Optimum Electron Distribution for Space Charge Dominated Beams

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- Minimum emittance
- 3D-Ellipsoidal electron bunch
  - Emittance performances compared to "Beer Can"
  - Linear Longitudinal Phase Space
  - Optimization for S-Band and L-Band guns
  - Sensitivity
- Generation of 3D-ellipsoidal laser pulse
  - "First thoughts"
- Conclusions

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Intrinsic Limits of Minimum emittance

$$\varepsilon_{tot} = \sqrt{\varepsilon^2_{cathode} + \varepsilon^2_{RF} + \varepsilon^2_{space\,charge}}$$

- Cathode "Intrinsic" emittance
  - for copper measured 0.6 mm.mrad per mm of r_{laser} [1,2,3]
    theoretical is 0.3 mm.mrad per mm of r_{laser}

$$\varepsilon_{cathode} = \sqrt{\varepsilon^2_{thermal} + \varepsilon^2_{roughness} + ??}$$

$$\varepsilon_{cathode} \alpha\ r_{laser\,spot}$$

  - Minimum r_{laser} set by "Space Charge Limit"
    Minimum r_{laser} or electrons cannot leave cathode (for metal cathodes)
    - $R_{min.}$ = 0.82 mm at 54 MV/m for a 1nC
    - $R_{min.}$= 1.34 mm at 20 MV/m for a 1nC

$$E = \frac{\sigma}{\varepsilon_o} = \frac{Q}{\pi r^2 \varepsilon_o} < E_{peak} \sin\phi$$

- RF emittance
  - small ε_{RF} (10 °,r = 1.2mm,Q = 1nC) < 0.15 mm.mrad for S-Band gun

- Space Charge
  - Emittance copensation to correct for linear space charge effects;
  - Non-linear components of SC forces can not be compensated for with linear optics elements

Uniform charge density inside 3D-Ellipsoid volume = Ideal Emitted pulse

  - Charge density remains uniform over volume as the space charge force is linear
  - Perfect emittance compensation is achieved with linear optics elements
  - $\Rightarrow$ $\varepsilon_{space\ charge}$ ==0

$$\varepsilon_{tot} \sim \varepsilon_{cathode}$$

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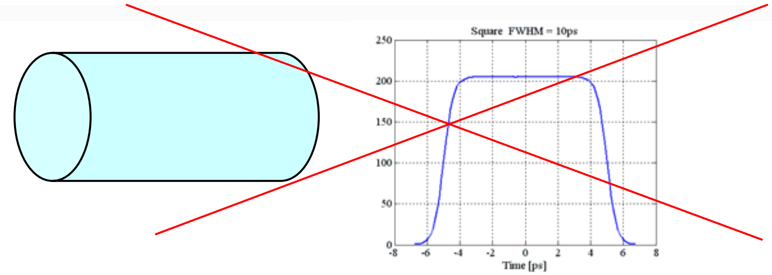
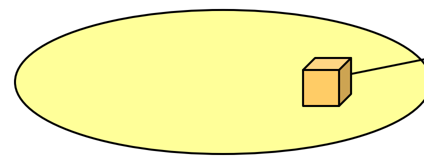
Ellipsoidal Emission pulse

- "Beer Can" shape is <u>NOT</u> the optimum shape
- Ideal Emitted pulse = Ellipsoid

Electrons are uniformly distributed inside a 3D ellipsoid volume

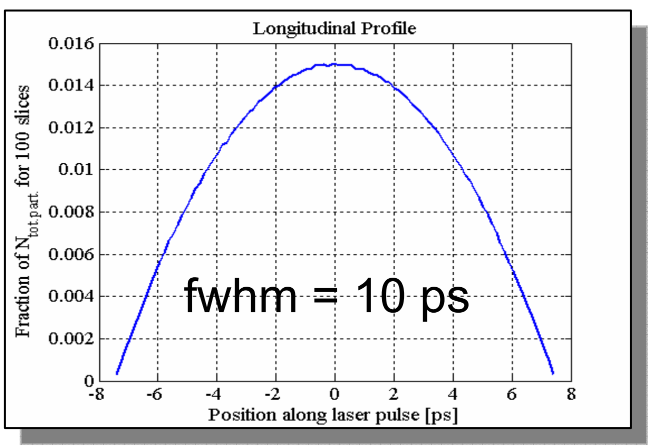


$$\frac{x^2}{a^2}+\frac{y^2}{b^2}+\frac{z^2}{c^2}=A^2$$



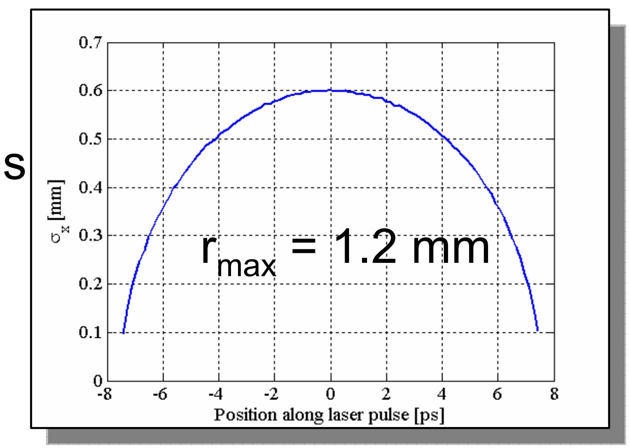
$$\frac{N}{dx\,dy\,dz}=const.$$

Line Density



Pulse length

Radius



Pulse length

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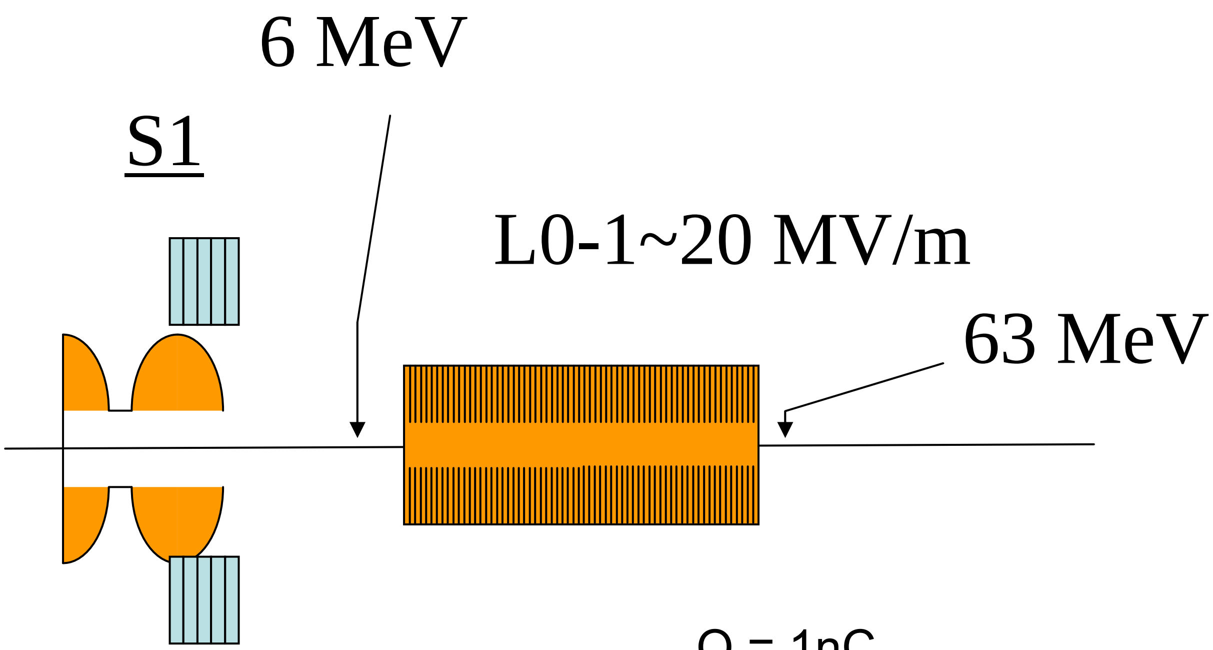

