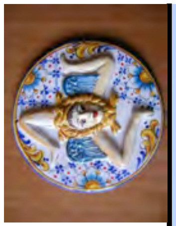

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Laser Shaping in Photoinjectors for High Brightness Beams

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LCLS

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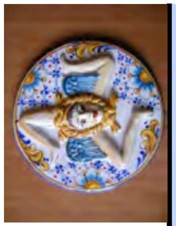

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Introduction

- Uniform "3D-ellipsoidal" photo-e bunches

  - KM [1], Sacherer [2], Reiser [3]

  - assumption: 3D ellipsoidal pulses available

• J.Luiten et al. fantastic idea of self-generated ellipsoidal e bunch[4], more ideas presented at FEL2005

$\Rightarrow$ revolution in the field (if it works)

Peak Brightness improved by <u>orders of magnitude</u>

• Laser (duration, size, power)

• Emitter ($\varepsilon_{thermal}$,QE, $\tau_{emission}$)

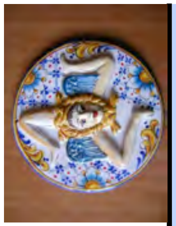
} Well characterized in running systems

• Flat-top laser pulses already difficult to produce

• 3D-ellipsoidal laser pulses more difficult ?

• Recommendation: 3D-ellipsoidal pulses for new projects and upgrades

Peak Brightness $\Uparrow$ >2.5



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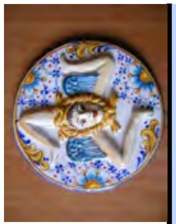
Outline

- 3D-Ellipsoidal e pulses
  - – Suppression of non-linear space charge effects
  - – Performances ellipsoidal vs flat-top distributions
    - Simulations for S-Band and L-Band guns
    - Sensitivity + linear Longi. Phase Space
  - – Maximizing brightness
- Production of 3D-ellipsoidal laser pulses
  - – stacker
  - – spectral masking
  - – DM + fiber bundle



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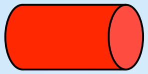
Beam Dynamics

After emittance compensation [5]

$$\varepsilon_{tot} = \sqrt{\varepsilon^2_{thermal} + \varepsilon^2_{RF} + \varepsilon^2_{Chrom.} + \varepsilon^2_{non-linear\ space charge}}$$

LCLS, TTF 2



$$\varepsilon_{thermal} \sim \sigma_r \sigma_{r'} \qquad \propto \qquad \sigma_r$$

→ ~ 60%

$$\varepsilon_{RF} \sim \frac{E_{peak}}{f_{rf}} \sigma_r^2 \sigma_z^2 \qquad \propto \qquad \sigma_r^2$$

$$\varepsilon_{chromatic} \sim \frac{\Delta p}{p} \frac{\sigma_r^2}{f} \qquad \propto \qquad \sigma_r^2$$

→ ~ few %

$$\varepsilon_{non-linear\ space charge} \sim F\left(\frac{Q}{\sigma_z \sigma_r^2}\right) \qquad \propto \qquad \frac{1}{\sigma_r^2}$$

→ ~ 40%

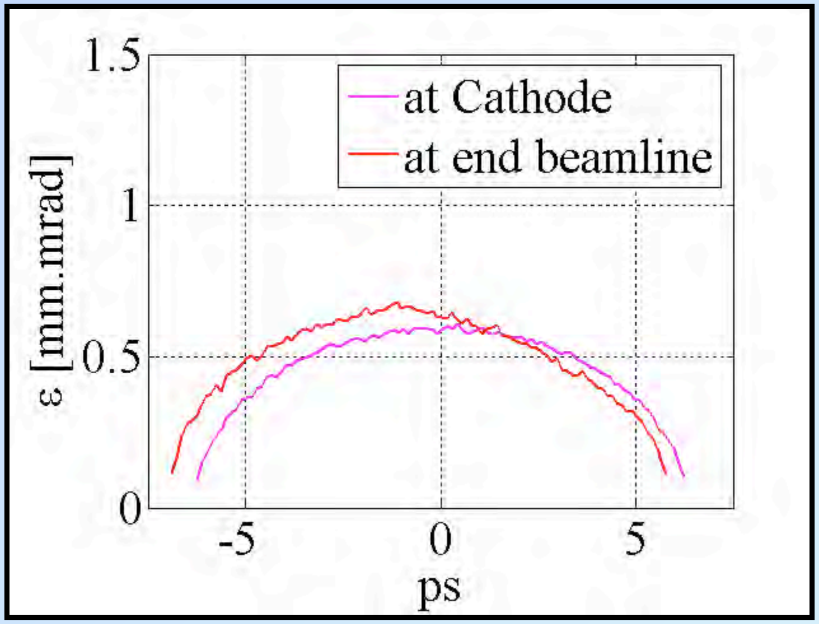
Suppressing Non-linear Space charge

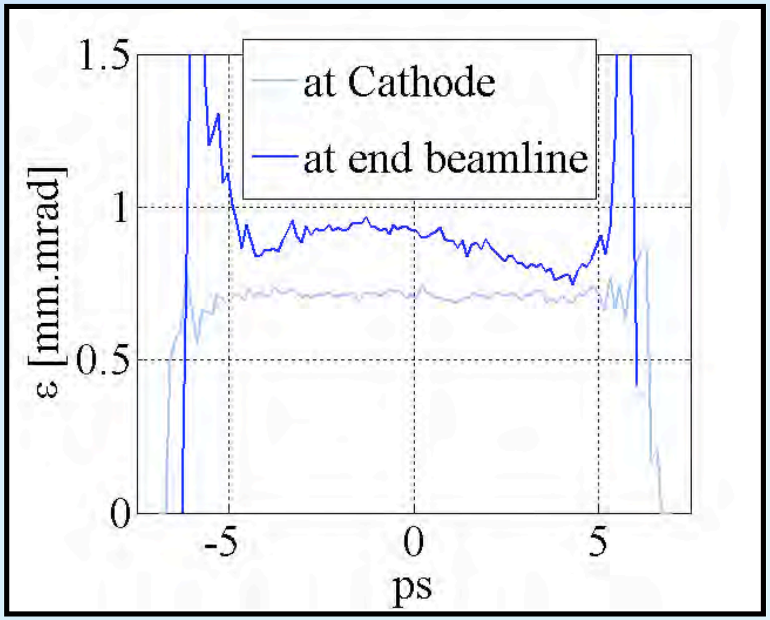
$$\varepsilon_{non-linear\ space charge} \sim F\left(\frac{Q}{\sigma_z \sigma_r^2}\right)^2$$

