High Energy High Luminosity e^+e^- Collider using Energy-Recovery Linacs

Nikhil Bachhawat[1], Yichao Jing[2,1], Vladimir N Litvinenko[1,2], Maria Chamizo Llatas[3] and Thomas Roser[2]

[1] Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY, USA

[2] Collider-Accelerator Department, Brookhaven National Laboratory, Upton, NY, USA

[2] Nuclear and Particle Physics Directorate, Brookhaven National Laboratory, Upton, NY, USA

We present an alternative approach for a high-energy high-luminosity electron-positron collider. Present designs for high-energy electron-positron colliders are either based on two storage rings with 100 km circumference with a maximum CM energy of 365 GeV or two large linear accelerators with a high energy reach but lower luminosity, especially at the lower initial CM energies. A shortcoming of the collider based on storage rings is the high electric power consumption required to compensate for the beam energy losses from the 100 MW of synchrotron radiation power [1]. We propose to use an Energy Recovery Linac (ERL) located in the same-size 100 km tunnel to mitigate this drawback. We show that using an ERL would allow large reduction of the beam energy losses while providing higher luminosity in this high-energy collider. Furthermore, our approach would allow for colliding fully polarized electron and positron beams and for extending the CM energy to 500 GeV, which would enable double-Higgs production, and even to 600 GeV for $t\bar{t}H$ production and measurements of the top Yukawa coupling.

BNL Snowmass discussion, March 31, 2020

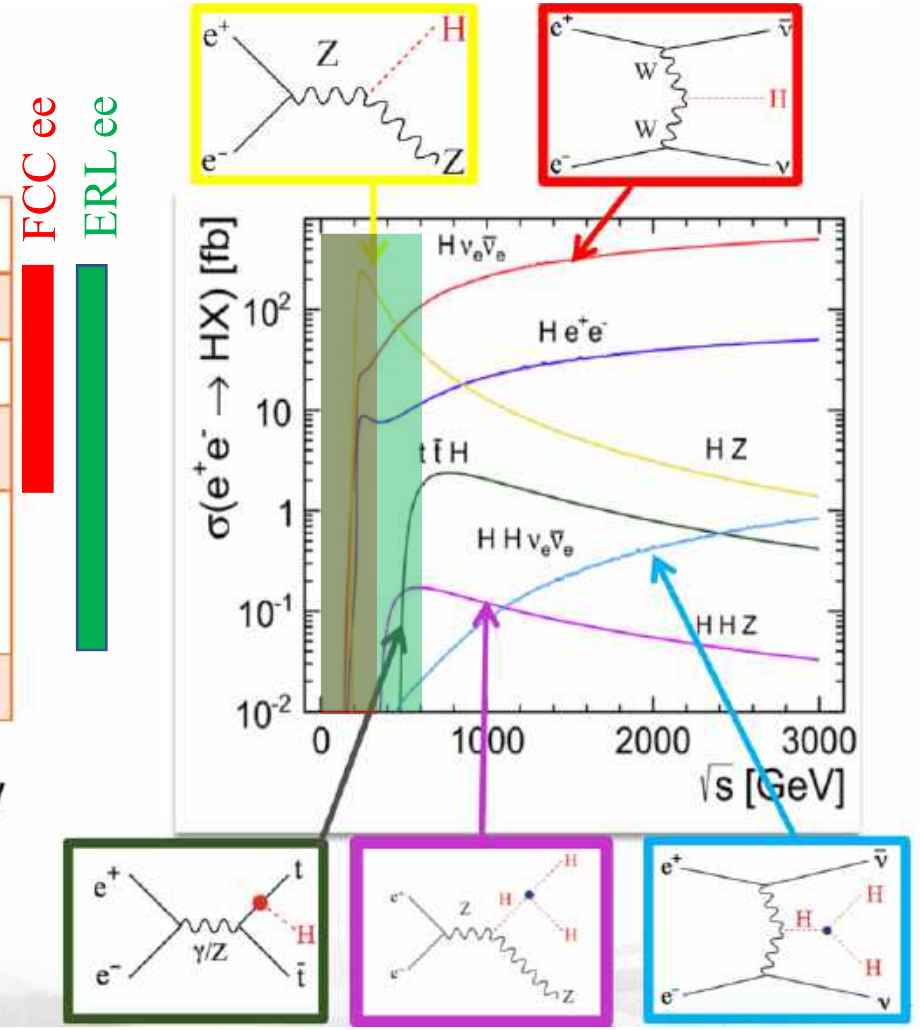
Motivation 1 – energy reach

e+e- colliders

√s [GeV]	Science Drivers
90-200	EW precision physics, Z, WW
250	Single Higgs physics (HZ), Hνν
365	tt
500-600	HHZ, ttH direct access to Higgs self-couplings, top Yukawa couplings
1000-3000	HHνν Higgs self-couplings in VBF

