ReLiC: polarized e^+e^- Recycling Linear Collider with high high-energy, high luminosity reach

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- Using linear collider approach for IRs: flat, low emittance beams with reasonable vertical disruption
- Recycling of the beam energy
- Recycle and re-use collided electrons and positrons
- Use damping rings to repair and polarize recycled beams for next collisions
- Keep under control the beamstrahlung – collide mono-energetic beams

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Baseline Layout

ReLiC – Recycling Linear Collider

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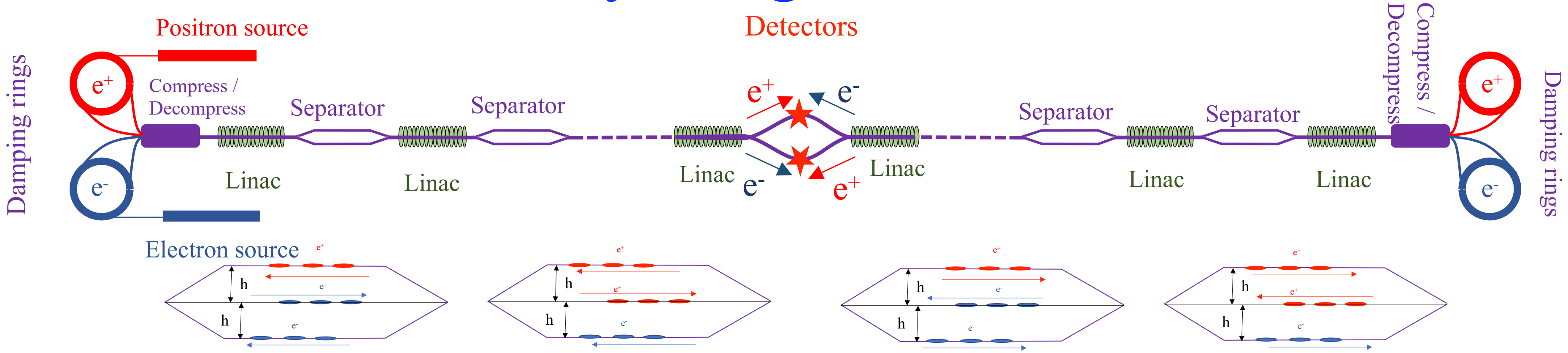

- Flat beams cooled in damping rings with "top off" to replace burned-off particles
- Bunches are ejected with collision frequency, determined by the distance between beam separators
- Beams are accelerated **on-axis** in SRF linacs collide in one of detectors
- After collision at the top energy, they are decelerated in the opposite linacs
- Bunch trains are periodically separated from opposite beam, with accelerating beam propagating **on-axis**
- 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 …..

