High Energy Recycling e^+e^- colliders

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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…
    - ❑ …..

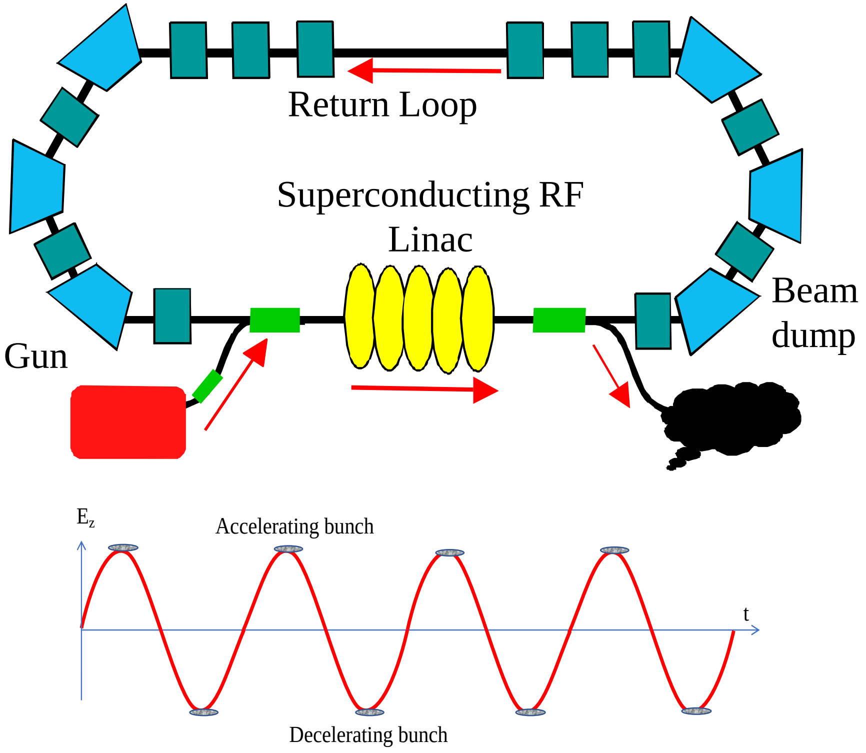
Stony Brook University

CASE Center for Accelerator Science and Education

Brookhaven National Laboratory

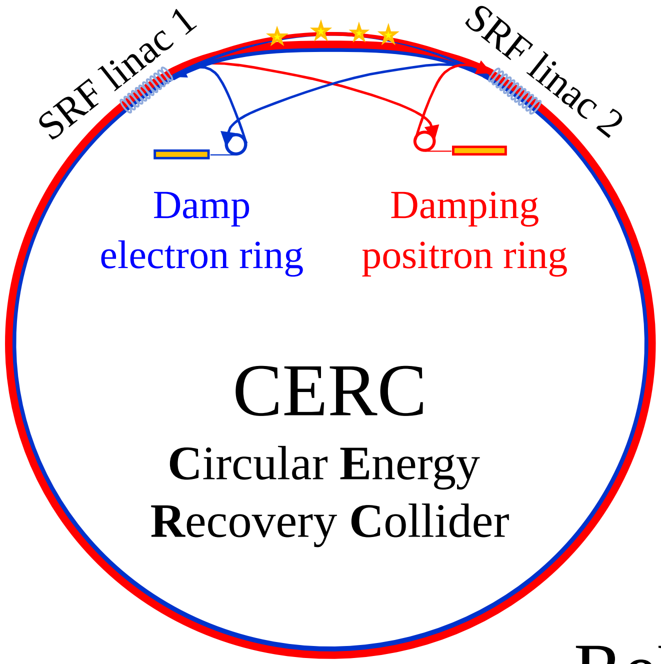
What is Energy Recovery Linacs (ERLs): Perpetua Mobile of Modern Accelerators

- 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 anf their potential is well understood and appreciated

