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… for a brighter future

Mission: **Studying the Physics and Developing the Technologies for Future HEP Accelerators.**

ANL Efforts Toward Two Beam Acceleration and Advanced Accelerator R & D Activities

Wei Gai

Tsinghua CLIC Workshop

March 24 - 25

U.S. Department of Energy

UChicago ▶ Argonne LLC

A U.S. Department of Energy laboratory managed by UChicago Argonne, LLC

Outline

- Overview and AWA Facility Description
- Recent Research Highlights and Planned Experiments
- AWA Upgrade
- Collaboration works with other groups
- ILC/CLIC Positron Sources
- Summary

Overview and AWA Description

Challenges for Future HEP Linear Colliders

- High gradient (~hundreds MV/m) and High Impedance (high R/Q)
  - Requires new or alternative accelerating structures.
- High Power RF Sources (~ GW Scale)
  - Requires new type sources.
- Higher order mode damping
  - Requires beam breakup control.
- Positron acceleration

- **Alternative Structures (Example, dielectric):**
  - **Comparable accelerating properties as metal structures; More material options; Possibly higher gradients;**
  - **Can be used as power extraction at GW level**
  - **Simpler geometry, easy to construct and HOM damping.**
  - **No difference for e- and e+.**

Alternative collider schemes beyond ILC/CLIC:

- Forward looking beyond the current CLIC parameters. Many advanced accelerator schemes are being studied (much less mature than CLIC, however) :
  - Laser driven plasma wakefield
  - Electron beam driven plasma wakefield
  - Dielectric wakefield accelerator

- History has shown many good designs may not materialize into real machines (cost and …).

- Technology breakthroughs will lead to better and cheaper machine.

We are operating a unique facility (AWA) to:

- High-Power/High-Brightness Electron Beams for Wakefield Accelerations and applications to future LC.

  Producing world record high current electron beams; developing technologies for beam generation, propagation, & characterization.

- Advanced Accelerating Structures and Concepts
  - Design, construction and testing of high gradient WF structures: dielectrics, photonic band gap, tunable dielectric and left-handed meta-materials.
  - Enhanced transformer, multi-drive beam wakefields and solid state PASER.

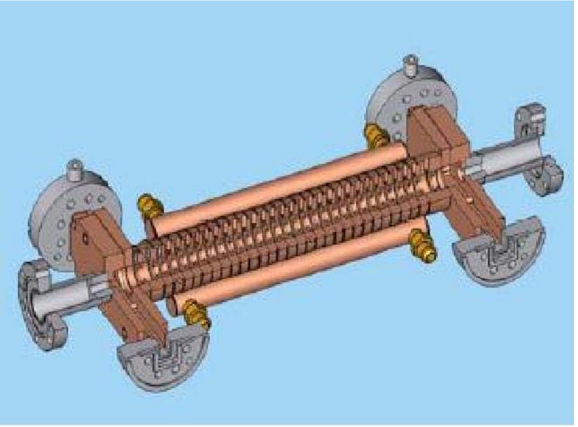
- Support for Existing HEP programs
  1. **Positron source for ILC/CLIC**
  2. **Lab Astrophysics**
  3. **Providing facilities for collaborator/user's research program.**

RF breakdowns in accelerating structures are not well understood, but …

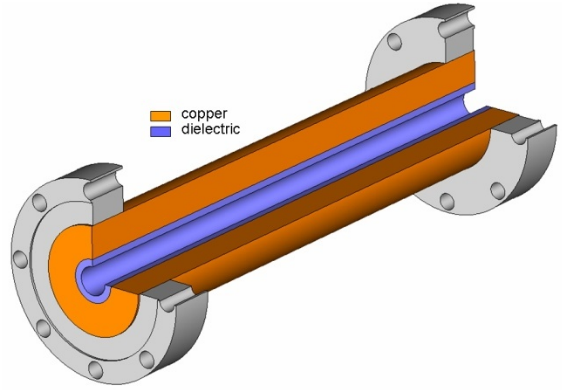
- Data seems to show higher RF breakdown threshold (or lower breakdown rate) with shorter pulse (~ 10 ns).
- This may give us a path to high gradients for multi-TeV class accelerator using Wakefield Acceleration:
  - Can generate RF with high current electron beam;
  - RF pulse length can be easily controlled;
  - Or Simply Using Collinear WF Accelerator.

