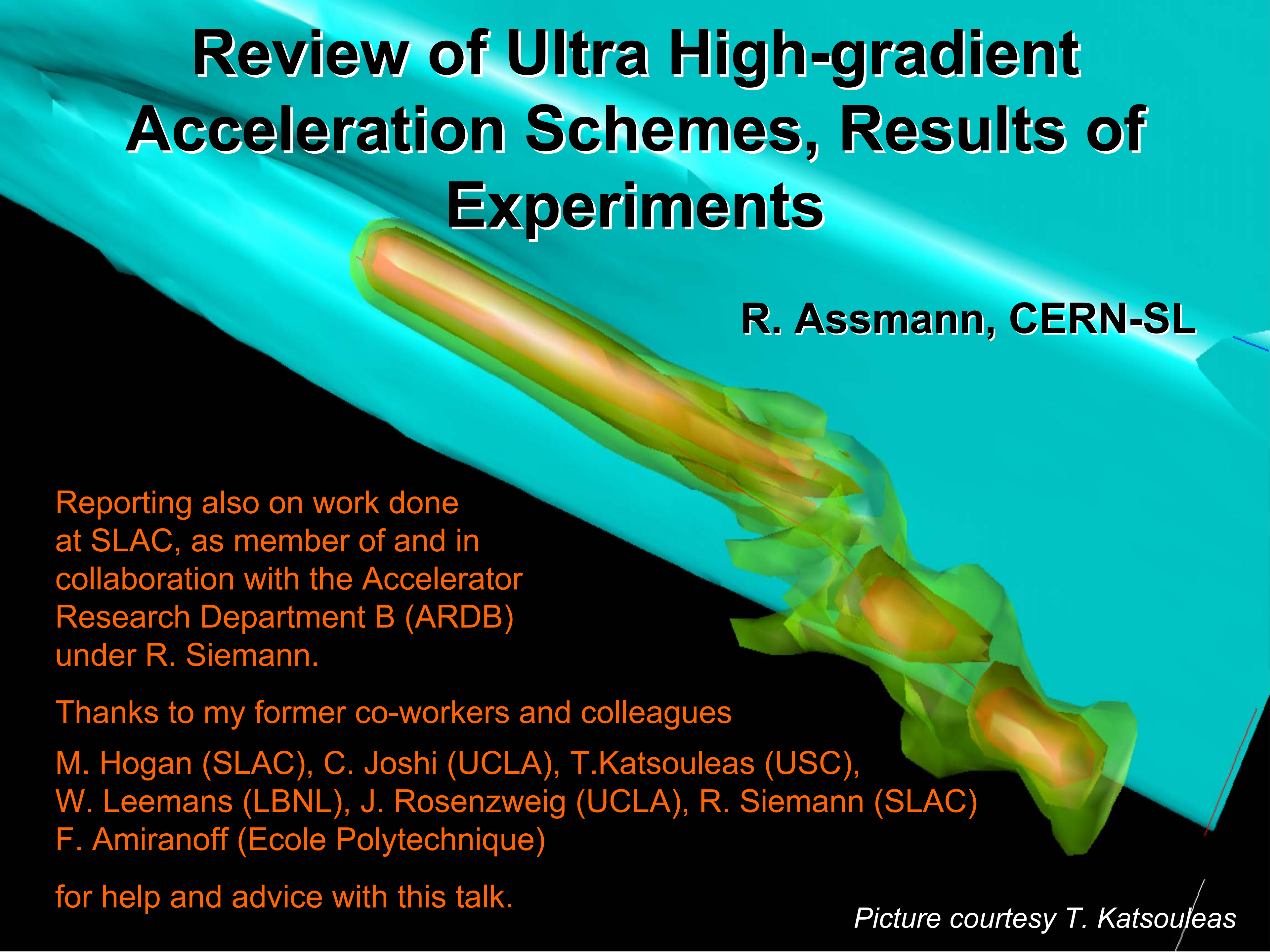
# Review of Ultra High-gradient Acceleration Schemes, Results of Experiments

**R. Assmann, CERN-SL**



Reporting also on work done at SLAC, as member of and in collaboration with the Accelerator Research Department B (ARDB) under R. Siemann.

Thanks to my former co-workers and colleagues

M. Hogan (SLAC), C. Joshi (UCLA), T.Katsouleas (USC),
W. Leemans (LBNL), J. Rosenzweig (UCLA), R. Siemann (SLAC)
F. Amiranoff (Ecole Polytechnique)

for help and advice with this talk.

*Picture courtesy T. Katsouleas*

# Contents

1) Why ultra-high gradients?
   - The Livingston plot
   - Limits for new particle accelerators
   - Basic requirements for particle physics
   - The promise of ultra-high gradients

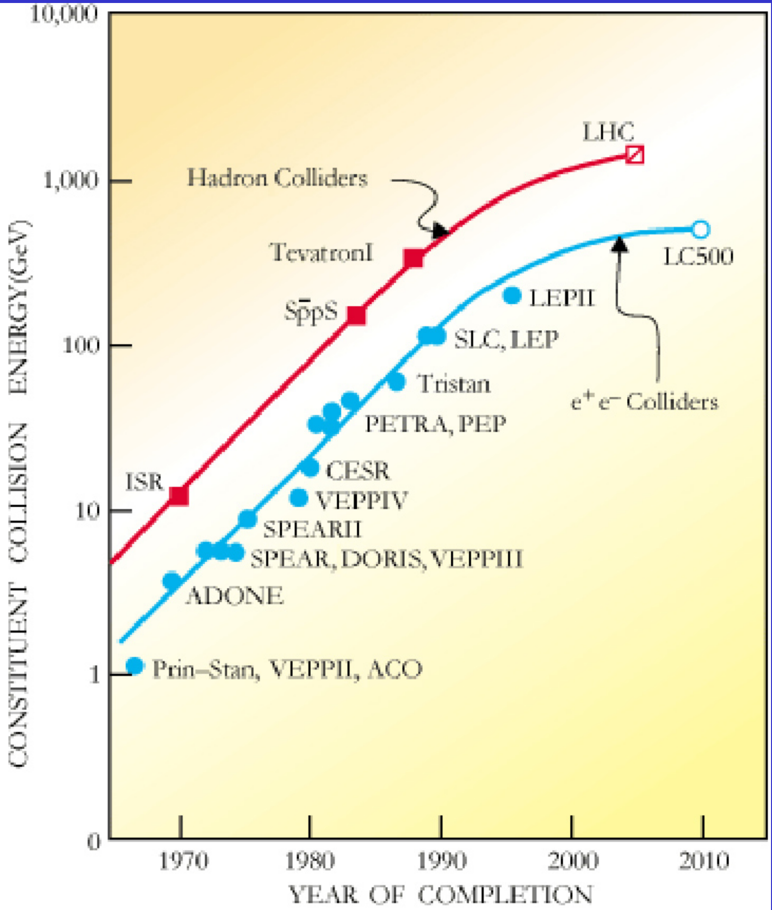
2) How to get ultra-high gradients?
   - Overview on schemes being followed
   - Principles (plasma and vacuum concepts)

3) Experimental results - Highlights
   - Plasma wakefield acceleration
   - Laser wakefield acceleration
   - Laser acceleration

4) Moving towards usage in a linear collider
   - Considerations
   - The plasma booster for the Higgs?

5) Conclusion

# The Livingston plot




M. Tigner: "Does Accelerator-Based Particle Physics have a Future?" Physics Today, Jan 2001 Vol 54, Nb 1

The Livingston plot shows a saturation effect!

Practical limit for accelerators at the energy frontier:

Project cost increases as the energy must increase!

*Cost per GeV C.M. proton has decreased by factor 10 over last 40 years (not corrected for inflation)!*

Not enough: Project cost increased by factor 200!

New technology needed…

# Basic requirements beyond next generation $e^+e^-$ linear colliders

Beam energy c.m. > 5 TeV

Luminosity > $10^{35}$ cm$^{-2}$ s$^{-1}$

Beam power(consequence): ~ 100 MW

$$P_b = 4\pi \cdot \frac{\sigma_x^* \sigma_y^*}{N_e} \cdot E \cdot L$$

Example:

Energy = 2.5 TeV
Luminosity = $10^{35}$ cm$^{-2}$ s$^{-1}$
IP spot size = 10 nm
Bunch population = 5 $10^9$

New technologies for high energy colliders must be compatible with reasonable beam power:

Good efficiency
Low emittance (beam size)
High bunch charge

# The promise of ultra-high gradients

Final energy = **Active acceleration length × Accelerating gradient**

Exponential increase in energy without exponential increase in accelerating gradient:

1. Accelerators become longer.
2. Without “cheap” technology they become more expensive.
3. They do not fit on the sites of existing laboratories (more difficult approval, additional infrastructure cost).

Ultra-high gradients of up to 100 GV/m have been observed (gain of 3 orders of magnitude).

What is the status of this technology? Can we build ultra-short high-energy colliders?

# What are ultra-high accelerating gradients?

**Feasible gradients in metallic structures:**

| Collider | Gradient | | |
|---|---|---|---|
| SLC | 20 | MeV/m | SLAC 1988-1997 |
| ILC | 70 - 85 | MeV/m | SLAC, KEK |
| TESLA | 25 - 35 | MeV/m | DESY |
| CLIC | 150 | MeV/m | CERN |

See talk by W. Wuensch…

Ultra-high accelerating gradients: **1 - 100 GeV/m**

*…obtained with various new technologies!*

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   Laser wakefield acceleration
   Laser acceleration

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# Advanced accelerator research

Two types of advanced accelerators:

1. Wakefield accelerators

   Dielectrics and microstructures (RF and two beam)

   Plasma

2. Laser accelerators

   Vacuum

   Plasma

# Concepts For Plasma-Based Accelerators

**Pioneered by J.M. Dawson**

- Plasma Wake Field Accelerator(PWFA)

  **A high energy electron bunch**

- Laser Wake Field Accelerator(LWFA)

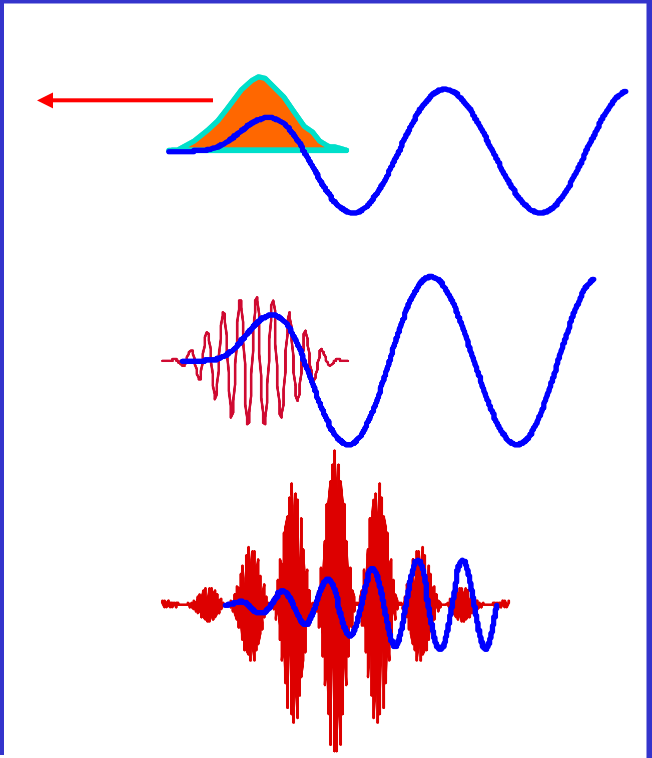
  **A single short-pulse of photons**

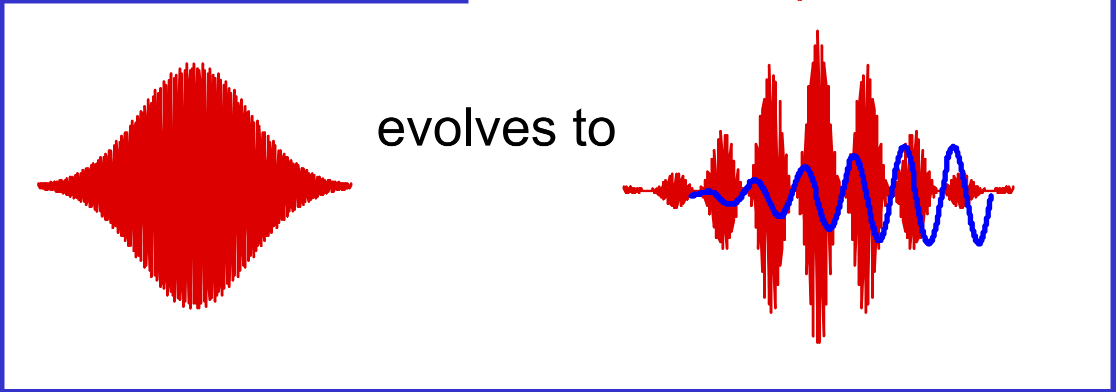
- Plasma Beat Wave Accelerator(PBWA)

