

# Ultrahigh Intensity Lasers at the ILC: Applications and Fundamental Physics

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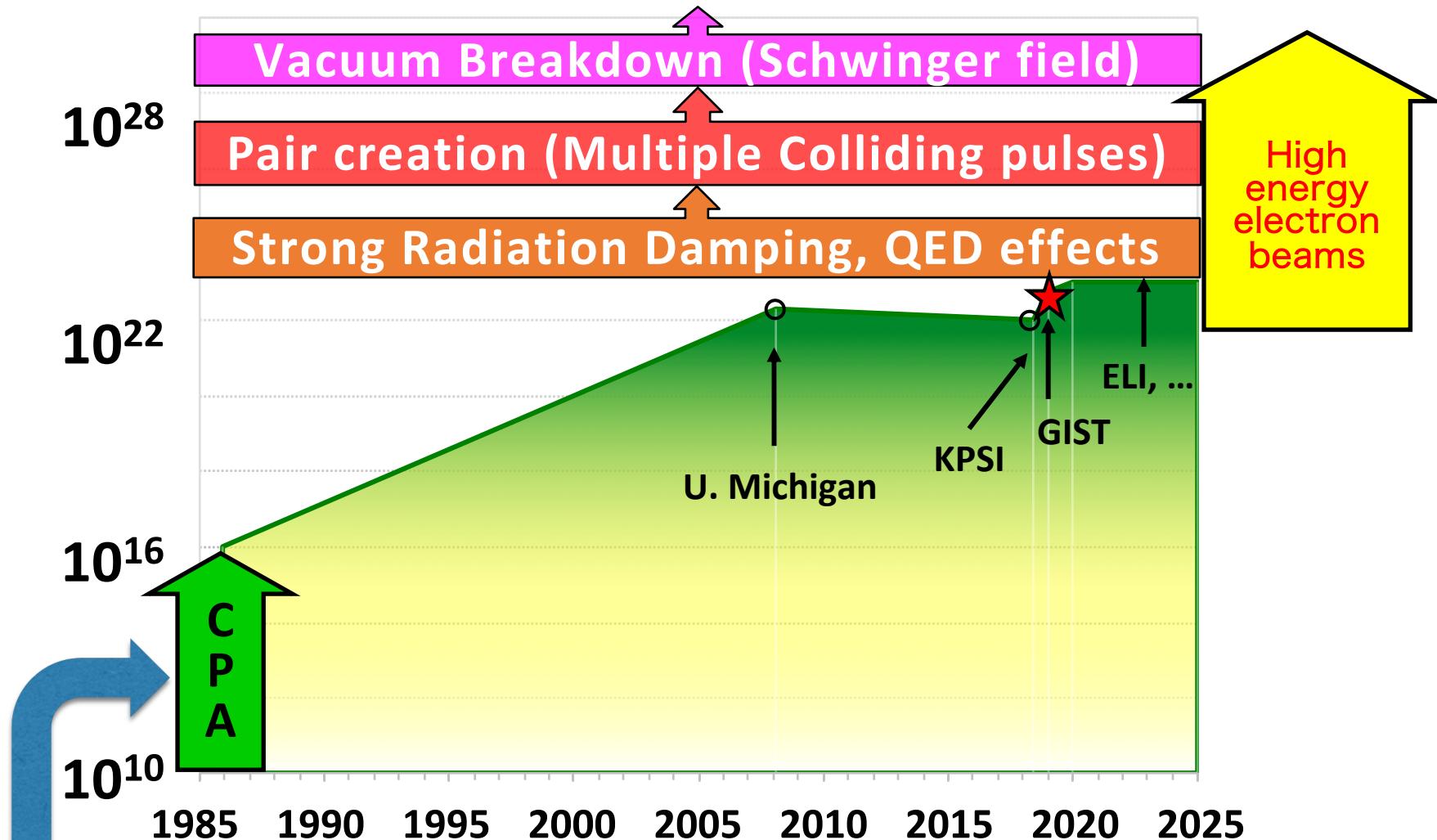
# Introduction

- ❖ Green ILC
- ❖ 500 GeV Beam Dumps 18 MW [4.5 GW peak]  
(ILC TDR, P. Satyamurthy et al. NIMA 2012)
  - Water - radioactivation, gas generation, heating, ...
  - Gas – long distance 1000 m
- ❖ Plasma decelerator or plasma beam dump  
(Wu et al., PRSTAB 2010, Bonatto et al., POP 2015, Hanahoe et al., POP 2017)
  - Beams decelerated over short distance, large decelerating fields
  - The front part of electron/positron bunch not decelerated.

