Progress Report on Design of the THz Diagnostics for PITZ SASE FEL

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

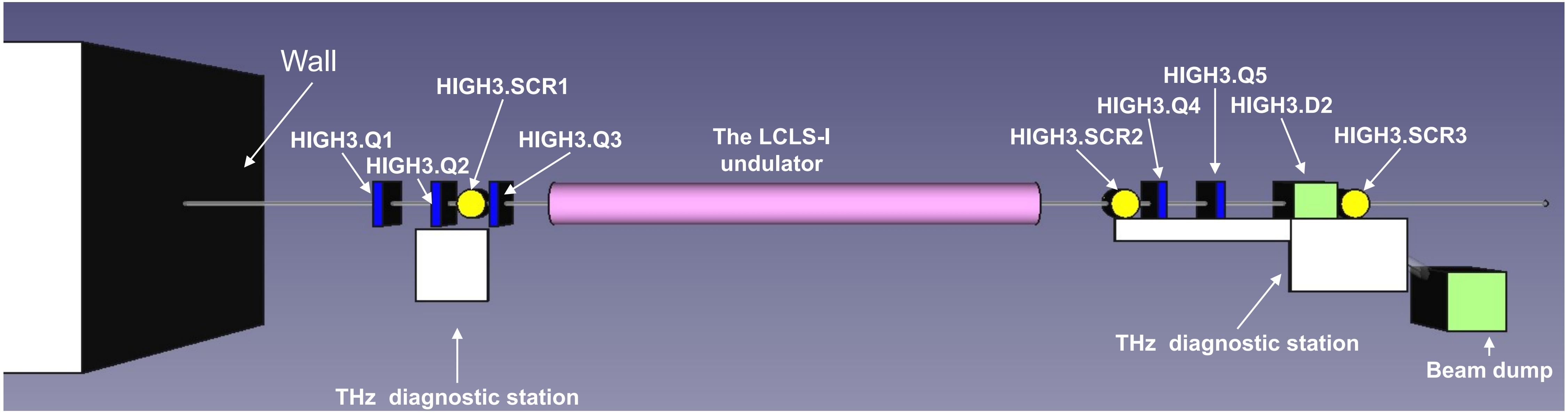
PITZ Photo Injector Test Facility Zeuthen

