Beam-Beam Considerations for Multi-TeV Colliders

Outcomes from Snowmass and new simulation efforts

Spencer Gessner, Tim Barklow,
Glen White, Michael Peskin, SLAC
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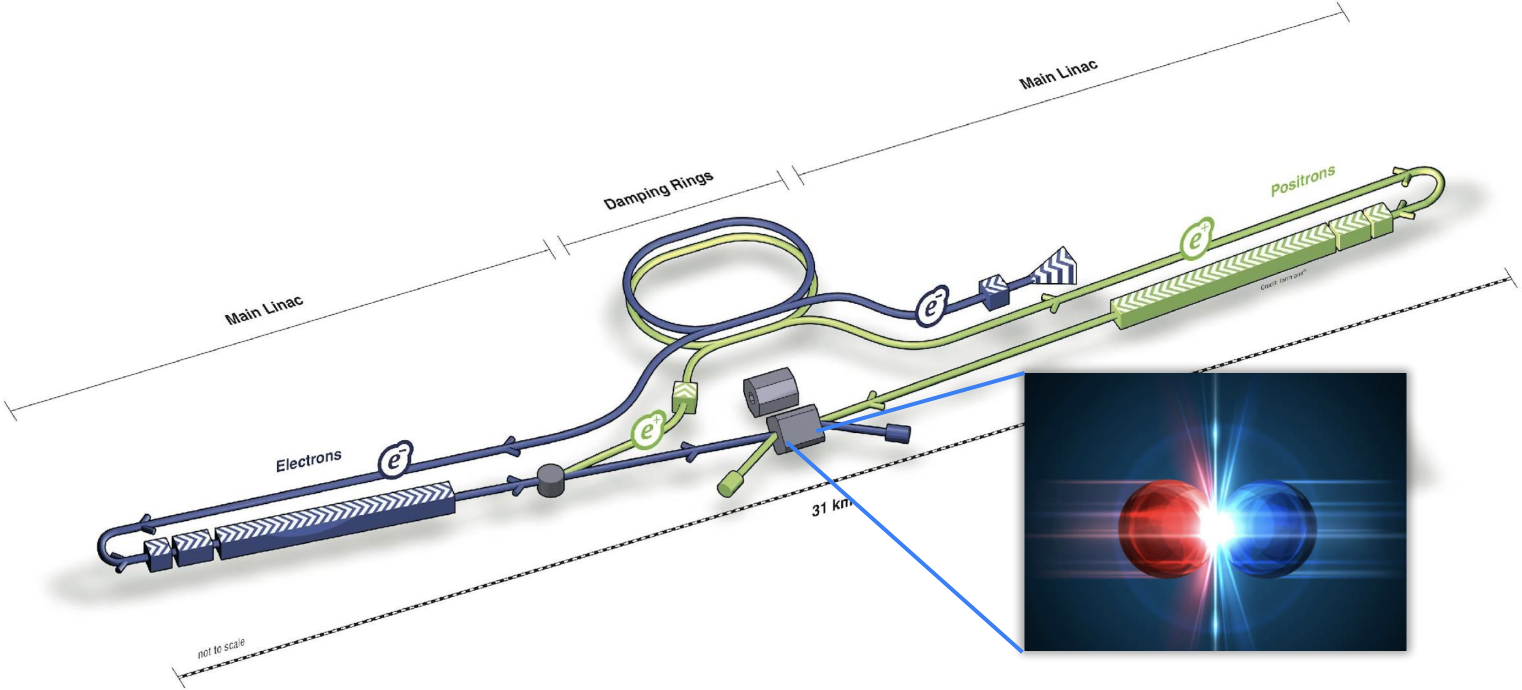
November 10, 2022

SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

Beam-Beam Interactions



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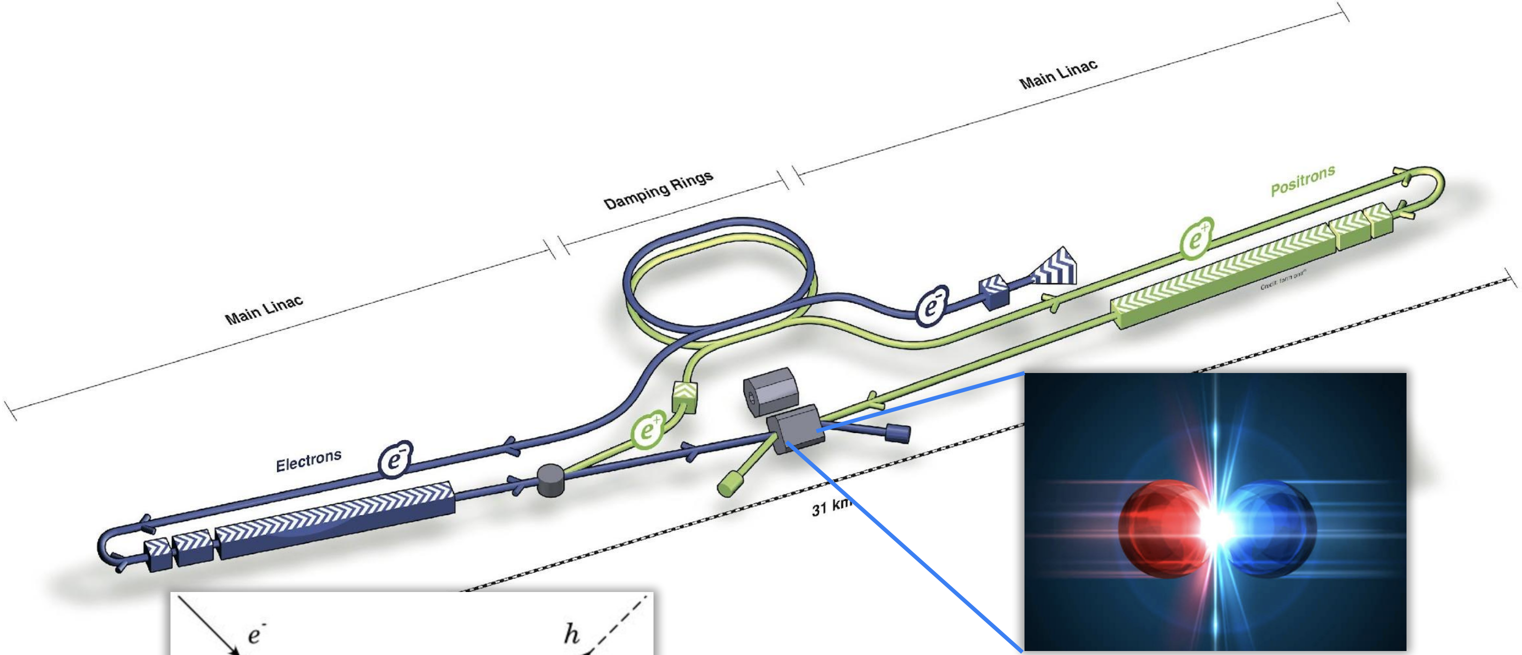

