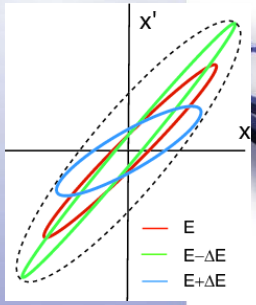
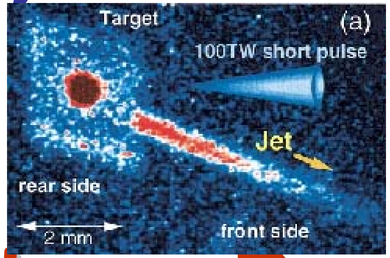
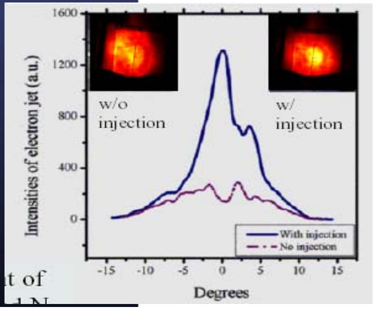
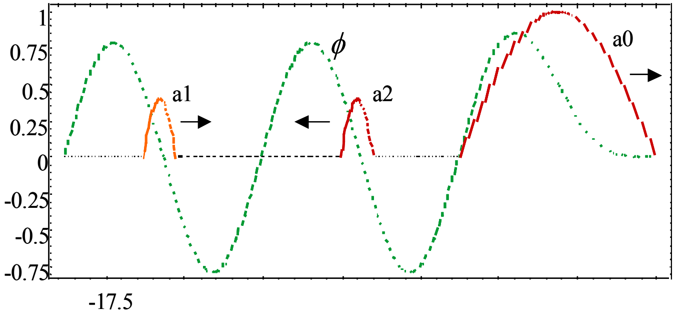


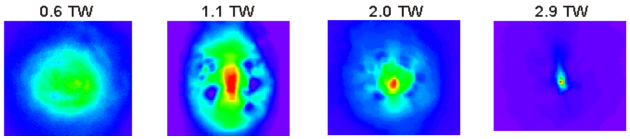


Progress In Understanding Plasma Based Electron Injectors

Experimental observations (based on the Self-Modulated Laser Wakefield Acceleration (SMLWFA)) have shown that nano Coulombs of electrons can be accelerated beyond relativistic energies (up into the neighborhood of 10 MeV) with a surprisingly small normalized transverse emittance of ~a few 10^{-7} π m rad. The longitudinal emittance is also small (MeV-ps) and poses an experimental and theoretical problem and opportunity. This talk describes results of an extension of the (transverse) K-V formalism to include a coupled longitudinal phase space.







DESY Accelerator Seminar 2/21/2003

Rainer Pitthan

Talk Is Based On….

….recent work on the west side of the SF of the Bay by Alex Chao, Rainer Pitthan, Toshi Tajima and Dian Yeremian with the title:

"Space Charge Dynamics of Bright Electron Beams",

published in SLAC-PUB-9189,

and on the experimental observations mentioned in the abstract.

We wanted: explore injection into an RF linac, while keeping the emittance below currently achieved values.

We realized that the longitudinal and the transverse phase space is coupled. This gives a better understanding of recent observation of low divergence electron beams emanating from plasma.

The nice thing about this work is a closed form, analytical, self-consistant, treatment, good for theoretical insight.

Meanwhile, across the Bay....

....Fubiani, Dugan, Leemans, Esarey and Bobin in Berkeley tried another approach:

An ellipsoidal macro-particle model in 6 dimensions which can handle arbitrarily large momentum spreads.

Important because the difference between any other electron source and plasma based: ~ 100% momentum spread.

This approach is great for modeling the evolution of the beam emerging from the plasma and making it graphically clear.

After proper calibration of different initial distributions the two approaches agreed in the results.

And more people have been involved:

To explore the possibilities of a plasma based injector a loose working group occasionally meets. Consists of people with a wide variety of experience in accelerators, emittance, lasers, and plasmas:

Yuri Batygin

Paul Bolton

Eric Colby

Rainer Pitthan

Ron Ruth

Carl Schroeder

Toshi Tajima

Dian Yeremian

What does this have to do with Lasers and RF Guns?

- First thought: Nothing.
- But at second thought: maybe a lot.
  - Physics of RF Guns and of Plasma Guns are not so dissimilar, just on a very different length scale: cm vs. μm.
  - Powerful lasers play a role in both.

We are always looking for the next good thing. When Fraser et al., proposed RF guns in 1985, it did not look not like such a hot thing.

It took Carlsten's insight into the emittance development and compensation to make RF Guns attractive for low emittance production. With Plasma-Guns we are in the pre-Carlsten stage.

Why do You Want even Smaller Emittances than an RF Gun? Need and Want!

Coherent Light Sources based on Linacs need small emittances (but not small spot sizes) for SASE to produce high brilliance:

- LCLS/TESLA for ~1-2 Angstrom wavelength needs $10^{-6} \pi$ m rad
- Future light sources in the sub-Angstrom regime need $10^{-7} \pi$ m rad

Linear Colliders need small emittances (and small spot sizes) for high luminosity:

- SLC was 400 nm vertical
- FFTB was ≈ 60 nm vertical
- 1 TeV linear colliders need ~ 5 nm
- 3 TeV linear colliders need ~ 1 nm

What We Have and What We Need:

- Emittances from existing "Injectors", with currents of typically 1 nCoul:

Injectors	Horizontal $\varepsilon_N\,(\pi\ \mathrm{m}-\mathrm{rad})$	Vertical $\varepsilon_N\,(\pi\ \mathrm{m}-\mathrm{rad})$
RF Photocathode Gun	1-3 10^{-6}	1-3 10^{-6}
SLC Damping Ring	3 10^{-5}	3 10^{-6}
ATF Damping Ring	5 10^{-6}	5 10^{-8}

- Future linear colliders need to achieve the requirements of the ATF damping rings, 3 10^{-6} and 3 10^{-8} π m rad in the horizontal and vertical, respectively.
- Linear collider damping ring emittance is not good enough for Coherent Light Sources. Bunches are too long (several mm) and horizontal emittance is too large.

What Y'all Know (1)

(Not carrying coals to Newcastle)

- In recent years short and bright bunches of electrons have been accelerated to relativistic energies in the MeV range in plasma, and driven out of the plasma, by the effects of intense short laser pulses.
- One features of these laser driven beams is the very short bunch length out of the plasma (100's of femto seconds). The short bunch length is due to the short pulse length of the laser and, therefore, within reason, a variable parameter of the experiment.
- The capture of electrons from the plasma bulk through the plasma wave proceeds through an instability and makes the energy spread **BIG.**

What Y'all Know (2)

- There are two remarkable properties of the ejected relativistic electrons:
  - the product of the bunch length and the energy spread, the longitudinal emittance, is comparable to conventional RF sources (in the range of MeV-ps)
  - the micron-size transverse spot size of the initial electron bunch corresponds to the laser spot size, is much smaller than in an RF source, and may, therefore, lead to a small transverse emittance.
- Unfortunately, "beam" properties of the electrons are not well defined experimentally (but work is going on on this). Foe example, pepper pot measurements difficult.
- In one experiment at $2\ 10^{11}$ electrons were originally produced and space collimated to $5\ 10^{8}\ e^{-}$ in an 5 millirad cone. In a nuclear physics spectrometer the energy spectrum was measured and gave energy of 7+-3 MeV with an "apparent" normalized transverse emittance possibly as low as a few 10-7 π m rad after 2~m of drift.

What Y'all Should Know (1)

(But maybe don't)

- The topic of the emittance is a subtle one, so we will define quantities which play a role. These quantities are a products of a spot size and a divergence, and sometimes loosely are called emittance, although maybe they shouldn't, because they aren't.
- In the following we will denote the location of the plasma exit with subscript 0 (zero) and the place of measurement with subscript 1 (one).
- We define a quantity ε_{01} which is derived from the product of the initial spot size at the plasma channel exit (location 0) and the divergence of the beam measured after a certain drift (20~cm and more, location 1), as in

$$\varepsilon_{01} = \sigma_0 \times \sigma'_1$$

This quantity is often called emittance in the plasma literature (although is is not an emittance) and we call it "apparent" emittance (which maybe a conceptual mistake).

What Y'all Should Know 2

- But, this quantity ε_{01} will be an upper limit on the original plasma exit emittance ε_{0}. Because, while we know the size σ_0 of the plasma channel quite precisely, the divergence σ'_1 at a distance has been subject to space charge forces during the drift.
- We define ε_0 to be the actual emittance at the exit point from the plasma.
- The quantity

$$\varepsilon_{11} = \sigma_1 \times \sigma'_1$$

at the place of measurement 1 is an upper limit on the actual emittance at location 1 (and this upper limit might be huge, although the emittance itself at location 1 might be quite small), because correlation between particle displacement and divergence in phase space is ignored.

