Studies for the laser cavity for the proposed $\gamma\gamma$-Collider at TESLA

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TESLA Group

- **Optics**
- **Luminosity**
- **$\gamma\gamma$ Physics Background**

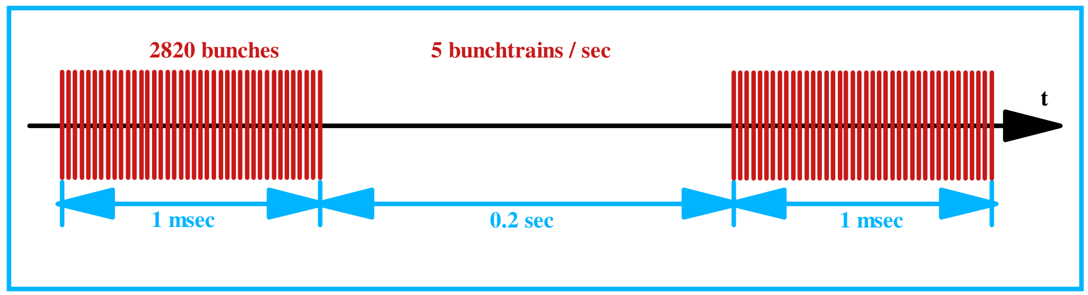
- **Optics**

Laser requirements

- **Laser pulses of**

$\approx 5\,$J	pulse energie
≈ 1 - $3\,$ps	pulse duration (FWHM)
$\approx 14\,\mu$m	spotsize $(1/e^2)$
$\approx 1\,\mu$m	wavelength
$2.5^\circ - 4^\circ$	e^- - IR crossing angle

- **have to match the TESLA bunch-structure:**
  - 2820 bunches/train
  - 337 ns spacing
  - 5 Hz repetition rate



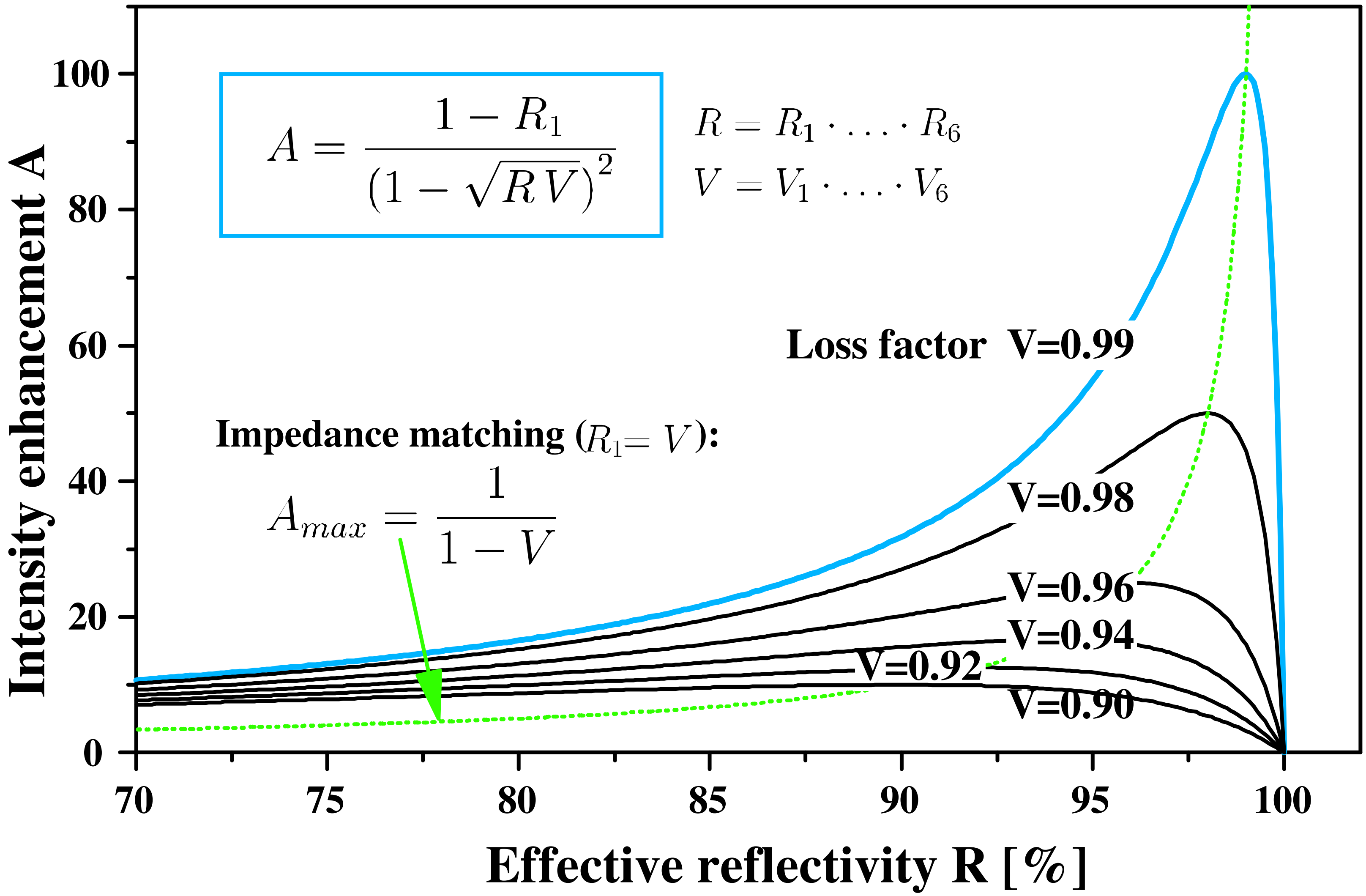
Requires:

- high peak power ($\approx$ 2 TW)
- high average power ($\approx$ 70 kW)
- precise timing, low jitter (1 ps)

One solution:

- **Pulsed laser with the correct timestructure and relaxed power requirements feeds a resonant cavity for enhancement of power**
- **telescopic active or passive ring resonator**

Intensity enhancement factor of a resonant cavity (simplified)



$$A = \frac{1 - R_1}{(1 - \sqrt{R\,V})^2}$$

$R = R_1 \cdot \ldots \cdot R_6$

$V = V_1 \cdot \ldots \cdot V_6$

desired enhancement factor: A= 100

Required accuracy of length control (resonant cavity)

power enhancement factor A:

$$A(\delta) = A_{max} \frac{1}{1 + \left[\frac{2\,\mathcal{F}}{\pi}\, sin\left(\pi\,\frac{\delta}{\lambda}\right)\right]^2}$$

δ : **cavity length detuning**

t_1, r_1 : **transmission & reflection coefficient of coupling mirror**

$$A_{max} = \frac{t_1^2}{(1 - r_{eff}\, v)^2} \qquad (r_{eff} = r_1 \cdot \ldots \cdot r_N) \qquad (v = e^{-pU})$$

p : **loss coefficient for 1 round-trip**

U : **perimeter of the cavity**

$$\mathcal{F} = \frac{\pi\sqrt{r_{eff}\, v}}{1 - r_{eff}\, v}$$: **Finesse**

criterion for acceptable length detuning δ_κ **:**

$$A(\delta_\kappa) = \kappa\, A_{max} \quad , \quad \kappa \leq 100\,\%$$

$$\Rightarrow \quad \delta_\kappa \approx \frac{\lambda}{2\,\mathcal{F}}\sqrt{\frac{1}{\kappa} - 1} \qquad (\mathcal{F} \gg 1)$$

example: $(\lambda = 1064\,\text{nm})$

$$A_{max} = 100 \implies \begin{cases} v = 0.99 \\ \mathcal{F} = 312.6 \end{cases}$$

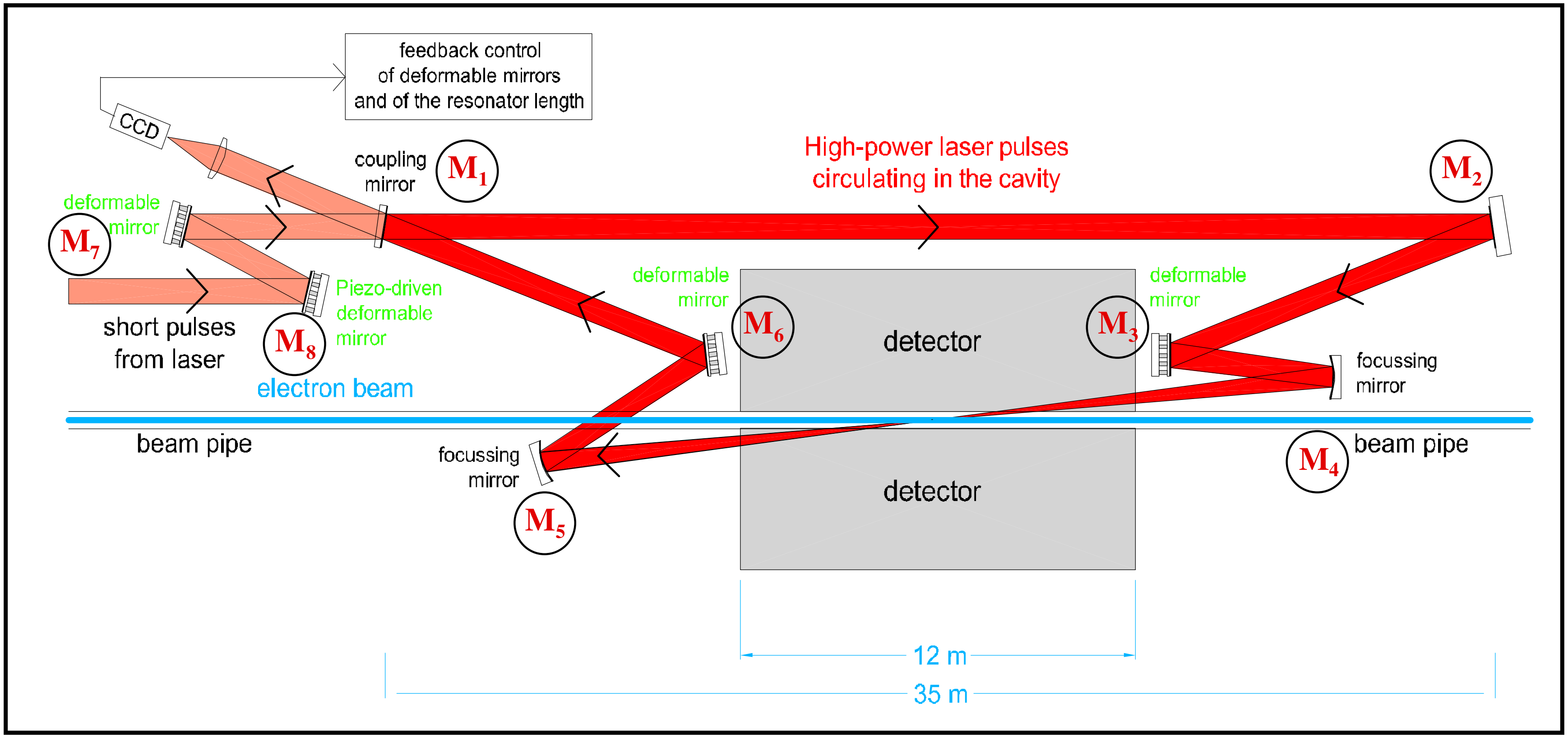
κ	δ_x	
$\kappa = 90\,\%$	$\delta_x = 5.3 \cdot 10^{-4}\,\lambda$	$\approx 0.57\,\text{nm}$
$50\,\%$	$1.6 \cdot 10^{-3}\,\lambda$	$\approx 1.7\,\text{nm}$

