High Gradient Wakefield Acceleration in Dielectric-Loaded Structures

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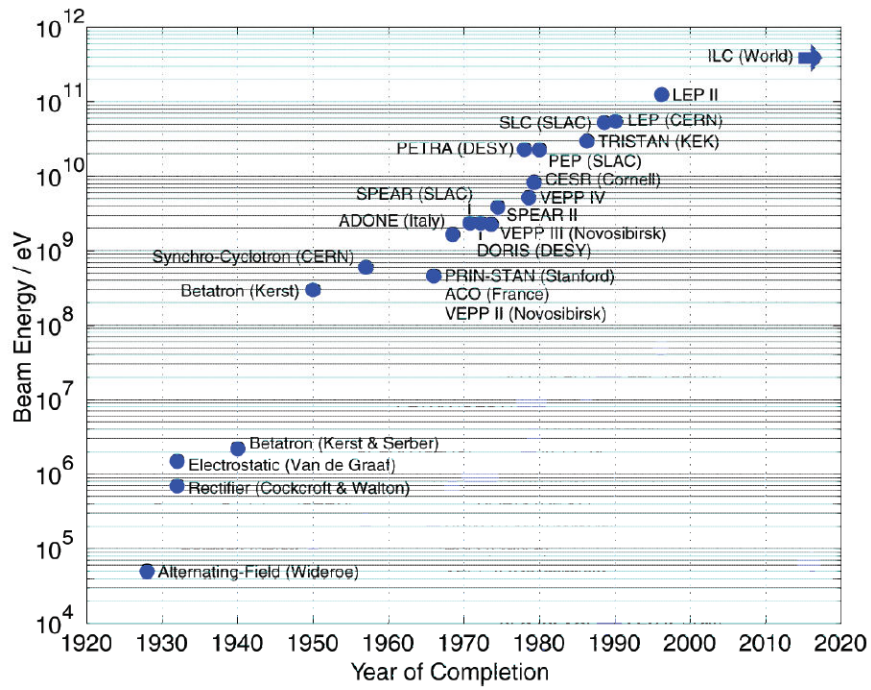
Outline:

- Introduction
- Wakefield acceleration
    1. Plasma Wakefield Accelerators
    2. Laser-driven Dielectric Structures
    3. Electron beam driven Dielectric Structures
- Dielectric Wakefield Acceleration
    1. Advantages, early times
    2. High transformer ratio
    3. Rectangular slabs (theory)
    4. Vorpal simulations
- Conclusions

Introduction

<u>Goal</u>: 10 TeV Electron Accelerator

- Circular machine. Synchrotron radiation $\propto E^4$
- Linear accelerator with current gradients of $\approx$ 0.05 GV/m => L > 200 km !



<u>Search for:</u>

- A lot higher field-gradients.
- High beam quality.
- Low cost.

$\Rightarrow$ New acceleration techniques

Introduction (2)

Cross section for $e^+e^- \propto 1/E^2$ => To keep σ the same as for E = 1 TeV
Luminosity must increase at least 100 x !

$$L = \frac{N^2 f}{4\pi\sigma_x\sigma_y}$$

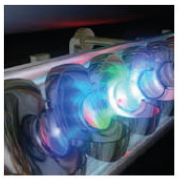
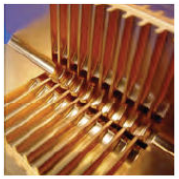
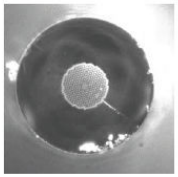
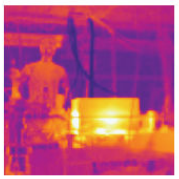
Electron bunch energy not enough. Beam quality also crucial.

Search for:

- Generate low emittance (< 1 μm) high charge beams (>1nC).
- Control "collective effects" to maintain beam quality.
- Increase repetition rate (>100 Hz).
- Many other things (transport line, beam diagnostics, materials, electronics, etc.).

Introduction (3)

Ultra-high fields are limited by the EM properties of the accelerating structure.

	Structure	Max. Field (MV/m)
	Superconducting	50
	Metallic	200
	Dielectric	$> 10^3$ ($\sim 10^4$)
	Plasma	$\sim 10^5$

Fused silica tubes (100 μm ID) breakdown onset at ≈14 GV/m !

M.C. Thomson, et al, PRL (2008)

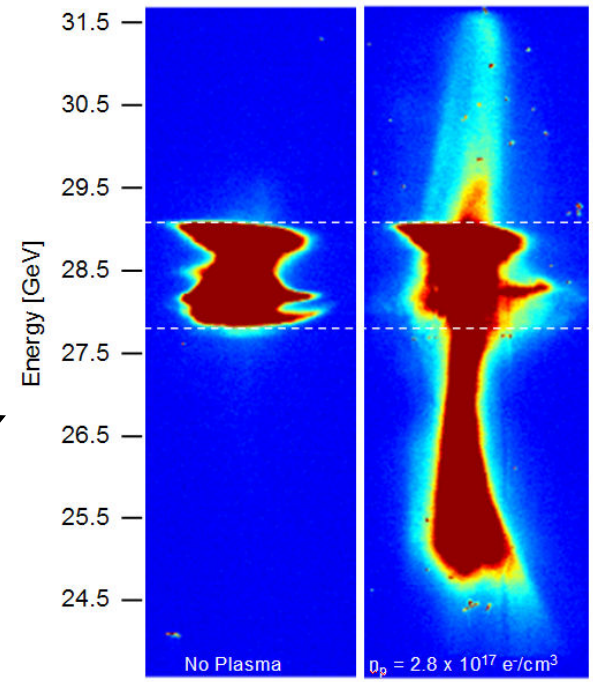
Plasma Wakefield Acceleration

Plasma wakes (linear):

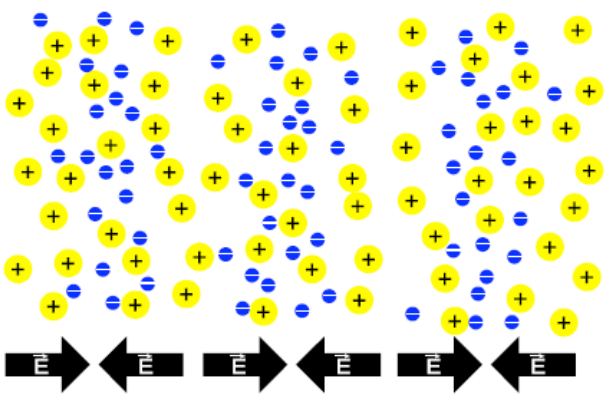
- Longitudinal electric field
- $E_z \propto \sqrt{n}$
- Wakes can be excited by:

  1. Electron drive beam
  2. Photons

Plasma length = 10 cm

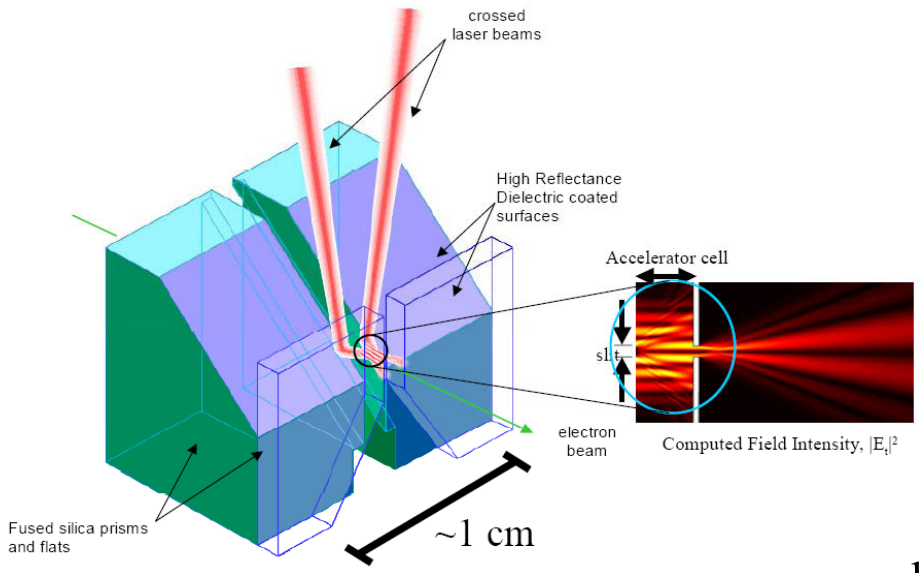


M. J. Hogan, et al, PRL (2005)



- Typical wavelength: 50 μm
- LBNL (L'Oasis: 1 GeV over 3.3 cm)

Direct Laser Acceleration

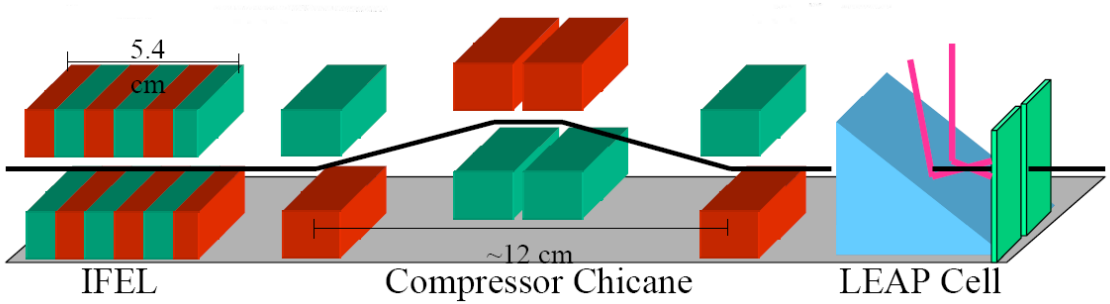


- Crossed laser beams (32 mrad)

to obtain a **<u>longitudinal</u>** component.

