Energy Recovery (*and particle recycling*) in Linear Colliders

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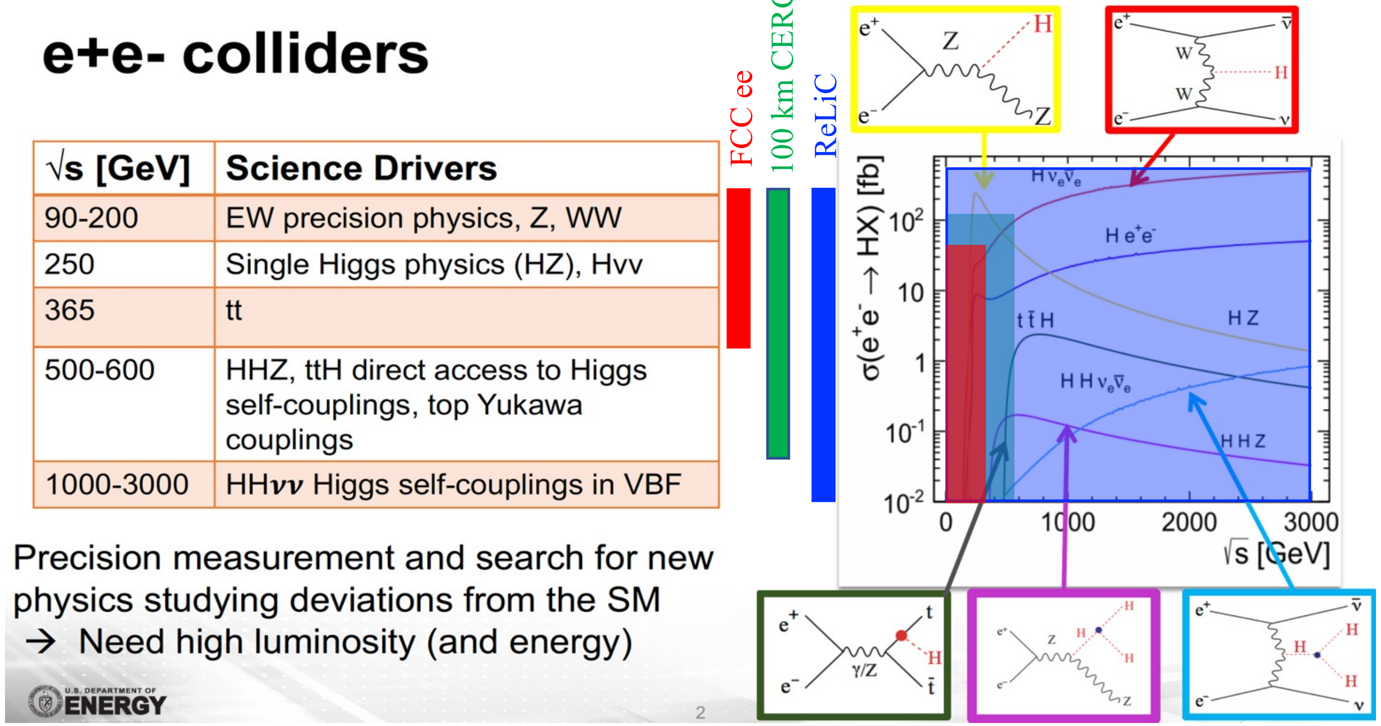
- Most important factor for efficient high energy linear e^+e^- colliders
  - Energy recovery linacs (ERLs) to recycle energy of collided beams
    - Reduces energy consumption and increases efficiency of colliders measured in luminosity/AC power
  - Recycling and restoring quality of collided beams provides for
    - Very high luminosity
    - Mono-energetic collisions (reduced beamstrahlung)
    - High polarization of both electron and positron beams
    - Eliminates "strong appetite" of linear colliders for fresh positrons
    - Environment-friendly operation: low radiation, reduced radiation waste…
    - …..