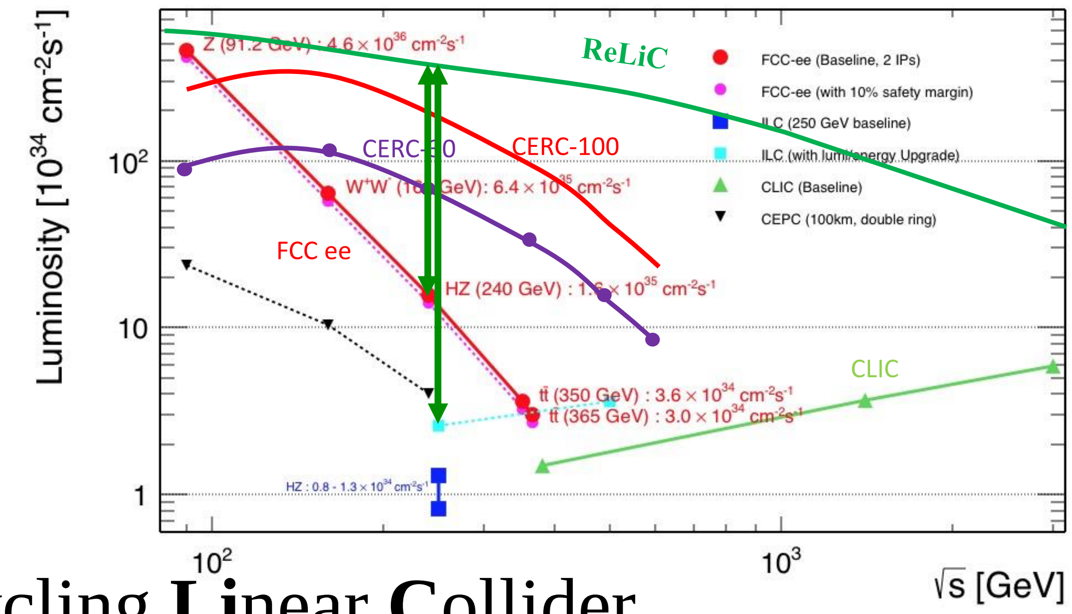


- ERLs are considered for multiple applications starting from e^+e^- and lepton-hadron (LHeC, FCC eh…) colliders, coolers for hadron beams (EIC), diffraction-limited light sources, X-ray FEL-divers, γ-ray sources, isotope production, EUV source for chip production, etc., etc.

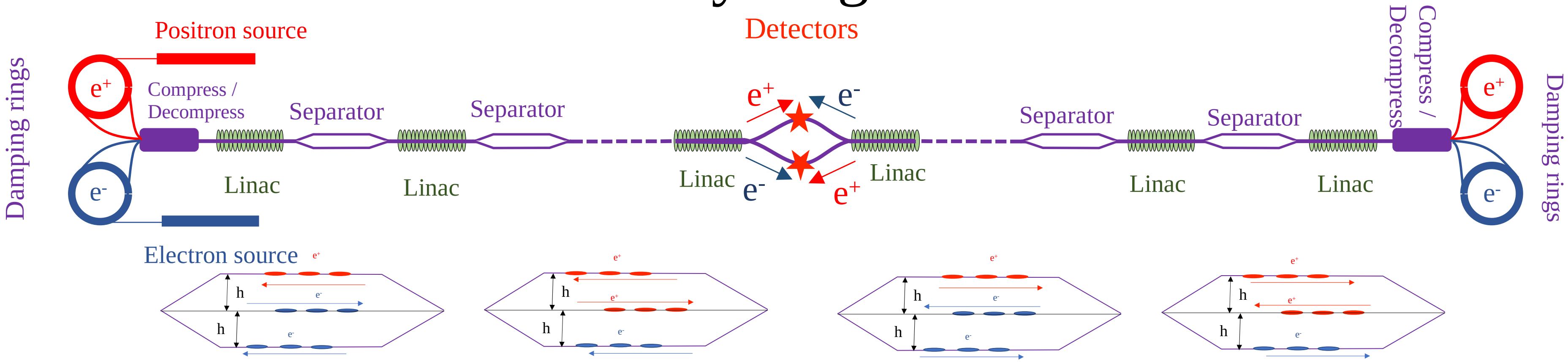
Adding particle recycling in damping storage rings makes ERL-based e^+e^- colliders into very efficient system