- Electric field amplitude: 1GV/m
- Interaction region: 1.5mm
- The two laser beams are in opposite phase.

laser $\lambda < \sigma_z$ $\Longrightarrow$ **Need prebunching and compression!**

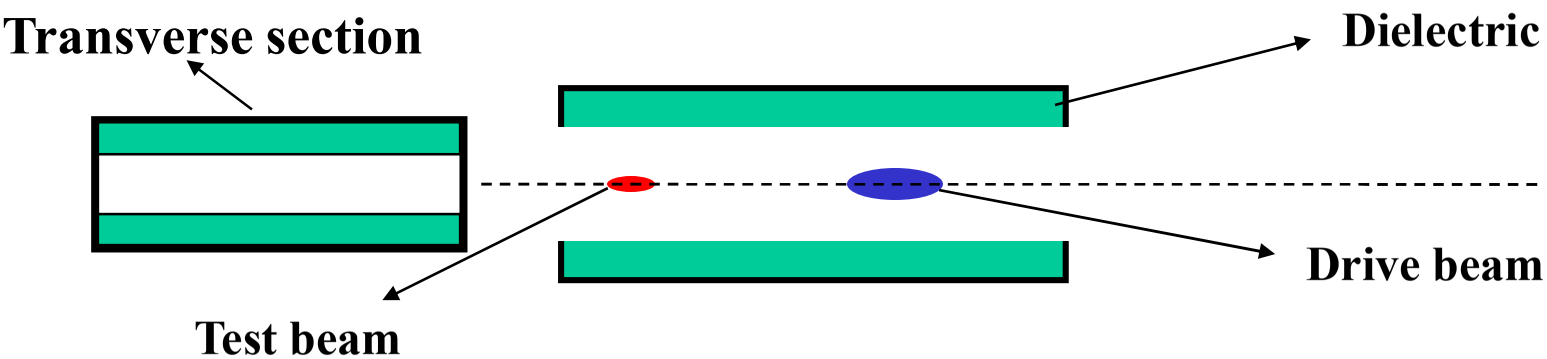


Problems:

- limited breakdown thresholds for laser optics
- low interaction efficiency

LEAP Collaboration

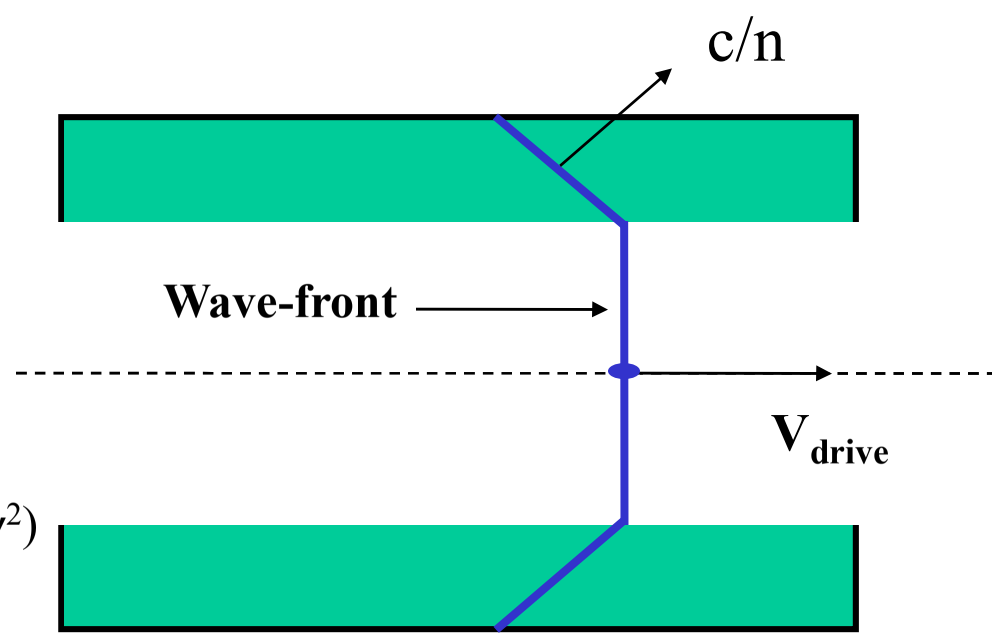
Dielectric Wakefield Acceleration (DWA)



Assume: $V_{drive} \approx c$ **(ultra-relativistic)**

In vacuum:

- $v_{phase} = \omega/k_z = v_{drive} \approx c$
- $k = k_z$
- static **E**: only radial component ($E_z \propto 1/\gamma^2$)
- wakefield L Cherenkov radiation



DWA (2)

<u>Synchronism condition</u>: OK for partially filled waveguides !

<u>Regular waveguides</u>: TE and TM normal modes

<u>Partially filled waveguides</u>: Longitudinal Section Magnetic (LSM)

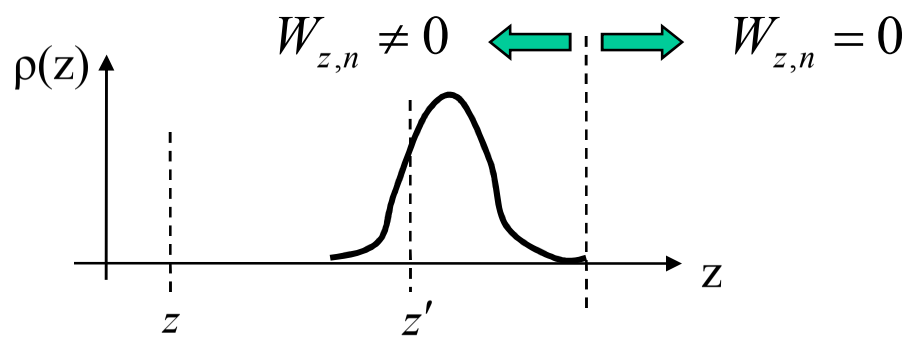
(H field || with dielectric surface; $H_y = 0$)

Longitudinal Section Electric (LSE)

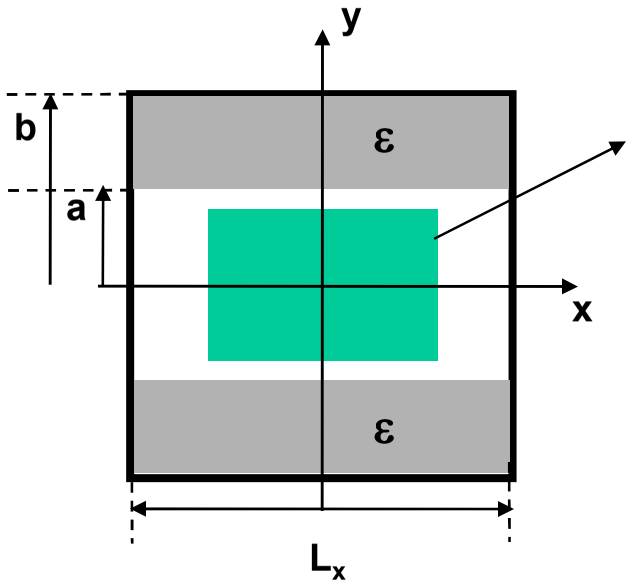
(E field || with dielectric surface; $E_y = 0$)

<u>Causality condition</u>: wakefield is 0 in front of the charge distribution !

$$W_z = \sum_n \int_z^{\infty} \rho(z') \cdot W_{z,n}(z - z') dz'$$



DWA (3)



