CERC – Circular Energy Recovery Collider

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

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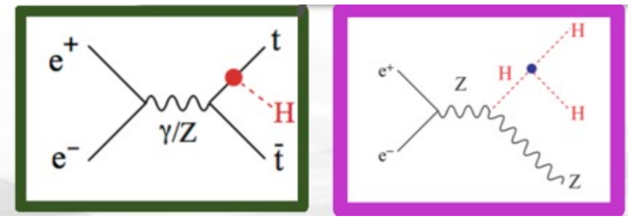
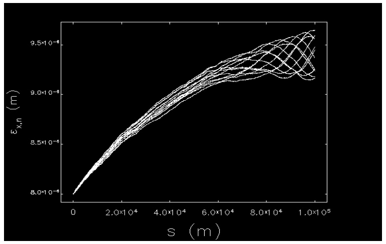
Key development: focus on reaching c.m. energy range of 500 - 600 GeV

Physics: Investigating details of:



Accelerator: Developing detailed lattice and start-to-end simulations



Exploring possibility of colliding polarized electron and positron beams

Stony Brook University

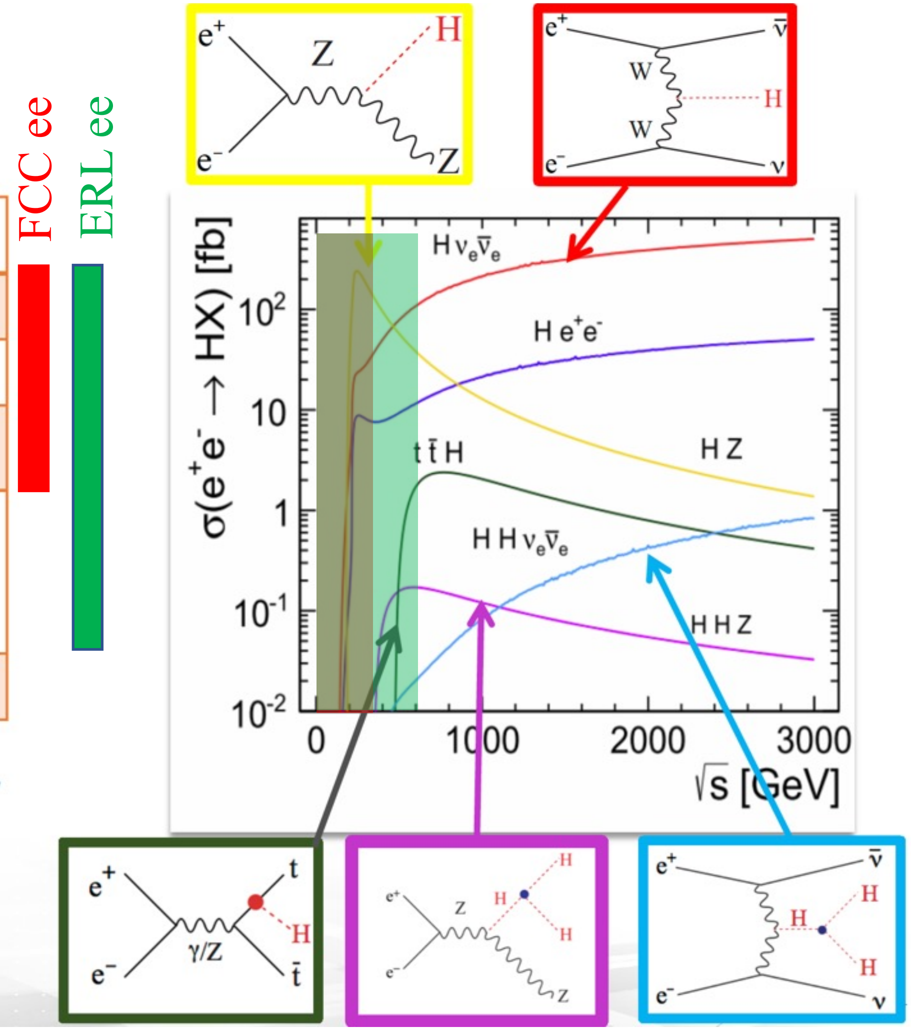
CASE Center for Accelerator Science and Education

