# Alternative Collider Modes

Linear Collider Vision Community Event 2025

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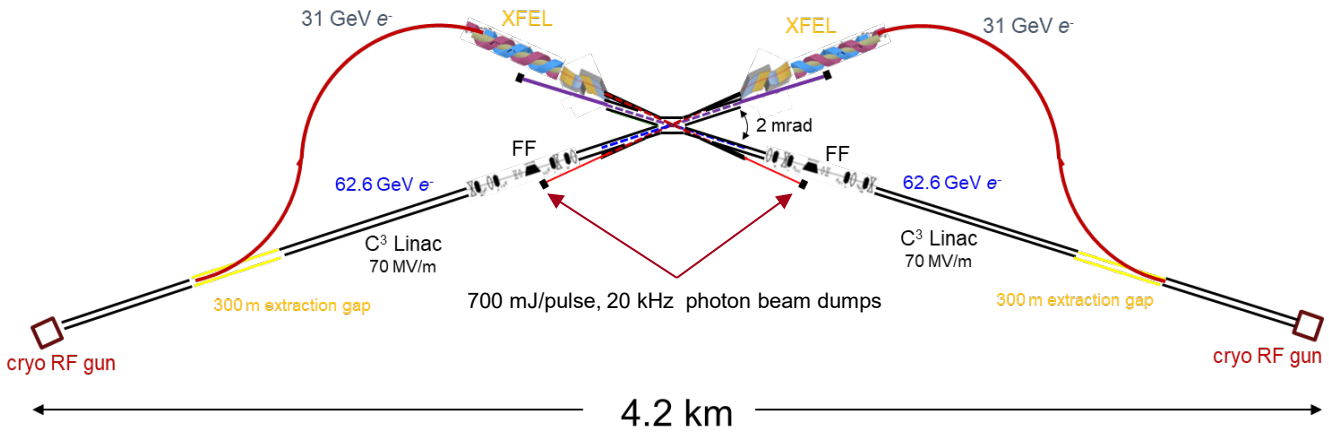
# Our Plan is to Summarize Existing Literature on Optical Laser-Based $\gamma\gamma$ Colliders, but then Focus Our Effort on an XFEL Compton Collider (XCC) Implemented at 2nd Interaction Region

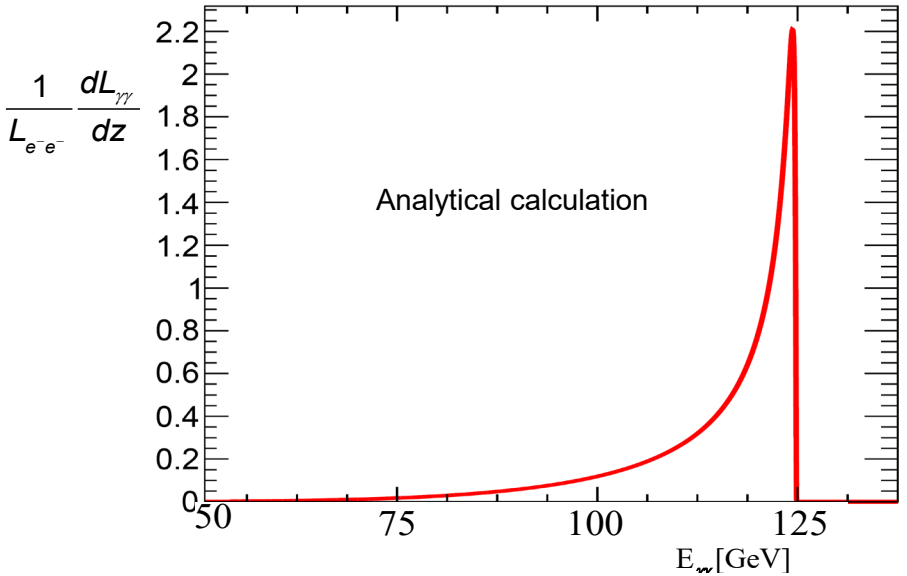
XCC s-channel $\gamma\gamma \to H$ @ $\sqrt{s} = 125$ GeV

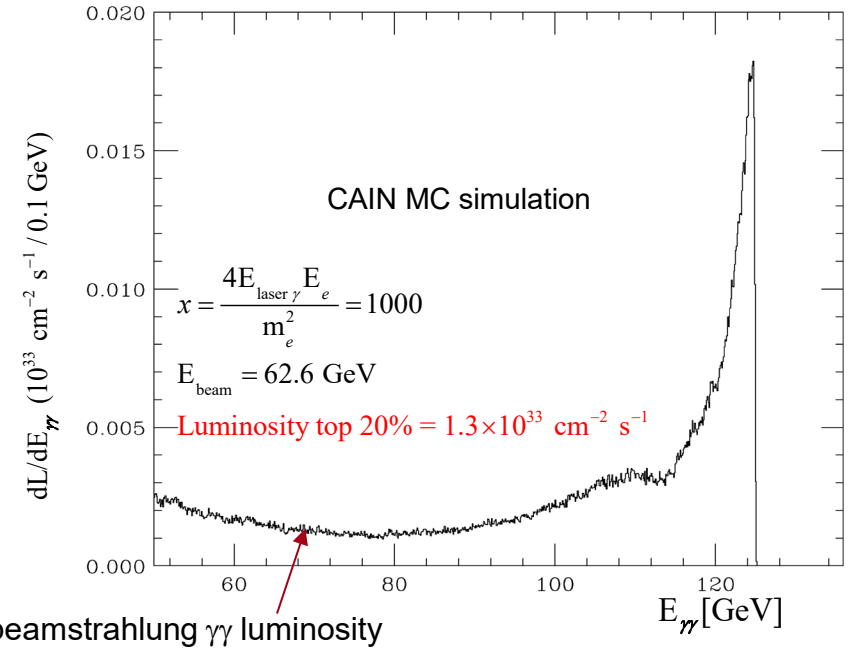
$\gamma\gamma \to HH$ @ $\sqrt{s} = 380$ GeV



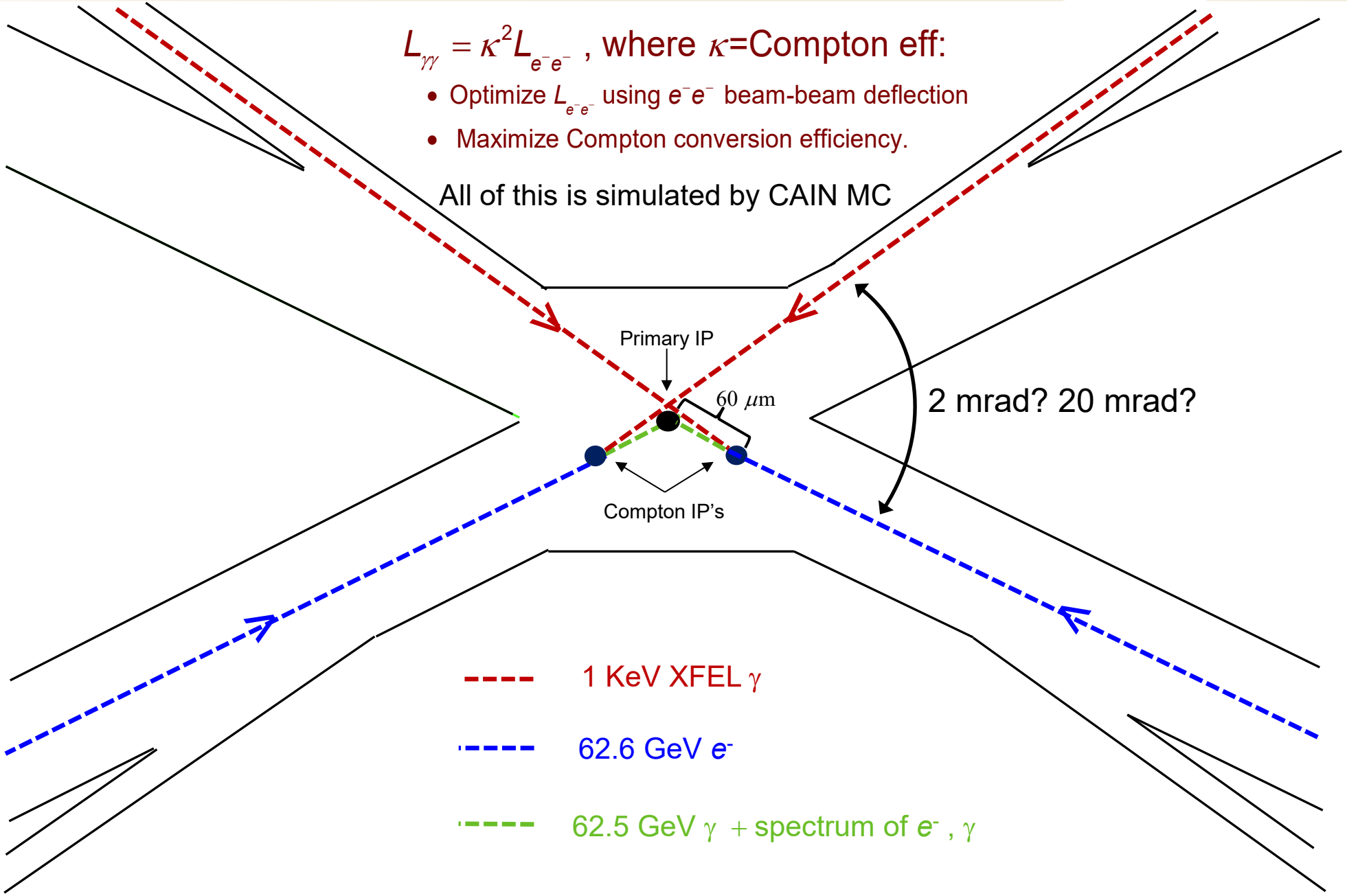

| Final Focus parameters | Approx. value | XFEL parameters | Approx. value |
|---|---|---|---|
| Electron energy | 62.8 GeV | Electron energy | 31 GeV |
| Electron beam power | 0.57 MW | Electron beam power | 0.28 MW |
| $\beta_x/\beta_y$ | 0.03/0.03 mm | normalized emittance | 120 nm |
| $\gamma\epsilon_x/\gamma\epsilon_y$ | 120/120 nm | RMS energy spread $\langle\Delta\gamma/\gamma\rangle$ | 0.05% |
| $\sigma_x/\sigma_y$ at $e^-e^-$ IP | 5.4/5.4 nm | bunch charge | 1 nC |
| $\sigma_z$ | 20 $\mu$m | Linac-to-XFEL curvature radius | 133 km |
| bunch charge | 1 nC | Undulator B field | $\gtrsim$ 1 T |
| Rep. Rate at IP | 120 x 167 Hz | Undulator period $\lambda_u$ | 9 cm |
| $\sigma_x/\sigma_y$ at IPC | 12.1/12.12 nm | Average $\beta$ function | 12 m |
| $\mathcal{L}_{\text{geometric}}$ | $9.7 \times 10^{34}$ cm$^2$ s$^{-1}$ | x-ray $\lambda$ (energy) | 1.2 nm (1 keV) |
| $\delta_E/E$ | 0.05% | x-ray pulse energy | 0.7 J |
| $L^*$ (QD0 exit to $e^-$ IP) | 1.5m | pulse length | 40 $\mu$m |
| $d_{cp}$ (IPC to IP) | 60 $\mu$m | $a_{\gamma x}/a_{\gamma y}$ (x/y waist) | 21.2/21.2 nm |
| QD0 aperture | 9 cm diameter | non-linear QED $\xi^2$ | 0.10 |

| Site parameters | Approx. value |
|---|---|
| crossing angle | 2 mrad |
| total site power | 85 MW |
| total length | 3.0 km |



