Dielectric Wakefield Acceleration

Recent test at ATF/BNL and FACET/SLAC

Sergey Antipov
Euclid Techlabs LLC
Argonne Wakefield Accelerator Facility

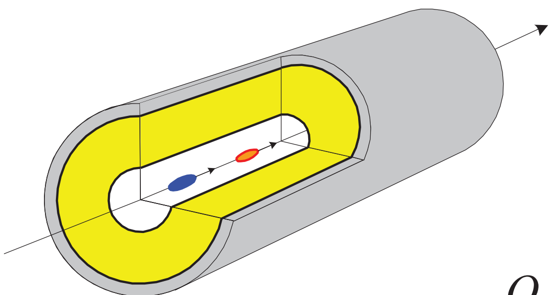
North American Particle Accelerator Conference 2013

Acknowledgements and Contributions:

UCLA –	G. Andonian, S. Barber, B. O’Shea, O. Williams, A. Fukasawa, A. Valloni, K. Fitzmorris, P. Hoang, J. Harrison, J.B. Rosenzweig
AWA/Euclid –	S. Antipov, M. Conde, C. Jing, A. Kanareykin, W. Gai, J. Power, AWA staff.
BNL ATF–	M. Babzien, M. Fedurin, K. Kusche, C. Swinson, ATF staff.
SLAC FACET–	M. Hogan, C. Clarke, M. Dunning, R.J. England, E. Hemsing, S. Li, V. Yakimenko, FACET staff.
MPI –	P. Muggli
Yale/Omega P –	S. Schelkunov, T. C. Marshall, G. Sotnikov, J.L Hirshfield
LANL –	E. Simakov, D. Shegolkov
FNAL/NIU-	P. Piot, D. Mihalcea

Dielectric Wakefield Acceleration (DWA)

Drive beam: Energy ↑, Charge ↑ Bunch length ↓ Emittance ↓



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

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

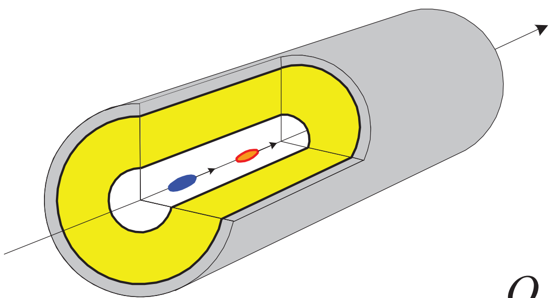
Dielectric based accelerator advantages:

- design simplicity: no tight tolerances;
- scalability: GHz, THz
- 0.5-1.0 GV/m gradient
- maximal field magnitude at the center
- small transverse size allows for magnet integration
- reduced sensitivity to the beam break-up (BBU)

- Acceleration:
  - Two-beam acceleration (CLIC-type)
  - Collinear acceleration
  - Radiation
- Structure side:
  - Type of ceramics: loss, multipactor, thermal management, fabrication, charging
  - Power extraction, coupling
  - Tuning
  - HOM suppression
- Beam side:
  - Phase space manipulation
  - Bunch trains
  - Beam shaping for transformer ratio
  - Beam transport and BBU studies

Dielectric Wakefield Acceleration (DWA)

Drive beam: Energy $\uparrow$, Charge $\uparrow$ Bunch length $\downarrow$ Emittance $\downarrow$



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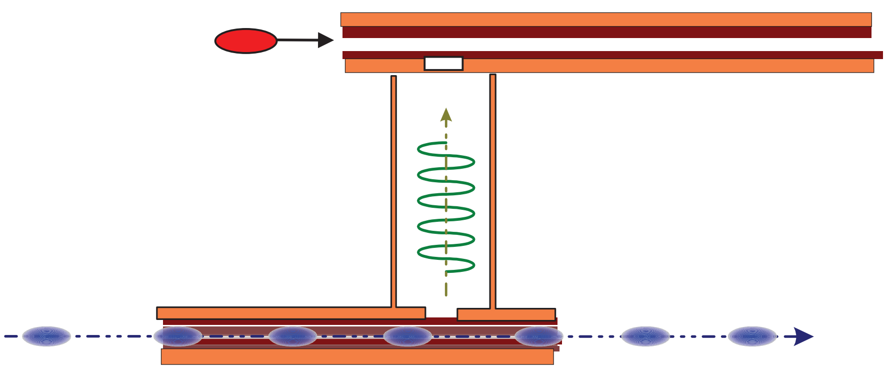

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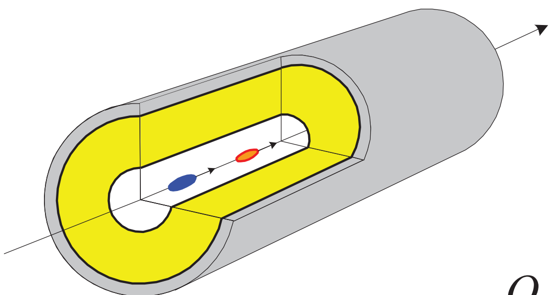

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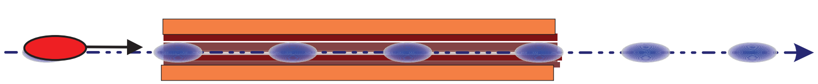

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Dielectric Wakefield Acceleration (DWA)

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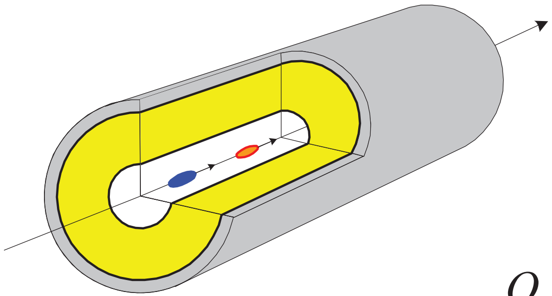

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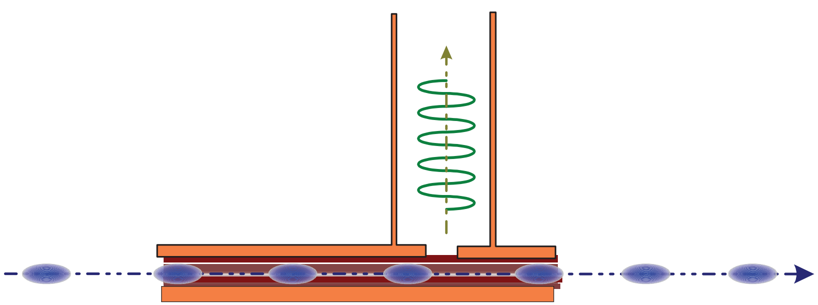

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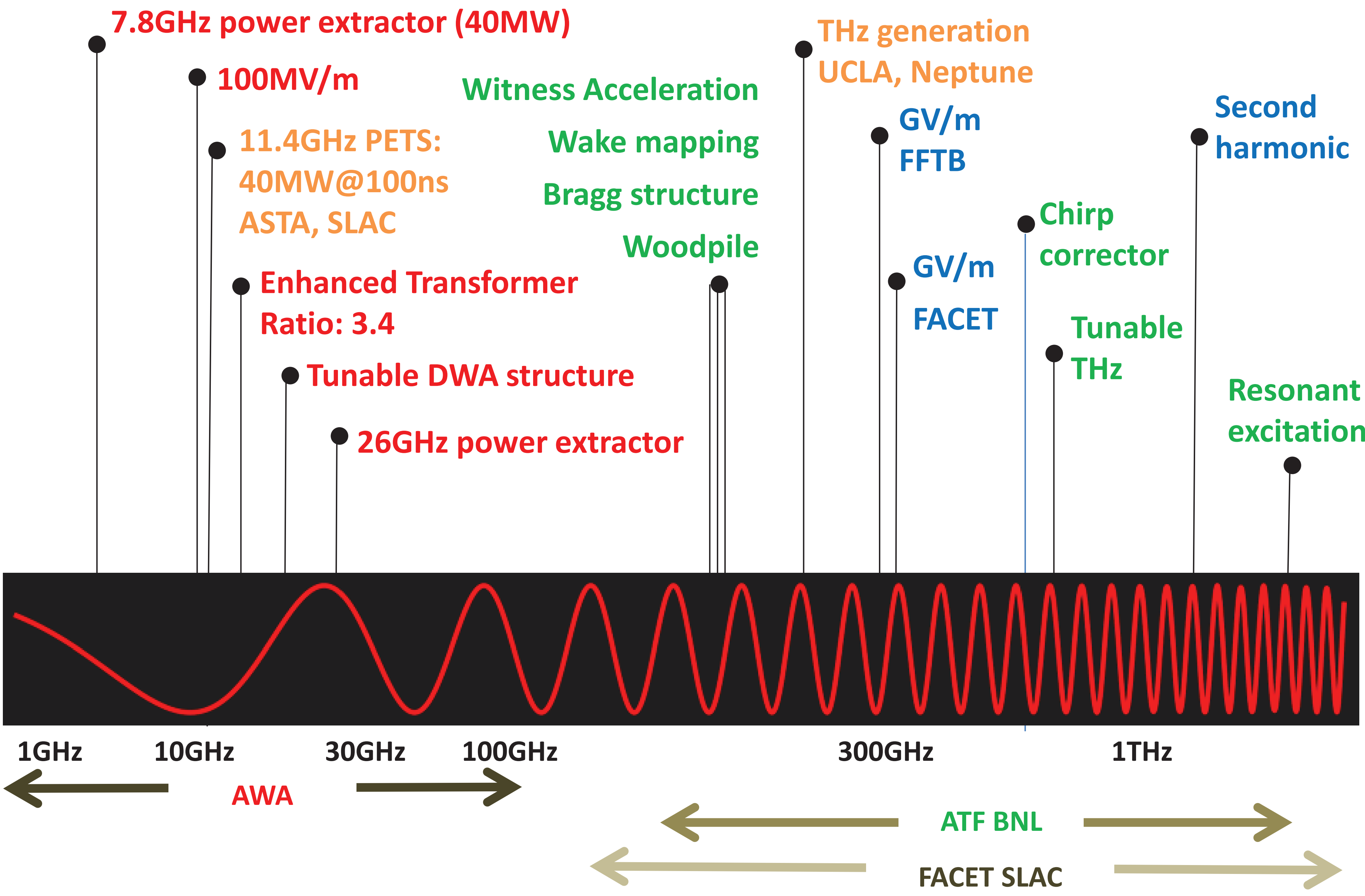
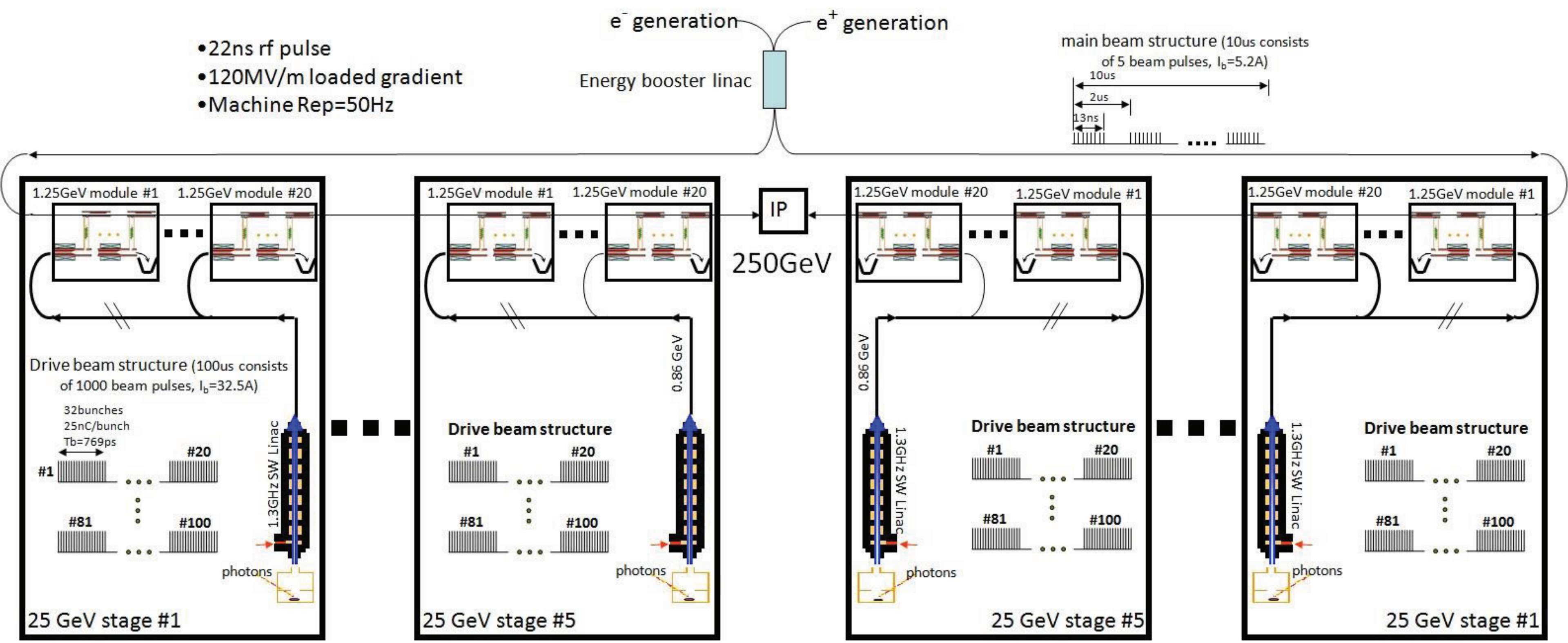
Recent Dielectric Wakefield Structures Experiments



Motivation: Argonne Flexible Linear Collider

Short pulse – high gradient (efficiency optimization) – low cost
Technology required: Broadband couplers, power extractor demonstration..

