Future *High Energy High Luminosity Polarized* e^+e^- Colliders using Recycling Energy Recovery Linacs

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- Most important factor for efficient high energy 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

Content

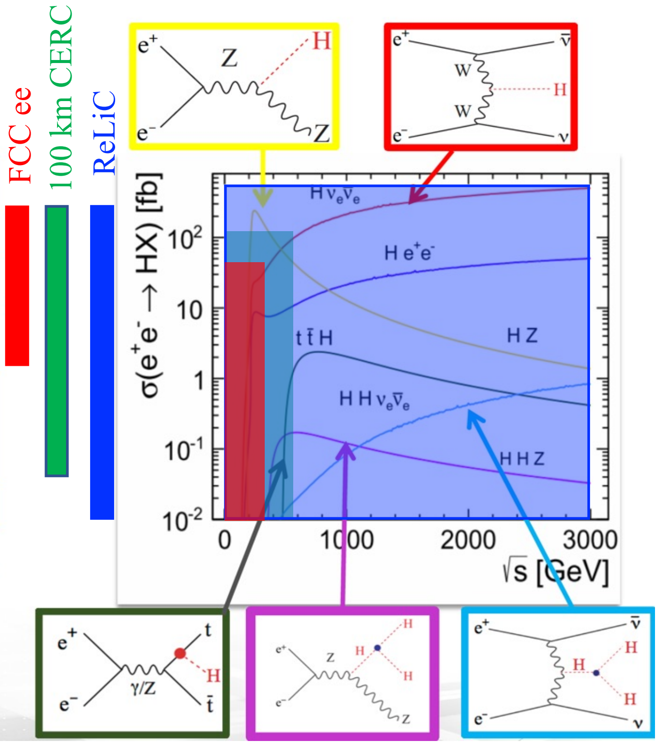
- The key points: Energy and Luminosity reach
- Energy Recovery Linacs (**ERL**s) – thanks to previous speaker
- Energy and luminosity reach of Recycling ERL e+e- colliders
- Three concepts
  - Recycling Linear Collider - **ReLiC**
  - Circular ERL Recycling Collider - **CERC** - in FCC and LHC tunnels
  - "Ring-Ring" type ERL collider - **ERLC**
- Advantages and challenges of particles recycling
- Ring-type and linac-type colliders
- Critical R&D
- Conclusions

Physics: Energy and Luminosities reach

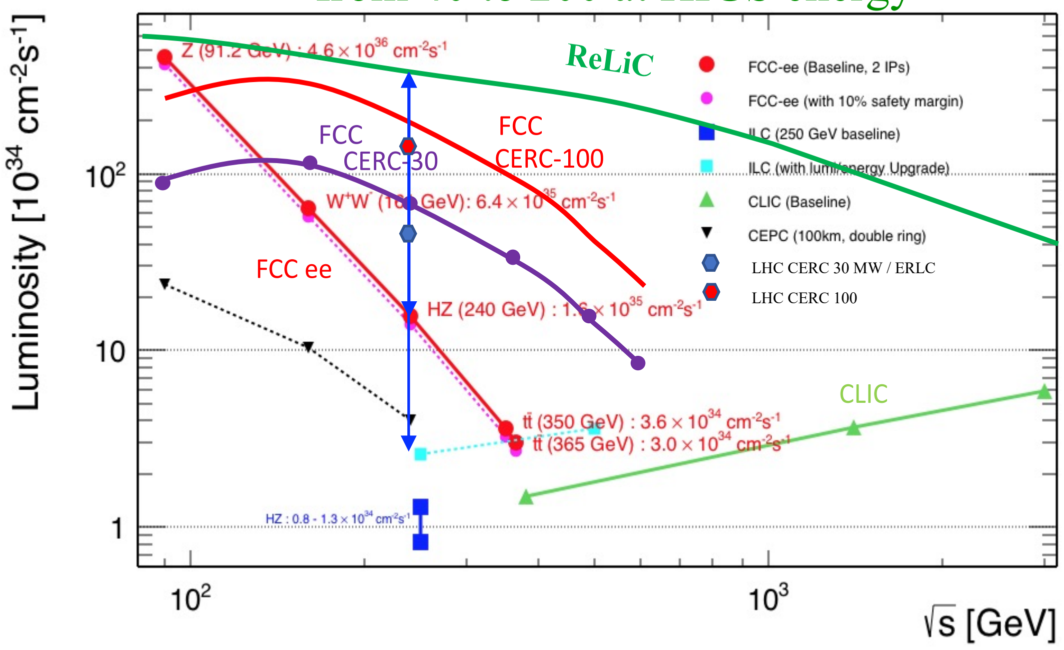
e+e- colliders

√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)



ERLs could offer luminosity boosts from 40 to 200 at HIGS energy



Recycling ERLs offer potential for high degree of polarization in e+e- beams

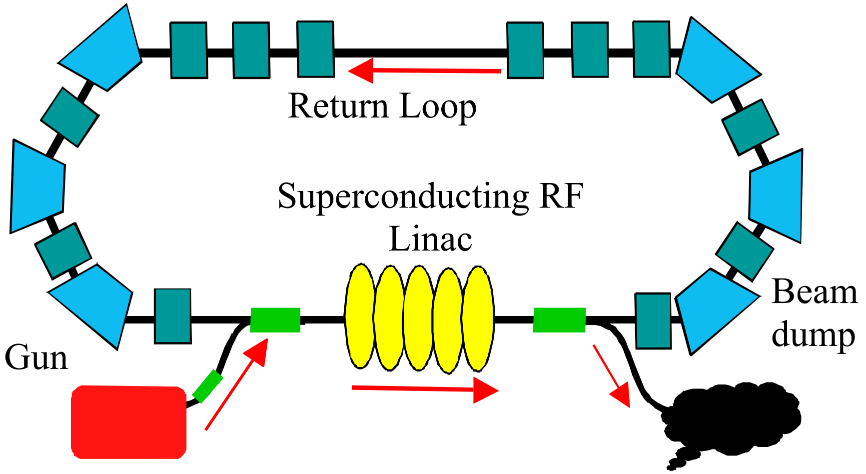
Example: The proper combination of polarization for electrons and positrons will significantly enhance the production cross section or will suppress it.

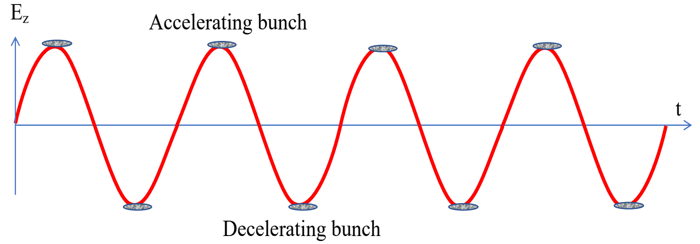
Polarization		Scaling factor		
e -	e +	ZH(240GeV)	ZHH(500GeV)	ttH(600GeV)
Unpolarized		1.	1.	1.
-70	0	1.15	1.15	1.23
-70	+50	1.61	1.61	1.87
-70	-50	0.69	0.69	0.73
-70	+70	1.78	1.79	2.07
-70	-70	0.51	0.51	0.51
-50	+50	1.47	1.47	1.69
+50	-50	1.03	1.03	0.82
+70	0	0.85	0.85	0.69
+70	+50	0.60	0.60	0.56
+70	-50	1.09	1.09	0.83
+70	+70	0.51	0.51	0.51

- Common features
  - Recycling used particles - no need for high intensity positron source
  - Energy recovery
  - High luminosity
  - High polarization of both electron and positron beams
  - Very small energy spread could open direct channel $e^+e^- \to H$ at $\sqrt{s}$=125 GeV
- Deference's
  - CERC c.m. energy reach is limited to sub-TeV by synchrotron radiation
  - 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