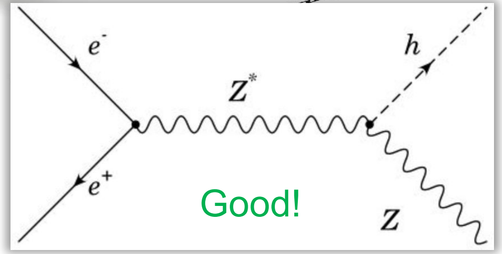

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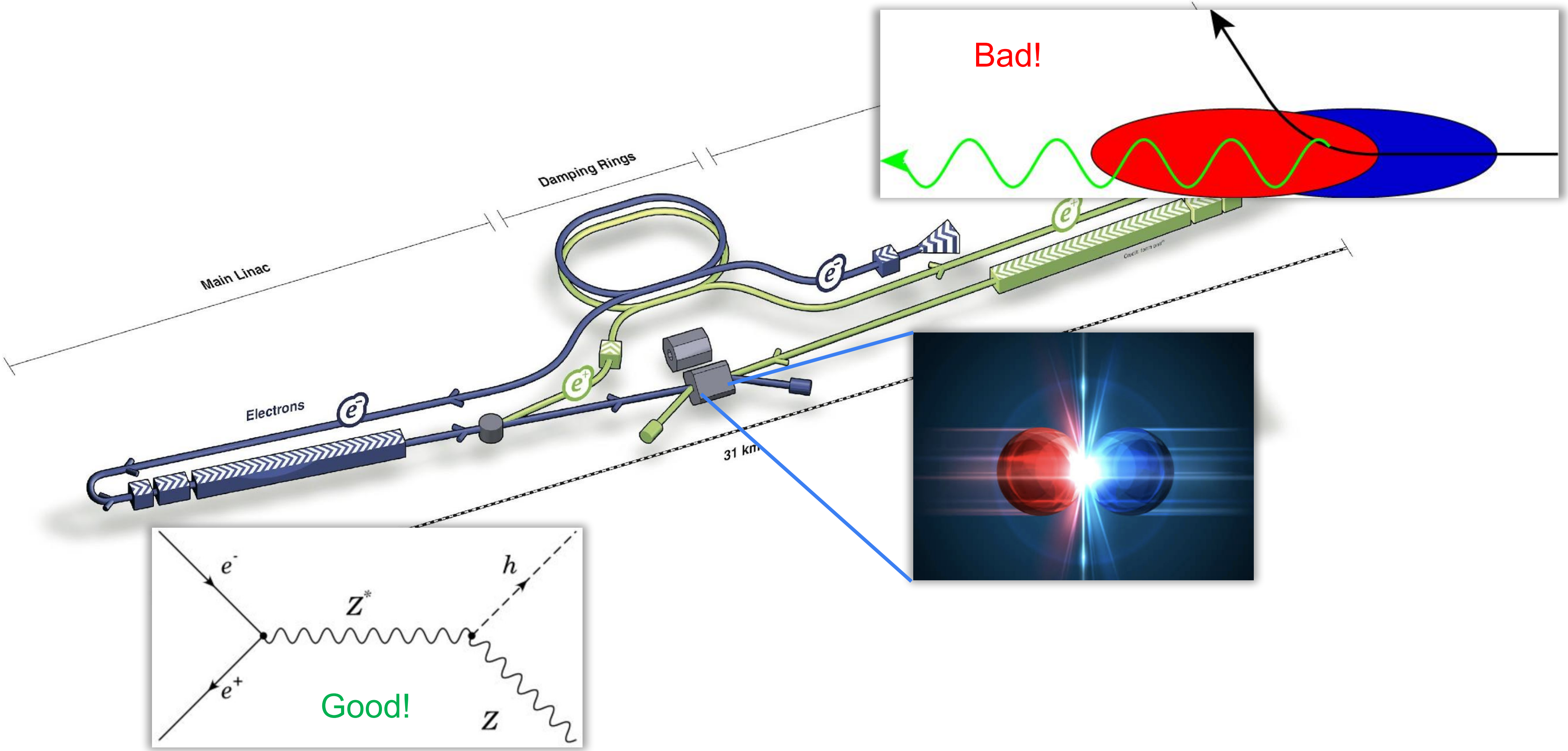


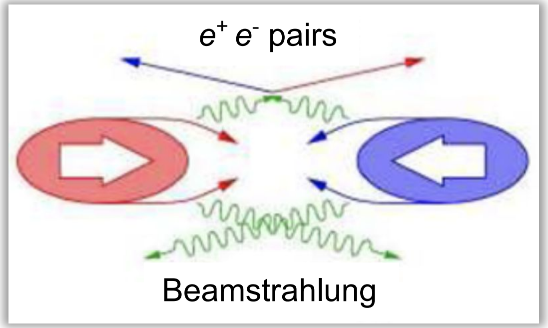
Beamstrahlung and Luminosity Spectrum

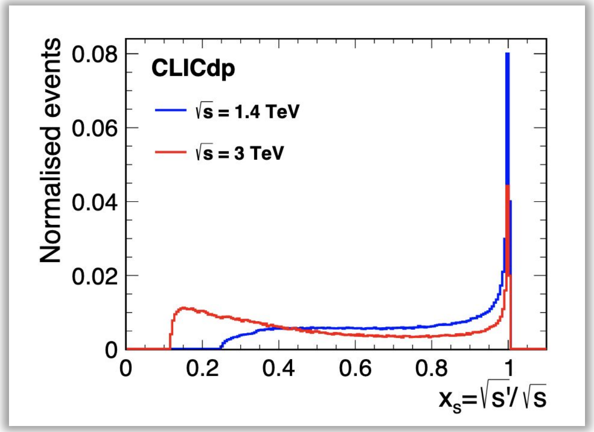
What is beamstrahlung?

- Incoming particles are focused by the field of the opposing beam and emit synchrotron radiation.
- The fields are enormous! The colliding particles emit hard photons.

Why is it a problem?

- The particles can lose a significant fraction of energy.
- The beamstrahlung photons create e^+e^- pairs which are backgrounds in the detector





https://arxiv.org/abs/1807.02441

The Beamstrahlung Parameter

The beamstrahlung parameter characterizes the strength of beam-beam interaction with respect to the Schwinger critical field:

$$\Upsilon = \frac{2}{3}\frac{\hbar\omega_c}{\mathcal{E}} = \gamma\frac{\langle E + cB\rangle}{B_c}$$

$$B_c = m_e^2 c^2/(e\hbar) = 4.4140\,\mathrm{GT}$$

Classical $\Upsilon \ll 1$

Quantum $\Upsilon \gg 1$

The number of photons emitted n_γ per particle can be estimated from the beamstrahlung parameter and is a proxy for the energy spectrum of the beam at collision.

$$\langle\Upsilon\rangle \approx \frac{5}{6}\frac{N r_e^2 \gamma}{\alpha\sigma_z(\sigma_x + \sigma_y)}$$

$$n_\gamma \approx 2.54\frac{\alpha^2\sigma_z}{r_e\gamma}\langle\Upsilon\rangle^{2/3}$$

Typically $n_\gamma < 2$

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Classical Υ

Quantum Υ

$$\frac{\mathcal{L}}{P_b} \propto \frac{\gamma^{1/2} n_\gamma^{3/2}}{\sqrt{\sigma_z}} \frac{1}{\sqrt{\varepsilon_y \beta_y}} \frac{1}{E_b}$$

$$B_c = m_e^2 c^2/(e\hbar) = 4.4140\,\mathrm{GT}$$

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Typically $n_\gamma < 2$

AAC Community has considered this before

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **15**, 051301 (2012)

Beamstrahlung considerations in laser-plasma-accelerator-based linear colliders

C. B. Schroeder, E. Esarey, and W. P. Leemans

Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

(Received 23 November 2011; published 4 May 2012)

Beam-beam interaction constraints modify the basic plasma density scalings for a linear collider based on laser-plasma accelerators. In the quantum beamstrahlung regime, it is shown that operating at low plasma density increases beamstrahlung effects, owing to the higher bunch charge and longer bunch length. At high plasma density, the bunch charge is limited by beam loading, and the required power is proportional to the square root of the plasma density. At low plasma density, the bunch charge is limited by beamstrahlung, which, for fixed luminosity, requires operation at higher laser repetition rate and, hence, higher power requirements, or the use of multibunch trains. If round beams are used in a multibunch train format with fixed beam loading, and the collider is constrained by beamstrahlung, then the required collider power is independent of plasma density.

DOI: 10.1103/PhysRevSTAB.15.051301 PACS numbers: 52.38.Kd, 41.75.Lx

AAC Community has considered this before

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Outline

- Discussions at Snowmass
- Challenges for Beam-Beam Interactions at multi-TeV
- New Directions with Beam-Beam Simulations