Layout of the ANL 26GHz 250GeV Flexible Linear Collider

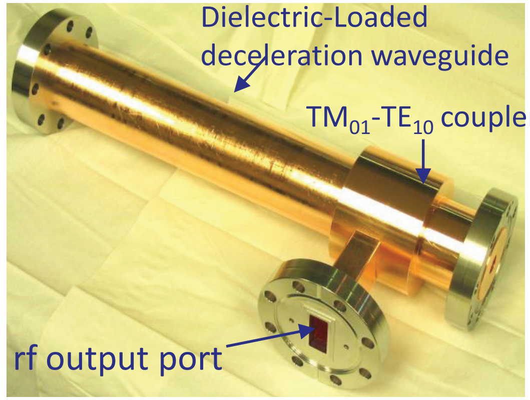


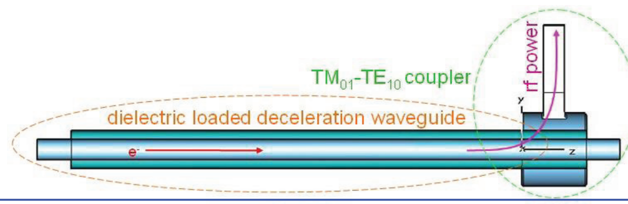
C.J. Jing, et. al. IPAC2012

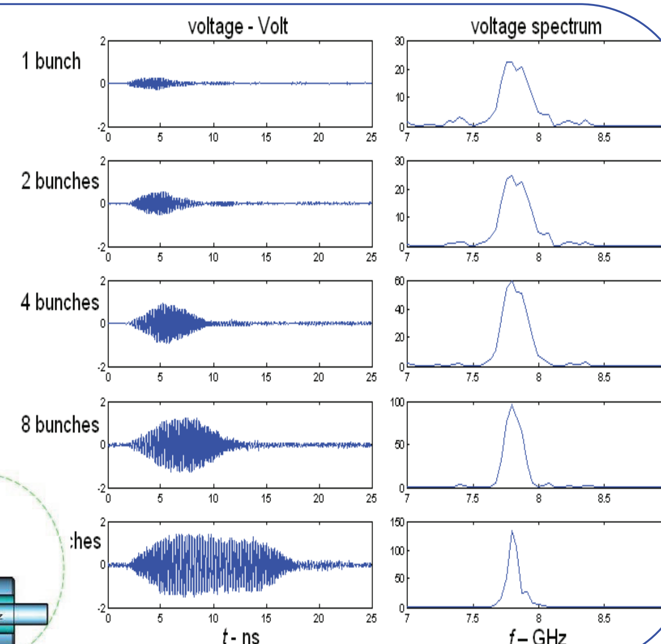
Development of Dielectric-Based Wakefield Power Extractors

C-Band Wakefield Power extractor

- 30ns,1MW & 10ns, 40MW 7.8GHz rf pulse produced



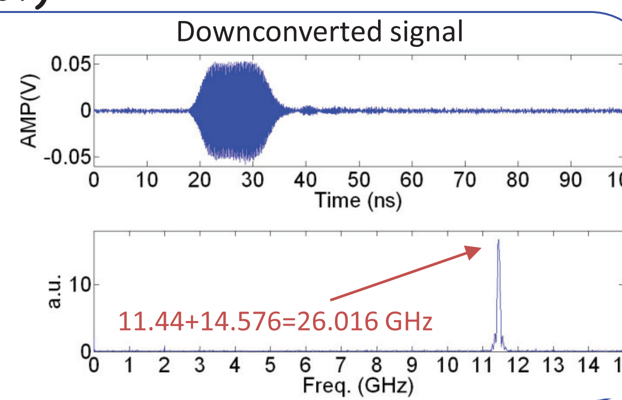




F. Gao et al. PRSTAB 11, 041301 (2008)

K-Band Wakefield Power extractor (Euclid SBIR Project)

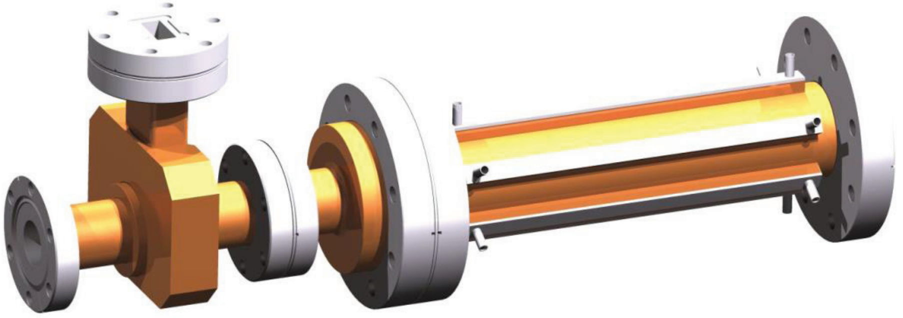
- 16ns,1MW & 10ns, 20MW 26GHz rf pulse produced



AWA ANL

C. Jing et al. PAC'09

Dielectric PETS (for CLIC) Parameters



Using CLIC Beam: σz=1mm, Q=8.4nC, Tb=83ps

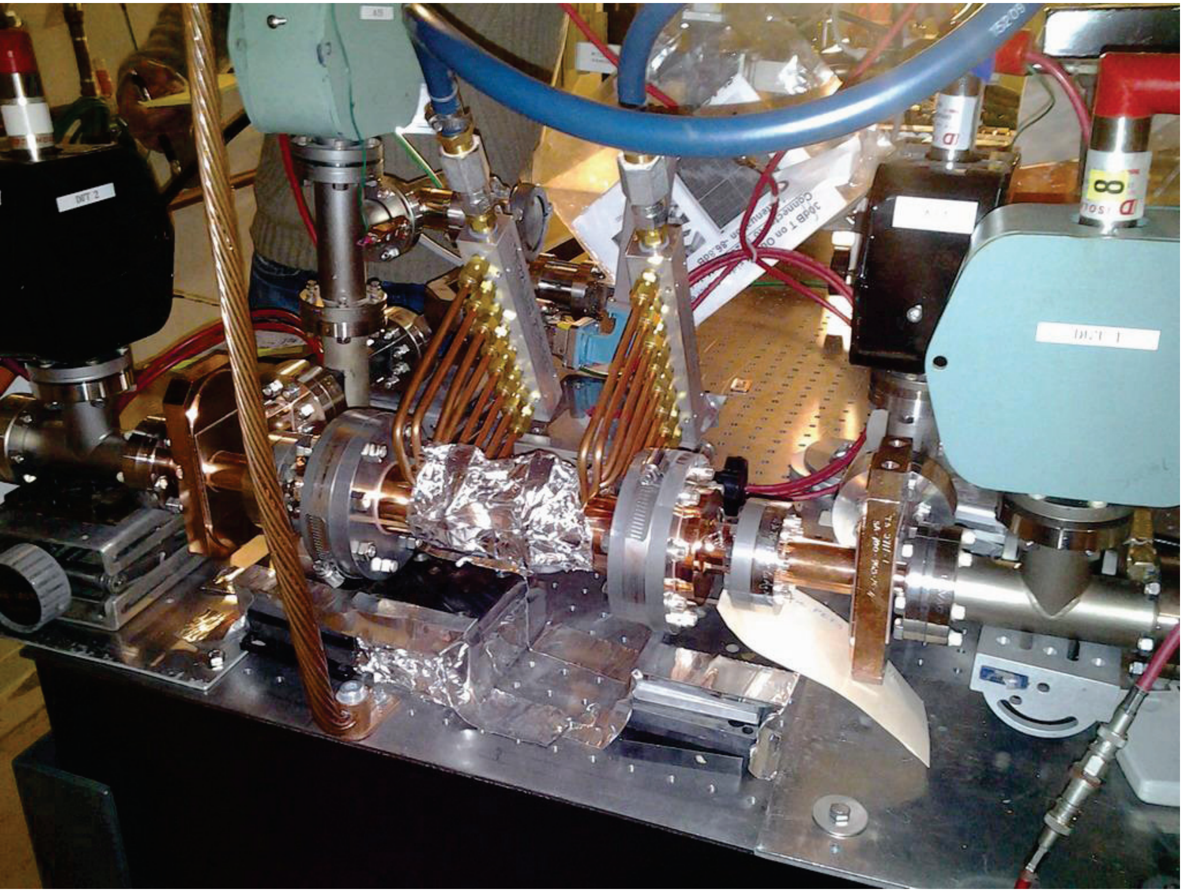
Freq	11.994GHz
Effective Length	23cm
Beam channel	23mm
Dielectric wall thickness	2.582mm
Dielectric const.	3.75(Quartz)
Q	7318
R/Q	2.171kΩ/m
Vg	0.4846c
Peak surface Gradient	$E_{\parallel}$=12.65MV/m; $E_{\perp}$=18.28MV/m
Steady Power	142MW

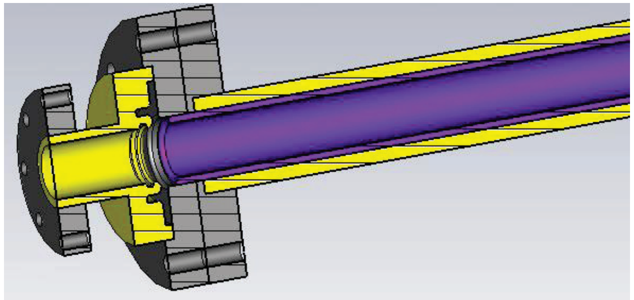
Euclid SBIR Project

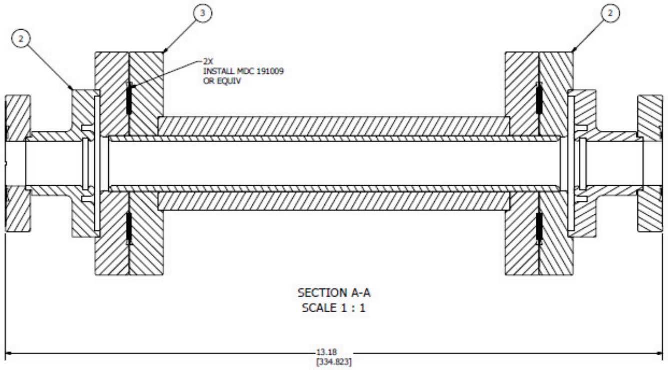
11.4GHz version is under high power rf test at SLAC

Currently conditioned to 40 MW, 100 ns (with the goal of 200ns)

Setup at SLAC ASTA facility





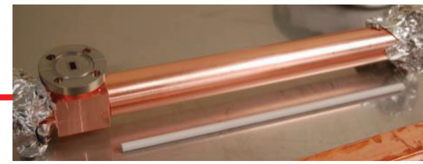


SLAC ASTA

Planned two beam acceleration experiment @AWA

75MeV drive beam
- 16 bunches x 60nC/per bunch
- σz=2mm

26GHz Stage I DWPE
a=3.5mm; b=4.53mm;
eps=6.64; L=30cm

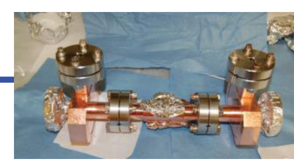


65MeV drive beam
(10MeV loss)

