Generation of Multi-bunch Trains with Sub-picosecond Separation for PWFA (and Other?) Applications

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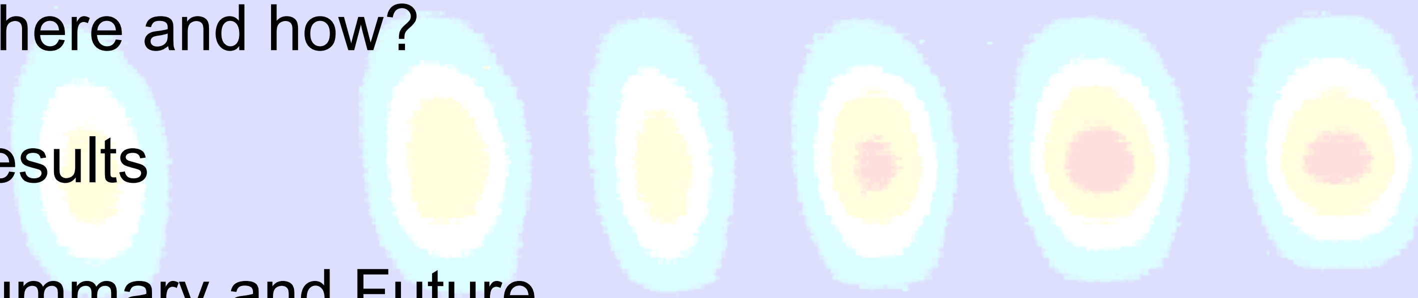
OUTLINE

- Motivation
- Mask idea
- Where and how?
- Results
- Summary and Future



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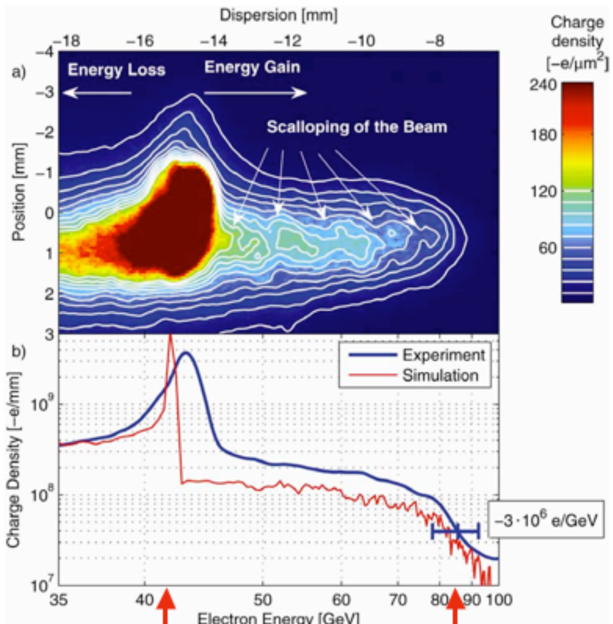
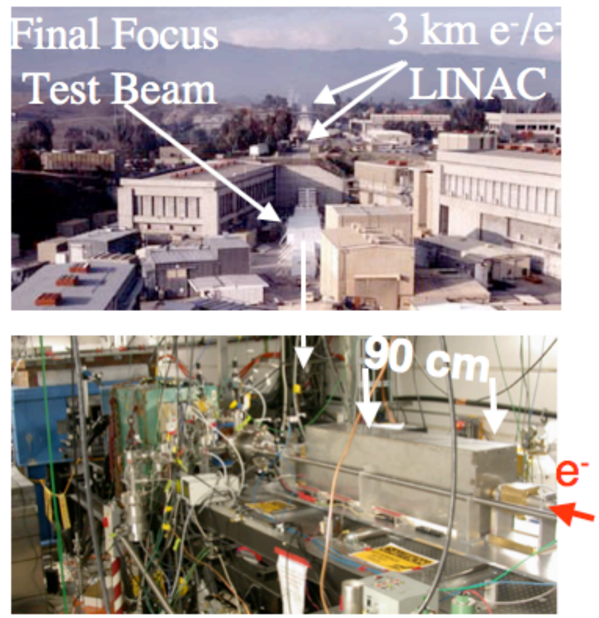
MOTIVATION

e⁻ ENERGY DOUBLING E_0=42 GeV

I. Blumenfeld *et al.*, Nature 445, 2007



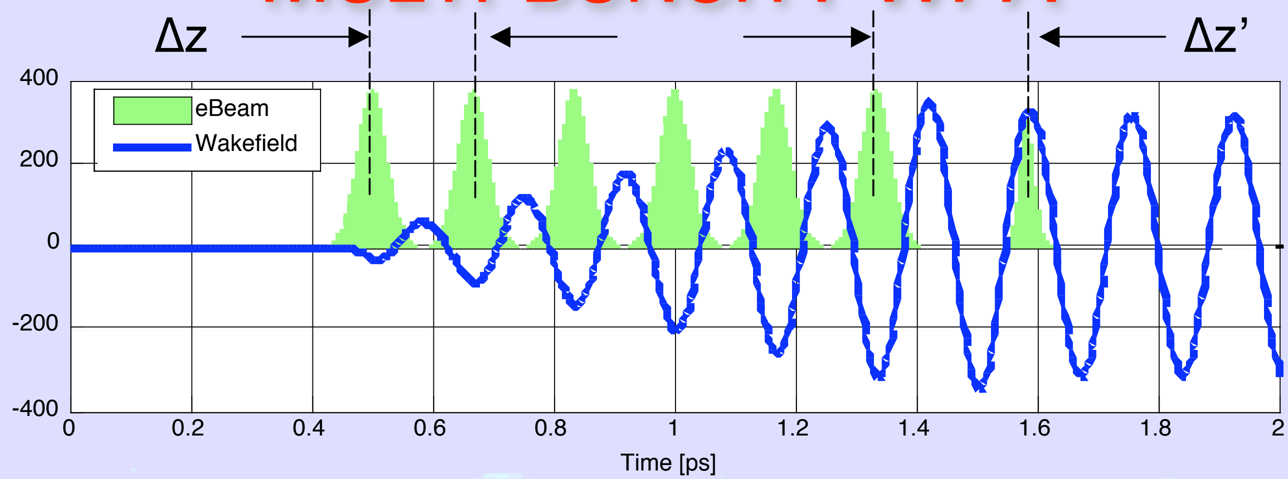


- Energy doubling of e⁻ over L_p≈85 cm, $2.7\text{x}10^{17}$ cm^{-3} plasma
- Unloaded gradient ≈52 GV/m (≈150 pC accel.)

P. Muggli, ICOPS 08, 06/17/08 25

- Tremendous progress with PWFA
- Need to accelerate a particle BUNCH
- Explore high transformer ratio scheme, beyond energy doubling

MULTI-BUNCH PWFA



- Bunch spacing/plasma density condition:

  $\Delta z = \lambda_p$ (resonance) $\sigma_z \ll \lambda_p$

  $\Delta z' \approx (m+1/2)\lambda_p$

Plasma wavelength: $\lambda_p = \frac{2\pi c}{\omega_{pe}}$ Plasma angular frequency, density n_e: $\omega_{pe} = \left(\frac{n_e e^2}{\varepsilon_0 m_e}\right)^{1/2}$

- Wake fields add up (linear theory):

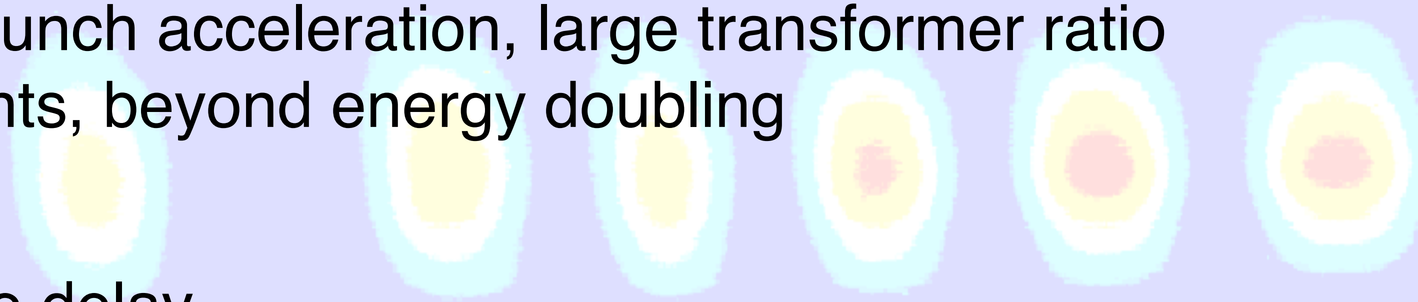
  $E_{z\ N\ bunches} \approx N \times E_{z\ 1\ bunch}$ (beyond energy doubling!)