Advanced Accelerating Structures Development

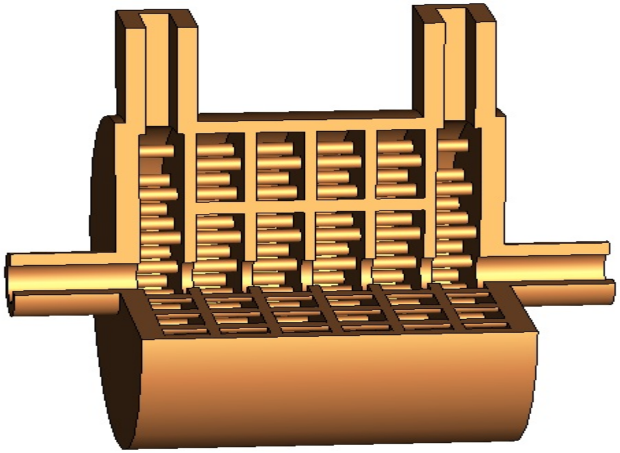
Improved Iris loaded structures



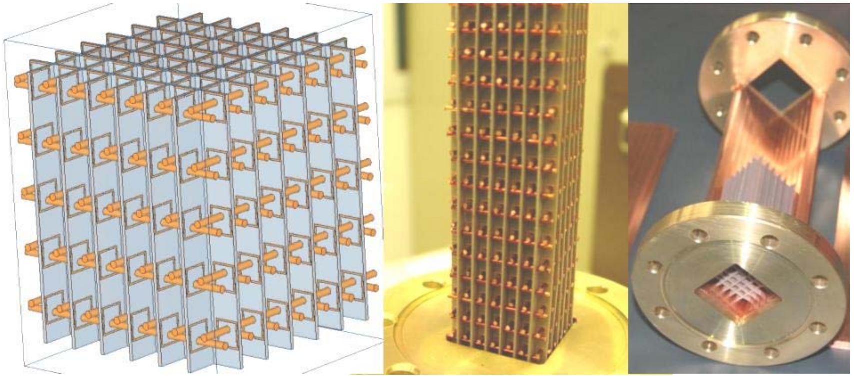
Dielectric loaded structures



Photonic band gap structures

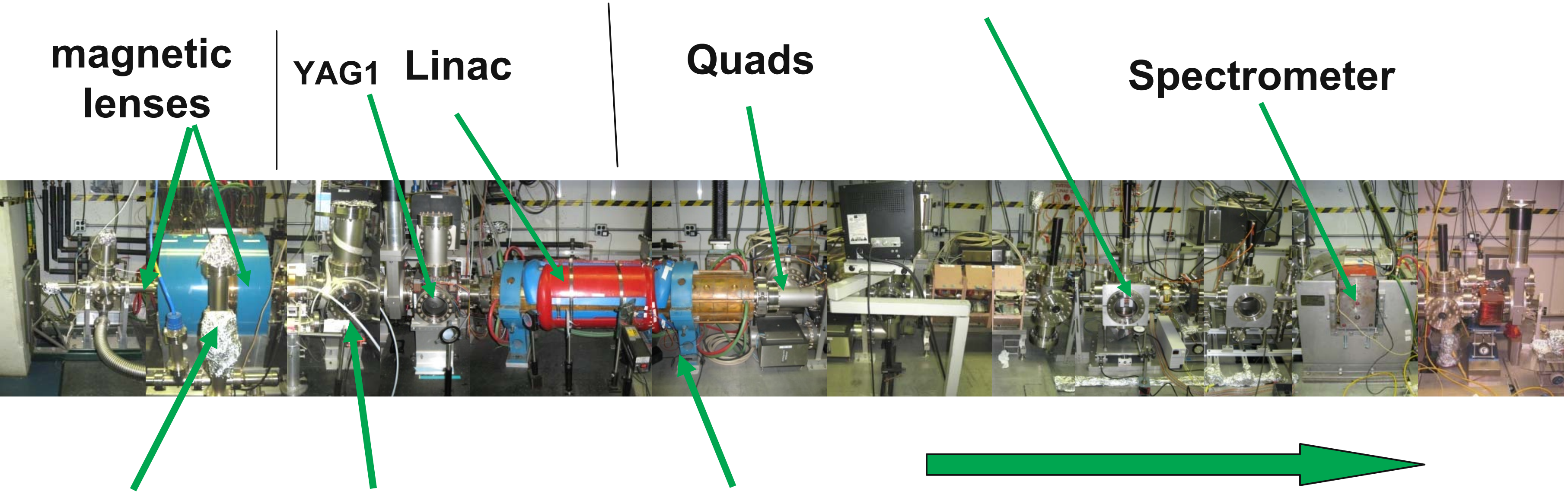


Meta/left-handed structures



Flexible Beam Parameters at the Argonne Wakefield Accelerator (AWA)

~ 1 meter



8 MeV

15 MeV

Experimental Area

magnetic lenses

YAG1

Linac

Quads

Spectrometer

rf-gun

Laser In
λ =248nm

YAG2

Direction of beam propagation

Single bunch operation

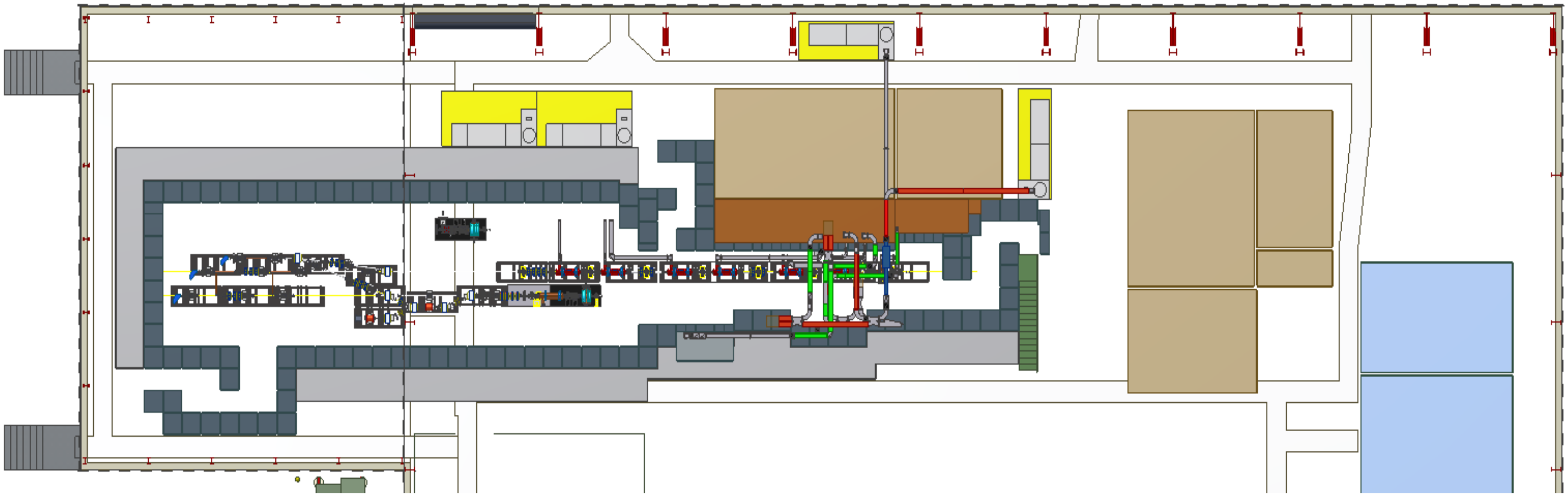
Q = 1-100 nC (reached 150 nC, World record?)
15 MeV, 2-2.5 mm bunch length (rms),
emittance < 200 mm mrad (at 100 nC)
High Current: ~10 kA

Bunch train operation

4 bunches x 20 nC (current)
16 bunches x 5 nC (current)
16 - 64 bunches x 100 - 50 nC → 10 - 50 ns long, 23 MeV (future, ~GW beam power).

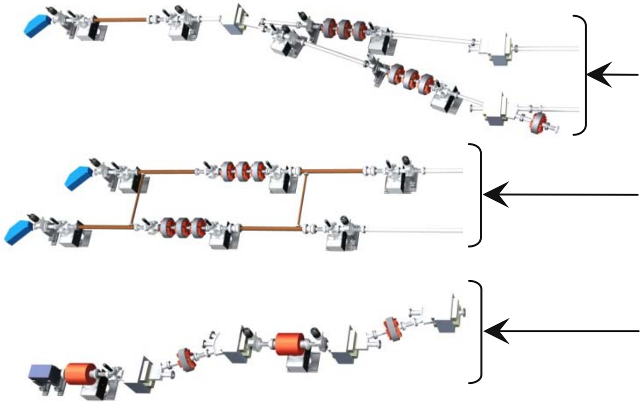
The beam energy will be up to 75 MeV in a few years

- Thanks for DOE support, we will able to upgrade the facility to 75 MeV
  - Two additional Klystrons and associated RF components.
  - 5 Additional Linac Tanks
  - Reconfigured Tunnel and Beamlines



The AWA Upgrade Plan

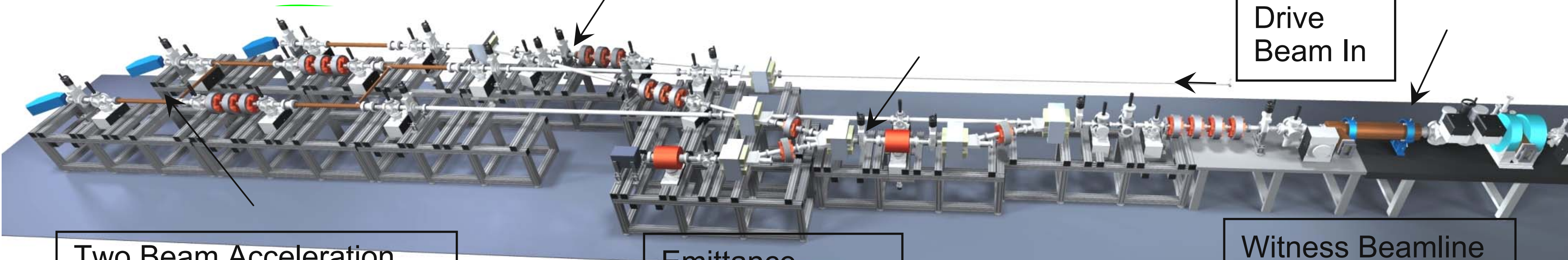
Reconfigured experimental area, 3 beam lines:



AWA Collinear Wakefield and High Brightness Beam

AWA Two Beam Acceleration

AWA Emittance Exchange and Diagnostic



AWA Collinear Wakefield and High Brightness Beam

AWA Drive Beam In

Two Beam Acceleration

Emittance Exchange and Beam Diagnostics

Witness Beamline Modified and Relocated Downstream

What we could do with the 75 MeV drive beam:

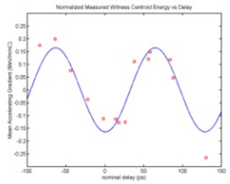
- Higher gradient excitation: ~ 0.5 – 1 GV/m in structures (~ 3 mm apertures)
  - Current: 100 MV/m

- Higher RF power extraction: ~ GW level (75 MeV, 130 Amps, 10 ns, 10 GW beam power)
  - Current: ~ 100 MW.