BROOKHAVEN NATIONAL LABORATORY

Motivation 1 – energy reach

e+e- colliders

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



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

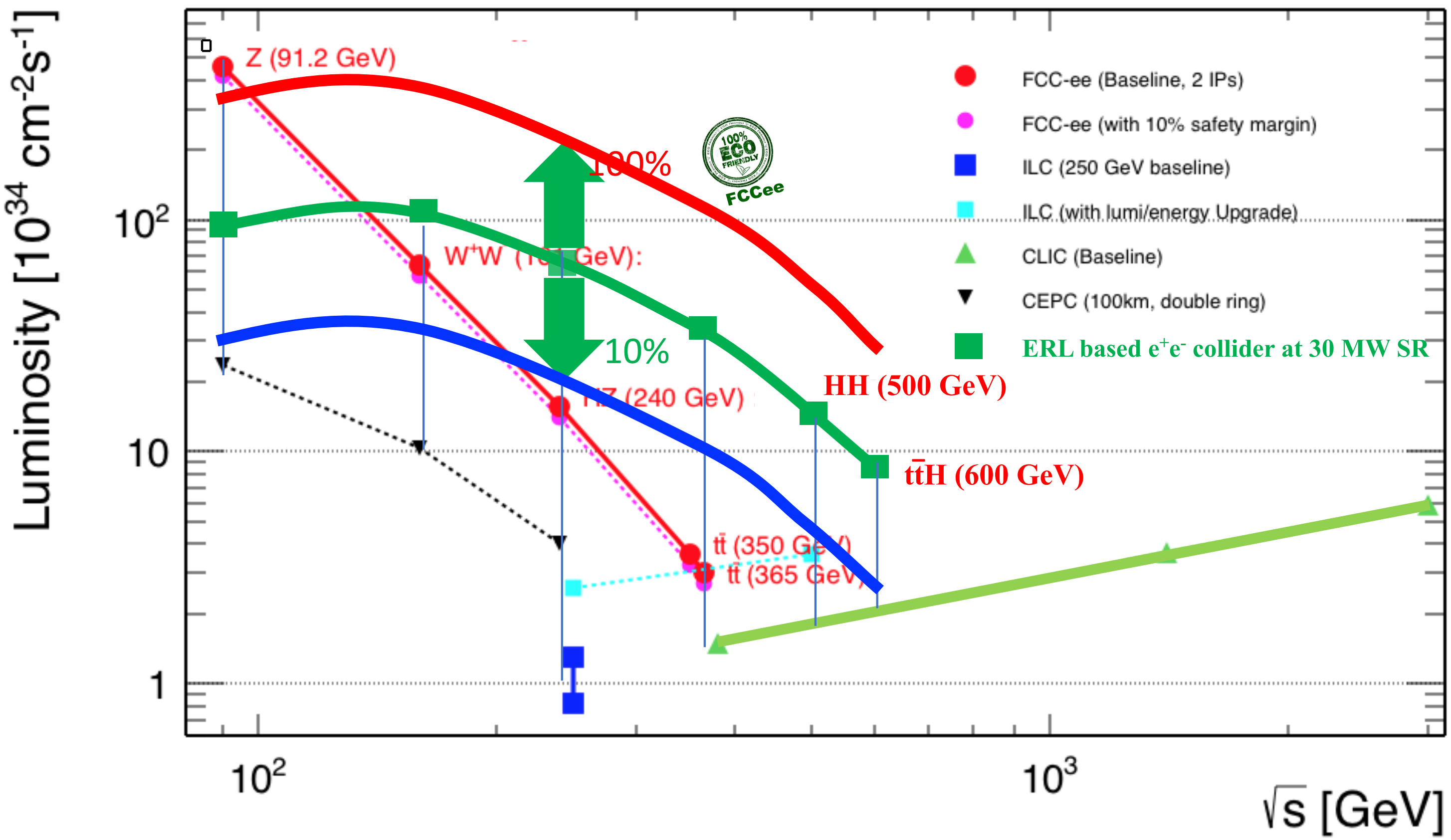
→ Need high luminosity (and energy)

