THz generation and transport

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Overview

- Motivation
- Design goals
- Simulation tools
  - POP ZEMAX
  - Mathematica code (B. Schmidt, DESY)
- THz beam extraction
- Optical design
- Simulation of the THz radiation transfer line
- Summary and outlook

Motivation

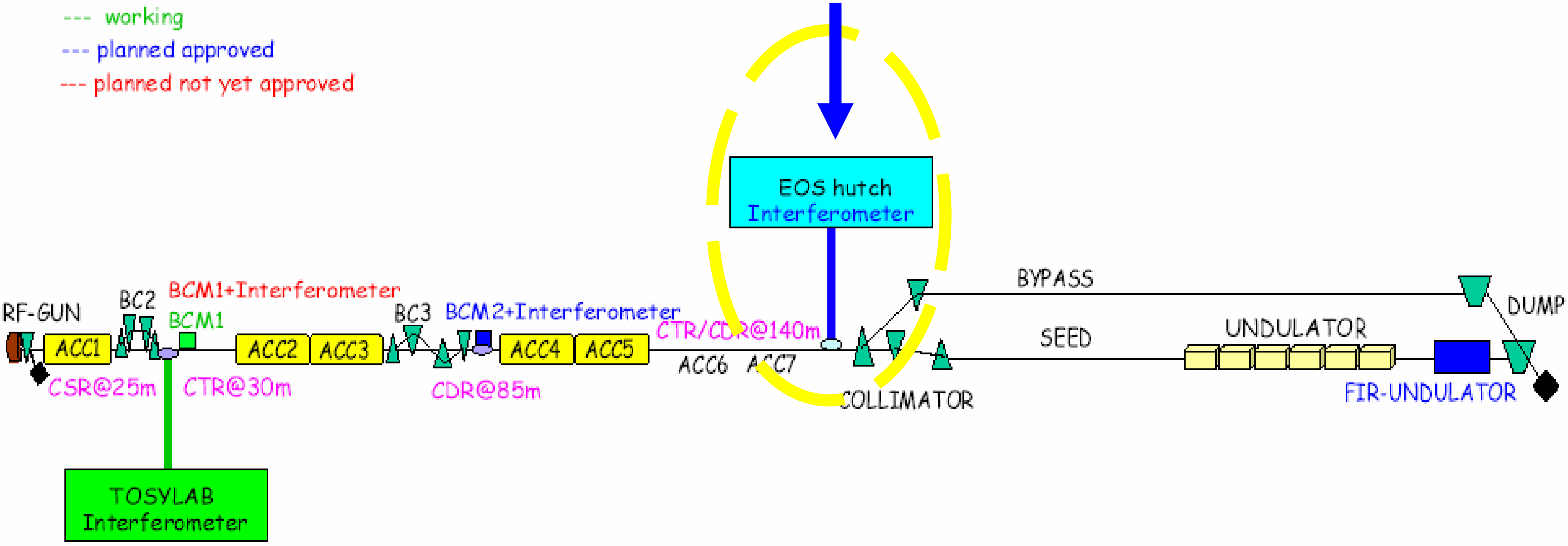
Bunch length measurements with interferometer

CTR=Coherent Transition Radiation
CDR=Coherent Diffraction Radiation
CSR=Coherent Synchrotron Radiation

CDR/CTR

140 m, γ = 1000, E_{el} = 500 MeV

--- working
--- planned approved
--- planned not yet approved



⬭ z-cut quartz window
⬭ diamond window (planned)

BCM=Bunch Compressor Monitor

~5m

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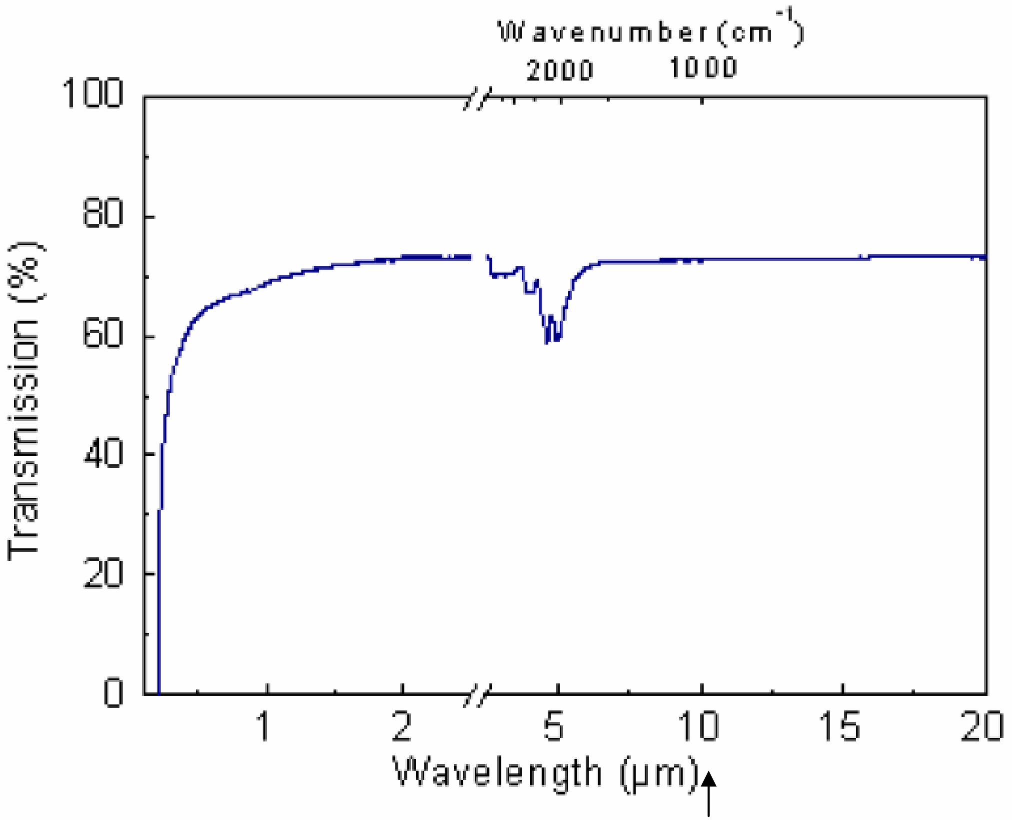
Design goals

- Flat frequency response
- Low frequency response limit as low as possible BUT
  - Finite dimensions of transfer line tube and mirrors ($\phi \approx$ 200mm)
  - Long transfer line ~20m
- High frequency structures expected from μbunching up to 30THz(10μm)

Diamond window



30THz

Optical transmission spectrum of CVD diamond

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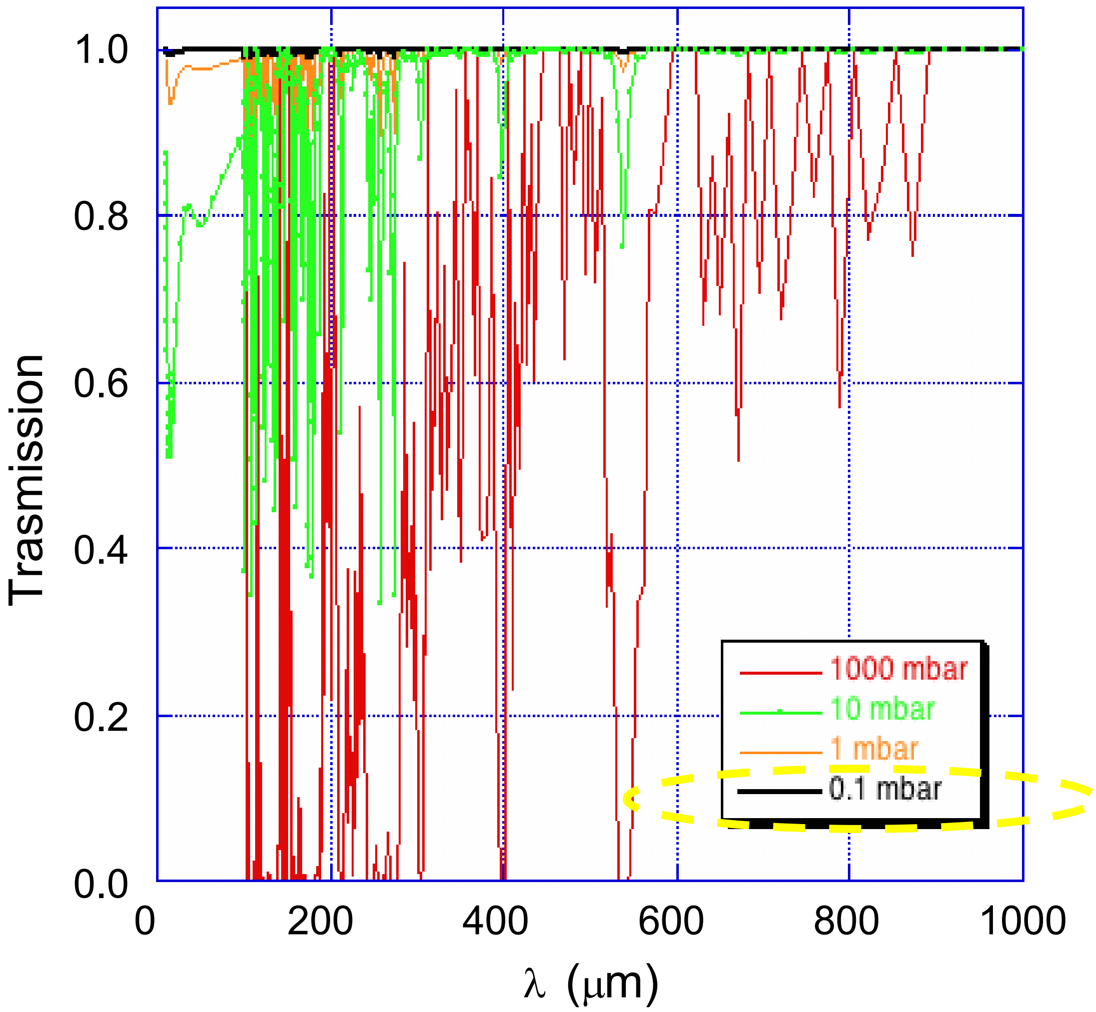
Vacuum needed

