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

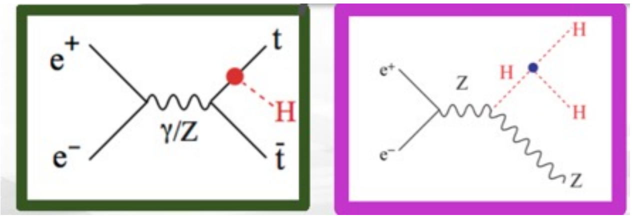
Nikhil Bachhawat, Yichao Jing, Vladimir N Litvinenko,
Francois Meot, Maria Chamizo Llatas, Irina Petrushina, and Thomas Roser

Key development: two concepts

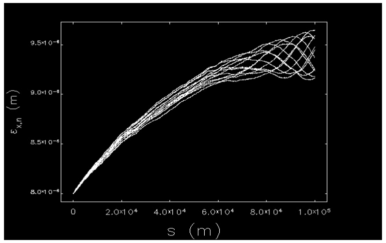
CERC (**C**ircular **E**nergy-**R**ecovery **C**ollider

ReLiC (**Re**cycling **Li**near **C**ollider)

Physics: Investigating details of:



Accelerator: Developing detailed start-to-end simulations



Checked possibility of colliding polarized electron and position beams

Stony Brook University

CASE
Center for Accelerator Science and Education

BROOKHAVEN NATIONAL LABORATORY

Key for both concepts

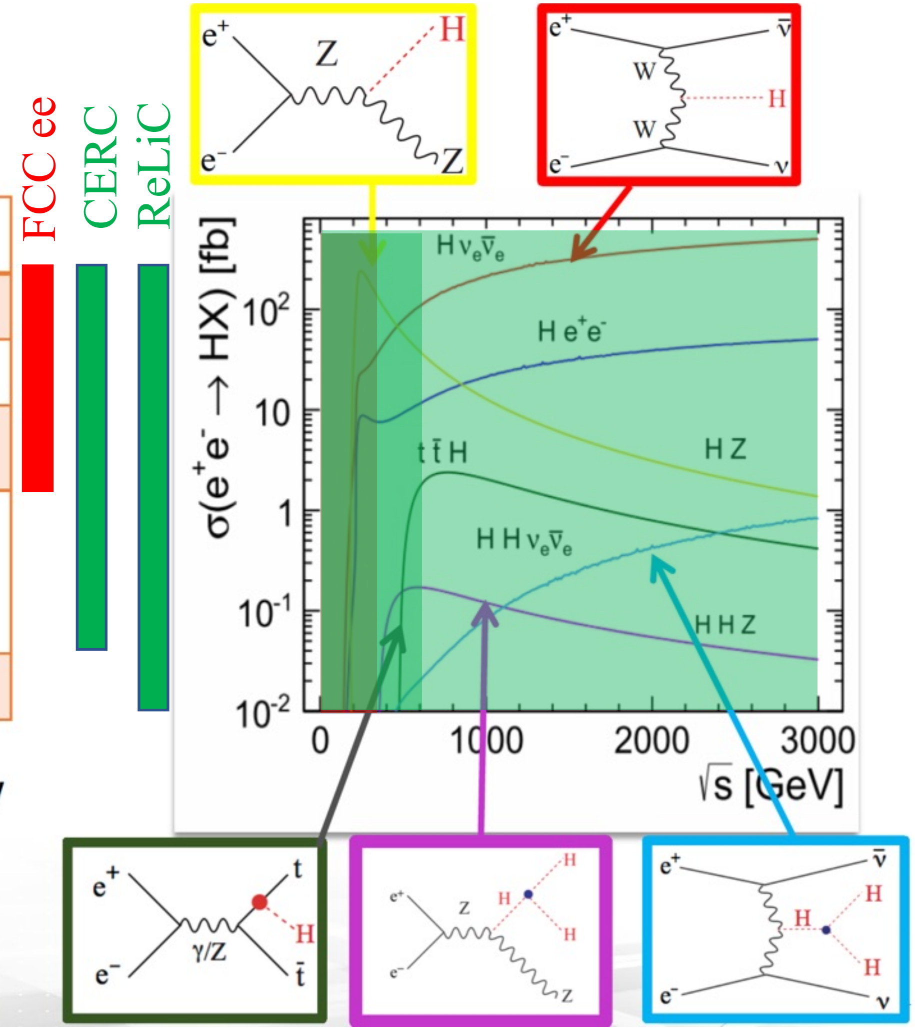
- Using linear collider approach for IRs: flat, low emittance beams with large vertical disruption parameters
- Recycling as much as possible of the beam energy
- Recycle and re-use collided electrons and positrons
- Use damping rings to prepare (and polarize) recycled beams for next collisions
- Resulting in
  - Increased luminosity and energy reach when compared with competing approaches
  - Natural environment for colliding highly polarized electron and position beams

ERL colliders would collide highly polarized e^+e^- beams, providing very high luminosity and high-energy reach (up to 3 TeV c.m. energy). They would span through **Higgs sector** and open window to explore **Physics beyond Standard Model**

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)

Motivation 2: Luminosity

Green curve – ReLiC, Recycling Linear Collider

Violet curve : CERC, Circular ERL collider, with 30 MW of synchrotron radiation

Red curve – for CIRC with 100 MW of synchrotron radiation (as in FCC ee)