How to meet the length control requirement

Use of 2 lasers:

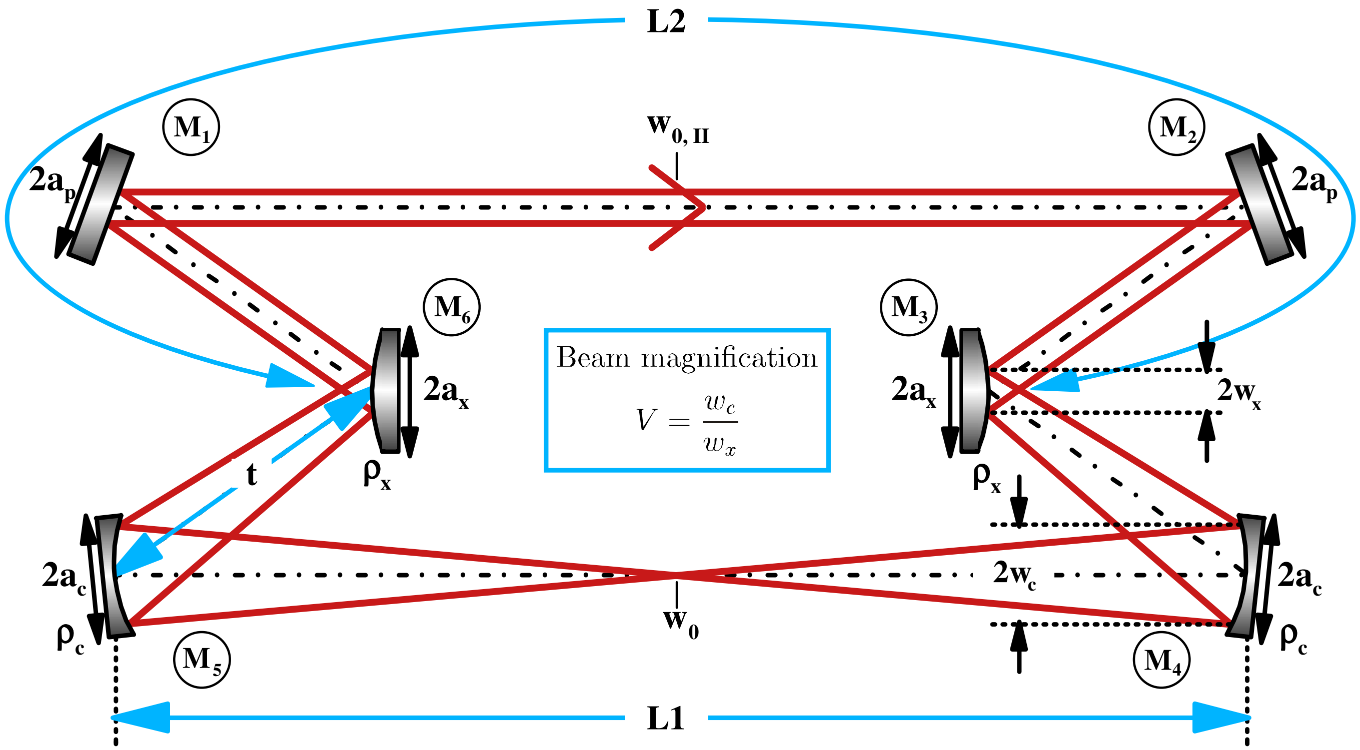
- **weak cw-laser for prealignement of the cavity - length control (Pound-Drever-Hall scheme: frequency side-bands)**
- **mode-locked high-power laser for compton process (deformable mirrors controlled by wavefront sensor)**

principle scheme of a passive cavity with deformable mirrors:



final focus: M4, M5: off-axis paraboloid ➡ no beam magnification (V=1)

telescopic cavity



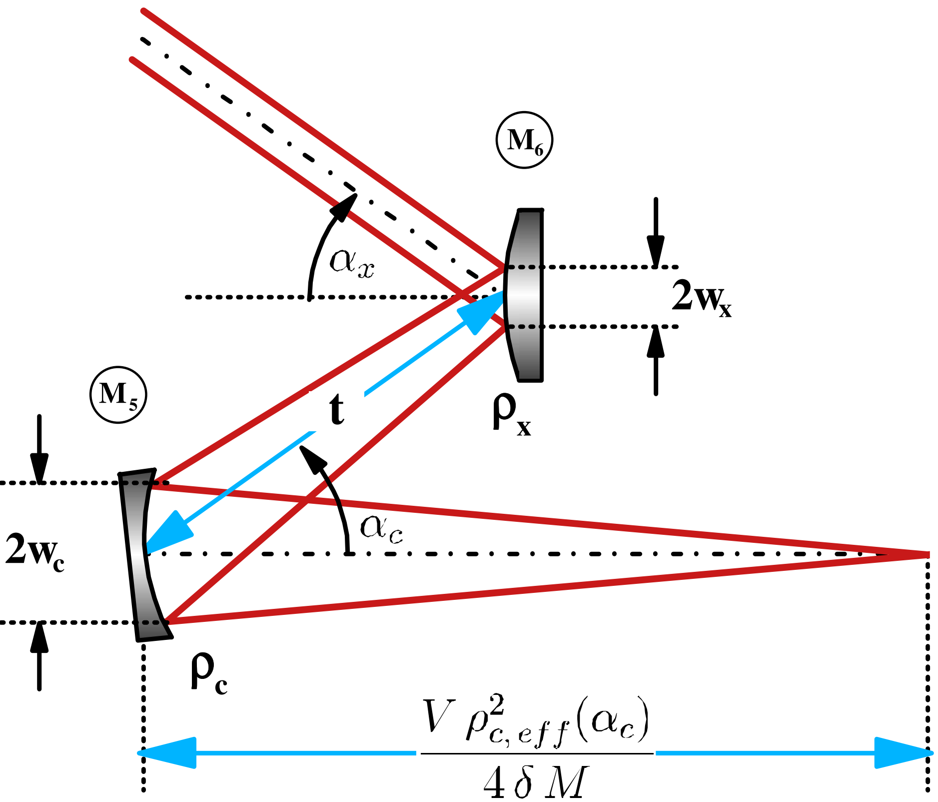
M3, M6: concave $\rho_c > 0$
M4, M5: convex $\rho_x < 0$

⇒ **Beam magnification V>1 possible**

advantage: reduced size of laser-optics and -beampipe outside the collimation region

⇒ **other surface profiles: e.g. spherical** ⇒ **requires special choice of mirror spacing, angle of incidene, radii of curvature ρ for compensation of aberrations**

Aberration-compensated focussing telescope



spherical surfaces:

$$V = \frac{w_c}{w_x} = 2 + \sqrt{5}$$

$$\rho_c = \frac{t}{4} \cdot (1 + \sqrt{5})$$

$$\rho_x = \frac{t}{4} \cdot (1 - \sqrt{5})$$

$$\alpha_x = f(\alpha_c)$$

⟹ **reduced spherical aberration, coma, astigmatism, field curvature**

general:

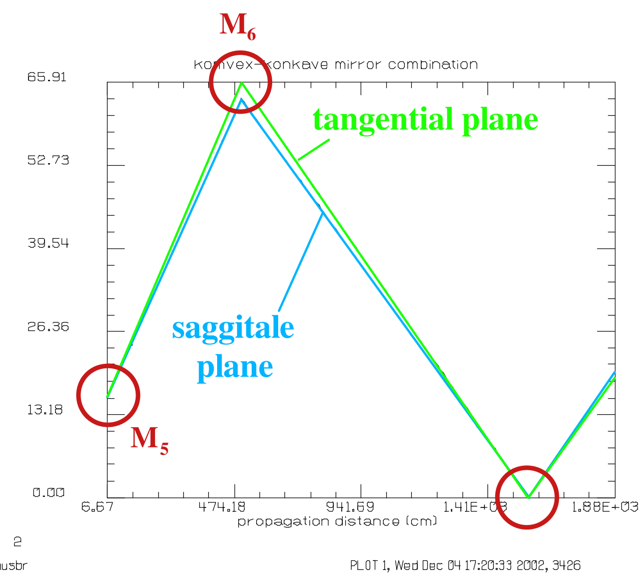
$$t = \frac{\rho_x + \rho_c}{2} + \delta$$

$$M = -\frac{\rho_c}{\rho_x}$$

$$V = M - \frac{2\,\delta}{\rho_x}$$

Aberration-compensated focussing telescope (spher. surfaces)

beam propagation



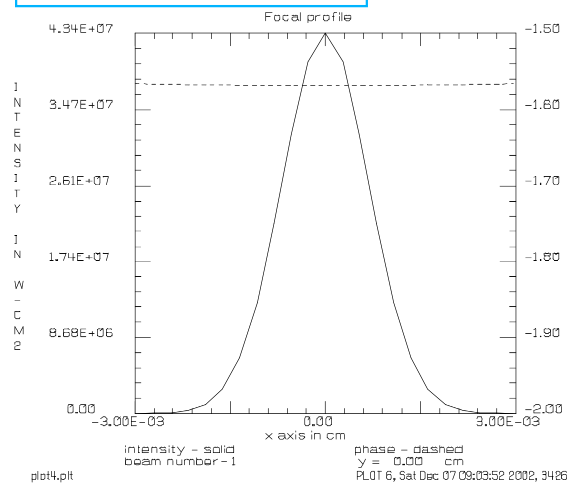
File: Kor8_10_v2.inp
= 500.00 alpha2 = 5.00
oh1 = -309.02 alpha1 = 13.04
oh2 = 809.02 z = 449.08
2 = 1059.02 y = -219.84

File: Kor8_10_Dez07.doc
t = 705.95
roh1 = -436.30 z = 634.05
roh2 = 1142.25 y = -310.39
alpha2 = 5.00 L2_sag = 1495.09
alpha1 = 13.04 L2_tan = 1495.09

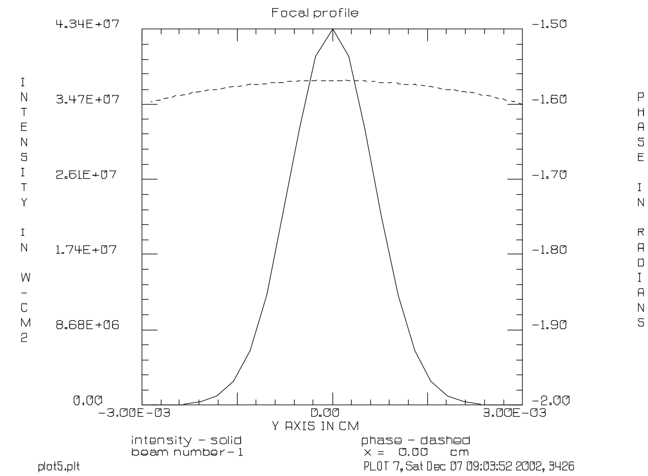
focussing properties

$\lambda = 1064\,\mathrm{nm}$

phase, x-direction



phase, y-direction

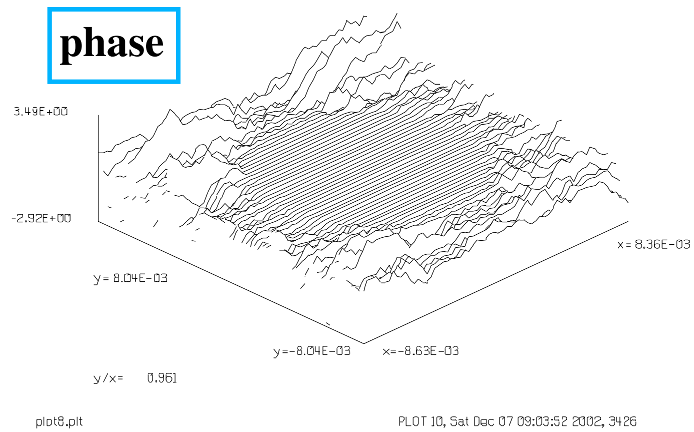


$\delta\phi_x < 10^{-3}\,\lambda$
$\delta\phi_x < 6 \cdot 10^{-3}\,\mathrm{rad}$

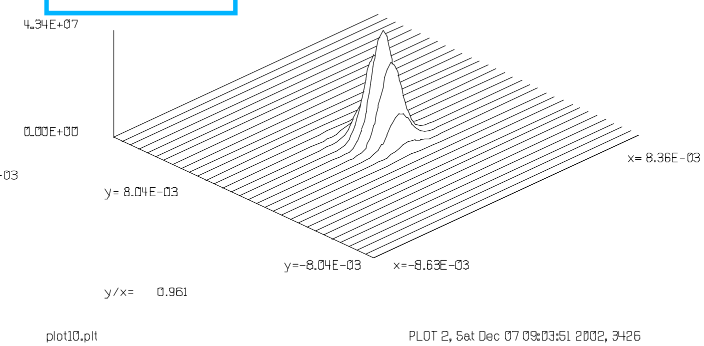
almost free of abberations

$\delta\phi_y < 5 \cdot 10^{-3}\,\lambda$
$\delta\phi_y < 3 \cdot 10^{-2}\,\mathrm{rad}$

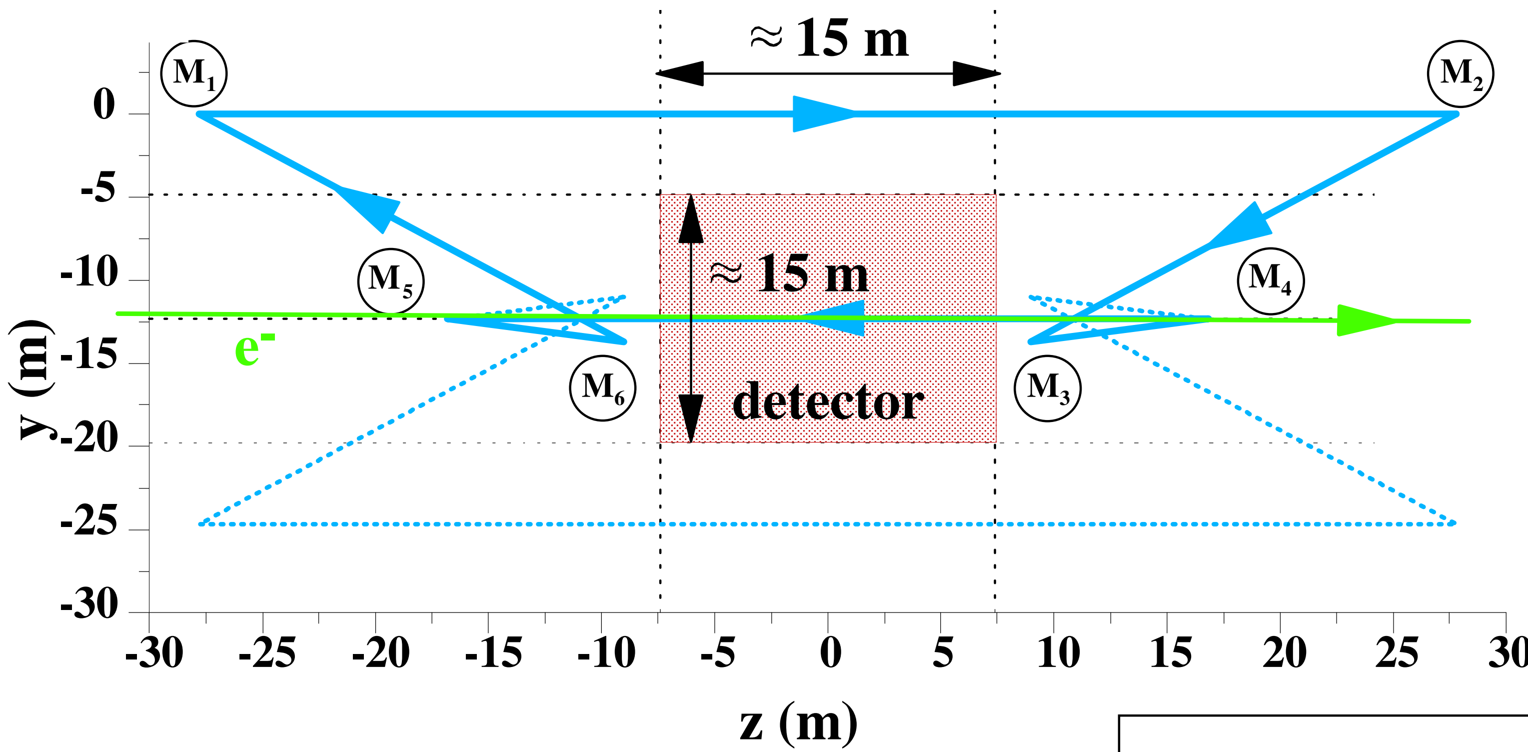
phase



intensity



Scaled layout of the telescopic cavity (preliminary)



t = 7.9 m
L1 = 33.6 m
L2 = 55.6 m
L3 = 23.2 m

γ_{123} = 36.1°
γ_{234} = 26.1°
γ_{345} = 10°

$\rho_{3,4}$ = -4.9 m
$\rho_{5,6}$ = 12.9 m

size of the cavity:

$$U_{cavity} = \frac{q}{p}\ c_0\ \Delta\tau_e$$

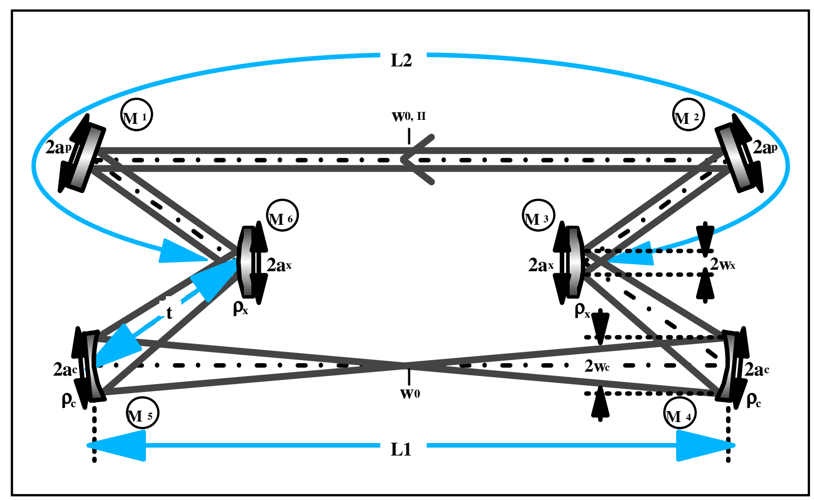
U_{cavity} : **perimeter**

c_0 : **speed of light**

$\Delta\tau_e = 337\,\text{ns}$

($p = q = 1 :\quad U_{cavity} = 101.0\,\text{m}$)