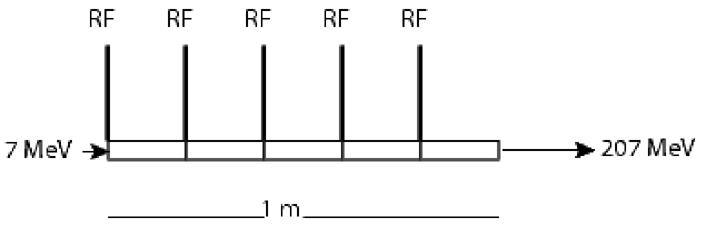
Now What? How to Process and Transport?

We put our money on RF Adiabatic Acceleration:

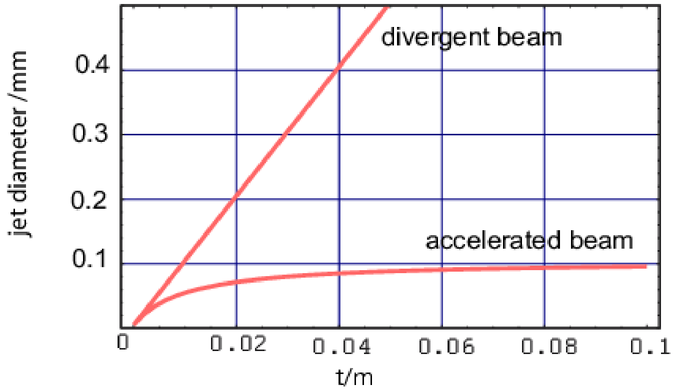
Conventional: built special X-band standing wave section with G=200 MeV/m. In lieu of continuous focusing.

$\Delta E/E$ (@2MeV)=50% ->

$\Delta E/E$(@200MeV)=0.5%.



Non-Conventional: use Plasma Acceleration with G=150 GeV/m. Only need a few mm (as shown by RAL). Can be integrated into the plasma gun, so no drift space. Further advantages: the charge is neutralized in the plasma channel during acceleration.



The question then is: what happens with the emittance, before you can RF-capture it?

How Does Plasma Acceleration Roughly Work?

Originally proposed by Toshi Tajima and John Dawson: PRL:43,167,1979

The E-field of the intense laser pulse grabs electrons and creates "quiver" motion. The fields are so intense, quiver electrons become relativistic.

This creates plasma waves through the action of non-linear ponderomotive (v x B) forces. Electrons are trapped in plasma wakes and can be accelerated to high energy.

Energies of 200 MeV have been observed and Gradients up to many GeV/cm.

There is a multitude of different mechanisms how this works in detail. Not discussed here in general.

One important concept to look for in the plasma acceleration field is self: self-focused, self channeled, self-fields, ... Murphy's Law does not seem to apply!

Get Some Numerical Feeling for Plasma Properties

Electric fields in plasmas: $E_0 \approx 97\sqrt{n_0}$ [cm^{-3}] V/m (n_0 plasma density)

Plasma wavelength: $\lambda_p \approx 3.3\ 10^{10}\ 1/\sqrt{n_0}$ [cm-3] μm

For $n_0 = 10^{18}$/cc (a supersonic gas jet): $E_0 \approx 100$ MeV/mm and $\lambda_p \approx 30$ μm

Plasma (electron) densities range from ≈ 10^{16}/cc (underdense plasma) to ≈10^{20}/cc in supersonic gas jets to 10^{24}/cc in metals.

Table Top Laser Power has reached Multi –Terawatt. Equally important is area intensity. Typical order of Intensity is $I \approx 10^{17} - 10^{19}$ W/cm^2.

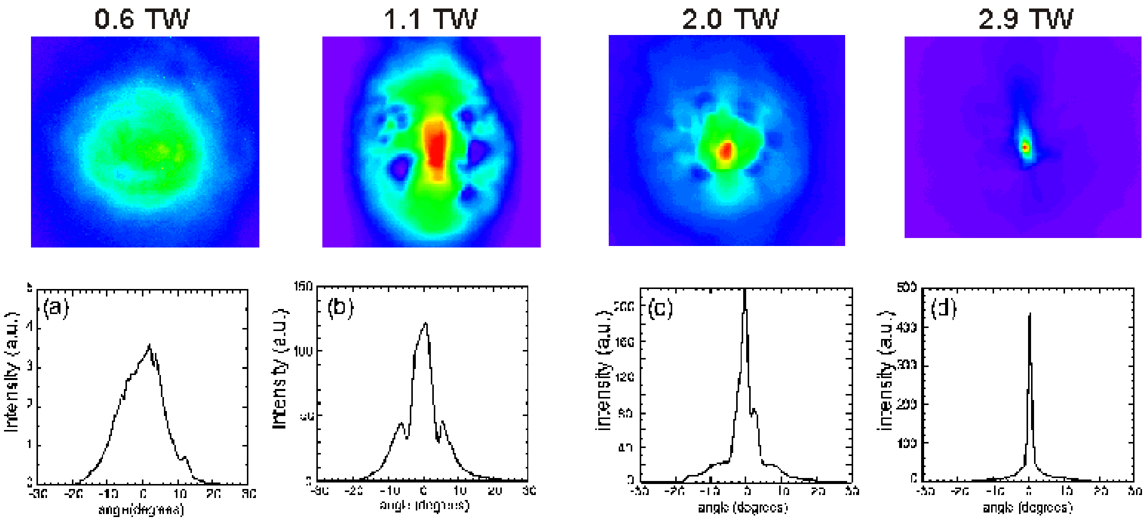
Also important: Laser Electric Field (of a linearly polarized laser):

$$E\ [\text{TV/m}] \approx 2.7\ 10^{-9}\ \sqrt{I}\ [\text{W/cm}^2];$$

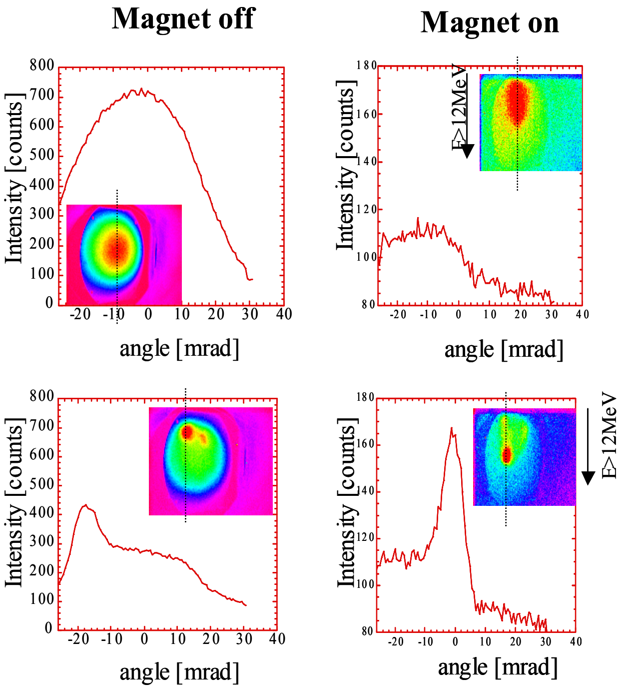
$$\text{with } I \approx 10^{18}\ \text{W/cm}^2 \Rightarrow 2.7\ \text{GV/mm}$$

Laser Magnetic Field: with 1 MV/300 m = 1T ⇒ 10kT or 100 MG

What Was Observed in Detail



Shine a Laser on suited matter (gas jet, foil)



Michigan:

Physics of Plasmas 6 (1999) 4739

Berkeley:

Physics of Plasmas 8 (2001) 4739

What Has Been Observed w.r.t. Emittance?

General Transverse Emittance definition:

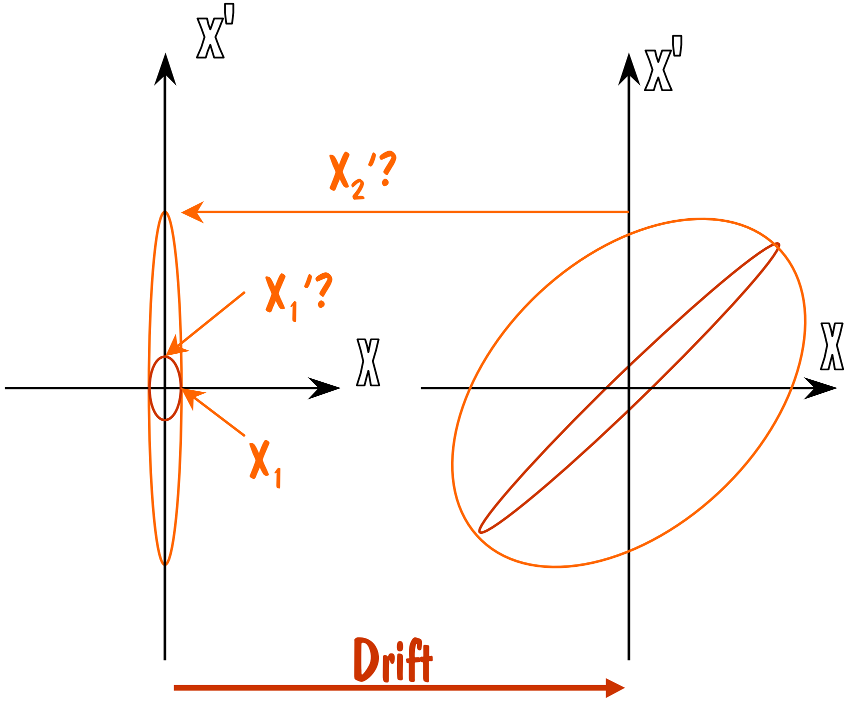
$$\varepsilon_{\perp}{}^2 = \langle x^2\rangle\langle x'^2\rangle - \langle x\, x'\rangle^2$$

X is determined from the plasma channel size x_1 at Position 1. Nothing is known about x_1', it could be as small as indicated in the small ellipse.