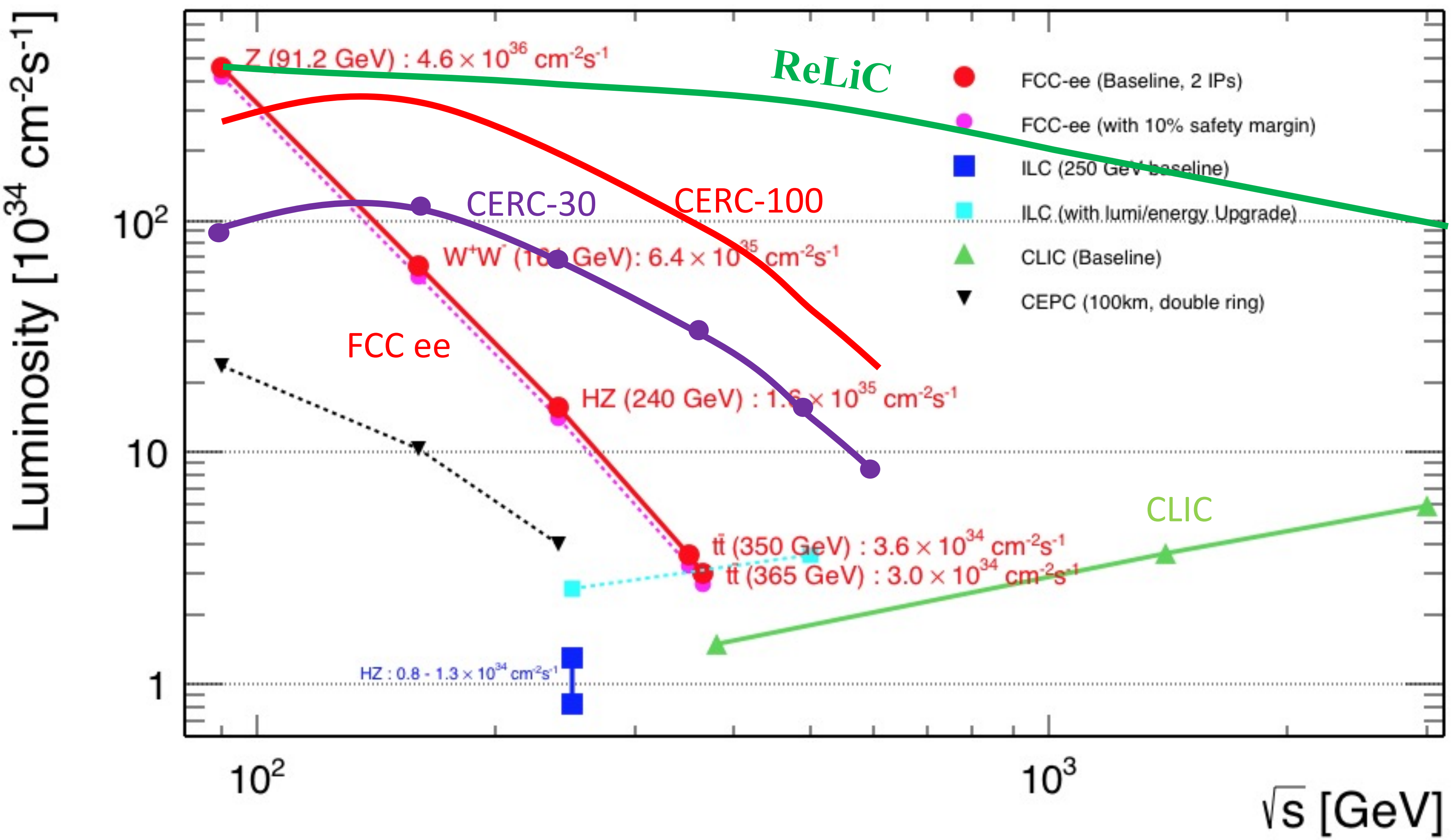
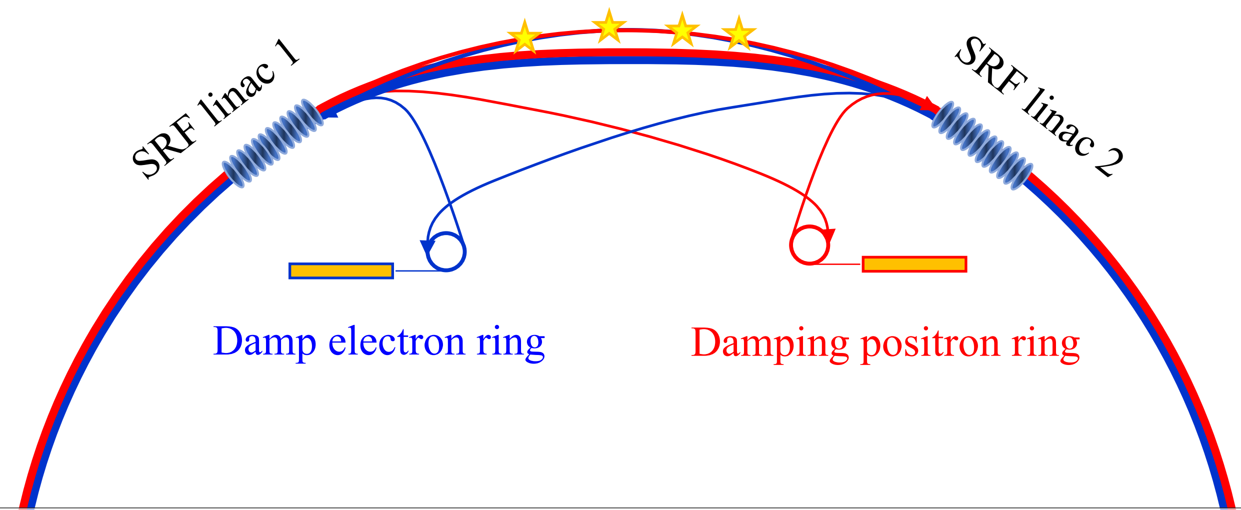


Table for two energies

Collder	e+e-	CERC		ReLiC	
C.M. energy	GeV	**240**	**600**	**240**	**3000**
Length of accelerator	km	**100**	**100**	**20**	**360**
Section length	m	**n/a**	**n/a**	**250**	**250**
Bunches per train		**1**	**1**	**10**	**21**
Particles per bunch	10^{10}	**15.600**	**11.9**	**2**	**1**
Collision frequency	MHz	**0.099**	**0.009**	**25.2**	**25.2**
Beam current	mA	**2.5**	**0.17**	**40.0**	**40.0**
εx, norm	mm mrad	**3.9**	**7.8**	**4**	**4**
εy, norm	µm mrad	**7.8**	**7.8**	**1**	**1**
βx	m	**1.75**	**3**	**3**	**100**
βy, matched	mm	**0.29**	**1**	**0.73**	**10**
σz	mm	**3**	**10**	**2**	**17**
Dx		**0.3**	**0.3**	**0.02**	**0.002**
Dy		**544**	**492**	**43**	**15**
Total luminosity	10^{34} cm^{-2}sec^{-1}	**93**	**4.4**	**343**	**94**

