

# Future e+e- Colliders using Recycling Energy-Recovery Linacs (**ERLs**)

Vladimir N Litvinenko

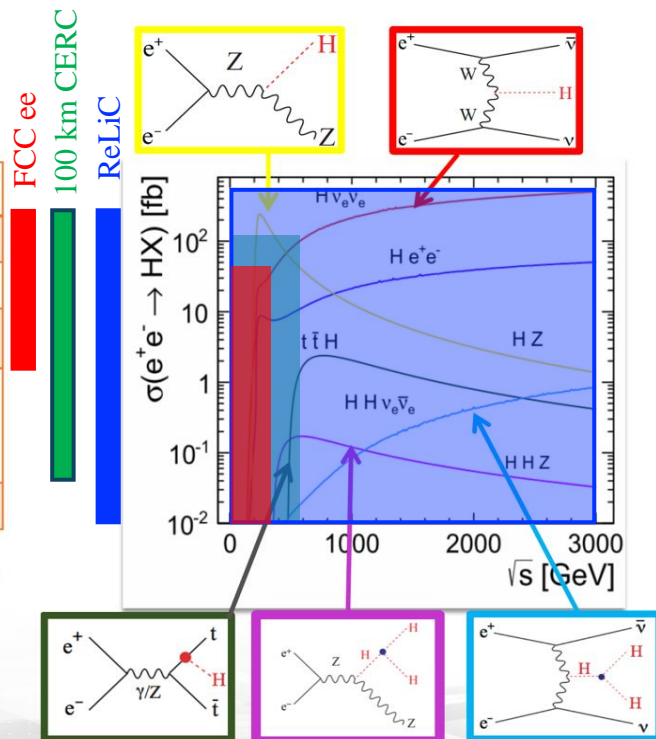
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- ❑ Energy-Recovery and Particle Recycling for boosting luminosity to  $O(10^{37} \text{ cm}^{-2}\text{sec}^{-1})$  level
- ❑ Energy-Recovery offers high energy efficiency measured in luminosity/AC power
- ❑ Recycling collided particles and their recuperations
  - ❑ Eliminates insane ILC/CLIC appetite for fresh positions
  - ❑ Offers high degrees of polarization in colliding beams
  - ❑ Offers low energy spread by reducing beamstrahlung
- ❑ There are currently three concept which I have time to describe very briefly
- ❑ Recycling colliders can become more attractive with possible future technical breakthroughs

# Physics: Energy and Luminosities reach

## e+e- colliders

$\sqrt{s}$ [GeV]	Science Drivers
90-200	EW precision physics, Z, WW
250	Single Higgs physics (HZ), H $\nu\nu$
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

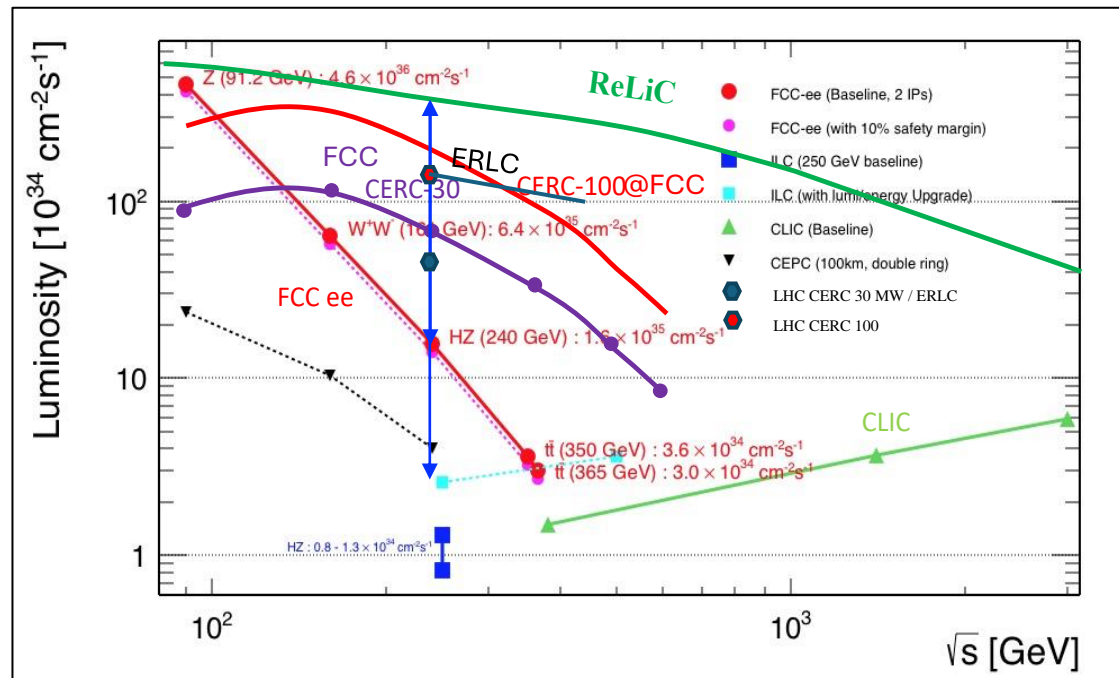


Precision measurement and search for new physics studying deviations from the SM  
 → Need high luminosity (and energy)



2

Recycling could offer luminosity boosts ~ 200 in HIGS sector



## Recycling offers potential for high degree of polarization in e+e- beams

**Example:** The proper combination of polarization for electrons and positrons will significantly enhance the production cross section or will suppress it: great tool to control systematics

Polarization		Scaling factor		
e <sup>-</sup>	e <sup>+</sup>	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