X′ was taken from position 2, from the projection onto the x′-axis, x_2'.

If ellipsoid area is not enlarged through space charge effects, or only through linear forces, then there are no correlations $\langle x\, x'\rangle^2$.

In this case the emittance calculation as x x′ is acceptable, but is really only an "apparent" emittance composed of $\varepsilon_{12} = x_1\, x'_2$



Position 1
(Plasma Channel)

Position 2
(Screen)

Envelope Equation Describes Transverse Emittance Only

$$r'' + k^2 r + \gamma' r'/\gamma^2 - 2I/(\gamma^3 I_A r) - \varepsilon^2/(\gamma r^3) = 0 \text{ (if uncoupled)}$$

Solen. field

Adiabatic acceleration

Charge spreading term

Emittance term

ε is sometimes called the edge (or envelope) emittance. Pay attention to the different powers of γ and r which lead to a subtle dance of emittance preservation in RF guns.

The emittance term dominates in classical electron transport near a sharp focus, or after the beam goes through a pinhole. But the whole equation probably does not apply to the non-classical situation here.

In the following we use σ instead of r to denote the transverse coordinate.

OK for RF Guns, when energy spread is small.

Coupling the Transverse and Longitudinal – I

Parabolic Ansatz (analog the K-V distribution) leads to the following differential equations for the longitudinal case. The solutions are self-consistent.

$\langle\delta^2\rangle' = 2\kappa^2\langle z\delta\rangle$

with $\Delta P = mc\delta$ the momentum deviation, or $\delta = \Delta(\beta\gamma)$

$\langle z\delta\rangle' = \langle\delta^2\rangle / \beta^2\gamma^3 + \kappa^2\langle z^2\rangle$

$\langle z^2\rangle' = 2\langle z\delta\rangle / \beta^2\gamma^3$

With $\kappa^2 = 2 N r_0 / [5^{3/2} \beta \gamma^2 \langle z^2\rangle^{3/2}][\ln\{(\gamma^2\langle z^2\rangle+4\sigma^2)^{1/2}/2\sigma\} + \frac{1}{2}]$

Coupling of the longitudinal dynamics to the transverse dynamics is described by the (relatively) weak dependence of σ in the logarithm of κ^2.

The time derivative of the longitudinal emittance, $[\langle\delta^2\rangle \langle z^2\rangle - \langle z\delta\rangle^2]'$, is zero which means it is a constant of the motion and determined by the initial condition of the beam.

Coupling the Transverse and Longitudinal – II

Derivation with the parabolic Ansatz of the K-V (Kapchinskij-Vladimirskij) distribution leads to the following differential equations for the transverse case. The solutions are self-consistent.

In the absence of acceleration and focusing fields

$$\sigma'' - \varepsilon^2_{N,RMS}/\beta^2\gamma^2\sigma^3 = \xi/8\sigma$$

where the coupling to the longitudinal is contained in the parameter ξ

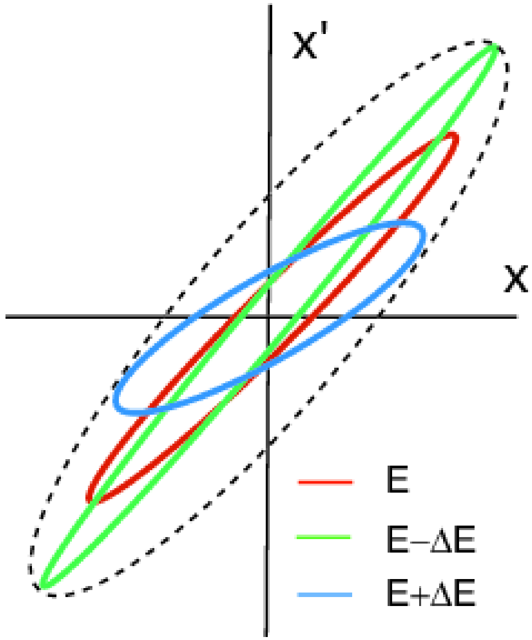
$$\xi = 3\,N\,r_0 / \sqrt{5}\,\beta^2\,\gamma^3\,\langle z^2\rangle^{1/2}$$

with ξ a modified line charge density evaluated at the bunch center.

Longitudinal and transverse emittances are constant of the motion, even with coupling. There are no intrinsic emittance growths in the model. These would have to come from the motion kinematics or non-linearities in the space charge force.

Problems in Emittance Preservation

- PARMELA simulations are in good agreement with the experimentally derived beam sizes and divergences, and our calculations of $\varepsilon_{01,rms} = \sigma_0 \times \sigma'_1$
- Main cause of emittance increase for plasma based electron injector is the energy spread. The emittance increases even after the divergence saturates. Transverse dynamics depends on $1/\gamma^3$, so low energy particles rotate faster in phase space x'-x, leading to the so-called <u>bow-tie effect</u>.

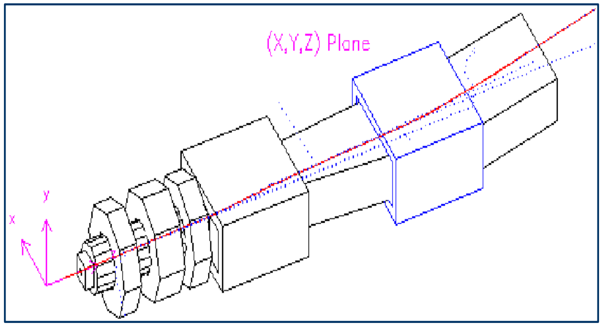


Cooperation between UMich and Hampton U/JLAB

NIM A438 (1999) 265

One important question is: is the core of the jet more energetic? Then radial collimation helps energy spread.

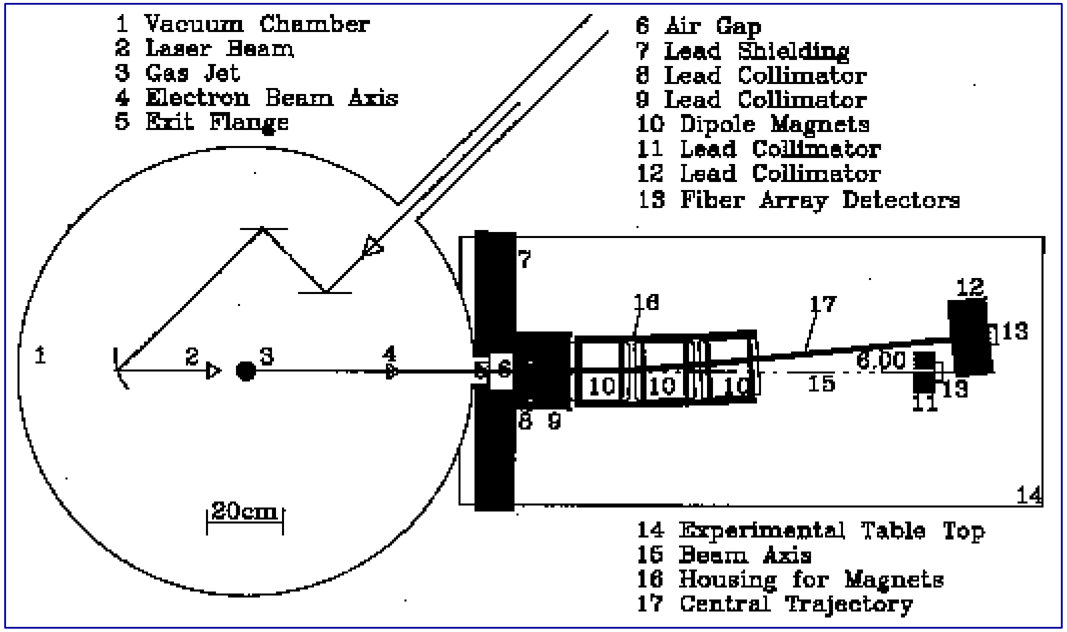
1 cm diameter collimator in 2 m distance from the gas jet (plasma) defines a cone of 5 mrad FWHM ($\sigma'=2.5$ mrad). The momentum in this cone is 7±3 MeV .