Gain of 40 to 200 at HIGS energy



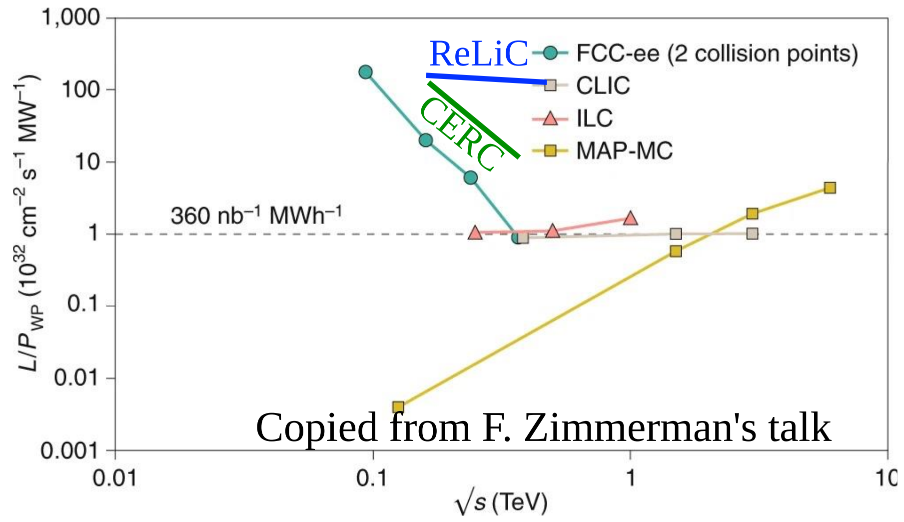
ReLiC: **Re**cycling **Li**near **C**ollider

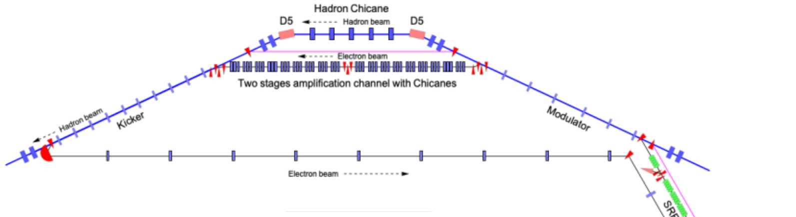


Short Summary

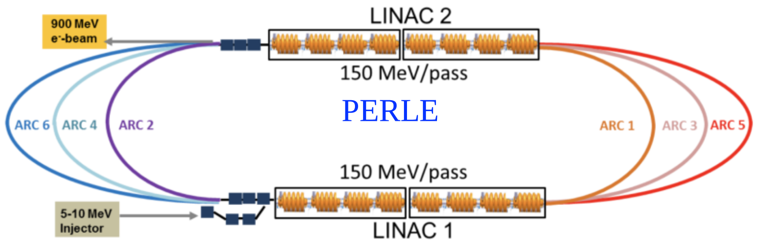
- ERL-based colliders promise significant luminosity boost in collision of polarized e^+e^- beam
- c.m. energy of ReLiC can be extended into TeV range, while multi-pass CERC would reduces length of SRF linac but limiting c.m. energy to 600 GeV in f FCC tunnel, and to HZ energy in the LHC tunnel
- Both CERC and ReLiC schemes can be staged, starting from operating 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