  **Two-frequencies, i.e., a train of pulses**

- Self Modulated Laser Wake Field Accelerator (SMLWFA)

  **Raman forward scattering Instability**

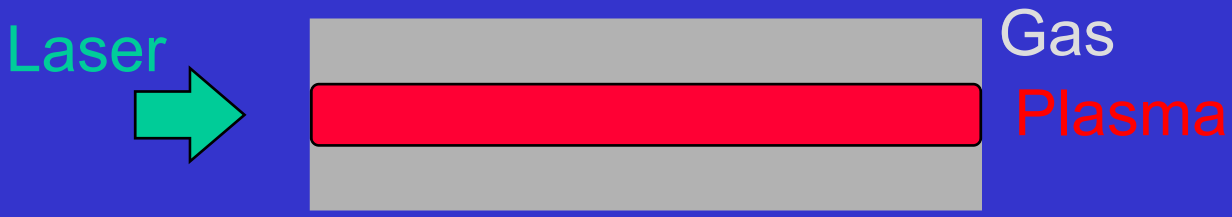




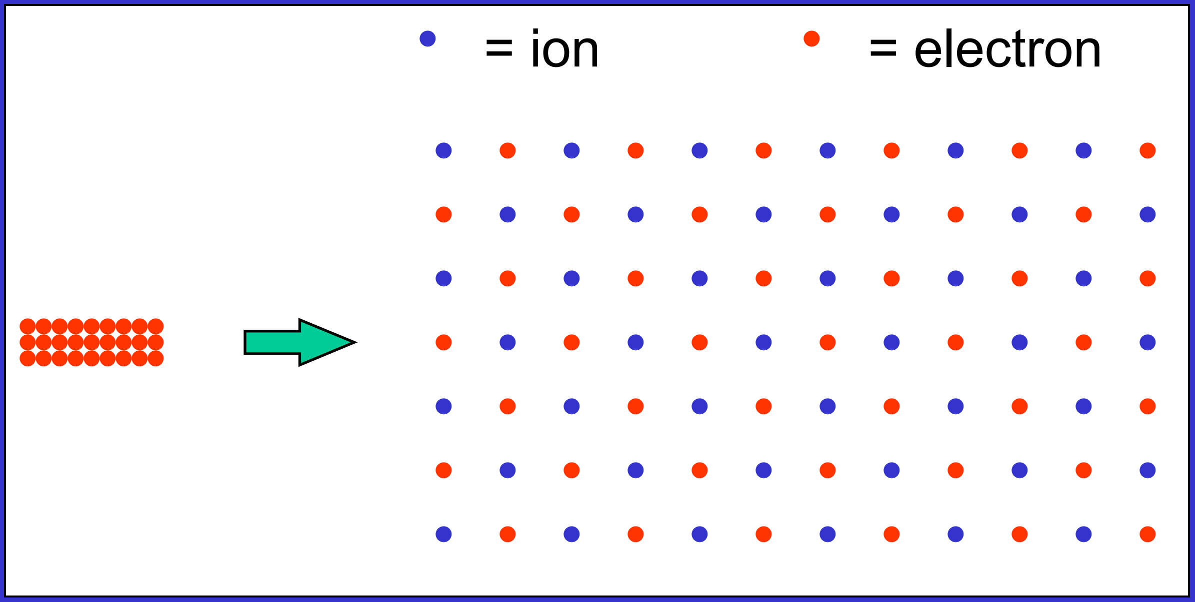

*Courtesy T. Katsouleas*

# Basic principle and scaling rules 1

I) Generate homogeneous plasma channel:




II) Send dense electron beam towards plasma:

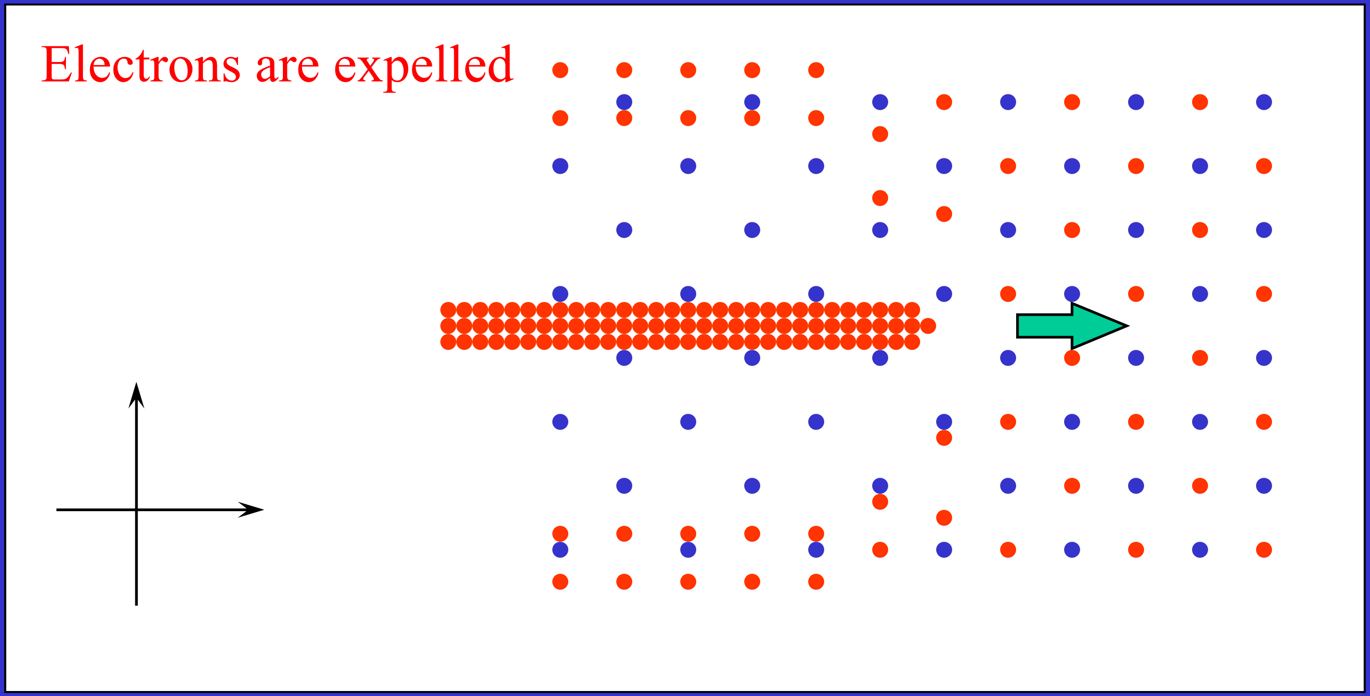



Beam density $n_b$ > Gas density $n_0$

Beam excited plasma. Also lasers can be used (laser wakefield acceleration).

# Basic principle and scaling rules 2

III) Excite plasma wakefields:




Space charge force of beam ejects all plasma electrons promptly along radial trajectories

Pure ion channel is left: Ion-focused regime, underdense plasma

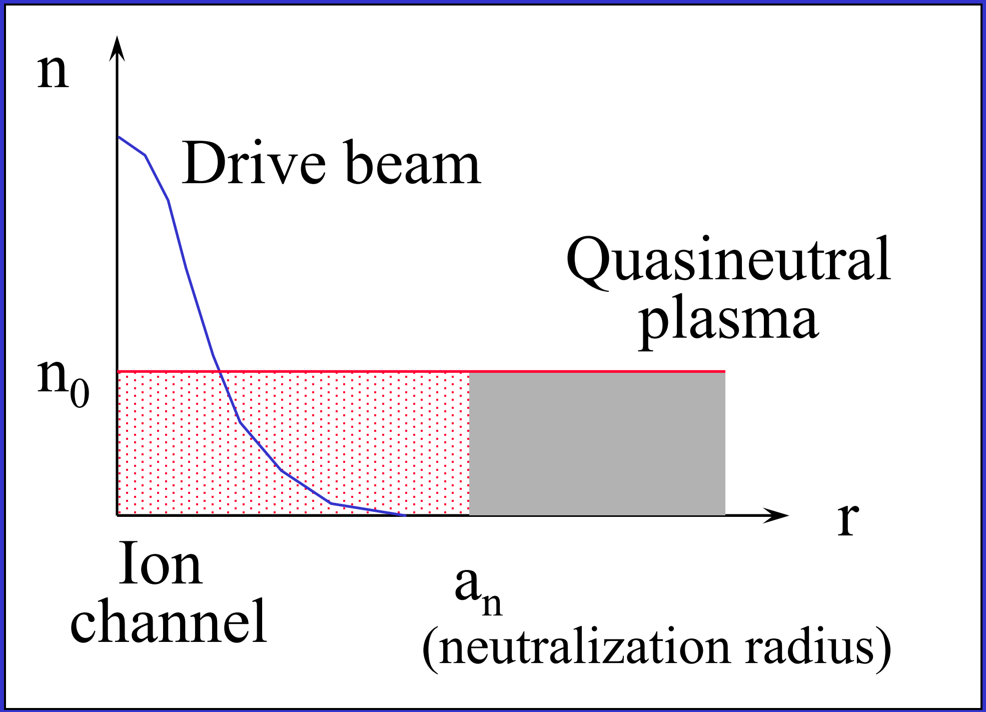
# Basic principle and scaling rules 3

## Equilibrium condition:

**Ion charge neutralizes beam charge:**

$$a_n = \sigma_r \cdot \sqrt{\frac{n_b}{n_0}}$$

Beam size




SLC:
$n_b/n_0 = 10$

Beam and plasma densities determine most characteristics of plasma wakefields!

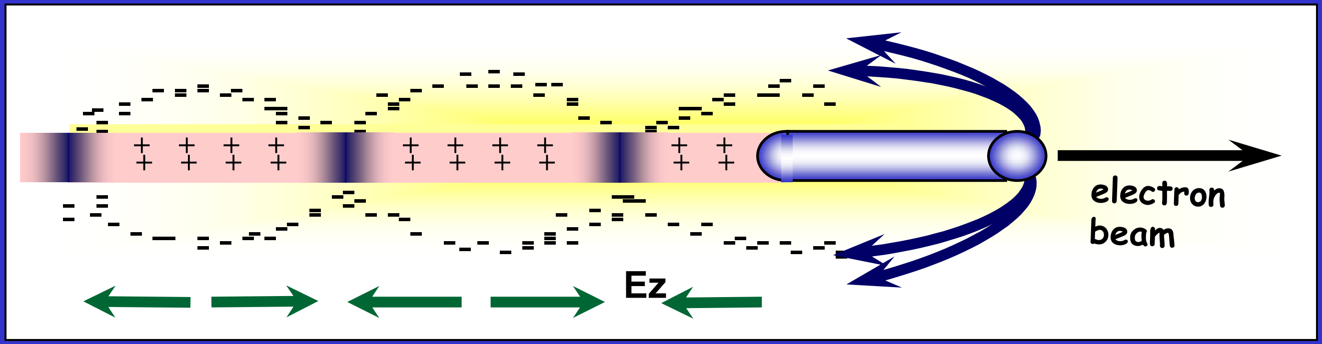
# Basic principle and scaling rules 4

Electron motion solved with ...

**driving force:** Space charge of drive beam displaces plasma electrons.

**restoring force:** Plasma ions exert restoring force

**Space charge oscillations (Harmonic oscillator)**




Longitudinal fields can accelerate and decelerate!

# Basic principle and scaling rules 5

Wavelength:

$$\lambda_p \approx 1\mathrm{mm} \cdot \sqrt{\frac{10^{15}\mathrm{cm}^{-3}}{n_0}}$$

Accelerating field

$$\frac{N_{e^-} \cdot r_e}{\sigma_z} \rightarrow 1 \qquad (\mathrm{SLC:} \approx 0.2)$$

$$W_z \approx 100 \cdot \sqrt{n_0} \cdot \mathrm{V/m}$$ (roughly)

$$\propto N_b / \sigma_z^2$$

Plasma density $n_0$ $10^{14}$ to $10^{15}$...

**$\lambda_p$ ~ mm**

**~ GV/m**

# Basic principle and scaling rules 6

Plasma ions move relatively little ⇒ Constant focusing gradient

$$\frac{W_r}{r} = 2\pi \cdot n_0 \cdot e^2 = 960\pi \frac{T}{m} \cdot \left( \frac{n_0}{10^{14} cm^{-3}} \right)$$

$$\beta = \sqrt{2\gamma} \cdot \frac{c}{\omega_p}$$

⇓

**Plasma "structures" are also super-strong "quadrupoles"!**
**(many thousand T/m)**

*... need to handle acceleration and focusing!*

# Basic observations

Plasma based acceleration:

- High accelerating gradients (many GV/m)
- Short wavelengths (< mm)

$\Rightarrow$ Short bunches (< 100μm)

- Strong transverse focusing (> kT/m), small β (< cm)

$\Rightarrow$ Small matched beam size
Rigid tolerances

Availability of short bunches for experiments is limited!