RF Power Generation
- 767MW x15ns
- 26GHz rf

witness (10 MeV)
Q=1nC, σz=1mm, ε=1.5 um

26GHz Stage II DLA
a=3mm; b=5.03mm;
eps=9.7; Vg=11%c; L=30cm



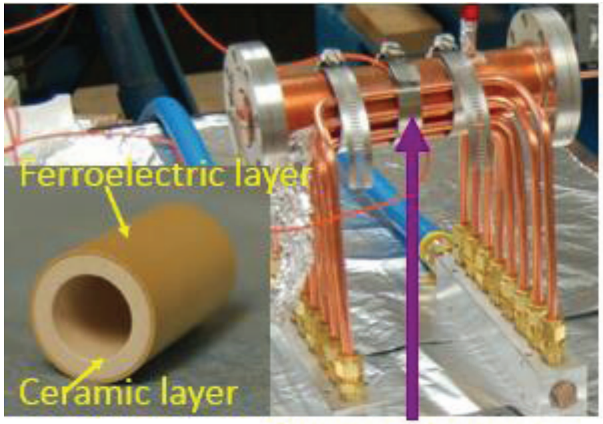
Ez = 250MV/m

witness (85 MeV)

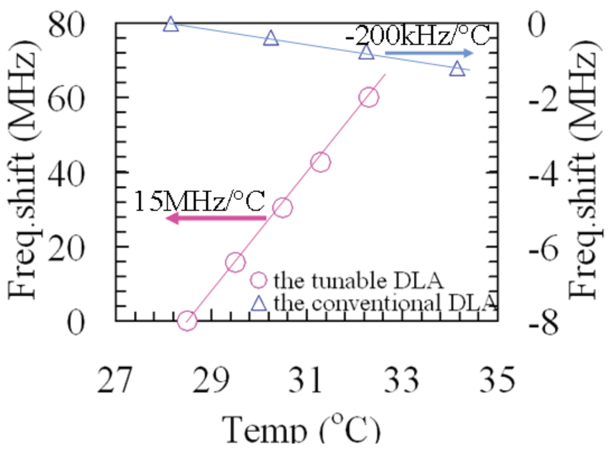
11

Non-linear ferroelectrics for DWA

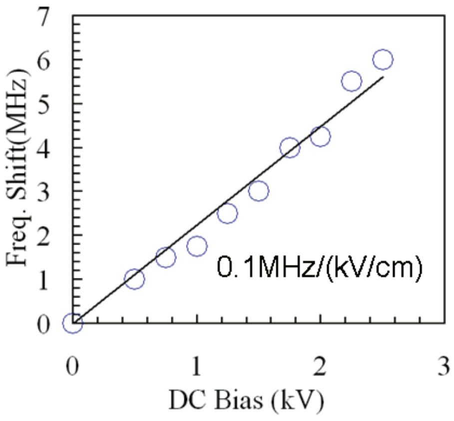
- BSTM – nonlinear ferroelectric
- Frequency tuning
- $\varepsilon(V_{DC})$ – fast, $\varepsilon(T)$ - slow
- Bench test (T, V_{DC})
- Beam test (T)



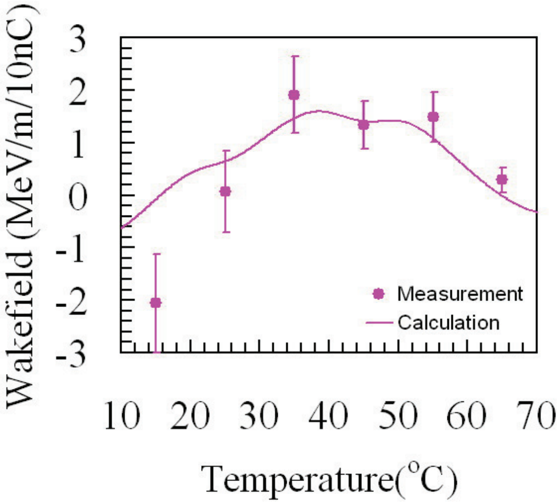
Temperature - tuning



Freq (T)



Freq (V_{DC})



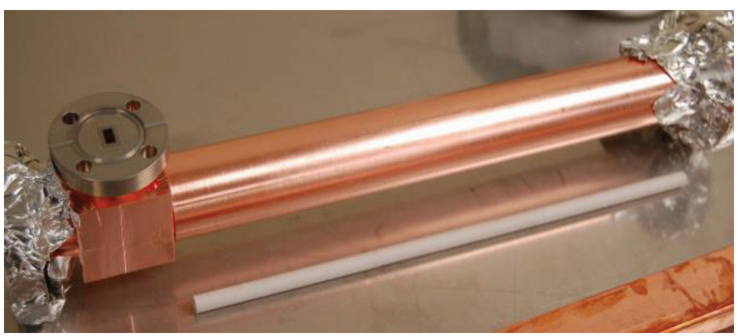
Witness beam energy change

AWA ANL

C. Jing et al. PRL, 106, 164802, April (2011)

Reducing the aperture…

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



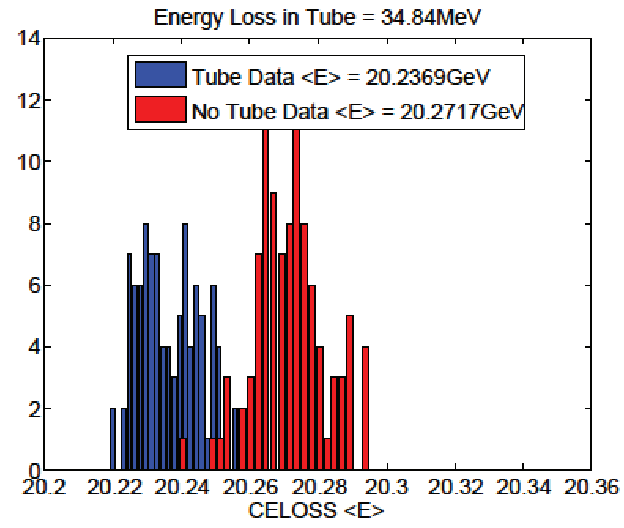
FFTB (2008)

- Fused silica tube, metallized OD=324um, ID = 100um, L=1cm
- SLAC beam σ_z = 10 – 100um, σ_r = 10um
- 16 GV/m maximum accelerating field achieved
- Metallization evaporated due to ohmic heating
- dielectric breakdown observed (maximum field on dielectric surface ~ 27 GV/m

Thompson et al PRL 100, 214801 (2008)

UCLA FACET DWA measurement (2013)

- Fused silica tube, metallized OD=640um, ID = 450um, L=10cm
- SLAC beam 3.2 nC, σ_z = 30um, σ_r = 40um
- <ΔE>=50 MeV!
- Ez >1 GV/m

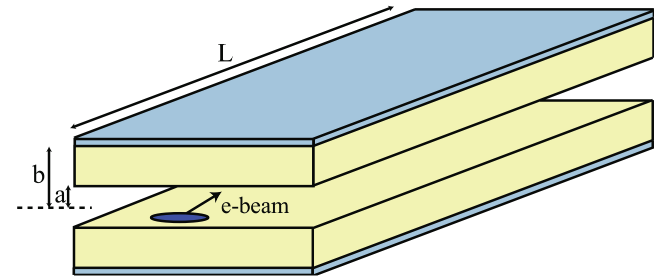


Courtesy G. Andonian
Being prepared for publication

FACET, SLAC

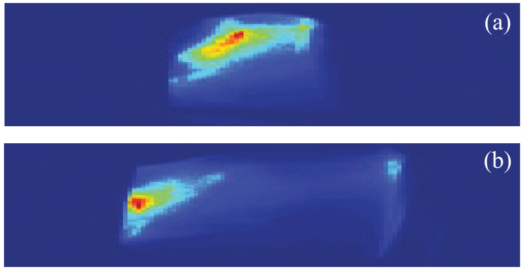
Acceleration in slab symmetric DWA

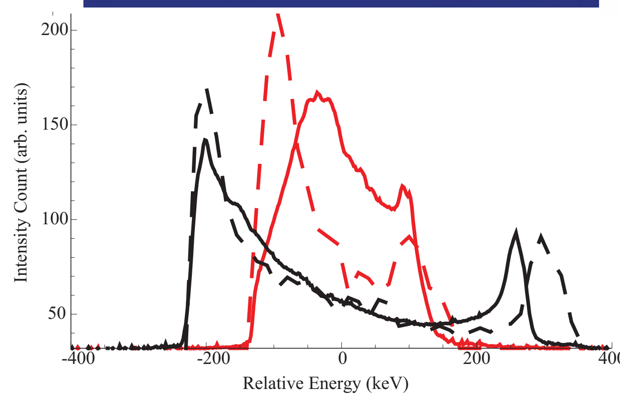
- Structure:
  - SiO2, beam gap 240μm
  - Metal boundary
- BNL ATF
  - E = 59MeV, Q=500pC
  - Flat beam
  - Long bunch structure with two peaks
- CCR interferometry
  - Characterized first two modes
- Observe acceleration
- Robust start-to-end simulations for benchmarking



No slab

slab





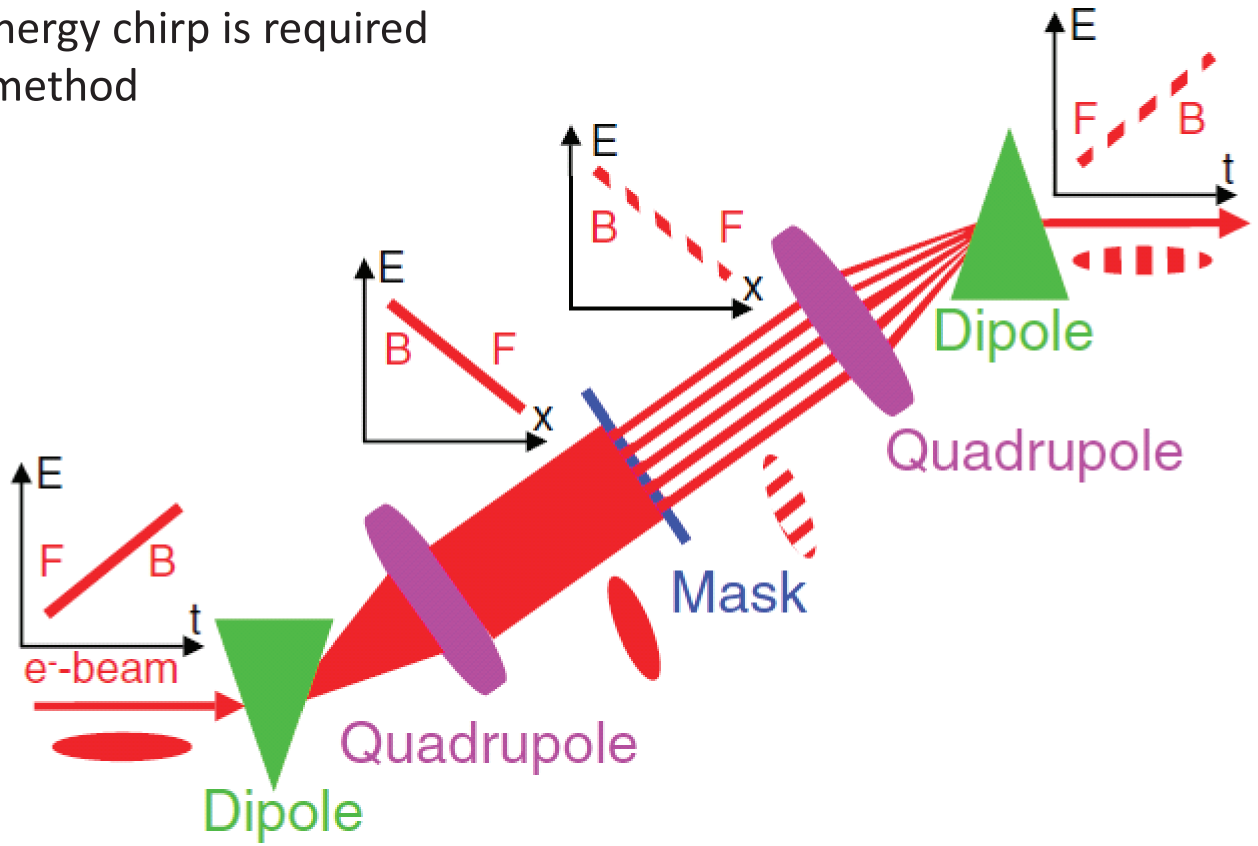
Projections + Simulations

ATF BNL

G. Andonian et al., PRL 108, 244801 (2012)

ATF beam shaping

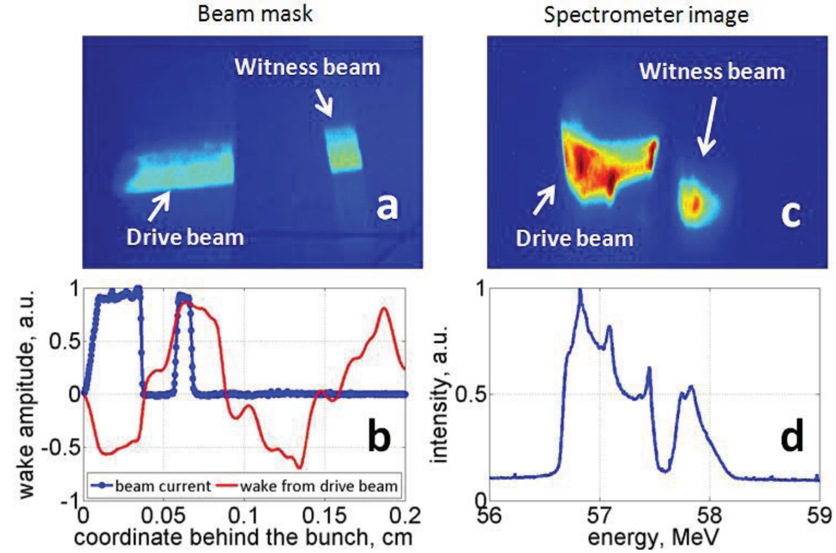
Linear energy chirp is required
for this method