QQQDD Beamline

P. Gueye, C. Keppel, R. Ent, K. Assamagan, R. Green, J. Taylor and W. Buck

Hampton U/JLAB

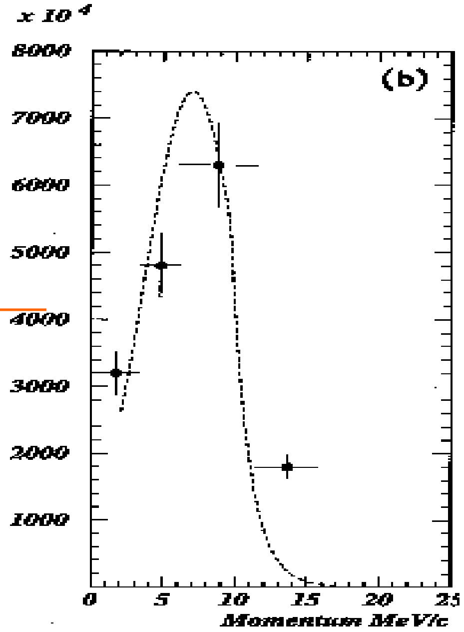


Correlation Free Emittance Assumed

From the μm-size radius plasma channel size and the divergence, one can calculate $\gamma\varepsilon$, if there are no non-linear space charge effects.

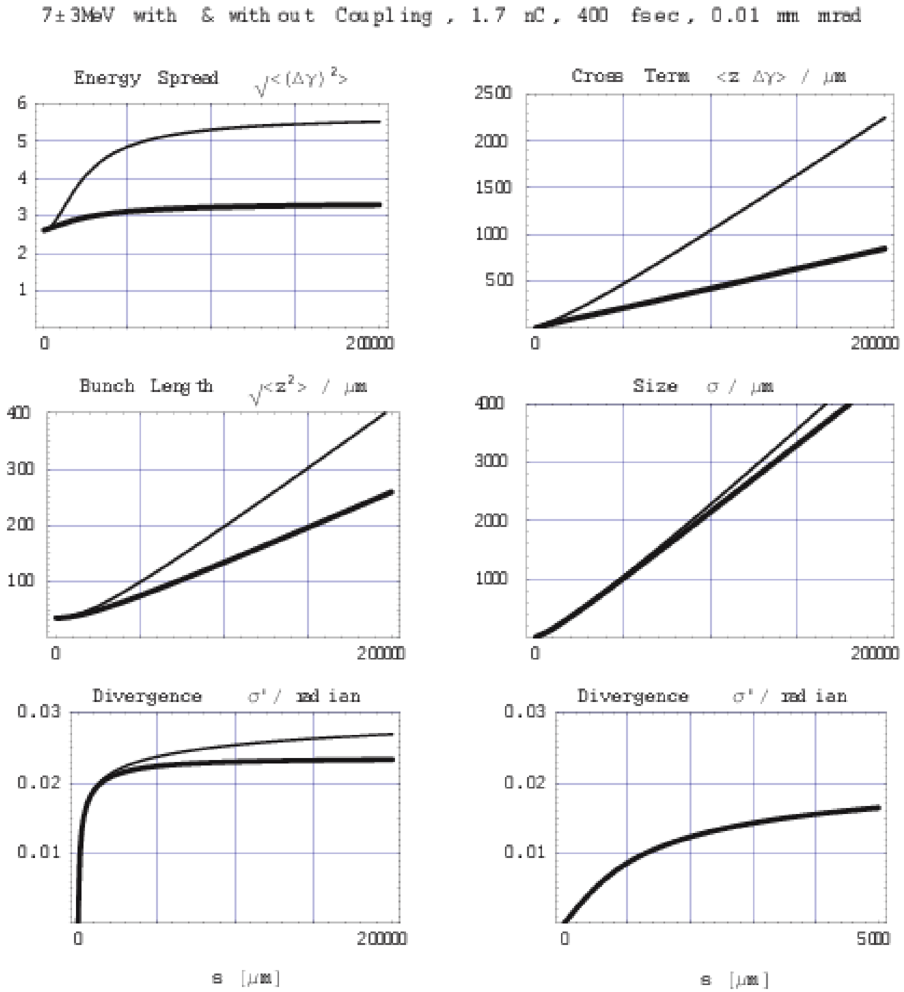
Comparison between two UMichigan experiments give low apparent envelope emittances ε_{12} for both. Both used 4-5TW lasers with 400 fs (120μm) pulse length on a gas jet. The main difference is the centroid collimation used in the second experiment.

Meas./Coll. divergence /mrad	10	2.5
N_e	10^{10}	$5\ 10^{8}$
Avg Energy/MeV	1	7
Energy spread	1	3
Laser/Plasma spot size/μm	9/5	14/8.5
$\gamma\varepsilon_{12}/\ 10^{-6}\ \pi$ m rad	0.13	0.3



Difference Between Coupled and Uncoupled Cases

- Coupled case: thick line
  Uncoupled case: thin line
- 20 cm drift before measurement, as in a typical Laser-Plasma experiment
- Charge (assumed) 10^{10} e^-, original laser pulse length (FWHM) 400 fs, equal to length of 54 μm rms
- Energy spread and bunch length grow substantially between coupled and uncoupled case



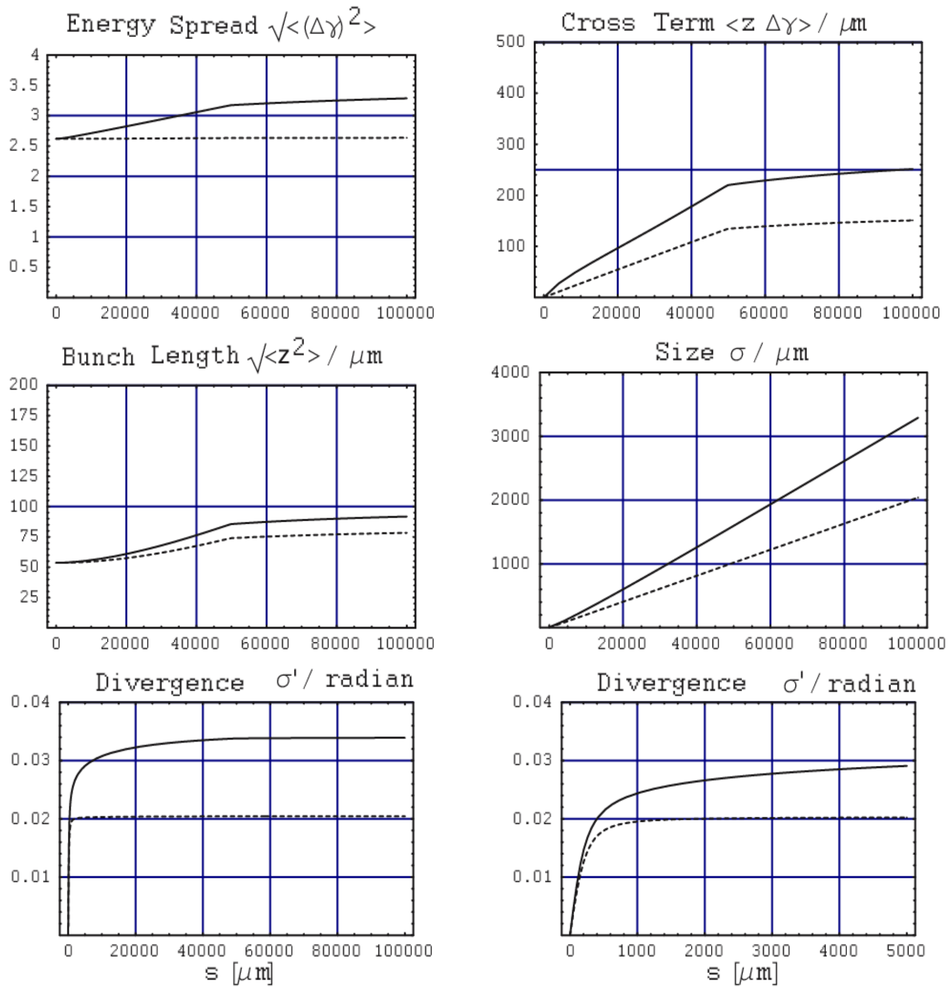
6-dim Development of $5\ 10^8$ and $2\ 10^{10}$ e^-

Look at coupled calculations only for the experiments just discussed. Take the (7±3) MeV case, with 100 MeV/m acceleration kicking in at 5 cm:

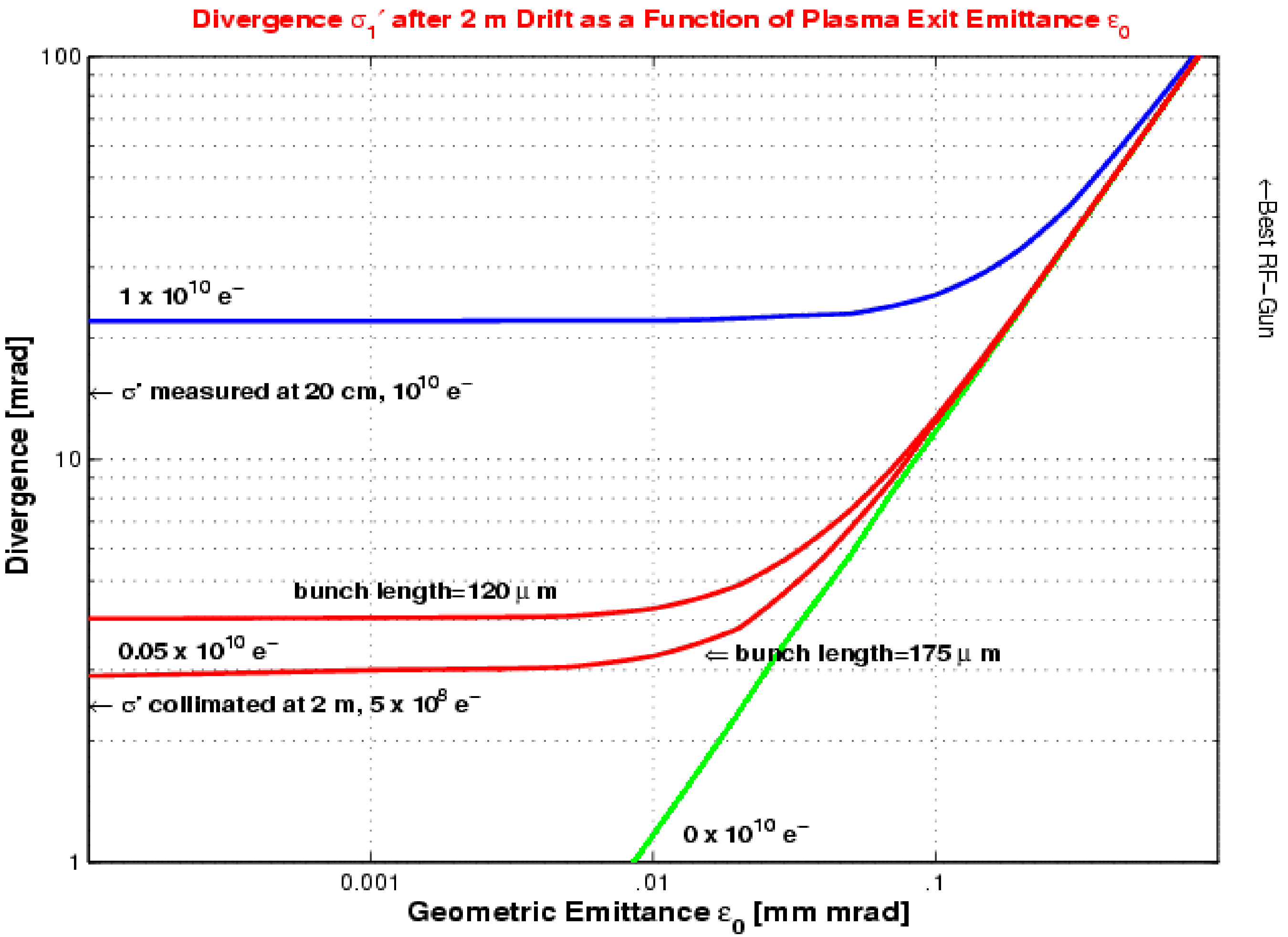
To stress the effect of the charge, larger charges were calculated as well.

Initial values:

- Plasma spot size $\sigma_0 = 8.5\ \mu m$
- Emittance $\varepsilon_0 = 0.1$ mm mrad
- Divergence $\sigma'_0 = 0$ mrad



Relating Measured Divergence to Initial Emittance



Relating Divergence to Initial Emittance

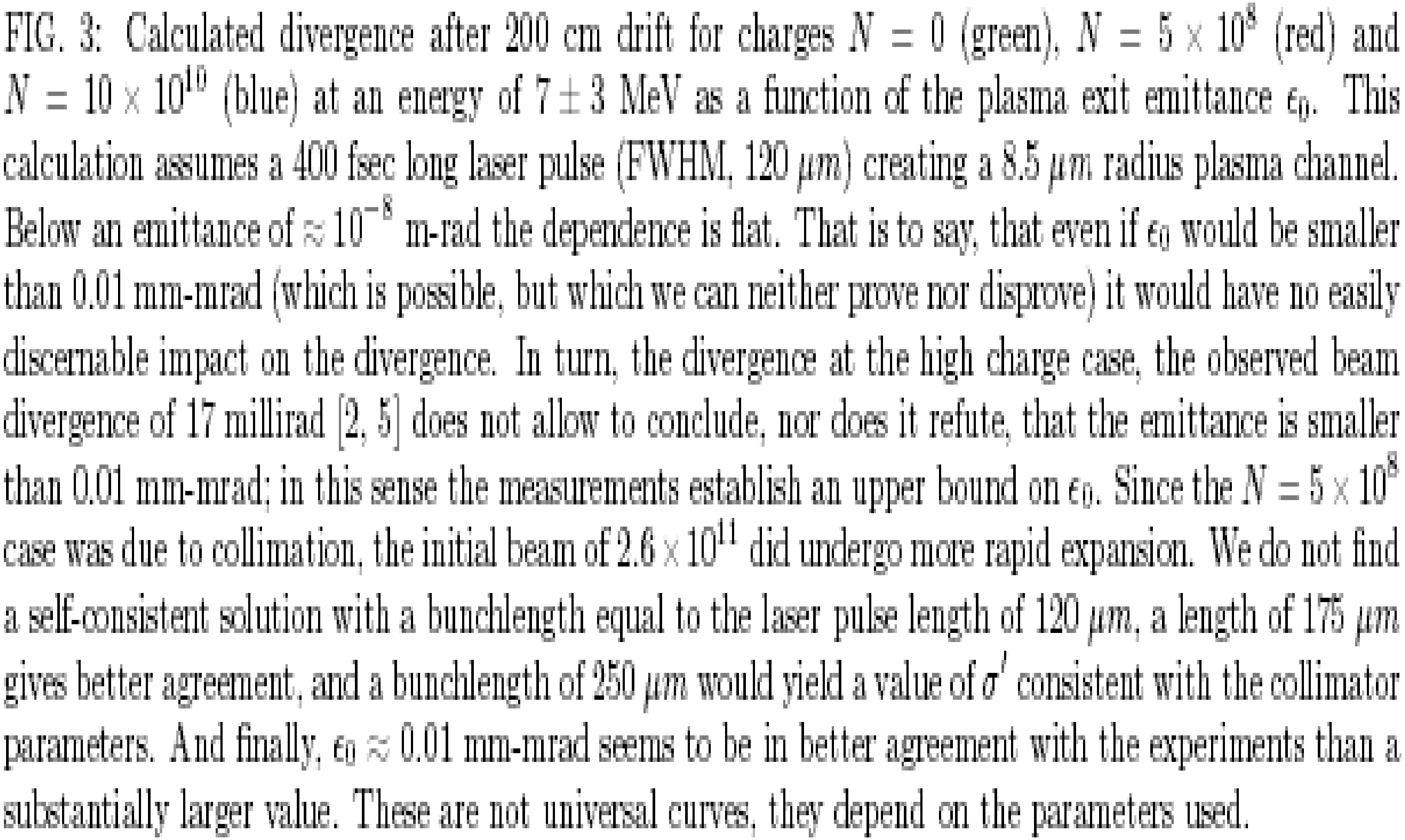
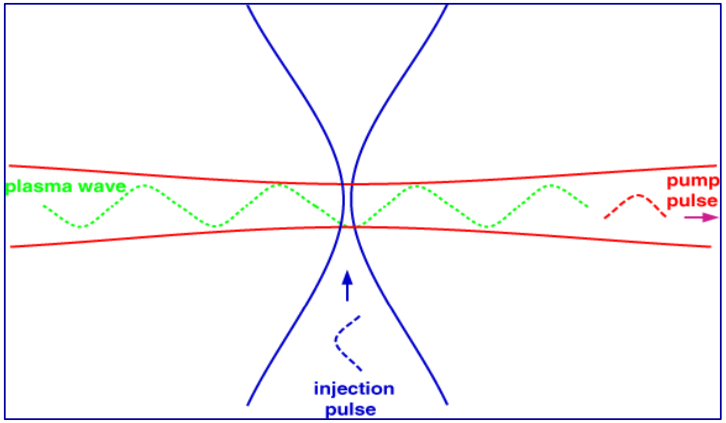
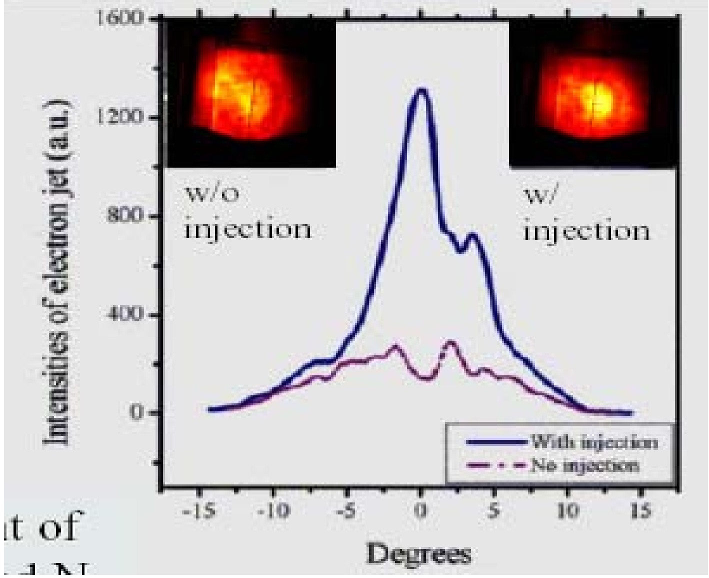


