Status of Beam Driven Wakefield Acceleration in the United States

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AARD Has Long History in U.S.

- Funded by DOE Office of High Energy Physics for ~30 years
- Trends and progress are disseminated and documented at the Advanced Accelerator Concepts Workshop (every two years)
  - Rapid growth in plasma acceleration in the last decade
- Most successful efforts involve University–National Lab collaborations
  - Labs bring expertise in accelerators and large scale engineering
  - Universities bring breadth of expertise in diverse areas (lasers, plasmas, computation...)
  - Attractive environment for students
- Opportunities for companies (SBIR)
  - e.g. Positive Light (lasers), Euclid Techlabs (exotic materials)

Geography of PWFA & DWA in the U.S.

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The Beam Driven Plasma Wakefield Accelerator

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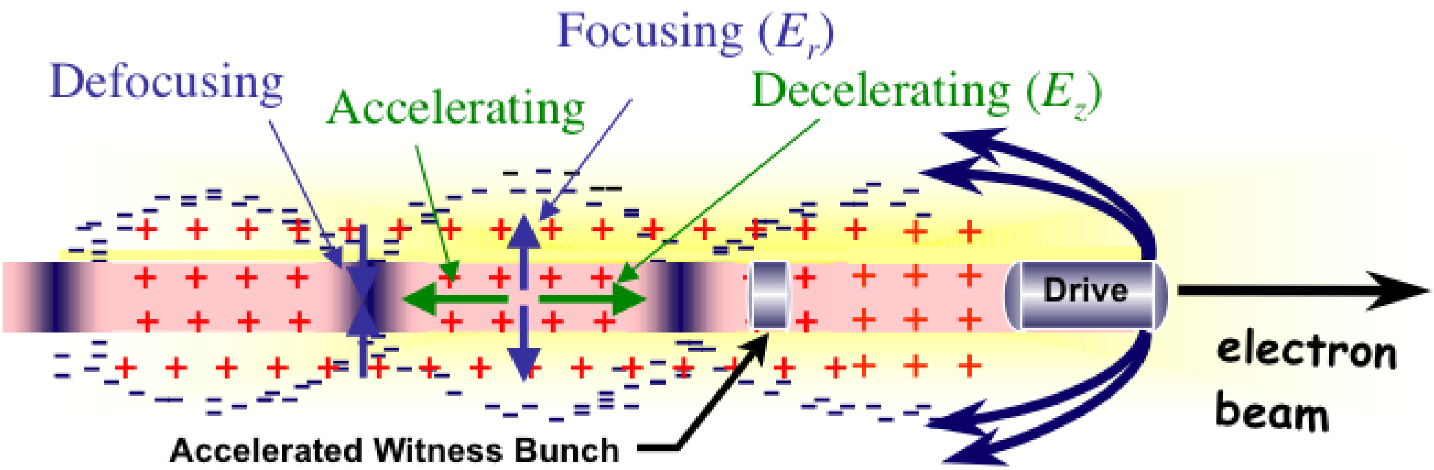
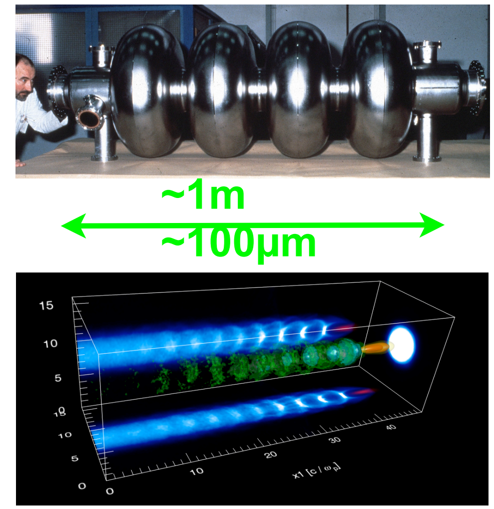
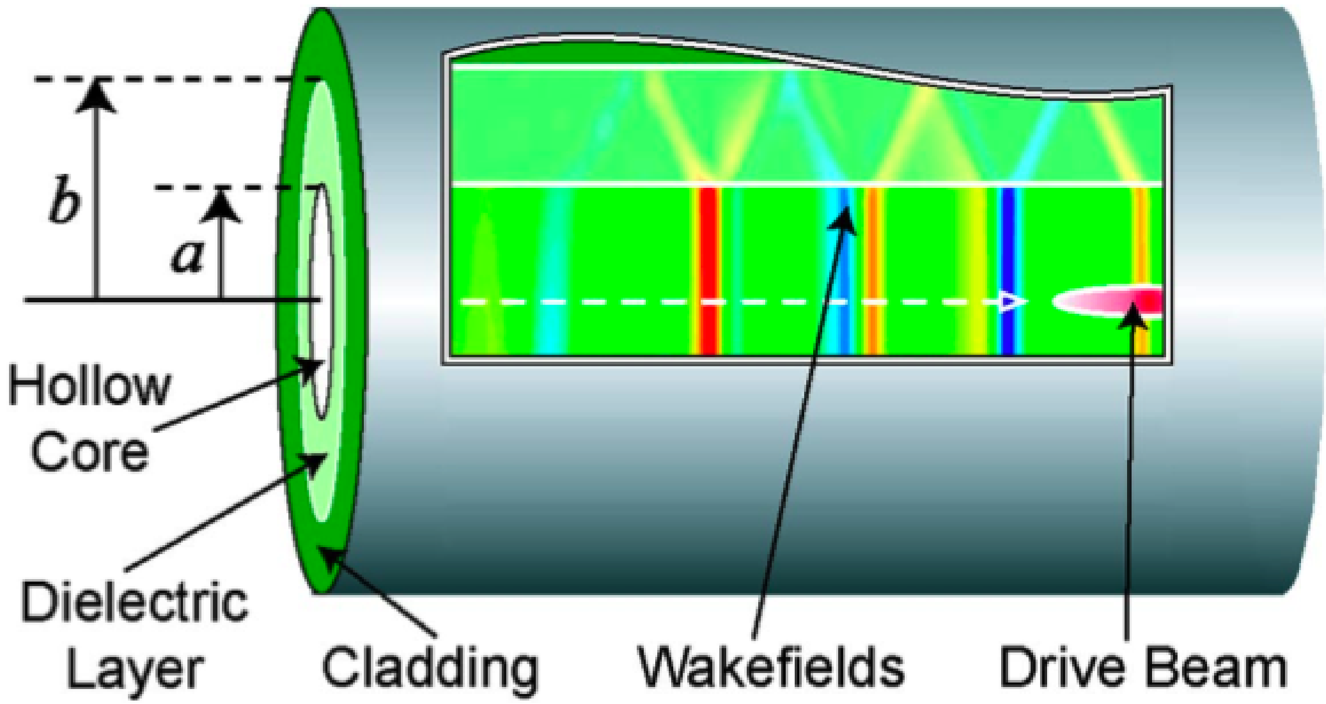




- * Two-beam, co-linear, plasma-based accelerator
- * Plasma wave/wake excited by relativistic particle bunch
- * Deceleration, acceleration, focusing by plasma
- * Accelerating field/gradient scales as $n_e^{1/2}$
- * Typical: $n_e \approx 10^{17}$ cm^{-3}, $\lambda_p \approx 100$ µm, G>MT/m, E>10 GV/m
- * High-gradient, high-efficiency energy transformer
- * "Blow-out" regime when $n_b/n_p \gg 1$

DWFA: Dielectric Wakefield Accelerator

- A “drive” beam excites wake-fields in the tube, while a subsequent witness beam (not shown) would be accelerated by the Ez component of the reflected wakefields (bands of color).



