Advanced Accelerator Concepts

ICFA

Jonathan Wurtele, UCB/LBNL

October 8, 1999

- Overview
- High Gradient Acceleration at 100GHz and Beyond
- Role of Plasma in Advanced Accelerators
  - Accelerating Structures
  - Focusing Elements
- Laser Acceleration
- Perspectives

Overview

- Employing NLC technology for high energy (> 3TeV) colliders leads to extremely large machines and average powers. Some alternatives are being investigated:

  Compact linear colliders → high-gradient → problems:

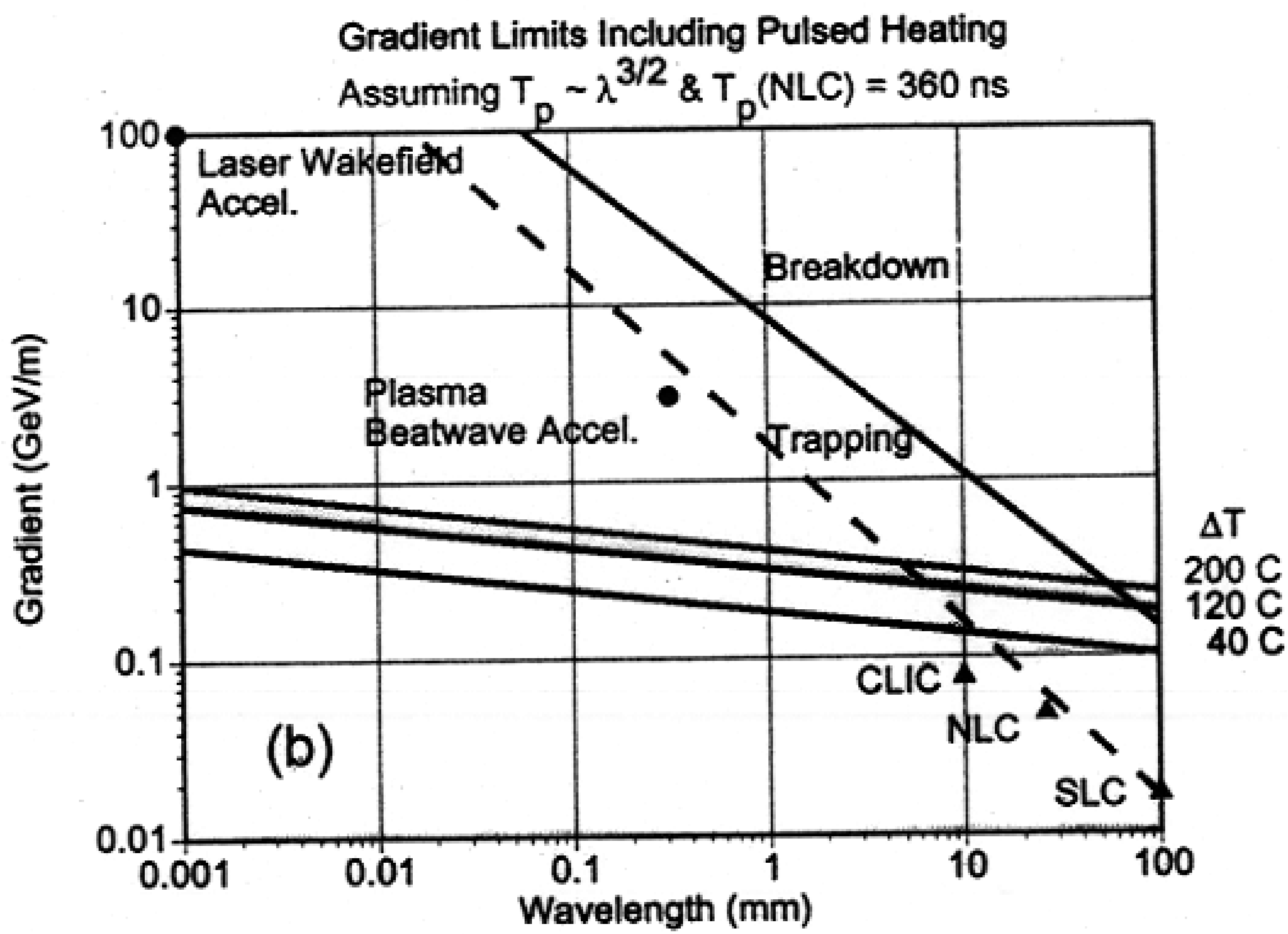
  - New structures : fabrication, breakdown, wakefields,jitter,alignment
  - New power sources: efficiency, pulse length, coupling
  - New final focus : pinch effect, beamstrahlung, length,& backgrounds

  luminosity for sensible emittance

AND

Muon colliders→muons → problems:

- Production
- Cooling
- Collision
- Decay



Pulse heating is thought to be the most serious limit to scaled solid-state structures

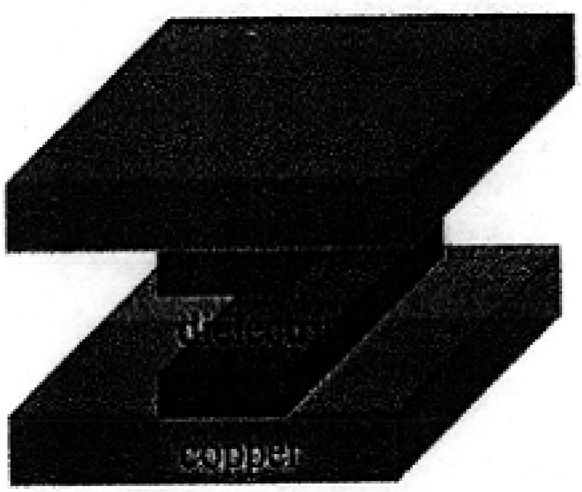
(Courtesy D. Whittum)

Composite Accelerator Structure

The traditional disk loaded waveguide, like those used at SLAC, use the periodic iris to slow down the phase velocity. The Composite Accelerator Structure (CAS) utilizes a dielectric to slow down the phase velocity to c. **M. Hill, et al., submitted to IEEE/MTT.**

Advantages:

- The structure is simple to manufacture--no bonding, tolerant to machining errors.
- The planar geometry also makes tuning easier.
- CAS has inherently lower surface electric field.

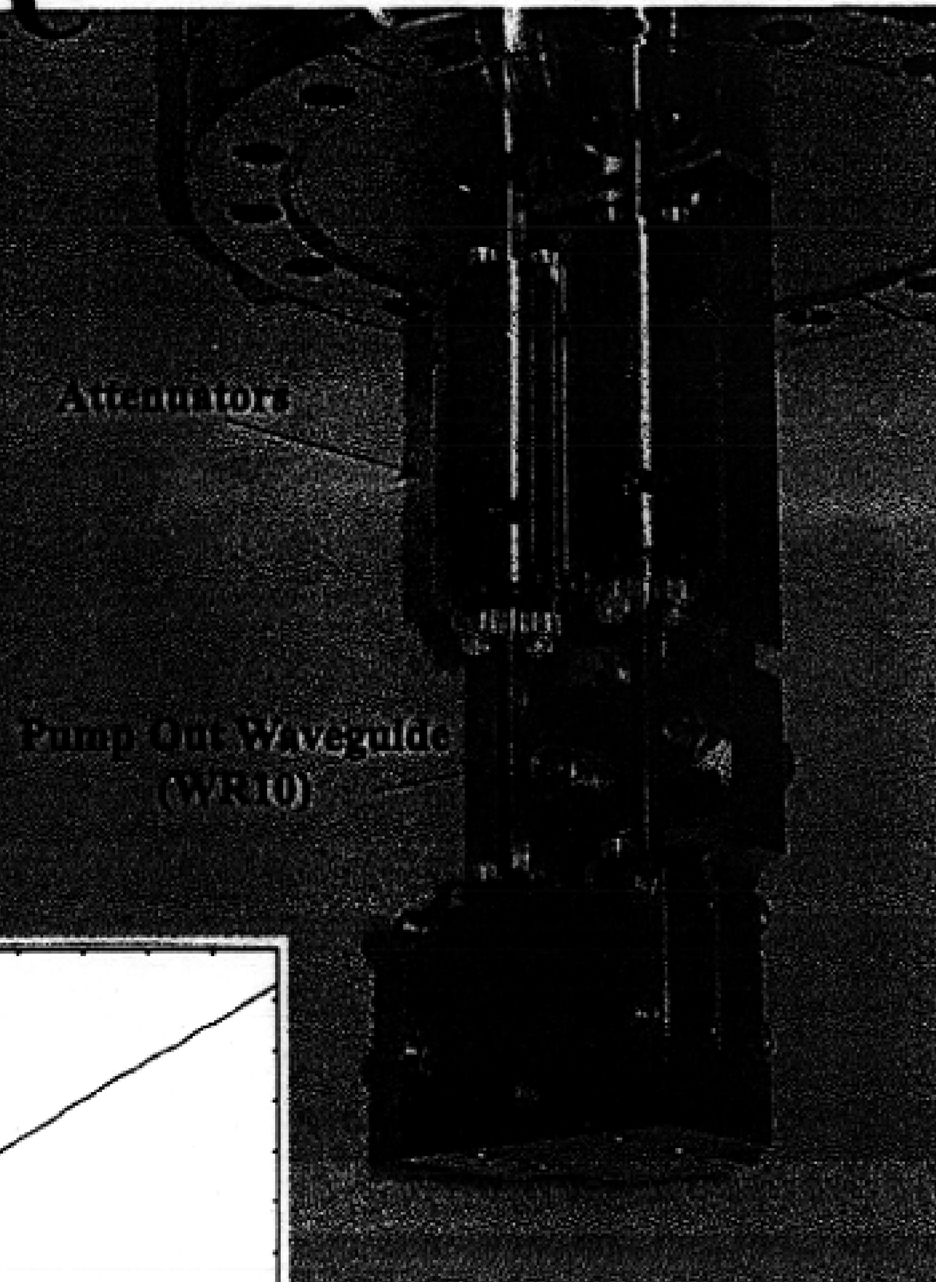


- Powered by beam 300MeV, .4A, 100ns beam of NLCTA
- Bunched at 11.4GHz (8'th subharmonic).
- Beam was focused to ~0.3mm with full transmission
- Resonant interaction yields power of 8kW output from structure. Fields in excess of SLAC linac. M. Hill, et al., in preparation.

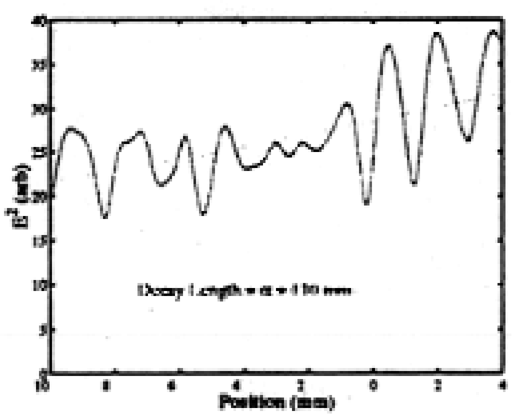
W-Band at SLAC

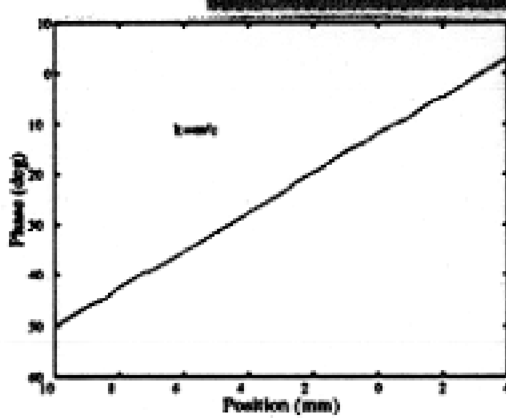
We have fabricated and tested a W-Band Alumina Dielectric Structure.

Tests include bench measurements under low power and beam tests producing high gradients.

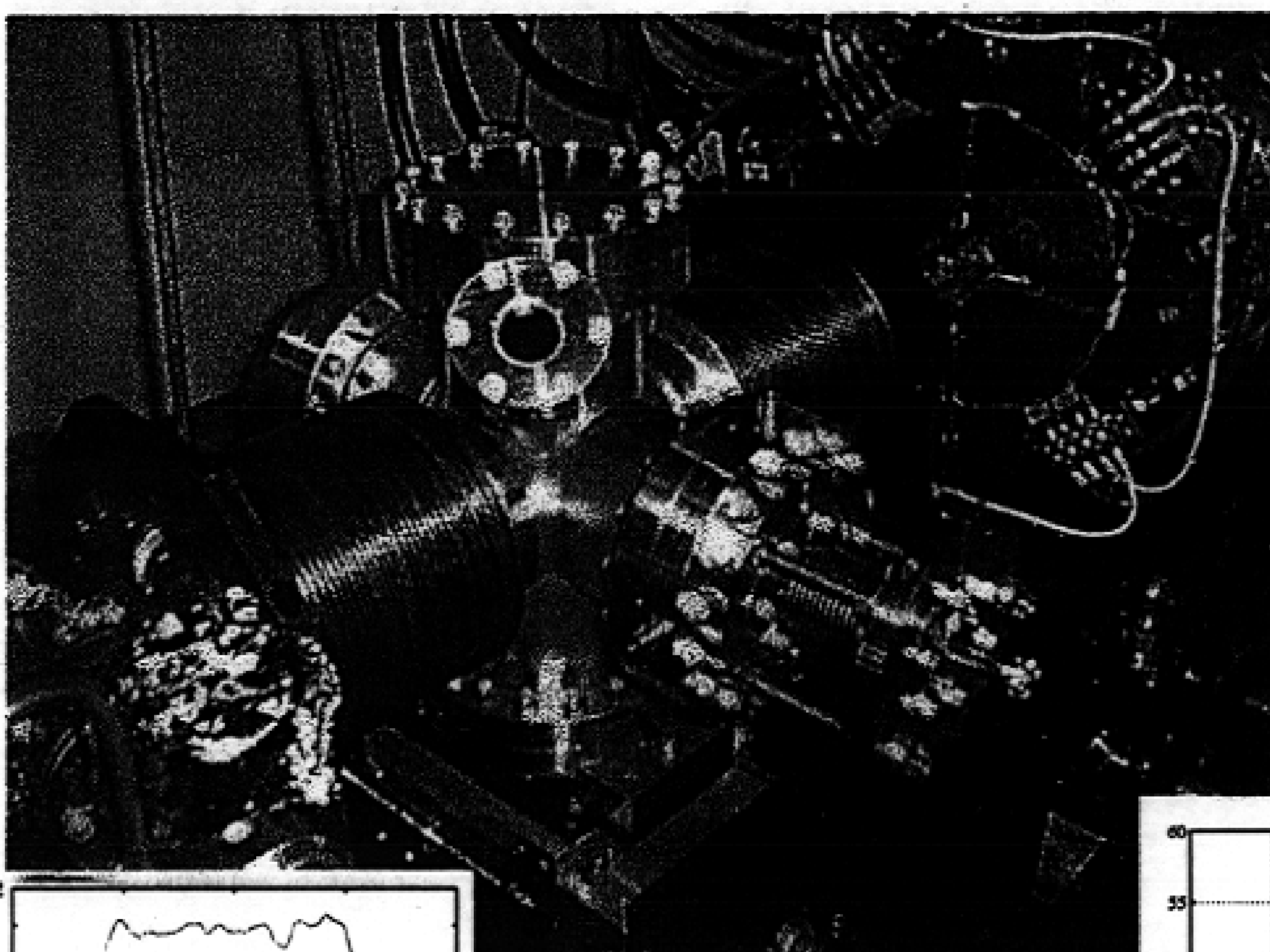


Beadpull measurements verify proper phase velocity and Q of the system.



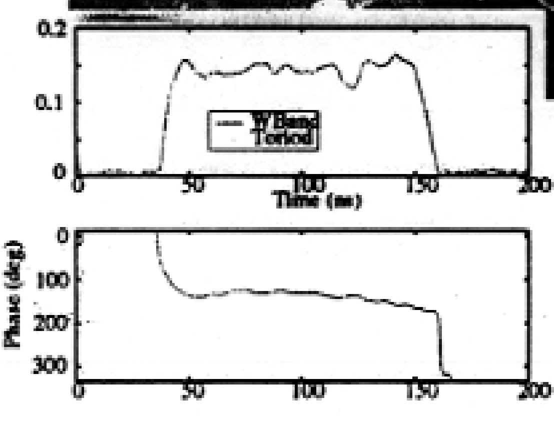


W-Band at SLAC

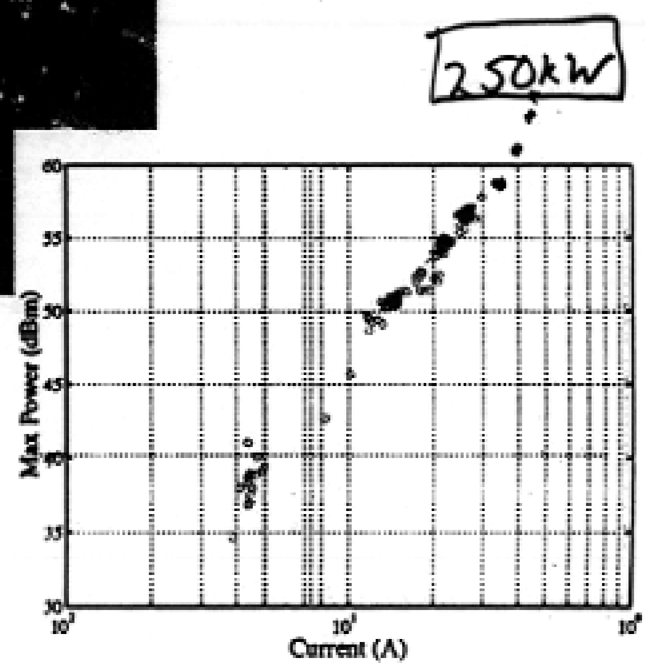


HARPP

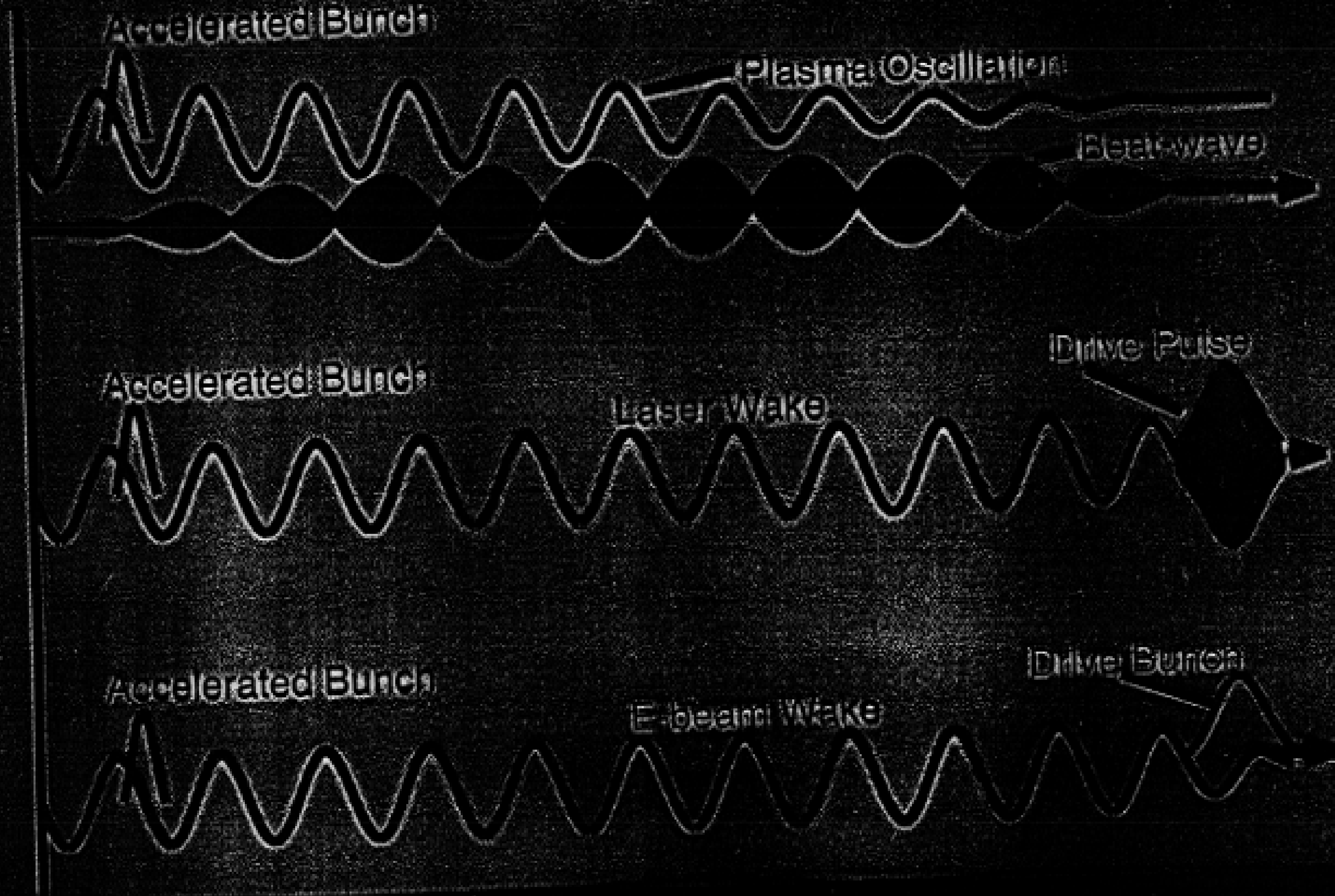
HARmonic Power Production experiments testing 91.4 GHz accelerator structures with a 0.5 A, 11.4 GHz bunched beam.