Stony Brook University

CASE Center for Accelerator Science and Education

Brookhaven National Laboratory

Physics: Energy and Luminosities reach



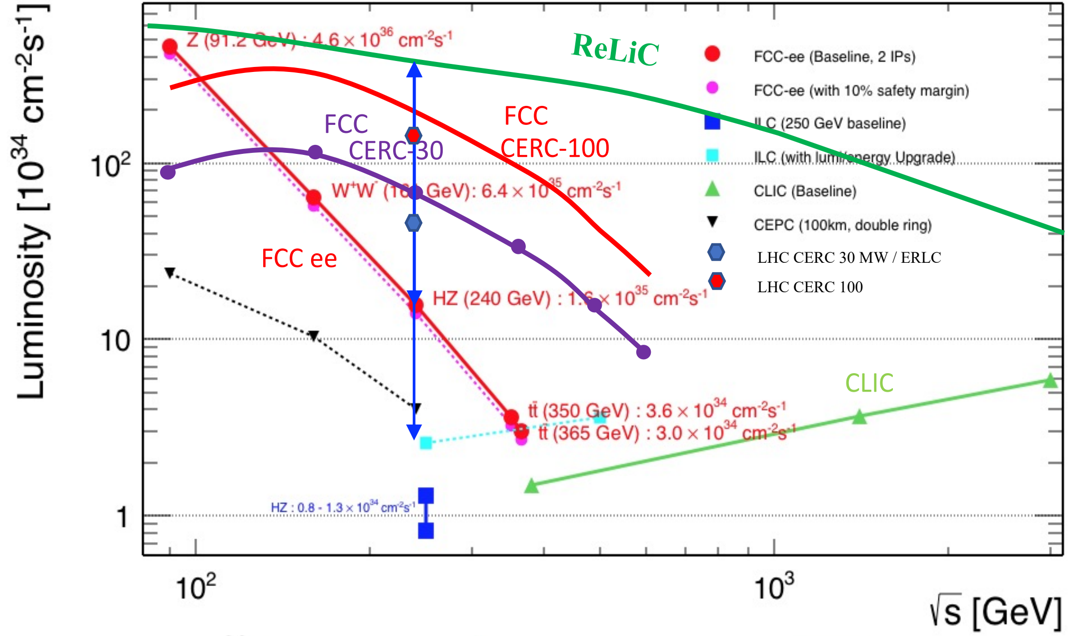
e+e- colliders

√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

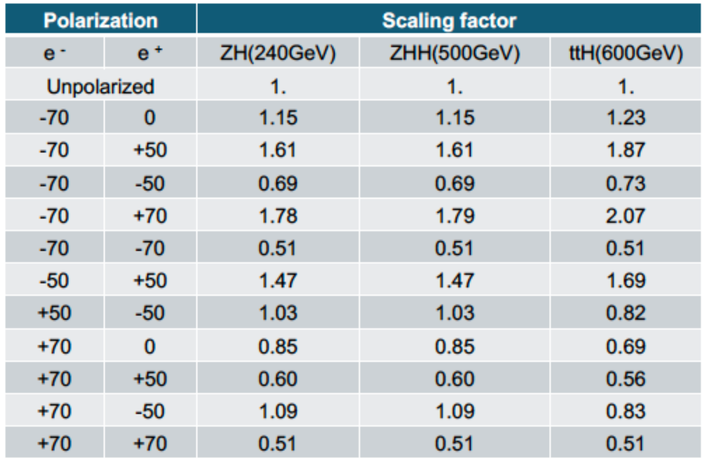
→ Need high luminosity (and energy)

Recycling could offer luminosity boosts ~ 200 at HIGS energy



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.



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

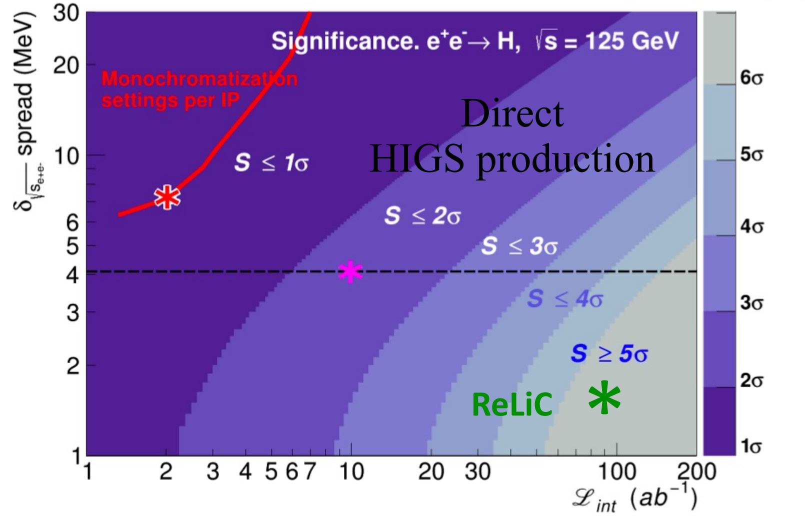
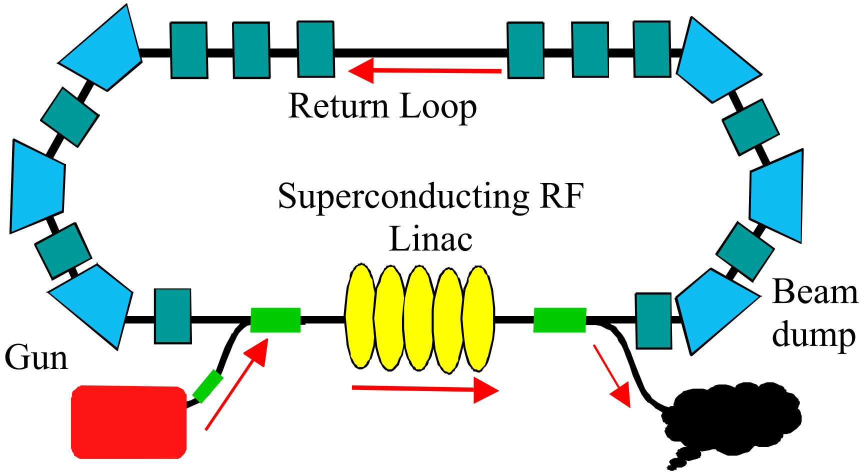
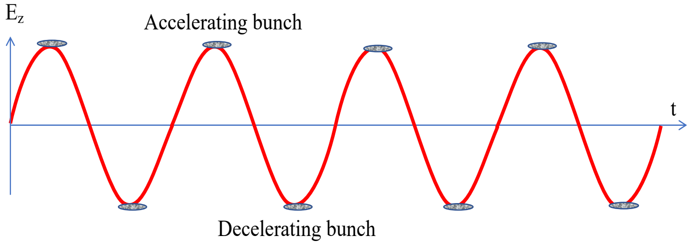