## New proposal

- ❖ Using a High Intensity Laser in addition to beam dump
- 1. X-FEL Facilities: SACLAC, LCLS, EXFEL,... → High Power Laser systems
- 2. The interaction of very high energy electrons with intense lasers is one of the active research fields in high-field science!

# Peak Laser Intensity ( $\text{W}/\text{cm}^2$ )



# Radiative Electron Dynamics

❖ Radiation reaction dominant regime

$$\frac{d\mathbf{p}_e}{dt} = q \left( \mathbf{E} + \frac{\mathbf{p}_e \times \mathbf{B}}{m_e c \gamma_e} \right) + \mathbf{F}_{rad}$$

$$\frac{d\mathbf{x}}{dt} = \frac{\mathbf{p}_e}{m_e \gamma_e}$$

$$\mathbf{F}_{rad} = G_e \mathbf{f}_{rad}$$

$$\begin{aligned} \mathbf{f}_{rad} = & \frac{2e^3}{3m_e c^3 \gamma} \left\{ (\partial_t + \mathbf{v} \cdot \nabla) \mathbf{E} + \frac{1}{c} [\mathbf{v} \times (\partial_t + \mathbf{v} \cdot \nabla) \mathbf{B}] \right\} \\ & + \frac{2e^4}{3m_e^2 c^4 \gamma} \left\{ \mathbf{E} \times \mathbf{B} + \frac{1}{c} [\mathbf{B} \times (\mathbf{B} \times \mathbf{v}) + \mathbf{E}(\mathbf{v} \cdot \mathbf{E})] \right\} \\ & - \frac{2e^4}{3m_e^2 c^5} \gamma^2 \mathbf{v} \left\{ \left( \mathbf{E} + \frac{\mathbf{v} \times \mathbf{B}}{c} \right)^2 - \left( \frac{\mathbf{v} \cdot \mathbf{E}}{c} \right)^2 \right\} \end{aligned}$$

$$G_e(\chi_e) \approx \frac{1}{(1 + 8.93\chi_e + 2.41\chi_e^2)^{2/3}}$$

$$\chi_e = \frac{\gamma_e}{E_S} \sqrt{\left( \mathbf{E} + \frac{\mathbf{p}_e \times \mathbf{B}}{m_e c \gamma_e} \right)^2 - \left( \frac{\mathbf{p}_e \cdot \mathbf{E}}{m_e c \gamma_e} \right)^2}$$

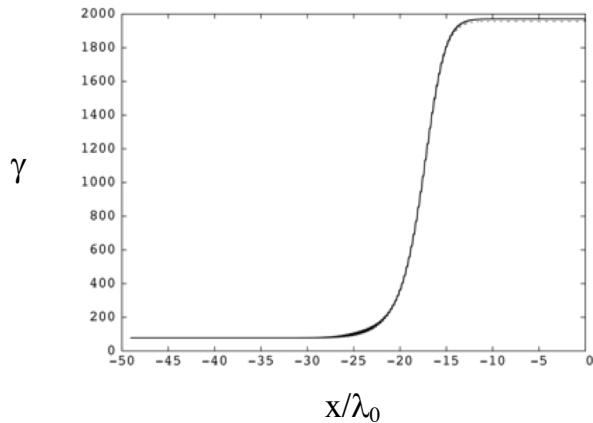
**G<sub>e</sub>** QED  
weakening  
of damping