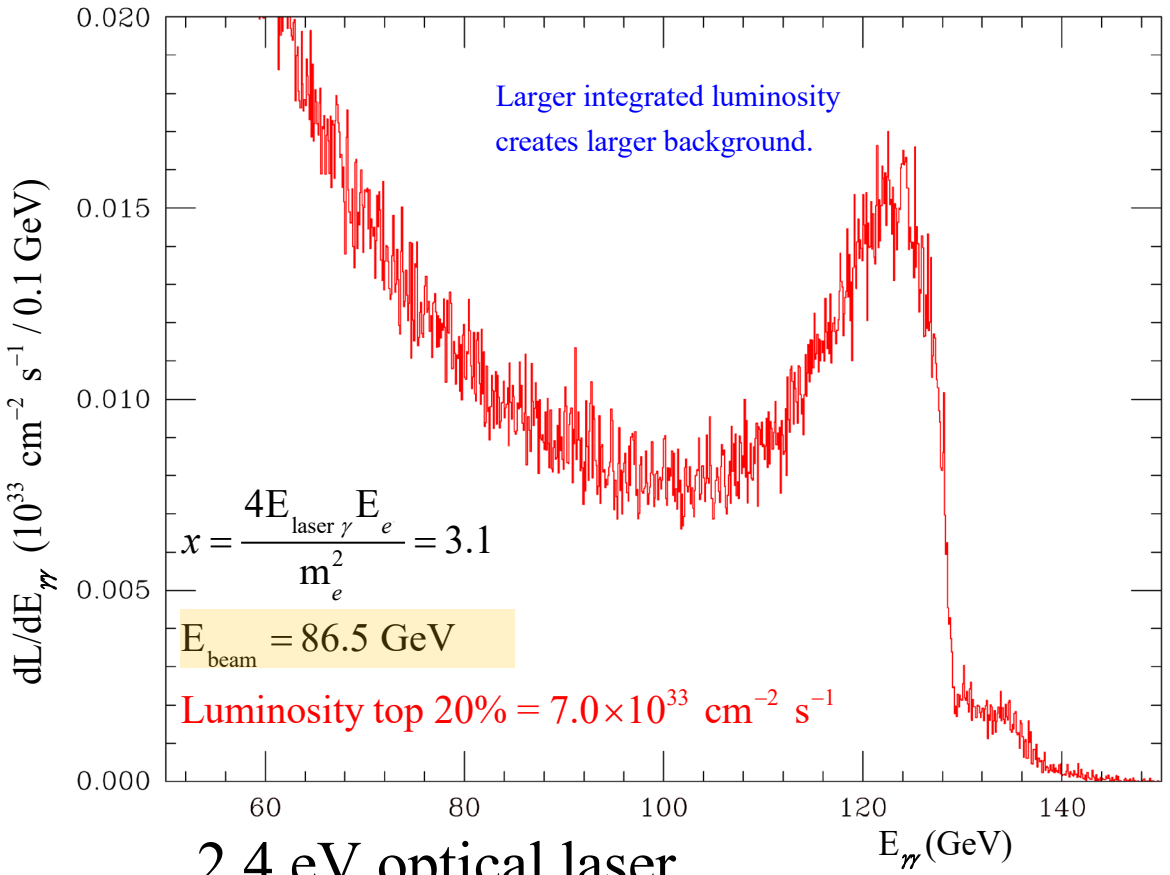
# XCC layout of 1 keV XFEL , 63 GeV $e^-$ Beams near Interaction Point



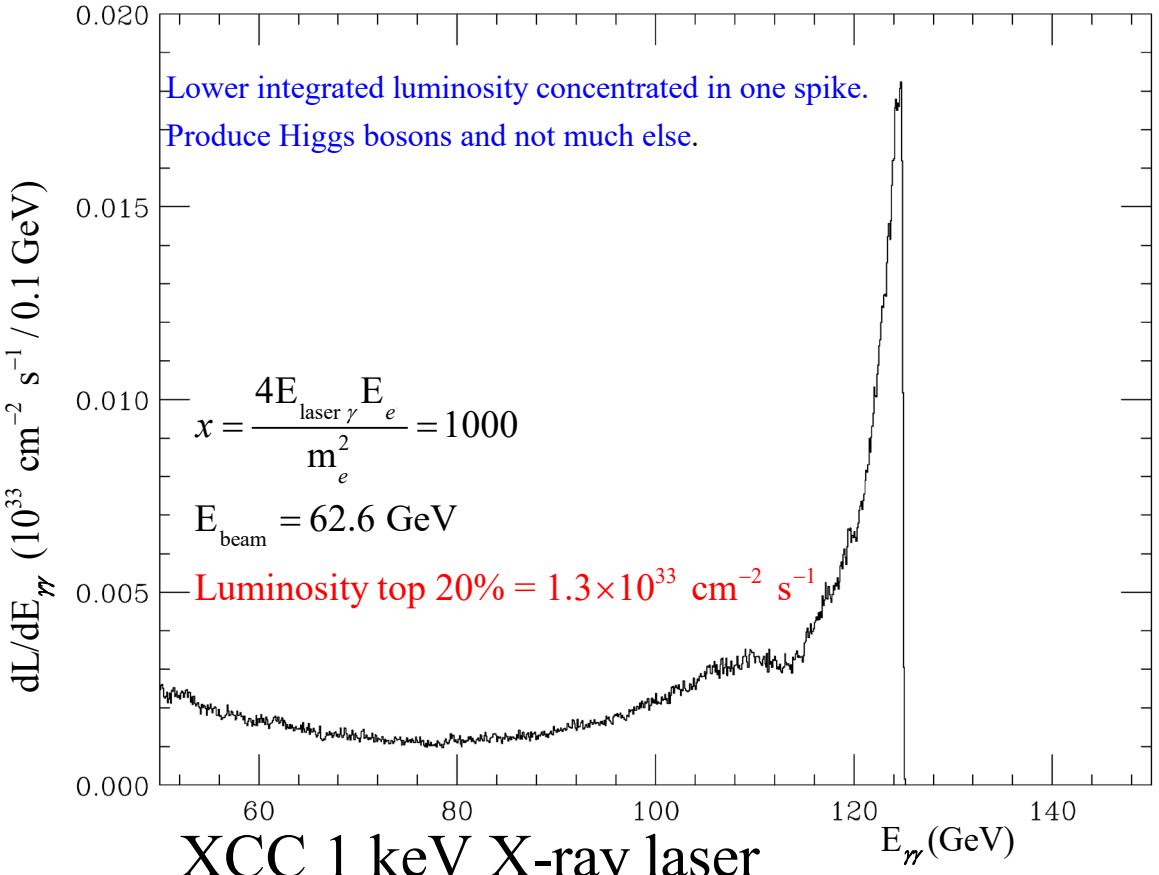
# The XCC experimental environment is qualitatively different from optical laser $\gamma\gamma$ – more like $e^+e^-$

| Machine | $E_{e^-}$ (GeV) | Polarization | $N_H$/yr | $N_{Bgnd}/N_H$ | $N_{pileup/BX}$ |
|---|---|---|---|---|---|
| XCC | 62.8 | 90% $e^-$ | 80,000 | 170 | 1.3 |
| 2.4 eV laser | 86.5 | 90% $e^-$ | 52,000 | 1310 | 6.8 |
| ILC | 125 | −80% $e^-$ +30% $e^+$ | 98,000 | 130 | 1.3 |
| ILC | 125 | +80% $e^-$ −30% $e^+$ | 65,000 | 50 | 1.3 |

Here we take the XCC parameters and only replace the XFEL laser with an optical laser




2.4 eV optical laser

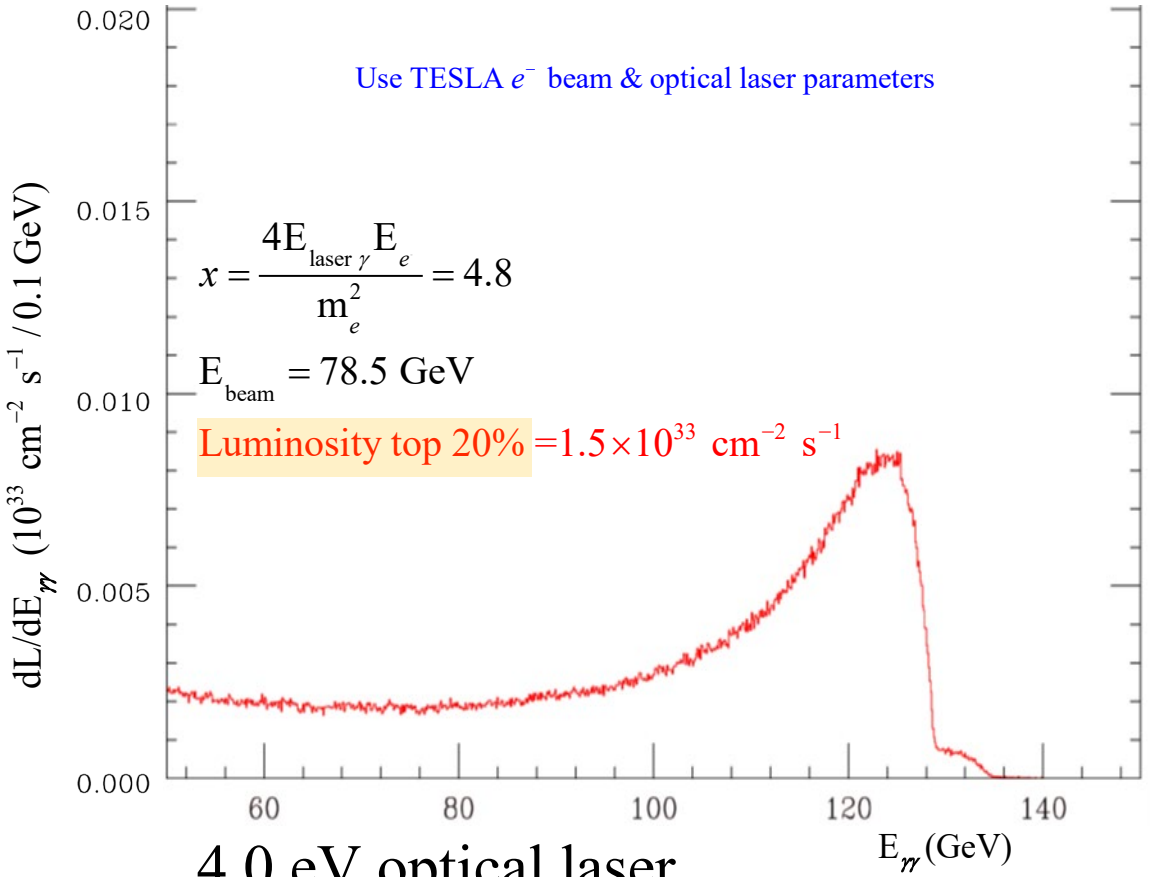



XCC 1 keV X-ray laser

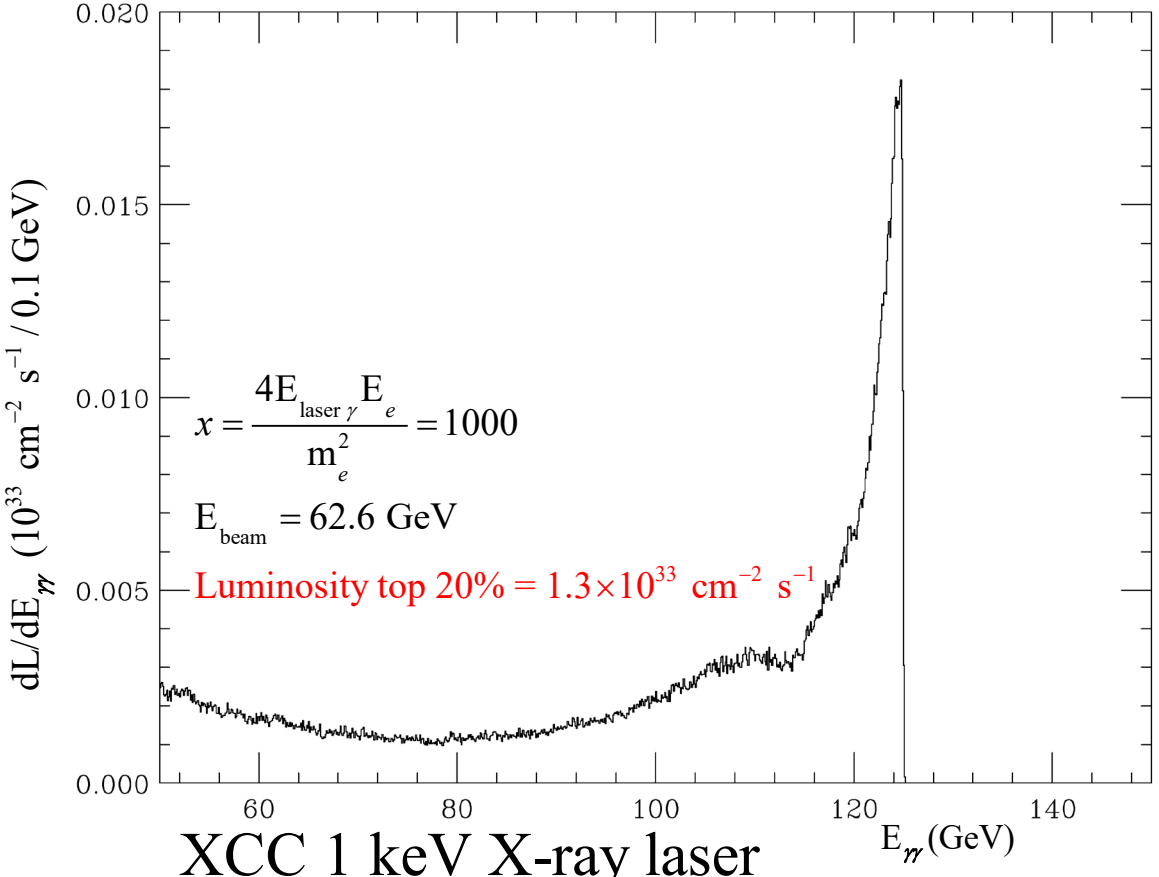
# Instead of taking XCC design and substituting Optical Laser for XFEL, Look at Original TESLA Design

| Machine | $E_{e^-}$ (GeV) | Polarization | $N_H$/yr | $N_{Bgnd}/N_H$ | $N_{pileup/BX}$ |
|---|---|---|---|---|---|
| XCC | 62.8 | 90% $e^-$ | 80,000 | 170 | 1.3 |
| 4.0 eV laser | 78.5 | 90% $e^-$ | 13,000 | 1050 | 0.2 |
| ILC | 125 | −80% $e^-$ +30% $e^+$ | 98,000 | 130 | 1.3 |
| ILC | 125 | +80% $e^-$ −30% $e^+$ | 65,000 | 50 | 1.3 |