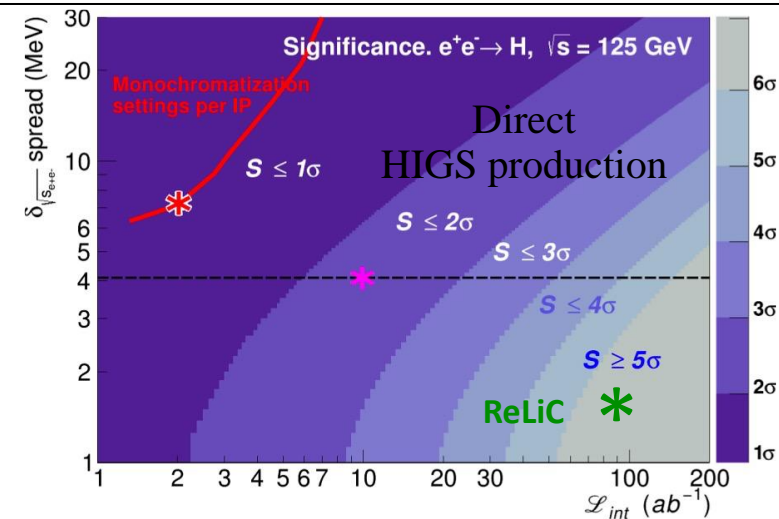


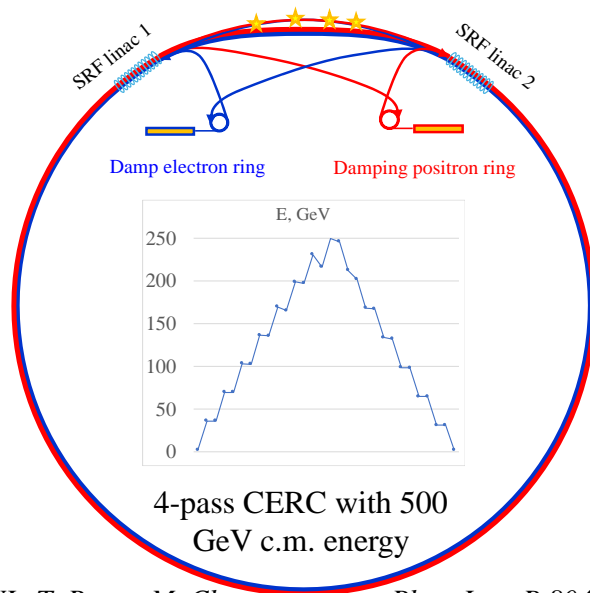
Figure is courtesy of David d'Enterria

# Three types of recycling $e^+e^-$ collider concepts

- There are currently three known concepts of recycling linear colliders (*listed in order of first appearances*), which have significant differences :
- **CERC – Circular Energy and particle Recovery  $e^+e^-$  Collider** (*Sept. 2019*)
  - Using multi-turn ERL located in a large semi-circular tunnel (such as FCC or LHC)
  - Collided particles are decelerated, cooled in damping rings and re-used
  - High luminosity is attained by high beam-beam disruption parameter, typical of linear colliders
- **ERLC – Energy Recovery Linear  $e^+e^-$  Collider** (*December 2021*)
  - Using dual linear accelerators to accelerate, collide and decelerate both  $e^+$  and  $e^-$  beams
  - Collided particles are decelerated, slightly cooled in a wiggler channel and re-used
  - High luminosity is attained by high beam current and rep-rate – beam's collision occurs at low disruption, and it is better described by the tune-shift typical for ring  $e^+e^-$  colliders
- **ReLiC – Recycling  $e^+e^-$  Linear Collider** (*March 2022*)
  - Using single linear accelerators to accelerate, collide and decelerate both  $e^+$  and  $e^-$  beams
  - Trains of accelerating and decelerating particles avoid parasitic collisions is separators
  - Collided particles are decelerated, cooled in damping rings and re-used
  - High luminosity is attained by high beam-beam disruption parameter, typical of linear colliders
- All three concept assume colliding flat beams to control beamstrahlung

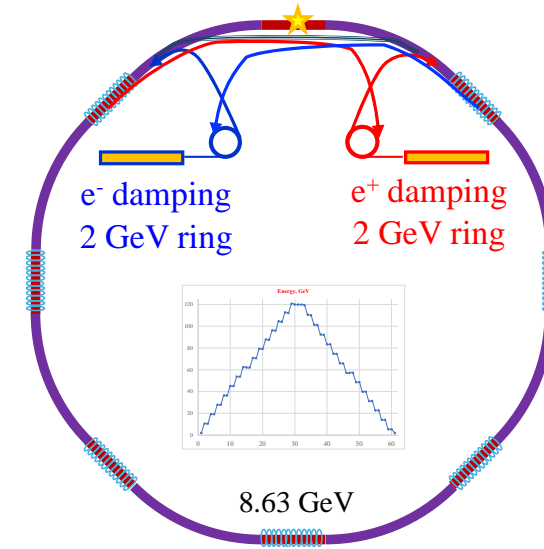
# CERC - Circular ERL recycling e<sup>+</sup>e<sup>-</sup> Collider

In FCC 100 km tunnel – 4 passes



- Beams accelerated by SRF linacs in number of (2 to 4) turns
- Only beams at top energy pass through detectors, the rest of beams bypass them
- After collision at top energy RF phases are changed to deceleration returning most energy – minus that lost for SR - to SRF linac
- After deceleration, all electrons and positrons are reinjected into the cooling rings
- Only beam losses compensated by top-off injection
- In few damping times flat beams are prepared and ejected with collision frequency
- In case of multiple detectors, luminosity can be shared in any desirable ratio
- **Main idea: low current and low collision frequency**

In LHC tunnel – 2 passes



Synchrotron radiation energy loss is 5.22 GeV. Total SR power is 30 MW

VNL, T. Roser, M. Chamizo-Llatas, Phys. Lett. B 804,135394, (2020)

Table 1. Main parameters of ERL-based e<sup>+</sup>e<sup>-</sup> collider with synchrotron radiation power of 30 MW.

CERC	Z	W	H(HZ)	ttbar	HH	Httbar
Circumference, km	100	100	100	100	100	100
<b>Beam energy, GeV</b>	<b>45.6</b>	<b>80</b>	<b>120</b>	<b>182.5</b>	<b>250</b>	<b>300</b>
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
<b>Bunch length, mm</b>	<b>2</b>	<b>3</b>	<b>3</b>	<b>5</b>	<b>7.5</b>	<b>10</b>
<b>Charge per bunch, nC</b>	<b>13</b>	<b>13</b>	<b>25</b>	<b>23</b>	<b>19</b>	<b>19</b>
Ne per bunch, 10 <sup>11</sup>	0.78	0.78	1.6	1.4	1.2	1.2
Bunch frequency, kHz	297	270	99	40	16	9
<b>Beam current, mA</b>	<b>3.71</b>	<b>3.37</b>	<b>2.47</b>	<b>0.90</b>	<b>0.31</b>	<b>0.16</b>
Luminosity, 10 <sup>35</sup> cm <sup>-2</sup> sec <sup>-1</sup>	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 <sub>h</sub>	2.2	1.9	0.8	0.5	0.3	0.3
Disruption, D <sub>v</sub>	503	584	544	505	459	492

$$L = f_c \cdot \frac{N_{e^+} N_{e^-}}{4\pi\sigma_x\sigma_y} \cdot h \propto \frac{I_{e^+} I_{e^-}}{f_c}$$

## • Important advantages:

- Using N passes and the same linacs for both positions and electron reduces required linac length by 2N-fold