Transmission through 20m of Humid Air (50% RH)



from B. Schmidt

S. Casalbuoni, DESY

Simulation Tools

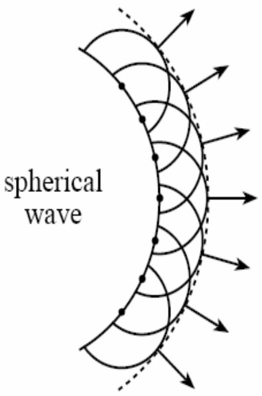
2 CODES

ZEMAX
Commercially available
POP (Physical Optic Propagation)

B. Schmidt (DESY)
Mathematica

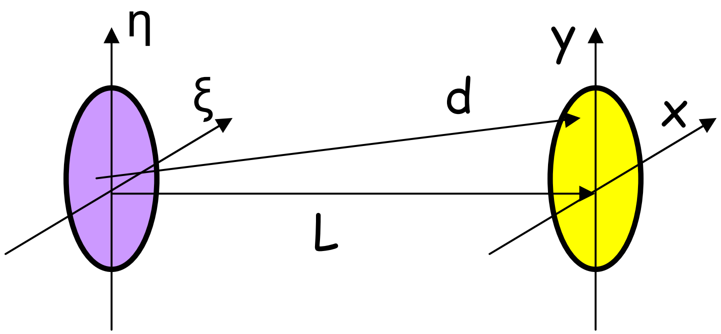
Huygens-Fresnel principle:

Every point of a wave front may be considered as a centre of a secondary disturbance which gives rise to spherical wavelets, and the wave-front at any later instant may be regarded as the envelope of these wavelets. The secondary wavelets mutually interfere.



Kirchhoff integral $$\tilde{E}(x,y,L,\omega)=\iint\limits_{Surf(\xi,\eta)}\tilde{E}(\xi,\eta,0,\omega)\,\frac{e^{ikd}}{i\lambda \underset{\simeq L}{d}}d\xi\; d\eta$$

finite size screen



$$d^2=L^2+(x-\xi)^2+(y-\eta)^2;d=L\sqrt{1+\left(\frac{x-\xi}{L}\right)^2+\left(\frac{y-\eta}{L}\right)^2}$$

$$|x-\xi|,|y-\eta|<<L$$

$$d\cong L+\frac{x^2+y^2}{2L}-\underbrace{\frac{x\xi+y\eta}{L}}_{\text{first order Fraunhofer}}+\underbrace{\frac{\xi^2+\eta^2}{2L}}_{\text{second order near field, Fresnel}}$$

first order
Fraunhofer

second order
near field, Fresnel

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Input for CTR

Fourier Transform with respect to the longitudinal coordinate ζ=z-vt of the radial electric field E_r of a uniform bunch charge distribution of radius ρ moving with velocity v in straight line uniform motion (M. Geitz, PhD Thesis).

r = radial coordinate ρ = beam radius   b = pipe radius $k = 2\pi/\lambda = \omega/c$

$$\tilde{E}_r(k,r) = r \cdot I_1(kr/\gamma) \cdot K_1(k\rho/\gamma) + \rho \cdot I_1(kr/\gamma) \cdot I_1(k\rho/\gamma)\frac{K_0(kb/\gamma)}{I_0(kb/\gamma)}; \quad r < \rho$$

$$\tilde{E}_r(k,r) = \rho \cdot I_1(k\rho/\gamma) \cdot K_1(kr/\gamma) + \rho \cdot I_1(kr/\gamma) \cdot I_1(k\rho/\gamma)\frac{K_0(kb/\gamma)}{I_0(kb/\gamma)}; \quad r > \rho$$

$$\varphi = \mathrm{atan}(y/x)$$

$$\tilde{E}_x = \tilde{E}_r \cdot \cos\varphi \qquad \tilde{E}_y = \tilde{E}_r \cdot \sin\varphi$$

Ginzburg-Frank

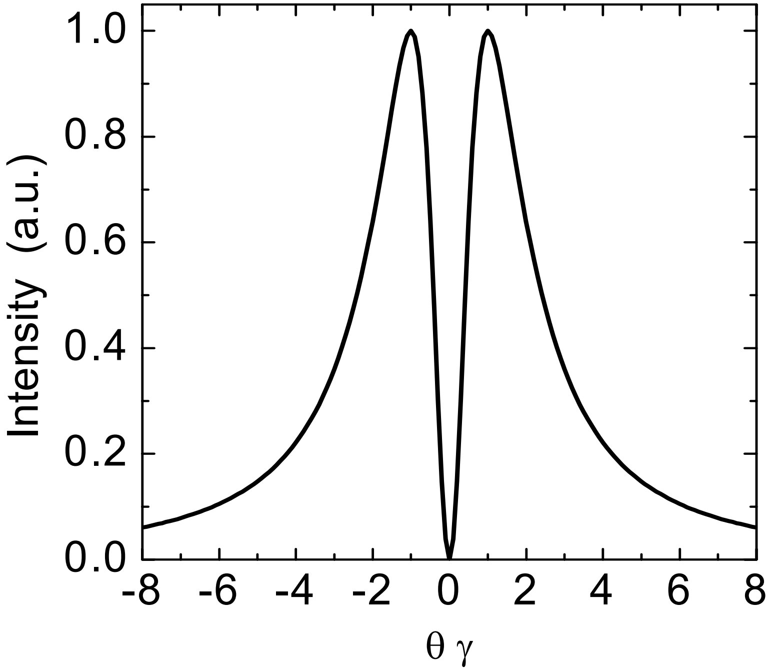
Valid: - if CTR screen radius $\gtrsim$ effective CTR radius

$a \gtrsim \lambda\gamma$

-if $L \gg \lambda \gamma^2 \Rightarrow$ far field (Castellano & Verzilov, Phy.Rev.ST-Accel. Beams ,1998)

$$I(x/L) \propto \frac{\beta^2 \sin^2(x/L)}{(1-\beta^2 \sin^2(x/L))} \qquad \frac{x}{L} = \theta$$

$\Rightarrow$ frequency independent



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$\gamma \equiv 100$ radius CTR screen [m]: a=30mm

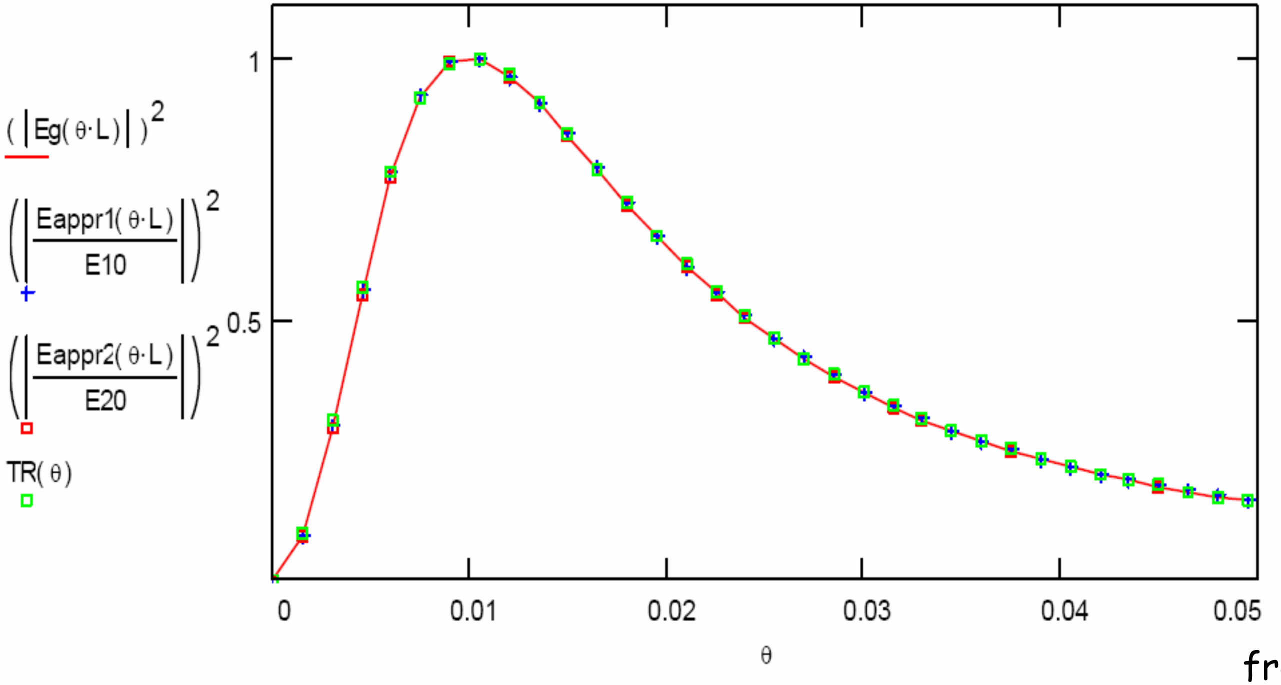
distance to observation screen [m]: L=10m