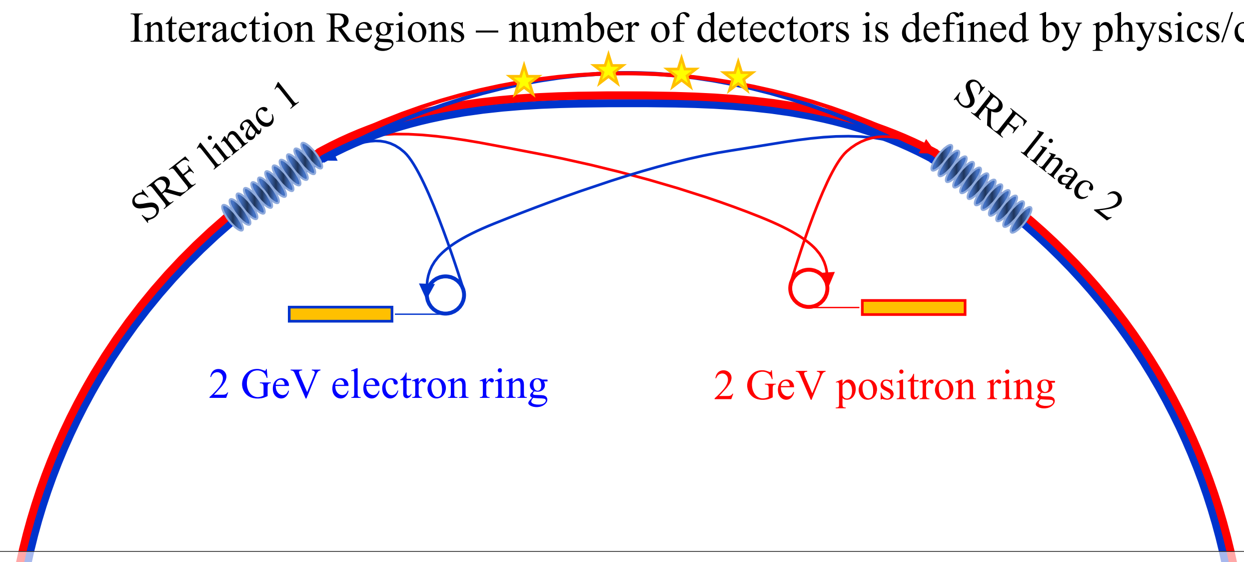
Precision measurement and search for new physics studying deviations from the SM

→ Need high luminosity (and energy)



An ERL e^+e^- collider would provide higher luminosity and high-energy up to c.m. energy of 600 GeV to enable double-Higgs and ttbarH production

ERL collider concept



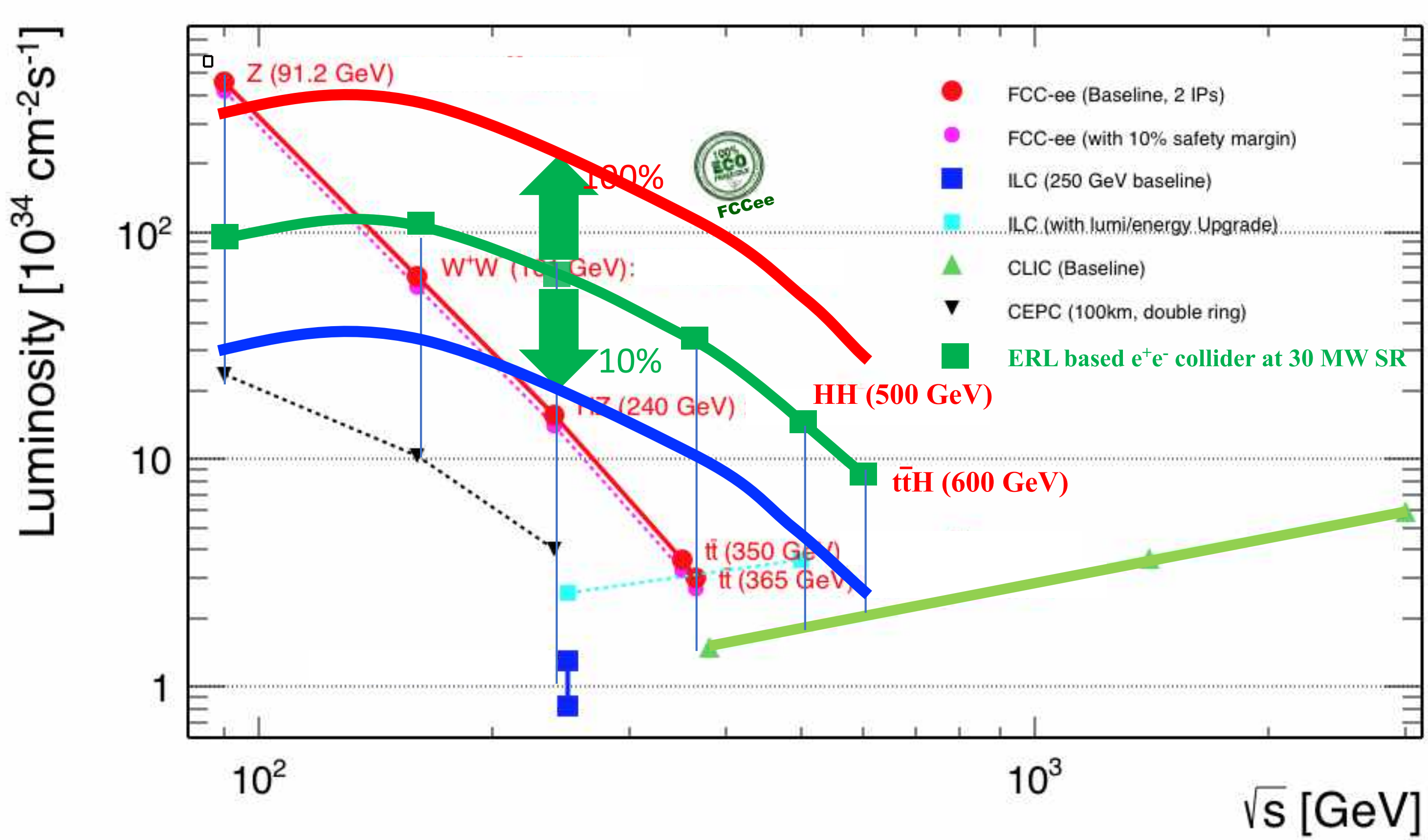
- Flat beams cooled in 2 GeV rings with “top off”
- Bunches are ejected with collision frequency
- Beams accelerated with SRF linacs over four 100 km long passes by-passing the IR
- After collision at top energy rf phases are changed to deceleration returning most energy to SRF linac
- Decelerated beams are reinjected into cooling rings, after 2 damping times (~ 4 ms) the trip repeats
- Luminosity is shared between detectors in any desirable ratio
- Only beams at top energy pass through detectors, the rest of beams bypass them