Transverse profile of the current density (**j**)

$$\rho(x,y) = \rho(-x,y)$$

$$\rho\left(-\frac{L_x}{2},y\right) = \rho\left(\frac{L_x}{2},y\right) = \rho(x,a) = \rho(x,-a) = 0$$

$$\rho(x) = \sum_{k_x} \lambda_{k_x} \cdot \cos(k_x x)$$

$$x = \pm\frac{L_x}{2} \Rightarrow E_{z,y} = 0 \Rightarrow k_x = (2m+1)\cdot\frac{\pi}{L_x}$$

Drive charge symmetry sets the symmetry of the fields:

<u>Vacuum region</u>

"monopoles" ($E_z(y)=E_z(-y)$):

$$E_z \propto \cos(k_x x)\cosh(k_x y)$$
$$E_x \propto \sin(k_x x)\cosh(k_x y)$$
$$E_y \propto \cos(k_x x)\sinh(k_x y)$$

"dipoles" ⟶ cosh(sinh) replaced by sinh(cosh)

<u>Dielectric region</u>

$$E_z \propto \cos(k_x x)\cos[k_y(b-y)]$$
$$E_x \propto \sin(k_x x)\sin[k_y(b-y)]$$
$$E_y \propto \cos(k_x x)\sin[k_y(b-y)]$$

$$k_x^2 + k_y^2 \equiv k_\perp^2$$

DWA (4)

Limit case: $k_x \to 0 \;\; (\text{or } L_x \to \infty)$ $\xrightarrow{\mathbf{L_x >> L_y}}$ **Drive beam = flat beam!**

$$E_0^{LSM} \to \frac{4\lambda}{a + \dfrac{\varepsilon \cdot (b-a)}{\sin^2\left[k_y (b-a)\right]}}$$

$$E_{z,n} = E_0^{LSM} \cdot \cos\left[k_n (z - vt)\right] \cdot \Theta(vt - z)$$

$$k_y = k_n \sqrt{\varepsilon - 1}$$

A. Tremaine and J. Rosenzweig, PR E, **56**, 7205, (1997)

$$E_0^{LSE} \to 0$$

Transformer ratio:

$$k = \frac{W_{\max}^{+}}{W_{\min}^{-}}$$

$W_{\max}^{+} \to$ maximum accelerating voltage

$W_{\min}^{-} \to$ |maximum decelerating voltage|

W_0 drive bunch energy $\longrightarrow$ kW_0 test bunch energy when drive bunch is brought to rest

Theorem: $k \le 2$

- drive charge is symmetric: $\rho(z - z_0) = \rho(z_0 - z)$
- drive charge and test charge are collinear

DWA (5)

Under quite general assumptions: $W_z \sim \frac{Q}{Area_\perp}$ $\sigma_z << \lambda$

Ultra-high W_z (>1 GVm) → Structures with small transverse area (<100μm x 100μm)

- high quality beam
- high energy

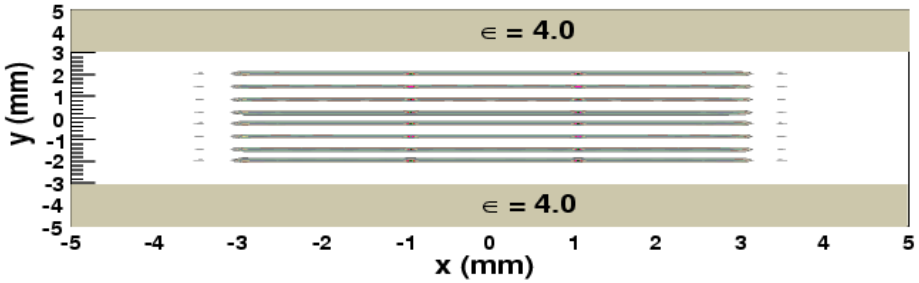
} To increase focusability

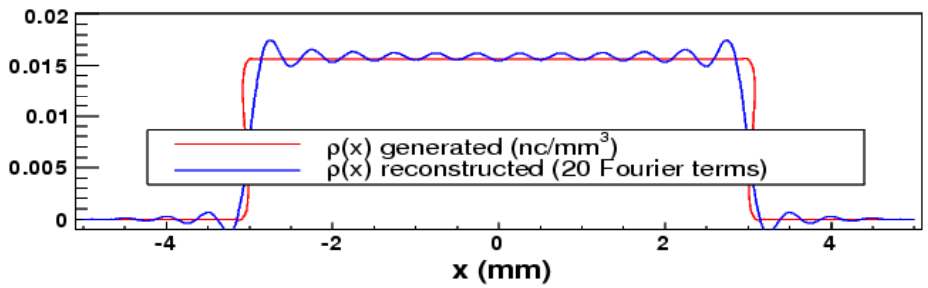
- must be able to deal with the very high frequency regime (THz)
- materials (breakdown)
- beam stability

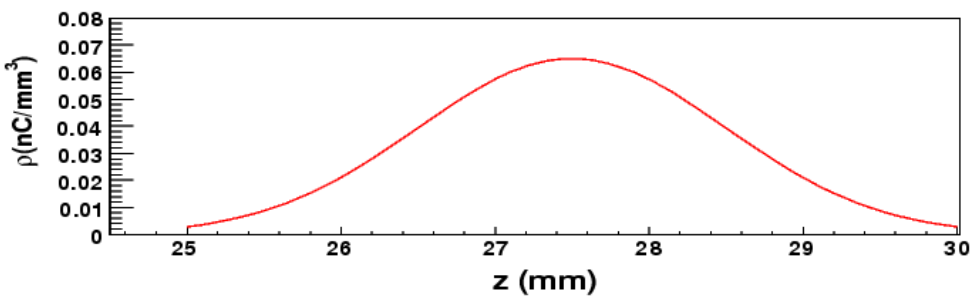
Use high bunch charge (~ 100 nC) → **Argonne Wakefield Accelerator (AWA)**

Few mm's structures; few 10's of GHz

Comparison with VORPAL simulations







http://www.txcorp.com

Theoretical model implementation:

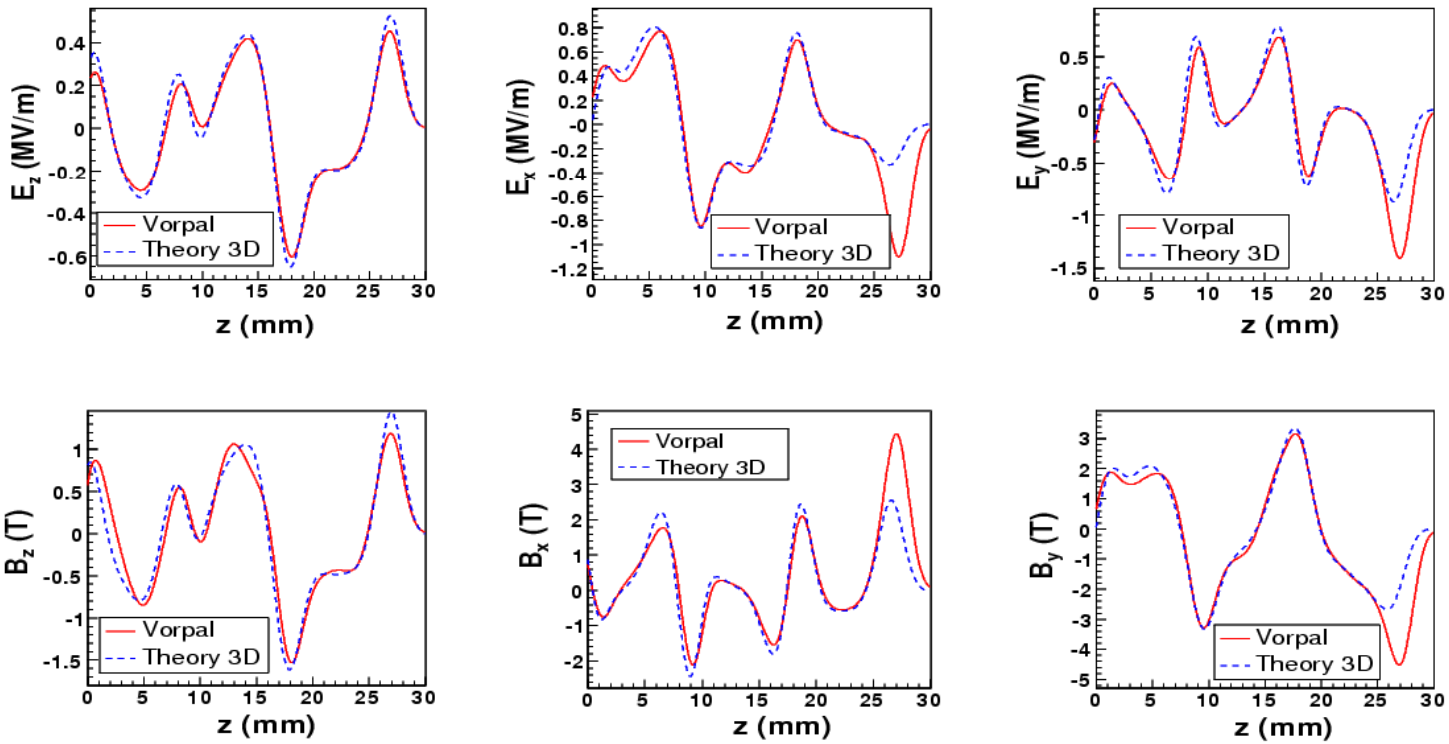
- Charge is deposited on grid to make it compatible with PIC simulations (Impact-T).
- y-charge distribution is symmetric. No dipole contributions.
- x-charge distribution simulated by the superposition of 20 Fourier terms.
- z-charge distribution is gaussian with z0 (center of drive charge) = 27.5 mm and σ_z = 1.0 mm.
- L_x = 10.0 mm
- a = 2.5 mm and b = 5.0 mm