CERC - Circular ERL Collider



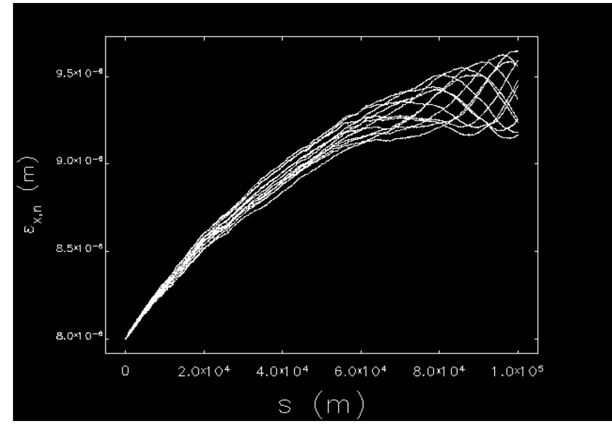
- Flat beams cooled in damping rings with "top off" for burn-off
- Bunches are ejected with collision frequency
- Beams accelerated with SRF linacs over four 100 km long passes by-passing the IR
- After collision at top energy rf phases are changed to deceleration returning most energy to SRF linac
- Decelerated beams are reinjected into cooling rings, after few damping times 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

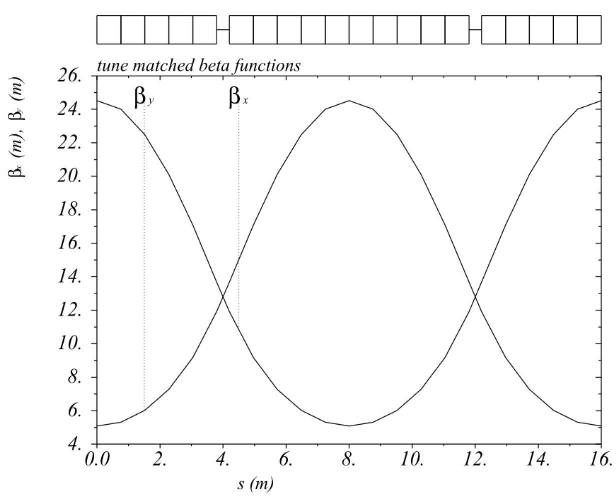
CERC recycles (polarized) electrons and positrons

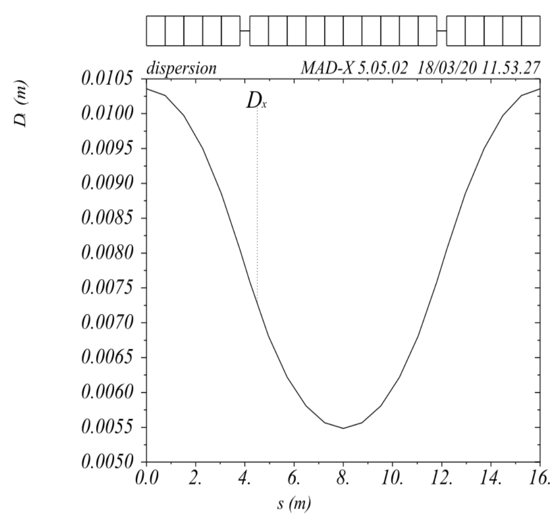
- After acceleration, collision, and deceleration all electrons and positrons are reinjected into the cooling rings. Only beam losses must be made up through top-off injection.