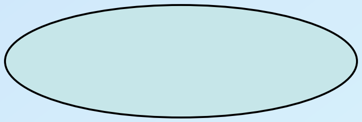
F $\Leftarrow$ initial bunch shape and uniformity
F = 0 for uniform 3D-ellipsoid

$$\varepsilon_{tot} \sim \varepsilon_{thermal}$$

PARMELA Simulations







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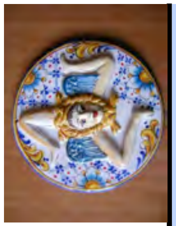

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Laser Pulse Dimensions for 1nC

- Cylindrical pulse

$$\varepsilon_{tot} = \sqrt{\left(C_{th.}\,\sigma_r\right)^2 + \left(F\frac{Q}{\sigma_r^2\sigma_z}\right)^2}$$

- required I_{peak} imposes σ_z

$\Rightarrow \sigma_r$ results from compromise

between two terms

for 100 A

r = 1.2 mm

- Ellipsoidal pulse

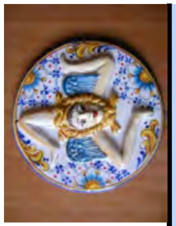
$$\varepsilon_{tot} \sim C_{th.}\sigma_r$$

- σ_r minimum $\Leftarrow$ image charge limit

$$r > \sqrt{\frac{Q}{\varepsilon_o \pi E_{RF}}} \quad \left\{ \begin{array}{l} E_{surface} = \dfrac{\sigma}{\varepsilon_o} \\ E_{RF} > E_{surface} \end{array} \right.$$

$E_{rf,peak}$ = 120 MV/m

r = 0.8 mm



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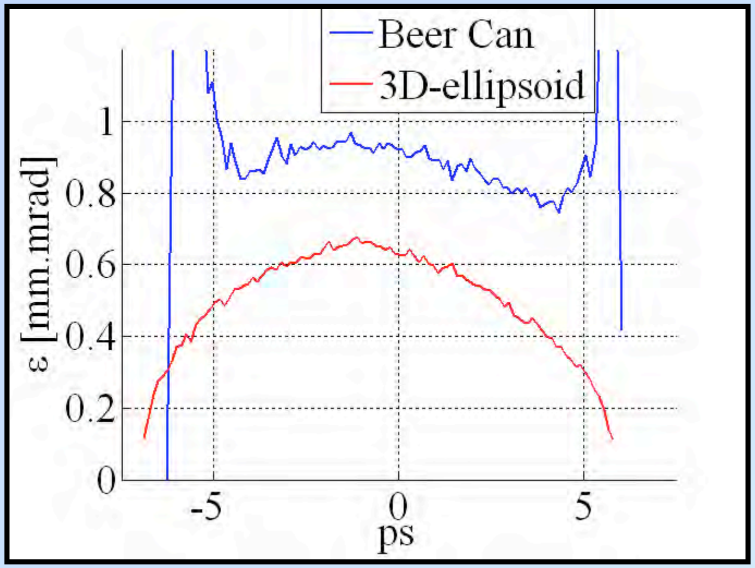
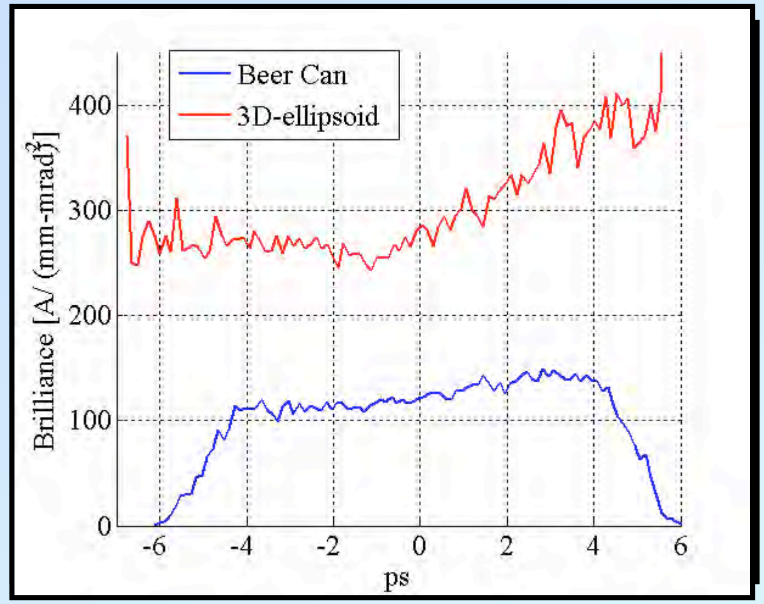
S-Band gun, LCLS