$$\boxed{L_x = L_y}$$

Both LSM and LSE

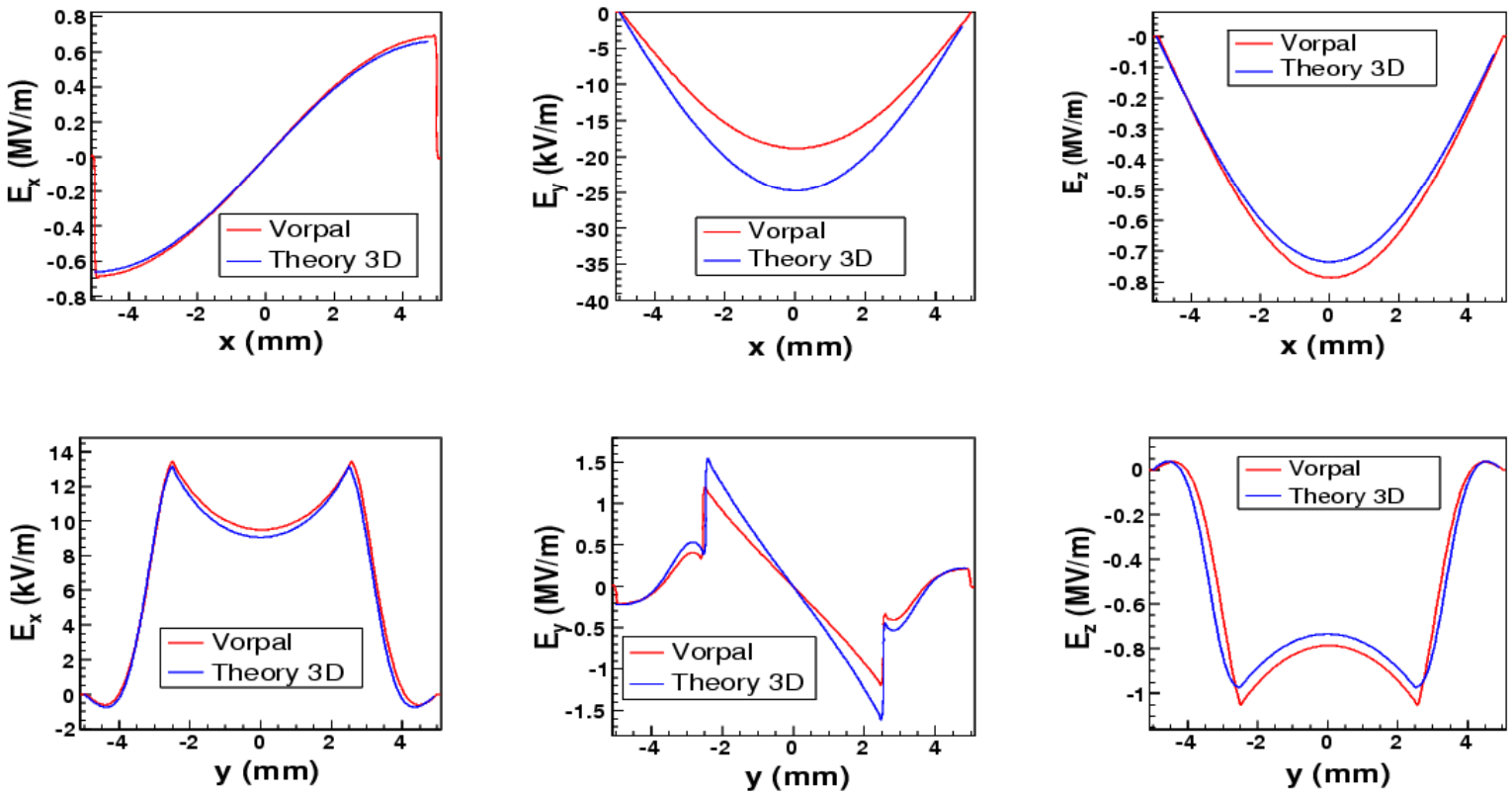
Comparison with VORPAL simulations (2)

- drive charge position: z = 27.5 mm
- fields are estimated at x = 3.0 mm and y = 2.0 mm
- Theoretical model ignores decaying modes and static fields.

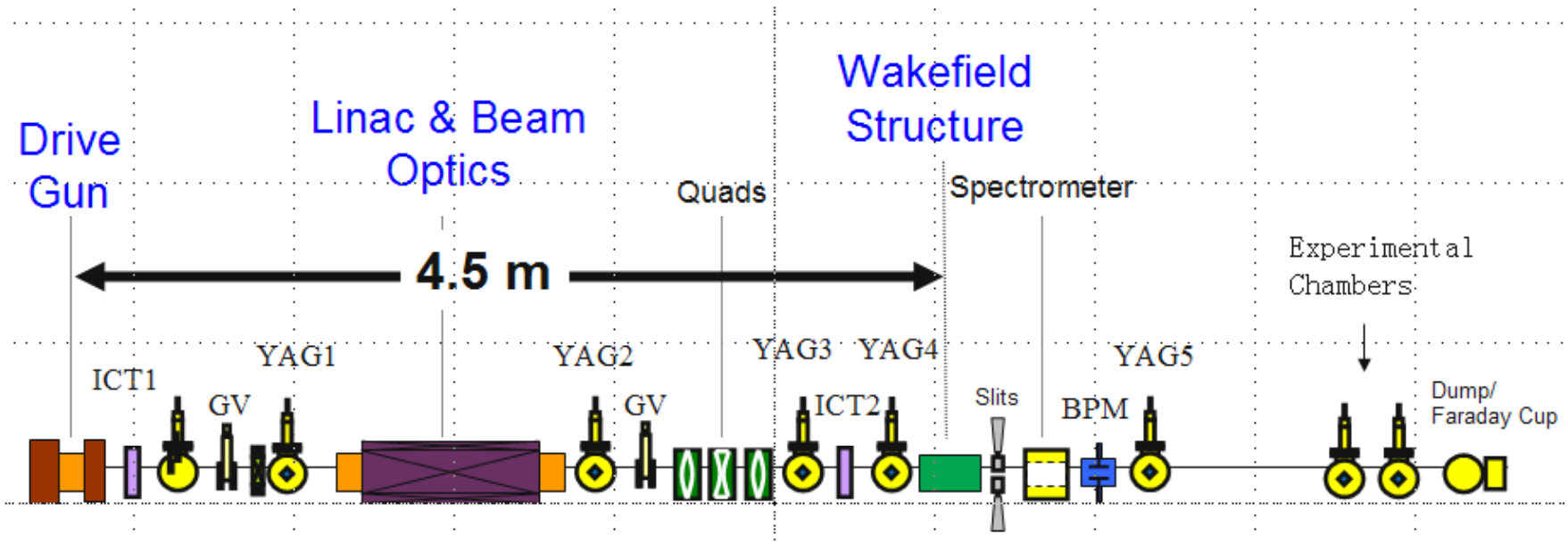


Comparison with VORPAL simulations (3)

- fields are estimated at z = 18.6 mm (≈ 8.9 mm behind the drive charge).
- first row: E-fields as functions of x at fixed y = 0.043 mm (half of bin)
- second row: E-fields as functions of y at fixed x = 0.043 mm



Argonne Wakefield Accelerator (AWA)



J. Power, ICTA Workshop (2006)

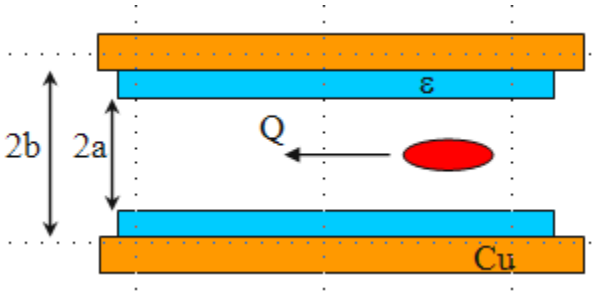
Single bunch operation:

- Q = 1-100 nC (reached 150 nC)
- 15 MeV; σ_z = 2.0 mm; $e_{x,n}$ < 200 μm (at 100 nC)
- Peak current: ~10 kA

Bunch train operation:

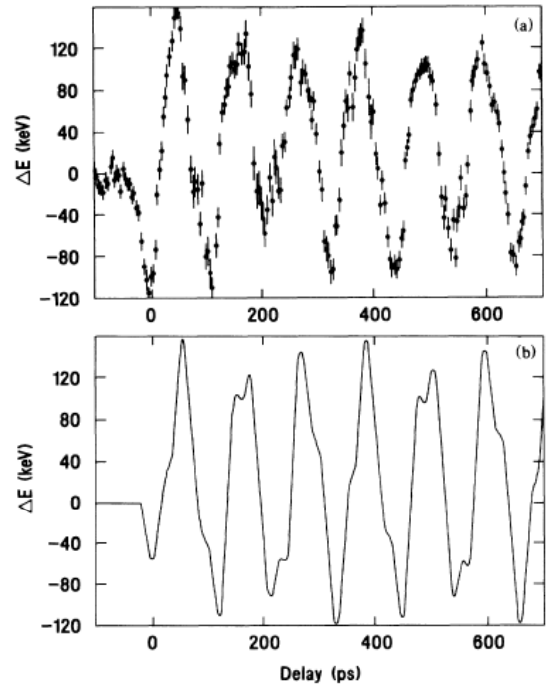
- 4 bunches x 25 nC or 16 bunches x 5 nC
- 16-64 bunches x 50-100 (future)

AWA: early results



AWA: 120 keV (1988)

W. Gai, et al., PRL 61, (2756) 1988.



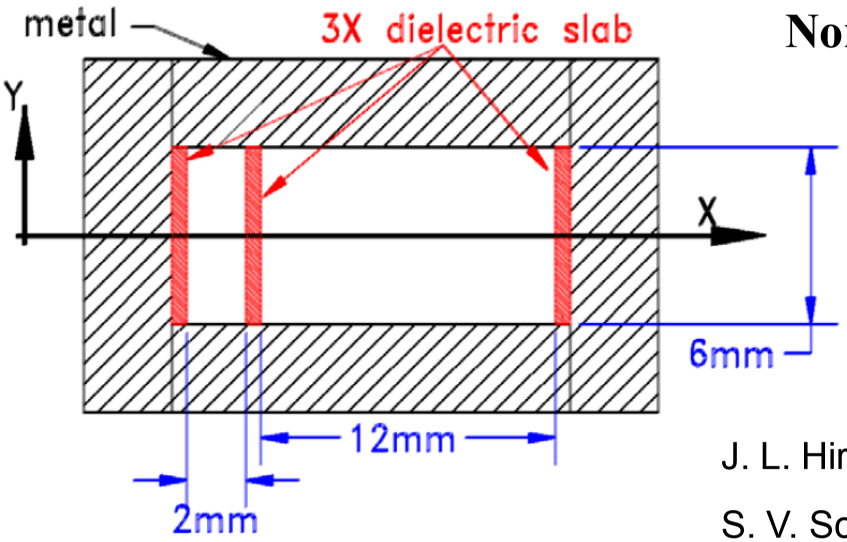
Measured energy gradient: >100 MeV/m (2008)

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

M. E. Conde, AAC08

AWA: high transformer ratio experiments

(Collaboration: Yale, ANL, NIU)



Non-collinear bunches

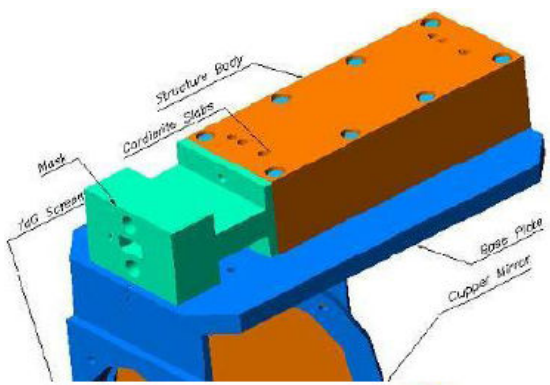
⇩

Increase transformer ratio

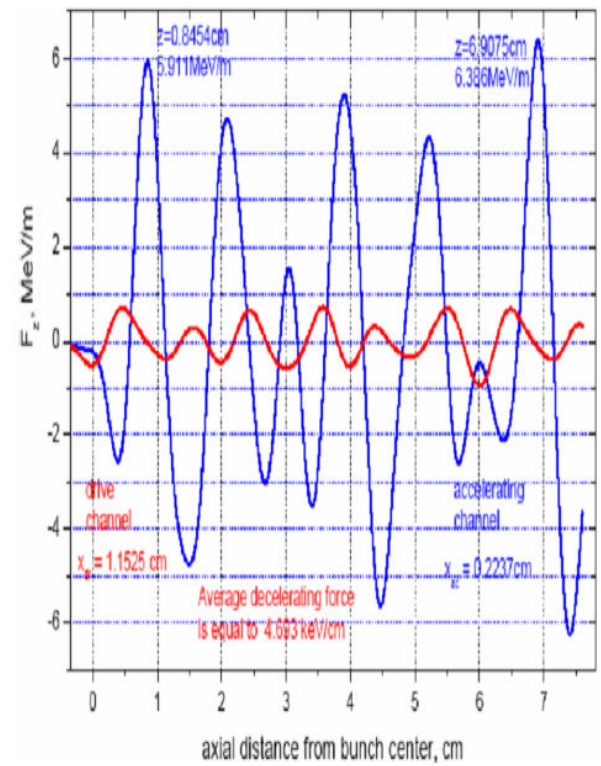
J. L. Hirshfield

S. V. Schelkunov

M. A. LaPointe



- **transformer ratio: ~ 10**
- multi-bunch drive train
- drive bunch stability
- low cost