Figure is courtesy of David d'Enterria

What is Energy Recovery Linacs (ERLs): Perpetua Mobile of Modern Accelerators

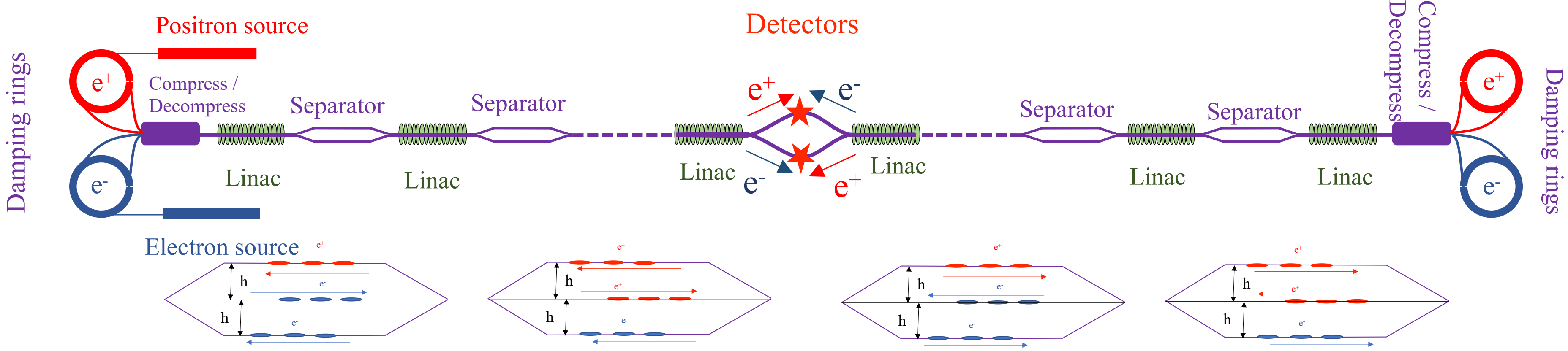
- Invented by Prof. M Tigner, Cornell U., (*Nuovo Cimento **37**, 1228, 1965*)
- In principle, the idea is very simple : return energy from used beam back to the RF cavity and use it to accelerate fresh beam
- Extremely low losses of Superconducting RF linacs making this process very efficient with potential of many 9s in efficiency of energy recycling
- There is number of operational ERLs and their potential is well understood and appreciated





- ERLs are considered for multiple applications starting from e^+e^- and lepton-hadron (LHeC, FCC eh…) colliders, coolers for hadron beams (EIC), diffraction-limited light sources, X-ray FEL-divers, γ-ray sources, isotope production, EUV source for chip production, etc., etc.

ReLiC – Recycling Linear Collider



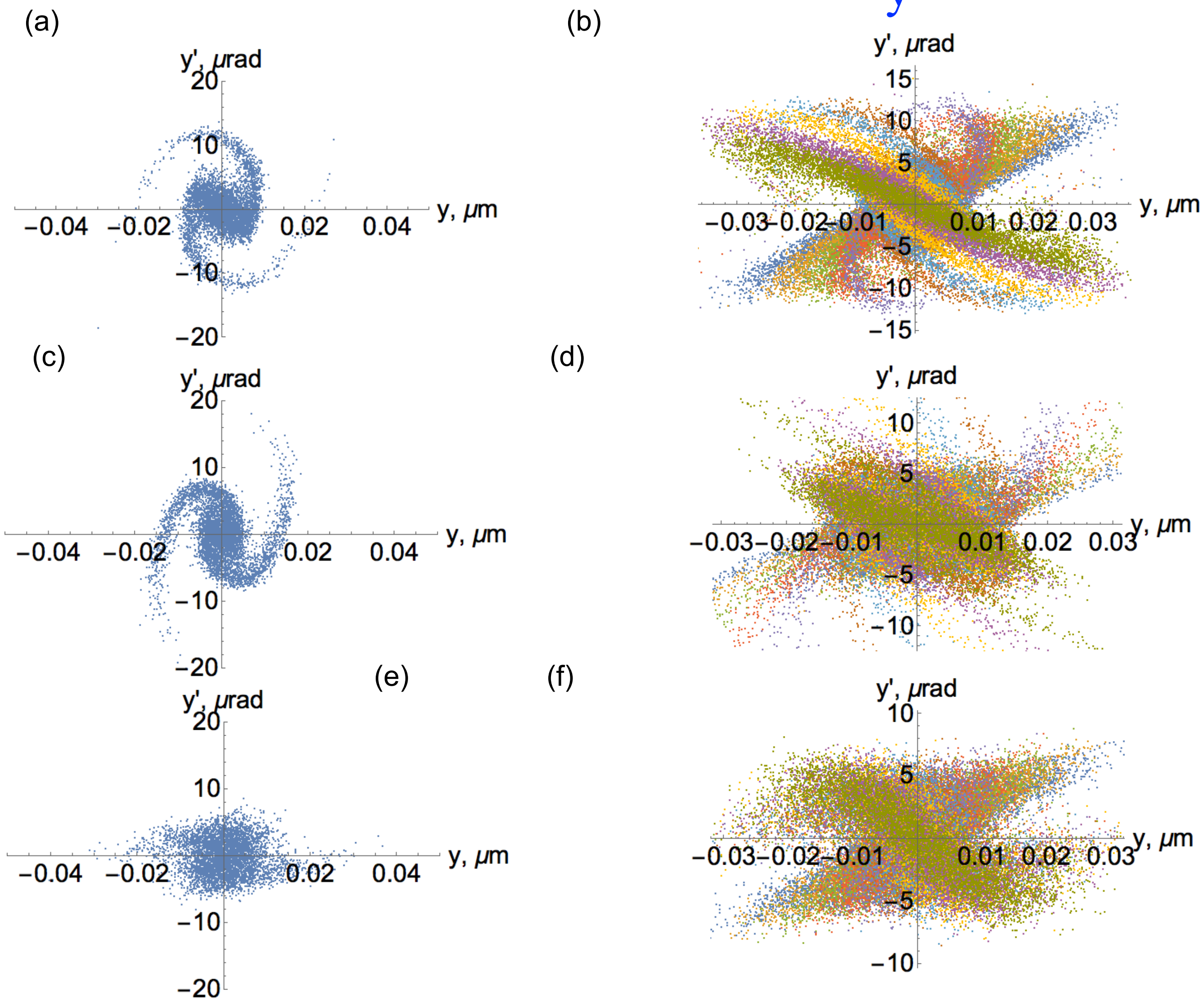
- Flat beams cooled in damping rings with “top off” to replace burned-off particles
- Bunches are ejected with collision frequency, determined by the distance between beam separators
- Beams are accelerated **on-axis** in SRF linacs collide in one of detectors
- After collision at the top energy, they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