$$E_S = \frac{m_e^2 c^3}{e \hbar}$$

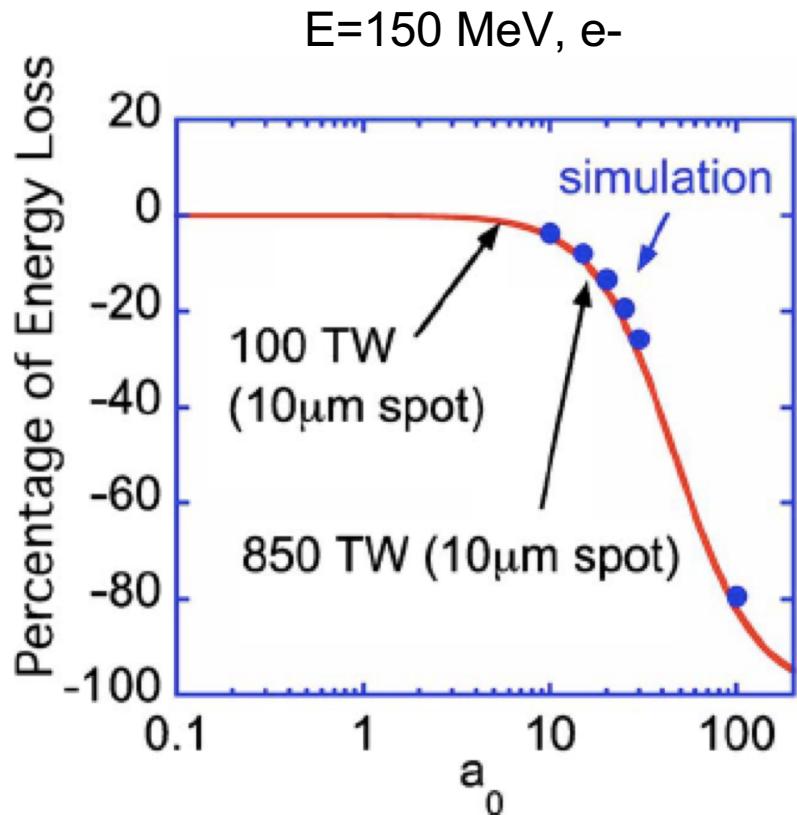
# Strong Radiation damping

J. Koga, T. Zh. Esirkepov, and S. V. Bulanov, Phys. Plasmas 12, 093106 (2005)

## ❖ Classical case



- 1 GeV electron stops ~3 cm in lead
- Converts > 95% to Bremsstrahlung.
- Nearly 4000 times longer



$$a_0 = \frac{eE}{mc\omega} = \left( \frac{\lambda[\mu\text{m}]}{1} \right) \sqrt{\frac{I[\text{W/cm}^2]}{1.37 \times 10^{18}}}$$

# Problems

- ❖ Classical radiation damping regime
- ❖ In linear colliders electron energies are very high (125 GeV), thus we enter the quantum regime and nonlinear QED regime.
- ❖ This regime itself is an active subject of high-field science.
- ❖ highly dissipative

# QED Parameters

- Gamma emission from electron, positron and EM wave interaction

$$\chi_e = \frac{\gamma_e}{E_S} \sqrt{\left( \mathbf{E} + \frac{\mathbf{p}_e \times \mathbf{B}}{m_e c \gamma_e} \right)^2 - \left( \frac{\mathbf{p}_e \cdot \mathbf{E}}{m_e c \gamma_e} \right)^2}. \quad E_S = \frac{m_e^2 c^3}{e \hbar} \approx 10^{18} V/cm$$

- Pair creation from photon-EM wave collision

$$\chi_\gamma = \frac{\hbar}{E_S m_e c} \sqrt{\left( \frac{\omega_\gamma}{c} \mathbf{E} + \mathbf{k}_\gamma \times \mathbf{B} \right)^2 - \left( \mathbf{k}_\gamma \cdot \mathbf{E} \right)^2}.$$

see: S. V. Bulanov, et al., Nucl. Instr. Meth. A 660, 31 (2011)  
and references cited therein

# Strong Damping and Pair creation

$$\chi_e, \chi_\gamma > 1$$

- ❖ Laser pulse collision with counterpropagating electron or photon [1]

$$a > \frac{2}{3} \frac{\alpha}{\gamma_{e,\gamma} \epsilon_{rad}} \quad \epsilon_{rad} \equiv 4\pi r_e / 3\lambda_0$$

125 and 250 GeV ( $\gamma_e = 2.4 \sim 4.9 \times 10^5$ )

$$a \approx 1.35(3.9 \times 10^{18} \text{W/cm}^2) \text{ or } a \approx 0.67(9.7 \times 10^{17} \text{W/cm}^2)$$

- ❖ Moderate Intensity laser!

- ❖ However, Quantum effects large  
→ significant reduction [2]

[1] S. V. Bulanov, et al., Nucl. Instr. Meth. A 660, 31 (2011)

[2] C. P. Ridgers, et al., J. Plasma Phys. 83, 715830502 (2017)

# SIMLA code

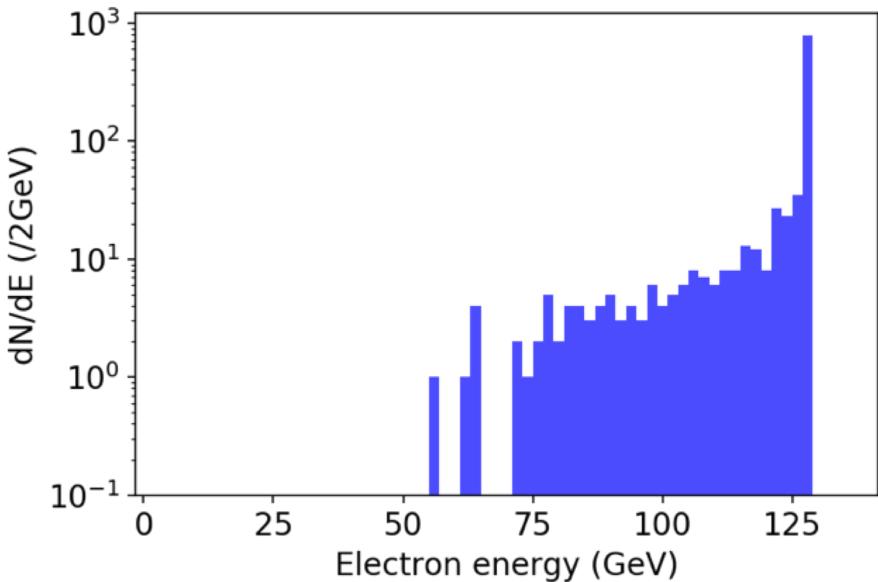
- ❖ Green and Harvey, Com. Phys. Comm. 192, 313 (2015)