A Pathway to TeV Class Linear Colliders

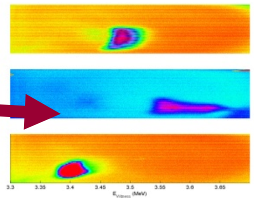
Wakefield Acceleration

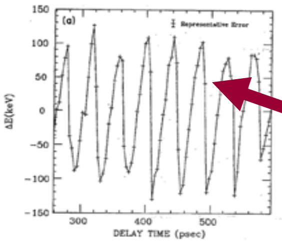
- **Advanced structures:** dielectric-loaded (and other novel) structures to reach high-gradient (hundreds of MV/m)
- **High power sources**: drive beam generates GW scale RF



First POP Data

At ANL





First Plasma and

Dielectrics

POP Data

At ANL

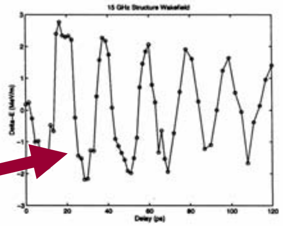
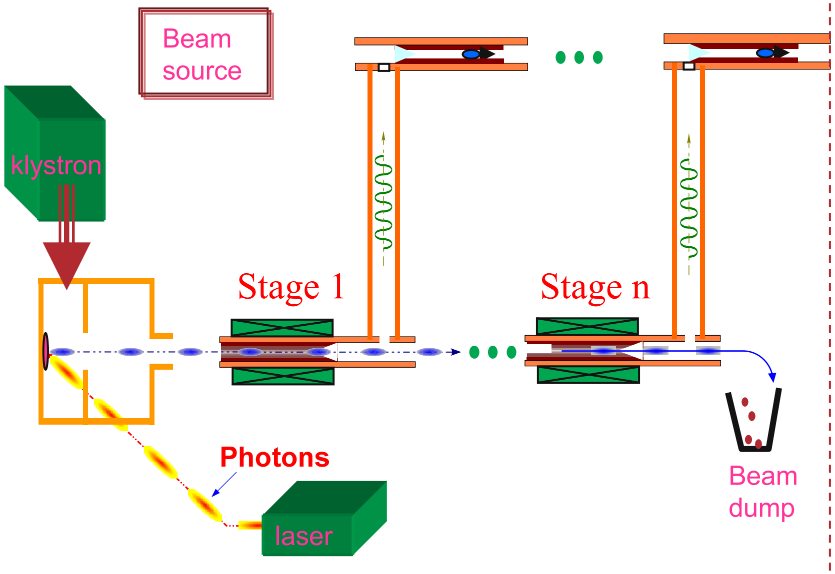
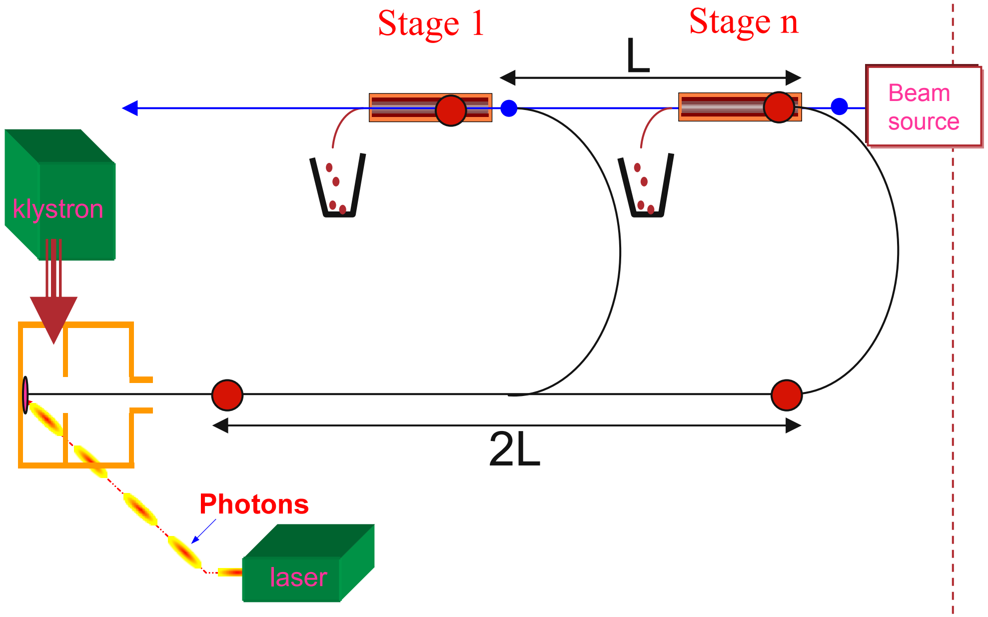


FIG. 3. Wake potential measurement for 15 GHz dielectric structure. Each data point is the change in the bend view centroid of the witness beam at the spectrometer 60° port.

Two-beam acceleration GeV Module



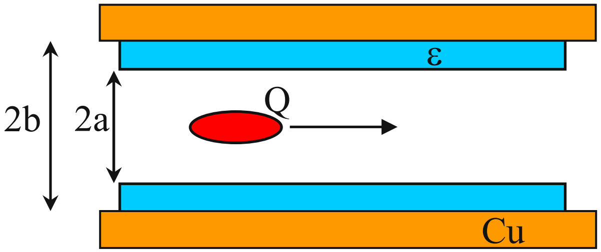
Collinear GeV Module



Conceptually, either scheme can be staged to TeV scale

Electron Beam Driven High Gradient Wakefields

- A new way to power the accelerating structure by transporting the power in the electron beam.
- Applications
  - ***Collinear wakefield acceleration***
  - ***Two-beam acceleration***



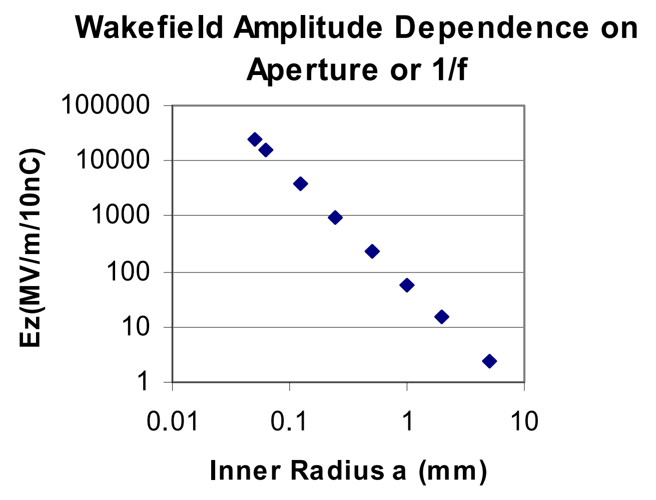
Keys to the success: Drive beam, drive beam and drive beam!

- Energy ↑, Charge ↑ Bunch length ↓ Emittance ↓

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

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

10 nC a=0.1 mm → 5 GV/m.



Some Thoughts on Linear Collider Scaling

- Luminosity

$$L = \frac{q^+ q^- N_b f}{\varepsilon_x \varepsilon_y} \cdot F$$

- Where
  - $q+$, q^- are the positron and electron charges. Nb is the number of bunches per train and f is the repetition rate. F is a constant makes the unit correct. ε_x ε_y are the transverse emittances.