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

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

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

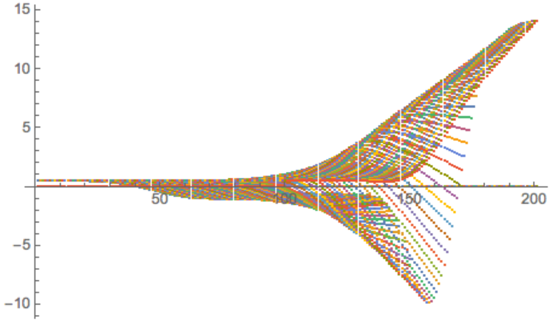


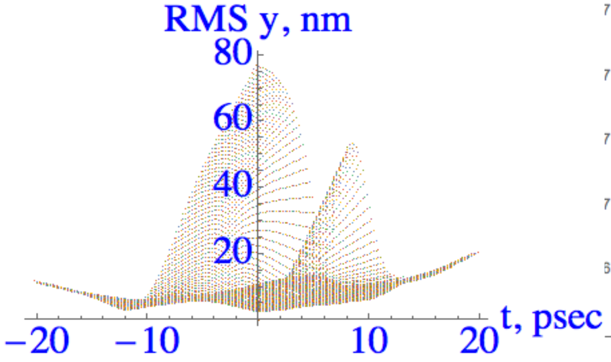
Beam distribution in the vertical phase space after the collision. Distributions of the central slice are on the left and combinations of 10 slices covering evenly $-3\sigma_z < z < 3\sigma_z$, are on the right: (a-b) are for center particles at x=0; (c-d) are for those at $x= \sigma_x$, (e-f) is for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

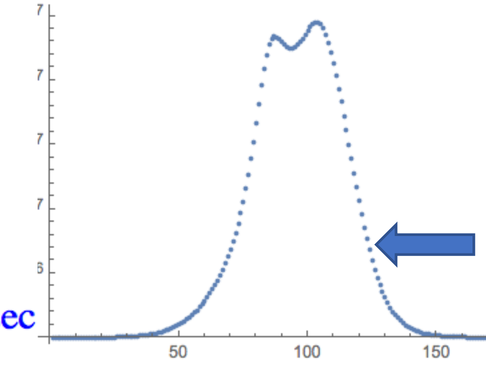
Initial beam axis separation is $\Delta y = 1\sigma_y$

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

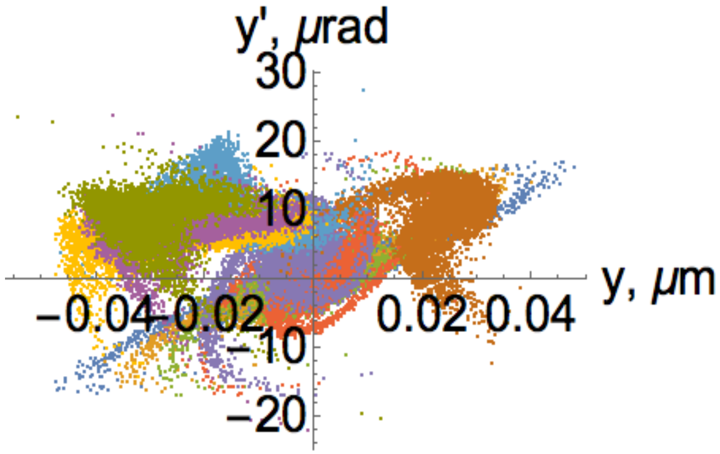


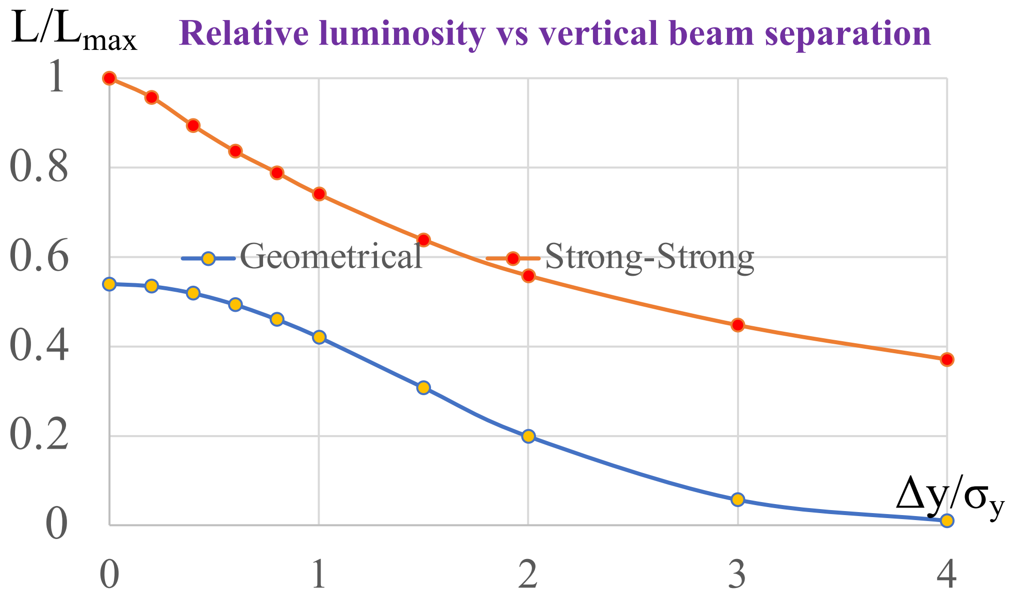


Instantaneous luminosity (a.u.)