S-Band Gun

E_{peak}~120MV/m

Q = 1nC

FWHM $_{laser}$ = 10ps

PARMELA Simulations

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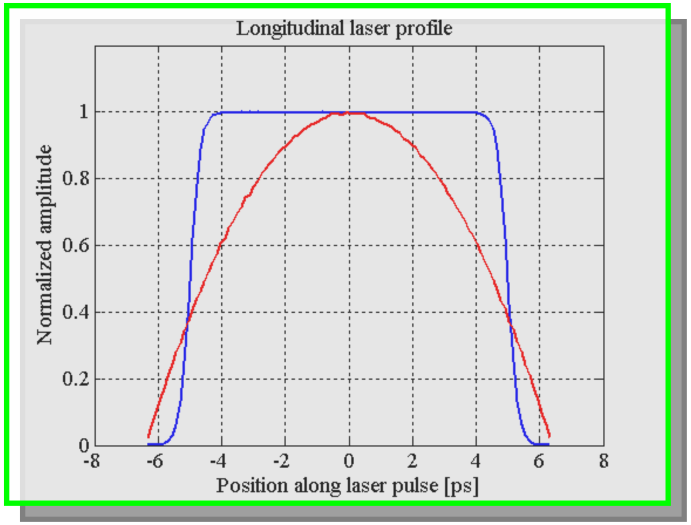
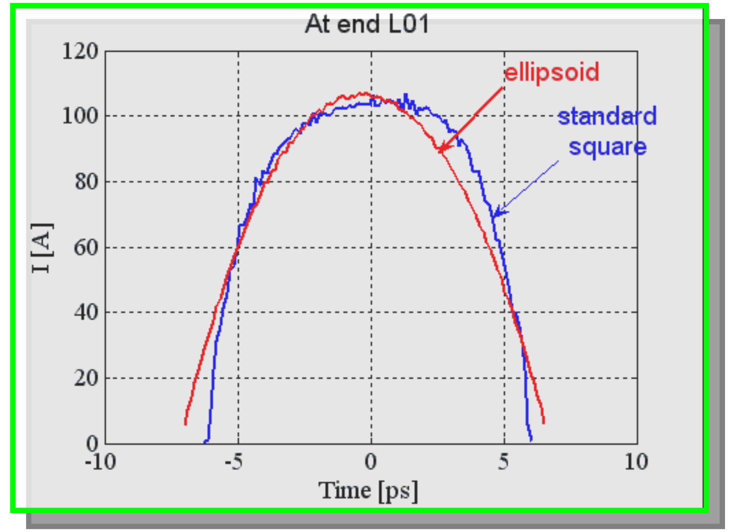
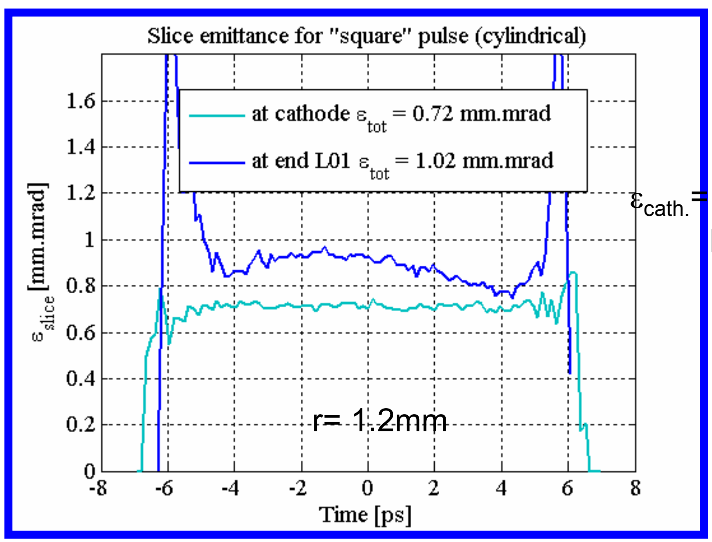
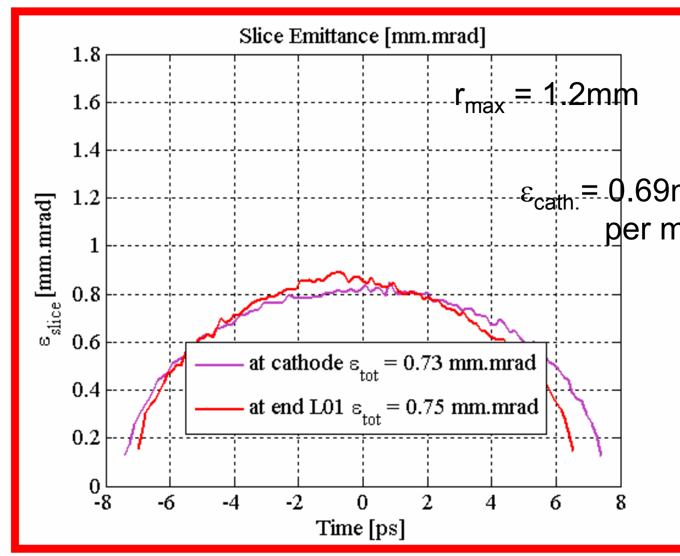
Comparison between“beer can” &“3D ellipsoid”







$\varepsilon_{cath.}$ = 0.6 mm.mrad per mm



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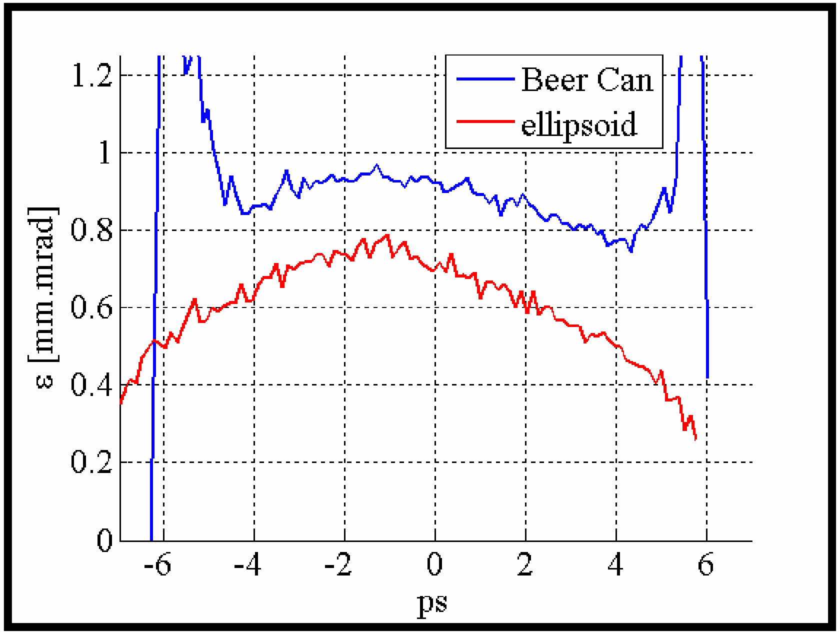
Comparison between"beer can" &"3D ellipsoid"