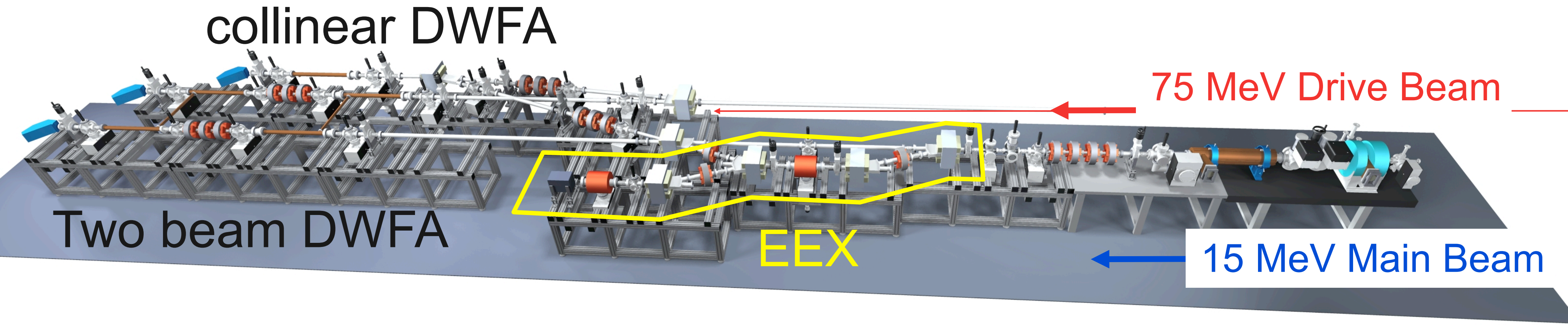
$$eE_{z,\mathrm{dec}} = eE_{r,\mathrm{surf}}\frac{\sqrt{\varepsilon-1}}{\varepsilon} \cong -\frac{4N_b r_e m_e c^2}{a\left[\sqrt{\frac{8\pi}{\varepsilon-1}}\varepsilon\sigma_z + a\right]}$$

- Work pioneered at ANL
- For large wakes want high charge, short bunches and narrow tubes

→ FACET

The Argonne Wakefield Accelerator

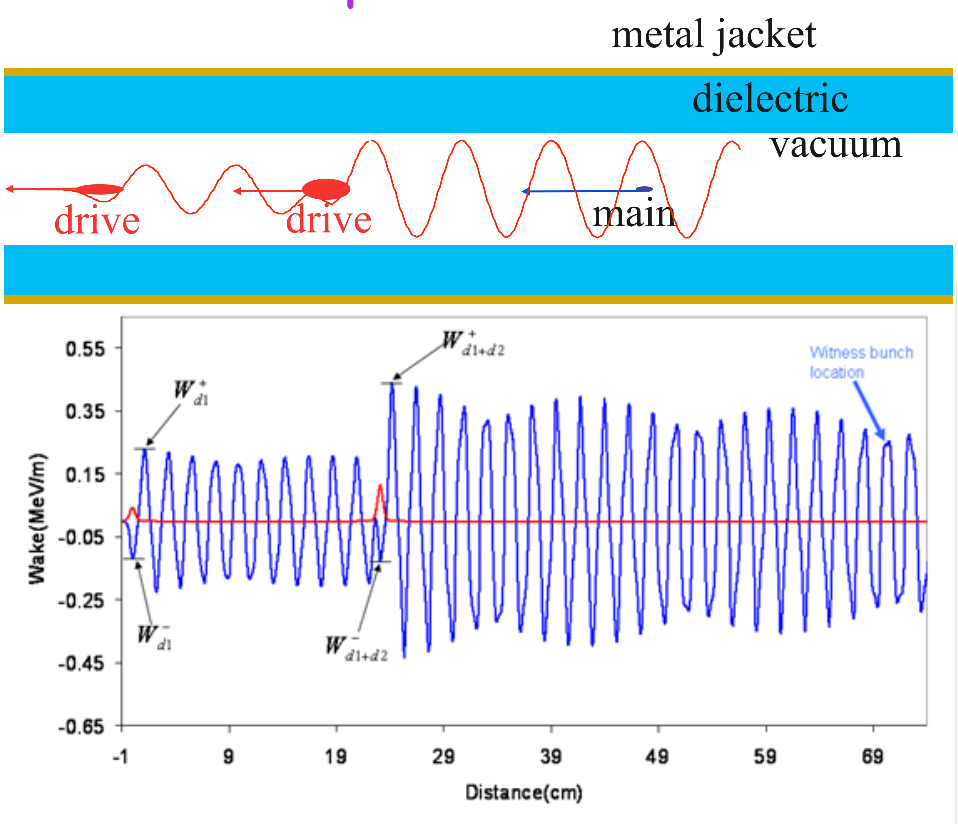
- AWA Photoinjector Facility
  - –Two RF photocathode guns for generation of Drive (CsTe PC) and Main (Mg PC) beams
  - –Drive Beam
    - Single Bunch {*100 nC*, σ_z=2 mm, I ~ *5 kA*}
    - Flat Bunch Trains {10x*100 nC … 64x15 nC*}
    - Ramped Bunch Trains {8 *nC, 24 nC …*}



Collinear DWFA at Argonne

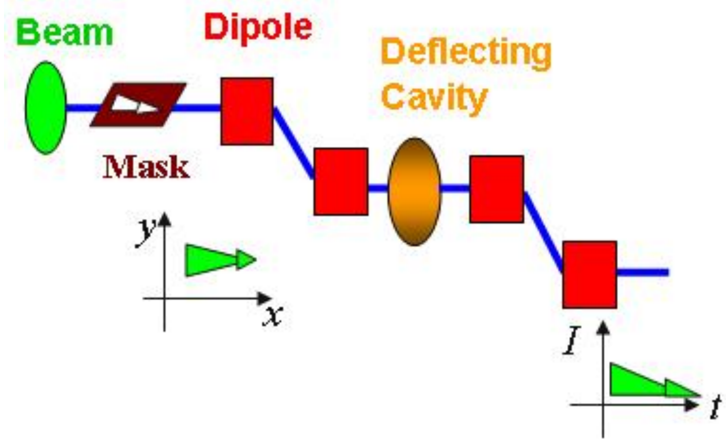
Key Technology: Generating High Transformer Ratio

with a Ramped Bunch Train



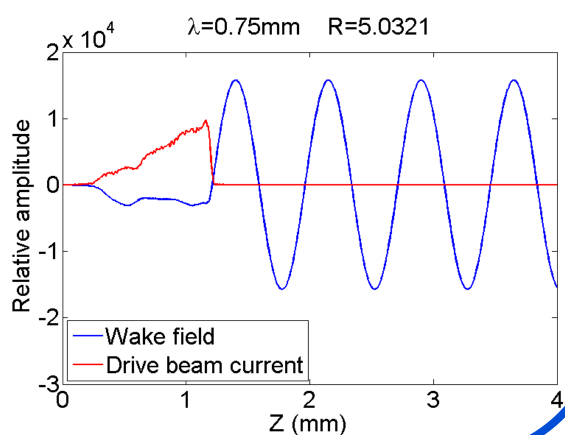
Highest R (= 3.4) experimentally demonstrated *C. Jing et al., *PRSTAB 2010*

with Ramped Bunches



Generating ramped pulses with the EEX beamline.

