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

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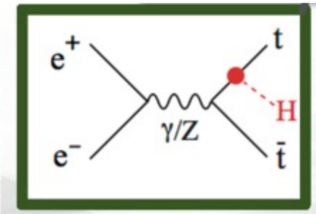
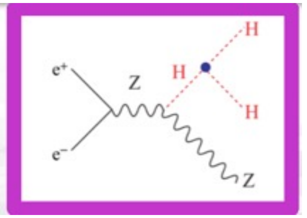
Key development: two concepts including

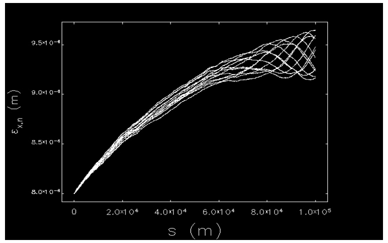
CERC (**C**ircular **E**nergy-**R**ecovery **C**ollider) and **ReLiC** (**R**ecycling **Li**near **C**ollider)

Physics: Investigating details of:





Accelerator: Developing detailed start-to-end simulations



Checked possibility of colliding polarized electron and position beams

October 5, 2022: ERL’22 workshop, Cornell University

CERC and ReLiC: polarized e^+e^- colliders

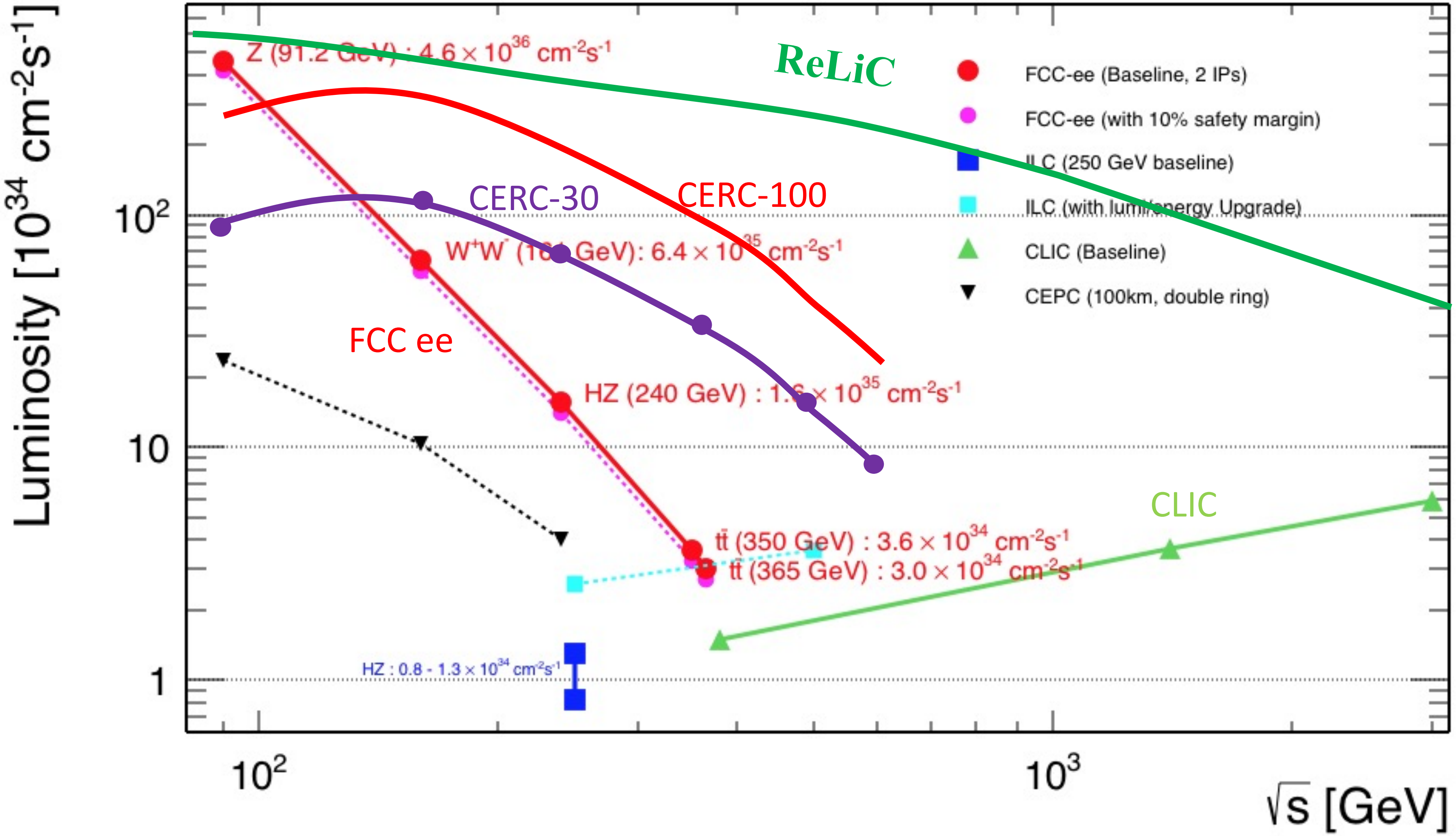
Impact of polarization

- Common features
  - Recycling of used particles - no need for high intensity positron source
  - Energy recovery
  - High luminosity
  - High polarization of both electron and positron beams
- Differences
  - CERC c.m. energy reach is limited to sub-TeV by synchrotron radiation of the beam at the top energy
  - ReLiC has potential of operating at higher luminosity that CERC
  - ReLiC can also go to few TeV c.m. energy, but requires full energy linacs

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.

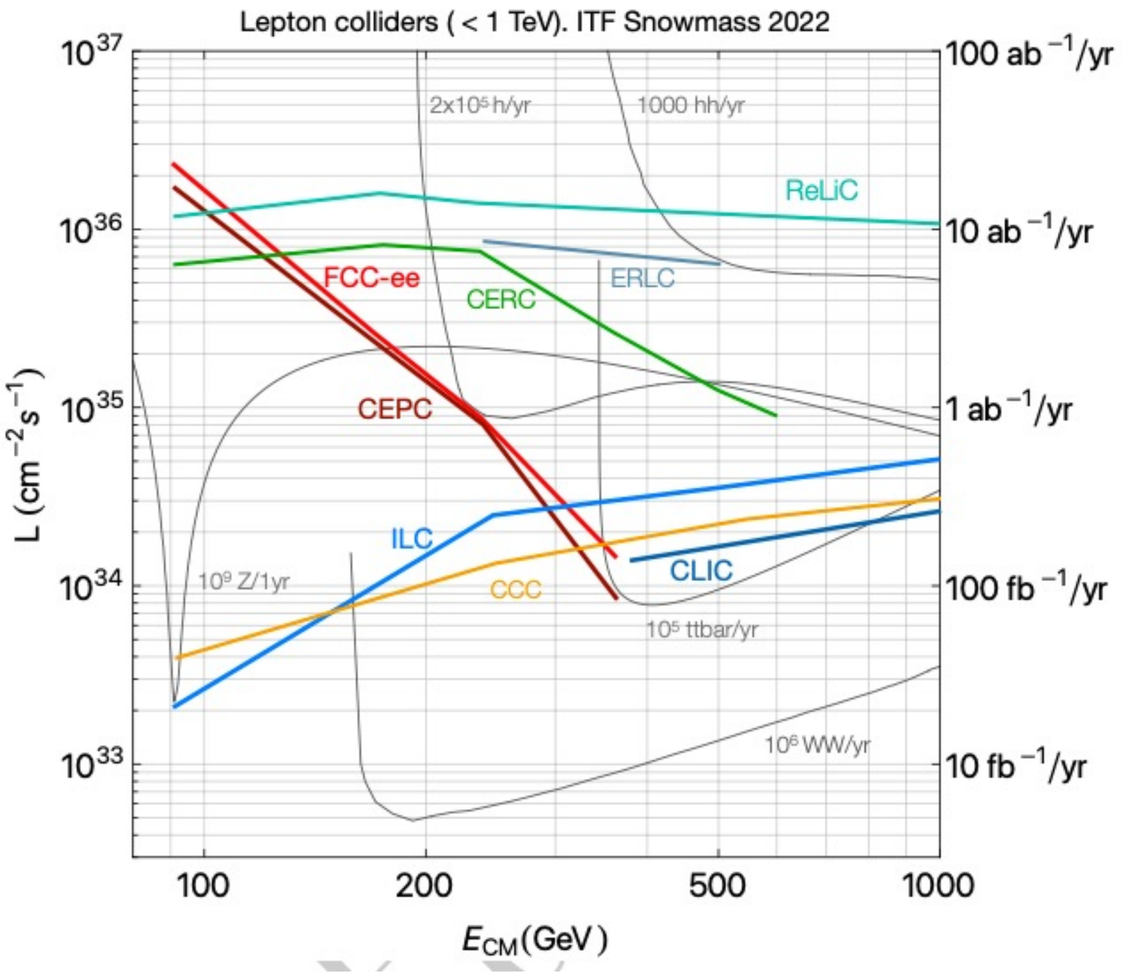
Both CERC and ReLiC would be capable of operating at high c.m. high energies with very high luminosity