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

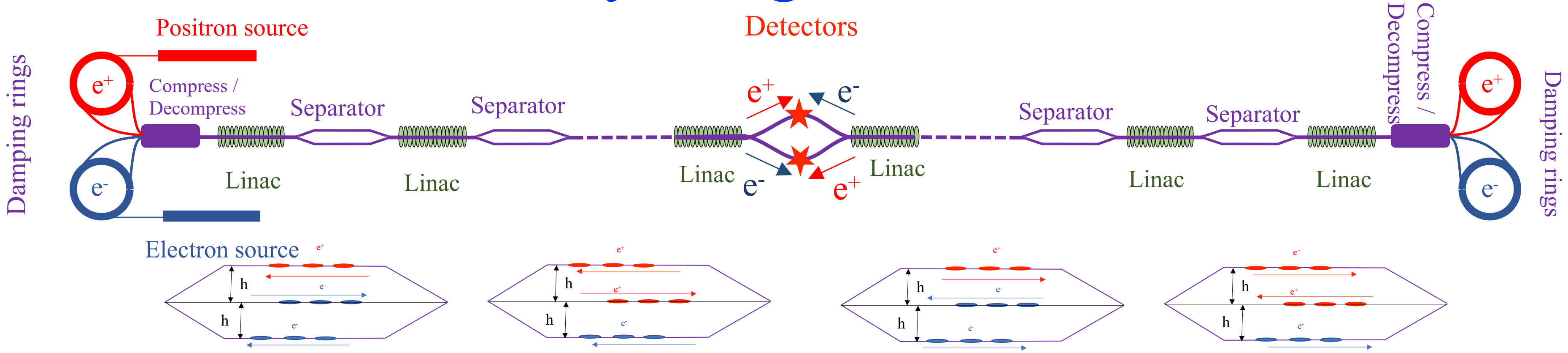
- Invented by Prof. M Tigner, Cornell U., (*Nuovo Cimento* ***37****, 1228, 1965*)
- In principle, the idea is very simple : return energy from used beam back to the RF cavity and use it to accelerate fresh beam
- Extremely low losses of Superconducting RF linacs making this process very efficient with 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 …..

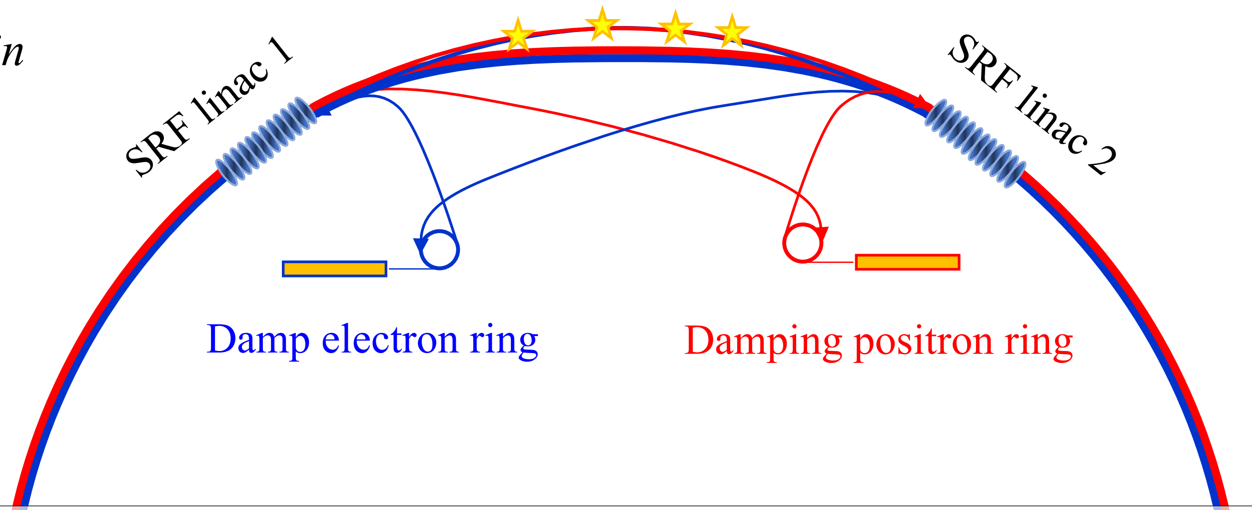
$$F_x = \pm e\left(E_x + \frac{v_z}{c} B_y\right) = \begin{cases} 0, \textit{acclerating} \\ 2eE_x, \textit{decelerating postions} \\ -2eE_x, \textit{decelerating electrons} \end{cases}$$

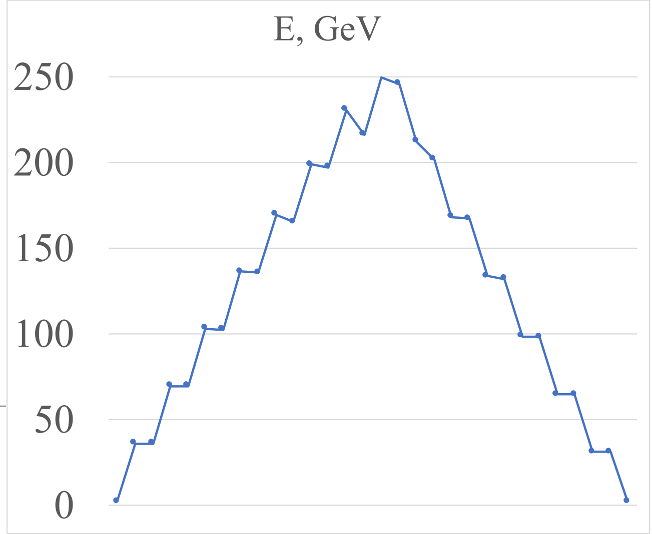
ReLiC collider recycles polarized electrons and positrons

- 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

CERC - Circular ERL Collider in FCC 100 km tunnel

Originally published in Phys. Lett. B Volume 804, 135394, (2020)





- Flat beams cooled in damping rings with "top off" for burn-off
- Bunches are ejected with collision frequency
- Beams accelerated with SRF linacs over four 100 km long passes by-passing the IR
- After collision at top energy rf phases are changed to deceleration returning most energy to SRF linac
- Decelerated beams are reinjected into cooling rings, after few damping times the trip repeats
- Luminosity is shared between detectors in any desirable ratio
- Only beams at top energy pass through detectors, the rest of beams bypass them

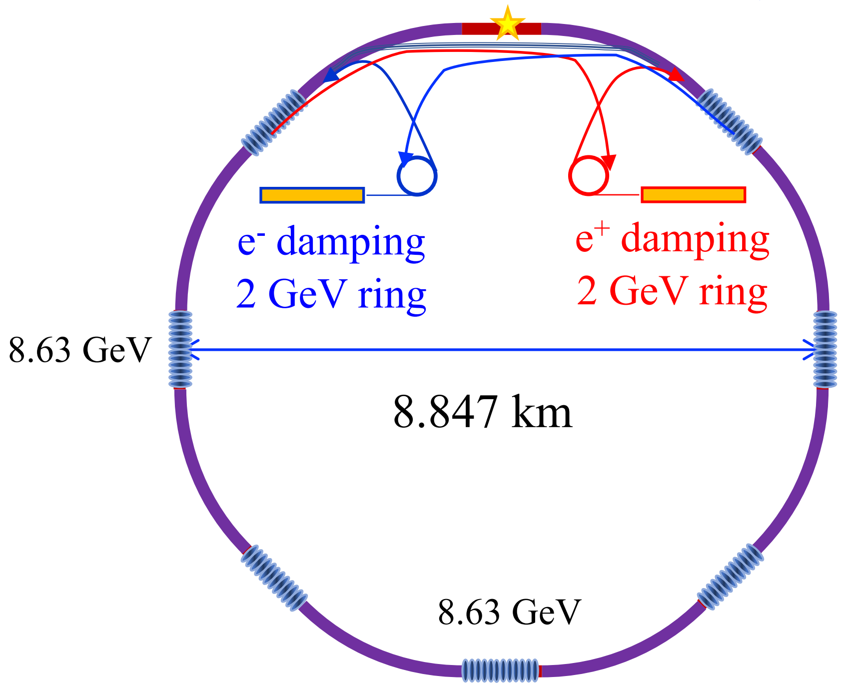
CERC recycles (polarized) electrons and positrons