## • Important limitations:

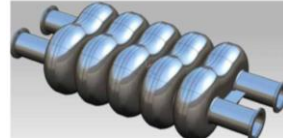
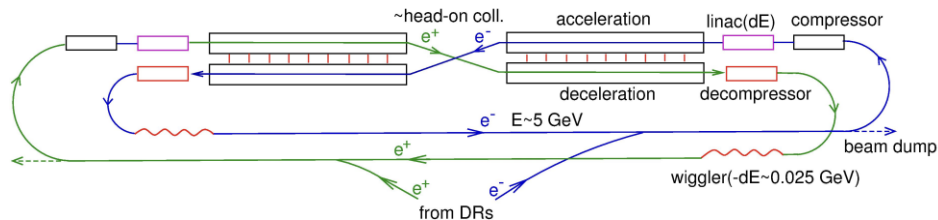
- Energy loss for synchrotron radiation is proportional to E<sup>4</sup> – the same as in ring-ring circular colliders
- This make achievable luminosity directly proportion to the power lost for synchrotron radiation
- And even in case of 100-km FCC type tunnel it limits collider c.m. energy well below 1 TeV

C.M. energy	GeV	240
<b>Length of accelerator</b>	km	<b>26.659</b>
<b>Particles per bunch</b>	10 <sup>10</sup>	<b>15.6</b>
<b>Collision frequency</b>	MHz	<b>0.065</b>
<b>Beam current</b>	mA	<b>1.63</b>
<b>ε<sub>x</sub>, norm</b>	mm mrad	<b>6</b>
<b>ε<sub>y</sub>, norm</b>	μm mrad	<b>15</b>
<b>β<sub>x</sub></b>	m	<b>1.75</b>
<b>β<sub>y</sub>, matched</b>	mm	<b>0.3</b>
<b>σ<sub>z</sub></b>	mm	<b>2</b>
<b>Disruption parameter, D<sub>x</sub></b>		<b>0.17</b>
<b>Disruption parameter, D<sub>y</sub></b>		<b>269</b>
<b>Luminosity</b>	10 <sup>34</sup> cm <sup>-2</sup> sec <sup>-1</sup>	<b>45</b>

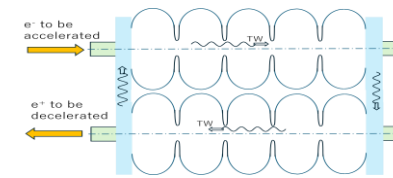
# ERLC – Energy Recovery Linear e<sup>+</sup>e<sup>-</sup> Collider

original concept with twin-cavities is by V. Telnov (BINP, Russia), Traveling Wave linac option is by K. Yokoya (KEK, Japan)

Twin LC with energy recovery



Traveling Wave (TW) SRF linac with energy circulation



*ILC Upgrade with Energy Recovery, Kaoru Yokoya, talk at LCWS, University of Tokyo, July 10, 2024*

V. Telnov, *A high-luminosity superconducting twin e<sup>+</sup>e<sup>-</sup> linear collider with energy recovery, Journal of Instrumentation 16 (2021) 12025*

Table for ERLC performance, by Kaoru Yokoya in “A Linear Collider Vision for the Future of Particle Physics”, arXiv:2503.19983v2 31 Mar 2025

	ILC	ERLC	ERLC	GeV
centre-of-mass energy	250	250	500	GeV
Accelerating gradient	31.5	40	40	MV/m
Cavity Q <sub>0</sub>	1	3	3	× 10 <sup>10</sup>
Aperture radius	35	35	35	mm
Shunt impedance per unit length	996	1690	1690	Ohm/m
Operating temperature	2	4.5	4.5	K
Bunch population	2	0.075	0.081	× 10 <sup>10</sup>
Bunch distance	166	0.23	0.23	m
Average beam current	0.021	157	169	mA
Beam energy in the return line		5	5	GeV
Total HOM power	0.014	2.9	5.85	MW
Energy acceptance of the return line		3	3	%
Radiation loss in the wiggler		25	25	MeV
Bunch length in main linac and IP	0.3	0.31	0.89	mm
Normalized emittance at IP (x/y)	5/35	10/35	10/35	μm / nm
Beta function at IP(x/y)	13/0.41	12/0.31	40/0.89	mm
Beam size at IP(x/y)	515/7.66	700/6.2	900/7.4	nm
Disruption parameter (x/y)	0.5/34.5	0.011/1.14	0.010/1.14	
Beam-beam tune shift (x/y)		0.033/0.097	0.036/0.098	
Upsilon (max)	0.068	0.00182	0.00106	
Luminosity	1.35	135	102	10 <sup>34</sup> /cm <sup>2</sup> /s
AC power for RF heat cooling	5	91	181	MW
AC power for HOM cooling	1	35	71	MW
Total site power	111	170	320	MW

*Most of the data shown in this slide is taken from materials developed by V. Telnov and K. Yokoya, except comments inside the area indicated by a dashed red rectangle*

ERLC consists of two parallel superconducting dual-axis linacs equalizing accelerating and decelerating fields

Collision do occur with beam-beam tune shift ~ 0.1 typical for ring colliders

Damping is provided by wigglers in the 5-GeV return lines with energy loss per turn is ~0.5%

Duration of the cycle is ~ few second and is determined by the LiHe refrigerator

**Main idea of the concept: Low charge per bunch, high rep-rate and very high average currents**

unit	ERLC pulsed	ERLC pulsed	ERLC contin.	ERLC contin.
	Nb	Nb	Nb <sub>3</sub> Sn	Nb <sub>3</sub> Sn
	1.8 K	1.8 K	4.5 K	4.5 K
	1.3 GHz	0.65 GHz	1.3 GHz	0.65 GHz

$$L = f_c \cdot \frac{N_{e^+} N_{e^-}}{4\pi\sigma_x \sigma_y} \cdot h \propto \frac{I_{e^+} I_{e^-}}{f_c}$$

Important advantage:

- Low beamstrahlung loss and induced energy spread in collisions

Important limitations:

- Use of dual linacs require 2X higher power of LiHe refrigerator
- Both dual-axis and TW SRF linacs are in R&D phase
- ERLC assumes futuristic 4K Nb<sub>3</sub>Sn SRF cavities operating at 40 MV/m gradient with Q from 3×10<sup>10</sup> to 1.2×10<sup>11</sup>
- Average currents at excess 100 mA would require strong suppression of transverse HOMs to avoid well known TBBU instability in ERLs