Physics potential in HIGS sector

√s [GeV]	Science Drivers
90-200	EW precision physics, Z, WW
250	EW Higgs precision (HZ), Hνν
365	tt
500-600	HHZ, ttH direct access to Higgs self-couplings, top Yukawa couplings
1000-3000	HH***νν*** Higgs self-couplings in vector-boson fusion sector

- CERC @ 30MW of SR and ReLiC provide much higher luminosity than ILC/CCC and FCC-ee/ CEPC at √s >120 GeV
- CERC can reach √s~600 GeV, while ReLiC can reach √s>1 TeV



Suitability for future experiments

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)

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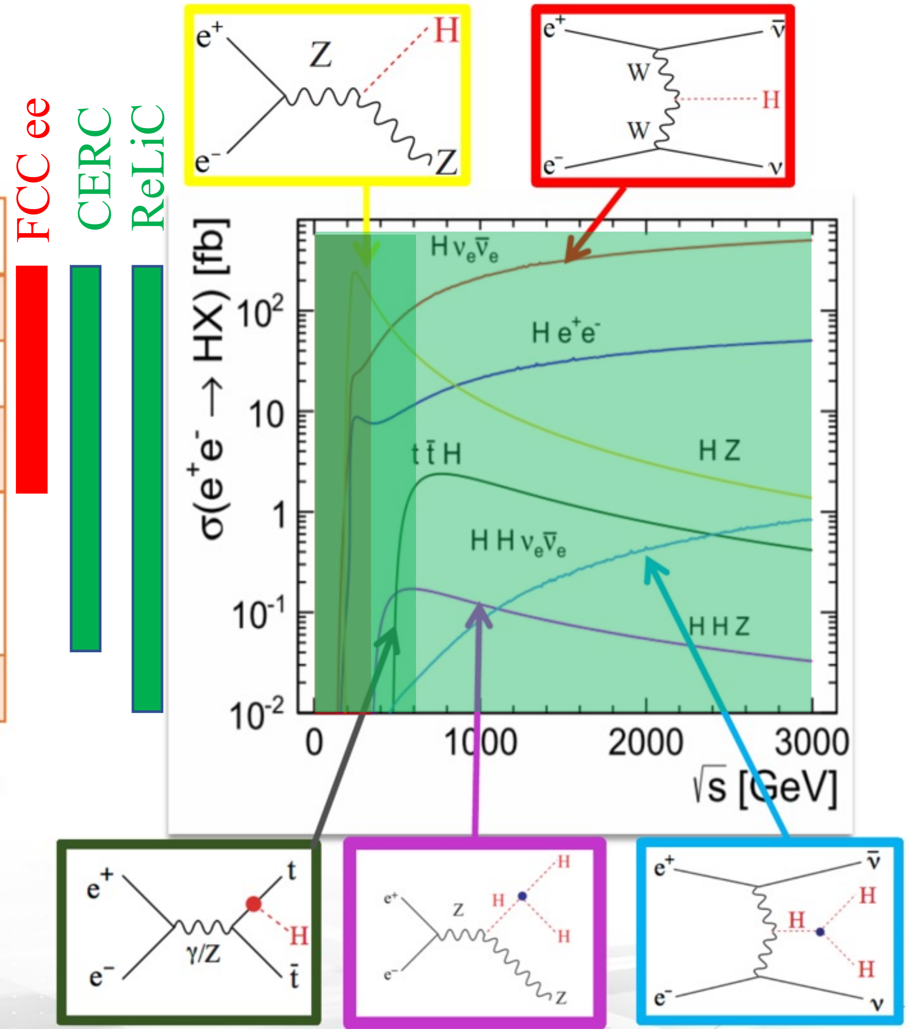
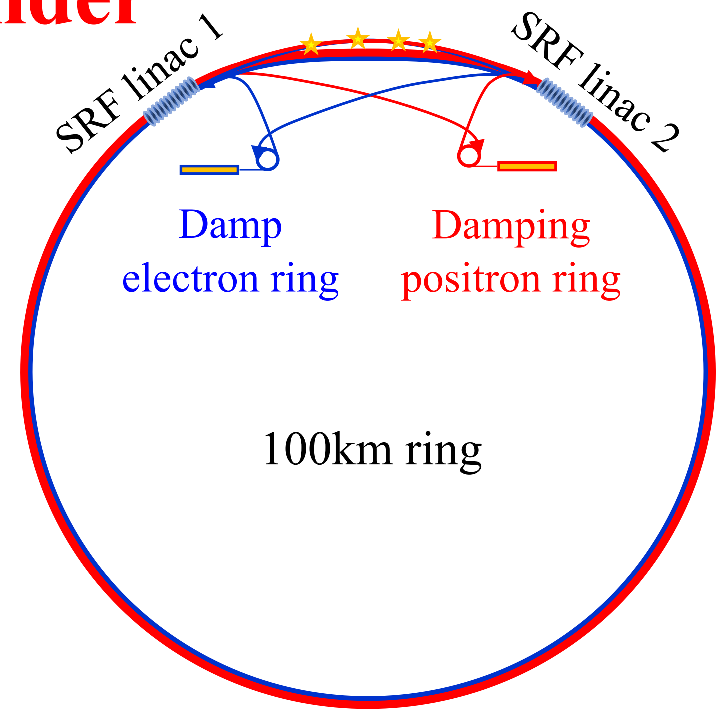


Can be also used for hadron-electron and hadron-positron collider in conjunction with LHC or FCC hh

CERC, Circular e+e- Energy Recovery Collider

Baseline design

- Flat beams cooled in damping rings with top off
- Bunches are ejected with collision frequency
- Beams accelerated with SRF linacs in two four-path ERLs
- 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



Combines advantages of existing colliders:

- Storage ring colliders: recycling beam energy and particles
- Linear colliders: efficient collisions using a large disruption parameter

CERC parameters

Table 1. Main parameters of ERL-based e^+e^- collider with synchrotron radiation power of 30 MW.