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

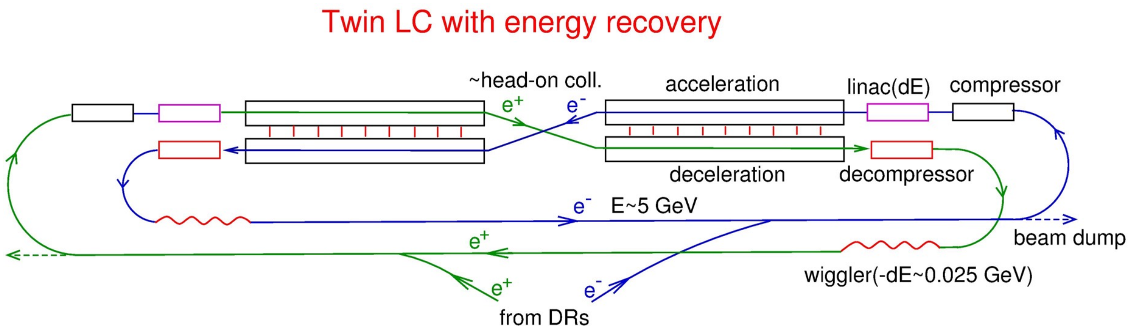
Main parameters of ReLiC

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**	0.0014	0.0013	**0.0004**
Disruption parameter, Dy		**109**	17	14	**3**
Luminosity per detector	10^{34} cm^{-2}	**215**	101	67	**20**
Total luminosity	10^{34} cm^{-2}	**429**	203	135	**40**

Parameters are not fully optimized

ERLC Proposal by Valeri Telnov (BINP, Novosibirsk)

Collision conditions are similar to ring-ring colliders



Dual axis cavity, JLab

1) LC consists of two parallel SC linac connected with each other with rf-coulpers, so that the fields are equal at any time. One line is for acceleration, the other for deceleration.
2) Damping is provided by wigglers (no damping rings) at the "return" energy about E~5 GeV. The energy loss per turn dE/E~1/200. Damping is needed to reduce the energy spread arising from collision of beams.
3) In the presence of a return path, e + and e- are always correctly focused by their own FF.
4) The duration of one cycle (several seconds) is determined by the refrigeration system (rise of temperature on ~0.1 K at 1.8 K).

V. Telnov, A high-luminosity superconducting twin e+e- linear collider with energy recovery, Journal of Instrumentation 16 (2021) P12025

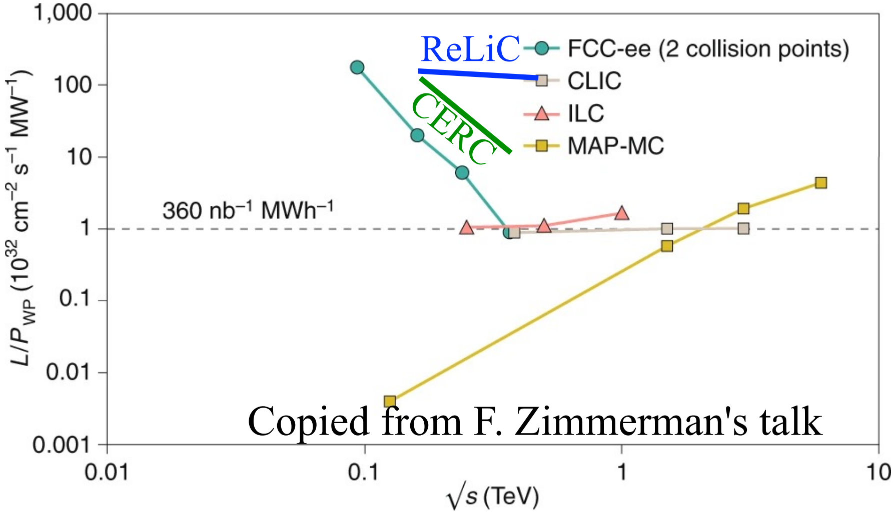
Notes: 1. The dual-axis linac is asymmetric with transverse EM fields on the beam trajectory resulting in synchrotron radiation and emittance growth.
2. A double-axis cavity will – at least – double the losses and will require 2X+ higher power of LiHe refrigerator when comparted with ILC or ReLiC

	unit	ERLC pulsed Nb 1.8 K 1.3 GHz	ERLC pulsed Nb 1.8 K 0.65 GHz	ERLC contin. Nb_3Sn 4.5 K 1.3 GHz	ERLC contin. Nb_3Sn 4.5 K 0.65 GHz
Energy $2E_0$	GeV	250	250	250	250
Luminosity $\mathcal{L}_{\text{tot}}$	10^{36} cm^{-2}s^{-1}	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^{10}	3	12	3	12
Length $L_{\text{act}}/L_{\text{tot}}$	km	12.5/30	12.5/30	12.5/30	12.5/30
N per bunch	10^9	1.13	2.26	0.46	1.77
Bunch distance	m	0.23	0.46	0.23	0.46
Rep. rate, f	Hz	$2.47 \cdot 10^8$	$2.37 \cdot 10^8$	$1.3 \cdot 10^9$	$6.5 \cdot 10^8$
$\epsilon_{x,n}/\epsilon_{y,n}$	10^{-6} m	10/0.035	10/0.035	10/0.035	10/0.035
β^*_x/β_y at IP	cm	2.7/0.031	10.8/0.031	0.46/0.031	6.8/0.031
σ_x at IP	μm	1.05	2.1	0.43	1.66
σ_y at IP	nm	6.2	6.2	6.2	6.2
σ_z at IP	cm	0.03	0.03	0.03	0.03
$(\sigma_E/E_0)_{\text{BS}}$ at IP	%	0.2	0.2	0.2	0.2