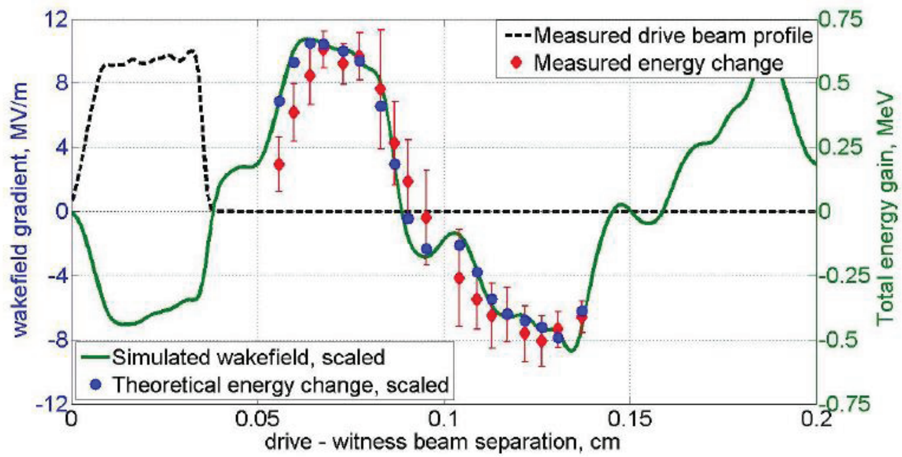
P. Muggli et al. Phys. Rev. Lett. 101, 054801 (2008)

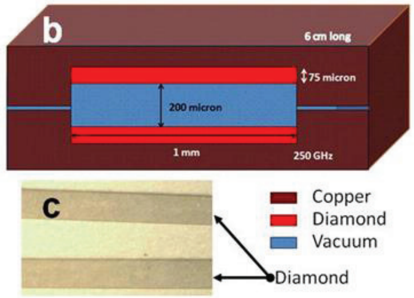
Wakefield mapping in planar DWA

- Diamond - Chemical vapor deposition (CVD)
  - Low loss tangent
  - High thermal diffusivity
  - High breakdown
- Rectangular waveguide
  - 6cm length; 200um x 1mm beam gap
- Experiment at BNL ATF
  - 57MeV, 70% charge transmission
  - Variable delay witness
- Results
  - Wakefield mapping (TM_{11}-like mode, 0.25THz)
  - No damage to diamond after beam interaction



Wakefield mapping





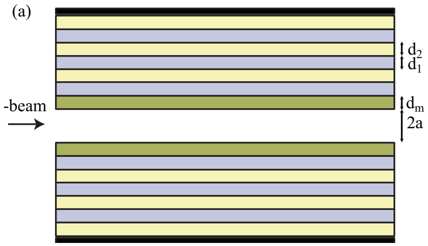
ATF BNL

S. Antipov, et al., Appl. Phys. Lett. 100, 132910 (2012)

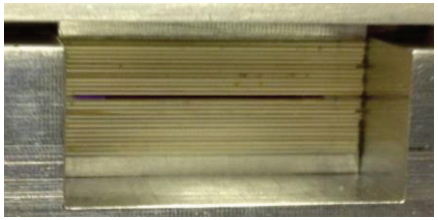
DWA with Bragg-like boundaries

UCLA

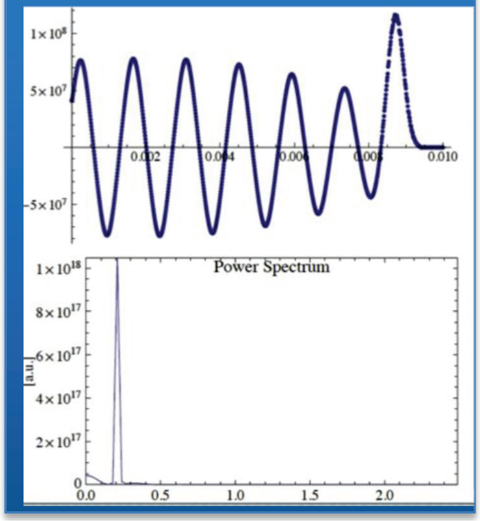
- Modal confinement
  - Constructive interference
  - Alternating dielectric layers
  - Eliminate metal cladding
- DWA: SiO2, 240µm beam gap
  - Bragg layers SiO2, ZTA
  - Assembled at UCLA
- BNL ATF experiment
  - 50MeV, 100pC, σt~1ps
- Results
  - λ =1.4mm (210GHz)
  - Energy chirp mitigation
  - Confirmed with simulation
  - Submitted to PRL



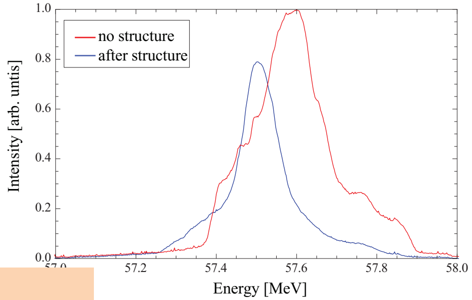
(b)



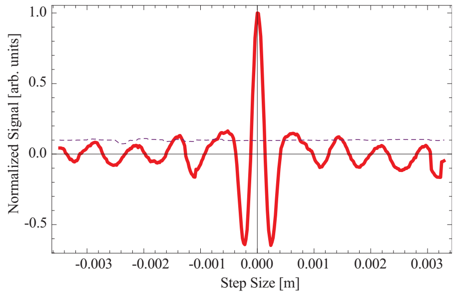
OOPIC Sims



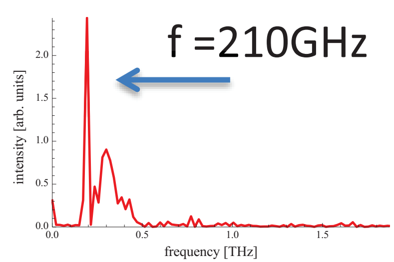
Beam Energy



Interferogram



FFT



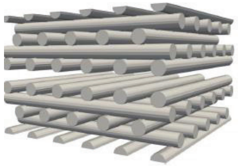
ATF BNL

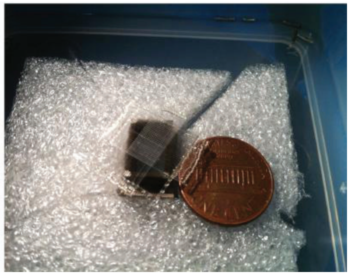
Courtesy G. Andonian, UCLA

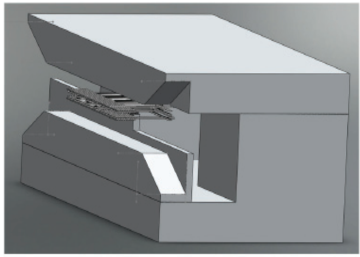
Woodpile Experiment

UCLA

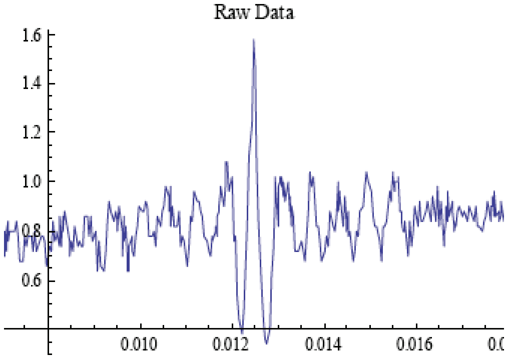
- Extension of Bragg to 3d
  - Photonic structures
  - Studies in laser coupling
- Woodpile structure
  - Sapphire rods for woodpile (125µm)
  - 240µm beam gap
  - Hand Assembled at UCLA
  - Matching horn incorporated in structure
- BNL ATF
  - 50MeV, 100pC
- Results under study
  - Scaled GALAXIE structure fabricate by *laser assisted etching* of sapphire



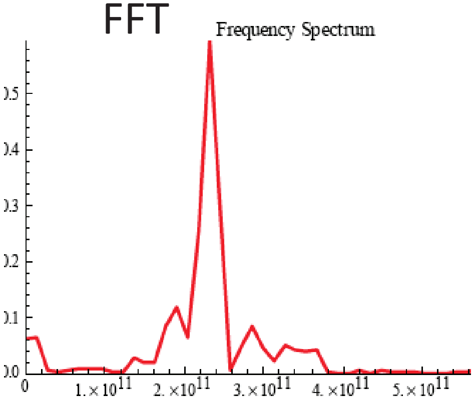




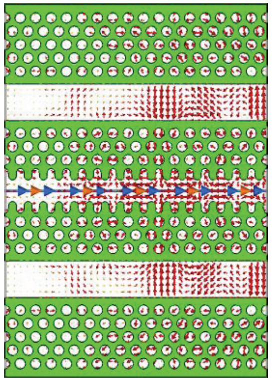
Interferogram



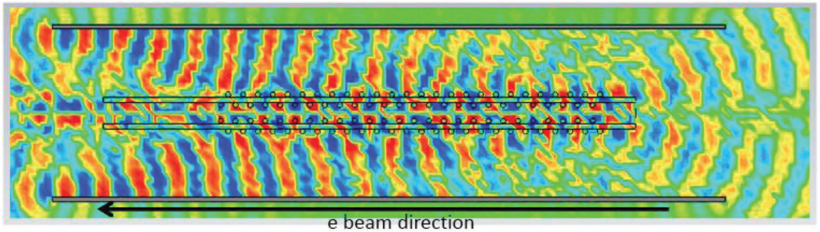
FFT



Scaled Galaxie



CST Simulations



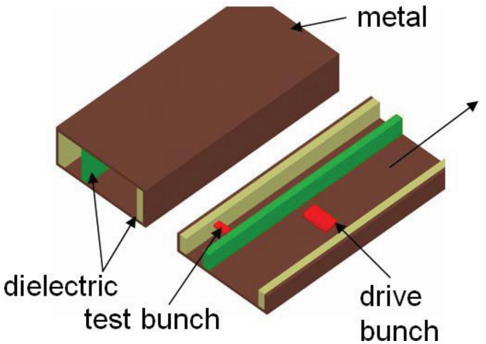
ATF BNL

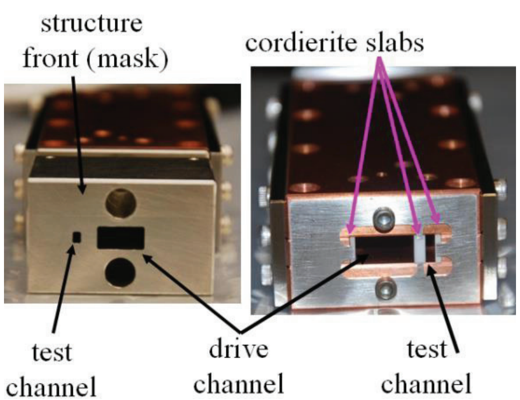
Courtesy G. Andonian, P.Hoang, UCLA

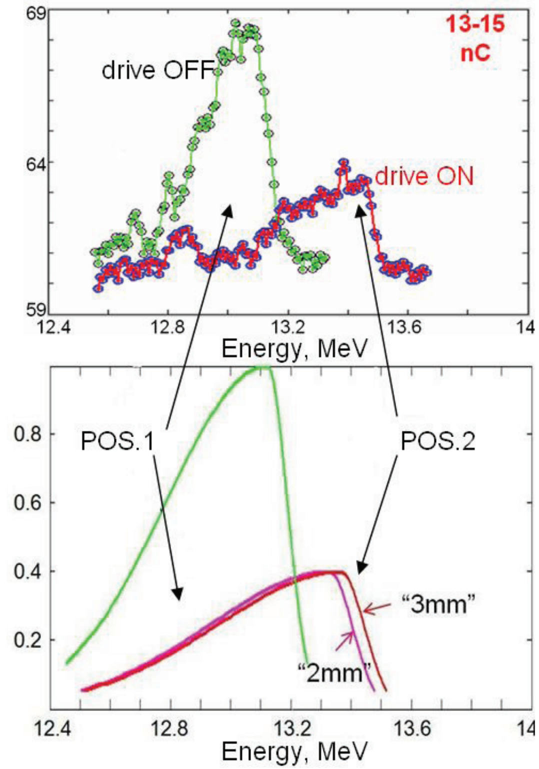
Two-beam acceleration in THz?