- 120 MV/m , 1nC , $\varepsilon_{thermal}$ = 0.6 mm-mrad /mm





$\varepsilon_{projected}$ = 1.02 mm-mrad

$\varepsilon_{projected}$ = 0.58 mm-mrad

~ 30 - 40 % reduction

$$B \propto \frac{I}{\varepsilon_x \varepsilon_y}$$

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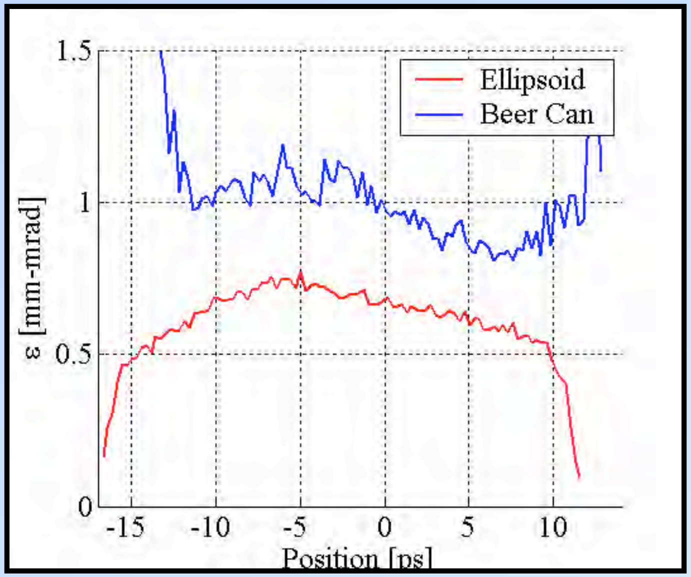
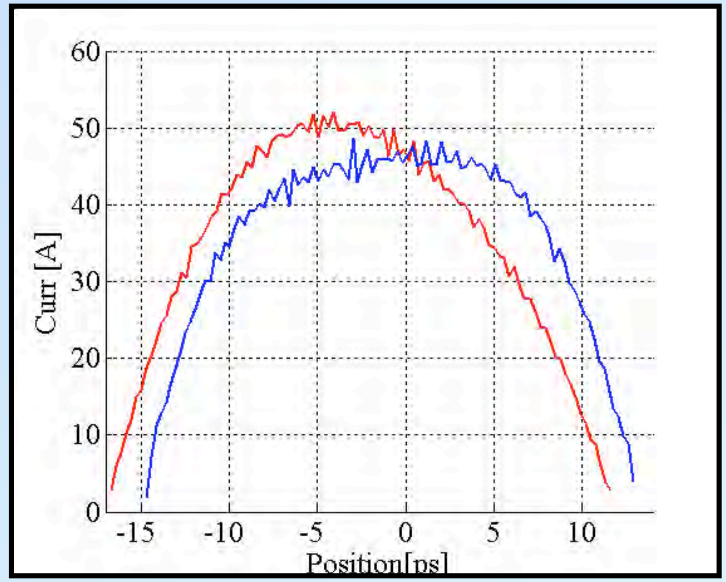
L-Band gun, TTF2

- 40 MV/m , 1nC , $\varepsilon_{thermal}$ = 0.43 mm-mrad /mm

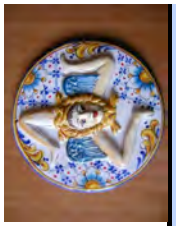




$\varepsilon_{projected}$ = 1.13 mm-mrad

$\varepsilon_{projected}$ = 0.67 mm-mrad

~ 30 - 40 % reduction



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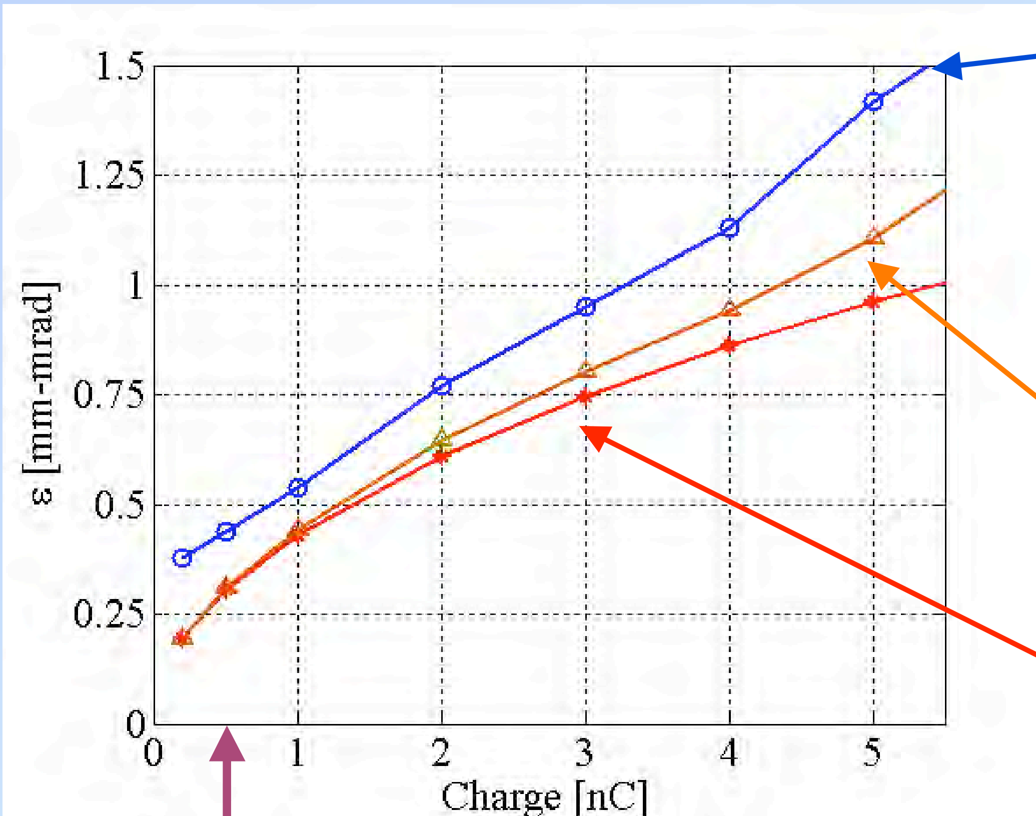
Minimizing emittance

140MV/m, $\varepsilon_{thermal}$ = 0.6 mm-mrad per mm



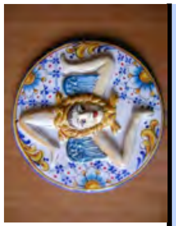
Simulations

Theory

$$\varepsilon_{tot} \sim \sqrt{\varepsilon_{thermal}{}^2 + (0.15r^2)^2}$$

$$\varepsilon_{thermal} = 0.6\sqrt{\frac{Q}{\varepsilon_o \pi E_{RF}}}$$

Highest brightness
0.5 nC



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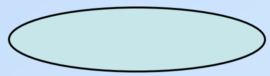
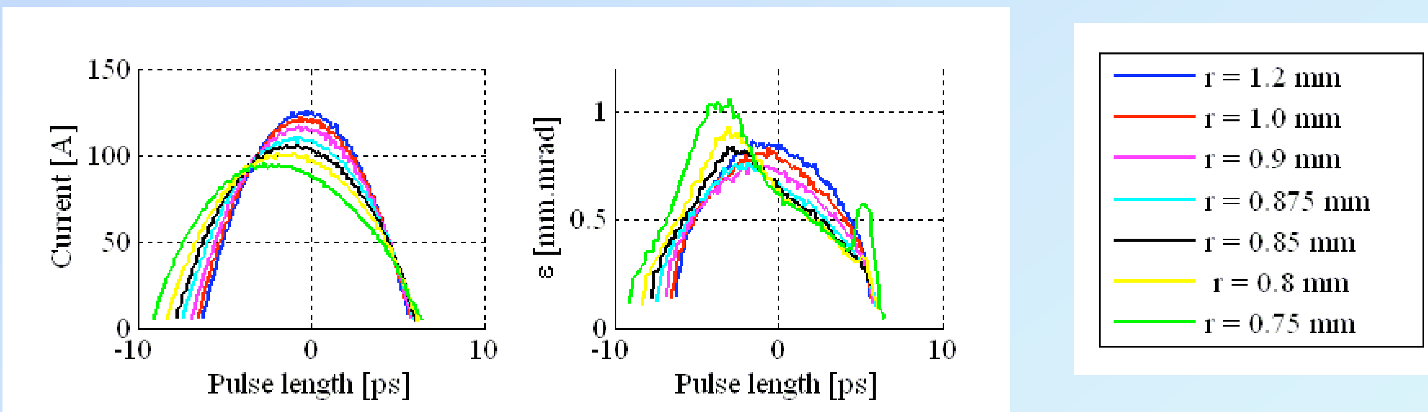
Limits on radius