150 MeV ERL for EIC coherent electron cooler of 275 GeV proton beam



Thank you for your attention

Back-up slides

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

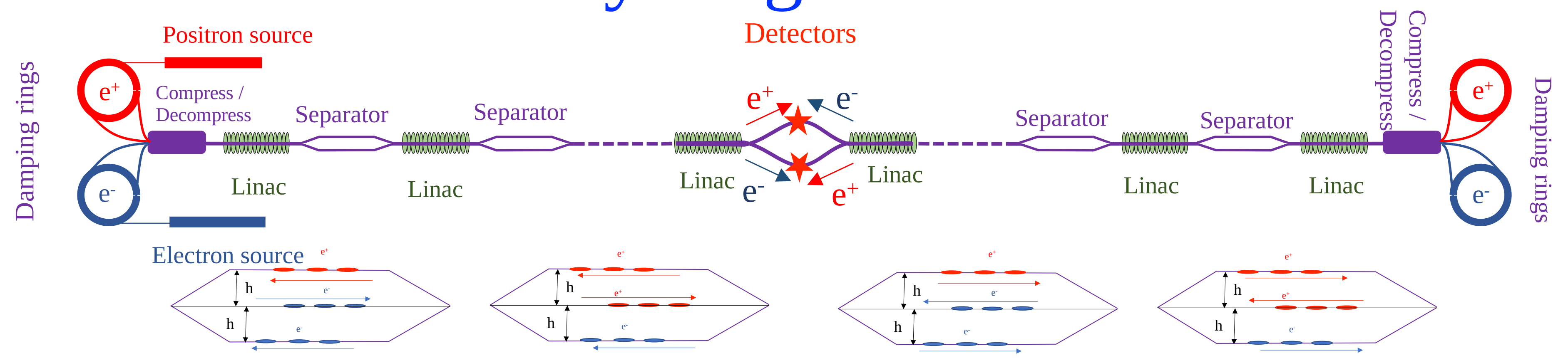
Impact of polarization

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

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

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

ReLiC – Recycling Linear Collider



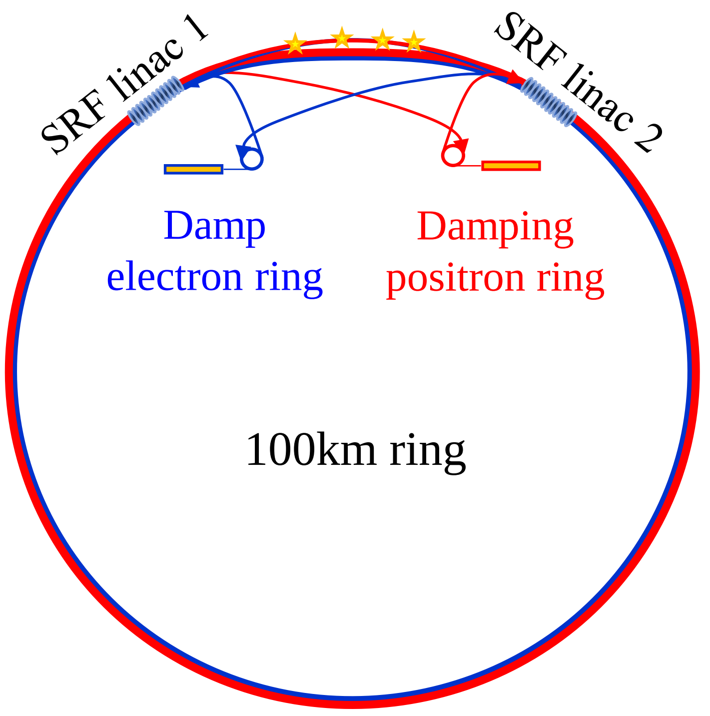
- Flat beams cooled in damping rings with “top off” to replace burned-off particles
- Bunches are ejected with collision frequency, determined by the distance between beam separators
- Beams are accelerated **on-axis** in SRF linacs collide in one of detectors
- After collision at the top energy, they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

Baseline design



- Flat beams cooled in damping rings with top off
- Bunches are ejected with collision frequency
- Beams accelerated with SRF linacs in two four-path ERLs
- After collision at top energy RF phases are changed to deceleration returning most energy to SRF linac
- Decelerated beams are reinjected into cooling rings
- After few damping times the trip repeats
- Luminosity is shared between detectors in any desirable ratio
- Only beams at top energy pass through detectors, the rest of beams bypass them

Combines advantages of existing colliders:

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

There is probably no significant advantage of multi-pass ERL for low energy operation and Low energy CERC can be build similar to ReLiC