Energy 2E <sub>0</sub>	GeV	250	250	250	250
Luminosity L <sub>tot</sub>	10 <sup>36</sup> cm <sup>-2</sup> s <sup>-1</sup>	0.39	0.75	0.83	1.6
P (wall) (collider)	MW	120	120	120	120
Duty cycle, DC		0.19	0.37	1	1
Accel. gradient, G	MV/m	20	20	20	20
Cavity quality, Q	10 <sup>10</sup>	3	12	3	12
Length L <sub>act</sub> /L <sub>tot</sub>	km	12.5/30	12.5/30	12.5/30	12.5/30
N per bunch	10 <sup>9</sup>	1.13	2.26	0.46	1.77
Bunch distance	m	0.23	0.46	0.23	0.46
Rep. rate, f	Hz	2.47 · 10 <sup>8</sup>	2.37 · 10 <sup>8</sup>	1.3 · 10 <sup>9</sup>	6.5 · 10 <sup>8</sup>
ε <sub>x,n</sub> /ε <sub>y,n</sub>	10 <sup>-6</sup> m	10/0.035	10/0.035	10/0.035	10/0.035
β <sub>x</sub> /β <sub>y</sub> at IP	cm	2.7/0.031	10.8/0.031	0.46/0.031	6.8/0.031

# ReLiC – Recycling Linear Collider

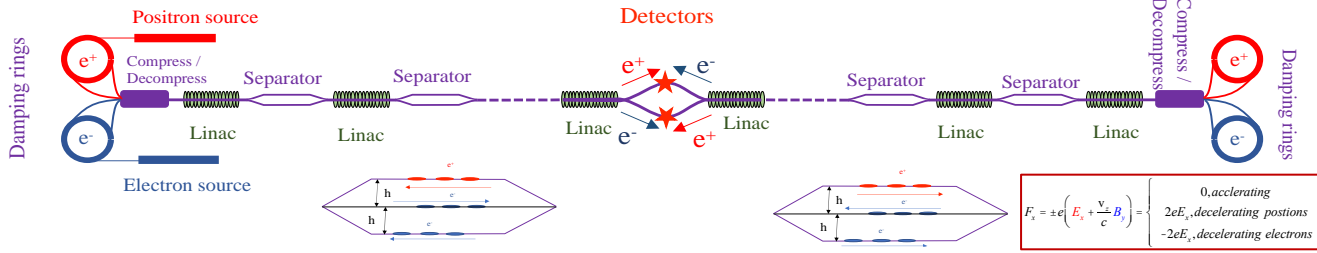


Table for ReLiC performance, by VL in “A Linear Collider Vision for the Future of Particle Physics”, arXiv:2503.19983v2 31 Mar 2025

	LCF	ReLiC <sup>1</sup>	ReLiC <sup>2</sup>	ReLiC <sup>3</sup>	ReLiC <sup>3</sup>
Centre-of-mass energy [ GeV ]	250	250	250	250	550
Accel. Grad. [ MeV/m ]	31.5	12.55	12.55	12.55	27.6
Cavity Q <sub>0</sub> [ 10 <sup>10</sup> ]	2	4	4	4	4
Liquid He temperature [ K ]	2	2	2	4.5	4.5
Bunch population [ 10 <sup>10</sup> ]	2	2.5	2.5	2.5	2.5
Collision frequency [ MHz ]	2.62	1.5	1.5	1.5	1.5
Duty cycle	0.0012	cw	cw	cw	cw
Beam current, all beams [ mA ]	0.042	12	12	12	12
Normalised emittance hor. [ μm ] / vert. [ nm ]	5/25	4/1	4/1	4/1	4/1
β <sub>x</sub> / β <sub>y</sub> [ m ] / [ mm ]	0.013/0.41	2.2/0.19	2.2/0.19	2.2/0.19	4/0.36
σ <sub>x</sub> / σ <sub>y</sub> at IP [ μm ] / [ nm ]	0.52/7.7	6/0.9	6/0.9	6/0.9	6/0.9
D <sub>x</sub> / D <sub>y</sub>	0.5/34.5	0.01/87	0.01/87	0.01/87	0.01/88
γ <sub>max</sub>	0.068	0.0028	0.0028	0.0028	0.0031
Luminosity [ 10 <sup>34</sup> cm <sup>-2</sup> s <sup>-1</sup> ]	2.7	140	140	140	153
AC Site Power [ MW ]	111	~135	~105	~95	~250

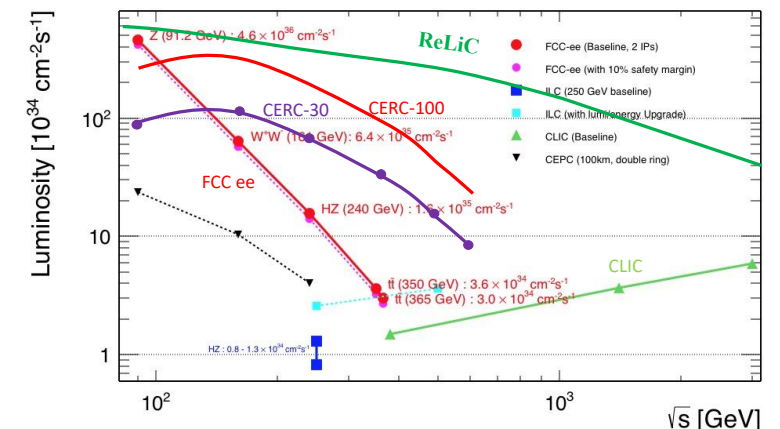
<sup>1</sup> ReLiC based on current “conventional” Nb SW SCRF technology [512]. Cryogenics system: 80 MW, damping rings: 70 MW + others  
<sup>2</sup> ReLiC based on Nb SW SCRF technology, but COP of 2K LiHe refrigerators improved 2-fold. Cryogenics system: 45 MW, damping rings: 70 MW + others  
<sup>3</sup> ReLiC based on futuristic SCRF technology for Nb<sub>3</sub>Sn SW cavity with Q<sub>0</sub> = 4E10.  
 250GeV: Cryogenics system: 35 MW, damping rings: 70 MW;  
 500GeV: Cryogenics system: 95 MW, damping rings: 140 MW

- Flat beams cooled in damping rings with “top off” to replace burned-off particles
- Bunch trains 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
- 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

• **Main idea: moderate beam currents and collision frequency**

$$L = f_c \cdot \frac{N_{e^+} N_{e^-}}{4\pi\sigma_x\sigma_y} \cdot h \propto \frac{I_{e^+} I_{e^-}}{f_c}$$

ReLiC luminosity is reducing at high c.m. energies: the main limitation the beamstrahlung



## Important advantage:

- Low beamstrahlung loss and induced energy spread in collisions (required for particle recycling!)
- Modest beam currents (~ 10 mA total) and collision frequency (~ 1 MHz)
- Potential to extend c.m. energy into TeV range with reasonable loss in luminosity