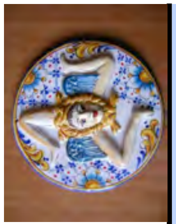
- Gauss law :

$$r > \sqrt{\frac{Q}{\varepsilon_o \, \pi \, E_{RF}}} \quad \begin{cases} E_{surface} = \dfrac{\sigma}{\varepsilon_o} \\ E_{RF} > E_{surface} \end{cases}$$

  – which r along 



- Gauss law can be very slightly “violated” but symmetry of ellipsoid is lost



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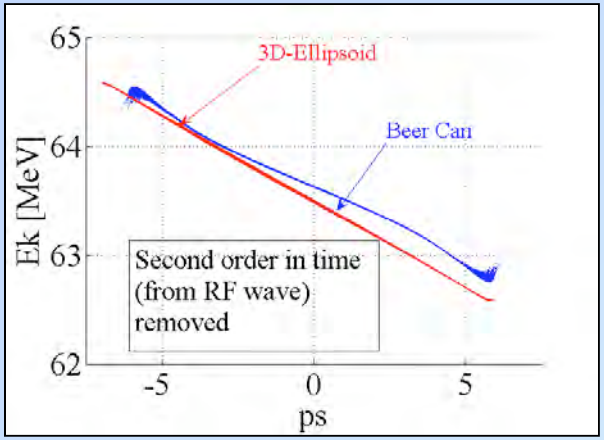
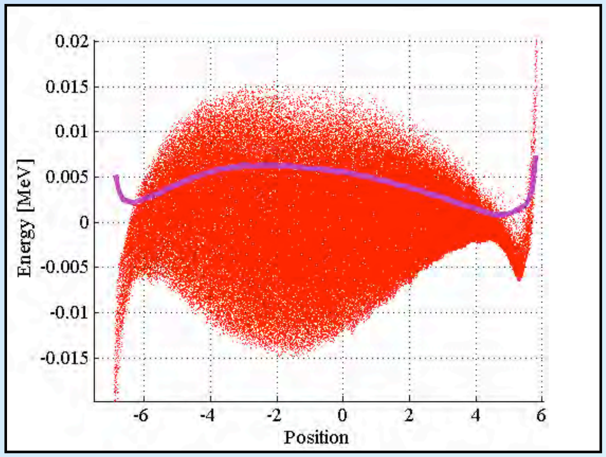
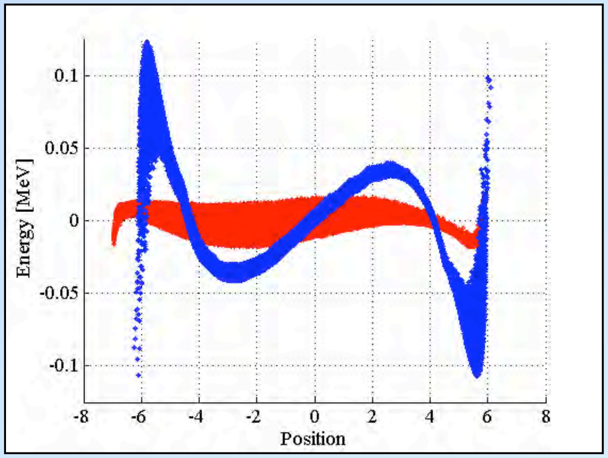
Longitudinal Phase Space