Here we use TESLA TDR electron and optical laser parameters; adjust electron and photon energies to get x=4.8 and luminosity peak at 125 GeV




4.0 eV optical laser



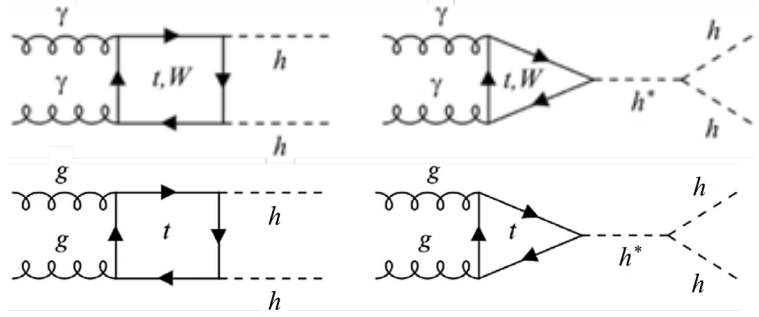

XCC 1 keV X-ray laser

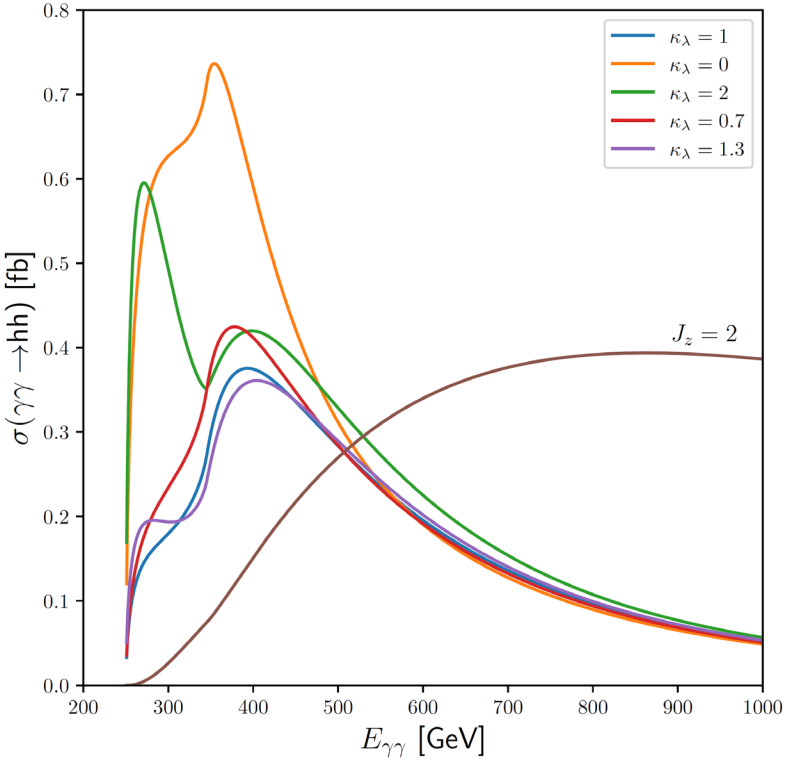
# Example $\gamma\gamma$ Physics Study

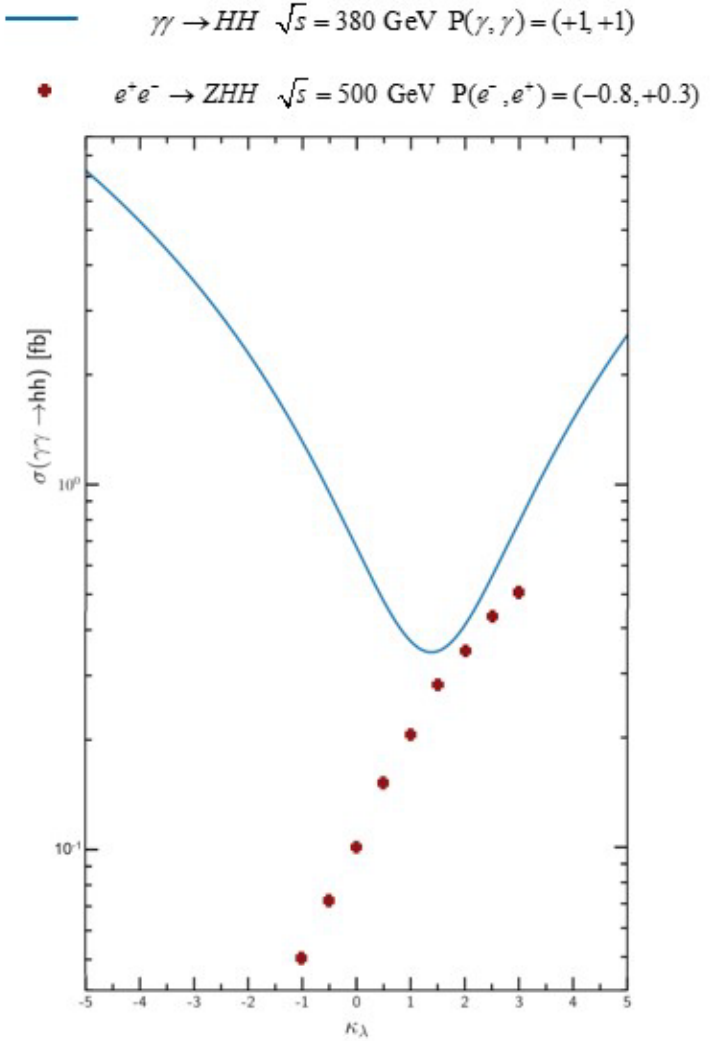
## $e^+e^-$ and $\gamma\gamma$ Have Complementary Approaches to Higgs Self-Coupling

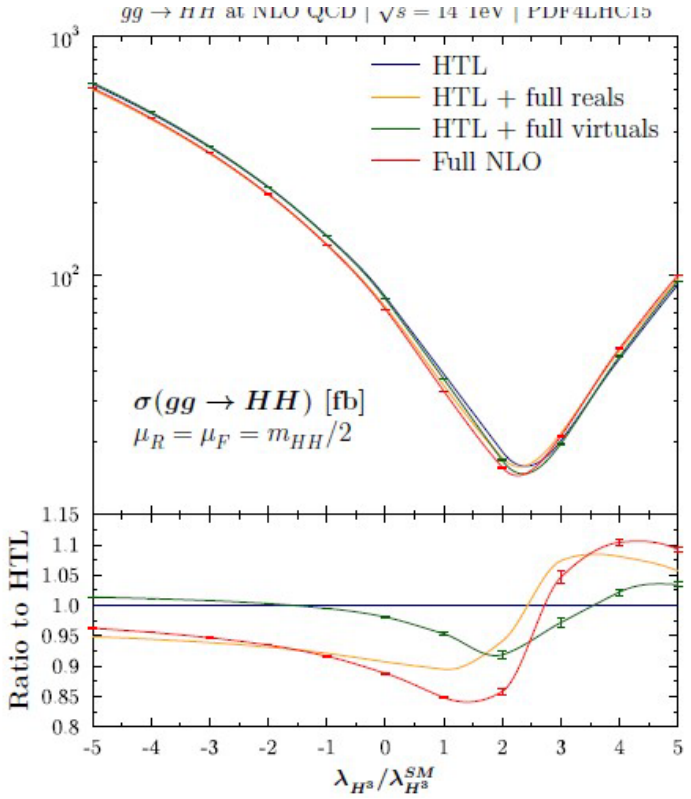
XCC

LHC



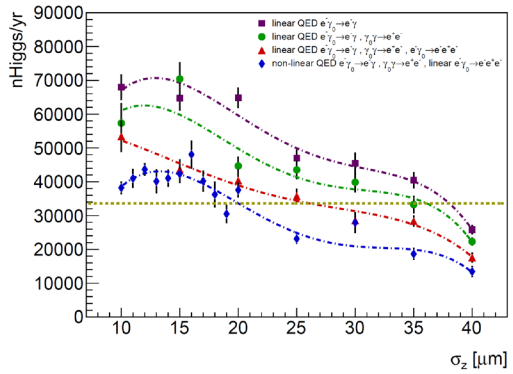

Marten Berger

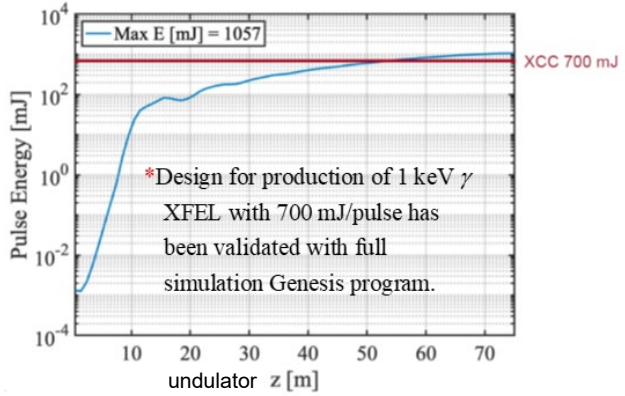
# XCC Accelerator Challenges

# XCC Accelerator Challenges

## Electron beam:

- Preferred XCC $e^-$ bunch length is 20 $\mu$m rms - how do we handle in LCVision?
- Polarized low emittance (120 nm) $e^-$ injector is baseline XCC but damping ring would also work
- Focusing of round $e^-$ beams to $\sigma_{x,y} = 5.5$ nm $(\beta_{x,y} = 0.03$ mm, $L_{geo} = 10^{35}$ cm$^{-2}$s$^{-1})$ or asymmteric $e^-$ beams if damping ring is used.



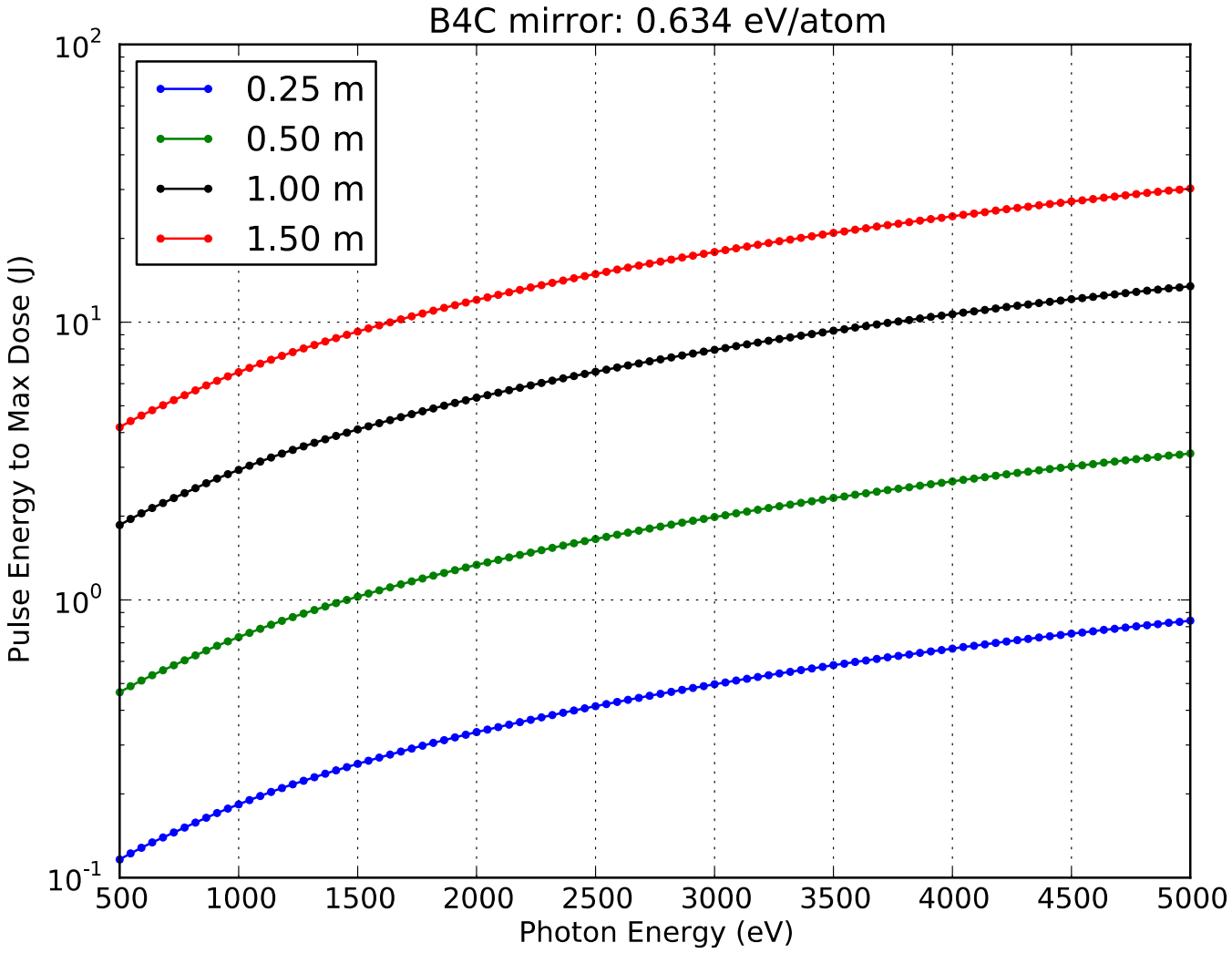

## XFEL beam and Compton IP:

- Production of 1 keV $\gamma$ XFEL with 700 mJ/pulse
- Focusing of 1 keV , 700 mJ/pulse XFEL beam to 70 nm FWHM waist
- XFEL and $e^-$ beamline layouts around the IP
- Timing and position stability of the XFEL laser beam and $e^-$ beam at Compton IP.

