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BBU in a blow-out regime: a proposal for an experiment

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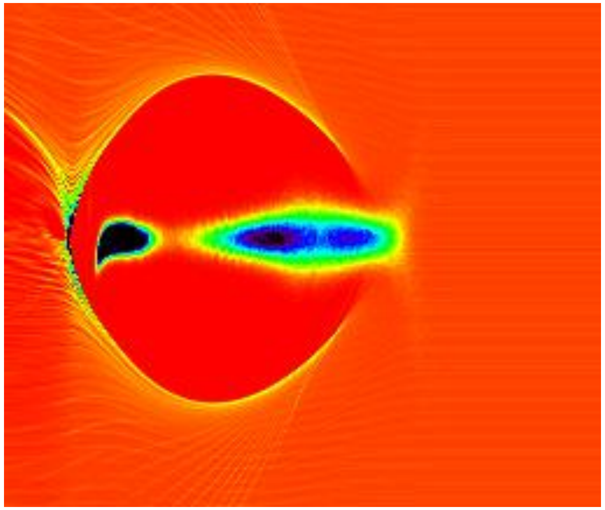
Summary

- We propose to study systematically the BBU in a blow-out regime with high beam loading and high efficiency

- Could be a follow up to the E200 experiment in FACET-II

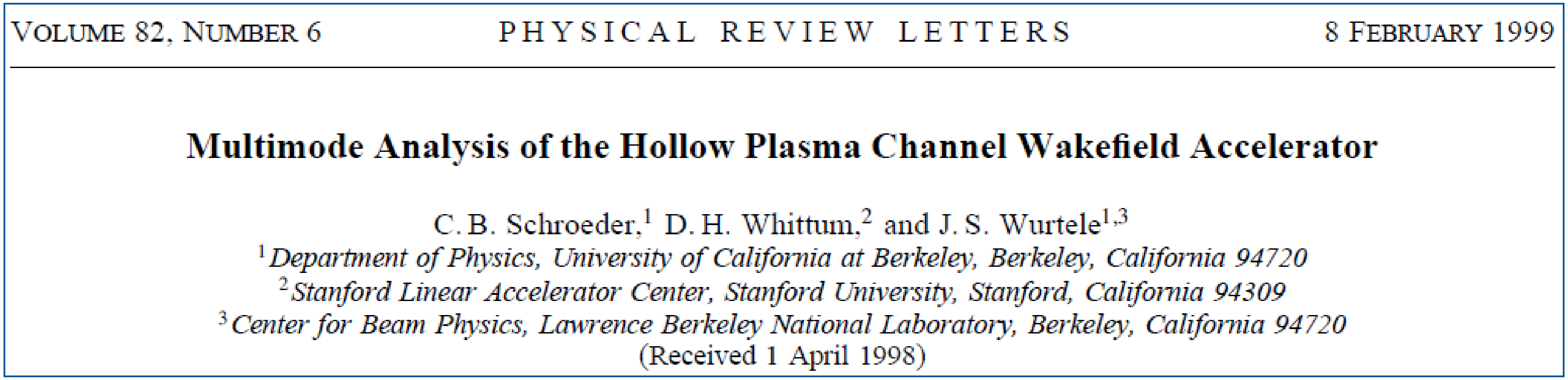
Transverse hosing (beam beak-up, BBU) in plasma



- This plot is for illustration only
- Courtesy of Warren Mori (UCLA)
- Observed in some runs of 3d simulations

- For reference, see https://arxiv.org/abs/1602.05260

Our BBU analysis is based on the following paper



VOLUME 82, NUMBER 6 PHYSICAL REVIEW LETTERS 8 FEBRUARY 1999

Multimode Analysis of the Hollow Plasma Channel Wakefield Accelerator

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(Received 1 April 1998)

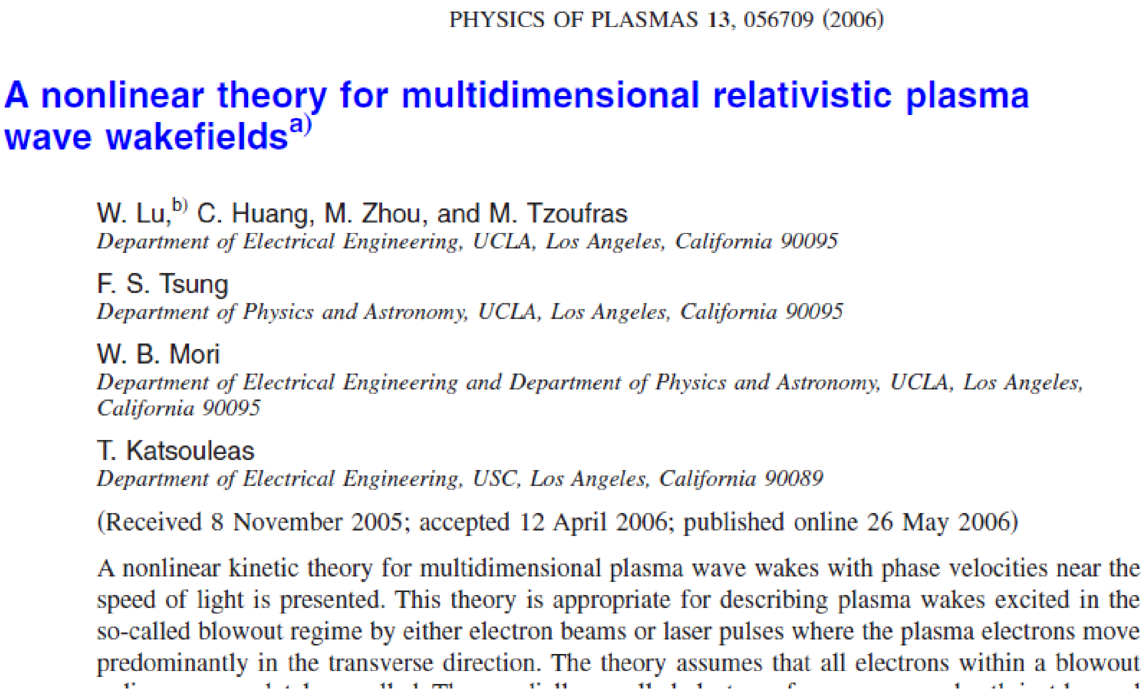
Transverse wake function of a plasma channel:

$$W_\perp = \frac{8\Delta z}{b^4}; \quad (\Delta z << b, k_p^{-1})$$

b – plasma channel radius

Transverse wake for an arbitrary (large) bubble

- Based on the following paper:



PHYSICS OF PLASMAS 13, 056709 (2006)

A nonlinear theory for multidimensional relativistic plasma wave wakefields[a)]

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A nonlinear kinetic theory for multidimensional plasma wave wakes with phase velocities near the speed of light is presented. This theory is appropriate for describing plasma wakes excited in the so-called blowout regime by either electron beams or laser pulses where the plasma electrons move predominantly in the transverse direction. The theory assumes that all electrons within a blowout

- And, on the Panofsky-Wenzel theorem…
- We request help from simulation groups to confirm our findings.

We start with the Lu plasma bubble equation (LE)

We assume the driving bunch intense enough to produce an electron-free plasma bubble with radius $R >> k_p^{-1}$. According to Lu et al. :

$$r_b r_b'' + 2 r_b'^2 + 1 = \frac{4\lambda(z)}{r_b^2};$$

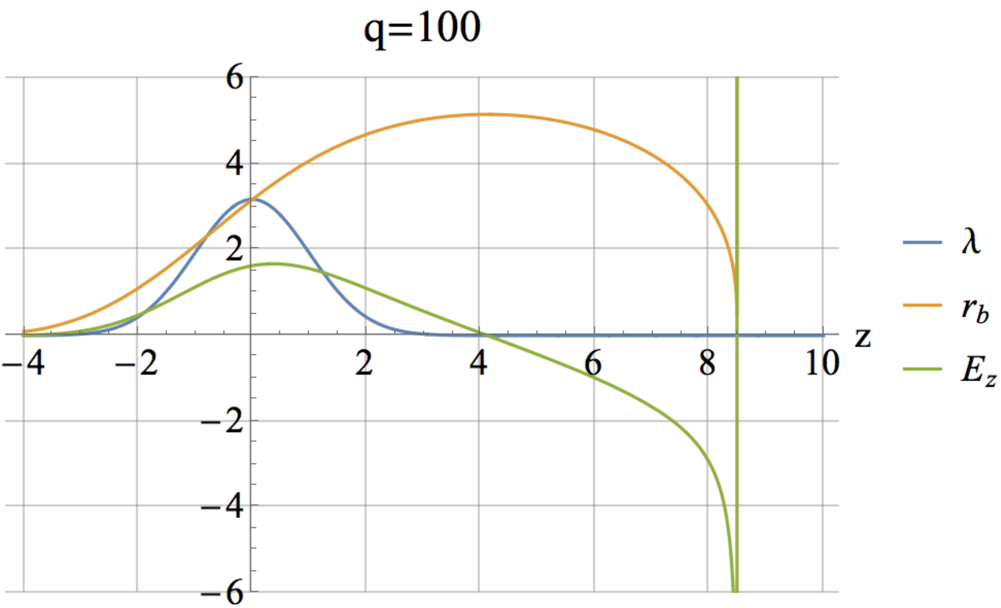
$r_b(z)$ -- plasma bubble boundary

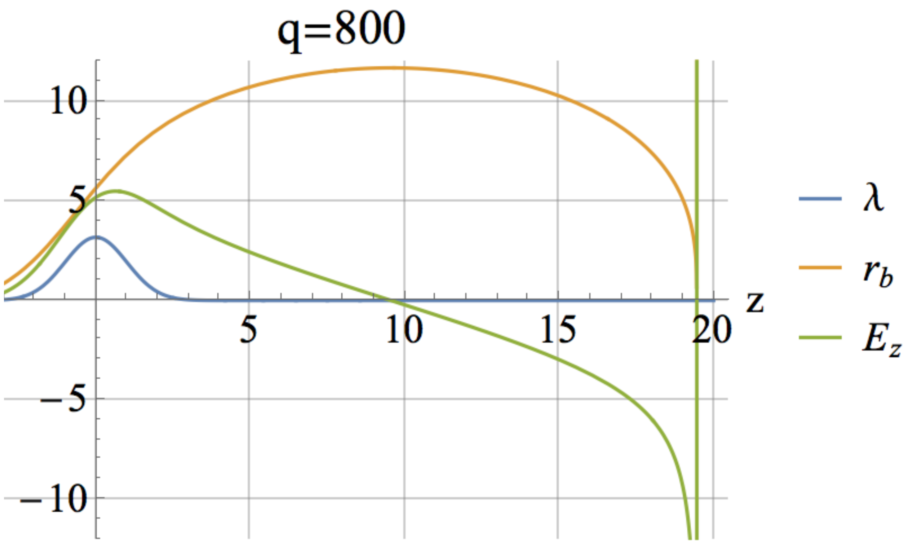
LE, solutions

The bubble is almost spherical, with its radius independent of the bunch length.

when $R >> \sigma$:

$$R \approx 1.1\sigma q^{1/3} = 1.1(N_d / n_e)^{1/3}$$





$$N_i \approx \frac{4}{3}\pi R^3 n_e \approx 5N_d$$

LE, wakes

Longitudinal (from the Lu equation): $$W_{\parallel} = \frac{4}{r_b^2}; \quad (\Delta z \ll r_b, k_p^{-1})$$

(*similar to a dielectric channel and periodic array of cavities*)

For reference, see: A. V. Fedotov, R. L. Gluckstern, and M. Venturini (PRST-AB 064401 (1999))

Transverse :

$$W_{\perp} \approx \frac{2}{r_b^2}\int W_{\parallel} dz = \frac{8\Delta z}{r_b^4}; \quad (\Delta z \ll r_b, k_p^{-1})$$

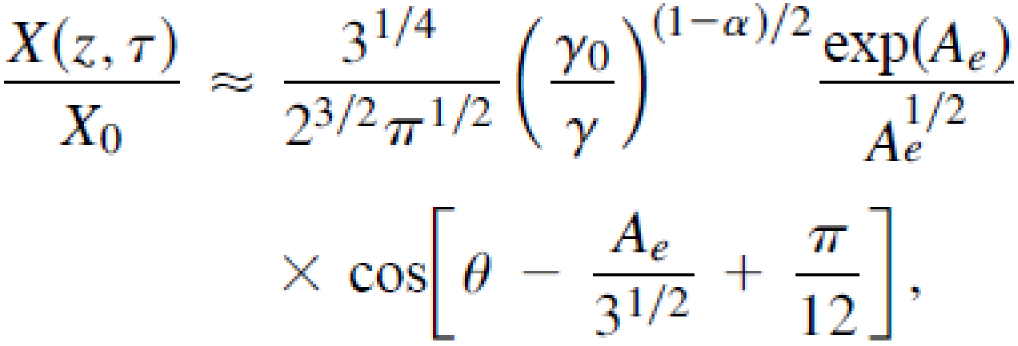
$r_b(z)$ -- local bubble radius at bunch location, z

(*Panofsky-Wenzel, true for a dielectric channel, array of cavities and resistive wall*)

For reference, see Karl Bane, SLAC-PUB-9663

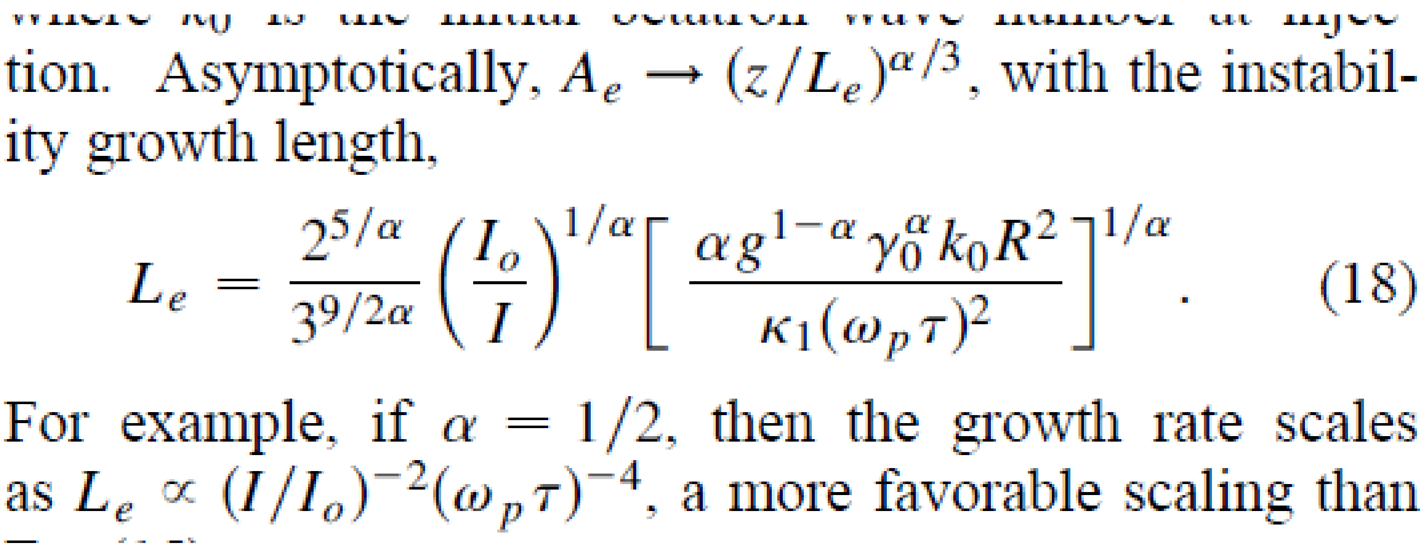
Needs to be confirmed by 3d simulations!