- Very linear
- Larger uncorrelated energy spread for ellipsoid

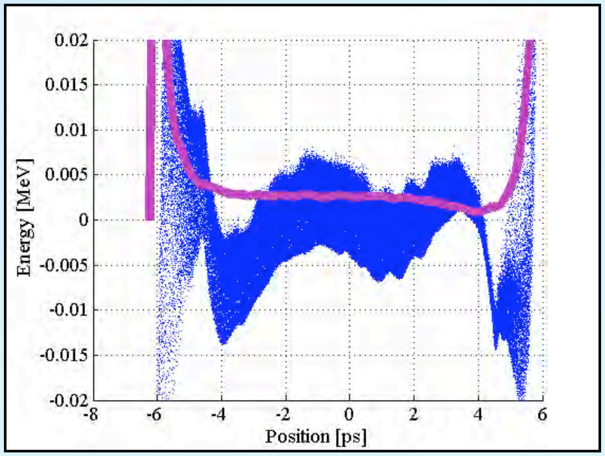


Ellipsoidal
~5 keV



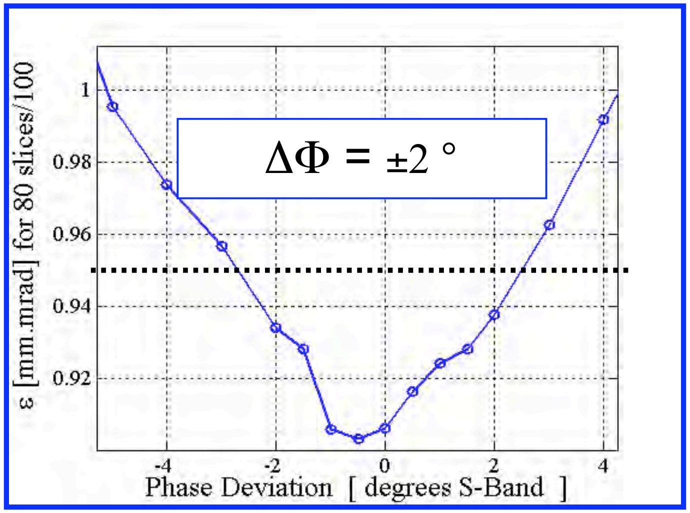


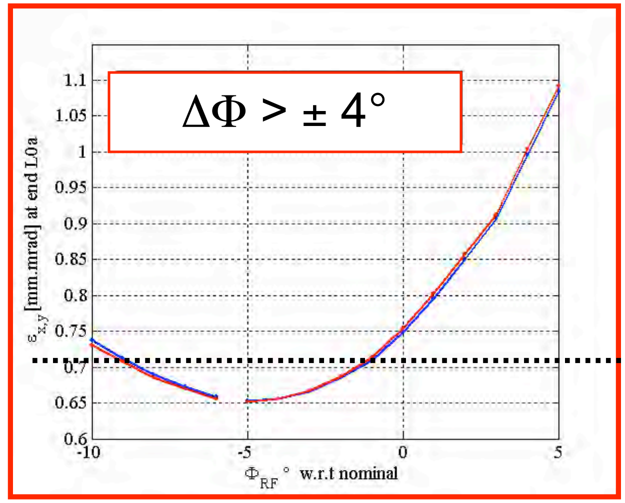
Flat-top
~3 keV

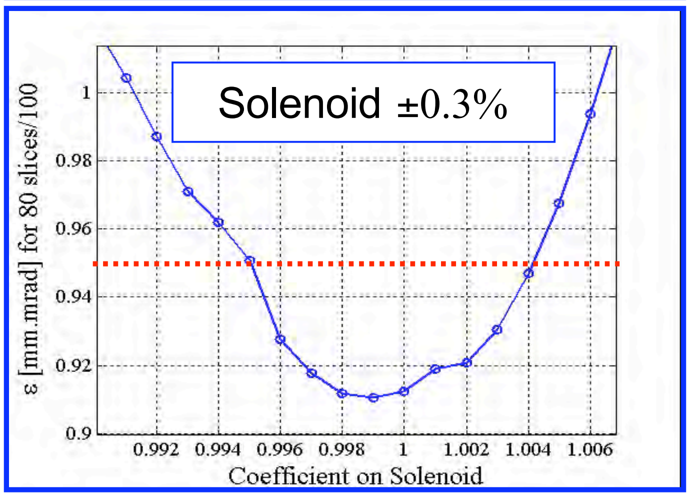


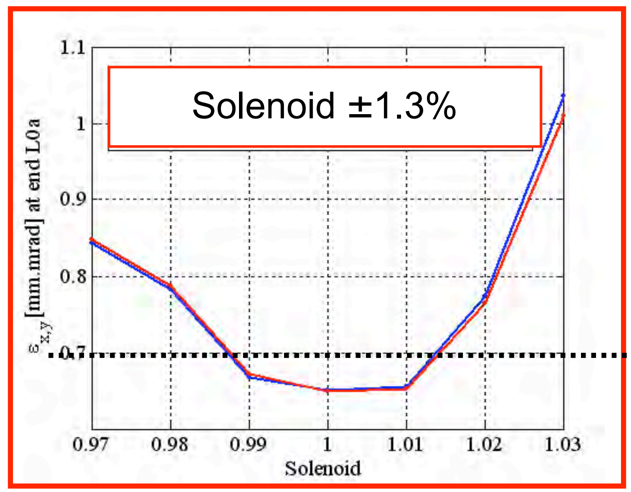
Reduced sensitivity for Ellipsoidal pulse

"Beer can" Variation in Phase and sol. Field $\Delta\varepsilon/\varepsilon$ of 5% Ellipsoid









Reduced sensitivity to r, σ_L , V_{rf}

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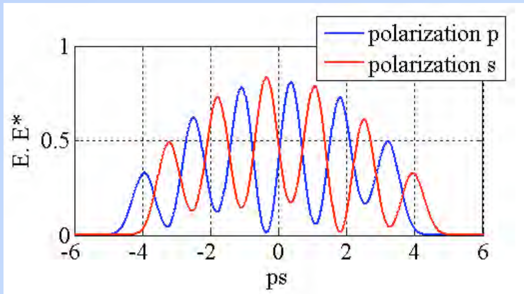
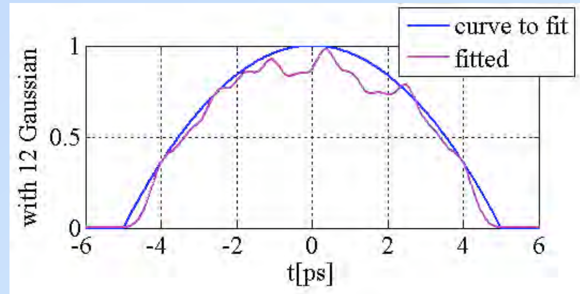
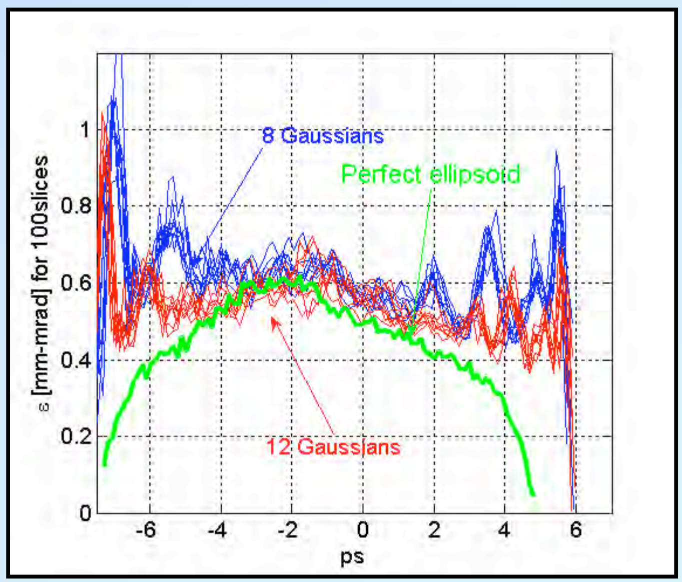
Production of 3D-Ellipsoidal laser pulses
1- Pulse stacker





- Interferences minimized by alternating p-s polarization
- $$$$ (at least 8 beamlets)