- Emittance Growth rate in Accelerating structures
  - $\delta\varepsilon \propto W_\perp \, \delta x$ (Difficult to control, contribute to single and multiple bunch beam instabilities).
  - $\delta E \propto W_{//}$ (This can be corrected)

Wakefield Scaling vs Frequency

- Normally the structure aperture a is a fraction of the wavelength (otherwise Er>>Ez). → a ~ λ for the first order approximation.
- In general, we have

$$W_{\perp} \propto \frac{1}{a^3} \propto \frac{1}{\lambda^3} \propto f^3$$

- Then, emittance growth rate without damping:

$$\Delta\varepsilon \propto W_{\perp} \propto f^3$$

- We chose to work on the WF scheme in the microwave (~ 10 – 100 GHz range).

Recent Research Highlights and Planned Experiments

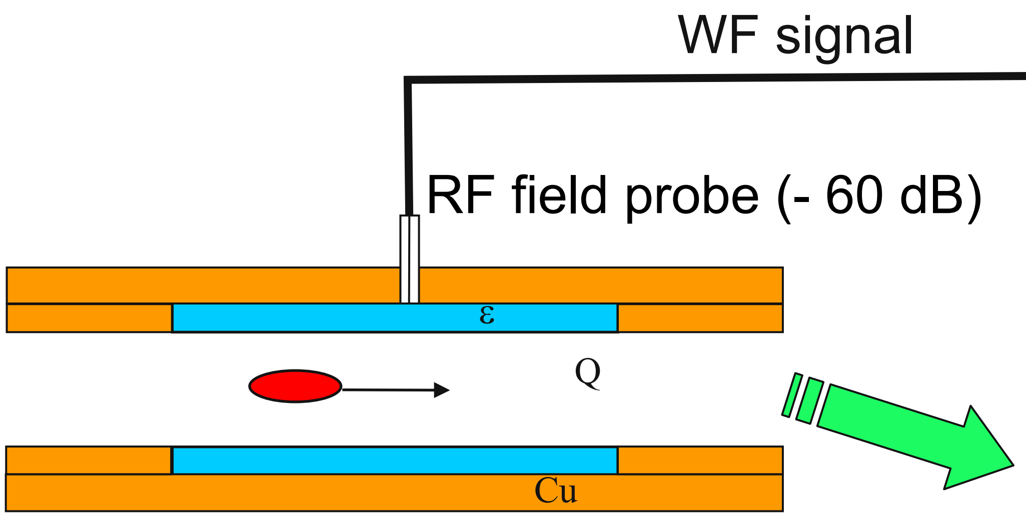
Research Highlights for the Last Three Years

- High Gradient WF Excitation (100 MV/m achieved)
- High Power generation and extraction (7.8 and 26 GHz)
- Advanced Concepts (PBG and Meta-material structure).
- High Brightness Beam and Beam Manipulation
- ILC/CLIC Positron Sources

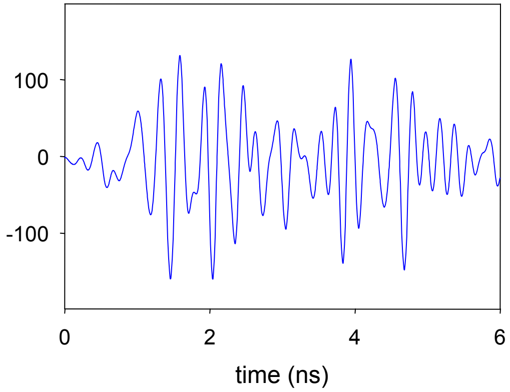
Experimental Setup for High Gradient Tests

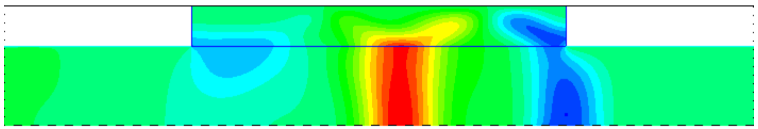
Goal:

Test breakdown thresholds of dielectric structures under short RF pulses.



Monitor for breakdown

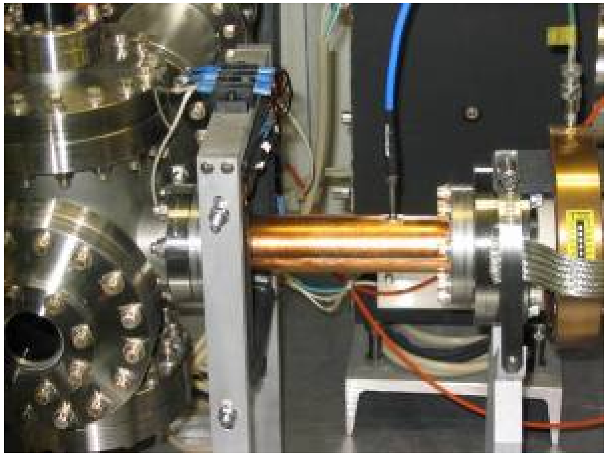




Infer Gradients from MAFIA

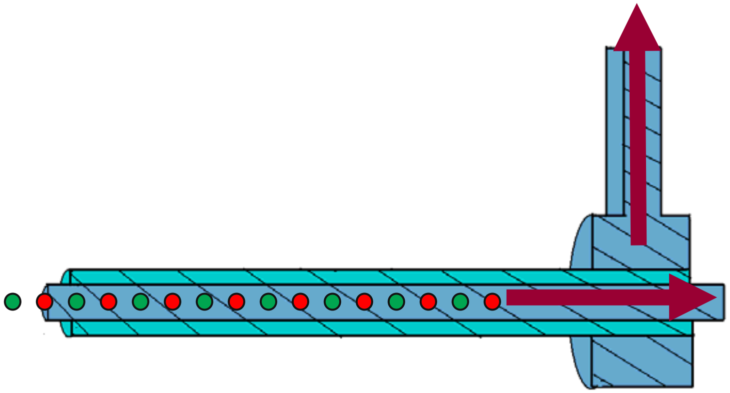
Dielectric Loaded Structures Tested

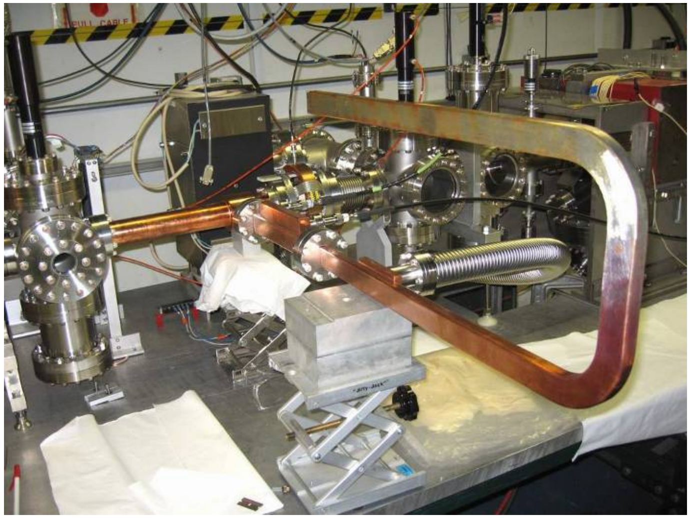
So far, no breakdown observed yet in this regime.