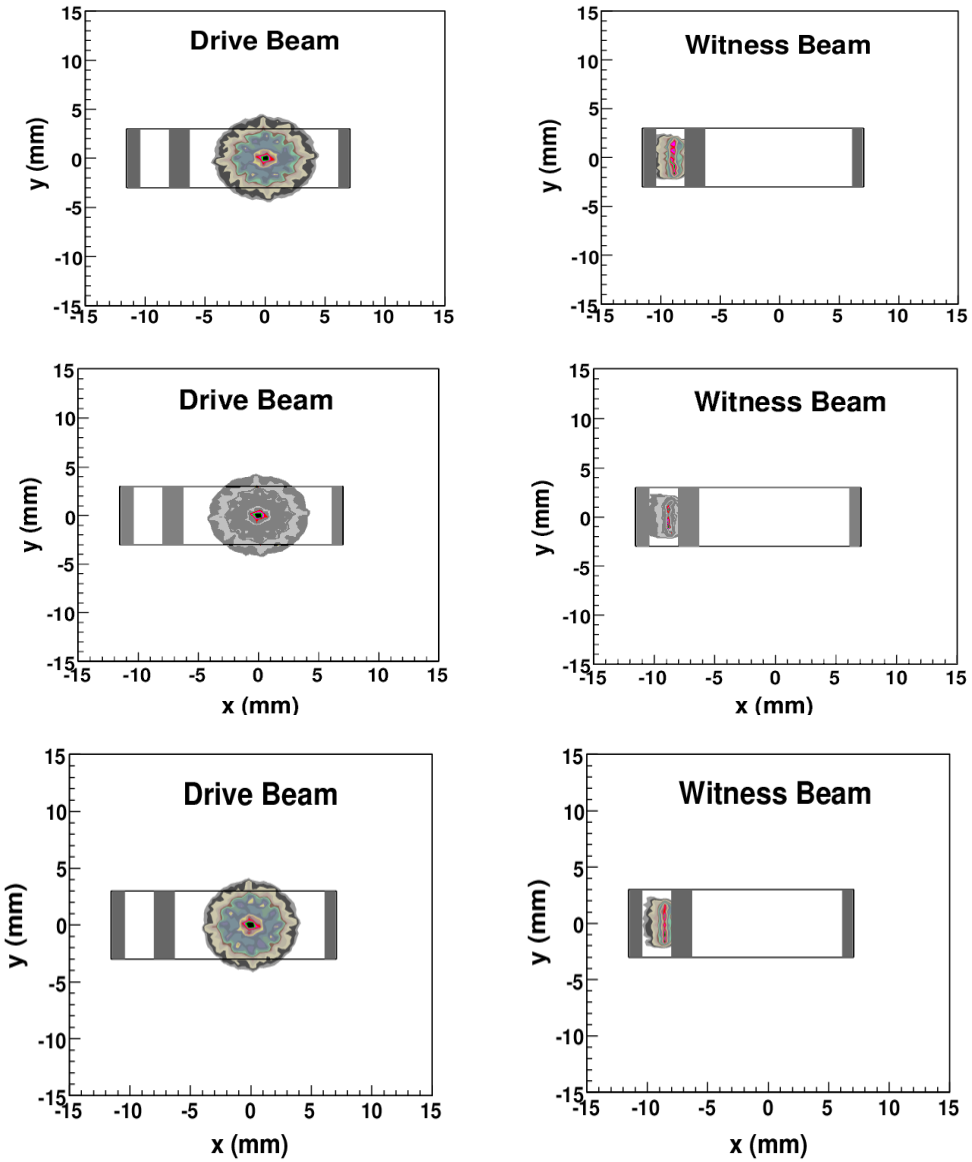


Fz-force vs. z in the channels

Critical tilt angle: ~ 70 mrad

S. Schelkunov, *et al*, PAC11

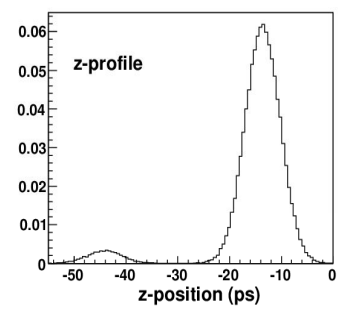
AWA: high transformer ratio experiments (2)

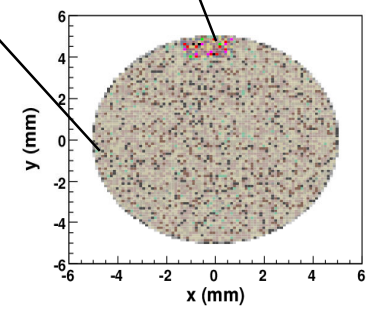


Drive: (R = 5.0 mm)

Witness:

Ring sector (r1 = 4mm; r2 = 5 mm; l = 2 mm)





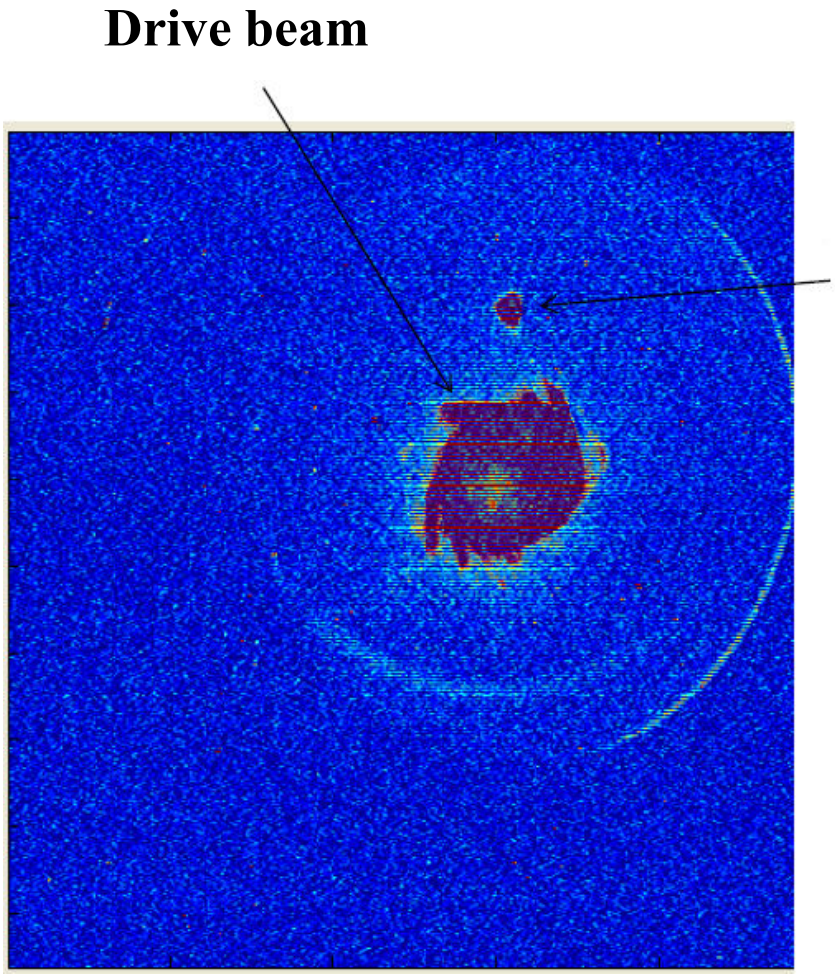
Q = 50 nC

Transmission:

- **drive: 82%**
- **witness: 38%**

Energy gain ≈ 500 keV

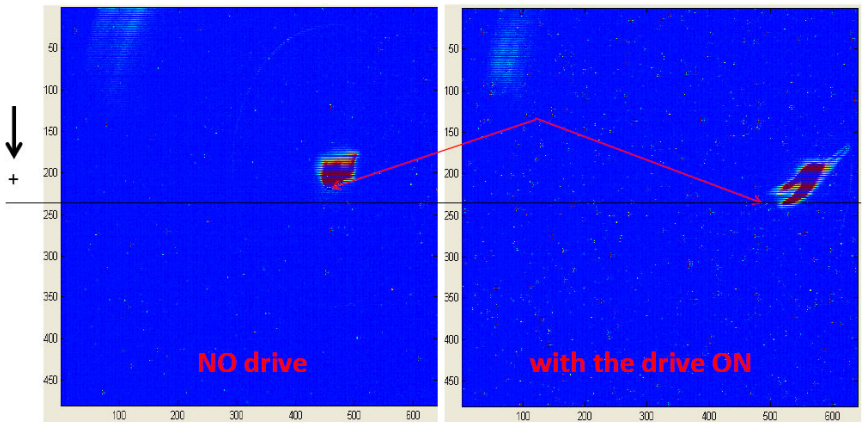
AWA: high transformer ratio experiments (3)

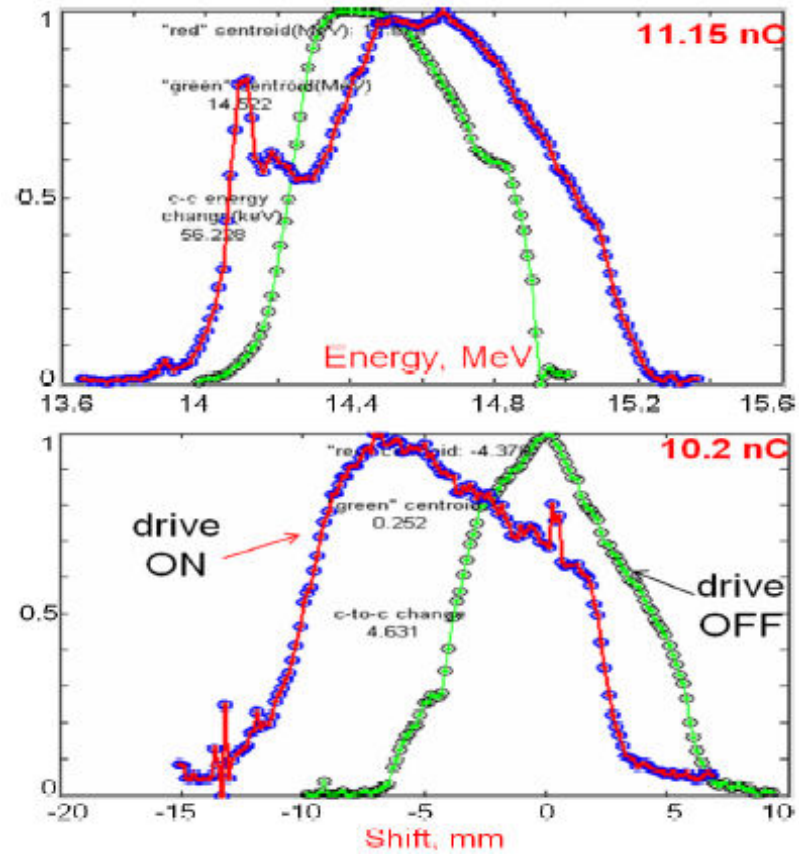


<u>Experimental challenges:</u>

- Separate the drive and test beams in transverse plane (laser, solenoids, gun phase).
- Separate the two beams longitudinally (laser).
- Control the tilt angle =>Alignment is critical!
- Measure the energy shift.