PARMELA
Simulation results

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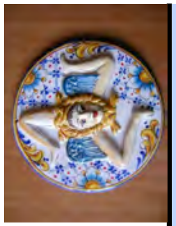
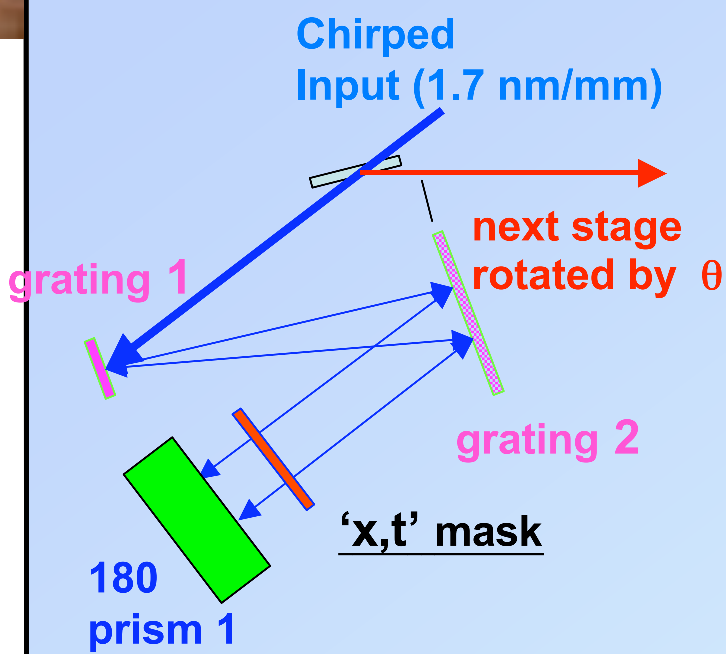


2- Spectral shaping



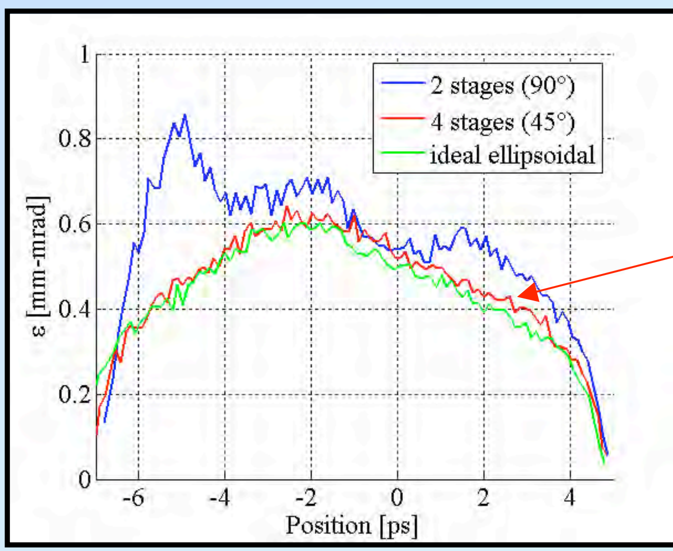
- Time-energy ⇒ projected in space

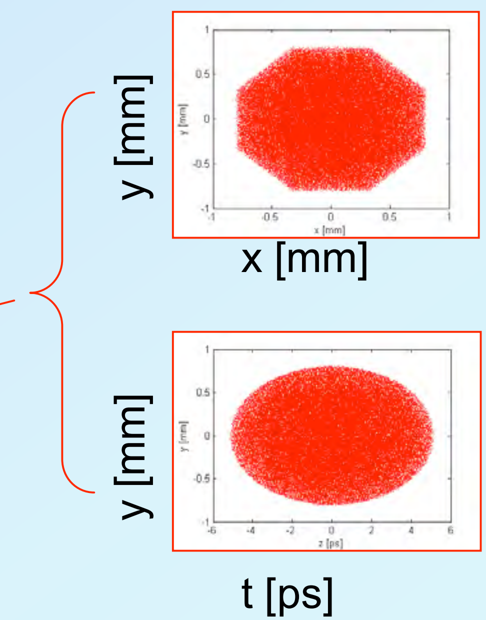
(x,t) Mask ⇒ Ellliptic cylinder along y

- Repeat in orthogonal plane
- Ellipsoid is well approximated by intersection of > 4 Elliptic cylinders