Tests performed in January '99 produced 1 kW of W-Band power using klystron output cavity tuned to the 8th harmonic of the X-Band beam.



PLASMA ACCELERATORS



Recent Experimental Advances

- High Gradients demonstrated with unstable laser pulse breaking up in plasma (no injection of electrons), >100GeV/m.

(e.g.,Umstadter, et al, Science 273,472 (1996);Gordon et al, PRL 80, 2133 (1998))

  - Disadvantages for accelerators: Based on instability (phase problems), requires low ω_p/ω---rapid dephasing of particles and wake
  - Preferable to have "Laser Wakefield Acclerator" --pulse length ~ c/ω_p

- First acceleration of injected electrons in Laser Wakefield Acclerator: 1.5 GeV/m, 1.5MeV acceleration. (Dorchies et al, Phys. Plas. 6, 2903 (1999)).
- Guiding of high laser powers (>10^{17}W/cm^2) in channel for ~10 diffraction lengths, low intensity for 100 diffraction lengths(LBNL; UM)
- Acceleration in channel is critical
- Recent review: Esarey, et al, IEEE Trans. Pl. Sci. 24,252 (96); Proc. of the AAAC98 workshop.

SUMMARY OF EXPERIMENTS

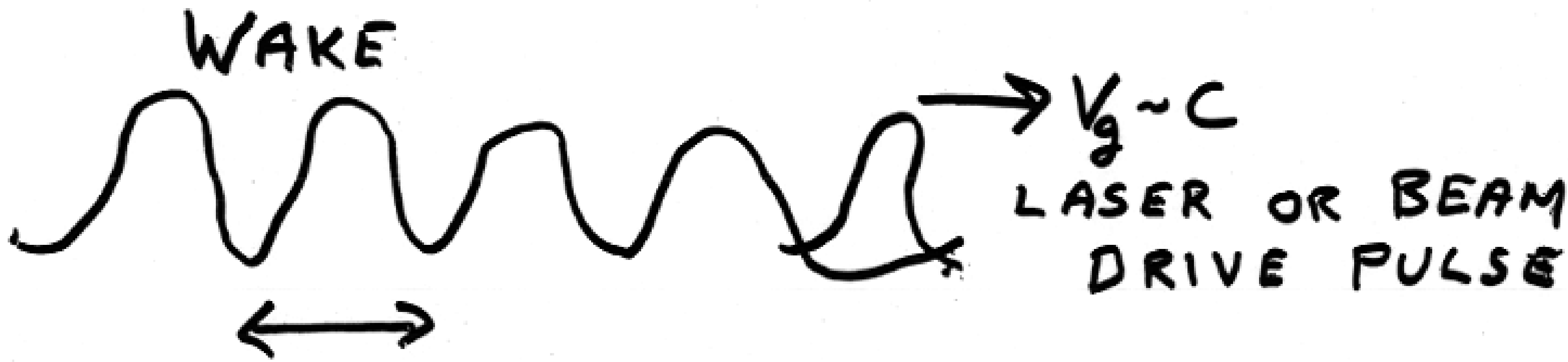
	$\gamma_{\rm drive}$ (MeV)	$Q_{\rm drive}$ (nC)	$L_{\rm drive}$ (mm)	n_p (cm^{-3})	$\Delta\gamma$ (MeV)	E (MV/m)	
ANL (USA)	21	4.0	2.1	10^{12}	0.2	5.0	→ 60MV/m [99]
KEK (Japan)	500	10	3.0	10^{12}	30	30	
KhFTI (Ukraine)	2	0.4	17	10^{11}	0.5	0.25	
SLAC (USA)	3×10^4	3.2	0.6	10^{15}	-	-	E157 IN PROGRESS

Table 1: Electron Beam Driven Plasma Accelerator Experiments (PWFA)

		I (W/cm^2)	τ_L (ps)	n_p (cm^3)	$\Delta\gamma$ (MeV)	E (GV/m)	
	PBWA:						
BEAT WAVE	ILE (Japan)	10^{13}	1000	10^{17}	10	1.5	
BEAT WAVE	UCLA (USA)	10^{14}	300	10^{16}	28	2.8	→ 2.8GV/m Injected Beam
BEAT WAVE	LULI (France)	10^{17}	90	10^{17}	1.4	0.6	
	SM-LWFA:						
SELF-MODULATED	KEK (Japan)	10^{17}	1.0	10^{19}	17	30	
SELF-MODULATED	LLNL (USA)	10^{18}	0.6	10^{19}	2	-	
SELF-MODULATED	RAL (UK)	10^{19}	0.8	10^{19}	44	100	
SELF-MODULATED	NRL (USA)	5×10^{18}	0.4	1.4×10^{19}	> 1	-	
SELF-MODULATED	CUOS (USA)	4×10^{18}	0.4	3.6×10^{19}	> 1	-	
	LWFA:						
WAKEFIELD	KEK (Japan)	10^{17}	1.0	10^{16}	5	0.7	
WAKEFIELD	LULI (France)	4×10^{17}	0.4	2×10^{16}	1.6	1.5	→ 1.5GV/m Injected Beam

Table 2: Laser-Driven Plasma-Based Accelerator Experiments

PLASMA Accelerators



$$\lambda_p \cong \frac{2\pi c}{\omega_p}$$

$$E_z \sim \left(\frac{\delta n}{n}\right) \frac{mc\omega_p}{e} \sim 100\sqrt{n(\text{cm}^{-3})}\ \text{V/m}$$

$$E_\perp \sim k_p r E_z$$

IN GENERAL, $\frac{\partial E_z}{\partial r} \neq 0$, $E_\perp$ has non linearity

The Creation of Plasma Structures

Mechanisms for Channel Creation

- Heating center of plasma
  - single pulse for ionization and heating (Milchberg et al 93-98)
  - dual pulse scheme (Leemans and Volfbeyn, 98)
- Capillary discharge (Ziegler et al 96-98)
- Laser Nonlinearity
  - relativistic guiding (Max et al 74)
  - Self-channeling (plasma blowout)(Umstadter)
  - Electromagnetic channels (Shvets et al, 98)

LASER WAKEFIELD REQUIRES PLASMA CHANNEL

$$L_D \sim \frac{\pi R^2}{\lambda}$$

$$\tilde{n}(r) \simeq 1 - \frac{n_p(r)}{2 n_c}$$

- Channels overcome diffraction of the drive laser pulse.
  - Guiding in a pre-formed channel gives the option to operate in a linear regime.
  - Transverse field profiles determined by the driver profile: $\nabla_\perp \boldsymbol{E} \sim \nabla_\perp \boldsymbol{a}$
  - Field structure similar to the homogeneous plasma case.

  Parabolic channels originally studied by Sprangle and co-workers [IEEE Trans. Plasma Sci. **PS-15**, 145, 1987]. Pulse propagation instabilities in channels Shvets and Wurtele [Phys. Rev. Lett. **73**, 3540, 1994] and by Antonsen and Mora [Phys. Rev. Lett. **74**, 4440, 1995].

- Hollow channels have additional desirable properties.
  - Electromagnetic mode.
  - Transversely uniform accelerating gradient: $E_z \sim$ const.
  - Linear focusing fields: $dE_r/dr \sim$ const.

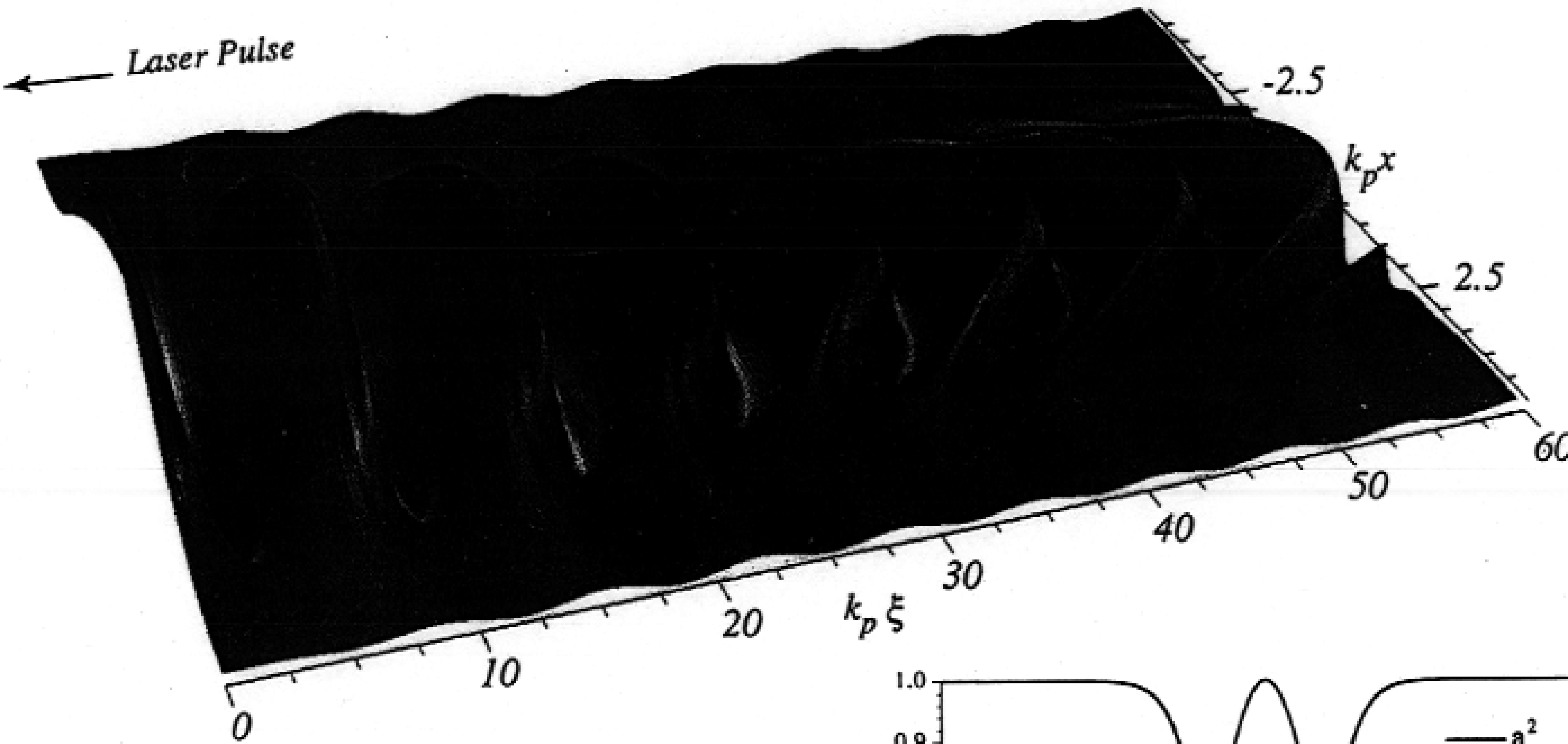
  Originally examined by Shvets *et al.* [IEEE Trans. Plasma Sci. **24**, 351, 1996].

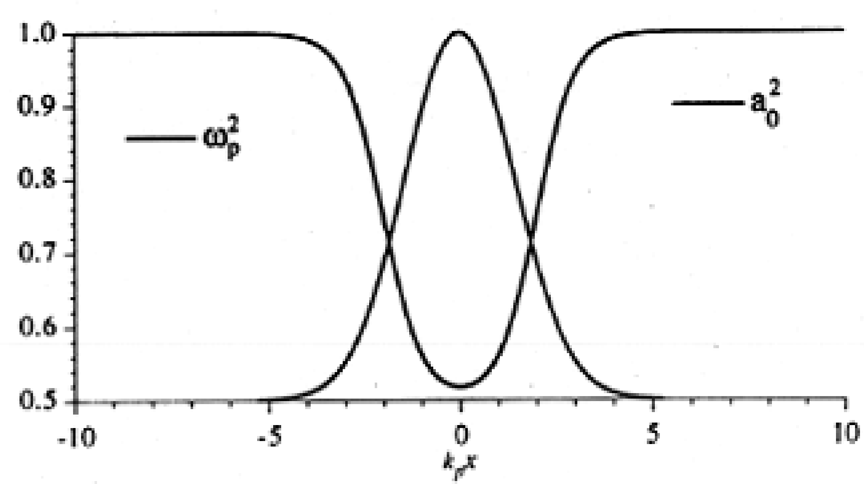
The Quality Factor of a Plasma Structures

Dissipation in a collisionless regime

Longitudinal Wake Field

Numerical Solution of the Linearized Cold Fluid Equations

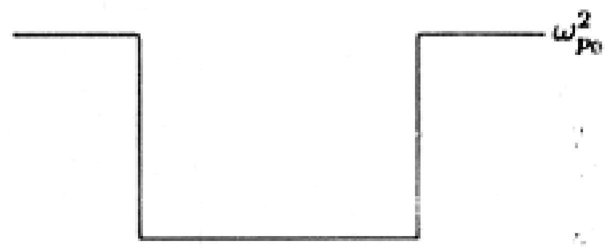




B. A. Shadwick, J.S. Wurtele, UC-Berkeley 1997

Hollow Channels

- Ideal Case
  - Analytic solution of linearized equations possible.
  - Mode is electromagnetic with $\omega_{ch} < \omega_{p_0}$.
  - Mode is undamped ($Q = \infty$).



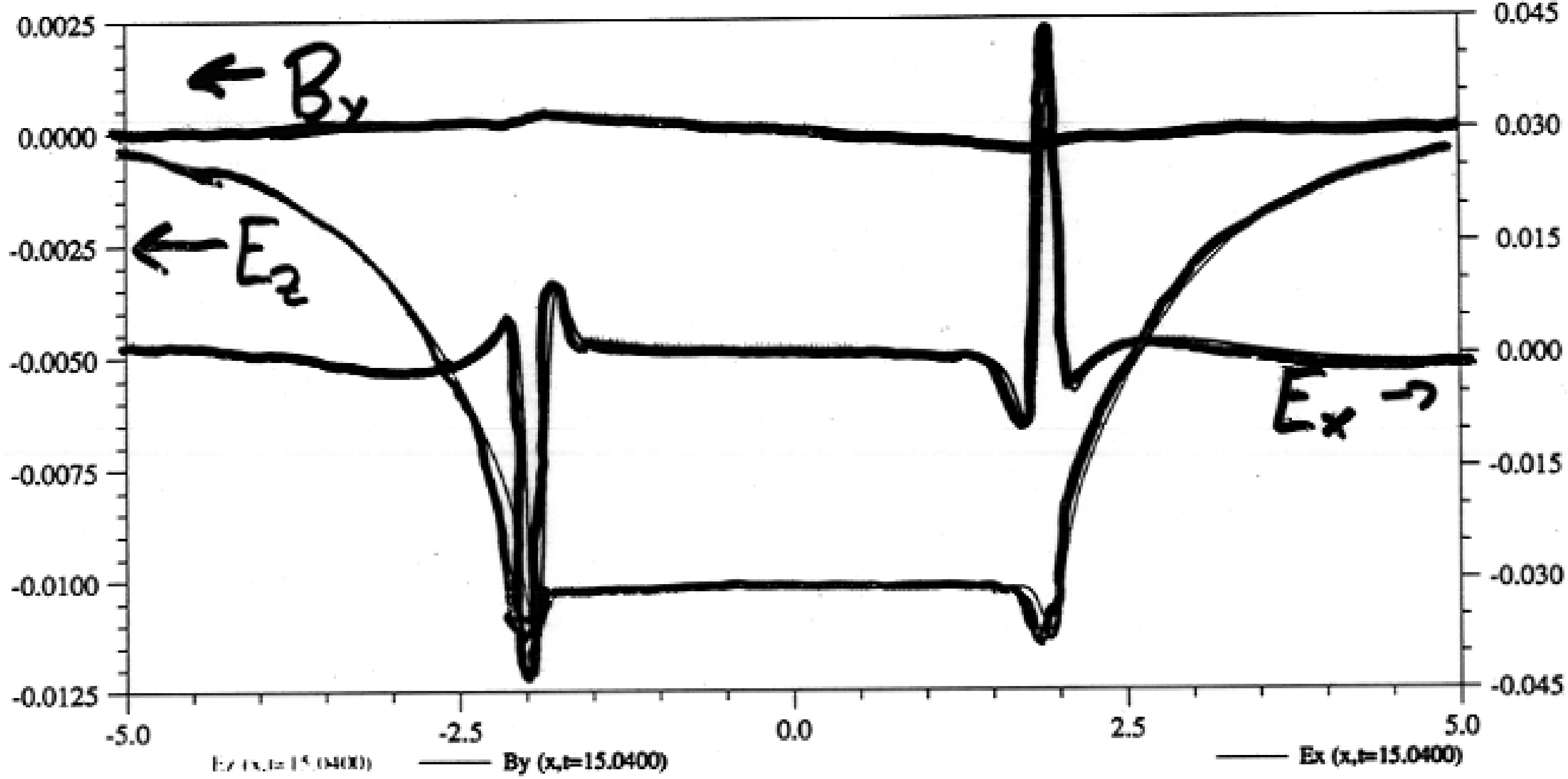
- Non-ideal Case
  - Linear equations analytically challenging.
  - Dielectric function is spatially dependent: $\epsilon = 1 - \omega_p^2(x)/\omega^2$.