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

Parameter table for CERC and ReLiC at two key energies

Collder	e+e-	CERC		ReLiC	
C.M. energy	GeV	240	600	240	3000
Length of accelerator	km	100	100	20	360
Section length	m	n/a	n/a	100	100
Bunches per train		1	1	10	21
Particles per bunch	1010	15.600	11.9	2	1
Collision frequency	MHz	0.099	0.009	3.7	12.6
Beam current	mA	2.5	0.17	12.0	20.2
εx, norm	mm mrad	3.9	7.8	4	4
εy, norm	µm mrad	7.8	7.8	1	1
βx	m	1.75	3	5	100
βy, matched	mm	0.29	1	0.34	20
σz	mm	3	10	1	50
Dx		0.3	0.3	0.01	0.01
Dy		544	492	43	32
Total luminosity	10^{34} cm^{-2}sec^{-1}	93	4.4	215	66

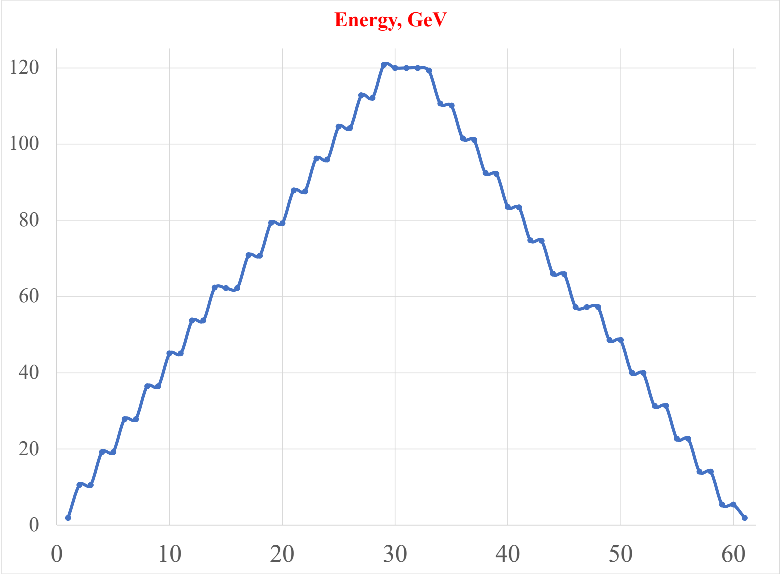
CERC in LHC tunnel at HZ (240 GeV c.m.) energy
Possible (not optimized) option of 2 pass ERL



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

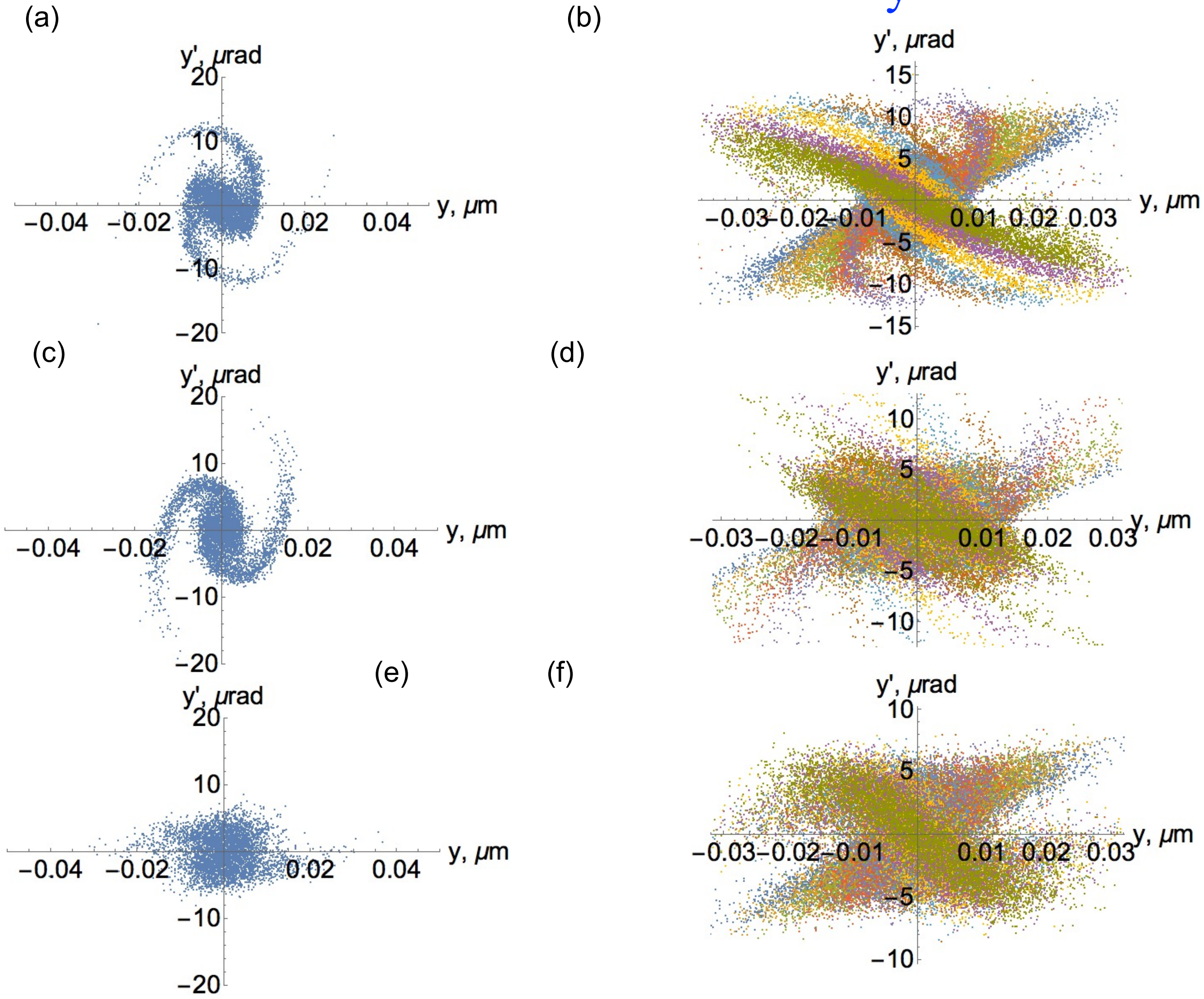
C.M. energy	GeV	240
Length of accelerator	km	26.659
Particles per bunch	10^{10}	15.6
Collision frequency	MHz	0.065
Beam current	mA	1.63
εx, norm	mm mrad	6
εy, norm	μm mrad	15
βx	m	1.75
βy, matched	mm	0.3
σ_z	mm	2
Disruption parameter, Dx		0.17
Disruption parameter, Dy		269
Luminosity	10^{34} cm^{-2}sec^{-1}	45