3D ellipsoid is even better optimized with r_{max} = 1mm

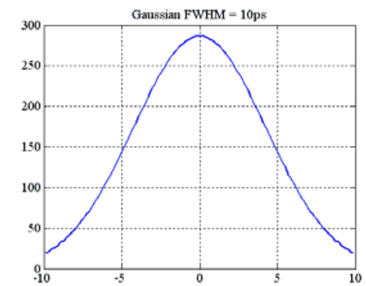


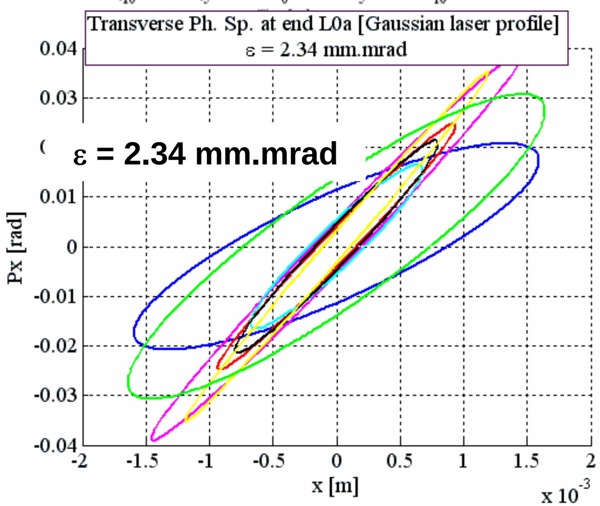
ε = 1.02 mm.mrad; $\varepsilon_{80\%}$ = 0.95 mm.mrad (with standard $\varepsilon_{\text{"cathode"}}$ =0.6)

ε = 0.71 mm.mrad ; $\varepsilon_{80\%}$ = 0.71 mm.mrad (with overestimated $\varepsilon_{\text{"cathode"}}$ =0.7)