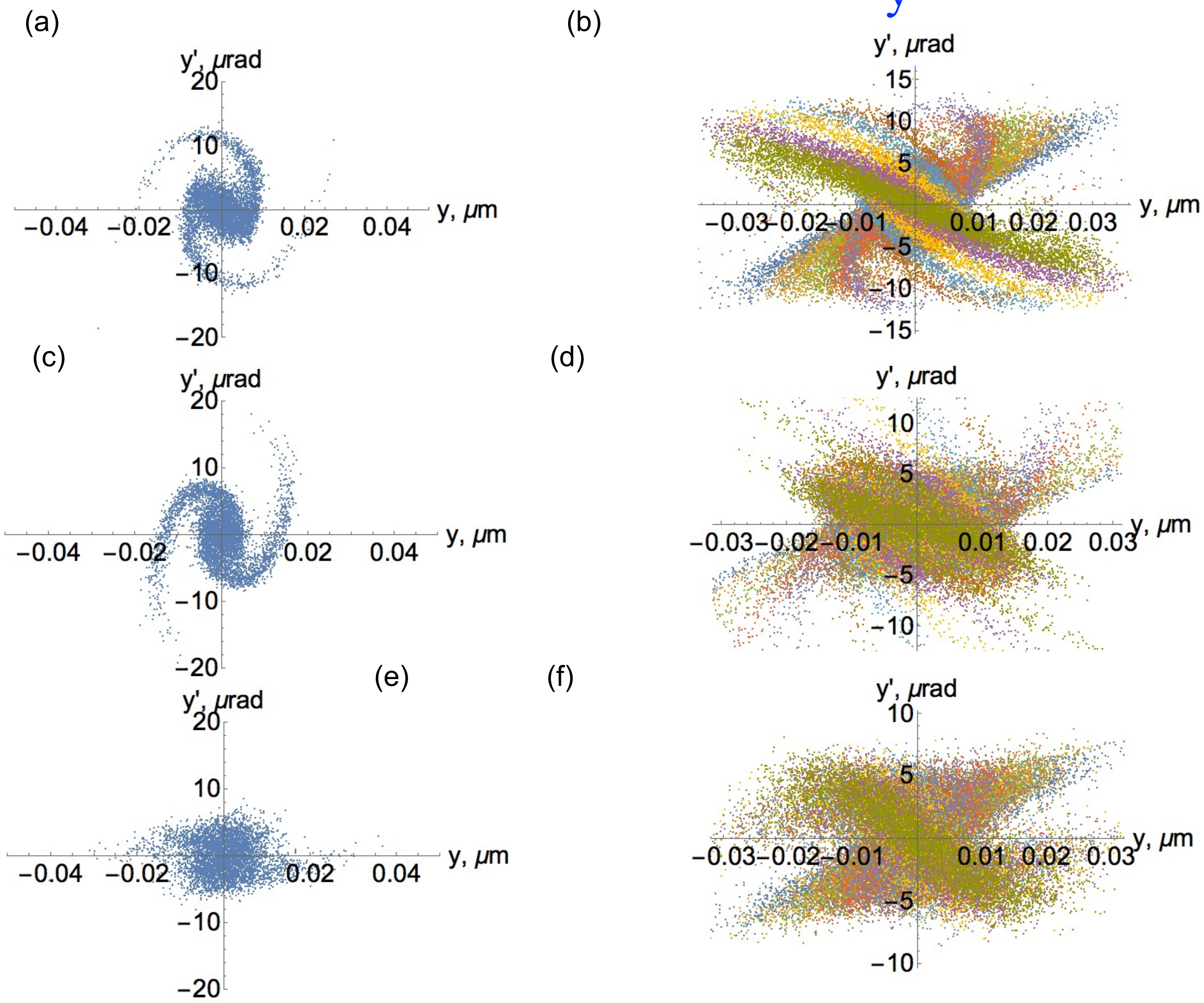
CERC	Z	W	H(HZ)	ttbar	HH	Httbar
Circumference, km	100	100	100	100	100	100
Beam energy, GeV	**45.6**	**80**	**120**	**182.5**	**250**	**300**
Hor. norm ε, μm rad	3.9	3.9	6.0	7.8	7.8	7.8
Vert. norm ε, nm rad	7.8	7.8	7.8	7.8	7.8	7.8
Bend magnet filling factor	0.9	0.9	0.9	0.9	0.9	0.9
βh, m	0.5	0.6	1.75	2	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
Damping ring energy [GeV]	2	2	2	3	4.5	8

Key technologies and Challenges

- Energy Recovery Linacs approach: the energy which the beam receive from the RF field in superconducting accelerating structures is fed back to the structures by decelerating the beams on the opposite RF phase after beams collide at the IP
- Two SRF Linacs
  - 703 MHz 5-cell cavity (so called BNL-3 design)
  - 16 m long cryostat housing 10 five-cell cavities
  - SRF $Q_0=10^{11}$
- 16 transport lines: due to synchrotron radiation the recirculating beam lines for accelerated and decelerated beams have to be different
- High energy acceptance damping rings to cool down beams at an energy of ~few GeV after collisions. Beamsstrahlung relative energy spread is amplified by a factor 60 with deceleration to the damping ring
- High repetition kickers to extract/inject up to 99k bunches into the damping rings
- NC magnets with ~15 mm gap

- Multi-pass, high energy ERL
- Transport beamline lattice preserving a small vertical emittance with large beam aspect ratio
- Flat beams and high disruption parameter need full 3D simulations
- Using small gap magnets to reduce power consumption and cost of the multiple 100 km beamlines
- Absolute beam energy measuring systems with accuracy $\sim 10^{-5}$ at IRs as pioneered at CEBAF
- High repetition rate extraction and injection kickers for a few GeV damping rings
- Compressing and de-compressing electron and positron bunches to match energy acceptance of the ~ GeV damping rings
- Recirculation lines for e+ and e- are different, 16 lines in total (4-pass ERL)

Strong-strong collisions of flat beams in ERL e^+e^- collider: D_y=142

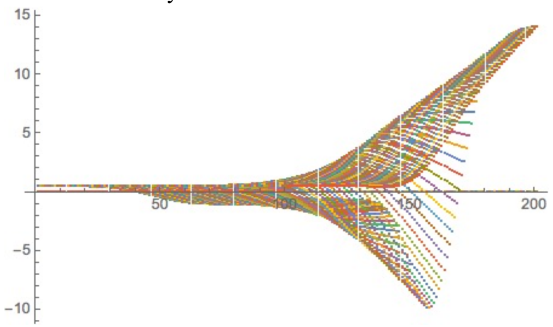


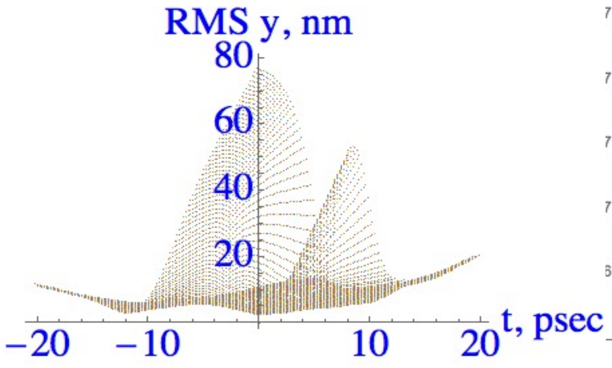
Beam distribution in the vertical phase space after the collision. Distributions of the central slice are on the left and combinations of 10 slices covering evenly $-3\sigma_z < z < 3\sigma_z$, are on the right: (a-b) are for center particles at x=0; (c-d) are for those at $x=\sigma_x$, (e-f) is for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