CERC parameters

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

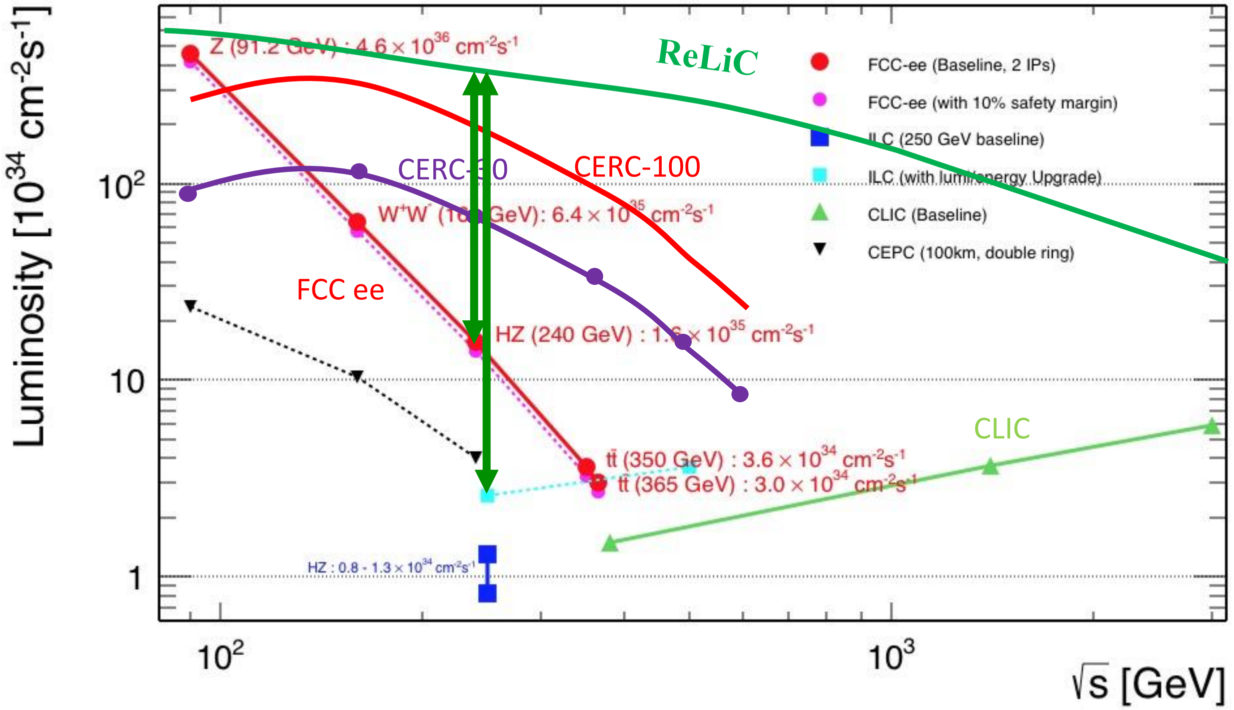
CERC	Z	W	H(HZ)	ttbar	HH	Httbar
Circumference, km	100	100	100	100	100	100
Beam energy, GeV	**45.6**	**80**	**120**	**182.5**	**250**	**300**
Hor. norm ε, μm rad	3.9	3.9	6.0	7.8	7.8	7.8
Vert. norm ε, nm rad	7.8	7.8	7.8	7.8	7.8	7.8
Bend magnet filling factor	0.9	0.9	0.9	0.9	0.9	0.9
βh, m	0.5	0.6	1.75	2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

ReLiC in HIGS sector

Main parameters

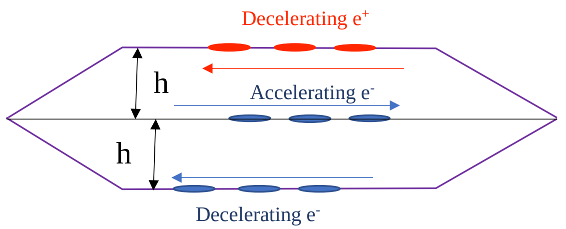
C.M. energy	GeV	240	365	500
		HZ	tt_bar	HHZ
Length of accelerator	km	20	30	41
Section length	m	250	250	250
Bunches per train		10	12	15
Particles per bunch	10^{10}	2.0	1.7	1.4
Collision frequency	MHz	12.0	14.4	18.0
Beam currents in linacs	mA	38	39	40
εx, norm	mm mrad	4.0	4.0	3.9
εy, norm	µm mrad	1.0	1.0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