Beam energy evolution in 2-pass ERL



- Existing LHC tunnel has specific features which require splitting SRF linac in seven parts filling 545 meters of straight sections with seven 8.63 GeV SRF linacs
- Eight's section is available for detector(s), where beam passes only at top energy. Beams with intermediate energy by-pass the IR.
- Arc length 2.45 km and arcs can not be straightened without making ~ 7 to 8 km of new tunnel
- Two pass ERL requires SRF linac with 16 MV/m real estate acceleration gradient (80% FF for 20 MV/m in cavities). It is possible that 3-pass is a better choice SRF linac wise, but it required 50% more beamlines
- Assumption about damping ring – keep beam for two damping times
- Luminosity is proportional to SR power –100 MW SR power loss corresponds to 1.5×10^{36} cm^{-2} sec^{-1}

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

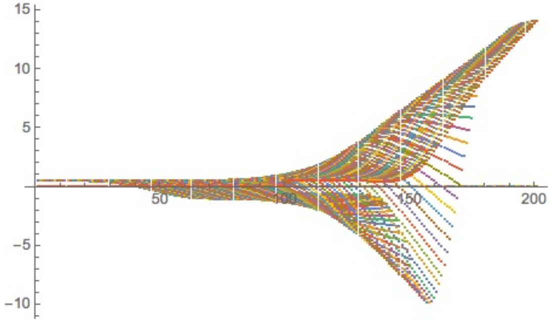


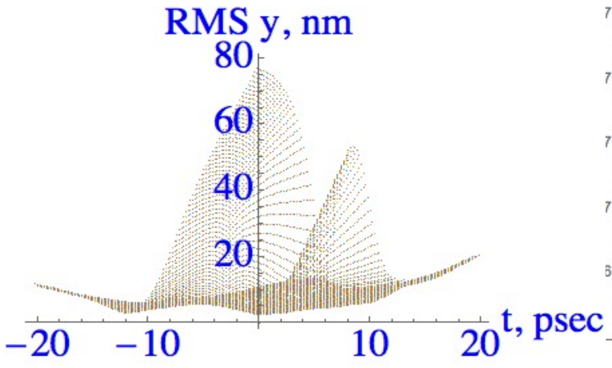
Beam distribution in the vertical phase space after the collision. Distributions of the central slice are on the left and combinations of 10 slices covering evenly $-3\sigma_z < z < 3\sigma_z$, are on the right: (a-b) are for center particles at x=0; (c-d) are for those at $x= \sigma_x$, (e-f) is for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

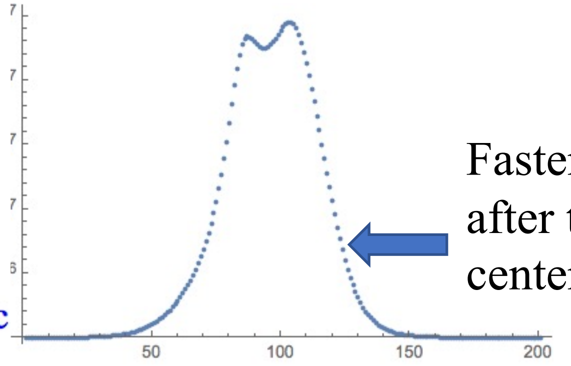
Initial beam axis separation is $\Delta y = 1\sigma_y$

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

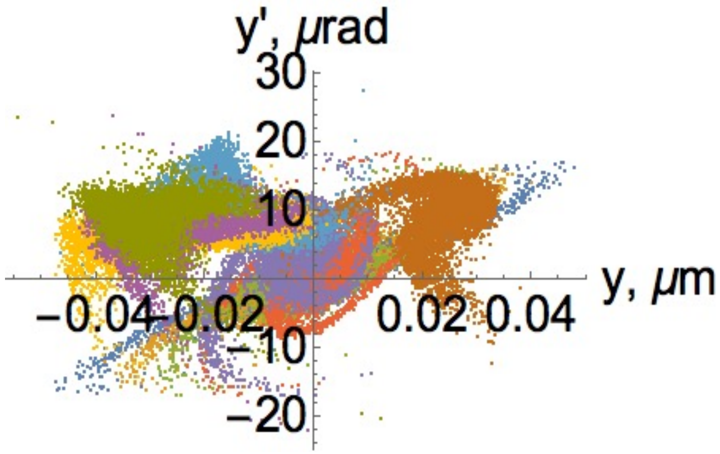


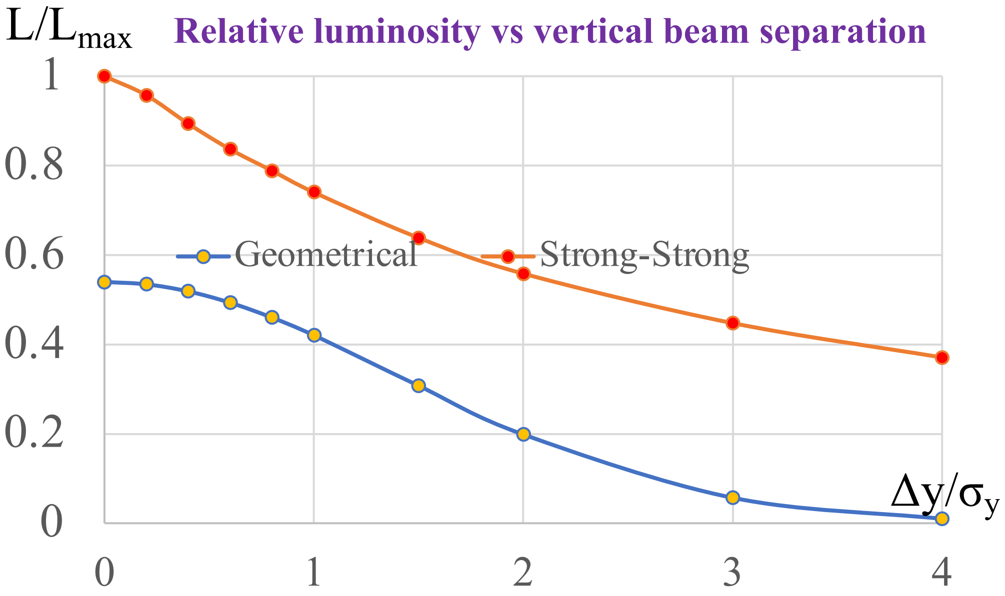


Instantaneous luminosity (a.u.)