U.S. DEPARTMENT OF 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

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)

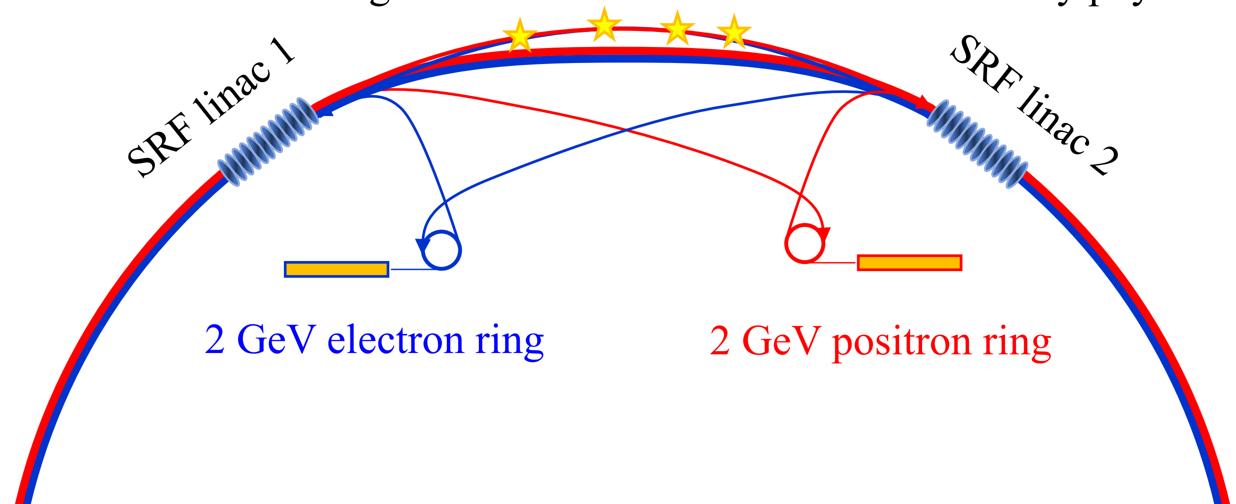


Luminosity scales linear with SR power – would see other limitations – but 100 MW SR power is not what we are proposing.

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

ERL collider concept

Interaction Regions – number of detectors is defined by physics/cost



- Flat beams cooled in 2-to-8 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

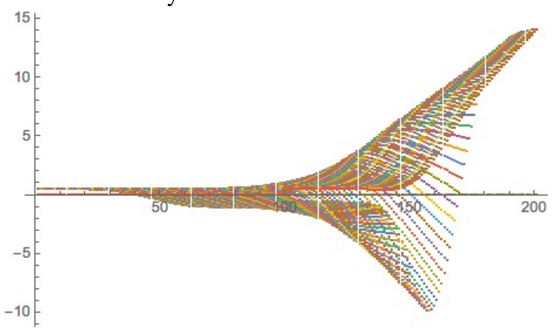
ERL collider recycles (polarized) electrons and positrons

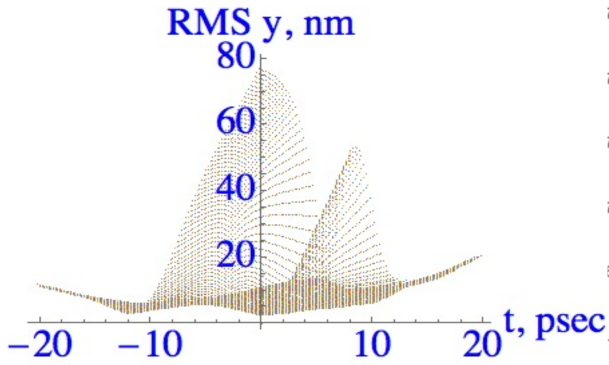
- After acceleration, collision, and deceleration all electrons and positrons are reinjected into the cooling rings. Only beam losses must be made up through top-off injection.

