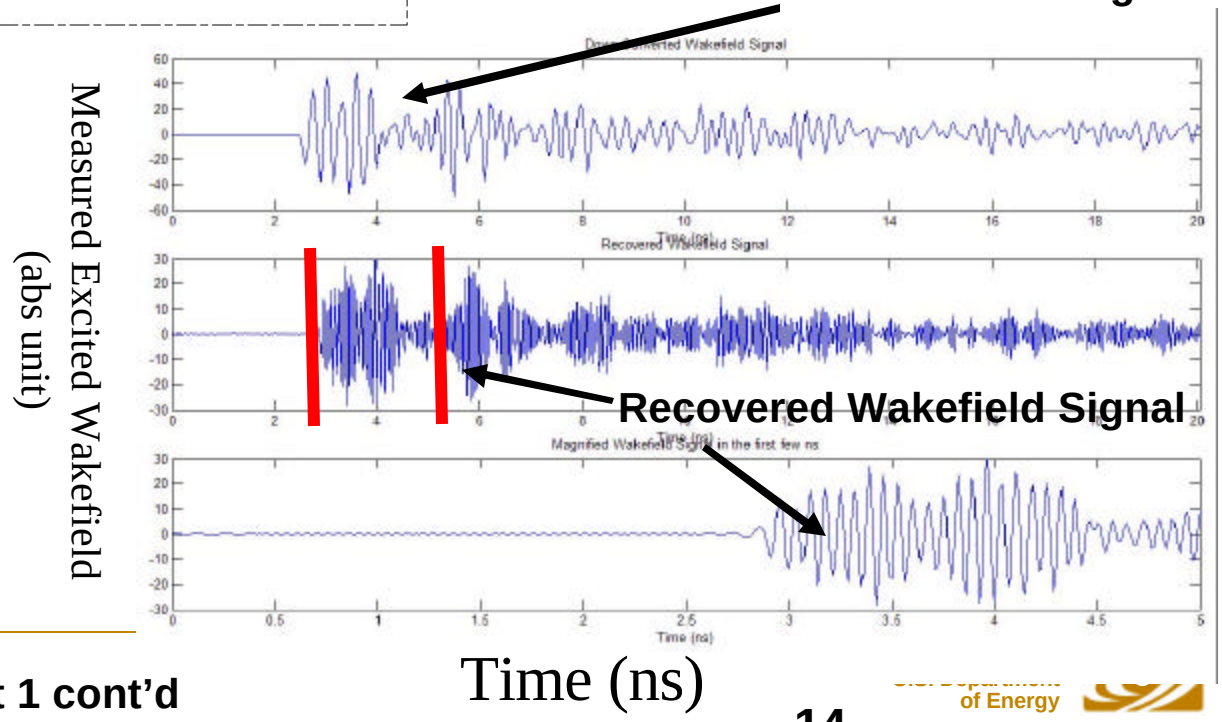
10 nC a=0.1 mm ? 5 GV/m. But our current beam limited our structure ~ a=2-5 mm.



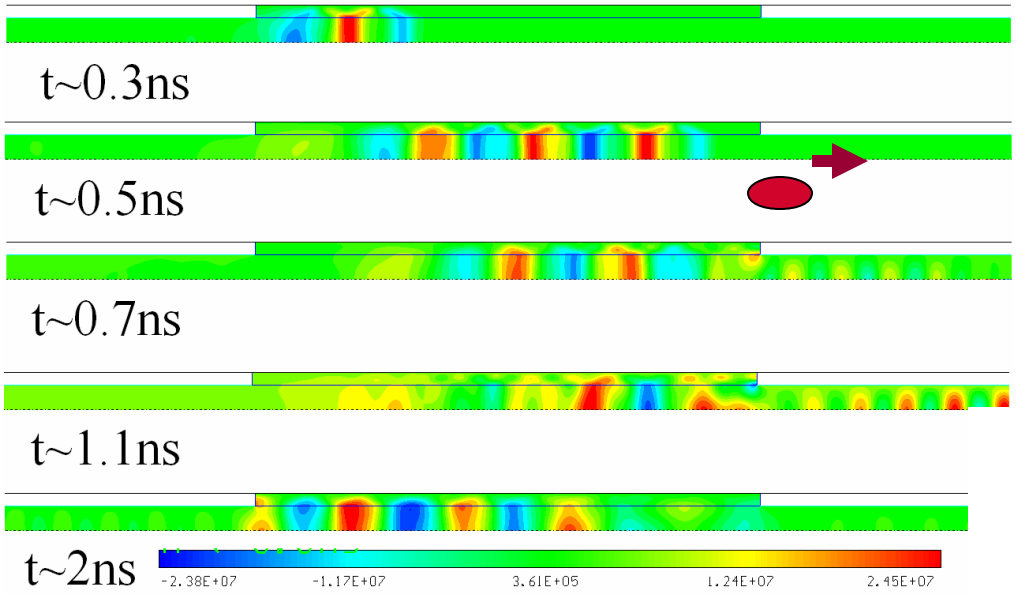
(#1) Wakefield signal detection



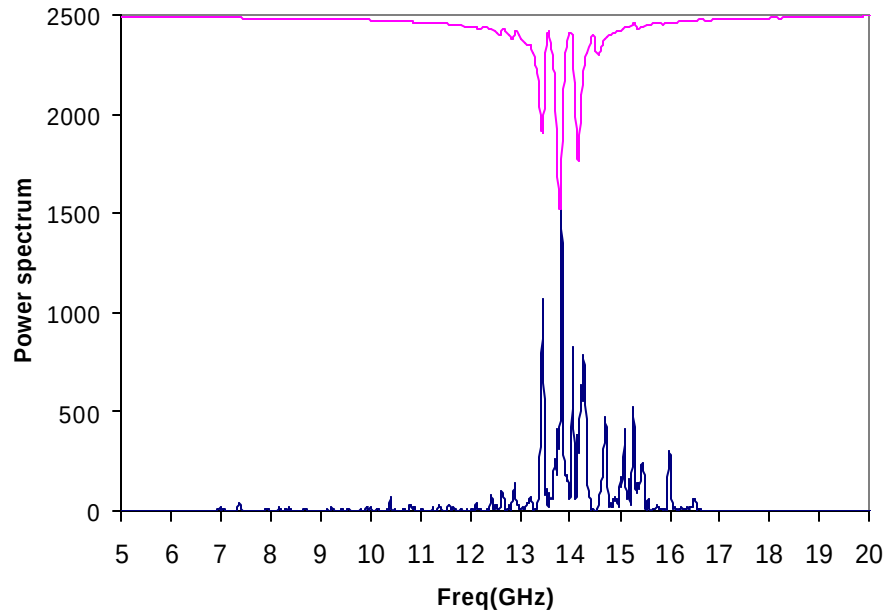




(#1) Comparison of Spectrum with Simulation



Waveform and Spectrum of the Simulated Wakefield signal



Most Recent Result:

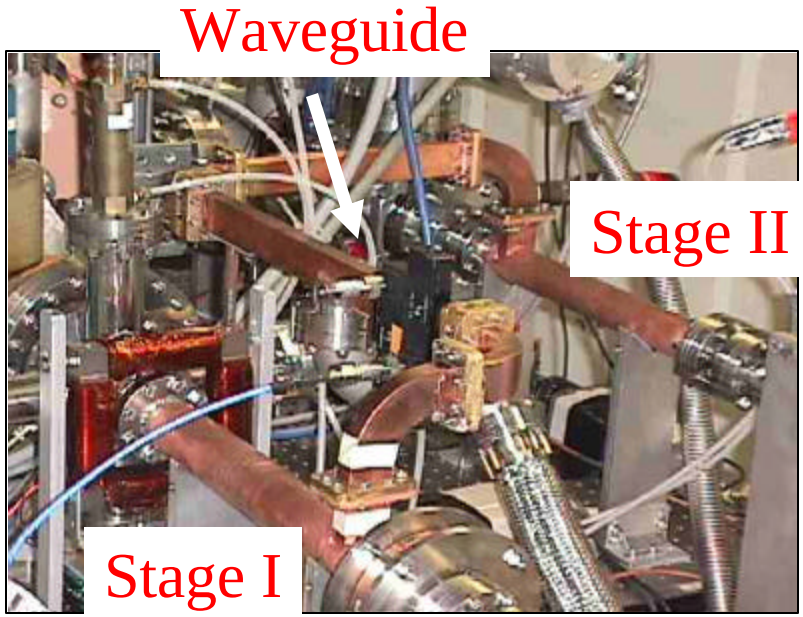
Doubled gradient from last year:

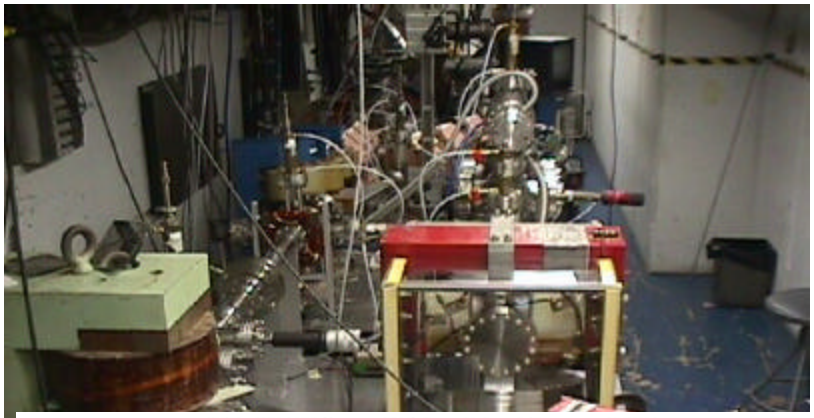
83 nC ~45 MV/m (2006)