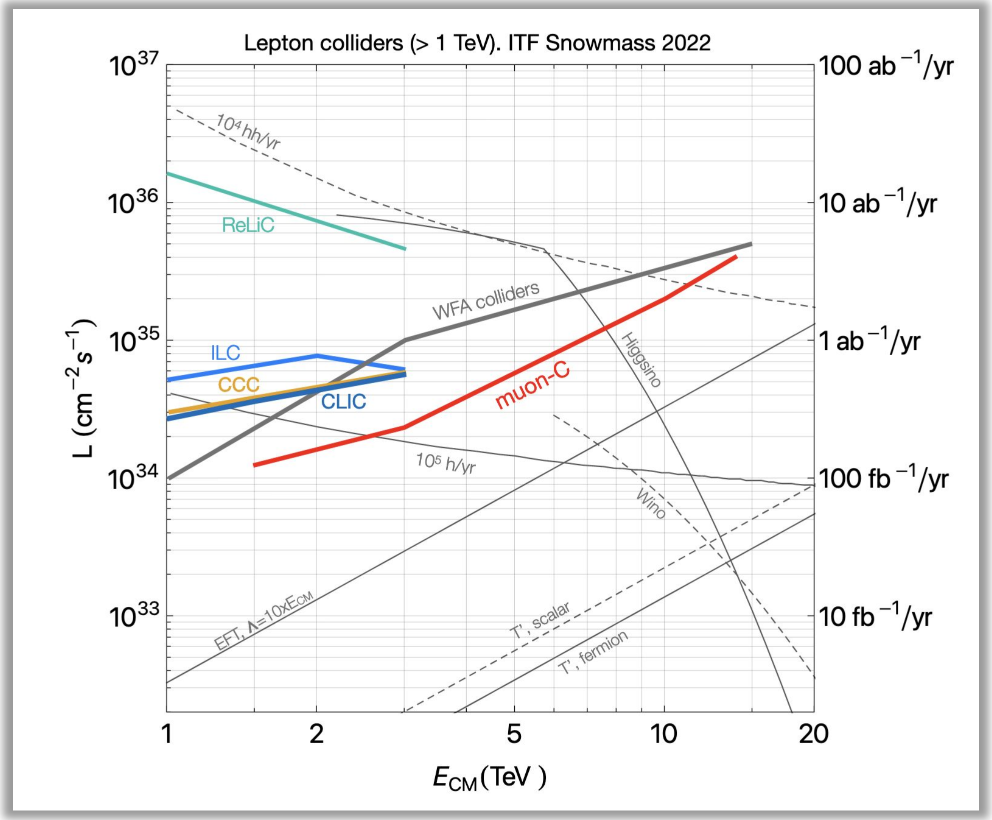
The Snowmass Process

https://arxiv.org/abs/2208.06030

The Advanced Accelerator Community (PWFA, LWFA, SWFA) provided input to the Implementation Task Force on parameters for future multi-TeV Lepton Colliders.

We adopted a unified set of parameters:

- 1 TeV CM @ 1 × 10^{34} cm^{-2} s^{-1}
- 3 TeV CM @ 10 × 10^{34} cm^{-2} s^{-1}
- 15 TeV CM @ 50 × 10^{34} cm^{-2} s^{-1}



Our message to Snowmass:

A high-energy linear collider can rival the discovery potential of FCC-hh.

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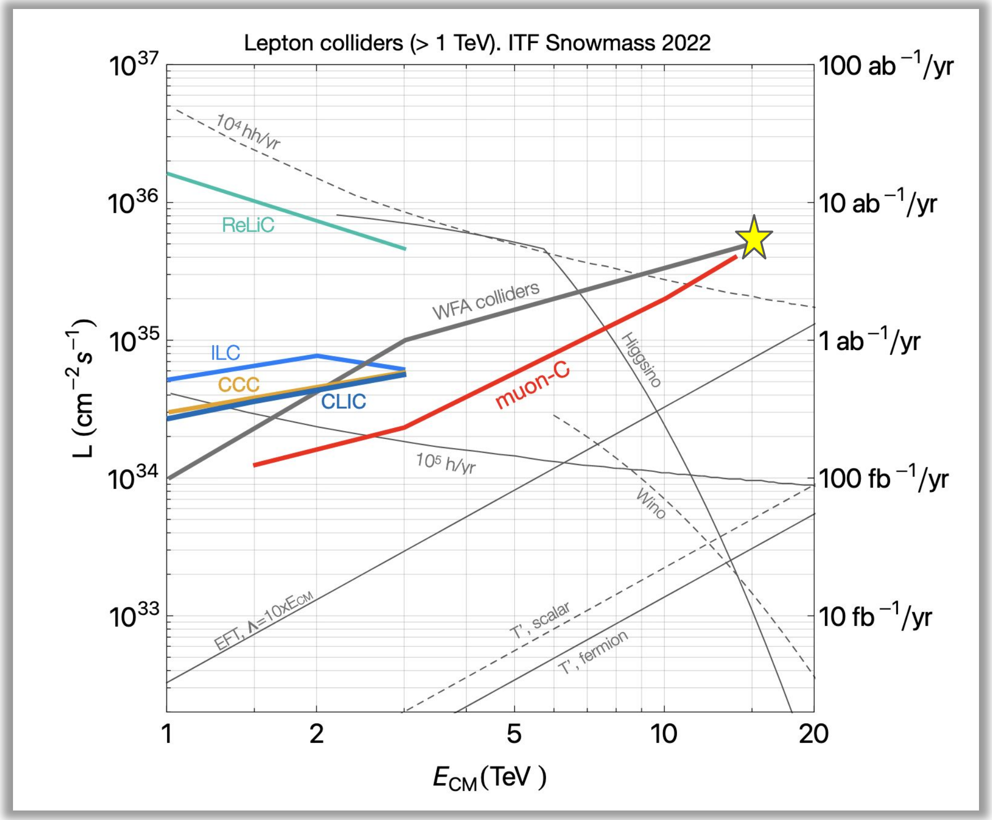


Feedback from Snowmass:

- What facility power is required for the highest luminosities?
- Are beamstrahlung effects properly considered at highest collision energies?

Luminosity and Power

Geometric Luminosity

$$\mathcal{L} = \frac{fN^2}{4\pi\sigma_x\sigma_y}$$

Site Power

$$P_{tot} = \frac{P_b}{\eta} = \frac{fNE_b}{\eta}$$

Efficiency

Figure of Merit

$$\frac{\mathcal{L}}{P_{tot}} = \frac{\eta N}{4\pi\sigma_x\sigma_y E_b}$$

Flat Beam Collisions

Linear Colliders use *flat beams*.

Why collide flat beams?

- Damping rings produce beams with $\varepsilon_x \gg \varepsilon_y$.
- Flat beams reduce the electromagnetic fields experienced by the opposing beam for a fixed beam area.

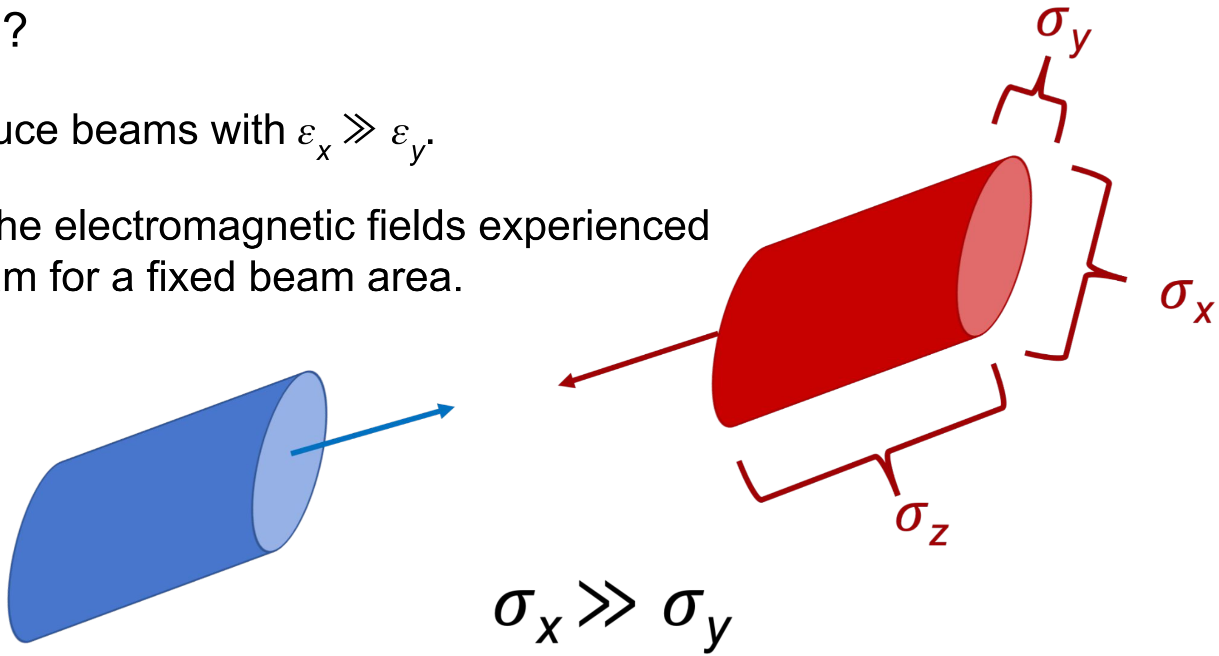


Figure of Merit

The Wakefield Accelerator concepts assumed “CLIC-like” flat-beam parameters scaled to 15 TeV CM.