Effects of orbits offsets in IP

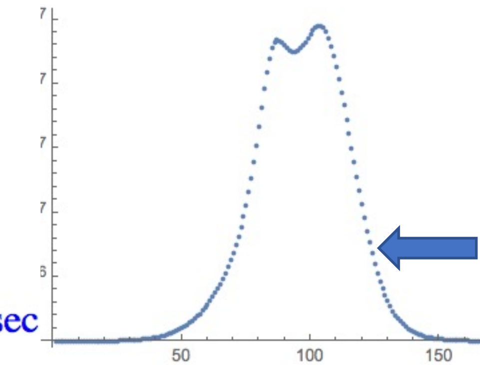
Initial beam axis separation is $\Delta y = 1\sigma_y$

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

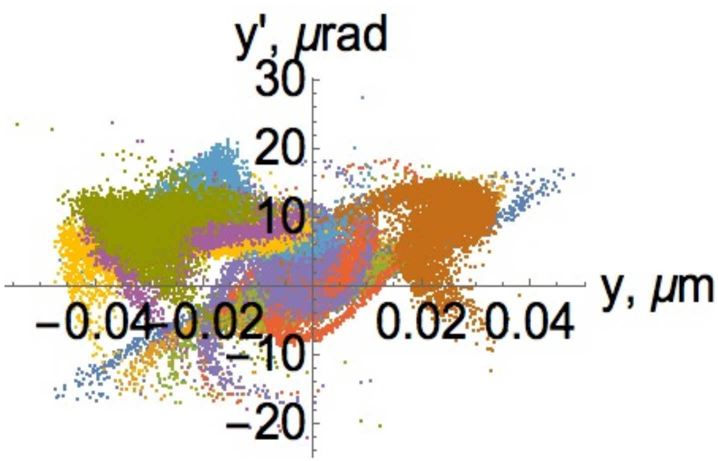


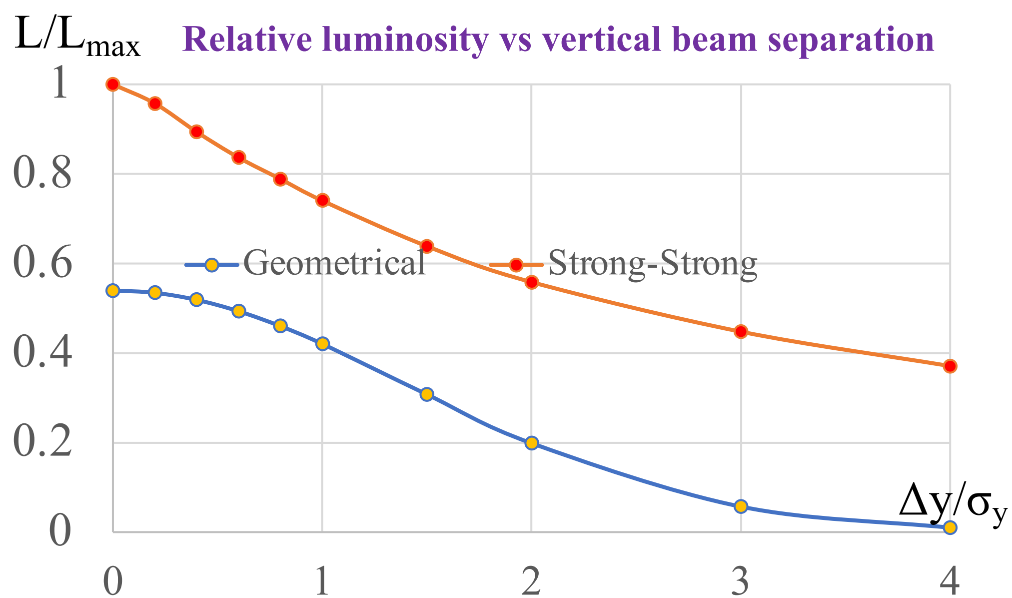


Instantaneous luminosity (a.u.)