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
Maximum charge	**46 nC**	**86 nC**	**86 nC**	**75 nC**
Maximum gradient	**21 MV/m**	**43 MV/m**	**78 MV/m**	**100 MV/m**

High Power RF generation using dielectrics and high current bunch train *(7.8 GHz Power Extractor)*





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

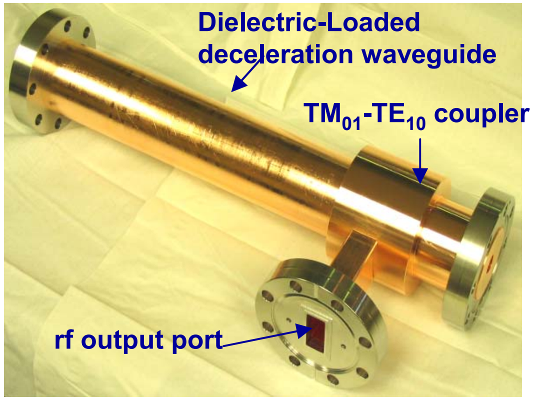
dielectric = cordierite

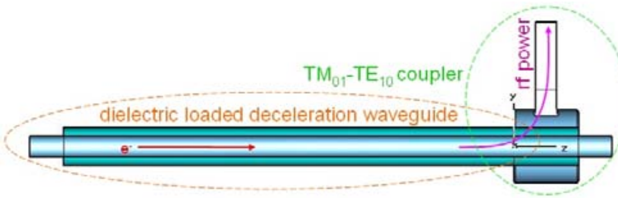
(If successful, this technology might have impact on CLIC)

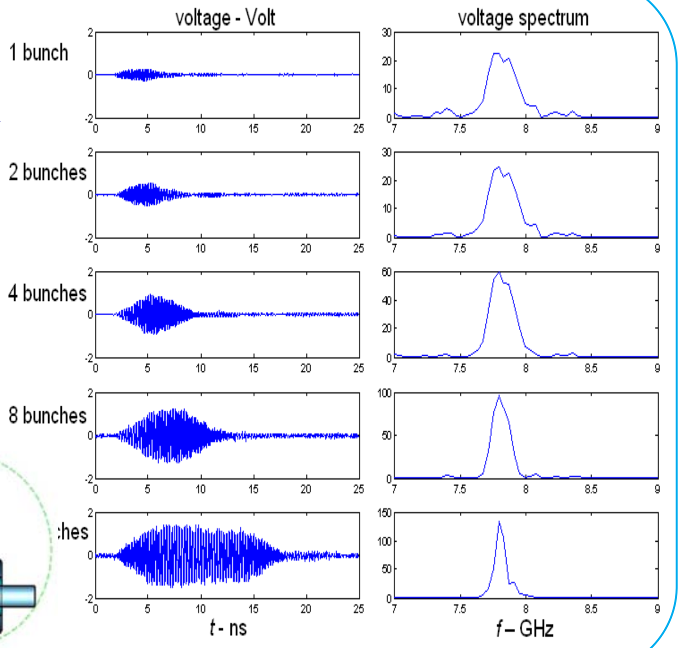
Development of Dielectric-Based Wakefield Power Extractors

C-Band Wakefield Power extractor

- 30ns,1MW & 6ns, 40MW 7.8GHz rf pulse produced
- 20ns, > 500MW with the upgraded AWA beamline.

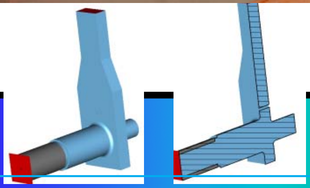


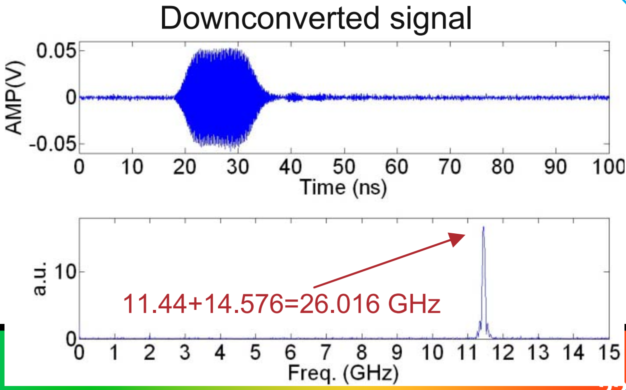




Ka-Band Wakefield Power extractor

- 16ns,1MW & 6ns, 30MW 26GHz rf pulse prodced
- Working toward 20ns 150MW.





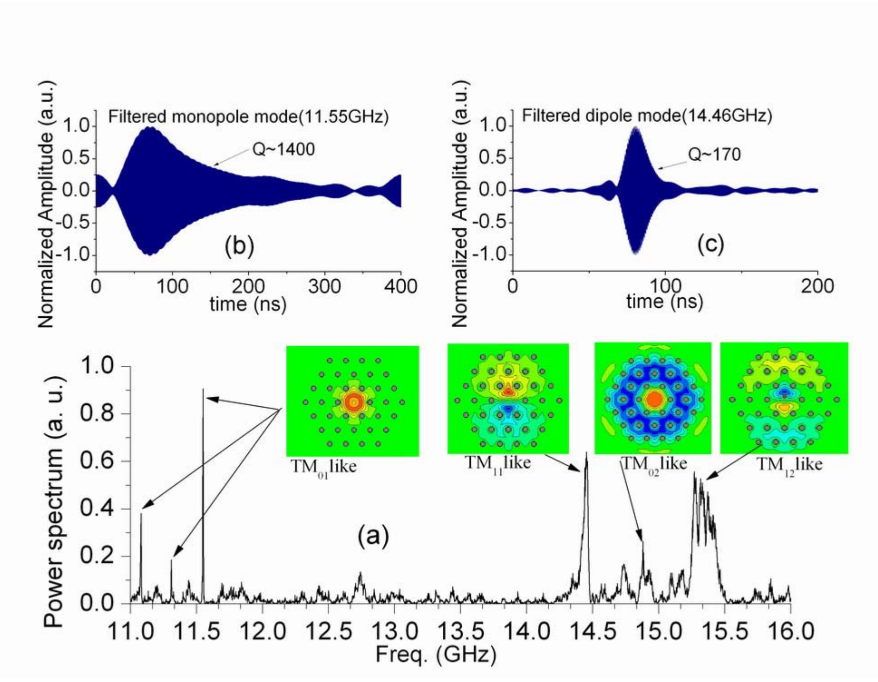
Wakefield Study of an X-band PBG Structure (ANL/Tsinghua/Euclid)

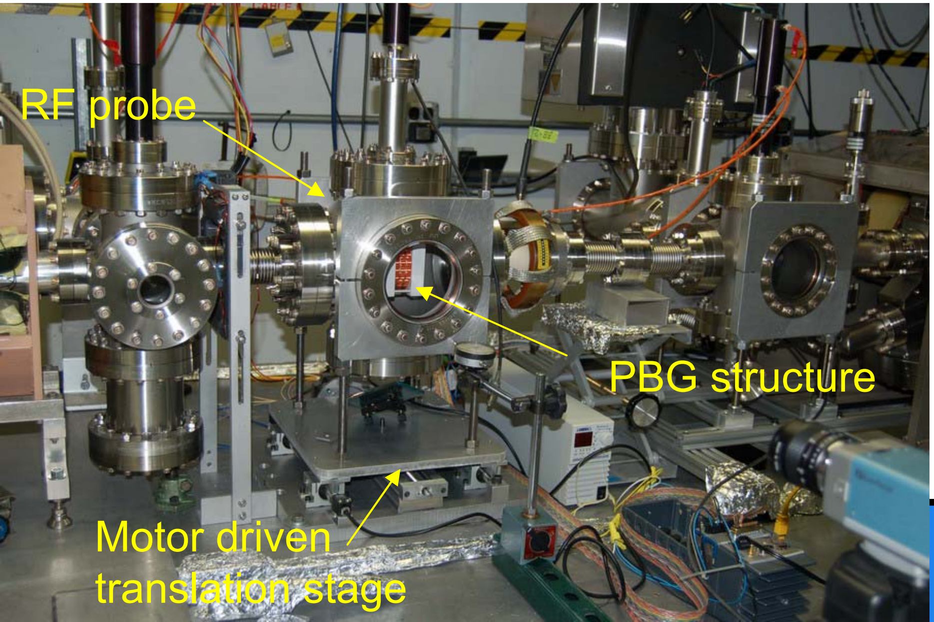
- Successfully identified and characterized the wakefield modes, including major monopole (TM_{01} like, TM_{02} like), and dipole modes (TM_{11} like and TM_{12} like) by the precisely beam offset control and high frequency rf probe.