Summary

- Recycling linear collider concept promises significant luminosity boost in collision of polarized e^+e^- beam
- In recycling linear colliders c.m. energy at high luminosity can extend from ~ 100 GeV into TeV range
- It also could be very effective for direct HIGS production $e^+e^- \rightarrow H$ at $\sqrt{s}=125$ GeV
- ReLiC scheme can be staged, starting from operating at Z, W, $\sqrt{s}=125$ GeV , then as HZ factory using current technology and extended further with advances in SRF R&D
- R&D, needed on high quality (Q) SRF, flat beams and high efficiency He refrigerators has synergy with ERL R&D for EIC hadron cooler (BNL), PERLE (France), Berlin-pro, Darmstadt ERL, MESA (Germany), Test ERL (Japan) and Cbeta (Cornell) …

Collider efficiency : L/P



Copied from F. Zimmerman's talk

Thank you for your attention

Final but important note:

- The most important investment for SRF linear colliders should be improving efficiency of 2K LiHe refrigerators from current **900 W/W** (or even worse) closer to Carnot cycle theoretical efficiency of **150 W/W**.
- This HUGE factor of **6** is the main obstacle for SRF accelerators to become even more energy efficient

Back-up slides

Recycling collided electrons and positrons

Advantages

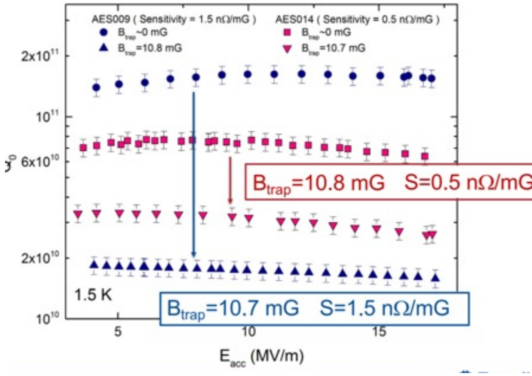
- Potential for high degree of polarization in colliding beams
- Possibility to operate with relatively high average currents and high polarization (*removing insane appetite for polarized positron in linear colliders*)
- Reduction of the power consumption
- Eliminating high power beam dumps and related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

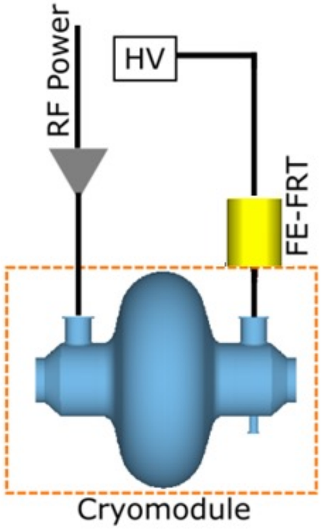
Challenges

- 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

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 ($\varepsilon_h/\varepsilon_v$ ~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 ~75

Comparison of Linac and Ring type colliders

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

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

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

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

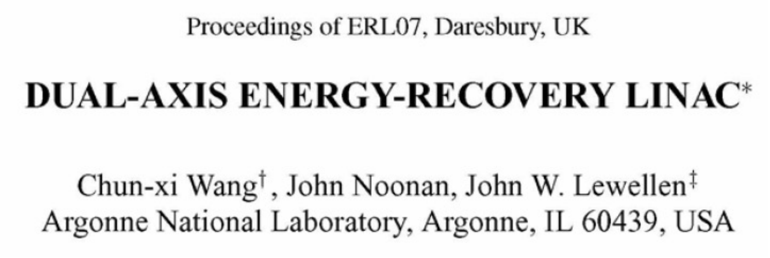
Linear and ERL colliders, where beams collide only once, do not have such limitations!

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

Collider	**ReLiC**	**ERLC**
I, Beam current, mA	12	45
L, Luminosicy, cm^{-2} sec^{-1}	2.15E+36	3.60E+35
L/I, cm-2 sec-1/mA	1.79E+35	8.00E+33
L/I^2, cm-2 sec-1/mA^2	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

Twin Axis Cavity Proposals



Proceedings of ERL07, Daresbury, UK

DUAL-AXIS ENERGY-RECOVERY LINAC*

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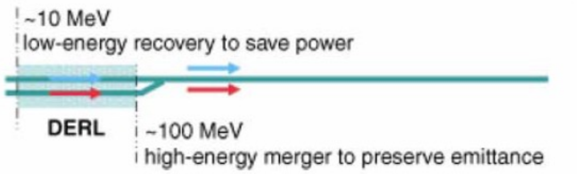
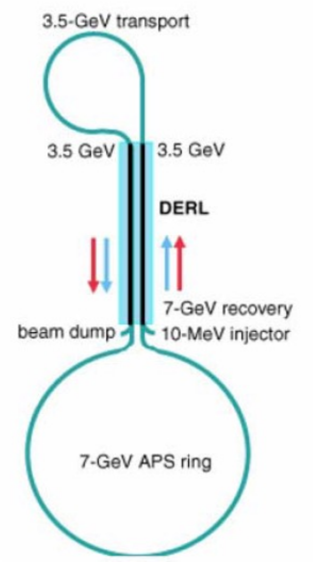
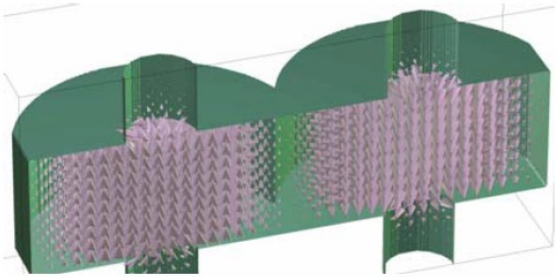
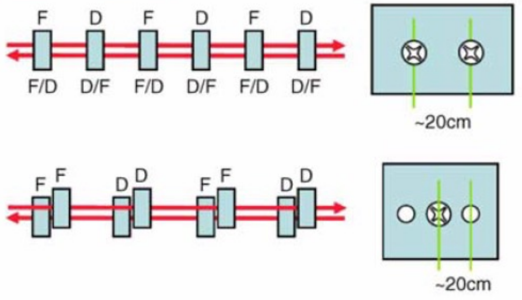
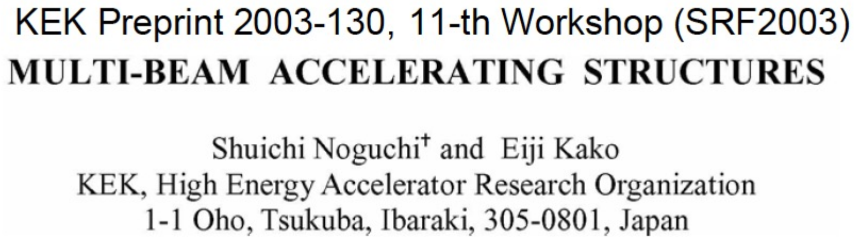


Fig. 2: DERL as a solution for beam merger. The red arrow indicates accelerating beam.