<https://github.com/cnharvey/SIMLA>

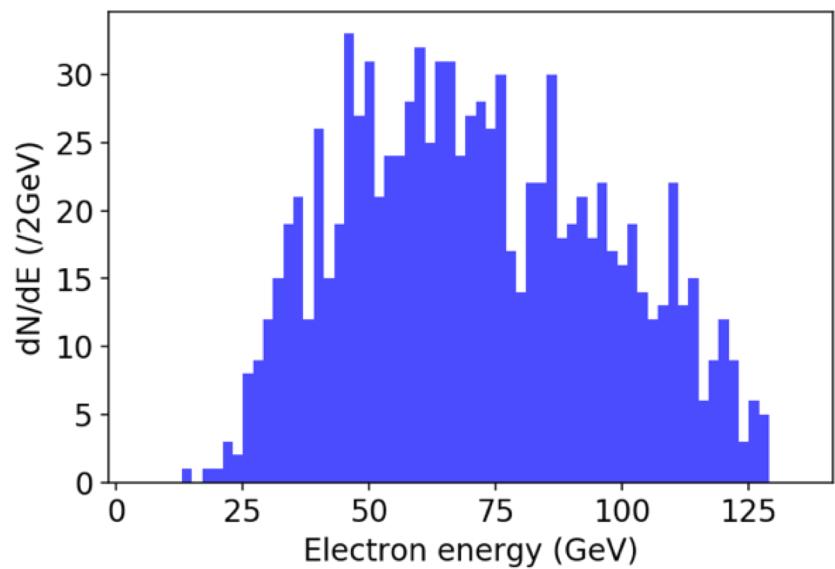
- ❖ Dynamics and emission spectra of charged particles
- ❖ Intense laser fields
- ❖ Both classical and quantum radiation reaction.
- ❖ Solves the
  - ❖ Landau-Lifshitz equation or
  - ❖ photon emission using strong-field quantum-electrodynamics amplitudes via Monte-Carlo.
- ❖ **Pair creation not included**