Although ambitious, this scaling is unsatisfactory at very high energy.

The 15 TeV machine requires site power in excess of 1 GW.

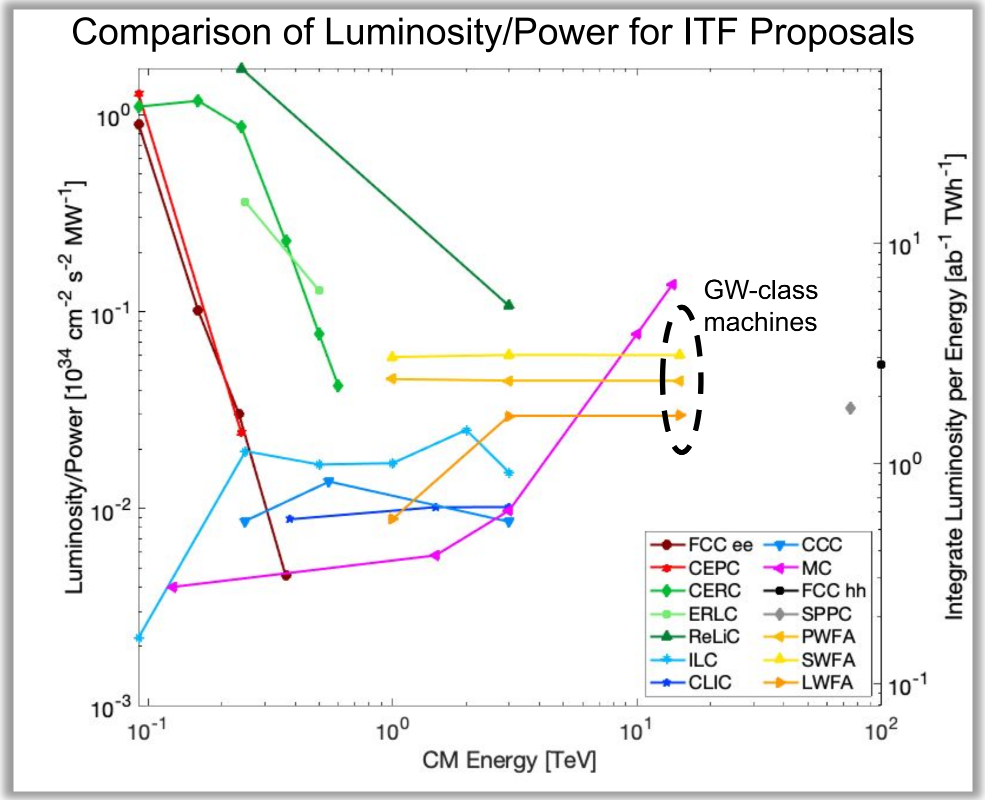
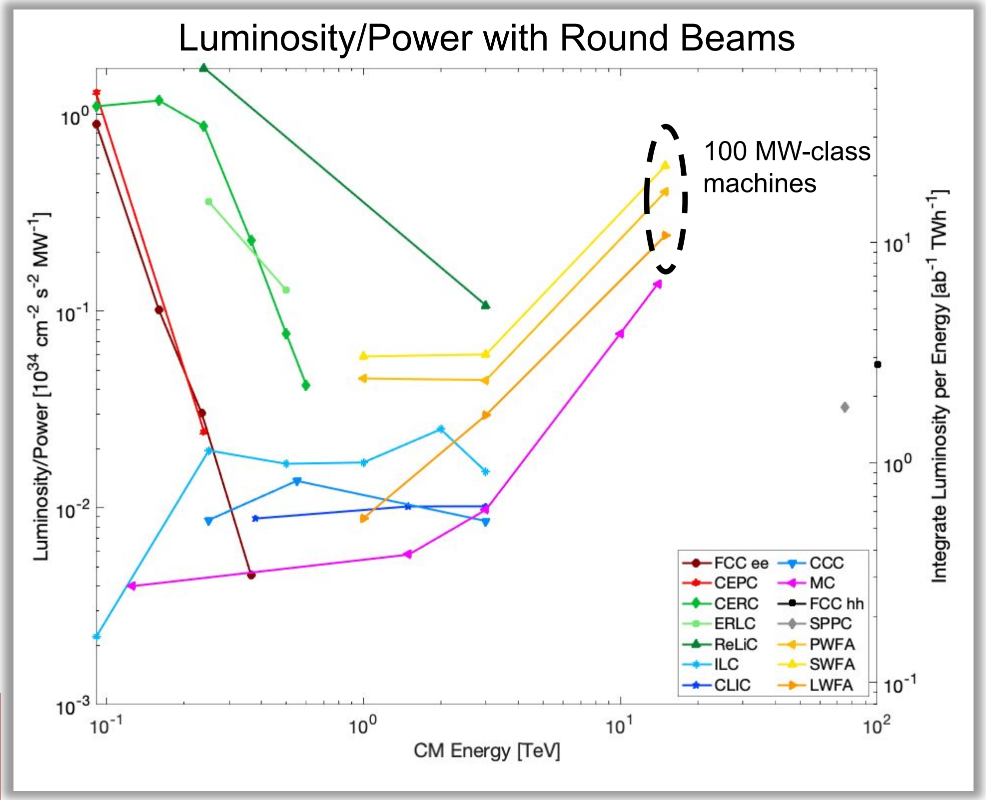


Figure of Merit

Optimistic approach:

- Why not use *round beams* in the collisions?

By reducing horizontal spot size by an order of magnitude, there is a matched improvement in luminosity for fixed beam power.



The round beam approach increases beamstrahlung, but a broader luminosity spectrum is tolerable for a discovery machine.

Attempt to Increase Luminosity and Reduce Power

	PWFA 1 TeV (Flat)	PWFA 3 TeV (Flat)	PWFA 15 TeV (Flat)	PWFA 15 TeV (Round)
Single beam energy (TeV)	0.5	1.5	7.5	7.5
Gamma	9.78E+05	2.94E+06	1.47E+07	1.47E+07
Emittance X (mm mrad)	0.66	0.66	0.66	0.1
Emittance Y (mm mrad)	0.02	0.02	0.02	0.1
Beta* X (m)	5.00E-03	5.00E-03	5.00E-03	1.50E-04
Beta* Y (m)	1.00E-04	1.00E-04	1.00E-04	1.50E-04
Sigma* X (nm)	58.07	33.53	14.99	1.01
Sigma* Y (nm)	1.43	0.83	0.37	1.01
N_bunch (num)	5.00E+09	5.00E+09	5.00E+09	5.00E+09
Freq (Hz)	4200	1.40E+04	14000	2575
Sigma Z (um)	5	5	5	5
Beamstrahlung param	1.49E+01	7.76E+01	8.67E+02	6.59E+03
n_gamma	1.49E+00	1.49E+00	1.49E+00	5.75E+00
Single Beam Power (MW)	1.7	16.8	84.1	15.5
Two Beam Power (MW)	3.4	33.6	168.2	30.9
Geo. Lumi (cm^-2 s^-1)	1.01E+34	1.01E+35	5.03E+35	5.01E+35
Beamstrahlung lumi	1.99E+34	1.99E+35	9.94E+35	5.07E+35
Photon lumi				
Wall plug to drive laser/beam eff	0.4	0.4	0.4	0.4
Laser/beam drive to main eff	0.375	0.375	0.375	0.375
Wall plug to main beam eff	0.15	0.15	0.15	0.15
Site power Wall to main only (MW)	22.4	224.3	1,121.5	206.3
Lumi/Power (1e34/MW)	**0.04**	**0.04**	**0.04**	**0.24**

These parameters reduce Luminosity in 1%

Attempt to Increase Luminosity and Reduce Power

Define "Luminosity in 20%" as a reasonable metric for a discovery machine.