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 but may require to spend more n the cooling rings

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

Beamstrahlung generated low energy tail
– *answer to critique by V. Telnov*

- We want to thanks Dr. Telnov for raising questions about low energy tail in collided beams, which indeed could be a problem. Beamstrahlung is a challenging problem for collision at energies exceeding FCC ee top energy of 120 GeV/beam.
- While we agree that this is a challenge, we do not agree with Dr. Telnov's assumption that CERC could not deliver luminosity at the levels indicated in our original paper "*High-energy high-luminosity e+e− collider using energy-recovery linacs*", *Phys. Lett. B* ***804****, 135394, (2020)* . While the core of our energy-efficient "recycling" concept remains intact, we made a number of adjustments, including matching of focusing of colliding bunching by increasing the bunch lengths from 10 to 20 fold at top CERC energies
- We want to confirm that our formula for average energy loss during beam collision is correct

$$\langle\Delta\gamma\rangle = \frac{4}{9}\sqrt{\frac{\pi}{3}}N^2\frac{r_e^3}{\sigma_x^2\sigma_z}\gamma^2;\ for\ \sigma_x >> \sigma_y;\ n_\gamma = \sqrt{2\pi}\frac{N_{e\pm}r_e^2}{\sigma_x \lambda_c} \sim 1.5; \langle\sigma_\gamma\rangle \propto \frac{\langle\Delta\gamma\rangle}{\sqrt{n_\gamma}} \propto \langle\Delta\gamma\rangle$$

Still, there is an exponential low energy tail which must be recovered.

- Matching with focusing from the opposite colliding bunch required increase of the bunch length

$$\langle K_y\rangle = \frac{N_e r_e}{\gamma\sqrt{2\pi}\sigma_x\sigma_y\sigma_z} = \bar{\beta}_{sc}^{-2} \Rightarrow \bar{\beta}_{sc} = \left(\frac{\sqrt{2\pi\gamma\varepsilon_n}\sigma_x\sigma_z}{N_e r_e}\right)^{2/3}$$

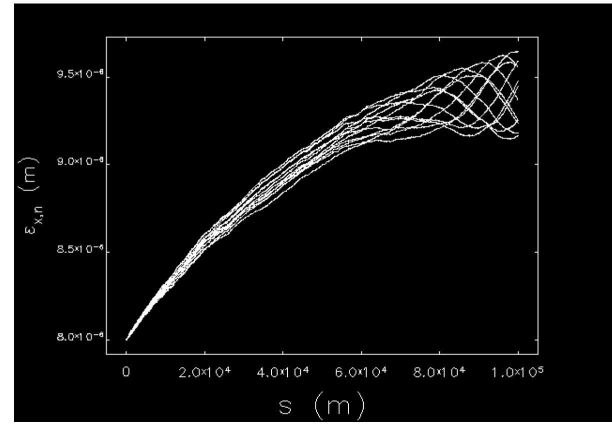
- As the result of such matching, at the proposed CERC c.m. energies from 90 to 600 GeV