AWA: high transformer ratio experiments (4)



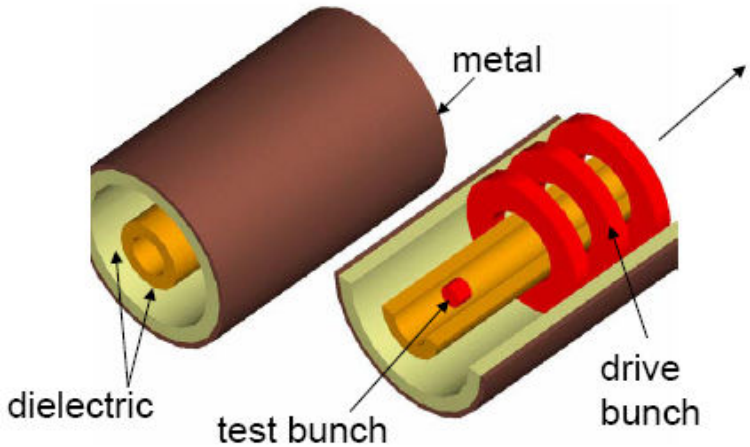


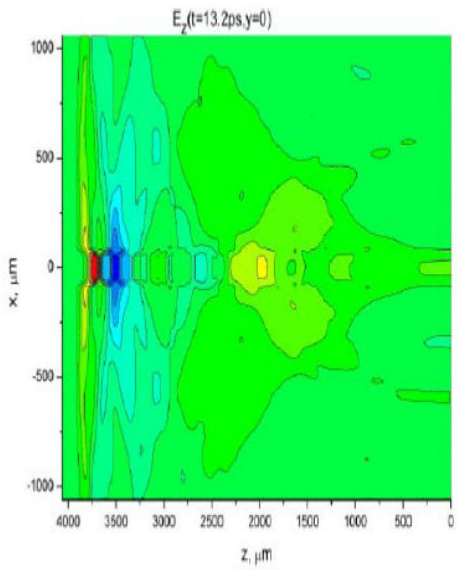
- Energy shift and horizontal kick were measured for 3 phase delays between drive and witness beams.
- Largest average energy shift was: ≈ 200 keV
- Energy shift and horizontal kick (F_X) excellent agreement with theory.
- Q (drive beam) too low to directly measure TR.

S. Schelkunov, *et al*, PAC11

A better choice for the drive beam: ring shape ⟹ **No off-axis beam**

AWA: ring beams

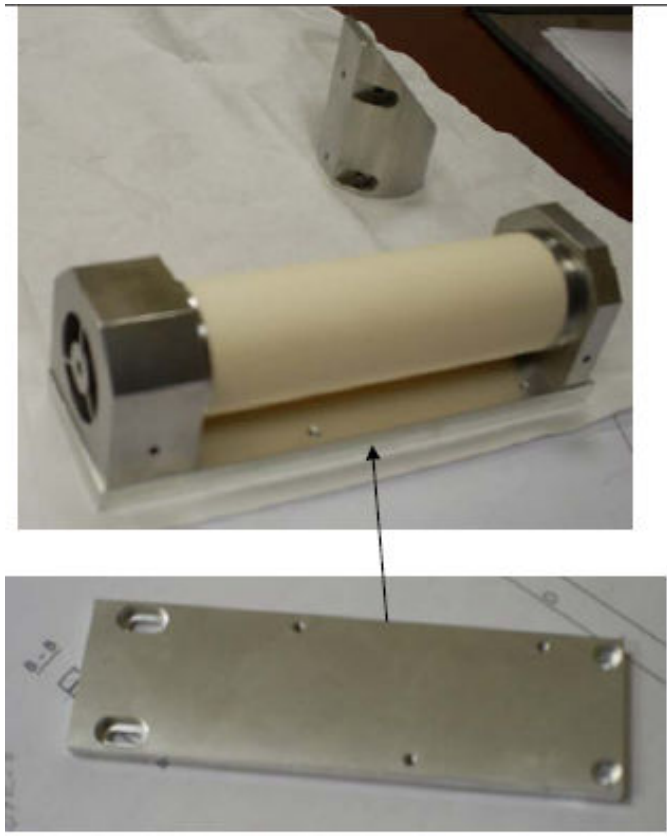




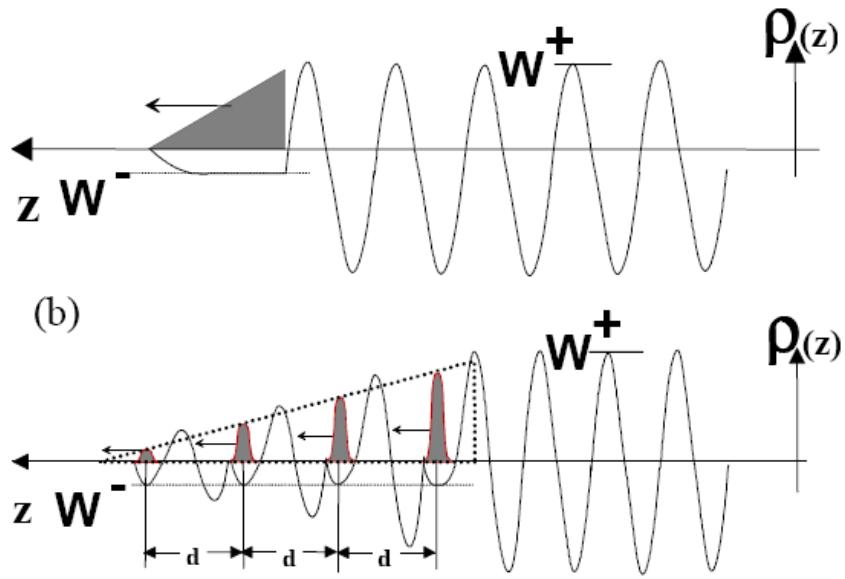
Ez(r,z) of single drive bunch at z = 4mm

- **transformer ratio: ~ 10**
- multi-bunch drive train
- **drive bunch stability**
- low cost

J. Hirshfield, *et al*, PRST-AB (2009)



AWA: triangular shaped beams



J. Power, *et al*, PAC01

Destroy drive bunch symmetry

⇩

Increase transformer ratio k

K is maximum when the decelerating voltage is constant across the drive bunch.

$$d = \frac{\lambda}{2}$$

	Accel	Decel.
q_1	q_1	$-q_1/2$
q_2	$q_2 - q_1$	$q_1 - q_2/2$
q_3	$q_3 - q_2 + q_1$	$q_2 - q_1 - q_3/2$
q_4	$q_4 - q_3 + q_2 - q_1$	$q_3 - q_2 + q_1 - q_4/2$
…		

Same deceleration

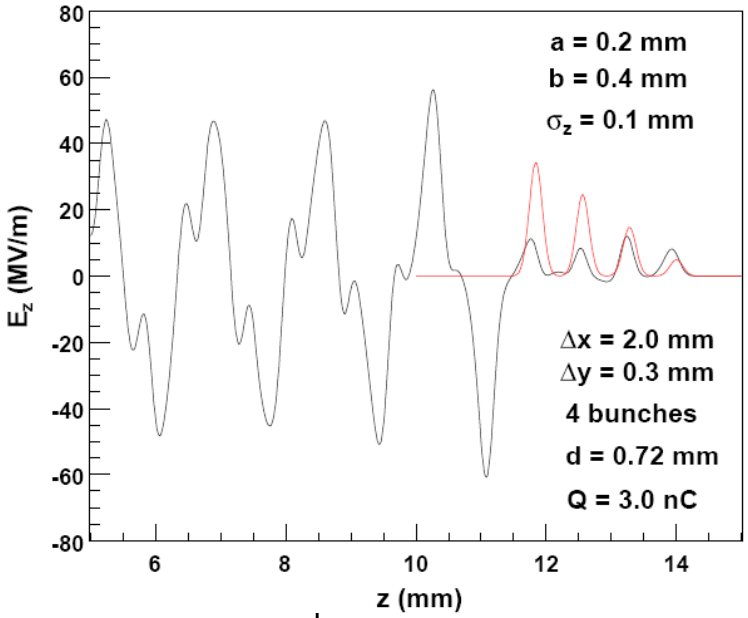
⇩

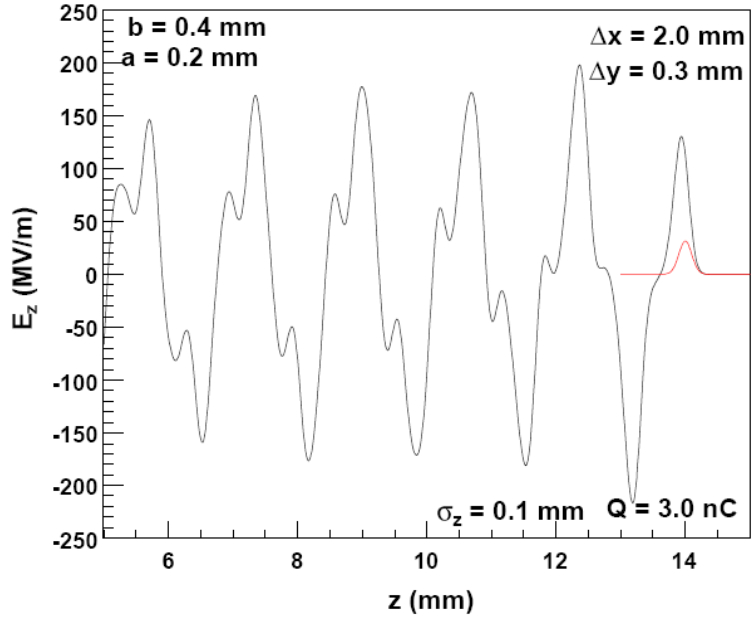
$$q_n = 2n + 1 \quad n = 1, \cdots, N$$

$$\boxed{K = N^2}$$

Experimental challenge:
control charge ratios

Triangular shaped beams (2)