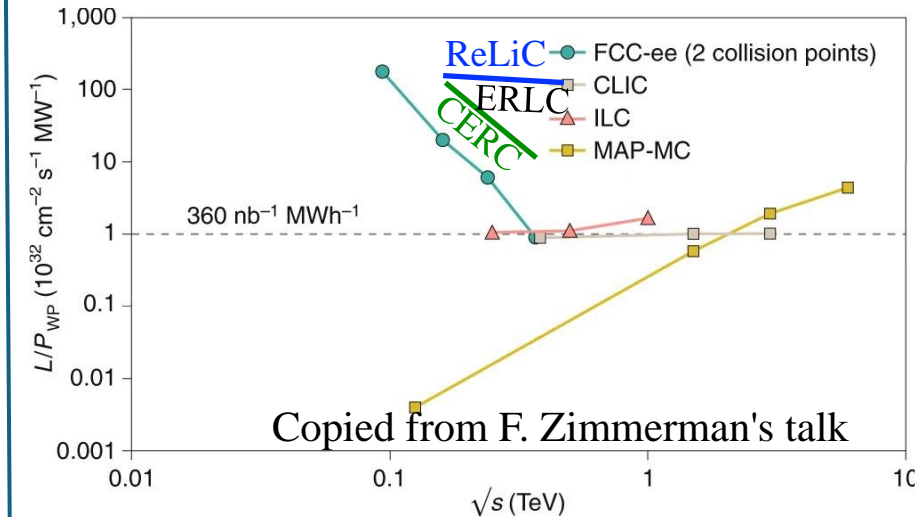
## Important limitations:

- Relatively low accelerating gradient and correspondingly longer tunnels
- Would require either 4K Nb<sub>3</sub>Sn SRF technology or strongly improved LiHe refrigerator efficiency to fit 550 GeV c.m. ReLiC in LHC tunnel with reasonable power consumption
- Requires very flat (1:6,000) beams at IP to control beamstrahlung and low energy tail in the decelerated beams
- Requires high frequency injection and ejection kickers

# Summary

- ERL-based colliders promise significant luminosity boost in collision of polarized  $e^+e^-$  beam in c.m. energy range from Z-pole to 1 TeV, with main advantages offered in Higgs sector
- C.m. energy of ReLiC/ERLC can be extended into TeV range
- Multi-pass CERC reduces length of SRF linacs, but limits c.m. energy to  $\sim 600$  GeV in FCC tunnel, and to  $\sim 250$  GeV in the LHC tunnel
- All ERL-based concepts could be very effective for direct HIGGS production  $e^+e^- \rightarrow H$  at  $\sqrt{s}=125$  GeV
- All ERL schemes can be staged, starting from operating at  $\sqrt{s}=90$  GeV, then as HZ factory using current technology and extended further with advances in SRF R&D
- R&D is needed on high quality SRF linacs (including, but not limited to  $Nb_3Sn$ ), flat beams and high efficiency LiHe refrigerators. Breakthrough in efficiency of LiHe refrigerators (from 900 W/W closer to Carnot cycle 150 W/W at 2K $^\circ$ ) is probably the most important investment for progress with all SRF accelerators.
- There is a lot of synergy with ERL R&D for EIC hadron cooler (BNL), PERLE (France), Berlin-pro, Darmstadt ERL, MESA (Germany), Test ERL (Japan) and Cbeta (Cornell) ...
- *I would like to thank my colleagues Nikhil Bachhawat Yichao Jing, Francois Meot, Maria Chamizo Llatas and Thomas Roser for their contribution in CERC studies*
- *I would like to especially thank Dr. Kaoru Yokoya (KEK) for his friendly criticism and pointing out inaccuracies in ReLiC concepts. His thoughtful comments allowed me to refine the concept.*

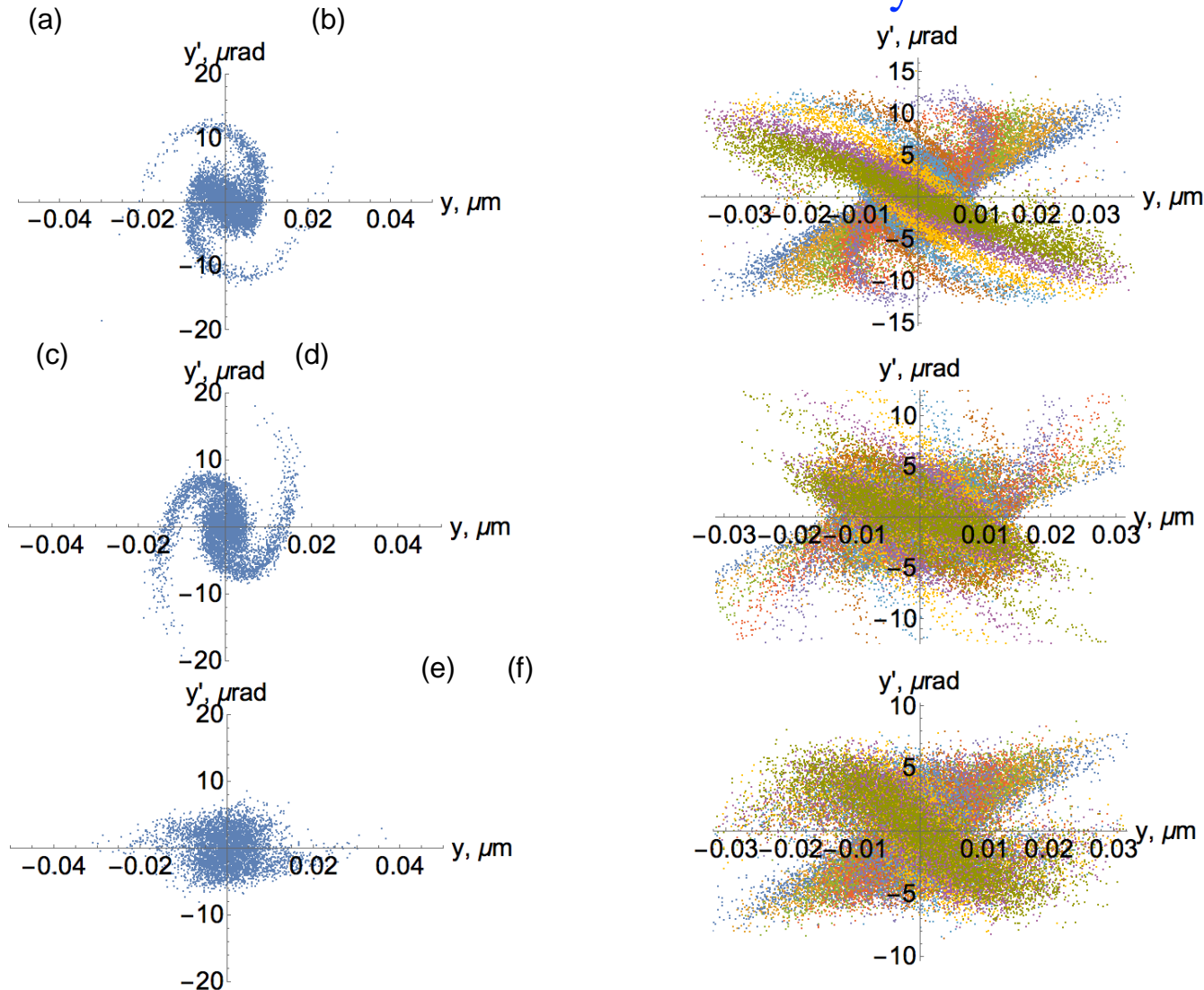
## Collider efficiency : Luminosity/AC Power