ERL collider recycles (polarized) electrons and positrons

- After acceleration, collision, and deceleration all electrons and positrons are reinjected into the cooling rings. Only beam losses must be made up through top-off injection.

Motivation 2: Luminosity at high energies

For ERL e+e- collider: Blue curve – for 10 MW RF power
Green curve – for 30 MW RF power
Red curve – for 100 MW RF power (as in FCC ee)



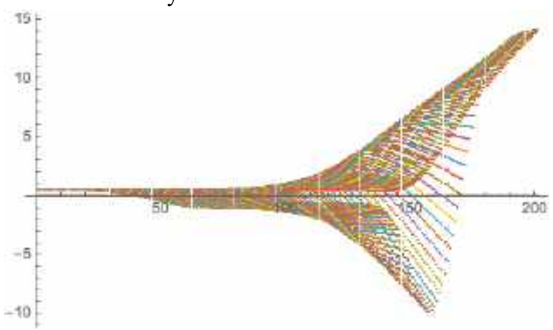
Luminosity scales linear with SR power – would see other limitations – but 100 MW SR power is not what we are proposing.

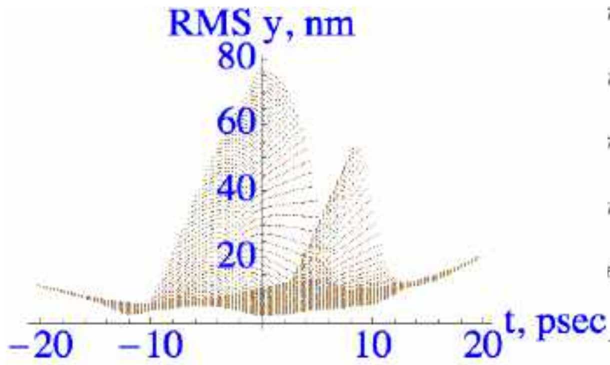
In ERL collider, the luminosity can be shared (split) by multiple detectors by alternating beam collision points.

Effects of orbits offsets in IP

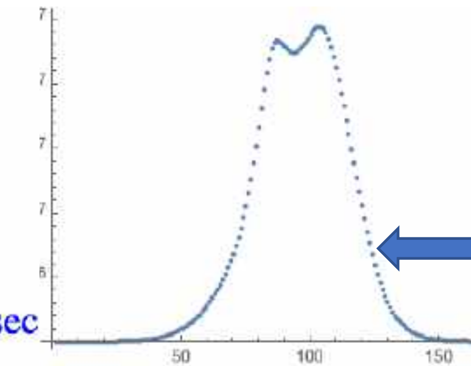
Initial beam axis separation is $\Delta y = 1\sigma_y$

Beam centroids evolution in units of σ_y at the beam waist.

