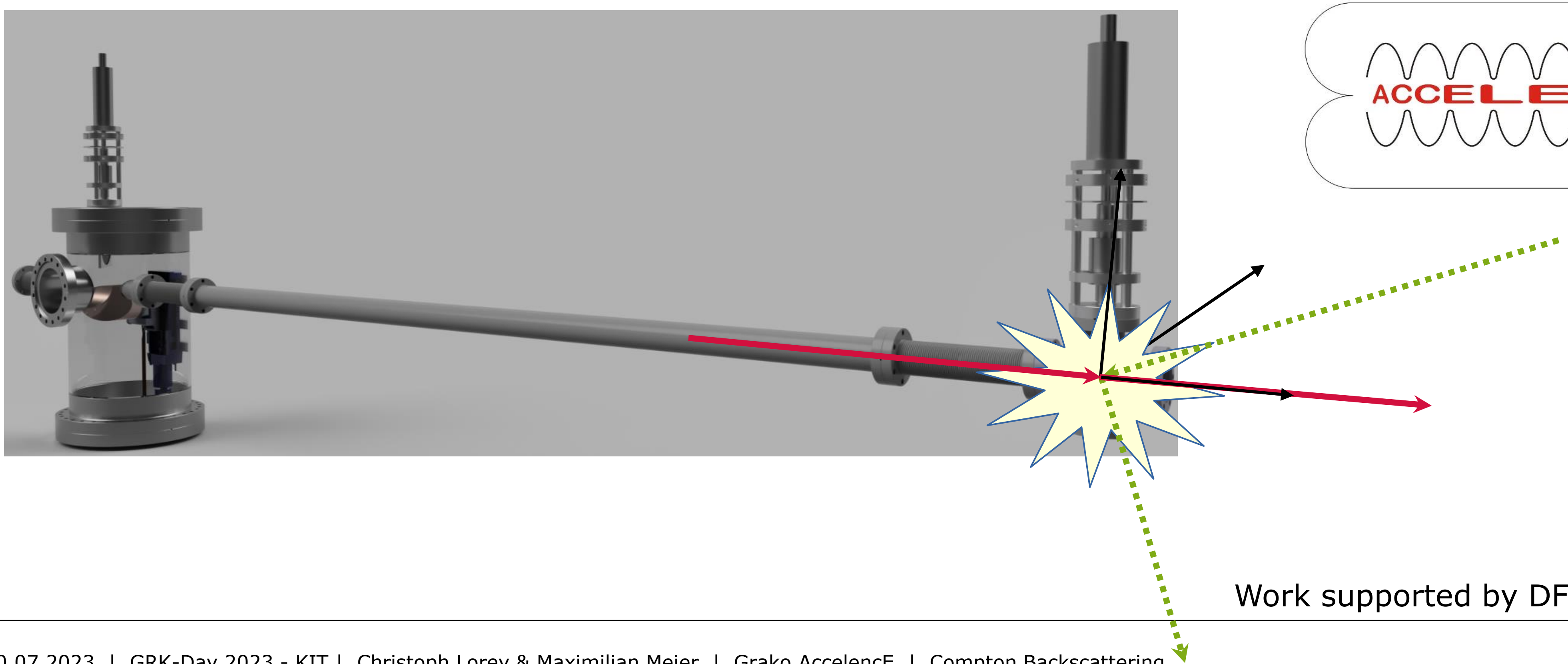
Compton backscattering

GRK-Day - 2023 KIT



Work supported by DFG through GRK 2128

Compton Backscattering used for…

Bright, monochromatic and tunable X-Ray (to γ Ray) sources of very small size

Near future:

Electron Beam Diagnostics

- ❖Non-destructive detection
- ❖Energy and energy spread
- ❖ERL with LCB development

Far future:

Photo Nuclear Reactions

- ❖Investigation of nuclear structure and cross-sections
- ❖Nuclear resonance fluorescence
- ❖Photo-Fission

+

Material & Biomedical Science

- ❖Brilliant light source at TU Darmstadt
- ❖Crystallography microscopic radiography…

Compton Backscattering – Photon Energy

Scattered photon gains energy

Higher photon energy preferred

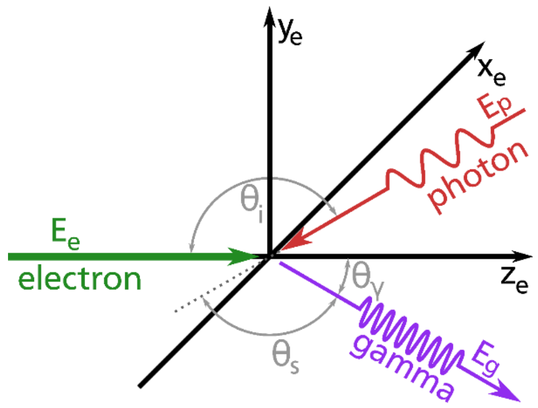
Scattered photon energy

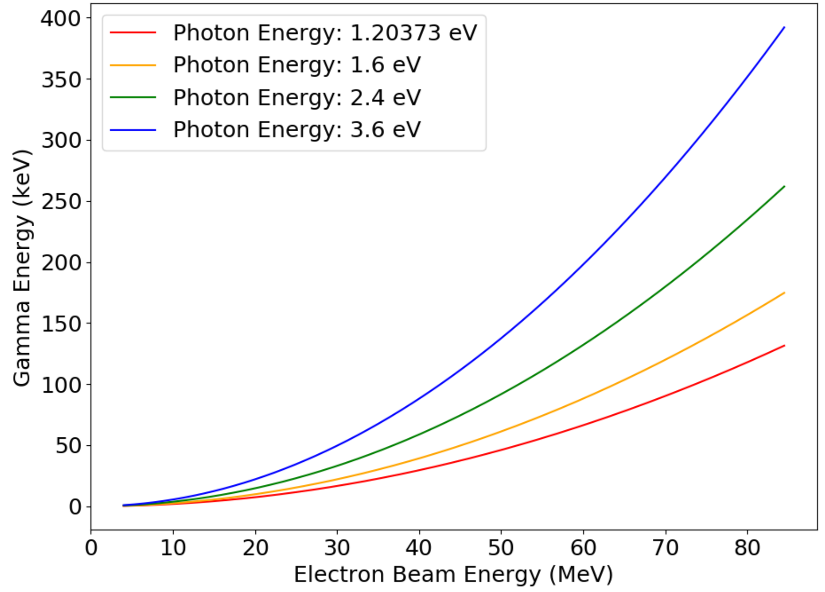
$$E_{ph} = \frac{(1 - \beta\cos(\Theta_i))E_L}{(1 - \beta\cos(\Theta_\gamma)) + (1 - \cos(\Theta_s))(E_L/E_e)}$$

$$E_{ph}^{max} = \frac{4\gamma^2 E_L}{1 + 4\gamma^2(E_L/E_e)}$$

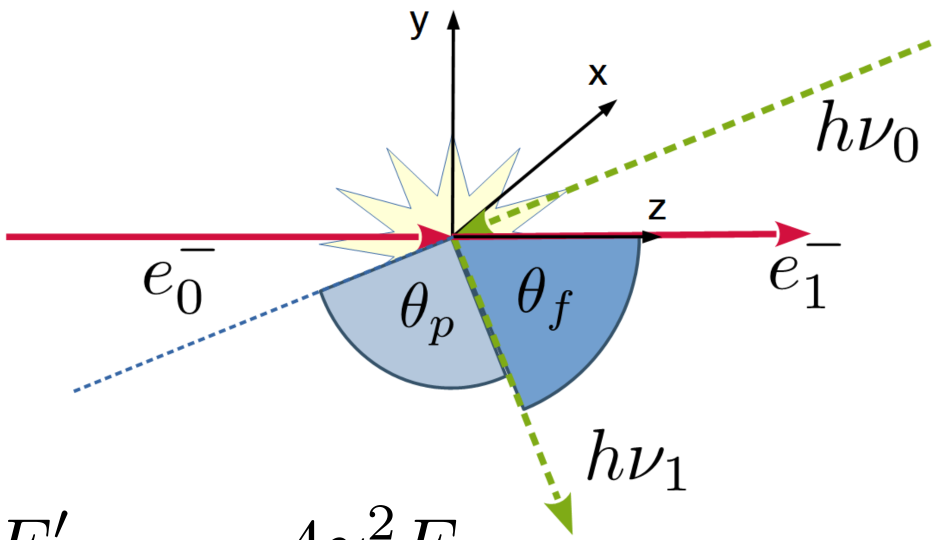
$$\gamma = E_e/(m_e c^2)$$

Lorentz boost $4\gamma^2$ of scattered photon energy





Compton/Thomson Backscattering - Recoil



$$E'_{ph,m} = 4\gamma^2 E_{ph}$$

ϑ : observation angle of scattered photon in lab reference system

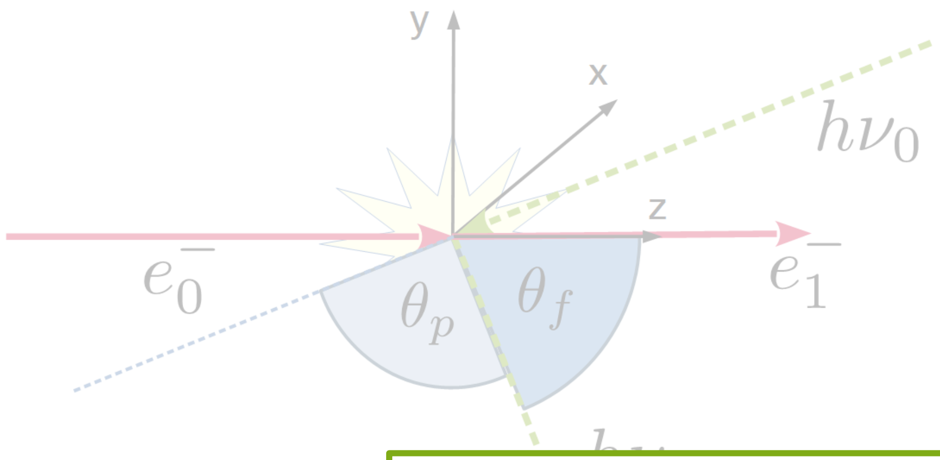
Thomson cross-section is very low:

$$\sigma_T = \frac{8\pi}{3} r_e^2 \simeq 6.6525 \cdot 10^{-29} m^2$$

3D Recoil factor : $\Delta \equiv \frac{2h\nu_0\gamma}{m_e c^2} + \frac{2\hbar c^2}{m_e^2 c^4}\left(k_x P_x + k_y P_y + k_z P_z\right)$

electron & photon 3D-momenta

Compton/Thomson Backscattering - Recoil



ϑ : observation angle of scattered photon in lab reference system

Thomson cross-section is very low:

$$\frac{8\pi}{3} r_e^2 \simeq 6.6525 \cdot 10^{-29} m^2$$

$$E'_{ph,m} = 4\gamma^2 \ldots$$

$$E_{cm} = E_e^* + h\nu^* = m_e c^2 \sqrt{1 + \Delta}$$

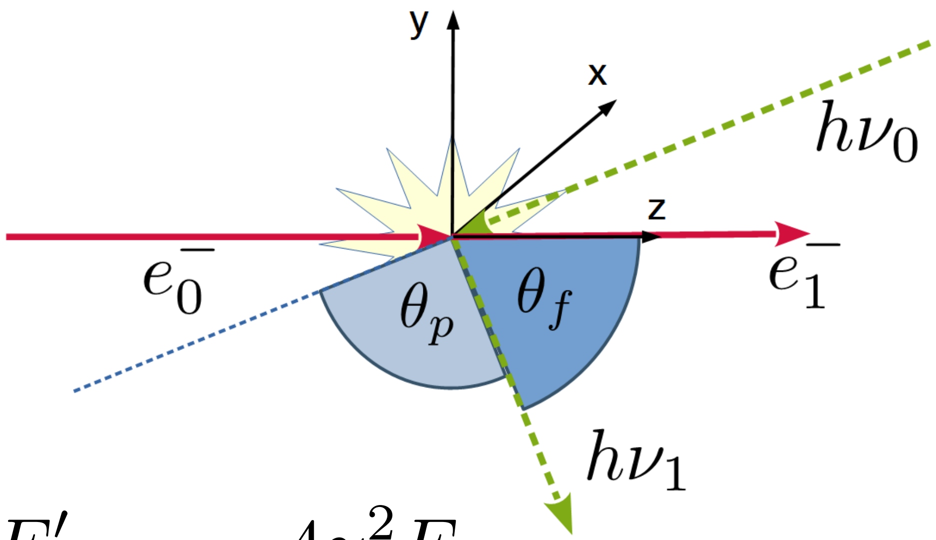
3D Recoil factor : $\Delta \equiv \frac{2h\nu_0\gamma}{m_e c^2} + \frac{2\hbar c^2}{m_e^2 c^4}(k_x P_x + k_y P_y + k_z P_z)$

electron & photon 3D-momenta

Compton/Thomson Backscattering - Recoil

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

TECHNISCHE UNIVERSITÄT DARMSTADT



$$E'_{ph,m} = 4\gamma^2 E_{ph}$$

ϑ : observation angle of scattered photon in lab reference system

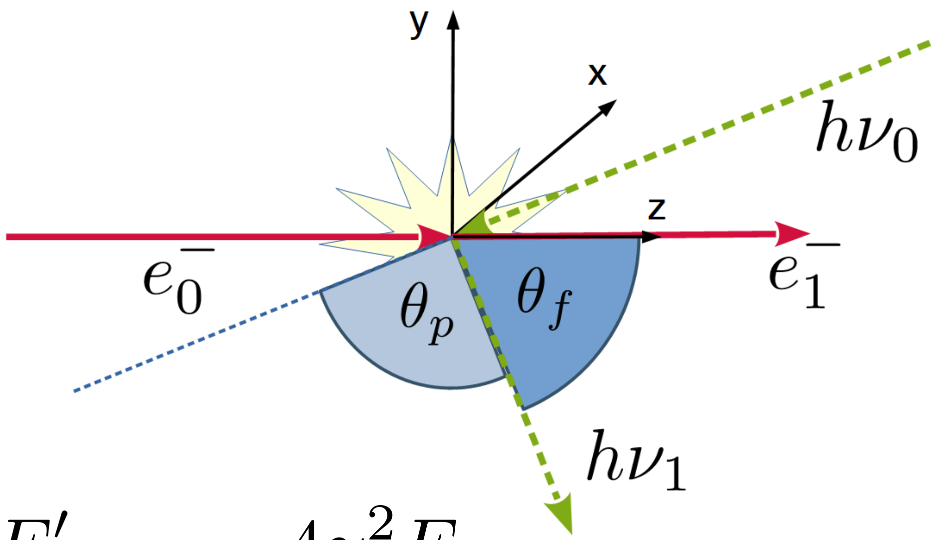
Thomson cross-section is very low:

$$\sigma_T = \frac{8\pi}{3} r_e^2 \simeq 6.6525 \cdot 10^{-29} m^2$$

3D Recoil factor : $$\Delta \equiv \frac{2h\nu_0\gamma}{m_e c^2} + \frac{2\hbar c^2}{m_e^2 c^4} \left(k_x P_x + k_y P_y + k_z P_z\right)$$

electron & photon 3D-momenta

Compton/Thomson Backscattering - Recoil



$$E'_{ph,m} = 4\gamma^2 E_{ph}$$

ϑ : observation angle of scattered photon in lab reference system

Thomson cross-section is very low:

$$\sigma_T = \frac{8\pi}{3} r_e^2 \simeq 6.6525 \cdot 10^{-29} m^2$$

3D Recoil factor : $$\Delta \equiv \frac{2h\nu_0\gamma}{m_e c^2} + \frac{2\hbar c^2}{m_e^2 c^4}\left(k_x P_x + k_y P_y + k_z P_z\right)$$

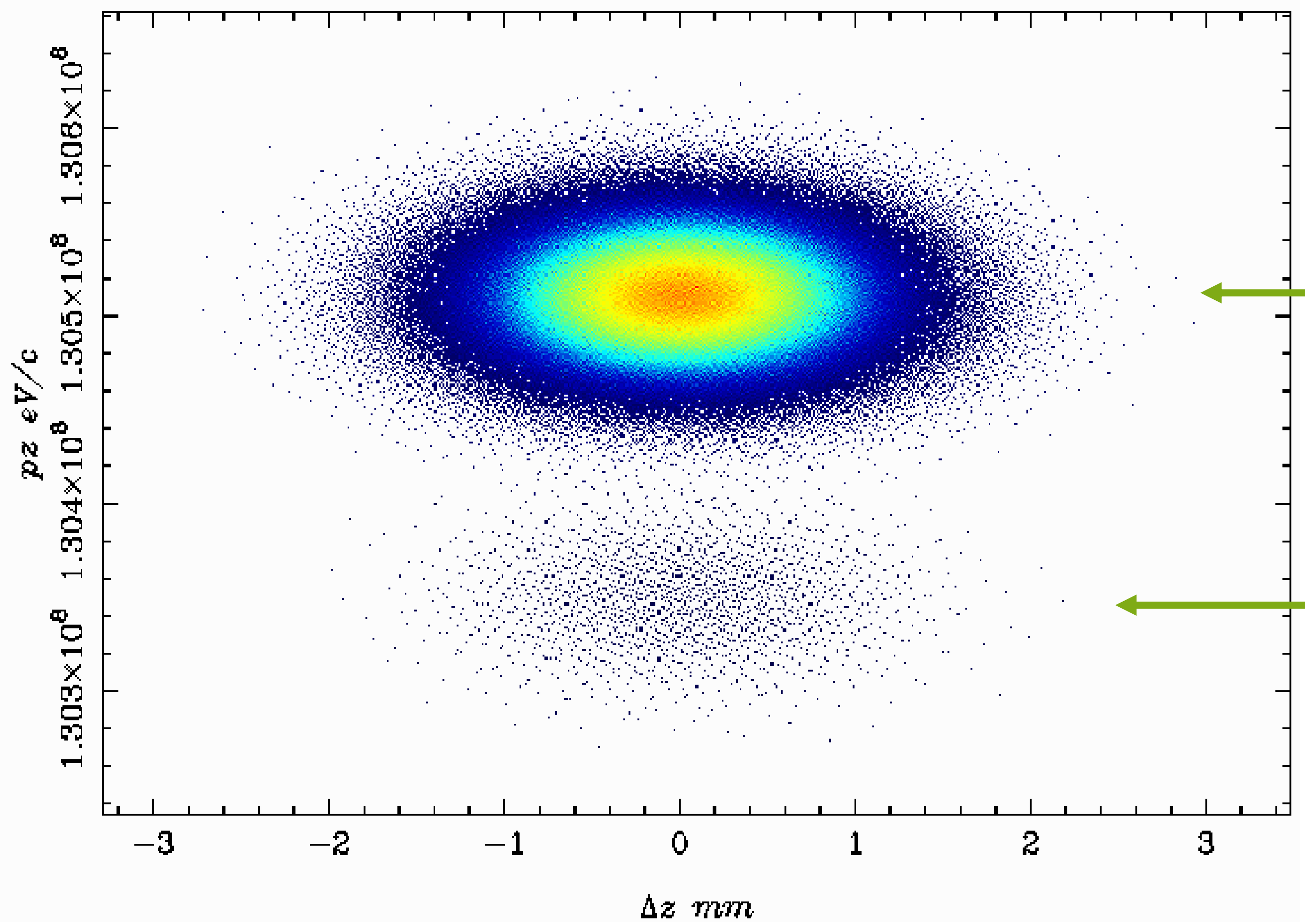
recoil examples:

$E_{e,0} = 105\mathrm{MeV}, E_{ph,0} = 1.20\mathrm{eV} \Rightarrow \Delta \approx 0.0019$ for $E_{ph,m} \approx 205\mathrm{keV}$

$E_{e,0} = 155\mathrm{MeV}, E_{ph,0} = 1.20\mathrm{eV} \Rightarrow \Delta \approx 0.0029$ for $E_{ph,m} \approx 445\mathrm{keV}$

$E_{e,0} = 155\mathrm{MeV}, E_{ph,0} = 4.38\mathrm{eV} \Rightarrow \Delta \approx 0.0104$ for $E_{ph,m} \approx 1.623\mathrm{MeV}$

Impacted Electron Phase Space



$\bar{E}_e \approx 130.511$ MeV

$\bar{E}_e \approx 130.197$ MeV

Q_{bunch} = 0.77 pC

mn_e = 2000

θ = 0

λ = 1030 nm

E_e = 130 MeV

E_{ph} ≈ 1.2037 eV

E'_{ph} ≈ 313.323 keV

$\sigma_{th} \approx 6.6525 \cdot 10^{-29} m^2$

Δ ≈ 0.0024

Compton Backscattering - Flux

Flux | $F = \sigma_T L$ | $\sigma_T = 66.5\ \text{fm}^2$, $\nu h \ll mc^2$

Luminosity

$$L = \frac{f N_e N_L \cos(\varphi/2)}{2\pi\sqrt{\sigma_{e,y}^2 + \sigma_{L,y}^2}\sqrt{(\sigma_{e,x}^2 + \sigma_{L,x}^2)\cos^2(\varphi/2) + (\sigma_{e,z}^2 + \sigma_{L,z}^2)\sin^2(\varphi/2)}}$$

$\varphi = \Theta_i - \pi$

→ Head-On

$$L = \frac{f N_e N_L}{2\pi(\sigma_e^2 + \sigma_L^2)}$$

Higher photon energy preferred

→ Head-On Collision

- For higher Energy
- Easier overlap

→ High Laser Pulse Energy (N_L)

→ High scattering frequency (f)

→ Small beam size at IP

Relative bandwidth

$$\frac{\Delta E_{ph}}{E_{ph}} \geq \sqrt{2\left(\frac{\sigma_{\Delta E_e}}{E_e}\right)^2 + \left(\frac{\varepsilon_n}{\sigma_e}\right)^4 + \left(\frac{\sigma_{\Delta E_L}}{E_L}\right)^2 + \left(\frac{M^2\lambda}{2\pi\omega_0}\right)^4}$$

Higher photon energy preferred

Head-On Collision

- For higher Energy
- Easier overlap

High Laser Pulse Energy (N_L)

High scattering frequency (f)

Small beam size at IP

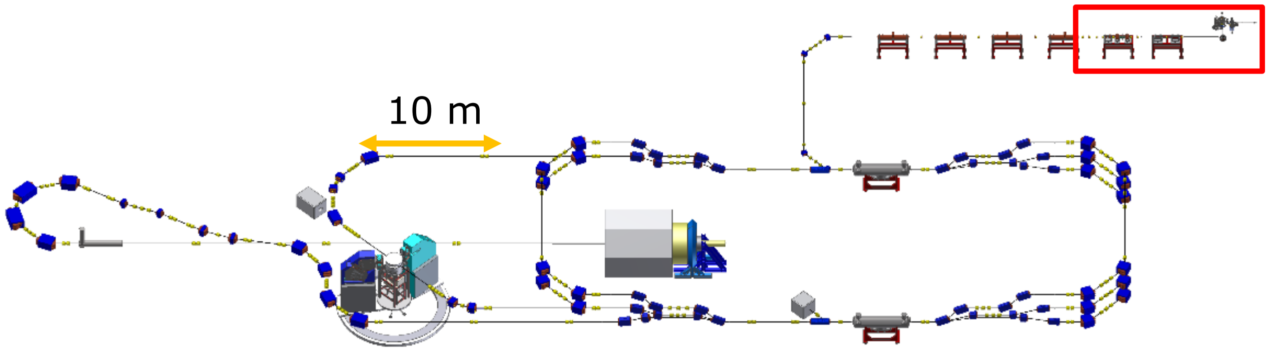
Low M^2

Low $\sigma_{\Delta E_p}$; $\frac{\sigma_{\Delta E_L}}{E_L} \leq \frac{\sigma_{\Delta E_e}}{E_e}$

R. Hajima et al., Phys. Rev. Accel. Beams 19, 020702 (2016)

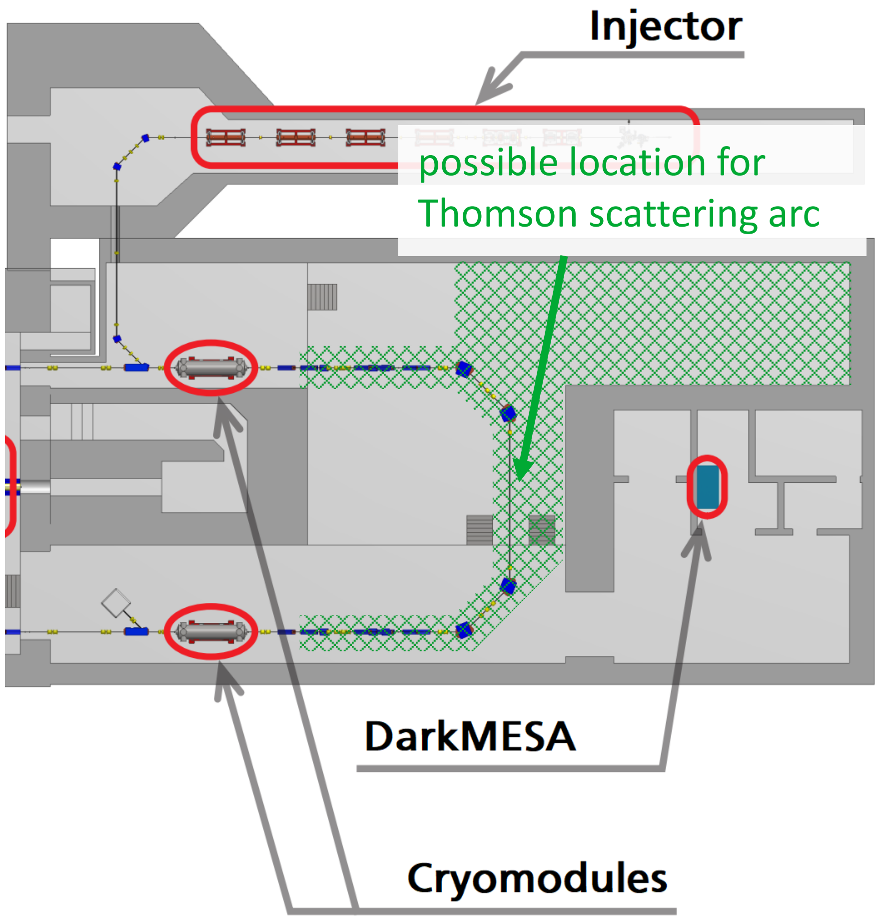
Thomson Backscattering at MESA

Mainz **E**nergy-recovering **S**uperconducting **A**ccelerator **MESA**



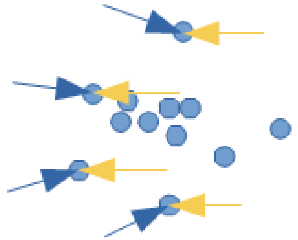
Courtesy of D. Simon

- MESA can generate electron beams up to 105-155 MeV
- 0.77 (7.7) pC bunch charge at 1300 MHz RF-frequency
- can run in Energy Recovery (ER) or External Beam (EB) mode
- spin polarization of the electron beam available at lower beam current of 150µA instead of 1mA