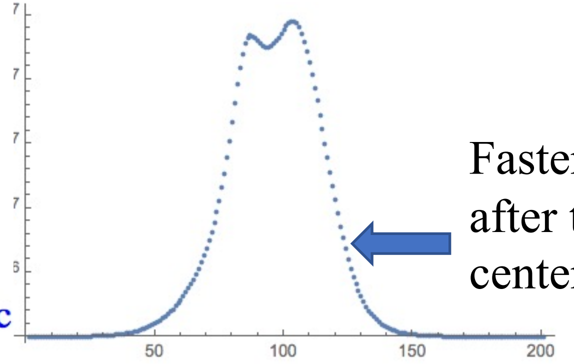
Initial beam axis separation is $\Delta y = 1\sigma_y$

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

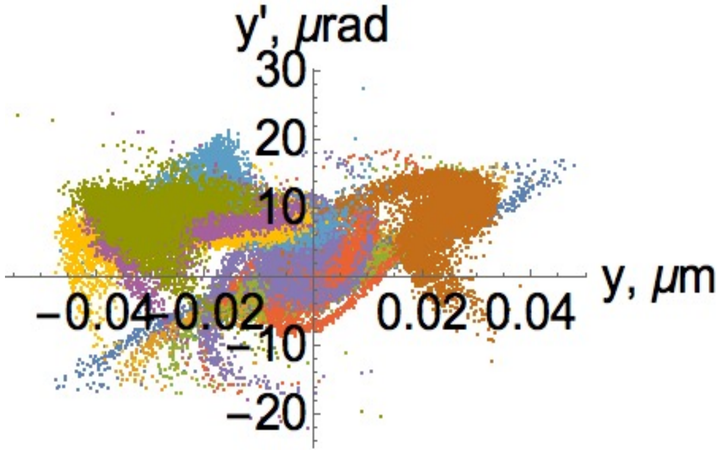


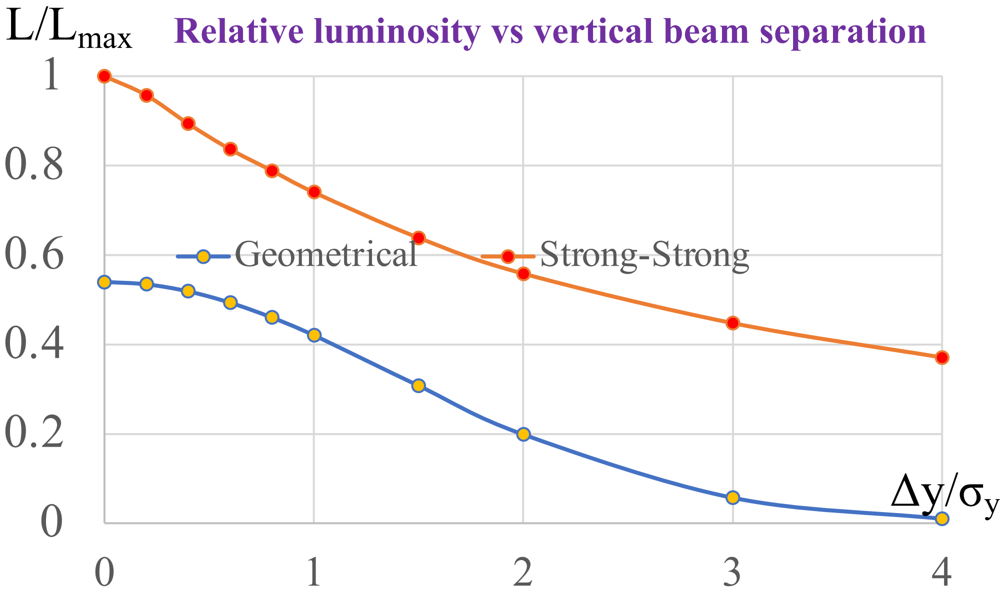


Instantaneous luminosity (a.u.)



Faster drop after the IP center

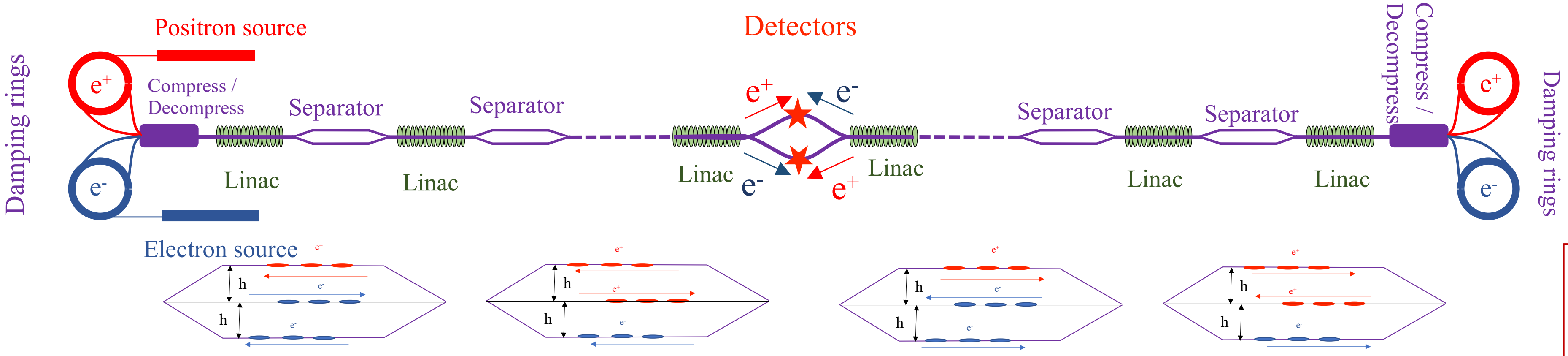




Main effect from offsets: RMS vertical beam emittance increases ~ 10X after collisions. It does not present any problems for the energy and particles recovery. It may require to increased time in the cooling rings to three-to-four damping times – this should be optimized for actual orbit deviations

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

ReLiC – Recycling Linear Collider



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

- Using **linear collider approach for IRs**: flat, low emittance beams with reasonable vertical disruption
- **Recycling** of the beam energy and **recycling and re-use** collided electrons and positrons
- Bunches are ejected with collision frequency and **accelerated on-axis** in SRF linacs **collide in one of two detectors**
- ReLiC **collides mono-energetic beams** by keeping the beamstrahlung under control
- Collided bunch trains are **decelerated** in the opposite linacs where they are periodically **separated** from colliding with accelerating beam
- Decelerated beams are injected into the damping rings to de **repaired and polarized.**
- After few damping times, the trip repeats in the opposite direction and beams collide in a detector located in the opposite
- Burned-off particles are replaced in the damping rings by “top off” from low current injectors