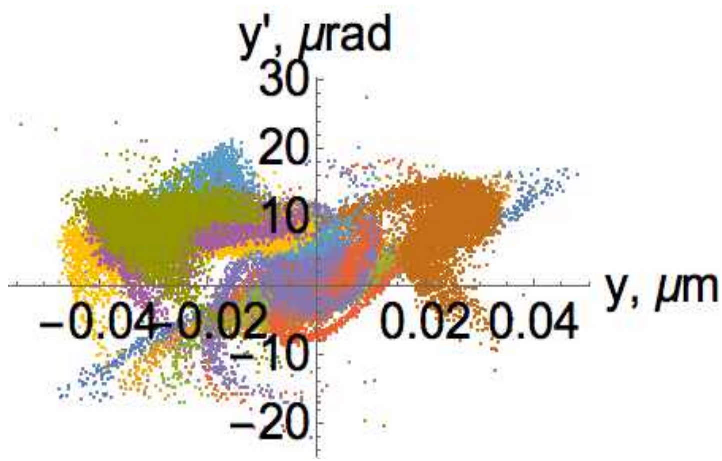


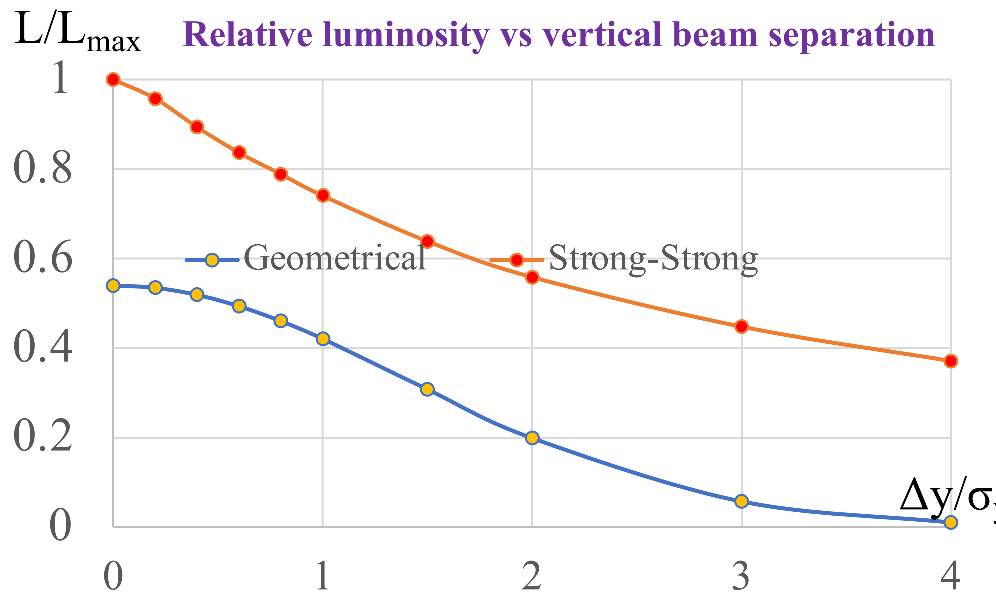


Instantaneous luminosity (a.u.)



Faster drop after the IP center



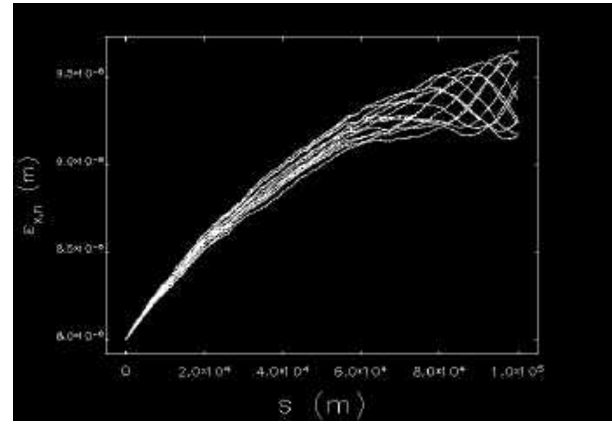


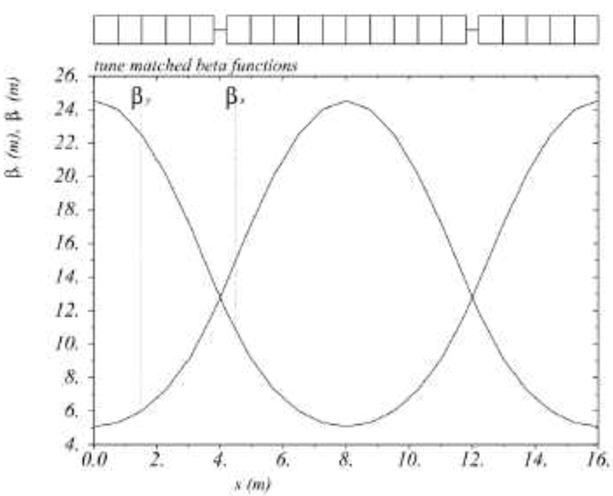
Main effect from offsets: RMS vertical beam emittance increases ~ 10X after collisions. It does not present any problems for the energy and particles recovery. It may require to increased time in the cooling rings to three-to-four damping times – this should be optimized for actual orbit deviations

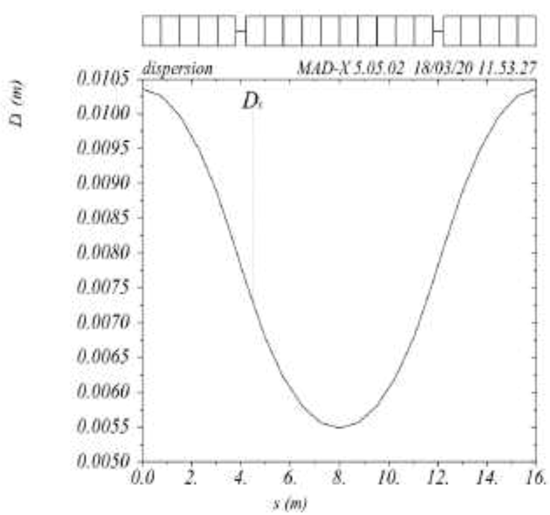
Reduction of the luminosity is modest – actually the pinch effect continued delivering significant gain at all deviations of beam orbits