Faster drop after the IP center



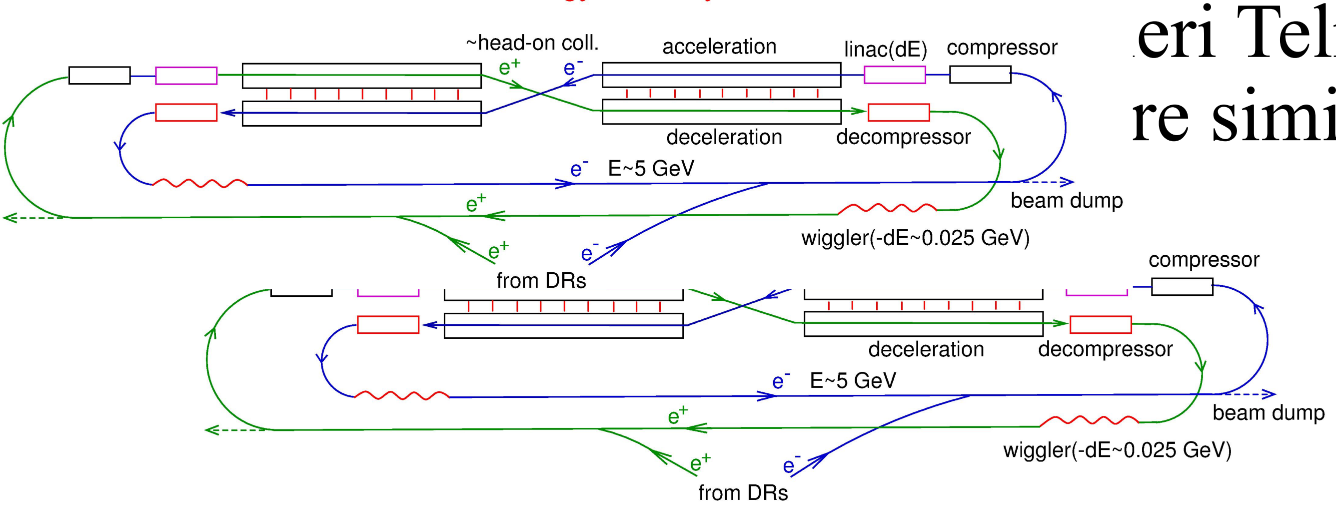


Main effect from offsets: RMS vertical beam emittance increases ~ 10X after collisions. It does not present any problems for the energy and particles recovery. It may require to increased time in the cooling rings to three-to-four damping times – this should be optimized for actual orbit deviations

Reduction of the luminosity is modest – actually the pinch effect continued delivering significant gain at all deviations of beam orbits eri Telnov (BINP, Novosibirsk)

re similar to ring-ring colliders

Twin LC with energy recovery



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

Note: Because of asymmetric nature of dual-axis structure, there is real potential for presence of transverse EM fields on the beam trajectory. This fields can result in significant synchrotron radiation and corresponding emittance growth. According to the experts in the field, this effect need further studies.

	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 $\mathcal{L}_{tot}$	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_{act}/L_{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
$(\sigma_E/E_0)_{BS}$ at IP	%	0.2	0.2	0.2	0.2

Recycling collided electrons and positrons

Advantages

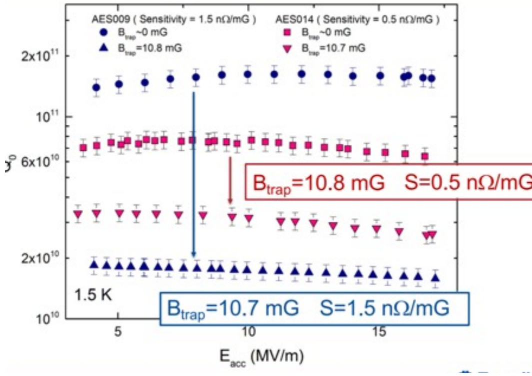
- Potential for high degree of polarization in colliding beams
- Possibility to operate with relatively high average currents and high polarization (*removing insane appetite for polarized positron in linear colliders*)
- Reduction of the power consumption
- Eliminating high power beam dumps and related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

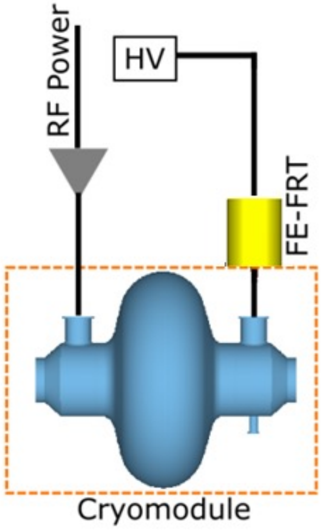
Challenges

- 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

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

In 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

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

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

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

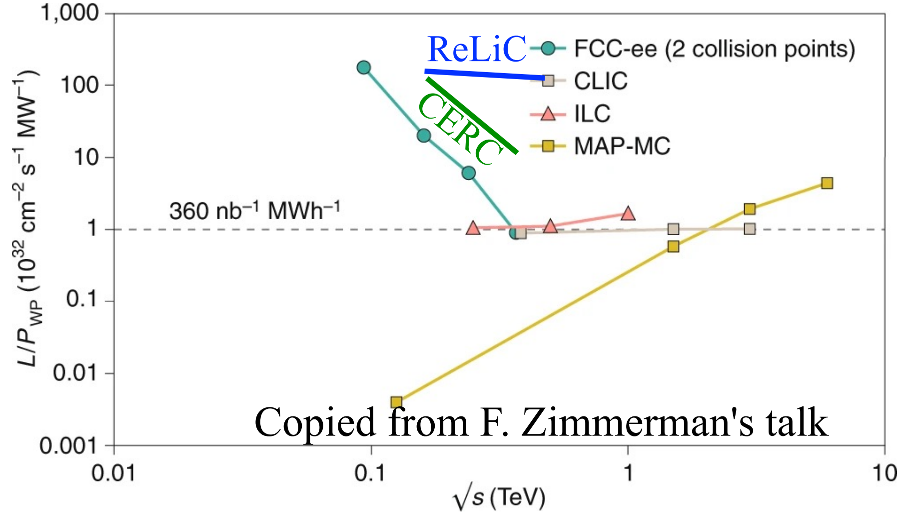
Collider	**ReLiC**	**ERLC**
I, Beam current, mA	12	45
L, Luminosicy, $cm^{-2} sec^{-1}$	2.15E+36	3.60E+35
L/I, cm-2 sec-1/mA	1.79E+35	8.00E+33
L/I^2, cm-2 sec-1/mA^2	1.49E+34	1.78E+32

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

Summary

- ERL-based colliders promise significant luminosity boost in collision of polarized e^+e^- beam
- c.m. energy of ReLiC can be extended into TeV range, while multi-pass CERC would reduces length of SRF linac but limiting c.m. energy to 600 GeV in f FCC tunnel, and to HZ energy in the LHC tunnel
- All ERL-based concepts could be very effecting for direct HIGS production $e^+e^- \rightarrow H$ at $\sqrt{s}$=125 GeV
- Both CERC and ReLiC schemes can be staged, starting from operating at $\sqrt{s}$=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) …
- But the most important investment should be in finding a way of improving efficiency of 2K LiHe refrigerators from 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 of breakthrough of the SRF accelerators, including ERL.