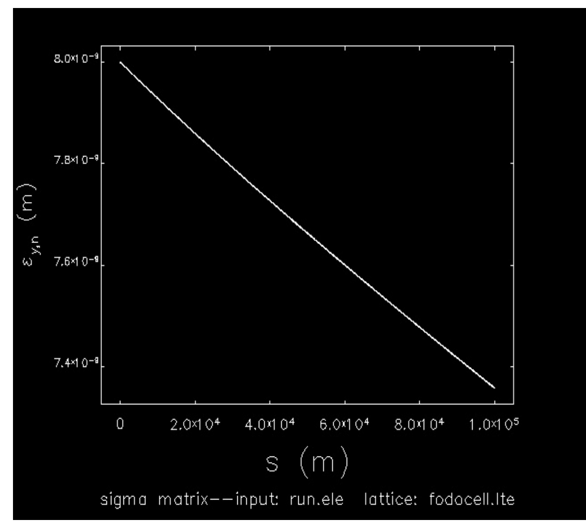
Lattice - 250 GeV path

- 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

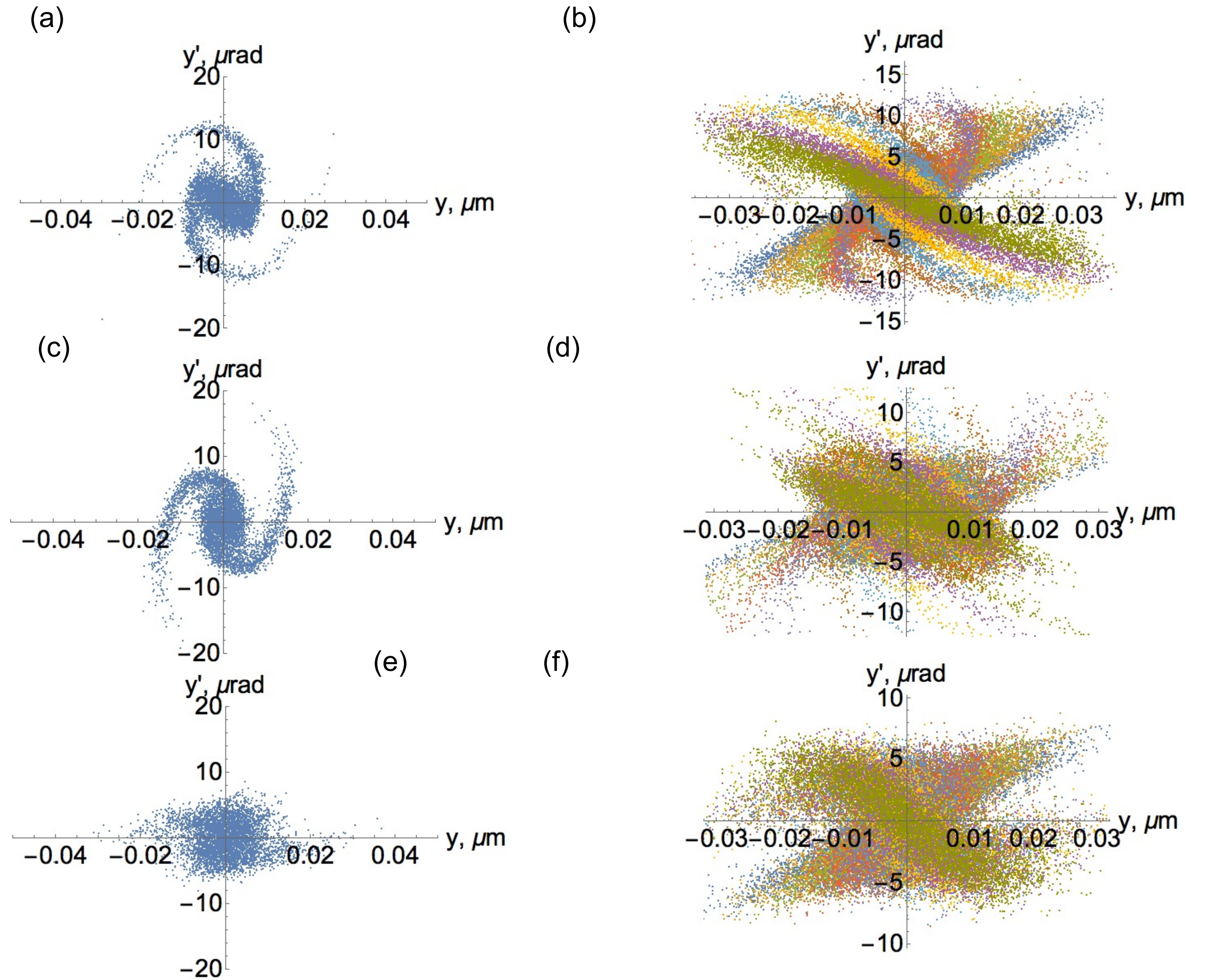








Strong-strong collisions of flat beams in ERL e^+e^- collider

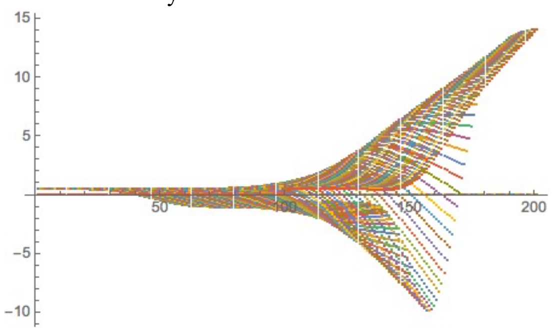


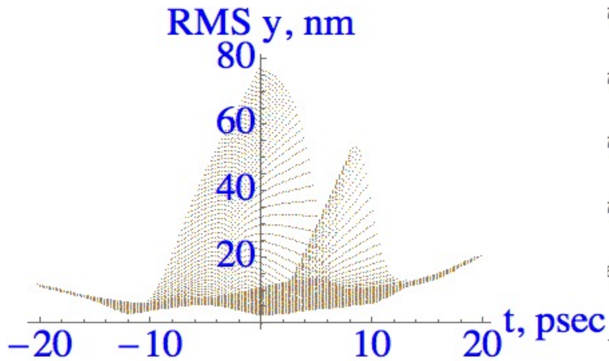
Beam distribution in the vertical phase space after the collision. Distributions of the central slice are on the left and combinations of 10 slices covering evenly $-3\sigma_z < z < 3\sigma_z$, are on the right: (a-b) are for center particles at x=0; (c-d) are for those at $x = \sigma_x$, (e-f) is for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

Effects of orbits offsets in IP

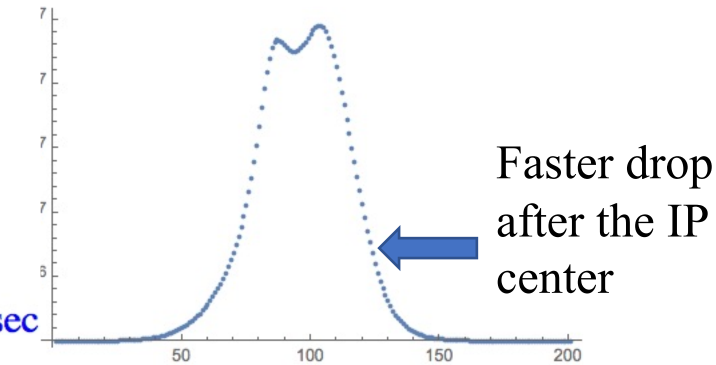
Initial beam axis separation is $\Delta y = 1\sigma_y$

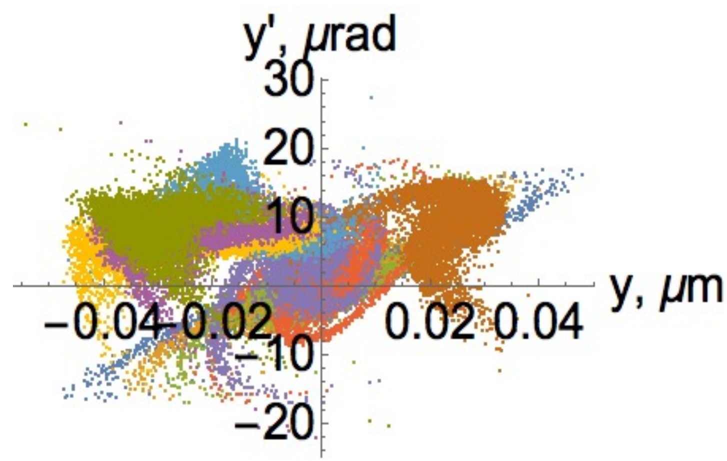
Beam centroids evolution in units of σ_y at the beam waist.