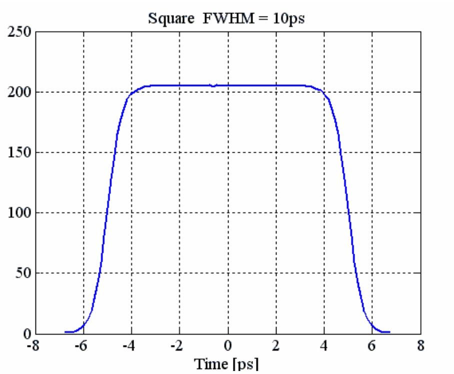
Transverse Ph.Space

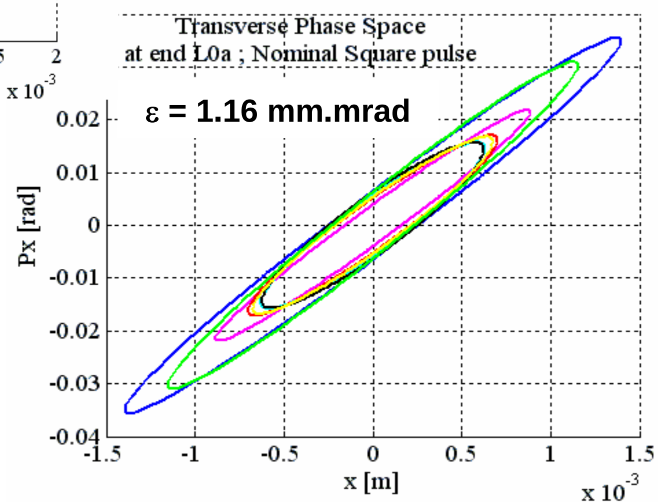
Gaussian





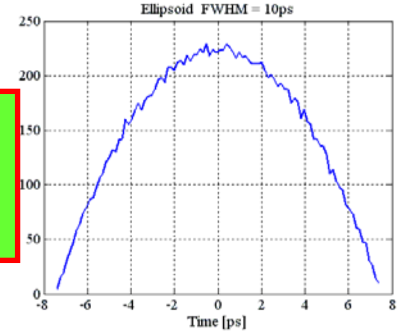
Square pulse

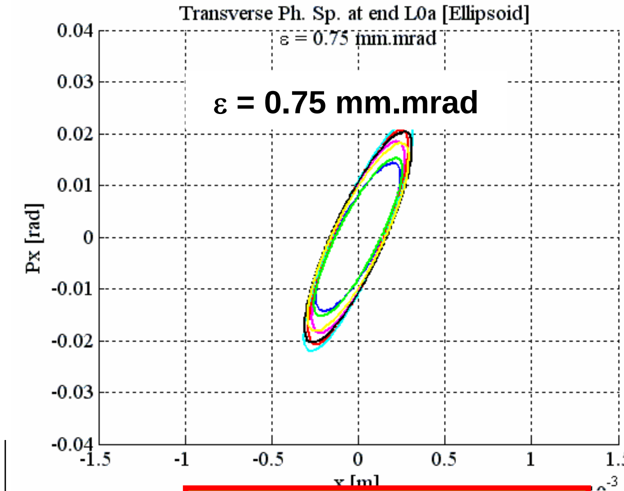




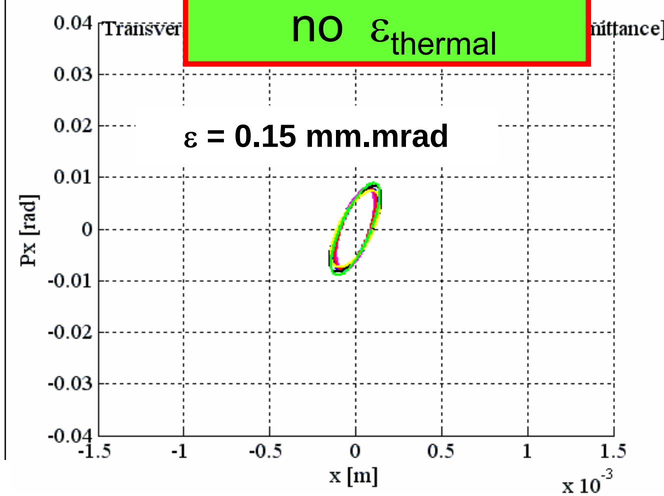
Ellipsoid

with $\varepsilon_{thermal}$

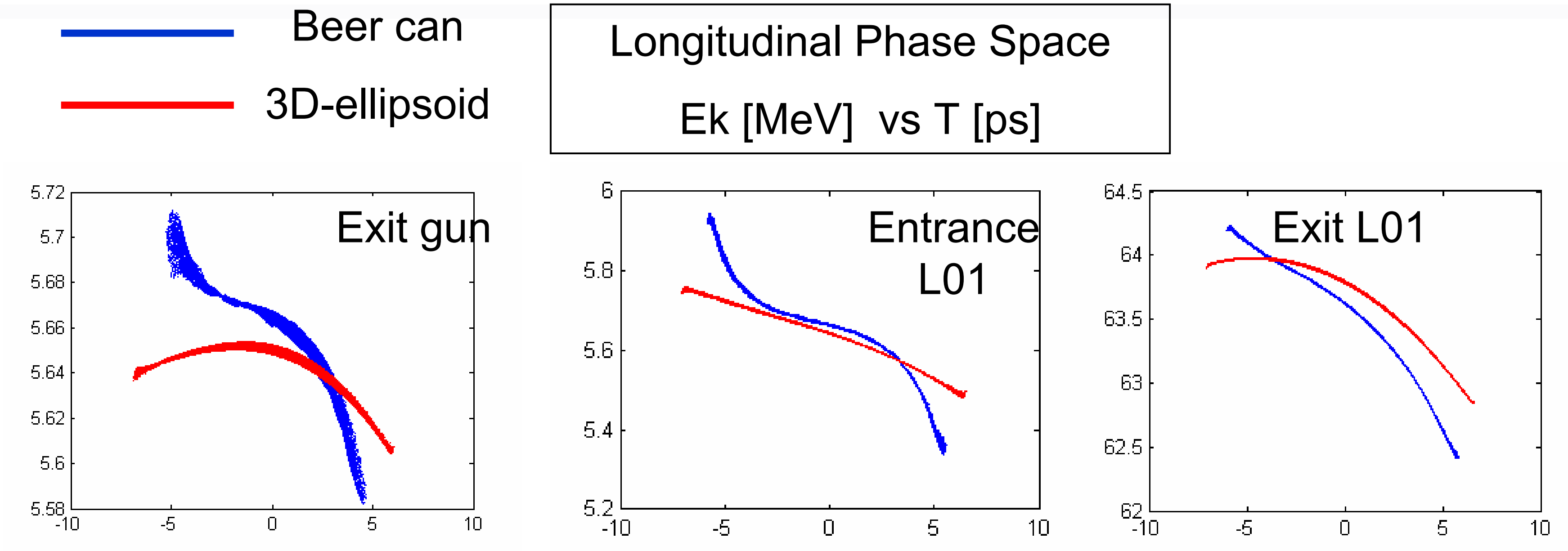




no $\varepsilon_{thermal}$



Linear Longitudinal Phase Space



- The longitudinal phase space gets linear
- Unfortunately, in the LCLS, does not prevent the production of large spikes after bunch compressor

⇐ those spikes come from wakefield which follow λ’

☼ LCLS would benefit from lower slice emittance, better matching and lower sensitivity to parameters

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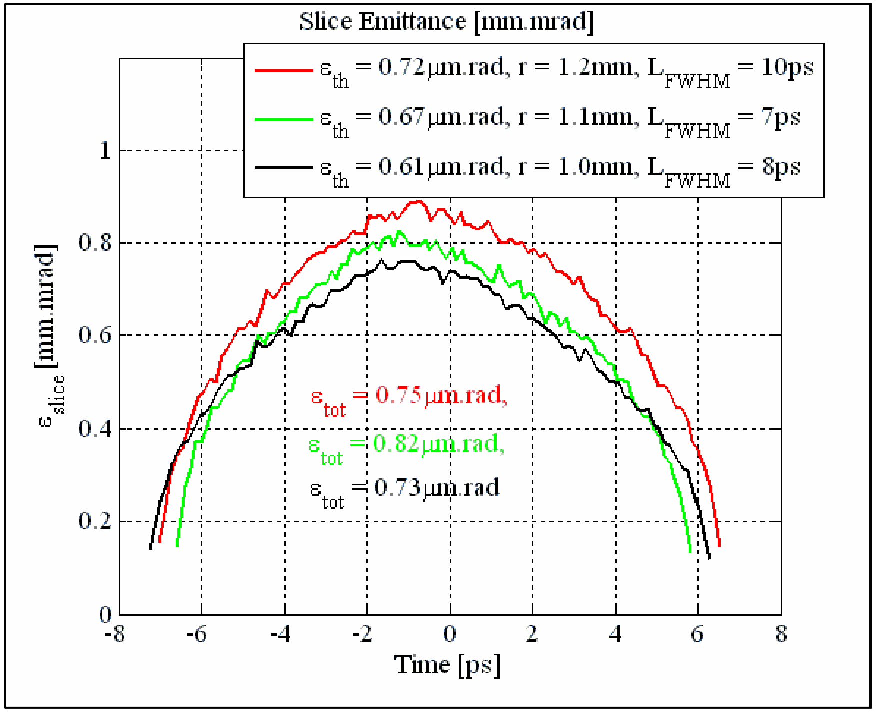
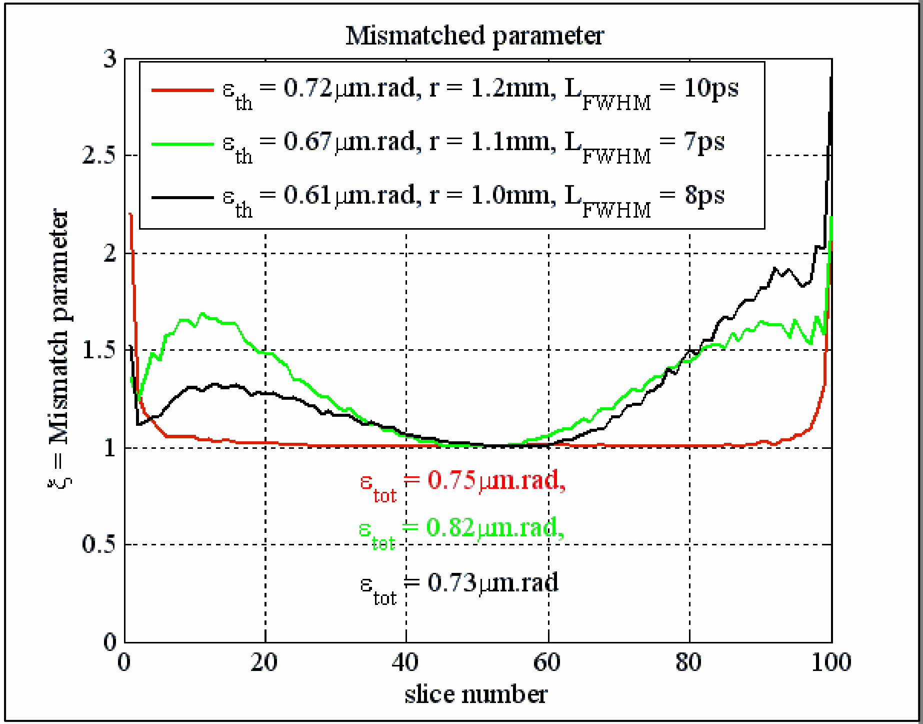
Optimization