wavelength λ=300μm

$\gamma \cdot \frac{\lambda}{a} = 1$ $\frac{L}{\gamma^2 \cdot \lambda} = 3.333$

Both conditions satisfied

green: Ginzburg-Frank blue: first order, red: exact SQRT resp. second order



from P. Schmüser

$\gamma \equiv 100$ radius CTR screen [m]: a=30mm

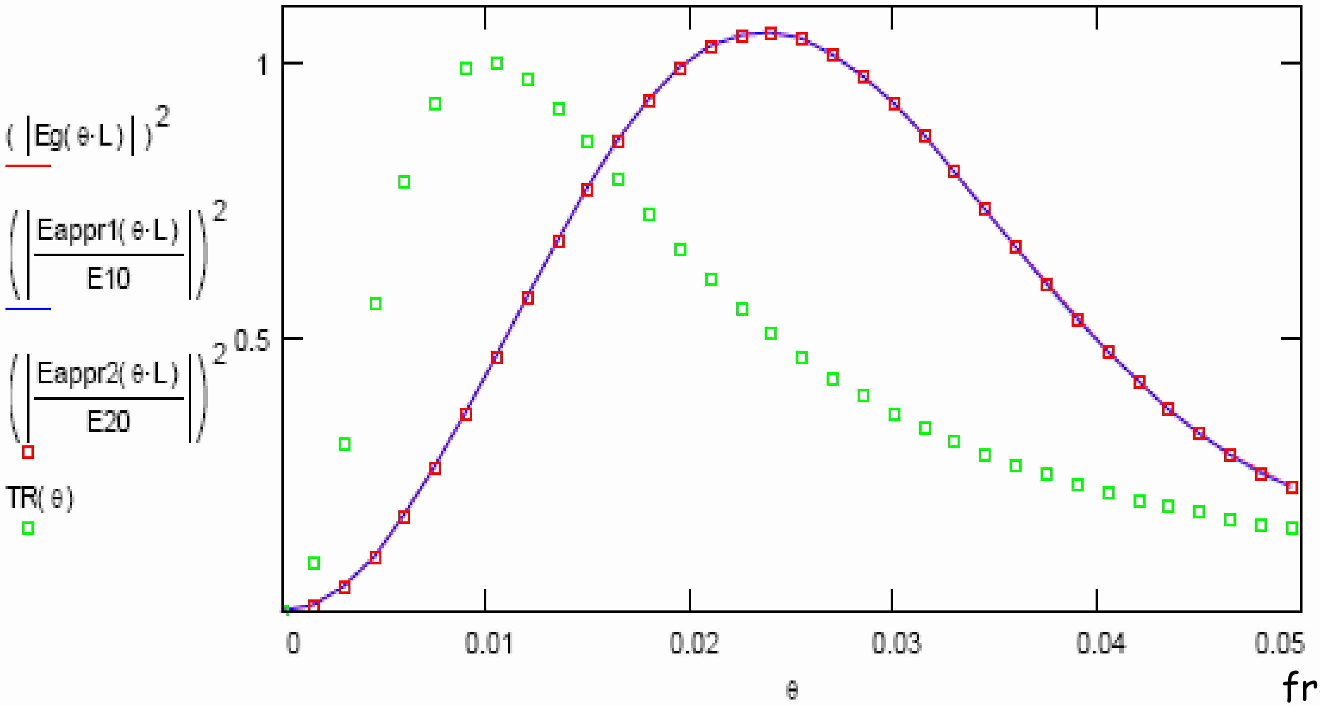
distance to observation screen [m]: L=20m

wavelength λ=1.5mm

Finite size CTR screen

$$\gamma \cdot \frac{\lambda}{a} = 5 \qquad \frac{L}{\gamma^2 \cdot \lambda} = 1.333$$

green: Ginzburg-Frank, blue: first order, red: exact SQRT resp. second order



from P. Schmüser

S. Casalbuoni, DESY

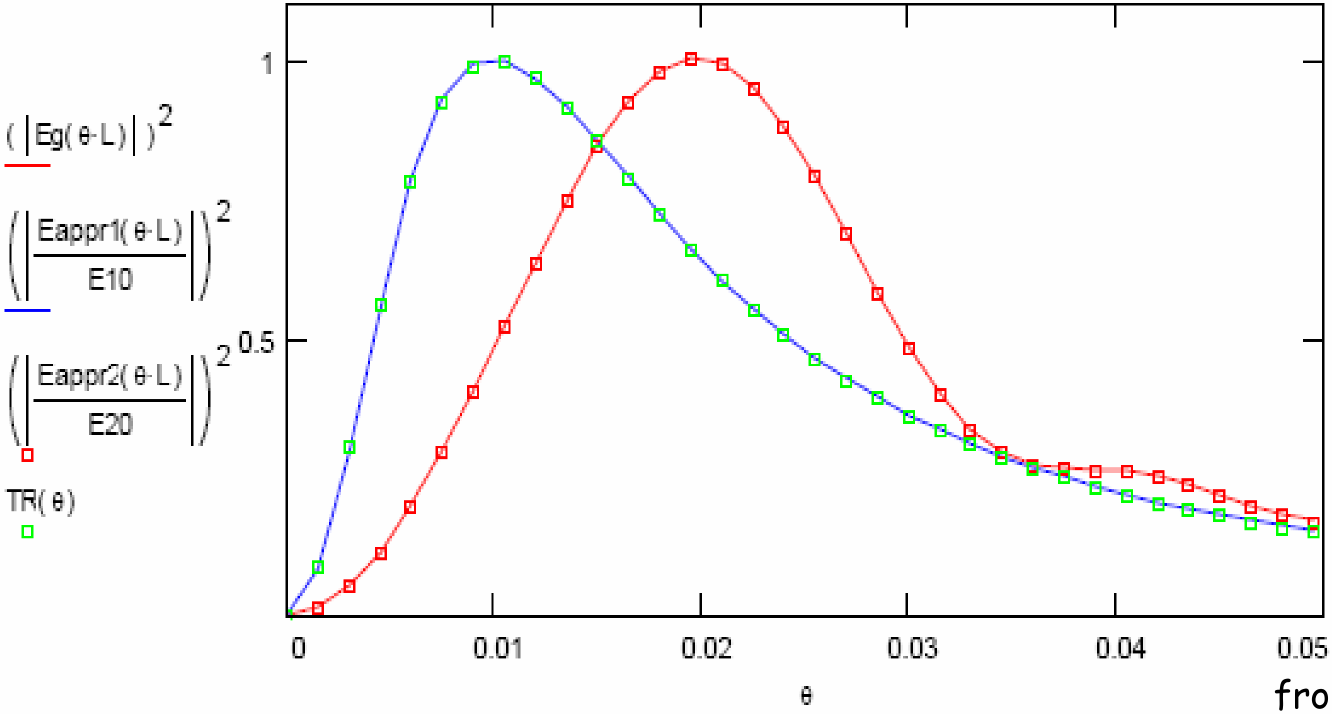
$\gamma \equiv 100$ radius CTR screen [m]: a=30mm

distance to observation screen [m]: L=0.5m

wavelength λ=300μm

$\gamma \cdot \frac{\lambda}{a} = 1$ $\frac{L}{\gamma^2 \cdot \lambda} = 0.167$ **Near field**

green: Ginzburg-Frank, blue: first order red: exact SQRT resp. second orde



from P. Schmüser

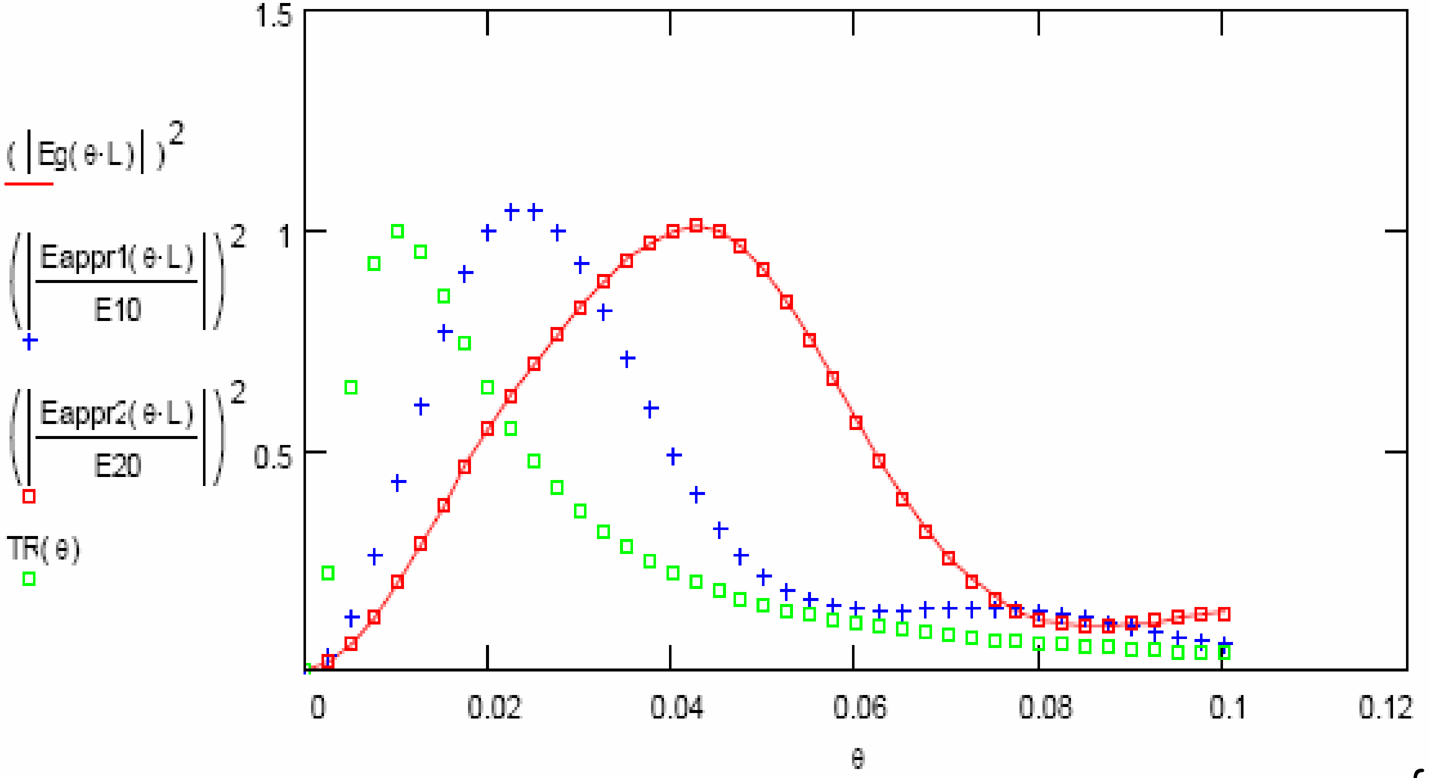
$\gamma \equiv 100$ L=0.5m a=30mm λ=1.5mm

$$\frac{\lambda\cdot\gamma}{a} = 5$$

$$\frac{L}{\lambda\cdot\gamma^2} = 0.033$$

Both conditions violated

green: Ginzburg-Frank, blue first order red: second order and exact SQRT



from P. Schmüser

Simulation Tools

2 CODES

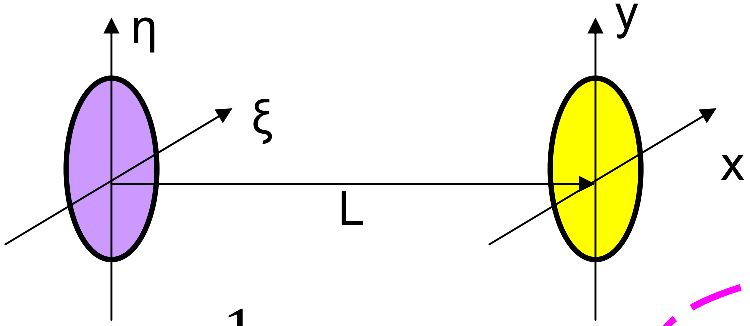
ZEMAX
Commercially available
POP (Physical Optic Propagation)