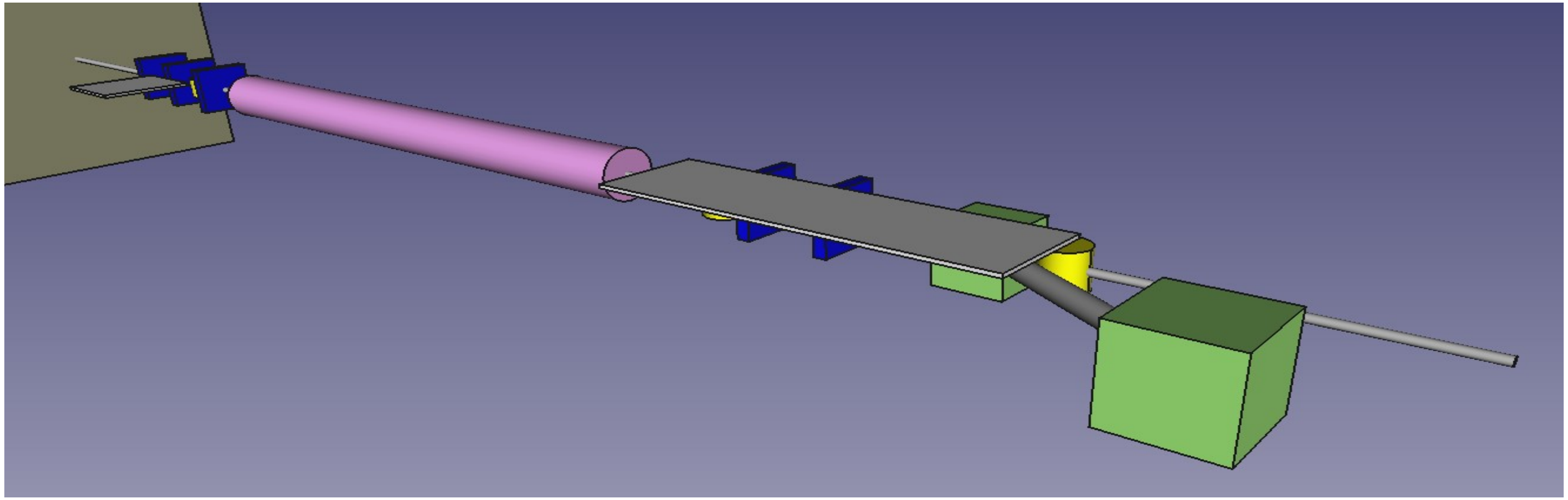
DESY

Outline

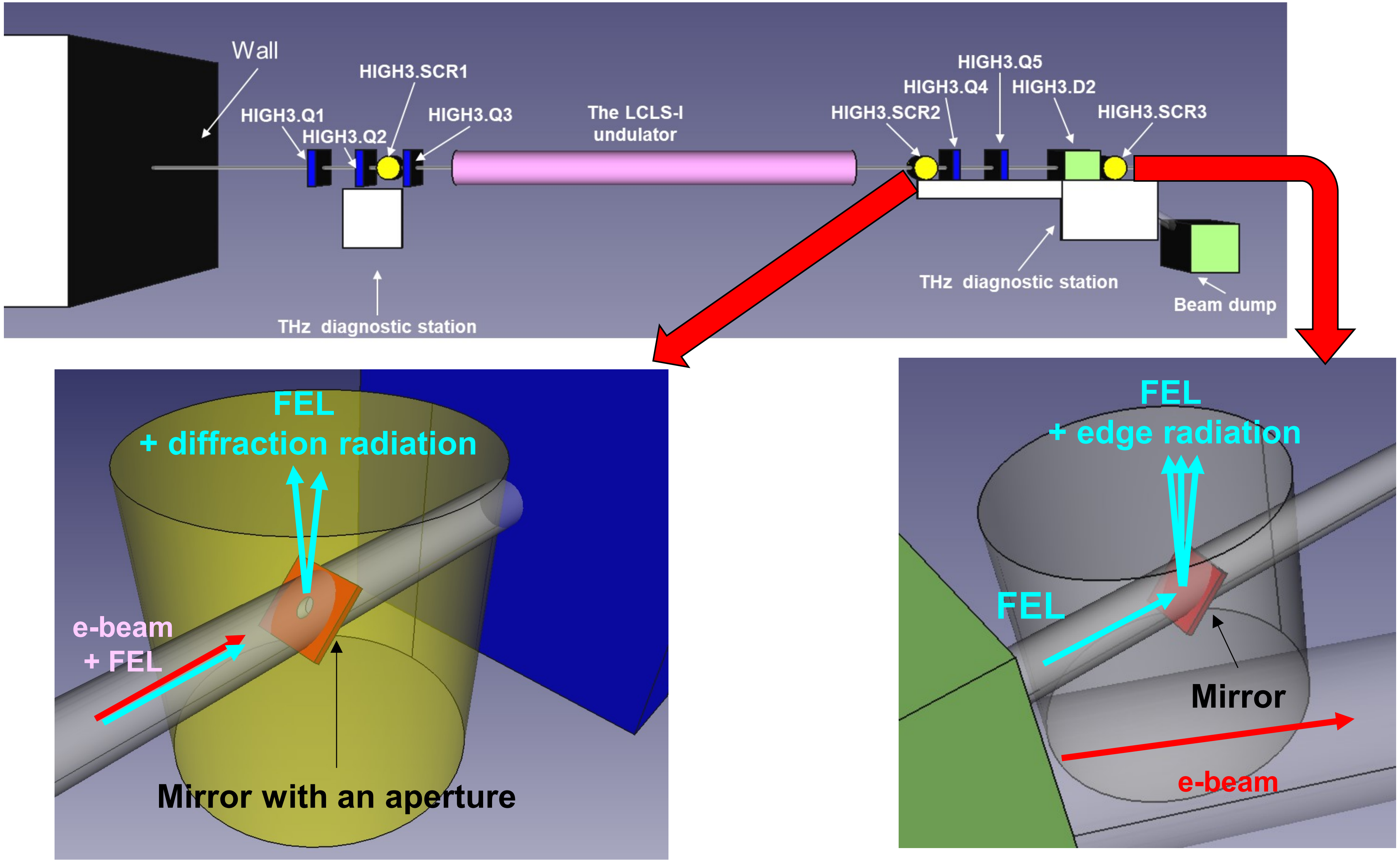
- Layout of the Tunnel Annex
- Gaussian Beam Propagation
- Properties of PITZ SASE FEL from WARP Simulation
- Optical Layout of the FEL Diagnostics system
- Gaussian Beam Propagation of the FEL
- Summary and Outlook

Layout of the Tunnel Annex





Layout of the Tunnel Annex



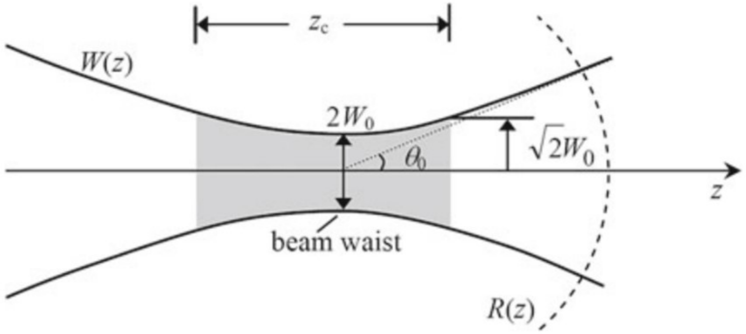
Reference: K-E. Peiponen et. al (Eds.), Terahertz Spectroscopy and Imaging, 2013.
https://doi.org/10.1007/978-3-642-29564-5