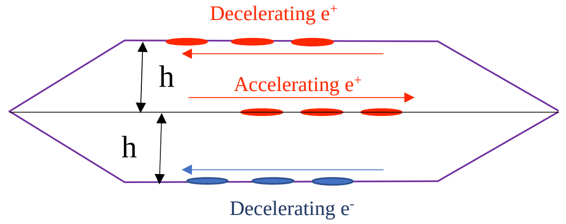
Gain of 40 to 200 at HIGS energy



Key technologies

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

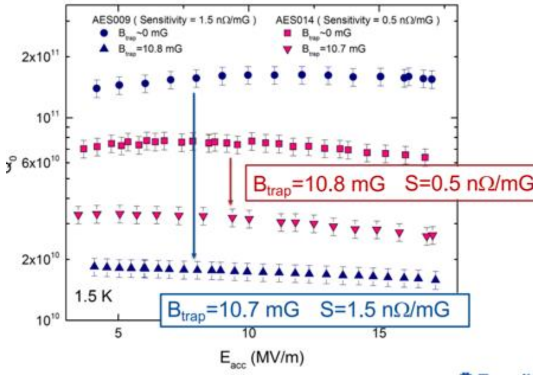


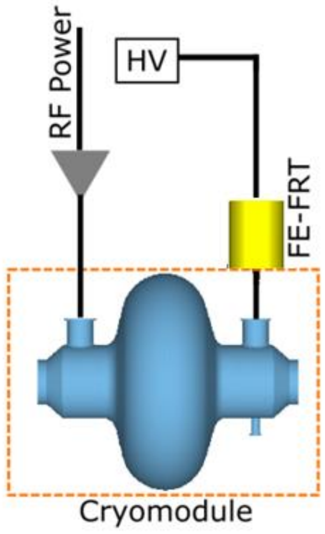


$$F_x = \pm e\left(E_x + \frac{v_z}{c}B_y\right) = \begin{cases} 0, acclerating \\ 2eE_x, decelerating\ postions \\ -2eE_x, decelerating\ electrons \end{cases}$$

Accelerator design and challenges

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





FoM ~75

Sustainability and Carbon footprint studies

- 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

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

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

- But the cryoplant power is proportional to the total collider energy. It can be further reduced by improving LiHe refrigerators from their current 19% ($1/5^{th}$) 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)**

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

Proposals for upgrades and extensions

Luminosity upgrades

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

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

Energy extension and upgrades until 1 TeV

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

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

$$Classical \Rightarrow QED$$

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

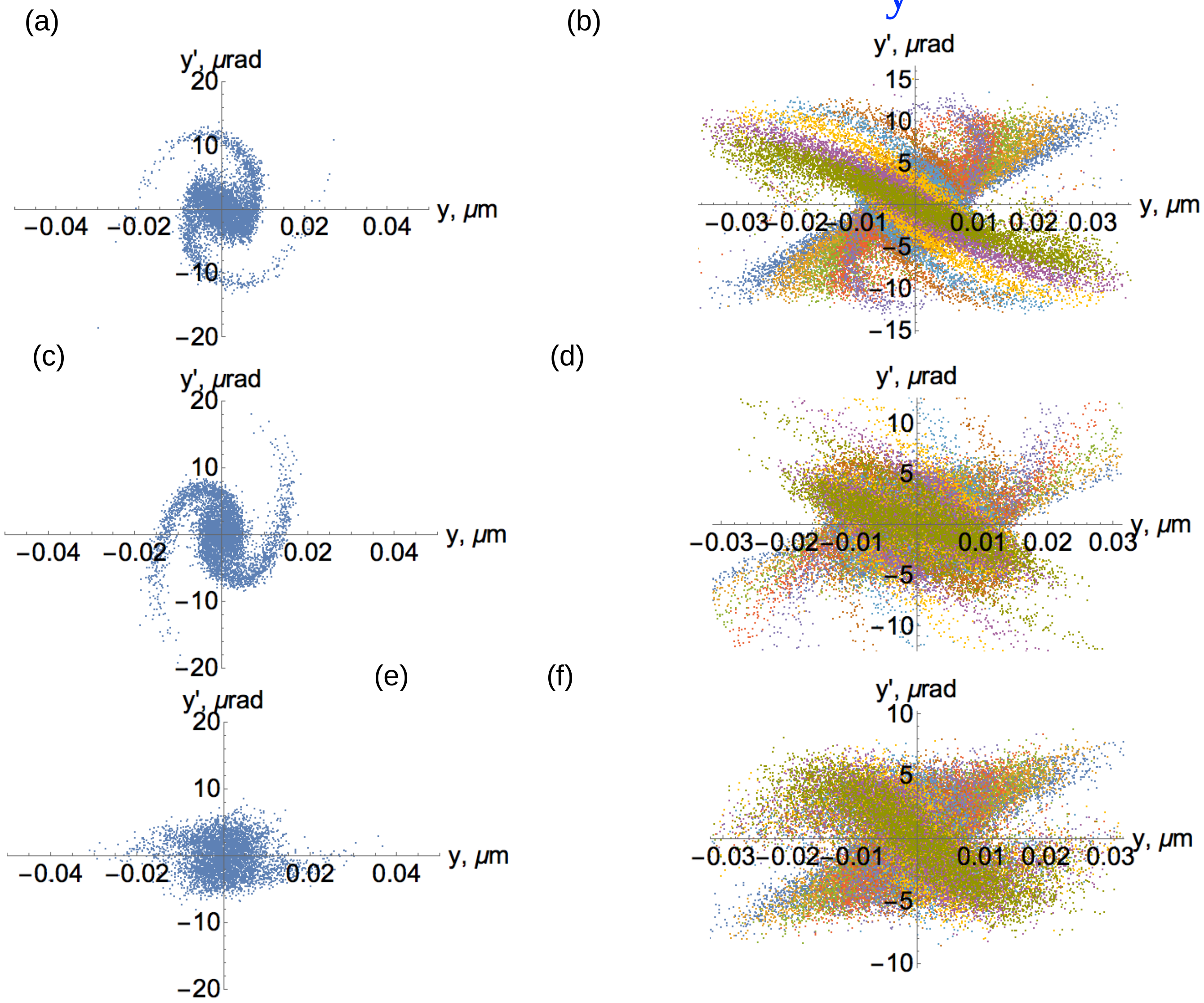
$$\langle\Upsilon\rangle \approx \frac{5}{6}\gamma N \frac{\lambda_c r_e}{(\sigma_x+\sigma_y)\sigma_z} \; (copied...) \approx \gamma N \frac{\lambda_c r_e}{\sigma_x \sigma_z} \Rightarrow \langle\Upsilon\rangle \approx \frac{5}{6}\gamma N \frac{\lambda_c r_e}{(\sigma_x+\sigma_y)\sigma_z}$$