Two-channel structures

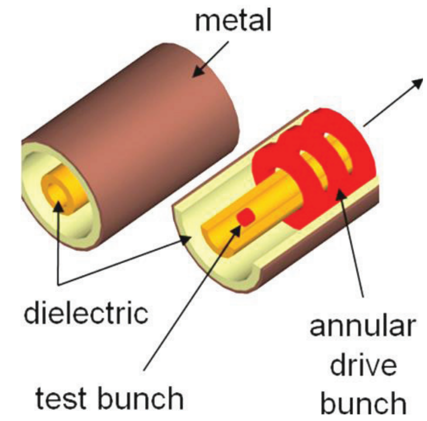
Yale – Omega P

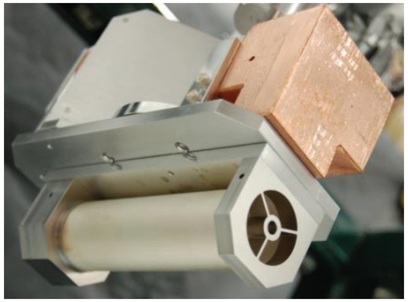


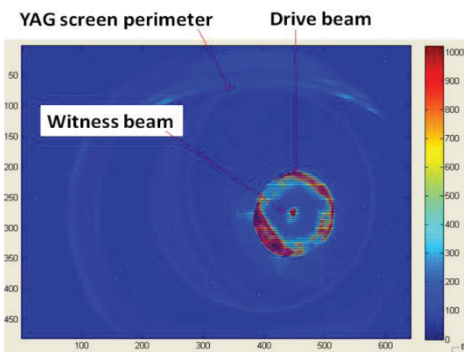




Measured at the AWA



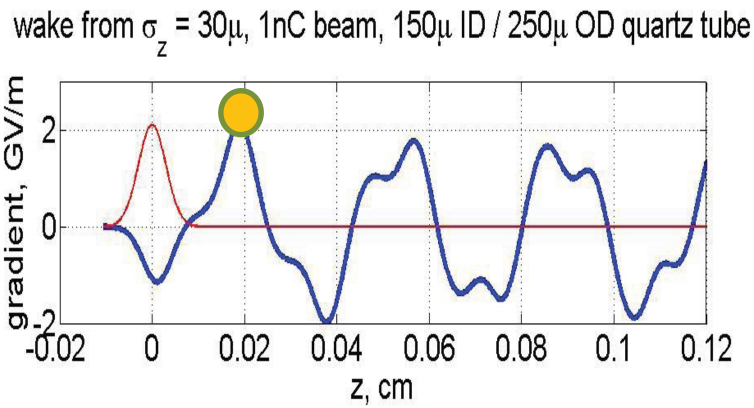


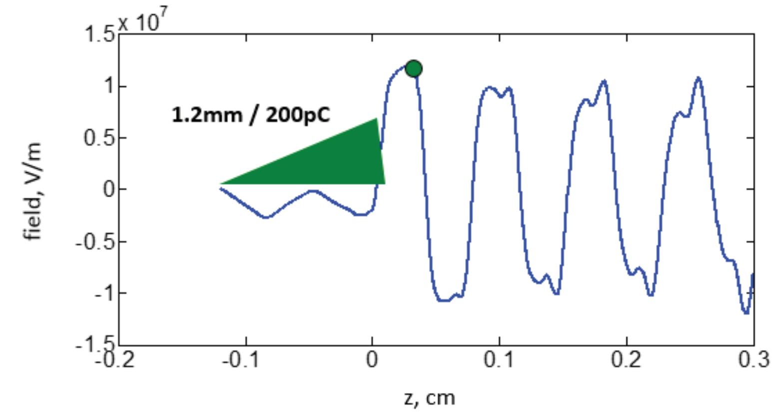


proposed

S. V. Shchelkunov, et al., Phys. Rev. ST Accel. Beams 15, 031301 (2012)

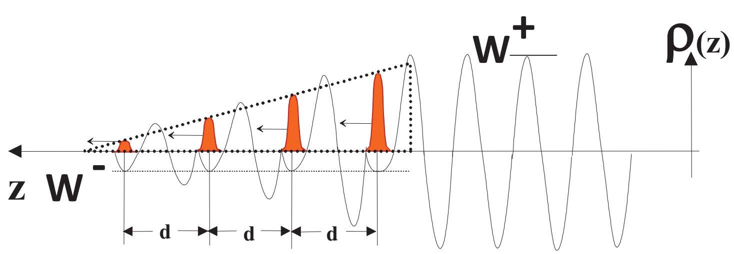
Collinear Acceleration, Transformer Ratio

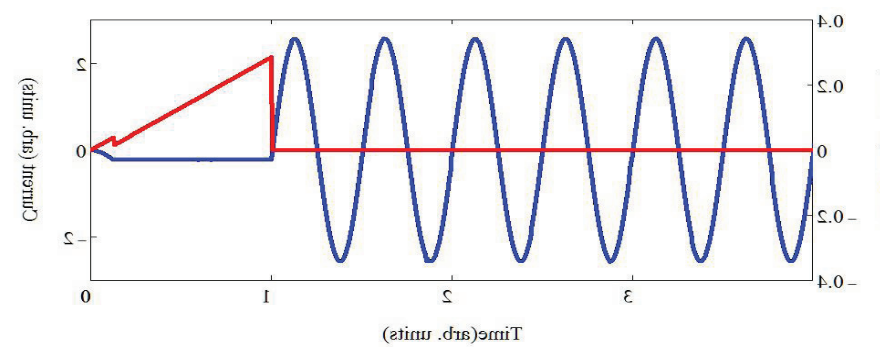




Transformer Ratio:

$$TR = \frac{E_{\max\, gain}}{E_{\max\, loss}}$$



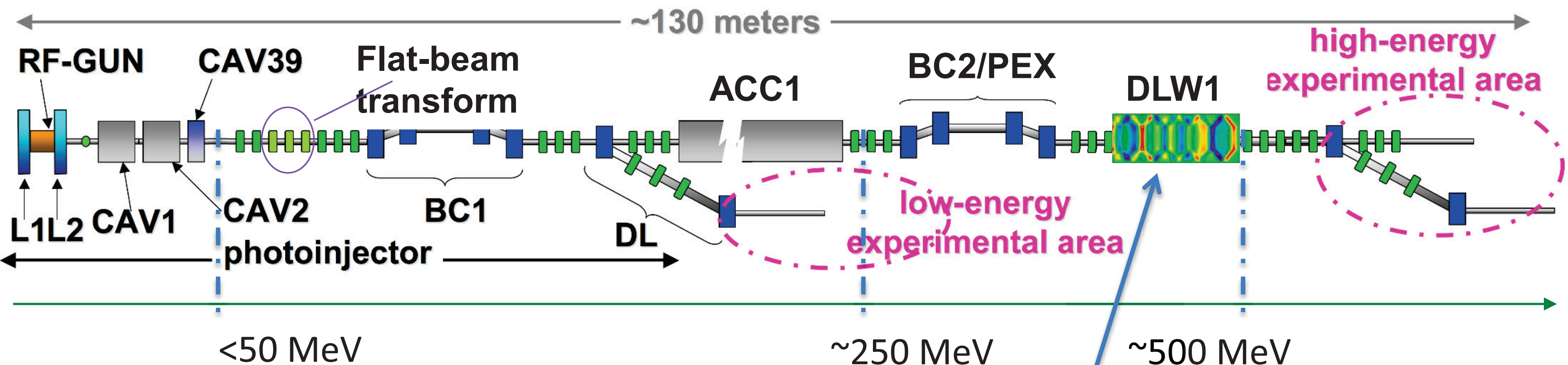


Using this method, TR = 3.4 was demonstrated experimentally at AWA, ANL

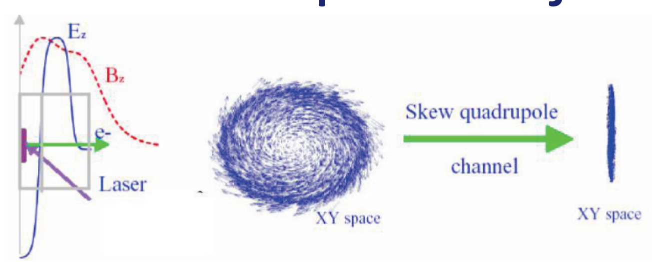
C. Jing et. al. PRL, 98, 144801, April (2007)
C.Jing et. al. PR ST-AB, 14, 021302, Feb. (2011)

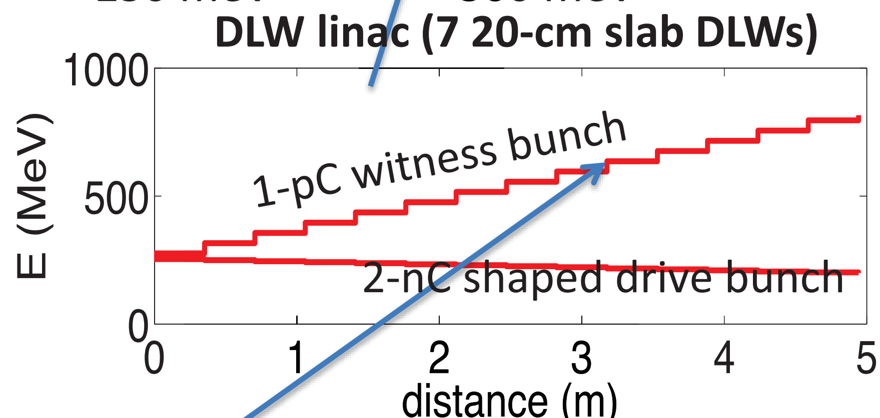
AWA ANL

Energy-doubling of the Advanced Superconducting Test Accelerator (ASTA) using a DWFA module