FIG. 3: Calculated divergence after 200 cm drift for charges $N = 0$ (green), $N = 5 \times 10^8$ (red) and $N = 10 \times 10^{10}$ (blue) at an energy of 7 ± 3 MeV as a function of the plasma exit emittance ϵ_0. This calculation assumes a 400 fsec long laser pulse (FWHM, 120 μm) creating a 8.5 μm radius plasma channel. Below an emittance of $\approx 10^{-8}$ m-rad the dependence is flat. That is to say, that even if ϵ_0 would be smaller than 0.01 mm-mrad (which is possible, but which we can neither prove nor disprove) it would have no easily discernable impact on the divergence. In turn, the divergence at the high charge case, the observed beam divergence of 17 millirad [2, 5] does not allow to conclude, nor does it refute, that the emittance is smaller than 0.01 mm-mrad; in this sense the measurements establish an upper bound on ϵ_0. Since the $N = 5 \times 10^8$ case was due to collimation, the initial beam of 2.6×10^{11} did undergo more rapid expansion. We do not find a self-consistent solution with a bunchlength equal to the laser pulse length of 120 μm, a length of 175 μm gives better agreement, and a bunchlength of 250 μm would yield a value of σ' consistent with the collimator parameters. And finally, $\epsilon_0 \approx 0.01$ mm-mrad seems to be in better agreement with the experiments than a substantially larger value. These are not universal curves, they depend on the parameters used.

Reduce Energy Spread: Several Lasers
First Proposal: Use Two (LILAC)





Laser Injected Laser Accelerator (LILAC):

PRL 76(1996) 2073

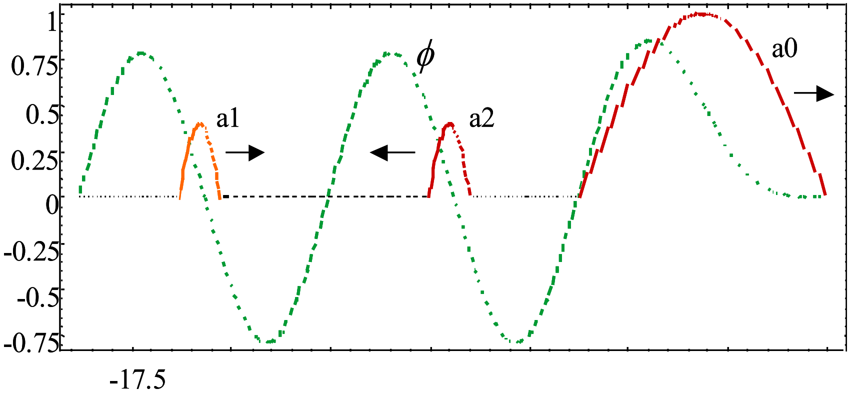
One Laser produces the Plasma.
A second laser beam intersects and accelerates.

Simulations from UMich give typically (there is wide variation in possible parameter space):

Power (pump)	≈ 15TW
E	≈ 40MeV
$\Delta E/E$	≈ 1.25% (500keV)
τ	≈ 5 fs
N	≈ 10^8 (one bucket)
$\gamma\varepsilon_\perp$	<1 mm mrad
$\varepsilon_\parallel$	≈ 2.5 10^{-9} eV sec

Reduce Energy Spread: Several Lasers Later Proposal: Use Three

- Increase control of plasma (and electron) parameters by using 2 or more lasers: for example, a high intensity pump laser with amplitude a_0, and two counter propagating lower intensity lasers a_1 and a_2 which create a beat wave.
- The beat wave corresponds to a physical RF structure designed to create ultra short bunch.
- Timescale of 1fs determined by pre-bunching of electrons in the plasma wave buckets. Number of electrons must be augmented by having many buckets.

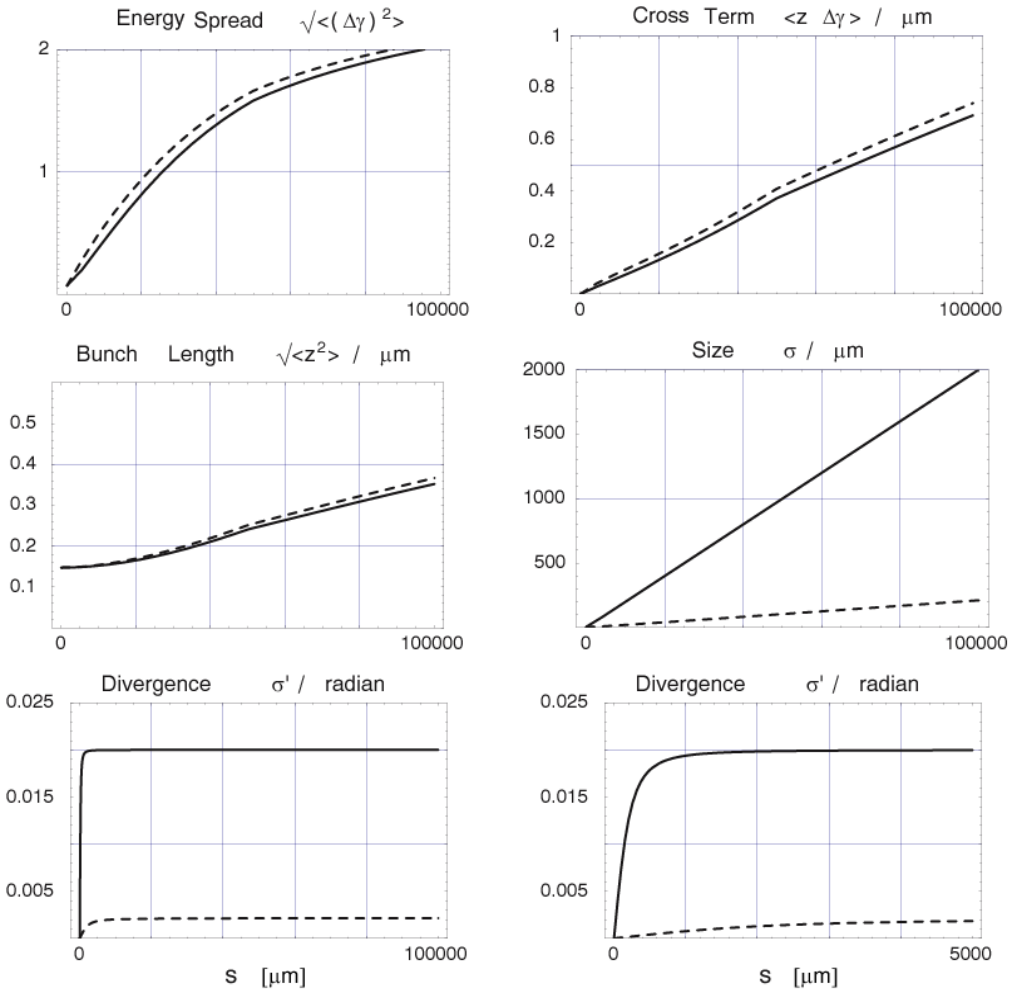


C. Schroeder et al., PRE 59(2000)6037

Simulations from LBL give typically (there is wide variation in the parameter space):

Power (pump)	≈ 15TW
E	≈ 40MeV
$\Delta E/E$	≈ 0.2% (=80KeV!)
τ	≈ 1 fs
N	> 1.5 10^7
$\gamma\varepsilon_\perp$	< 1 mm mrad
$\varepsilon_{\|\|}$	≈ ~0.1 10^{-9} eV sec

Simulation of the Berkeley 3-Laser (Simulation) Results



Initial values:

Plasma spot size: $\sigma_0 = 5\ \mu m$

- **Energy** 40 MeV
- **Energy spread** 80 keV
- **Emittance:**
  - ε_0 = 0.1 mm mrad (solid line)
  - ε_0 = 0.01 mm mrad (dashed line)
- **Divergence** σ'_0 = 0 mrad

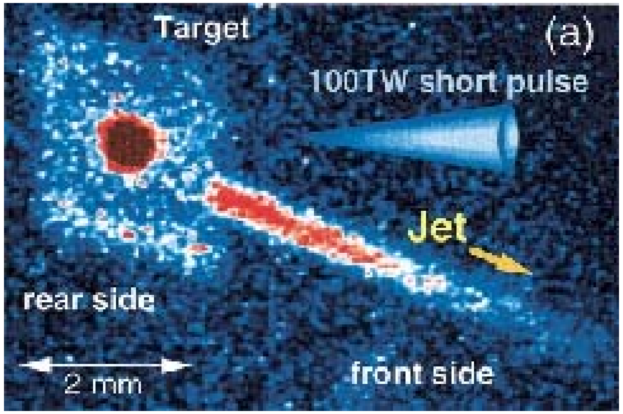
2 Laser Experiment: Pre-formed Plasma

- 100 TW 500 fs Laser light reflected from a pre-formed plasma (GEKKO) produces jet of electrons in the direction of the reflected light.
- Electrons self-generate magnetic field (2-3 10^6 Tesla!). Explains collimation of the electrons (there is also some self-focusing).
- Electron motion from the Laser E-field in the magnetic field produces 10-30 keV X-rays).
- X-ray pinhole camera maps the jet: divergence is constant. No space charge effects noticeable.