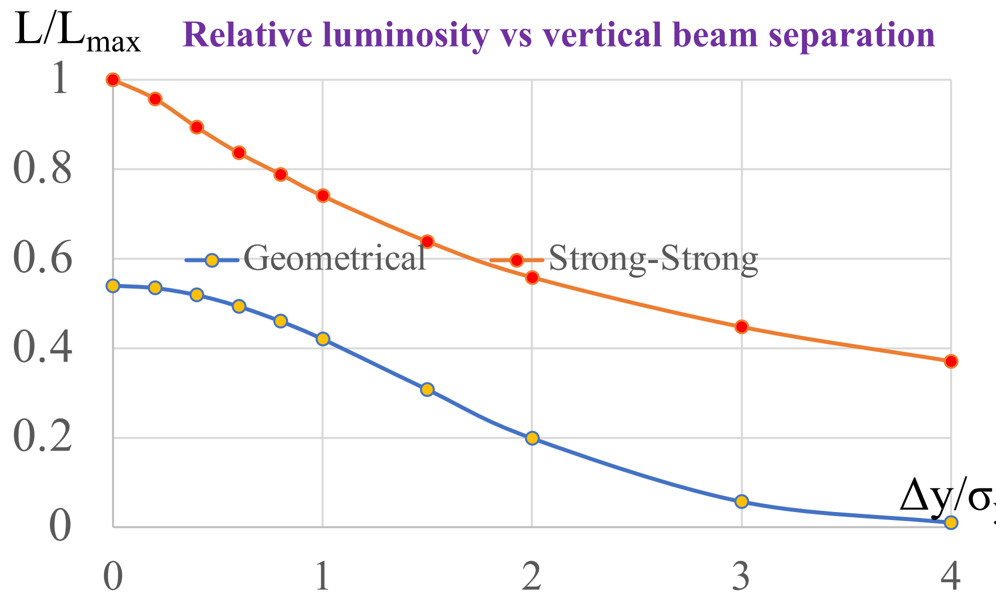




Instantaneous luminosity (a.u.)



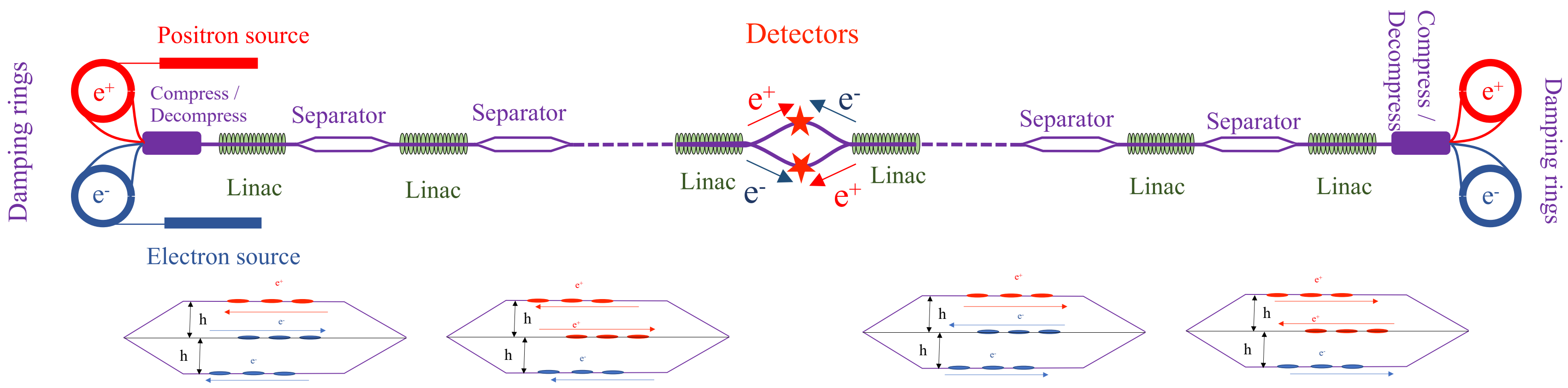




Main effect from offsets: RMS vertical beam emittance increases ~ 10X after collisions. It does not present any problems for the energy and particles recovery. It may require to increased time in the cooling rings to three-to-four damping times – this should be optimized for actual orbit deviations

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

ReLiC – Recycling Linear Collider



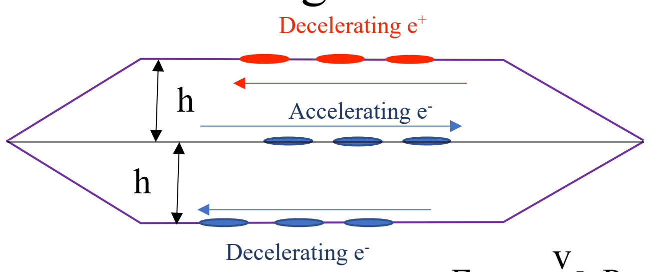
- Flat beams cooled in damping rings with "top off" to replace burned-off particles
- Bunches are ejected with collision frequency, determined by the distance between beam separators
- Beams are accelerated **on-axis** in SRF linacs collide in one of detectors
- After collision at the top energy, they are decelerated in the opposite linacs
- Decelerated beams are injected into cooling rings
- After few damping times the trip repeats in the opposite direction and beams collide in a detector located in the opposite branch of the final separator …..

ReLiC collider recycles (polarized) electrons and positrons

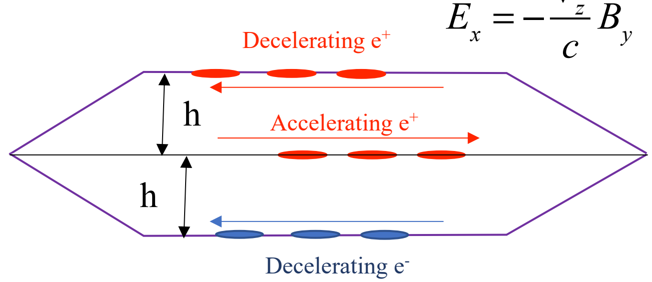
- After acceleration, collision, and deceleration all electrons and positrons are reinjected into the cooling rings. Only beam losses must be made up through top-off injection.