  - Every $\omega < \omega_{p_0}$ is resonant with the local plasma frequency at some location in the wall.
  - Resonant layer leads to absorption of the wake.
  - Low Q means a large spread around ω_{ch} resonantly exciting much of the wall.

$$B_y'' - \underbrace{\frac{\epsilon'}{\epsilon}}_{\text{resonance}} B_y' - \frac{\omega_p^2(x)}{c^2} B_y = 0 .$$

B_y : WELL-BEHAVED

E_x : LARGE @ $x = x_c$

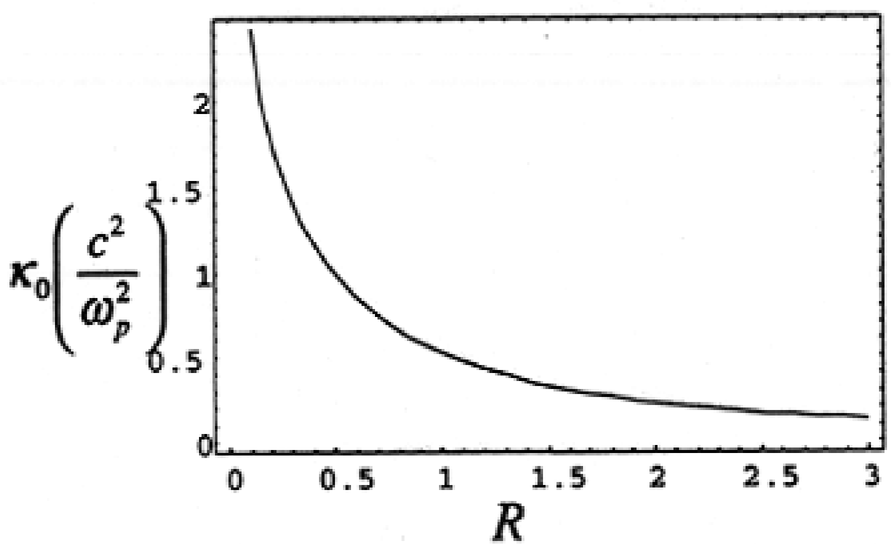


Loss Factor:

Definition: $\kappa_m = E_z^2 / 4U_m$

independent of excitation mechanism, geometrical factor of structure

$$\kappa_m = \frac{\omega_p^2}{c^2}\left[\frac{K_m(R)}{RK_{m+1}(R)}\right]\left[1+\frac{RK_m(R)}{2(m+1)K_{m+1}(R)}\right]^{-1}$$



Comparison: conventional conducting structure,

$$\kappa_0 = \frac{3.55\times10^3}{\lambda^2[cm]}\frac{V}{pC-m}\left[\frac{K_0(R)}{RK_1(R)}\right]$$

$$\kappa_{SLAC} = \frac{2.1\times10^3}{\lambda^2[cm]}\frac{V}{pC-m}$$

Linearity requires: $\omega_p r_e N_b / l c << R^2$

C. B. Schroeder *et al.*
PRL '99

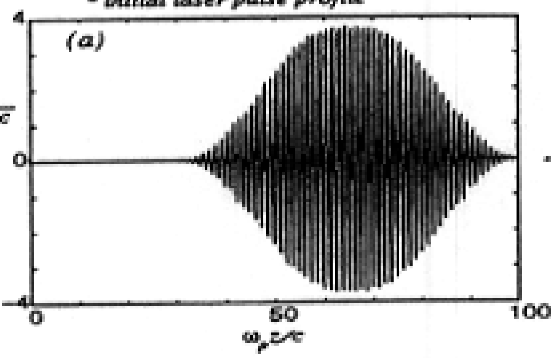
Katsouleas

Comparison of Laser Instabilities

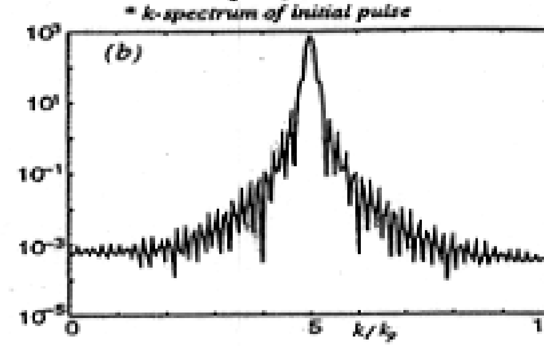
z F.T.

initial pulse

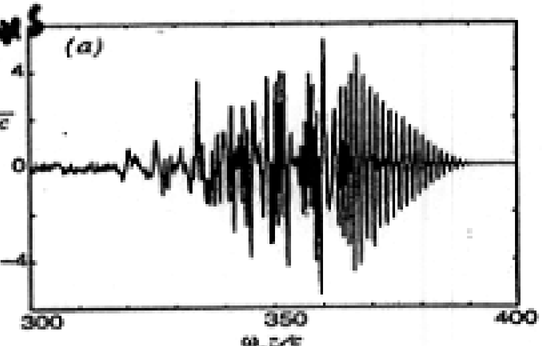
* initial laser pulse profile



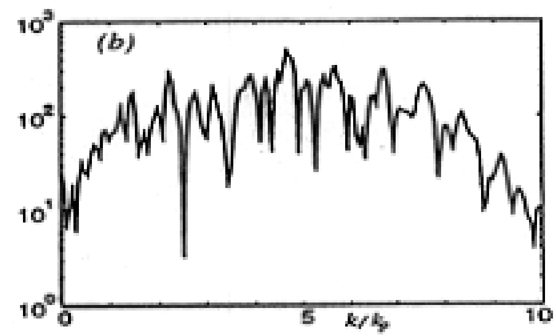
* k-spectrum of initial pulse



Homogeneous plasma

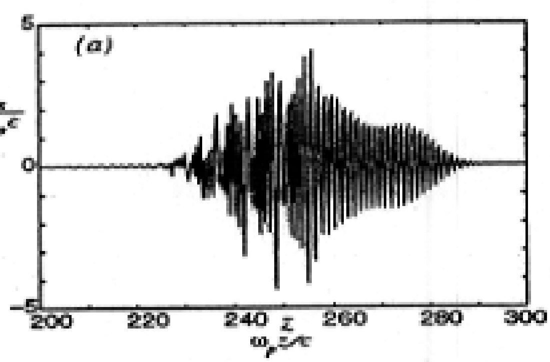


* Pulse profile in 1-D homogeneous plasma at t=300

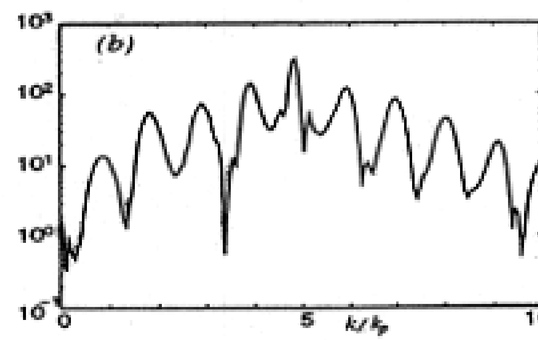


* k-spectrum of the pulse in 1-D homo. plasma at t=300

parabolic channel



* Pulse profile in parabolic channel plasma at t=200

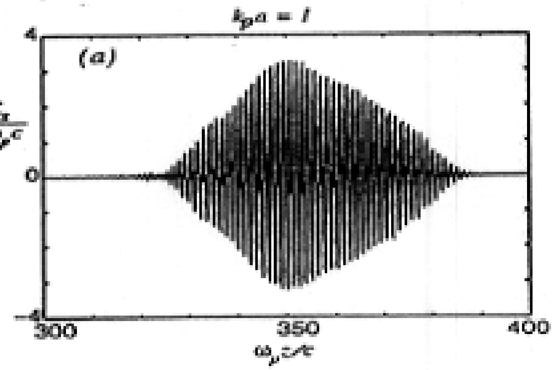


* k-spectrum of the pulse in parabolic channel plasma at t=200

Hollow channel

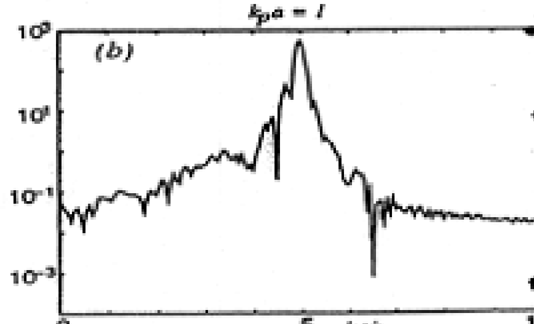
$k_p a = 1$ STABLE

$k_p a = 1$



* Pulse profile in hollow channel plasma at t=300

$k_p a = 1$

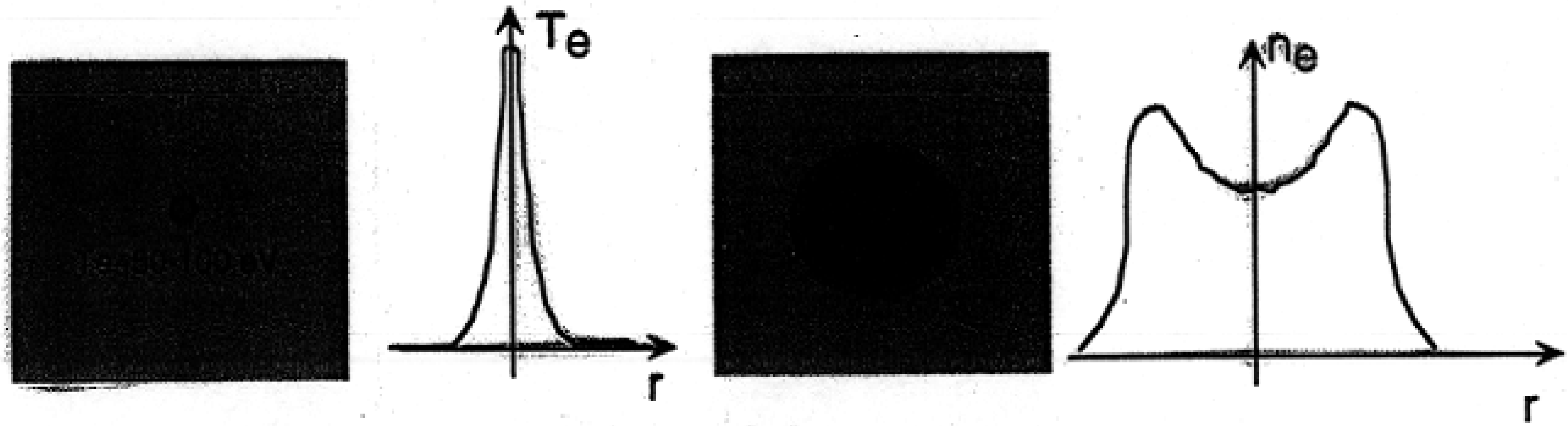


* k-spectrum of the pulse in hollow channel plasma at t=300

300 $\omega_p z/c$ 400 0 k/k_p 10

Channel Creation*

Ionizing and Inverse Brehmsstrahlung Heating a thin cylinder of gas leads to hydrodynamic expansion and a Plasma Channel with a density minimum on axis is formed.

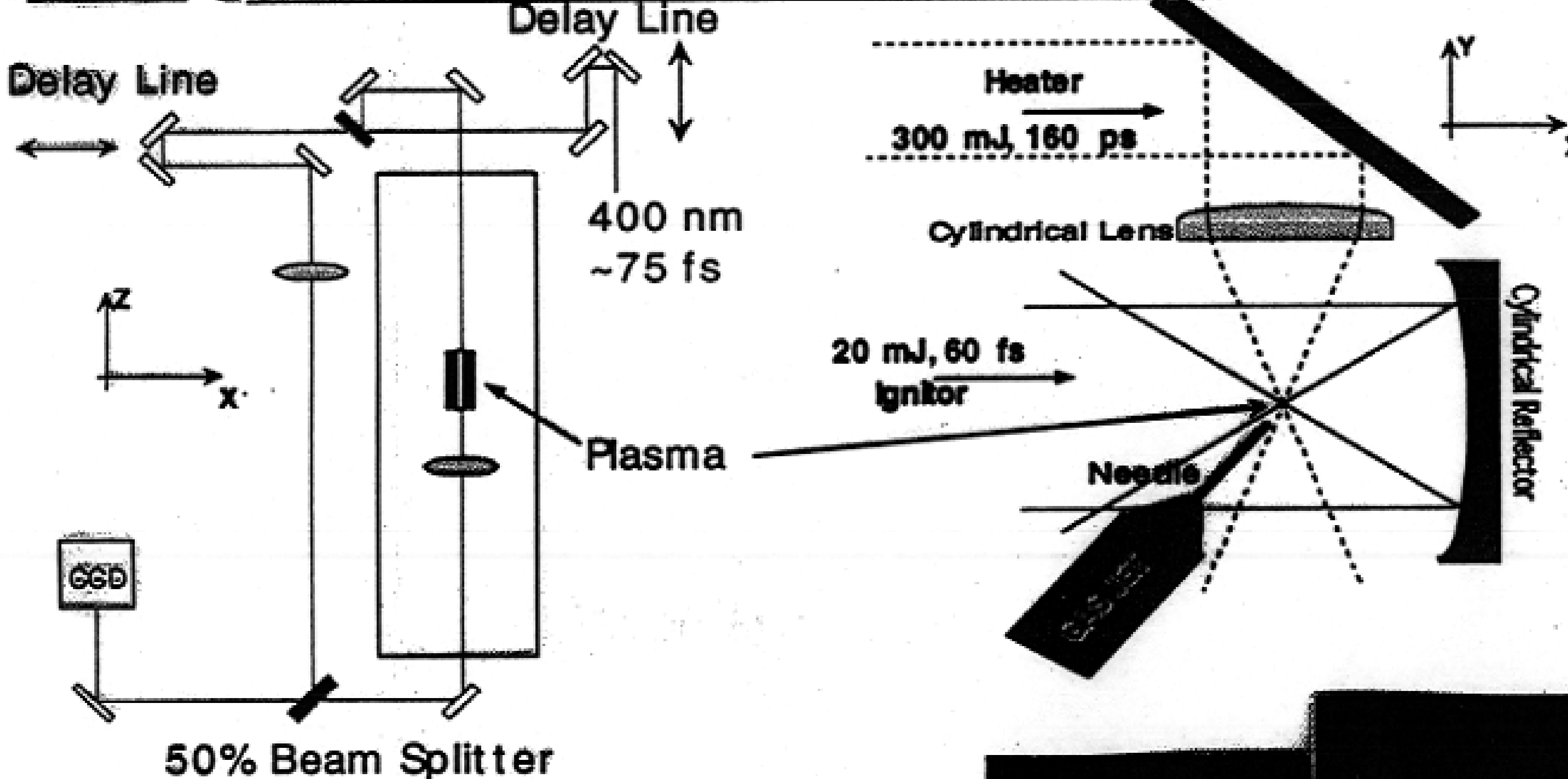


Heated Plasma Spark creates a Hydrodynamic shock that leaves a density minimum on-axis

*G. J. Durfee et al. Phys. Rev. E, v. 51, no. 3, 2368 (1995)
P. Volfbeyn et al. Phys. Plasmas, v. 6, no. 5, 2269 (1999)

Ehrlich, et al, PRL 77, Dorchies et al, PRL 23, 4655 (1999);-capillary

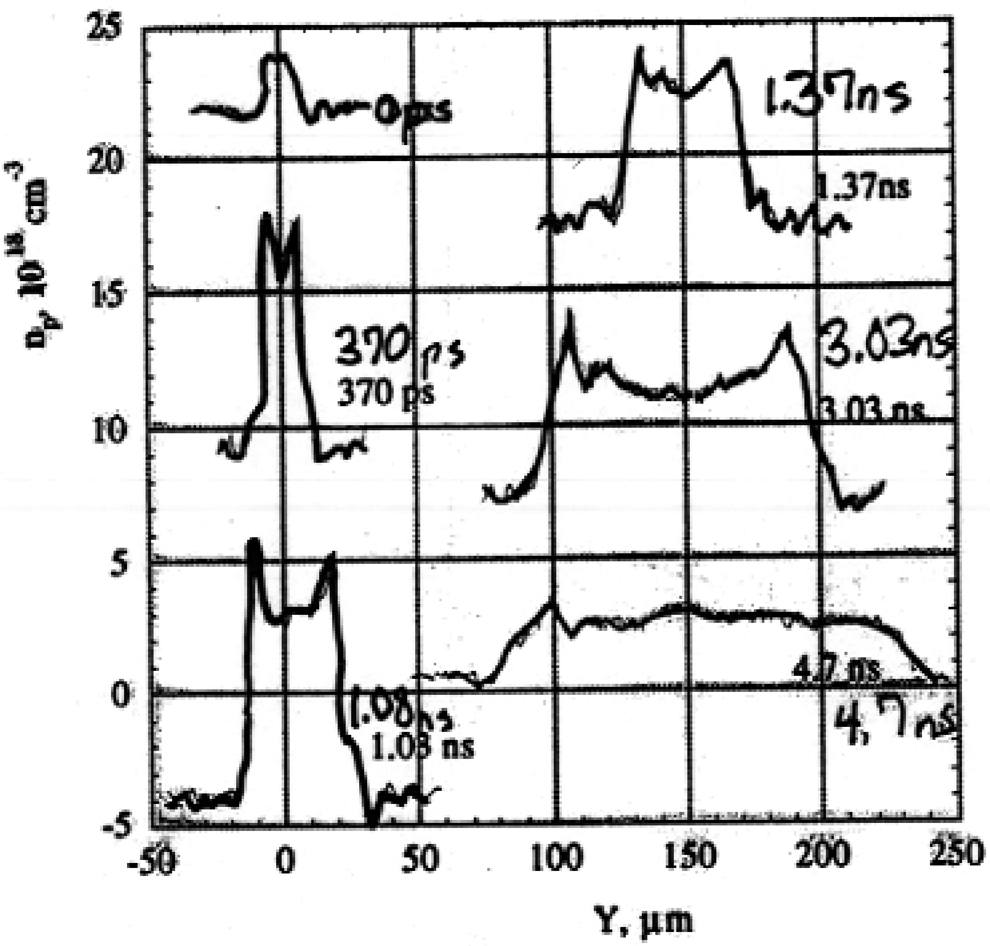
Ignitor-Heater Plasma Channel Creation Method*



Transverse Interferometry With Femtosecond Resolution

*P. Volfbeyn et al. Phys. Plasmas, v. 6, no. 5, 2269 (1999)

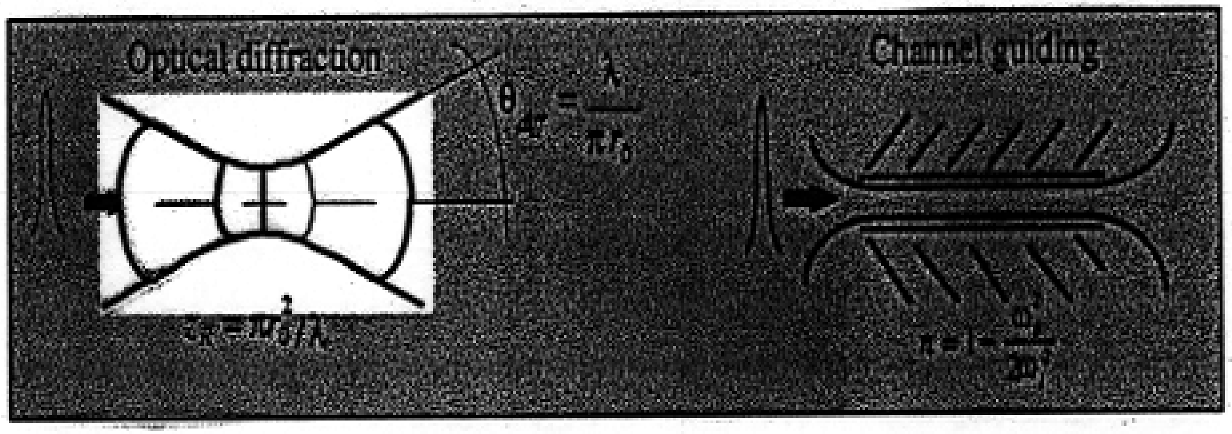
Channel Formation in N_2 Gas Jet



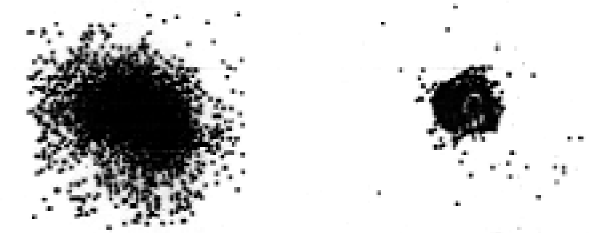
E_{short}=50 mJ , E_{long}=280 mJ
1000 psi, 0.450 mm from nozzle