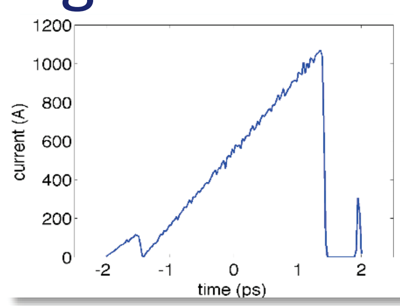


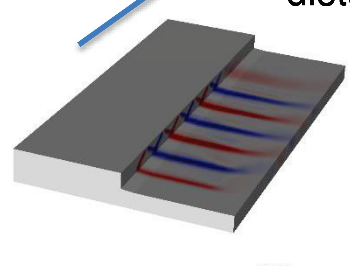
- Flat-beam photoinjector

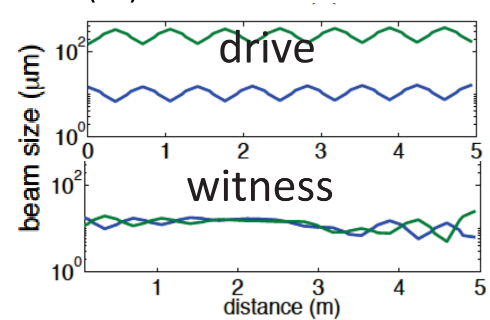




- Phase-space-exchanger current shaping



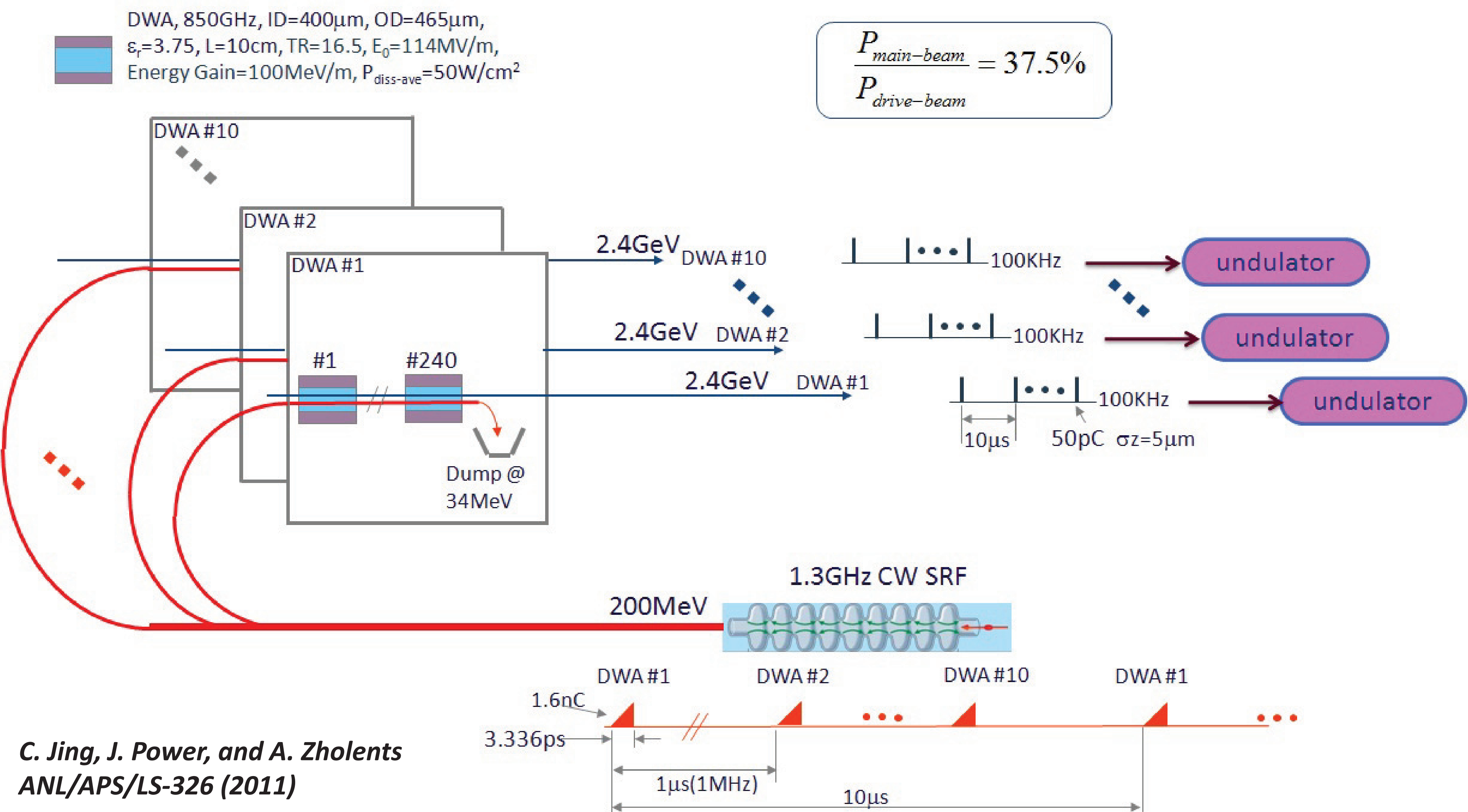




Courtesy of P. Piot, NIU / FNAL

Application for high efficiency dielectric collinear wakefield acceleration: soft X-Ray FEL example

A Schematic of a FEL facility based on a 2.4 GeV DWA



C. Jing, J. Power, and A. Zholents
ANL/APS/LS-326 (2011)

Dielectric wakefield accelerator project at LANL

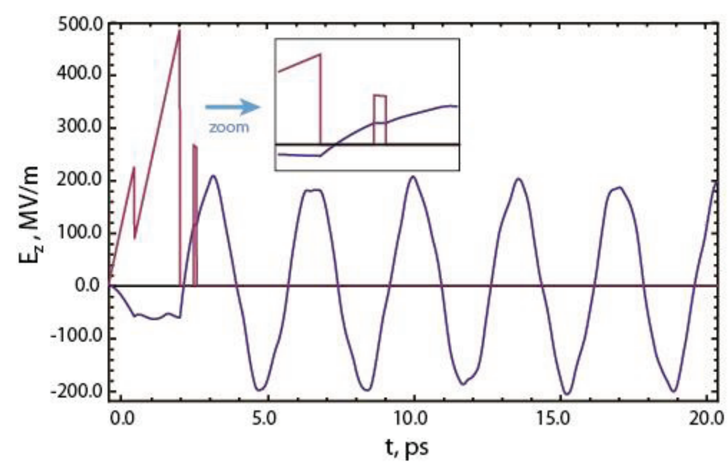
- The pre-conceptual design for Matter-Radiation Interactions in Extreme (MaRIE) future signature facility is underway at LANL, with the design of the 12 GeV electron linear accelerator being one of the main research goals.

- A dielectic wakefield accelerator (DWA) has a potential to be employed as a future afterburner for the MaRIE linac if the energy spread in the witness bunch can be made below 10^{-4}.

- Energy spread in the witness bunch can be made very small if the shape of the witness bunch is properly customized.

marie.lanl.gov

The wakefield excited by the shaped drive and witness electron bunches.

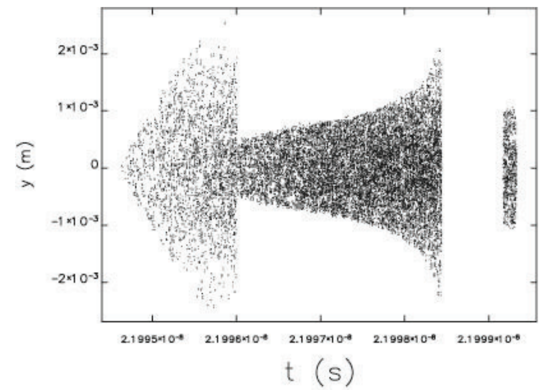


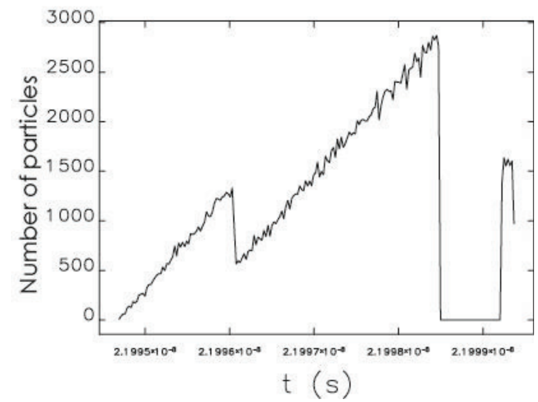
Courtesy of E. Simakov (Smirnova), LANL

Shaping electron bunches with an Emittance Exchanger

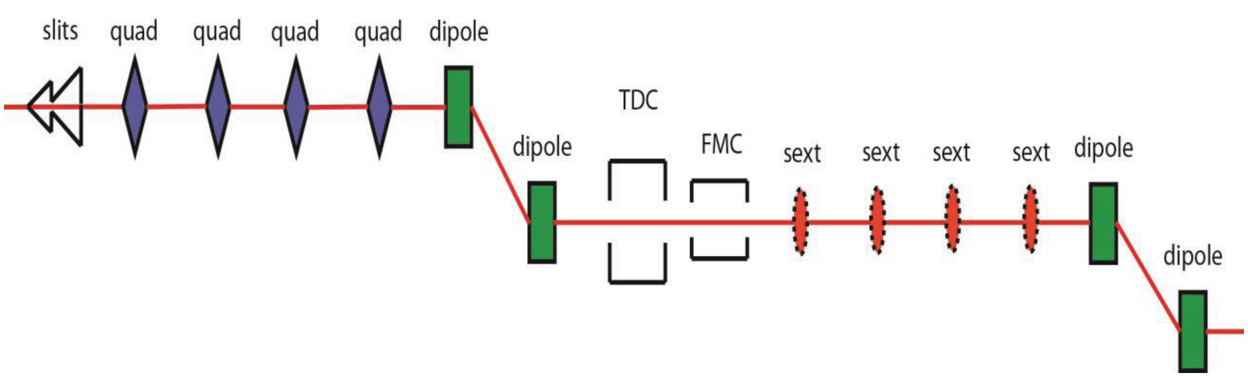
- A double triangular drive bunch and a trapezoidal witness bunch can be cut out from a single Gaussian shaped bunch with a specially shaped mask.
- An Emittance Exchanger (EEX) in either double-dogleg or a chicane configuration can convert the shaped x-y distribution into the shaped t-y distribution of electrons.

Distribution of electrons within shaped electron bunches.





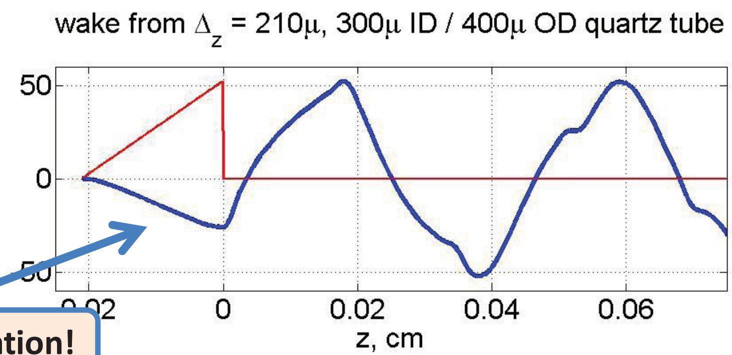
A schematic of a bunch shaping beamline: mask is followed by an EEX in a double-dogleg configuration.



Courtesy of E. Simakov (Smirnova), LANL

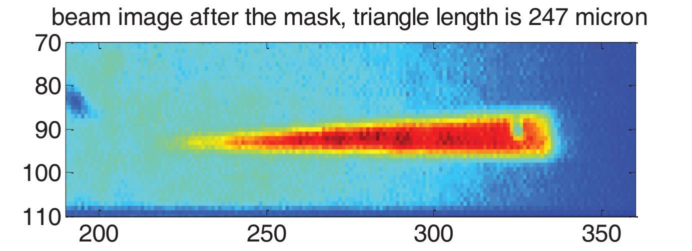
Energy Chirp Correction Experiment at ATF

Triangular-shaped (current) beam with energy chirp

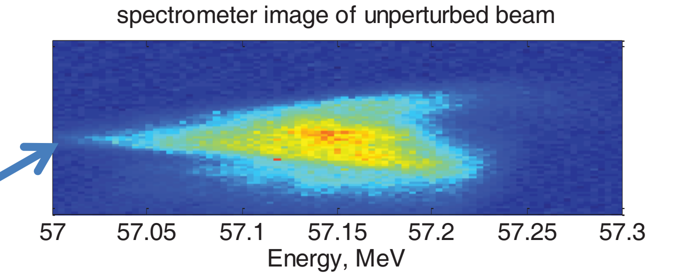


Self-deceleration!

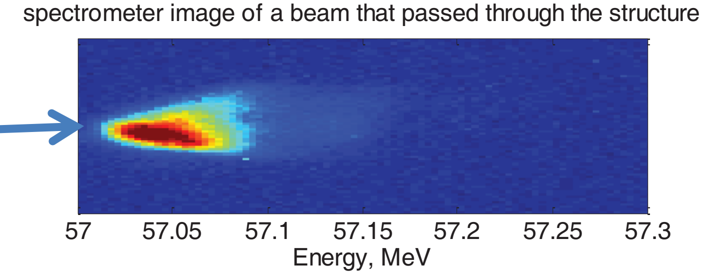
Chirp corrector – passive wakefield tube: dielectric loaded waveguide



Spectrometer image of the original beam



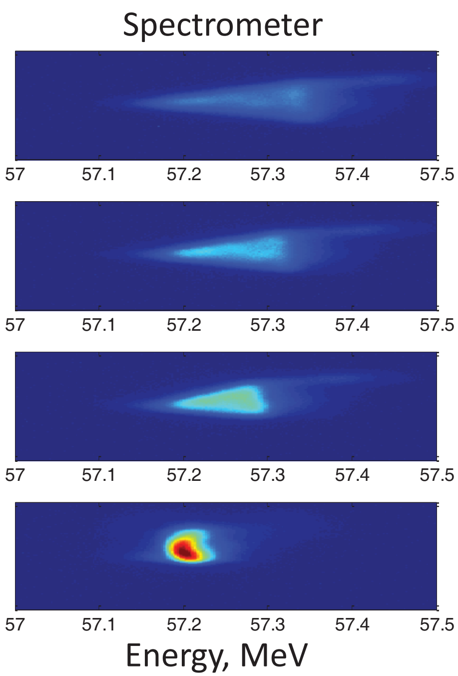
Spectrometer image after chirp corrector