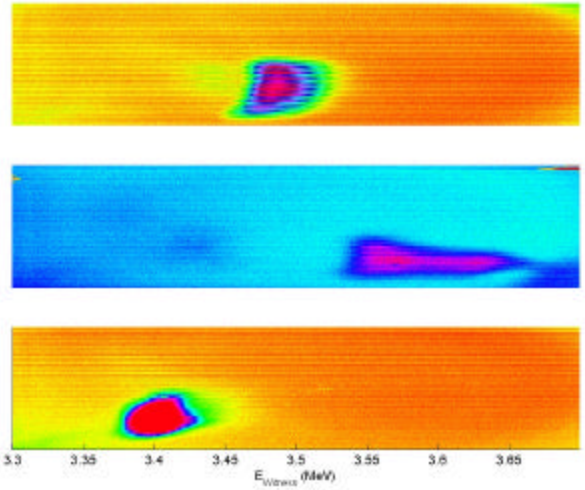
(#1) Heading toward +100 MV/m

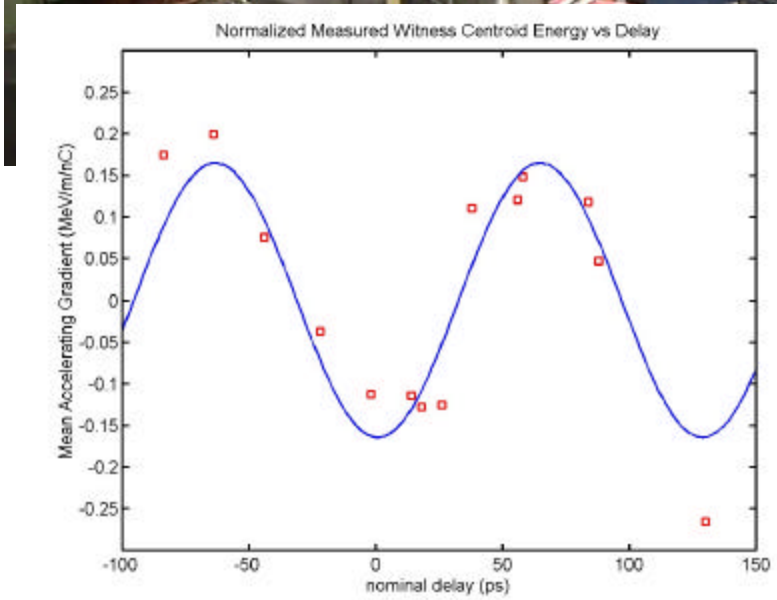
- **Progress so far…**
  - Acceleration Gradient ~10 MV/m before initial completion of facility upgrade (prior to 2004)
  - Acceleration Gradient to ~20 MV/m (doubled in 2005)
  - Acceleration Gradient to ~45 MV/m (doubled in 2006)
- **Next steps…**
  - Smaller structure aperture
  - Improved beam quality
  - Pulse train development
  - Implement CsTe Cathode

(#2) Dielectric Two-beam Acceleration Experiment (2000)

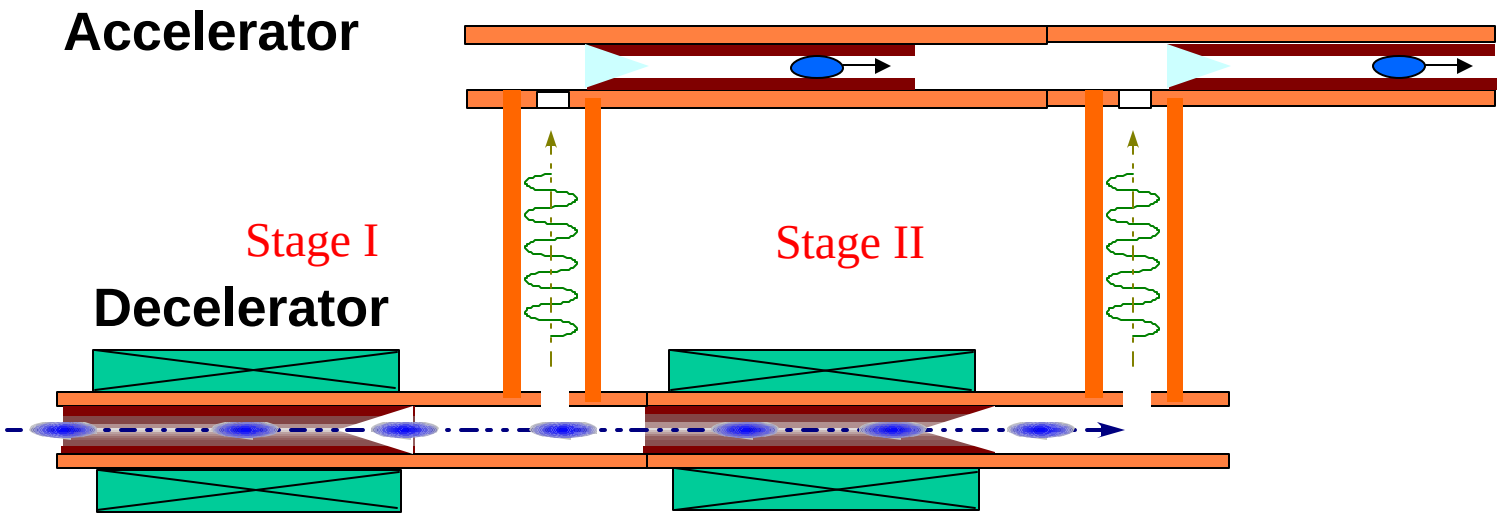








(#2) Planned Two-beam, Staged, Acceleration Experiment

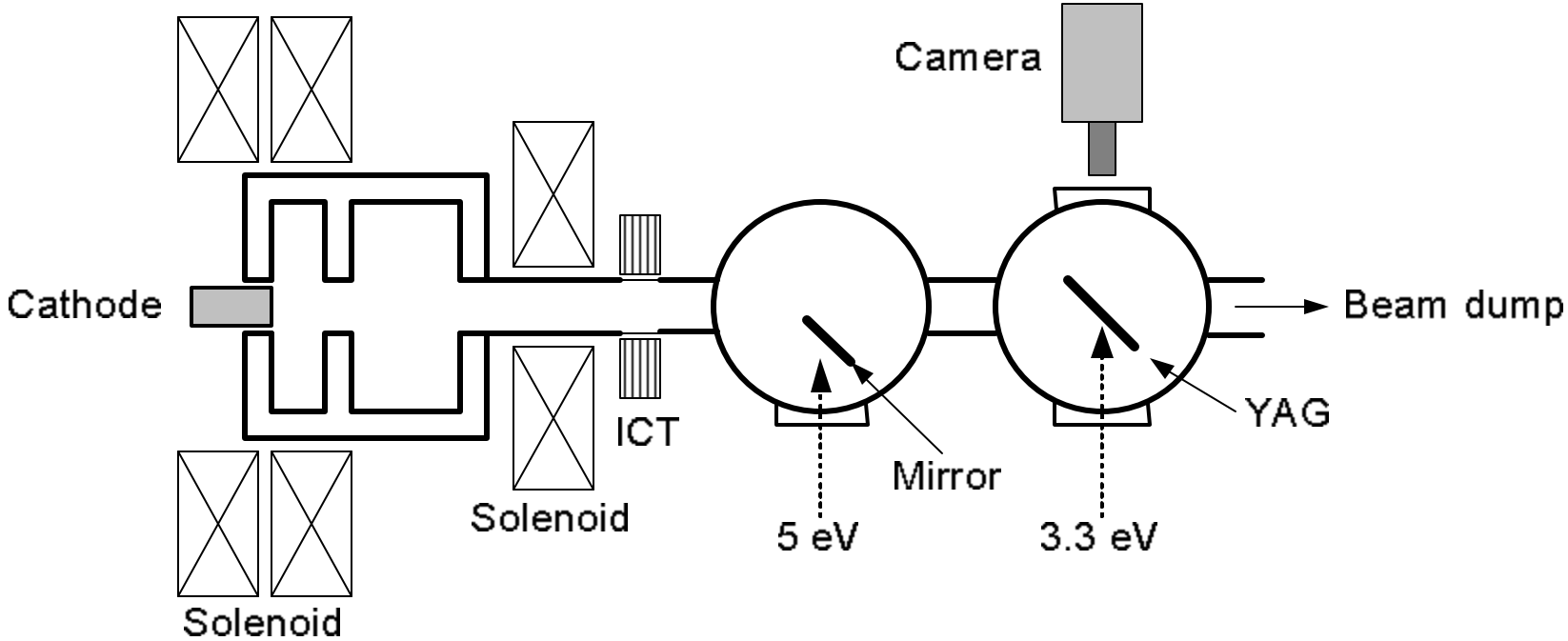


2 stage example:

Drive beam: 64 bunches of 50 nC, each separated by 0.78 ns, total 50 ns long.

Total energy gain: ΔE=120 MeV (2 deceleration & 2 acceleration stages

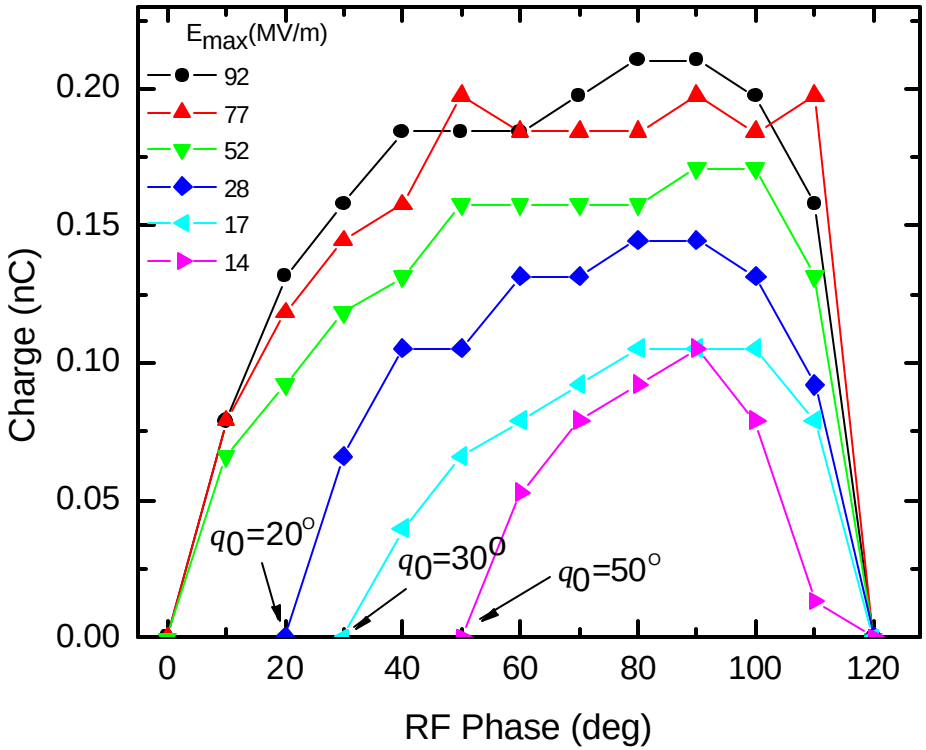
(#3) Schottky-Enabled photoemission: Generating electrons with low energy photons.