- ❑ *Recycling collider's efficiency is orders of magnitude above that of FCC-ee, linear collider designs and muon collider at c.m. energies below few TeV*
- ❑ *Only at c.m. energy  $\sim 10$  TeV, the muon collider concept could come close to the efficiency offered by recycling  $e^+e^-$  colliders*
- ❑ *Investing in relevant LiHe technologies and SRF R&D can bring this exciting possibilities closer to reality*

# Back-up slides

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

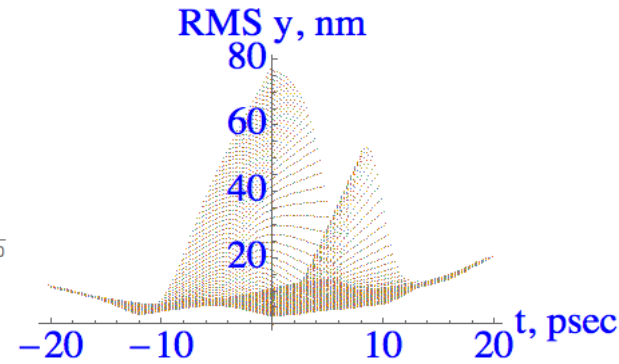
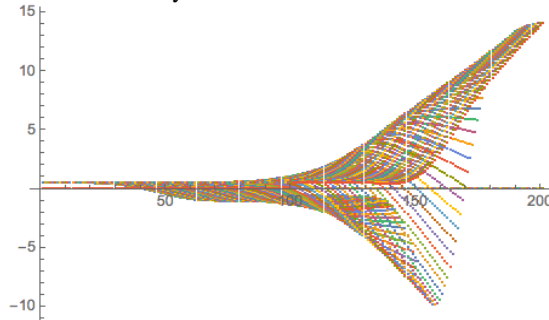


Beam distribution in the vertical phase space after the collision. Distributions of the central slice are on the left and combinations of 10 slices covering evenly  $-3\sigma_z < z < 3\sigma_z$ , are on the right: (a-b) are for center particles at  $x=0$ ; (c-d) are for those at  $x=\sigma_x$ , (e-f)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

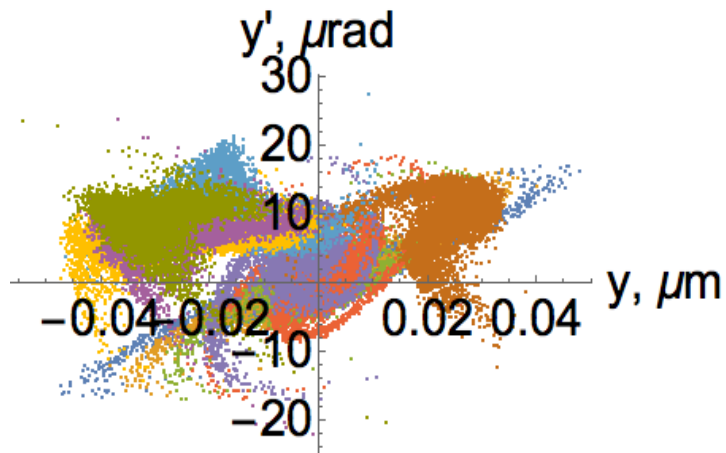
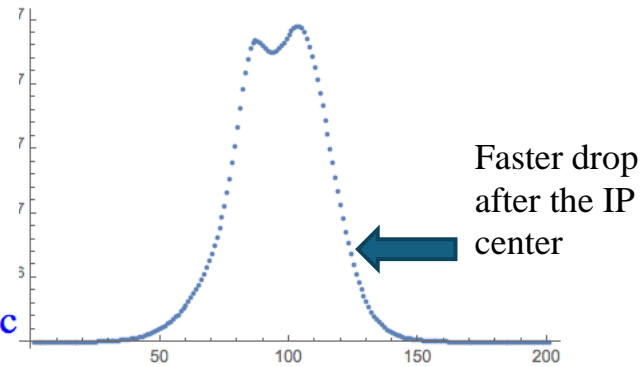
# Effects of orbits offsets in IP

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

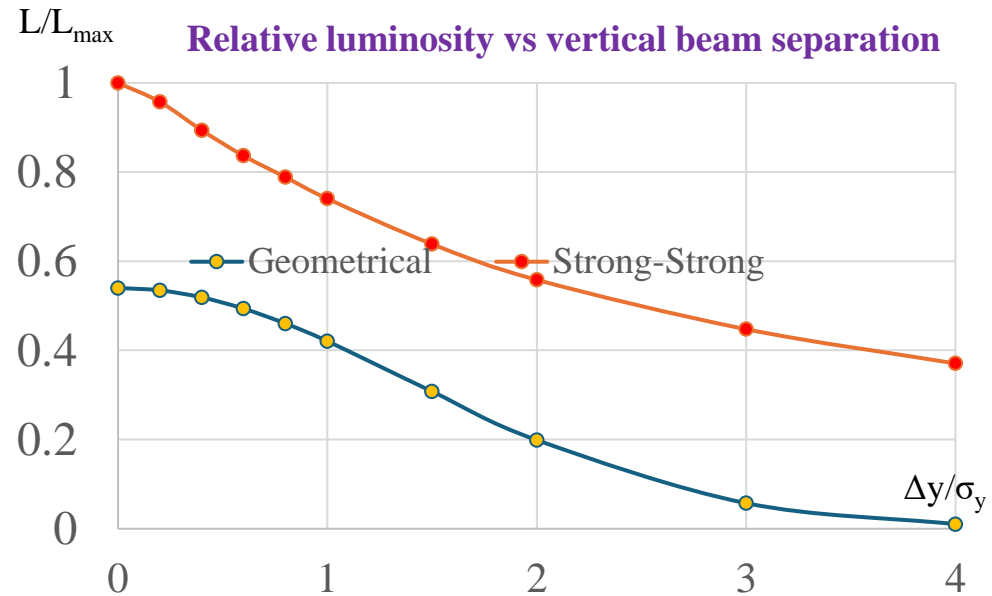
Beam centroids evolution in units of  $\sigma_y$  at the beam waist.