B. Schmidt (DESY)
Mathematica

Both make use of scalar Fresnel diffraction theory

Valid if objects and apertures >> λ |x-ξ|,|y-η|<<L

$$\tilde{E}(x,y,L,\omega)=\frac{1}{i\lambda d}\iint_{Surf(\xi,\eta)}\tilde{E}(\xi,\eta,0,\omega)\; e^{ikd}d\xi\; d\eta$$



Fourier transform of

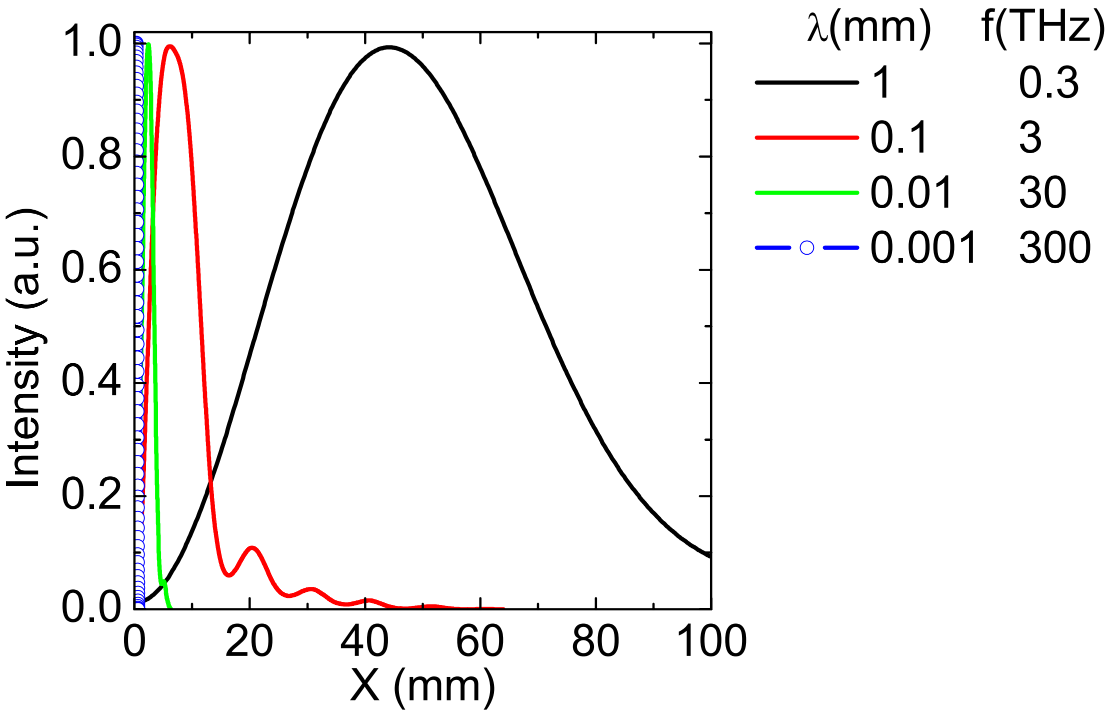
$$\tilde{E}(x,y,L,\omega)=\frac{1}{i\lambda L}\; e^{ik(x^2+y^2)/2L}\iint_{Surf(\xi,\eta)}\boxed{\tilde{E}(\xi,\eta,0,\omega)\; e^{ik(\xi^2+\eta^2)/2L}}e^{ik(x\xi+y\eta)/2L}d\xi\; d\eta$$

$$k=\frac{2\pi}{\lambda};\qquad \lambda=\frac{2\pi c}{\omega}$$

Free propagation

if $a \lesssim \gamma\lambda$ and/or $L \lesssim \lambda\,\gamma^2 \Rightarrow I\,(x, L,\omega)$ frequency dependent

L=1 m; a=10 mm; γ =1000



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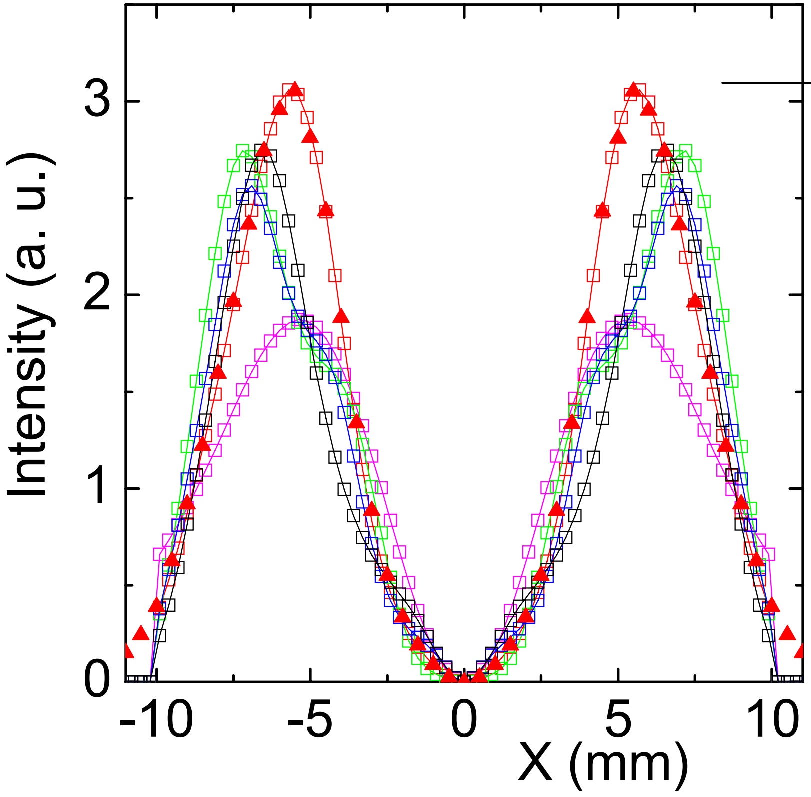
Dimensions of the CTR screen

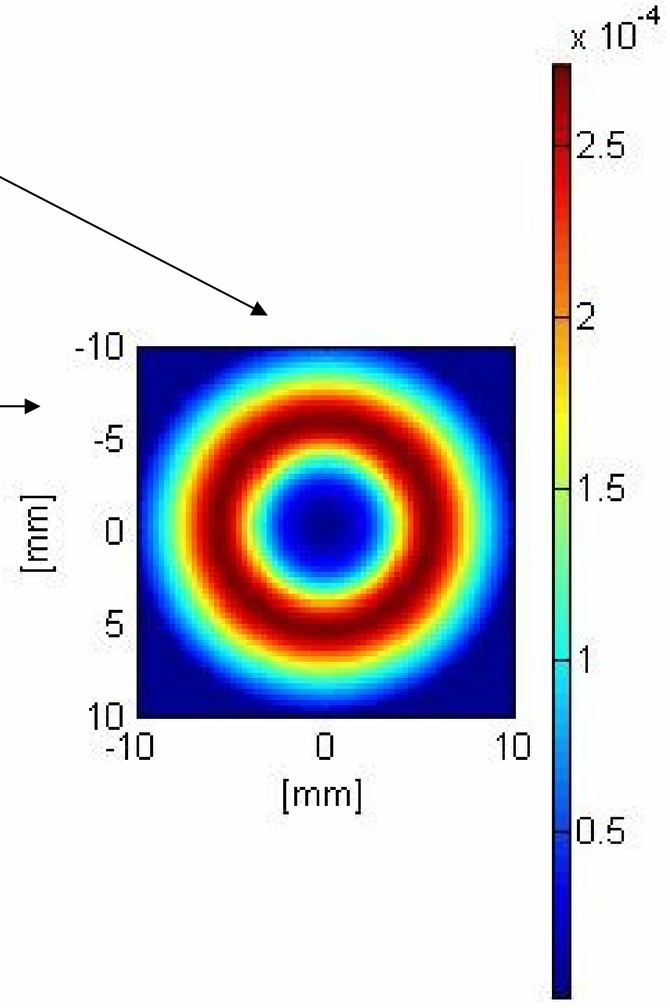
window ϕ=20mm

L=40mm; γ =1000
λ=1.5mm ⇒ f=200GHz

screen ϕ (mm)	intensity @window/@screen
10	0.74
20	0.84
25	0.83
30	0.79
40	0.70

ZEMAX
▲ Mathematica





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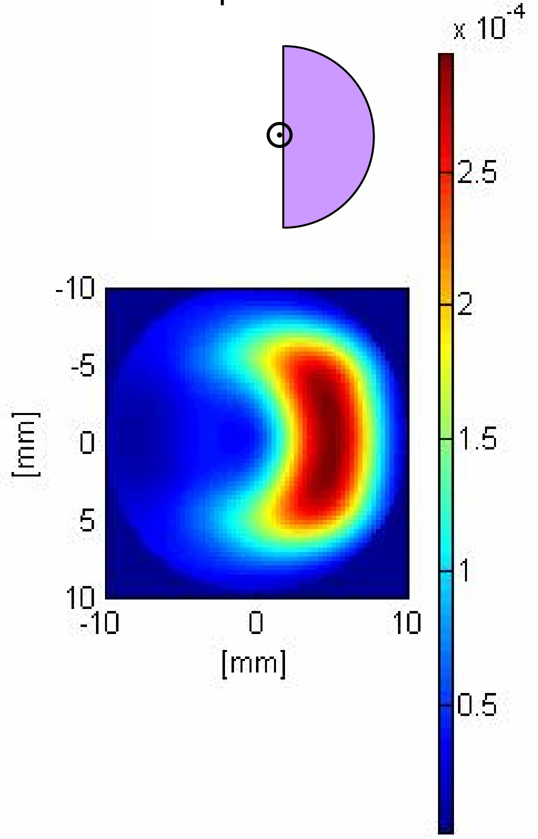
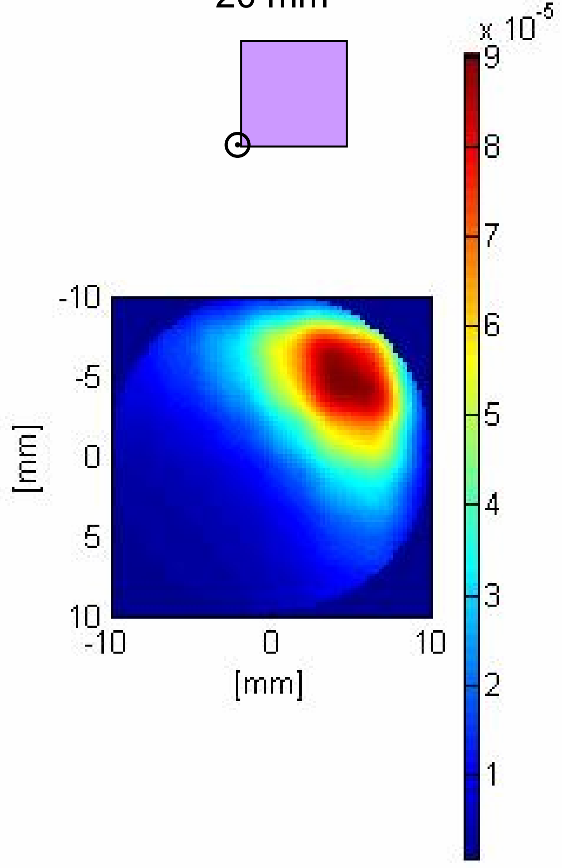
CDR screen