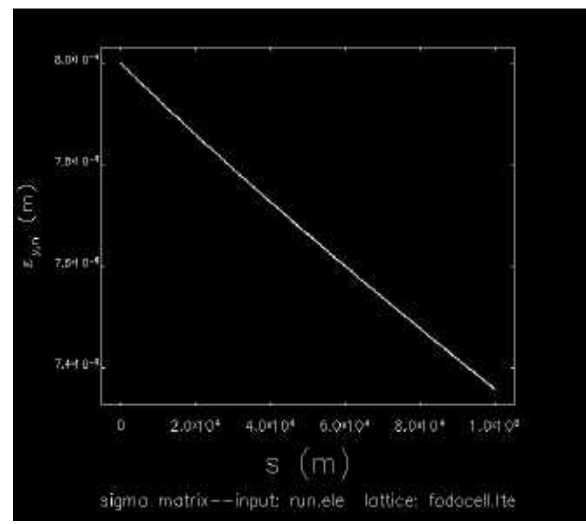
Lattice - 250 GeV path

- 6250 FODO cells with combined function (B,G,S) magnets and zero chromaticity
- Cell – 16 m, 90-degrees phase advance
- Gaps between magnets – 0.4 m, filling factor 95%
- B= 0.0551 T (551 Gs); $G_{F,D}$=±32.24 T/m (3.224 kGs/cm)
- Focusing magnet: SF=267 T/m^2 (2.67 kGs/cm^2); SD=-418 T/m^2; (-4.18 kGs/cm^2)
- Aperture ±1.5 cm – pole tip fields ~ 5 kGs – perfect for magnetic steel









Conclusions

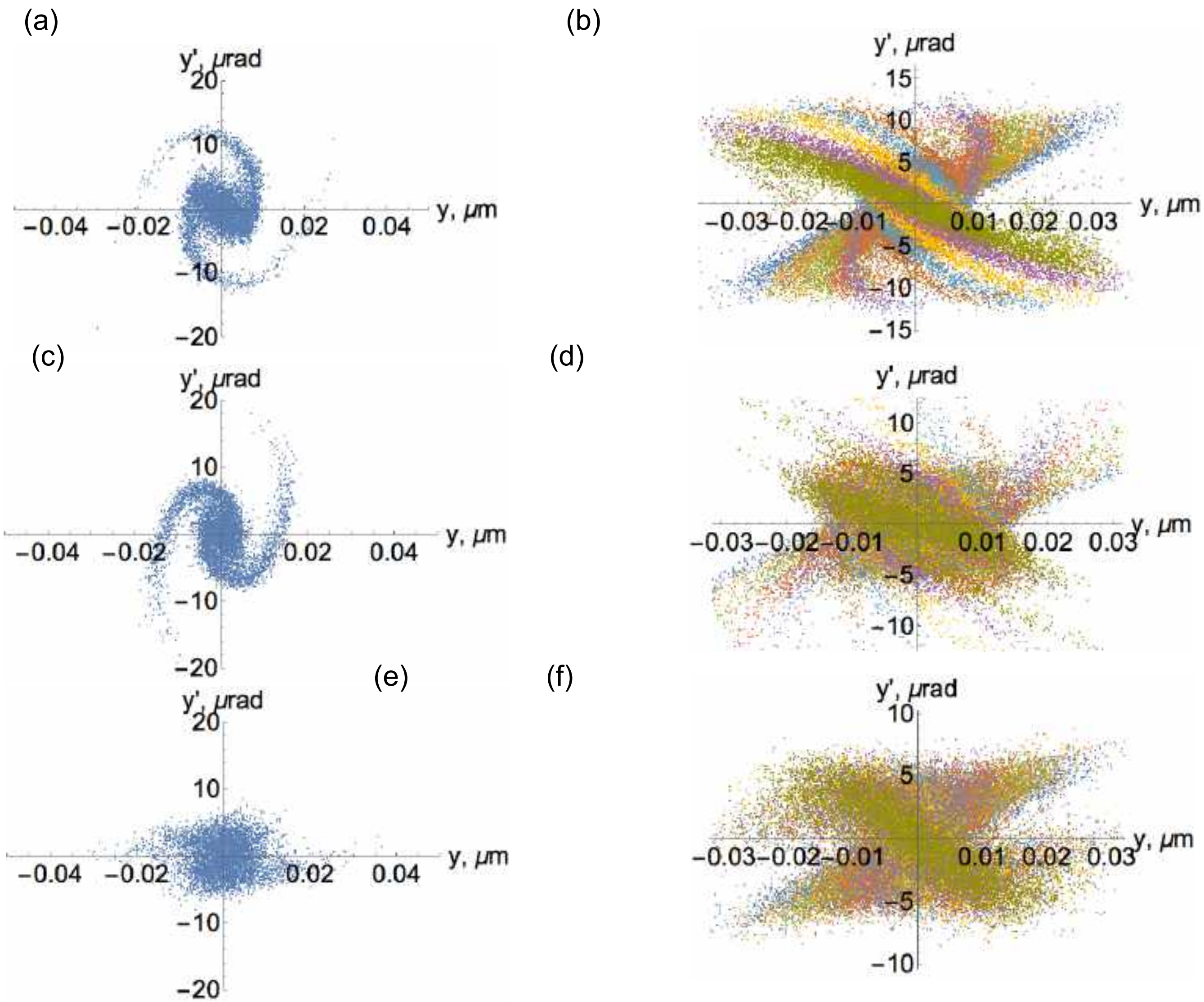
- The ERL-based high-energy e^+e^- collider promises significantly higher luminosities at CM energies above 140 GeV while consuming a fraction ~ 30% of electric power required in a corresponding SR e^+e^- collider design
- The CM energy reach is extended to 500-600 GeV for double-Higgs and $t\underline{t}H$ production
- The ERL scheme is fully capable of colliding polarized electron and positron beams opening a new set of observables for the relevant physics
- These features of the ERL-based collider are unique in this energy range. It outperforms the ring-ring design - by colliding beams only once - and linear colliders by using the energy recovery and recycling of the particles
- Detailed studies are needed to fully validate the concept. Many opportunities for interested partners to collaborate