BBU growth length (from C. Schroeder)



$$\frac{X(z,\tau)}{X_0} \approx \frac{3^{1/4}}{2^{3/2}\pi^{1/2}}\left(\frac{\gamma_0}{\gamma}\right)^{(1-\alpha)/2}\frac{\exp(A_e)}{A_e^{1/2}} \times \cos\left[\theta - \frac{A_e}{3^{1/2}} + \frac{\pi}{12}\right],$$

$$\alpha = \frac{1}{2}$$



where κ_0 is the initial betatron wave number at injection. Asymptotically, $A_e \to (z/L_e)^{\alpha/3}$, with the instability growth length,

$$L_e = \frac{2^{5/\alpha}}{3^{9/2\alpha}}\left(\frac{I_o}{I}\right)^{1/\alpha}\left[\frac{\alpha g^{1-\alpha}\gamma_0^{\alpha}k_0 R^2}{\kappa_1(\omega_p\tau)^2}\right]^{1/\alpha}. \qquad (18)$$

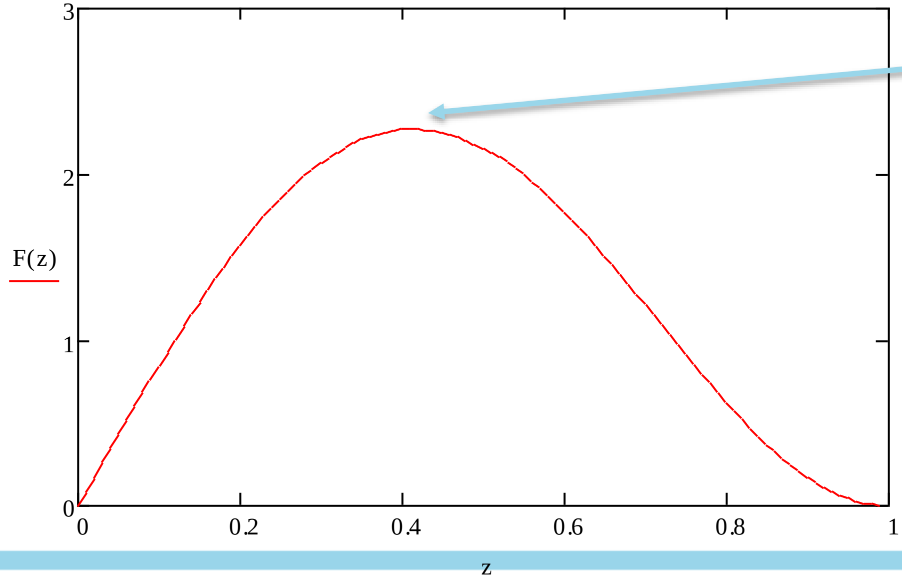
For example, if $\alpha = 1/2$, then the growth rate scales as $L_e \propto (I/I_o)^{-2}(\omega_p\tau)^{-4}$, a more favorable scaling than

Growth length

$$L_e \propto \left(\frac{N_d}{N_w}\right)^2 \left(\frac{r_b^2}{\kappa_1 \sigma_z}\right)^2 \frac{d\gamma}{dz} \qquad r_b(\xi) = \sqrt{1-\xi^2}; \quad \frac{d\gamma}{dz} = E_0 \xi$$

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

$z := 0, 0.01 .. 0.99$ $\quad r(z) := \sqrt{1 - z^2}$ $\quad F(z) := \left(\frac{r(z)^2}{k1(r(z))}\right)^2 \cdot z$