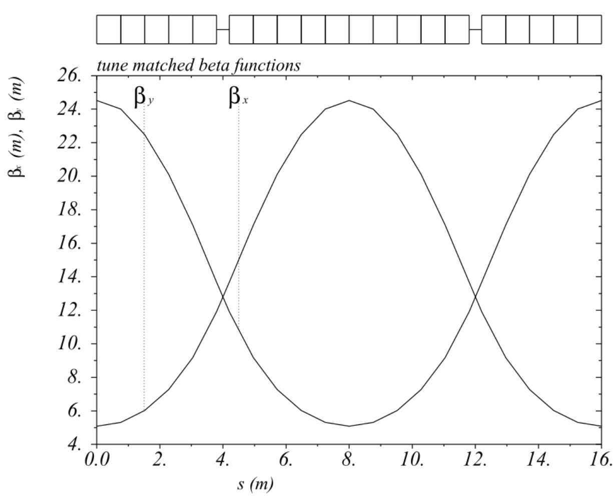
$$\frac{\Delta\gamma_{c\max}}{\gamma} = (0.2 \div 1.2)\cdot 10^{-3}$$

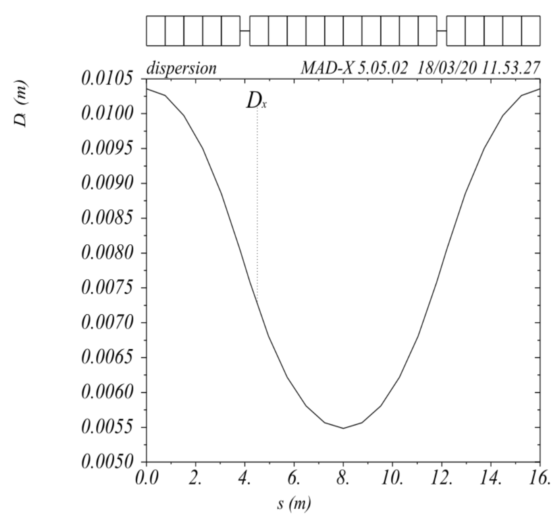
, which can be recovered and cooled in the CERC