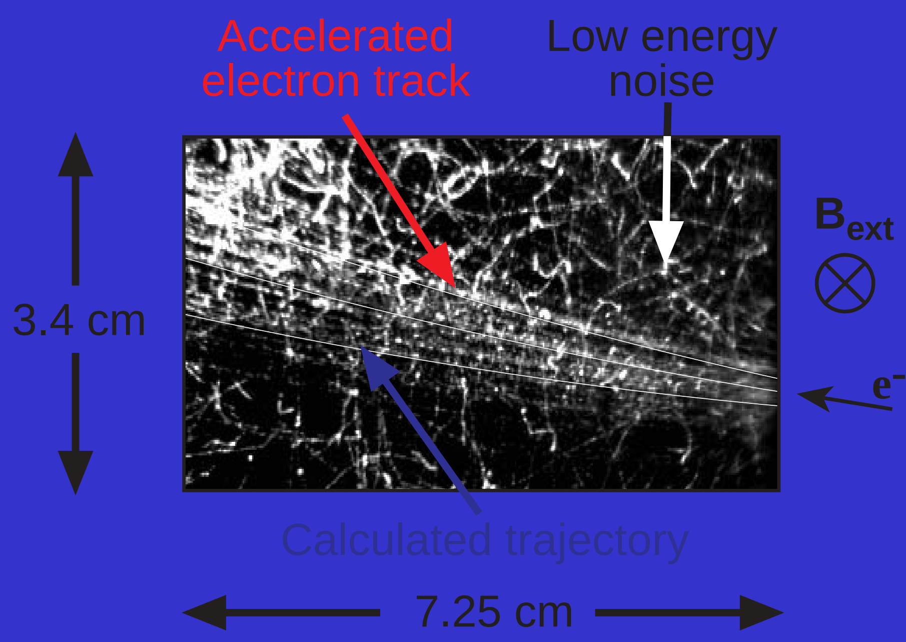
# Contents

# Ultrahigh-gradient acceleration of injected electrons by laser-excited relativistic electron plasma waves

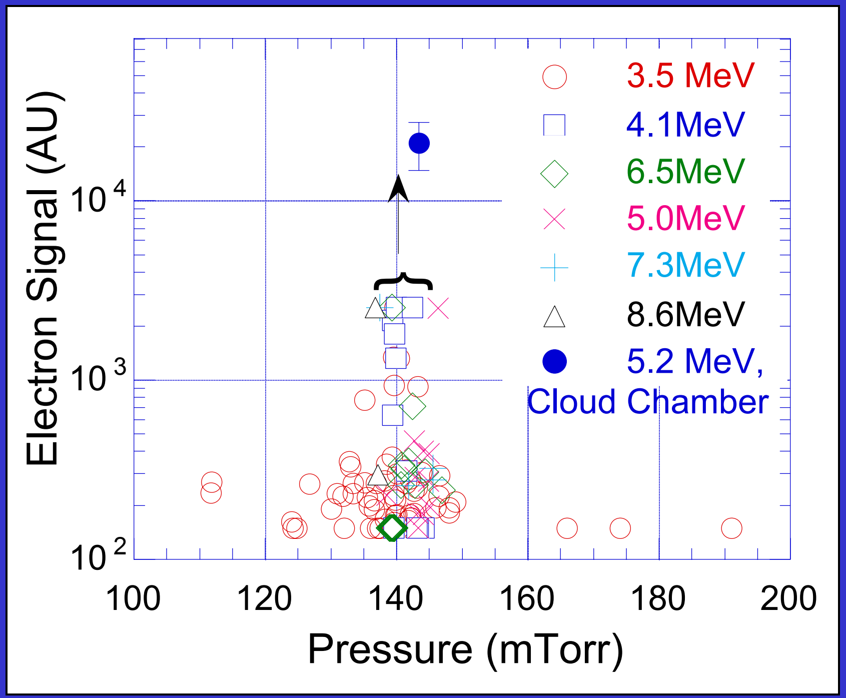
UCLA

C.E. Clayton et al., **Phys. Rev. Letters** 70, 37 (1993)

## Cloud chamber photograph




## Resonance curve




Conclusive evidence of injected electron acceleration.

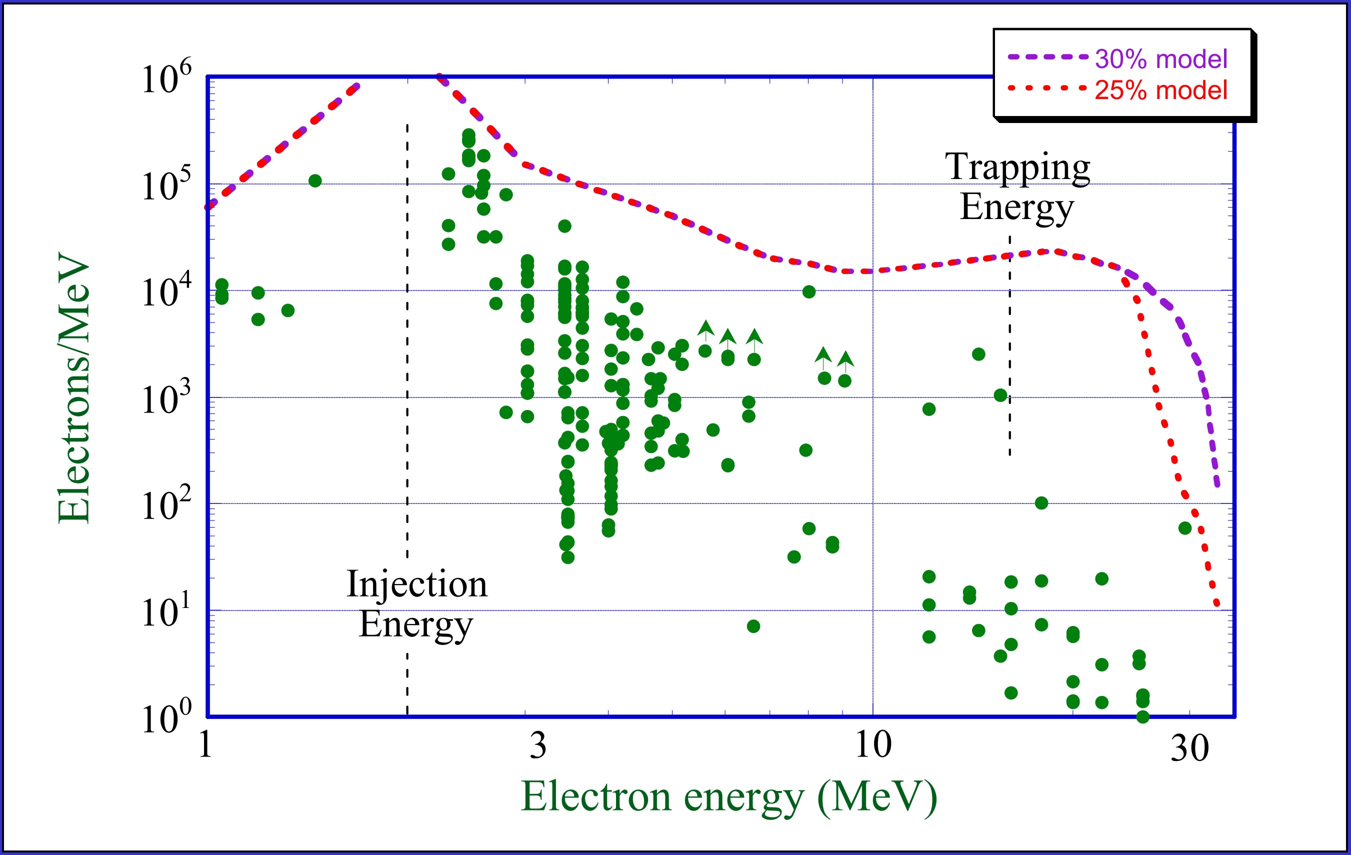
First evidence of resonant acceleration.



*Courtesy C. Joshi, UCLA*

# Trapped electron acceleration by a laser-driven relativistic plasma wave

M. Everett et al. **Nature** 368, 527 (1994)




First observation of energy gain beyond trapping threshold

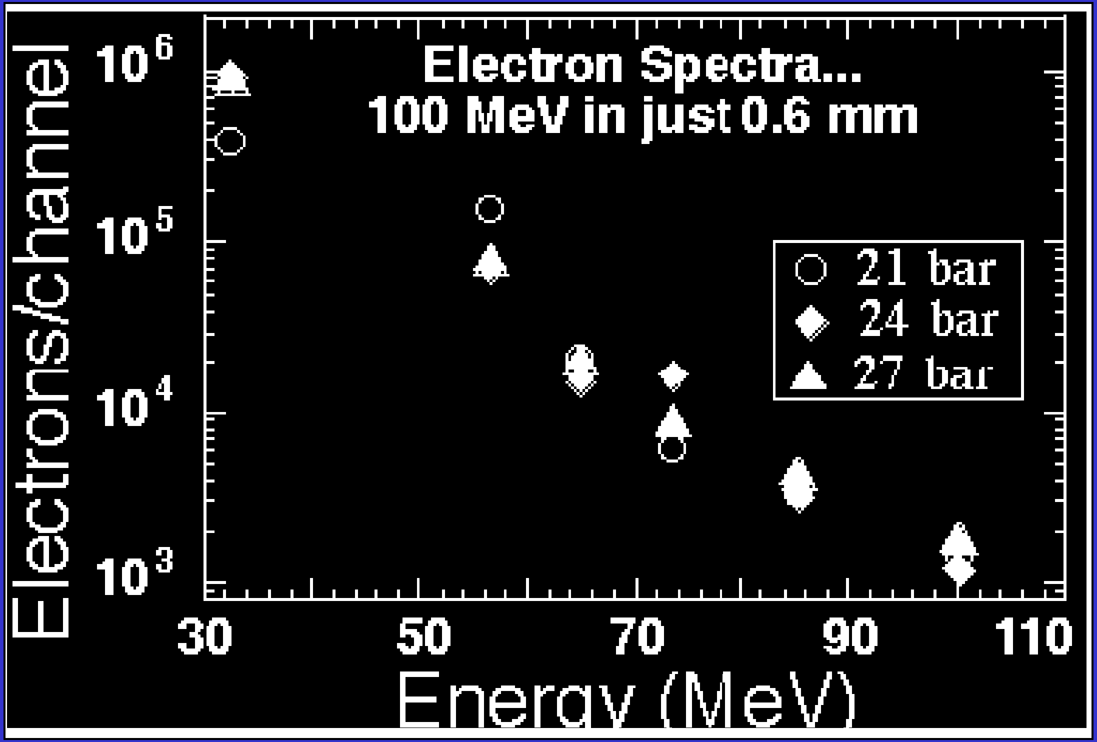
Evidence for energy loss as well as energy gain by plasma wave



*Courtesy C. Joshi, UCLA*

# Observation of electron energies beyond the linear dephasing limit from a laser-excited relativistic plasma wave

D. Gordon et al., Phys. Rev. Letters 80, 2133 (1998)




Observation of energy gain:

100 MeV

over

0.6 mm

=> at least 160 GeV/m acceleration gradient

*Done at Rutherford Laboratories, UK*

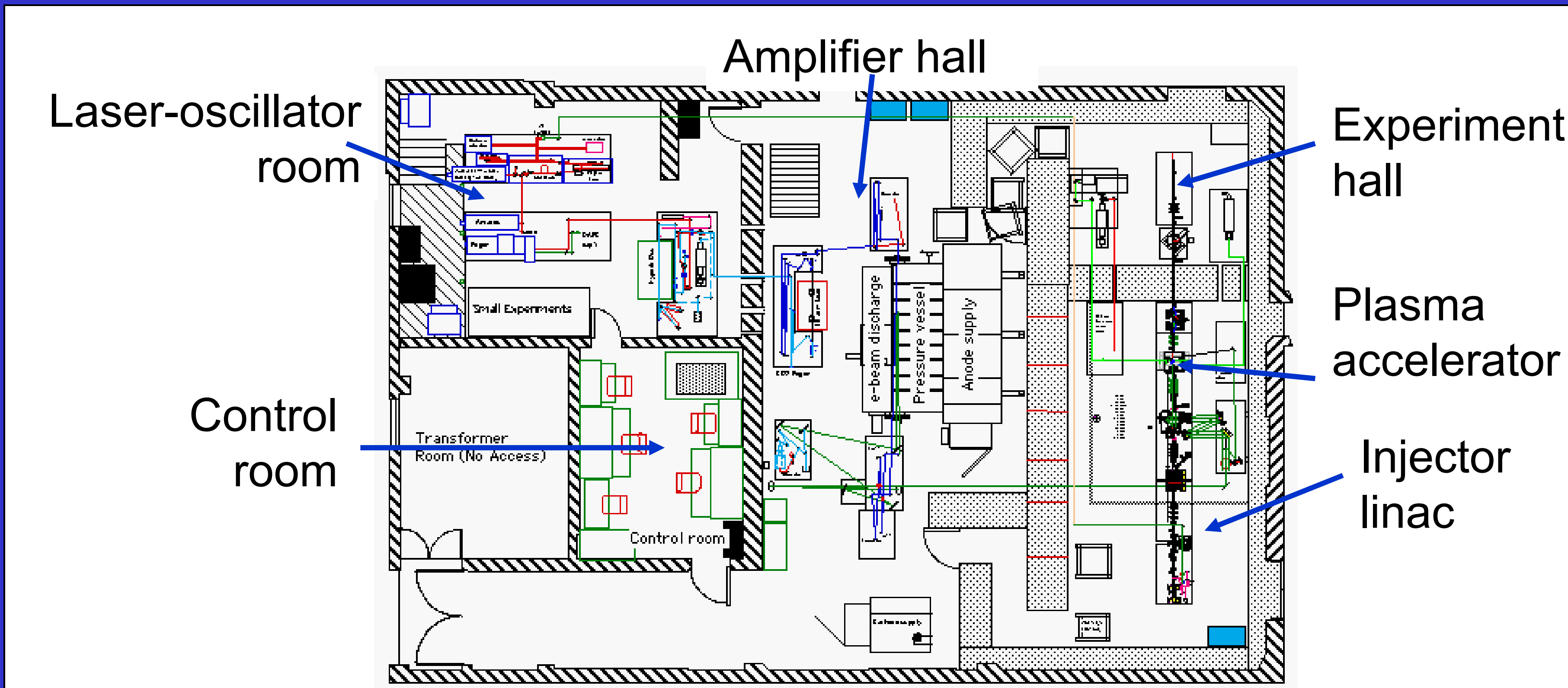




*Courtesy C. Joshi, UCLA*

# The NEPTUNE Facility for 2nd Generation Advanced Accelerator Experiments

C. Joshi, J. Rosenzweig, C. Pellegrini, K.A. Marsh,
S. Tochitsky, and C.E. Clayton

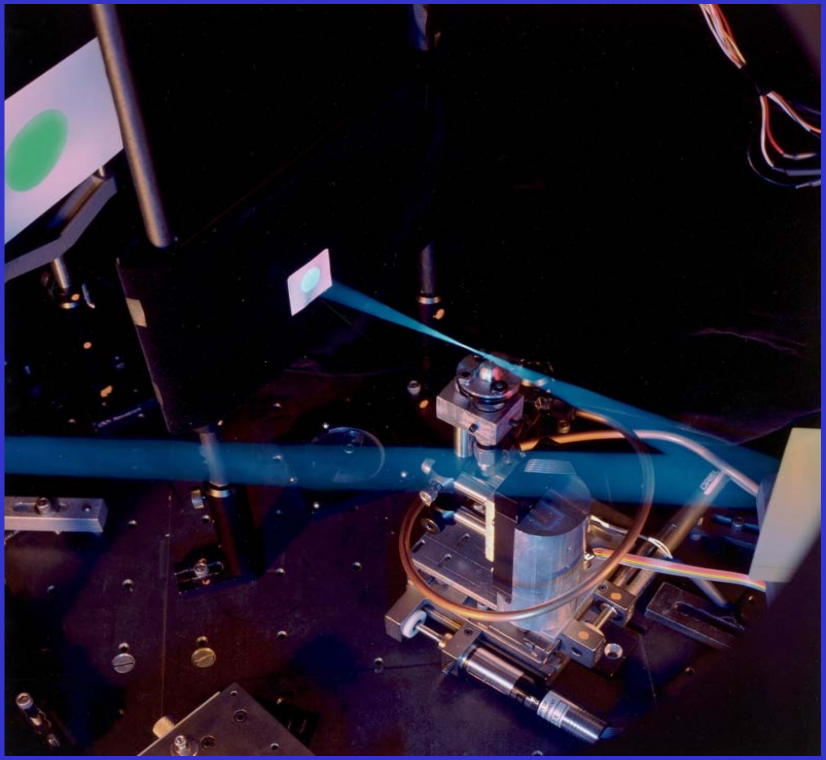



**Goals:**
- Acceleration of injected, high-current beam to 100 MeV.
- Acceleration of a pre-bunched electron beam.
- Beam-physics studies.



*Courtesy C. Joshi, UCLA*

# Table-top Laser-Driven Electron Acceleration
## (via self-modulated laser wakefield in plasma)



D. Umstadter,
S.-Y. Chen,
A. Maksimchuk,
R. Wagner,



*Courtesy T. Katsouleas, USC*

# NRL EXPERIMENTAL PROGRAM

Antonio C. Ting, Chris I. Moore, Rich Fischer, Dmitri Kaganovich, Ted Jones

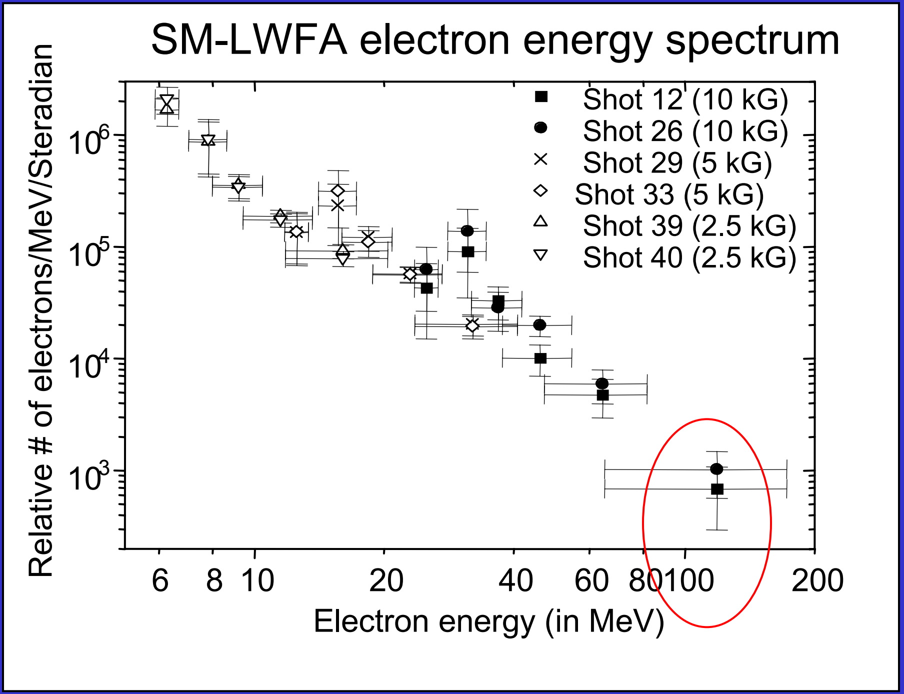
Self-Modulated Laser Wakefield Accelerator:

Production of up to

**100 MeV** electrons

at **>100 GV/m** gradient

has been observed (over ~ mm).




A. Ting, et al, Phys. Plasmas, 4, 1889 (1997)
D. Kaganovich, et al, PRE, 59, R4769 (1999)

Injection and channel guiding for the GeV range (longer).



*Courtesy T. Katsouleas, USC*

# 100 TW LULI laser facility

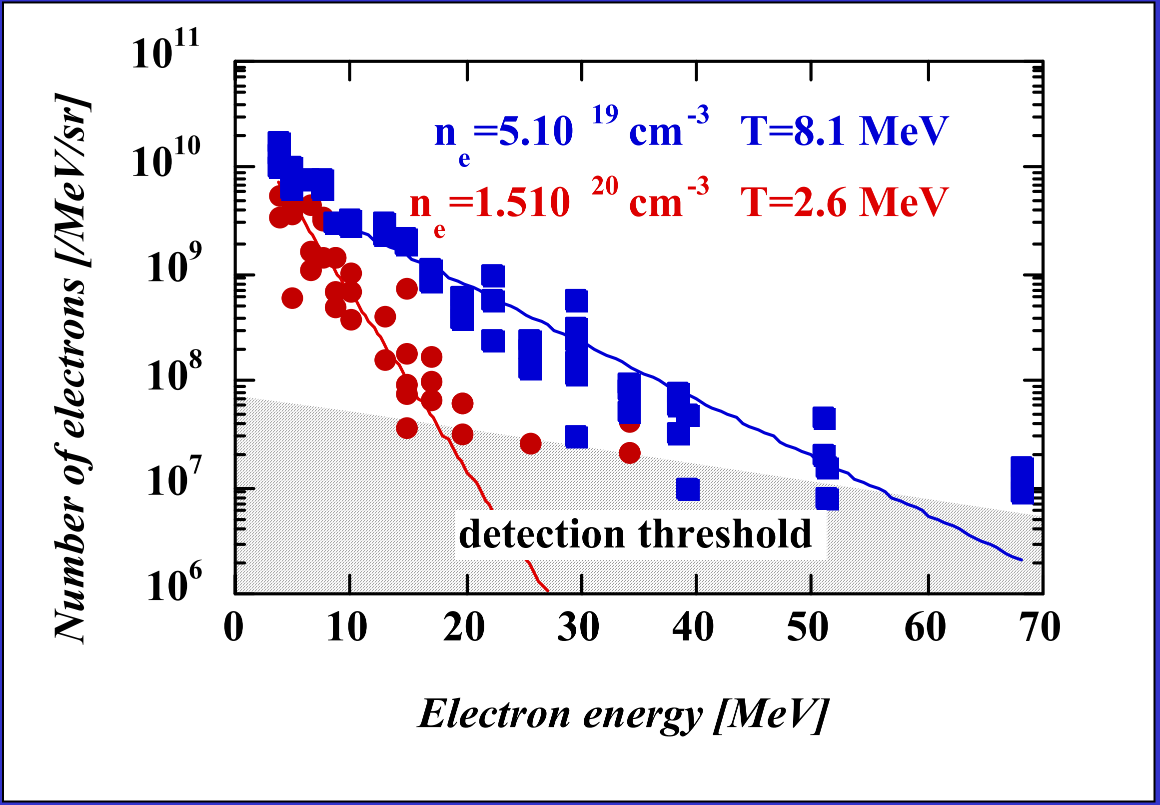
*LPNHE - LSI –LPGP - IC - LOA - CPTH*

**Self-modulated wakefield experiments - 1 single laser pulse focused in a gas jet**

**≈ 100 MeV in**

**E >100 GV/m**

Few nC > 4 MeV
Divergence : few mrad



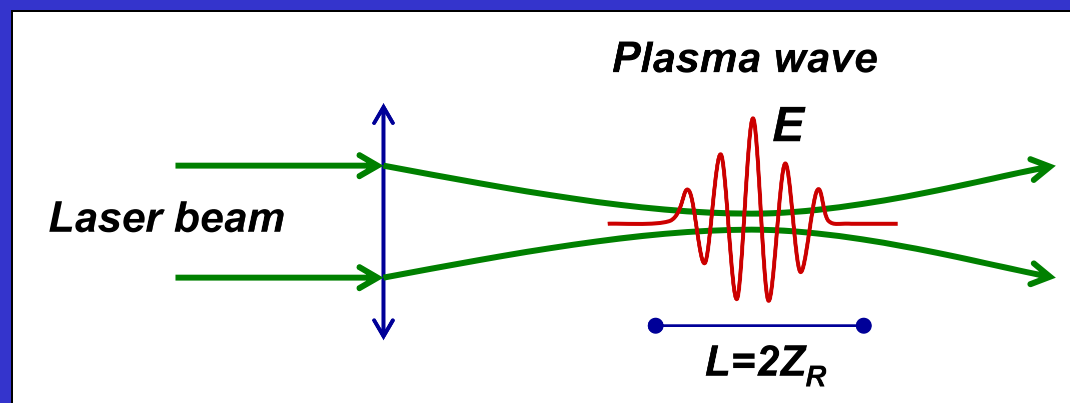

35 fs, 600 mJ, 2.10$^{19}$W/cm$^2$, 10 Hz

# Some laser guiding scheme is necessary to reach high energy gains

The potential energy gain is huge

**$I_0$ = 1 µm , $n_e$ = $10^{17}$e-/cm$^3$ , g = 100 : ∆W = 20 GeV over L = 1 m**

The effective acceleration length is limited by diffraction of the laser beam




What about guiding the laser beam over 1 m ?