	PWFA 1 TeV (Flat)	PWFA 3 TeV (Flat)	PWFA 15 TeV (Flat)	PWFA 15 TeV (Round)
	0.5	1.5	7.5	7.5
	9.78E+05	2.94E+06	1.47E+07	1.47E+07
	0.66	0.66	0.66	0.1
	0.02	0.02	0.02	0.1
	5.00E-03	5.00E-03	5.00E-03	1.50E-04
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Sigma Z (um)	5	5	5	5
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n_gamma	1.49E+00	1.49E+00	1.49E+00	5.75E+00
Single Beam Power (MW)	1.7	16.8	84.1	15.5
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Geo. Lumi (cm^-2 s^-1)	1.01E+34	1.01E+35	5.03E+35	5.01E+35
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Wall plug to drive laser/beam eff	0.4	0.4	0.4	0.4
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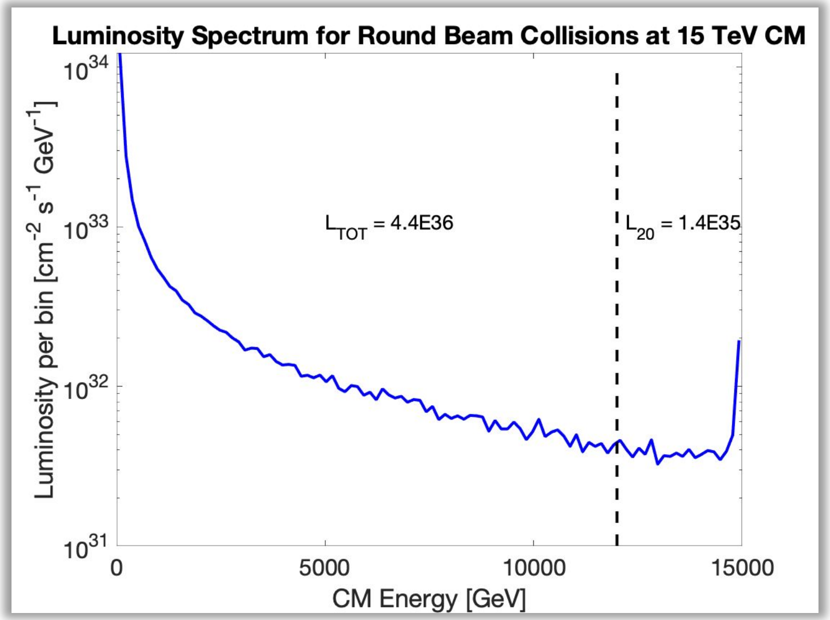
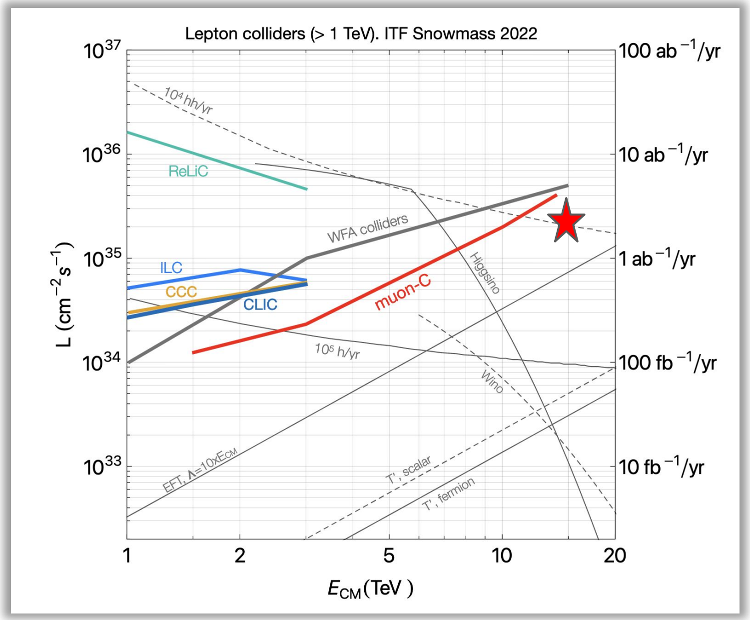
These parameters reduce Luminosity in 1%

Simulations in GUINEA-PIG

Round e^+e^- collisions in GUINEA-PIG, G. Cao, U. of Oslo

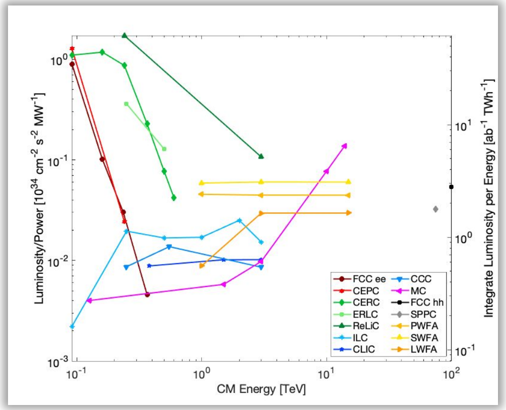




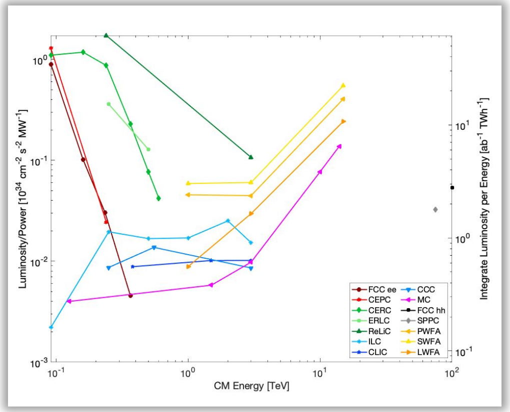
Using the parameters from the previous table and the “Luminosity in 20%” figure-of-merit, we miss our target by a factor of 3.