KEK Preprint 2003-130, 11-th Workshop (SRF2003)

MULTI-BEAM ACCELERATING STRUCTURES

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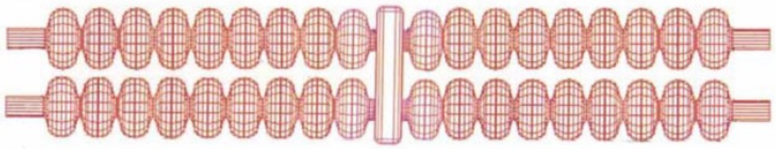

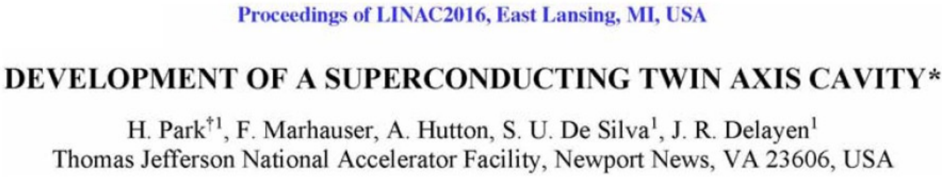

Proceedings of LINAC2016, East Lansing, MI, USA

DEVELOPMENT OF A SUPERCONDUCTING TWIN AXIS CAVITY*

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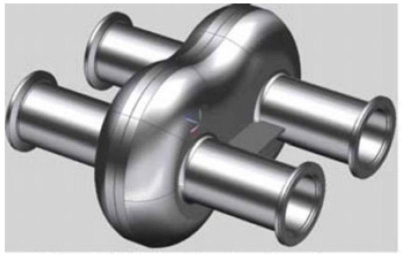


Figure 2: Single cell twin axis cavity.

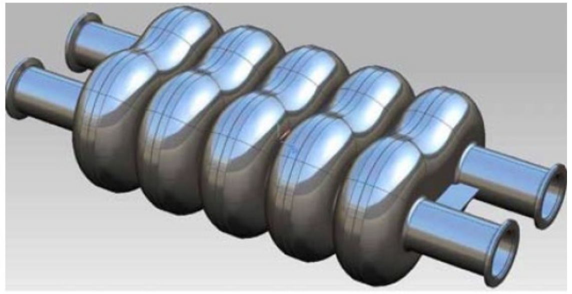


Figure 9: Multicell twin axis cavity.

VL: Serious potential challenge for TeV-scale e+e- colliders is potential for on-axis transverse EM fields and corresponding synchrotron radiation and emittance growth

QED effects

$$\mathit{Classical} \Rightarrow \mathit{QED}$$

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

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

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

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

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

C^3 or CLIC at 2x250 GeV
n_γ=1.6; Y_{max}=20.4%; <Y>=8.5%

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

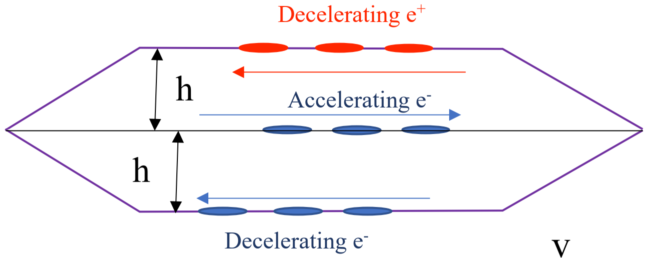
- RF powers needed in damping rings is proportional to ReLiC luminosity and can be reduced if $4x10^{36}$ $cm^{-2}sec^{-1}$ luminosity is not needed. Operating 250 GeV c.m. ReLiC with luminosity of $4x10^{35}$ $cm^{-2}sec^{-1}$ will reduce accelerator power consumption to 50 MW.

- 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.

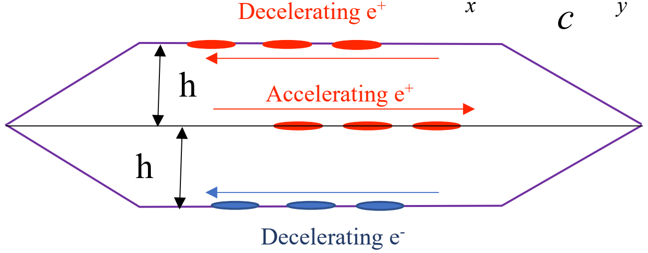
*** Estimation is provided by Dr. Sergey Belomestnykh (FNAL)**

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



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



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

** 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

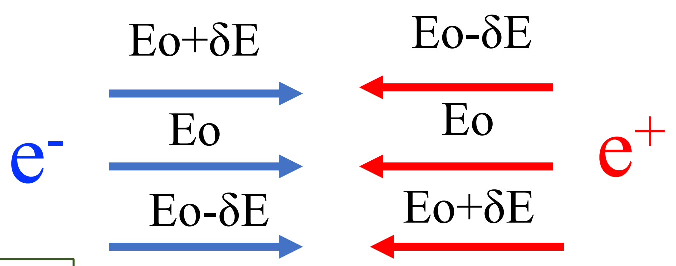
- At high energies the most dangerous effect is beamstrahlung: synchrotron radiation in strong EM field of opposing beam during collision
- It can cause significant amount of energy loss, induce large energy spread and loss of the particles
- Using very flat beams is the main way of mitigating this effect
- Our goal was to maintain energy spread in colliding beams at the same level as in ring-ring FCC ee: 0.15-0.2%

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

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 then 1% of particles radiate beamstrahlung photons, which reduces mono-energetic collisions by ~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 β^*_x=5 cm will provide for energy spread in e^+e^- collision of less then 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.