LBNL PLASMA WAKEFIELD - FORMATION OF CHANNEL

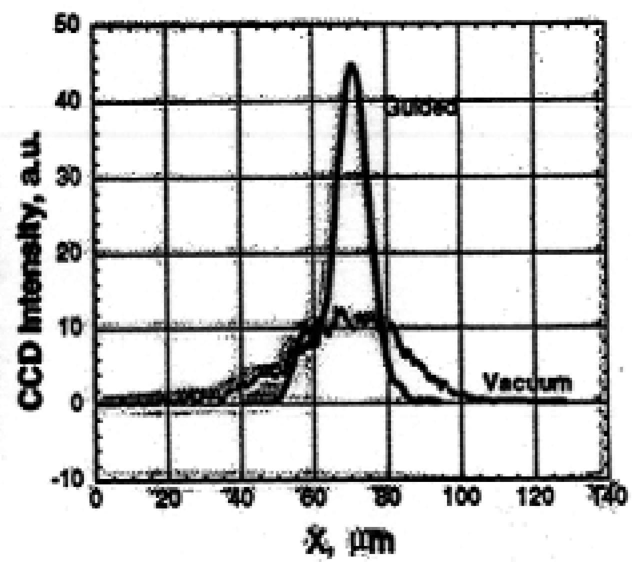
$2x10^{17}$ W/cm^2 Guided over 5 Rayleigh lengths (1 mm)

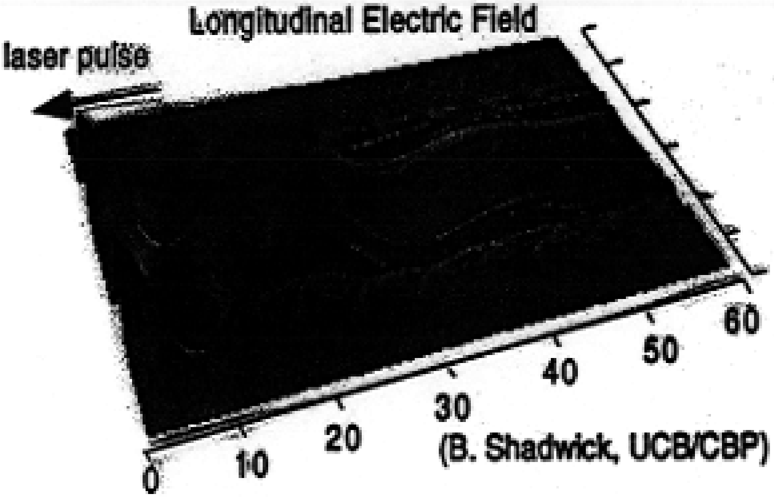


Laser Beam Images:

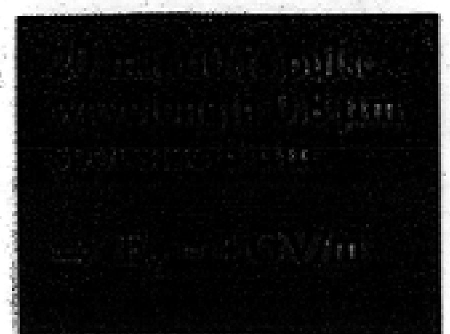


Vacuum Focus Intensity ~2 10^{17} W/cm^2

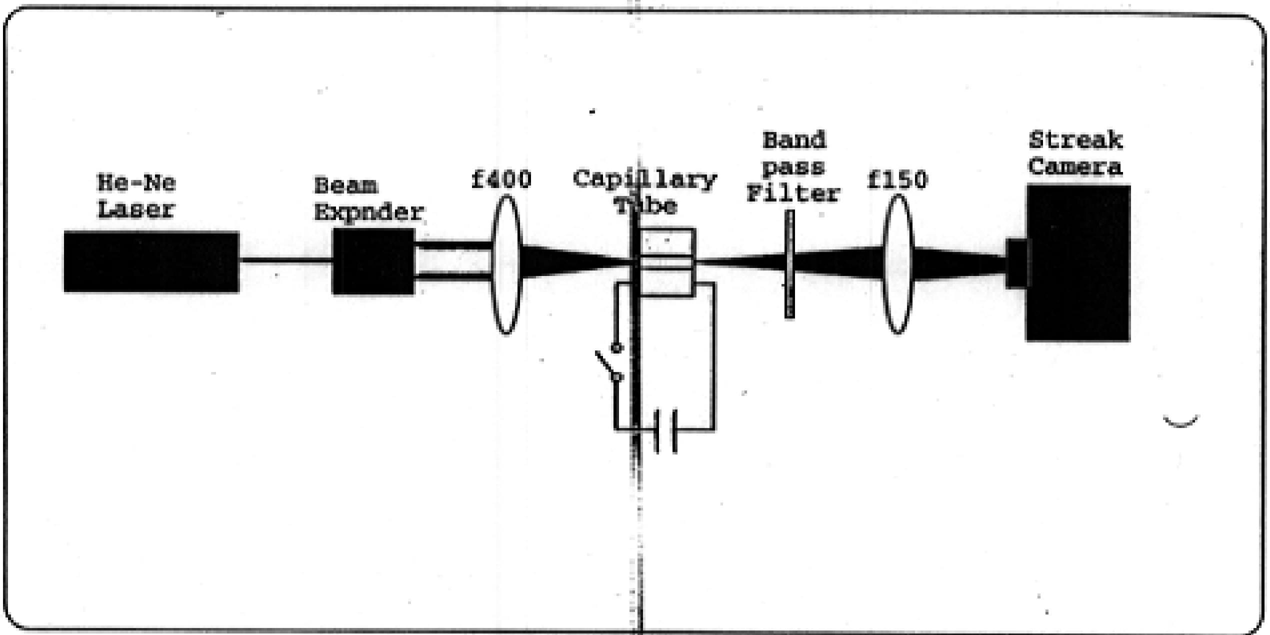




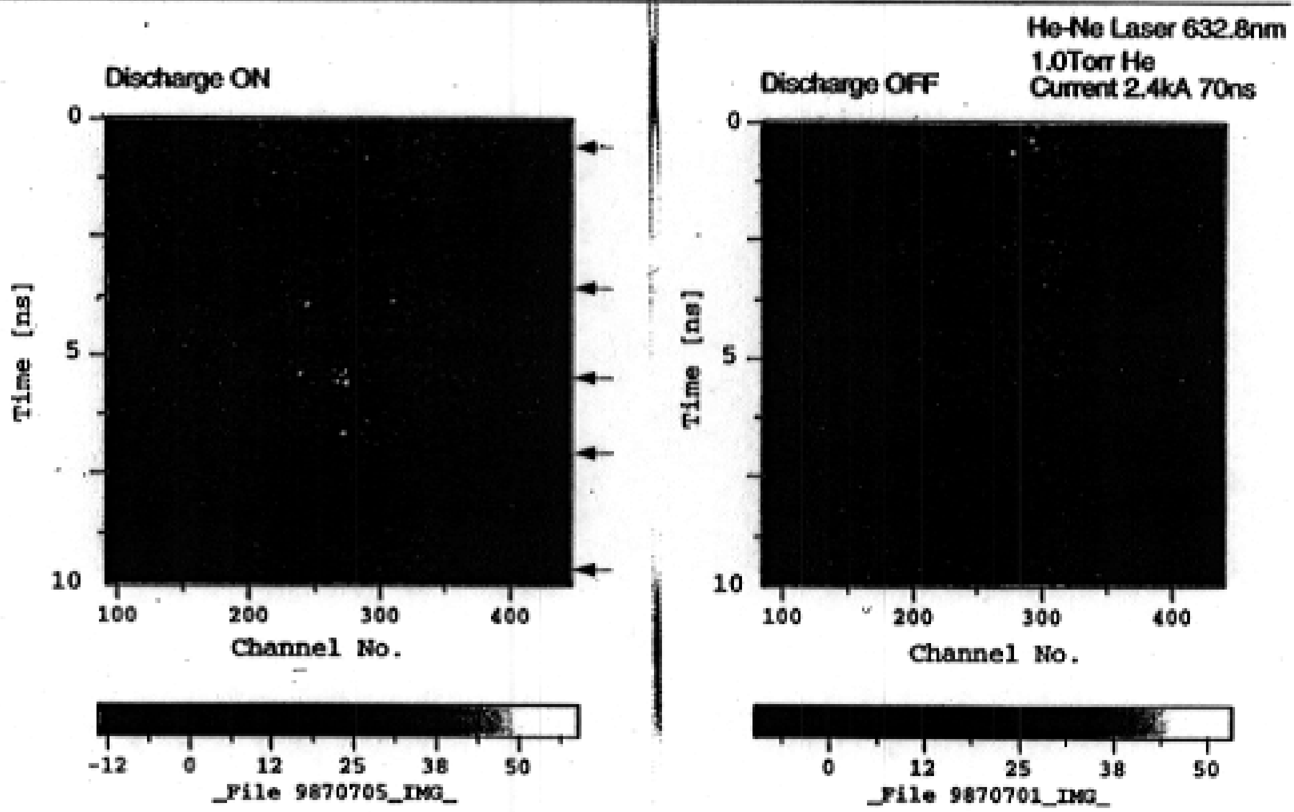
(B. Shadwick, UCB/CBP)



Experimental Set up for Plasma wave guide

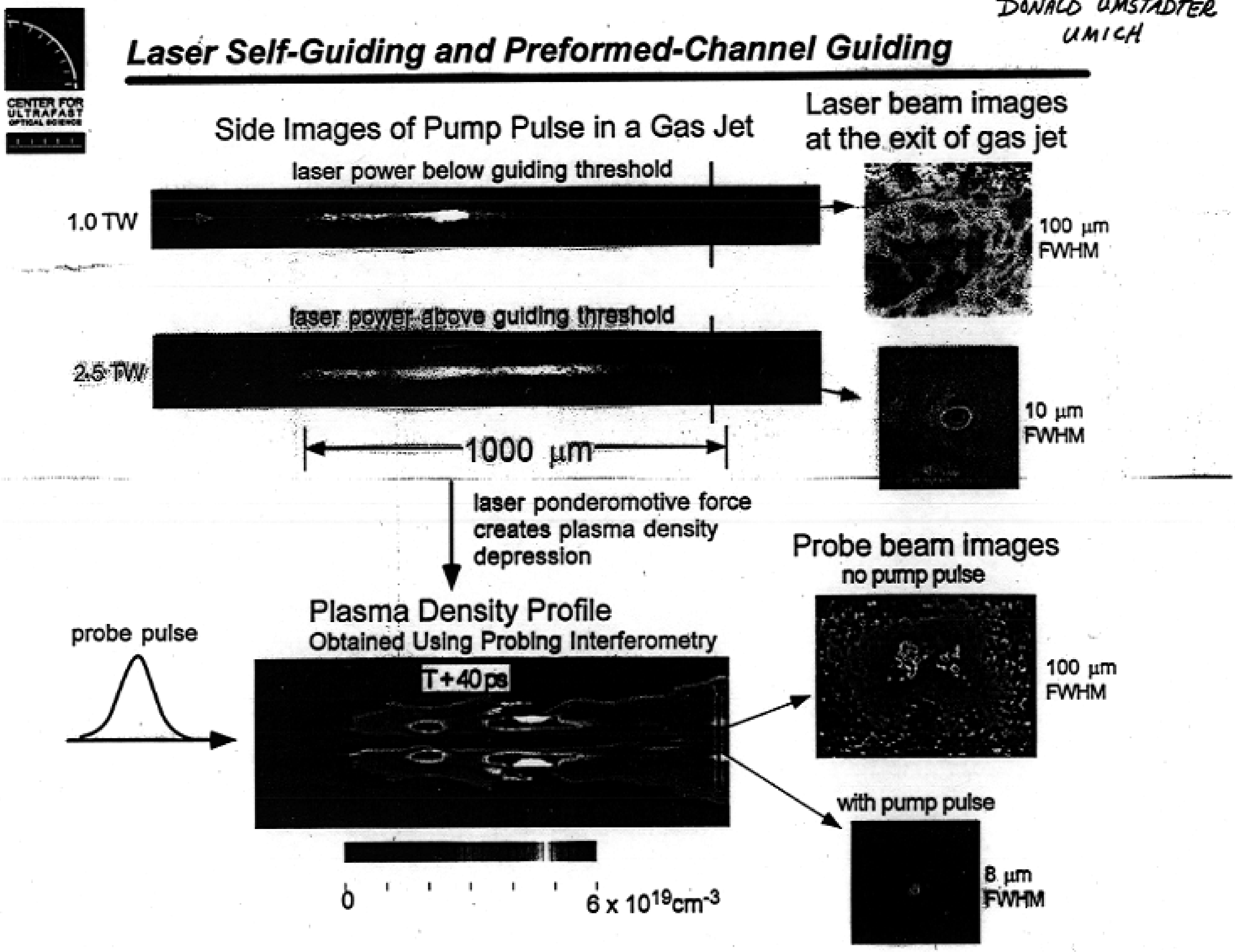


Laser Beam Profile at Exit of Capillary



DONALD UMSTADTER
UMICH

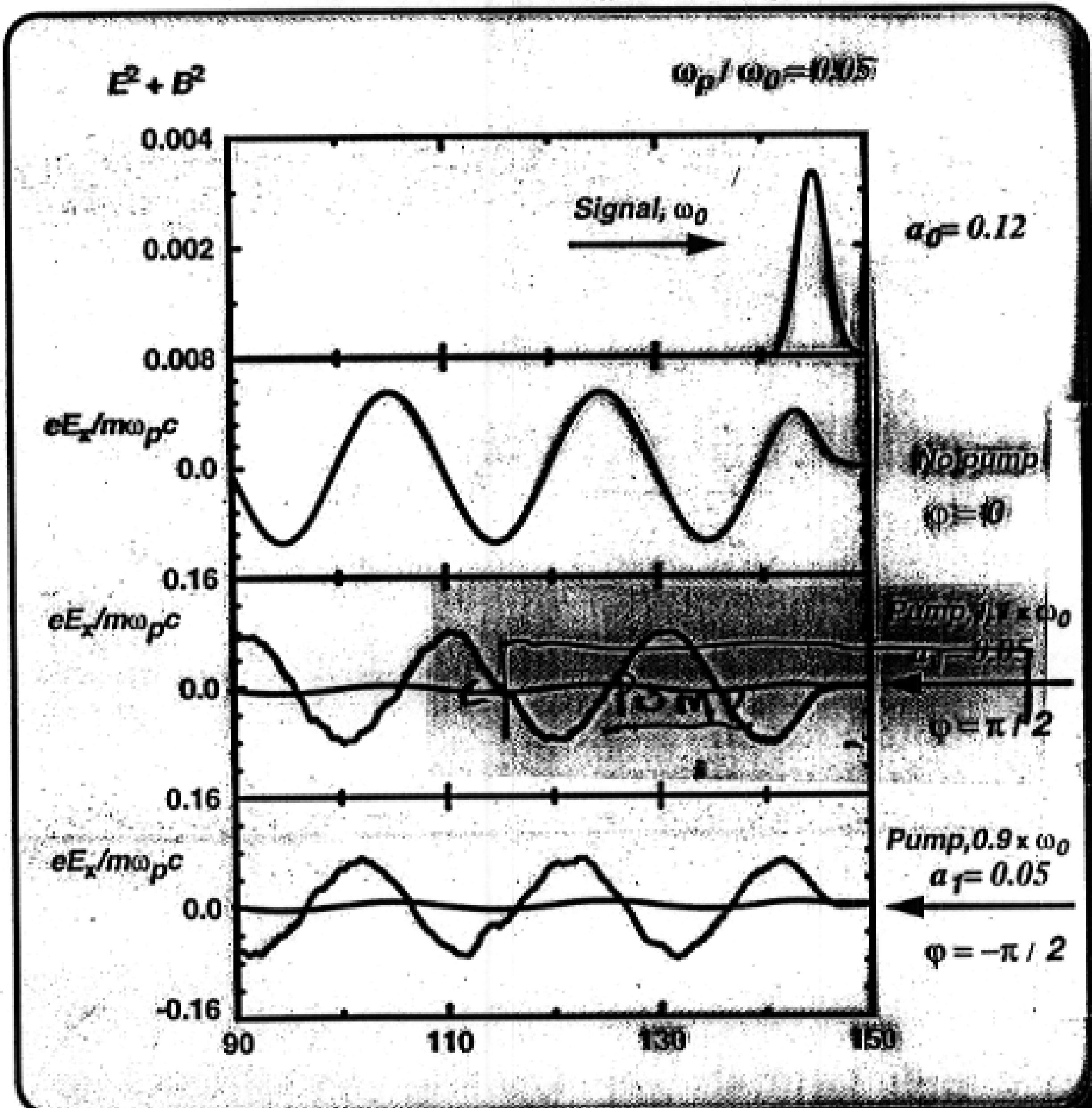
Laser Self-Guiding and Preformed-Channel Guiding



Enhanced Wake Field Generation by Colliding Laser Beams

Standard wake: $eE_x/m\omega_p c \sim a_0^2$

Enhanced wake: $eE_x/m\omega_p c \sim (a_0 a_1)^{1/2}$



Shvets, Fisch, PPPL

Pukhov. Meyer-ter-Vehn, Max Planck

Plasma Wakefield Accelerator

- Linear excitation
  - Nonlinearities in accelerating and focusing fields
  - Higher accelerating gradient
- Nonlinear excitation
  - most of beam focused linearly by ions
  - Lower accelerating gradient
- Physics issues:
  - Beam dynamics--drive bunch and accelerated bunch
  - Efficiency
- Potential advantages in ultrarelativistic regime
  - Stiff beam driver--longer interaction lengths,
  - higher coupling efficiency (?).

NO NEED FOR Preformed Plasma Structure

Ultra-Relativistic Beam-Plasma Dynamics

- Goal: Develop diagnostics, benchmark simulations, improve design tools, understand plasma as a *dynamic* element of a accelerator.
- Experiments: UCLA,USC,LBNL, BINP,SLAC E150 & E157

Is a multi-GeV beam driver superior to a laser?