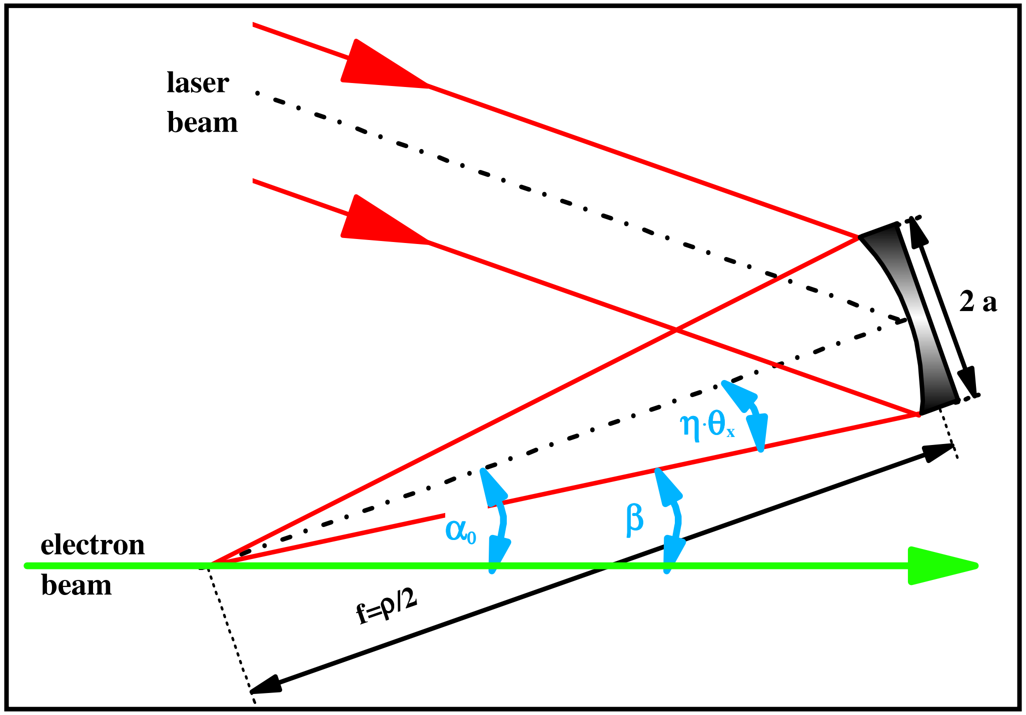
$p = 2,\ q = 3 :\quad U_{cavity} = 151.5\,\text{m},\quad \Delta\tau_{laser} = 168.5\,\text{ns}$



3 circulating laser bunches

Laser-electron crossing angle α_0

determined by the tolerated optical loss of the cavity



$$\alpha_0 = \eta\,\theta_x + \beta \;\approx\; \frac{a}{f} + \beta$$

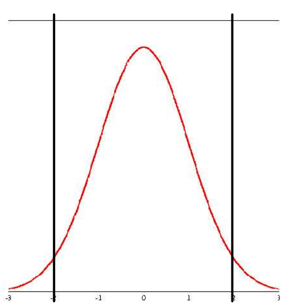
$$\eta = \frac{a}{f} \cdot \frac{1}{\theta_x}$$

α_0 : Laser angle

β : Offset angle ($\beta = 17\,\text{mrad}$)

θ_x : laser divergence (r.m.s - value)

Earlier rough estimate:



- **gaussian beam**
- **geometrical "spill over" losses**
- **100-fold intensity enhancement**

$\Rightarrow$ $\eta = 3.58$

Loss factor determines aperture and crossing angle of final focus

$t_i^2 + r_i^2 = 1:$ **lossless mirror**

$LF = v^2:$ **diffraction (power) loss factor for 1 round-trip**

$R_i = r_i^2:$ **power reflectivity**

$V := \sqrt{R_2 \cdot \ldots \cdot R_N \cdot LF}:$ **cavity loss factor**

$$\Rightarrow \quad A_{max} = \frac{1 - r_1^2}{(1 - r_{eff}\, v)^2} = \left.\frac{1 - R_1}{\left(1 - \sqrt{R_1\, V}\right)^2}\right|_{R_1 = V} = \frac{1}{1 - V}$$

(impedance matched enhancement)

$$\Rightarrow \quad A_{max} = 100 \quad \longrightarrow \quad V = 0.99$$

example for $N = 6$: high reflectors with

i) $R_2 = \ldots = R_6 =: R = 99.8\,\%$ $\Rightarrow$ $LF = \frac{V}{R^5} = 0.99996$ $\Rightarrow$ $\frac{a}{w_f} \geq 1.91$ $\Rightarrow$ $\eta = 3.80$

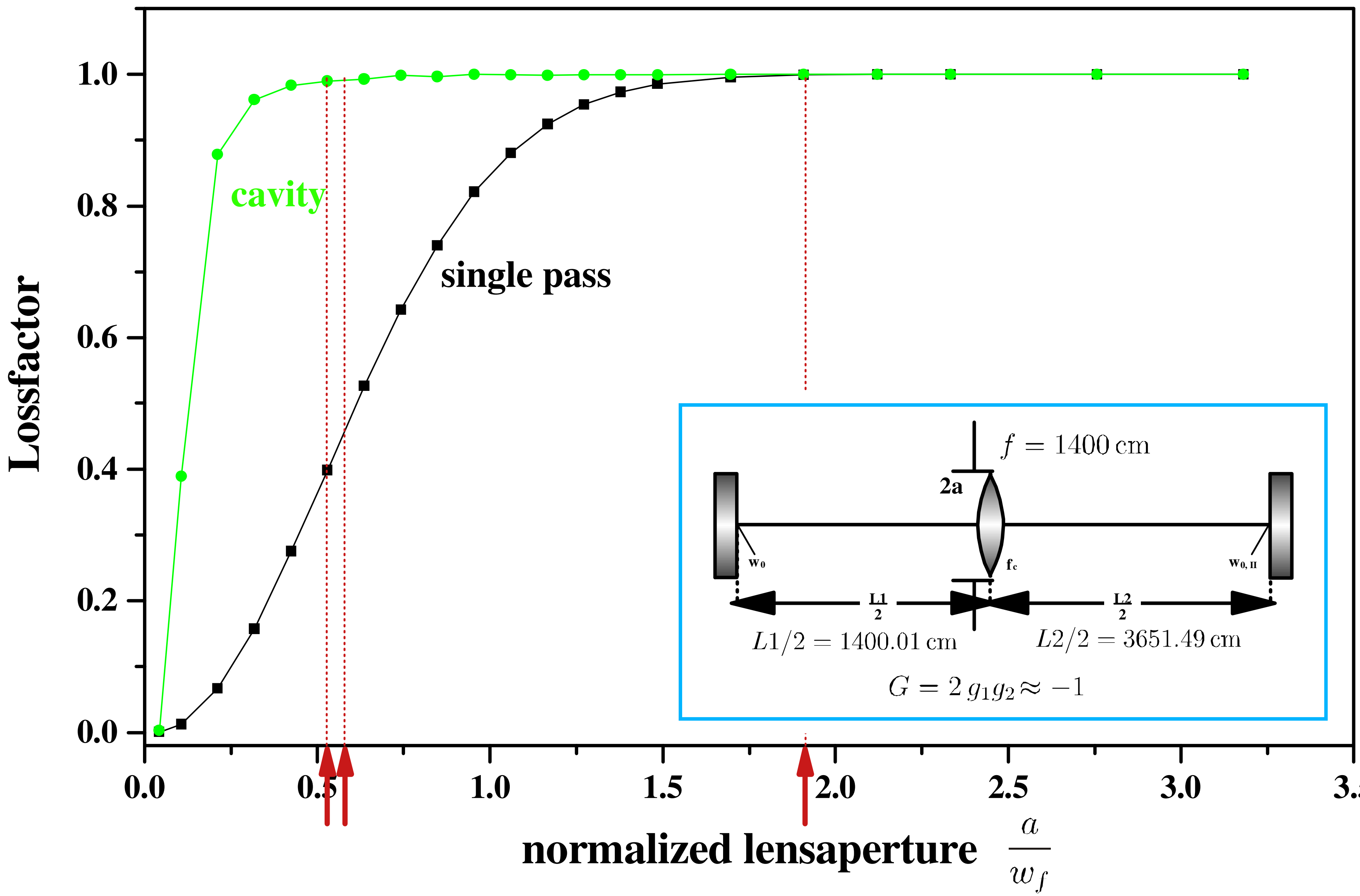
ii) $R_2 = \ldots = R_6 =: R = 99.9\,\%$ $\Rightarrow$ $LF = 0.99496$ $\Rightarrow$ $\frac{a}{w_f} \geq 0.58$ $\Rightarrow$ $\eta = 1.15$