2 stages ok, 4 stages very good

PARMELA Simulations results

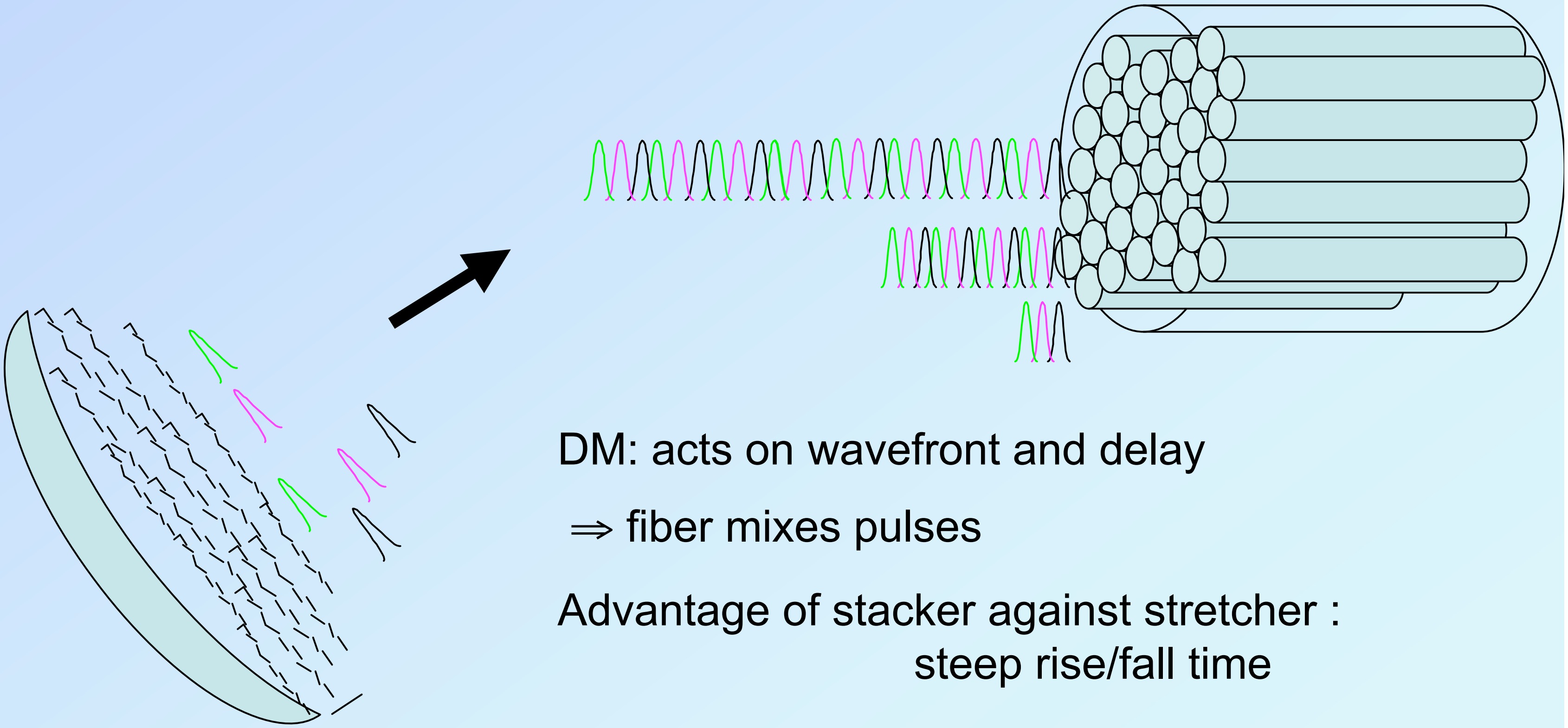




3- Fiber Bundle

To the courtesy of H.Tomizawa[6]

- Only for back-illumination
- Pulse stacker
  - DM (Difformable Mirrors) ⇒ (delay + intensity)
  - Fiber bundle



DM: acts on wavefront and delay

⇒ fiber mixes pulses

Advantage of stacker against stretcher :
steep rise/fall time

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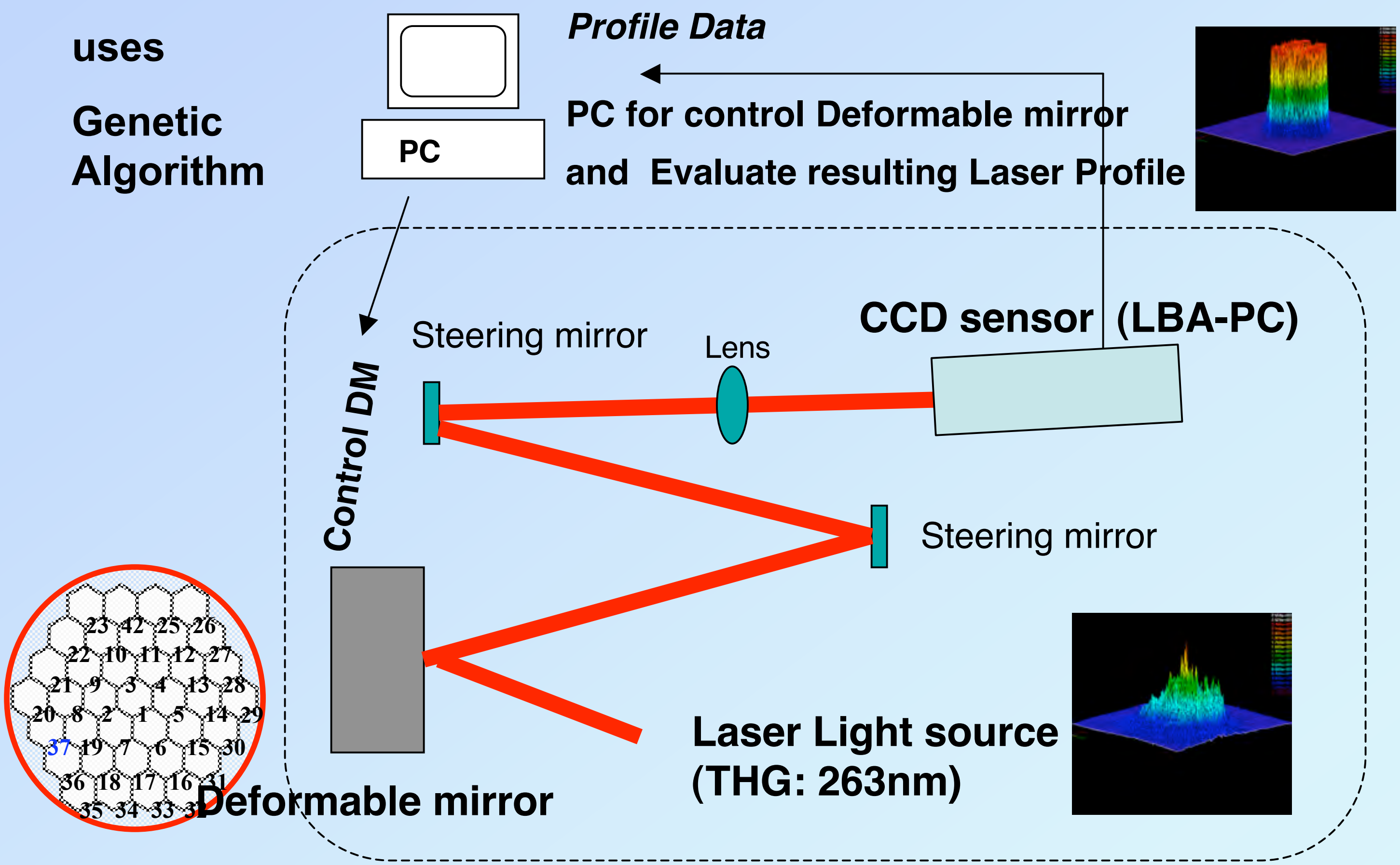
3- Fiber Bundle