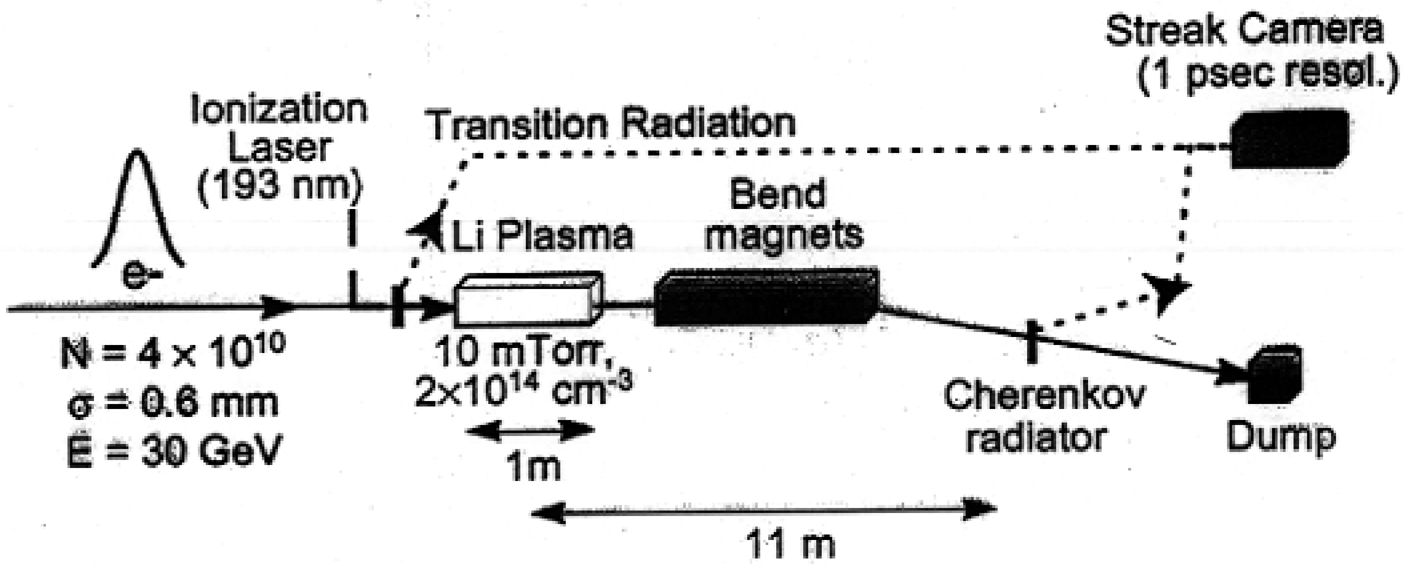
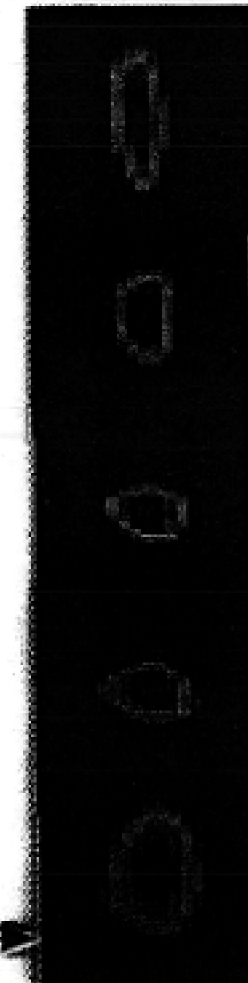
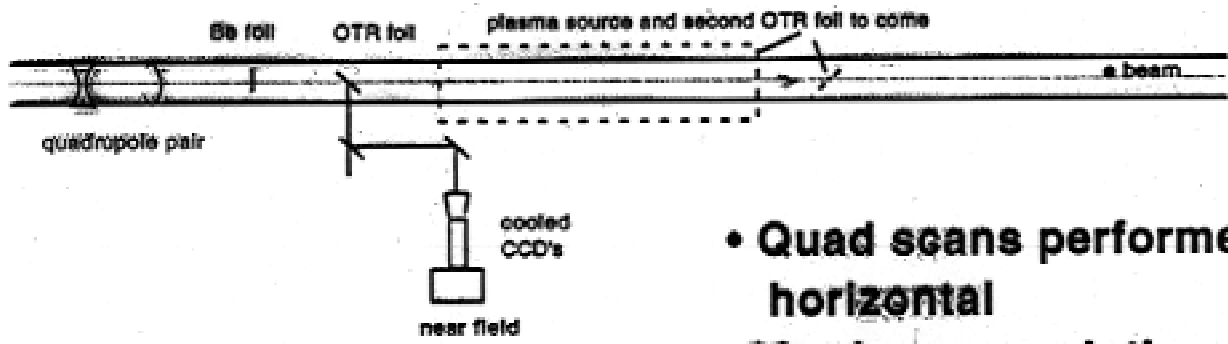


Figure 1: Layout of E-157 (PAC99).

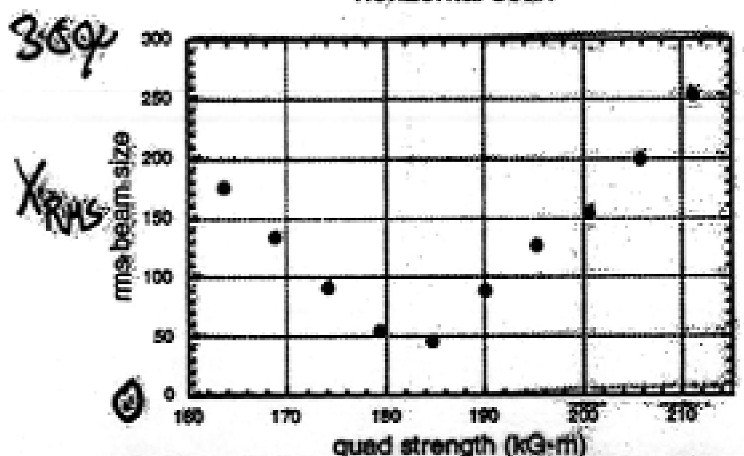


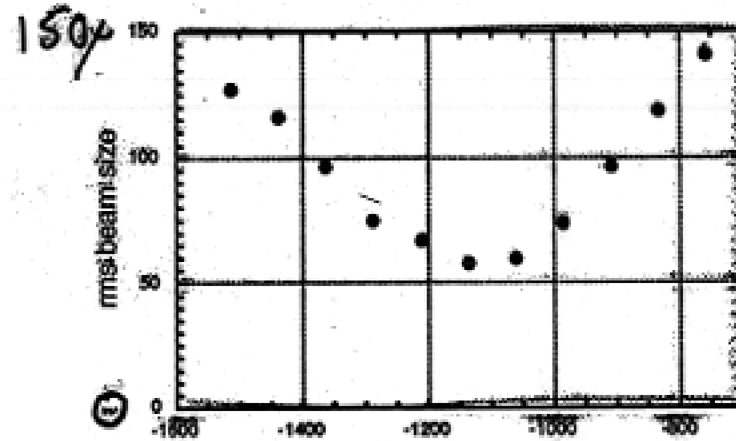
Transition radiation diagnostic of beam size with quad scan

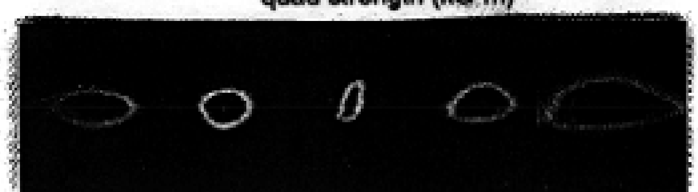
OTR at 30 GeV - Beam spot size resolution



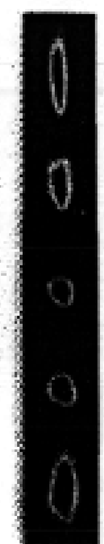
- Quad scans performed in vertical and horizontal
- 50 micron resolution achieved in both axes using visible wavelength OTR.







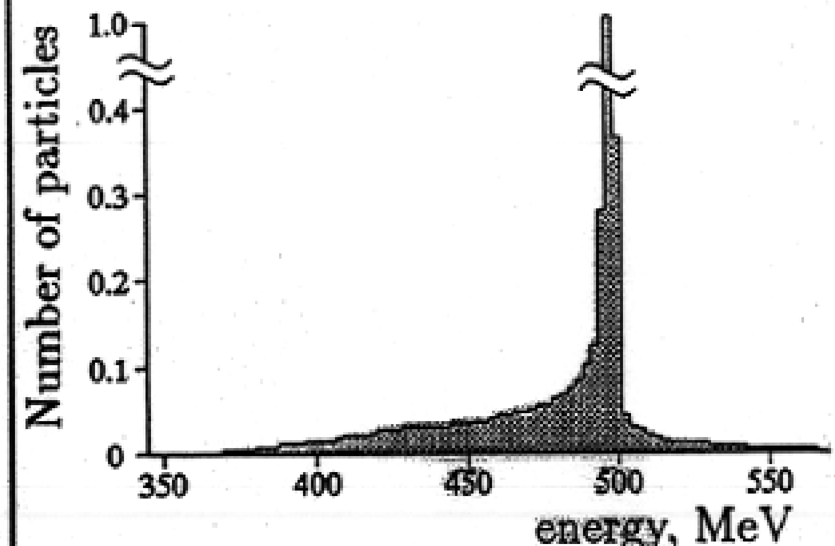
← OTR near field images →



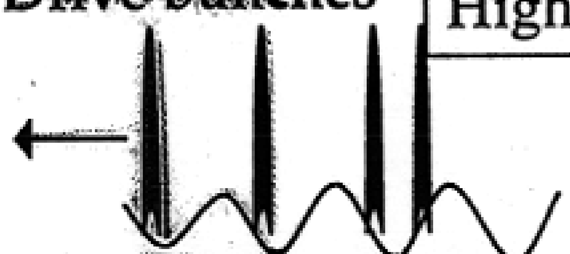
E157: FROM CATRAVAS et al, PAC 99

The BINP beam-driven plasma linac

- Density: $10^{15}/cm^3$
- Gradient: 1GeV/m, 100 stages @10m each
- Final energy: 1TeV,energy spread 3%, $N=5X10^9$,
- Excitation by train of drive pulses
- From Kudryatsev et al. in Proc. ICFA workshop on Advanced Accelerators, NIM 410, 1998. Also work by Chen, Katsouleas, Nakajima,Rosenzwieg, others.



Predicted performance of initial experiment at BINP



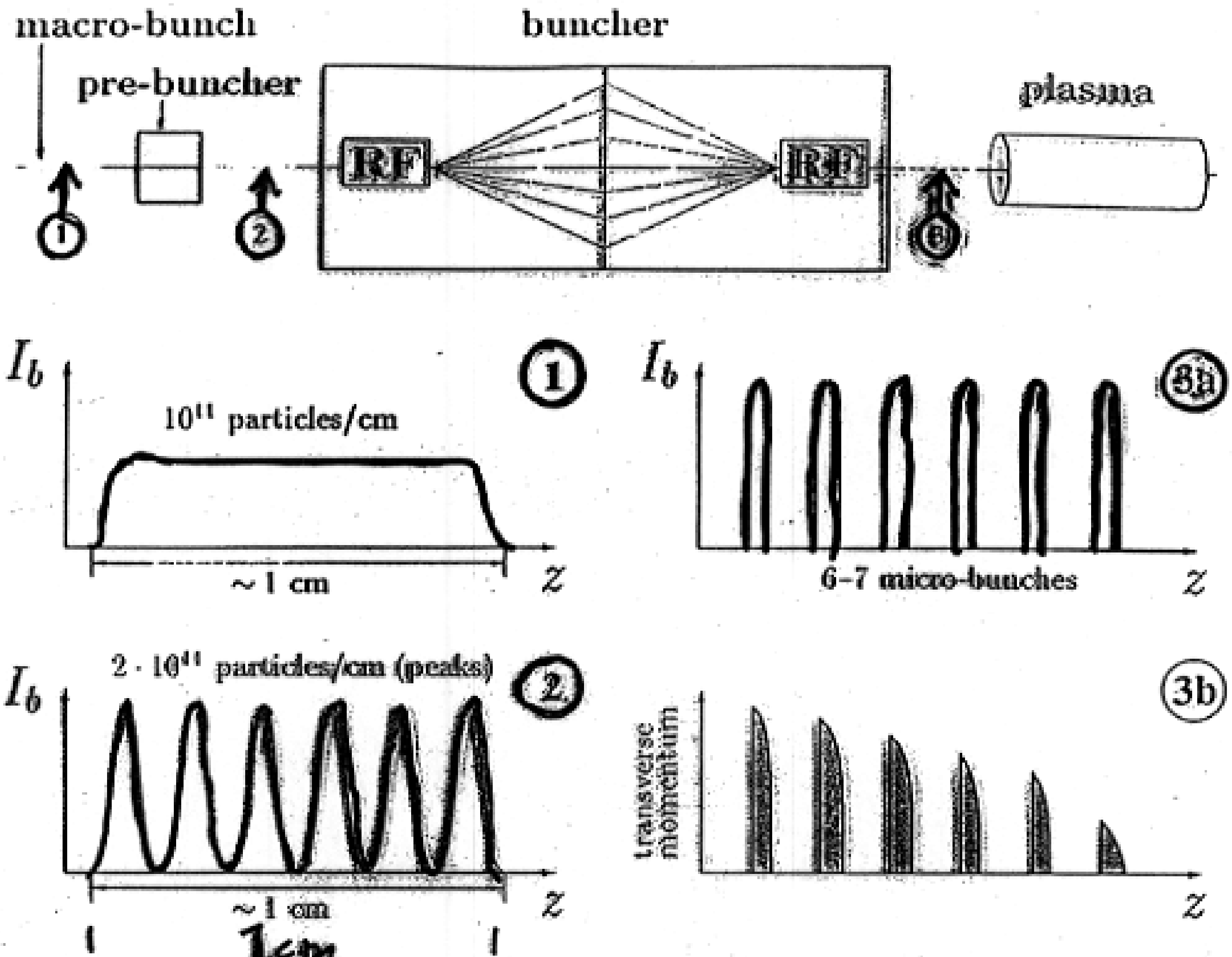


Fig. 5. Driver preparation with the transverse cutting.

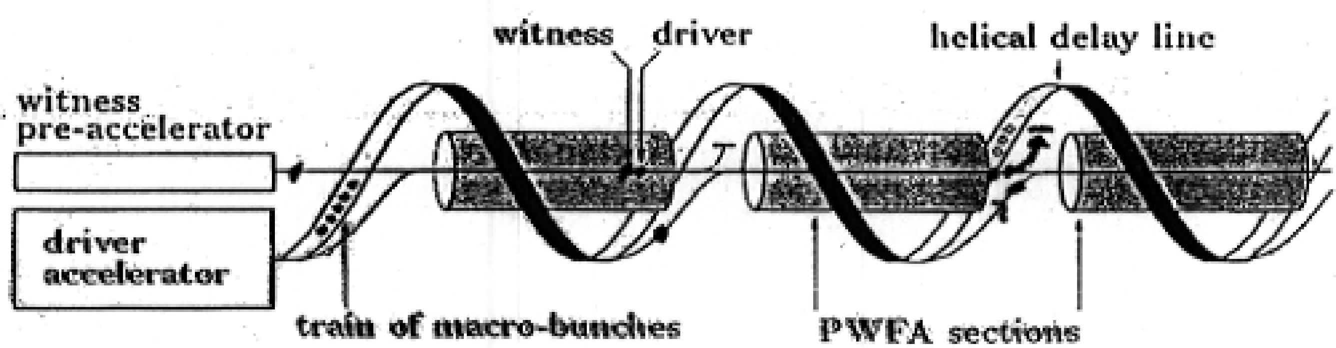
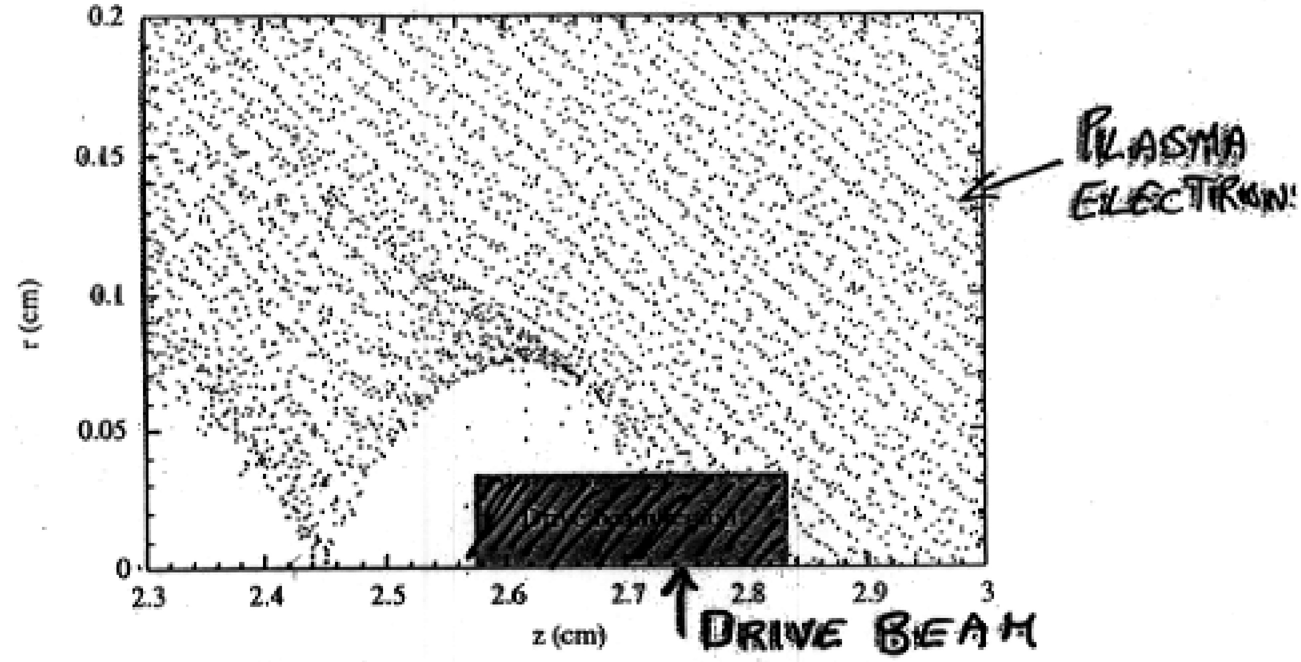


Fig. 6. The staging scheme for the PWFA-based collider.

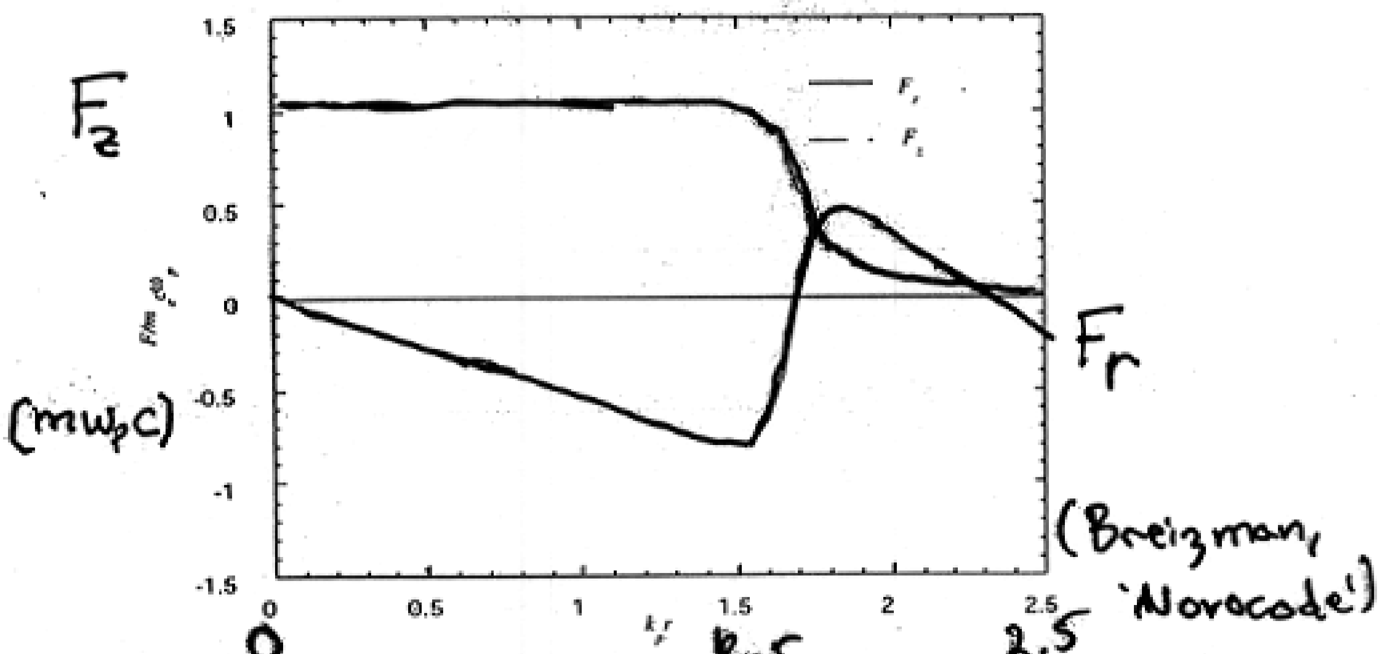
SKRINSKY, et al
BINP

NONLINEAR STRUCTURE FORMATION

PHYSICS OF THE PWFA BLOW-OUT REGIME



PIC simulation results of blow-out regime case.