window ϕ=20mm
L=40mm; γ =1000
λ=1.5mm ⇒ f=200GHz

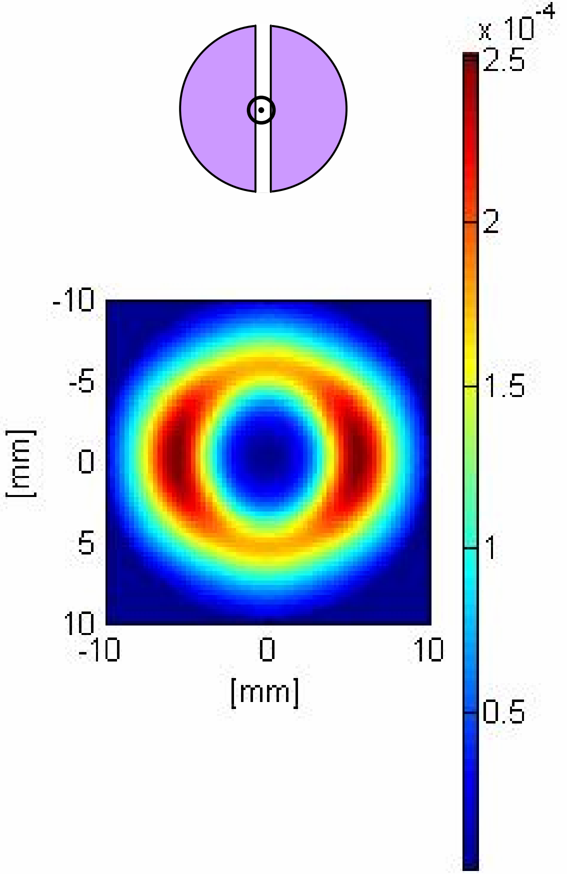
ϕ=20 mm



20 mm



ϕ=20 mm, slit=1mm



intensity
@window/@screen
0.75 0.55 0.78

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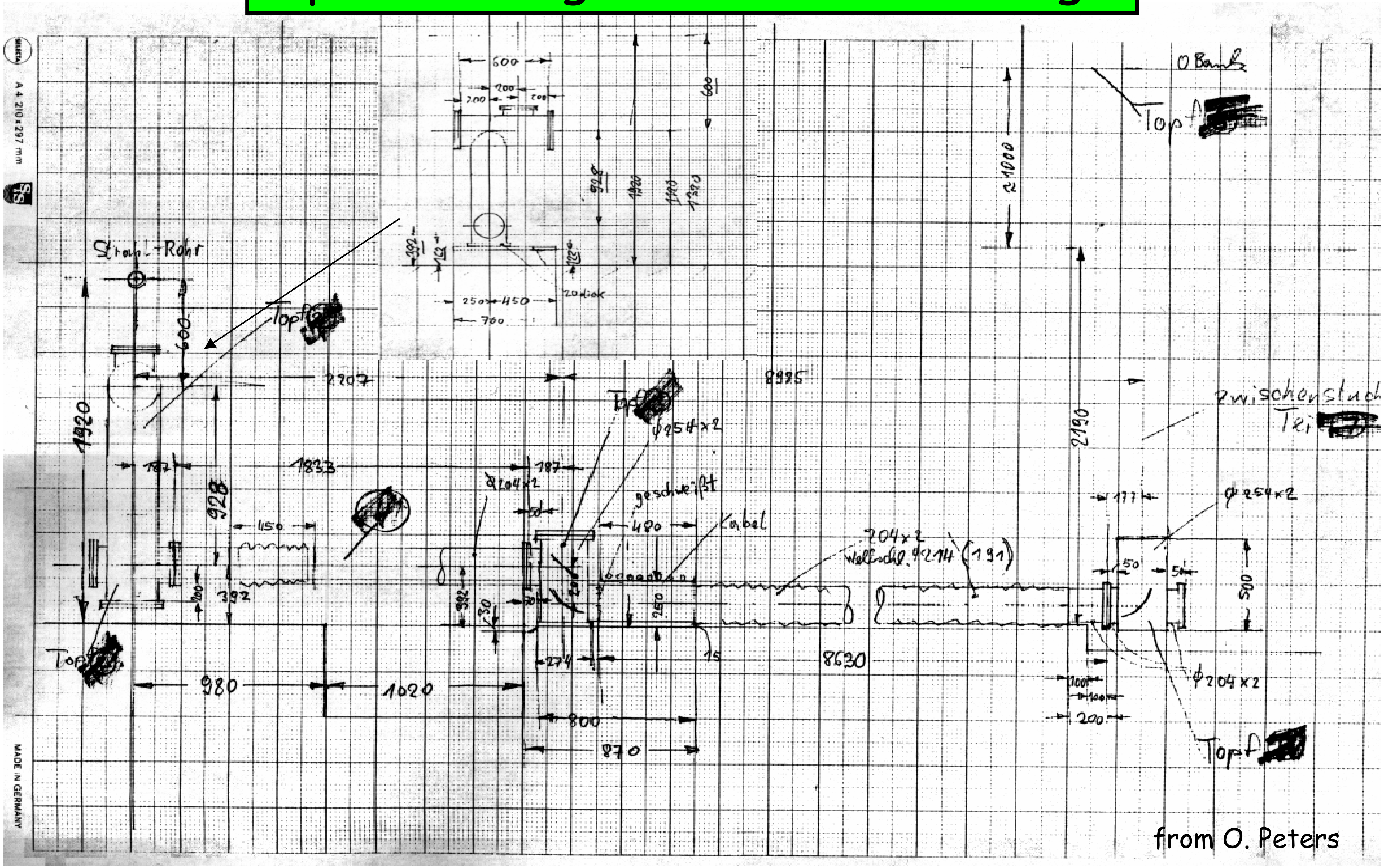
Optical design: technical drawing



from O. Peters

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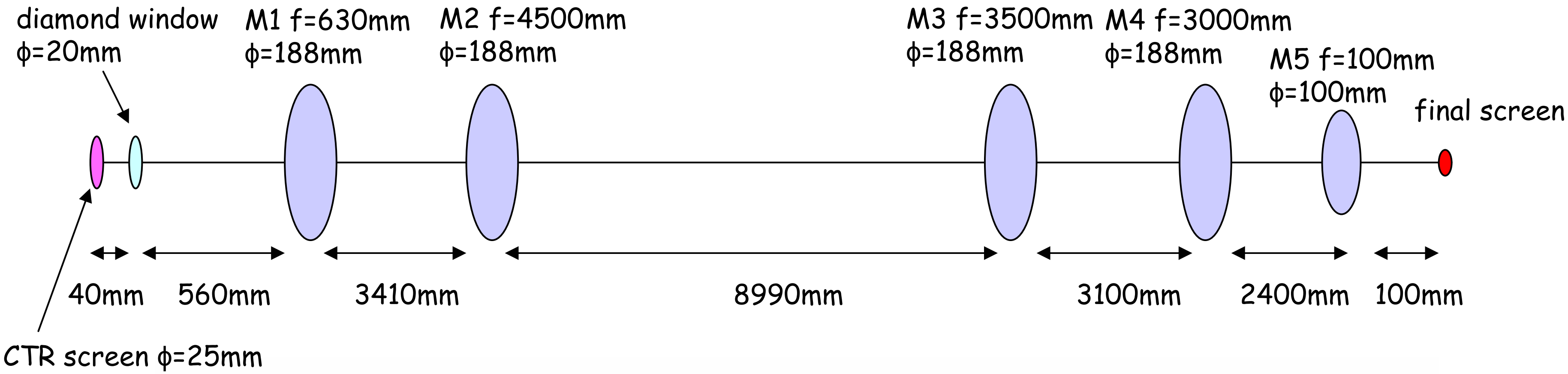
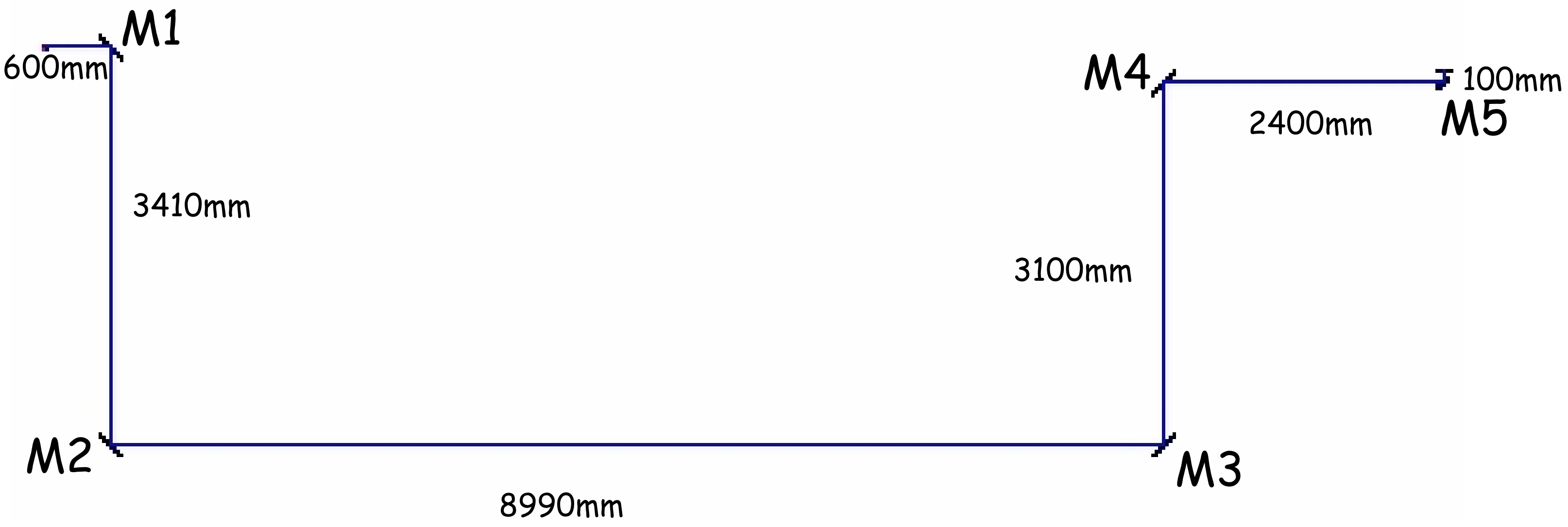
Optical design