1. ***High brightness electron beam – minimize thermal emittance from cathode.***

2. ***Experimental Determination of Mg photocathode Field enhancement ß (PRL 09/04)***

(#3) Determining the Field Enhancement Factor



$$Q \propto \left[hn - \Phi + a\sqrt{bE(q)} \right]^2$$

$$E(q) = E_{max} \sin(q)$$

$$a = \sqrt{e/4pe_0}$$

At threshold, Q = 0. This allows us to make a reasonable estimate of the maximum b.

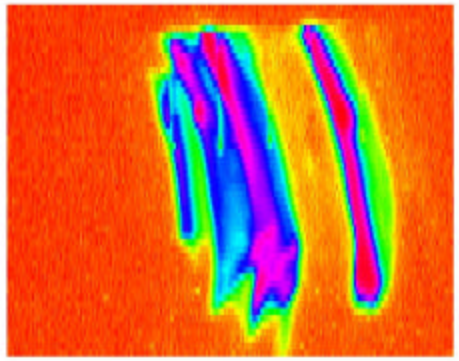
q_0 (deg)	E_{max} (MV/m)	$E_0 = E_{max} \sin(q_0)$ (MV/m)	b
20	28	9.2	6.8
30	17	8.5	7.3
50	14	11	5.8

hn = 3.3 eV; Φ = 3.6 eV

This is a *new* and viable technique to realistically determine the field enhancement factor of the cathode in a photoinjector

(#4) High Brightness Beam Developments: Measurements and Applications.

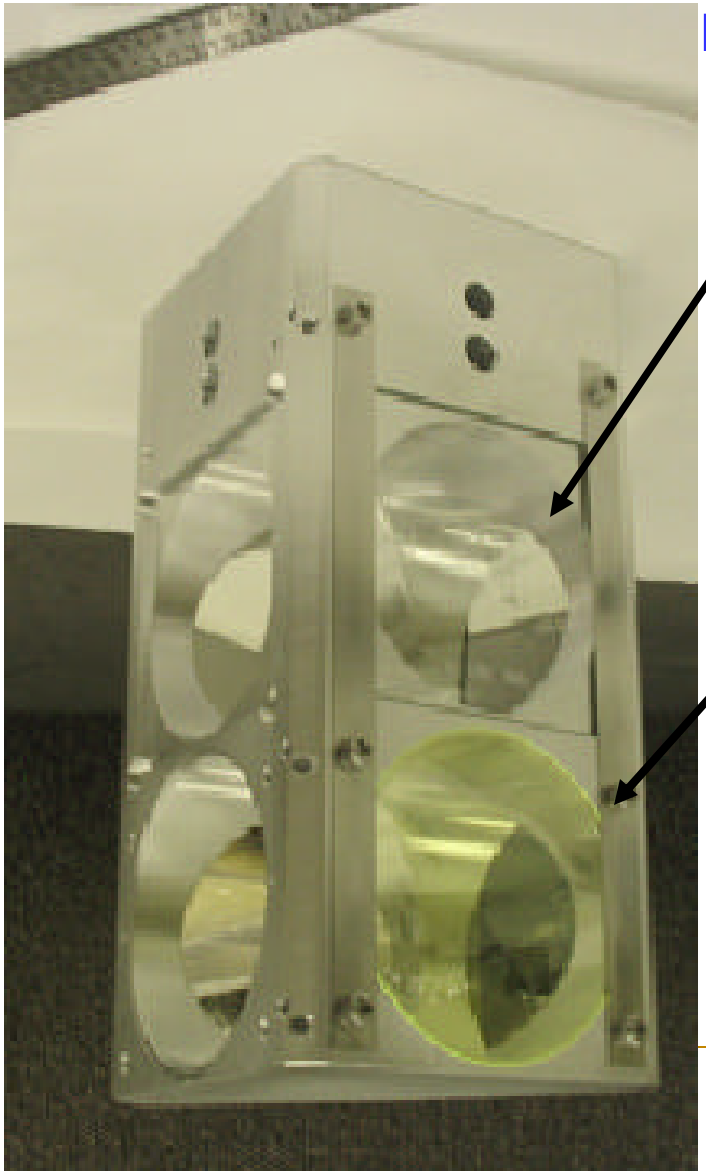
1. **AWA Operation is outside of well-establish (~1nC) photoinjector parameter space**
   - **Single bunch:** Q_0 = 1 nC – 100 nC; ε_n = 5 mm mrad – 180 mm mrad; Z_{FWHM} = 6 psec – 13 psec;
   - **High-current pulses train:** 2-64 pulses (Q up to 50 nC).

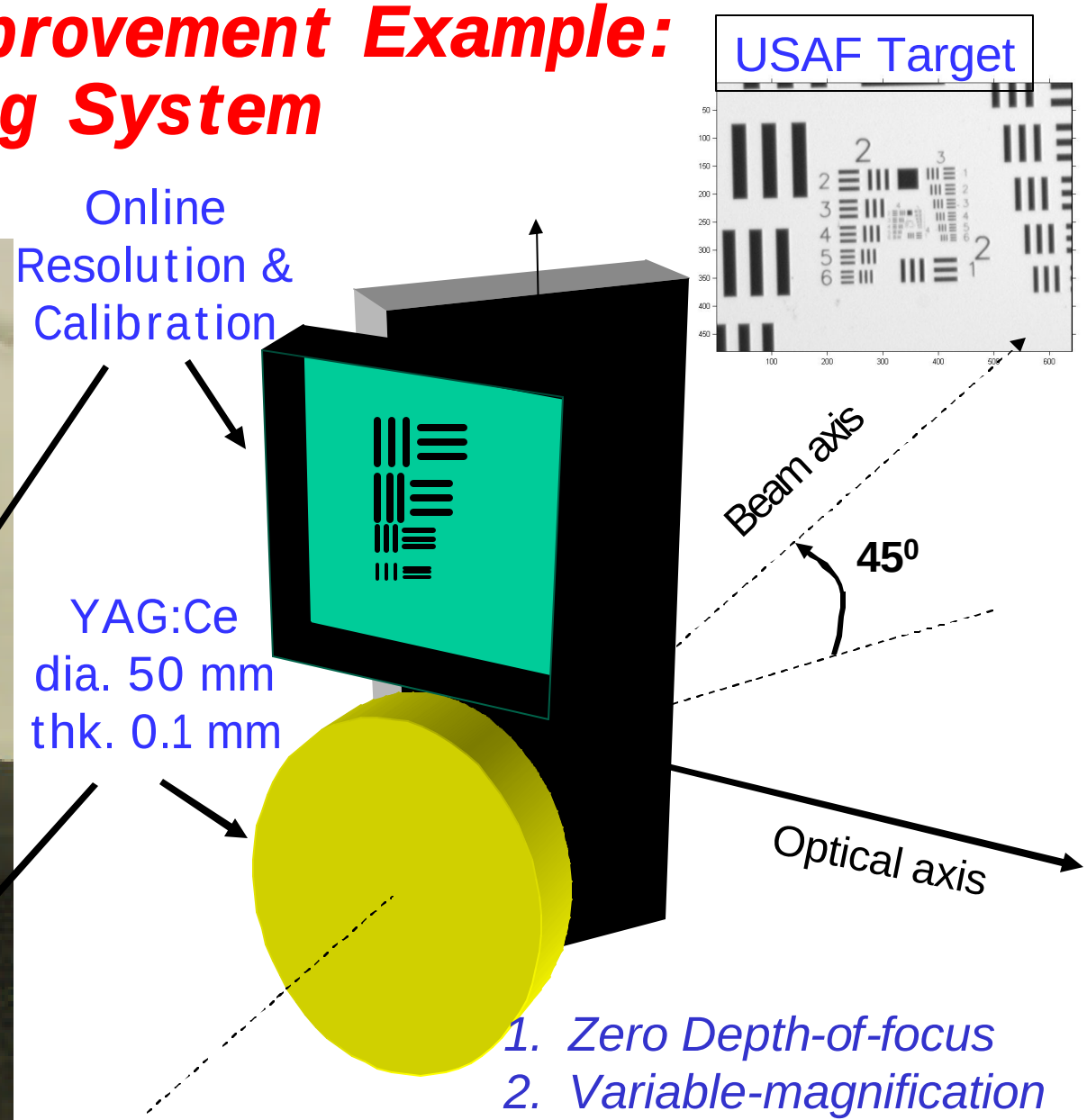


Spectrometer with 4 beams

2. **Challenging characterization and modeling**
   - Diagnostics must cover a large dynamic range
   - Beam properties must be understood over the length of the pulse train
3. **Development of new beam diagnsotics**
   - 2x2 pepper pot grid for 4D phase space measurement
   - OTR-like emittance diagnostic for (low γ regime) photoinjector (UMD)
   - Time resolved BPM using EO effect (NIU)

(#4) Facility Improvement Example: Upgraded Imaging System





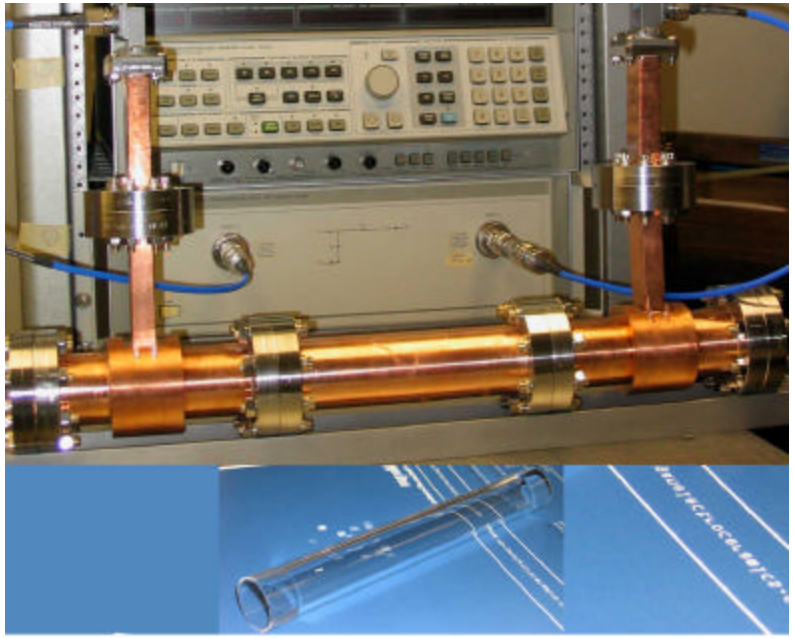
1. *Zero Depth-of-focus*
2. *Variable-magnification*
3. *Improved light collection*