Complete rarefaction of beam channel allows linear electrostatic focusing and electromagnetic acceleration independent of *r*.

J. Rosenzweig, et al

<u>ACCELERATION EXPERIMENTS</u>

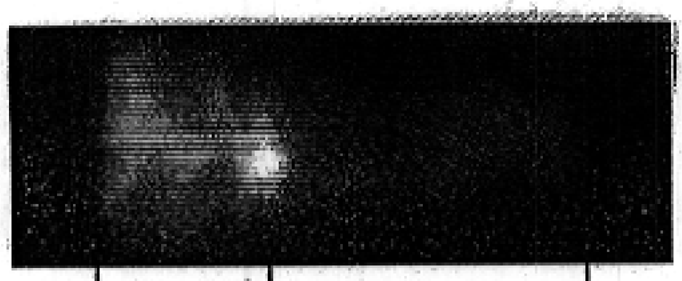
- Drive beam deceleration, with acceleration of tail observed in high resolution spectrometer
- Beam parameters: E=15.6 MeV, Q=18 nC, Pulse length 20-22 psec FWHM, norm. emittance 180 mm-mrad.

<u>Spectrometer images</u>

$\frac{n_b}{n_0} \sim 3$

$n_0 = 1.3\times10^{13}/cm^3$

14 MeV No plasma case 18.6 MeV



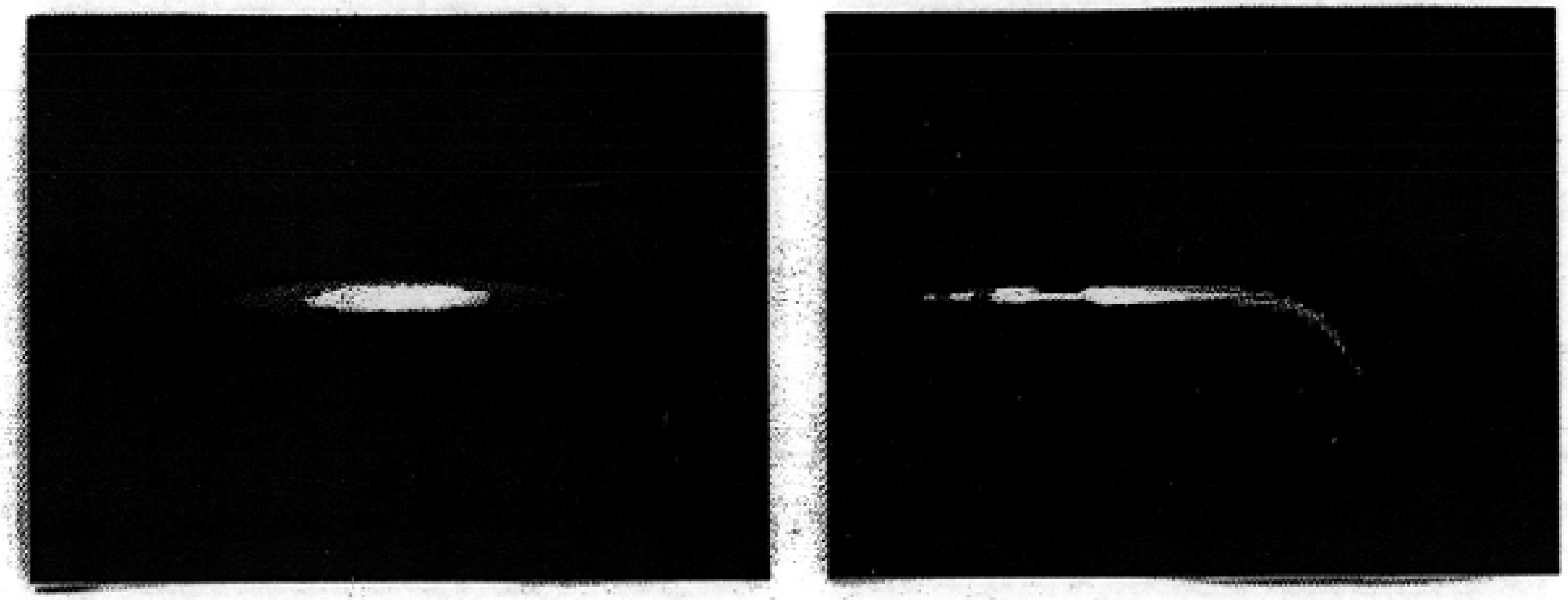
$k_p \sigma_z \sim 2$

14 MeV Plasma case 18.6 MeV

(deceleration of 13 MeV/m, acceleration of 25 MeV/m)

FINAL 'PLAN': · Photocathode
· Compress Drive Beam
· GV/m Gradients
· Efficiency Studies

Wakefield Amplification



- Incoming head-tail "tilt" is amplified and distorted after 1.5 meter plasma

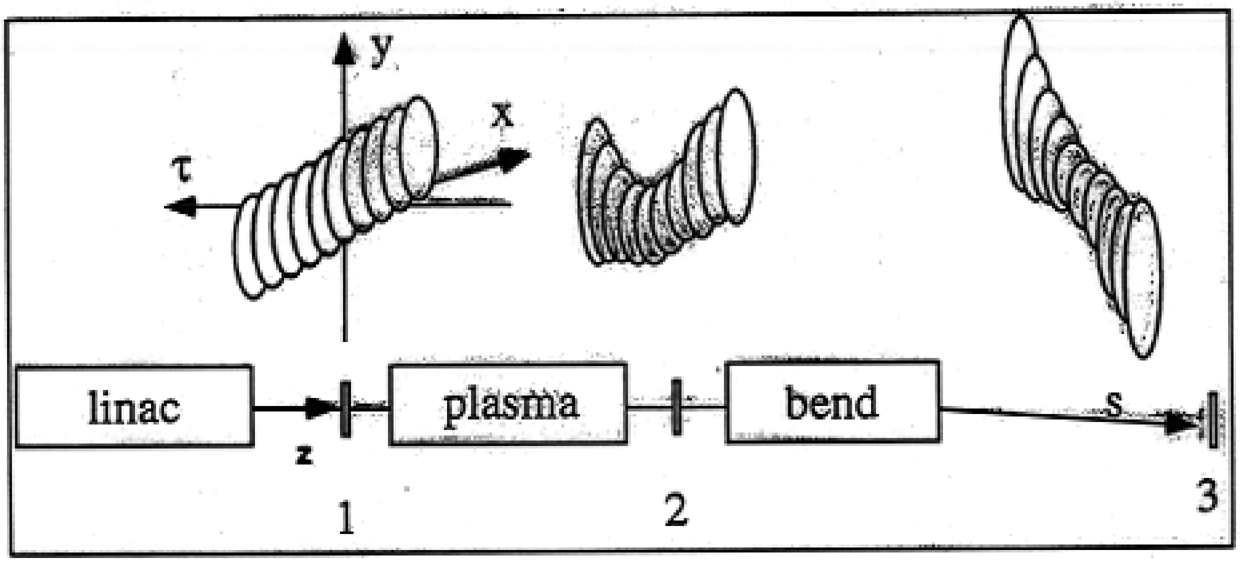
A. Geraci (SLAC)

Nominal Parameters

Electrons in Bunch	4. E10
Bunch Length (sigma _z)	0.7 mm
RMS Emittance	6. E-5 m-rad
RMS Beam size	1. E-5 m-rad
Beam Energy	30. GeV
Peak Beam Density	1.45 E15 cm^-3
Plasma Density	3 E14 cm^-3
Plasma Channel Radius	1 mm
Plasma Length	1.5 m

Dipole Perturbation

Transverse Centroid differs by 0.3 * (beam radius), e.g. between beam head(-3σ) and tail($+3\sigma$), i.e linear "tilt"



Courtesy A. Geraci and D. Whittum, SLAC

Injectors into high-frequency structures

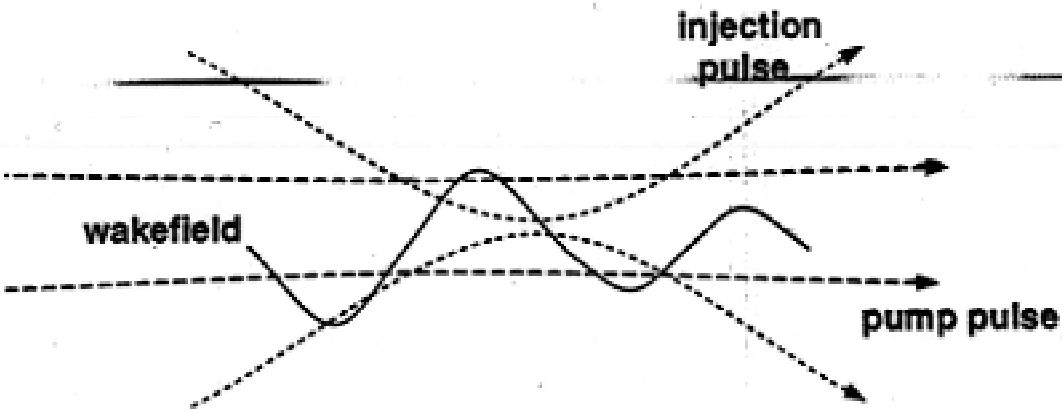
- fs laser and RF gun+chicane (e.g., UCLA Neptune Lab)
- Optical injection concepts
- Inverse free-electron laser

DONALD UMSTADTER
U MICH

LILAC: Laser Injected Laser ACcelerator

- Laser wakefield accelerators have ultrashort acceleration buckets (10-50 fs).
- They require an injector that produces femtosecond duration electron bunches.
- We proposed an all-optical single-stage plasma-cathode injector/accelerator

D. Umstadter, J. K. Kim, and E. Dodd, Phys. Rev. Lett. **76**, 2073 (1996).



Several potential advantages:

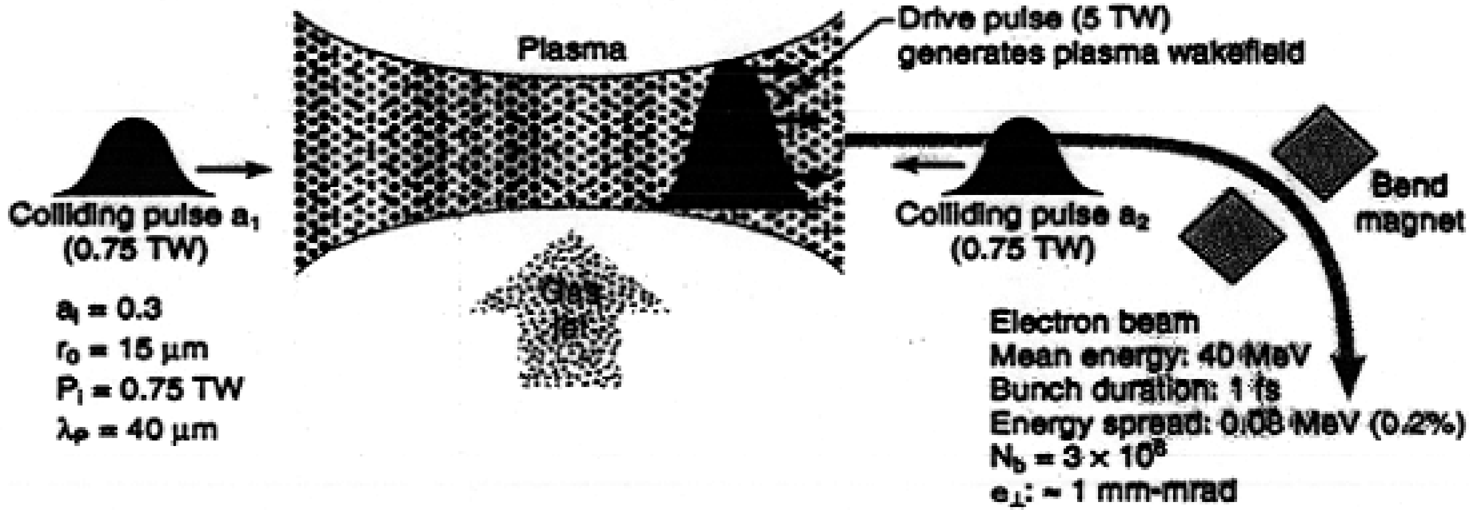
- higher first-stage accelerating fields
  $\Longrightarrow$ lower transverse emittance
- monoenergetic ultrashort electron bunches
- absolute synchronization between wakefield and electrons
- compact and economical

Simulations show LILAC has excellent beam characteristics:

- Single bunch $\tau_b = 9.0$ fs (3. μm) with $n_b = 1 - 4 \times 10^7$ **per bunch** (2-6 pC)
- Emittances $\epsilon_{\perp n} =\sim 2\pi$mm · mrad and $\Delta E/E$@100 MeV $= 2.0\%$

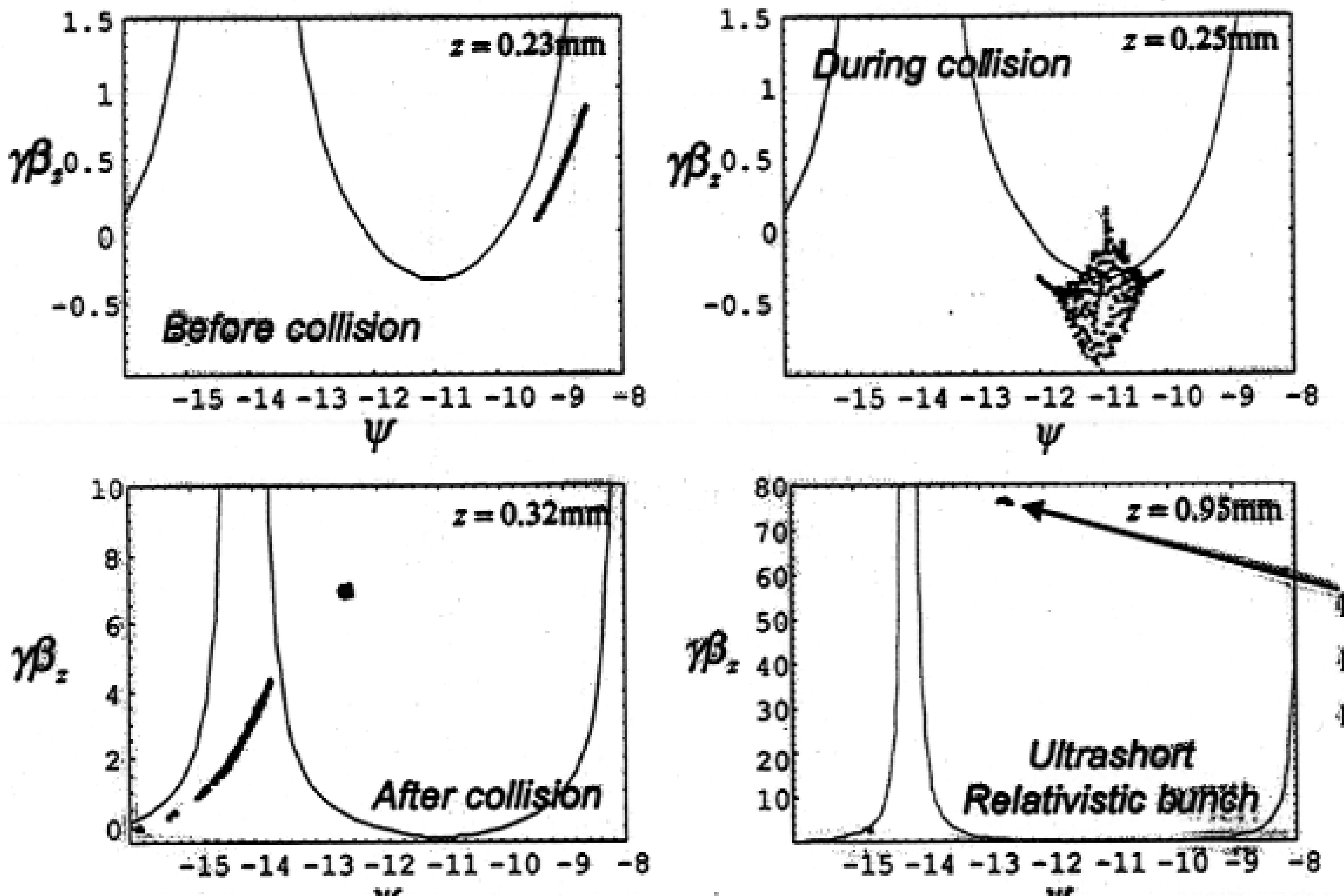
Optical injection using colliding pulse method

Injection pulses collide, producing a slow-moving beat wave that allows electrons to be trapped.