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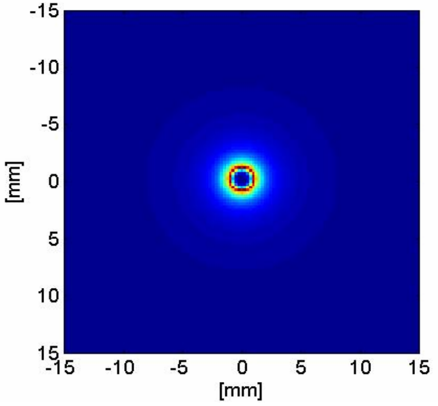
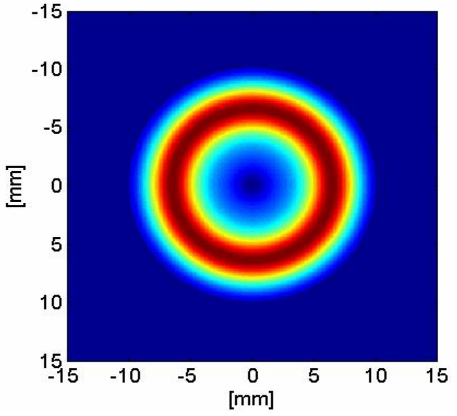
Simulation of the THz radiation transfer line with ideal thin lenses

λ=1.5mm ⇒ f=200GHz; γ =1000

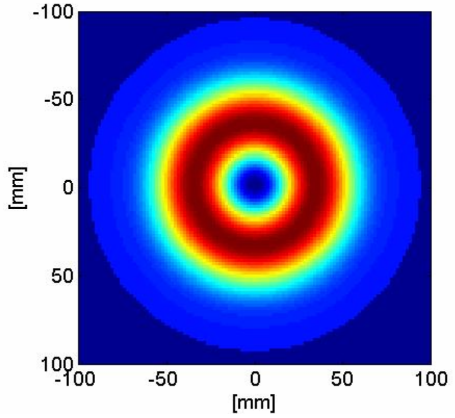
CTR screen ϕ=25mm



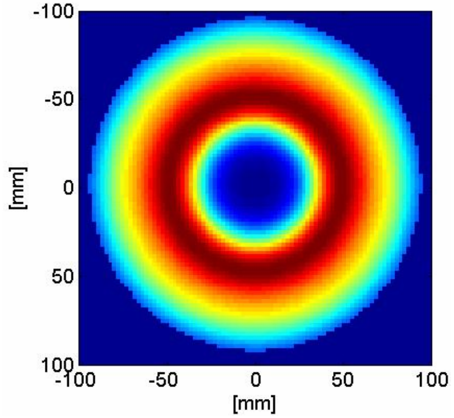
Diamond window ϕ=20mm



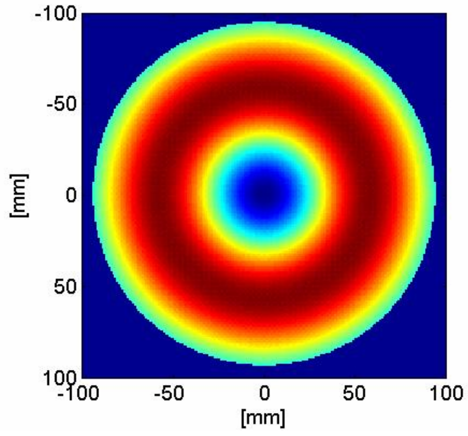
M1



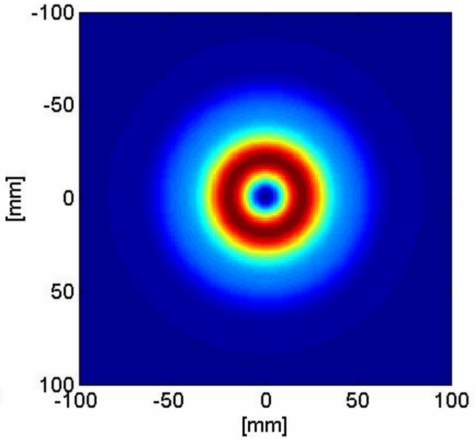
M2



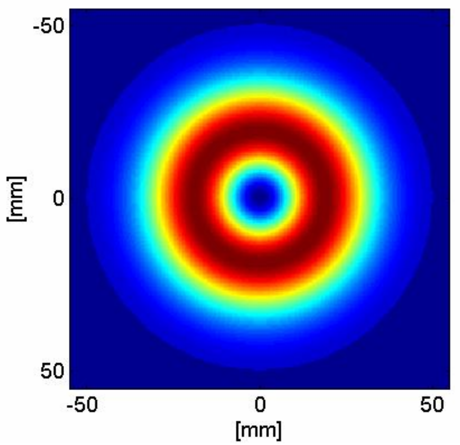
M3



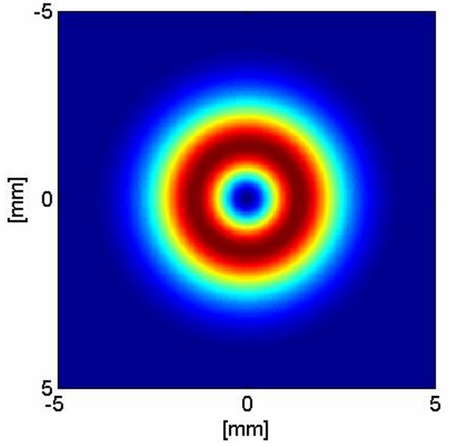
M4



M5



final screen ϕ=8mm



Intensity @final screen/@window=0.49

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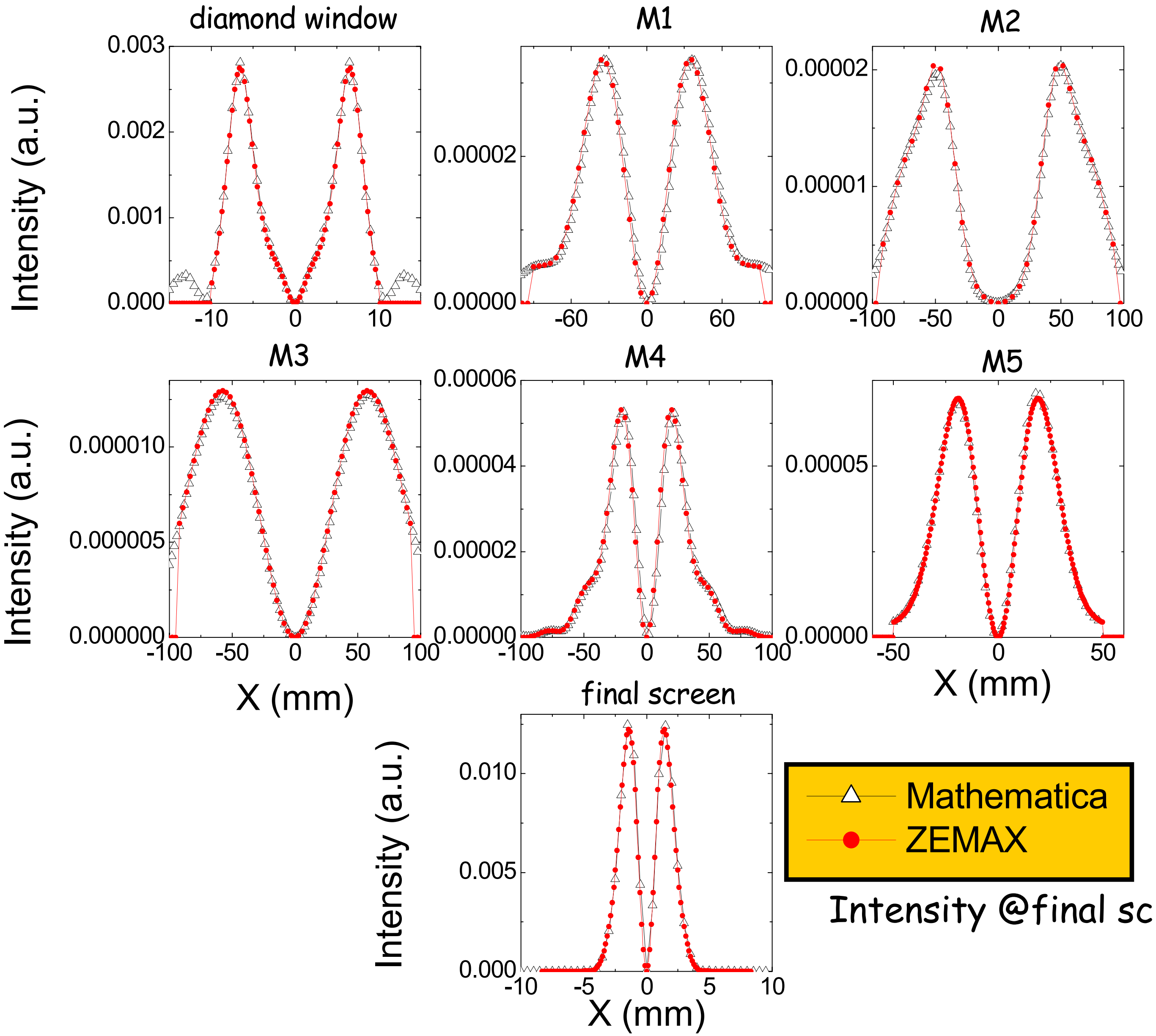
Simulation of the THz radiation transfer line with ideal thin lenses