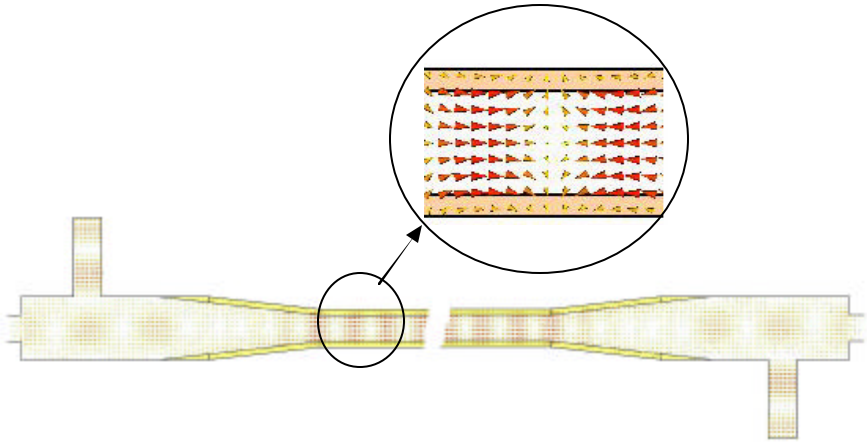
III. High Power Testing of External RF Driven Dielectric Loaded Accelerating (DLA) Structures Using NRL 11.4 GHz Magnicon

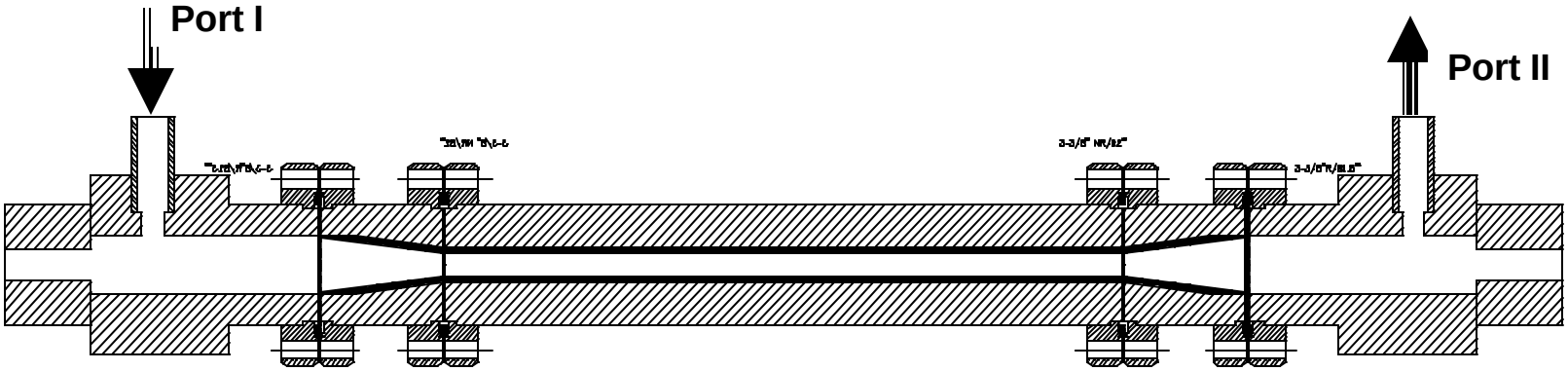
Motivation:

We seek to gain fundamental physics understanding of dielectrics operating under high EM fields. This will help to determine if dielectric structures can provide an alternative to conventional accelerating structures.

Design, Construction and EM Simulations of the Modular DLA Structure







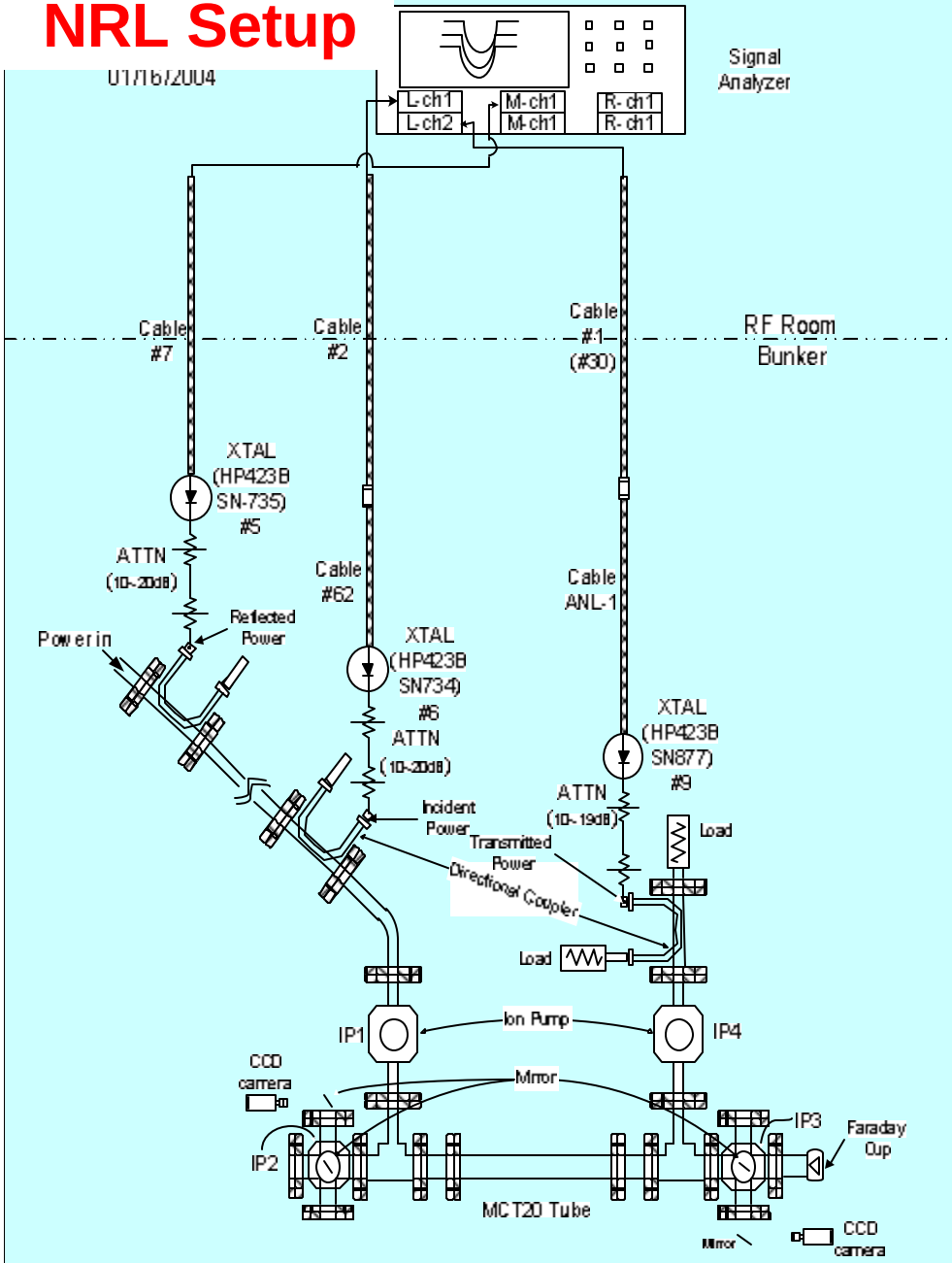
High Power Structures Tested at NRL

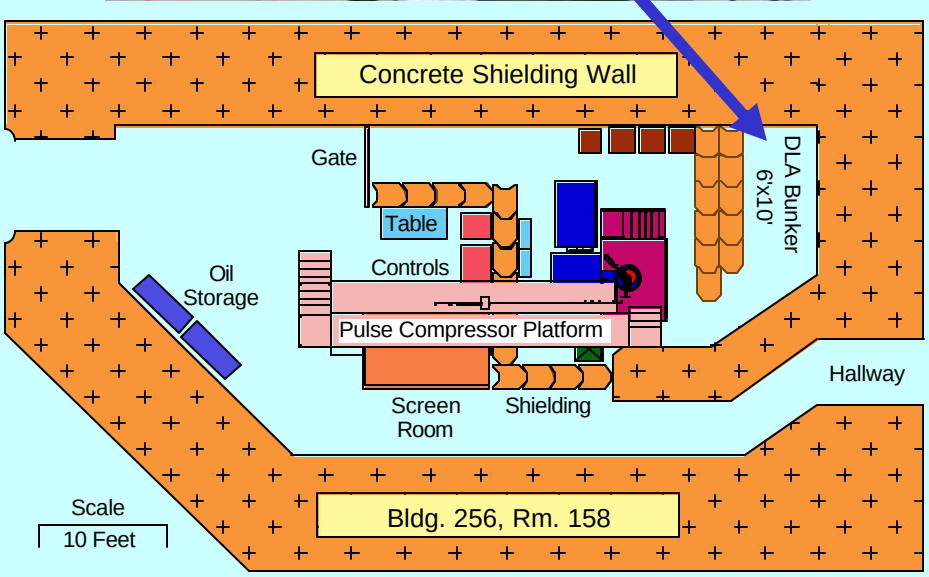
Material	Al_2O_3	$Mg_xCa_{1-x}TiO_3$
Dielectric constant	9.4	20
Loss tangent	$2x10^{-4}$	$3x10^{-4}$
Inner radius	5 mm	3 mm
Outer radius	7.185 mm	4.567 mm
R/Q	6.9 k? /m	8.8 k? /m
Group velocity	0.134*c*	0.057*c*
RF power for 1MV/m gradient	80 kW	27 kW
Demonstrated Gradient	8 MV/m	7.2 MV/m
Principal Problem	Multipactor	Breakdown at joints

→Next Step:

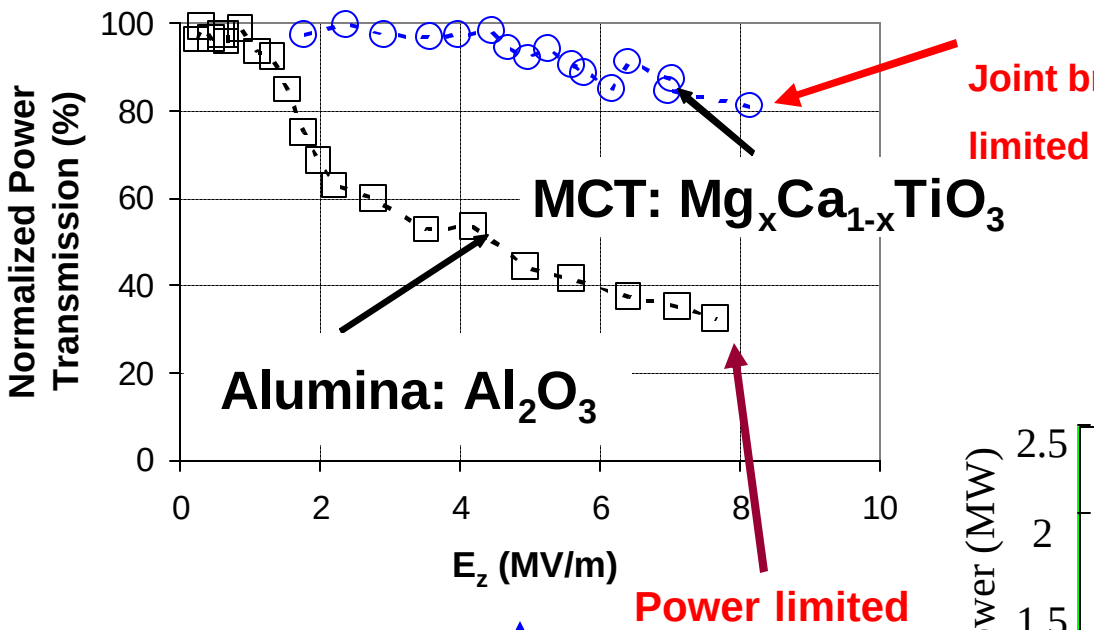
- →Quartz, Cordierite, TiN coated,…
- →More structures (different coupling schemes)
- →Commission a compact DLA accelerator

NRL Setup


01/16/2004
Signal Analyzer
L-ch1
L-ch2
M-ch1
M-ch1
R-ch1
R-ch1
Cable #7
Cable #2
Cable #1 (#30)
RF Room
Bunker
XTAL (HP423B SN-735) #5
ATTN (10-20dB)
Cable #62
Cable ANL-1
Power in
Reflected Power
XTAL (HP423B SN734) #6
ATTN (10-20dB)
XTAL (HP423B SN877) #9
ATTN (10-19dB)
Incident Power
Transmitted Power
Directional Coupler
Load
Load
IP1
Ion Pump
IP4
CCD camera
Mirror
IP3
Faraday Cup
IP2
MCT20 Tube
Mirror
CCD camera

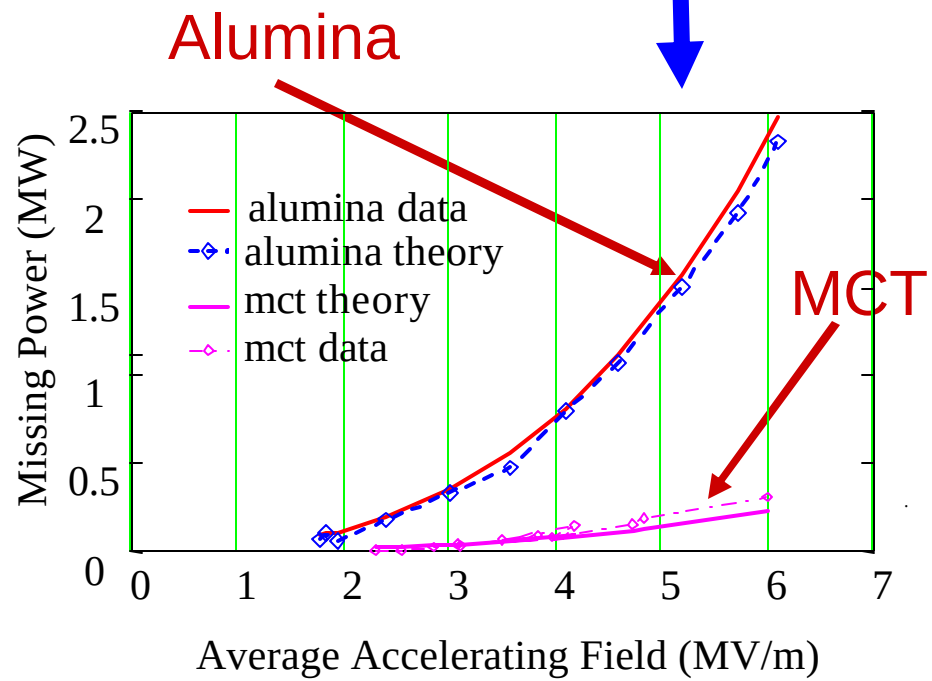

Concrete Shielding Wall
Gate
DLA Bunker 6'x10'
Table
Controls
Oil Storage
Pulse Compressor Platform
Hallway
Screen Room
Shielding
Scale
10 Feet
Bldg. 256, Rm. 158

*Discovered Anomalous High Power RF Absorption in DLA Structures due to New Multipactor Regime**



Measured RF Power Absorption

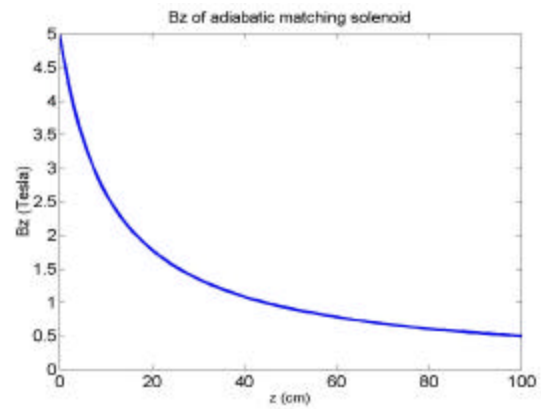
Absorption scales with aperture

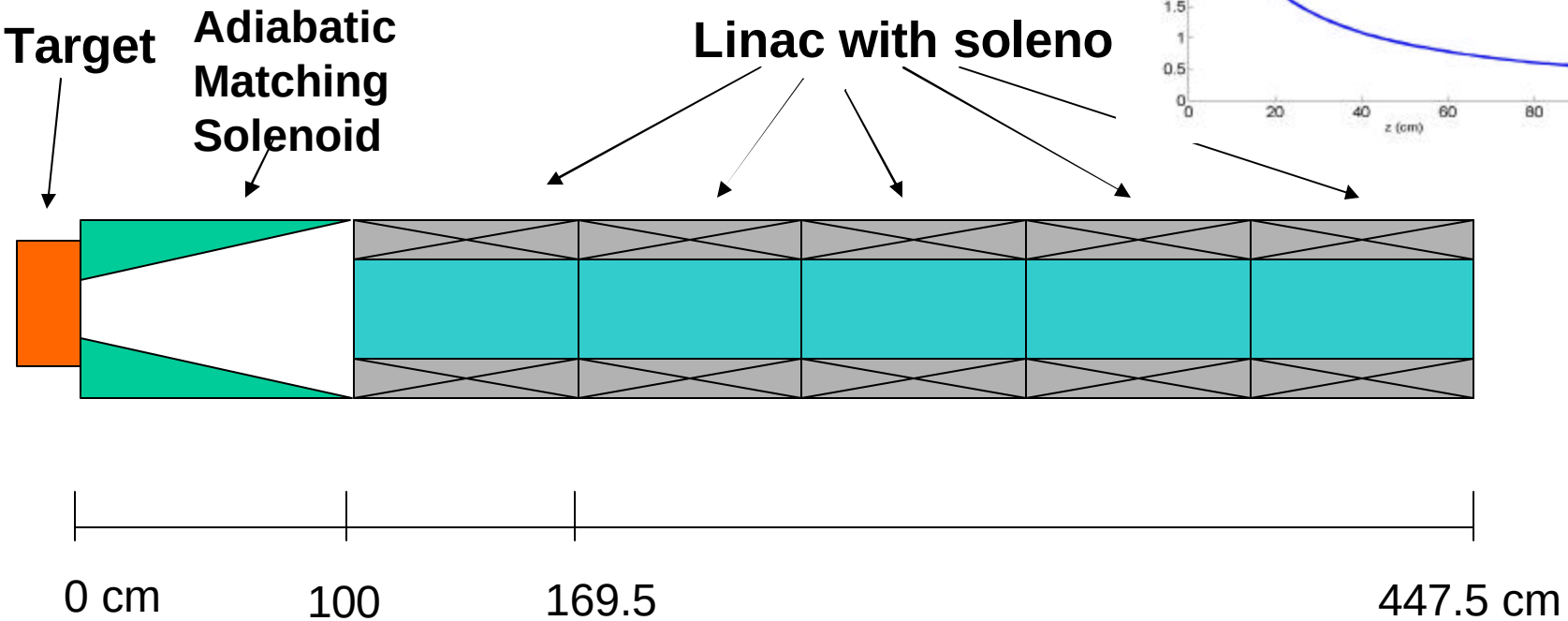


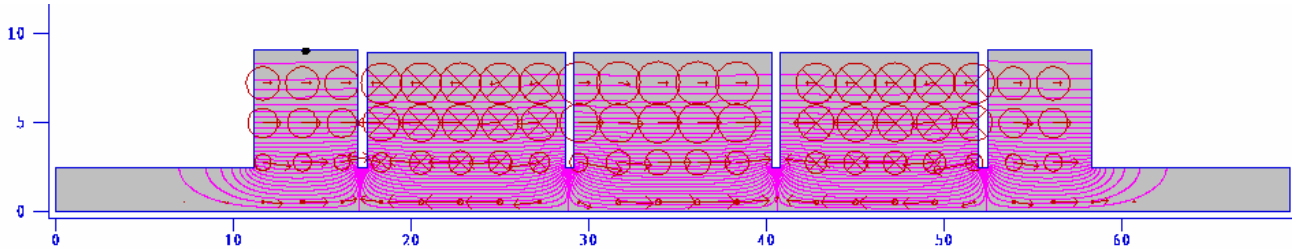
IV. Additional Activities

Schematic of Positron Source and Pre-Accelerator Layout for ILC

Target (1.4 cm Ti), Adiabatic Matching Solenoid (5 – 0.25 Tesla). 15 Linac Sections (~ 8 MeV each).