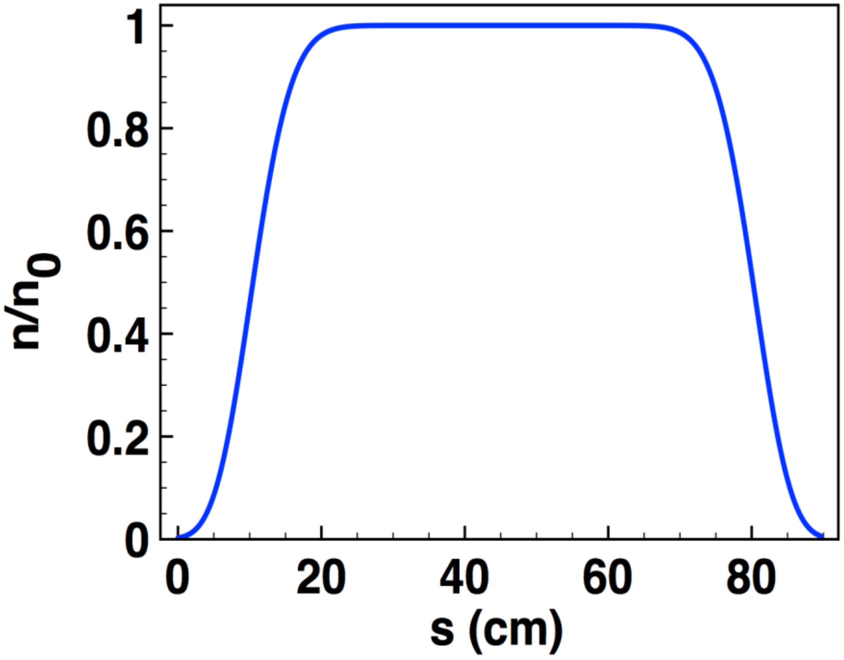


Maximum growth length

$\xi \approx 0.4$

E200 proposed parameters (FACET-II)

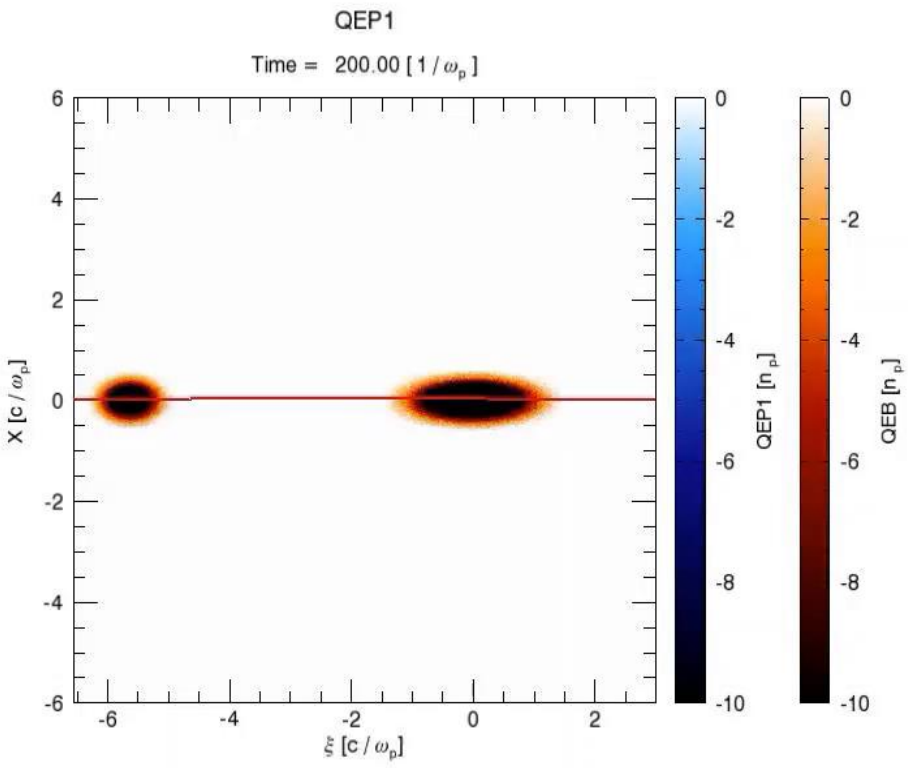
Plasma Density Profile



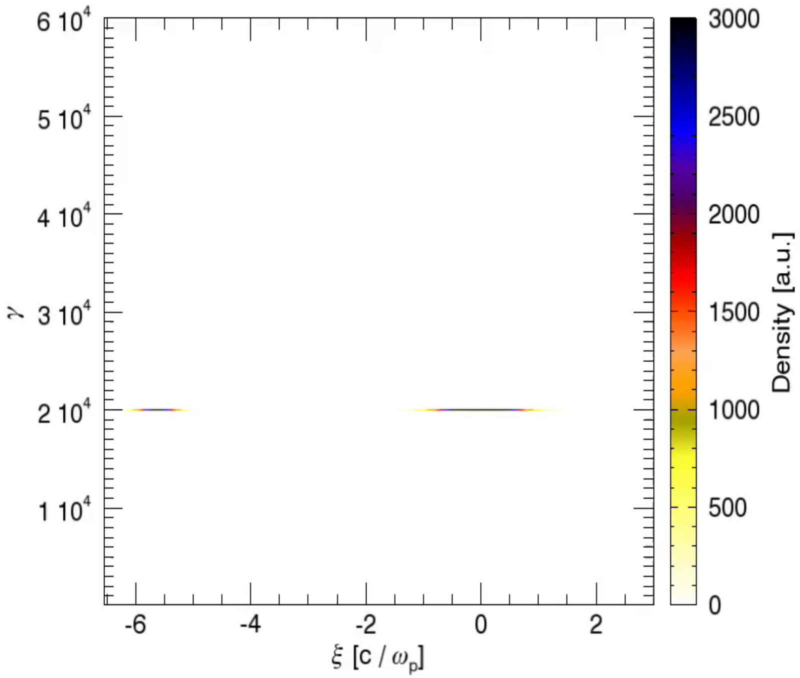
Drive Beam: E = 10 GeV, I_{peak}=15 kA
β = 89.61 cm, α = 0.0653,
σ_r = 21.17 µm, σ_z = 12.77 µm ,
N =1.0 x 10^{10} (1.6 nC),
ε_N = 10 µm
Trailing Beam: E = 10 GeV, I_{peak}=9 kA
β = 89.61 cm, α = 0.0653,
σ_r = 21.17 µm, σ_z = 6.38 µm ,
N =0.3 x 10^{10} (0.48 nC),
ε_N = 10 µm
Distance between two bunches: 150 µm
Plasma Density: 4.0 x 10^{16} cm^{-3} (with ramps)