- Maximize transformer ratio with "shaping"

- Finite energy spread $\Delta E/E \ll 1$, beam acceleration

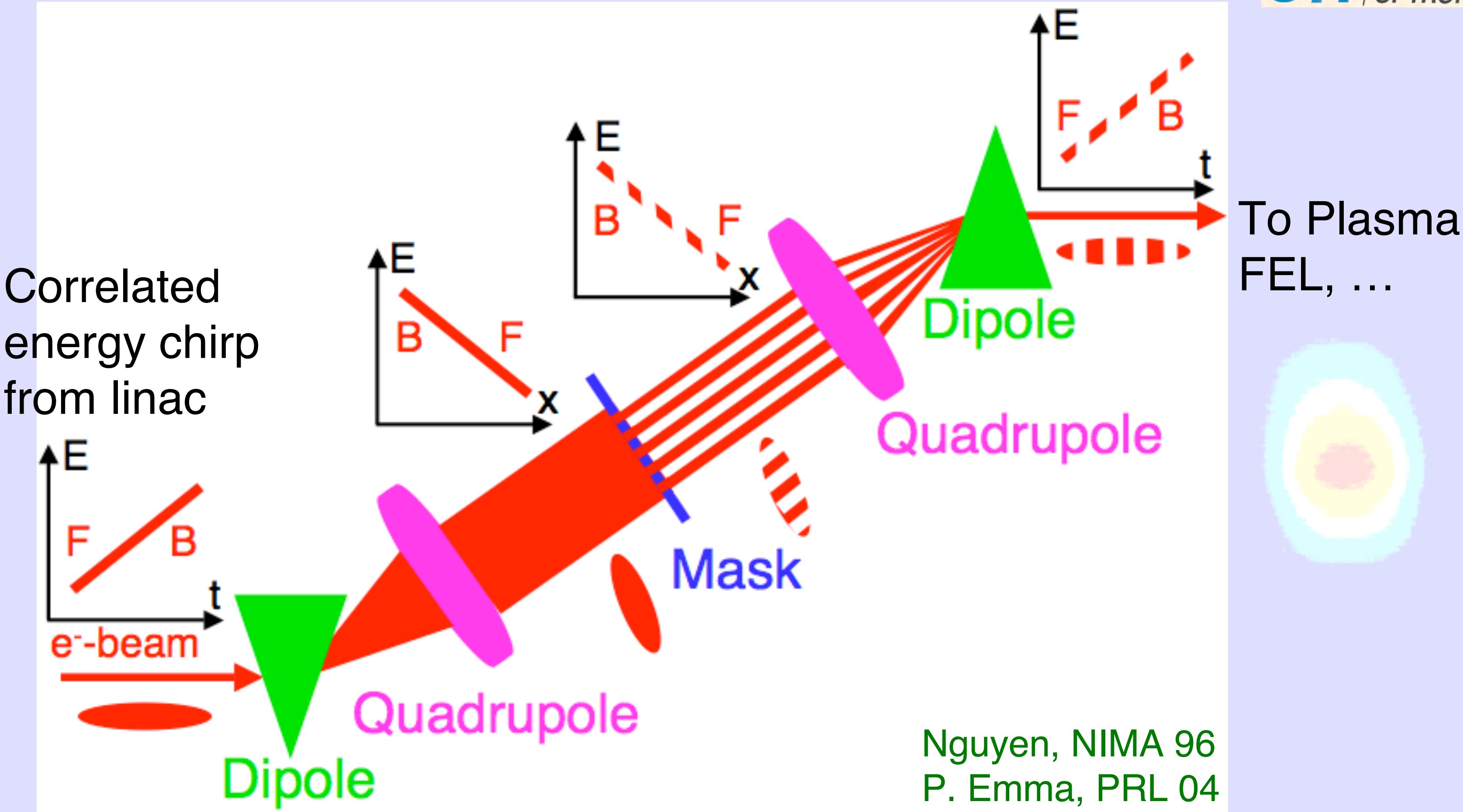
PURPOSE & REQUIREMENTS

- PWFA
  - ✓ Equidistant drive bunch train
  - ✓ Witness bunch
  - ✓ Variable charge
- Witness bunch acceleration, large transformer ratio experiments, beyond energy doubling
- FEL
  - ✓ Variable delay
  - ✓ Variable energy
  - ✓ Variable charge
- Pump-probe experiments
- Stability in time and energy



MULTIBUNCH GENERATION

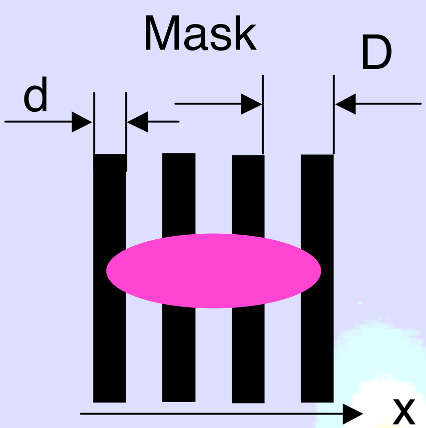
Correlated energy chirp from linac



- Emittance selection: scattered electrons are lost
- Choose microbunches spacing and widths with mask and beam parameters: N, Δz, σ_z, Q

BUNCH TRAIN PARAMETERS

β_x=1.9 m
ε_N=1 mm-mrad
η_{mask}=1.372 m
γ_0=117
$\Delta E/E_0$=1%



Beam size at the mask: $\sigma_x = \sqrt{\frac{\beta_x \varepsilon_N}{\gamma_0} + \left(\eta_{mask}\left|\frac{\Delta E}{E_0}\right|\right)^2}$ =1.372 cm

127 μm <<< 1.372 cm

D=1270 μm

Number of μbunches: $N_b = \frac{\sigma_x}{D} \cong \frac{\eta_{mask}}{D}\left|\frac{\Delta E}{E_0}\right|$ =10 to 11

L_z=1650 μm
R_{56}=4 cm

Mask transparency

$$T = \frac{(D-d)}{D}$$

μbunches spacing: $\Delta z = \frac{L_z'}{N} \cong D\frac{L_z + R_{56}\Delta E/E_0}{\eta_{mask}|\Delta E/E_0|}$ =200 μm