⇨ **Laser guiding in dielectric capillary tubes**

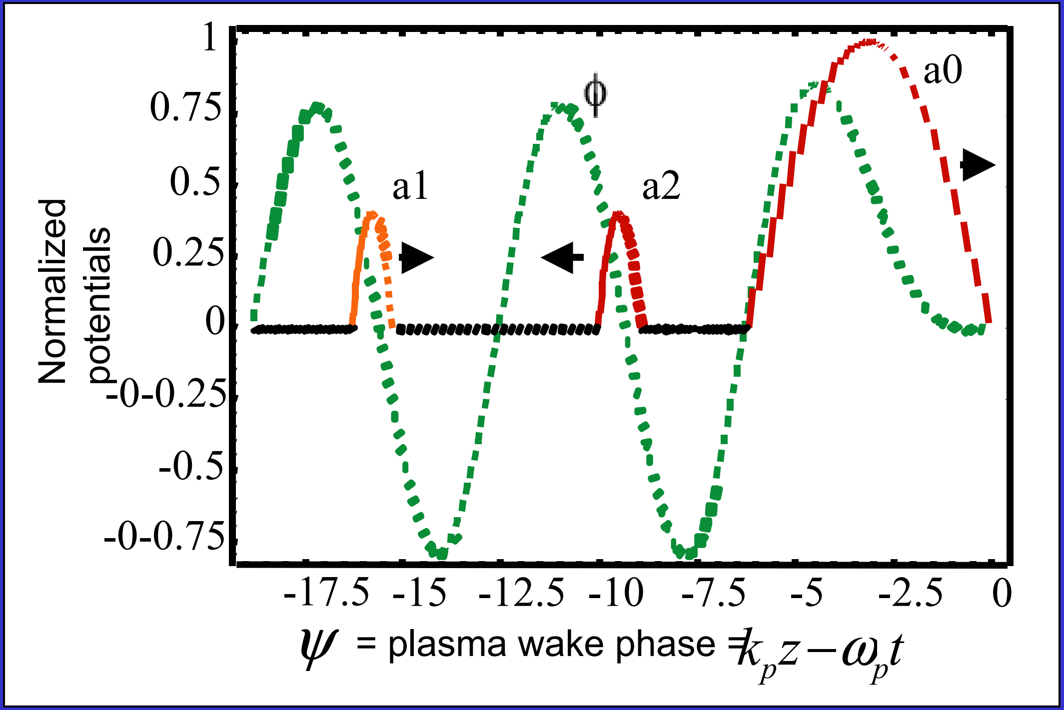
# Colliding pulse injector

Production of electron beams with low energy spreads and pulse-to-pulse energy stability in a plasma-based accelerator requires:

- Injection of femtosecond electron bunches
- Injection with femtosecond timing

**Laser triggered injection of background plasma electrons into a plasma wake by beating of two colliding pulses**

[E. Esarey et al., PRL, 79, 2682 (1997)]




Reference:
E.Esarey et al., PRL '97
C.B. Schroeder et al., PRE '99

# Plasma Wakefield Acceleration in Meter-long Plasmas

UCLA

## *E-157 & E-162 & E-164 Collaborations*

R. Assmann, F.-J. Decker, P. Emma, M. J. Hogan*, R.H. Iverson,
C. O'Connell, P. Krejcik, P. Raimondi, R.H. Siemann, D. Walz
*Stanford Linear Accelerator Center*

B.E. Blue, C.E. Clayton, C. Huang, C. Joshi*,
K.A. Marsh, W.B. Mori, S. Wang
*University of California at Los Angeles*

T. Katsouleas*, S. Lee, P. Muggli
*University of Southern California*

- **Extraordinarily high fields developed in beam plasma interactions**
- **Many questions related to the applicability of plasmas to high energy accelerators and colliders**

***Address these questions via experiments ⇨***

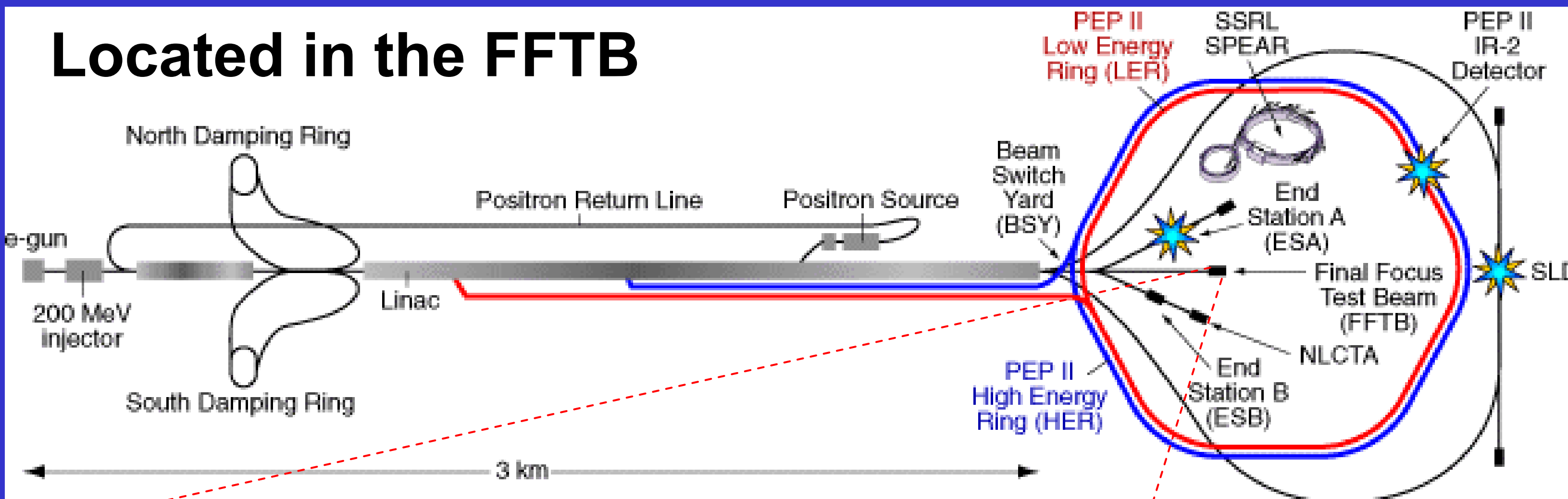
- **E-157: First experiment to study Plasma Wakefield Acceleration (PWFA) of electrons over meter scale distances**
- **Physics for positron beam drivers qualitatively different (flow-in vs. blow-out) ⇨E-162**
- **Opportunity for dramatically shorter bunches in the FFTB in 2003 with correspondingly higher gradients (> GeV/m) ⇨ E-164**

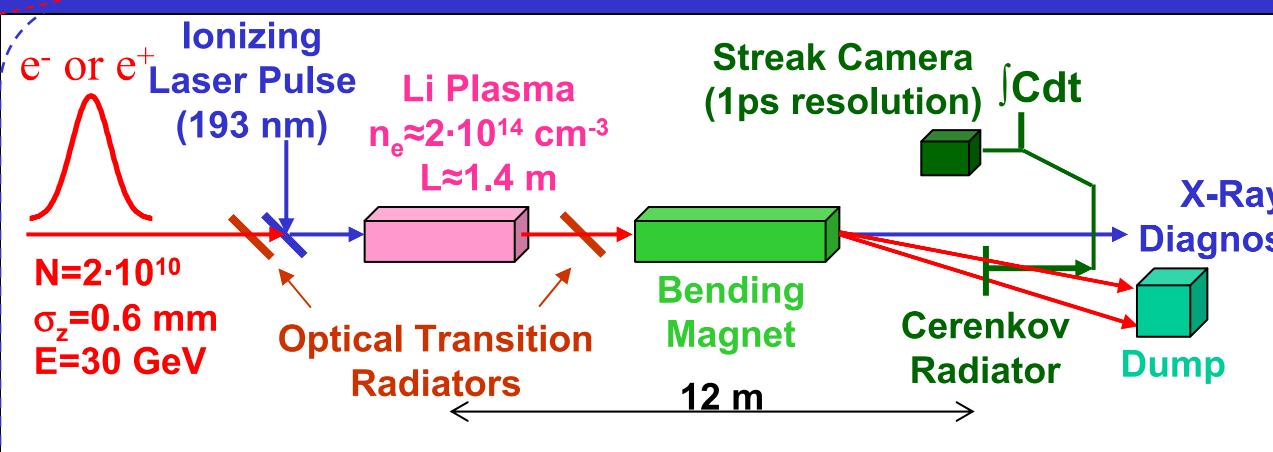


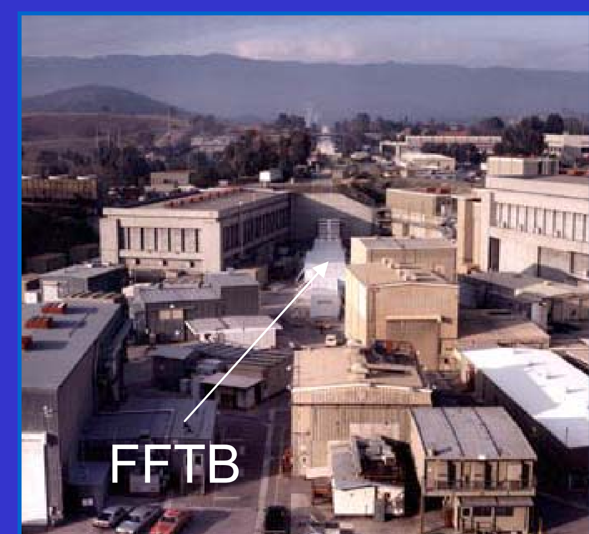
*Courtesy M. Hogan, T. Katsouleas*

# Experimental Layout





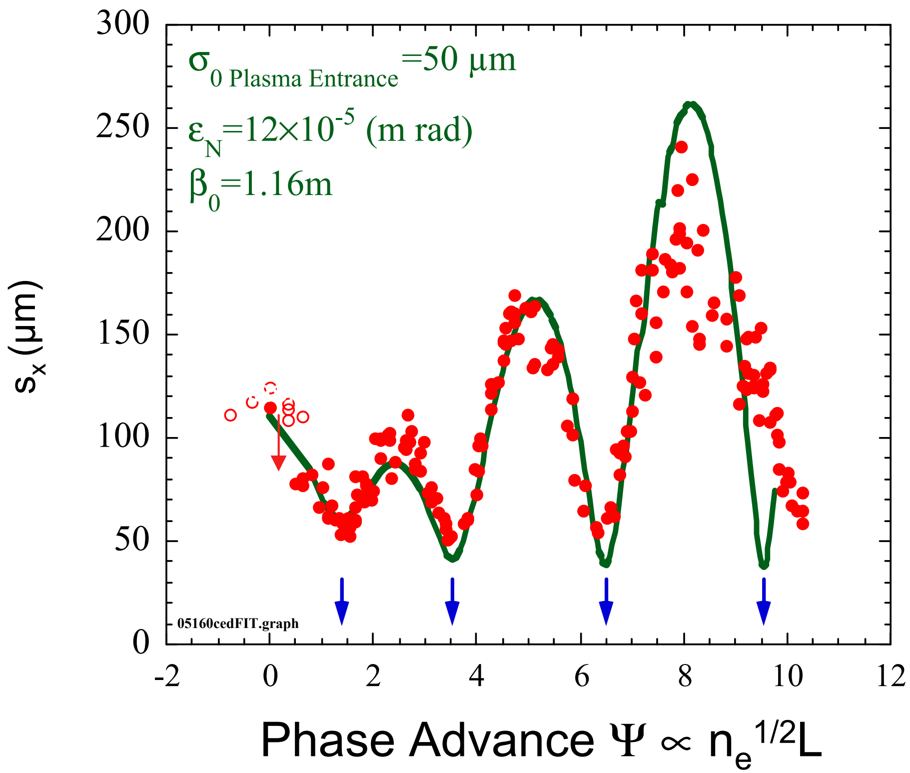



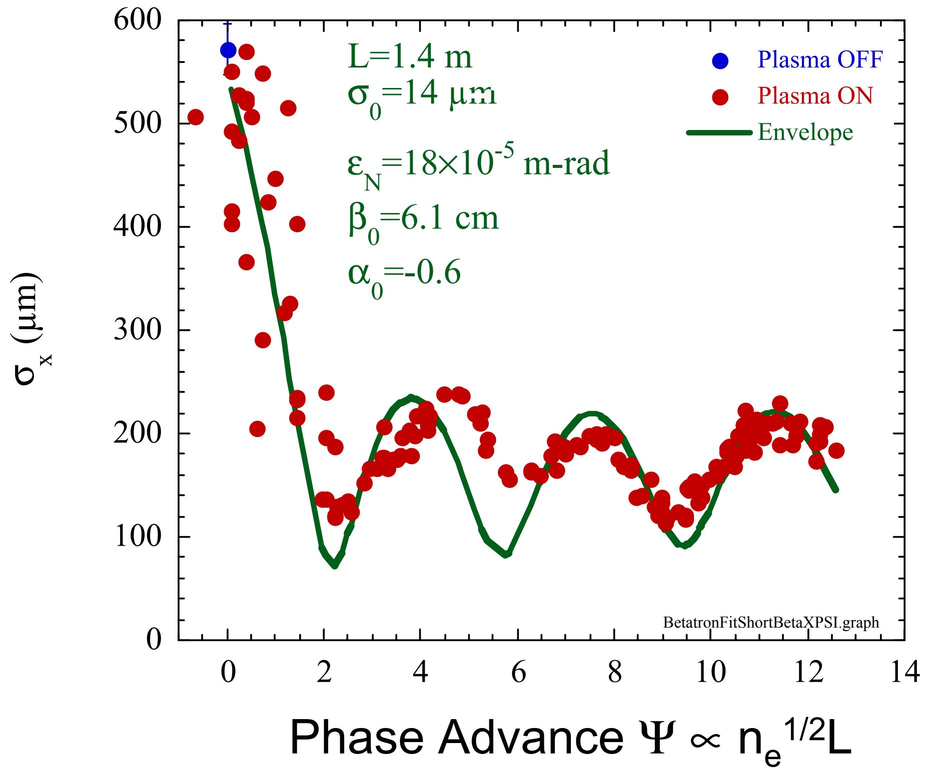



# Beam Propagation Through A Long Plasma

• Smaller "matched" beam size at the plasma entrance reduces amplitude of the betatron oscillations measured at the OTR downstream of the plasma