Instantaneous luminosity (a.u.)



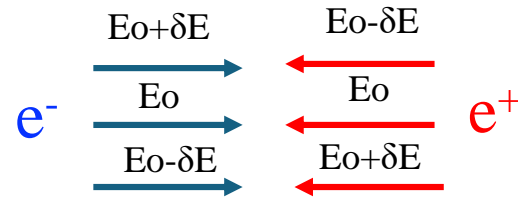
Main effect from offsets: RMS vertical beam emittance increases  $\sim 10X$  after collisions. It does not present any problems for the energy and particles recovery. It may require to increased time in the cooling rings to three-to-four damping times – this should be optimized for actual orbit deviations



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

# ReLiC for direct HIGS production

## $e^+e^- \rightarrow H$



- There is no luminosity loss because we kept horizontal beam size the same, but now it is dominated by dispersion and energy spread

$$S_x = \sqrt{e_x \cdot b_x^* + \left(D_x \cdot \frac{S_E}{E}\right)^2} \approx |D_x| \cdot \frac{S_E}{E} \quad DE_{c.m.} = E \cdot \frac{\sqrt{2 \cdot e_x \cdot b_x^*}}{D_x} = 1.4 \text{ MeV}$$

- 3-fold bunch decompression is sufficient to recover all collider particles in 1.5 GeV damping ring. Typical relative energy spread in damping ring is  $\sim 10^{-3}$ , i.e.  $\sigma_E \sim 1.5 \text{ MeV}$
- After 3-fold compression  $\sigma_E$  becomes  $\sim 4.5 \text{ MeV}$ .
- Curvature of RF adds total  $\pm 3.75 \text{ MeV}$  of correlated energy spread
- I assume  $\sigma_E \sim 10 \text{ MeV}$  in IR, which likely is an overestimation of the wakefields and other effects. If real simulation will show that  $\sigma_E$  is too small, a correlated spread can be added by running one of cavities off-crest

1 year -  $2 \times 10^7 \text{ sec}$  -  $90 \text{ ab}^{-1}$

C.M. energy	GeV	125.0
Length of accelerator	km	5
Particles per bunch	$10^{11}$	1.0
Beam current	mA	38
$\epsilon_x$ , norm	mm mrad	4.0
$\epsilon_y$ , norm	$\mu\text{m mrad}$	1.0
Relative beam spread in IR	$\sigma E/E$	$1.6 \times 10^{-4}$
$\beta_x$	m	0.05
$\beta_y$ , matched	mm	0.2
$D_x$	m	0.08
$\sigma_z$	mm	1
Disruption, $D_x$		0.0
$D_y$		109
Total luminosity	$10^{36} \text{ cm}^{-2}\text{sec}^{-1}$	4.5

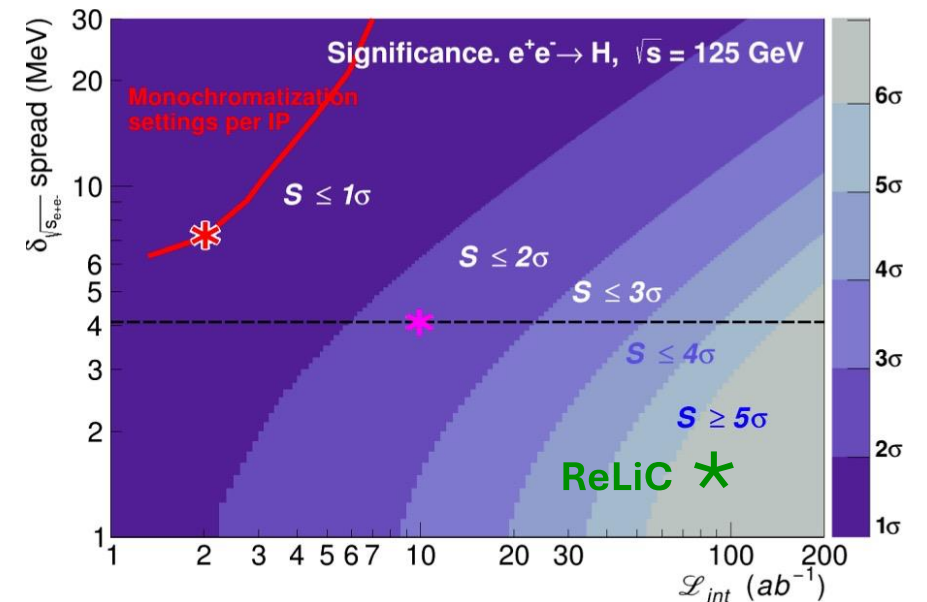


Figure is courtesy of David d'Enterra

# Specifics for $\sqrt{S}=125$ GeV

- From the onset of our studies, we focused on high energy reach of  $e^+e^-$  collisions where beamstrahlung effects are critically important both for the energy spread in collisions and for recovery of particles in damping rings. A 10-x bunch compression and decompression is needed for TeV scale operations.
- 62.5 GeV/beam energy is relatively low, which warrants completely different approach to the IR. As an example, a very modest 2-x to 3-x bunch compression/decompression is sufficient for lossless particles recovery
- Less than 1% of particles radiate beamstrahlung photons, which reduces mono-energetic collisions by  $\sim 2\%$
- Since ERL-based colliders uses fresh beams, necessary dispersion can be introduced in IR for monoenergetic collisions without adverse effect on beam emittance.
- Since electron and positrons beams propagate through different (left and right) accelerator structures, dispersion with opposition signs of electrons and positrons  $D_{e^+} = -D_{e^-}$  can be created using magnets – no electrostatic elements are needed.
- Using  $D_x = 12$  cm in IR with  $\beta_x^* = 5$  cm will provide for energy spread in  $e^+e^-$  collision of less than 1 MeV. This mode can be achieved in ReLiC and CERC without loss of luminosity.
- In this presentation I am giving estimates, which are based on reasonable assumptions about beam dynamics.