Collider efficiency : L/P

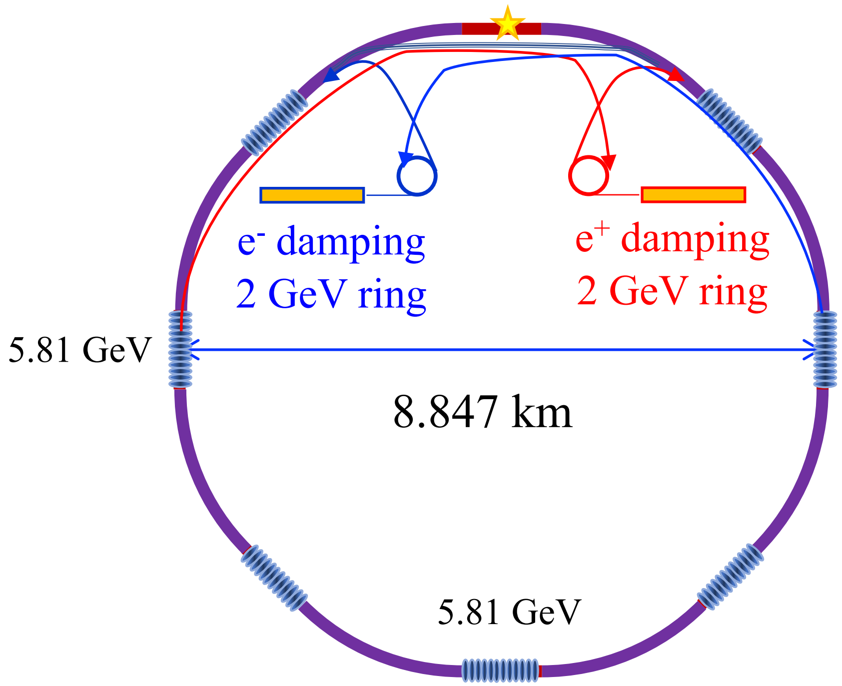


Copied from F. Zimmerman's talk

Thank you for your attention

Back-up slides

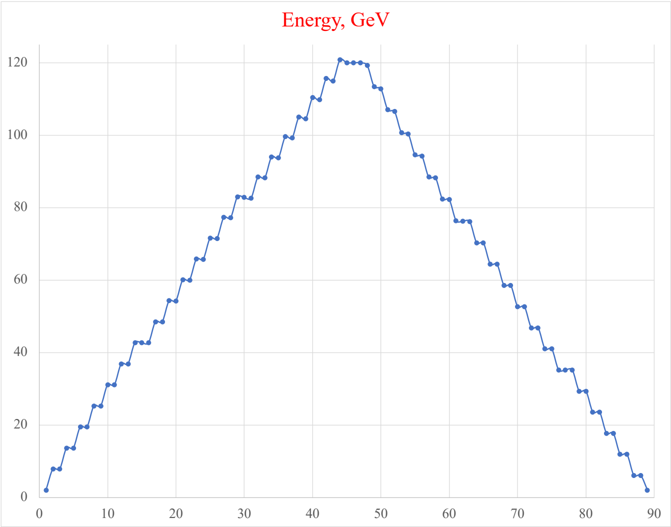
CERC in LHC tunnel at HZ (240 GeV c.m.) energy
3 pass ERL



Synchrotron radiation energy loss is 7.52 GeV. Total SR power is 30 MW

C.M. energy	GeV	240
Length of accelerator	km	26.659
Particles per bunch	10^{10}	15.6
Collision frequency	MHz	0.270
Beam current	mA	1.30
εx, norm	mm mrad	6
εy, norm	μm mrad	15
βx	m	1.75
βy, matched	mm	0.3
σ_z	mm	2
Disruption parameter, Dx		0.17
Disruption parameter, Dy		269
Luminosity	10^{34} cm^{-2}sec^{-1}	36

Beam energy evolution in 3-pass ERL



- Existing LHC tunnel has specific features which require splitting SRF linac in seven parts filling 545 meters of straight sections with seven 5.81 GeV SRF linacs (about 2/3 of the 2-pass system!)
- Eight's section is available for detector(s), where beam passes only at top energy. Beams with intermediate energy by-pass the IR.
- Arc length 2.45 km and arcs can not be straightened without making ~ 7 to 8 km of new tunnel
- Three pass ERL requires SRF linac with 10.7 MV/m real estate acceleration gradient, but it has more beam beamlines and slightly lower luminosity as compared with 2-pass ERL
- Assumption about damping ring – keep beam for two damping times
- Luminosity is proportional to SR power –100 MW SR power loss corresponds to 1.2×10^{36} cm^{-2} sec^{-1}

Twin Axis Cavity Proposals

Proceedings of ERL07, Daresbury, UK

DUAL-AXIS ENERGY-RECOVERY LINAC*

Chun-xi Wang†, John Noonan, John W. Lewellen‡
Argonne National Laboratory, Argonne, IL 60439, USA

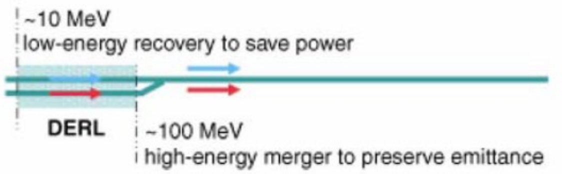
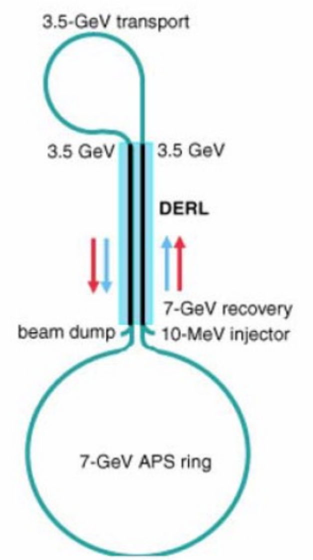
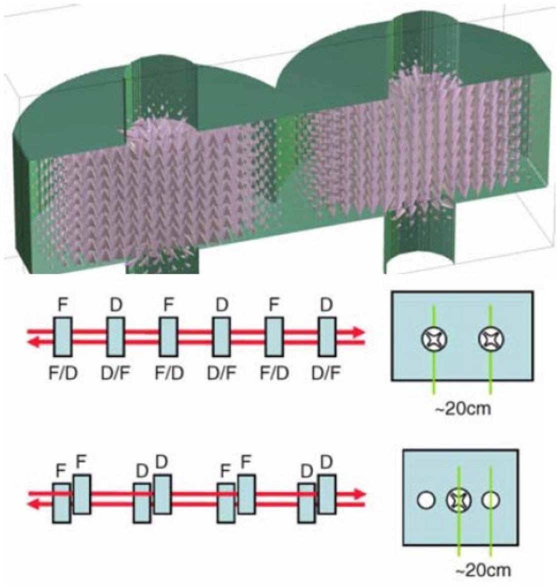


Fig. 2: DERL as a solution for beam merger. The red arrow indicates accelerating beam.





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

MULTI-BEAM ACCELERATING STRUCTURES

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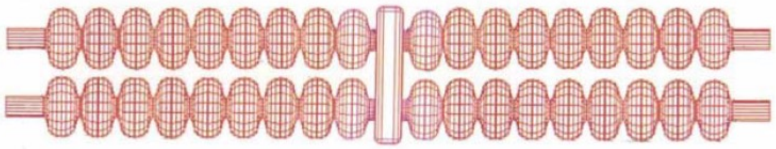

Proceedings of LINAC2016, East Lansing, MI, USA

DEVELOPMENT OF A SUPERCONDUCTING TWIN AXIS CAVITY*

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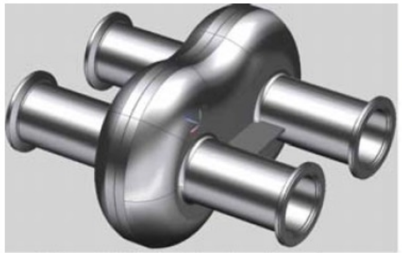

Figure 2: Single cell twin axis cavity.

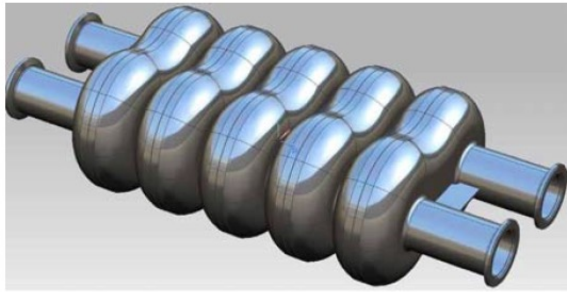

Figure 9: Multicell twin axis cavity.