Table of XCC KB mirror parameters

| Focal Size (nm) | Photon Energy (eV) | Rayleigh Range (um) | RMS Source Size (um) | AOI (deg) | Max E w/ 10x SF (J) | Substrate Length (m) | Unfocused Beam Size (mm) | Source Distance (m) | Reflectivity | Focal Length (m) | IP Distance from Mirror (m) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 50 | 1000 | 4.5 | 10 | 1.30 | 0.31 | 1.00 | 11.34 | 487 | 0.872 | 1.032 | 0.532 |
| 100 | 1000 | 18.2 | 10 | 0.90 | 0.68 | 1.50 | 11.78 | 505 | 0.926 | 2.144 | 1.394 |
| 50 | 2000 | 9.1 | 10 | 0.80 | 0.54 | 1.00 | 6.98 | 600 | 0.933 | 1.27 | 0.770 |
| 100 | 2000 | 36.4 | 10 | 0.60 | 1.05 | 1.40 | 7.33 | 629 | 0.967 | 2.668 | 1.968 |
| 50 | 2000 | 9.1 | 10 | 0.65 | 1.21 | 1.50 | 8.51 | 731 | 0.962 | 1.548 | 0.798 |
| 100 | 2000 | 36.4 | 10 | 0.50 | 2.14 | 2.00 | 8.73 | 750 | 0.976 | 3.176 | 2.176 |
| 40 | 4000 | 11.6 | 10 | 0.4 | 1.06 | 1.13 | 3.93 | 675 | 0.982 | 1.143 | 0.581 |
| 70 | 4000 | 35.7 | 10 | 0.3 | 2.40 | 1.50 | 3.93 | 675 | 0.992 | 2.001 | 1.251 |
| 40 | 4000 | 11.6 | 10 | 0.4 | 2.39 | 1.50 | 5.24 | 899 | 0.982 | 1.525 | 0.775 |
| 70 | 4000 | 35.7 | 10 | 0.3 | 4.27 | 2.00 | 5.24 | 899 | 0.992 | 2.668 | 1.668 |

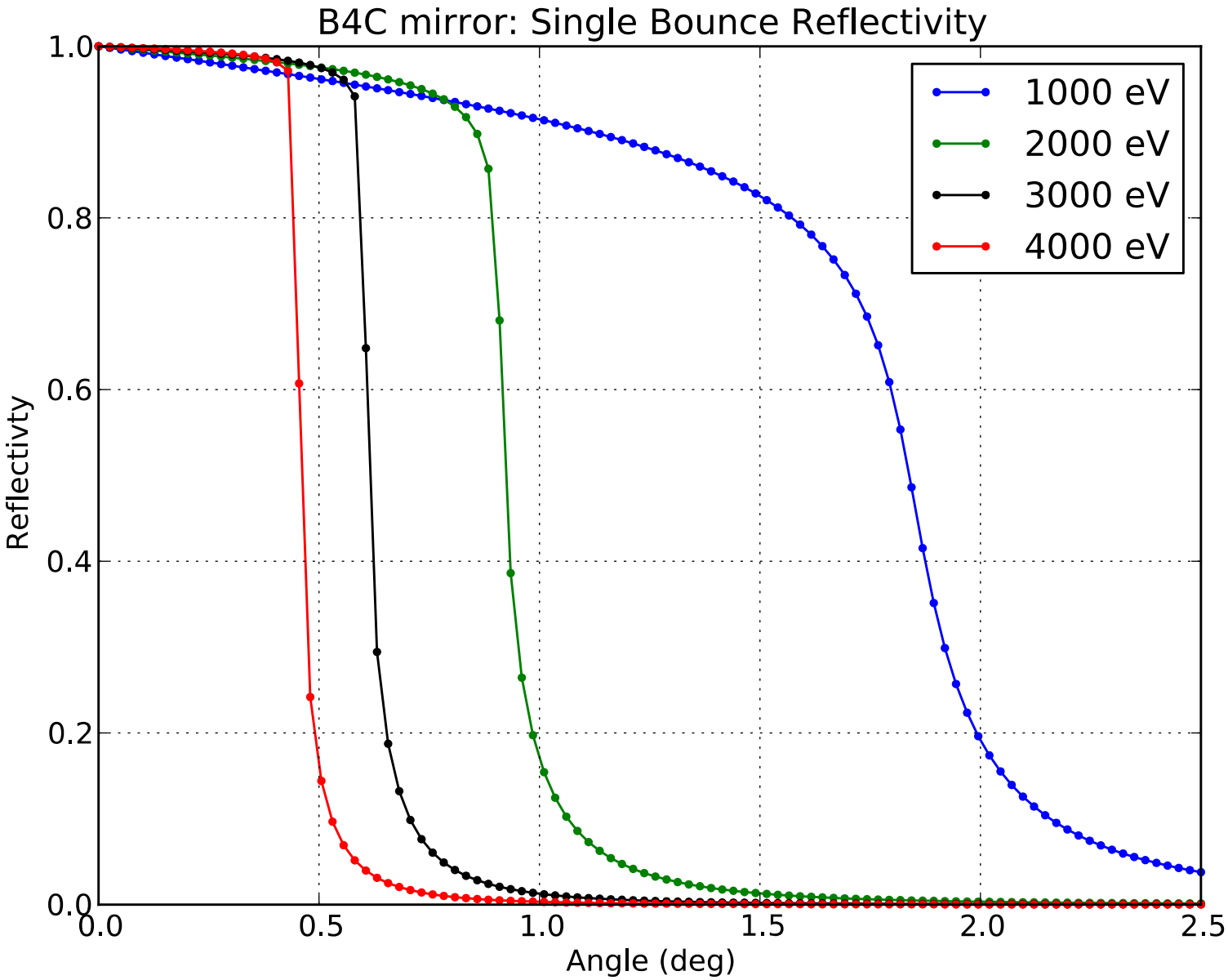
# Mirror Damage Limit (single pulse)



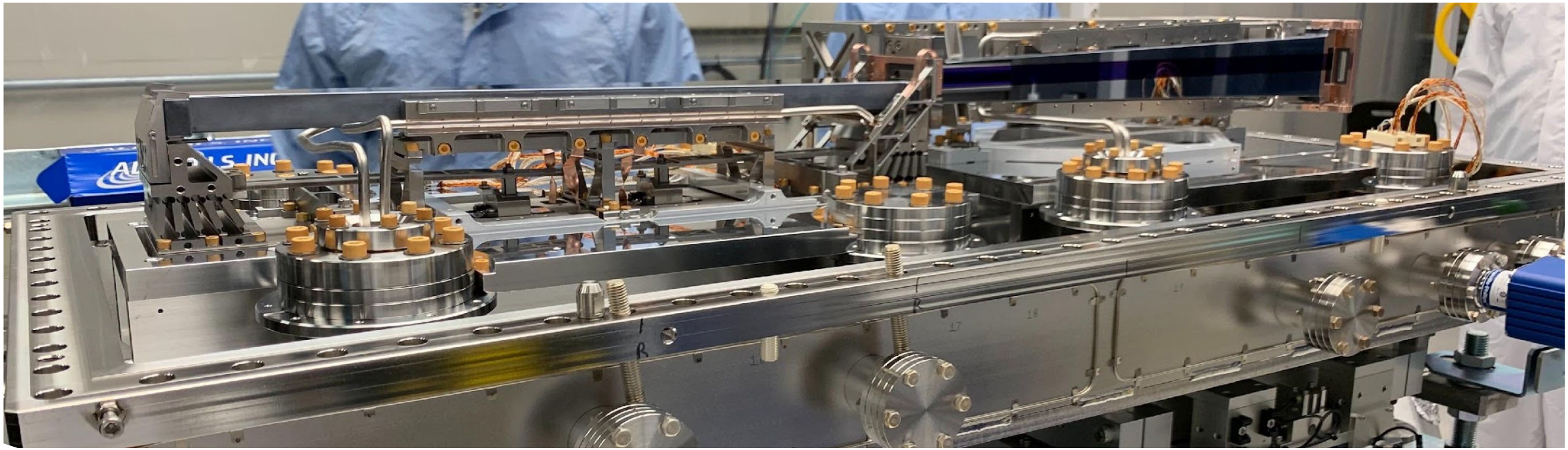

- Boron carbide is the highest damage threshold coating and is used for this calculation
- Assumes the incident fwhm beam size is ½ the substrate length
- No safety factor is included in these calculations – 5-10x below this value should be planned for
- Calculation is weakly dependent on incident angle below the mirror cutoff (0.3 deg AOI used)

**A large mirror (> 1 m) is needed to survive ~ 1 J pulse energies**

# Mirror Reflectivity



# KB Mirror Chamber



This KB mirror parameter table did not account for placement of mirrors outside detector. Substrate and focal lengths will actually be 2.5 times those shown here:

| Focal Size (nm) | Photon Energy (eV) | Rayleigh Range (um) | RMS Source Size (um) | AOI (deg) | Max E w/ 10x SF (J) | Substrate Length (m) | Unfocused Beam Size (mm) | Source Distance (m) | Reflectivity | Focal Length (m) | IP Distance from Mirror (m) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 50 | 1000 | 4.5 | 10 | 1.30 | 0.31 | 1.00 | 11.34 | 487 | 0.872 | 1.032 | 0.532 |
| 100 | 1000 | 18.2 | 10 | 0.90 | 0.68 | 1.50 | 11.78 | 505 | 0.926 | 2.144 | 1.394 |
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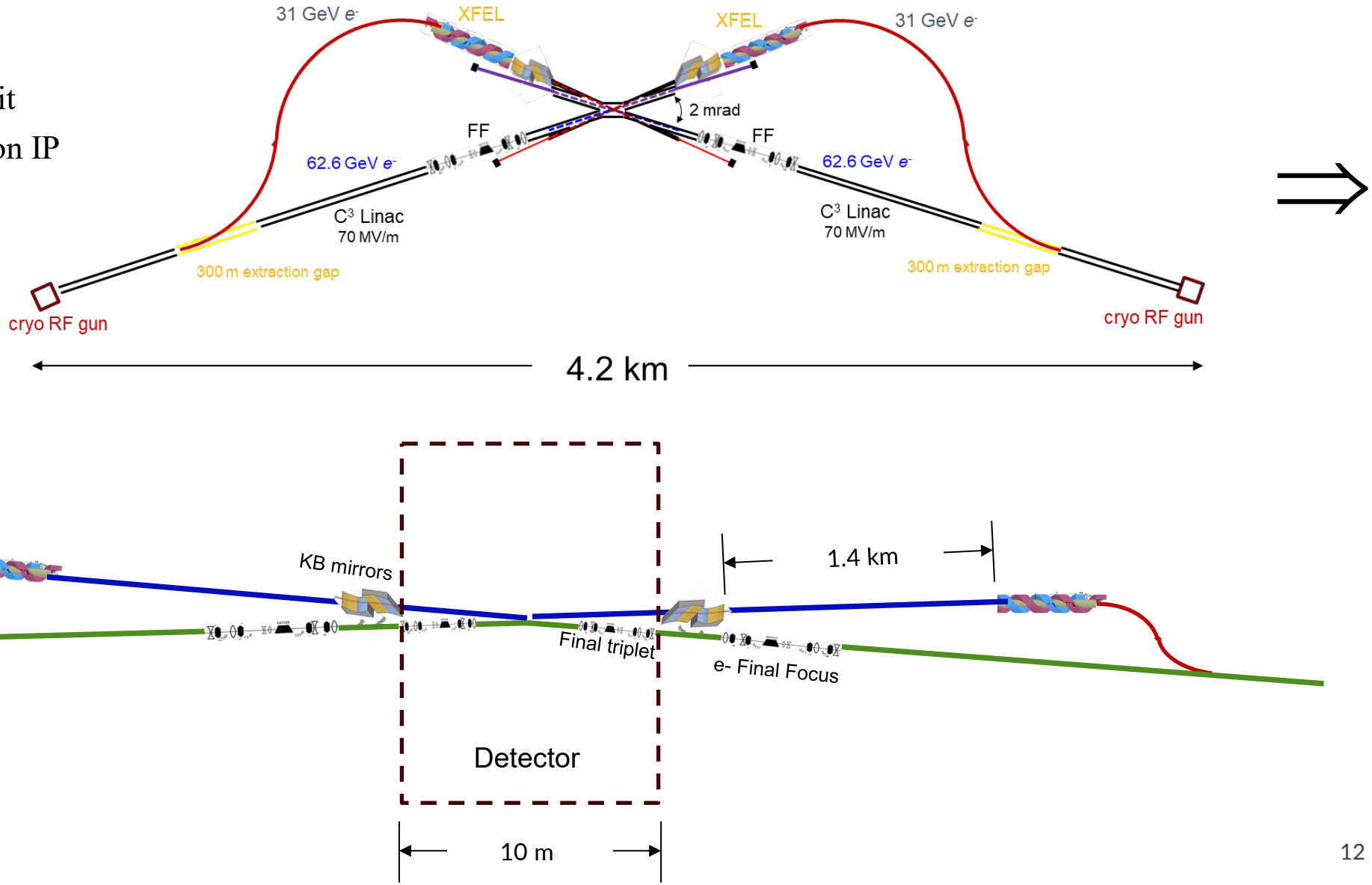
| 70 | 4000 | 35.7 | 10 | 0.3 | 4.27 | 2.00 | 5.24 | 899 | 0.992 | 2.668 | 1.668 |