# QED effects

*Classical*  $\Rightarrow$  *QED*

$$\Upsilon_{\max} = \frac{2 \square W_c}{3 g m c^2} = 3gN \frac{\square r_e}{(s_x + s_y) s_z} \Rightarrow \Upsilon_{\max} \approx 2gN \frac{r_e^2}{a(s_x + 1.85s_y) s_z}$$

$$\langle \Upsilon \rangle \approx \frac{5}{6} gN \frac{\square r_e}{(s_x + s_y) s_z} \text{ (copied...)} \approx gN \frac{\square r_e}{s_x s_z} \Rightarrow \langle \Upsilon \rangle \approx \frac{5}{6} gN \frac{\square r_e}{(s_x + s_y) s_z}$$

$$n_g \approx 1.08 N a r_e \frac{2}{s_x + s_y} U_o(\langle \Upsilon \rangle); U_o(\Upsilon) \approx \frac{1}{\sqrt{1 + \Upsilon^{2/3}}}$$

$$d_E = \left\langle -\frac{DE}{E} \right\rangle \approx 0.209 N^2 \frac{g r_e^3}{s_z} \left( \frac{2}{s_x + s_y} \right)^2 U_1(\langle \Upsilon \rangle) \approx 1.20 \frac{a s_z}{\square g} \langle \Upsilon \rangle^2 U_1(\langle \Upsilon \rangle)$$

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

# Main parameters of ReLiC

<b>C.M. energy</b>	<b>GeV</b>	<b>250</b>	<b>500</b>	<b>1000</b>	<b>3000</b>
<b>Length of accelerator</b>	km	<b>21</b>	47	93	<b>276</b>
<b>Section length</b>	m	<b>500.00</b>	250.00	250.00	<b>250.00</b>
<b>Bunches per train</b>		<b>5</b>	5	7	<b>21</b>
<b>Particles per bunch</b>	$10^{10}$	<b>4.0</b>	4.0	3.0	<b>1.0</b>
<b>Collision frequency</b>	MHz	<b>2.9</b>	4.3	6.0	<b>18.0</b>
<b>Beam currents in linacs</b>	mA	<b>18</b>	27	29	<b>29</b>
$\epsilon_x$ , norm	mm mrad	<b>4.0</b>	8.0	8.0	<b>8.0</b>
$\epsilon_y$ , norm	$\mu\text{m mrad}$	<b>1.0</b>	2.0	2.0	<b>2.0</b>
$\beta_x$	m	<b>5</b>	20	40	<b>100</b>
$\beta_y$ , matched	mm	<b>0.2</b>	0.5	1.5	<b>6.8</b>
$\sigma_z$	mm	<b>1</b>	1	3	<b>5</b>
<b>Disruption parameter, Dx</b>		<b>0.01</b>	0.0014	0.0013	<b>0.0004</b>
<b>Disruption parameter, Dy</b>		<b>109</b>	17	14	<b>3</b>
<b>Luminosity per detector</b>	$10^{34} \text{ cm}^{-2}$	<b>215</b>	101	67	<b>20</b>
<b>Total luminosity</b>	$10^{34} \text{ cm}^{-2}$	<b>429</b>	203	135	<b>40</b>

*Parameters are not fully optimized*

# Recycling collided electrons and positrons

## Advantages

- Potential for high degree of polarization in colliding beams
- Possibility to operate with relatively high average currents and high polarization (*removing insane appetite for polarized positron in linear colliders*)
- Reduction of the power consumption
- Eliminating high power beam dumps and related radiative waste

## Challenges

- Eliminating particles loss caused by low energy tail induces by the beamstrahlung
- Damping rings with large energy acceptance
- Bunch compressing and decompression to fit into the damping ring energy acceptance
- High rep-rate injection and ejection kickers

# Comparison of Linac and Ring type colliders

$$L = f_c \frac{N_{e^-} N_{e^+}}{4\rho s_x s_y} h = \frac{I_{e^-} I_{e^+}}{4pe^2 \cdot f_c s_x s_y} h \rightarrow L = \frac{1}{16\rho_y \cdot s_x s_y \cdot f_c} \left( \frac{P_{SR}}{eV_{SR}} \right)^2 h; h \sim 1$$

In ring and ring-type colliders there are strong limitations on maximum allowable beam-beam tune shift and IP chromaticity (e.g. how small is  $\beta^*$ ). It favors larger emittances, higher collision frequencies and higher beam currents to reach the same luminosity

$$X_{x,y}^\pm = \frac{N_{e^\pm} r_e b_{x,y}^\pm}{2pgs_{x,y} (s_x + s_y)} \text{ £ } 0.1, 0.15$$

$$s_{x,y} = \sqrt{e_{x,y} b_{x,y}^*}$$

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

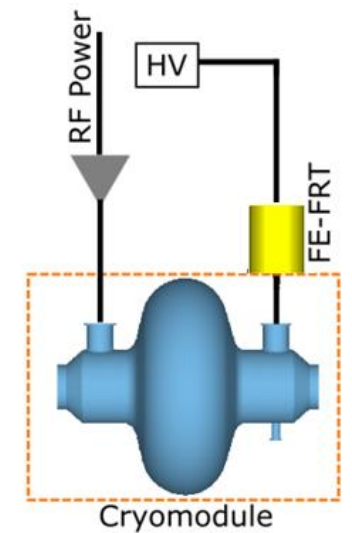
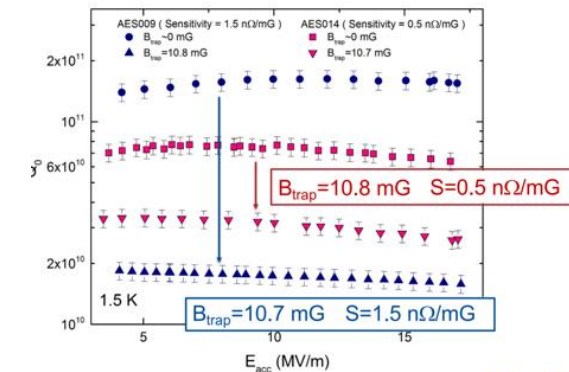
Example: “ring type” ERLC and “linac-type” ReLiC colliders

Collider	ReLiC	ERLC
I, Beam current, mA	12	45
L, Luminosity, cm <sup>-2</sup> sec <sup>-1</sup>	2.15E+36	3.60E+35
L/I, cm-2 sec-1/mA	1.79E+35	8.00E+33
L/I <sup>2</sup> , cm-2 sec-1/mA <sup>2</sup>	1.49E+34	1.78E+32

ReLiC produces 22.4 fold higher luminosity per unit of beam current and has 84-fold higher efficiency in generating luminosity

# Accelerator designs and challenges

- On-axis acceleration and deceleration of high energy beams is main advantage of CERC and ReLiC, allowing using existing SRF linac technology and other conventional equipment
- But still there are a lot of challenges:
- High efficiency LiHe refrigerators
- 1.5 GHz SRF cavities with quality factor  $Q > 10^{11}$  at 1.5 K (or 2 K)
- $N_3Sb$  4K SRF cavities with quality factor
- Reactive tuners to reduce power to suppressing microphonics
- Damping rings with very flat beams ( $\epsilon_h/\epsilon_v \sim 2,000-4,000$ )
- Damping rings with 10% energy acceptance
- 10-to-40 fold bunch decompressors
- MHz scale rate injection/ejection kickers
- Vertical beam stabilization at the Ips



FoM  $\sim 75$