Gaussian Beam Propagation

Introduction to properties of a simple Gaussian beam mode

- Optics in different regimes
  - Optical regime (λ << d) ➔ geometrical optics (λ/d = 0)
  - Terahertz regime (λ < d) ➔ Gaussian beam optics
  - Microwave regime (λ ~ d) ➔ Physical optics
- Diffraction effects are neglected in geometrical optics
- Physical optics techniques are very accurate but can be computationally slow for multi-element systems.
- This study uses Gaussian beam optics.
- Gaussian beam modes are solutions of the paraxial Helmholtz equation (intensity doesn't change with propagation).
- Helmholtz equation $\nabla^2 E + k^2 E = 0$; $E(x,y,z) = u(x,y,z)e^{-ikz}$
- Paraxial equation ➔ $\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{2ik\partial^2 u}{\partial z} = 0$
- Solution ➔ $u(x,y,z) = \frac{u_0}{(q_0+z)} e^{-i\frac{k(x^2+y^2)}{2(q_0+z)}}$; u_0, q_0 = constant
- Re-express the solution

$$E_G(x,y,z) = \sqrt{\frac{2}{\pi W^2(z)}}\, e^{-\frac{(x^2+y^2)}{W^2(z)} - ik\left(z + \frac{(x^2+y^2)}{2R(z)}\right) + i\phi_0(z)}$$



- By setting $z_0 = \pi W_0^2/\lambda$,
  - Beam width: $W^2(z) = W_0^2(1 + (z/z_0)^2)$
  - Phase radius of curvature: $R(z) = z + z_0^2/z$
  - Phase-slippage: $\phi_0(z) = \tan^{-1}(z/z_0)$
- The power flux (power per unit area):

$$I = \langle \boldsymbol{E} \times \boldsymbol{H}^* \rangle = \frac{|E|^2}{2\mu_0 c} = \frac{c\epsilon_0 |E|^2}{2}$$

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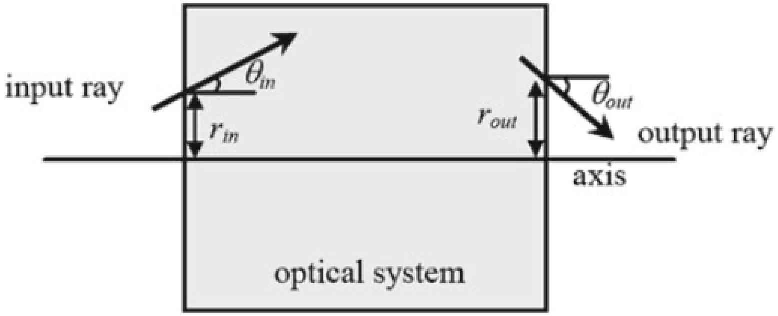
Gaussian Beam Propagation

Transfer Matrices formalism (ABCD Matrices)

- In geometrical optics, transformation of the input ray to the output ray through a transfer matrix can be expressed as:

$$\begin{bmatrix} r_{out} \\ \theta_{out} \end{bmatrix} = \mathbf{M} \cdot \begin{bmatrix} r_{in} \\ \theta_{in} \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} r_{in} \\ \theta_{in} \end{bmatrix} = \begin{bmatrix} Ar_{in} + B\theta_{in} \\ Cr_{in} + D\theta_{in} \end{bmatrix}$$