PARMELA simulation

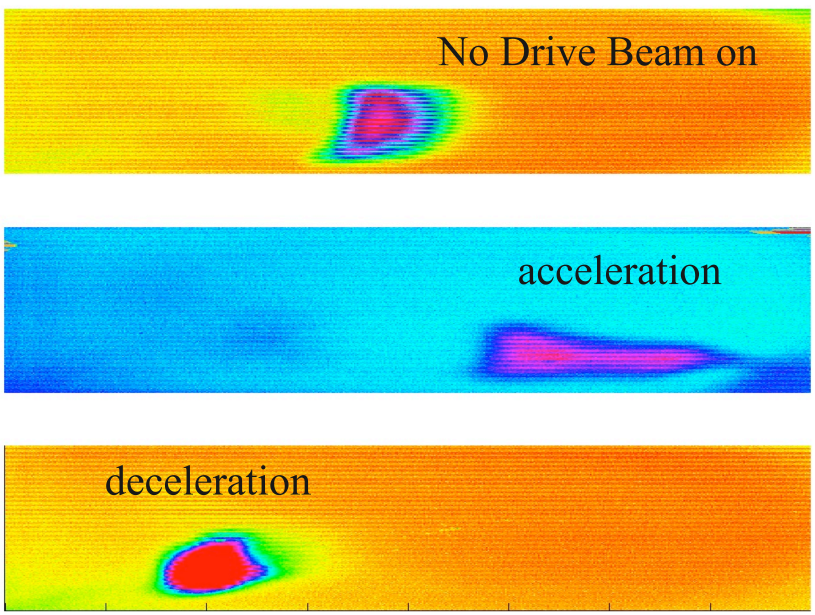


Two Beam DWFA at Argonne

Previous Accomplishments

- Higher gradient excitation: **~ 100 MV/m** in short structures.
- Proof of Principle Acceleration of witness beam.
- High RF power extraction: **~ 44 MW**

Demonstrated dielectric two-beam acceleration in first ever POP experiment

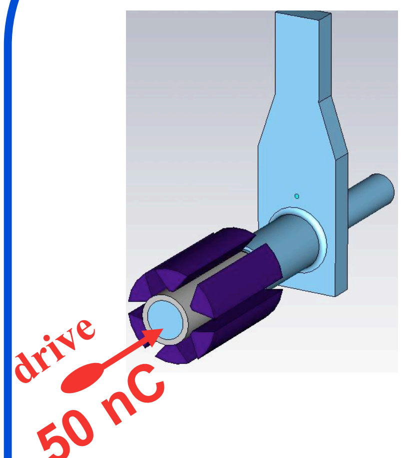


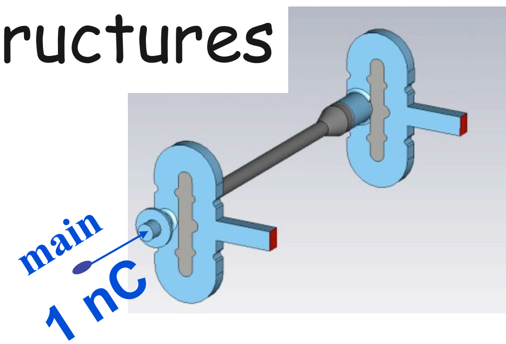
Energy of the Witness Beam

Future Objectives

- Higher gradient excitation: **~ 0.5 GV/m** in long structures.
- Acceleration of witness beam: **~ 100 MeV**
- Higher RF power extraction: **~ GW level**

26 GHz structures





Accelerator

ID / OD / length (mm)
3.0 / 5.025 / 300
Eacc 316 MV/m
Eloaded 267 MV/m
Energy gain 80.1 MeV

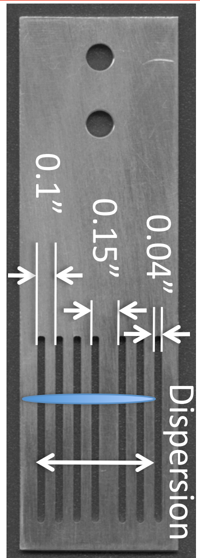
Decelerator

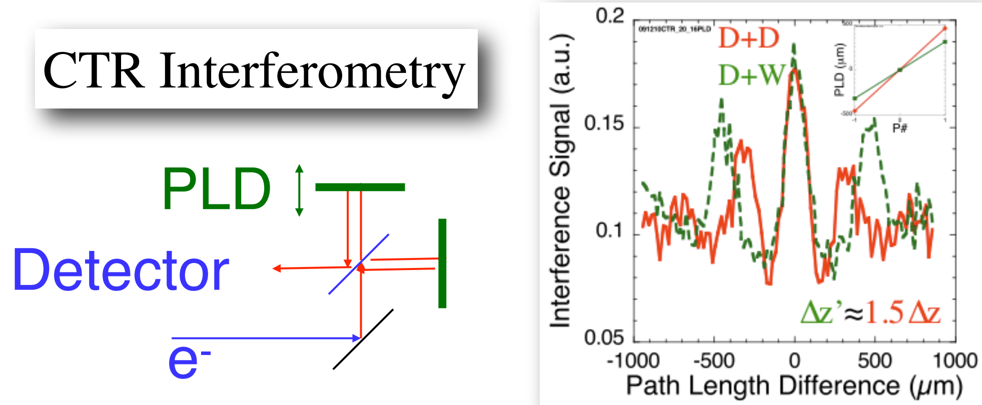
ID / OD / length (mm)
7.0 / 9.068 / 300
RF power 1.33 GW
Peak gradient 167 MV/m
Energy loss 20.5 MeV

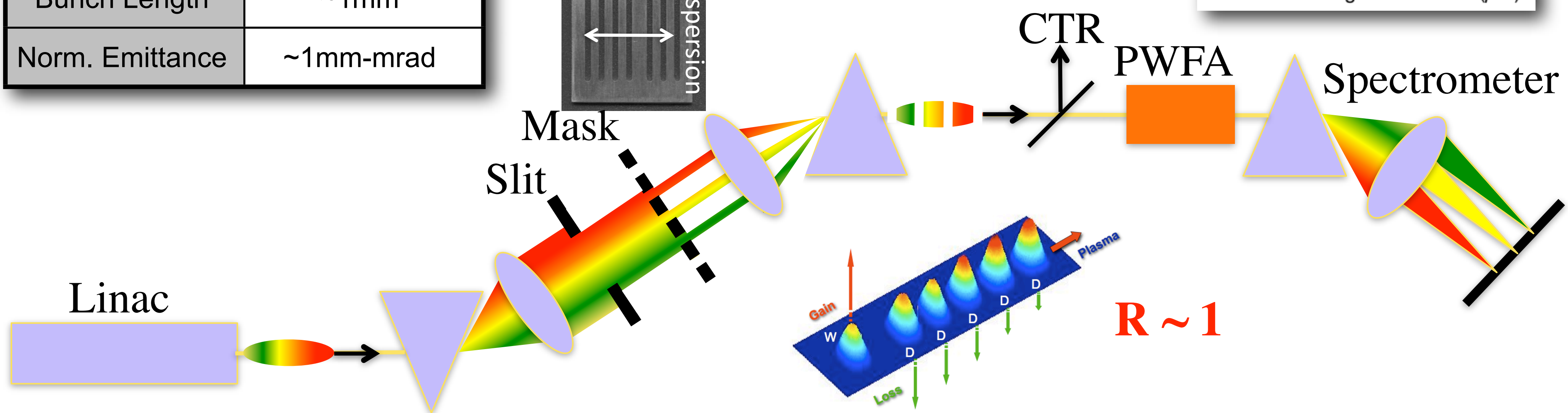
BNL mask slicing technique generates adjustable bunch trains