# SIMLA results: 127.5 GeV e-

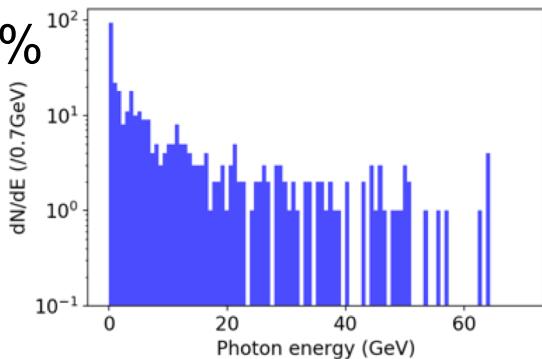
❖ RUN000:  $a_0=0.6$ , 50fs, N=1000



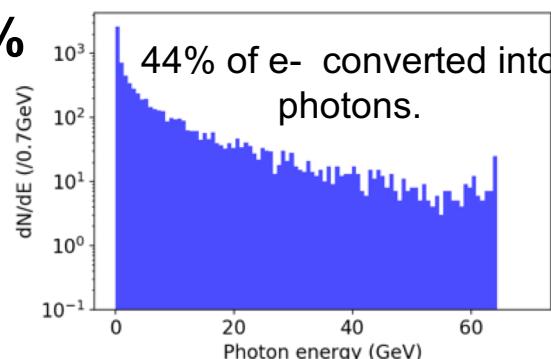
❖ RUN001:  $a_0=0.6$ , 1ps, N=1000



❖ e-Dump 3.16%



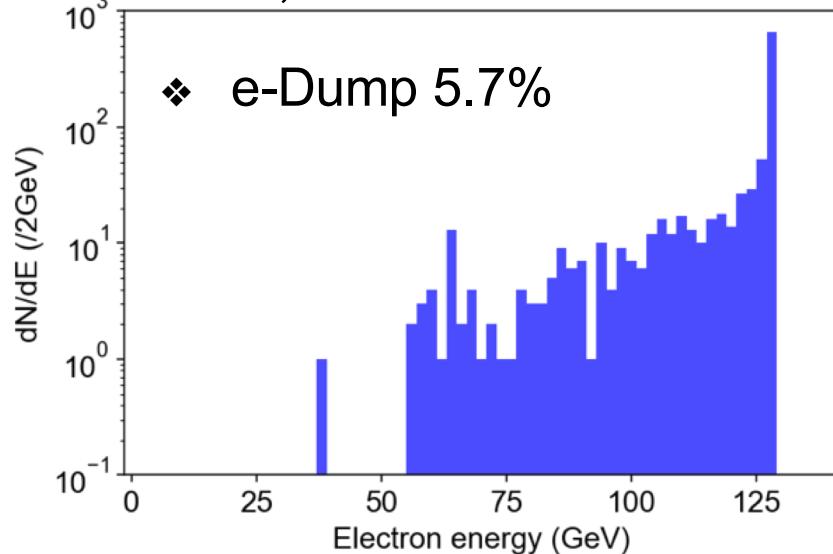
❖ e-Dump 44%



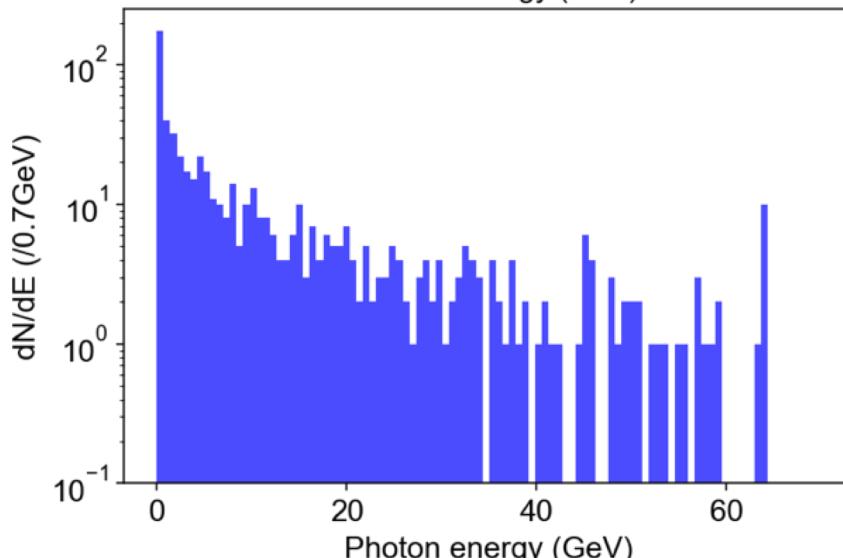
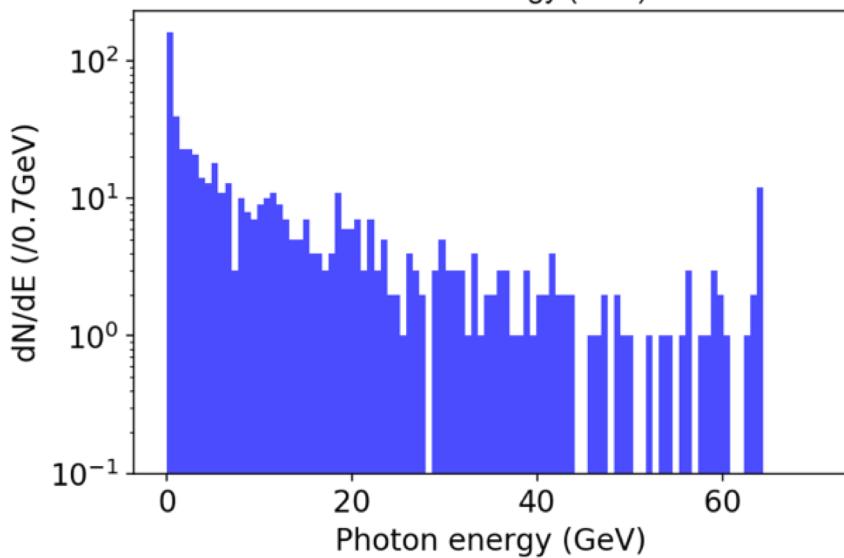
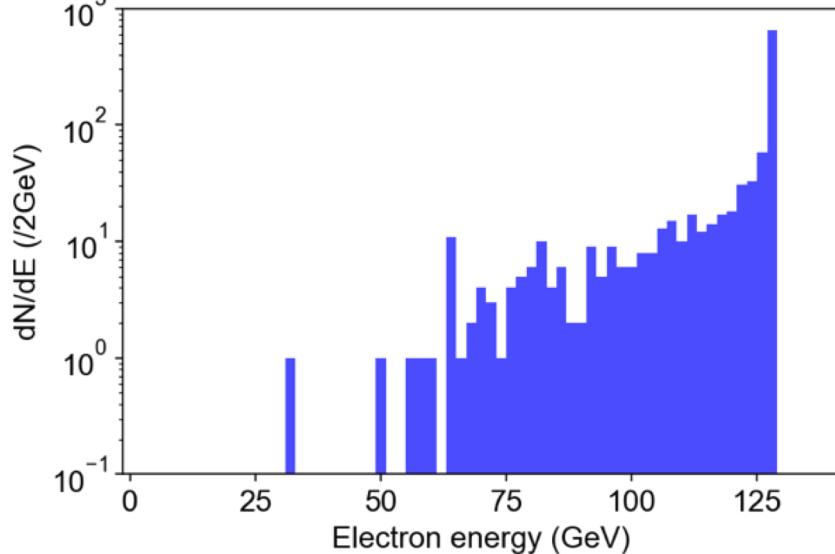
► Longer pulse duration is better