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

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

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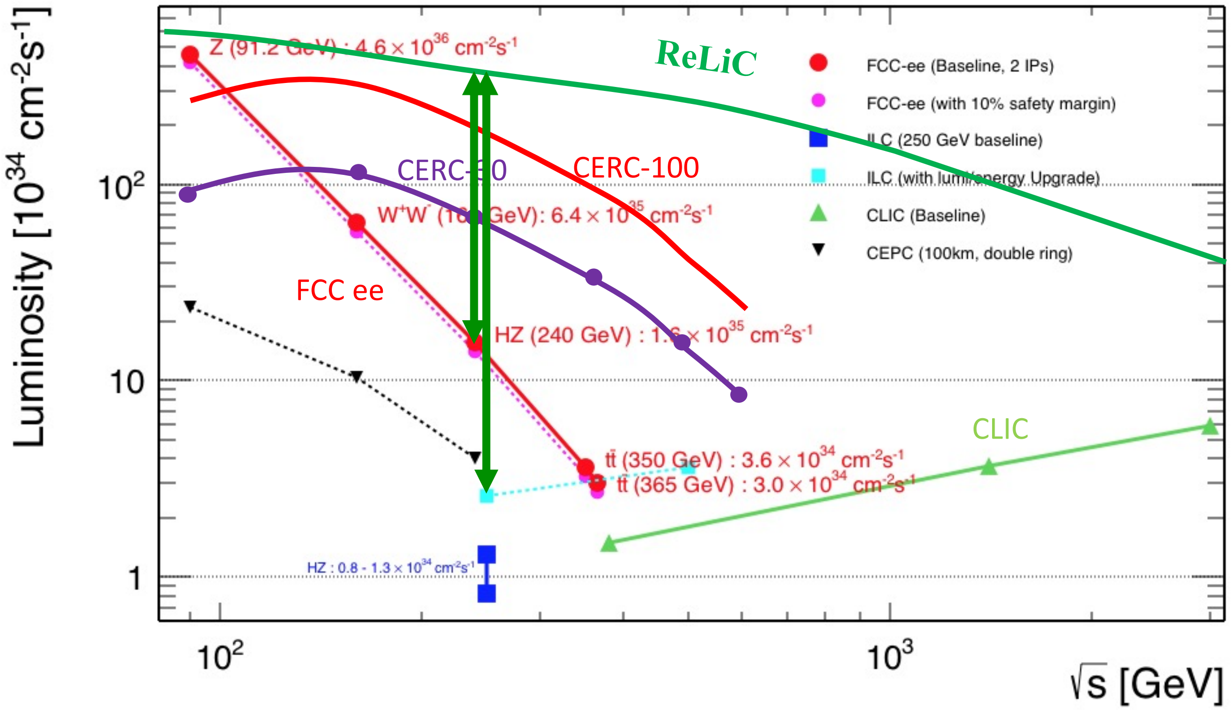
ReLiC would be capable of very high luminosity

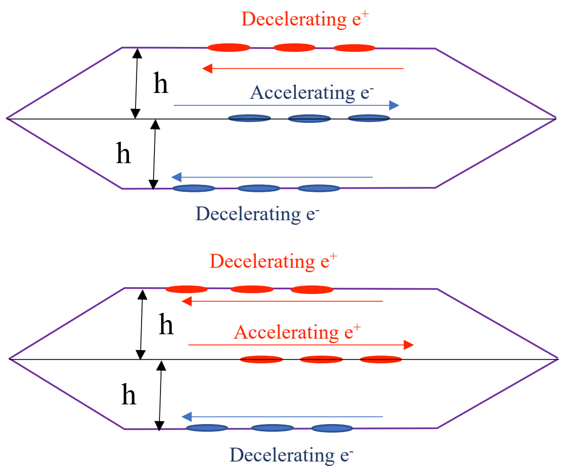
Main parameters

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**

Gain of 40 to 200 at HIGS energy



Key technologies

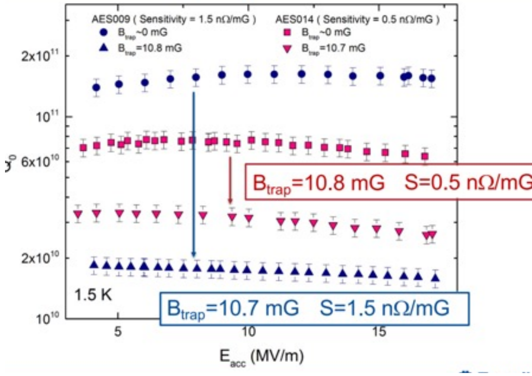


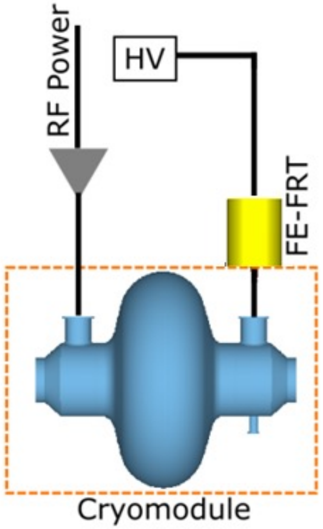
- CW superconducting RF (SRF) linacs with high Q
- 5-cell 1.5 GHz SRF cavities with effective HOM damping
- Electro-magnetic separators for contra-propagating bunch-trains
- Low emittance damping rings with flat beams and large energy acceptance
- Bunch compressor/decompressor
- MHz rate injection/ejection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