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

ReLiC Main parameters

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

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

QED effects

$$\text{Classical} \Rightarrow \text{QED}$$

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

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

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

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

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

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 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

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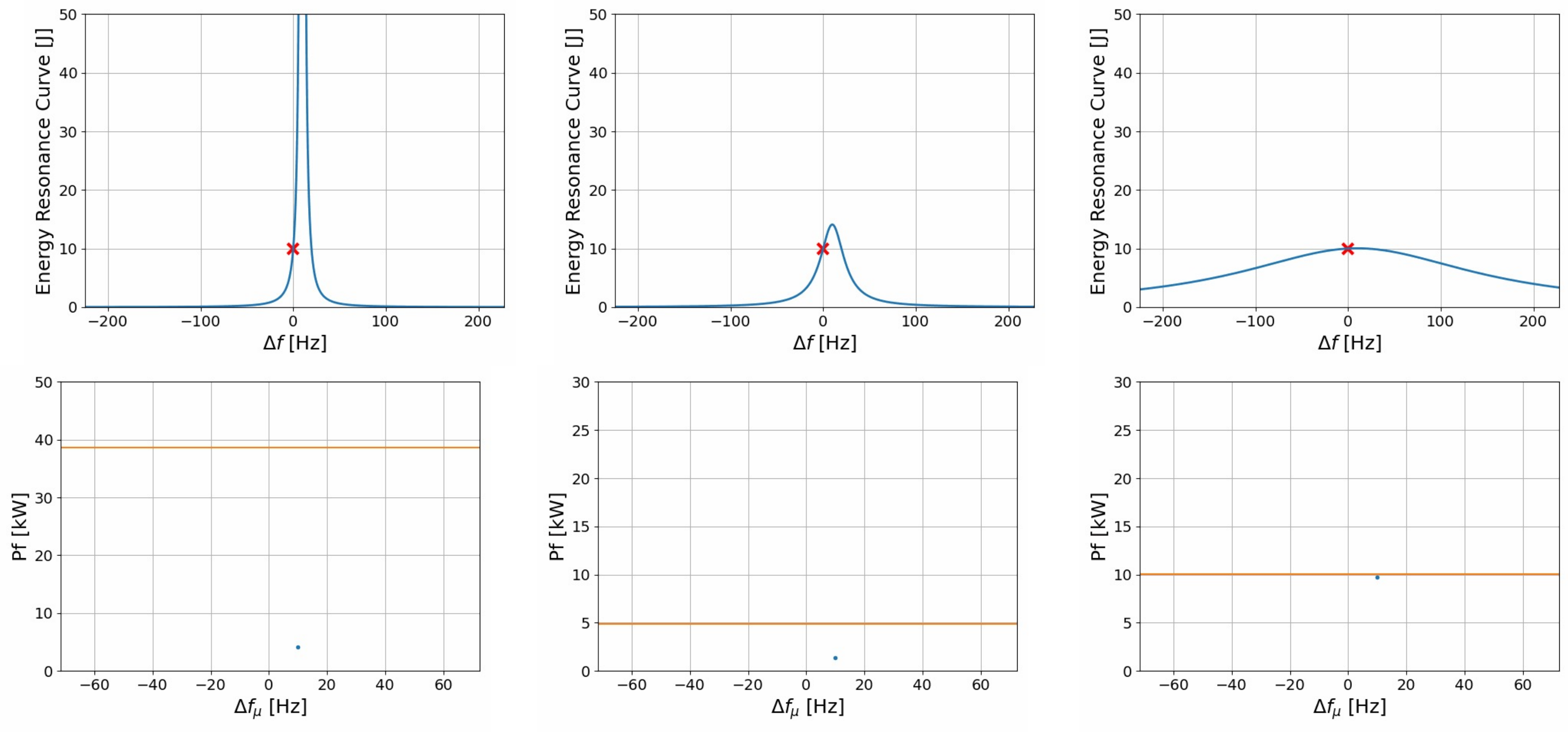
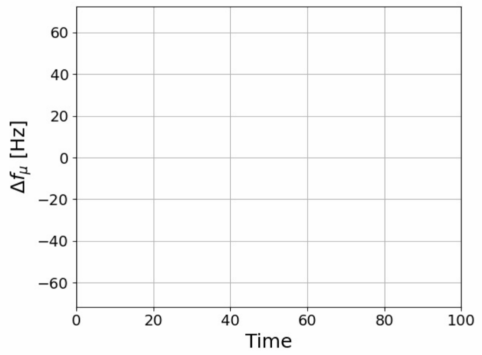
ERL power needs

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



Decreasing Q_L

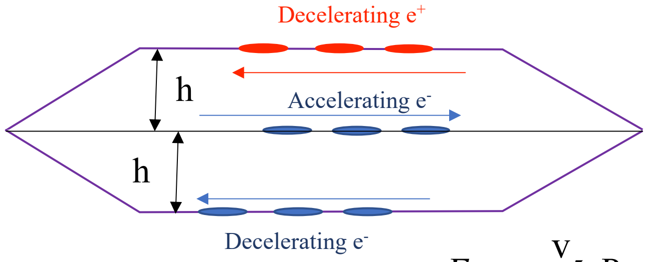
Microphonics vs Time



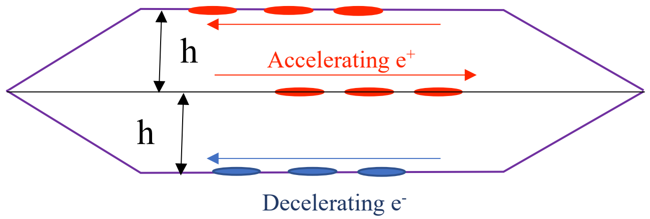
- ERL power needs often dominated by microphonics
- FE-FRTs can almost eliminate microphonics
- Huge power savings possible
  - Peak power FoM/2
  - Average power FoM/4
- **FoM >~75 @ 800MHz**