Sampling scheme as currently under development

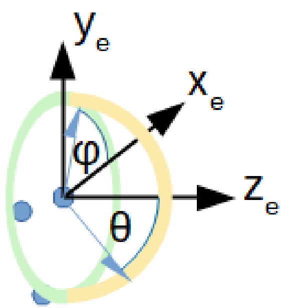
initial (macro) electron distribution



determine which electrons scatter with total Thomson cross section dependent on 4D recoil factor:

$$\sigma_{tot} = \frac{2r_e^2}{\Delta}\left[\left(1 - \frac{4}{\Delta} - \frac{8}{\Delta^2}\right)\log(1+\Delta) + \frac{1}{2} + \frac{8}{\Delta} - \frac{1}{2(1+\Delta)^2}\right]$$

only scattering electrons

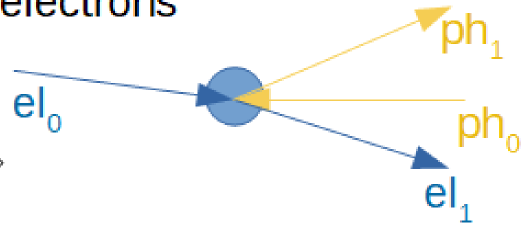


select direction of scattered photon momentum with polarized angular Thomson cross section:

$$\frac{d\sigma}{d\Omega} = (1/2)\,(1,\mathbf{Q})\,T\begin{pmatrix} I \\ \mathbf{P} \end{pmatrix}$$ (1)

random σ-weighted single combination selection of θ-φ-grid

only scattering electrons



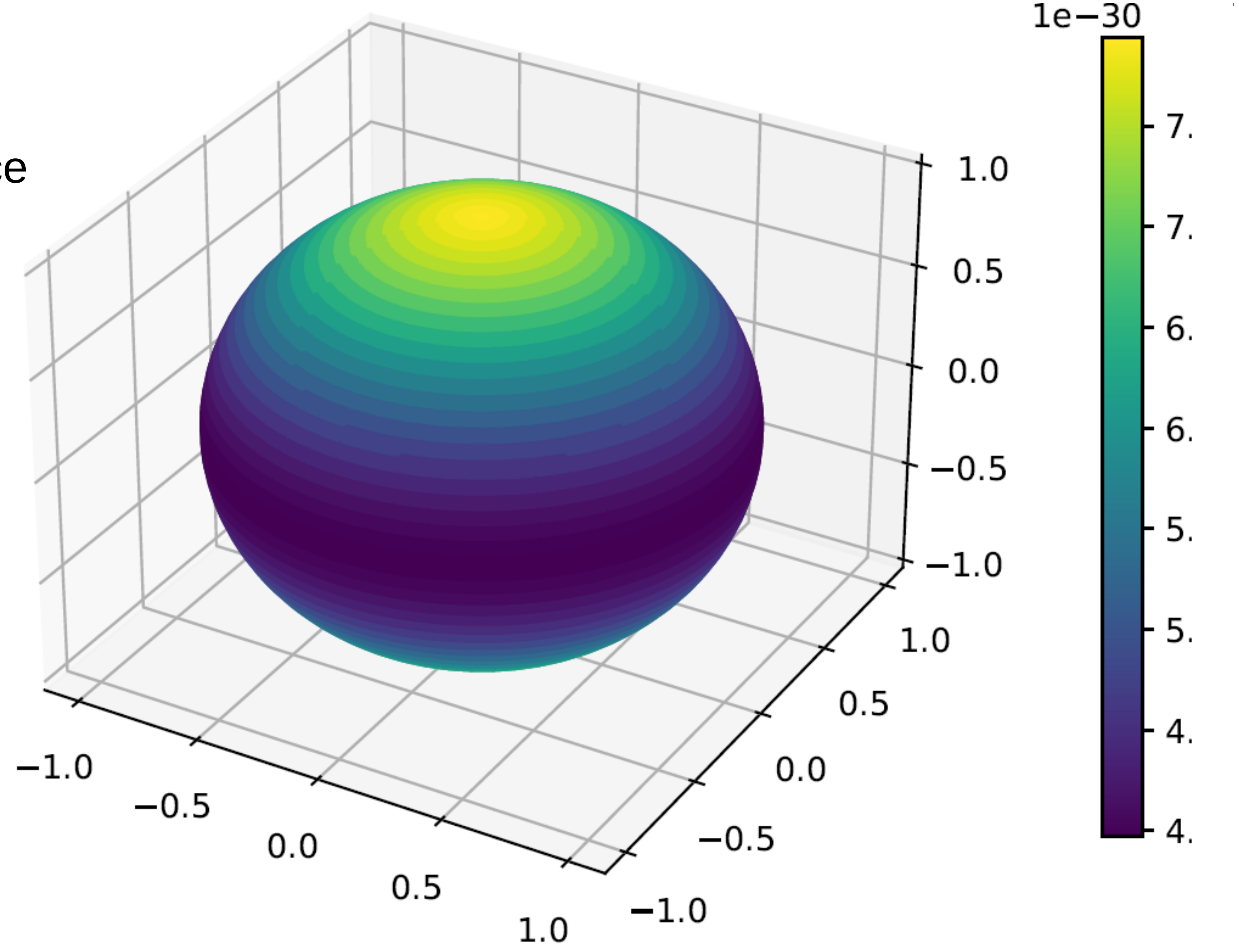
perform relativistic 4D collision under chosen scattering angle:

$$\begin{bmatrix} E^*_{ph} \\ k^*_x \\ k^*_y \\ k^*_z \end{bmatrix} = \begin{bmatrix} \frac{m_e c^2 \Delta}{2\sqrt{1+\Delta}} \\ E^*_{ph}\sin\theta^*_{ph}\cos\phi^*_{ph} \\ E^*_{ph}\sin\theta^*_{ph}\sin\phi^*_{ph} \\ E^*_{ph}\cos\theta^*_{ph} \end{bmatrix}$$

(1): William H. McMaster, American Journal of Physics 22, 351 (1954)