Approximated RF power required for the same luminosity

Parameter	Storage ring	ERL-ERL	ILC	CLIC
Beam energy, GeV	182.5	182.5	250	190
Beam current, mA	5.400	1.010	0.021	0.015
Luminosity, 10^{34} cm^{-2} s^{-1}	1.5	31.4	1.8	1.5
Total power loss, MW	100.0	30.0	10.4	5.6
Total power loss for the same lumi as ERL-ERL MW	**2093**	**30.0**	**181.4**	**117.2**

Back-up slides

Strong-strong collisions of flat beams in ERL e^+e^- collider

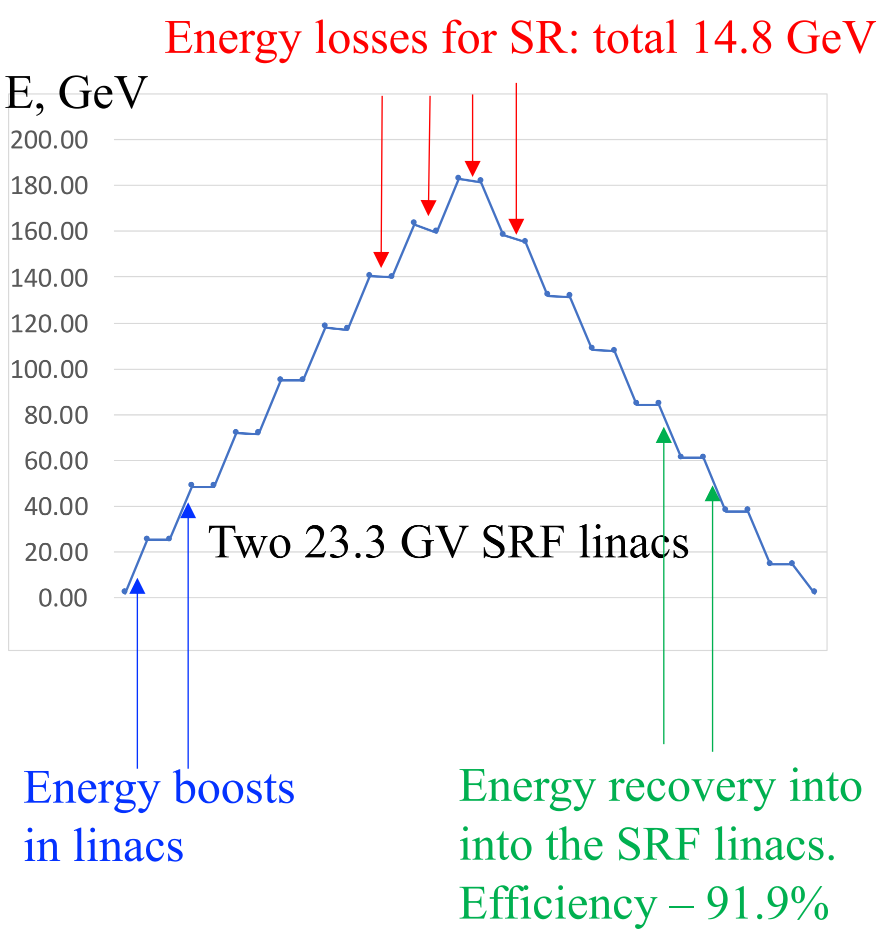


Beam distribution in the vertical phase space after the collision. Distributions of the central slice are on the left and combinations of 10 slices covering evenly $-3\sigma_z < z < 3\sigma_z$, are on the right: (a-b) are for center particles at x=0; (c-d) are for those at $x = \sigma_x$, (e-f) is for that at $x = 2\sigma_x$. The horizontal axes are the vertical coordinate and the vertical axes are vertical angle of the particle

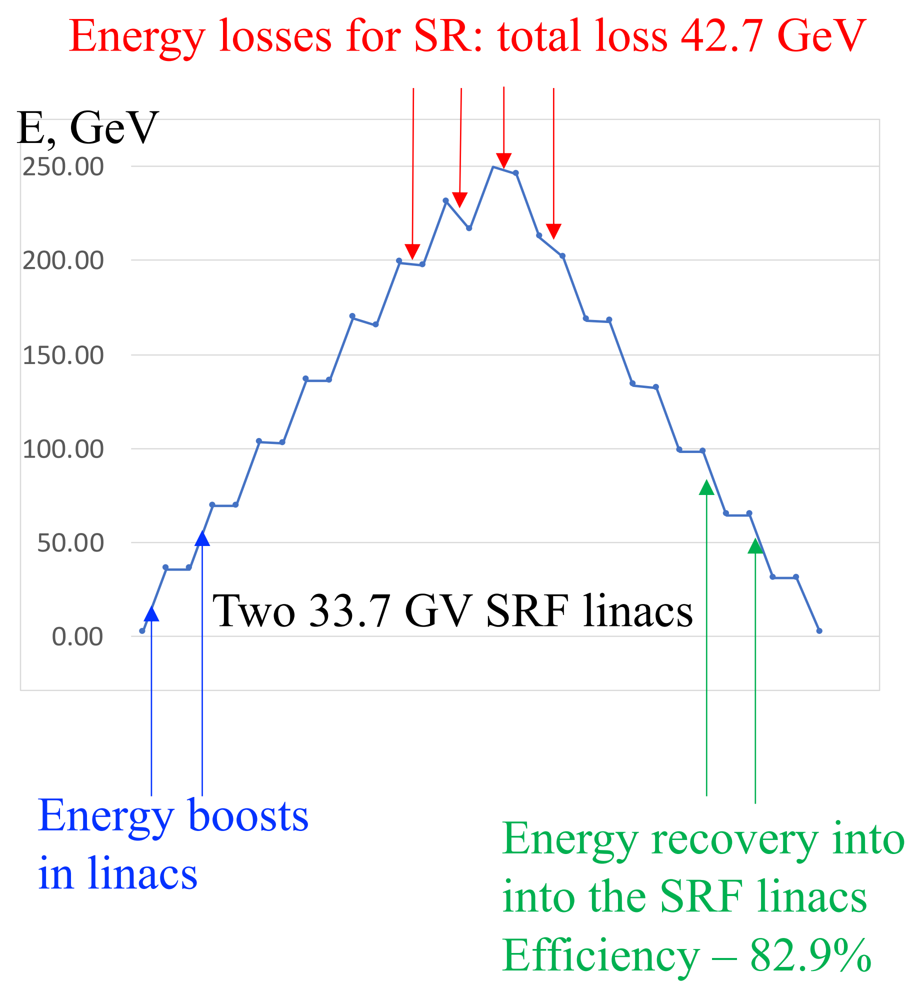
The e$^-$ and e$^+$ beam energy evolutions