• Allows stable propagation through long plasmas (> 1 meter )

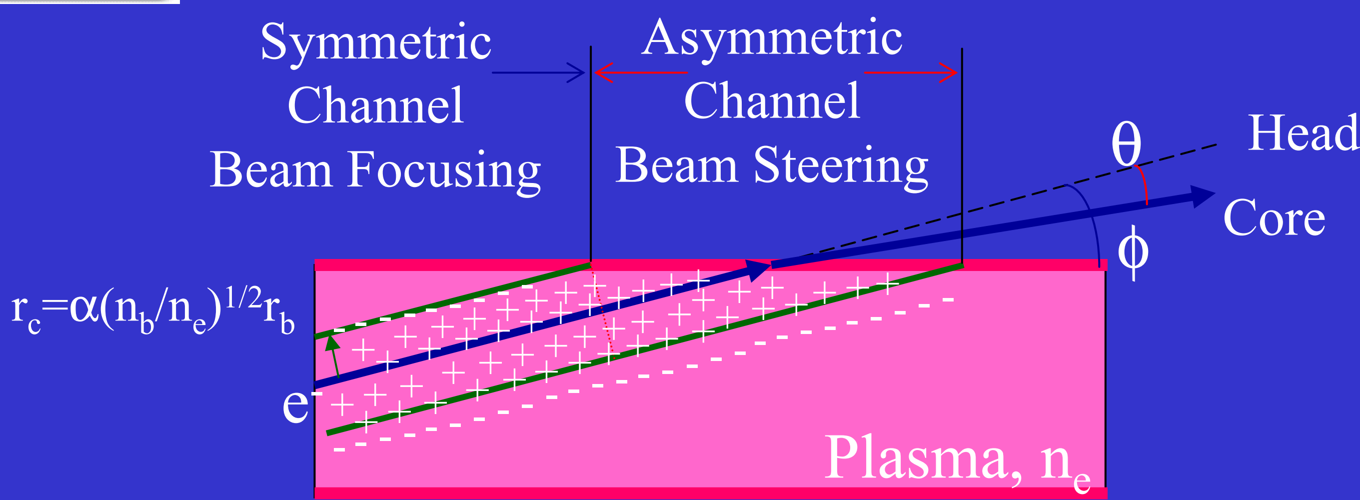



*C. E. Clayton et al., PRL 1/2002*

*E-157/E-162 collaboration*

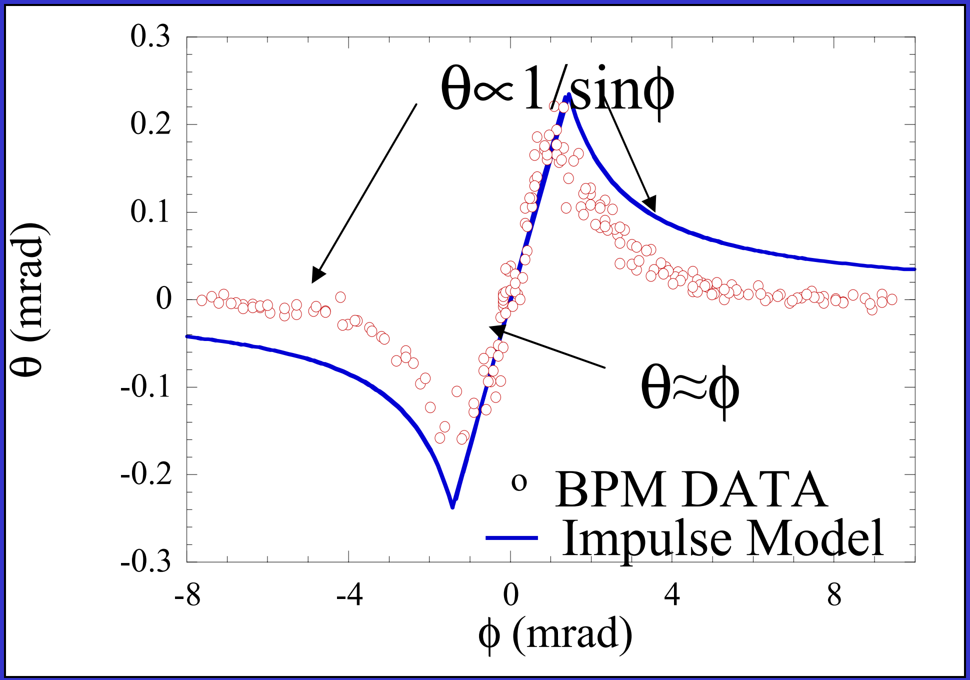
# Electron Beam Steering:
## Refraction At Plasma–Gas Boundary




- Vary plasma – $e^-$ beam angle $\phi$ using UV pellicle

- Beam centroid displacement @ BPM6130, 3.8 m from the plasma center

*P. Muggli et al., Nature 411, 2001*




*E-157 collaboration*

RA EPAC02

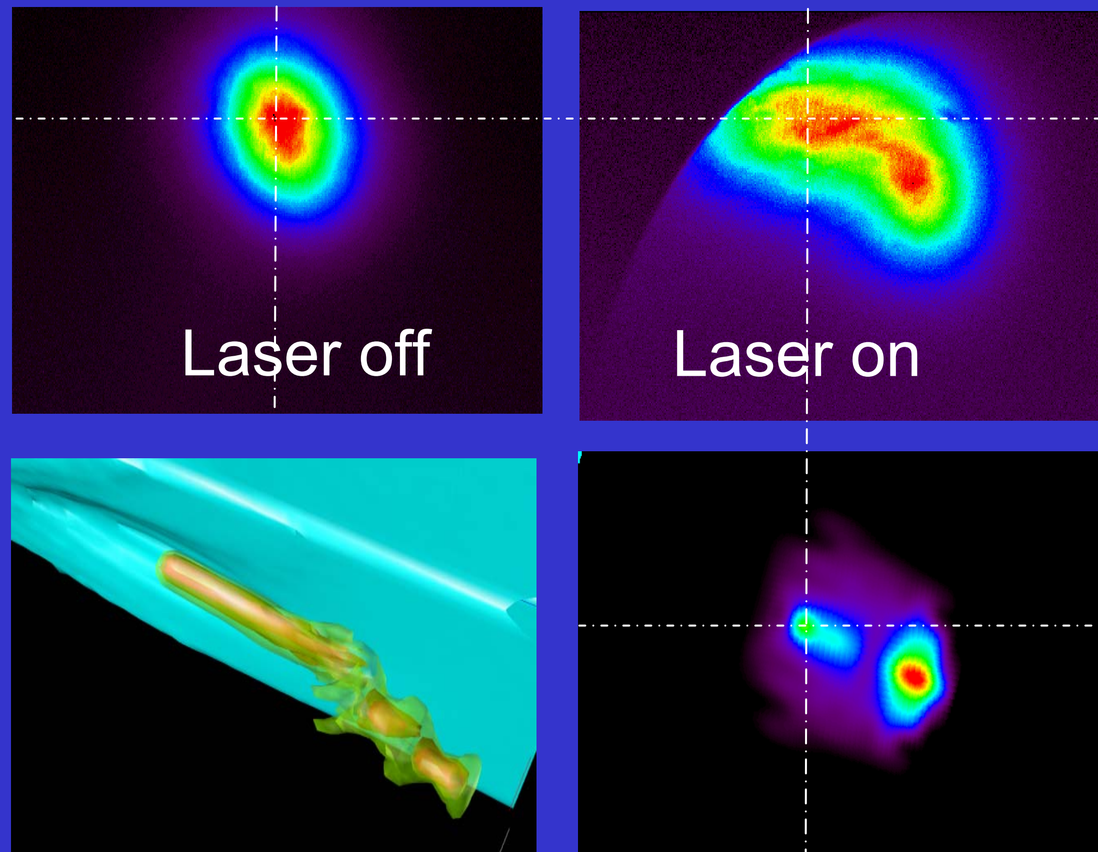
# Refraction of an Electron Beam: Interplay Between Simulation & Experiment



Experiment (Cherenkov images)

3-D OSIRIS

PIC Simulation



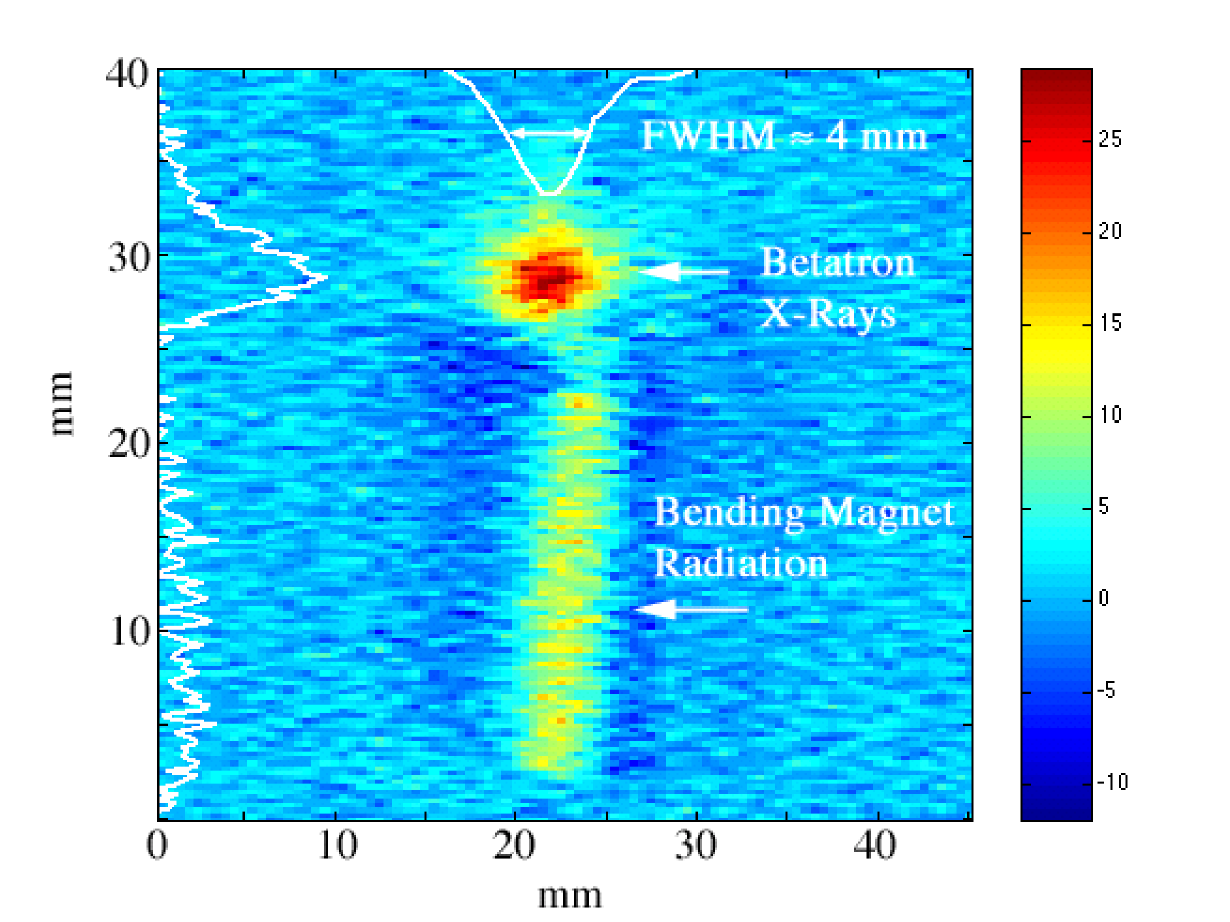

1 to 1 modeling of meter-scale experiment in 3-D!