Figure of Merit with Luminosity Spectrum

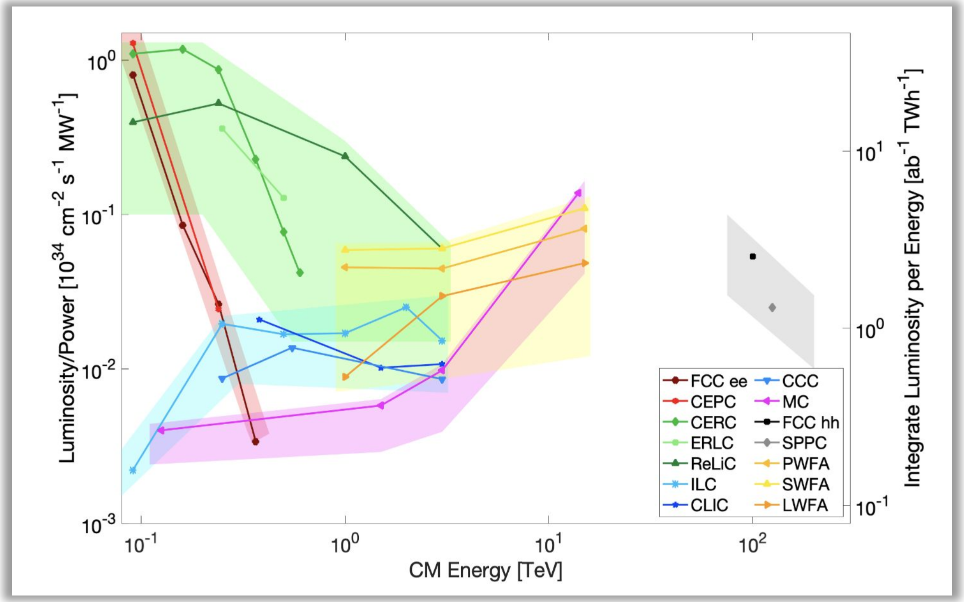
Flat Beams



Round Beams Full Lumi



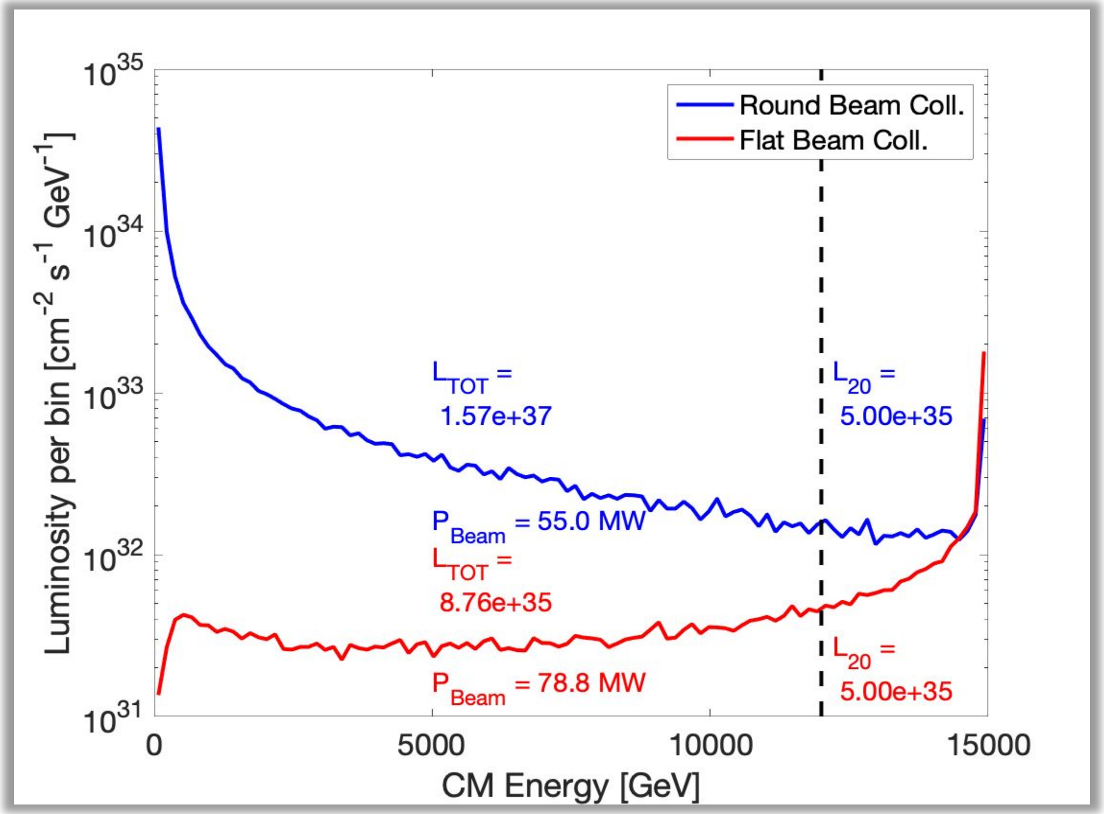
Final Version for ITF Report



https://arxiv.org/abs/2208.06030

Round beams do not provide huge improvement

Although total luminosity increases by a factor of 18, luminosity in 20% only increases by a factor of 1.4.



GUINEA-PIG simulations by Gevy Cao, University of Oslo

Alternatives. . .

Gamma-Gamma Colliders (T. Barklow)

https://arxiv.org/pdf/2203.08484.pdf

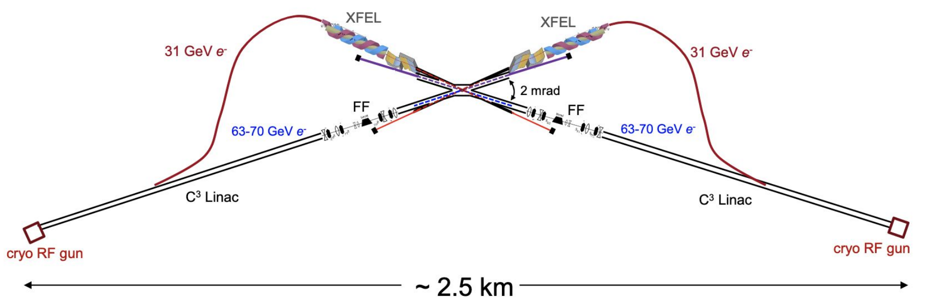
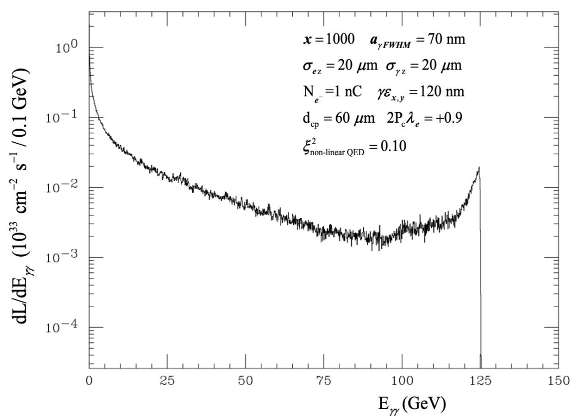


Figure 1: Schematic of XCC including cryogenic RF injector, C^3 Linac, electron beam final focus (FF) and XFEL.



The XCC is the lowest-energy, most-compact collider proposal for a Higgs Factory.

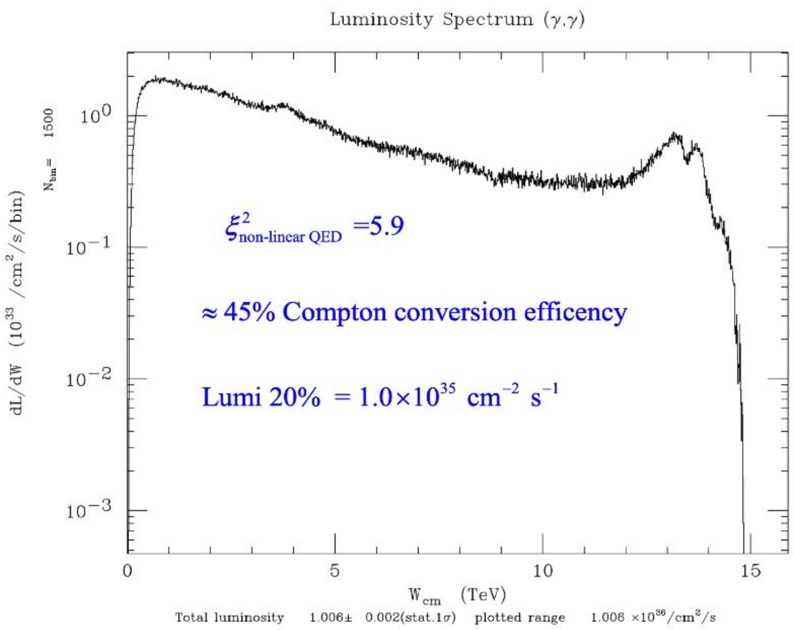
Novel approach: use x-ray beam instead of laser at Compton IP.

Does it scale to 15 TeV?

T. Barklow, CAIN

While the gamma-gamma collider avoids beamstrahlung between colliding photon beams, there are other affects that degrade the luminosity spectrum:

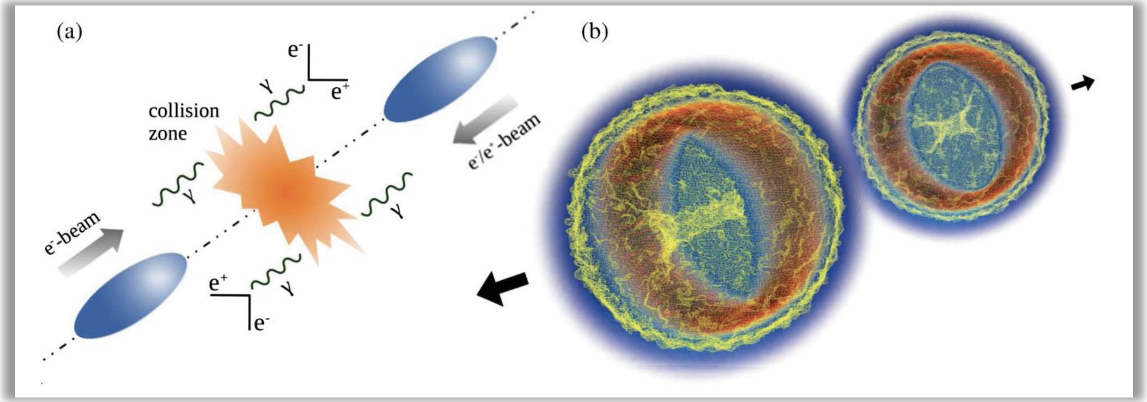
- Non-linear QED at Compton -> multi-photon interaction.
- Secondary particles travel with beam -> creates backgrounds.
- Interactions between photons and electrons in colliding beams reduces luminosity.



Comparable luminosity/power to flat-beam parameter set.

Ultrashort Bunch Collisions

V. Yakimenko, S. Meuren,
https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.122.190404



Ultra-short bunches (10 nm) suppress beamstrahlung.

Possible to simplify collider concept by colliding electron beams with electron beams (effectively a photon collider).