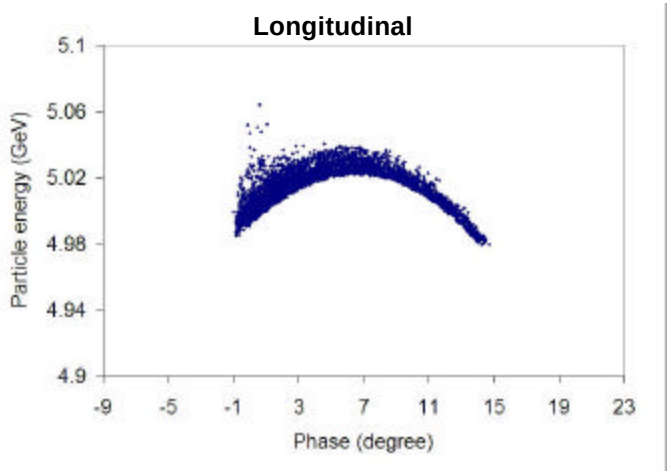


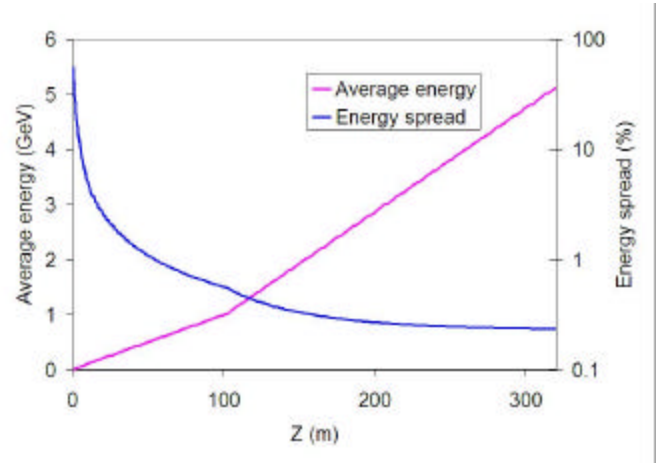


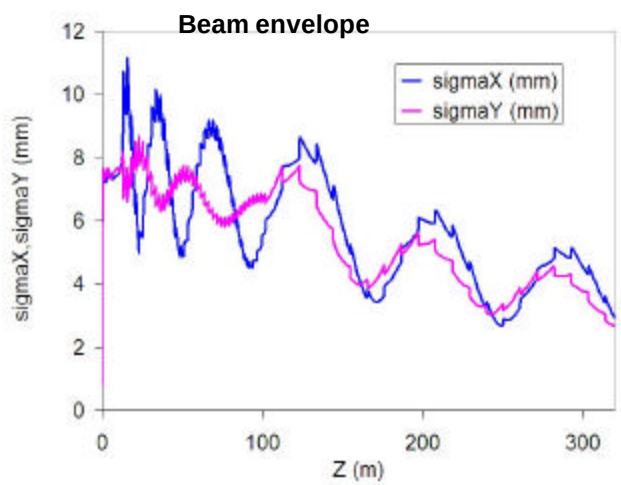


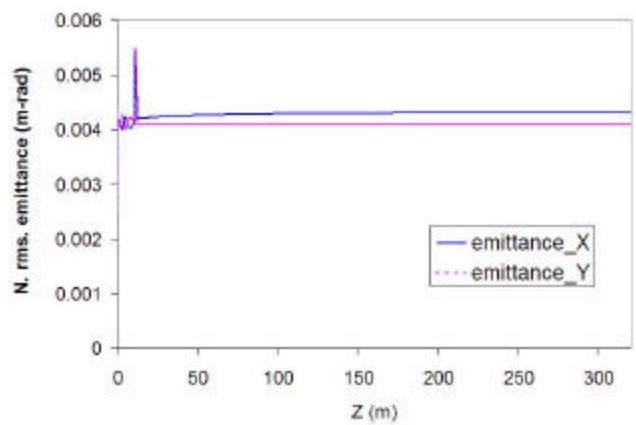
5 cell p mode iris loaded L band linac, the aperture D=5cm, T is about 0.74, E_0T=12MV/m, P=4.4MW. Total energy gain=8.4 MeV, Q=25000, r/Q=613 Ohm

6-D phase distribution @ 5 GeV (before the damping ring)







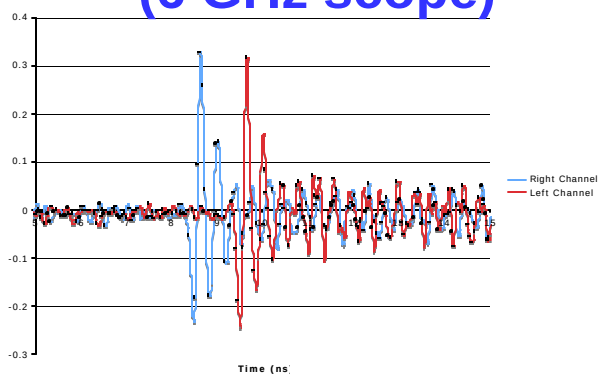


Undergraduate Student Projects at the AWA

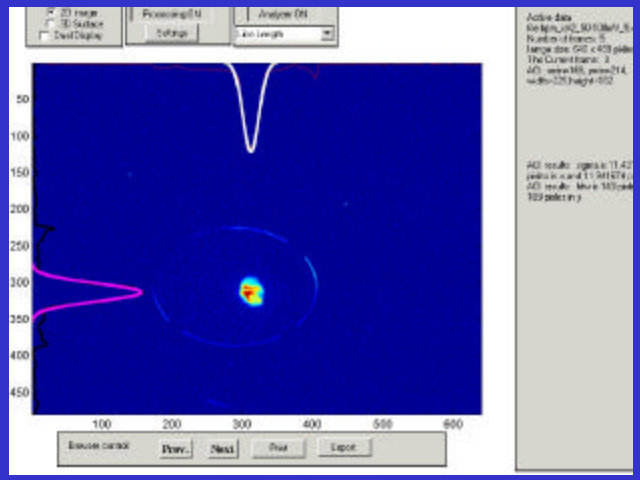
THE UNIVERSITY OF CHICAGO

1. Which diagnostic can measure the **beam-centroid** with better resolution, a YAG screen or a stripline? (J. Hsin)

Raw BPM signal (6 GHz scope)

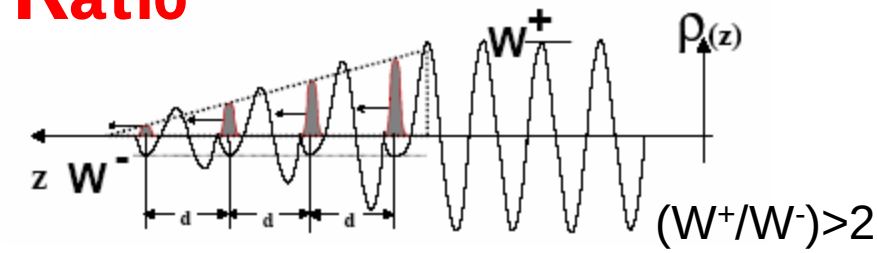


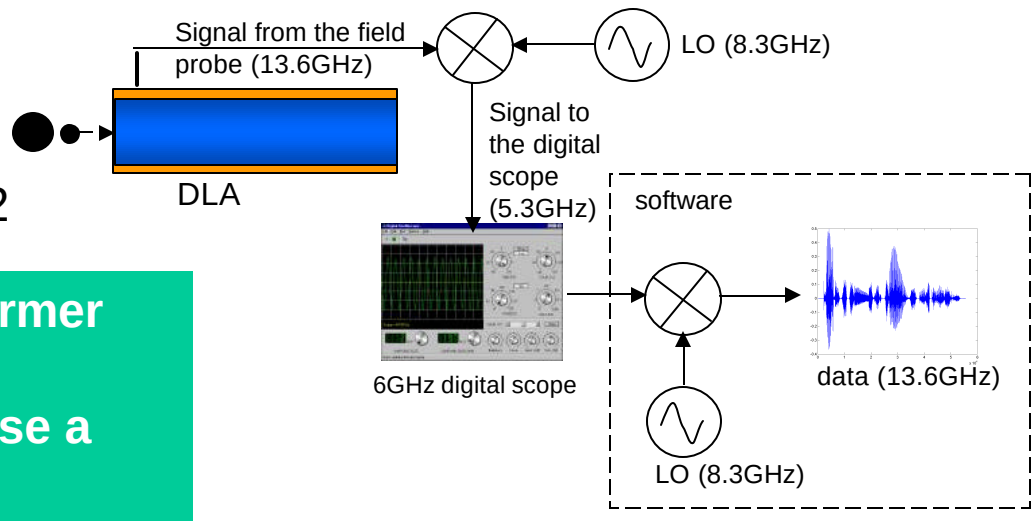
YAG Image



2. How can we use the stripline to measure the **timing-jitter** between the laser and RF systems? (J. Walsh)

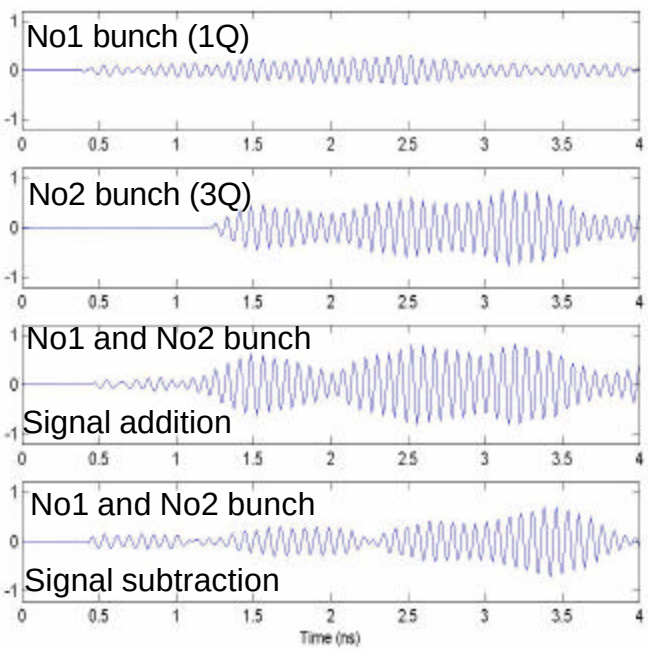
Ramped Bunch Train to Enhance Transformer Ratio