in a 4-pass ERL

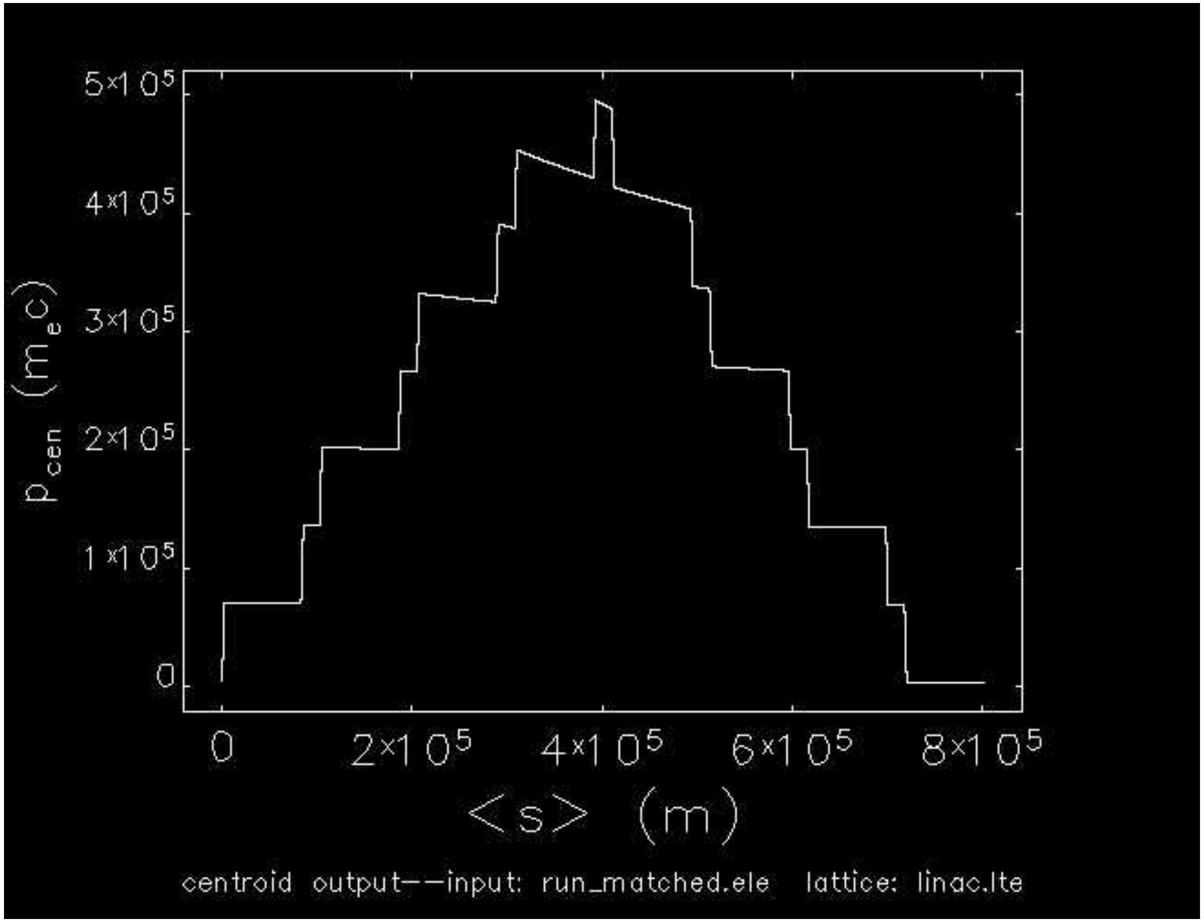
2 x 182.5 GeV: **365 GeV CM GeV $t\bar{t}$**