After scanning solenoid and $\phi_{RF,injection}$

$$\xi = ½(\beta_o\gamma - 2\alpha_o\alpha + \beta\gamma_o)$$





Too small r or too small length ⇒ more mismatch

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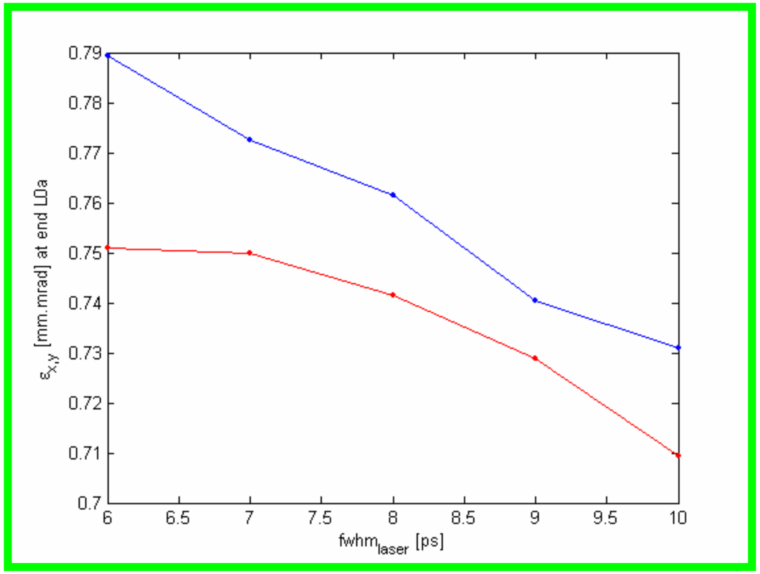
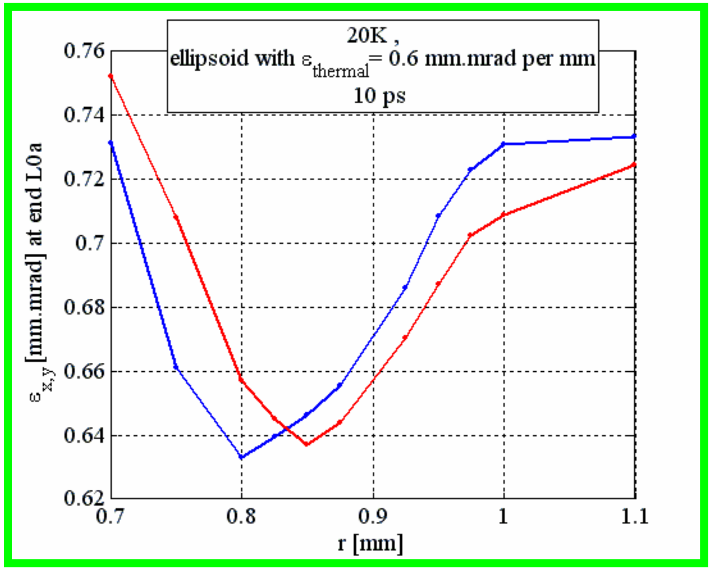
Optimization
vs pulse length and radius





Vs laser pulse length

Vs laser spot size radius

- Increasing pulse length reduces emittances
  - limited by ε_{RF} and desired pulse length before compressors
- Optimum radius would be between 0.8 and 1mm
  - unfortunately at 0.8 mm , too strong image charge distorts bunch profile;
  - 1mm gives better matching

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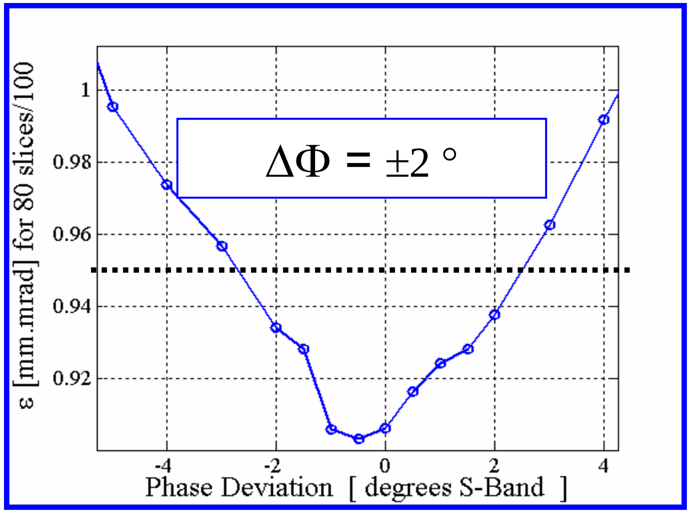
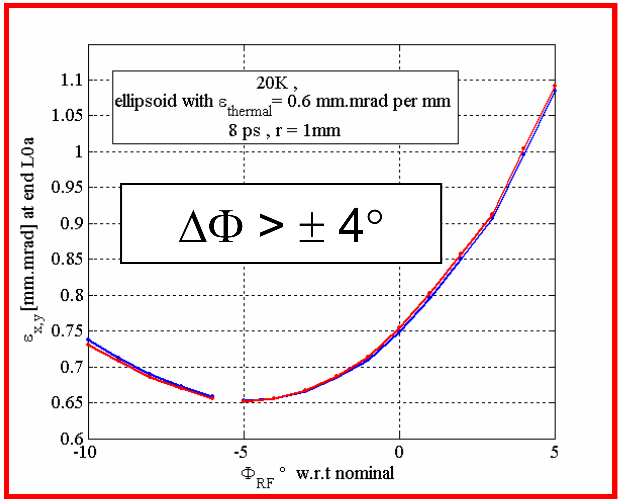
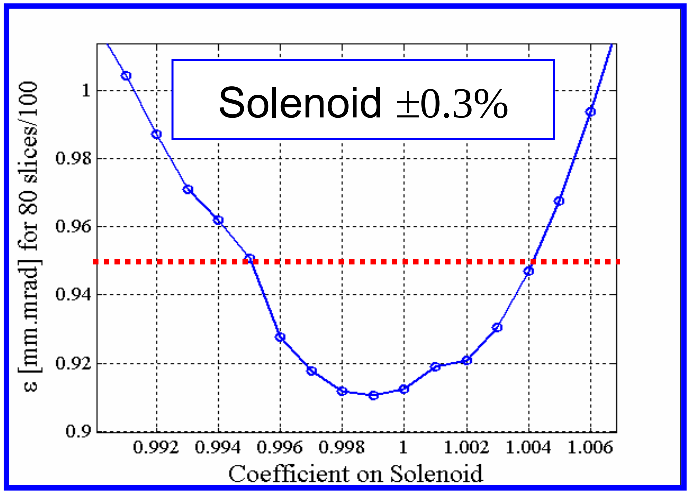
Much less sensitive !

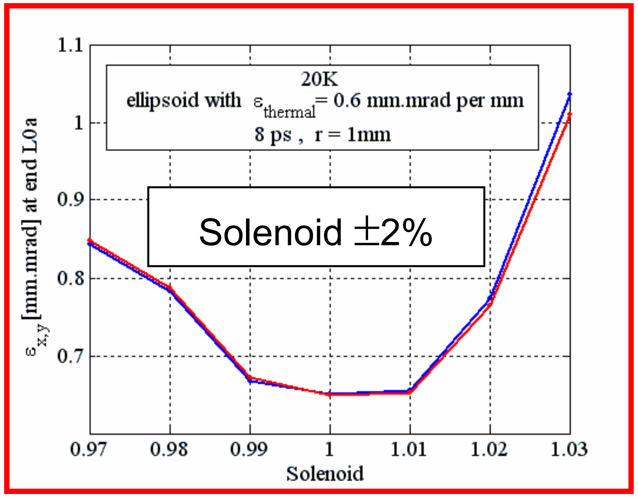
"Beer can"

Ellipsoid









Tuning will be much easier in 19D-parameter space

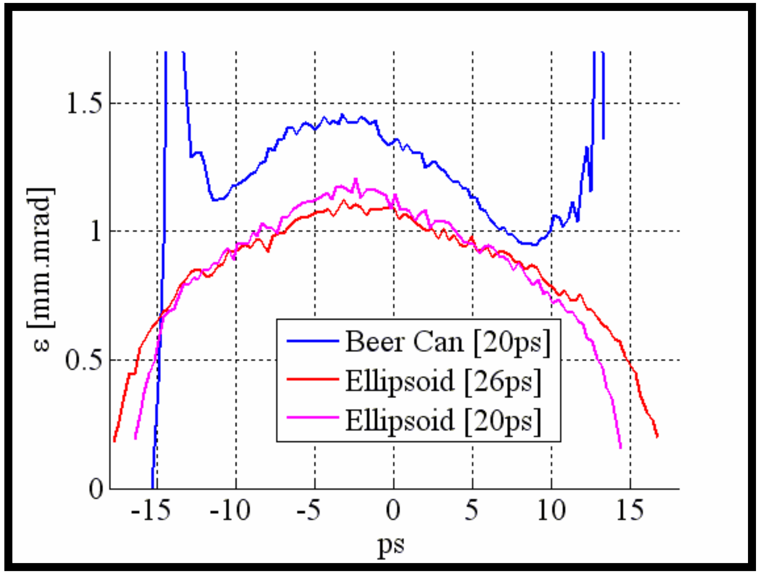
How much distorsion on that perfect shape until we start losing this low sensitivity ?