ReLiC collider recycles polarized electrons and positrons

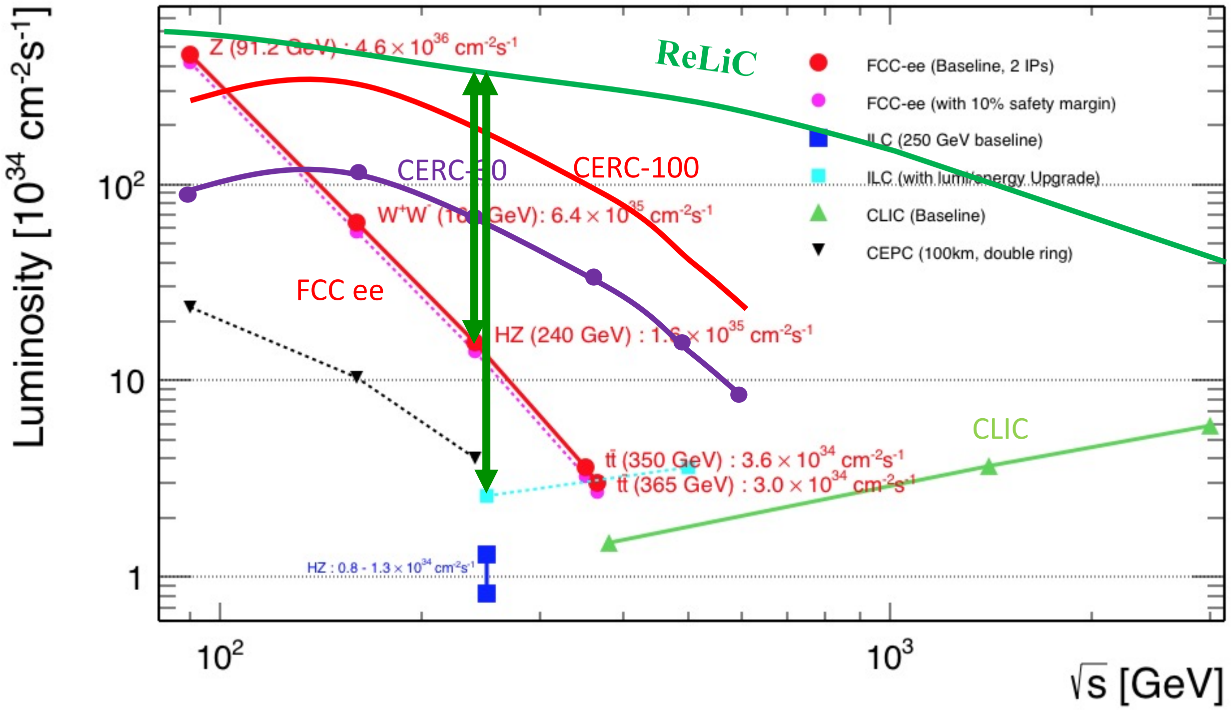
- Reusing electron and positron beams beam cooled in damping rings provides for natural polarization of both beam via Sokolov-Ternov process. Depolarization in the trip between damping ring is minuscular, which would provide for high degree of polarization. With lifetime ~ 10 hours, necessary replacement of electrons and positrons is at 1 nA level – this is major advantage of ReLiC

ReLiC in HIGS sector

Main parameters

C.M. energy	GeV	240	365	500
		HZ	tt_bar	HHZ
Length of accelerator	km	20	30	41
Section length	m	250	250	250
Bunches per train		10	12	15
Particles per bunch	10^{10}	2.0	1.7	1.4
Collision frequency	MHz	12.0	14.4	18.0
Beam currents in linacs	mA	38	39	40
εx, norm	mm mrad	4.0	4.0	3.9
εy, norm	μm mrad	1.0	1.0	2.0
βx	m	4	4	3
βy, matched	mm	0.32	0.56	0.73
σ_z	mm	1	2	2
Disruption parameter, Dx		0.01	0.01	0.01
Disruption parameter, Dy		50	64	38
Luminosity per detector	10^{34} cm^{-2}sec^{-1}	199	197	165
Total luminosity	10^{34} cm^{-2}sec^{-1}	398	395	330

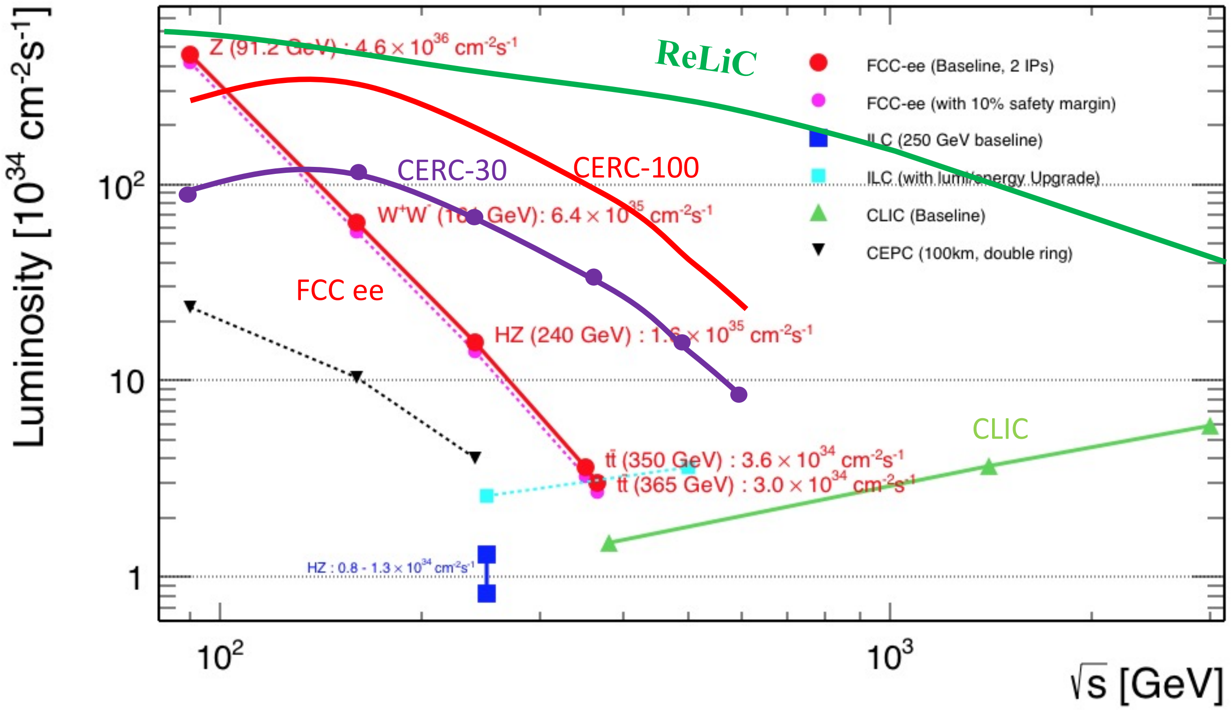
Gain of 40 to 200 at HIGS energy



ReLiC would be capable of very high luminosity at very high energies

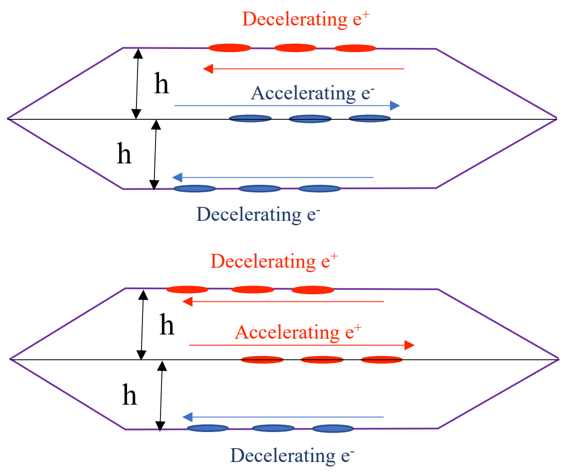
Main parameters

C.M. energy	**GeV**	**250**	**3000**
Length of accelerator	km	**21**	**276**
Section length	m	**500**	**250**
Bunches per train		**5**	**21**
Particles per bunch	10^{10}	**4**	**1**
Collision frequency	MHz	**3**	**18**
Beam currents in linacs	mA	**18**	**29**
εx, norm	mm mrad	**4**	**8**
εy, norm	μm mrad	**1**	**2**
βx	m	**5**	**100**
βy, matched	mm	**0**	**7**
σ_z	mm	**1**	**5**
Disruption parameter, Dx		**0**	**0**
Disruption parameter, Dy		**109**	**3**
Luminosity per detector	10^{34} cm^{-2}sec^{-1}	**215**	**20**
Total luminosity	10^{34} cm^{-2}sec^{-1}	**429**	**40**