Experiment

X-ray

picture

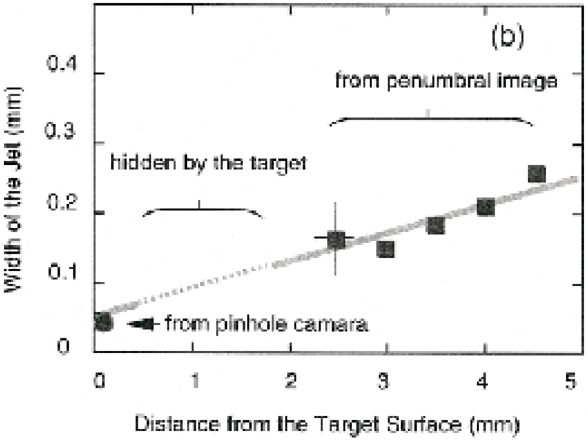


Constant

divergence:

What does

it mean?



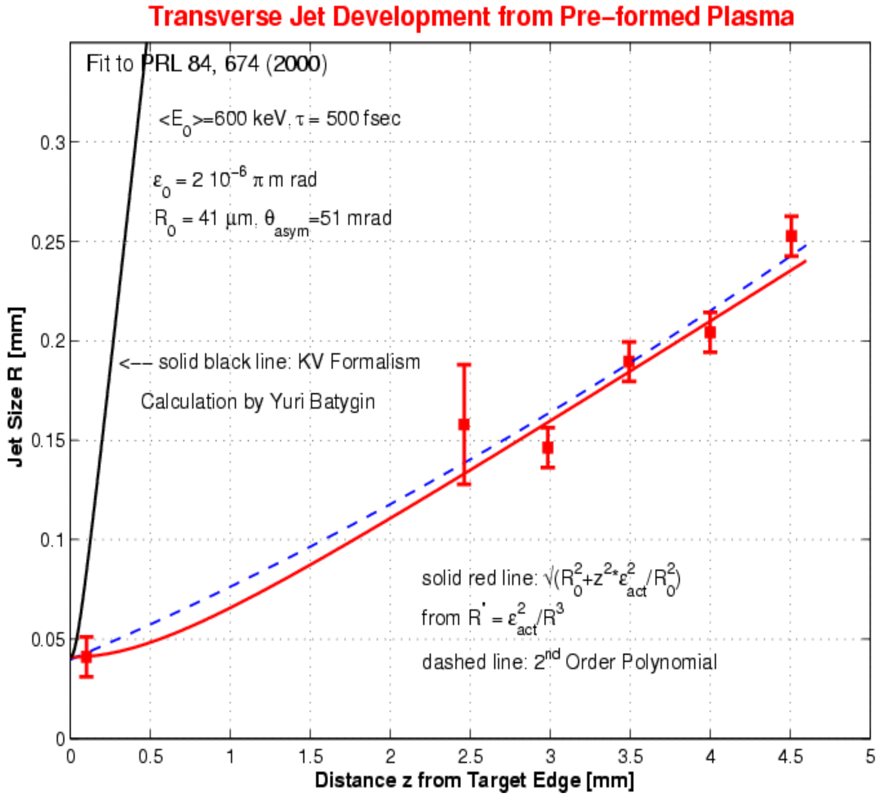
Phys. Rev. Letters 84:674,2000

Emittance and Space Charge Considerations

Important to remember: the emittance of an RF gun is spot size dominated, the emittance of a Plasma Gun is divergence dominated.

The divergence allowed for the beam from the Plasma Gun is 10 mrad but only 10-100 μrad for a RF gun. The plasma gun is, for equal emittance, a factor of 100-1000 more robust against Space Charge kicks.

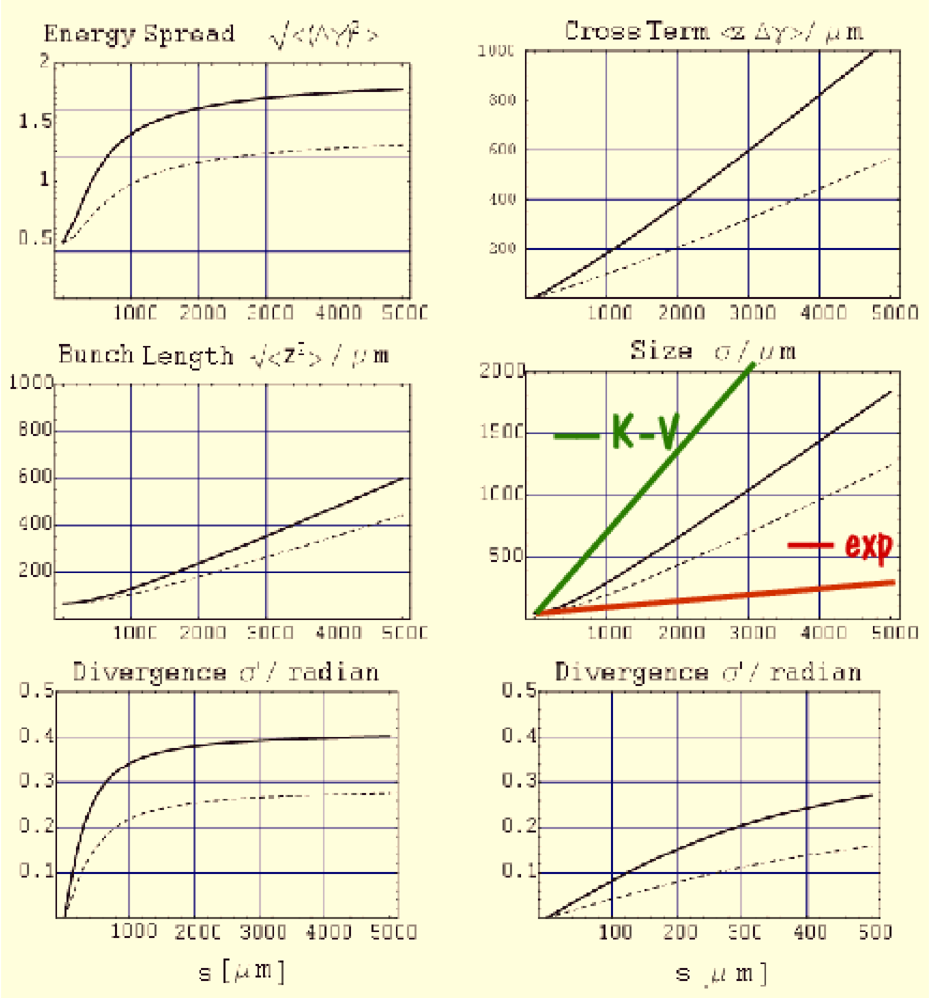
The neutralized electron bunch does not experience a space charge force (F_c) in the plasma channel.



The experimental evidence from the 2-Laser experiment does not show any obvious space charge effect (linear curve). However, KV based calculation show the bunch radius should grow rapidly outside – but it doesn't.

Does Our Coupled Theory Do Better Than KV?

- Well, yes, some, but....
- The 2 curves are for 4 10^{10} and 8 10^{10} e-, respectively.
- Phase space coupled simulations show the importance of initial energy, which is only 600keV (average) here. If it would be 1.5 MeV, the simulation would describe the experiment quite well. But it isn't 1.5 MeV!!!
- There must be other physics be buried in it.
- Simulation by the authors of the experiment shows plasma acceleration and plasma focusing as a possibility.