2 x 250 GeV: **500 GeV CM HHZ**



Simulations are in progress



Comparison of ERL and Ring colliders

$$P_{SR} = V_{SR}\left(I_{e-} + I_{e+}\right) \propto \frac{E^4}{R}\left(I_{e-} + I_{e+}\right) \cong 2\frac{E^4}{R} I_{e\pm}$$

$$L = f_c \frac{N_{e-} N_{e+}}{4\pi\sigma_x\sigma_y} h = \frac{I_{e-} I_{e+}}{4\pi e^2 \cdot f_c \sigma_x \sigma_y} h \to L = \frac{1}{16\pi_y \cdot \sigma_x \sigma_y \cdot f_c}\left(\frac{P_{SR}}{eV_{SR}}\right)^2 h; \; h \sim 1$$

In storage rings there are strong limitations on maximum allowable beam-beam tune shift and IP chromaticity (e.g. how small is β*). It favors larger emittances and higher collision frequencies.

$$\xi^{\pm}_{x,y} = \frac{N_{e\pm} r_e \beta^{\pm}_{x,y}}{2\pi\gamma\sigma_{x,y}\left(\sigma_x + \sigma_y\right)} \le 0.1 \div 0.15$$

$$\sigma_{x,y} = \sqrt{\varepsilon_{x,y}\beta_{x,y}^{*}}$$

Linear and ERL colliders, where beams collide only once, do not have such limitations!

Reduction of SR power, e.g. beam currents in both beams while keeping the luminosity high requires reduction of one, two or all factors in the luminosity denominator

$$\sqrt{\beta_x^*\beta_y^*} \cdot \sqrt{\varepsilon_x\varepsilon_y} \cdot f_c$$

For simplicity and better comparison, we decided to use the same IR and β* as in FCC ee design

Motivation 3 – lowering power consumption

The ring-ring FCC e^+e^- collider is power hungry

100 MW SR losses, ~ 200 MW wall plug power

parameter	Z	W	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
arc cell optics	60/60	90/90	90/90	90/90
momentum compaction [10^{-5}]	1.48	0.73	0.73	0.73
horizontal emittance [nm]	0.27	0.28	0.63	1.45
vertical emittance [pm]	1.0	1.0	1.3	2.7
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	2
length of interaction area [mm]	0.42	0.5	0.9	1.99
tunes, half-ring (x, y, s)	(0.569, 0.61, 0.0125)	(0.577, 0.61, 0.0115)	(0.565, 0.60, 0.0180)	(0.553, 0.59, 0.0350)
longitudinal damping time [ms]	414	77	23	6.6
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.10	0.44	2.0	10.93
RF acceptance [%]	1.9	1.9	2.3	4.9
energy acceptance [%]	1.3	1.3	1.5	2.5
energy spread (SR / BS) [%]	0.038 / 0.132	0.066 / 0.153	0.099 / 0.151	0.15 / 0.20
bunch length (SR / BS) [mm]	3.5 / 12.1	3.3 / 7.65	3.15 / 4.9	2.5 / 3.3
Piwinski angle (SR / BS)	8.2 / 28.5	6.6 / 15.3	3.4 / 5.3	1.39 / 1.60
bunch intensity [10^{11}]	1.7	1.5	1.5	2.8
no. of bunches / beam	16640	2000	393	39
beam current [mA]	1390	147	29	5.4
luminosity [10^{34} cm^{-2}s^{-1}]	**230**	**32**	**8**	**1.5**
beam-beam parameter (x / y)	0.004 / 0.133	0.0065 / 0.118	0.016 / 0.108	0.094 / 0.150
luminosity lifetime [min]	70	50	42	44
time between injections [sec]	122	44	31	32
allowable asymmetry [%]	±5	±3	±3	±3
required lifetime by BS [min]	29	16	11	10
actual lifetime by BS ("weak") [min]	> 200	20	20	25

FCC-ee: The Lepton Collider, M. Benedikt et al., Eur. Phys. J. Spec. Top. (2019) 228: 261

Key differences

Parameter	Ring-Ring	ERL-ERL	ILC@250 GeV	CLIC@190 GeV
Norm. emittance $\varepsilon_x/\varepsilon_y$, μm rad	518/0.964	8/0.008	10/0.035	1/0.030
IP beta function β_x/β_y, cm	100/0.20	100/0.20	10/0.05	80/0.01
RMS bunch length, mm	2.00	2.00	0.30	0.07
Bunch charge, nC	46.2	22.5	3.2	0.8
Bunch frequency, kHz	116.9	45	6.5	17.6
Beam current, mA	5.400	1.010	0.021	0.015
Disruption parameter, D_x/D_y	N/A	0.20/143.0	0.30/24.3	0.24/12.5
Crossing angle	YES	NO	YES	YES
Energy spread at collision, %	0.18	0.16	-	-
Particle energy loss, GeV	9.2	14.8	250.0	190.0
Total radiated power, MW	100.0	30.0	10.4	5.6

Important consideration

- At high energies the most dangerous effect is beamstrahlung: synchrotron radiation in strong EM field of opposing beam during collision
- It can cause significant amount of energy loss, induce large energy spread and loss of the particles
- Using very flat beams is the main way of mitigating this effect
- Our goal was to maintain energy spread in colliding beams at the same level as in ring-ring FCC ee: 0.15-0.2%

$$\langle \Delta\gamma \rangle = \frac{4}{9}\sqrt{\frac{\pi}{3}} N^2 \frac{r_e^3}{\sigma_x^2 \sigma_z} \gamma^2;$$

$$for\ \ \sigma_x >> \sigma_y$$