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

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 GeV
- MHz rate injection/ejection kickers
- Vertical beam stabilization at the IPs





FoM ~75

Sustainability and Carbon footprint studies

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- 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 $4\mathrm{x}10^{36}$ cm^{-2}sec^{-1} luminosity is not needed. Operating 250 GeV c.m. ReLiC with luminosity of $4\mathrm{x}10^{34}$ 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)**

Proposals for upgrades and extensions

Luminosity upgrades

- Luminosity of ReLiC can be upgraded by increasing beam currents
- RF power required in damping rings will grow proportionally to the beam currents, e.g. proportionally to the luminosity
- This proportionally allow to stage luminosity upgrades by building up ring's RF system

Energy extension and upgrades until 1 TeV

- We explored possibility of extending c.m. energy in ReLiC to 3 TeV
- Main challenge is maintaining low energy of beamstrahlung photons
- This extension also requires increasing energy of damping ring

C.M. energy	GeV	250	500	1000	3000
Length of accelerator	km	21	47	93	276
Section length	m	500.00	250.00	250.00	250.00
Bunches per train		5	5	7	21
Particles per bunch	10^{10}	4.0	4.0	3.0	1.0
Collision frequency	MHz	2.9	4.3	6.0	18.0
Beam currents in linacs	mA	18	27	29	29
εx, norm	mm mrad	4.0	8.0	8.0	8.0
εy, norm	µm mrad	1.0	2.0	2.0	2.0
βx	m	5	20	40	100
βy, matched	mm	0.2	0.5	1.5	6.8
σ_z	mm	1	1	3	5
Disruption parameter, Dx		0.01	0.00	0.00	0.00
Disruption parameter, Dy		109	17	14	3
Luminosity per detector	10^{34} cm^{-2}sec^{-1}	215	101	67	20
Total luminosity	10^{34} cm^{-2}sec^{-1}	429	203	135	40

C.M. energy	GeV	250	500	1,000	3,000
Ymax		2.4E-03	2.4E-03	1.4E-03	7.7E-04
ΔE, max	MeV	294	589	707	1161
<Y>		9.8E-04	9.8E-04	5.9E-04	3.2E-04
nγ		2.0E-01	9.8E-02	7.3E-02	2.7E-02
δE		9.0E-05	4.5E-05	2.0E-05	4.0E-06