# XCC Schematic with 1.4 km line between XFEL and KB mirrors

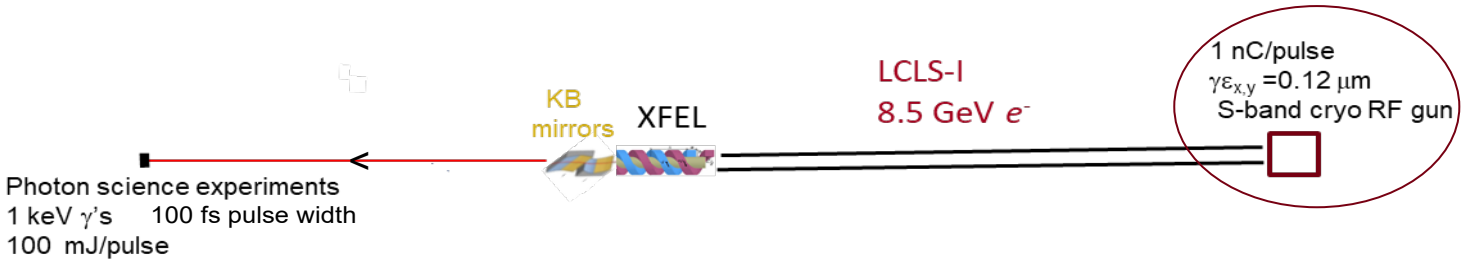
Demagnify 20 $\mu$m FWHM
XFEL beam at undulator exit
to 70 nm FWHM at Compton IP

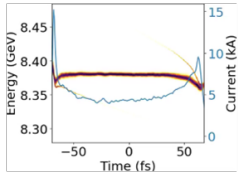


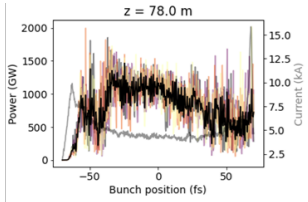
# LCLS High Brightness Injector Upgrade

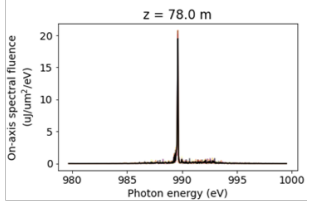
1 nC 120 nm-rad S-band cryo RF gun, also serves as injector demonstrator for $C^3$ and XCC.

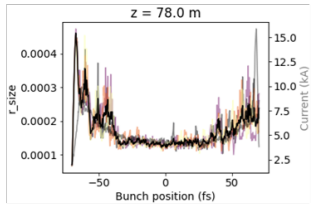
When gun is attached to LCLS-I, we get a high brightness upgrade to LCLS-I with new photon science opportunities. Also, an XCC demonstrator for X-ray focusing at 100 mJ/pulse.




Preliminary results:

- >110 mJ of 1 keV X-rays within 20 undulators
- <0.01% FWHM bandwidth (0.18% rms)

Caveats:

- Simulation done with pure seed so FWHM bandwidth may be a bit larger with a full simulation (full sim: first stage, clean spectrum, second stage)

Resistive wall wake fields

- increased FWHM bandwidth by 40%
- decreased pulse energy by 12%
- Increasing undulator chamber gap from 5 to 7 mm could halve wake field strength.
- Shaping the beam (shortening) may shape space charge wake

# XCC BDS & MDI Issues

# Beam Delivery and Machine Detector Interface at XCC

## BDS Accelerator Issues Related to Getting Four Particle Beams In and Out of IP Region

(1) Crossing angle and Aperture of final quad (for 2 mrad crossing angle choice, $e^+, e^-, \gamma$ from primary & Compton IP's must pass through this aperture; for 20 mrad angle need collimators to protect final quad)

(2) L*, KB mirror length and location

(3) Shared vacuum pipe: point of entry of XFEL beam into $e^-$ beampipe, passing of electron beam through KB mirror chamber (?), beam dump design

## Detector issues due to backgrounds from $e^+, e^-, \gamma$ produced at Compton IP's and primary IP:

(1) Vertex detector inner radius (incoherent $e^+e^-$ pairs from primary IP - same situation as $e^+e^-$ linear colliders)

(2) Beampipe $X_0$ (moderate soft X-ray flux from Compton IP's $|\cos\theta| < 0.95$)

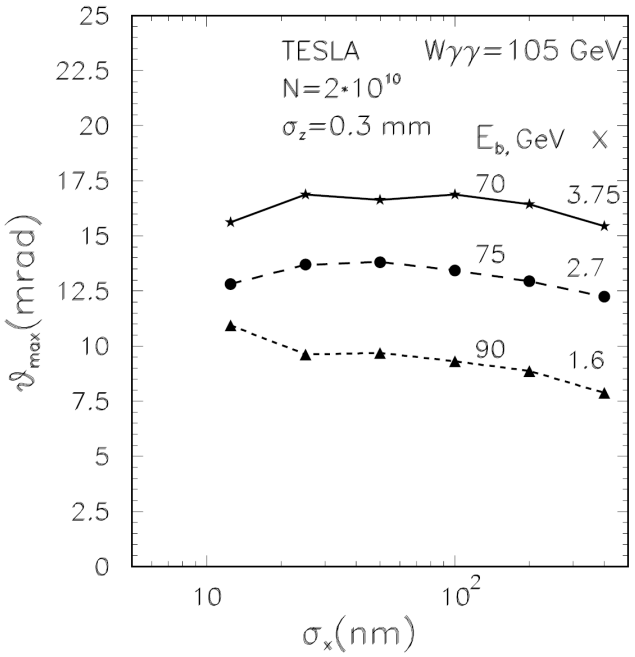
(3) Forward boundaries of the main tracker/calorimeter and solid angle coverage of forward detector (large hard X-ray flux from Compton IP's $|\cos\theta| > 0.95$)

# TESLA TDR $\gamma\gamma$ Collider Specifies 34 mrad Crossing Angle

The crossing angle for the TESLA $\gamma\gamma$ collider is discussed in section 1.4.4.2 of

TESLA TDR, Part VI, Chapter 1: The Photon Collider at TESLA

The concern is low energy, large angle particles striking the quads. For fixed $\sqrt{s_{\gamma\gamma}}$ the maximum disruption angle $\vartheta_{\max}$ is given by $\vartheta_{\max} \propto \dfrac{x}{\sqrt{(1+x)\sigma_c(x)}}$ where $\sigma_c(x)$ is the Compton cross section with leading term $\sigma_c(x) \propto \dfrac{1}{x}$ .




They conclude that for a fixed laser $\lambda$=1.06 $\mu$m and 200 GeV $\leq \sqrt{s_{\gamma\gamma}} \leq$ 500 GeV, the the maximum disruption angle is $\vartheta_{\max} \approx 14$ mrad, and they set the crossing angle at $\theta_c = 34$ mrad.

# Let's check this with CAIN. Calculate energy incident on 6 cm dia. cryostat at L*=3m.

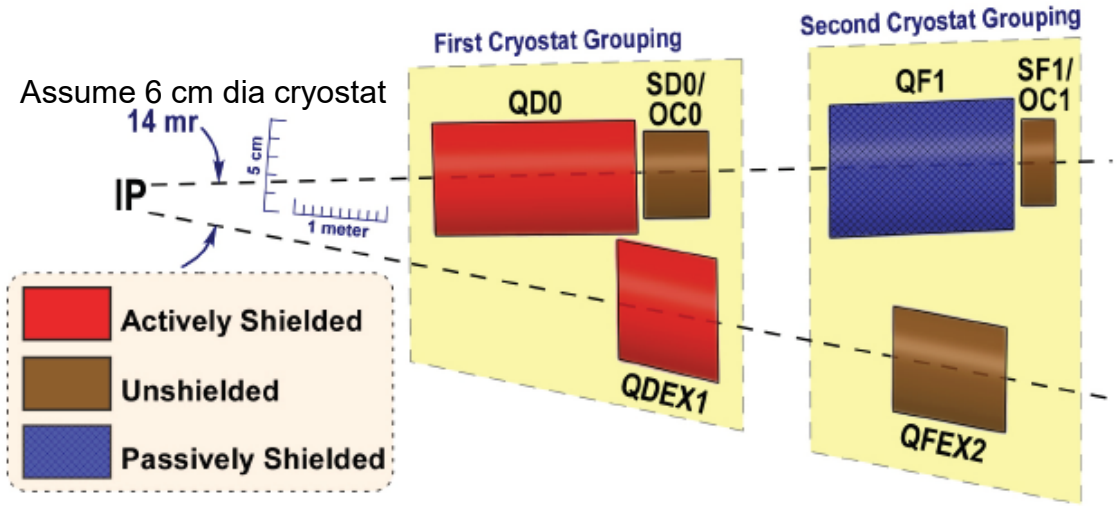
Use parameters for TESLA TDR $\sqrt{s_{\gamma\gamma}} = 500$ GeV, $x = 4.5$

| | | TESLA-500,$\gamma\gamma$ |
|---|---|---|
| Repetition rate | $f_{rep}$ [Hz] | 5 |
| Beam pulse length | $T_P$ [$\mu$s] | 950 |
| RF-pulse length | $T_{RF}$ [$\mu$s] | 1370 |
| No. of bunches per pulse | $n_b$ | 2820 |
| Bunch spacing | $\Delta t_b$ [ns] | 337 |
| Charge per bunch | $N_e$ [$10^{10}$] | 2 |
| Emittance at IP | $\gamma\varepsilon_{x,y}$ [$10^{-6}$m] | 3, 0.03 |
| Beta at IP | $\beta^*_{x,y}$ [mm] | 4, 0.4 |
| Beam size at IP | $\sigma^*_{x,y}$ [nm] | 157, 5 |
| Bunch length at IP | $\sigma_z$ [mm] | 0.3 |
| Geometric luminosity | $L_{geom}$ [$10^{34}$cm$^{-2}$s$^{-1}$] | 5.8 |
| Effective $\gamma\gamma$ luminosity | $L_{\gamma\gamma}$ [$10^{34}$cm$^{-2}$s$^{-1}$] | 0.6 |