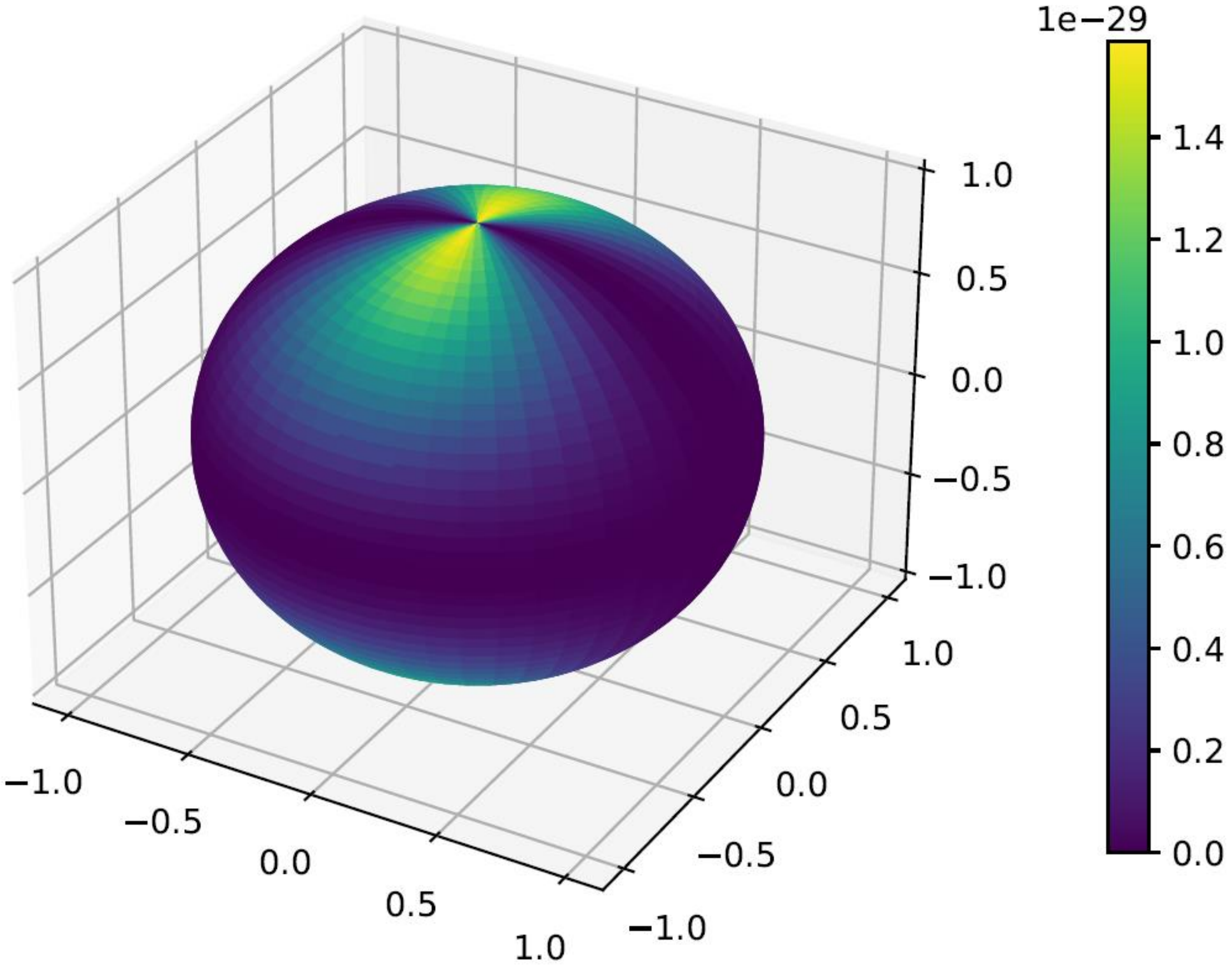
Results of Comparse

Cross-section
in 3D
electron rest frame space



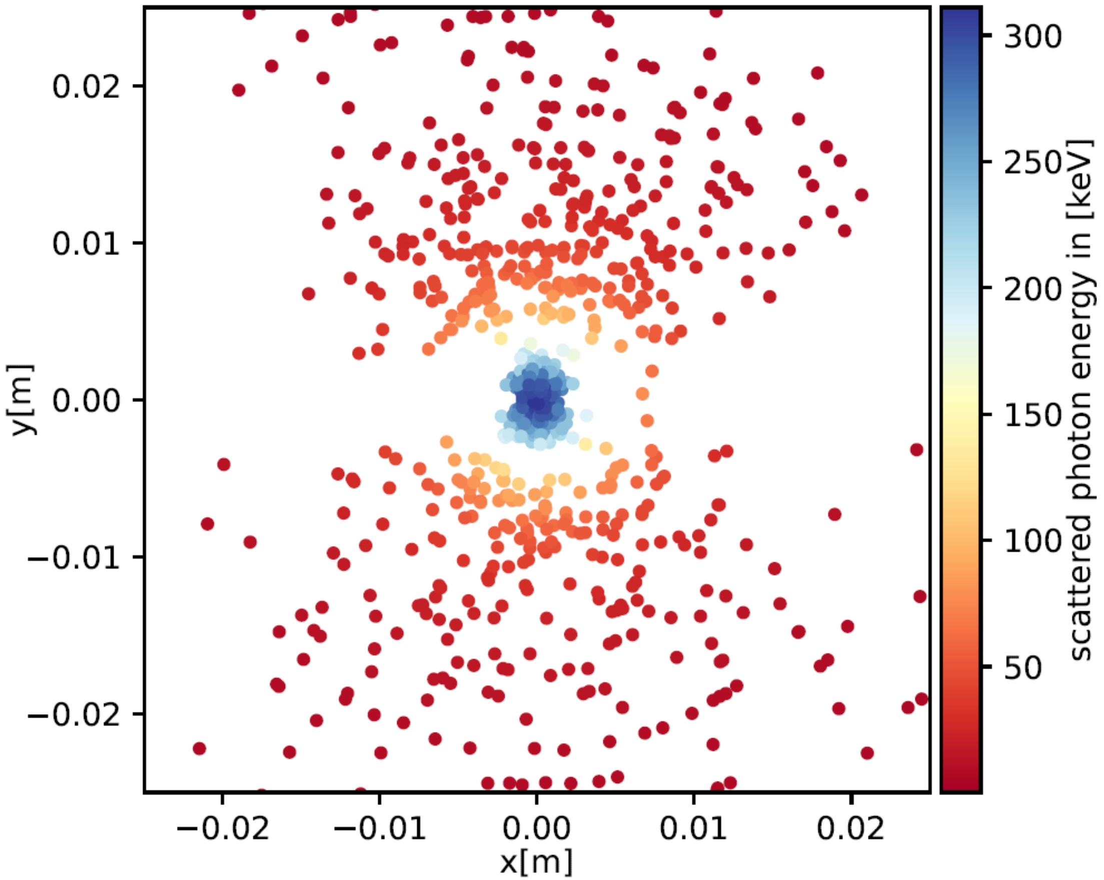
Results of Comparse

Polarized (fully linear)
cross-section
in 3D
electron rest frame space

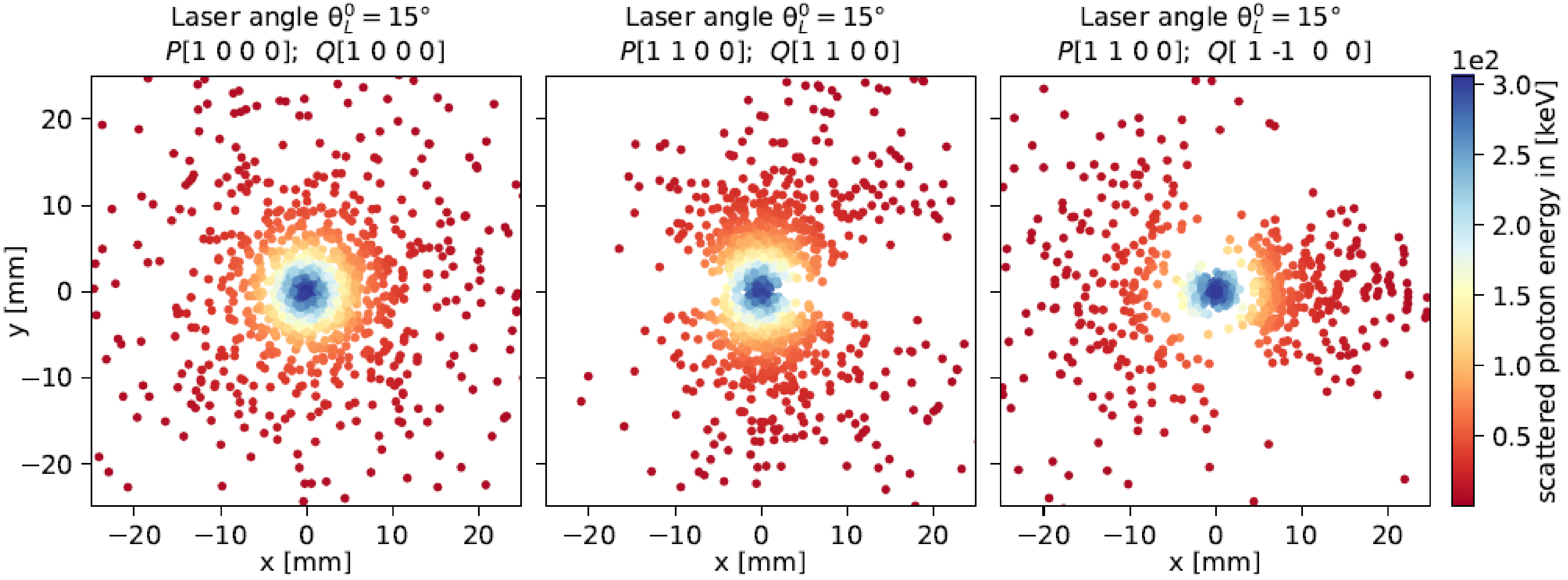


Results of Comparse

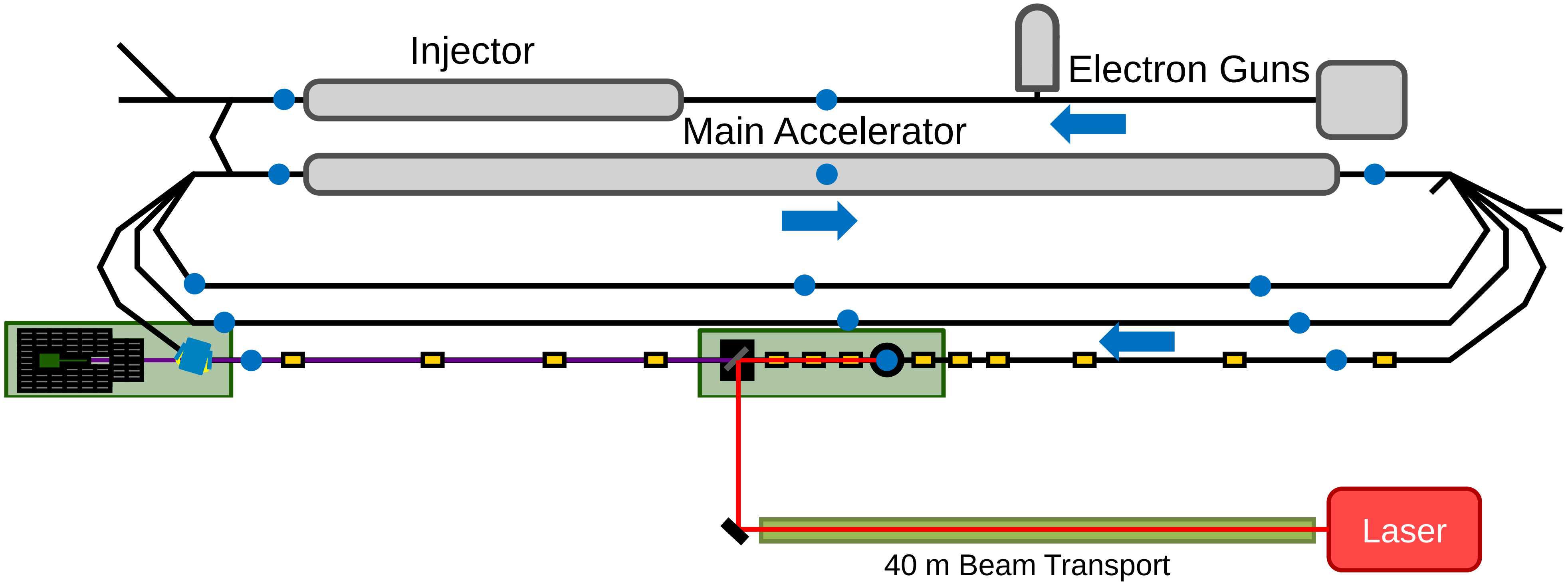
Polarized (fully linear)
scattered photons
on screen