λ=1.5mm ⇒ f=200GHz

γ =1000

CTRscreenϕ=25mm

Diamond windowϕ=20mm

Intensity @final screen/@window=0.49

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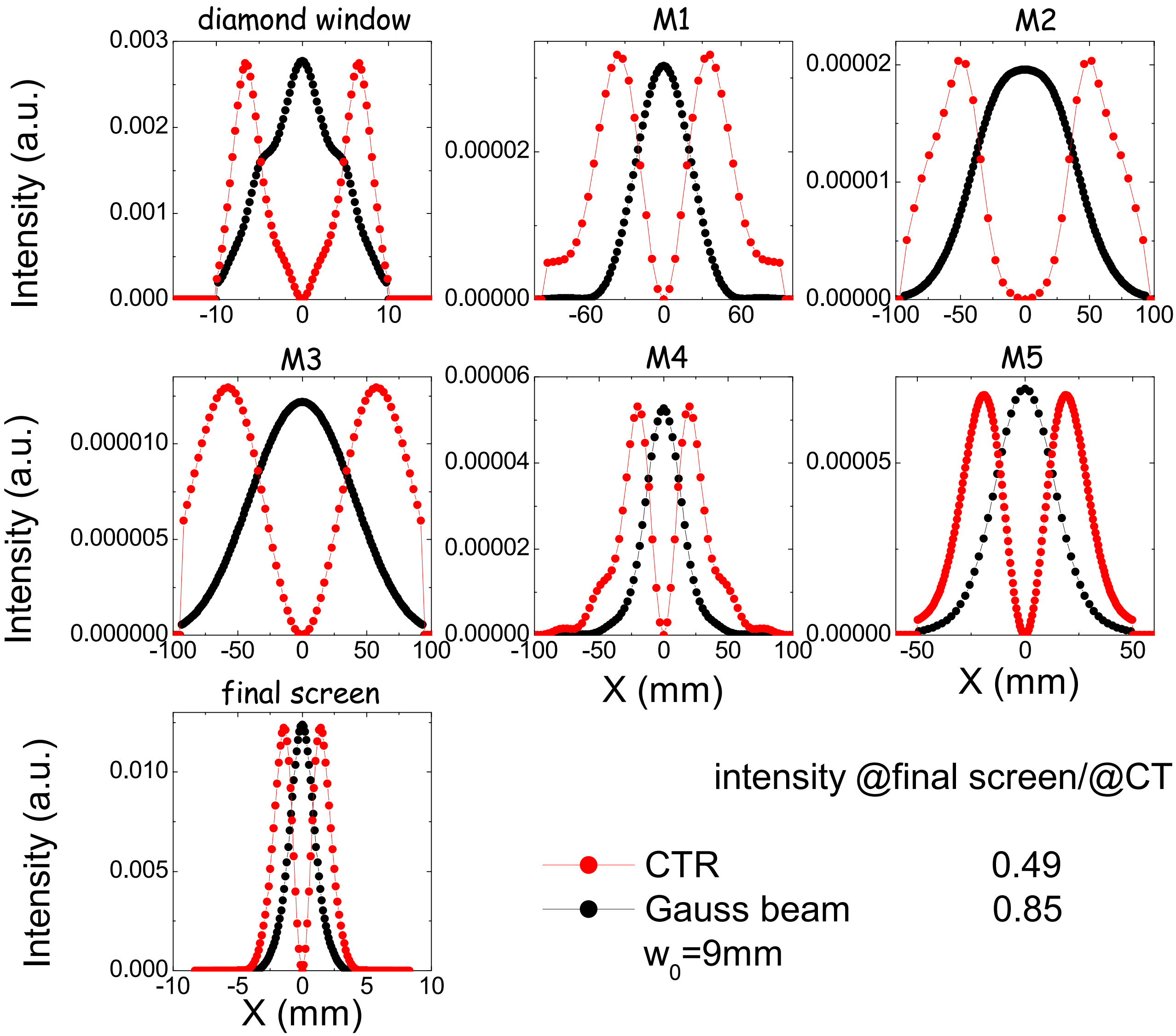
Good also for a Gaussian beam



λ=1.5mm ⇒ f=200GHz
γ =1000
CTRscreenϕ=25mm
Diamond windowϕ=20mm

intensity @final screen/@CTR screen

● CTR	0.49
● Gauss beam w_0=9mm	0.85

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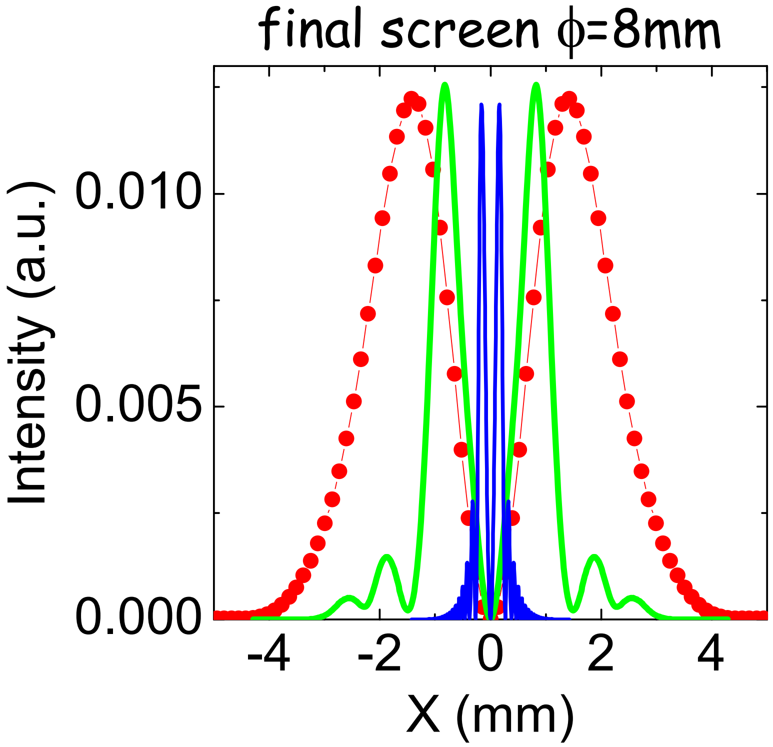
Simulation of the THz radiation transfer line at different frequencies



γ = 1000

CTR screen ϕ = 25mm

diamond window ϕ = 20mm

	λ (mm)	f(THz)	Intensity @final screen/@window
🟥	1.5	0.2	0.49
🟩	0.3	1	0.90
🟦	0.01	30	0.99

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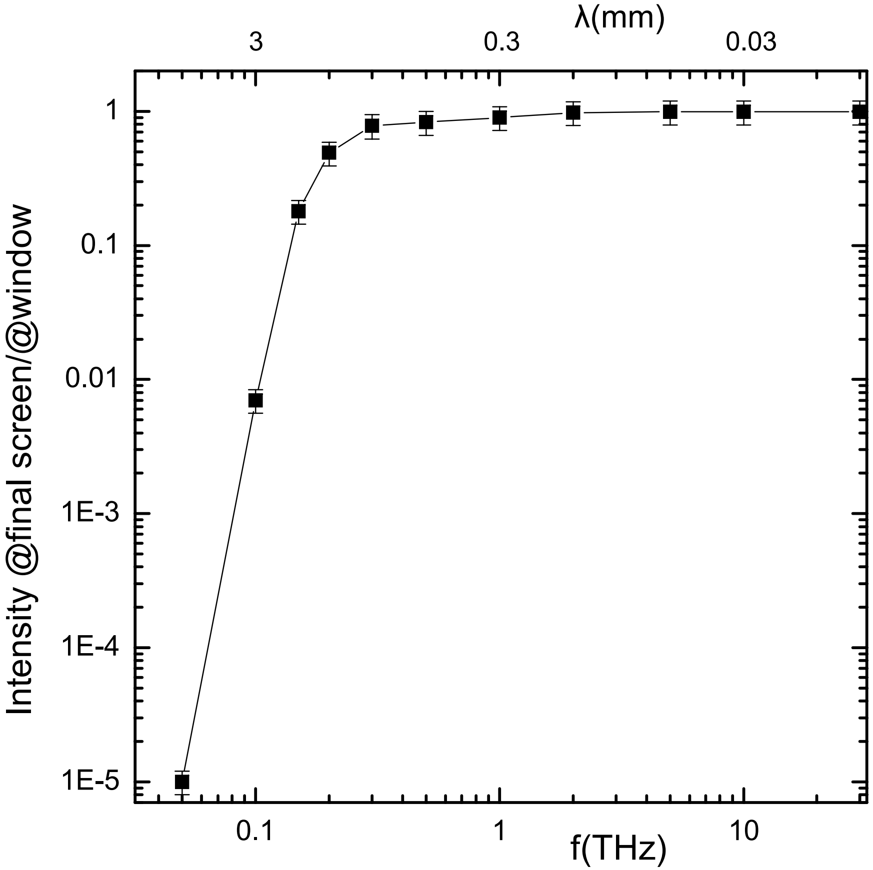
Transfer function