Q_0=500 pC
d=500 μm

Bunch chirp:

$$\Delta E/E_0$$

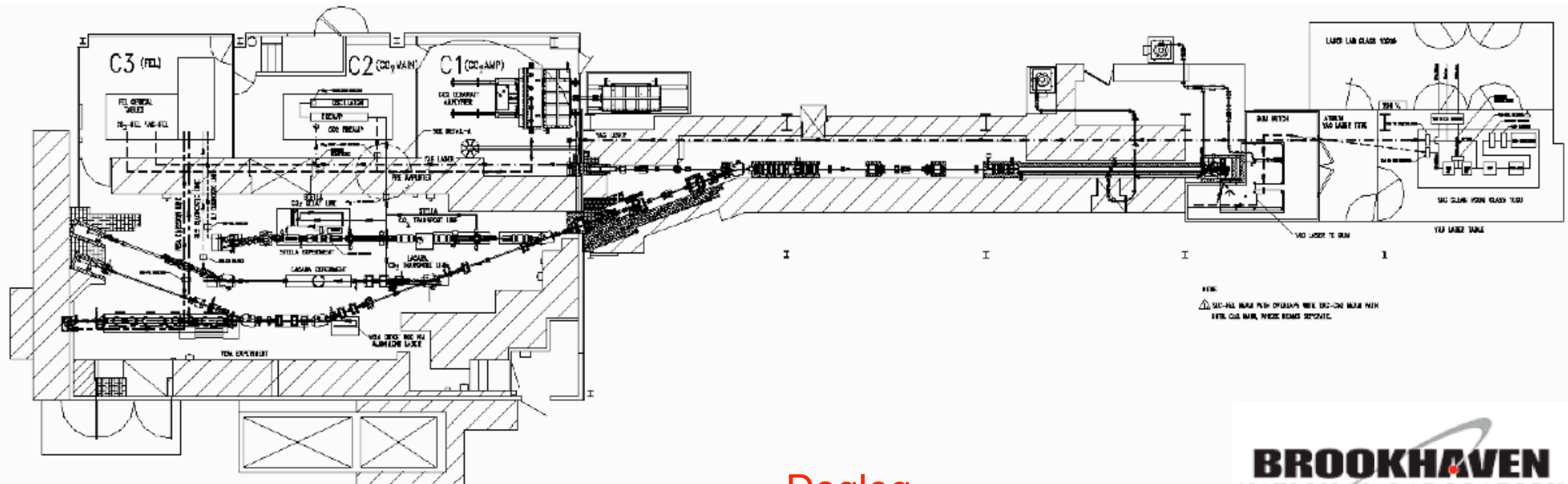
μbunches charge: $Q_{mb} = T\frac{Q_0}{N_b} \cong \frac{Q_0(D-d)}{\eta_{mask}|\Delta E/E_0|}$ =30 pC

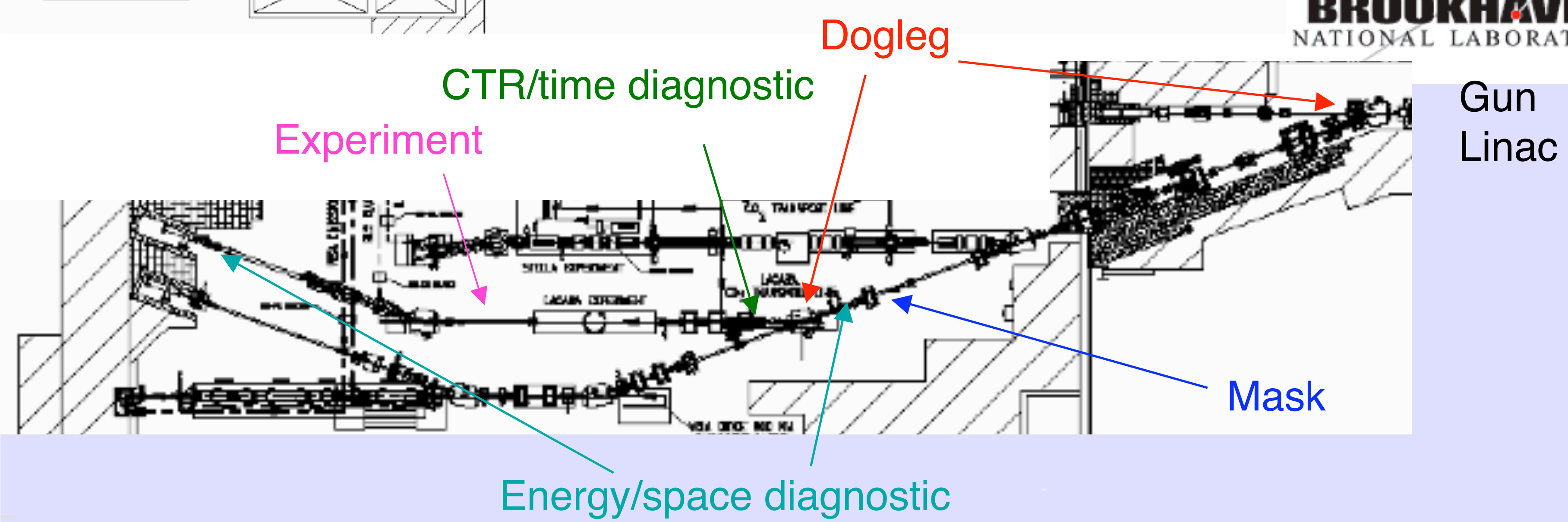
Bunch compression:

$$L_z' = L_z + R_{56}\Delta E/E_0$$

μbunches current: $I_{mb} = \frac{Q_0 c}{L_z'} = \frac{Q_0 c}{L_z + R_{56}\Delta E/E_0}$ =73 A