Key technologies

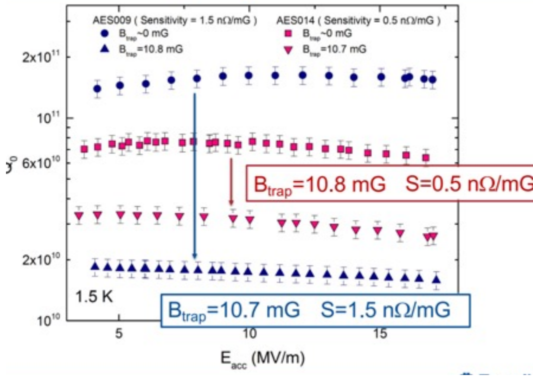
- CW superconducting RF (SRF) linacs with high Q
- 5-cell 1.5 GHz SRF cavities with effective HOM damping
- Electro-magnetic separators for contra-propagating bunch-trains
- Low emittance damping rings with flat beams and large energy acceptance
- Bunch compressor/decompressor
- MHz rate injection/ejection kickers
- nA-scale top-off e^+e^- injectors
- Two collision areas (IPs)
- Vertical beam stabilization at the IPs

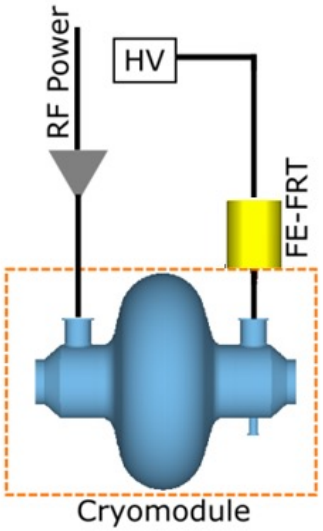


$$F_x = \pm e\left(E_x + \frac{v_z}{c}B_y\right) = \left\{ \begin{array}{c} 0, \textit{acclerating} \\ 2eE_x, \textit{decelerating postions} \\ -2eE_x, \textit{decelerating electrons} \end{array} \right\}$$

Accelerator design and challenges

- On-axis acceleration and deceleration of high energy beams is main advantage of ReLiC, allowing using existing SRF linac technology and other conventional equipment
- But still there are a lot of challenges:
- 1.5 GHz SRF cavities with quality factor Q > 10^{11} at 1.5 K
- High-efficiency 1.5K LiHe refrigerators
- Reactive tuners to reduce power to suppressing microphonics
- Damping rings with very flat beams ($\varepsilon_h/\varepsilon_v$ ~2,000-4,000)
- Damping rings with 10% energy acceptance
- 10-fold bunch compressor/decompressor at 10-20 GeV
- MHz rate injection/ejection kickers
- Vertical beam stabilization at the IPs





FoM ~75

Summary and Acknowledgements

- CERC
  - Higgs sector collider that promises high luminosities with a center of mass energy reach up to 600 GeV
  - Fists concept proposed as a high-energy, high-luminosity e+e- collider using Energy Recovery Linacs
  - Capable of sustaining high degree of polarization in both electron and positron beams
  - Strawman lattice developed and initial tracking simulations in IR were performed
  - *Main challenges – high Q SRF, high-repetition kickers, very flat beams*
- ReLiC
  - ReLiC would excel in HIGS sector – "reasonable" in size and power consumption with huge boost in luminosity and high degree of polarization
  - Radiation losses and emittance growth are negligible in separators - c.m. energy can be 3 TeV *or even higher*
  - Beamstrahlung is minuscular when compared with ILC – i.e. ReLiC would collide monoenergetic beams
  - Disruption parameters reasonable at HIGS energy and very small at 3 TeV c.m.
  - *Main challenges – High Q- SRF linac, reactive tuners, MHz rep-rate of kickers, high SR power in damping rings*

- Acknowledgements
  - Authors are thankful to Dr. Sergey Belomestnykh (FNAL) for very detailed estimation of AC power requirement for ReLiC using current SRF technology. We also want to thank Tor Raubenheimer, Spencer Gessner, Vladimir Shiltsev and Marlene Turner for pointing out for inconsistencies in our initial proposals and for thoughtful comments and estimations.

Personal notes (VL)

- I like **ReLiC** concept for following reasons:

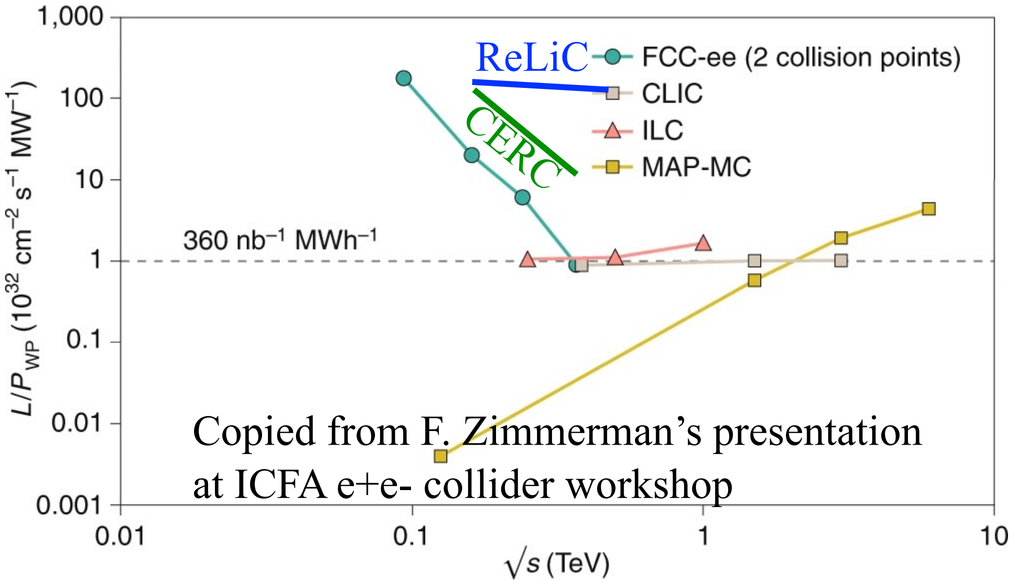
  - In contrast with ILC or CLIC, ReLiC does not suffer from huge energy spread in colliding beams introduced by beamstrahlung and from the insane appetite for fresh polarized positrons.

  - At HIGS energy, ReLiC could provide luminosity 40x of FCC ee and 200x of ILC. In other words, “boom for a buck” or Luminosity per unit of AC power would be at least 100 times better.