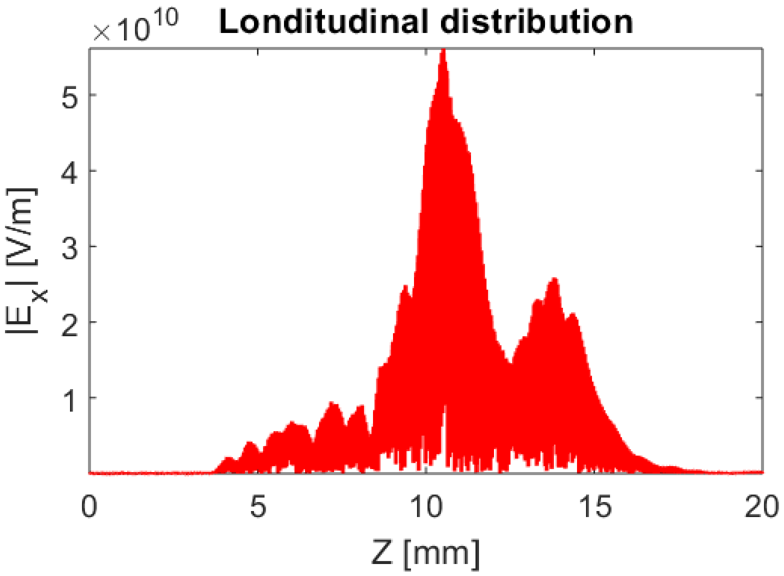


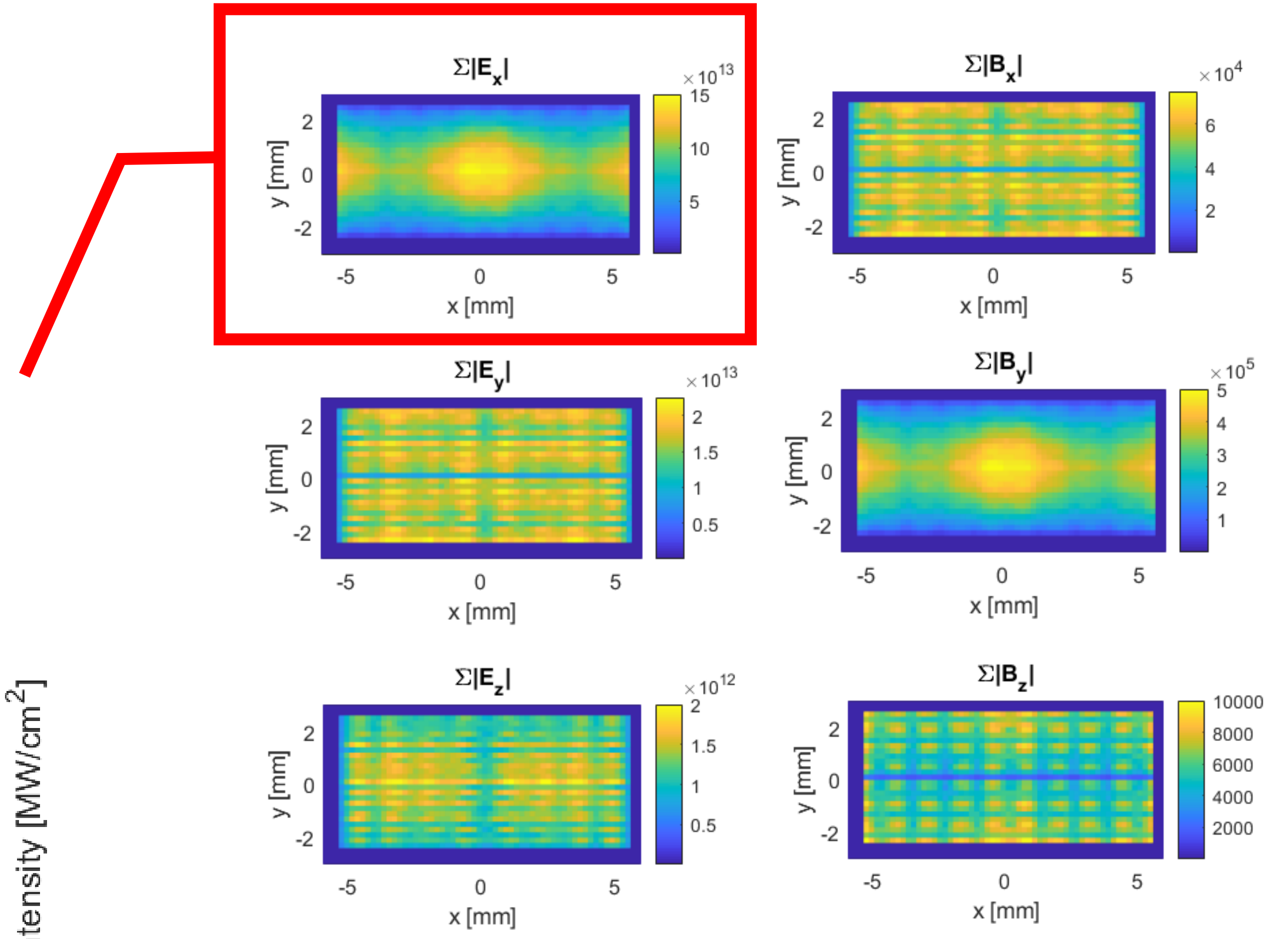
- Example of ABCD matrices
  - Drift space: $\begin{bmatrix} 1 & L \\ 0 & 1 \end{bmatrix}$
  - Thin lens: $\begin{bmatrix} 1 & 0 \\ -1/f & 1 \end{bmatrix}$

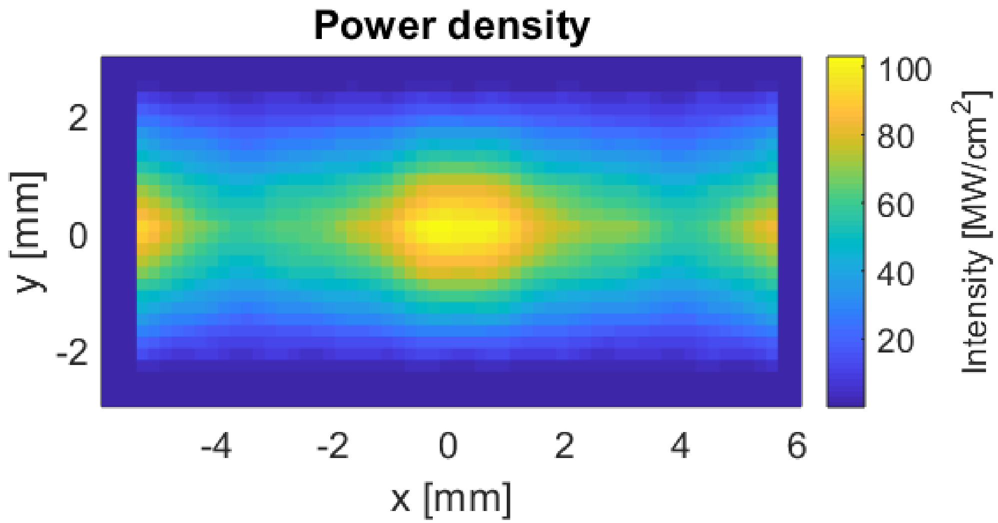
- In Gaussian beam optics, by treating it as a complex beam parameter $q(z)$,
$$\frac{1}{q(z)} = \frac{1}{R(z)} - i\frac{\lambda}{\pi W^2(z)},$$
the transformation using the ABCD matrix are
  - $\frac{1}{q_{out}} = \frac{C+D\left(\frac{1}{q_{in}}\right)}{A+B\left(\frac{1}{q_{in}}\right)}$
  - $R_{out} = \left(Re\left[\frac{C+D/q_{in}}{A+B/q_{in}}\right]\right)^{-1}$
  - $W_{out} = \sqrt{\frac{-\lambda}{\pi}\left(Im\left[\frac{C+D/q_{in}}{A+B/q_{in}}\right]\right)^{-1}}$
  - $\phi_{0,out} = \phi_{0,in} - \mathrm{Arg}[A + B(1/q_{in})]$