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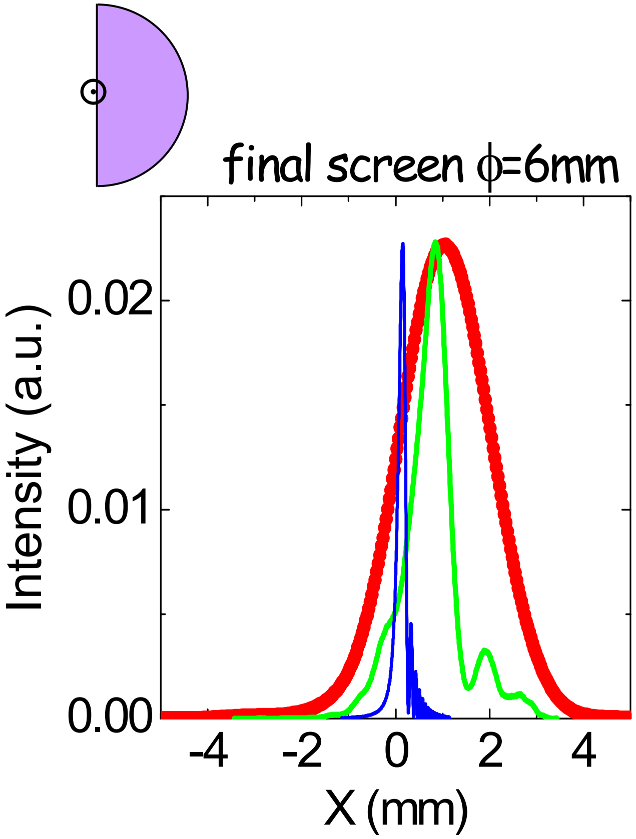
Half screen and horizontal polarization: frequency response

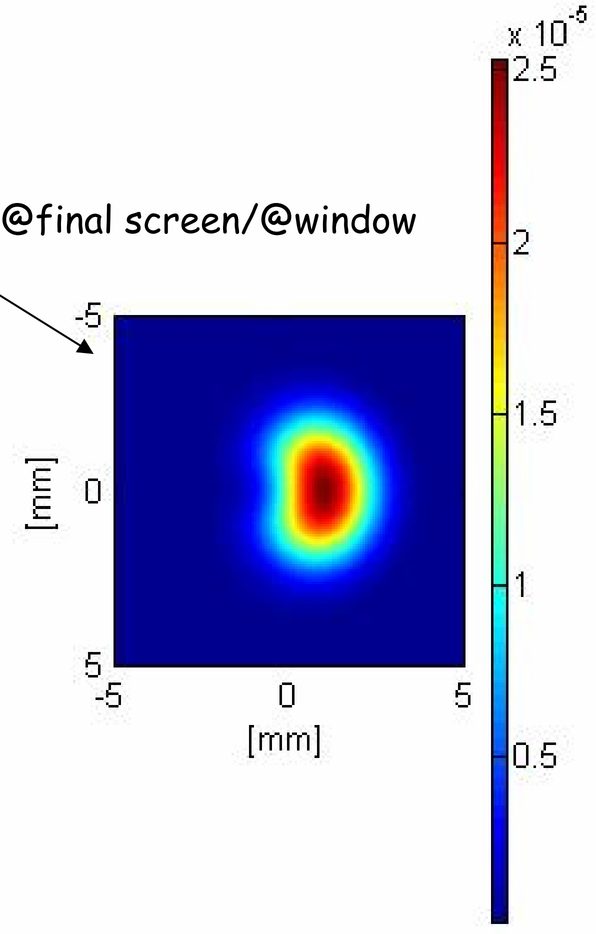


γ = 1000

CTR screen ϕ = 25mm

diamond window ϕ = 20mm

	λ (mm)	f(THz)	Intensity @final screen/@window
●	1.5	0.2	0.52
—	0.3	1	0.91
—	0.01	30	0.99



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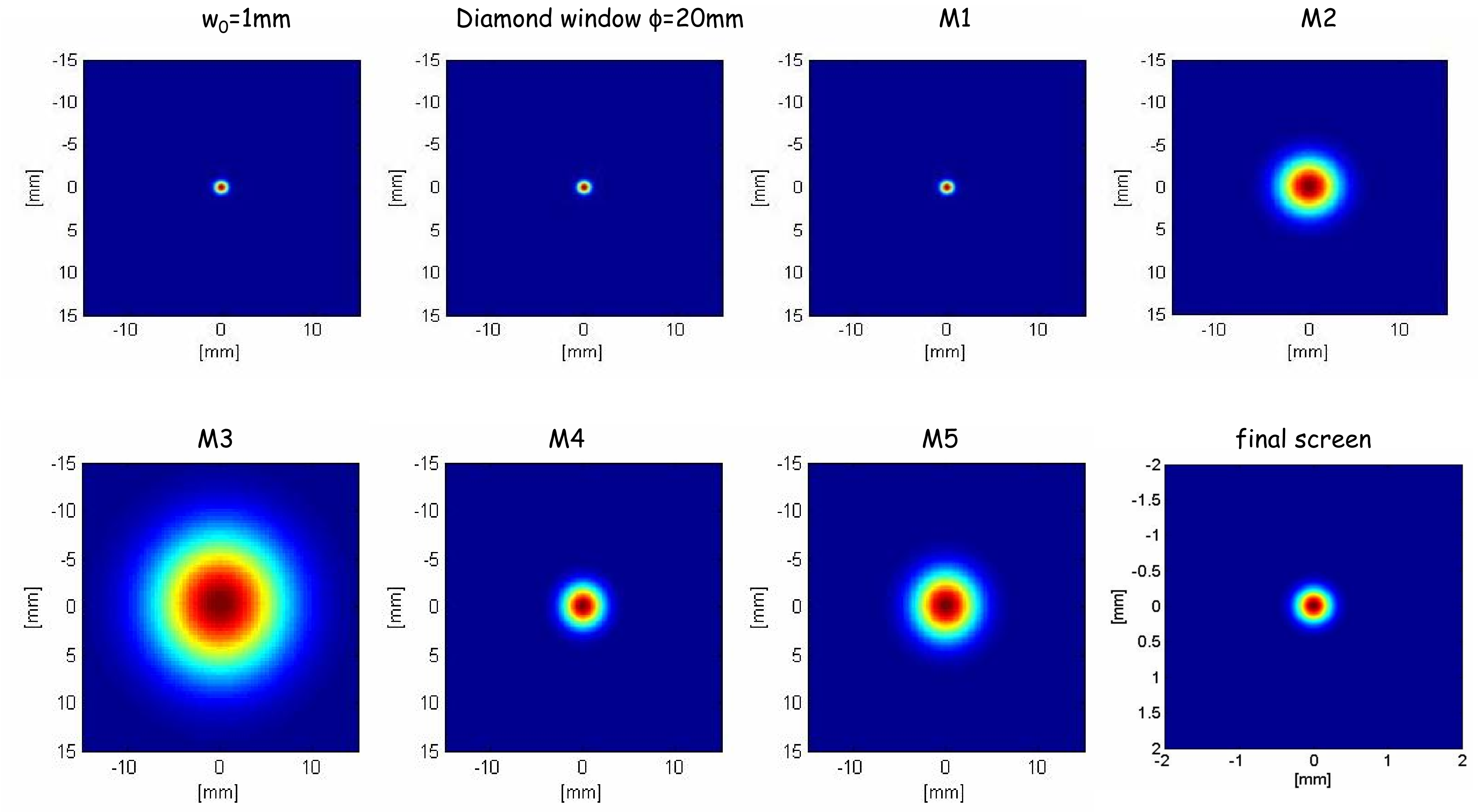
Gaussian beam λ=500nm



w_0=1mm

Diamond window ϕ=20mm

M1

M2

M3

M4

M5

final screen

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Summary and outlook

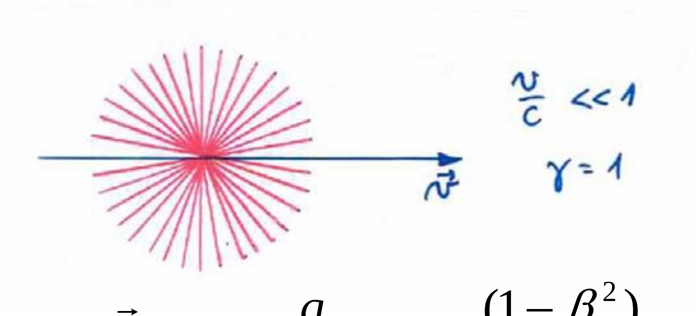
- 2 simulation tools: very good agreement
- Optical design for the THz beam line transfer @140m in TTF2: tested for CTR, CDR and Gaussian beam
- Outlook

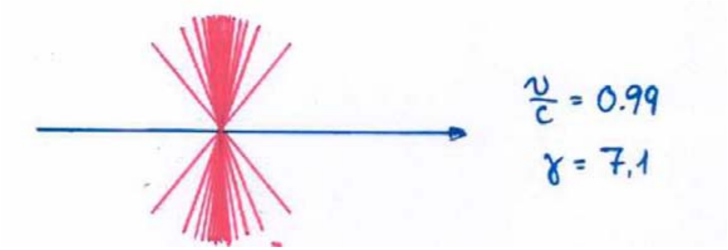
-"ideal" mirror surface

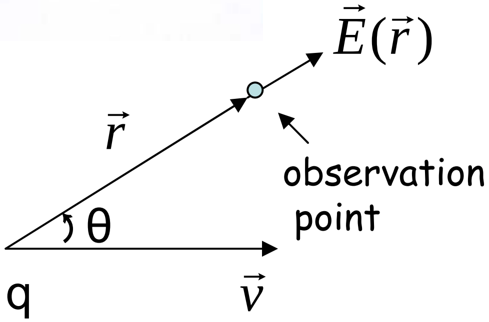
-tests for stability against beam displacement and mirrors misalignment

-effect of tilting CTR screen

Electric field of a charge in the laboratory system







$$\vec{E}(\vec{r}) = \frac{q}{4\pi\varepsilon_0} \cdot \frac{(1-\beta^2)}{\left(1-\beta^2 \sin^2\theta\right)^{3/2}} \cdot \frac{\vec{r}}{r^3}$$

$$E_z \cong 0; \qquad E_r = \frac{q}{4\pi\varepsilon_0} \cdot \gamma \cdot \frac{r}{\left[\gamma^2 (z-vt)^2 + r^2\right]^{3/2}}$$

$$\zeta = z - vt = z - \beta ct$$

$$\tilde{E}_r(k,r) = \int_{-\infty}^{\infty} E_r(k,r) \cdot e^{ik\zeta} d\zeta$$

$$\tilde{E}_r(k,r) = \frac{q}{4\pi\varepsilon_0} \cdot \frac{k}{\gamma} \cdot K_1\left(\frac{kr}{\gamma}\right)$$

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