iii) $R_2 = \ldots = R_6 =: R = 100\,\%$ $\Rightarrow$ $LF = 0.99$ $\Rightarrow$ $\frac{a}{w_f} \geq 0.53$ $\Rightarrow$ $\eta = 1.05$

calculation of diffraction loss $\longrightarrow$ **plot**

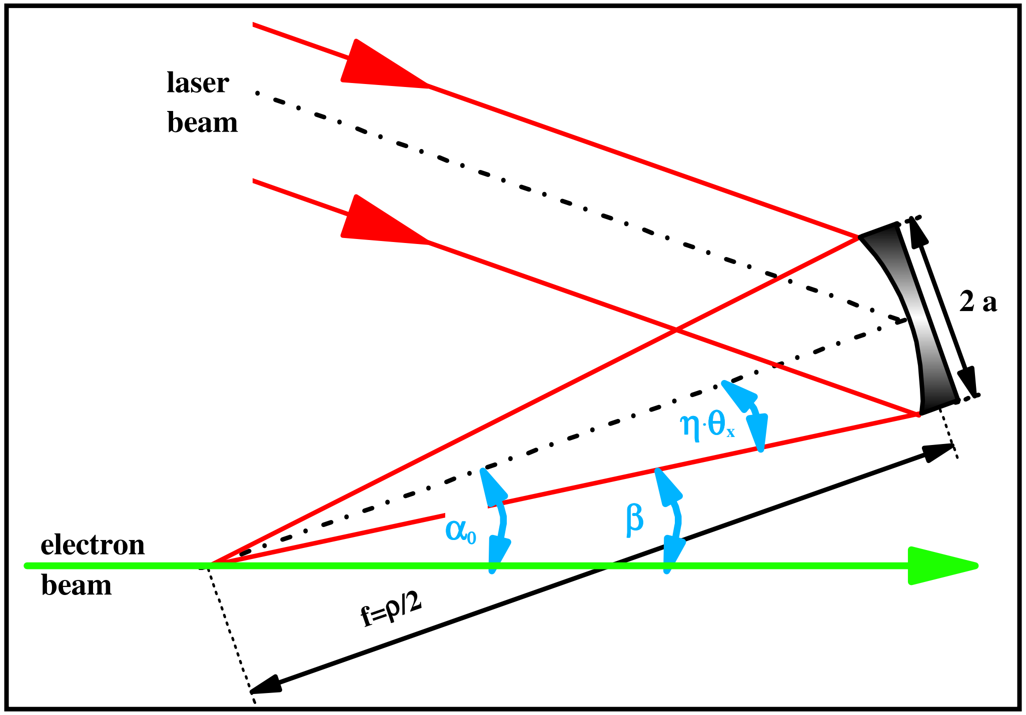
Loss factor of non-telescopic cavity (off-axis paraboloid)

Fox-Lee treatment of non-telescopic cavity with w_0=0.01 cm (off-axis paraboloid)



- **Luminosity**

Laser-electron crossing angle α_0



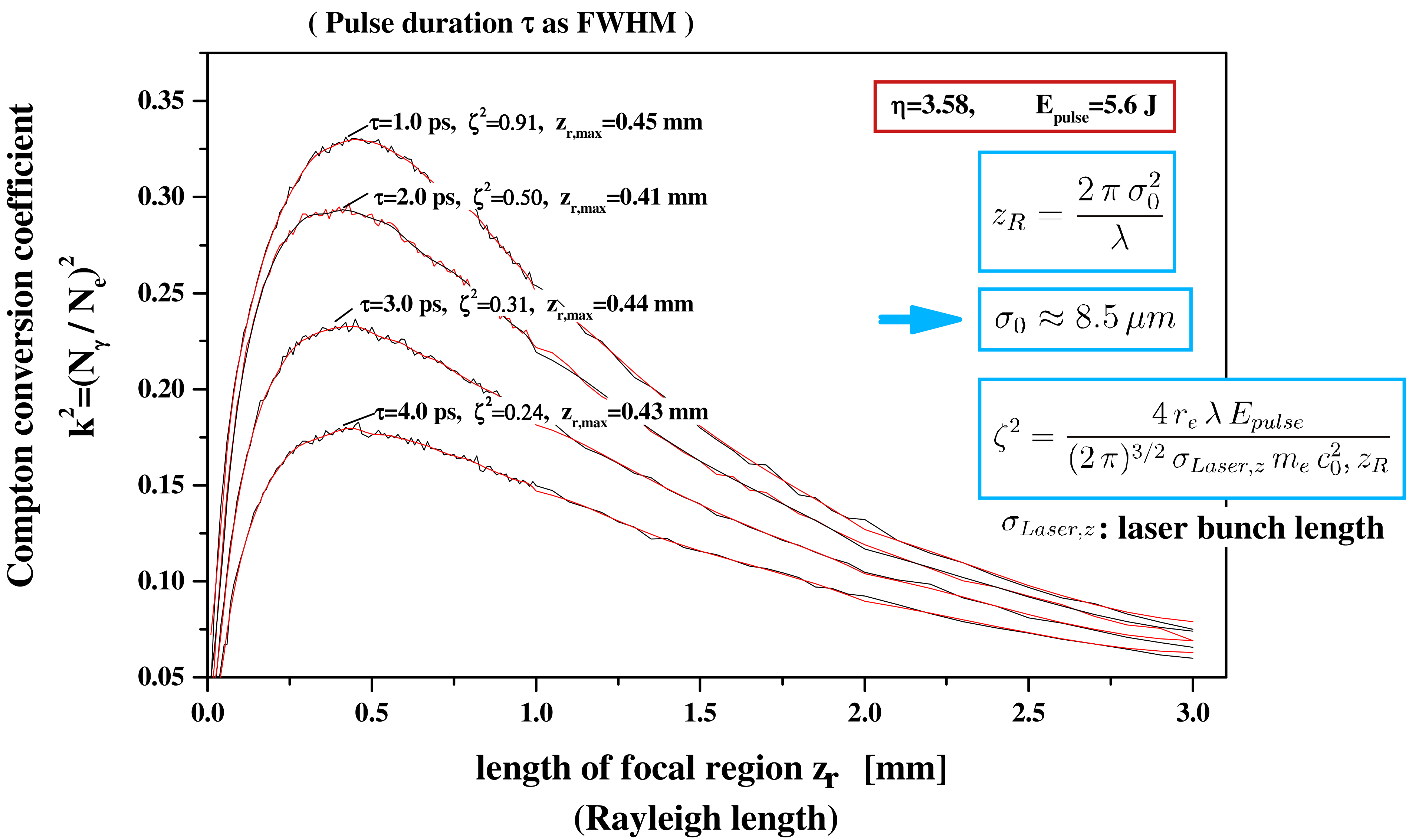
$$\alpha_0 = \eta\,\theta_x + \beta$$

α_0 : Laser angle

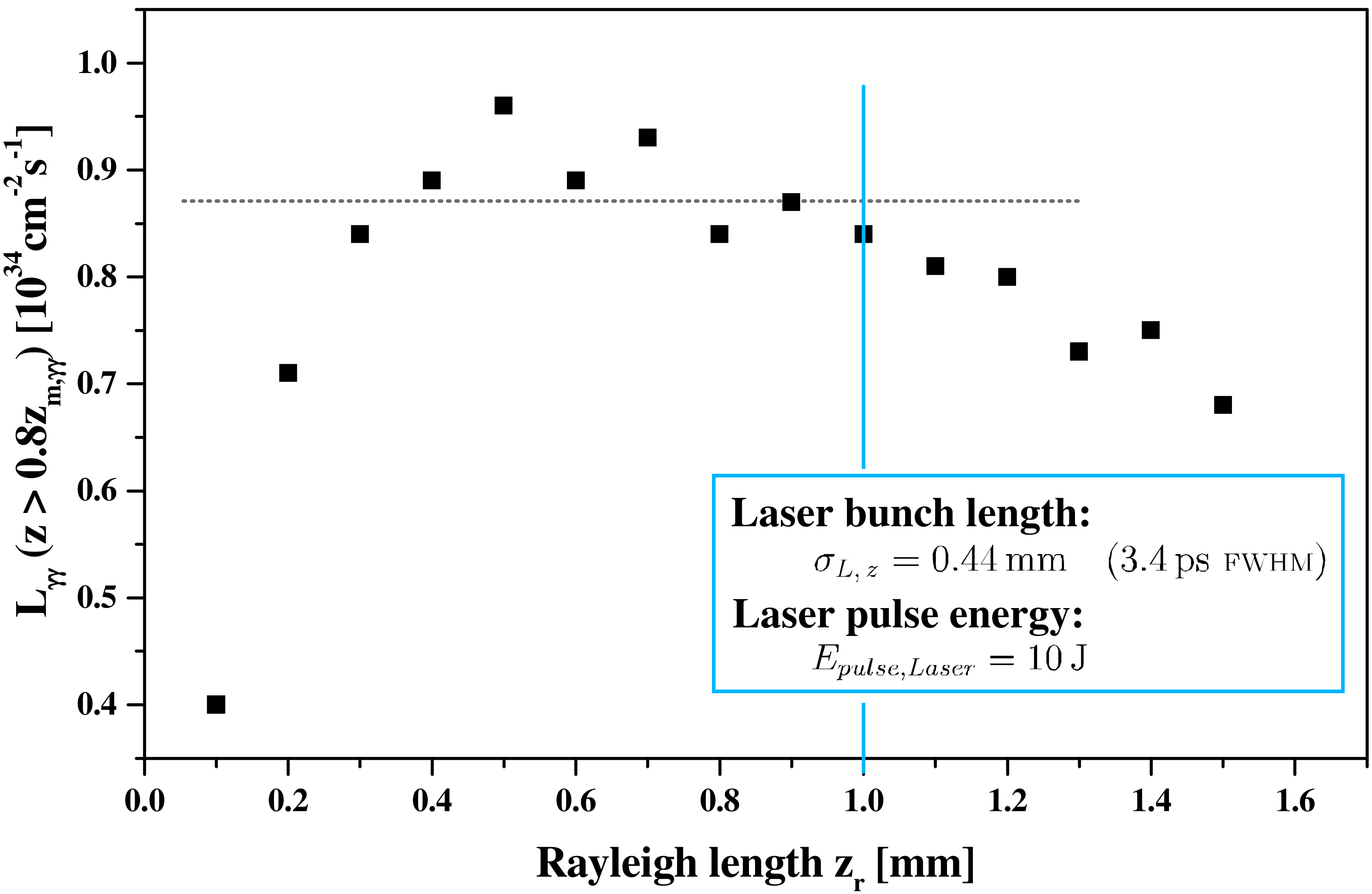
β : Offset angle ($\beta = 17\,\mathrm{mrad}$)