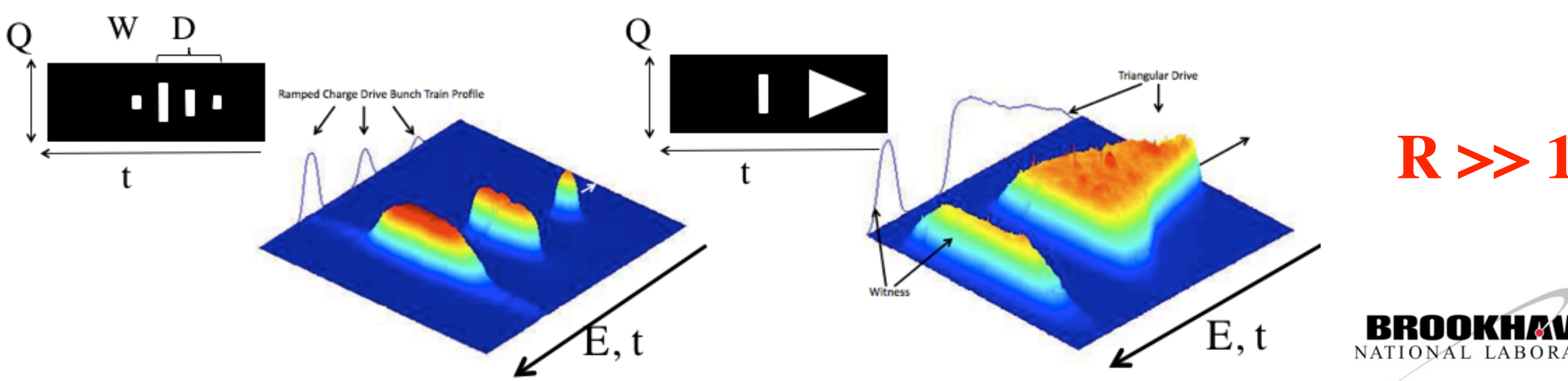
BNL ATF

Energy	~70MeV
Charge/bunch	~500pC
Bunch Length	~1mm
Norm. Emittance	~1mm-mrad









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MULTIBUNCH PWFA

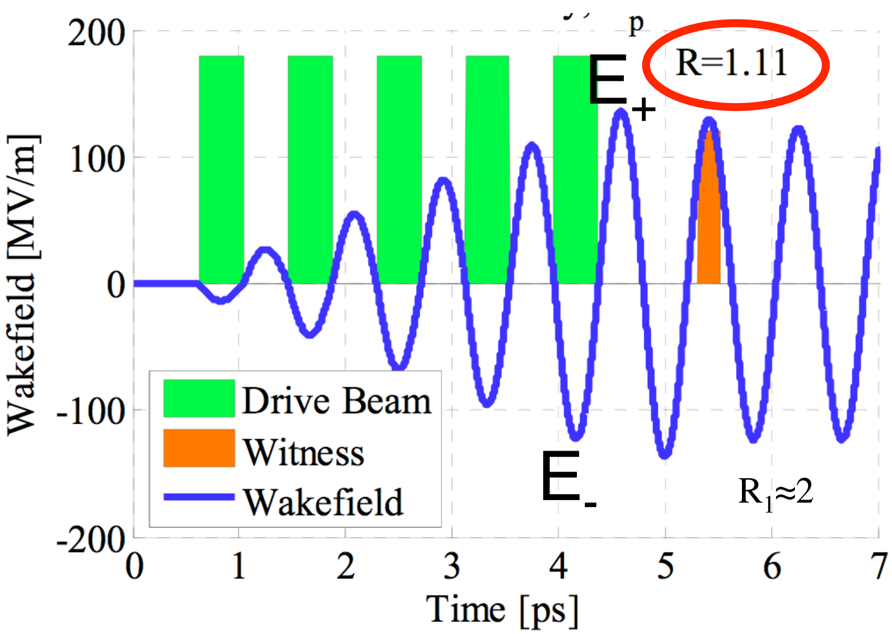
Transformer Ratio: $R = E_{+}/E_{-}$ Energy Gain: $\leq RE_0$

σ_r=125 μm, n_e=1.8x10^{16} cm^{-3}, λ_p=250 μm

E_0: incoming energy

Q=30 pC/bunch, Δz=250 μm≈λ_p

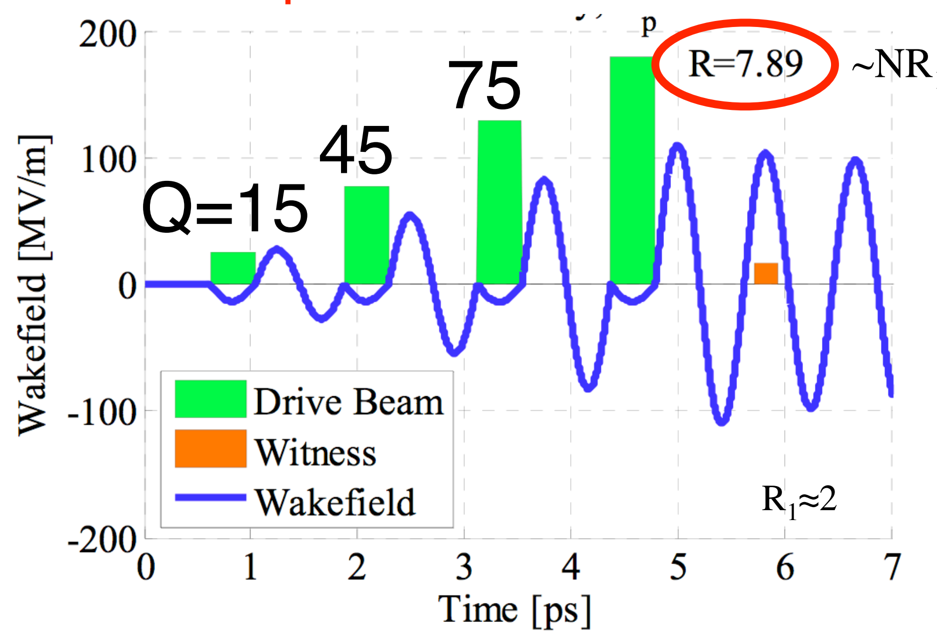
Bunch Train



Kallos, PAC'07 Proceedings

Δz=375 μm≈1.5λ_p

Ramped Bunch Train*



*Tsakanov, NIMA, 1999

- Linear (2D) theory for n_b<<n_e!
- R=7.9 => add 8 times the incoming energy in a single PWFA stage!