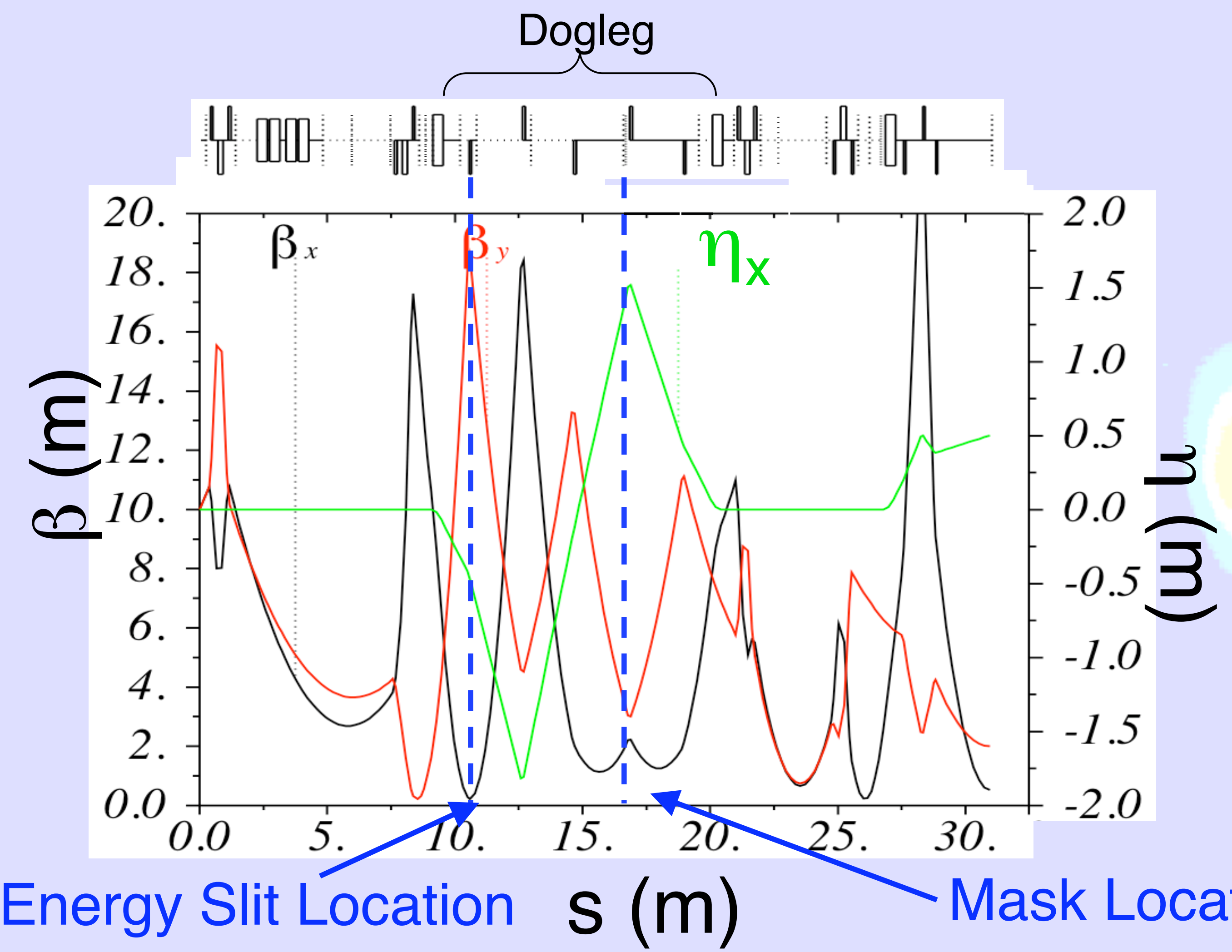
ATF BEAM LINE





ATF BEAM PARAMETERS

MAD Results

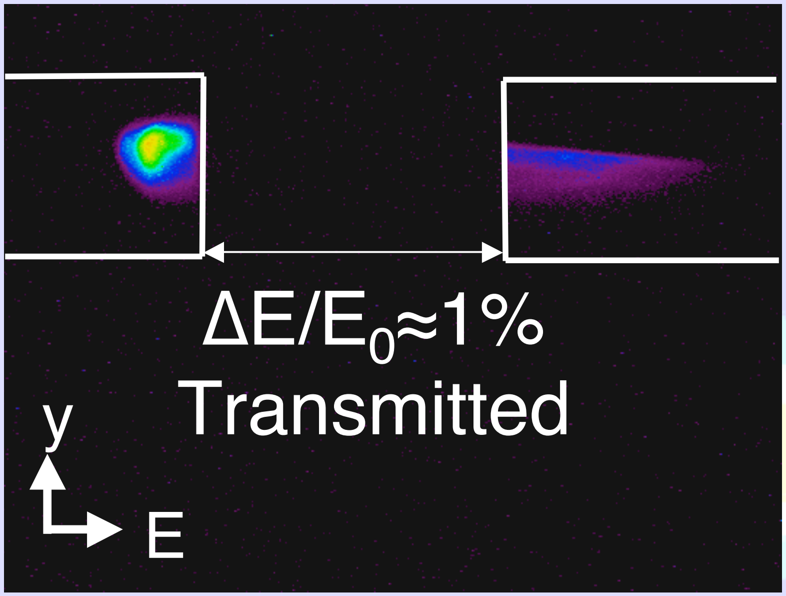


E_0=50 MeV
ε_N<2 mm-mrad
Q=350 pC
τ_{in}≈5.5 ps
$\Delta E/E_0$ =±1%
R_{56}=+4 cm
τ_{out}≈5.5±1.3 ps

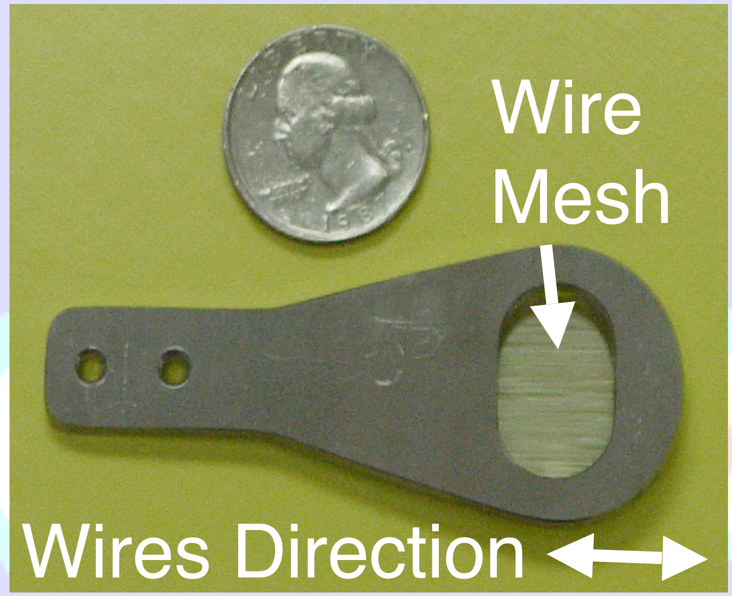
- Dogleg configured for large dispersion η_x and small beta function β_x at mask location