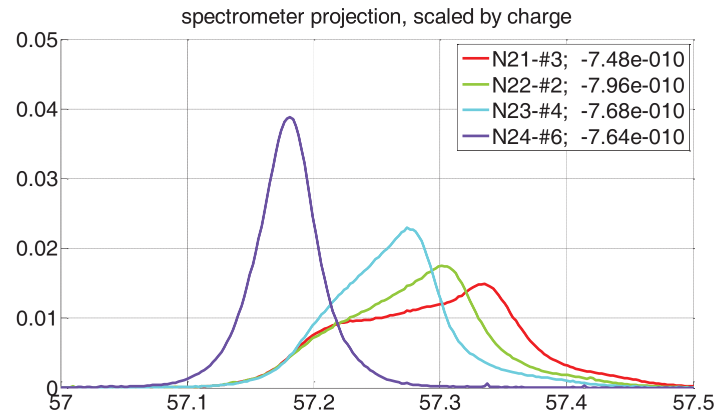


S. Antipov, et al, Phys. Rev. Lett. 108, 144801 (2012)

ATF BNL

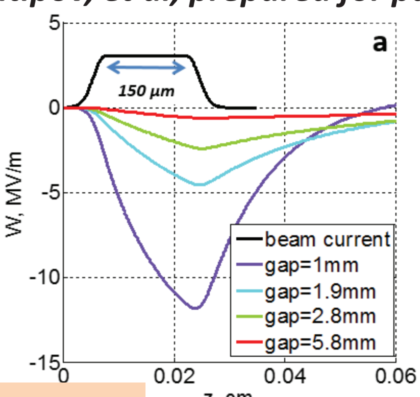
Experimental results: triangular current with chirp





Gap ~ 2.8mm, 2.7mm, 1.9mm, 1mm
100% charge transmission
54pC total charge, ~160keV corrected
~60keV/m/mm/pC – chirp correction number
Say, 300pC beam with σ_z = 100um, goes through 1m of chirp corrector → 1.8 MeV corrected

S. Antipov, et al, prepared for publication



Dielectric chirp corrector @ ATF, BNL – May, 2013
Corrugated chirp corrector @ PAL-ITF – August, 2013
Corrugated chirp corrector @ ATF, BNL – September, 2013

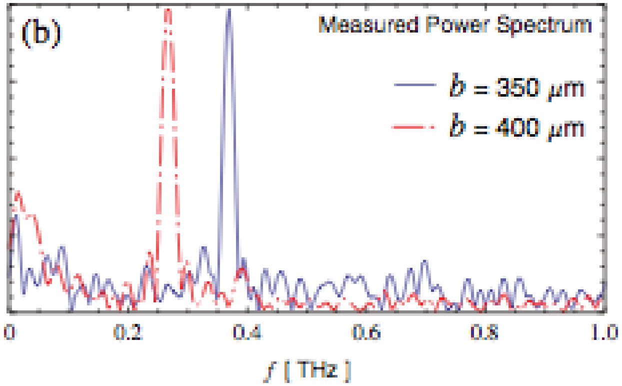
Beam-based THz sources

GHz

THz

UCLA Neptune
- CCR as a tunable THz source
- Q~200pC, E=14MeV, σ_z~200µm,
- Varied outer radius (b=350µm,400µm),L=1cm
- ~10µJ of THz, narrowband

UCLA Neptune 2009

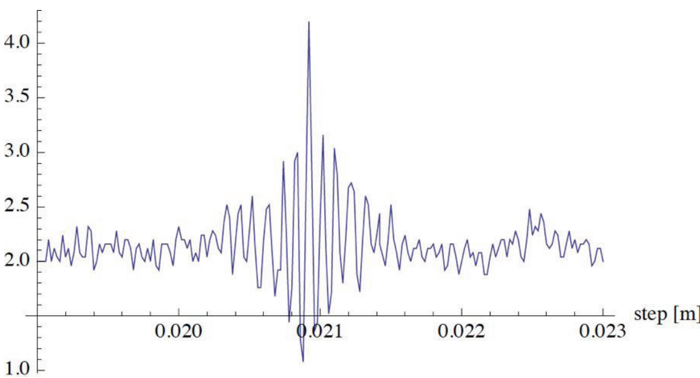


A. Cook, et al., PRL 103, 095003 (2009)

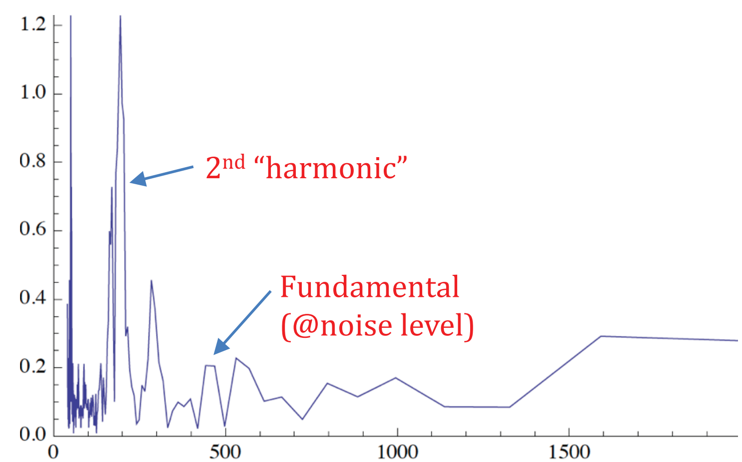
UCLA

Resonant excitation of higher-order modes

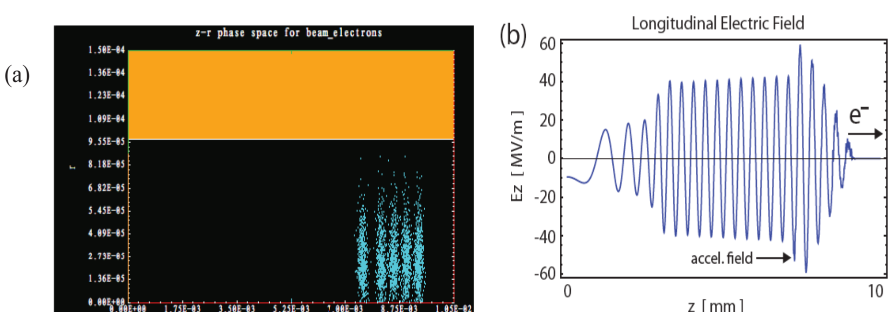
- Structure: SiO_2 tubes (Al coating, 100µm)
- Pulse train
  - Sextupole correction to mitigate chromatic aberrations
- Resonant wake excitation, CCR spectrum measured
  - Excited with 190 µm spacing (2^{nd} "harmonic"=TM_{02})
  - Suppression of fundamental
- Developed techniques to characterize structures



CCR autocorrelation



Frequency spectrum



OOPIC simulations

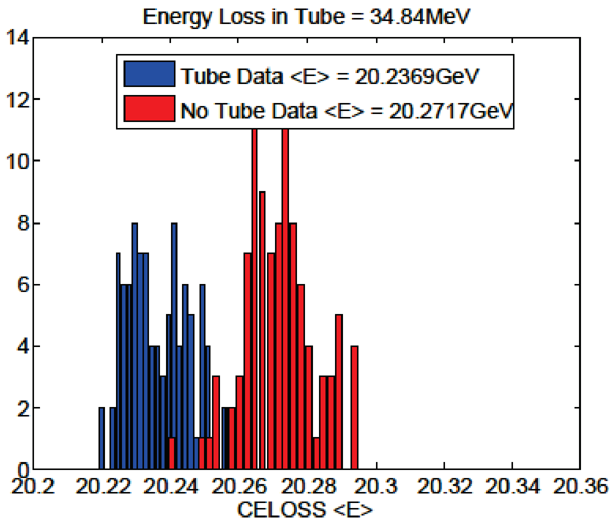
ATF BNL

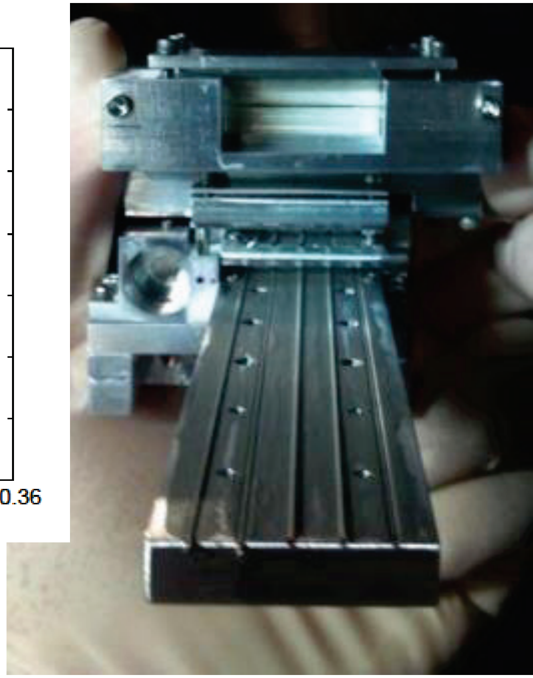
G. Andonian, et al., Appl. Phys. Lett. 98, 202901 (2011)

UCLA FACET DWA Measurements

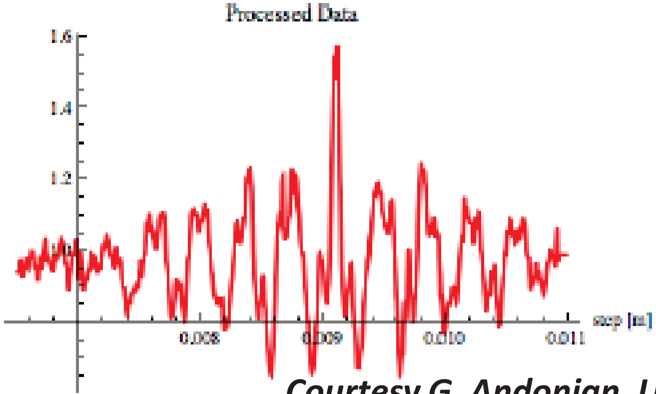
UCLA

- DWA: 10cm long, SiO2
- Robust Cu coating
- FACET beam parameters
  - Q=3.2nC, E=20.5GeV
  - $\sigma_x=\sigma_y=20\mu m$, $\sigma_z=45\mu m$
- Results:
  - $\langle\Delta E\rangle$=50 MeV!
  - Ez >1 GV/m
  - **0.4 THz: ~135mJ, BW=0.4%, 0.22GW**
  - **1.2 THz: ~40mJ, BW=0.3%, 0.14GW**