Important details od ReLiC design

- Both accelerating and decelerating beams propagate on axis of SRF cavities where <u>transverse fields are zero</u>. There is no need for asymmetric dual-cavities – unexplored SRF technology.
- Focus on limiting energy spread in colliding beams
  - We capped critical energy of beamstrahlung photons to 200 MeV and 700 MeV at c.m. energies of 240 GeV and 3 TeV, correspondingly – it is significantly smaller then in ILC and CLIC
  - We limited number of bunches in trains to keep the beam loading below 10^{-3}*
- Separators use commination of DC electric and magnetic fields, which do not affect trajectory of accelerating bunches. This choice preserves emittances of colliding bunches



$$E_x = -\frac{v_z}{c} B_y$$



$$F_x = \pm e\left(E_x + \frac{v_z}{c} B_y\right) = \begin{cases} 0, acclerating \\ 2eE_x, decelerating\ \ postions \\ -2eE_x, decelerating\ electrons \end{cases}$$

** Even though, the energy of each colliding bunch is known and can be used for data analysis. If this feature is used, luminosity can be further increased*

Impact of polarization

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

The proper combination of polarization for electrons and positrons will significantly enhance the production cross section or will suppress it.

Agora: ITF Comparison Categories

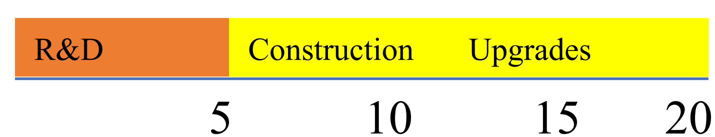
	CERC-30	ReLiC
CoM Energy and expandability, GeV	46 -600	46-3,000
Peak Luminosity (10^{34} cm^{-2} s^{-1})	4 - 94	329 - 94
IP difficulties, beamstrahlung	beamstrahlung	none
Length of facility, km	100	20-360
Length of new accelerators, km	800	20-360
Beam parameters challenges (e+, alignment…)	Flat beam	Flat beam
Special technologies	High Q SRF HF kickers	High Q SRF HF kickers
R&D/validation (yrs. needed); constr. start year	R&D 5 year, 2030	R&D 5 year, 2035
Construction time, yrs.	5-10	5-15 (upgrades)
Cost (wrt ILC) (+/-, %) Level of maturity	~50% Concept	Depends on c.m. energy Concept
Environment issues: AC power consumption of facility, resources (Nb, LHe…) needed	61-216 Nb, LHe	300 – 800 Nb, LHe

Technical Maturity

- Overall Technical Maturity: 1 – Significant R&D required

- Critical Technologies
  - High Q for low frequency SRF cavities, needed R&D
  - High rep-rate kickers, needed R&D
  - Flat beams with $\varepsilon_h/\varepsilon_v$ =1,000, need of R&D

- Technically limited timeline



Conclusions

- CERC: energy reach 500-to-600 GeV
  - Originally published in Phys. Lett. B Volume 804, 135394, (2020)
  - We updated beam parameters, specifically bunch lengths of colliding beams and energies of damping ring, to address weak low energy tail associated with beamstrahlung. Energy acceptance of the system is increased to keep particle loss bellow 1 p.p.m.
  - Preliminary simulations confirmed our expectation that system will be capable of sustaining high degree of polarization in both electron and position beams
  - We developed a straw-man lattice and performed initial tracking simulation
  - *Main challenges – maintaining flatness of beams in transport and high rep-rate kickers*
- ReLiC: energy reach tested to 3TeV, further increase is possible
  - This approach was obvious when we publish our CERC paper, but we had not time to explore it till last November. It is much simpler than CERC, but is less explored and optimized
  - In contrast with circular ERL, synchrotron radiation losses and emittance growth can be kept ay negligible level in separators. This is indication that c.m. energy can be 3 TeV or even higher.
  - Beamstrahlung is much smaller than in CERC and ILC
  - Disruption parameters are 10x smaller than in CERC
  - Main energy losses will occur in damping rings, with operating energies 2 to 2.5 GeV
  - *Main challenges – MHz rep-rate of kickers, high SR power in damping ring*
  - The concept also can be used for pulsed SRF linac, with the average luminosity reduced proportionally to the duty factors
- Detailed studies and extensive R&D are needed to fully validate both of concepts

Web page for people who are interested to support the high energy high luminosity e+e colliders: register at https://indico.bnl.gov/event/15344/

Personal note

- My personal preference is **ReLiC**. Its 3 TeV version is more expensive, but its potential is terrific
- CERC design was triggered by observing that FCCee plans to compensate 100 MW of SR losses. It was clear that energy recovery may help.
- While CERC is valid concept, as any colliders planning to turn around full energy e+ or e- beams, energy rich is limited and luminosity plumets at high energies
- In contrast, ReLiC does not have such limitations. It utilized the same concept of recycling as CERC, but not suffers from a need to turn-around full energy beam
- In contrast with ILC or CLIC, ReLiC does not suffer from beamstrahlung and insane appetite for fresh polarize positrons.