# SIMLA results: circular polarization

- ❖ RUN002:  $a_0=0.6$ , 50fs,  
 $N=1000$ , circ

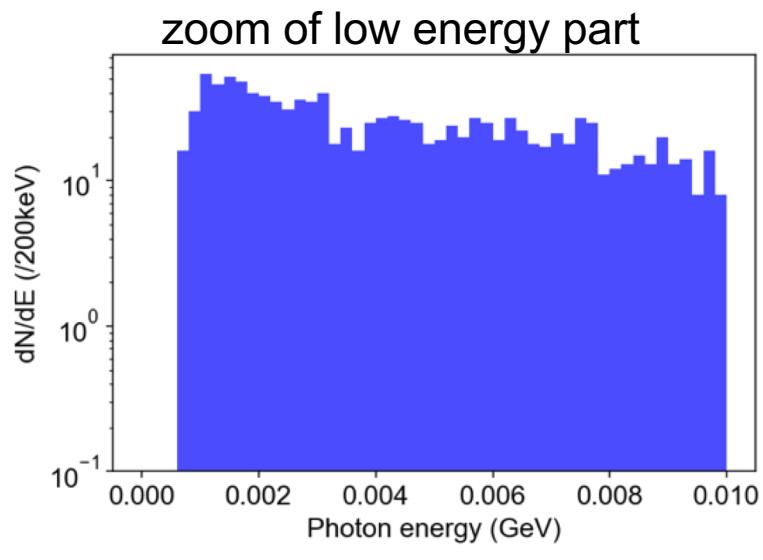
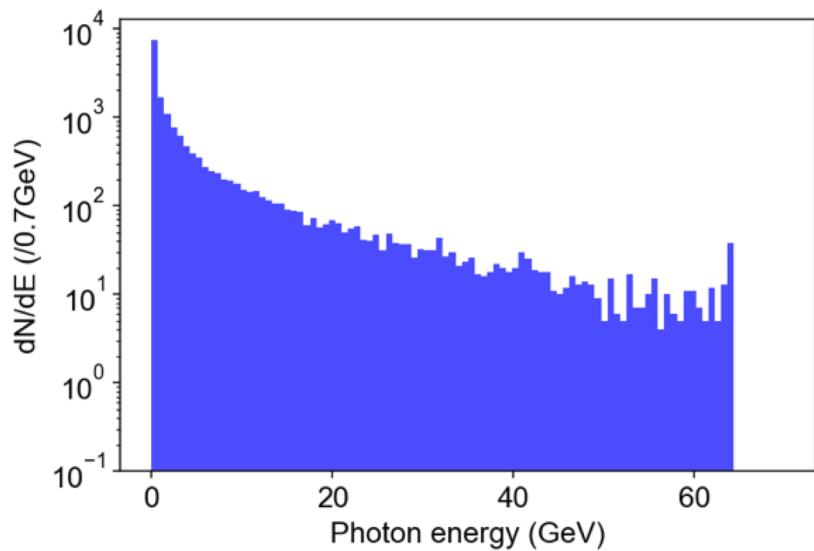
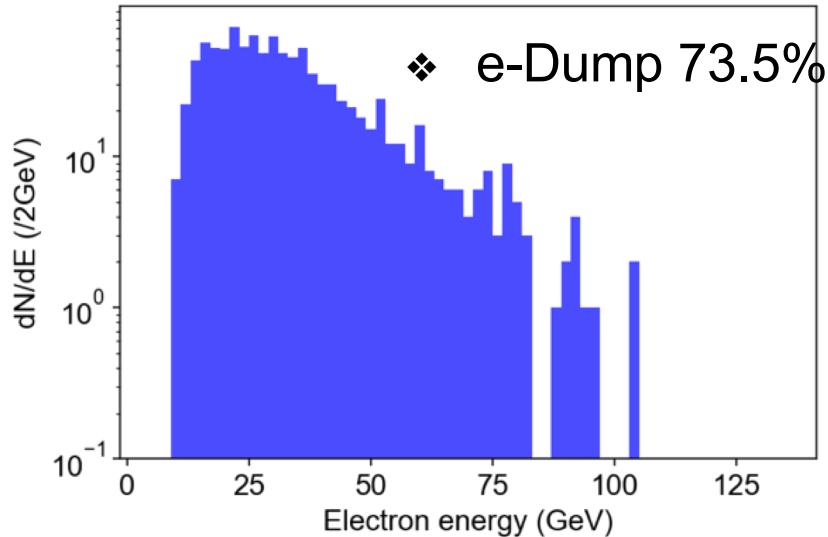