*P. Muggli et al., Nature 411, 2001*

*E-157 collaboration*

# Betatron Radiation of X-rays

*Plasma focusing strength of 6000T/m acts as a strong undulator*




- Peak brightness ~ $10^{19}$ photons/sec-mm$^2$-mrad$^2$-.1%bw!

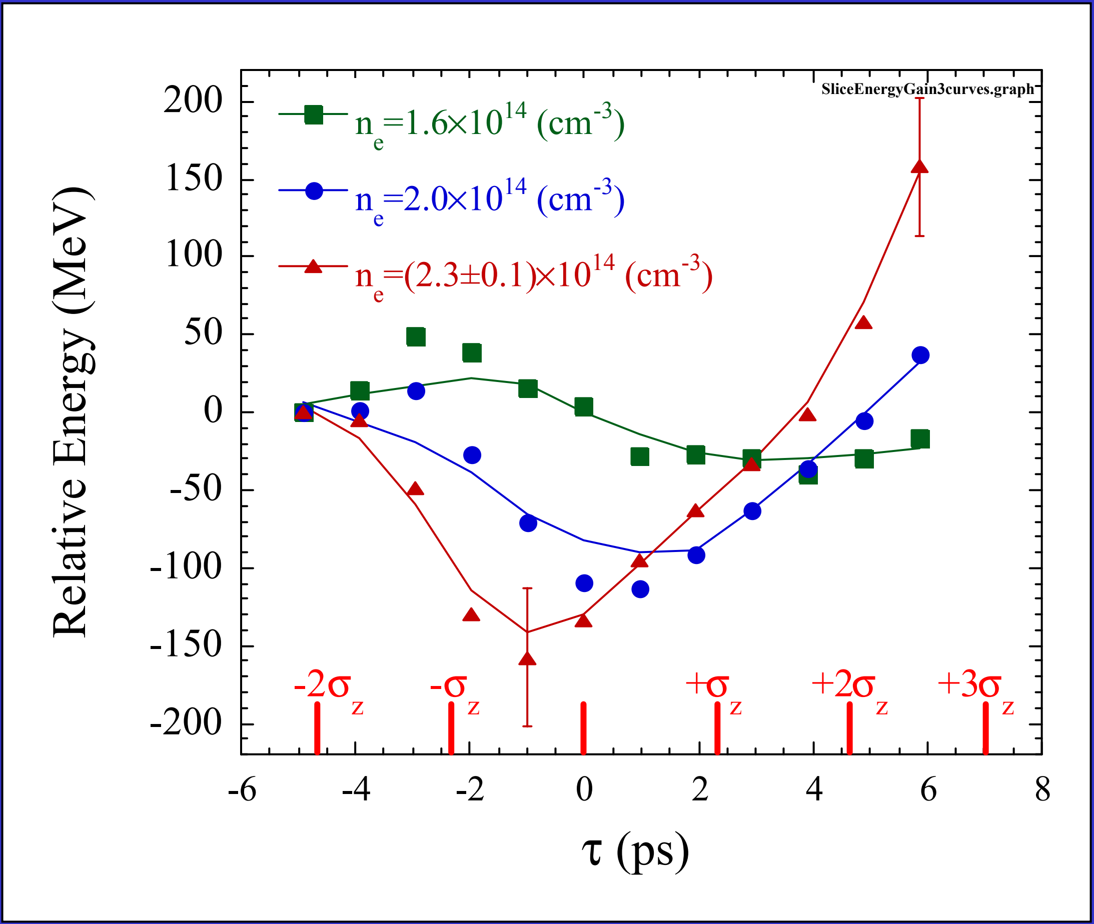


*E-157 collaboration*

# E-162: Use Imaging Spectrometer To Measure Energy Loss & Gain

***Preliminary…***

Picosecond
Gaussian
Slice Analysis
of Many Events




Average energy loss
(slice average): 159 ± 40 MeV

Average energy gain (slice average): **156 ±40 MeV**
**(≈1.5 ×10$^8$ e$^-$/slice)**

E-164: > 1 GeV/m (2003)

*E-162 collaboration*

# Other schemes

Laser acceleration in vacuum (LEAP):

Two crossed laser scheme: “Only tantalizing of the interaction signature”.
Power source: Laser.
New proposal…

Inverse free electron laser (STELLA):

Power source: Laser.
Successful staging. 90 MeV/m goal.
Limit from synchrotron radiation at ~ 200 GeV.
Bunches of femto-second length.

Di-electric wakefield accelerator:

Possible gradients: 100 MeV – 1GeV
Power source: Drive beam.

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# Efficiency 1

High beam power requires:

$$P_b = 4\pi \cdot \frac{\sigma_x^* \sigma_y^*}{N_e} \cdot E \cdot L$$

**Efficient power generation**

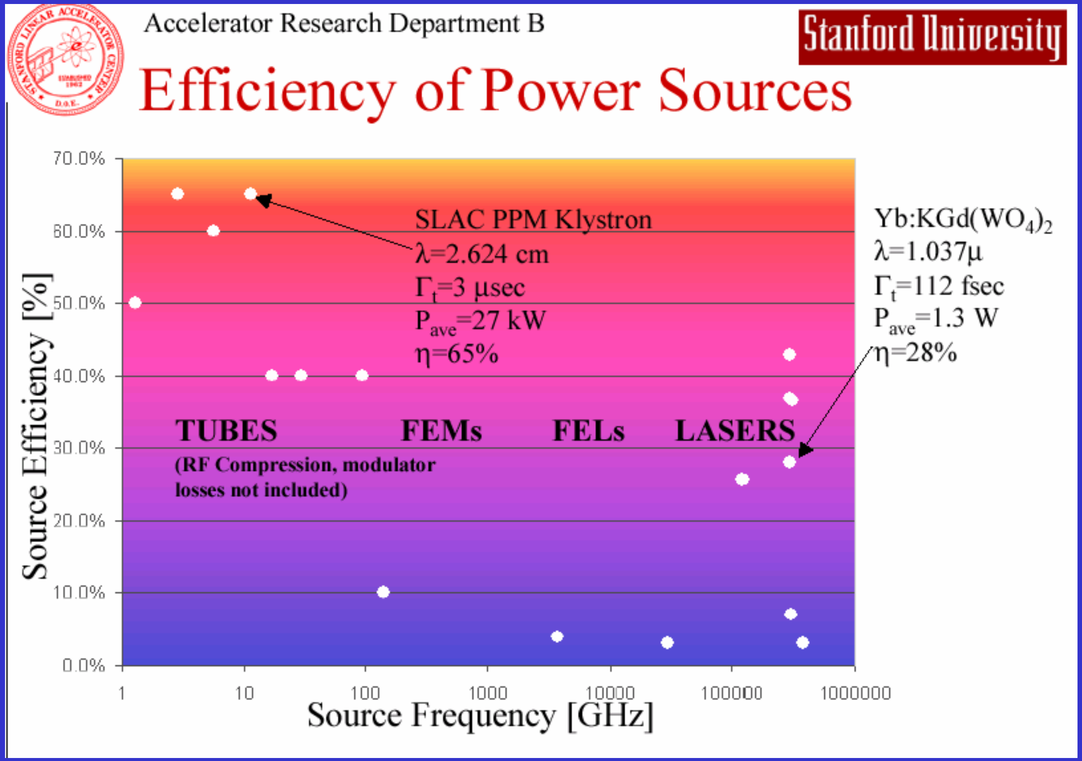
Progress in the field of lasers:

High peak power
is possible (~ 100 TW )

Wall-plug-to-photon
efficiency: **20 – 40 %**

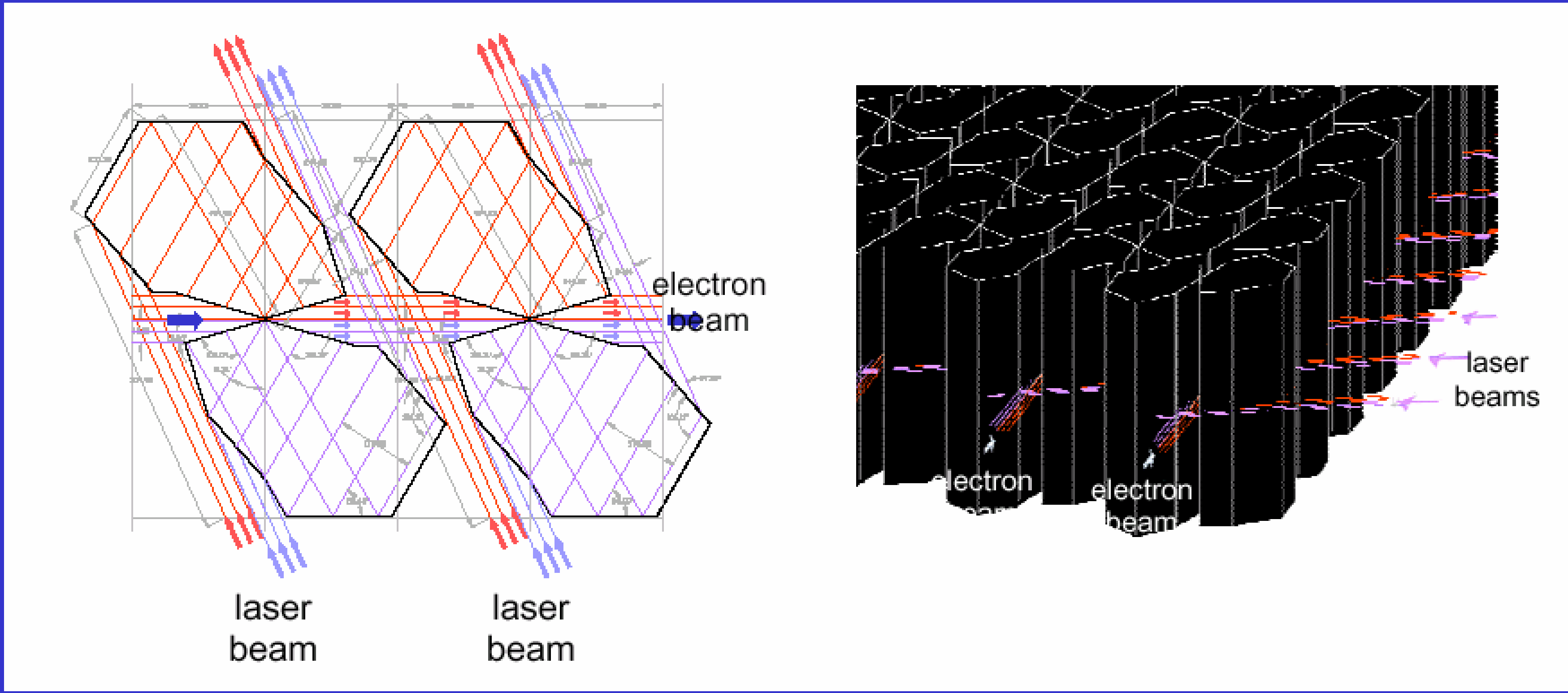
Better stability (pointing
stability in sub µrad regime)

Efficiency of beam-driven
PWFA: ~ 30%




**LEAP at the ORION Center**
Robert L. Byer & Robert H. Siemann

# Efficiency 2




C. D. Barnes et al, SLAC PROPOSAL E-163

Accelerating Microstructures:
Re-use the laser beams for increasing efficiency!