Thank you for your attention

Back-up slides

ReLiC– main parameters

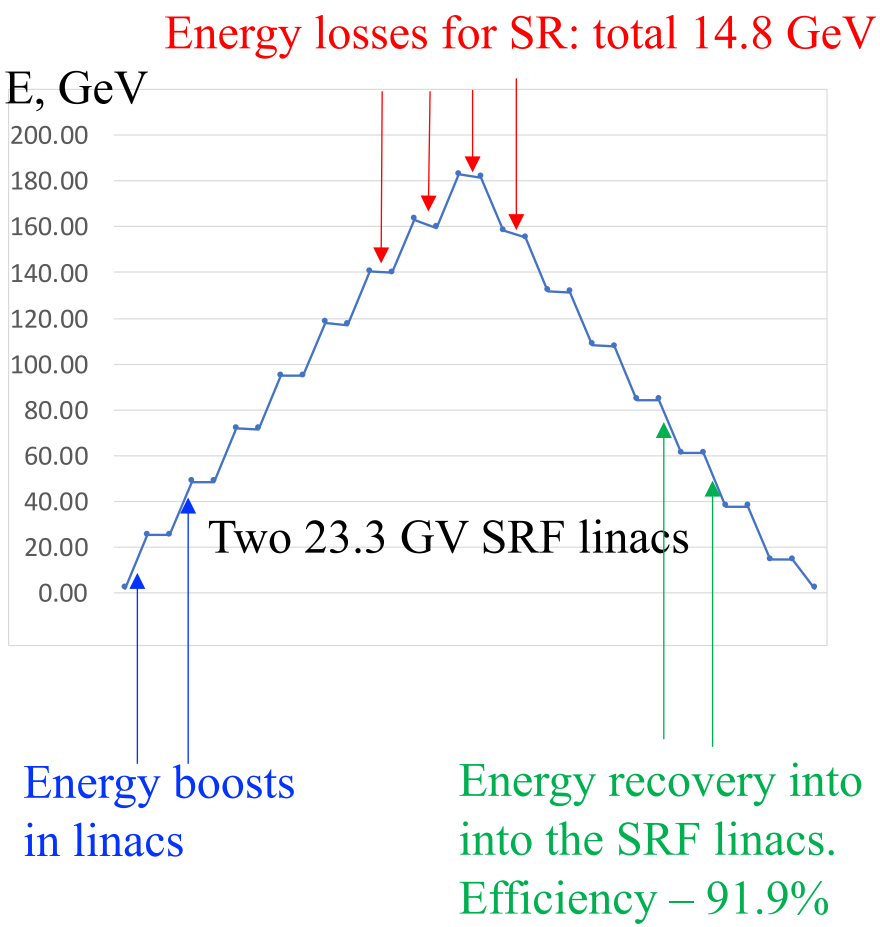
C.M. energy	**GeV**	**91**	**240**	**500**	**1,000**	**3,000**
Length of accelerator	km	7	20	41	85	288
Section length	m	250	250	250	250	250
Bunches per train		5	10	15	21	21
Particles per bunch	10^{10}	4.0	2.0	1.4	1.0	1.0
Collision frequency	MHz	6.0	12.0	18.0	25.2	25.2
Beam currents in linacs	mA	38	38	40	40	40
εx, norm	mm mrad	4.0	4.0	3.9	3.9	4.0
εy, norm	μm mrad	1.0	1.0	2.0	2.0	1.0
βx	m	5	5	3	5	100
βy, matched	mm	0.21	0.34	0.73	2.22	9.7
σ_z	mm	1	1	2	6	17
Disruption parameter, Dx		0.01	0.01	0.01	0.02	0.002
Disruption parameter, Dy		109	43	38	37	15
Luminosity per detector	10^{34} cm^{-2}sec^{-1}	164	172	165	107	47
Total luminosity	10^{34} cm^{-2}sec^{-1}	329	343	330	213	94

CERC – main parameters

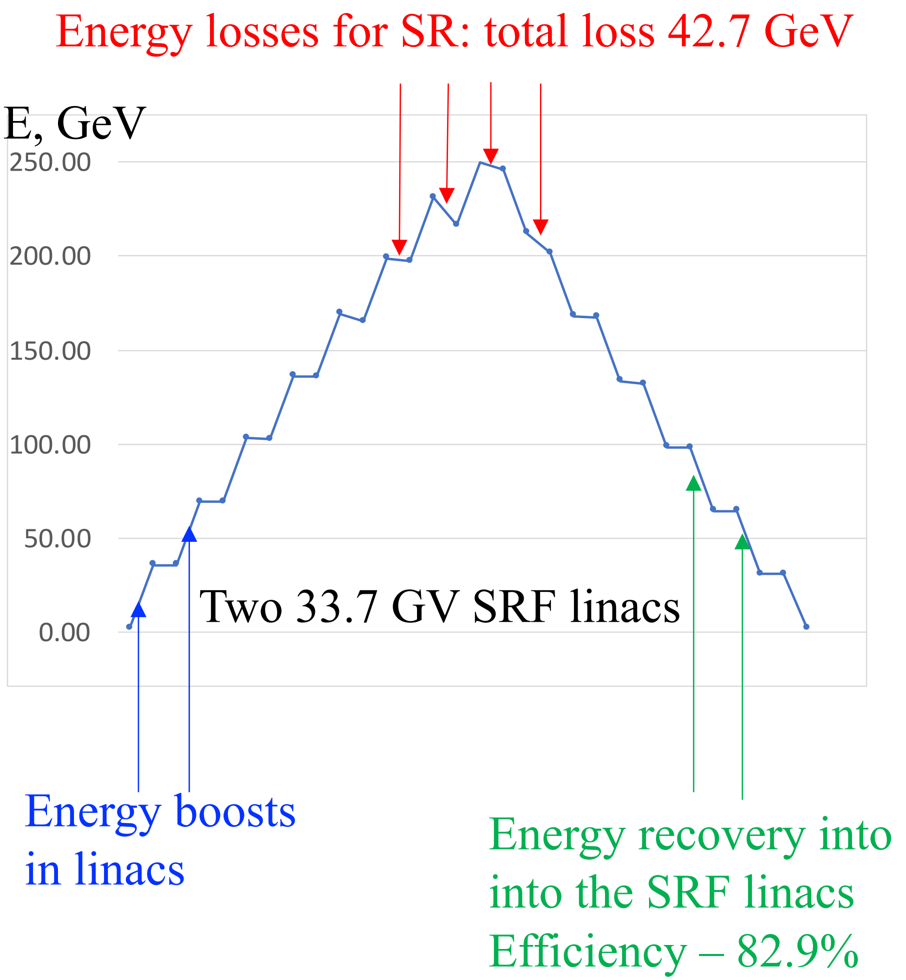
CERC	Z	W	H(HZ)	ttbar	HH	Httbar
Circumference, km	100	100	100	100	100	100
Beam energy, GeV	**45.6**	**80**	**120**	**182.5**	**250**	**300**
Hor. norm ε, μm rad	3.9	3.9	6.0	7.8	7.8	7.8
Vert. norm ε, nm rad	7.8	7.8	7.8	7.8	7.8	7.8
Bend magnet filling factor	0.9	0.9	0.9	0.9	0.9	0.9
βh, m	0.5	0.6	1.75	2	2.5	3
βv, mm (matched)	0.2	0.3	0.3	0.5	0.75	1
Bunch length, mm	2	3	3	5	7.5	10
Charge per bunch, nC	13	13	25	23	19	19
Ne per bunch, 10^{11}	0.78	0.78	1.6	1.4	1.2	1.2
Bunch frequency, kHz	297	270	99	40	16	9
Beam current, mA	3.71	3.37	2.47	0.90	0.31	0.16
Luminosity, 10^{35} $cm^{-2}sec^{-1}$	6.7	8.7	7.8	2.8	1.3	0.9
Energy loss, GeV	4.0	4.4	6	17	48	109
Rad. power, MW/beam	15.0	14.9	14.9	15.0	16.8	16.9
ERL linacs, GV	10.9	19.6	29.8	46.5	67.4	89
Disruption, D_h	2.2	1.9	0.8	0.5	0.3	0.3
Disruption, D_v	503	584	544	505	459	492