Stageability to 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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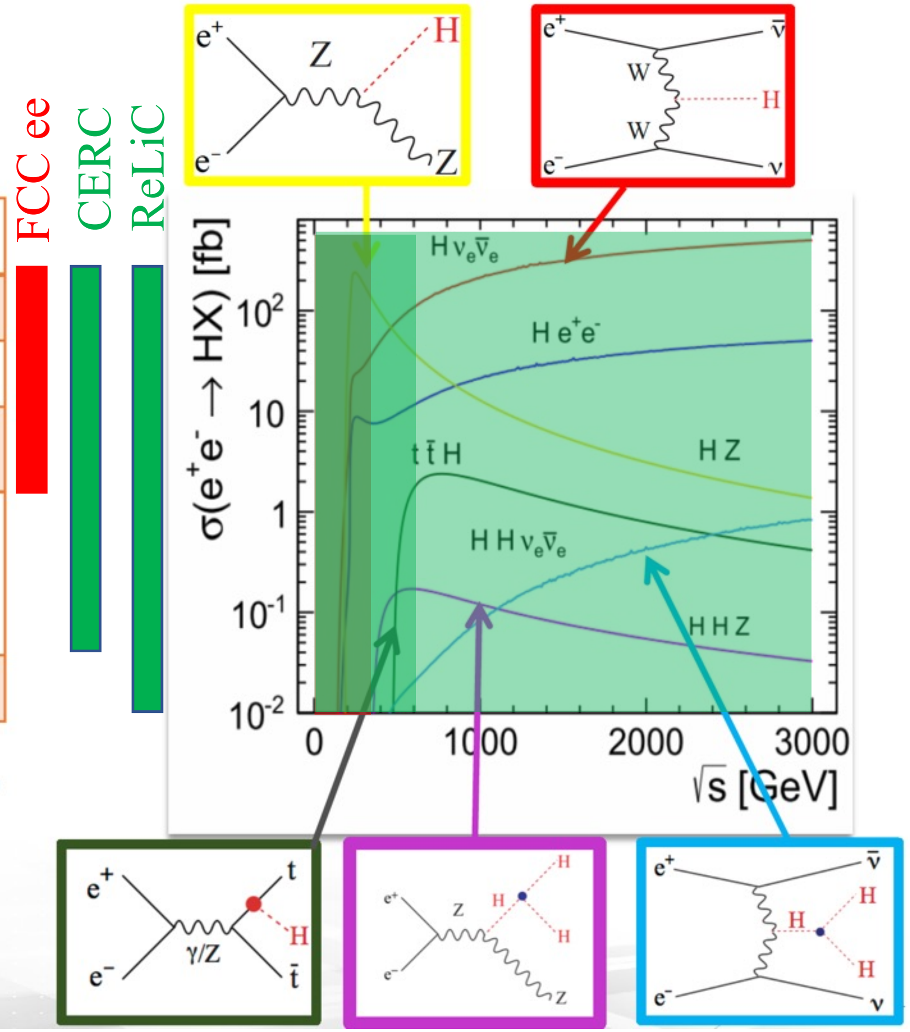


Can be used for hadron-electron and hadron-positron collider in conjunction with LHC or FCC hh

State of Proposal and R&D needs (5-10 years)

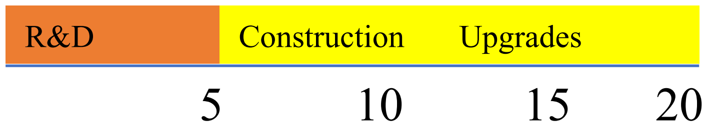
- Proposal is at conceptual development stage
- Only major processes (beam-beam collisions, beamstrahlung, effect of beam separators were either simulated or scaled from other projects such as CERC etc.). No realistic cost estimate is generated.
- Power estimations may miss significant components – cooling of the tunnel, heat losses for LiHe transfer lines, etc.
- Main needed R&D
  - High efficiency LiHe refrigeration systems
  - Very high-Q SRF cavities
  - Reactive tuners in SRF systems
  - Damping rings
  - MHz rated kickers

Technical Maturity

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

- Critical Technologies
  - High efficiency LiHe refrigerators
  - High Q SRF cavities, needed R&D
  - High rep-rate kickers, needed R&D
  - Flat beams with $\varepsilon_h/\varepsilon_v$ =2,000, need of R&D

- Technically limited timeline



Conclusions and Acknowledgements

- ReLiC
  - 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 minuscular when compared with ILC – i.e. ReLiC 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*
  - The concept also can be used for pulsed SRF linacs, with reduction in the luminosity. But losses in damping rings can not be avoided, if particle's recycling is preserved…
- 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 proposal and for thoughtful comments and estimations.