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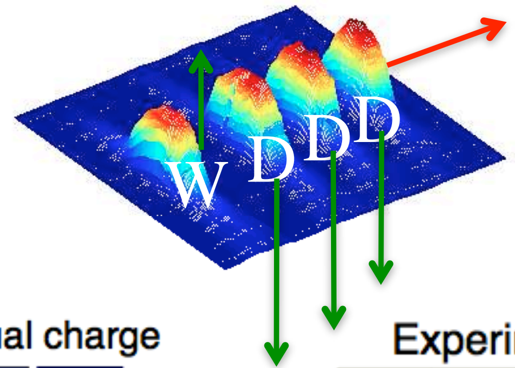
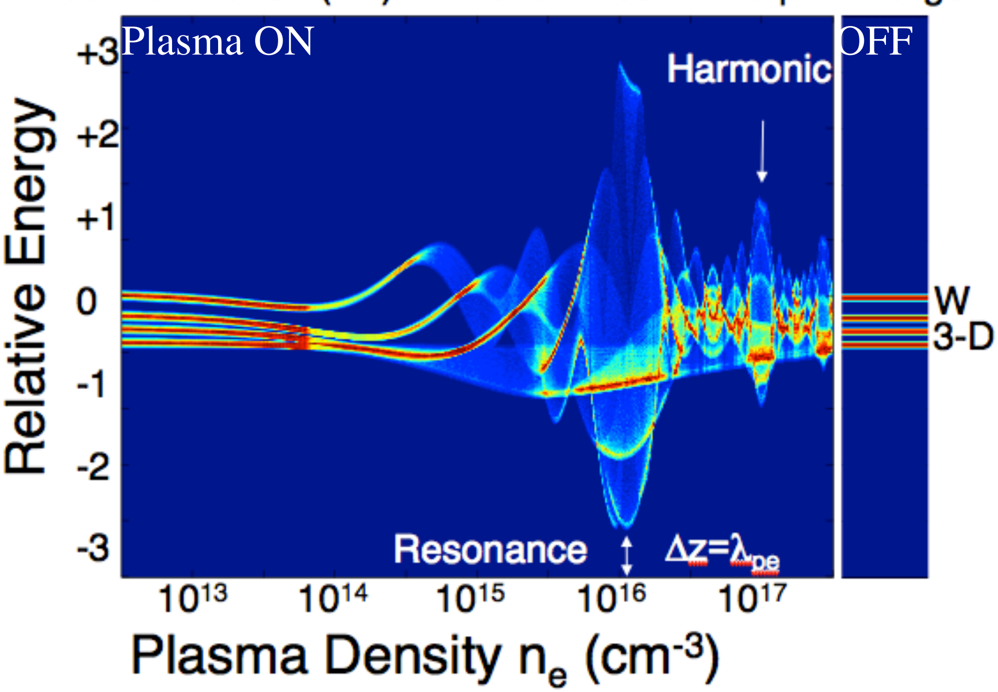
MULTI-BUNCH PWFA: ENERGY CHANGE

E_0=59 MeV, σ_r=100 um
Δz=284 μm, d=142 μm, $\Delta z'$=426 μm
Q_{tot}=140 pC, N_d=, Q_b=35 pC
L_p=2 cm

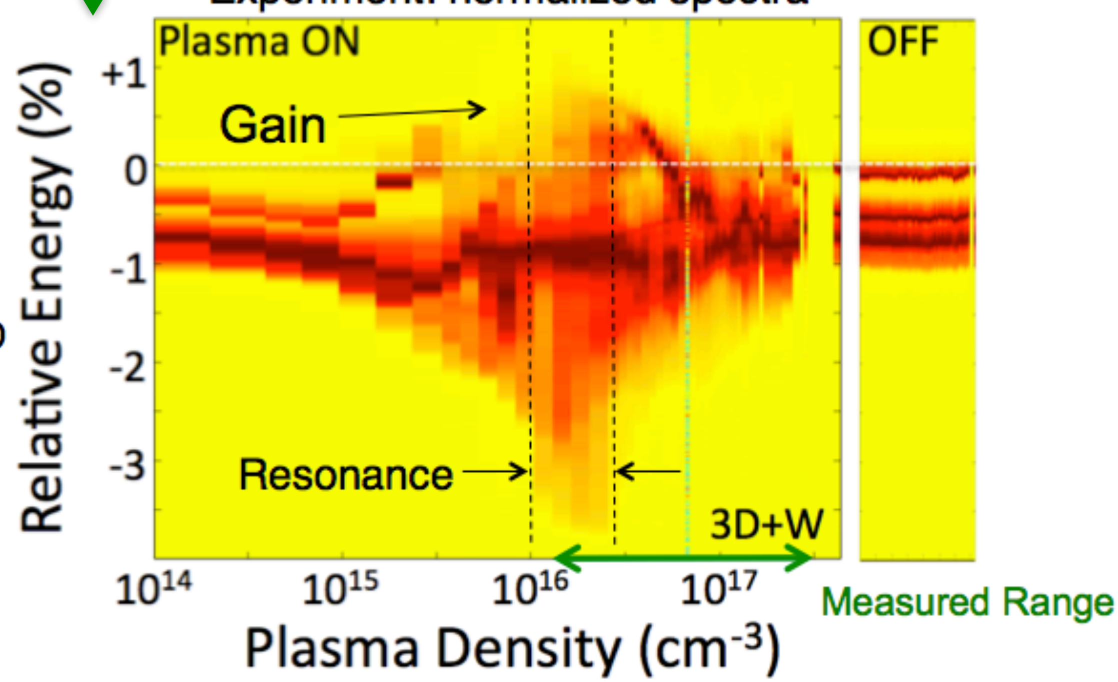


$n_b \approx 4\times10^{13}$cm^{-3} << n_e
Linear Regime!

Linear calculation (2D): microbunches with equal charge



Experiment: normalized spectra



- Similarities between experiment and calculations
- Resonance clearly observed, $n_{e,\,res} \approx 1.4\times10^{16}$ cm^{-3}, as expected for $\lambda_{pe} \approx \Delta z$
- Large energy loss, ~1.95 MeV or ~97MeV/m (over 2cm)
- Energy gain, 0.74MeV, or ~37MeV/m

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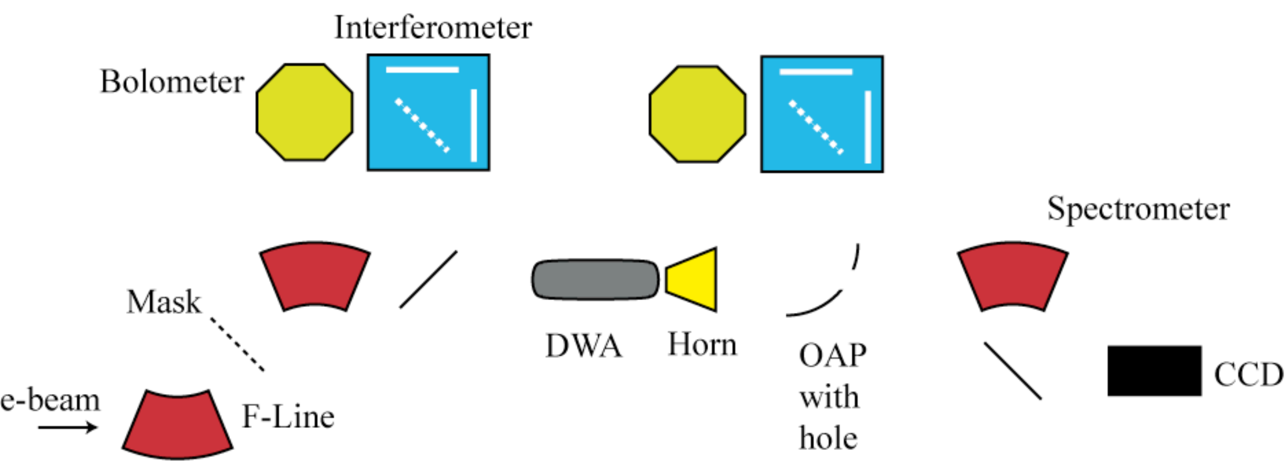
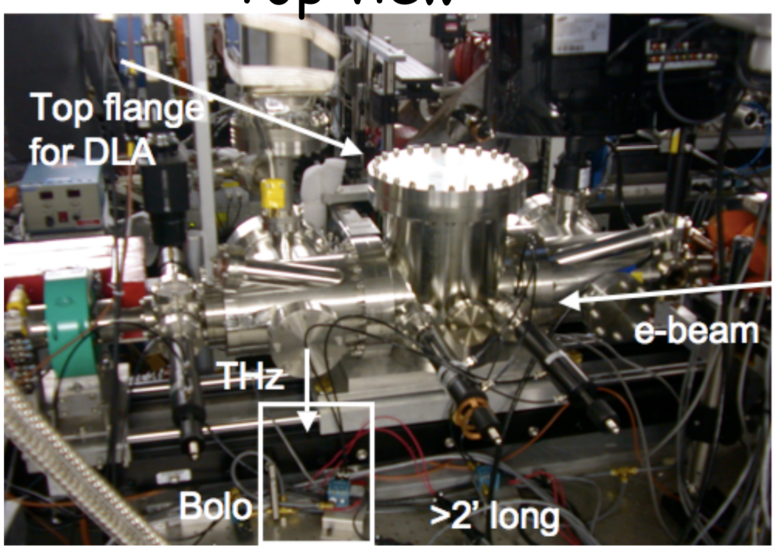
DWF Experiment description