The e$^-$ and e$^+$ beam energy evolutions *in a 4-pass ERL*

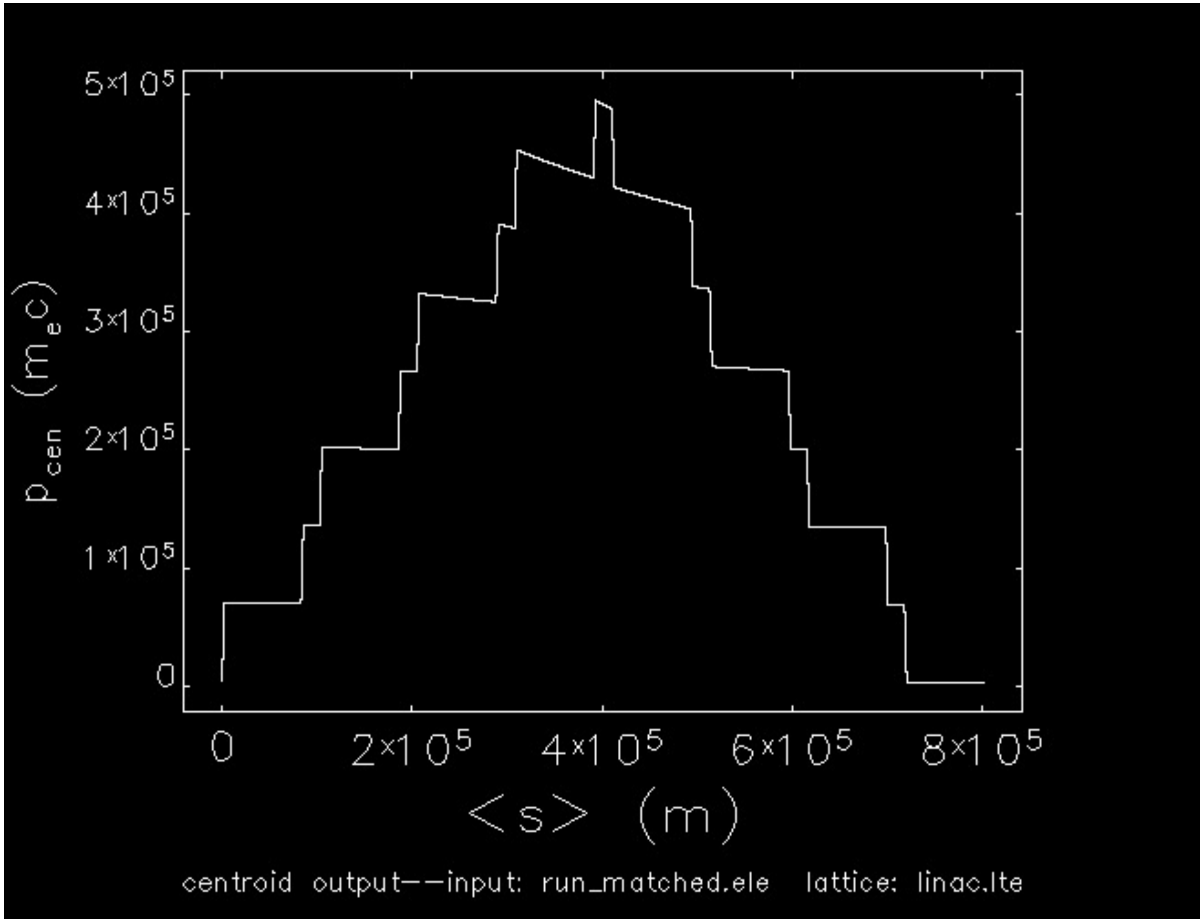
2 x 182.5 GeV: **365 GeV CM GeV $t\bar{t}$**



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



Simulations are in progress



Comparison of ERL and Ring colliders

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

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

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

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

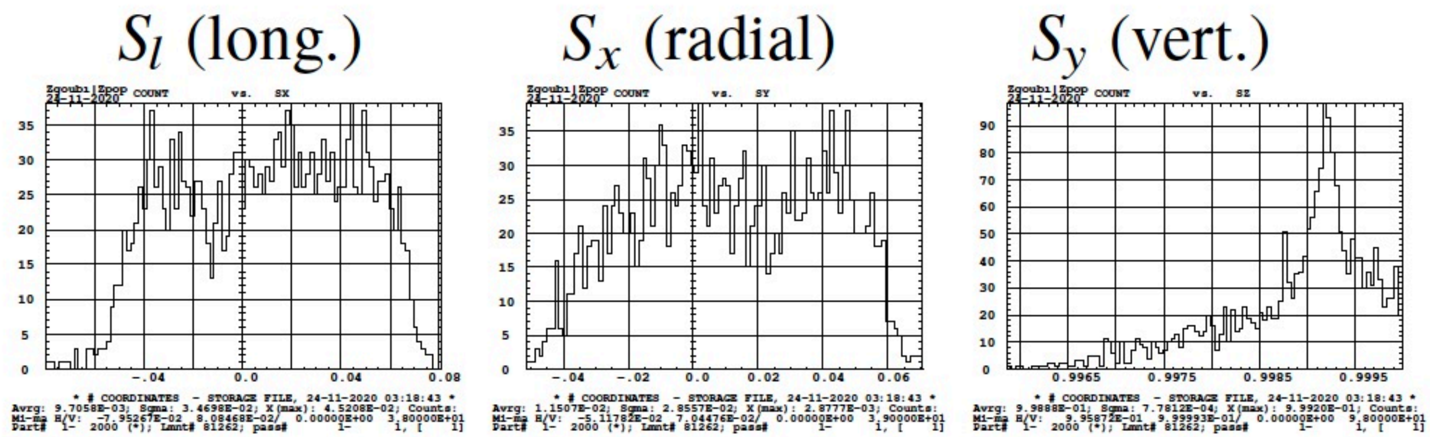
For simplicity and better comparison, we decided to use the same IR and β* as in FCC ee design

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%

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

Preliminary simulation of spin dynamics



Density distribution of spin components in the 219 GeV e^+ and e^- beams after passing around the 100 km circular trajectory in the ERL-based collider