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

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

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

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

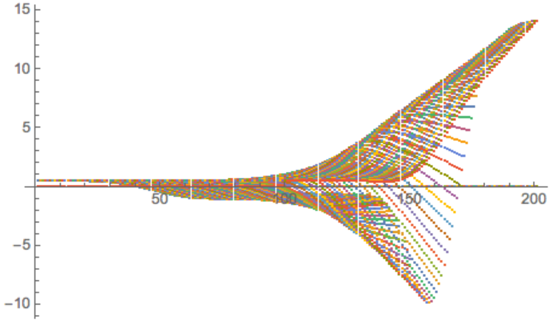


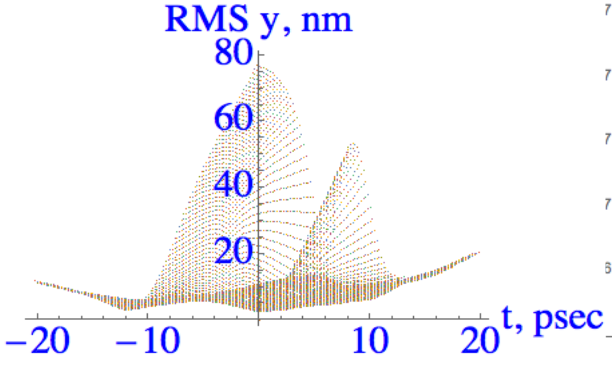
Beam distribution in the vertical phase space after the collision. Distributions of the central slice are on the left and combinations of 10 slices covering evenly $-3\sigma_z < z < 3\sigma_z$, are on the right: (a-b) are for center particles at x=0; (c-d) are for those at $x= \sigma_x$, (e-f) is for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

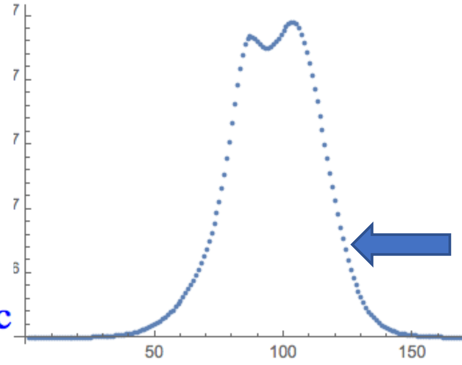
Initial beam axis separation is $\Delta y = 1\sigma_y$