3-D simulation of colliding pulse: high quality bunch

Longitudinal phase space evolution of distribution of plasma electrons



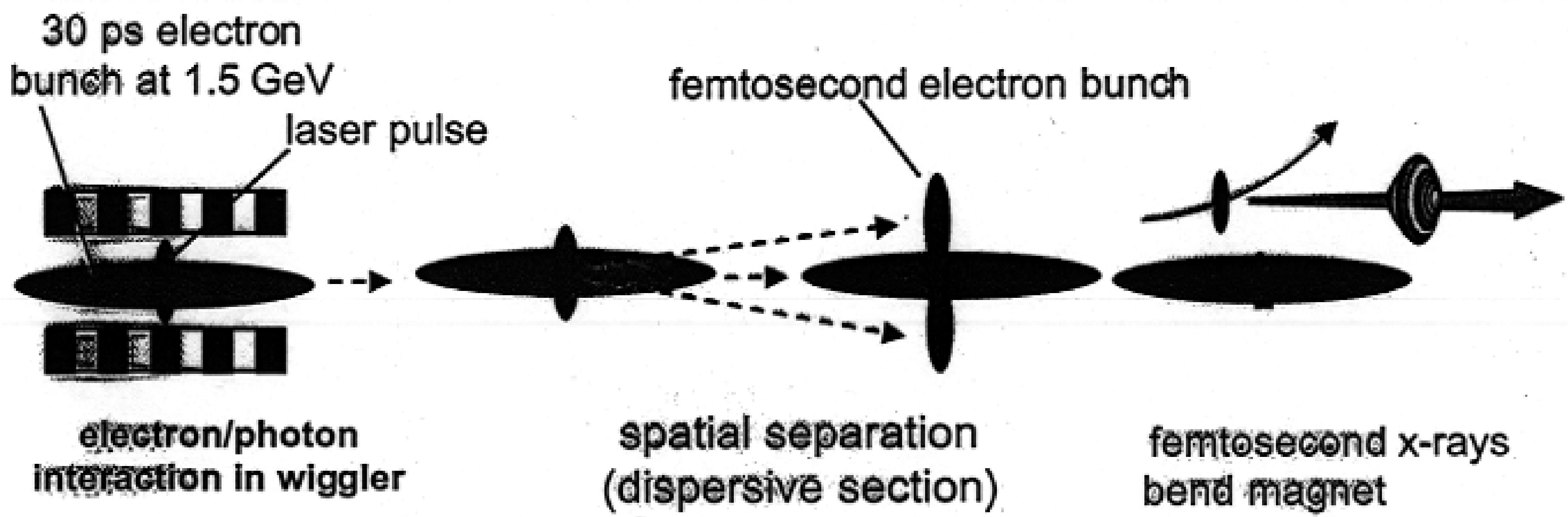
Mean energy = 39 MeV

Bunch duration = 1 fs

Energy spread = 0.08 MeV

Generation of Femtosecond X-rays

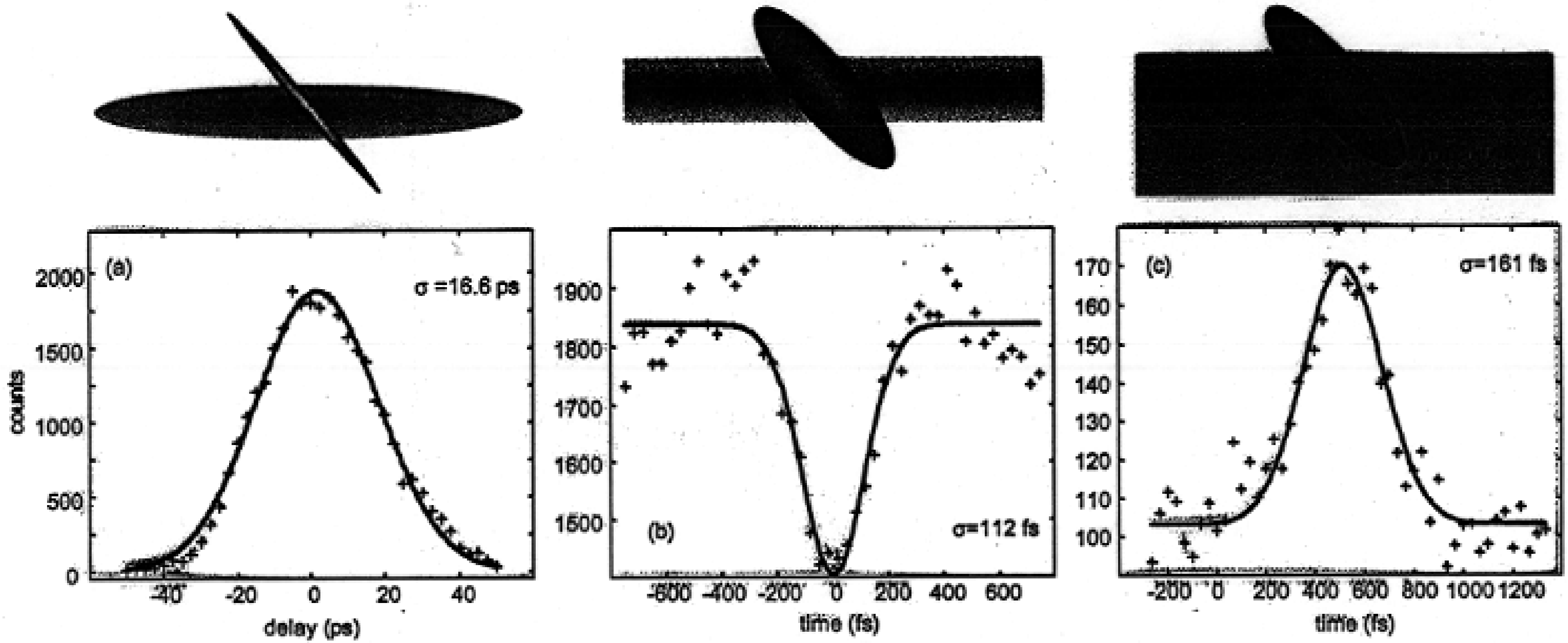
A. Zholents, M. Zolotorev, PRL, 76, 916, 1996



$t(\mathcal{E}), \quad r(\mathcal{E}), \quad r'(\mathcal{E}), \quad \omega(\mathcal{E})$

Correlation Measurements of Visible Femtosecond Synchrotron Pulses

[redacted]



Zholents & Zolotorev '99

ALSO, BNL/ATF I FEL BUNCHING '98
Ben Zvi, et al

Plasma Lens

- Underdense $n_p < n_b$

  NONLINEAR RESPONSE
  LINEAR $W_\perp, W_\parallel$

- Overdense $n_b < n_p$

  LINEAR RESPONSE

NONLINEAR $W_\perp, W_\parallel$ (depend on k_p)

- Current Neutralization

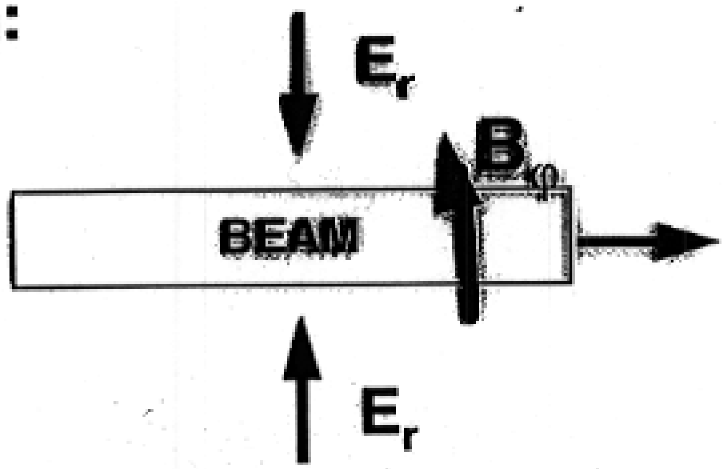
$$k_p R_b > 1 \quad k_p \sigma_z \lesssim 1$$

(adiabatic if [illegible])

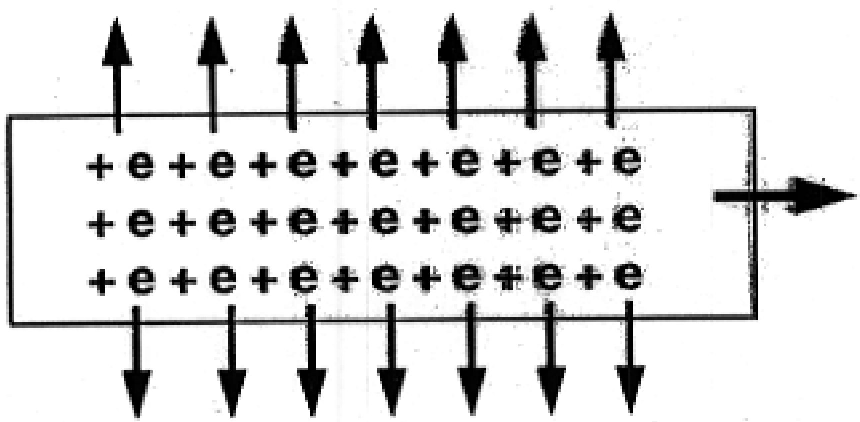
Groups: ANL, UCLA, LBNL, USC, SLAC

Ion Focusing

- **In vacuum:**



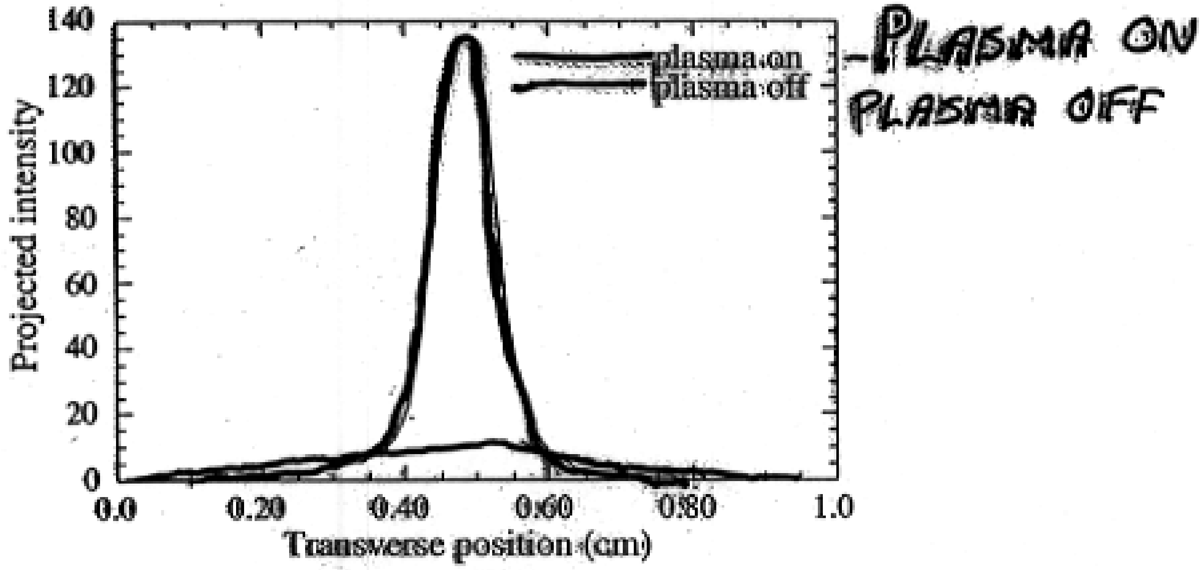
- **In underdense case ($n_p < n_b$, ion focused regime):**



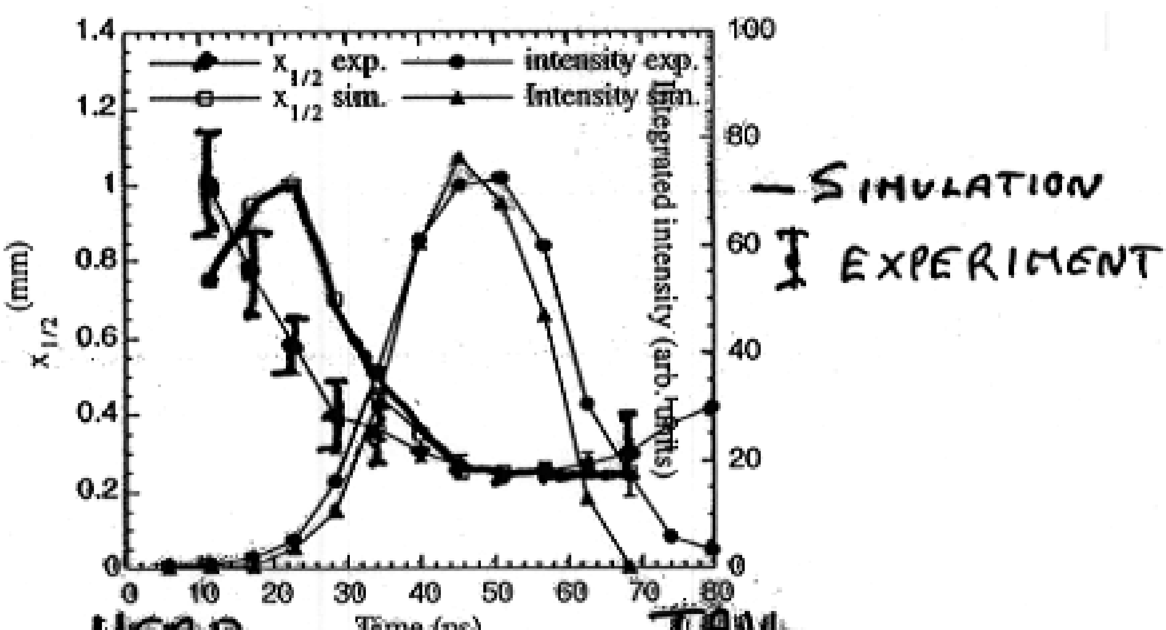
$$F_r = \frac{4\pi e^2}{r}\int_0^r n_b(r)(1-\beta^2)\,r\,dr - 2\pi e^2 n_p r$$

PROPAGATION EXPERIMENTS

- Time-resolved (psec resolution) and time integrated measurement of beam profiles at plasma exit. Near equilibrium confinement over 12 β-functions!



Time integrated images



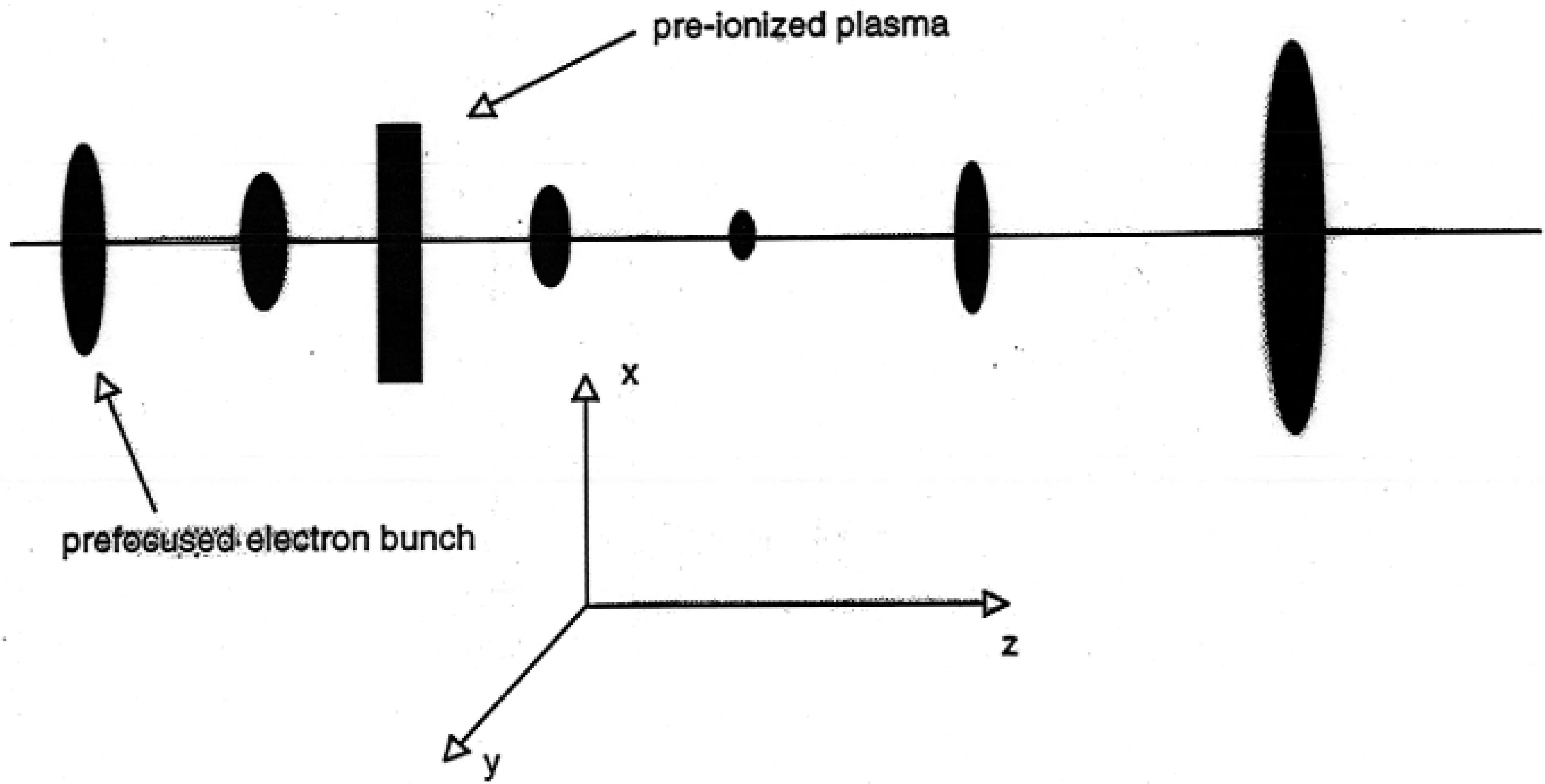
Time resolved profiles and comparison to PIC simulation

BAROV, et al

ANL/UCLA EXP

RETURN CURRENT PHYSICS LBNL/BTF
(ALS INJECTOR)

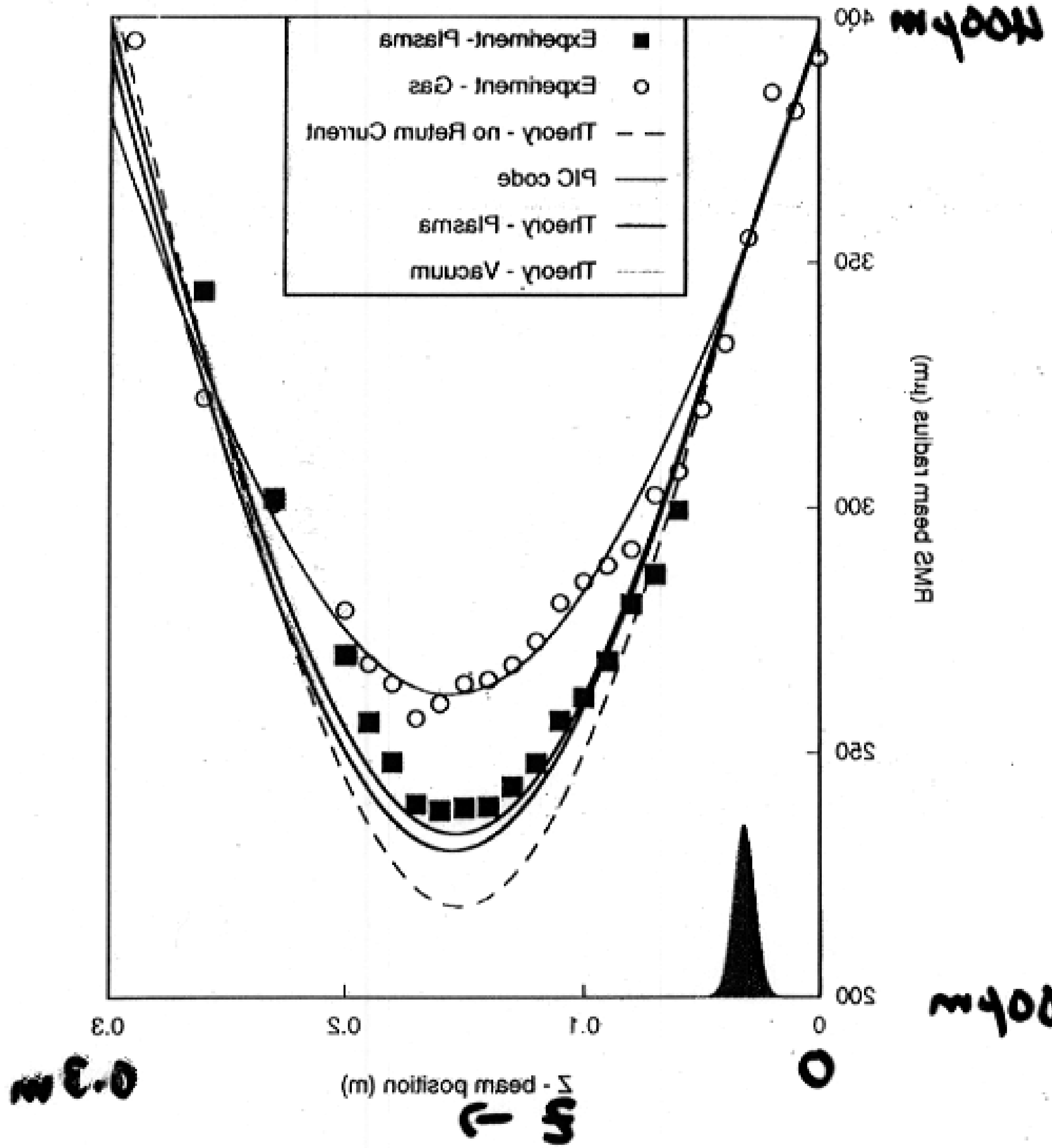
$k_p \sigma_r$ variable, $n_b < n_p$



Katya Backhaus Th.
(+J. W.)