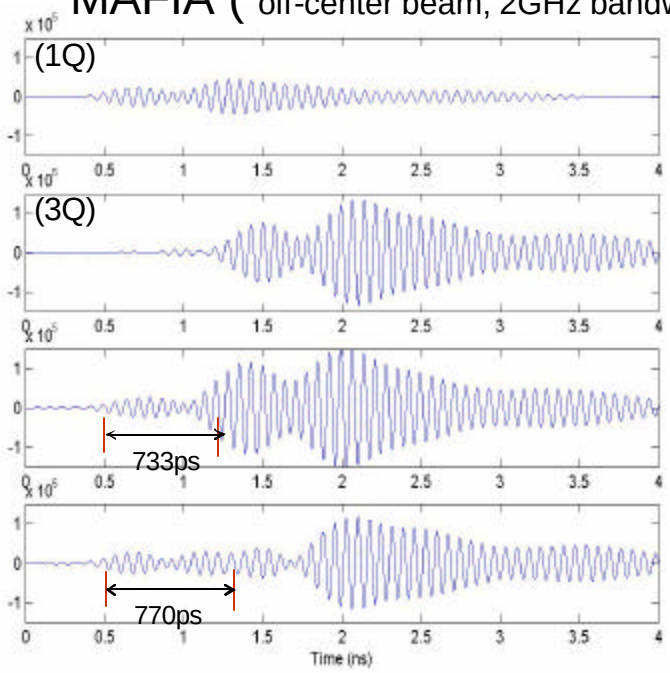


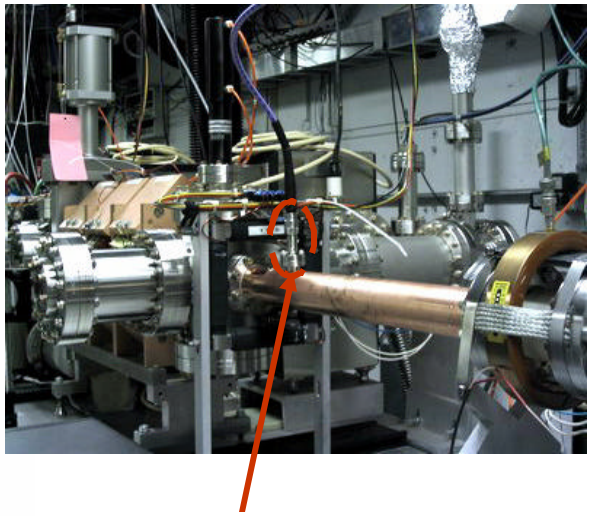
Goal: to achieve a wakefield transformer ratio greater than 2 by applying asymmetric drive bunch, here, we use a ramped bunch train.

Experiment



MAFIA (off-center beam; 2GHz bandwidth BPF)

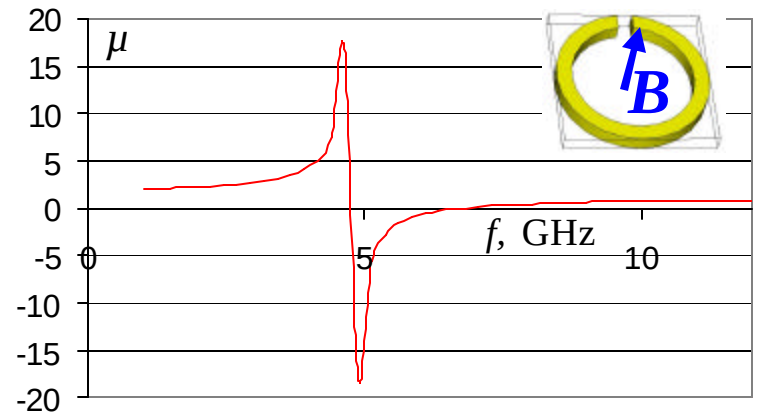




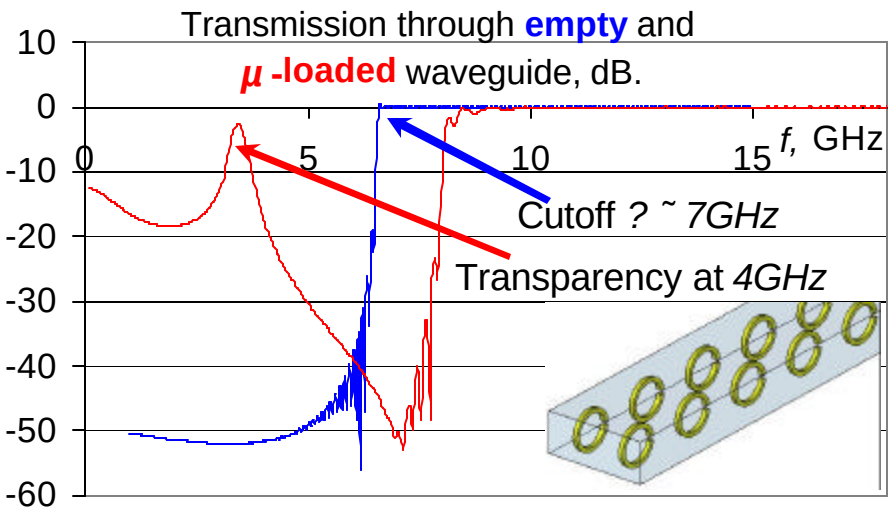
Left Handed Metamaterials

At AWA we study, design, produce and test artificial materials (metamaterials) with different electromagnetic properties.

Split ring resonator structure



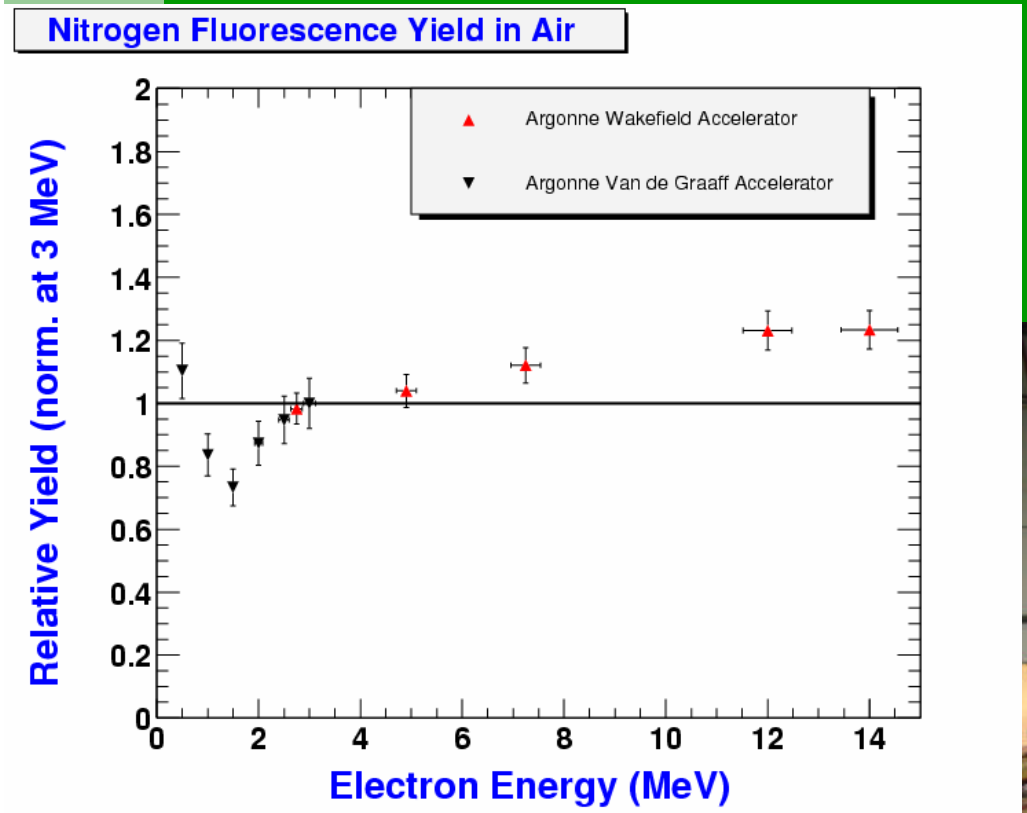
Waveguides, loaded with dispersive materials possess interesting properties. Example: Transmission through overcritical waveguide.



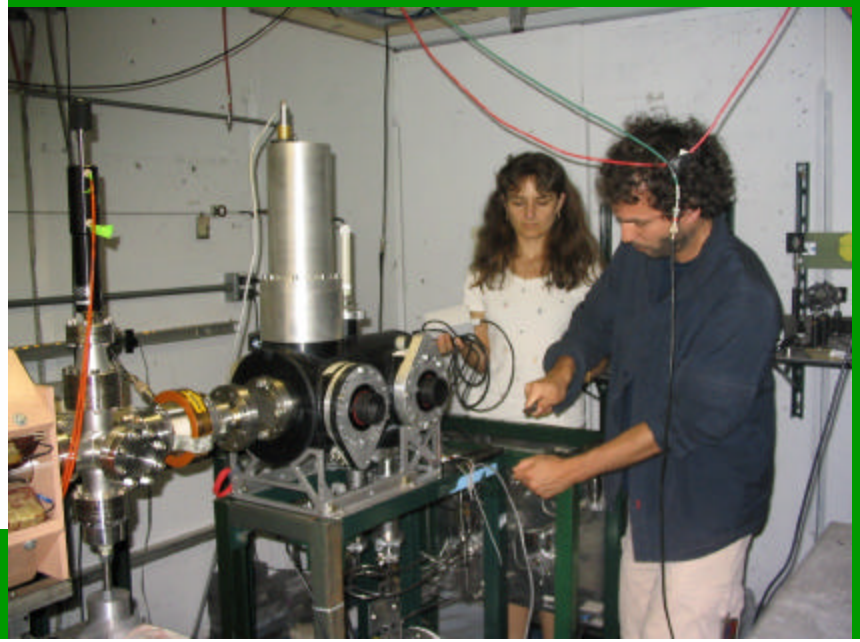
$$k_z = \frac{w}{c}\sqrt{m(w)e\left(1-\frac{w_{cutoff}^2}{w^2}\right)}$$