Properties of PITZ SASE FEL from WARP Simulation

Preliminary simulations including waveguide boundary conditions (performed by X.-K. Li)

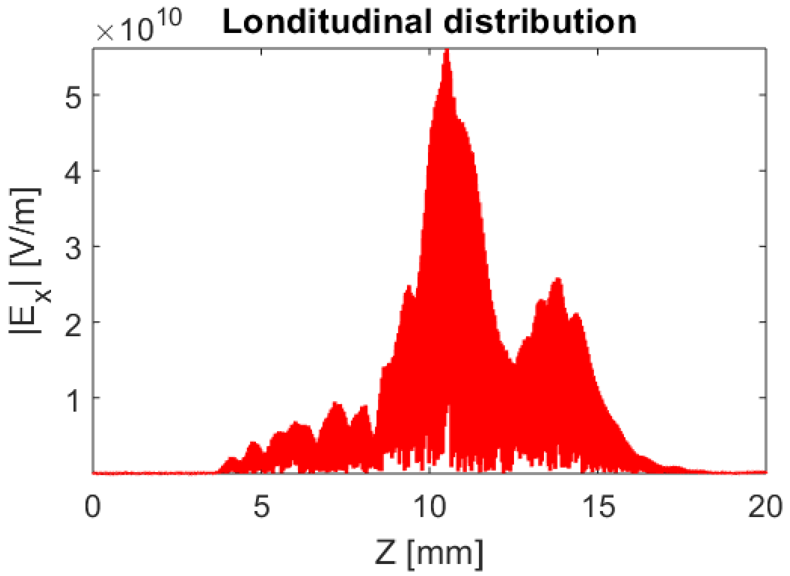


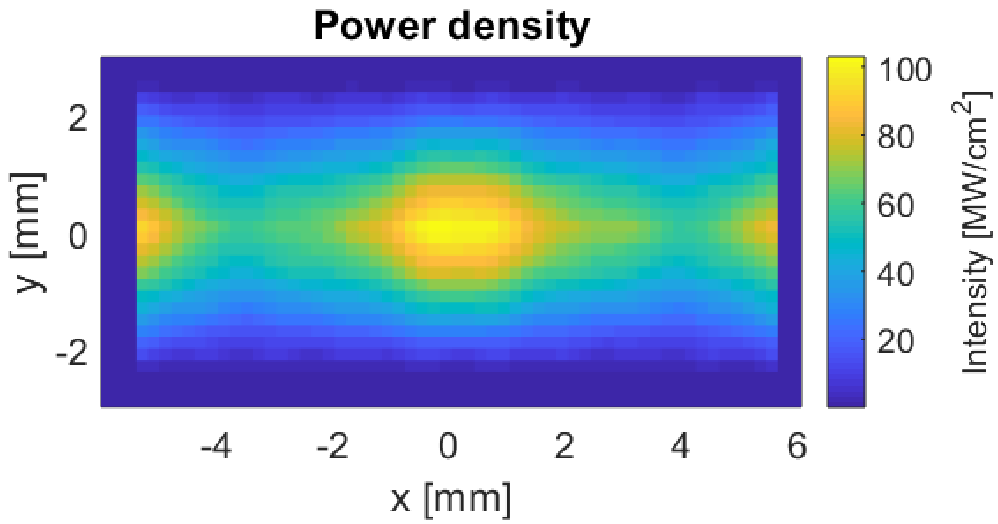




Properties of PITZ SASE FEL from WARP Simulation

Calculation of Gaussian beam parameters





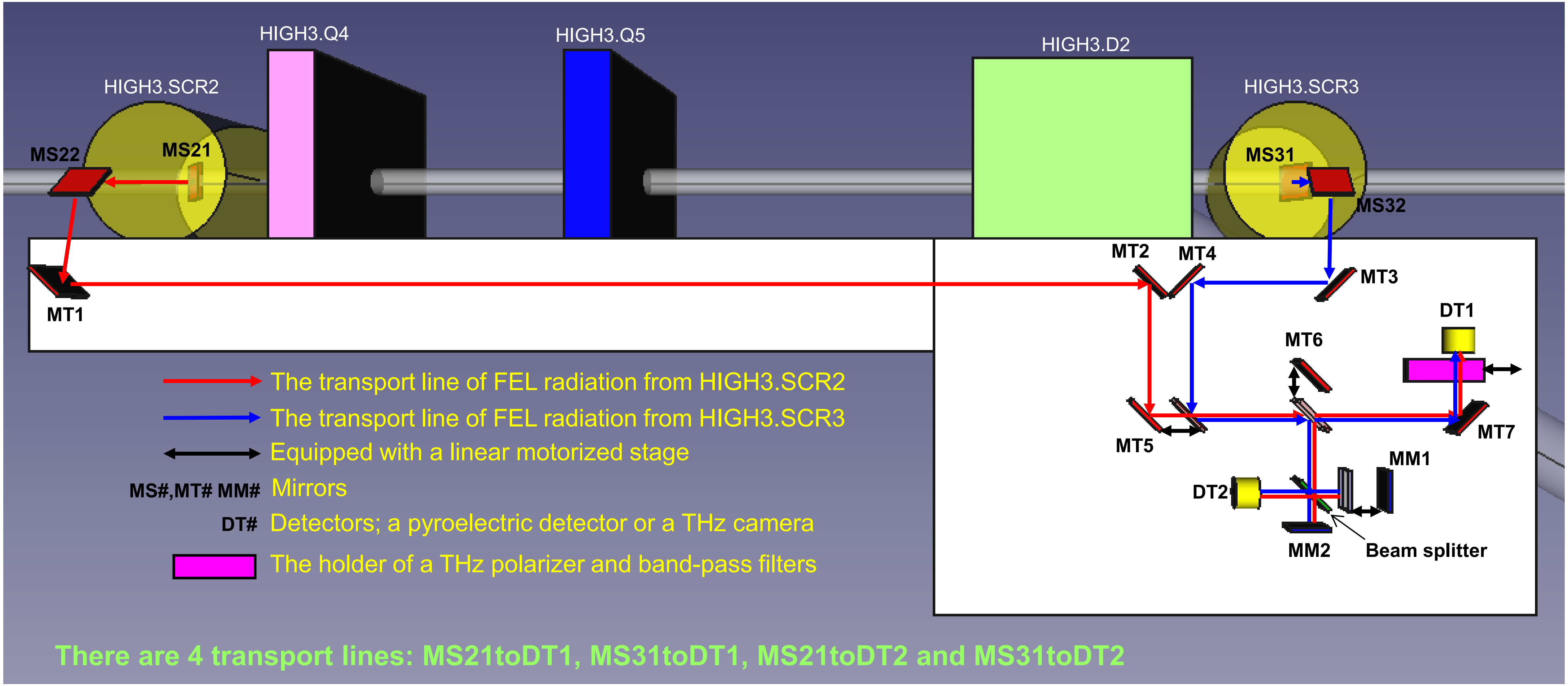
- The second moment method is used for the calculation

$$\sigma_u = \sqrt{\frac{\int_{-\infty}^{\infty}(u-u_0)^2 I(x,y)dx\,dy}{\int_{-\infty}^{\infty} I(x,y)dx\,dy}} \quad ; u = x, y$$

- Calculated parameters
  - σ_x = 3.072 mm, $W_{x0} = 2\sigma_x$=6.144 mm