Personal note (VL)

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- 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 polarize 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

Thank you for your attention

Back-up slides

Impact of polarization

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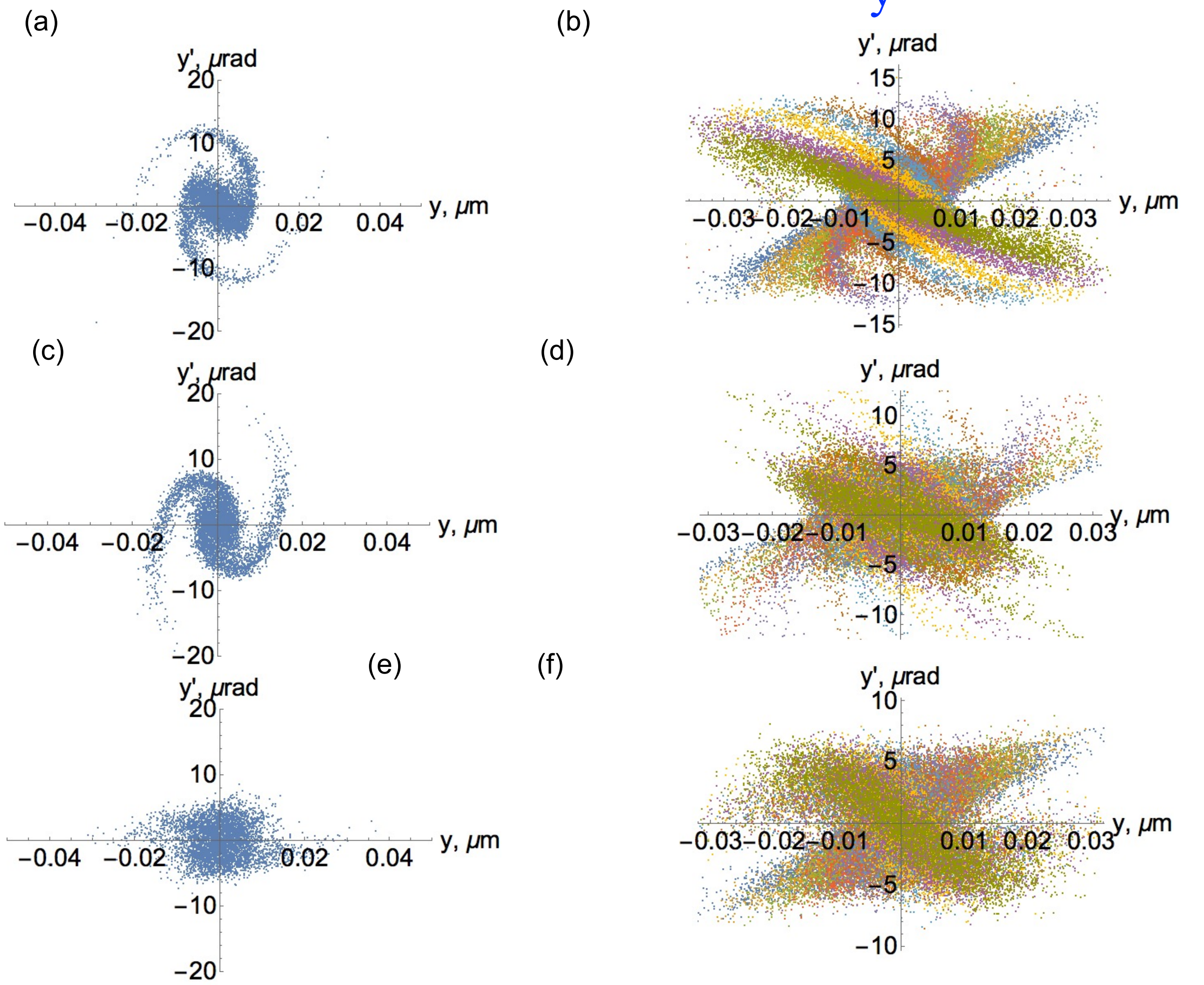
Polarization		Scaling factor		
e -	e +	ZH(240GeV)	ZHH(500GeV)	ttH(600GeV)
Unpolarized		1.	1.	1.
-70	0	1.15	1.15	1.23
-70	+50	1.61	1.61	1.87
-70	-50	0.69	0.69	0.73
-70	+70	1.78	1.79	2.07
-70	-70	0.51	0.51	0.51
-50	+50	1.47	1.47	1.69
+50	-50	1.03	1.03	0.82
+70	0	0.85	0.85	0.69
+70	+50	0.60	0.60	0.56
+70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