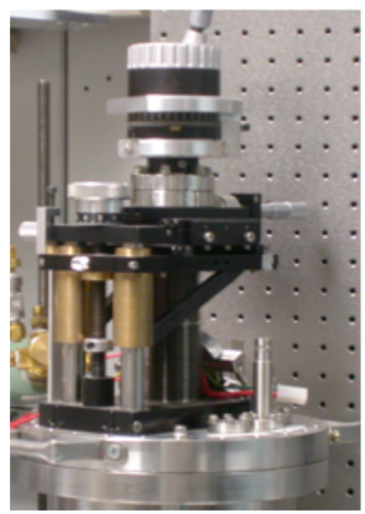


- Pulse train generated with mask
- Phase feedback loop (0.5deg)
- CTR measurement of bunch spacing
- DWA mount and alignment in old plasma chamber
- CCR measurement
- Hole in OAP allows simultaneous energy spectrum measurement

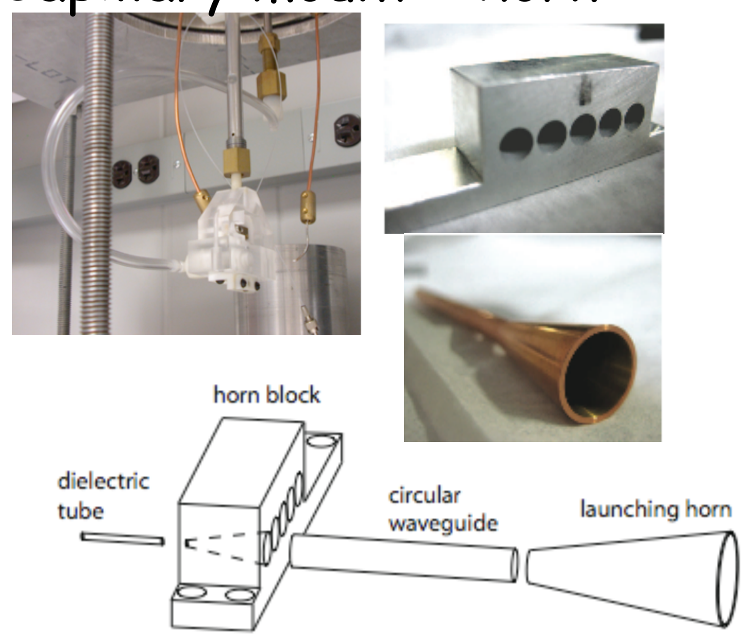
Top view



Actuator



Capillary mount + horn



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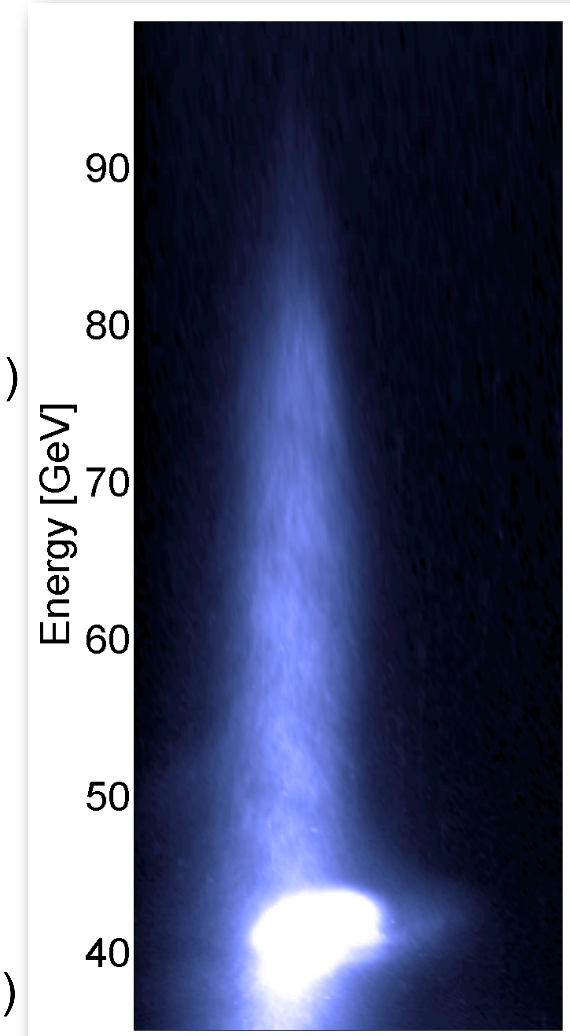
Wakefield Acceleration @ SLAC

- SLAC/UCLA/USC FFTB experiments 1998 - 2006
  - **Plasma Wakefield Acceleration** of electrons over meter scales
    - 50GeV/m accelerating gradient
    - Total energy gain of 43GeV
  - First plasma acceleration of positrons
  - Systematic studies of integrated & time dependent focusing
    - electrons (extended propagation, emittance preservation @ 10^{-4}m)
    - positrons (halo formation, emittance growth)
  - Refraction of electron beam at plasma boundary
  - Betatron radiation from strong plasma focusing
    - x-rays @ 10^{14} e^-/cc (kT/m)
    - gammas (e+ production) @ 10^{17} e^-/cc (MT/m)
  - **Dielectric Wakefield Acceleration**
    - Proof of principle studies of material breakdown threshold
      - 14GeV/m induced catastrophic breakdown in 1cm long, 100µm diameter fused Si tubes (we turned the dielectrics into plasmas!)