  - The fact that ReLiC technology can be extended to TeV range of energies

Key parameters : the productivity

	CERC	ReLiC
C.M. Energy	Luminosity/MW	Luminosity/MW
GeV	10^{34} cm^{-2} sec^{-1} MW^{-1}	10^{34} cm^{-2} sec^{-1} MW^{-1}
240.00	0.88	1.26
365.00	0.23	1.16
40.00	0.08	0.92



Thank you for your attention

Back-up slides

- 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%

$$Classical \Rightarrow QED$$

$$\Upsilon_{\max} = \frac{2}{3}\frac{\hbar\omega_c}{\gamma mc^2} = 3\gamma N \frac{\lambda\!\!\!^{-}_c r_e}{(\sigma_x+\sigma_y)\sigma_z} \Rightarrow \Upsilon_{\max} \approx 2\gamma N \frac{r_e^2}{\alpha(\sigma_x+1.85\sigma_y)\sigma_z}$$

$$\langle\Upsilon\rangle \approx \frac{5}{6}\gamma N \frac{\lambda\!\!\!^{-}_c r_e}{(\sigma_x+\sigma_y)\sigma_z} \ (copied...) \approx \gamma N \frac{\lambda\!\!\!^{-}_c r_e}{\sigma_x\sigma_z} \Rightarrow \langle\Upsilon\rangle \approx \frac{5}{6}\gamma N \frac{\lambda\!\!\!^{-}_c r_e}{(\sigma_x+\sigma_y)\sigma_z}$$

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

$$n_\gamma \approx 1.08 N\alpha r_e \frac{2}{\sigma_x+\sigma_y} U_o(\langle\Upsilon\rangle); U_o(\Upsilon) \approx \frac{1}{\sqrt{1+\Upsilon^{2/3}}}$$

$$\delta_E = \left\langle -\frac{\Delta E}{E}\right\rangle \approx 0.209 N^2 \frac{\gamma r_e^3}{\sigma_z}\left(\frac{2}{\sigma_x+\sigma_y}\right)^2 U_1(\langle\Upsilon\rangle) \approx 1.20\frac{\alpha\sigma_z}{\lambda\!\!\!^{-}_c\gamma}\langle\Upsilon\rangle^2 U_1(\langle\Upsilon\rangle)$$

$$U_1(\Upsilon) \approx \frac{1}{\left(1+\Upsilon^{2/3}\right)^2}$$

C^3 or CLIC at 2x250 GeV

n_γ=1.6; Y_{max}=20.4%; <Y>=8.5%

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

Sustainability: CERC

Table 3. Estimation of the CERC AC power consumption

Mode	Beam Energy [GeV]	SR power [MW]	Microphonics [MW]	HOM [MW]	Total RF power [MW]	Magnet [MW]	1.8K Cryo load [kW]	Cryoplant AC power [MW]	Total AC power [MW]
Z	45.6	30.0	1.6	0.1	31.7	2.0	5	6.25	61
W	80	30.0	2.9	0.2	33.1	6.2	10	12.5	74
HZ	120	30.0	4.5	0.3	34.8	13.9	15	18.75	90
ttbar	182.5	30.0	7.0	0.2	37.2	32.0	23	28.75	123
HHZ	250	30.0	10.1	0.1	40.2	60.1	34	42.5	169
Httbar	300	30.0	13.4	0.0	43.4	86.6	45	56.25	215

Sustainability and Carbon footprint studies

- With current SRF technology (LSLS HE) ReLiC operating at 250 GeV c.m. energy will consume about 350 MW of AC power, which is about equally split between beam energy losses for radiation and cryogenic
- Increasing energy to 3 TeV c.m. with current technology will result in AC power requirement exceeding 2 GW
- There is potential of 5-fold in crease in Q, which would make ReLiC operation at all energy from HIGS to 3 TeV much more energy efficient. Still HIGS factory ReLiC will require ~ 200 MW of AC power, and the 3 TeV c.m. operation to under 1 GW.

Current SRF technology: $Q=3\ 10^{10}$

C.M. energy	GeV	250
Suppress microphonics by RF power	MW	2
HOMs losses	MV	3
Damping rings. 70% RF efficiency	MW	152
Cryoplant *	MW	176*
Others. 0.1 MW/km,	MW	1
Total	MW	333

Future SRF technology: 1.5 K $Q=1.5\ 10^{11}$

C.M. energy	GeV	250	3000
Suppress microphonics by RF power	MW	2	23
HOMs losses	MV	3	12
Damping rings. 70% RF efficiency	MW	152	426
Cryoplant	MW	29	349
Others. 0.1 MW/km,	MW	1	14
Total	MW	187	824

- RF powers needed in damping rings is proportional to ReLiC luminosity and can be reduced if 4×10^{36} cm^{-2}sec^{-1} luminosity is not needed. Operating 250 GeV c.m. ReLiC with luminosity of 4×10^{35} cm^{-2}sec^{-1} will reduce accelerator power consumption to 50 MW.

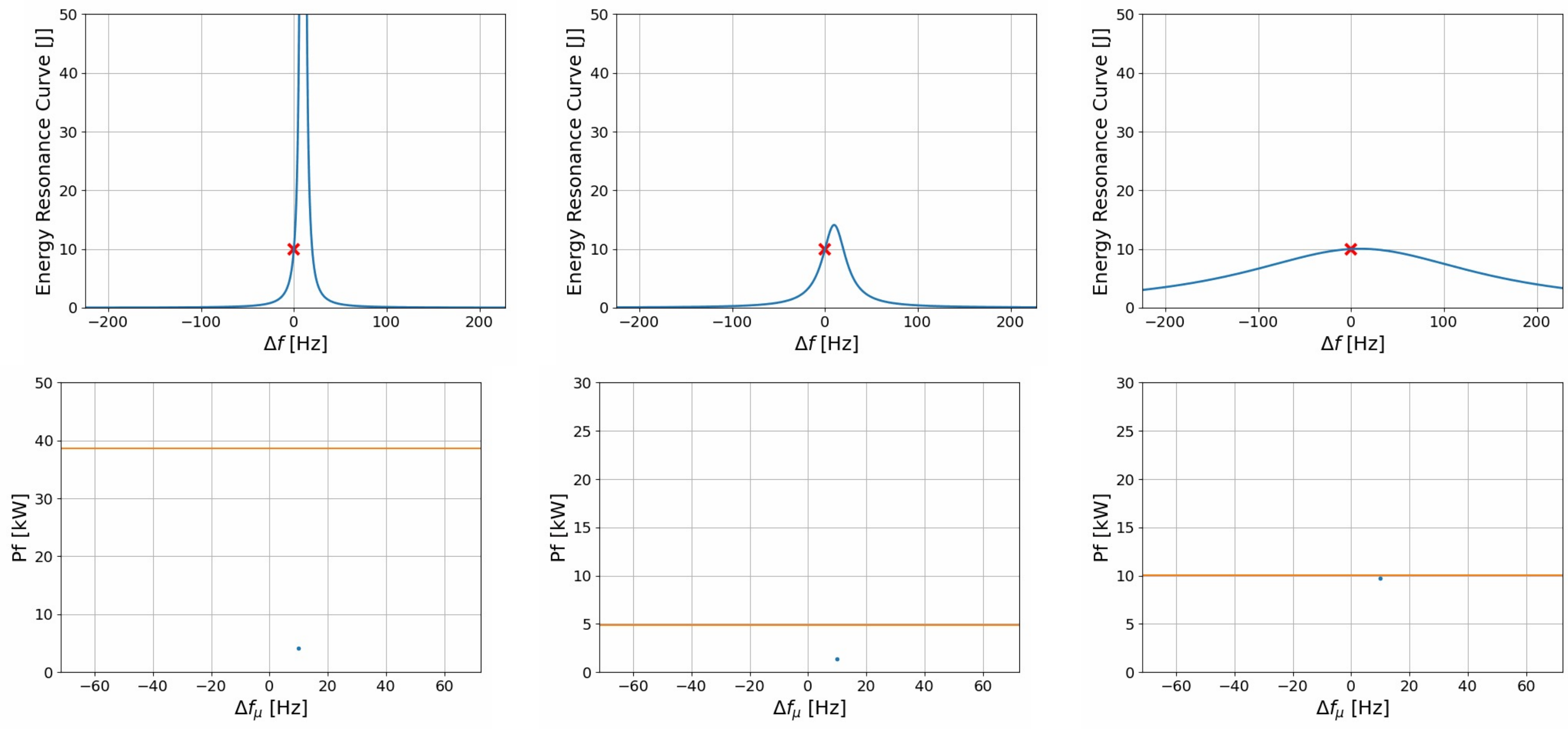
- But the cryoplant power is proportional to the total collider energy. It can be further reduced by improving LiHe refrigerators from their current 19% (1/5th) of theoretically possible Carnot ($\eta=T_1/T_2$) efficiency. Investments in LiHe refrigerator R&D is probably the best chance of improving Carbon footprint of SRF system, including ReLiC.