MASK PRINCIPLE

Energy Slit



Mask



W wires: Diameter d=500 μm

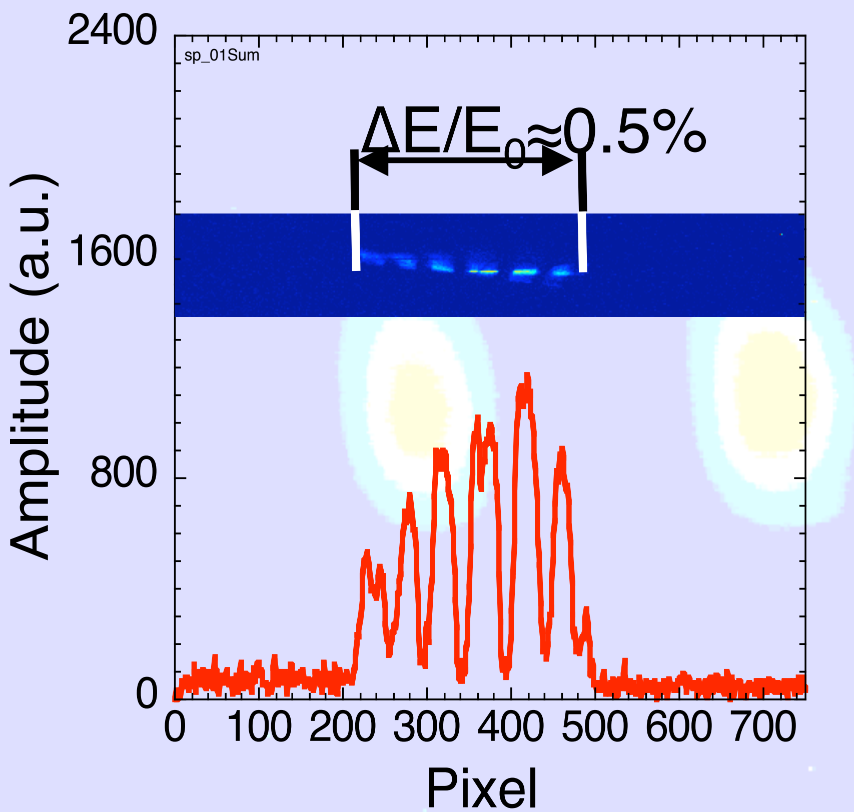
Periodicity: D=1270 μm

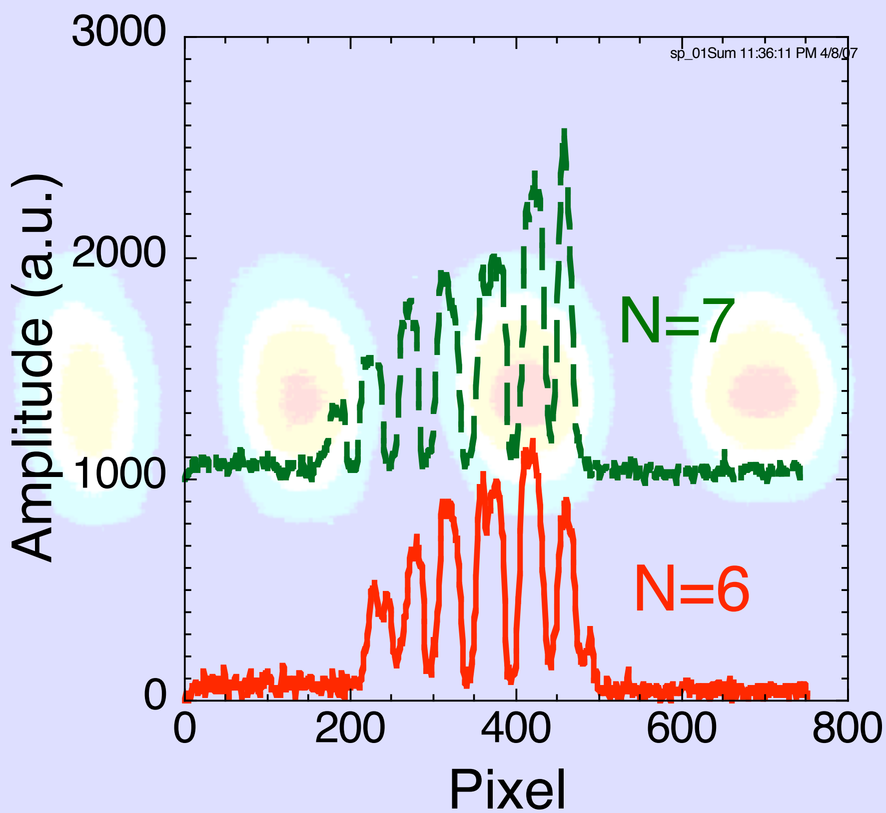
- Mask transparency: $T=(D-d)/D$=0.6
- Scattering: $\theta_0 \cong \frac{13.6 MeV}{\beta c p}\sqrt{\frac{x}{X_0}}$ $\varepsilon_s = \left(\varepsilon^2 + \sigma_x^2 \theta_0^2\right)^{1/2} >> \varepsilon$
- Energy loss ≈3%

For stainless Steel x>10 μm

MULTIBUNCHES IN ENERGY

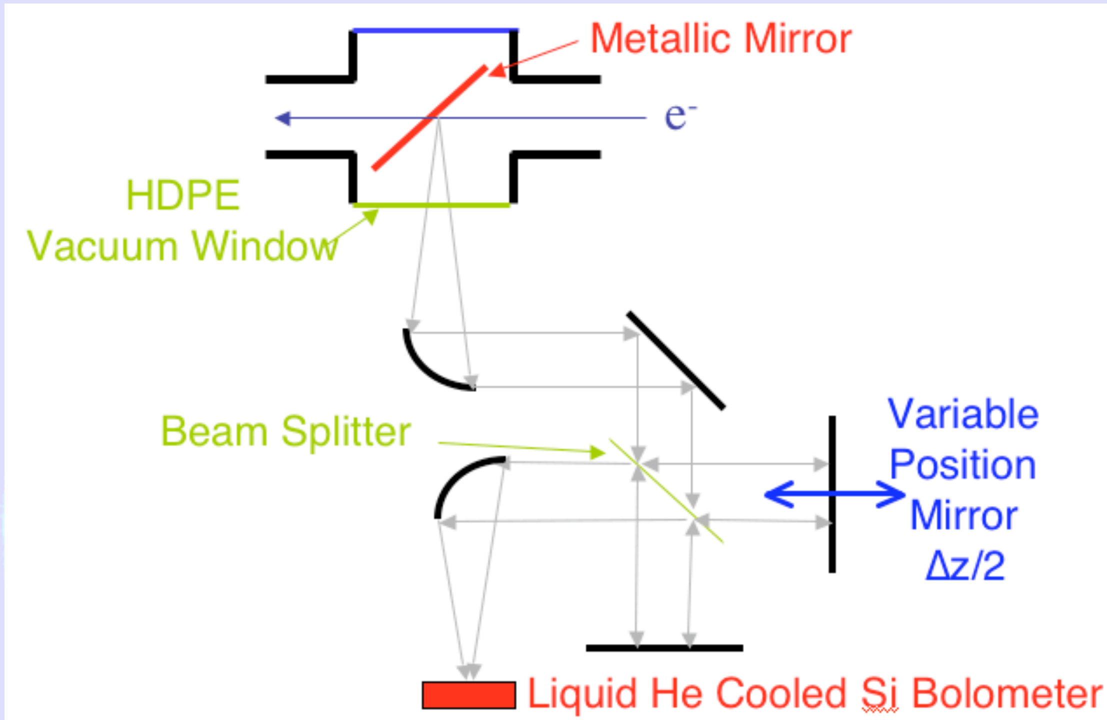
Energy Spectrometer Image/spectra





- Select # of bunches with energy slit (aperture)
- Charge per microbunch determined by incoming bunch profile (here)

CTR INTERFEROMETRY



- CTR:

$$I_{tot}(k) = I_{incoh} + I_{coh} = N_e I_e + N_e(N_e - 1) I_e |F(k)|^2$$

$\lambda << \sigma_z$ $\lambda >> \sigma_z$

Incoherent << Coherent

- Autocorrelator signal:

$$S(\Delta z) = \int_{-\infty}^{\infty} dt \left(\frac{1}{2} E(t) + \frac{1}{2} E(t - \frac{\Delta z}{c}) \right)^2$$

F(k)=Fourier transform of the bunch shape

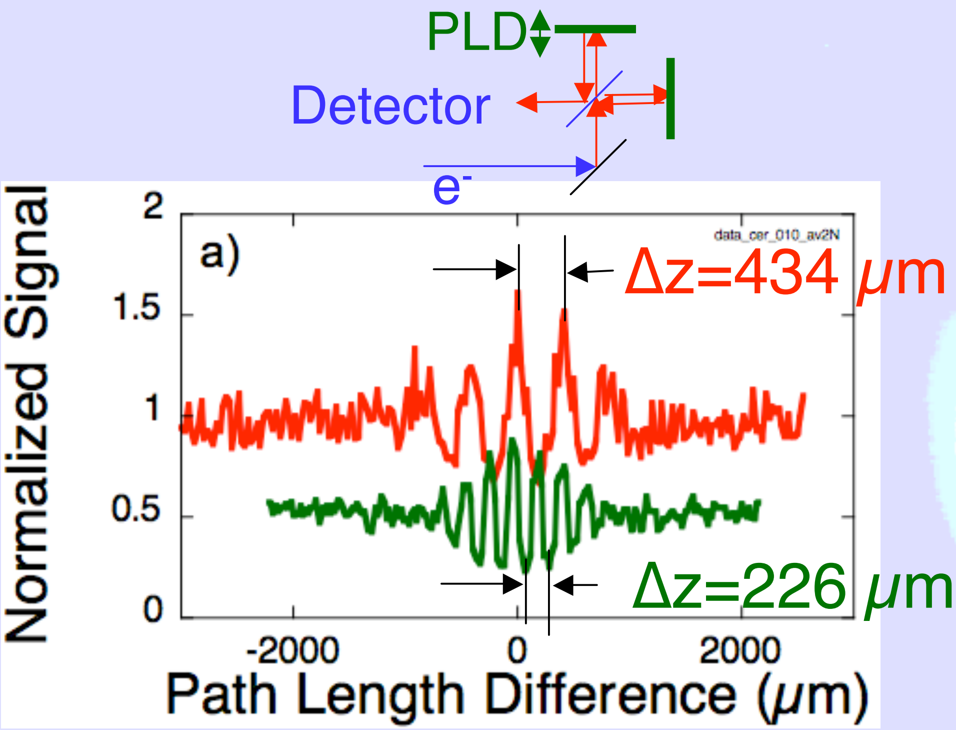
- Autocorrelation (cross term):