Results of Comparse



Laser Compton Backscattering @ S-DALINAC



Higher photon energy preferred

Head-On Collision ✓

- For higher Energy
- Easier overlap

High Laser Pulse Energy (N_L)

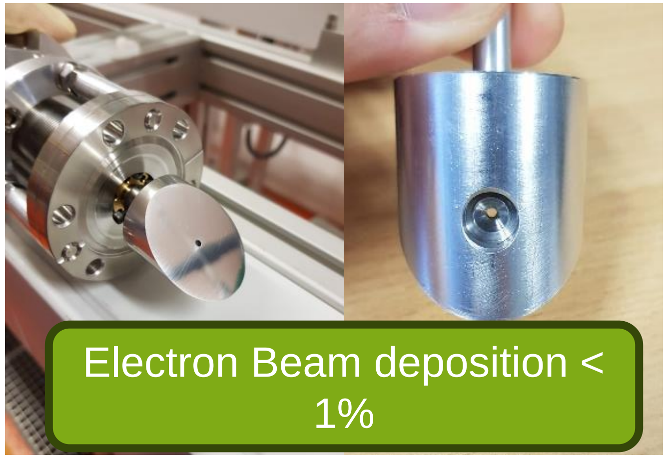
High scattering frequency (f)

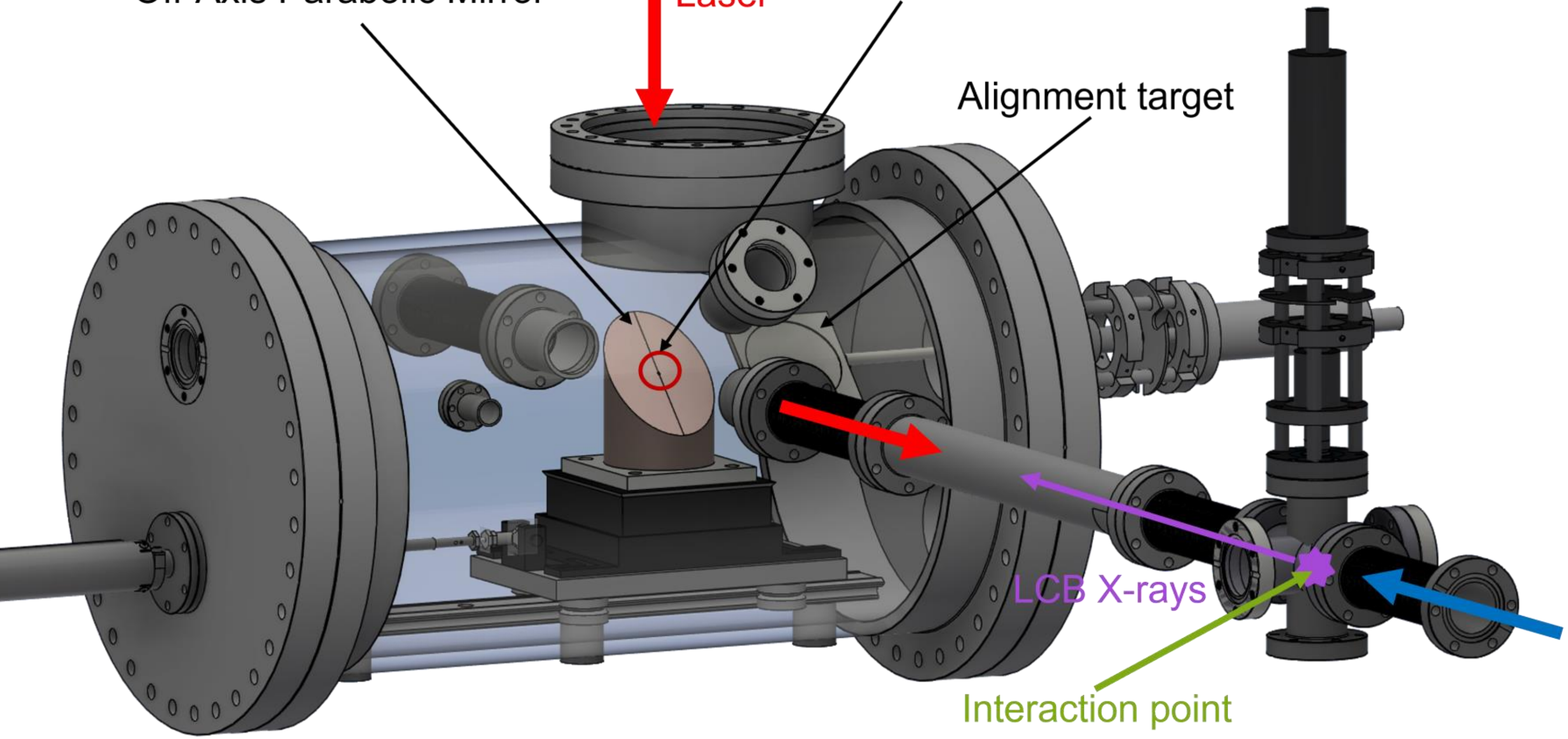
Small beam size at IP

Low M^2

Low $\sigma_{\Delta E_p}$; $\frac{\sigma_{\Delta E_L}}{E_L} \leq \frac{\sigma_{\Delta E_e}}{E_e}$

Coupling Chamber of LCB-Source





Laser System

Amplitude – Laser Tangor 100

- λ =1030 nm (Ytterbium)
- $\frac{\Delta\lambda}{\lambda} \sim 1 \cdot 10^{-3}$
- P_{avg} =100 W
- $E_{Pulse} \leq 0.5$ mJ
- f =200 kHz – 40MHz
- $M^2 < 1.3$
- $\sigma_z = 3$ ps

Higher Harmonic Generation

- SHG:
  $\lambda = 515$ nm
  $\eta > 50$ %
- THG:
  $\lambda = 343$ nm
  $\eta > 25$ %

Higher photon energy preferred

Head-On Collision ✓
- For higher Energy
- Easier overlap

High Laser Pulse Energy (N_L) ✓

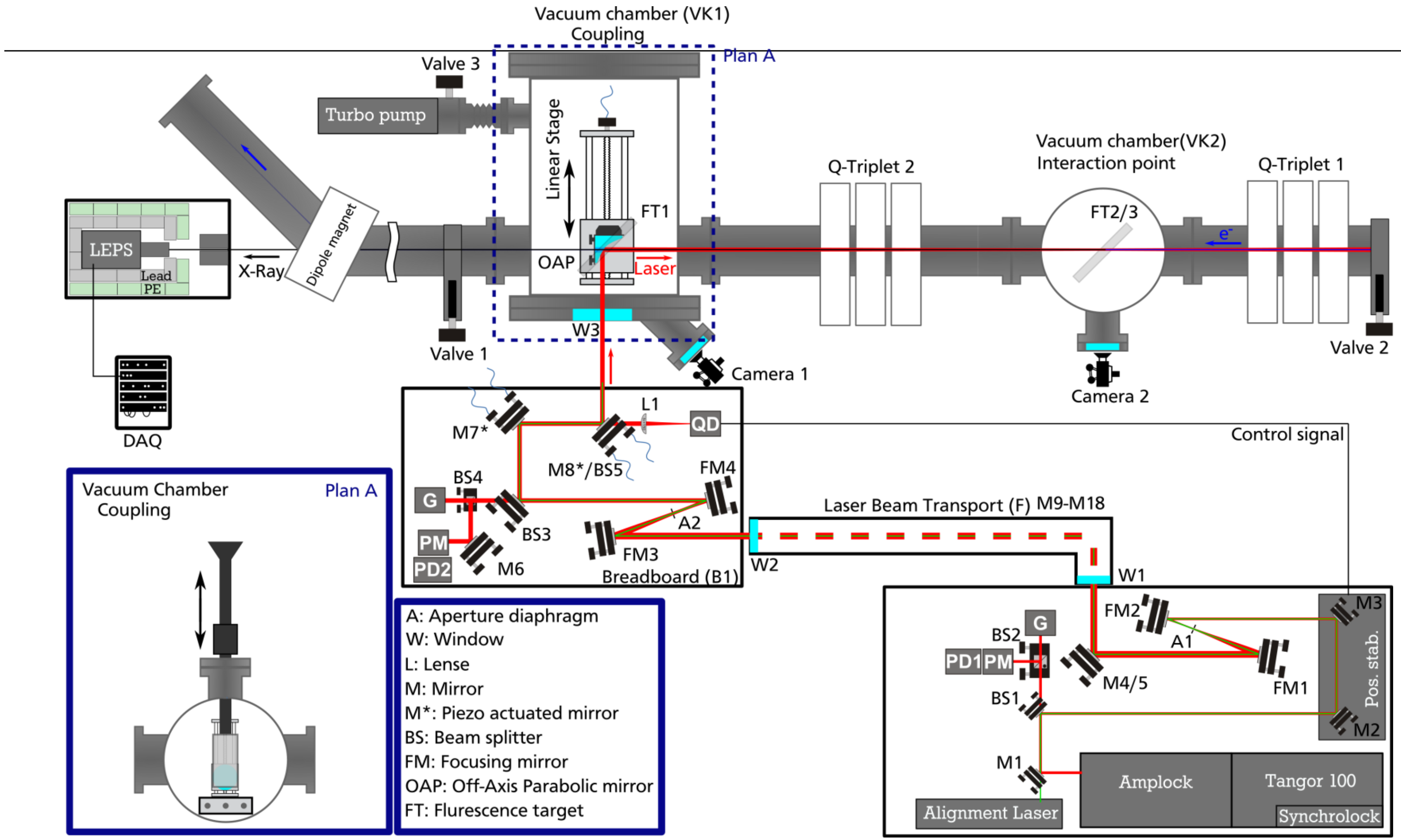
High scattering frequency (f) ✓

Small beam size at IP ✓

Low M^2 ✓

Low $\sigma_{\Delta E_p}$; $\frac{\sigma_{\Delta E_L}}{E_L} \leq \frac{\sigma_{\Delta E_e}}{E_e}$ ✓