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



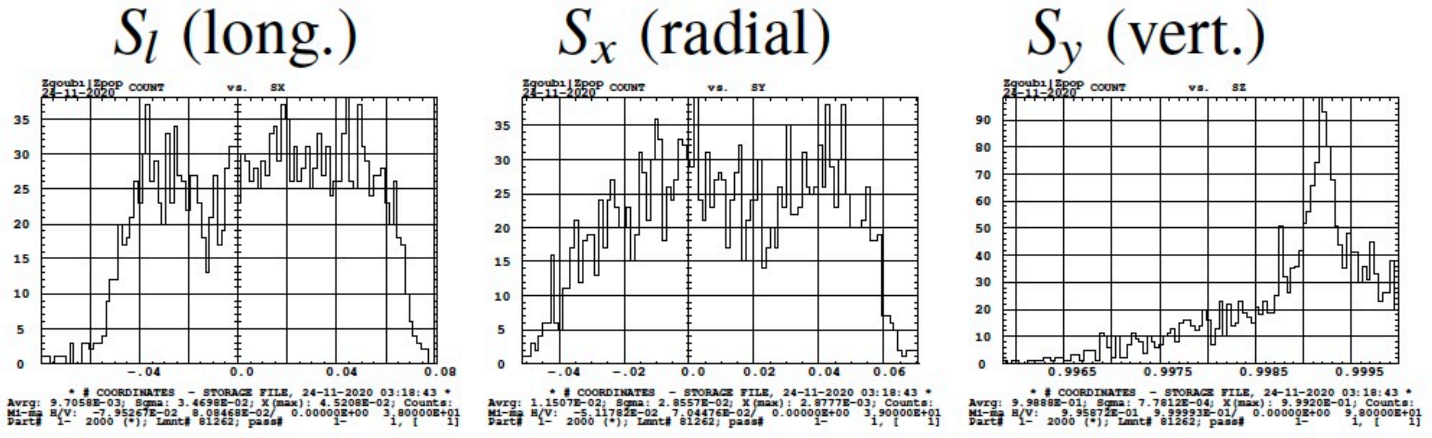
$$E_x = -\frac{v_z}{c} B_y$$



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

** 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*

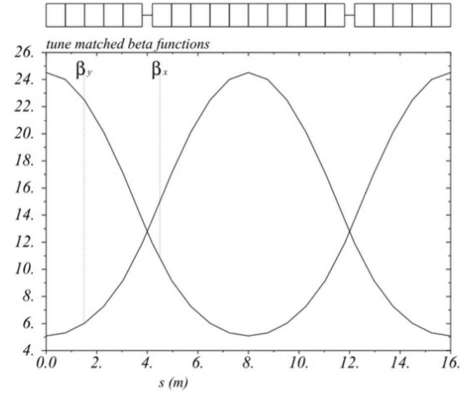
Preliminary simulation of spin dynamics



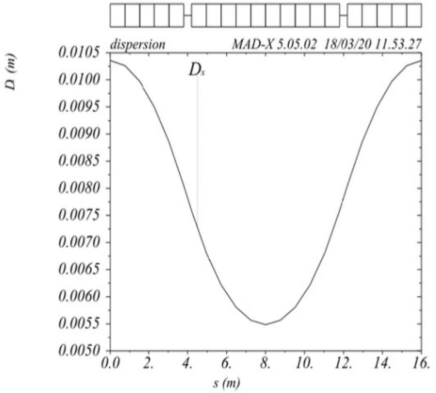
Density distribution of spin components in the 219 GeV e^+ and e^- beams after passing around the 100 km circular trajectory in the ERL-based collider

CERC lattice: in FCC tunnel

- 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)



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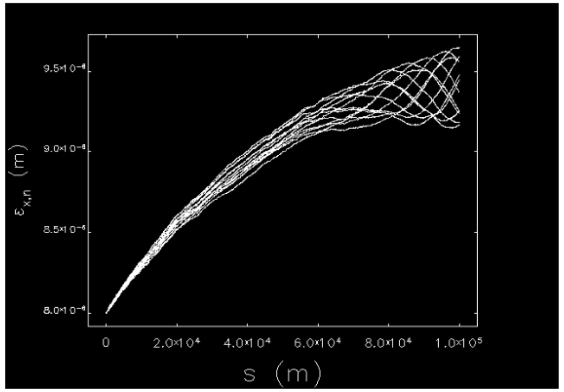
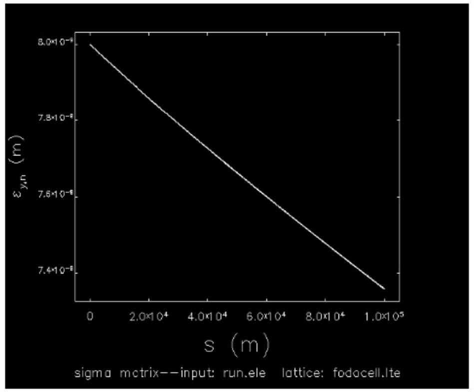


(c)



(d)

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Important consideration

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

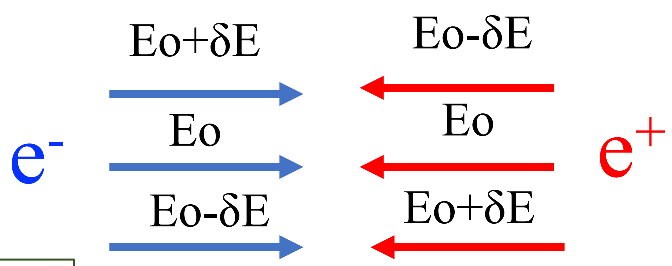
$$\langle \Delta\gamma \rangle = \frac{4}{9}\sqrt{\frac{\pi}{3}} N^2 \frac{r_e^3}{\sigma_x^2 \sigma_z} \gamma^2;$$

$$for \;\; \sigma_x >> \sigma_y$$

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 $\mathbf{D_{e+}=-D_{e-}}$ 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

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

- 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	1.6×10^{-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 - 2x10 ^{7} sec - 90 ab^{-1}

Direct HIGS production

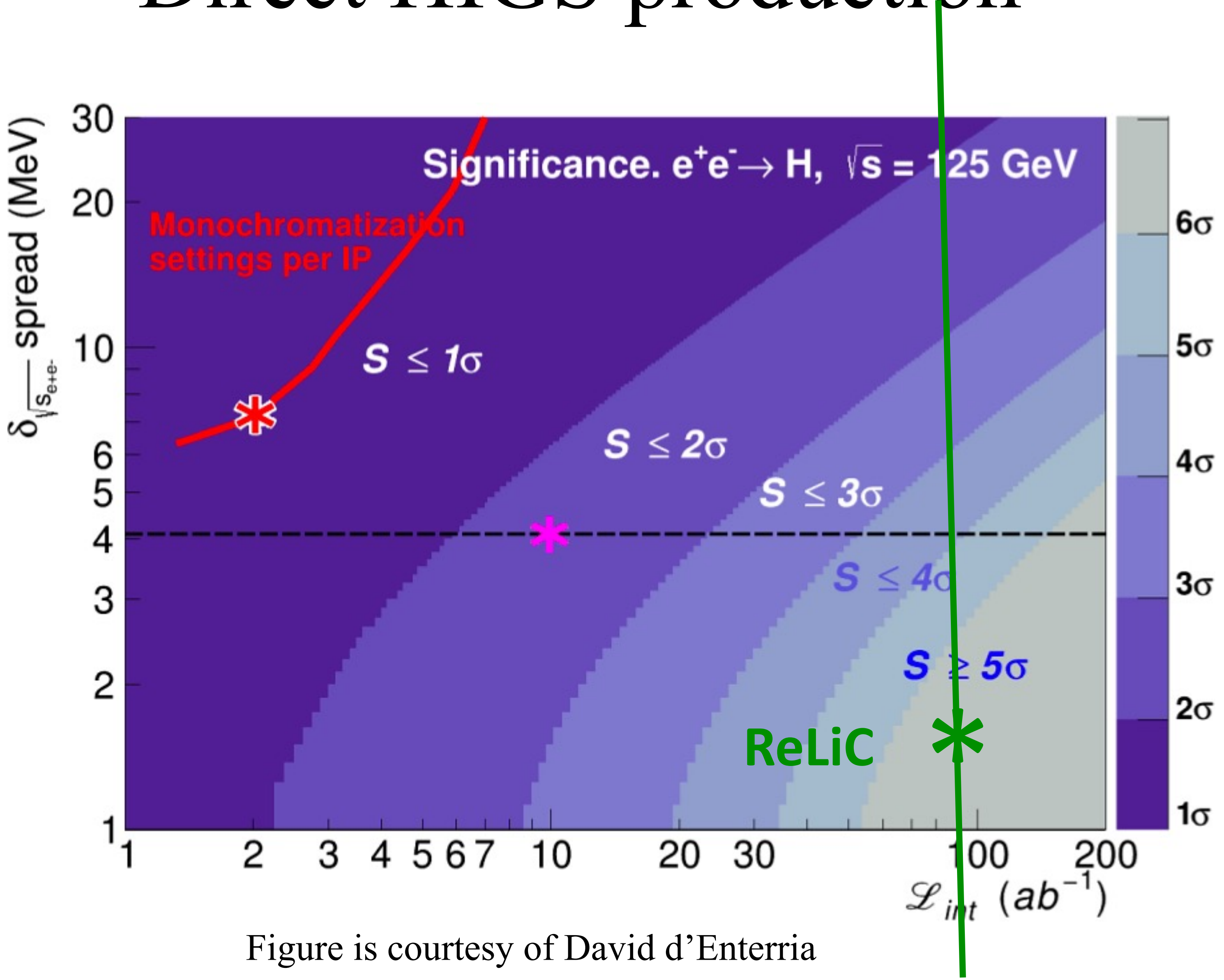


Figure is courtesy of David d'Enterria

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

Personal note (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 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