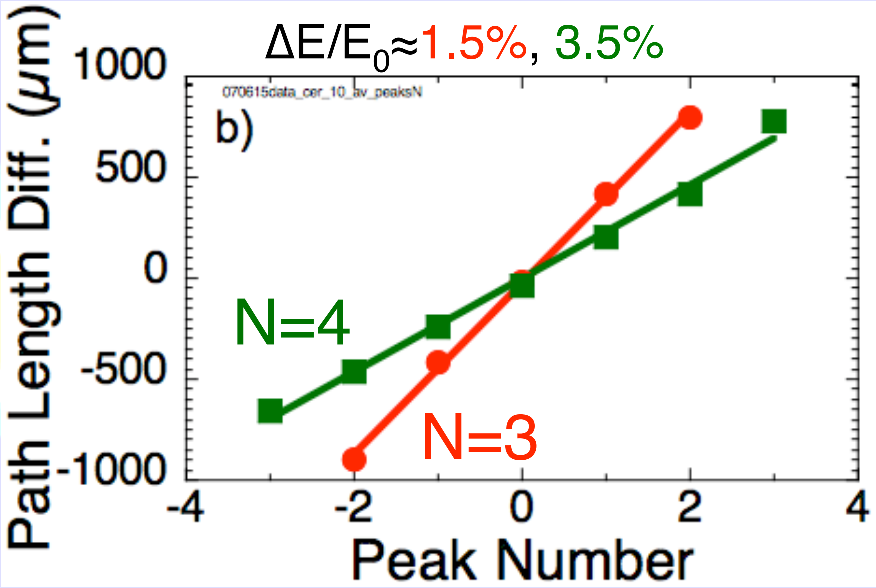
$$A(\Delta z) = \int_{-\infty}^{\infty} dt\, E(t) E(z - \frac{\Delta z}{c})$$

Bunch shape

MULTIBUNCHES IN TIME

Coherent Transition Radiation (CTR) Interferometry



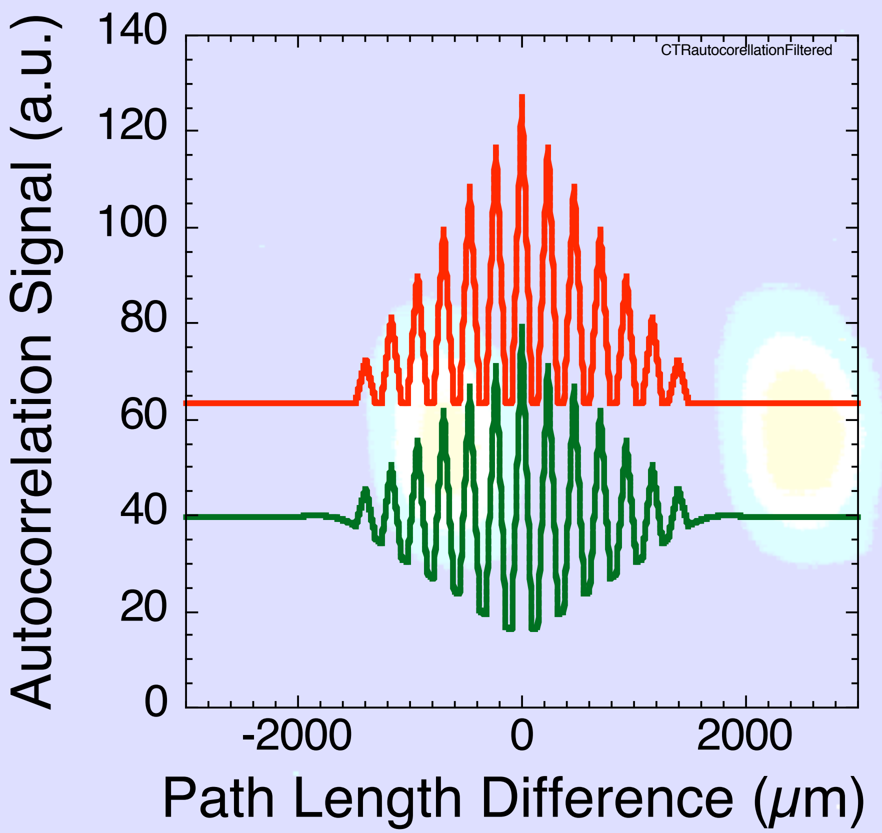


Muggli et al., PRL 101, 054801 (2008).

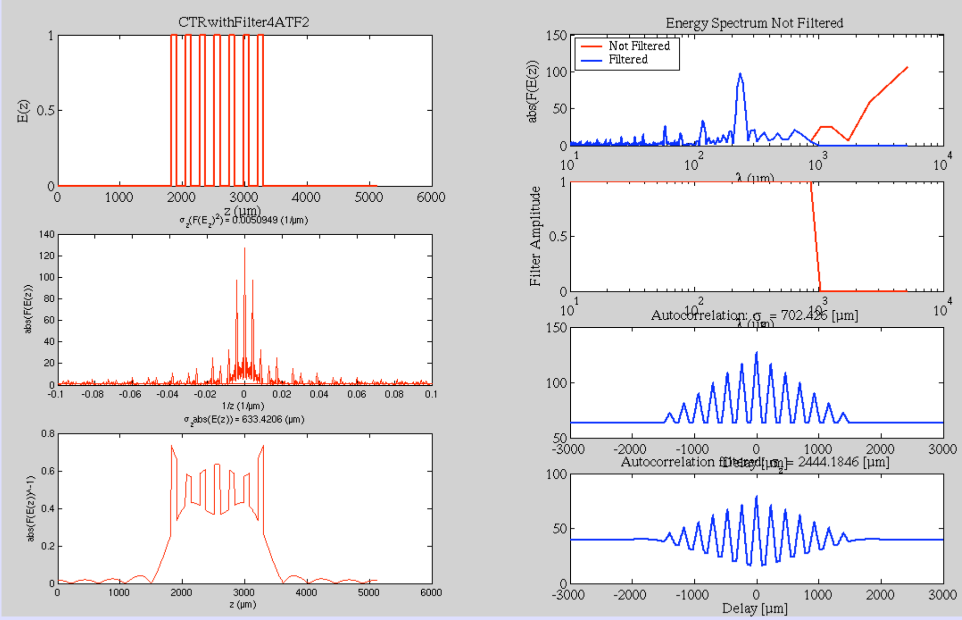
- Autocorrelation leads spacing Δz
- N microbunches => 2N-1 peaks
- Control N and Δz (I mean Δt!)

USC	# AUTOCORRELATION TRACE	BROOKHAVEN NATIONAL LABORATORY / STI OPTRONICS

Calculated



Bolometer response: ??->1000 μm
Filtering effect of the various apertures and windows



- Including filtering reproduces features of measured trace
- Filtering affects bunch width measurement, but not μbunch spacing measurement!