Laser Beam Line



Higher photon energy preferred

Head-On Collision

- For higher Energy
- Easier overlap

High Laser Pulse Energy (N_L)

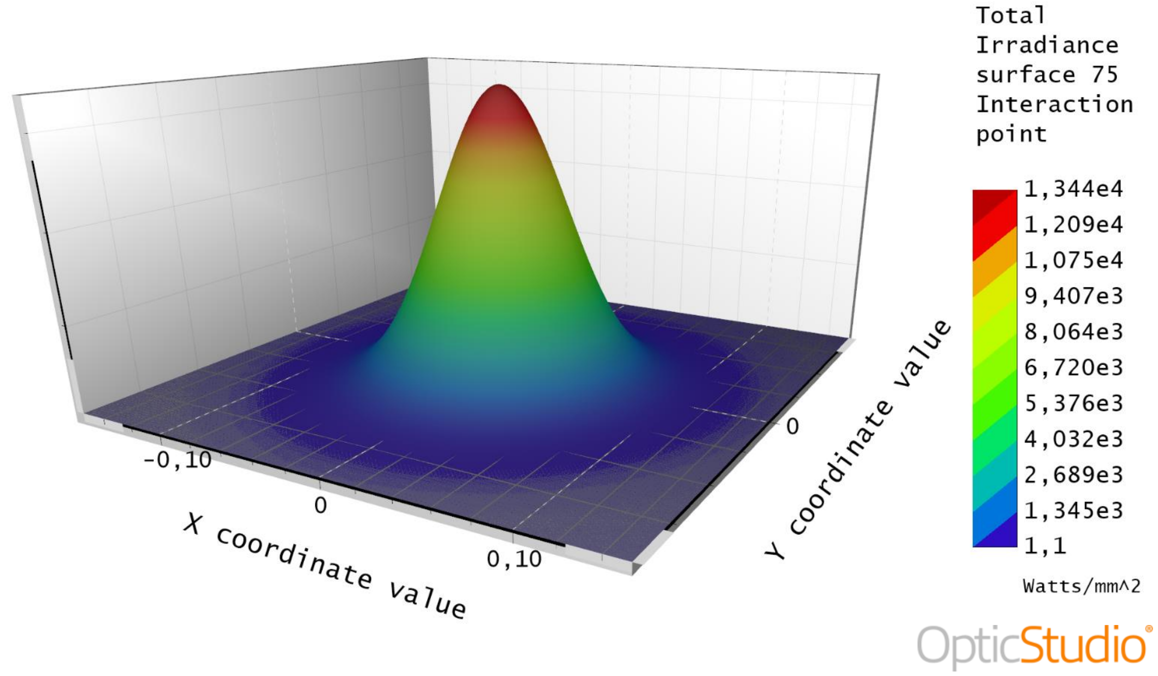
High scattering frequency (f)

Small beam size at IP

Low M^2

Low $\sigma_{\Delta E_p}$; $\frac{\sigma_{\Delta E_L}}{E_L} \leq \frac{\sigma_{\Delta E_e}}{E_e}$

Laser Beam Transport



Total Irradiance surface 75 Interaction point

Beam wavelength is 1,03000 µm in the media with index 1,00000 at 0,0000 (deg)
Display X Width = 3,0766E-01, Y Height = 3,0767E-01 Millimeters
Peak Irradiance = 1,3439E+04 Watts/Millimeters^2, Total Power = 9,8445E+01 Watts
Pilot: Size= 6,7106E-02, Waist= 5,3623E-02, Pos= 6,5988E+00, Rayleigh= 8,7703E+00

Simulation:

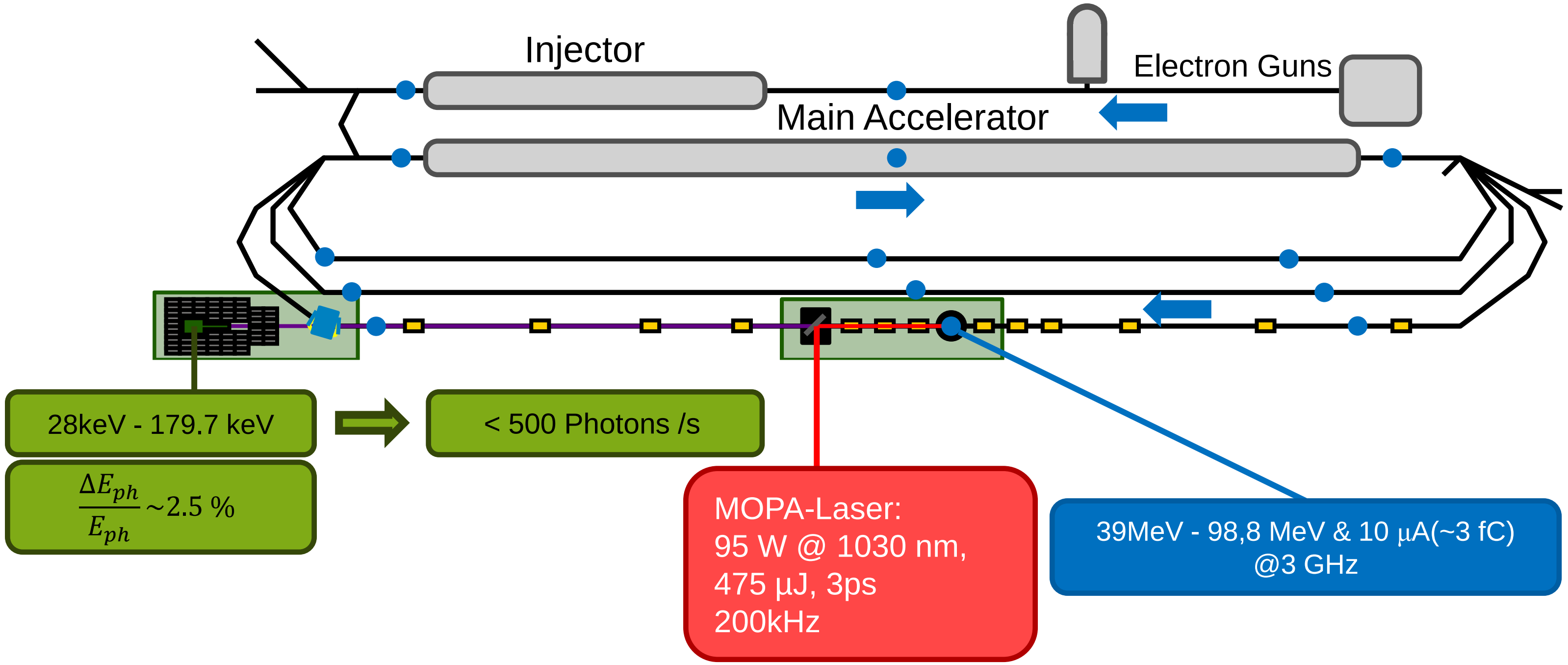
- Zemax OpticStudio
  - Physical optics propagation
- 40 m beam transport
- Telescopes and “relay imaging“
- Off-axis parabolic mirror with hole

Physical optics propagation @ IP:

- Total power: 94.5 W (100 W)
- Waist size: 53.6 µm (12 mm)
- Rayleigh length: 8.8 mm

Laser Compton Backscattering @ S-DALINAC

Parameters	Values
Electron Beam	
Electron Energy (E_e)	39 MeV – 98.8 MeV
Rel. Error of Electron Energy (ΔE_e)	$< 10^{-3}$
Beam Current (I)	10 µA
Beam normalized emittance	$5 \cdot 10^{-6}$ m rad
Electron Beam Size ($\sigma_{e,rms}$)	≤ 100 µm
Laser Beam	
Wavelength (λ)	1030 nm
Photon Energy (E_L)	1.2 eV
Error Photon Energy (ΔE_L)	$1 \cdot 10^{-3}$ eV
Pulse Energy (E_{pulse})	0.25 mJ
Repetition Rate (f_{rep})	200 kHz
Beam Size ($\sigma_{pulse,rms}$)	≤ 100 µm
Scattered Photon – Results for Head-On Collision	
Energy	28 keV – 179 keV
Min. rel. Energy Bandwidth, FWHM	0.7 %
Total Flux	$6 \cdot 10^3$ Ph/s
Spectral Flux at min. Bandwidth	38 Ph/s