Courtesy of Chan Joshi

Plasma and beam density with on-axis Ez line out



Beam Energy



Courtesy of Chan Joshi

Witness bunch with an initial offset, X_0

- Let's look for the length, *z*, needed to increase the initial betaron oscillation amplitude by a factor of 10

$$\frac{X(z,\tau)}{X_0} \approx \frac{3^{1/4}}{2^{3/2}\pi^{1/2}}\left(\frac{\gamma_0}{\gamma}\right)^{(1-\alpha)/2}\frac{\exp(A_e)}{A_e^{1/2}} \times \cos\left[\theta - \frac{A_e}{3^{1/2}} + \frac{\pi}{12}\right],$$

$$A_e \approx 4.6$$

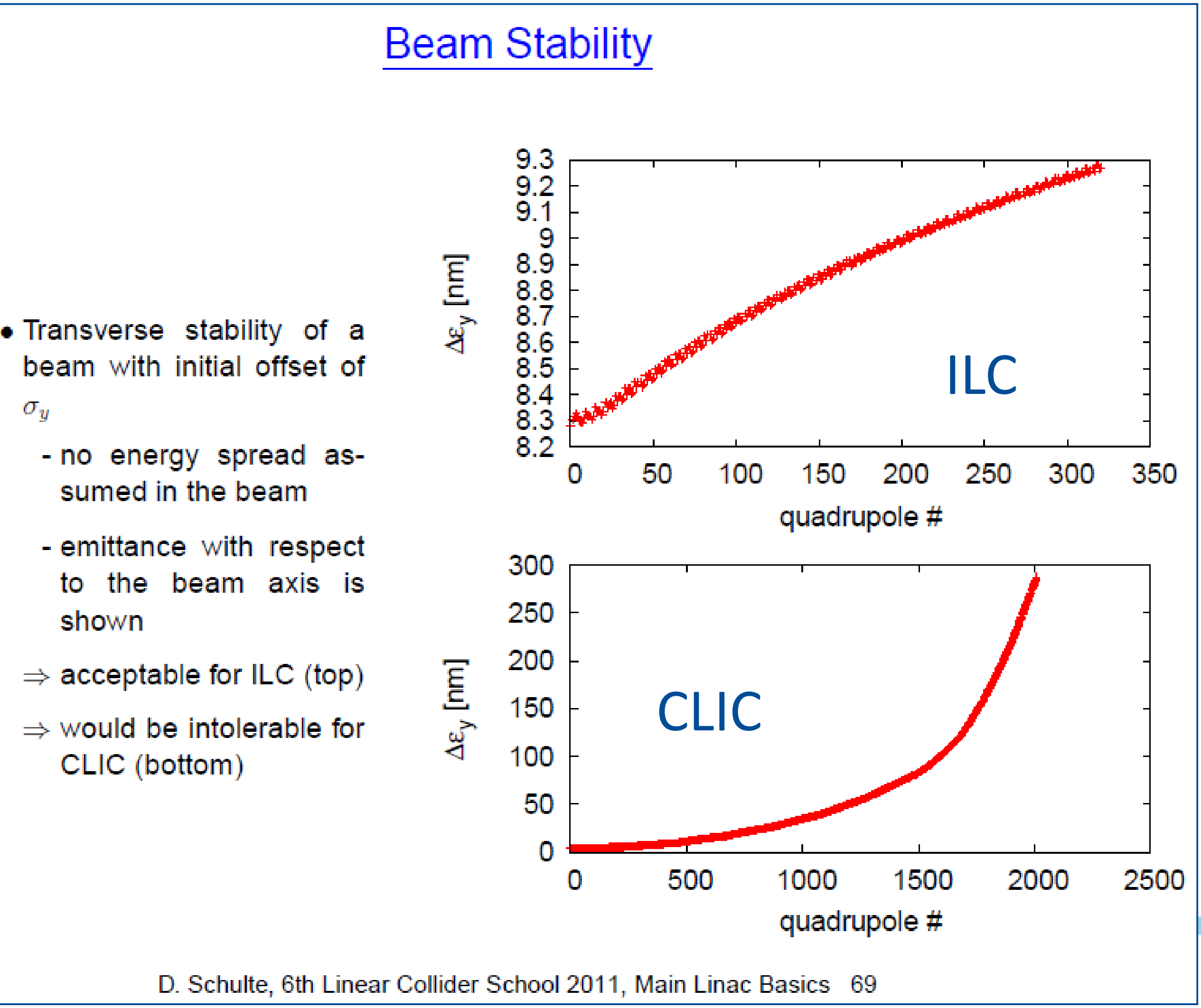
$$z = A_e^6 L_e \approx 60 \text{ cm}$$

For $\xi \approx 0.7$

Numbers need to be confirmed!!!