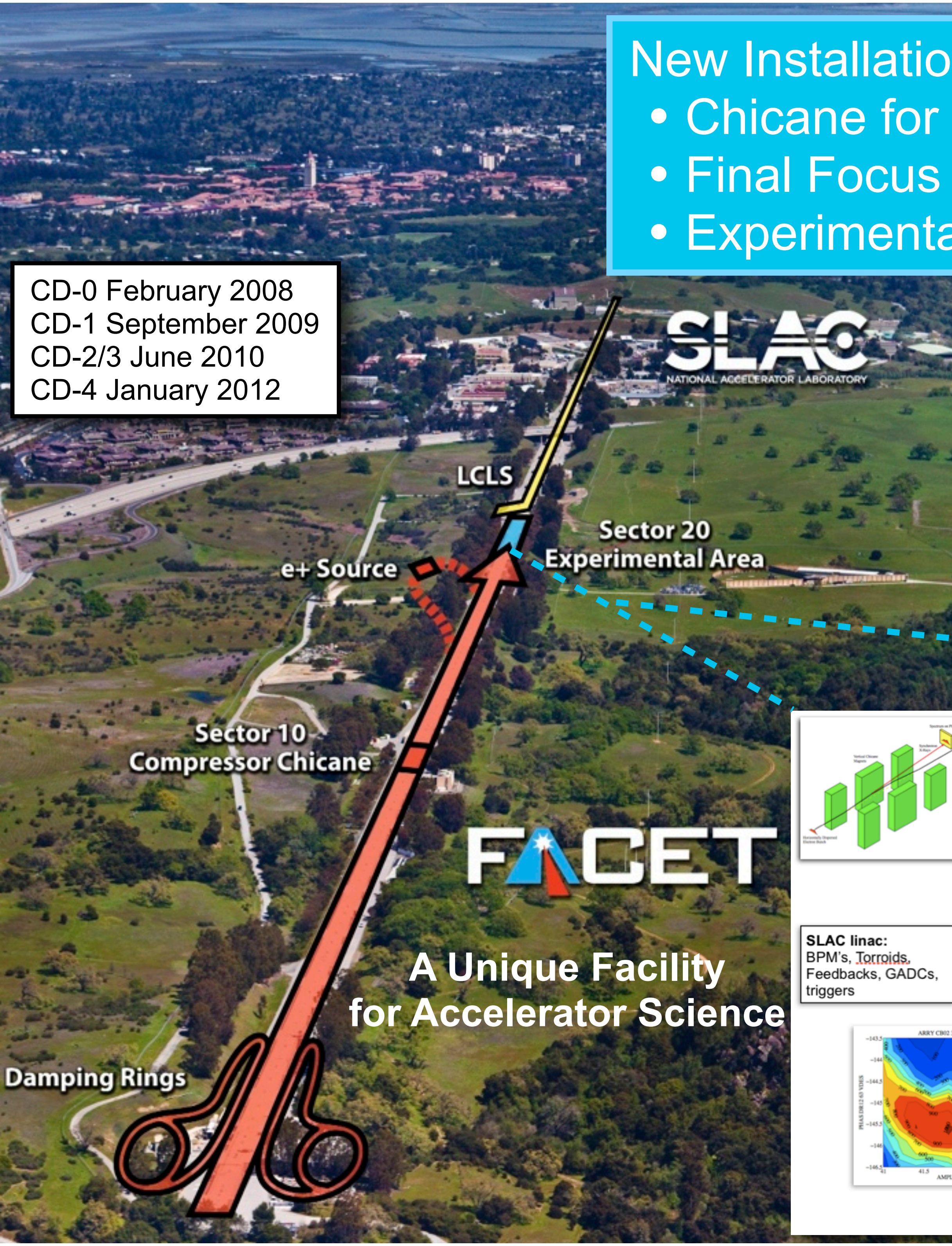


- Expanded collaborations will continues at FACET starting in 2011

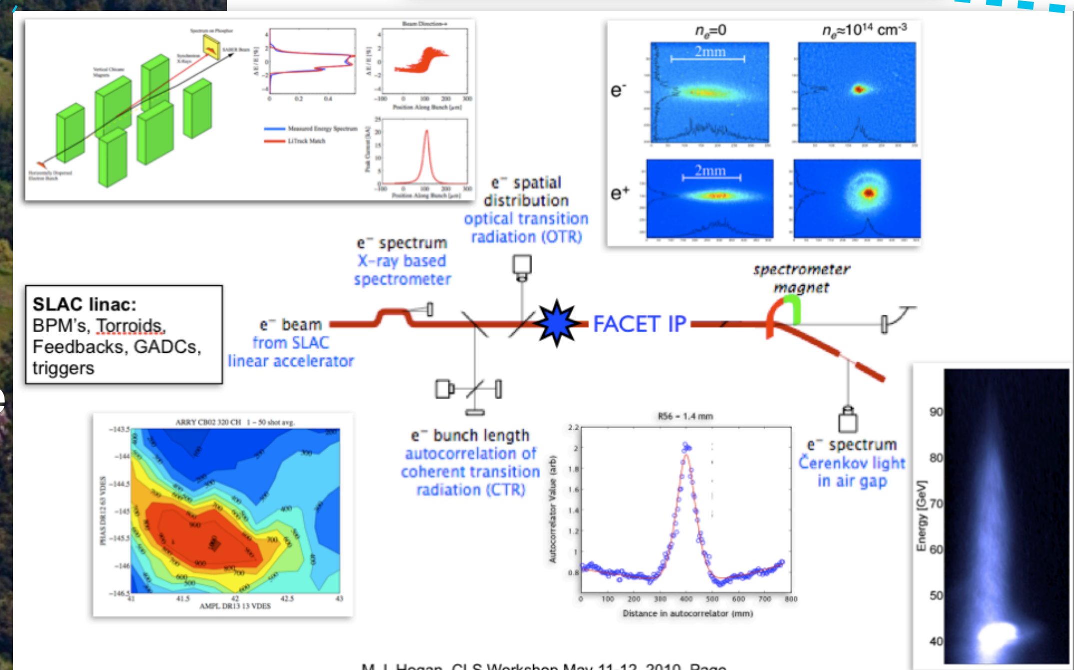
New Installation @ 2km point of SLAC linac:

- Chicane for bunch compression
- Final Focus for small spots at the IP
- Experimental Area (25m)

CD-0 February 2008
CD-1 September 2009
CD-2/3 June 2010
CD-4 January 2012



Beam Parameters	
Energy	23 GeV
Charge	3 nC
Sigma z	20 μm
Sigma r	10 μm
Peak Current	22 kAmps
Species	e^- & e^+



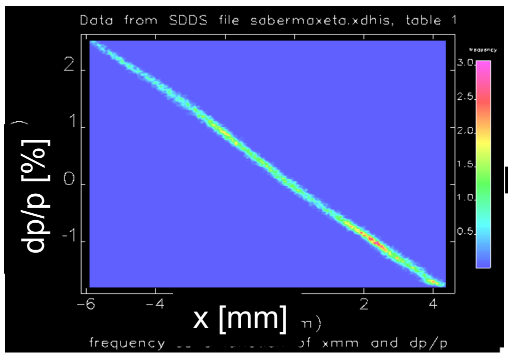
Multi-GeV PWFA Experiments at FACET

Study wake loading in the non-linear regime for the first time

- Collimation system to craft drive/witness bunch from single bunch (similar to BNL ATF wire system)