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

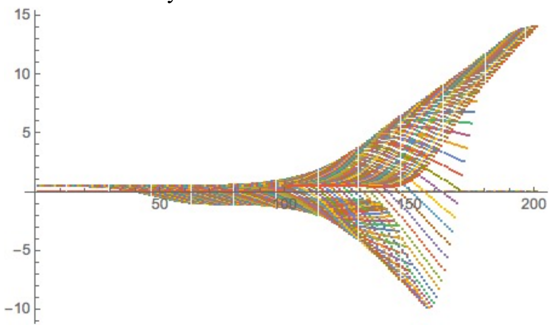


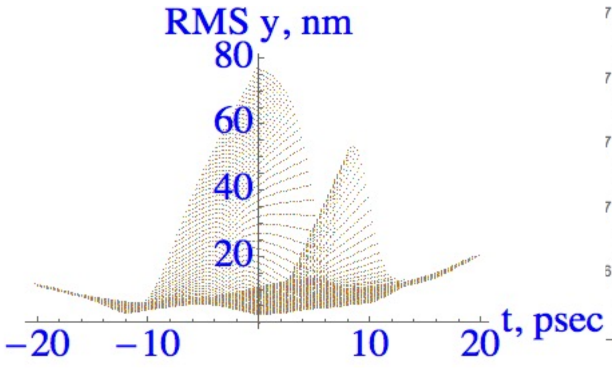
Beam distribution in the vertical phase space after the collision. Distributions of the central slice are on the left and combinations of 10 slices covering evenly $-3\sigma_z < z < 3\sigma_z$, are on the right: (a-b) are for center particles at x=0; (c-d) are for those at $x= \sigma_x$, (e-f) is for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

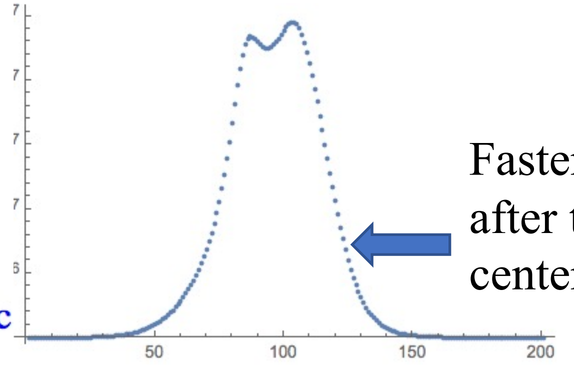
Initial beam axis separation is $\Delta y = 1\sigma_y$