Transverse beam break-up (head-tail instability)

- Transverse wakes act as deflecting force on bunch tail
  - beam position jitter is exponentially amplified



Beam Stability

- Transverse stability of a beam with initial offset of σ_y
  - no energy spread assumed in the beam
  - emittance with respect to the beam axis is shown

⇒ acceptable for ILC (top)

⇒ would be intolerable for CLIC (bottom)

D. Schulte, 6th Linear Collider School 2011, Main Linac Basics 69

Short-range transverse wake

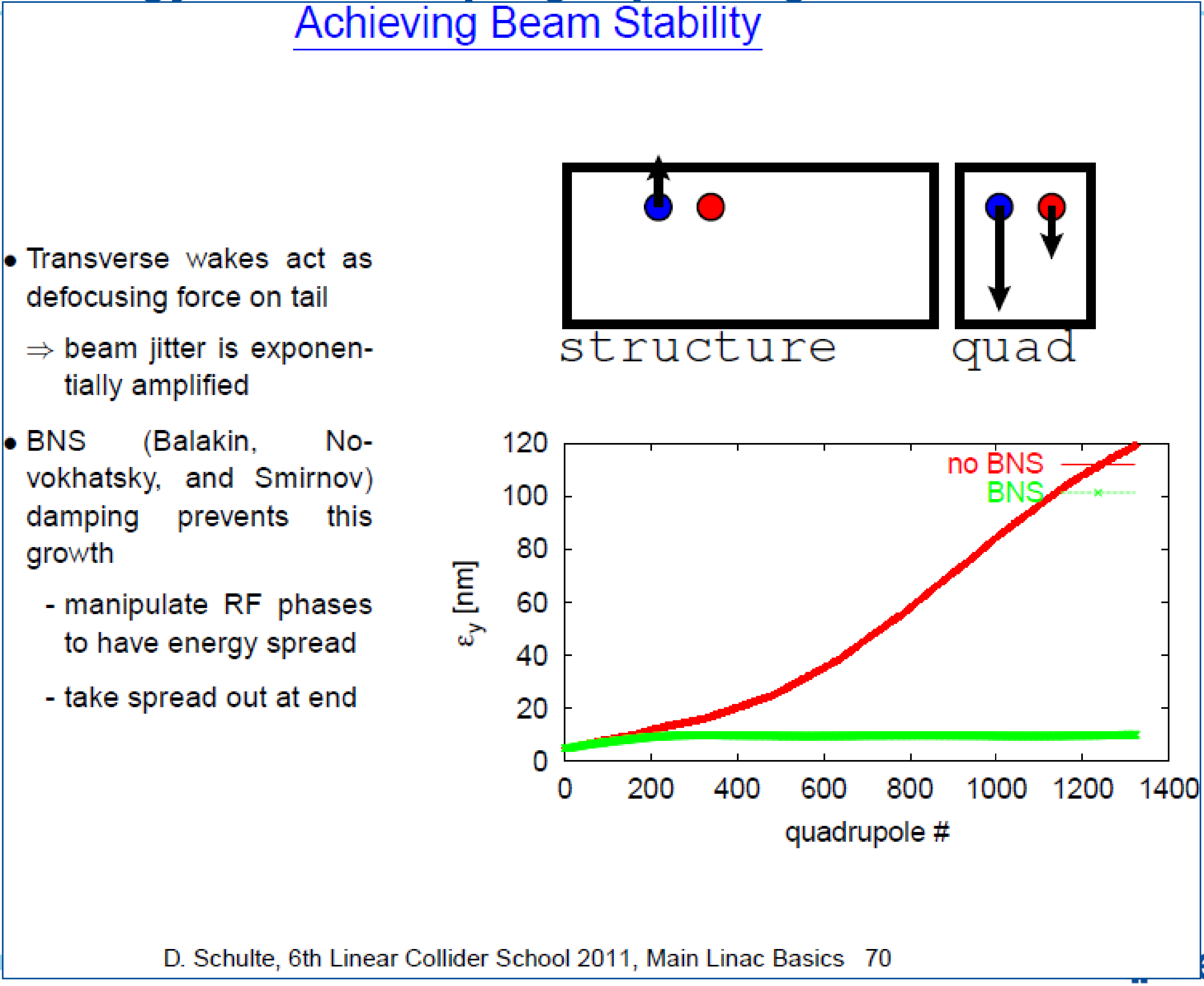
$$W_\perp(z) \sim \frac{Z_0 c z}{a^4}$$

$a \approx 35$ mm (ILC)