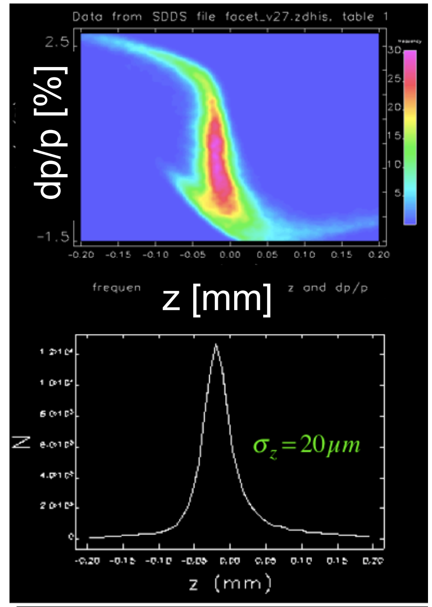
Disperse the beam in energy

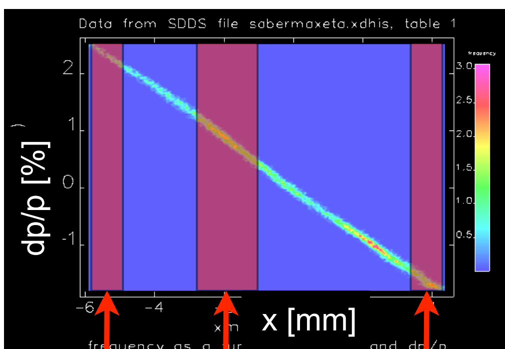
$$x \propto \Delta E/E \propto t$$



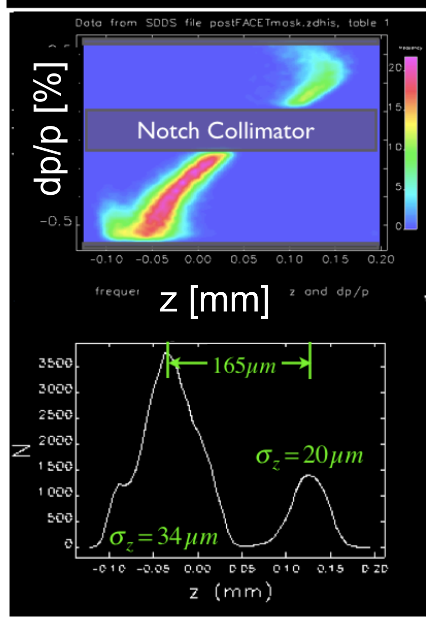
R56 = 4mm

Adjust final compression



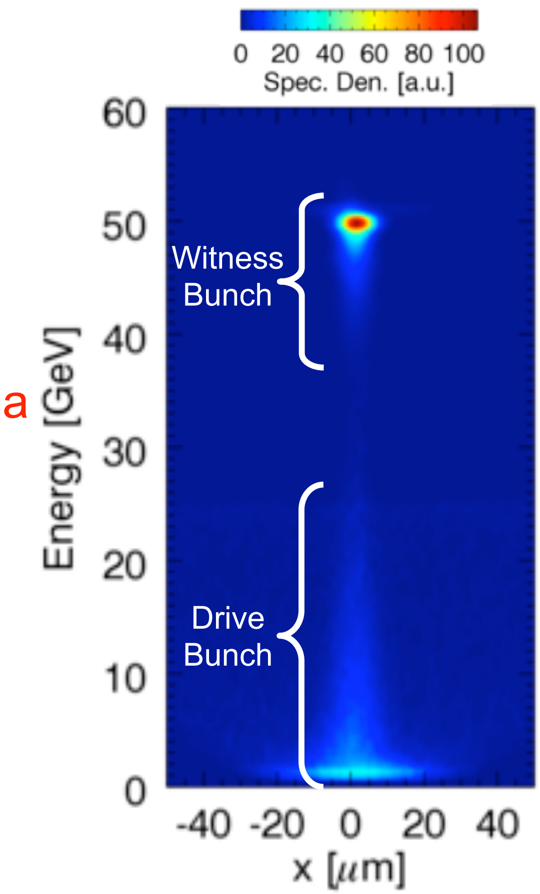


R56 = 10mm



...selectively collimate

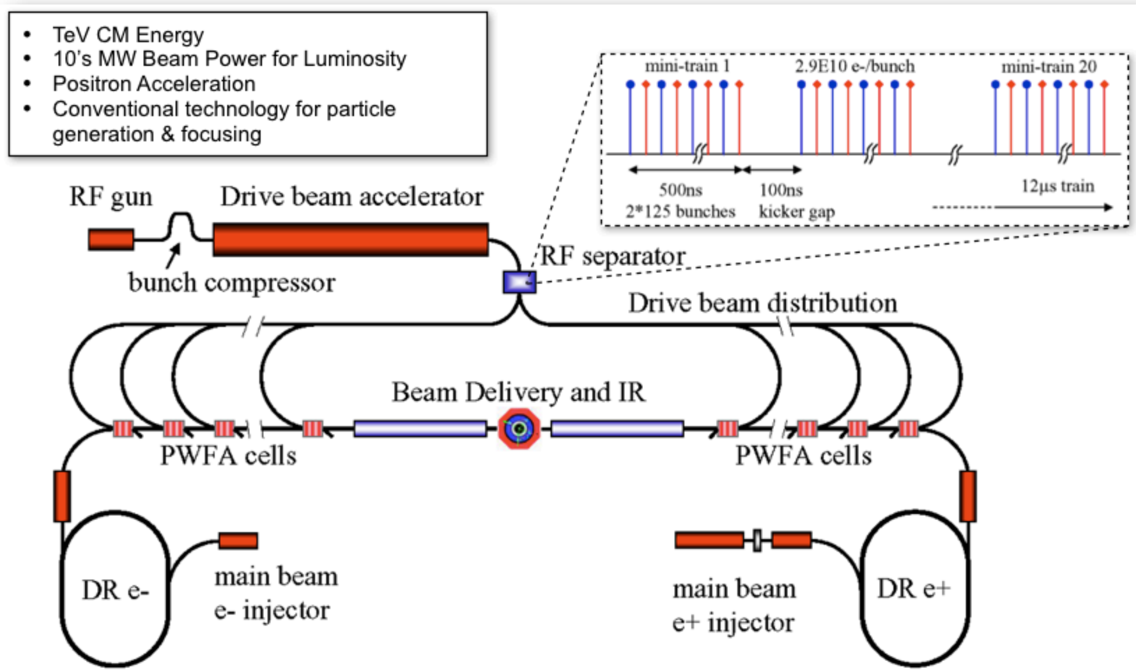
Plasma



- Vary charge ratio, bunch lengths, spacing by changing collimators and linac phase, R56

A Self-consistent Design of a 1 TeV e^-e^+ Linear Collider Based on PWFA

- TeV collider design has multiple acceleration stages, each adding ~25 GeV/stage
- FACET PWFA program aims to demonstrate a single stage with needed Q, $\Delta E/E$, efficiency, emittance preservation
- Results will inform designs for future applications (HEP, Photon Science)



see A. Seryi et al., PAC09 Proceedings

E_{cm} = 1 TeV, L = 10^{34} cm^2s^{-1}

Luminosity	3.5×10^{34} $cm^{-2}s^{-1}$
Luminosity in 1% of energy	1.3×10^{34} $cm^{-2}s^{-1}$
Main beam: bunch population, bunches per train, rate	1×10^{10}, 125, 100 Hz
Total power of two main beams	20 MW
Main beam emittances, $\gamma\epsilon_x$, $\gamma\epsilon_y$	2, 0.05 mm-mrad
Main beam sizes at Interaction Point, x, y, z	140 nm, 3.2 nm, 10 μm
Plasma accelerating gradient, plasma cell length, and density	25 GV/m, 1 m, $1\times10^{17}cm^{-3}$
Power transfer efficiency drive beam=>plasma =>main beam	35%
Drive beam: energy, peak current and active pulse length	25 GeV, 2.3 A, 10 μs
Average power of the drive beam	58 MW
Efficiency: Wall plug=>RF=>drive beam	50% × 90% = 45%
Overall efficiency and wall plug power for acceleration	15.7%, 127 MW
Site power estimate (with 40MW for other subsystems)	170 MW

Goals of The FACET Wakefield Collaborations over the Next Five Years

Plasma Wakefield Acceleration:

- Demonstrate a single plasma stage with beam parameters close to required for use in multi stage PWFA-LC or X-FEL
  - Meter scale >10GeV/m acceleration of beams (not particles)
  - Acceleration with narrow energy spread (few percent level)
  - Emittance preservation (e.g. no hosing - see E. Aldi)
  - Quantify efficiency for gaussian current profiles
    - Enhanced efficiency with shaped high-transformer ratio profiles
  - Identify optimum method for positron acceleration in a plasma
    - e+e+ afterburner, e-e+ with sailboat

Dielectric Wakefield Acceleration:

- Demonstrate a single dielectric stage with beam parameters close to required for use in multi stage PWFA-LC or X-FEL
  - Identify optimum materials & structure geometry (cylindrical, slab...)
  - Push to high gradients over meter scale w/ no BBU

Summary

- Very exciting time for beam driven wakefield accelerators in the U.S.
- New and existing facilities poised to make significant progress in the next several years
- Science at the facilities driven by University–National Lab collaborations
- Thank you to the organizers – I am looking forward to learning about the plans/ideas/possible collaborations in Europe!
- I could talk for well over an hour on all of this, so if this seemed rushed please grab me or my colleagues at the coffee break!