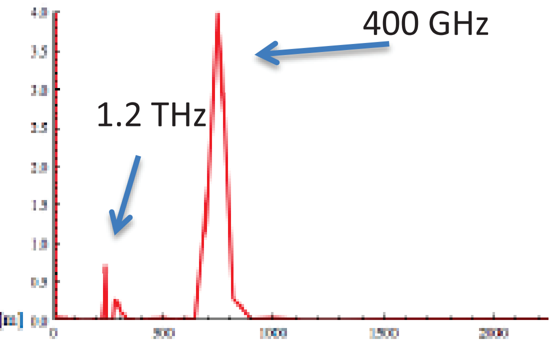




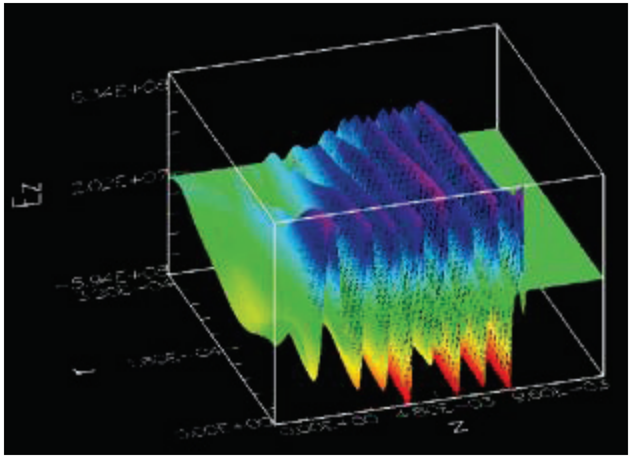
Interferogram



FFT

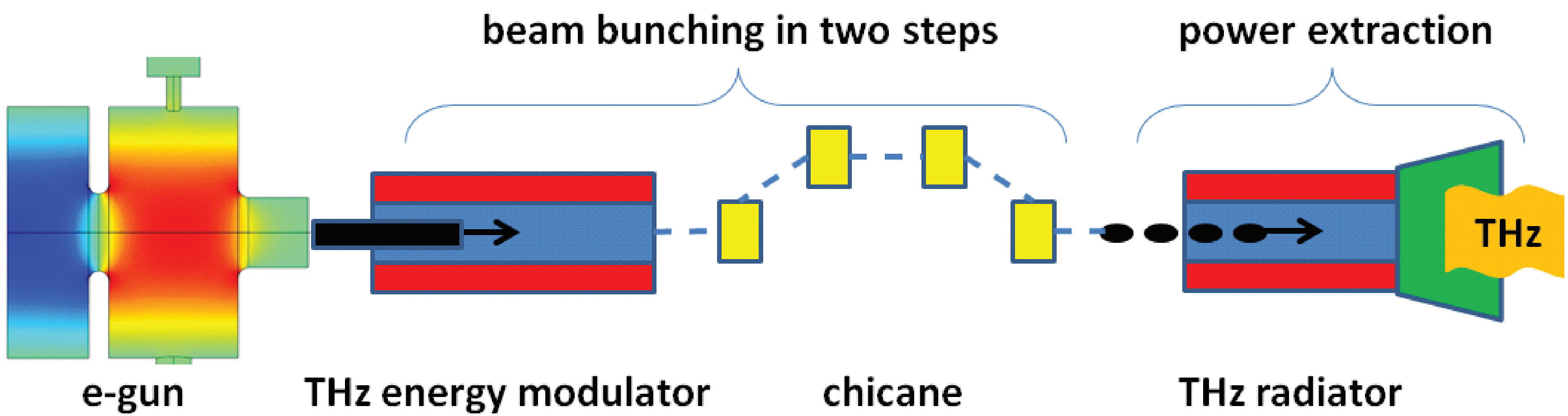


OOPIC Simulations



Courtesy G. Andonian, UCLA, in prep for publication

Beam based THz source

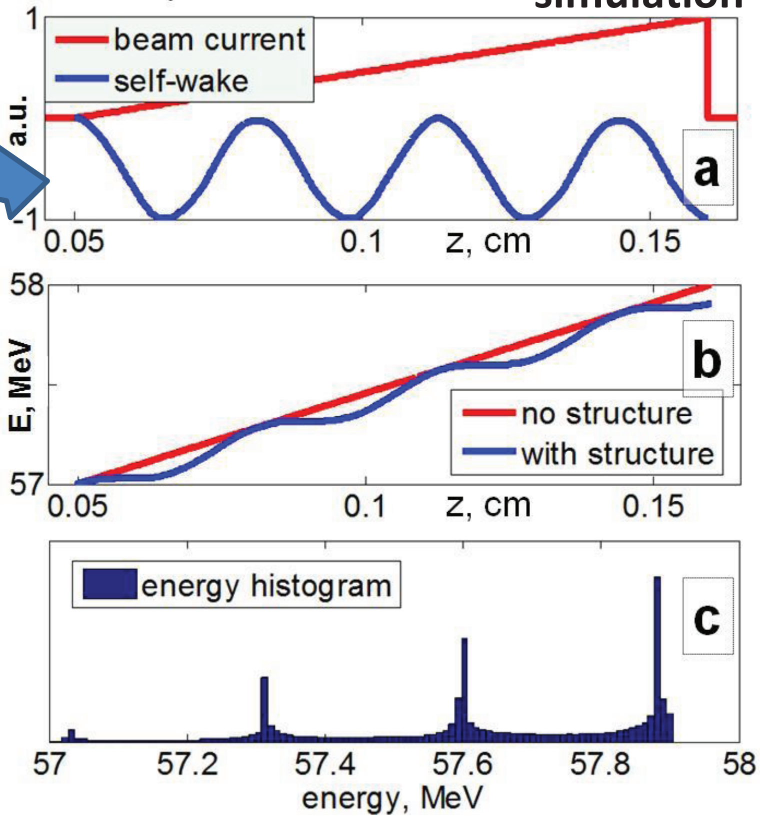


1 nC beam generates wakefield and looses 1 MeV = 1 mJ of energy generated in a pulse!

Observation of energy modulation at ATF

Periodic self-deceleration!

simulation

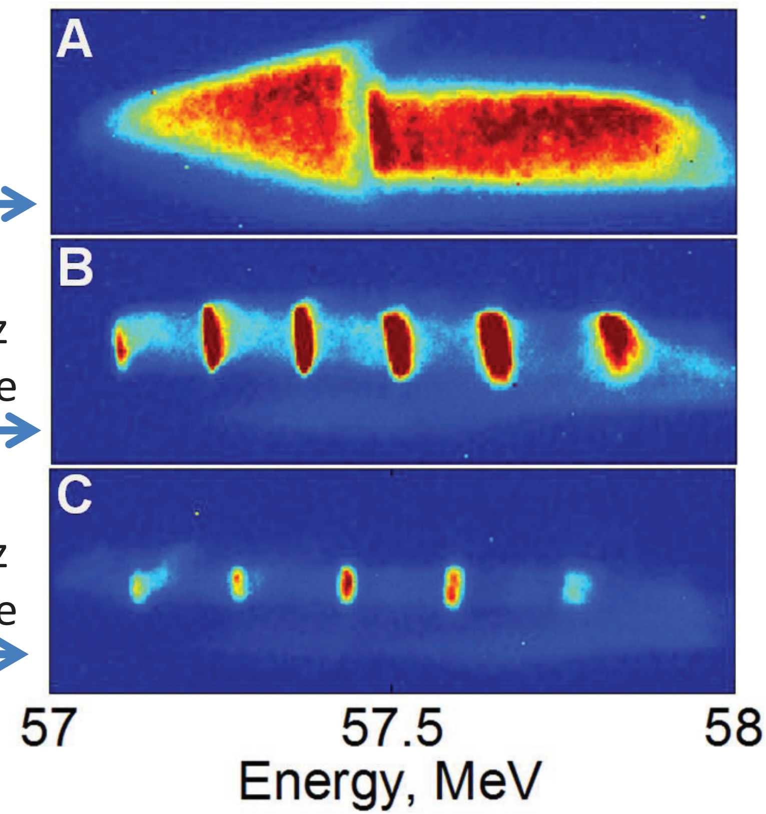


Measurement: spectrometer

Original chirped beam

0.95 THz structure

0.76 THz structure

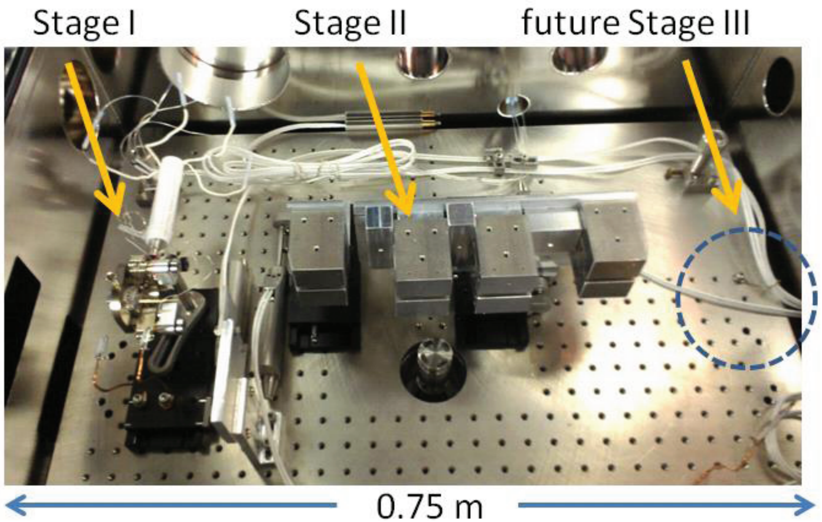


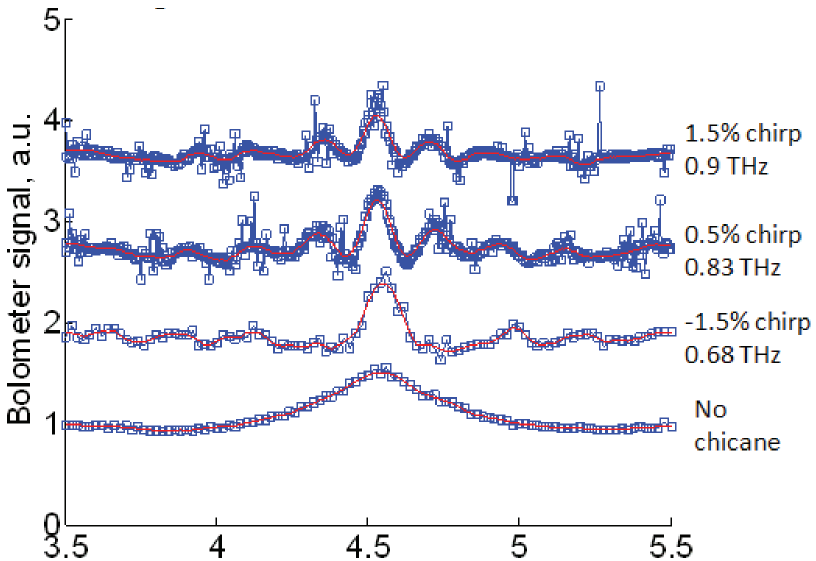
S. Antipov, et. al., Phys. Rev. Lett. 108, 144801 (2012)

Sub-picosecond bunch train production at ATF

PM chicane is used to convert energy modulation into density modulation

CTR interferometry shows that THz periodicity can be tuned by energy chirp





We proposed a high power terahertz radiation source based on this scheme (electron beam wakefields). A third stage, yet another dielectric tube will be installed after chicane to coherently extract THz power from the bunch train

S. Antipov, et. al., Phys. Rev. Lett. 111, 134802 (2013)

High power beam-based THz source

ATF (0.8nC / 2.4mm) 6 MW peak, 0.7THz, 160ps pulse, 1%BW, 1.4mJ pulse

AWA (20nC / 6.3mm) 0.5 GW peak, 0.3THz, 320ps pulse, 1%BW, 155mJ pulse

Stage I

S. Antipov, C. Jing et. al. Phys. Rev. Lett. 108, 144801 (2012)

Energy modulation via self-wakefield

Stage II

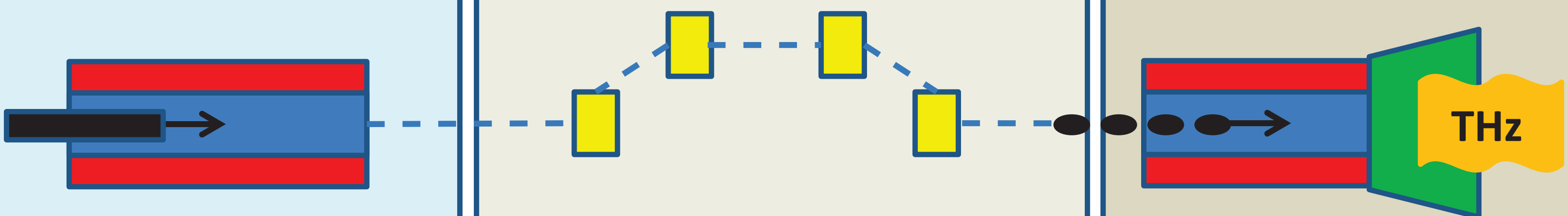
D. Xiang et. al PRL. 108, 024802 (2012)
S. Antipov, et. al., PRL. 111, 134802 (2013)

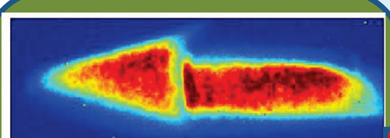
Chicane energy modulation conversion to bunch train

Stage III

G. Andonian et. al. Appl. Phys. Lett. 98, 202901 (2011)

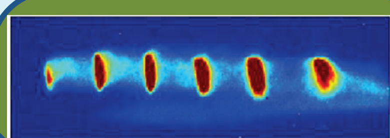
THz radiation wakefield structure





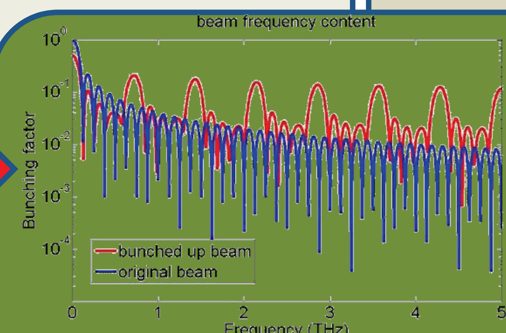
Measured beam spectrum

Energy chirped rectangular beam



Measured beam spectrum

Energy modulated rectangular beam



Bunch train frequency content

Tunable 100% source:
Range: 0.3-1.5 THz
Pulse bandwidth: 1%
Energy in pulse: ~ mJ

Flexible: each step has a tuning range

Summary

- A large number of exciting experiments on DWA had been reported by several groups
- GHz, THz
- High gradient acceleration
- High power THz radiation
- Two beam acceleration
- Transformer ratio
- … and more to come