θ_x : laser divergence (r.m.s - value)

Simulated Compton conversion efficiency



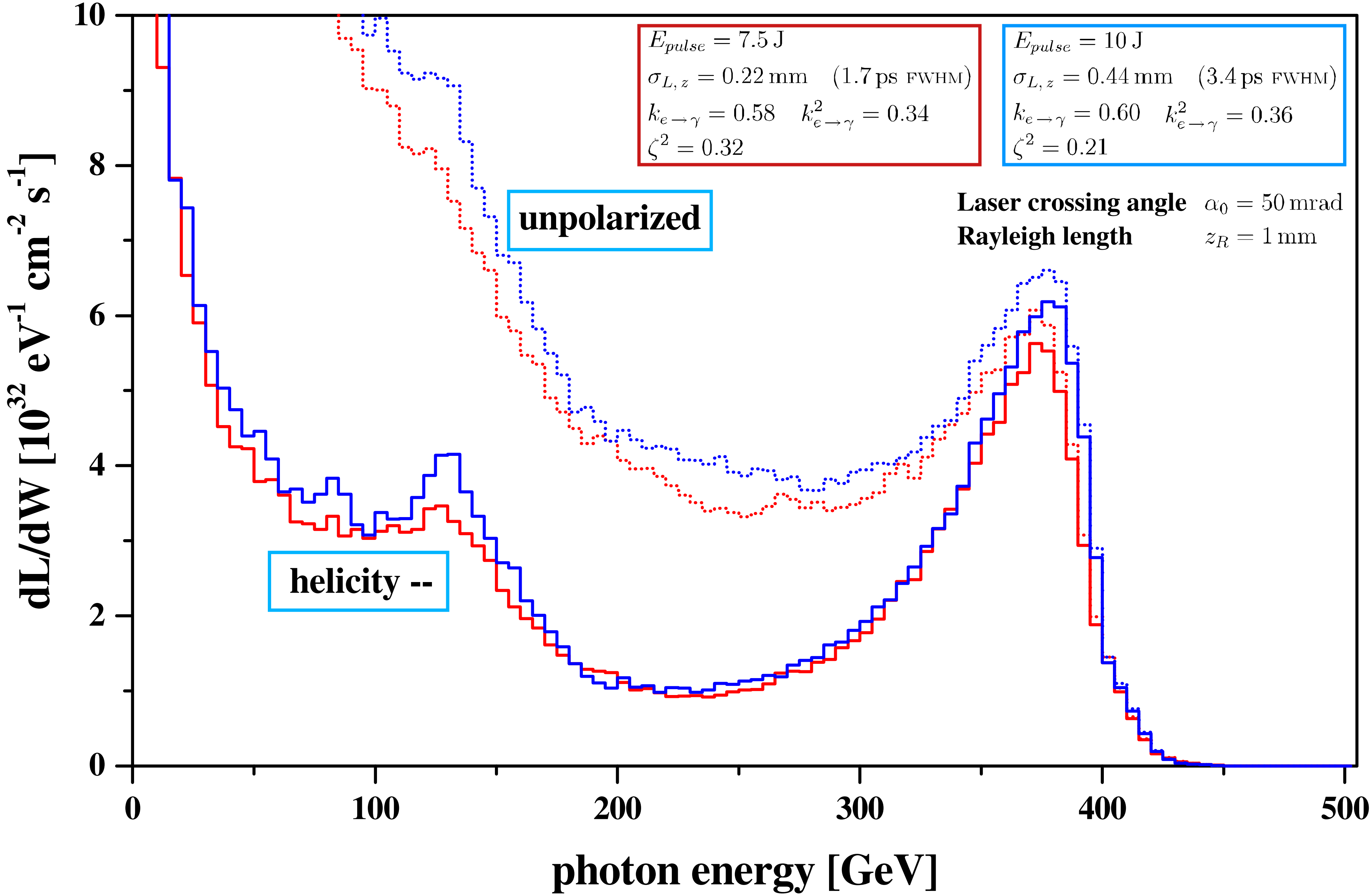
Total Luminosity vs. Rayleigh length



$z_R = 1$ mm ⟹ **laser beam radius at focus:**

$$\begin{cases} w_{0;1/e^2} = 18.4\,\mu\text{m} \\ a_{rms} = 13.0\,\mu\text{m} \end{cases}$$

Simulated γγ-Luminosity



Total Luminosity ($2\,E_0 = 500\,\mathrm{GeV}$)

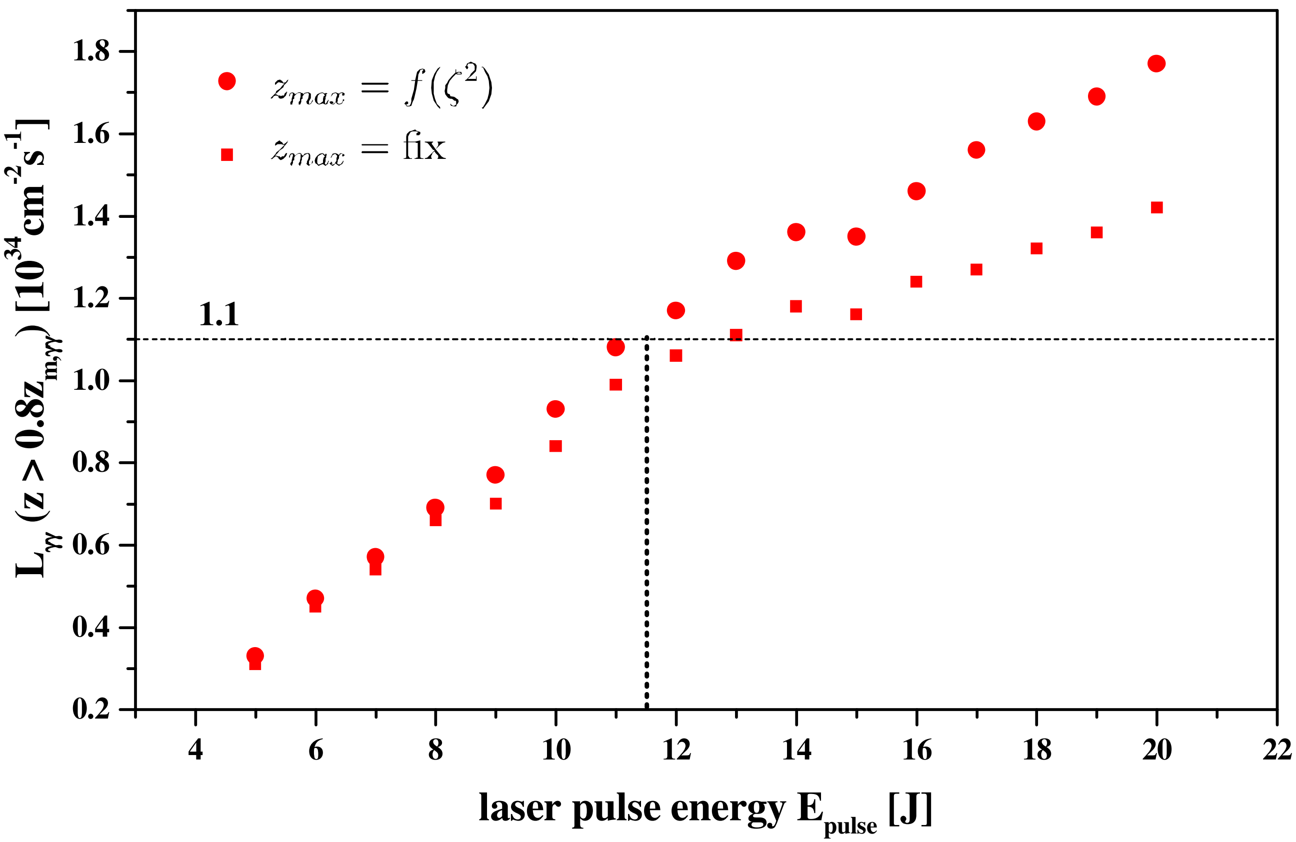
Laser crossing angle:

$$\alpha_{e^-,\mathrm{Laser}} = \eta \underbrace{\sqrt{\frac{\lambda}{4\,\pi\,Z_r}}}_{\text{laserdivergence}} + \underbrace{\alpha_{\mathrm{offset}}}_{=17\,\mathrm{mrad}}$$