Neutralizing the beam

Particle Accelerators, 1990, Vol. 34, pp. 89–104
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PLASMA SUPPRESSION OF BEAMSTRAHLUNG

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Accelerator and Fusion Research Division, Lawrence Berkeley Laboratory, University of California, 1 Cyclotron Road, Berkeley, CA 94720

JOHN J. STEWART and SIMON S. YU‡

Lawrence Livermore National Laboratory, University of California, Livermore, CA 94550

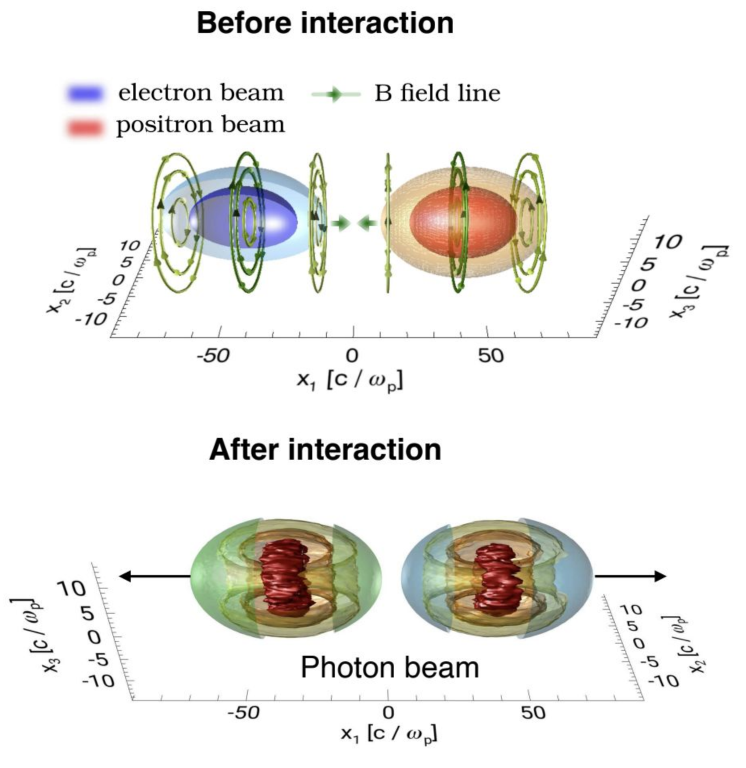
(Received February 10, 1989; in final form July 5, 1989)

Current neutralization in a plasma at the interaction point of an electron-positron collider is considered for the purpose of suppressing beamstrahlung. Conditions are derived for good current neutralization by plasma return currents, and the results of numerical simulations confirming the theory are reported. Parameters are presented for a TeV-class Linear Collider (TLC) employing plasma compensation. The problem of beam-plasma background reactions is noted.

Simulation Challenges

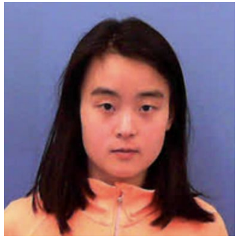
- In addition to GUINEA-PIG and CAIN, there are new PIC codes that can be used to model beam-beam interactions.
- Challenges include:
  - Tracking 1000X secondary particles per initial particle.
  - Beam disruption due to intense electron-positron secondary plasma.
  - Proper modeling of all QED effects.

T. Grismayer: OSIRIS-QED example



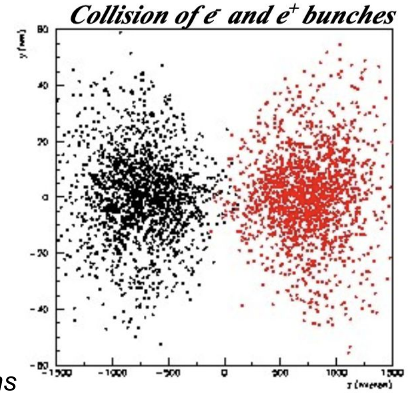
* F. Del Gaudio et al., PRAB **22**, 023402 (2019)

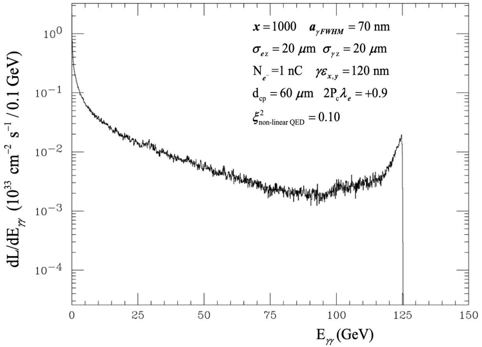
Simulation Efforts at SLAC



Gevy Cao (U of Oslo)
GUINEA-PIG

Asymmetric beam collisions



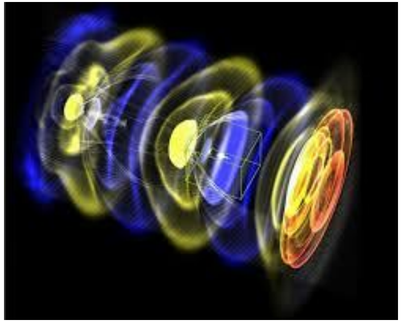


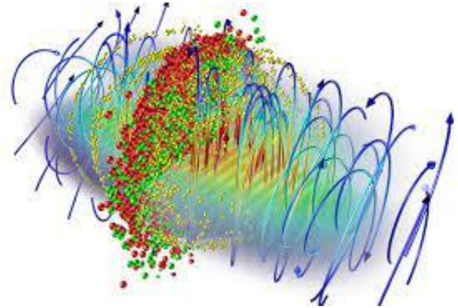
Tim Barklow
CAIN

$\gamma\gamma$ collisions

Cho-Kuen Ng
WarpX QED

Simulation Scaling





Spencer Gessner
OSIRIS-QED

Round beam collisions

Conclusions

- Beamstrahlung is a challenge for multi-TeV colliders. We haven’t found a silver bullet yet.

- There are novel ideas worth pursuing that may lead to fruitful discoveries.

- We are devoting resources at SLAC to study this problem in PIC simulations.

- The results of the new simulation studies may benefit collider designs below 1 TeV CM.

Backup

The Beamstrahlung Parameter

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Typically $n_\gamma < 2$

Luminosity for Precision Machines

ILC Parameter Table: https://arxiv.org/abs/1903.01629

Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade	TDR	Upgrades	
Centre of mass energy	$\sqrt{s}$	GeV	250	250	250	500	1000
Luminosity	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.35	2.7	0.82	1.8/3.6	4.9
Polarisation for $e^-(e^+)$	$P_-(P_+)$		80 %(30 %)	80 %(30 %)	80 %(30 %)	80 %(30 %)	80 %(20 %)
Repetition frequency	f_{rep}	Hz	5	5	5	5	4
Bunches per pulse	n_{bunch}	1	1312	2625	1312	1312/2625	2450
Bunch population	N_{e}	10^{10}	2	2	2	2	1.74
Linac bunch interval	Δt_{b}	ns	554	366	554	554/366	366
Beam current in pulse	I_{pulse}	mA	5.8	5.8	8.8	5.8	7.6
Beam pulse duration	t_{pulse}	μs	727	961	727	727/961	897
Average beam power	P_{ave}	MW	5.3	10.5	10.5	10.5/21	27.2
Norm. hor. emitt. at IP	$\gamma\epsilon_{\mathrm{x}}$	μm	5	5	10	10	10
Norm. vert. emitt. at IP	$\gamma\epsilon_{\mathrm{y}}$	nm	35	35	35	35	30
RMS hor. beam size at IP	σ^*_{x}	nm	516	516	729	474	335
RMS vert. beam size at IP	σ^*_{y}	nm	7.7	7.7	7.7	5.9	2.7
Luminosity in top 1 %	$\mathcal{L}_{0.01}/\mathcal{L}$		73 %	73 %	87.1 %	58.3 %	44.5 %
Energy loss from beamstrahlung	δ_{BS}		2.6 %	2.6 %	0.97 %	4.5 %	10.5 %
Site AC power	P_{site}	MW	129		122	163	300
Site length	L_{site}	km	20.5	20.5	31	31	40

CLIC Parameter Table: https://project-clic-cdr.web.cern.ch/

Description [units]	**500 GeV**	**3 TeV**
Total (peak 1%) luminosity	$2.3\ (1.4)\times10^{34}$	$5.9\ (2.0)\times10^{34}$
Total site length [km]	13.0	48.4
Loaded accel. gradient [MV/m]	80	100
Main Linac RF frequency [GHz]	12	12
Beam power/beam [MW]	4.9	14
Bunch charge [10^9 e^+/e^-]	6.8	3.72
Bunch separation [ns]	0.5	0.5
Bunch length [μm]	72	44
Beam pulse duration [ns]	177	156
Repetition rate [Hz]	50	50
Hor./vert. norm. emitt. [$10^{-6}/10^{-9}$m]	2.4/25	0.66/20
Hor./vert. IP beam size [nm]	202/2.3	40/1
Beamstrahlung photons/electron	1.3	2.2
Hadronic events/crossing at IP	0.3	3.2
Coherent pairs at IP	200	6.8×10^8

$$\frac{\mathcal{L}}{P_b} \propto \frac{\gamma^{1/2} n_\gamma^{3/2}}{\sqrt{\sigma_z}} \frac{1}{\sqrt{\varepsilon_y \beta_y}} \frac{1}{E_b}$$

The luminosity within 1% of the CM energy is a figure-of-merit for precision machines.