R. Govil (Exp)
(+ W. Leemans)

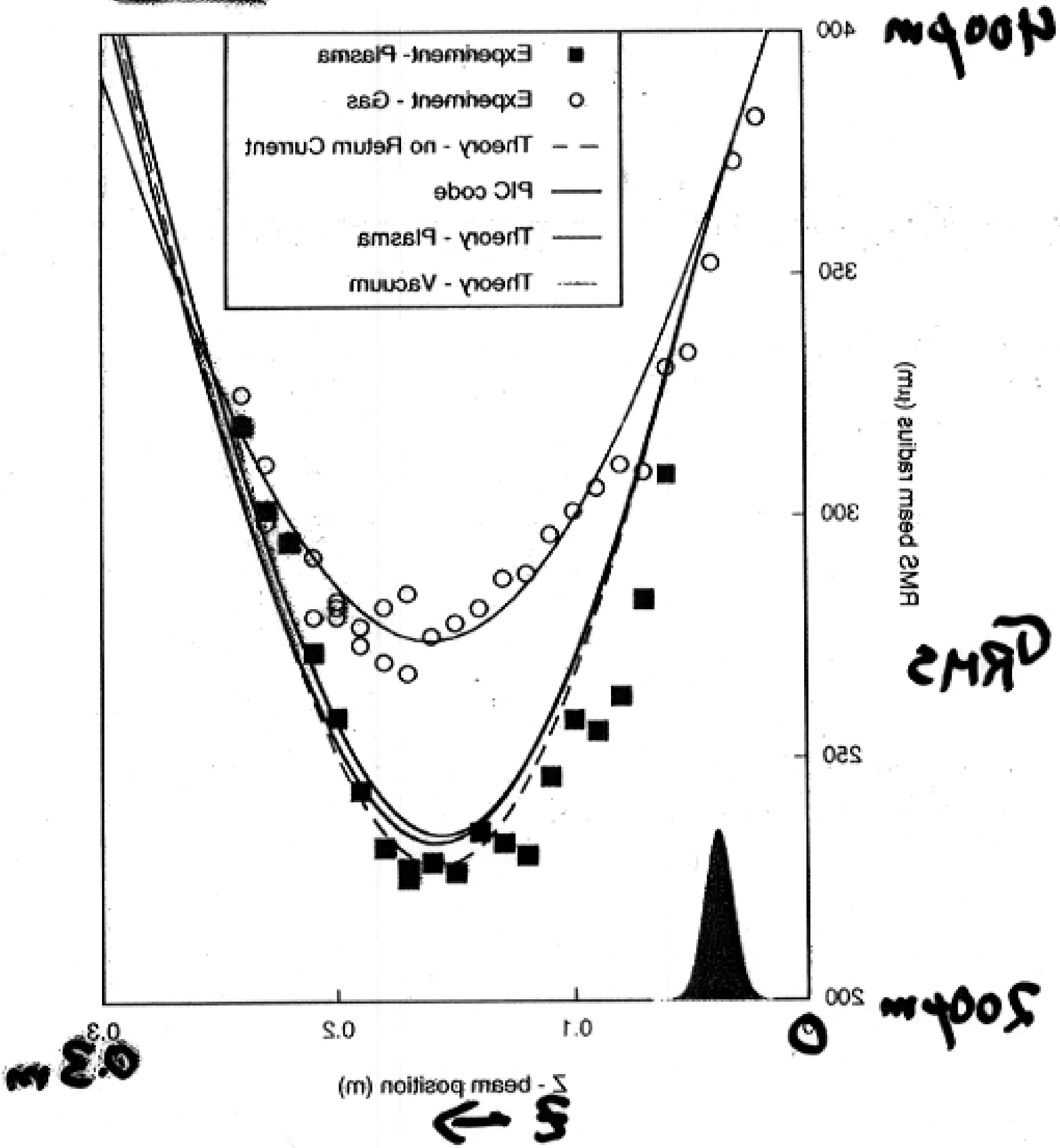
Plasma Lens with Large Return Current ($k_pR = 1.1$)



NOTE: PIC SIMULATION; ENVELOPE EQN
& EXP. AGREE.

Govil, et al; PRL 10/99

Plasma Lens with Small Return Current ($k_p R = 0.33$)



Plasma Lens

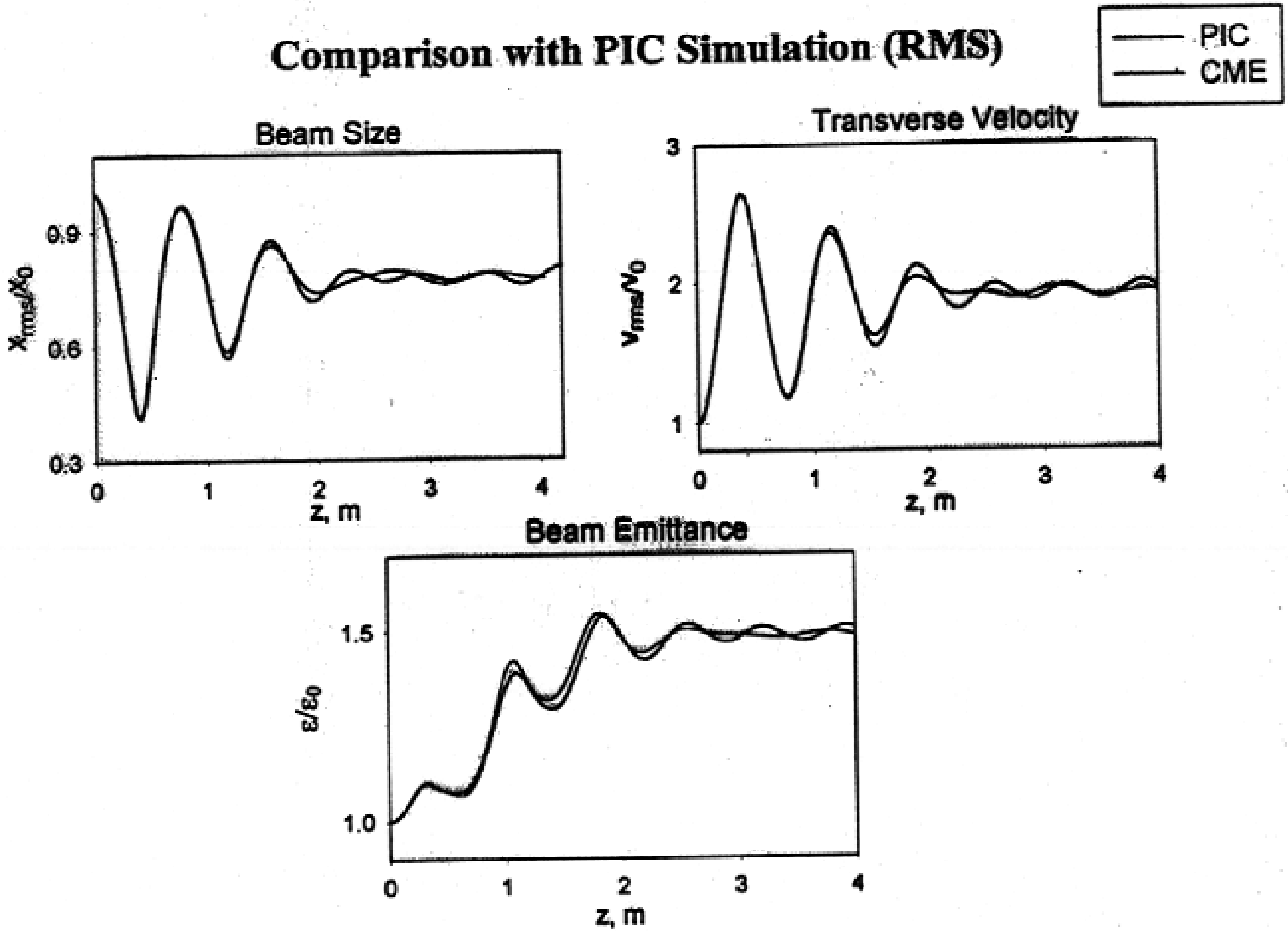
- LONG LENS $k_p \sigma_z > 1$
- $n_p > n_b$ space-charge neutralization
- $v_z \lesssim c$ and CONSTANT

$$X''_{rms} = \frac{\varepsilon^2}{X^3_{rms}} + \frac{1}{\gamma m c^2} \frac{\langle x F_x \rangle}{X_{rms}}$$

SAME EQNS FOR SELF-GRAVITATING SLAB!

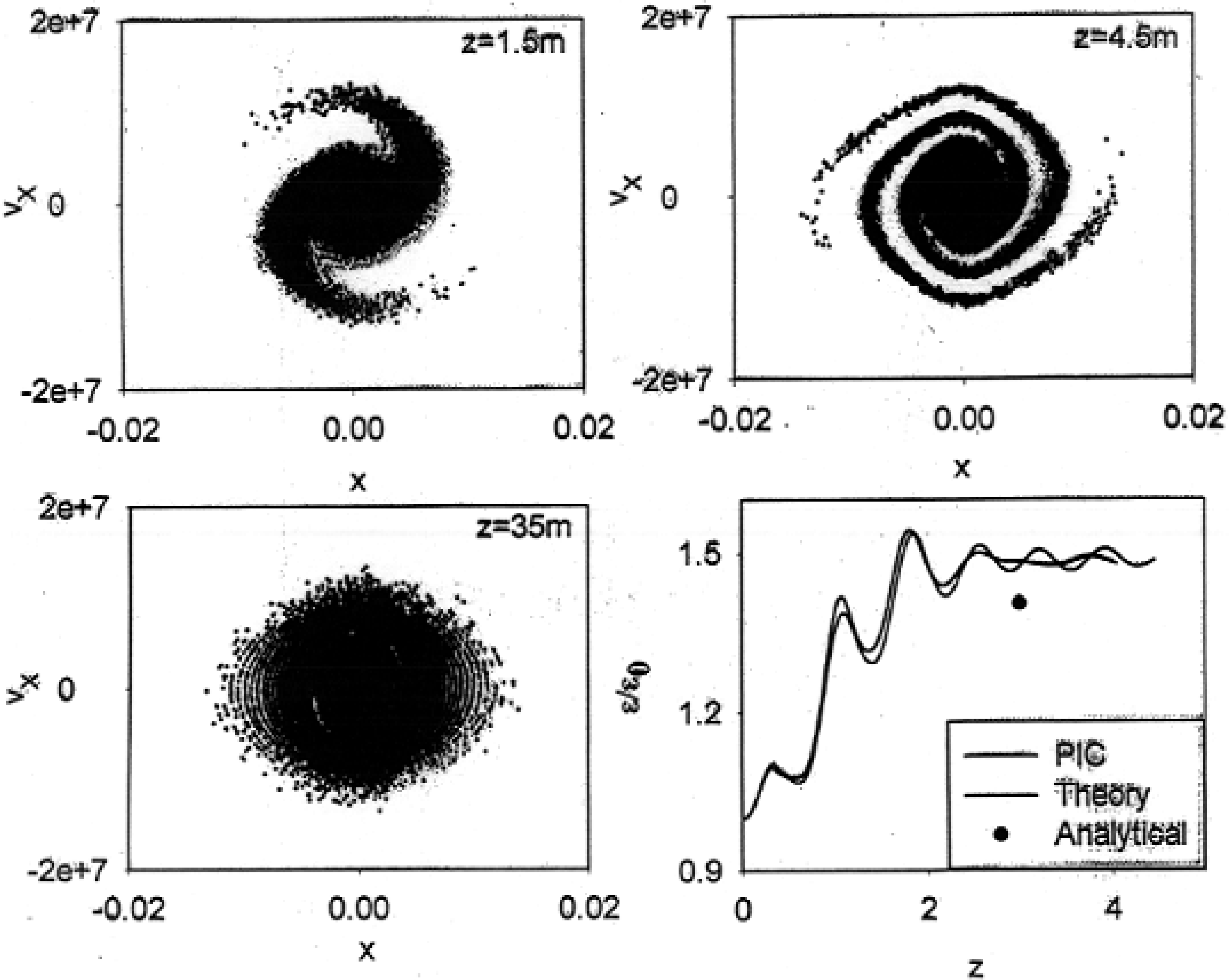
$$F_x = -qcB_y \qquad B_y = qc\mu_0 \int_0^x dx' \, n_b(x')$$

Comparison with PIC Simulation (RMS)

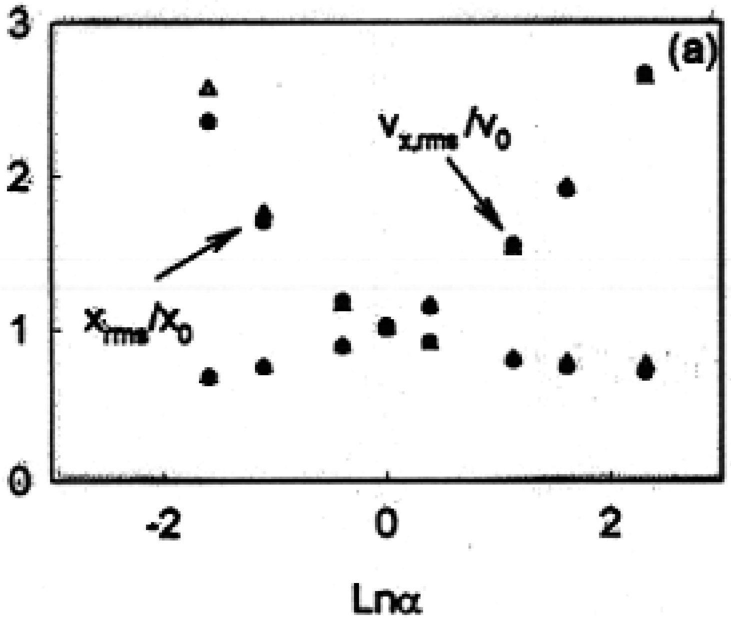


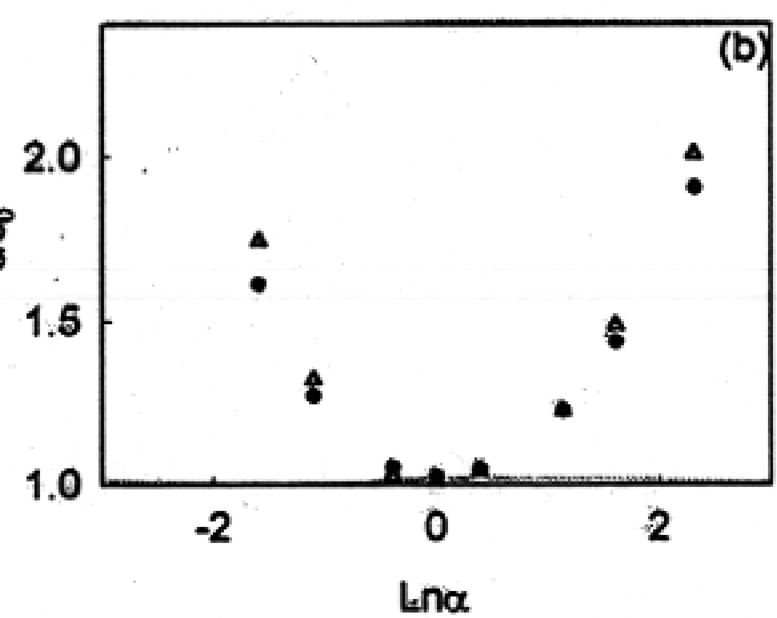
$k_{max} = l_{max} = 20$

Beam Transport in Slab Plasma ($k_p \sigma_z \gg 1$)



RMS Equilibrium in a long overdense plasma lens: Analysis and Simulation





Important considerations for accelerating structures (plasma and others)

- Method of excitation: ebeam or laser.
- Number of oscillations (Q) of wake
  - limits number of bunches--more charge/bunch at fixed efficiency
- Gradient/stored energy (loss factors k_n)
  - Determines beam dynamics and stored energy requirements
- Dark Current *(Nonlinear kinetic plasma physics)*
  - Must be controlled for high-energy applications
  - High gradient (~100GeV/m) plasma experiments operate in this regime. Earlier results (e.g., Joshi et al) achieved ~1.5GeV without dark current.
  - Limitations unclear

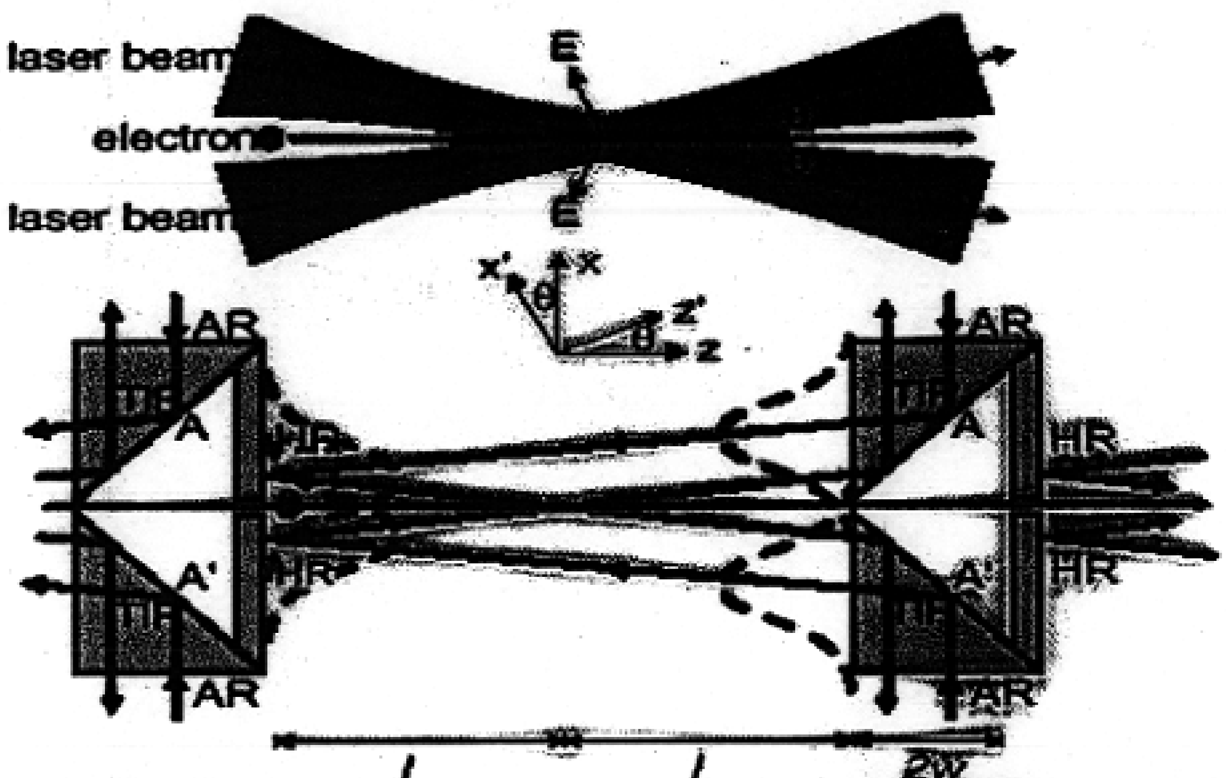
Summary: Plasma-based concepts

- Significant progress in plasma-based concepts: Experiment, theory, simulations, diagnostics.
- Next few years:
  - LASER driver: High power (10^{18}W/cm^2) propagation ($L >> Z_r$) and wake generation in channels
  - BEAM driver: Ultra-relativistic dynamics in plasmas (SLAC E150/E157)
  - Short bunch generation: Optical injection
  - Dark current limits
  - *Plasma structure design*--Femtosecond engineering
- For the future: High energy, beam quality and intensity, staging, efficiency

Vacuum Acceleration

- Laser (no plasma): Construct and excite small scale overmoded structures. Directly use the intense electric field of the laser.
- Issues: very short bunch length, structure damage, wakefields.
- A schematic (Laser Acceleration Experiment, Byer et al.). Bunch from

Stanford FEL. Accelerate 330keV at ~1GeV/m:



Summary

- Many ideas for solving critical problems towards building high-energy colliders. There are no obvious "show stoppers" for any of the schemes--but *strong* opinions on the correct direction to proceed. Even if all fail, a clever student may come up with a better idea!
- Significant research ongoing involving extended collaborations of laboratories and universities
- The timescale for investigating these concepts is longer than most would like.
- The next generation of colliders will not be the last!