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

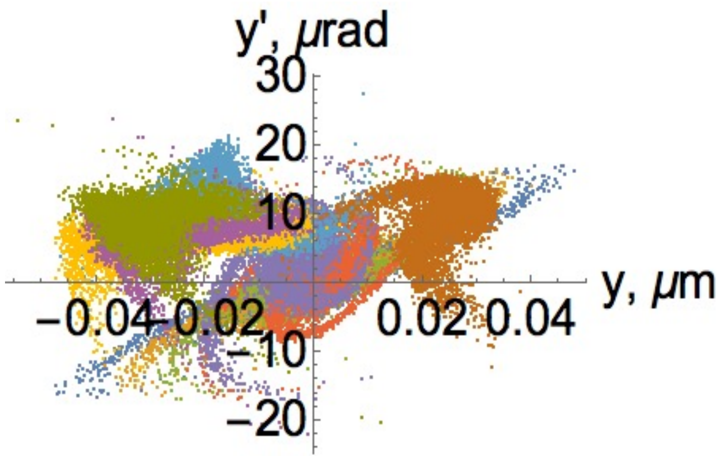


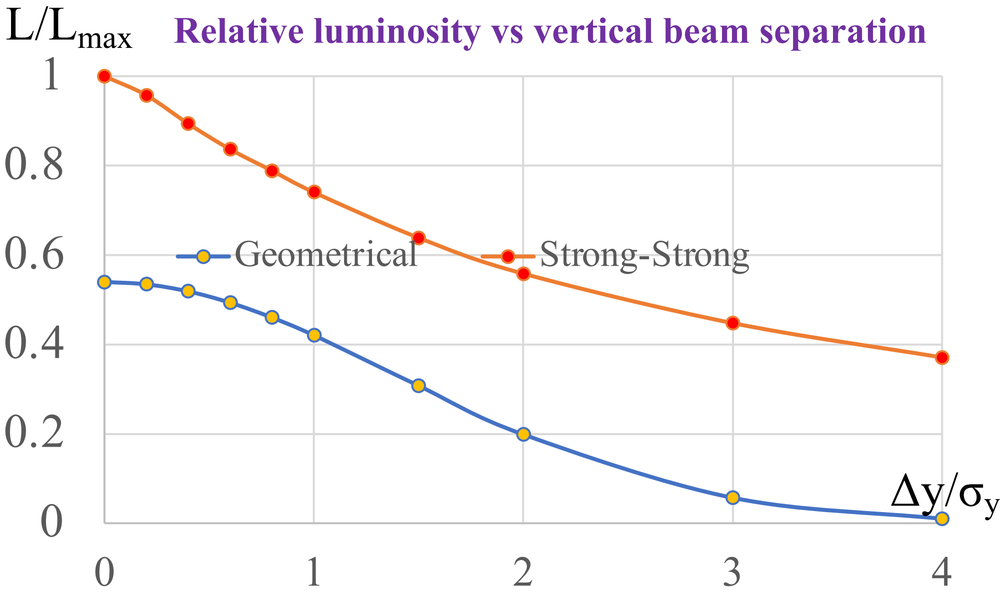


Instantaneous luminosity (a.u.)



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

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.

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

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

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 details of ReLiC design

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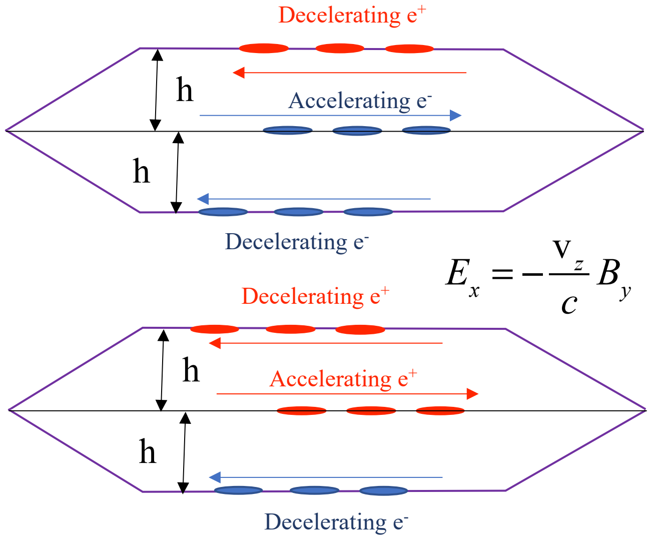
- Both accelerating and decelerating beams propagate on axis of SRF cavities where transverse fields are zero. There is no need for asymmetric dual-cavities – unexplored SRF technology.
- Focus on limiting energy spread in colliding beams
  - We capped critical energy of beamstrahlung photons to 200 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