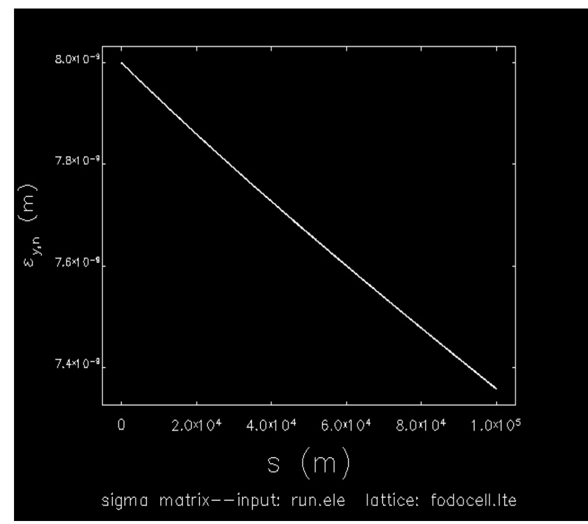
Lattice - 250 GeV path

- 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



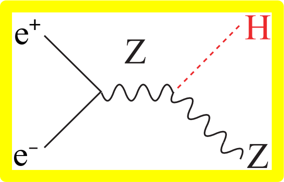


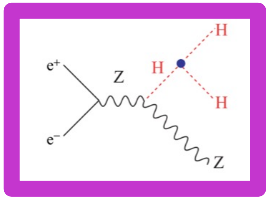


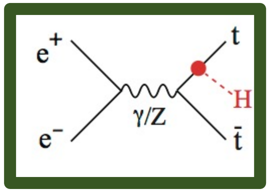


Effect of Polarization

Preliminary results using Madgraph



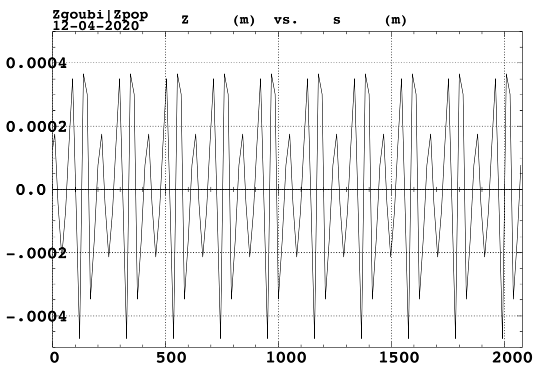




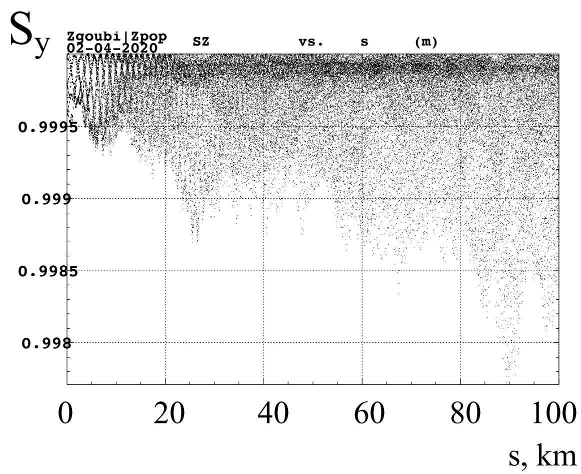
Polarization		Scaling factor		
e -	e +	ZH(240GeV)	ZHH(500GeV)	ttH(600GeV)
Unpolarized		1.	1.	1.
-70	0	1.15	1.15	1.23
-70	+50	1.61	1.61	1.87
-70	-50	0.69	0.69	0.73
-70	+70	**1.78**	**1.79**	**2.07**
-70	-70	0.51	0.51	0.51
-50	+50	1.47	1.47	1.69
+50	-50	1.03	1.03	0.82
+70	0	0.85	0.85	0.69
+70	+50	0.60	0.60	0.56
+70	-50	1.09	1.09	0.83
+70	+70	0.51	0.51	0.51

Simulating effect of polarization

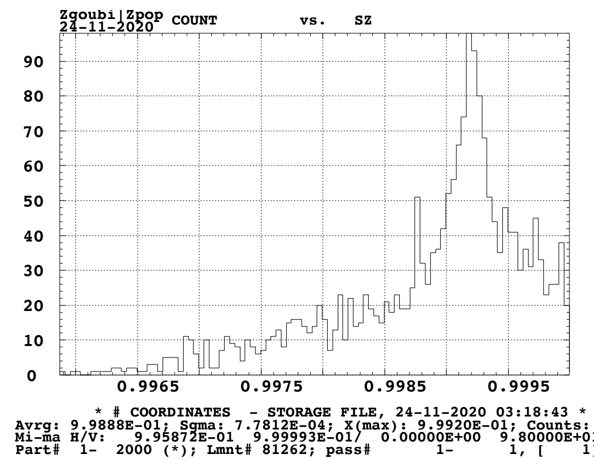
- Depolarization of lepton beam is proportional to high power of the beam energy
- We run preliminary simulation of depolarization for 219 GeV electron and positron beam in 100 km transport for beams with 8 μm horizontal and 8 nm vertical normalize emittances and vertical orbit distortions with 350 μm amplitude tuned for resonant depolarization for particles at 211.85 GeV
- Gγ ισ decreasing from 497 to 467 over the 100km loop due to SR,
- We found that depolarization is very weak – most importantly because of the single pass – and that CERC can indeed operate highly polarized electron and positron beams



Vertical orbit over first 2 km (13-cell pattern repeats itself over the 100 km).



S_y (s), vertical spin components along the 100 km beam line.



Densities of S_y spin component after 100km path

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 highly polarized electron and positron beams opening a new set of observables for the relevant physics or simply boosting cross-section of relevant processes
- 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
- The core of the CERC concept remains the same – collide bunches only once, then recover, cool and reuse them. But details of the concept, such as matching of the colliding beams, using second harmonic RF system for compensation of the SR losses or details of the ERL lattice are evolving.
- We continue pursuing preliminary studies using our personal time, but detailed studies similar to that of the FCC ee, are needed to fully validate the concept. Many opportunities for interested partners to collaborate