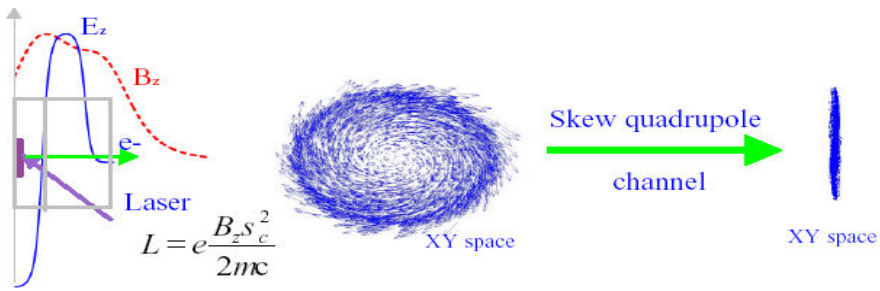
Ramped beam of 4 bunches ⟹ Lower contribution from higher order modes

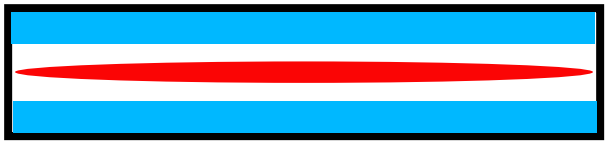
1-bunch beam

High transformer ratio (≈ 10) but lower field gradient (≈ 60 MV/m)

High field gradient (≈ 200 MV/m) but lower transformer ratio (≈ 2)

Use of Flatbeams





Brinkmann, Derbenev, Flotmann, PRST-AB (2001)

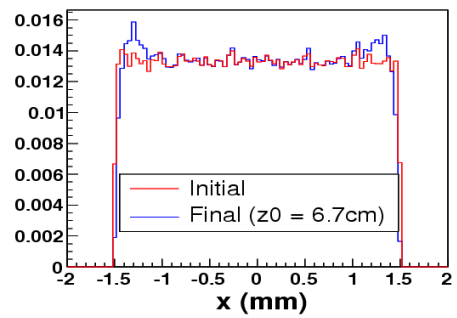
Fermilab A0 Photoinjector

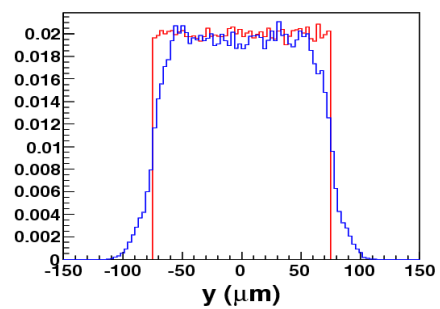
Proof of principle: D. Edwards, *et al*, PAC01 (2001)

$\varepsilon_x/\varepsilon_y \approx 100$ Piot, Sun, Kim, PRST-AB (2006)

- $\varepsilon_x = 40\ \mu m$; $\varepsilon_y = 0.4\ \mu m$
- $\sigma_x = 2$ mm; $\sigma_y \approx 100\ \mu m$
- Q = 0.5 nC

$\Delta z = 6.7$ cm

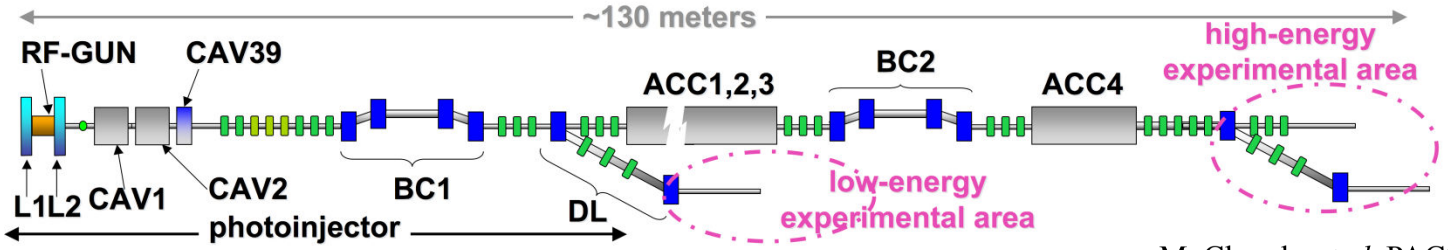




Advantages:

- The beam maintains its transverse shape over a large distance => Higher energy gain for the witness beam.
- Can obtain large field gradients.
- In the limit $\sigma_z << \lambda$ => $F_y = q(E_y + vB_x) \approx 0$ => **no beam break-up**.
- Match well with slab-symmetric structures.

NML/A0 (?): flatbeams

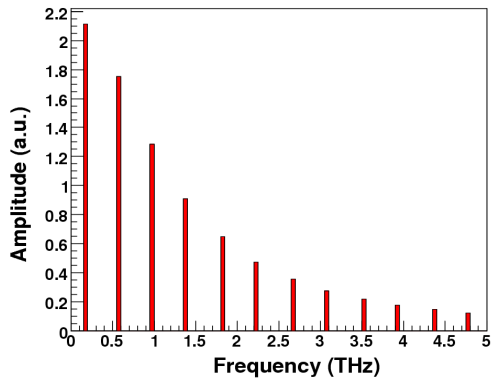


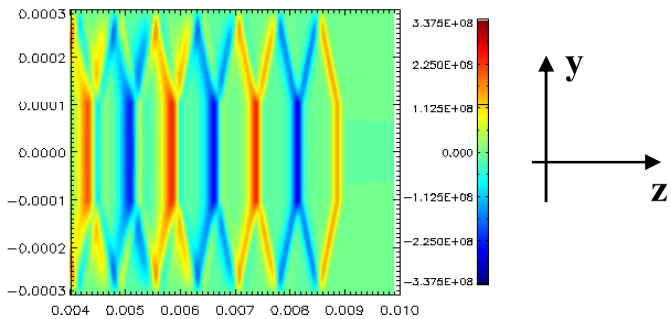
M. Church, *et al*, PAC07

P. Piot, *et al*, AAC8

Desired beam parameters:

- $\sigma_y = 50\ \mu m$; $\sigma_x \approx 20\sigma_y$
- $\varepsilon_y \leq 1\ \mu m$; $\varepsilon_x \approx 100\varepsilon_y$
- $\sigma_z = 50\ \mu m$
- $Q = 3.0$ nC

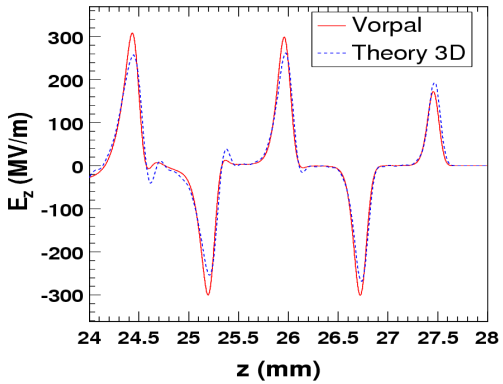




Structure parameters:

- a = 100 μm
- b = 300 μm
- ε = 4.0

$$E_z \approx 0.3\ GV/m$$



Conclusions:

- **Dielectric loaded waveguides can sustain ultra-high field gradients (> 1 GV/m).**

- **Low charge drive beams (~ 1nC) can produce ultra-high field gradients if focused to the level of 10's of microns.**

- **Field gradients of about 100 MV/m were already obtained at AWA.**

- **Rectangular structures allow:**

  - beam focusing in one direction
  - use of flatbeams
  - higher energy gain (longer structures)
  - limited beam beak-up
  - low cost

- **Beam tailoring is the key or high field gradients and high transformer ratio.**