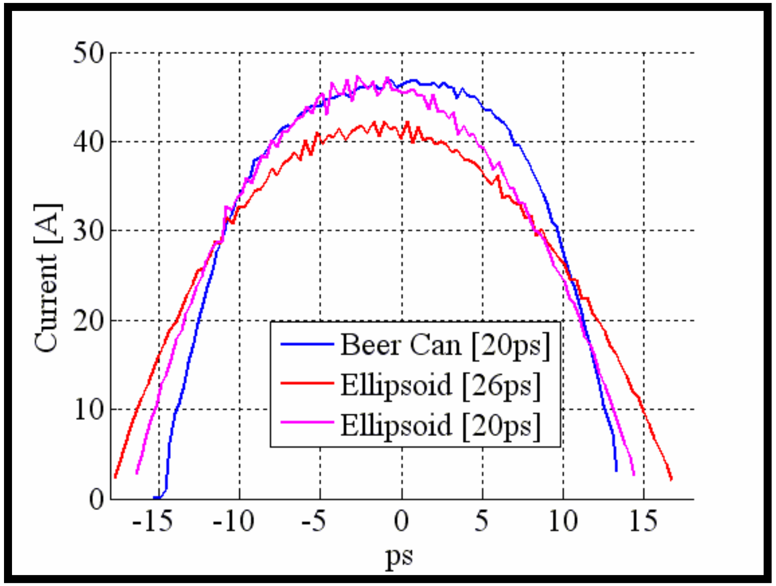
Optimization for L-Band Gun

- 1nC, with little effort in optimizing/retuning

L-Band gun 40MV/m, ϕ = 33 °

ε at 140 MeV





ε =1.42 mm.mrad; $\varepsilon_{80\%}$ = 1.34 mm.mrad

ε = 0.93 mm.mrad ; $\varepsilon_{80\%}$ = 0.96 mm.mrad

ε = 1.02 mm.mrad; $\varepsilon_{80\%}$ = 1.03 mm.mrad

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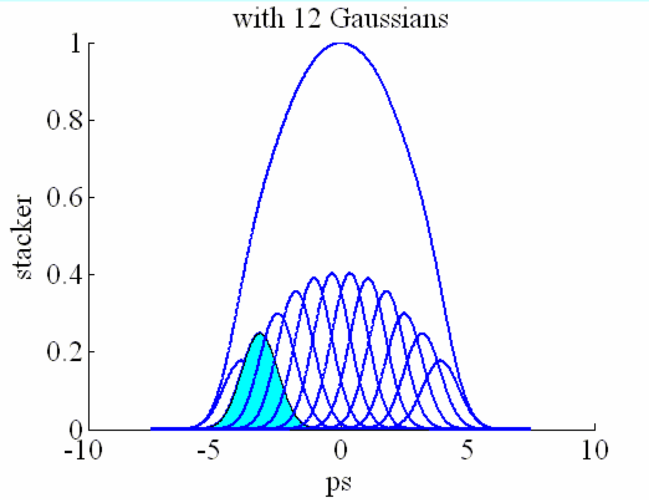
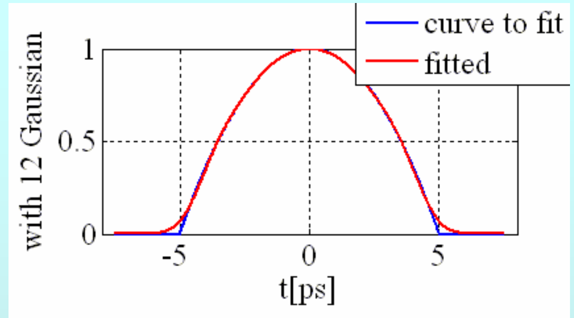
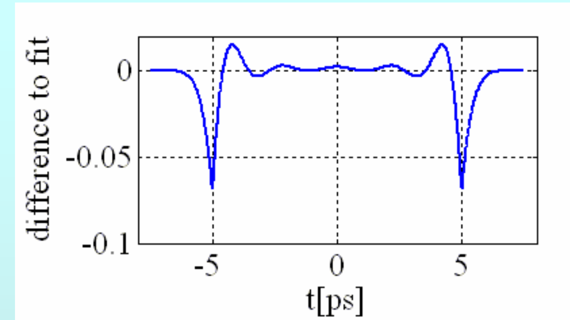
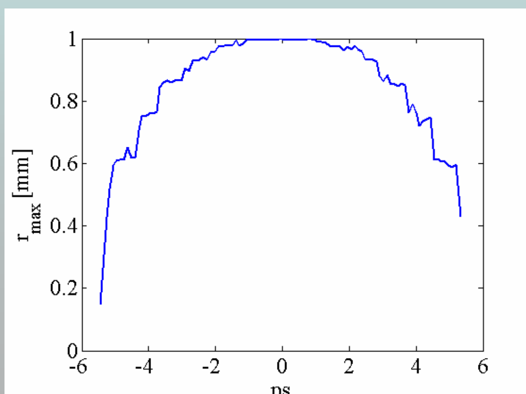
Stacking pulses