Background Measurement @S-DALINAC

Measurement

Maximum Electron Beam Energy:
85 MeV

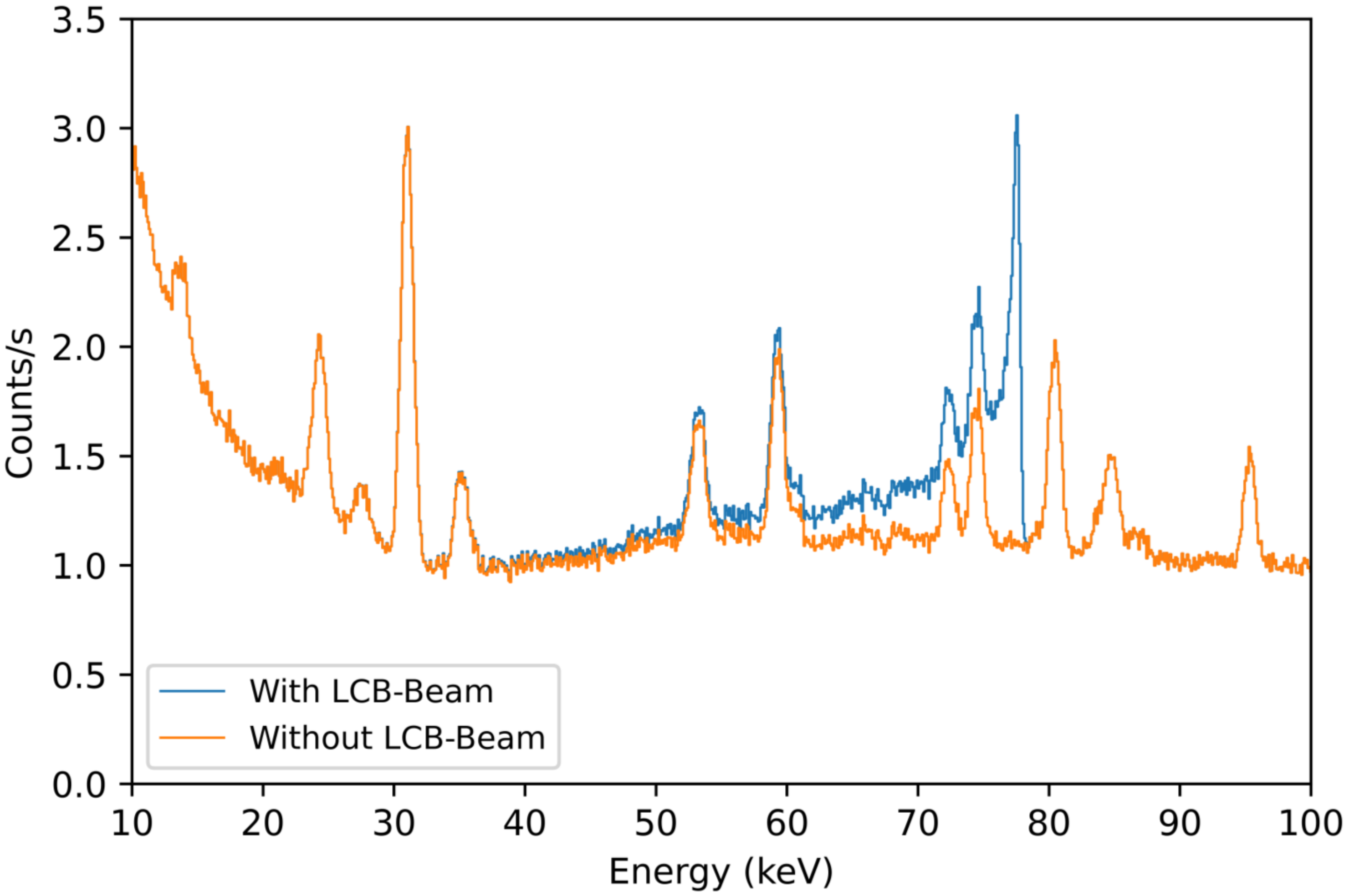
Electron Beam Energy in 3. Recirculation:
65 MeV

Electron Beam Current:
5 µA

Simulation

MOPA-Laser:
100 W @ 1030 nm,
0.5 mJ, 3ps,
200kHz,
σ = 100µm

LCB: 77.8keV
473 Ph/s
$\frac{\Delta E_{ph}}{E_{ph}}$ ~2.5 %



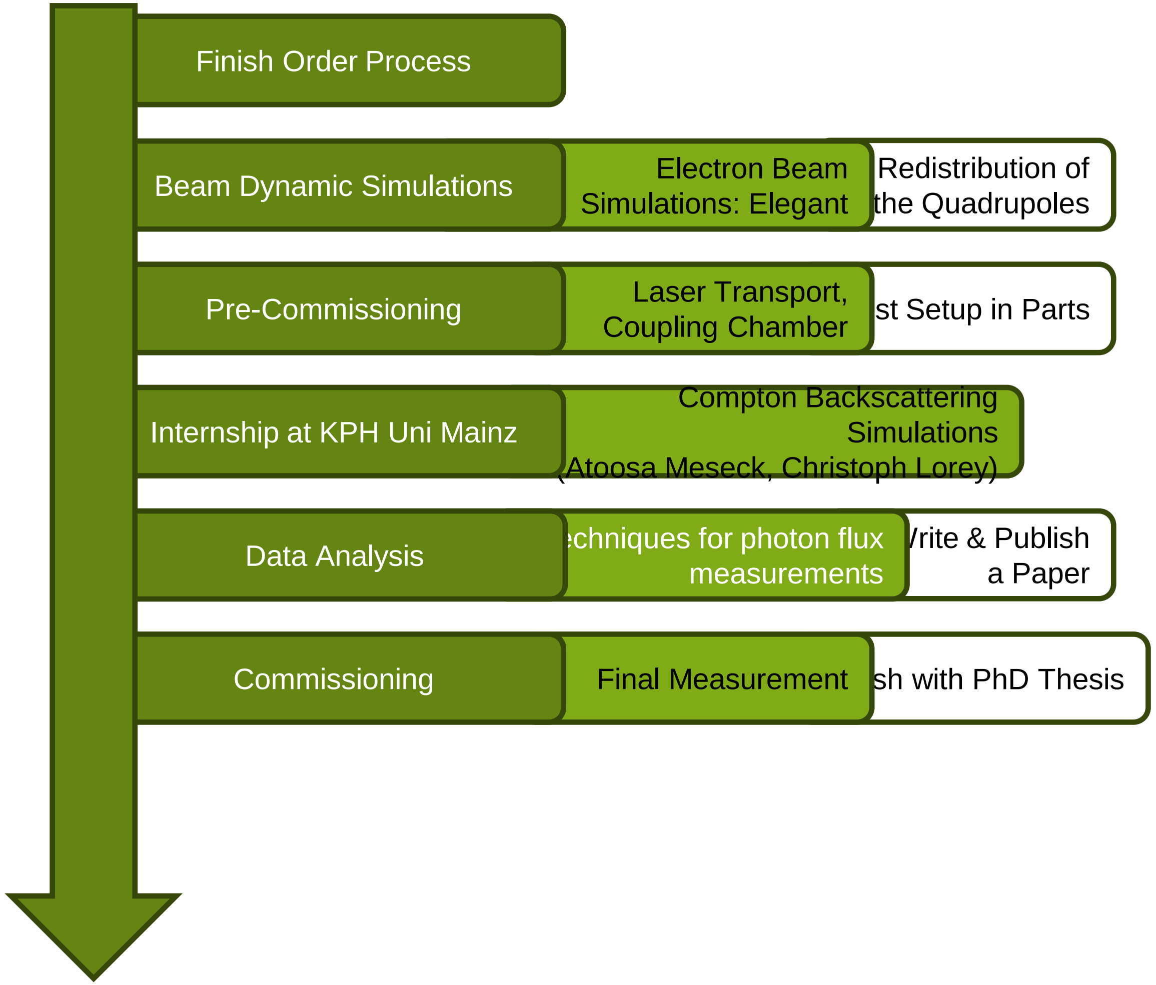
Current Status and Outlook

- We can calculate the polarized and unpolarized angular Thomson cross section with linear laser polarization and the relativistic 3D collision between photon and electron with recoil

- The sampling routine combining the polarized cross section and relativistic collision calculation with a flux formula to estimate realistic scattered photon distributions in space will be finalized

- We will verify our results using simulation software and measurements

- Finally, several case studies of varying laser and electron beam energies and polarizations including concrete MESA implementation scenarios will form the feasibility study



Thank you!

Supported by…

LOEWE
Exzellente Forschung für Hessens Zukunft

Nuclear Photonics

DFG Deutsche Forschungsgemeinschaft

ACCELENCE

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

TECHNISCHE UNIVERSITÄT DARMSTADT

Fin. ...for now

Thank you for your attention!