  - σ_y = 0.996 mm, $W_{y0} = 2\sigma_x$=1.992 mm
- Assumed parameters
  - $z_{waist} = z_{undulator\ exit} = 0$
  - $\lambda = 100\ \mu m$

Optical Layout of the THz FEL Diagnostics system (Top view)

A preliminary layout for the design optimization



- 🟥 → The transport line of FEL radiation from HIGH3.SCR2
- 🟦 → The transport line of FEL radiation from HIGH3.SCR3
- ↔ Equipped with a linear motorized stage
- **MS#,MT# MM#** Mirrors
- **DT#** Detectors; a pyroelectric detector or a THz camera
- 🟪 The holder of a THz polarizer and band-pass filters

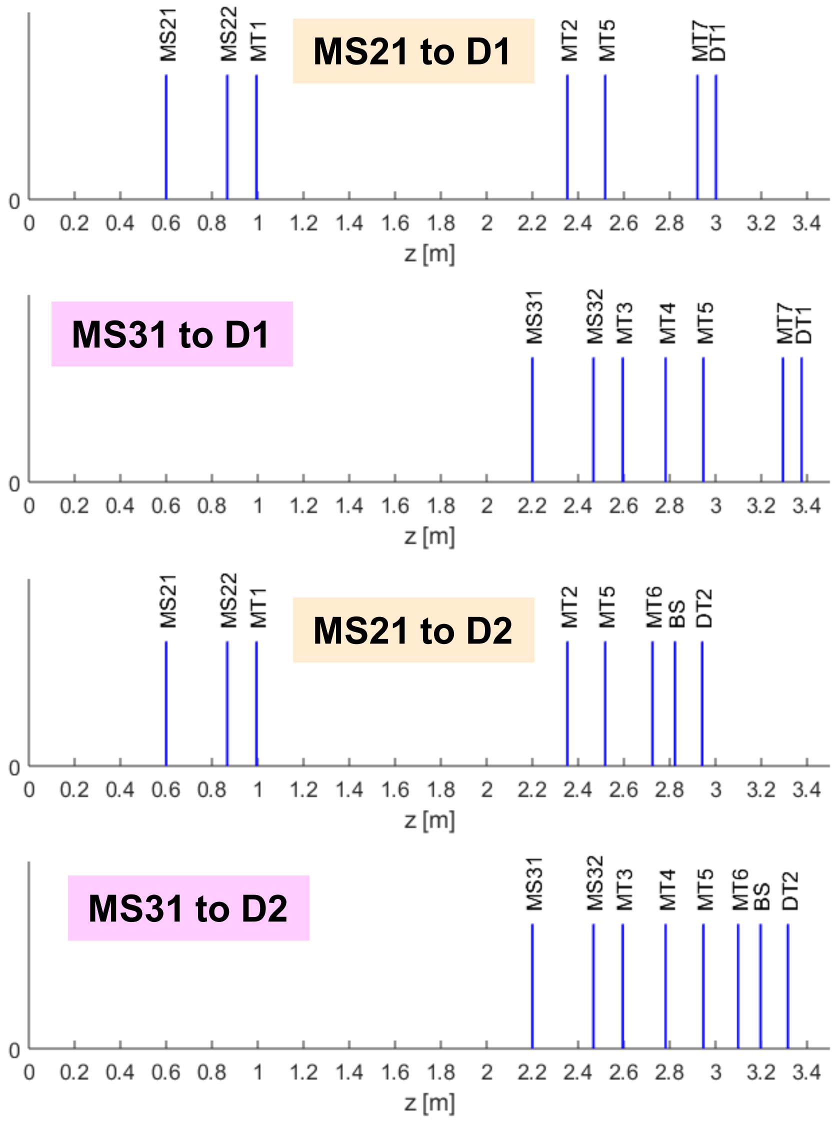
There are 4 transport lines: MS21toDT1, MS31toDT1, MS21toDT2 and MS31toDT2