Possible IP parameters for ReLiC



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

$$\sigma_x = \sqrt{\varepsilon_x \cdot \beta_x^* + \left(D_x \cdot \frac{\sigma_E}{E} \right)^2} \approx |D_x| \cdot \frac{\sigma_E}{E}$$

- 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 ~ 10^{-3}, i.e. σ_E~ 1.5 MeV
- After 3-fold compression σ_E becomes ~ 4.5 MeV.
- Curvature of RF adds total ±3.75 MeV of correlated energy spread
- I assume σ_E~ 10 MeV in IR, which likely is an overestimation of the wakefields and other effects. If real simulation will show that σ_E is too small, a correlated spread can be added by running one of cavities off-crest

C.M. energy	GeV	125.0
Length of accelerator	km	5
Particles per bunch	10^{11}	1.0
Beam current	mA	38
εx, norm	mm mrad	4.0
εy, norm	µm mrad	1.0
Relative beam spread in IR	σE/E	$1.6\text{x}10^{-4}$
βx	m	0.05
βy, matched	mm	0.2
Dx	m	0.08
σ_z	mm	1
Disruption, Dx		0.0
Dy		109
Total luminosity	10^{36} $cm^{-2}sec^{-1}$	4.5

$$\Delta E_{c.m} = E \cdot \frac{\sqrt{2 \cdot \varepsilon_x \cdot \beta_x^*}}{D_x} = 1.4\,MeV$$

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

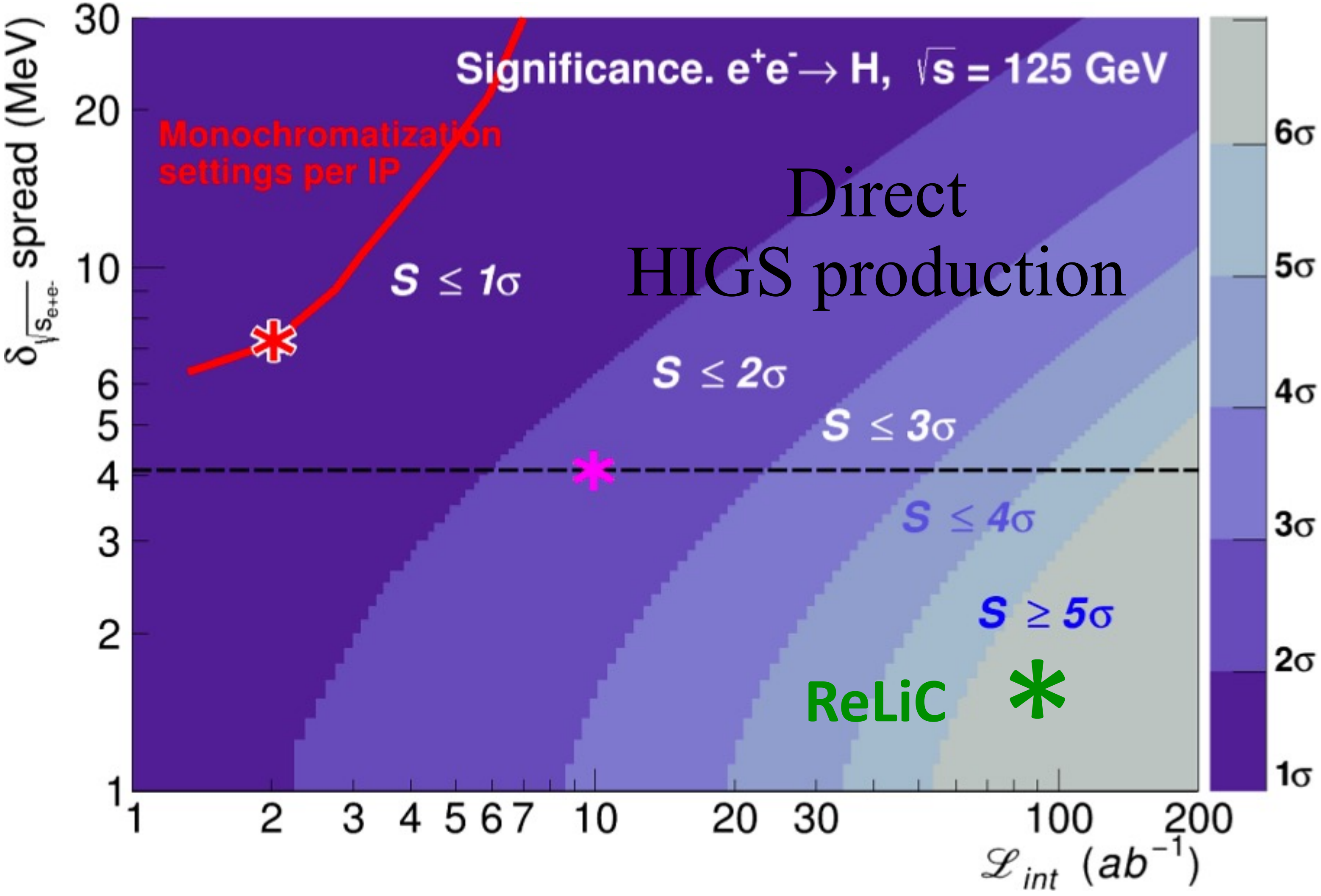


Figure is courtesy of David d'Enterria