To the courtesy of H.Tomizawa

– DM (Difformable Mirrors) + genetic algorithm tested



http://www.okotech.com/

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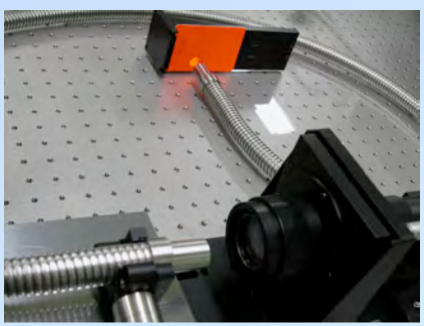
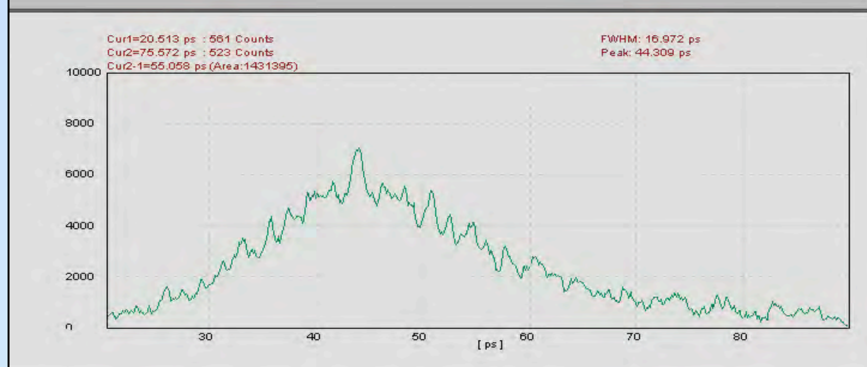
3- Fiber Bundle

To the courtesy of H.Tomizawa

- Fiber bundle: stacking of 2000 pulses demonstrated from homogenized tran. profile





Width (FWHM): 16 ps

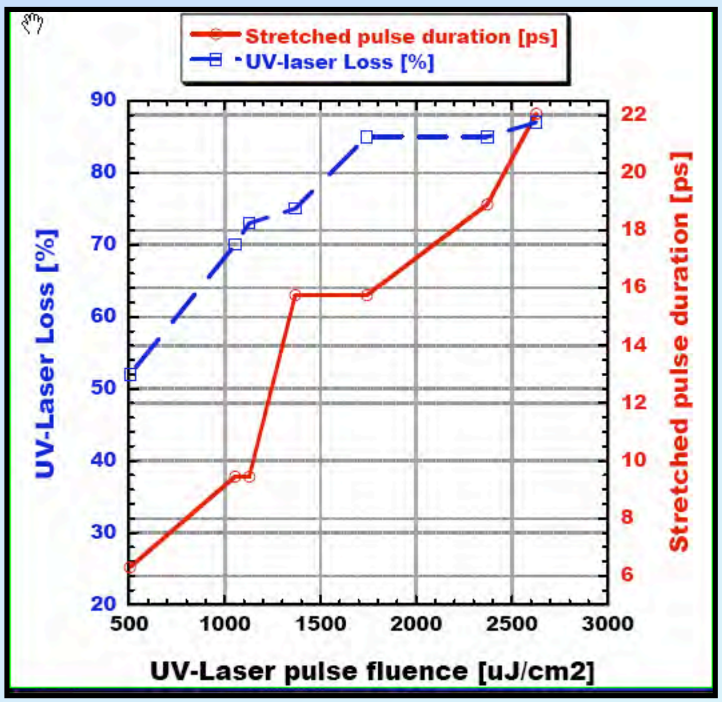
Fiber Bundle Length: 1 m

Mapping: Random

Input UV-pulse energy: down to 60 nJ

3- Fiber Bundle
To the courtesy of H.Tomizawa

- Using dispersive effects for stretching the beam is not satisfactory
  - Requires too large fluence variation at different r



UV pulse in Silica Rod

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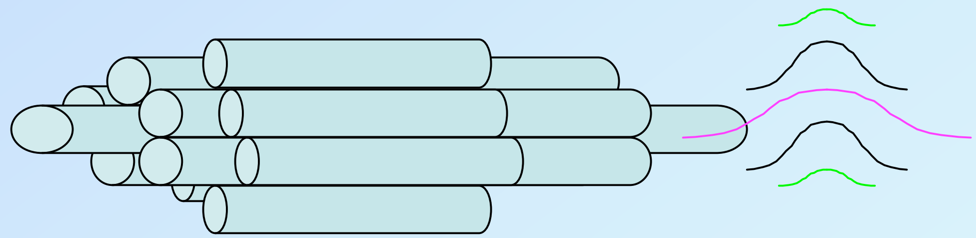
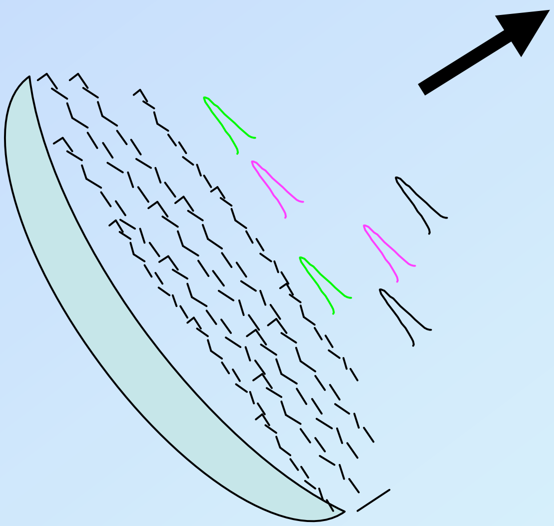
4- Fiber Bundle with pulse stretching

– Fiber bundle adapted to I(r) requirement
  - fiber length varies with r position in bundle (stretching)
  - DM helps controlling intensity





DM: adds delay, adapts intensity

but pulse shape does not have hard edges

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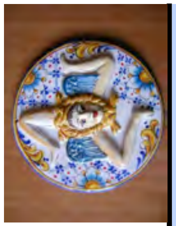

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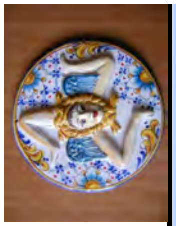
CONCLUSIONS

- Uniform 3D-ellipsoidal laser pulses are the ideal shapes for RF photoinjectors
  - Start-to-End simulations remain to be done
- For 1nC beam, improvements
  - 35/40% in slice/projected emittance
  - 2.5 in brightness
  - Linear longitudinal phase space
  - Low sensitivity
  - Optimum charge for maximum brightness
- Early solutions to produce such laser pulses in the UV are being worked out
  - any other idea is welcome!
  - DM + fiber bundle very promising
- Such pulses so easy to produce in the IR !



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[4]J.Luiten, “How to realize uniform 3-dimensional ellipsoidal electron bunches”, Phys.Rev.Letters Aug04

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[6] H.Tomizawa, “Adaptive Shaping System for both spatial and temporal profiles of a highly stabilized UV pulse for RF PhotoInjectors”, ERL05 Proceedings

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