- ❖ RUN003:  $a_0=0.65$ , 50fs,  
 $N=1000$ , circ



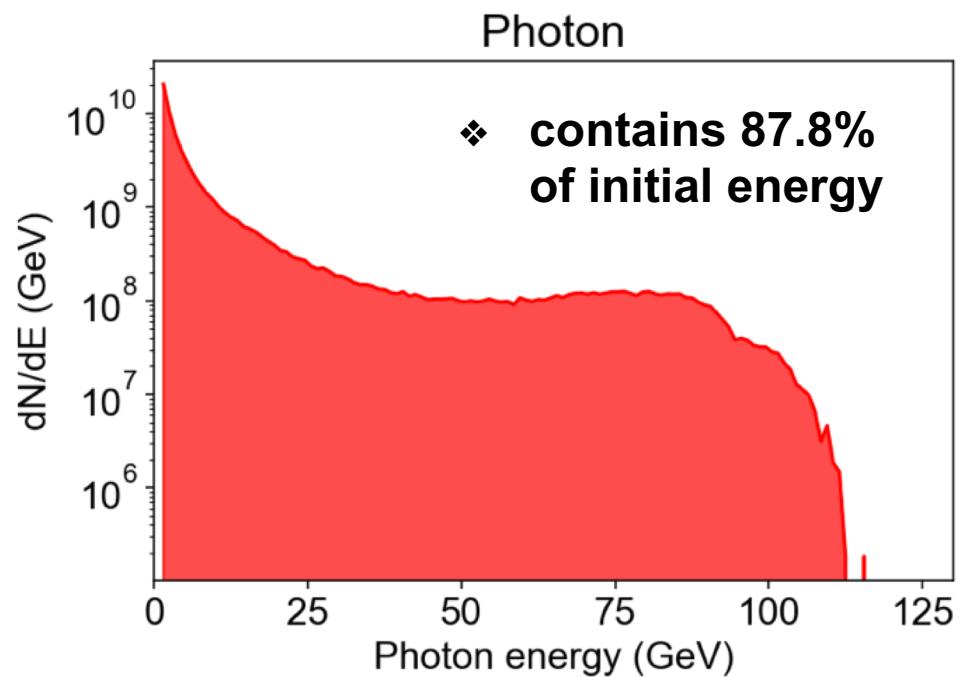
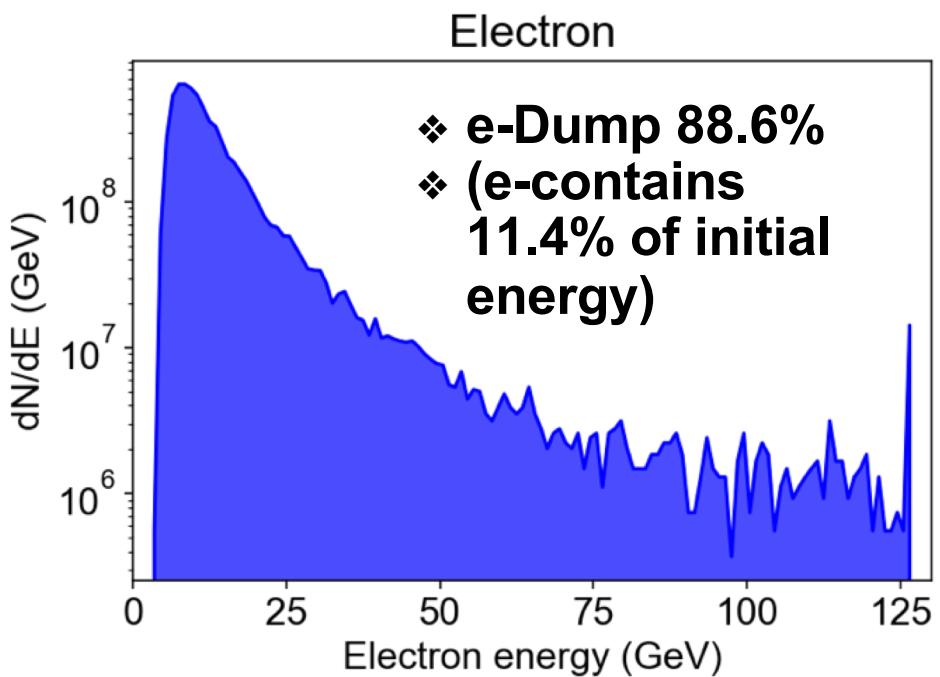
# SIMLA: longer pulse duration