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

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

** 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*

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%

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

Fast Reactive Tuner and RF power needs for ERLs

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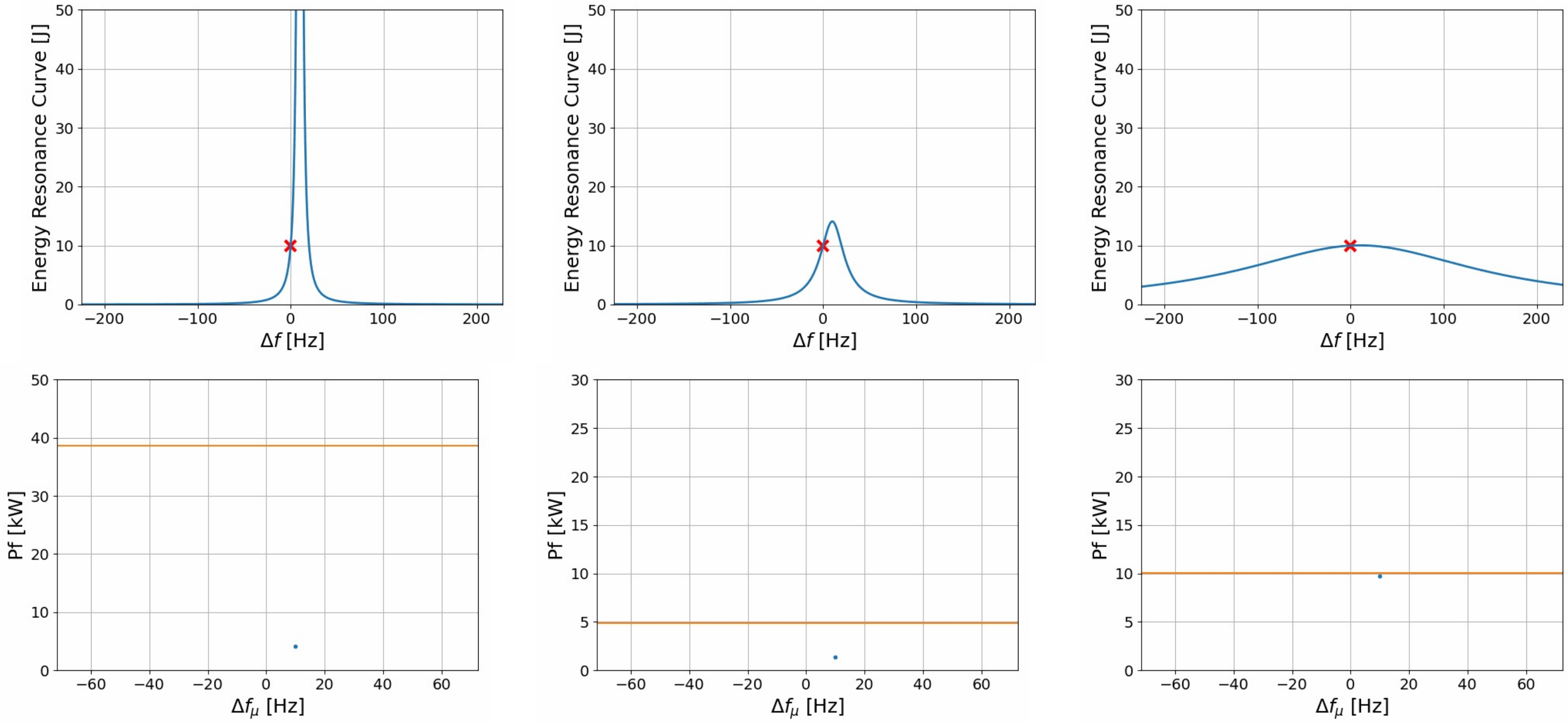
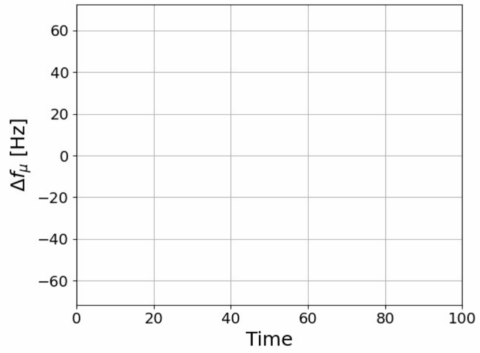
ERL power needs

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



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**

Agora: ITF Comparison Categories

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	CERC-30	ReLiC
CoM Energy and expandability, GeV	46 -600	46-1,500
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