Luminosity for Precision Machines

ILC Parameter Table: https://arxiv.org/abs/1903.01629

Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade	TDR	Upgrades	
Centre of mass energy	$\sqrt{s}$	GeV	250	250	250	500	1000
Luminosity	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.35	2.7	0.82	1.8/3.6	4.9
Polarisation for $e^-(e^+)$	$P_-(P_+)$		80 %(30 %)	80 %(30 %)	80 %(30 %)	80 %(30 %)	80 %(20 %)
Repetition frequency	f_{rep}	Hz	5	5	5	5	4
Bunches per pulse	n_{bunch}	1	1312	2625	1312	1312/2625	2450
Bunch population	N_{e}	10^{10}	2	2	2	2	1.74
Linac bunch interval	Δt_{b}	ns	554	366	554	554/366	366
Beam current in pulse	I_{pulse}	mA	5.8	5.8	8.8	5.8	7.6
Beam pulse duration	t_{pulse}	μs	727	961	727	727/961	897
Average beam power	P_{ave}	MW	5.3	10.5	10.5	10.5/21	27.2
Norm. hor. emitt. at IP	$\gamma\epsilon_{\mathrm{x}}$	μm	5	5	10	10	10
Norm. vert. emitt. at IP	$\gamma\epsilon_{\mathrm{y}}$	nm	35	35	35	35	30
RMS hor. beam size at IP	σ^*_{x}	nm	516	516	729	474	335
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Coherent pairs at IP	200	6.8×10^8

Keeping n_γ fixed, the only practical way to increase luminosity is by reducing vertical emittance.

$$\frac{\mathcal{L}}{P_b} \propto \frac{\gamma^{1/2} n_\gamma^{3/2}}{\sqrt{\sigma_z}} \frac{1}{\sqrt{\varepsilon_y \beta_y}} \frac{1}{E_b}$$

The luminosity within 1% of the CM energy is a figure-of-merit for precision machines.

Where do we go from here?

- The round-beam parameter set does not provide the luminosity enhancement that we were looking for.

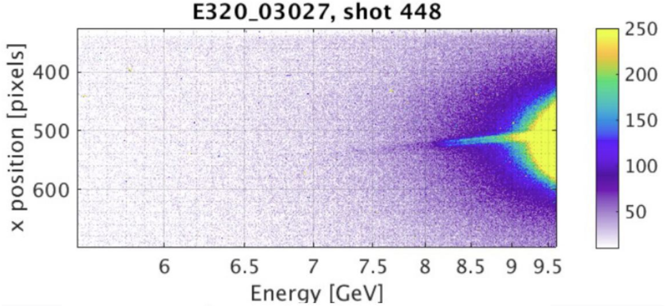
- Gamma-Gamma collisions are an alternative to electron-positron collisions. There is no beamstrahlung between colliding photon beams.

- Colliding ultra-short bunches is another concept worth investigating.

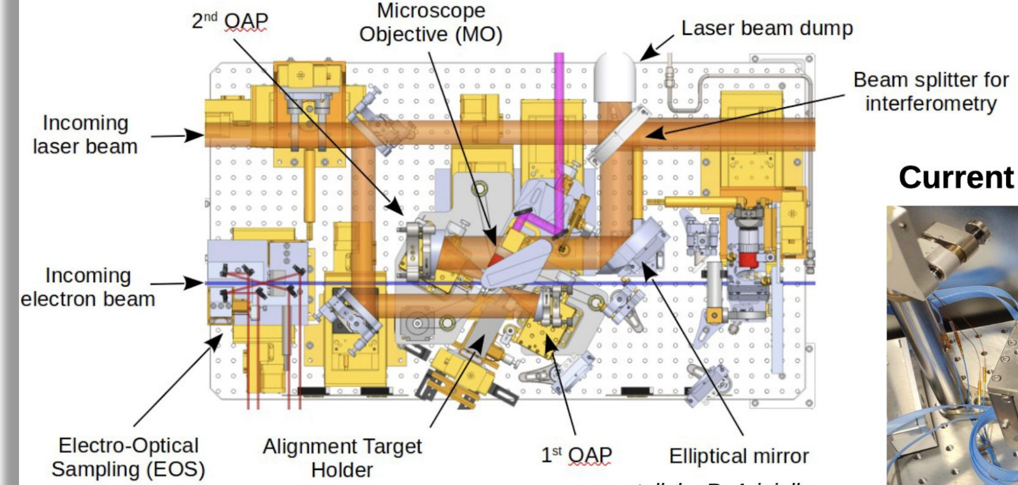
- Revival of old ideas like neutral beam collisions.

Non-Linear QED Effects

Scattered electrons – 1st and 2nd harmonic

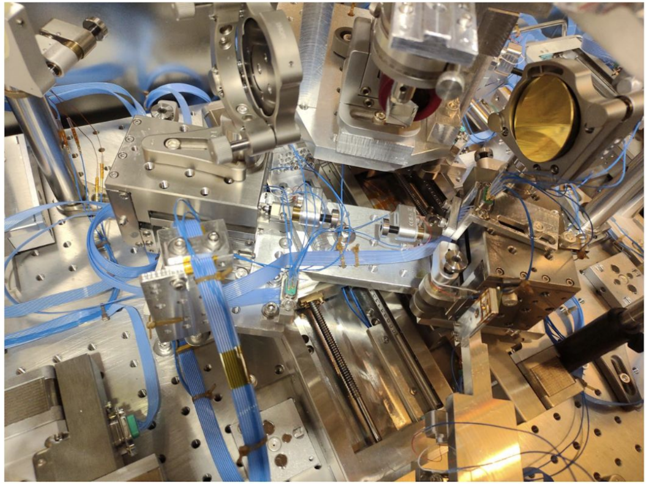


Progress: E-320 IP installation in the FACET-II pi



see talk by R. Ariniello

Current E-320 setup



Setup fully functional, improvements envisioned

- Common baseplate needs further engineering & tests
- Dielectric OAPs require a safe environment
- Interferometer hasn't been used for alignment yet

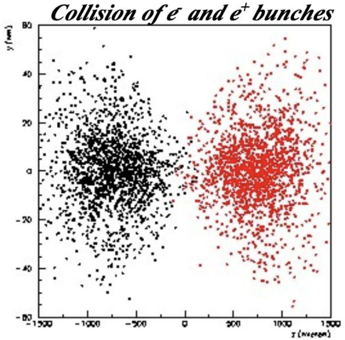
Physics Included in Different Codes

GUINEA-PIG

- Coherent pair production

- Incoherent pair production
- *Breit-Wheeler*
- *Bethe-Heitler*
- *Landau-Lifshitz*

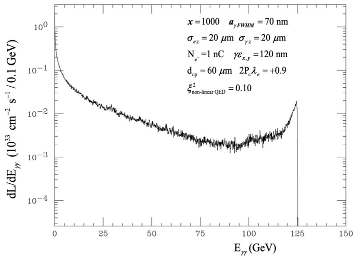
- Trident-cascade



CAIN

- Compton and multi-photon Compton/non-linear QED

- Incoherent pair production
- *Breit-Wheeler*
- *Bethe-Heitler*
- *Landau-Lifshitz*



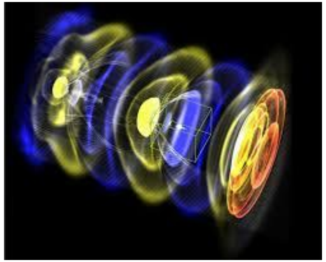
WarpX QED

- Quantum synchrotron rad

- Incoherent pair production
- *Breit-Wheeler*

- Schwinger process

- Self-consistent treatment of fields



OSIRIS-QED

- Quantum sync rad

- Coherent pair production

- Self-consistent treatment of fields

- Particle merging and culling