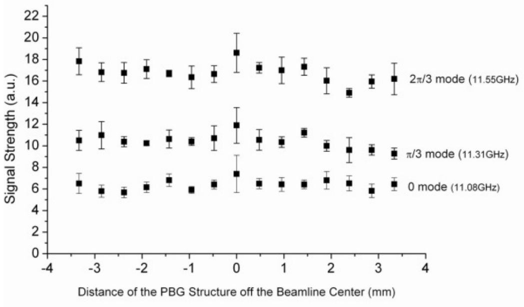
- Demonstrated Q of the dipole mode is ~10 weaker than that of the monopole mode.

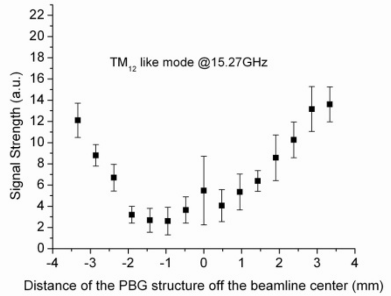
- Performed high charge wakefield excitation. 80nC bunch was transmitted, which is equivalent to 30MV/m of gradient on axis. The gradient was calibrated in a collinear wakefield acceleration test.

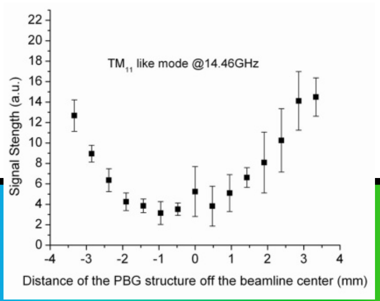
- Demonstrated the techniques to experimentally study the wakefield of geometrical complicated accelerating structures

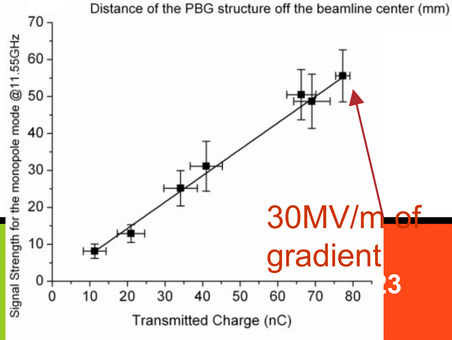












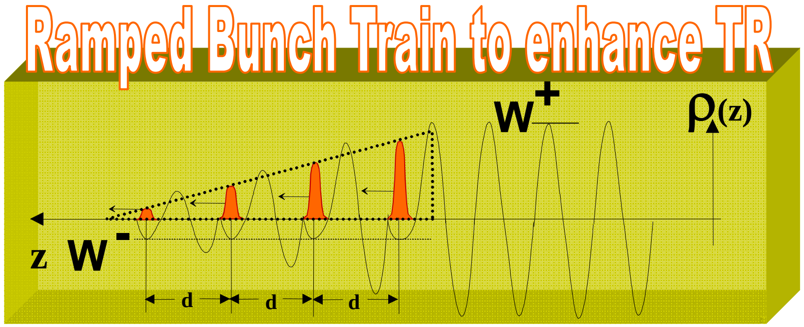
Experiment of Wakefield Transformer Ratio Enhancement

- We demonstrated the enhanced wakefield transformer ratio in a dielectric based collinear wakefield accelerator using a ramped drive bunch train.

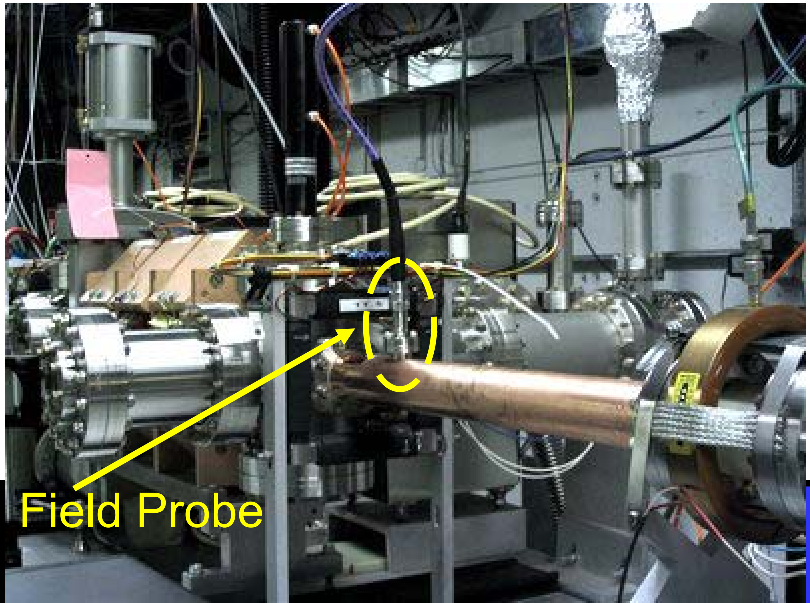
- The enhanced wakefield transform ratio for two ramped drive bunches is 3 in theory and 2.3 in measurement.

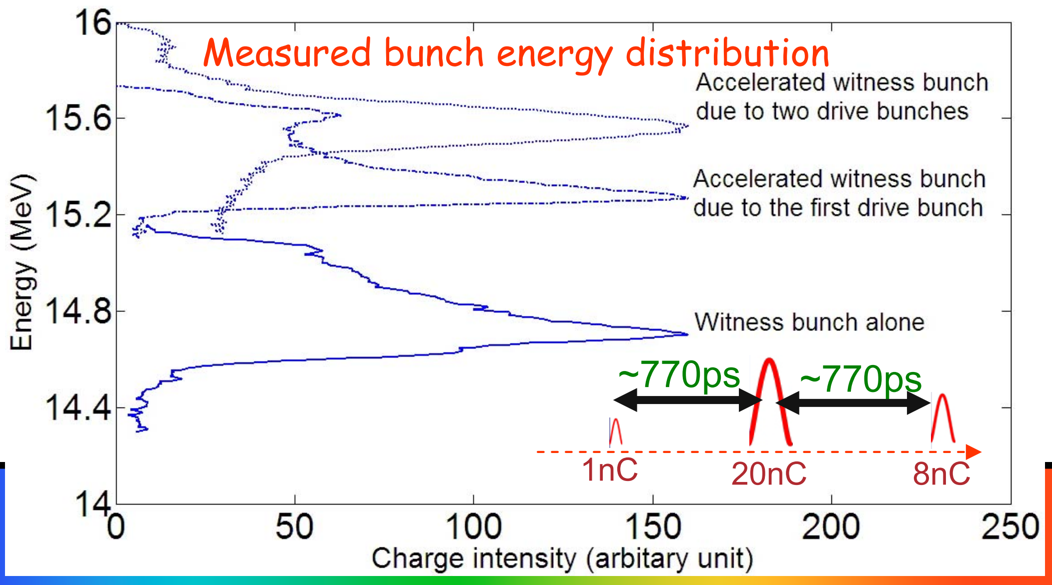
$$\text{Transformer ratio} = \frac{\textit{Max energy gain of the witness bunch}}{\textit{Max energy loss of the drive bunch}}$$

Transformer ratio limited: R≤2 @ a longitudinally symmetric drive bunch, but it can be enhanced greater than 2 using asymmetric bunch.