BUNCH CONTRAST

$$T(x_0;x_{w,i},d,\sigma_x) = 1 - \frac{1}{2}\sum_i \left[erf\left(\frac{\left(x_{w.i} + d/2 - x_0\right)}{\sqrt{2}\sigma_x}\right) - erf\left(\frac{\left(x_{w.i} - d/2 - x_0\right)}{\sqrt{2}\sigma_x}\right)\right]$$

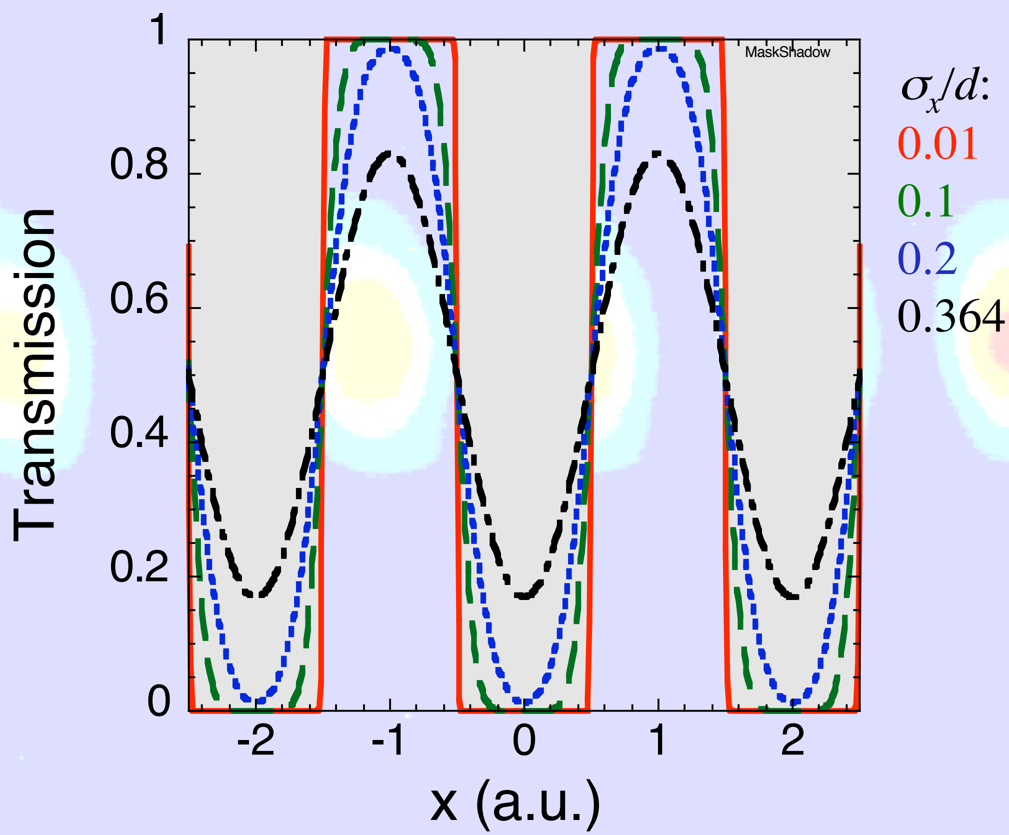
Convolution function mask and beam betatron size

Beam betatron size:

$$\sigma_x = \sqrt{\frac{\beta_x \varepsilon_N}{\gamma_0}}$$

Wire positions:

$$D = x_{i+1} - x_i$$

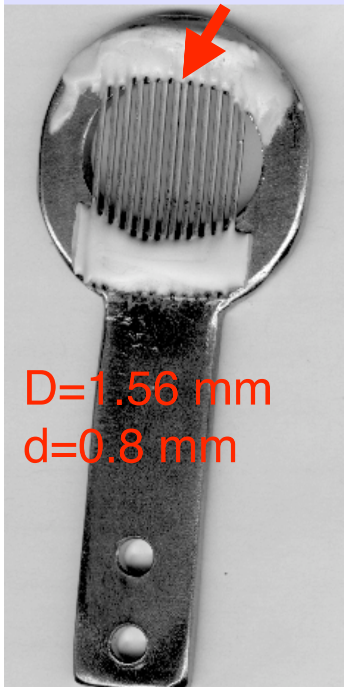


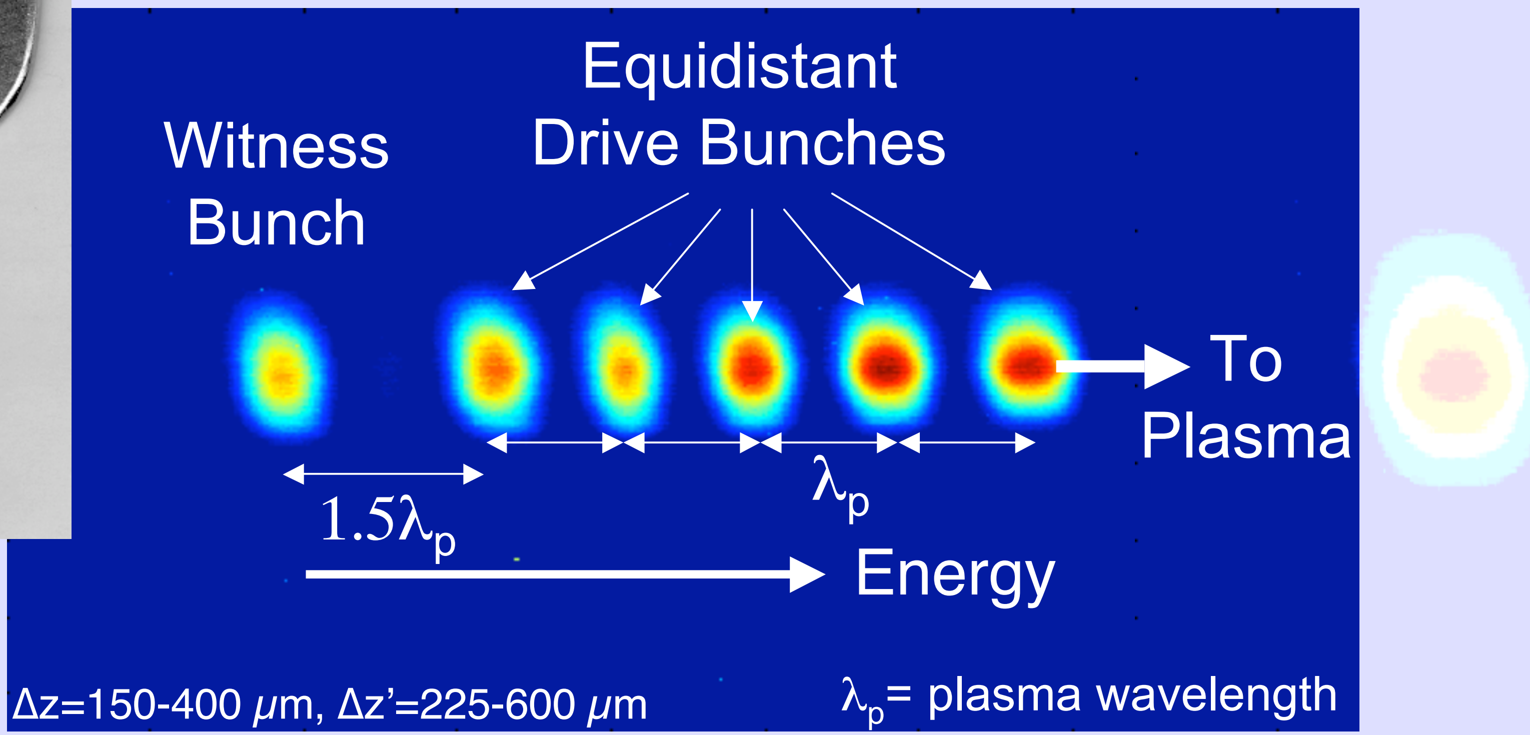
➡ Contrast decreases as σ_x/d increases

➡ Present experiments: $\sigma_x/d \approx 0.2$

TRAIN FOR PWFA

Mask with non-equidistant "wires"
Measurement in energy plane

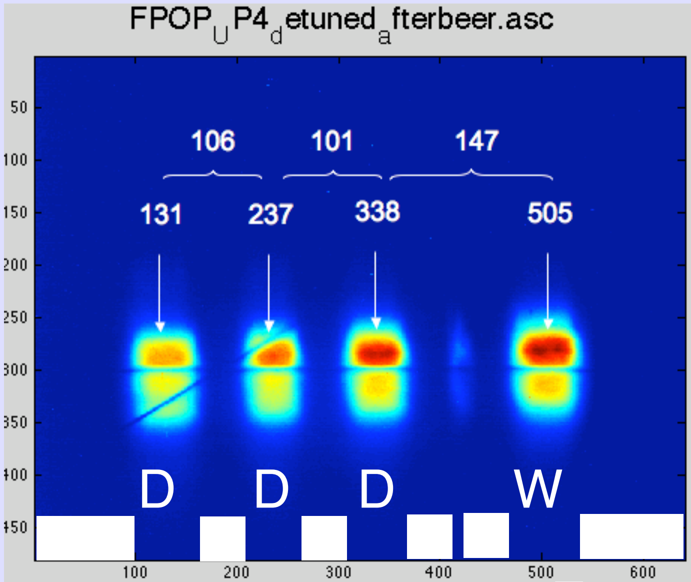




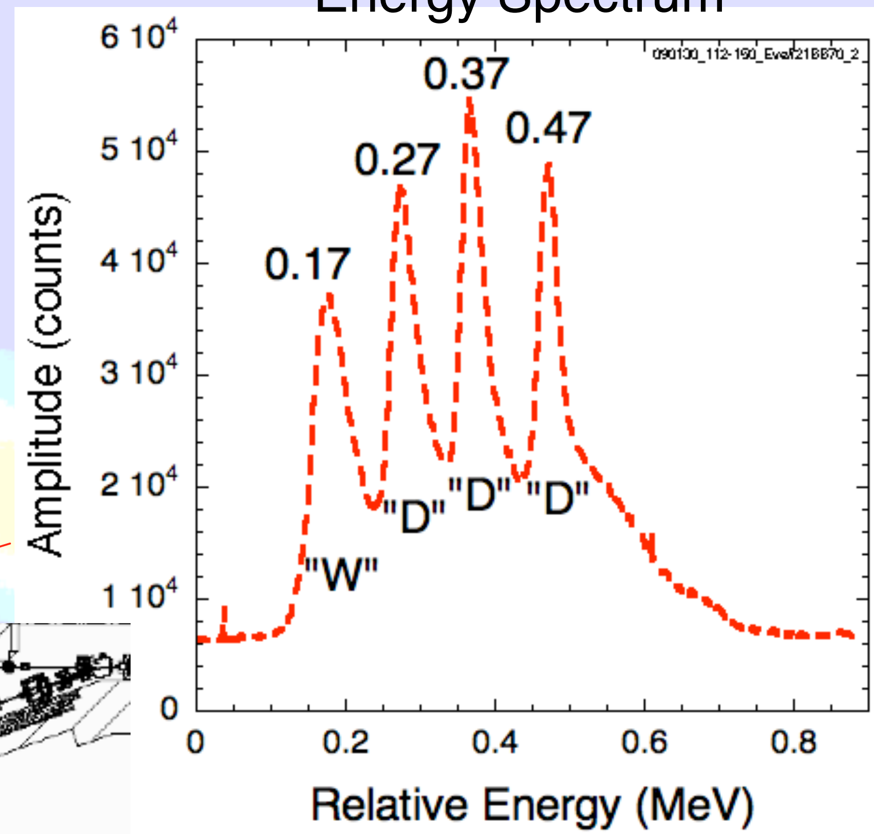
- Generate "ideal" spacing for resonant PWFA
- Charge modulation optimization possible
- Plasma density must be adjusted for resonant excitation

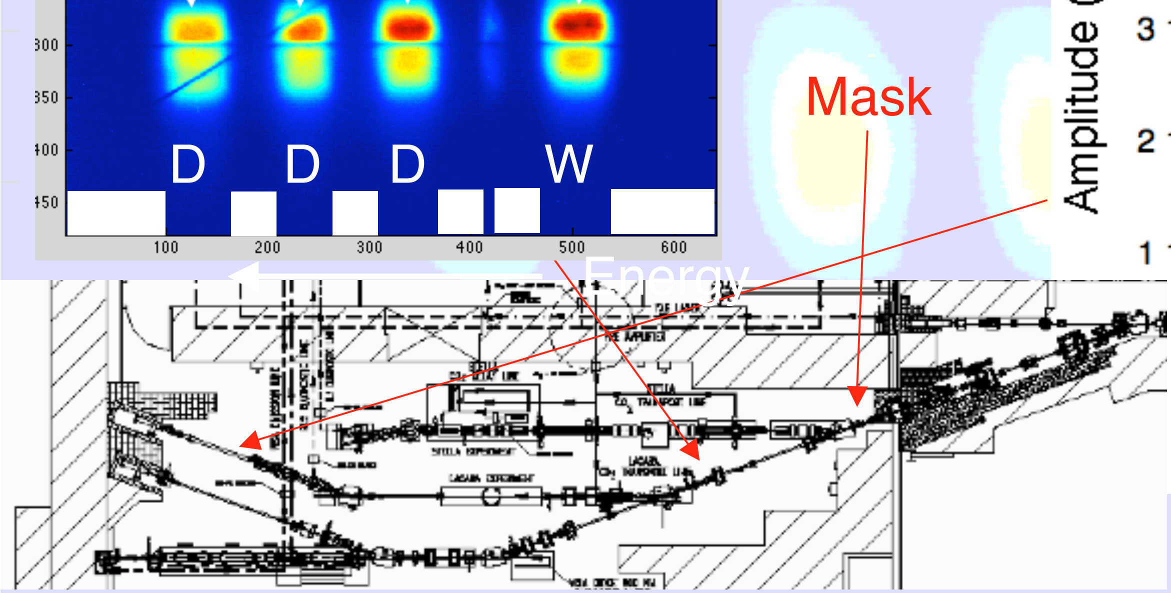
MULTI-BUNCH TRAIN FOR PWFA

Mask Shadow



Energy Spectrum





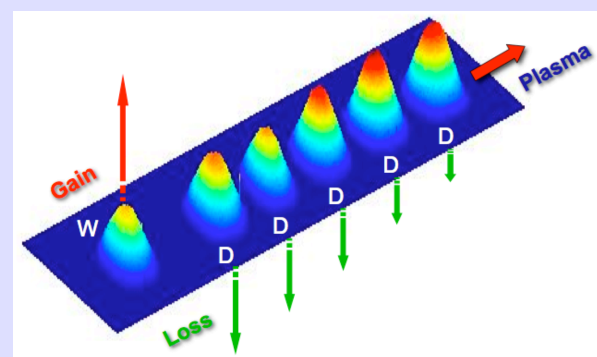
- Select number of drive bunches (high energy slit).
- Witness bunch appears with drive bunch spacing on energy spectrometer CSR? See proposal by Alexei Fedotov

SUMMARY / CONCLUSION

- Simple method to produce picosecond bunch train
- Proof-of-principle with wire mesh

  Muggli et al., PRL 101, 054801 (2008).
- Stability in time and energy guaranteed by mask
- Number of μbunches and their spacing can be selected
- Bunch train pattern can be tailored for specific applications

  Bunch spacing non-periodic, # bunches, length of bunches, charge, …
- Train length can be varied trough bunch compression
- Application to PWFA experiments at ATF: train of drive bunches+witness bunch



- Influence, study of CSR effects

Thank you!

AND

Thank you very much to every one at ATF!