$a \approx 3.5$ mm (CLIC)

$a \sim 0.1$ mm (PWFA)

CLIC strategy: BNS damping + µm alignment of cavities



Achieving Beam Stability

- Transverse wakes act as defocusing force on tail

  $\Rightarrow$ beam jitter is exponentially amplified

- BNS (Balakin, Novokhatsky, and Smirnov) damping prevents this growth
  - manipulate RF phases to have energy spread
  - take spread out at end

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Strategy was also used at the SLC…

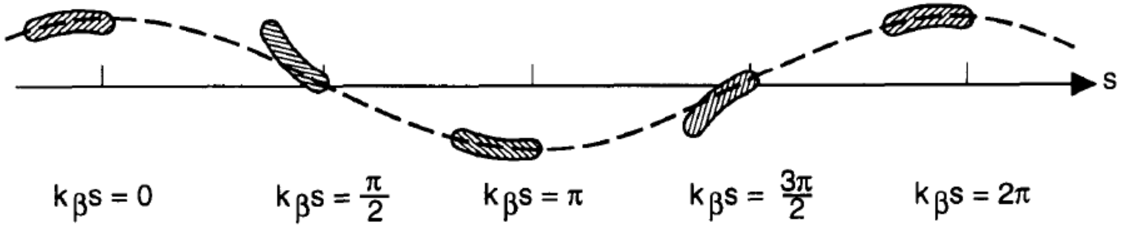

Figure 3.3. Sequence of snapshots of a beam undergoing dipole beam breakup instability in a linac. Values of $k_\beta s$ indicated are modulo 2π. The dashed curves indicate the trajectory of the bunch head.

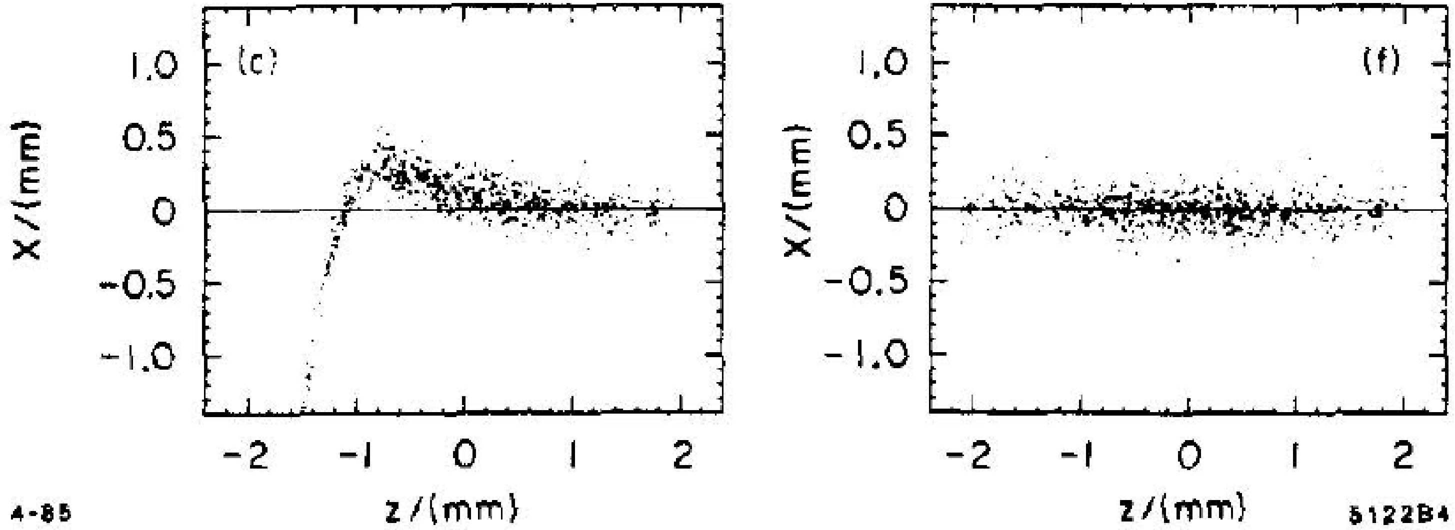

Figure 34: Multiparticle simulation of a particle bunch passing through the SLAC linac without (left) and with BNS damping (right) [36].

BNS requirement

The BNS energy spread is:

$$\left.\frac{\delta p}{p}\right|_{BNS} \geq \frac{5}{r_t^2}\left(\frac{P_w}{P_d}\right)^2$$

Consequences of this BNS damping

- The transformer ratio, r_t , is typically ~2
- Thus, $$\left.\frac{\delta p}{p}\right|_{BNS} \geq \left(\frac{P_w}{P_d}\right)^2$$
- Example: for a 10% power transfer (beam loading) between the drive and the witness beam, one needs to have a 1% energy spread for BNS damping.
- This needs to be confirmed by computer simulations!

Experimental proposal

- Test BBU models and the required BNS energy spread by injecting the E200 witness bunch off axis and with controlled energy spread 0 – 10%

- Observe amplitude growth of betatron oscillations as a function of beam loading and bunch longitudinal position inside the bubble.