TDR $(\eta = 2)$**:**

- $\alpha_{offset} = 0$
- $E_{pulse,Laser} \approx 5\,\mathrm{J}$
- $L_{\gamma\gamma}(z > 0.8 z_{m,\gamma\gamma}) = 1.1 \cdot 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

for $\eta = 3.58$**:** **(Breit-Wheeler process** $\gamma\gamma \longrightarrow e^+e^-$ **enabled)**



Laser bunch length:
$\sigma_{L,z} = 0.44\,\mathrm{mm}$ (3.4 ps FWHM)

Laser crossing angle:
$\alpha_0 = 50\,\mathrm{mrad} = 2.9^\circ$ $(\eta = 3.58)$

Rayleigh length: $z_R = 1\,\mathrm{mm}$

Total Luminosity ($2\,E_0 = 800\,\mathrm{GeV}$)

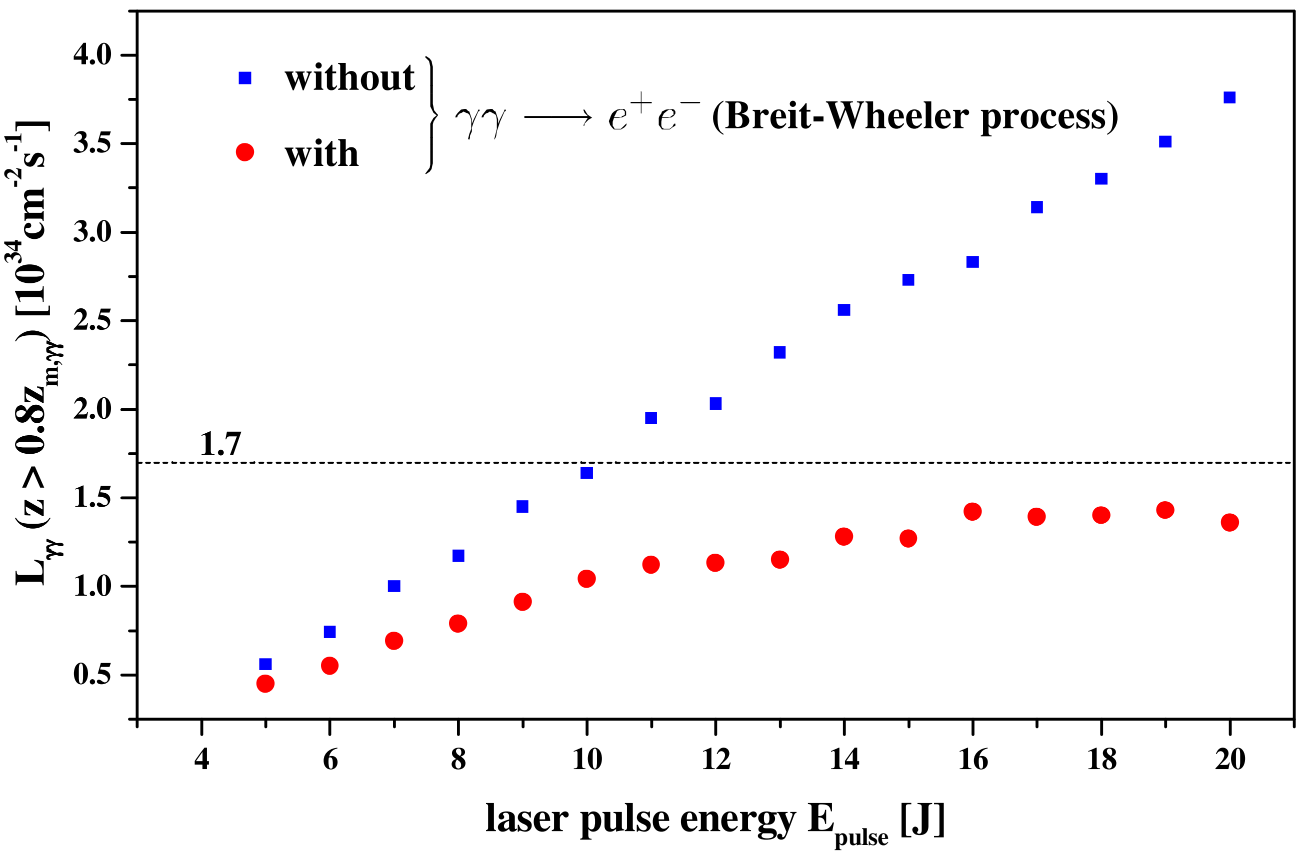
Laser crossing angle:

$$\alpha_{e^-,\,\mathrm{Laser}} = \eta \underbrace{\sqrt{\frac{\lambda}{4\,\pi\,Z_r}}}_{\text{laserdivergence}} + \underbrace{\alpha_{\mathrm{offset}}}_{=17\,\mathrm{mrad}}$$

TDR ($\eta = 2$)**:**

- $\alpha_{offset} = 0$
- $E_{pulse,Laser} \approx 5\,\mathrm{J}$
- $L_{\gamma\gamma}(z > 0.8 z_{m,\gamma\gamma}) = 1.7 \cdot 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

for $\eta = 3.58$ **:**



Laser bunch length:

$\sigma_{L,z} = 0.22\,\mathrm{mm}$ (1.7 ps FWHM)

Laser crossing angle:

$\alpha_0 = 50\,\mathrm{mrad} = 2.9^\circ$ ($\eta = 3.58$)

Rayleigh length: $z_R = 1\,\mathrm{mm}$

- **$\gamma\gamma$ Physics Background**

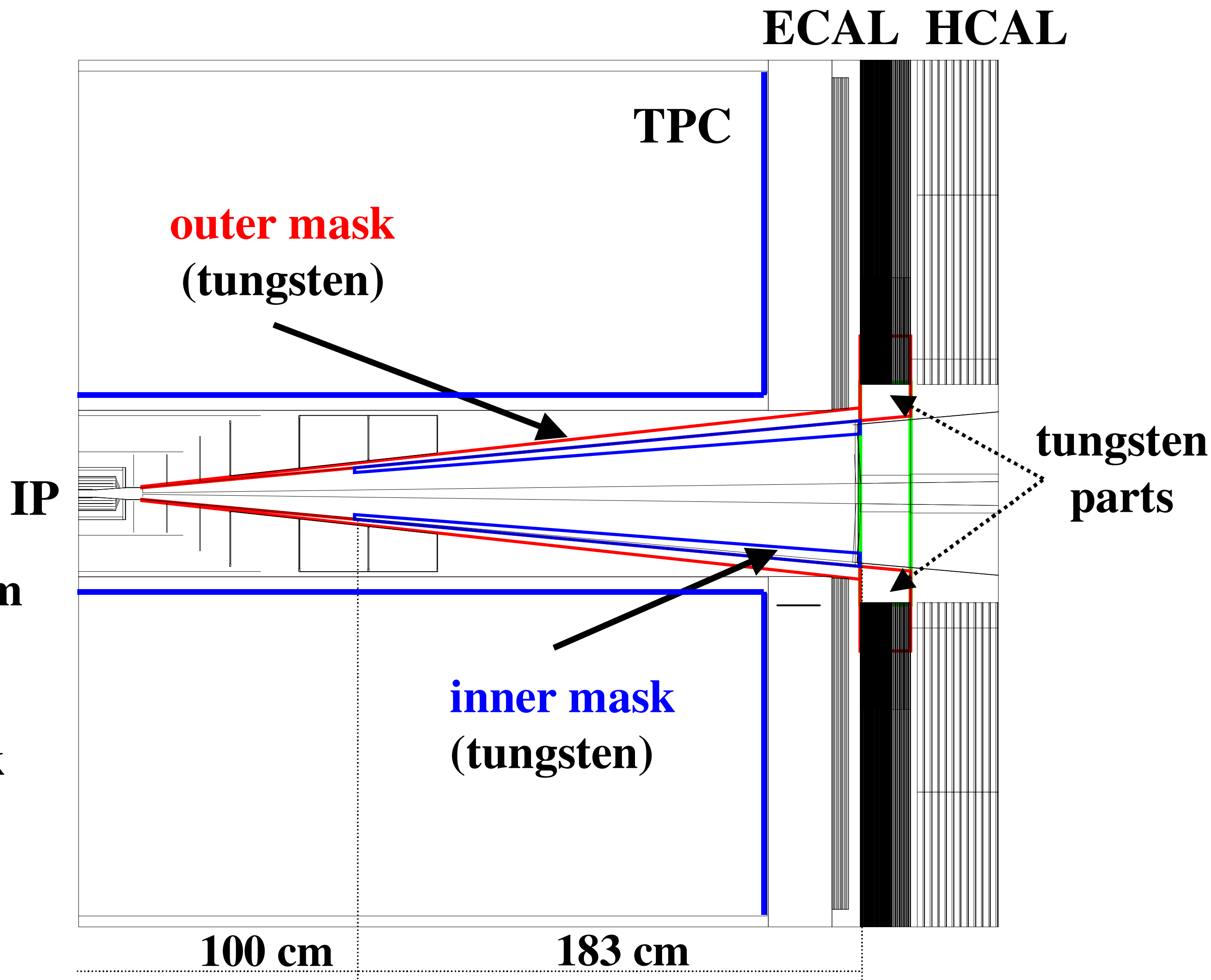
Background studies for $\gamma\gamma$ - collider

mask design in forward region – minimization of background in TPC and VTX

BACKGROUND :
(BEAM –BEAM interactions)
- **incoherent pair production**
- **coherent pair production**