Ramped Bunch Train to enhance TR





Measured bunch energy distribution

Planned experiments using the existing 15 MeV beamline:

- High transformer ratio:
  - Ramped bunch (Euclid) (2010, ongoing, R>3 observed)
  - Rectangular two channel (Yale/Omega) (2010, installed next month))
  - Ring beam (Yale/Omega). (2010)
- Advanced Structures
  - High gradient Photonic Band Gap (2010, Tisnghua)
  - Tunable Dielectric Structure Wakefield Experiment. (2010, Euclid)
  - Beam Break Up control (2010, Euclid)
  - High Power extraction (2010, ANL/Euclid)
- High brightness beam experiment.
  - Demonstrate Emmittance exchange (appilcations to beam cooling and LC sources).

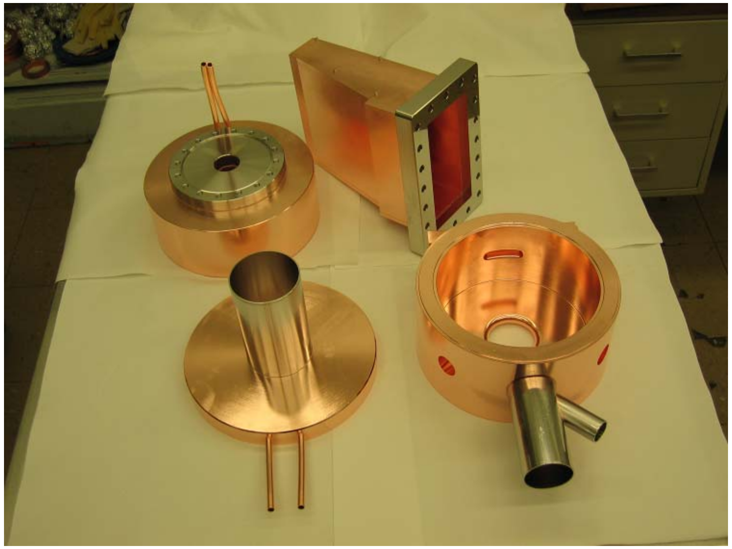
- Facility Upgrade (details to follow)

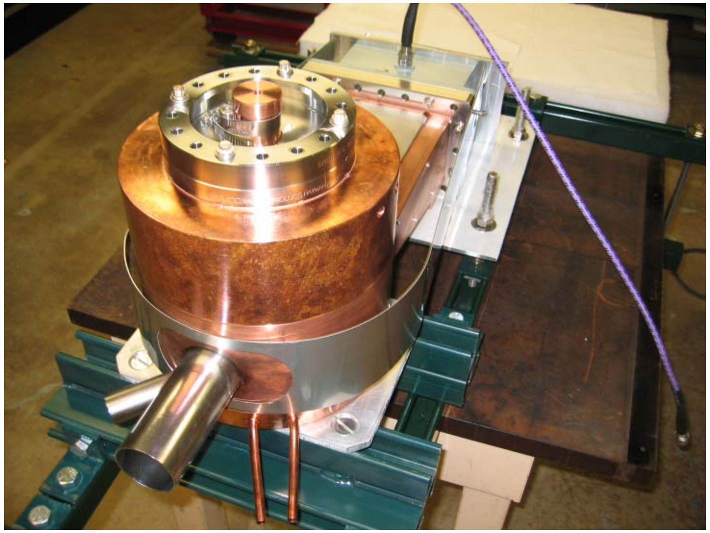
Pathways to higher gradients and higher powers (beams, beams, beams)

- We are approaching the limitations of the single beam capabilities. We need to generate a higher charge bunch train to increase the gradient. Currently, we are installing new gun and cathode to:
  - Increase the QE by a factor of 100 (using cesium telluride photocathodes). These high QE photocathodes will make possible the generation of long, high charge bunch trains. (Jointly supported by ONR and ANL LDRD).
  - Build additional L-band RF power station klystron (thanks to DOE and B. Carlsten & S. Russell (LANL), for loaned klystron). This will increase the beam energy from 15 MeV to 23 MeV using an existing spare Linac, or even higher with additional Linac.
- With additional funding from DOE (2 millions), we are furthering upgrade the facility to 75 MeV.

New RF Gun

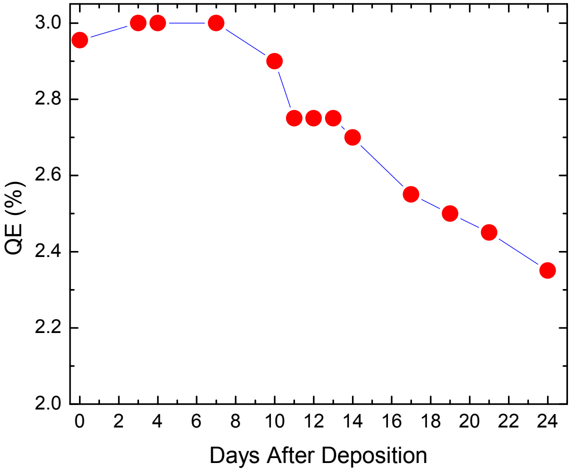
- Final brazing cycle has been done
- The fine tuning of the RF properties are under way (resonant frequency, field balance between the two cells, and critical coupling)
- Installing in the beamline now (see tour)



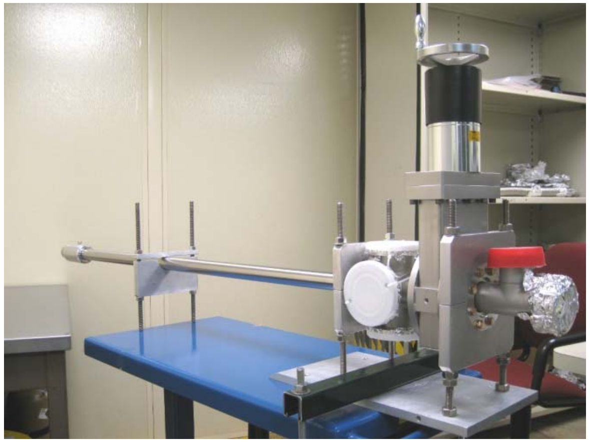


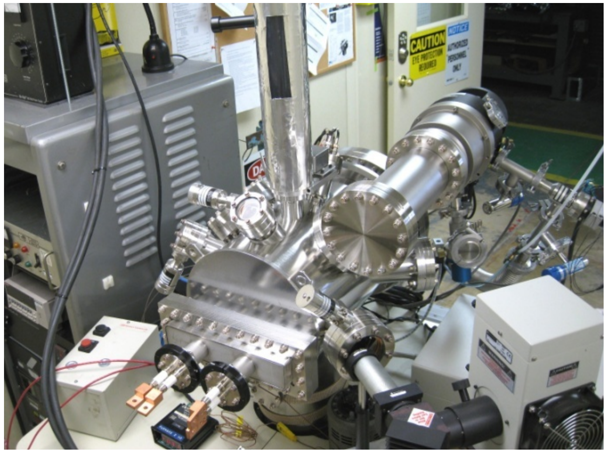
Cesium Telluride Photocathode

- Quantum efficiencies of a few percent (13% max) are achieved routinely; need 0.5%,.
- Still working on improving the QE uniformity across the cathode surface.
- Transport system from preparation chamber to RF gun is basically ready.