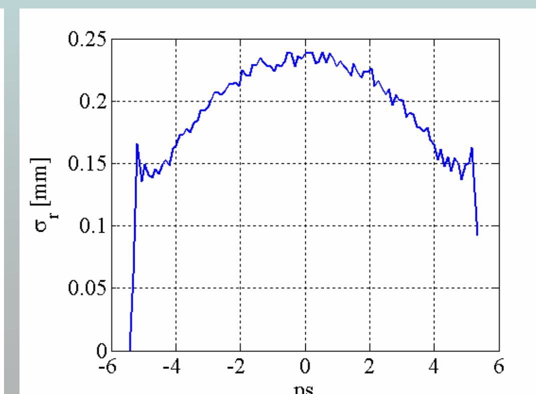




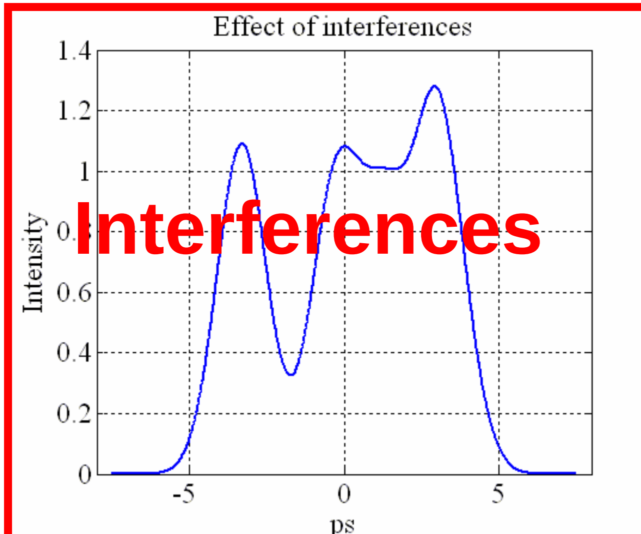


6+6 beamlets of different radii





Gaussians Wash out discrete steps of rms value



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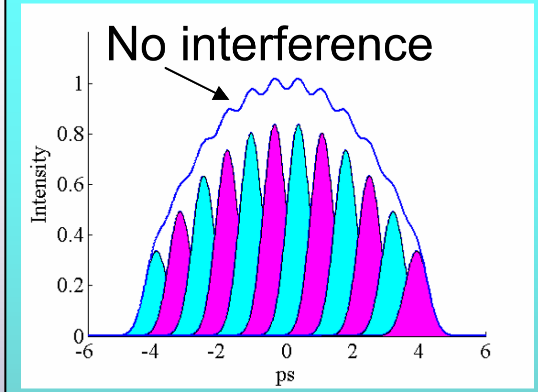
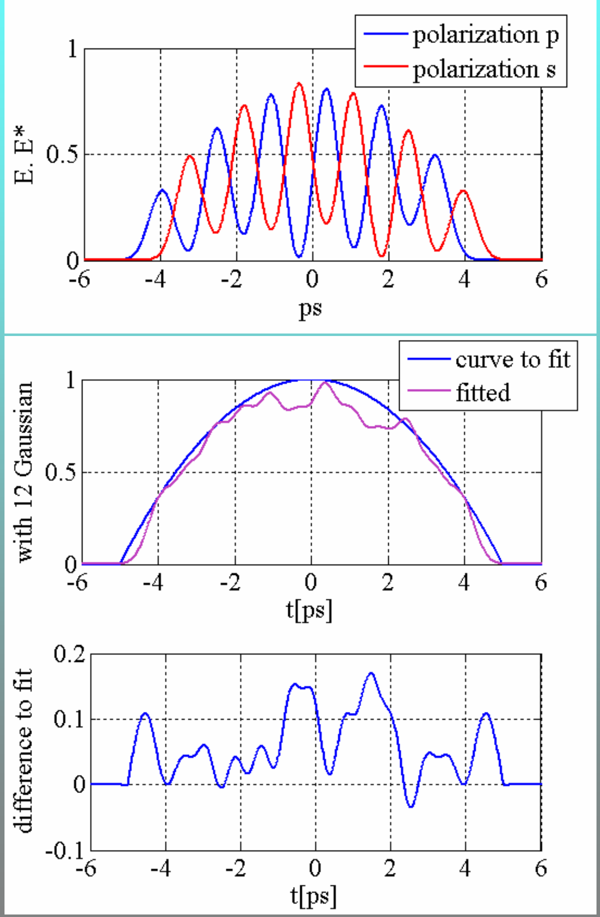
Fighting interferences in Stacker

Alternating polarization + appropriate choice of σ, interference effect is minimized



Interferences random phases



$$E_p = \sum_i A_{2i}\, e^{-\frac{(t-t_{2i})^2}{4\sigma^2}}\, e^{i2\pi\varphi_i}$$

$$E_s = \sum_i A_{2i+1}\, e^{-\frac{(t-t_{2i+1})^2}{4\sigma^2}}\, e^{i2\pi\varphi_i}$$

$$I = I_p + I_s$$

$$I_p = E_p.E_p{}^*$$

$$I_s = E_s.E_s{}^*$$

~<15 %

for all draws

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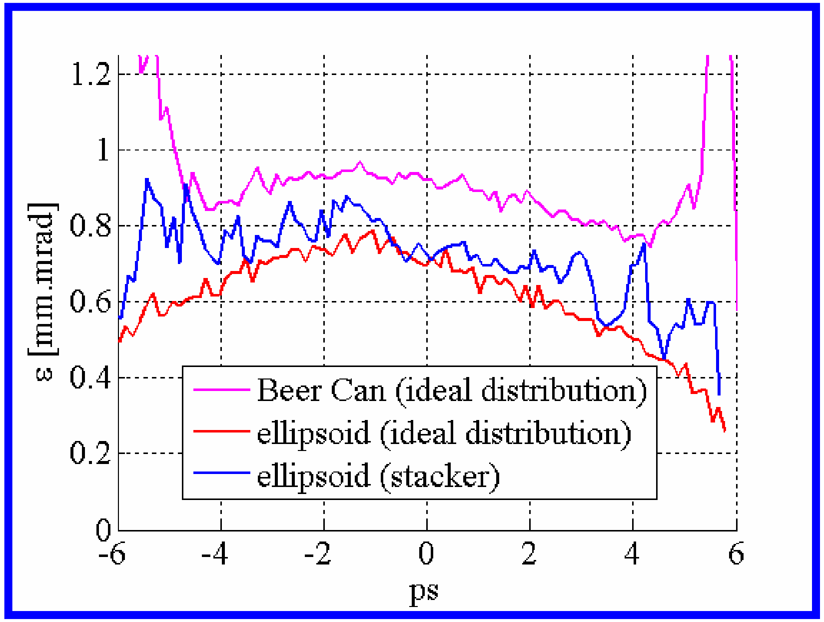
PARMELA simulations using stacker distributions