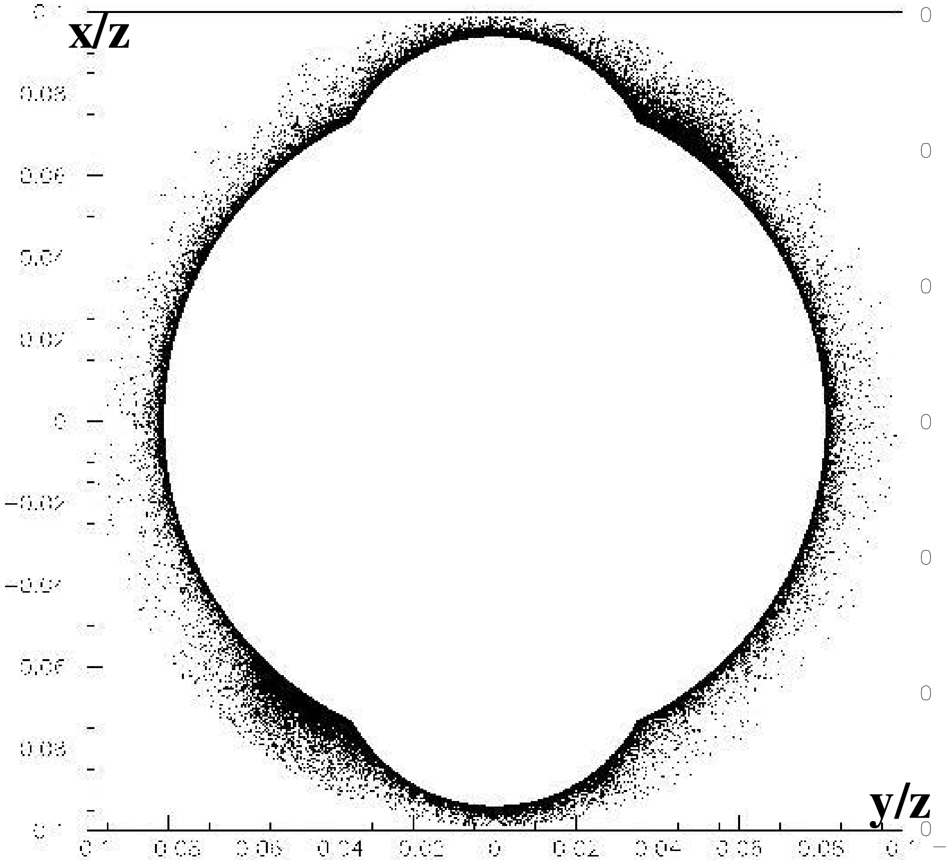
(simulated by CAIN)

- several changes from last design (Prague) :
1. **two masks**
2. **longer outer mask**
3. **tungsten parts**



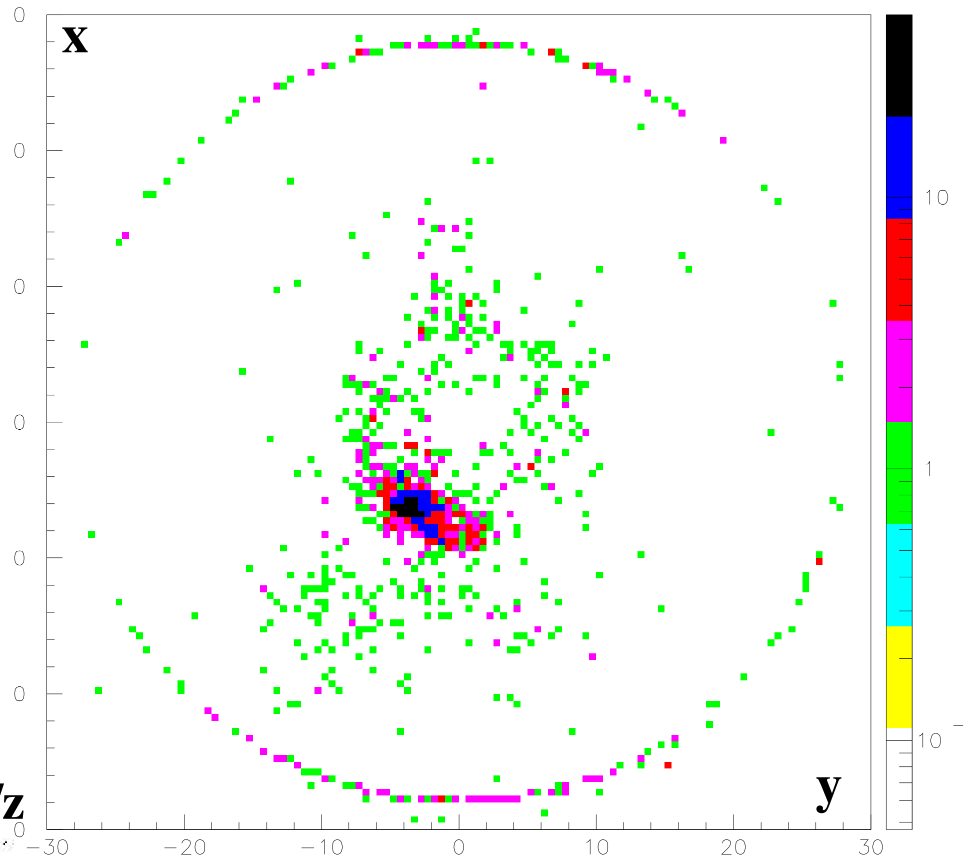
Simulated γγ-Luminosity

particles entering the inner mask/BX



inner mask

particles leaving the outer mask/BX



outer mask

In :
CP ~ (8000000) γ/BX
ICP ~ 62879 γ/BX

Out (reduced background):
CP ~ (9800) γ/BX
ICP ~ 1809 γ/BX

Background studies for $\gamma\gamma$ - collider

TPC

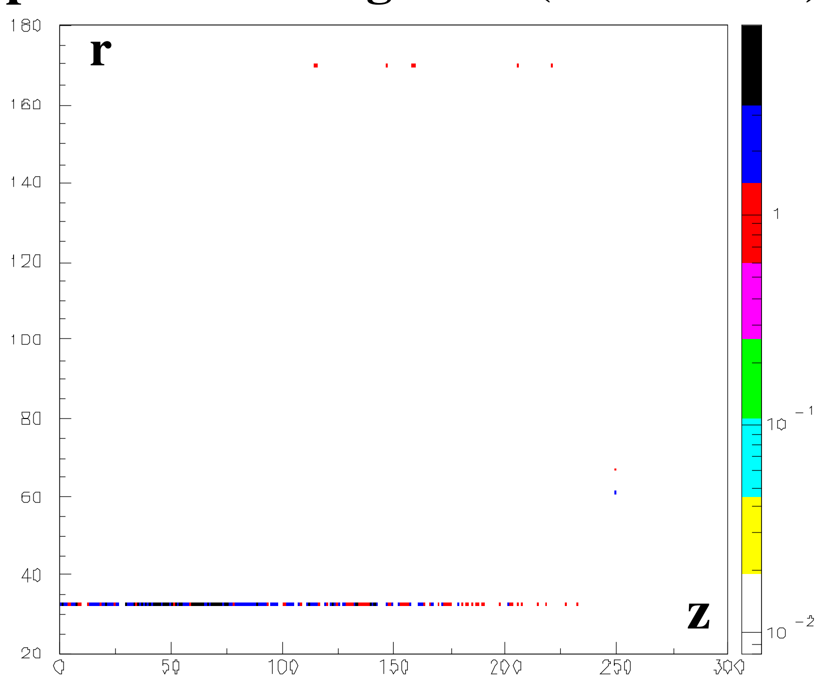
- actual mask design TPC background — **- CP ~ 2440 γ/BX**, **- ICP ~ 927 γ/BX**

Reduces background for a factor ~ 2.5 (previous setup, Prague)

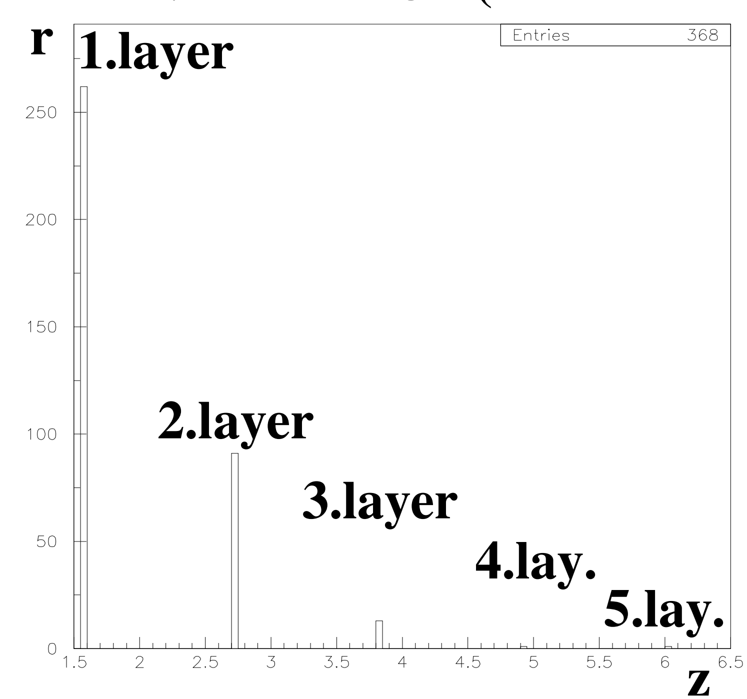
VTX

- **CP** - 1 hit in the first layer and 3 hits in three last layers, from one event each
- **ICP** ~ 368 hits

photons entering TPC (20% of BX)



hits in VTX for ICP (100% of BX)



Outlook

Optics

- **assignment of final value to** η
- **final cavity design**

Luminosity

- **reason for the discrepancy @ 800 GeV**

$\gamma\gamma$ Background

- **minor improvements of mask still possible**