Optical Layout of the THz FEL Diagnostics system

Positions [mm]

Components	HIGH3.SCR2 MS21 to D1	HIGH3.SCR3 MS31 to D1
Uexit	0	0
MS21	600	
MS22	867	
MS31		2200
MS32		2467
MT1	995	
MT2	2353	
MT3		2595
MT4		2782
MT5	2518	2947
MT7	2921	3295
DT1	3002	3376

Components	HIGH3.SCR2 MS21 to D2	HIGH3.SCR3 MS21 to D2
Uexit	0	0
MS21	600	
MS22	867	
MS31		2200
MS32		2467
MT1	995	
MT2	2353	
MT3		2595
MT4		2782
MT5	2518	2947
MT6	2725	3099
Beam splitter	2823	3197
DT2	2942	3316

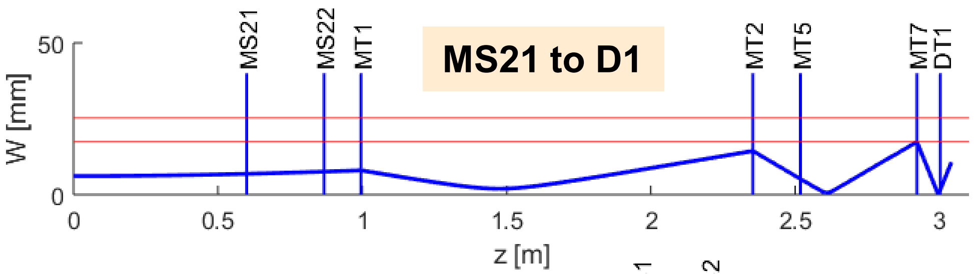


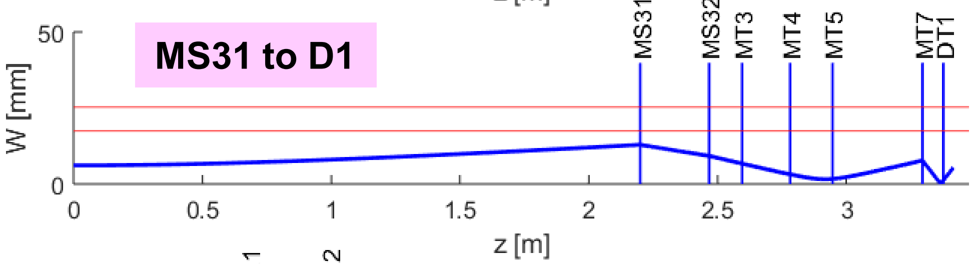
Gaussian Beam Propagation of the FEL

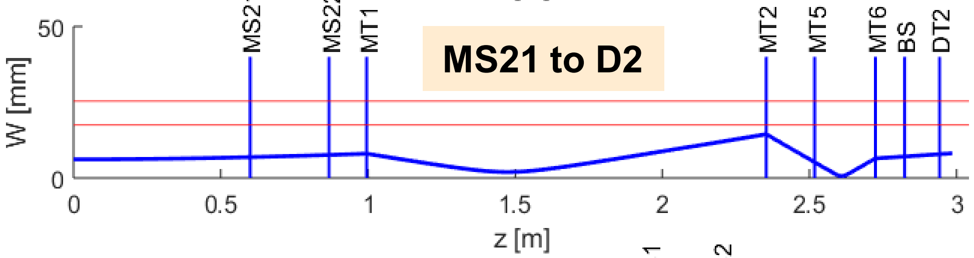
Horizontal axis (x-axis)

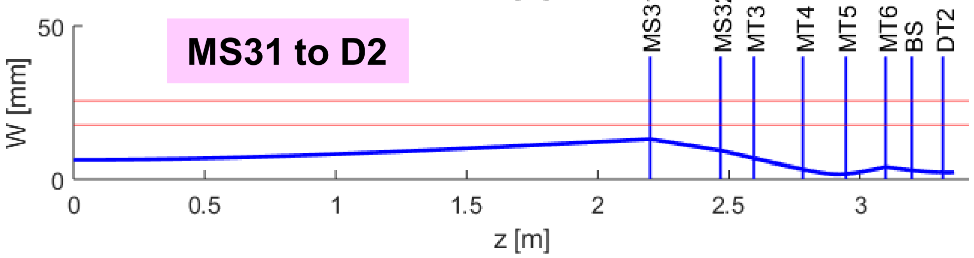
- Calculate the beam propagation with flat mirrors and thin lenses.
- $W_{x0} = 2\sigma_x$ = 6.144 mm
- $z_{waist} = z_{undulator\ exit} = 0$
- $\lambda = 100\ \mu m$
- Optimized focal length of each component