*** Estimation is provided by Dr. Sergey Belomestnykh (FNAL)**

Fast Reactive Tuner and RF power needs for ERLs

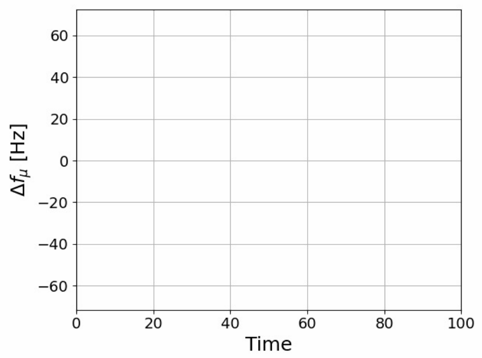
N. Shipman, I. Ben-Zvi, G. Burt, J. Cai, A. Castilla, A. Macpherson, I. Syratchev

$$P_{RF} = \frac{V_c^2}{4 R/_Q Q_L} \frac{\beta + 1}{\beta} \left[1 + \left(2 Q_L \frac{\Delta\omega_\mu}{\omega_0} \right)^2 \right]$$



Decreasing Q_L

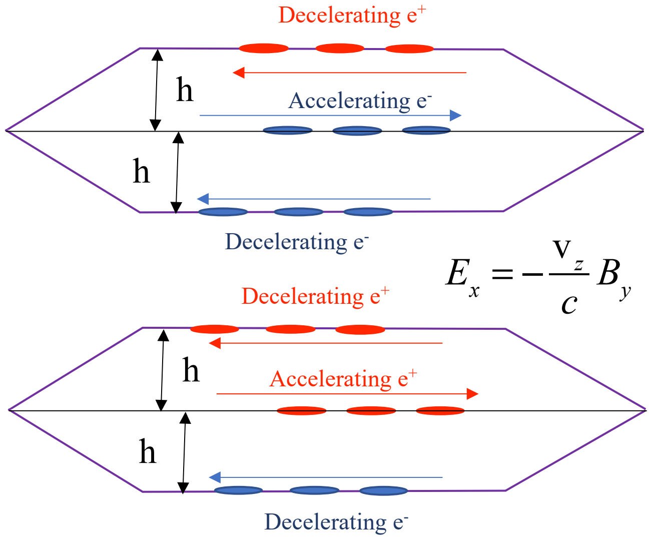
Microphonics vs Time



- ERL power needs often dominated by microphonics
- FE-FRTs can almost eliminate microphonics
- Huge power savings possible
  - Peak power FoM/2
  - Average power FoM/4
- **FoM >~75 @ 800MHz**

Important details of ReLiC design

- Both accelerating and decelerating beams propagate on axis of SRF cavities where transverse fields are zero. 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



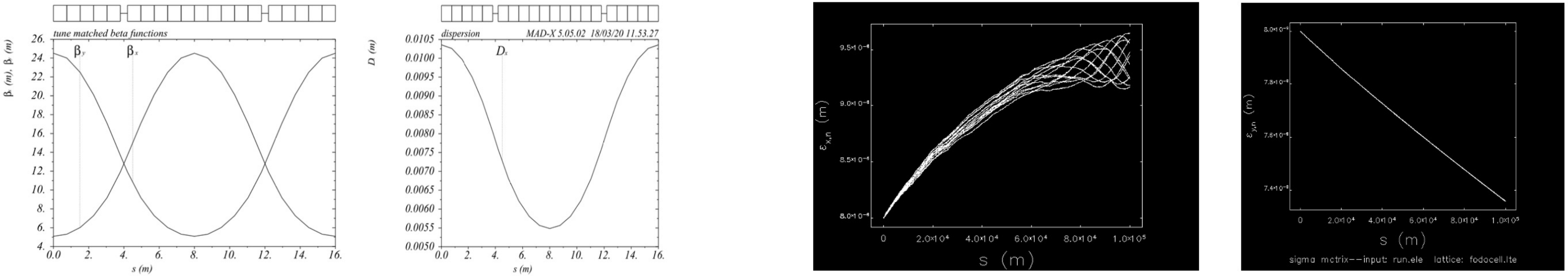
$$E_x = -\frac{v_z}{c} B_y$$

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

** 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*

CERC lattice

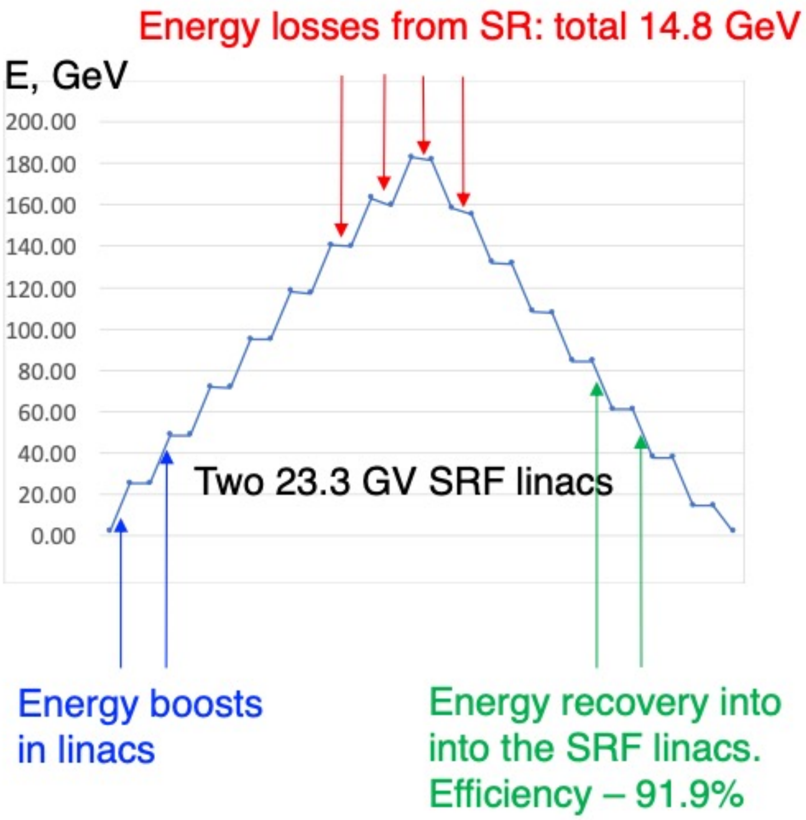
- 6250 FODO cells with combined function (dipole, quadrupole and sextupole) magnets and zero chromaticity
- Cell length: 16 m, phase advance: 90 degrees
- Gaps between magnets: 0.4 m, filling factor 95%
- B= 0.0551 T (551 G); GF,D=±32.24 T/m (3.224 kG/cm) Sextupole moments: SF=267 T/m2 (2.67 kG/cm2);
- SD=-418 T/m2; (-4.18 kG/cm2)
- Aperture: ±1.5 cm; pole tip fields: ~ 5 kG Emittances: H: 8 -> 9.5 um; V: 8 -> 7.3 nm



(a) (b) (c) (d)

CERC beam energy evolution in 4-pass ERL

E_{beam}= 182.5 GeV



E_{beam}= 250 GeV