Simulation of an electron bunch with large energy spread (LBL Simulations) l'OASIS Group

$N_p = 50000$

$Q = 1\,\text{nC}$

$p_z : 0.1 \rightarrow 6\ \text{MeV}$

$x_m = 6\ \mu\text{m}\ ,\ x'_m = 2\ \text{mrad}$

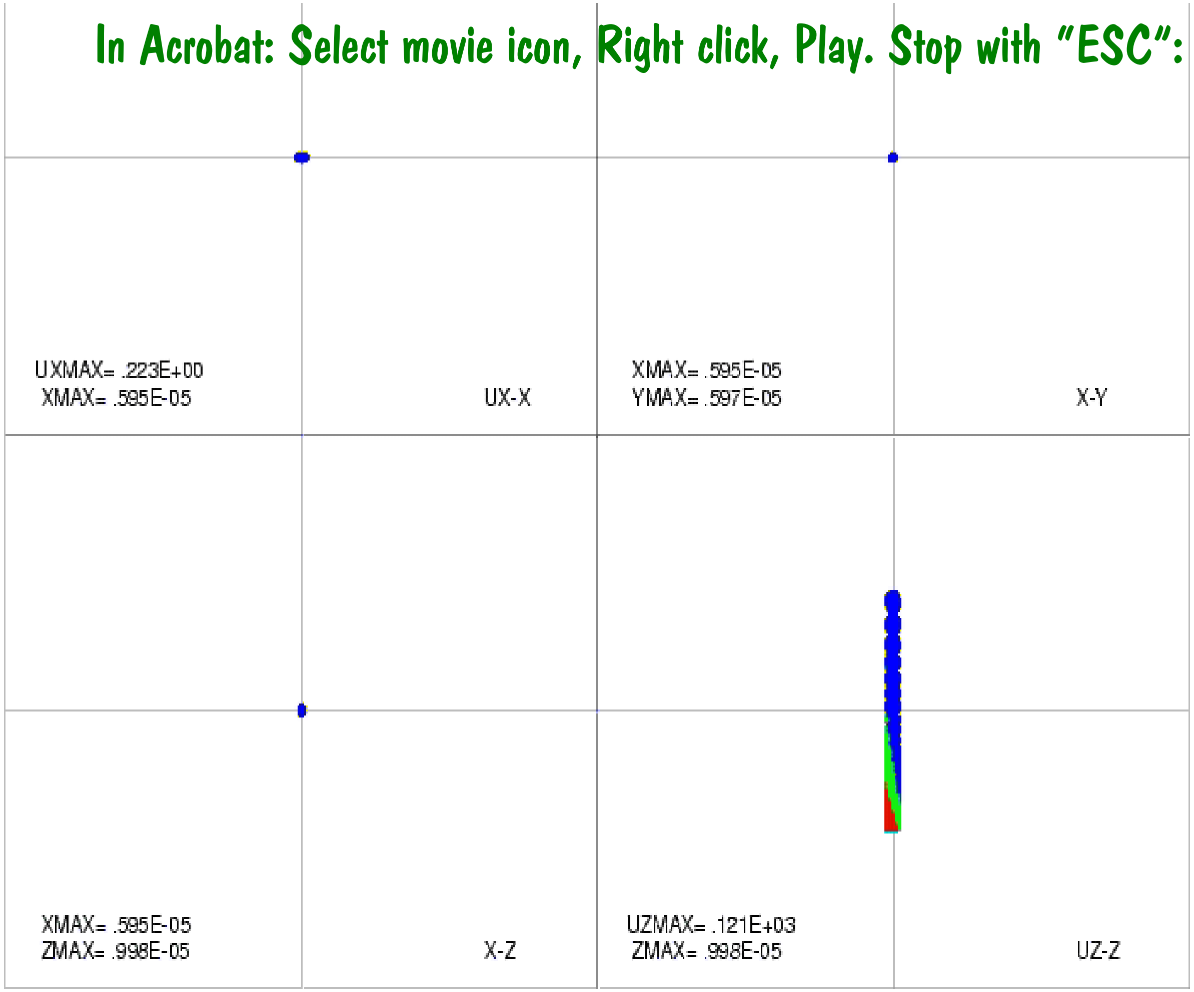
$z_m = 10\ \mu\text{m}$

200 time steps

$p_{z_{\max}} \geq 5\ \text{MeV}\ ,\ p_{z_{\min}} \leq 1\ \text{MeV}$

type : *smlwf* , $kT = 2\ \text{MeV}$

Space charge blowout occurs at a very early stage (a few microns) then the motion is purely ballistic. We clearly see a low energy tail formation and a highly non linear interaction between particles.



In Acrobat: Select movie icon, Right click, Play. Stop with "ESC":

G. Fubiani et al., AAC 2002 Proc.

After 220 µm
(more Berkeley Simulations)

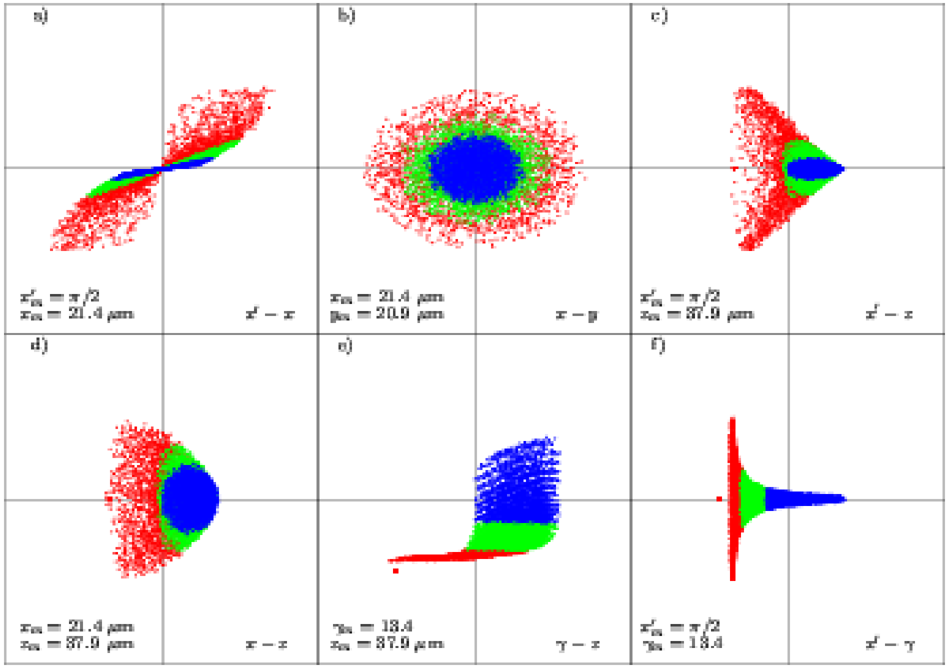


FIGURE 3. Phase-space plot of the bunch distribution function after 220 μm. The top-left figure (a) shows transverse phase-space $x' - x$, (b) a beam cross section $x - y$ and (c) divergence versus propagation distance $x' - z$. On the bottom-right (d), a beam side view $x - z$ is shown, (e) the longitunal phase-space $\gamma - z$ and (f) divergence x' versus γ. Electrons that have an initial momentum greater than 5 MeV/c are shown in blue (black); low energy electrons with $p_z < 1$ MeV/c are shown in red (dark gray); the remaining electrons are in green (light gray).

Summary

- Due to the availability of high intensity lasers with short pulse length, plasma acceleration has made great progress. Using such an "accelerator" as an injector for a coherent light source Linac seems possible. The electrons come in short bunches, making the use of less charge than ~1nC feasible for applications requiring coherence.
- Progress has been made in understanding the dynamics of short bunches emanating from μ-size "cathodes" and in overcoming the gut reaction: this can't work!
- **LCLS**: It will take much work to produce an "industrial" grade reliable injector, but the potential pay-off, both in cost savings for the a coherent light source wiggler, and in enhancement of the physics, are large. On a sociological plane, shorter wigglers would allow to construct more beam lines, thus creating a true "Synchrotron User Facility".
- **NLC:** Low emittance beams as promised by a Plasma Gun may not need damping rings for electrons. Short beams (femto seconds and below) for e^-e^- collisions reduce the beamstrahlung and coherent pair production background at high energy (Derbenev). If these beams can be polarized, they will make e^-e^- competitive with e^+e^-.

Acknowledgements

Many people have contributed to the ideas, insights and the directions to go expressed here.

In particular I thank Y. Batygin, A. Chao, P. Bolton, R. Colby, R. Ruth, C. Schroeder, T. Tajima, D. Yeremian .

Without S. Chattopadhyay, J. Clendenin, F.-J. Decker, G. Dugan, P. Emma, E. Esarey, K. Floettmann, G. Fubiani, J. Frisch, J. Irwin, K. Ko, W. Leemans, R. Miller, H.-D. Nuhn, C. Pellegrini, C. Prescott, T. Raubenheimer, A. Seryi, R. Siemann, J. Sheppard, R. Tatchyn, V. Telnov, D. Umstadter, D. Whittum, H. Winick, F. Zimmermann .... and others, with advice, challenge, and good questions about possible show stoppers, the ideas presented here would not have progressed to where they are now.