Resonant values of dispersive μ can make a waveguide transparent below the cutoff frequency

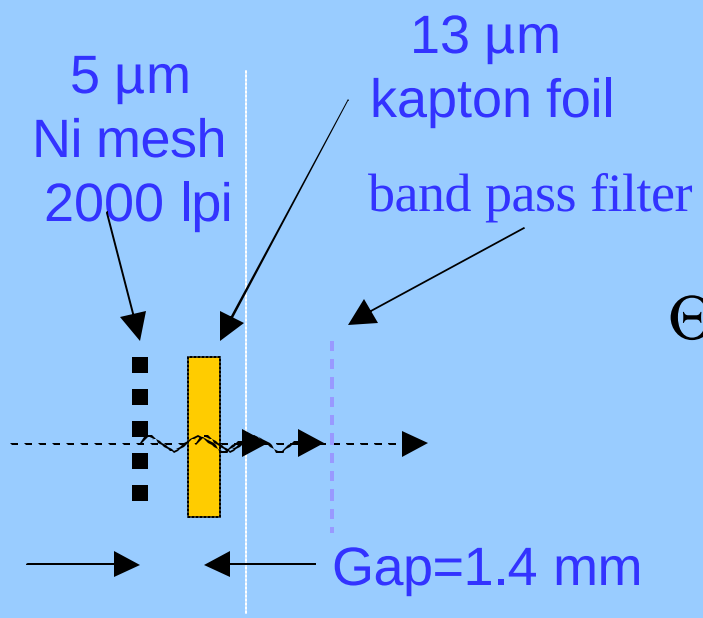
Auger Detector Calibration



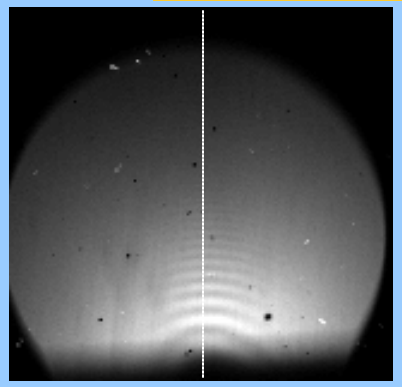
Provided calibration of the Nitrogen Fluorescence spectra in the 3-14 MeV energy range for the Auger Collaboration.



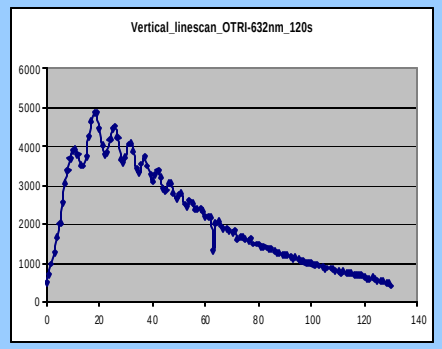
Advanced Diagnostic Development



Θ_V



Θ_H

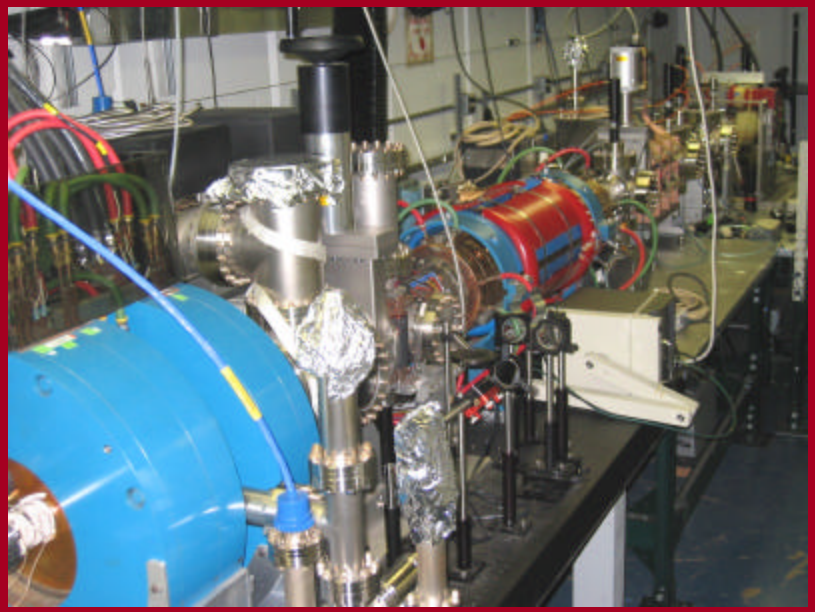


1. A specially design low-energy emittance diagnostic (ideally suited for RF photocathode guns)
2. An Optical Diffraction Radiation – Dielectric Foil Radiation Interferometer (ODR-DFRI)
3. Dielectric foil allows for a large angular acceptance of the light cone
4. Recently Observed ODR-Dielectric Foil Radiation Interferences at ANL-AWA at 14.2 MeV (Oct. 7, 2005)

*Diagnostic designed & built by UMD. Experiment performed at ANL.

Argonne Advanced Wakefield Accelerator

- Photocathode electron source
- 1-100 nC single bunches
- 15 nC bunches in 2-bunch 'train'
- Larger bunch trains (4-64) possible
- Equipped with standard diagnostics

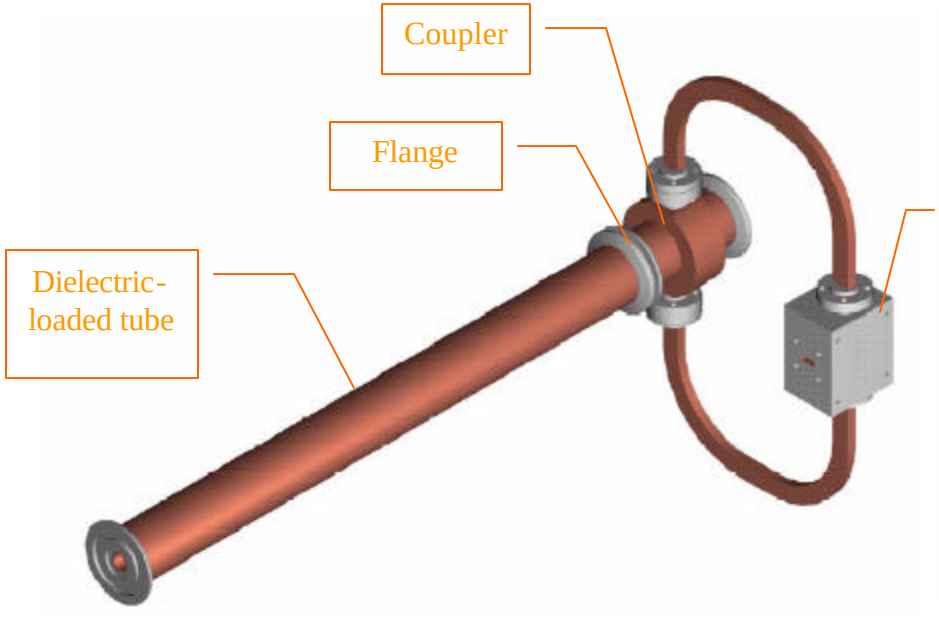


NIU is planning to use AWA for:

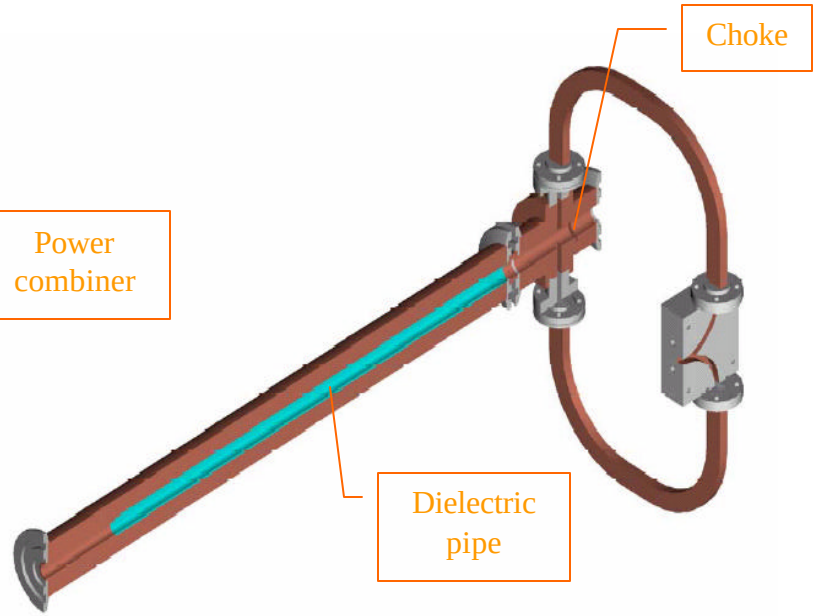
- Experiments to validate space-charge algorithms in beam simulation codes
- Measuring beam degradation due to multibunch wakefields (including coherent synchrotron radiation in magnetic bends)
- Developing and testing new beam diagnostics, including
  - ✓ interferometric measurements of longitudinal charge density, and
  - ✓ electro-optic measurement of three-dimensional charge density

21GHz power extractor
→ Experimentally Tested at CTF (2002)

ANL designed with DULY, and beam tested at CLIC TEST FACILITY. More works to follow. Improved PETS at AWA.



3-D model of the DULY 21GHz wake fields extractor



Cross-section of the DULY 21GHz wake fields extractor

V.

Summary

Summary:

Progress on Accelerating Structures and Beam Physics

- **Beam generation and diagnostics at the AWA facility.** High-Charge, High-Brightness, and Schottky-enhanced Photoemission studies.
- **High-gradient wakefield excitation.** Beam transmission at 90%. ~ 45 MV/m gradient excited.
- **High-power tests of DLA structures at NRL.** Gaining comprehensive knowledge of physics and engineering issues.

Future Plans.

- **High-charge pulse train and high RF power generation.** Investigate high-gradient generation and sustained acceleration.
- **X-band dielectric structures.** Construct a compact accelerator at NRL's Magnicon facility. **Investigate accelerator physics issues** (new structures, geometry, materials and schemes).
- **Demonstration high total energy gain.** Use dielectric TBA technique developed at AWA.
- **External collaborators.** Accommodate their experimental requests.