# High quality beam transport 1

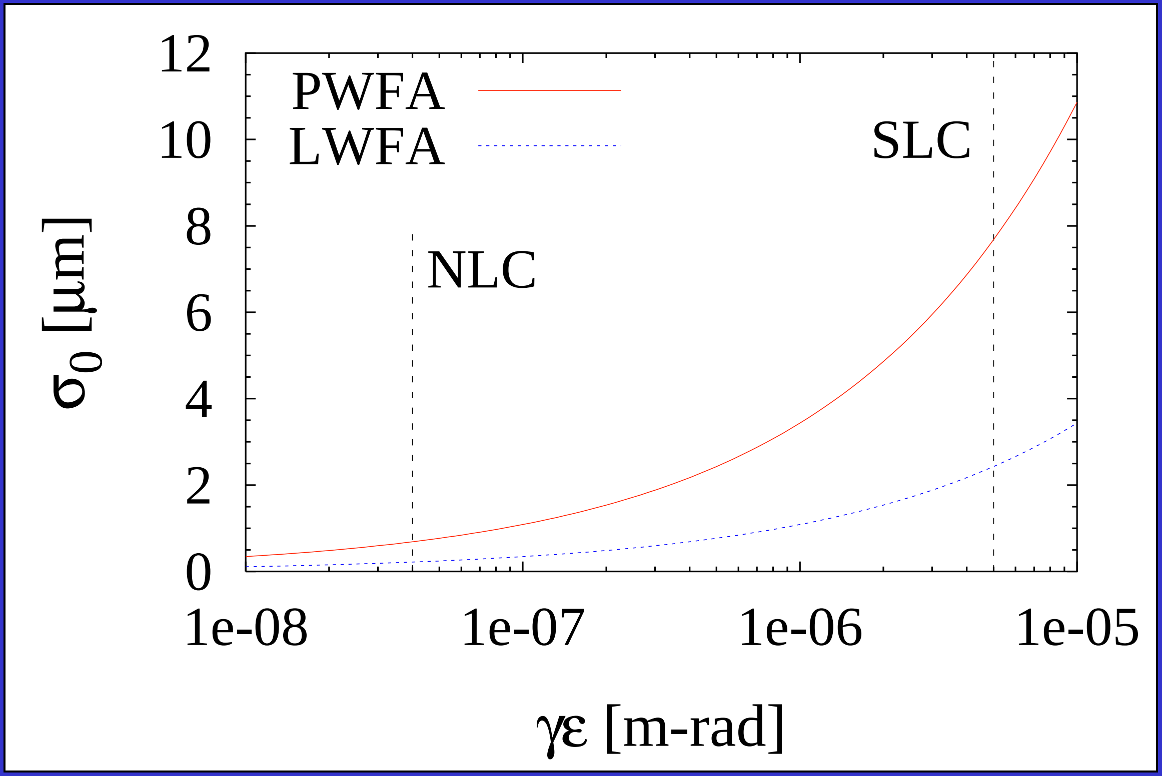
## Short accelerator, but what about emittance?

R. Assmann, K. Yokoya, NIM 1997

| Parameter | PWFA | LWFA |
|---|---|---|
| Acceleration | 1 GeV/m | 30 GeV/m |
| Wavelength | 2 mm | 100 μm |
| Focusing field | 6,000 T/m | 600,000 T/m |
| Module length | 6 m | 1 m |
| Injection energy | 1 GeV | 1 GeV |
| Final energy | 1 TeV | 1 TeV |
| Acc. length | 1 km | 33 m |

# High quality beam transport 2

Matched beam size at injection energy:




NLC type emittance requires sub-micron spot size!

|

**$4\ 10^{-8}$ m rad**

# High quality beam transport 3

Tolerance for alignment beam - plasma wakefield:

- emittance 4 $10^{-8}$ m rad with **200%** emittance growth
- Number of plasma cells: 167 or 33 (LWFA)

RMS alignment tolerance: < **300 nm** (PWFA) **30 nm** (LWFA)

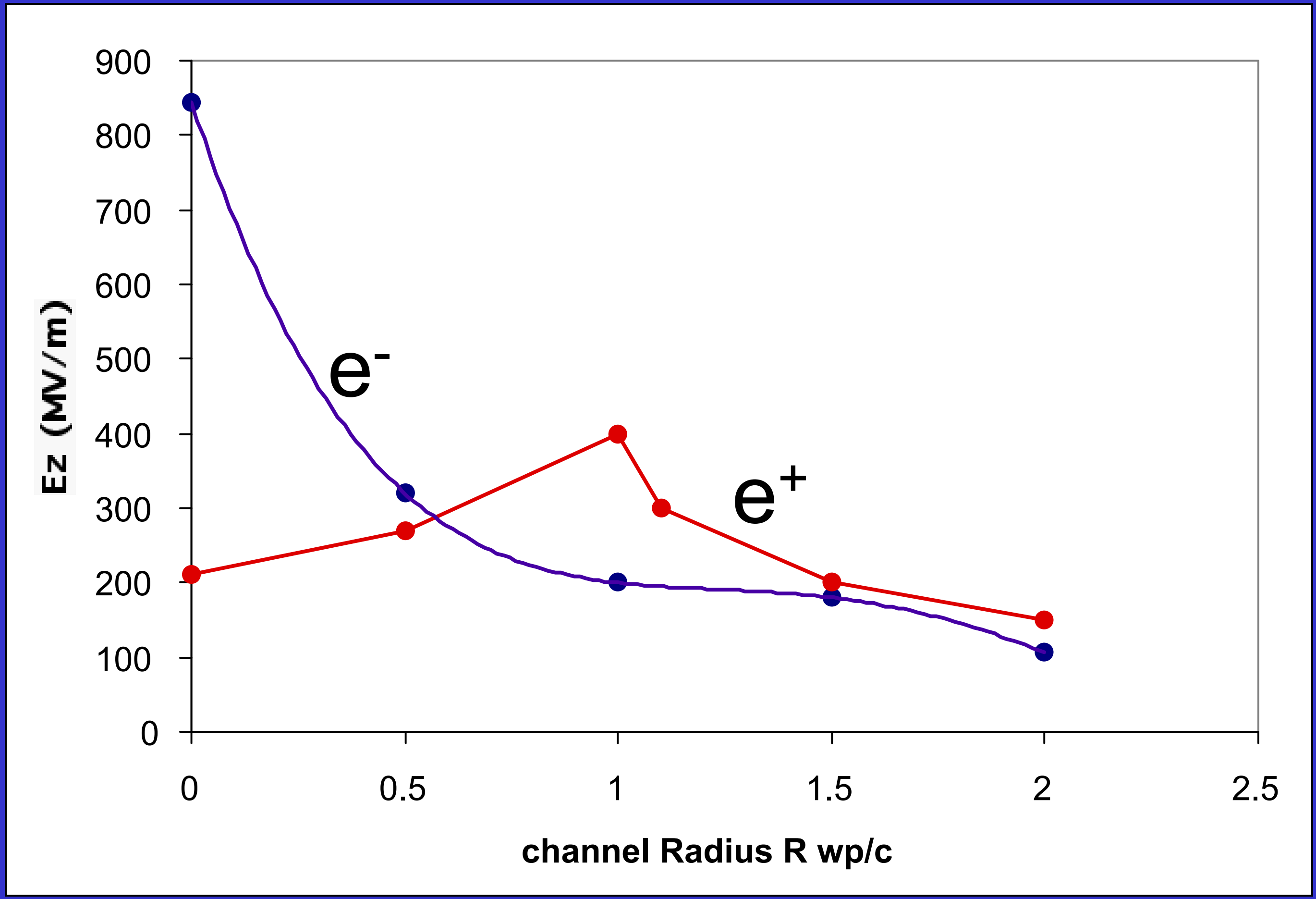
High energy plasma-wakefield accelerator will have difficult alignment problems, but...

New ideas: Hollow plasma channels

No ions on axis, no focusing!
Acceleration still works...

# Hollow plasma channels with $e^+$ and $e^-$

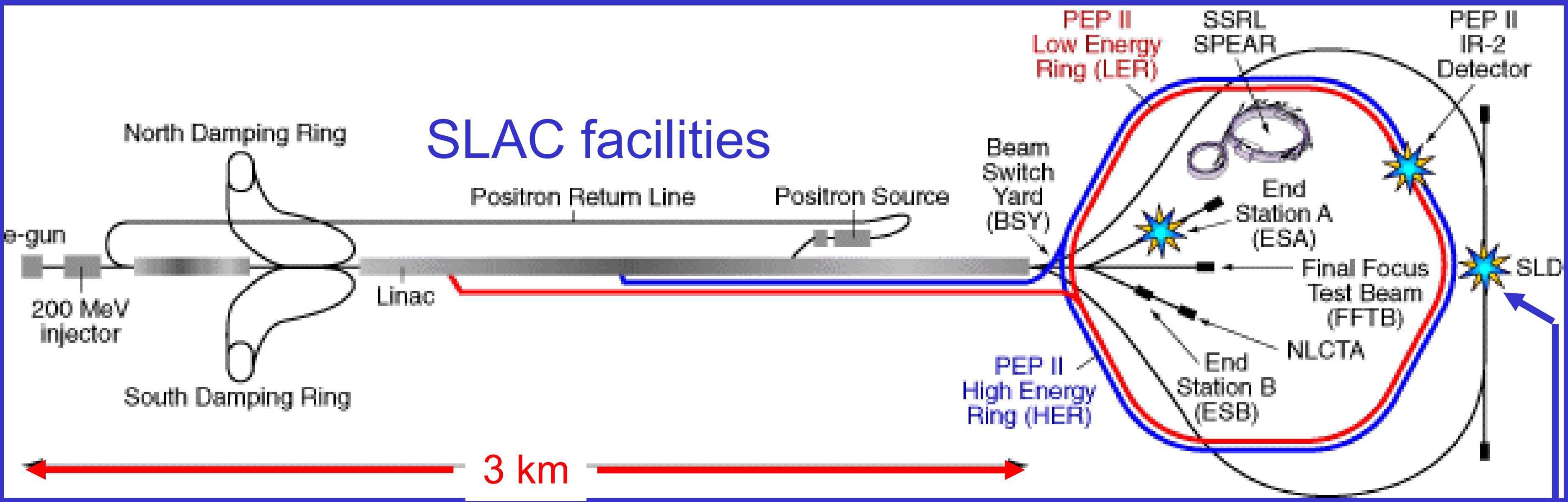
Positron longitudinal wake amplitude is comparable to e- in a hollow plasma:

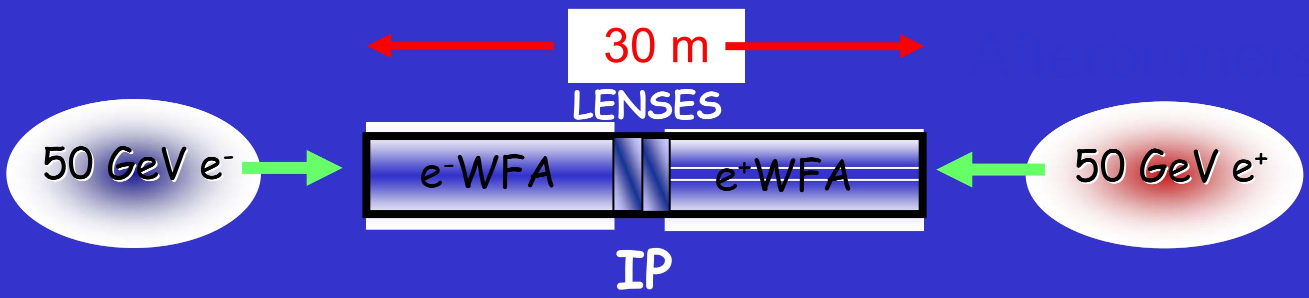



*T. Katsouleas, USC*

# The first step: A plasma afterburner?

**A 100 GeV-on-100 GeV $e^-e^+$ Collider at SLAC based on Plasma Afterburners**




*E-157 collaboration*

# Afterburner vs. E157 Comparison

E-157

- Bunch:
  - Number: 1
  - $\sigma_z$= .65mm
- Plasma
  - Density: 0 - 5e14 $cm^{-3}$
  - Length: 1.4 m
- Betatron Oscillations:
  - 0-5

Afterburner

- Bunches:
  - Number: 2
  - $\sigma_z$= .065mm, .033 mm
  - Separation: .019 mm
- Plasma
  - Density: 2e16 $cm^{-3}$
  - Length: 7 m
- Betatron Oscillations:
  - 100

Can we control 7 m of plasma?

*Studies are ongoing for this idea…*

# Contents

1) Why ultra-high gradients?
   - The Livingston plot
   - Limits for new particle accelerators
   - Basic requirements for particle physics
   - The promise of ultra-high gradients

2) How to get ultra-high gradients?
   - Overview on schemes being followed
   - Principles (plasma and vacuum concepts)

3) Experimental results - Highlights
   - Plasma wakefield acceleration
   - Laser wakefield acceleration
   - Laser acceleration

4) Moving towards usage in a linear collider
   - Considerations
   - The plasma booster for the Higgs?

5) Conclusion

# Conclusion

Advanced accelerator concepts have made impressive progress:

High gradient acceleration up to **160 GV/m** demonstrated.

Beam-plasma interaction of 30 GeV SLAC beam in **1.4m long plasma**.

Experimental results in excellent **agreement with predictions**.

New **applications** (fsec science, plasma wiggler, kicker, lens,…).

Many problems still to be addressed for building a high energy collider…
… but **no fundamental show stopper!?**

Accelerator physics moves into the right direction (small emittance, short bunches).

Can a **plasma afterburner** on a “conventional” accelerator be the first step?

# Plasma Accelerator Progress and the Livingston Curve

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