Table 1.3.2: *Beam parameters for the $\gamma\gamma$ option. The effective luminosity takes into account only the high energy peak of the luminosity spectrum ($E_{cm,\gamma\gamma} \approx 400\,GeV$), see part VI, chapter 1 for details.*

| $2E_0$ [GeV] | 200 | 500 | 800 |
|---|---|---|---|
| $\lambda_L$ [$\mu$m]/$x$ | 1.06/1.8 | 1.06/4.5 | 1.06/7.2 |
| $t_L$ [$\lambda_{scat}$] | 1.35 | 1 | 1 |
| $N/10^{10}$ | 2 | 2 | 2 |
| $\sigma_z$ [mm] | 0.3 | 0.3 | 0.3 |
| $f_{rep} \times n_b$ [kHz] | 14.1 | 14.1 | 14.1 |
| $\gamma\epsilon_{x/y}/10^{-6}$ [m·rad] | 2.5/0.03 | 2.5/0.03 | 2.5/0.03 |
| $\beta_{x/y}$ [mm] at IP | 1.5/0.3 | 1.5/0.3 | 1.5/0.3 |
| $\sigma_{x/y}$ [nm] | 140/6.8 | 88/4.3 | 69/3.4 |
| b [mm] | 2.6 | 2.1 | 2.7 |
| $L_{ee}$ $(geom)$ [$10^{34}$ cm$^{-2}$s$^{-1}$] | 4.8 | 12 | 19 |
| $L_{\gamma\gamma}(z > 0.8z_{m,\gamma\gamma})$[$10^{34}$ cm$^{-2}$s$^{-1}$] | 0.43 | 1.1 | 1.7 |
| $L_{\gamma e}(z > 0.8z_{m,\gamma e})$[$10^{34}$ cm$^{-2}$s$^{-1}$] | 0.36 | 0.94 | 1.3 |
| $L_{e^+e^-}(z > 0.65)$[$10^{34}$ cm$^{-2}$s$^{-1}$] | 0.03 | 0.07 | 0.095 |

Table 1.4.1: *Parameters of the $\gamma\gamma$ collider based on TESLA. two options.*




As discussed in Section 1.3.2.1 the 5 $\mu$m spot size of the laser beam matches the effective crabbed horizontal beam size of

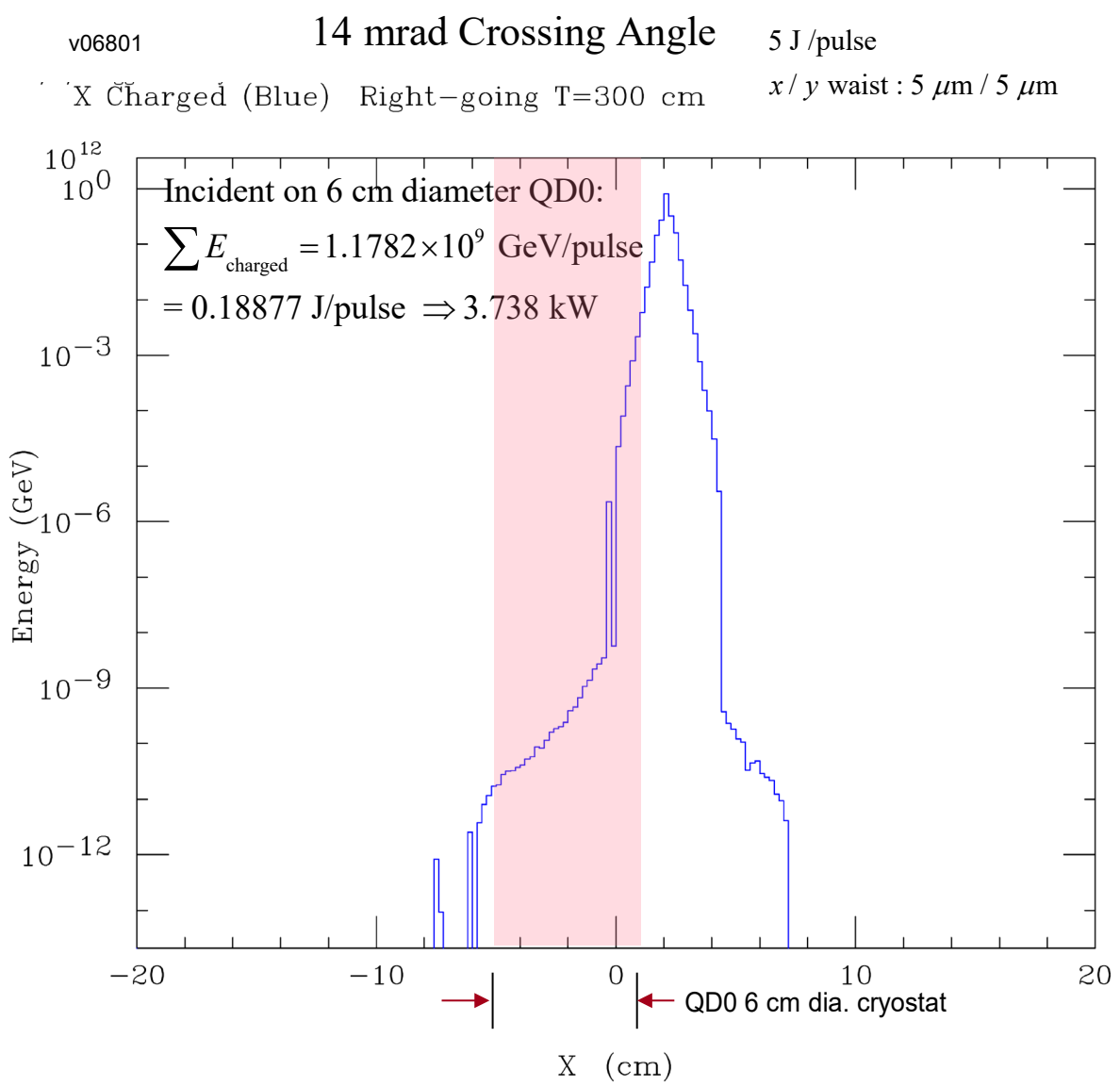
$\sigma_x = \sigma_z \alpha_c / 2 = 5\ \mu$m for $\sigma_z = 300\ \mu$m and $\alpha_c = 34$ mrad

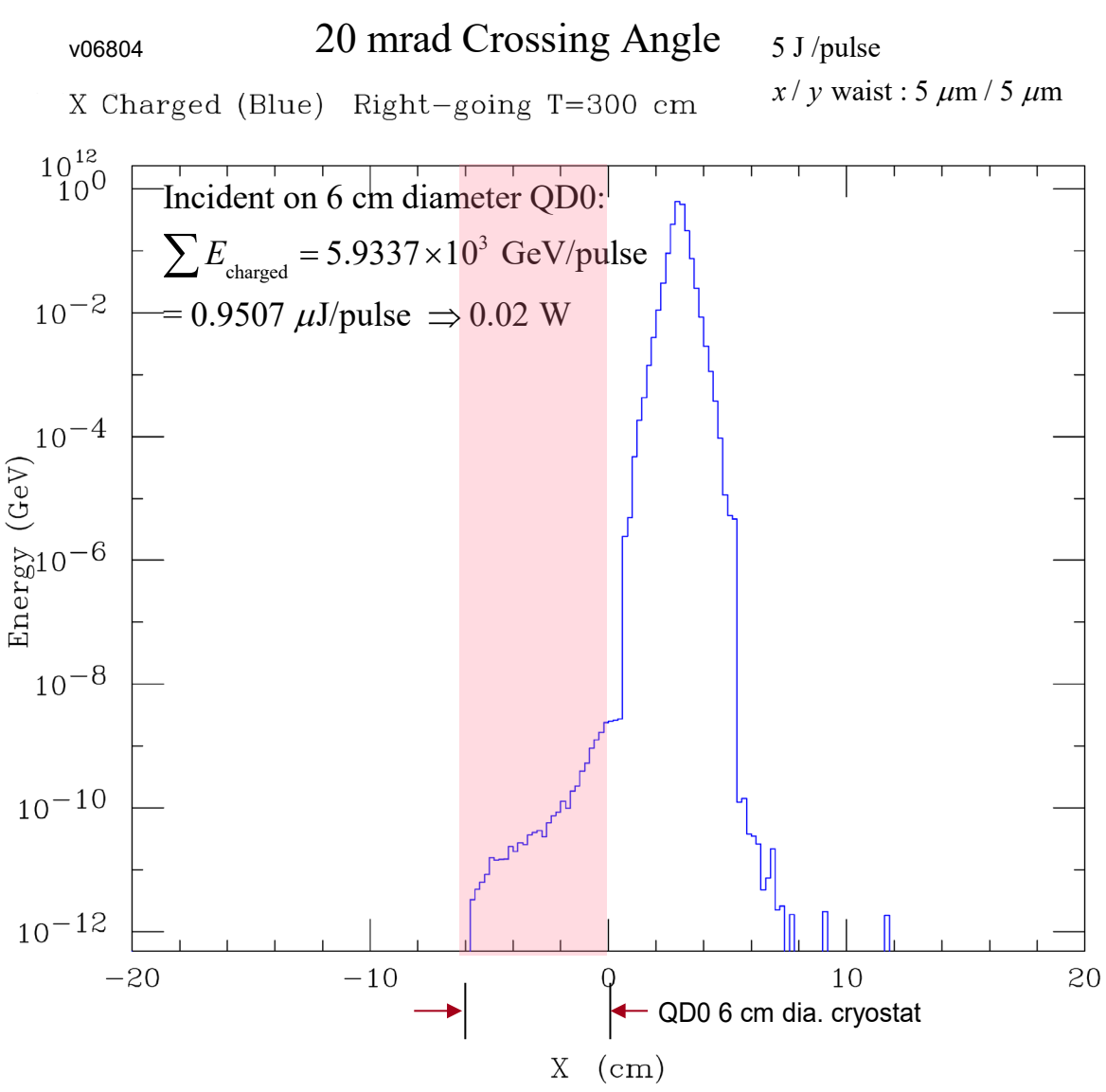
Hence there is little luminosity degradation for $0 < \alpha_c < 34$ mrad

Not the case for XCC where laser spot size is 21 nm and

$\sigma_x = \sigma_z \alpha_c / 2 = 340\ \mu$m for $\sigma_z = 20\ \mu$m and $\alpha_c = 34$ mrad

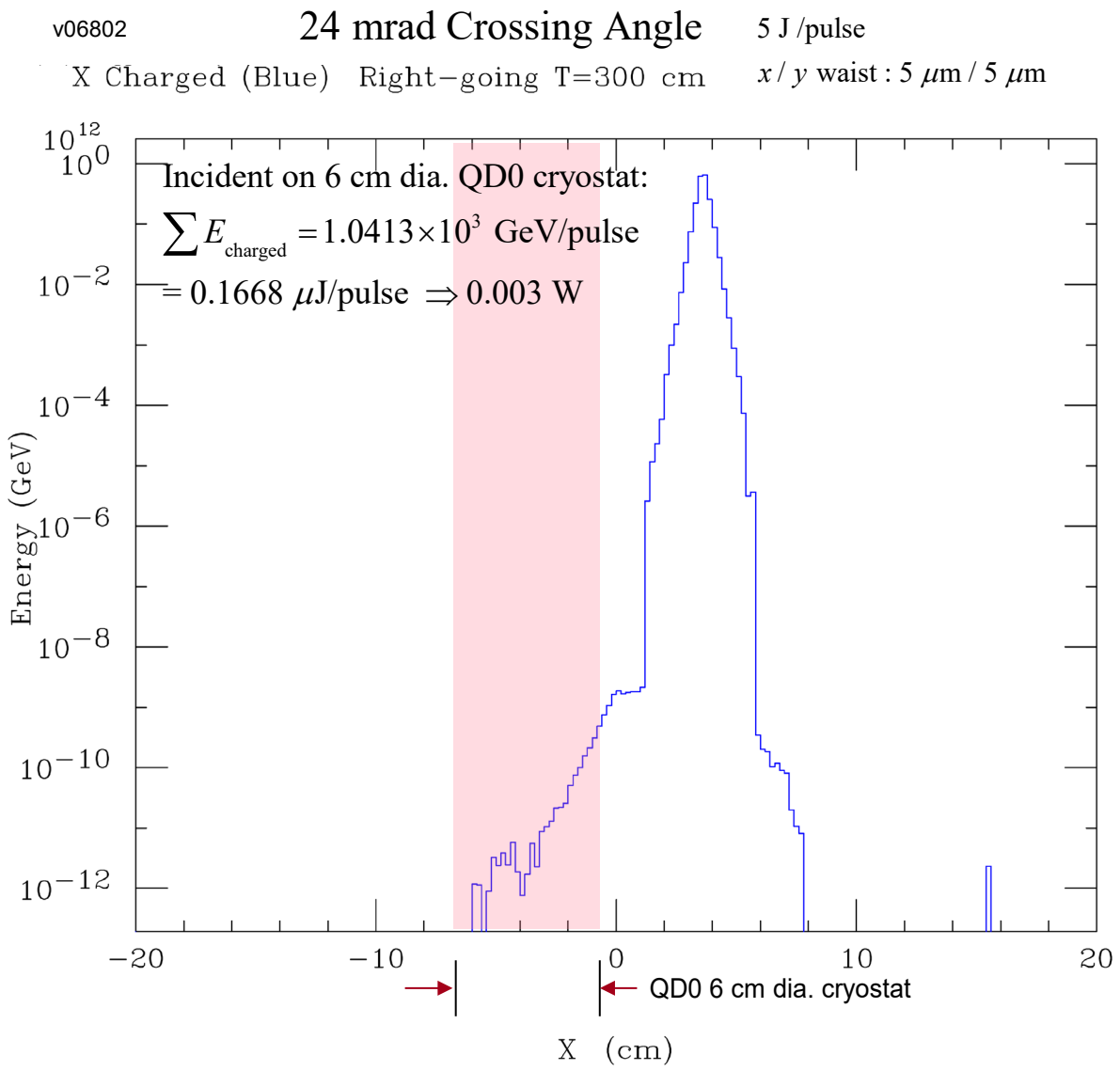
# TESLA TDR $\gamma\gamma$ Collider $\sqrt{s} = 500$ GeV