QE Lifetime





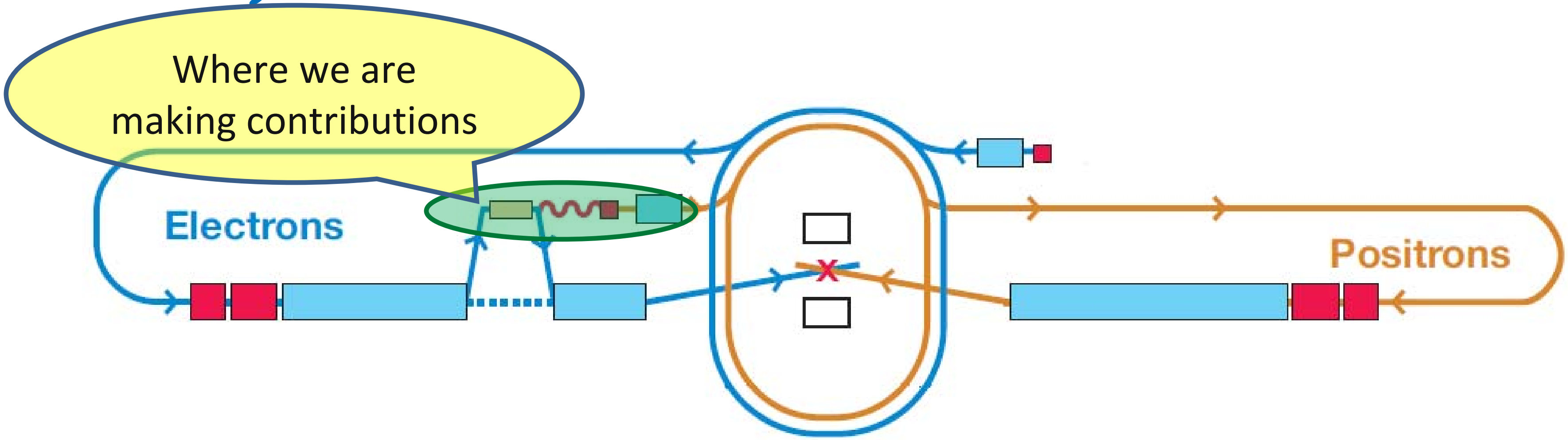
Major deliverables in the next three years:

- Complete the RF upgrade and deliver the 20 MW RF power to the bunker (done)
- Install and commission the Cs_2Te RF photocathode gun, initial beam testing for the high current beam (ongoing)
- Construct two new RF modulators (2010), install two klystrons and associate RF components (2011).
- Expand bunker (2010)
- Design, fabricate and install the 4 additional L-band tanks (2010-2011).
- Generate and characterize the high current beam to 25 MeV. Then 75 MeV (2009 – 2010 – 2012).
- Demonstrate high RF power (~ GW) extraction experiments. (2011-2012)
- Starting high gradient wakefield (~ 500 MV/m) experiments using high charge bunch train. (2011).

- Collaboration works with other groups

- ILC/CLIC Positron Sources

Positron source study for ILC (under the framework of the GDE)

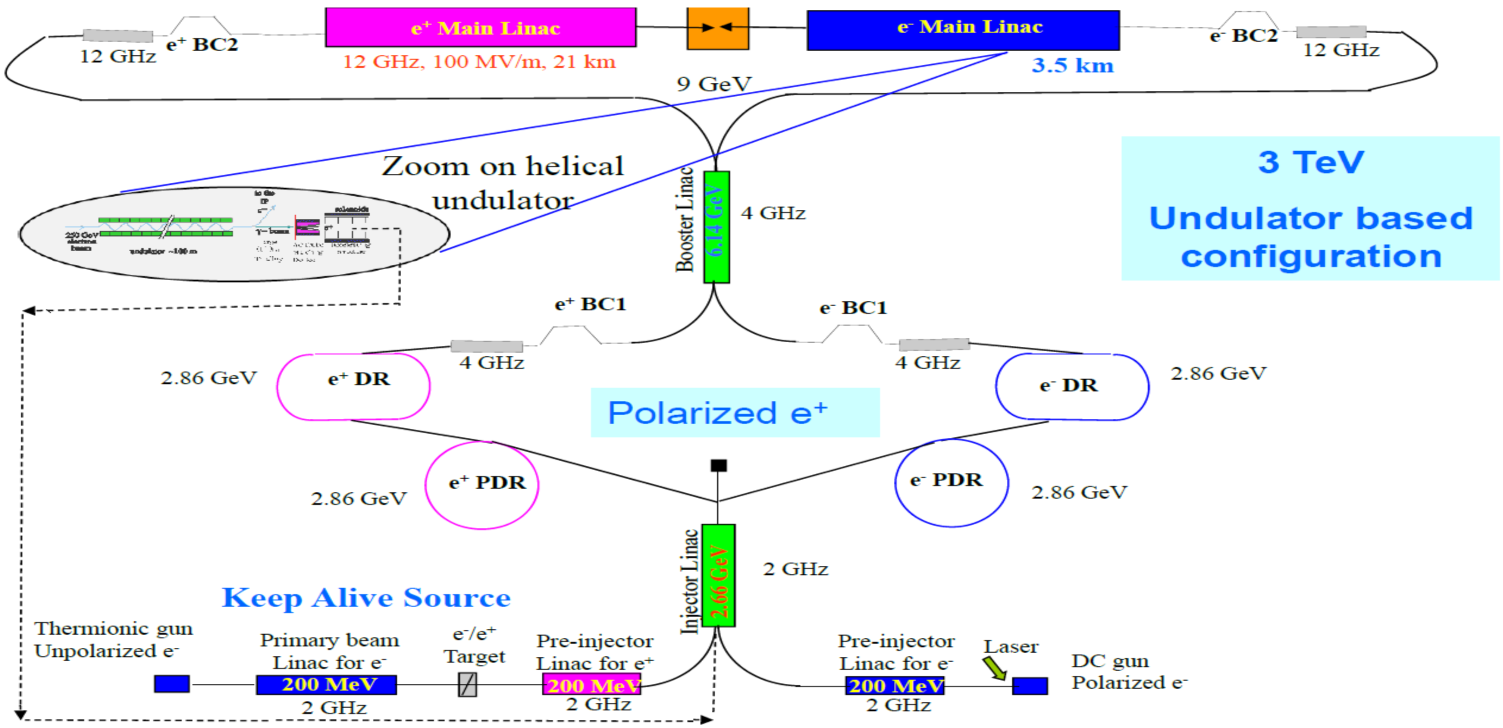


➢ANL responsible for

- end to end simulation of ILC positron source: numerical model of undulator radiation; investigated and compared many different undulator parameters proposed by collaborators; the impact on yield for different OMD options
- the energy deposition calculating in the targets (Ti, liquid pb).
- collaborating with KEK on their conventional e+ source scheme and compton scattering based e+ source.
- emittance evolution of drive electron beam passing through undulator.

➢ Currently working on undulator parameters for Minimum Machine option.

Undulator Based Positron Source for CLIC (official CLIC Collaboration Member)



➢We study

- Alternative e+ source, undulator based positron source.
- Effect of undulator to the drive beam emittance.
- Correlation between yield and polarization for this undulator.
- Overall CLIC complex layout with undulator based e+ source.

Summary:

- Wakefield acceleration → a path toward future HEP colliders.
  - A dedicated high charge facility constructed to study the beam-structure interactions
  - Many experiments performed, systematically achieving 50 – 100 MV/m and short RF pulses at ~ 50 MW.
  - Further experiments planned with the upgraded facility, using multiple beam, we are expecting higher gradients (~ 200 - 500 MV/m) and power (~ GW MW) for short pulses.
  - Demonstrate our WF technology that could lead to future HEP LC.
- Serving HEP communities.

RF breakdowns in accelerating structures are not well understood, but … (keep this one?)

- Data seems to show higher RF breakdown threshold (or lower breakdown rate) with shorter pulse (~ 10 ns).
- This may give us a path to high gradients for multi-TeV class accelerator using Wakefield Acceleration:
  - Can generate RF with high current electron beam;
  - RF pulse length can be easily controlled;
  - Or Simply Using Collinear WF Accelerator.