Components	f (m)
MS21	0
MS22	0
MS31	0.7
MS32	1.5
MT1	0.42
MT2	0.2
MT3	0
MT4	0
MT5	0
MT6	0.13
MT7	0.06







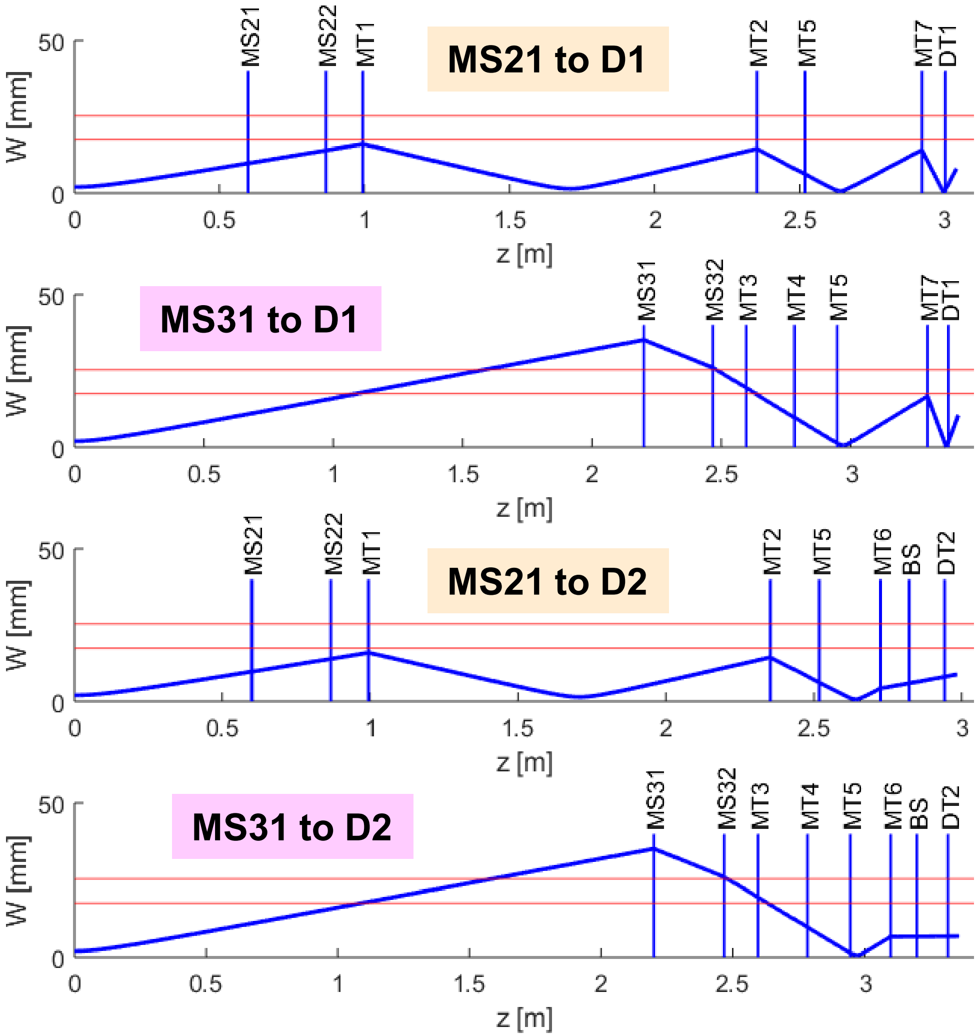


Gaussian Beam Propagation of the FEL

Vertical axis (y-axis)

- Calculate the beam propagation with flat mirrors and thin lenses.
- $W_{y0} = 2\sigma_y$ = 1.992 mm
- $z_{waist} = z_{undulator\ exit} = 0$
- $\lambda = 100\ \mu m$
- Optimized focal length of each component

Components	f (m)
MS21	0
MS22	0
MS31	0.7
MS32	1.5
MT1	0.42
MT2	0.2
MT3	0
MT4	0
MT5	0
MT6	0.13
MT7	0.06



Summary and Outlook

Summary

- Layout of the THz diagnostics system for the PTZ SASE FEL is presented.
- Calculations of FEL beam propagation for the THz diagnostics system of the PTZ SASE FEL have been performed.
- For the case of HIGH3.Scr3, the FEL beam size is larger than the beam pipe before it reaches the coupler mirror.

Outlook

- Change coordinates of the electron beamline?
- Continue the studies with the Gaussian propagation method
  - Thin lens ➔ Toroidal mirror or parabolic mirror
  - Including phase and wave front into the studies
- Verify the studies results with EMW simulation codes ➔ SRW(ESRF) ➔ ZEMAX
- Finalize the hardware design
  - Screen stations: HIGH3.Scr2 and HIGH3.Scr3
  - Optical table
  - Components: optics, THz detectors and motorized stages
  - Cables pulling
  - Control GUI, measurement scripts