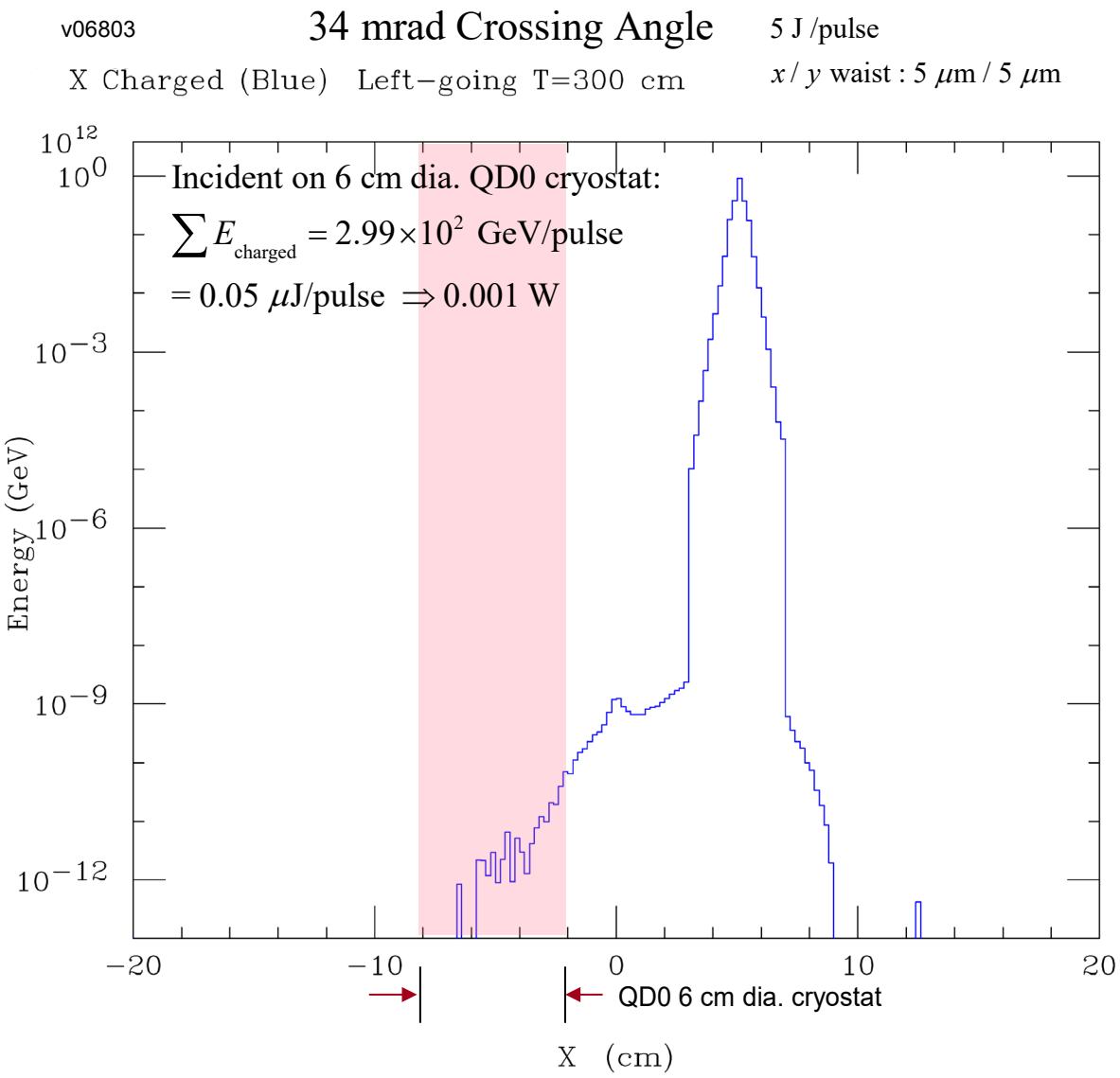



Assuming only few Watts on QD0 is tolerable, we conclude that 14 mrad is insufficient and 20 mrad is the minimum crossing angle.

# TESLA TDR $\gamma\gamma$ Collider $\sqrt{s} = 500$ GeV

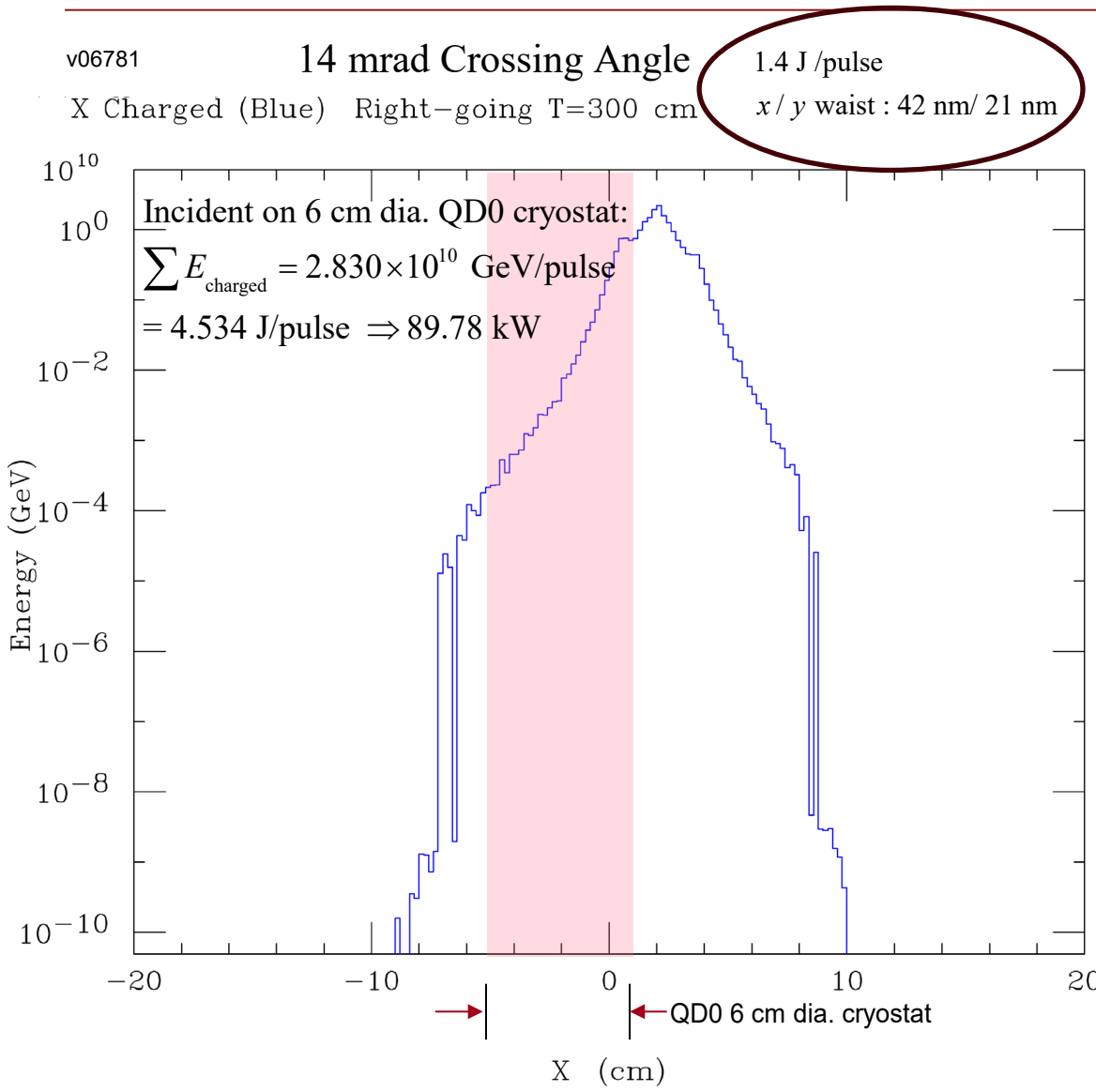


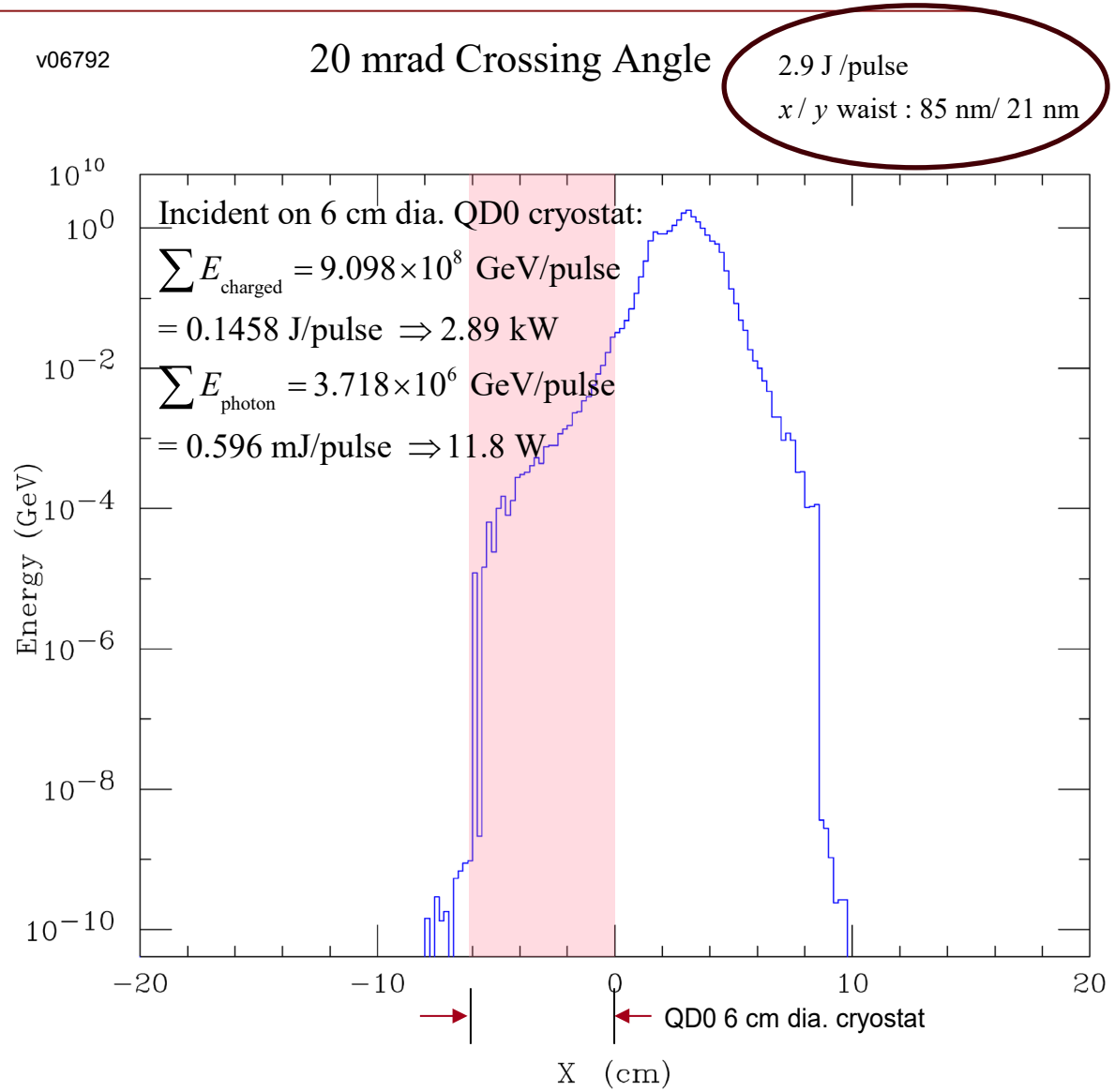




Conclude from CAIN that 24 mrad is more comfortable than 20 mrad and 34 mrad is overkill

# XCC $\gamma\gamma$ Collider $\sqrt{s} = 125$ GeV

Increase horizontal laser spot size from 21 nm to 42 (85) nm to better match $\sigma_x = \sigma_z \alpha_c / 2$. Increase pulse energy to maintain laser photon density




20 mrad will work if collimators are installed to protect QD0; must study size of collimator backscatter into detector