- ❖ RUN004:  $a_0=0.65$ , 1.5ps,  
 $N=1000$ , circ

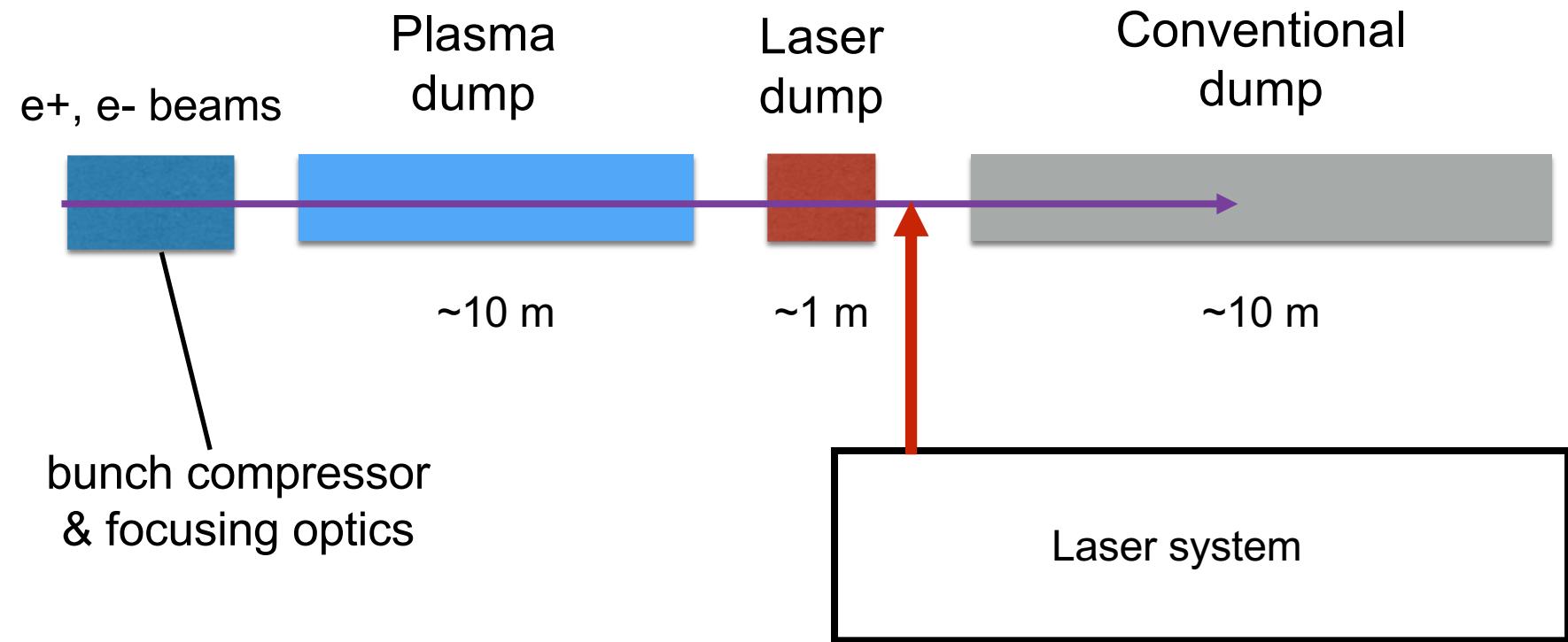


# CAIN 2.42 results: 125 GeV e<sup>-</sup>

- ❖  $a_0=1.73$ ,  $6.5 \times 10^{18}$  W/cm<sup>2</sup>
- ❖  $\tau=0.766$  ps,  $\lambda=800$ nm, circ.pol.
- ❖ MP=50000



# Hybrid dump or plasma research facility



# Conclusions

- ❖ Substantial conversion of beam energy to  $e^+e^-$  possible at ILC Beam dumps
- ❖ Moderate intensity lasers
- ❖ Simulations show possibility

## Next steps

- Particle-in-cell with QED effects
  - J. Magnusson et al., PRL **122** (2019).
  - Shower cascade, prolific  $e^+e^-$  production
  - $e^+e^-$  plasma interacting with plasma
  - Plasma instabilities, nuclear fusion, transmutation...
- **Energy recovery!**