IDEAL

Beer Can

Direct beer can

Ellipsoid ideal **IDEAL**

50 Beamlets no interference

Stacker

12 Beamlets and random phase

NOT IDEAL

ε = 1.02 mm.mrad; $\varepsilon_{80\%}$ = 0.95 mm.mrad

ε = 0.71 mm.mrad ; $\varepsilon_{80\%}$ = 0.71 mm.mrad

ε = 0.80 mm.mrad; $\varepsilon_{80\%}$ = 0.80 mm.mrad

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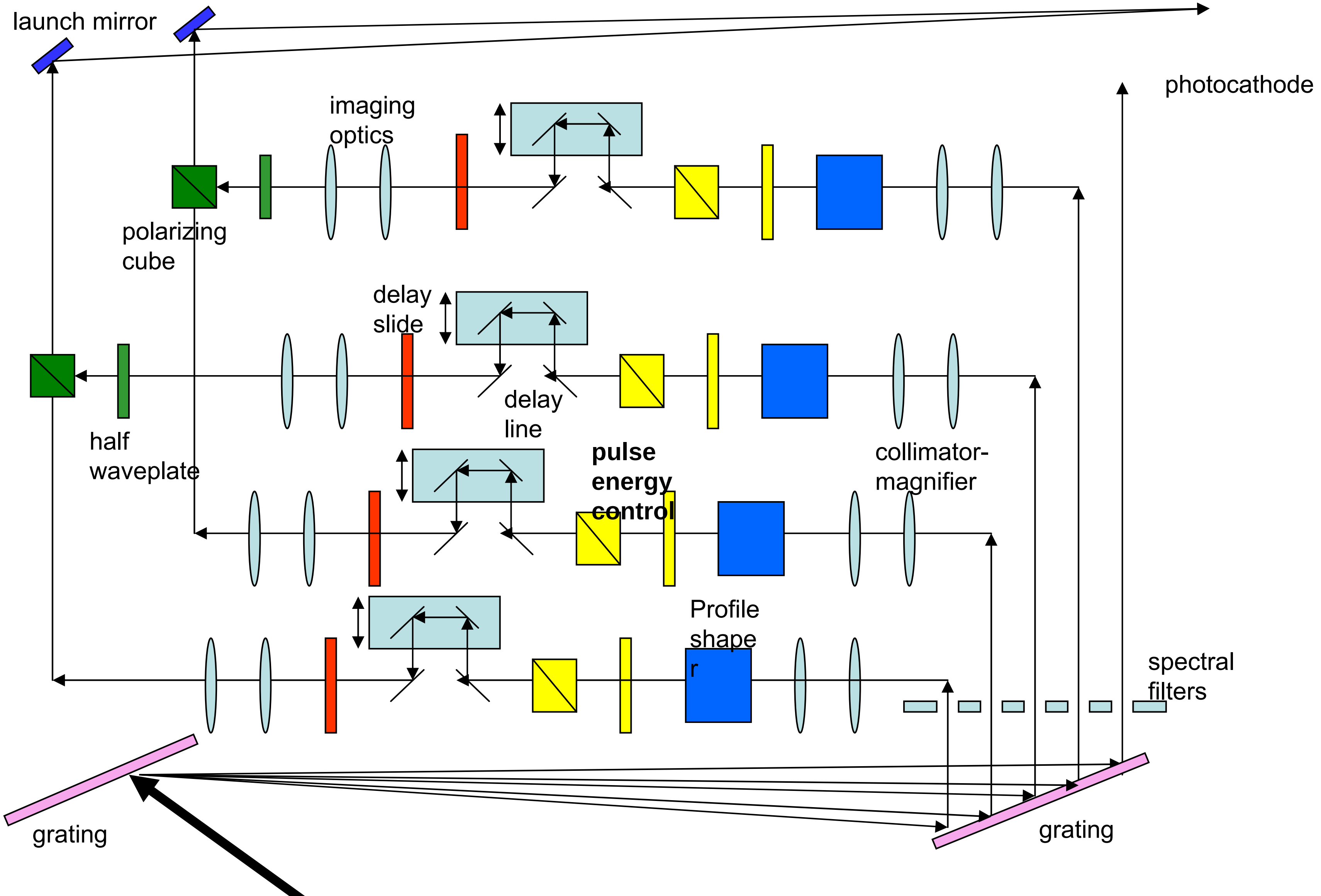
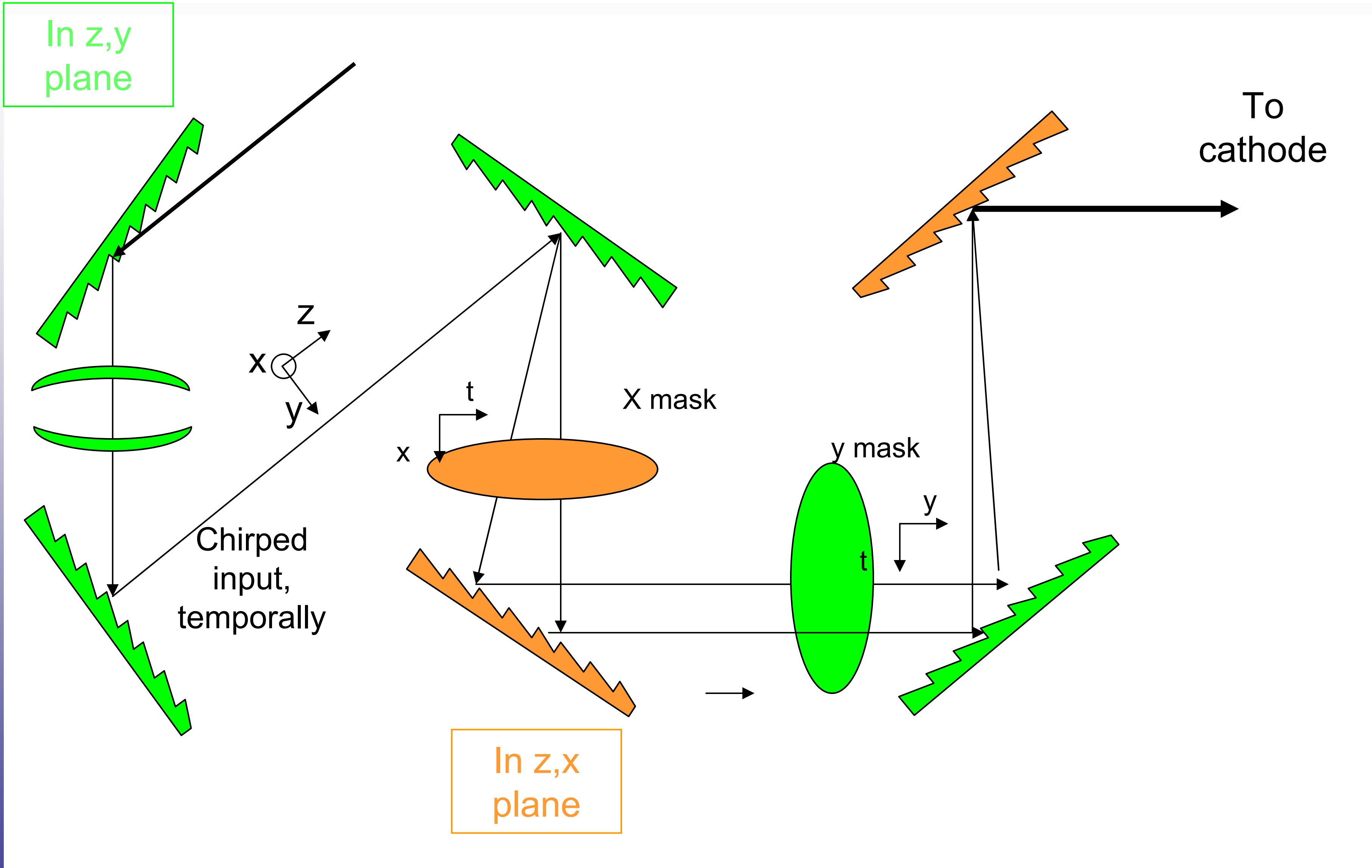
Stacker Layout



To the Courtesy of P.Bolton

“what to try to avoid…” from P.Bolton

Spectral Control Principle



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Production of the 3D ellipsoidal pulse

- Two solutions proposed
  - **Pulse Stacker**
    - Too complex
    - Too lossy
    - Uses too much space
    - Technically feasible with many $$$$$$$ for
      - controls, to achieve alignment , timing
      - measurement to adjust amplitude coefficient
  - **Spectral Control technique**

    UV shaping using Four-gratings with masking array in dispersive environment
    - Principle :
      - for highly chirp beam ,projects (t,x) into a 2D surface , use masking matrix (2D)
      - A second pair of gratings : same for (t,y)
    - masking technology for IR exists
      - but given present difficulties direct UV might be more appropriate; masking technilogy needs to be developed (transmissive or reflective scheme)
    - fluence limits on optics (even worse upstream)
    - efficiency low
    - probably better for space and money than previous solution

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Conclusion

- Ideal emission pulse = “3d-ellipsoid” not “beer can”
  - Perfect emittance compensation in high charge regime
  - Impressively less sensitive to tuning parameter
    - tolerances are 1 order of magnitude above those defined for “beer can” pulse
  - More exploration required for L-Band gun
  - Exploration for low gradient gun (10MV/m)
- Ellipsoidal Laser Pulse is a Technical challenge
    - maybe slightly more challenging than “beer can” generation?
    - if direct UV shaping is considered for “beer can”, the “ellipsoid generation” shares many of the same difficulties

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References

[1] Yang, Sumitomo Industries

[2] B.Graves, DUVFEL

[3] J.Schmerge, GTF

[4] O.J.Luiten, et al. "How to realize uniform 3-dimensional ellipsoidal electron bunches", Phys.Rev. August 2004

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