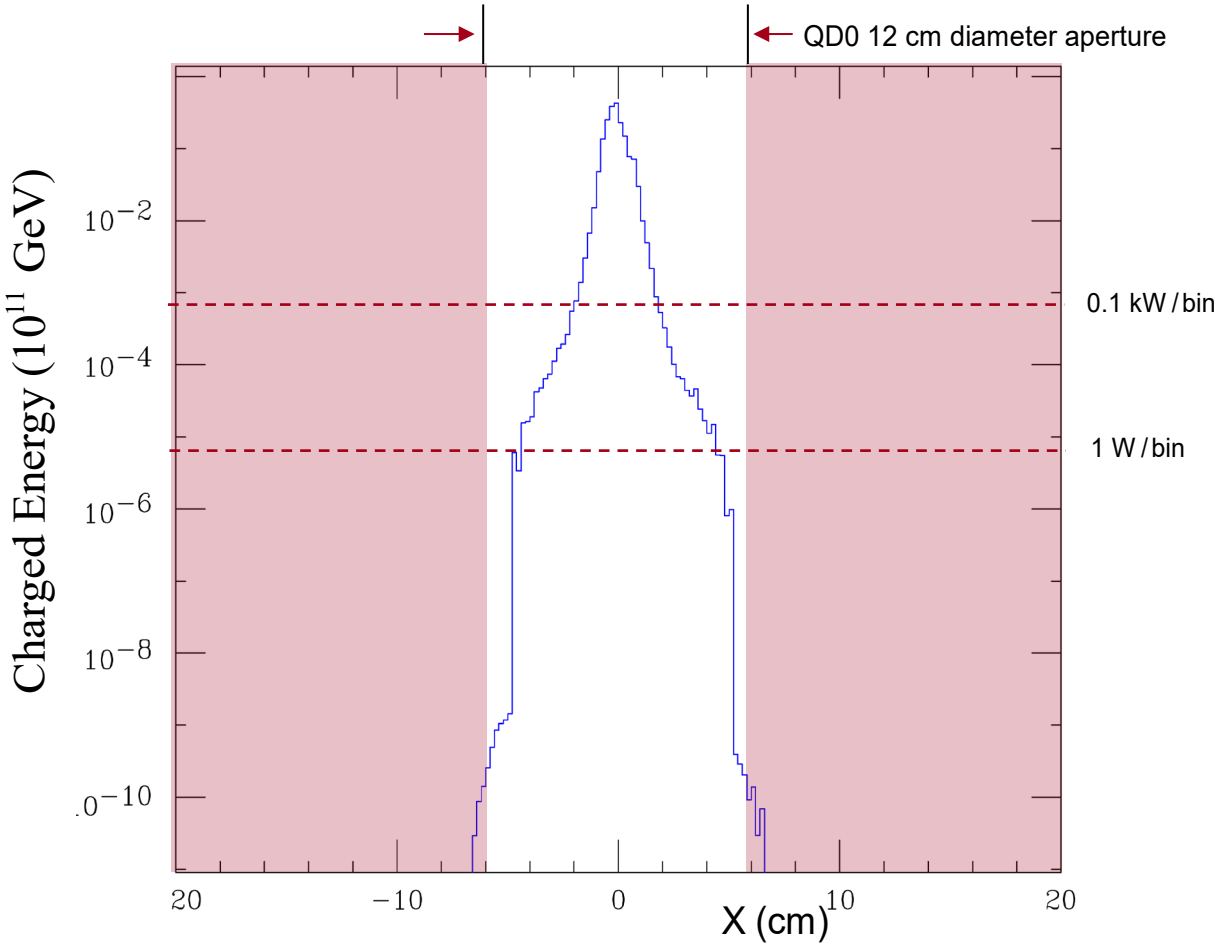
# 2 mrad crossing angle, L*=1.5 m

CAIN Simulation from IP to Face of Quad at L*=1.5 m, Assume 5 T Solenoid

Incident on Triplet Cryostat:

$\sum E_{\text{charged}} = 4.2306 \times 10^{2}$ GeV/pulse

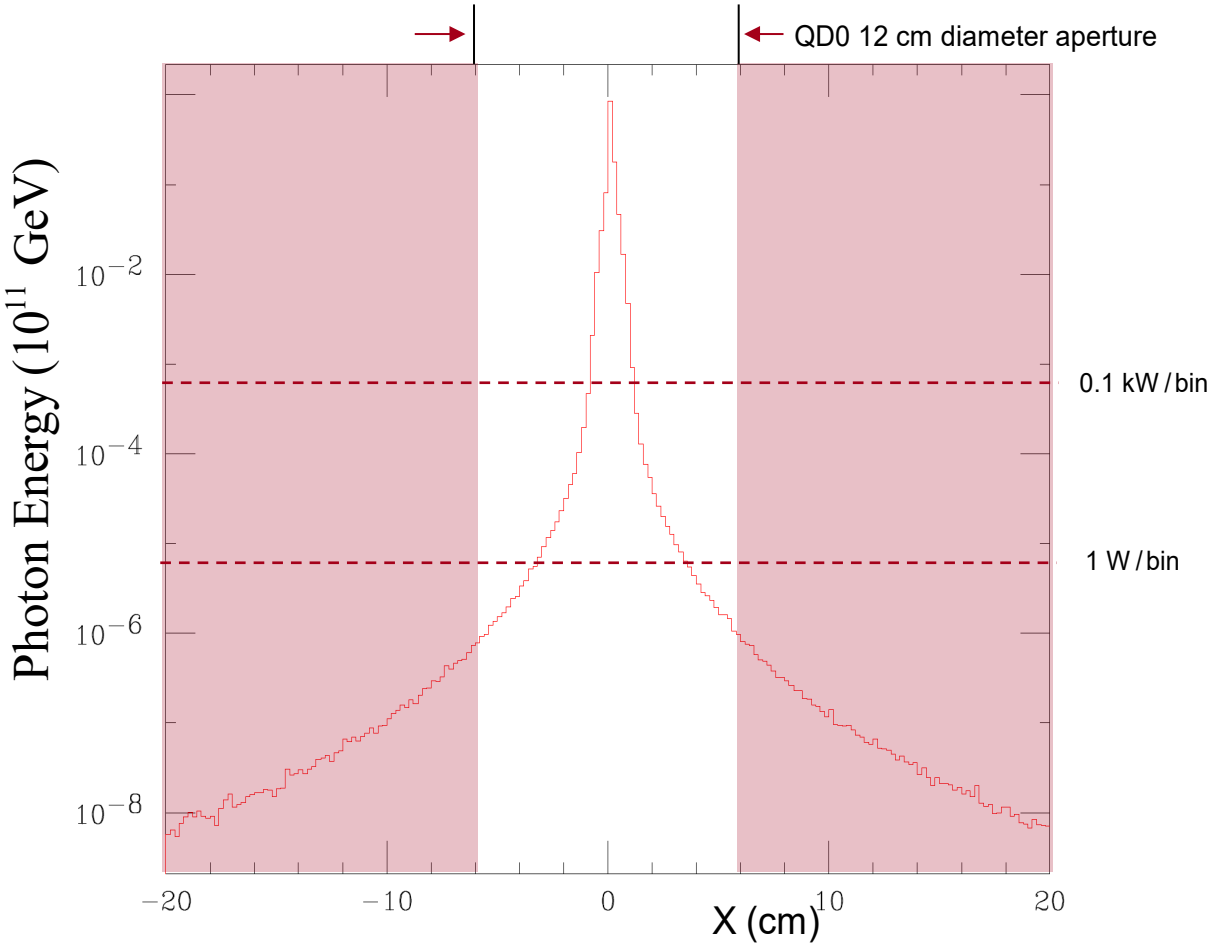
$= 0.07\ \mu$J/pulse $\Rightarrow 0.001$ W




Incident on Triplet Cryostat:

$\sum E_{\text{photon}} = 4.2306 \times 10^{2}$ GeV/pulse

$= 0.29$ mJ/pulse $\Rightarrow 5.8$ W



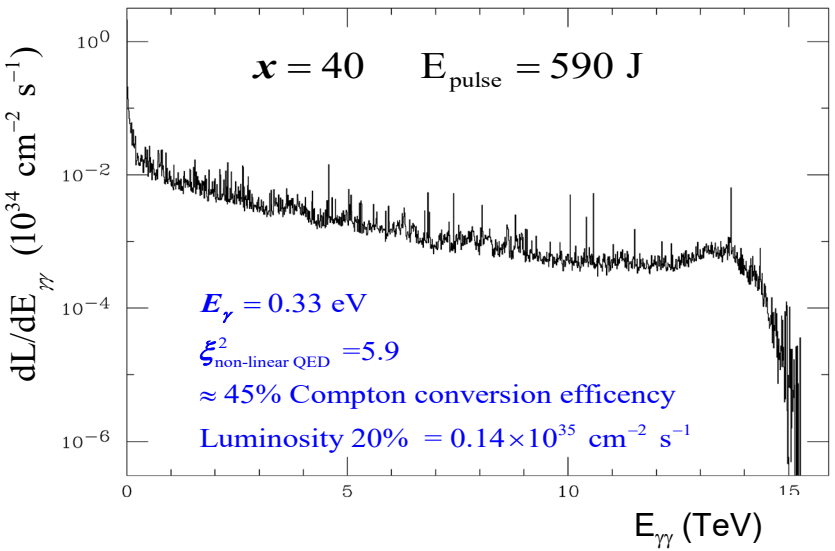

Solution requires large aperture HL-LHC-like final triplet. Significant departure from usual e+e- collider design

# 10 TeV PWFA $\gamma\gamma$ Colldier

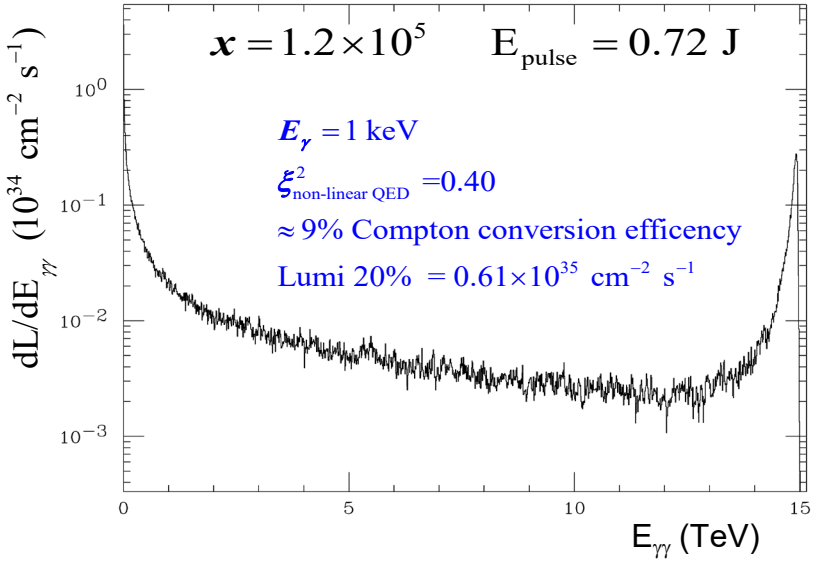
# 10 TeV PWFA γγ Collider

| Technology | PWFA | γγ PWFA |
|---|---|---|
| Aspect Ratio | Round | Round |
| CM Energy | 15 | 15 |
| Single beam energy (TeV) | 7.5 | 7.5 |
| Gamma | 1.47E+07 | 1.4E+07 |
| Emittance X (mm mrad) | 0.1 | 0.12 |
| Emittance Y (mm mrad) | 0.1 | 0.12 |
| Beta* X (m) | 1.50E-04 | 0.30E-04 |
| Beta* Y (m) | 1.50E-04 | 0.30E-04 |
| Sigma* X (nm) | 1.01 | 0.48 |
| Sigma* Y (nm) | 1.01 | 0.48 |
| N_bunch (num) | 5.00E+09 | 6.2E+09 |
| Freq (Hz) | 7725 | 7725 |
| Sigma Z (um) | 5 | 5 |
| Geometric Lumi (cm^2 s^1) | 1.50E+36 | 6.58E+36 |

In limited survey of configs, XFEL lasers give the best luminosity spectra for multi-TeV PWFA γγ colliders.




Unscattered $e^-$ from Compton IP have full beam energy. Runaway coherent $e^+e^-$ pair-production due to positrons pinching the electron beams: fields as high as 0.6 ×Schwinger




$e^-$ from Compton IP have much reduced energy due to multiple trident $e^-\gamma \to e^-e^+e^-$ . EM fields are 3 orders of magnitude smaller.

# 2nd Interaction Region Accelerator Tasks

- Investigate feasibility of collimators for 20 mrad crossing angle. If this works, then this would be the preferred crossing-angle since it makes everything more "normal": standard aperture quads, easier to design laser and e- beamlines, extraction is easier, ...

- Need to decide between high-brightness gun vs. damping ring, and choose parameters.

- What is our XFEL e- beam? Do we kick out every other bunch as in XCC? If so, how do we deal with the bunch length?

- What is our concept for the beam dumps? In particular what is the concept for the 1 keV , 1 Joule/pulse XFEL dump?

- Develop e- and XFEL beam parameter table for 2nd interaction region XFEL $\gamma\gamma$ collider.