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

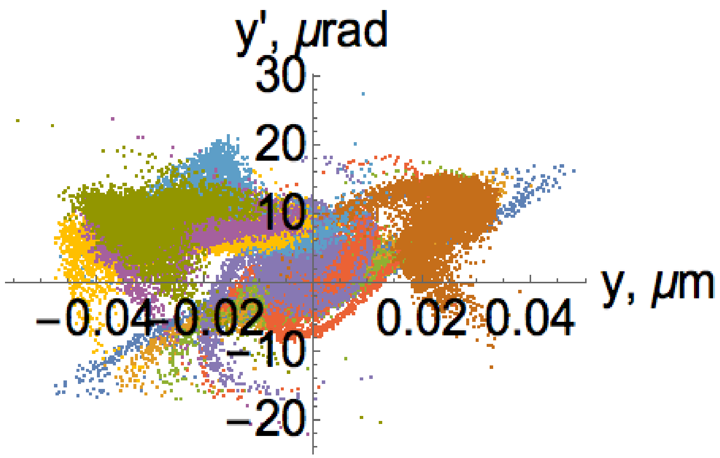


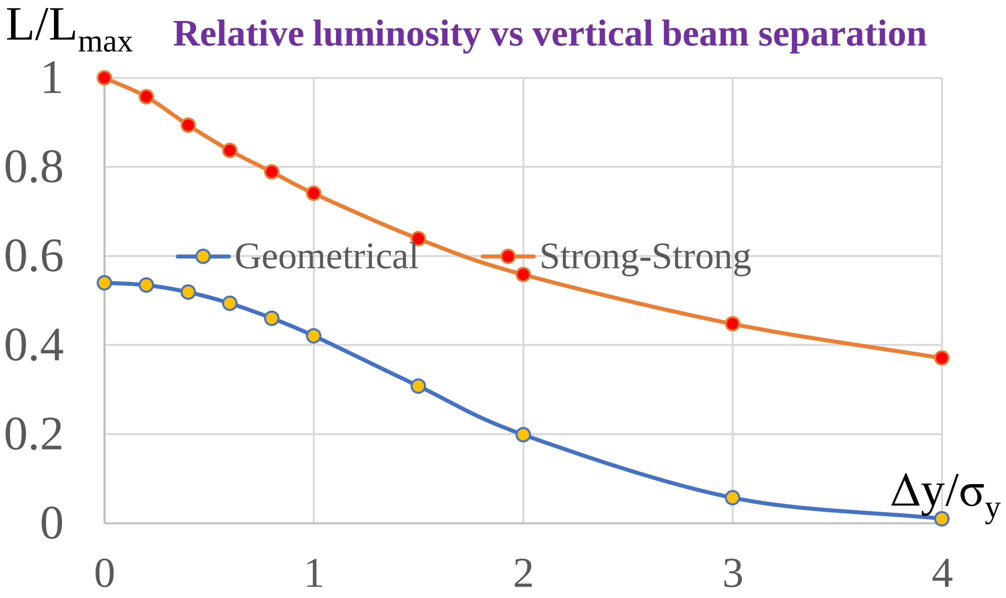


Instantaneous luminosity (a.u.)



Faster drop after the IP center



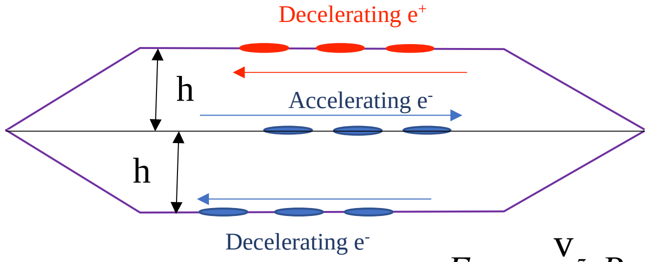


Main effect from offsets: RMS vertical beam emittance increases ~ 10X after collisions. It does not present any problems for the energy and particles recovery. It may require to increased time in the cooling rings to three-to-four damping times – this should be optimized for actual orbit deviations

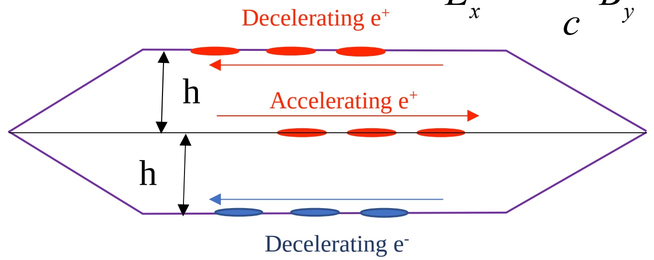
Reduction of the luminosity is modest – actually the pinch effect continued delivering significant gain at all deviations of beam orbits

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*

Important consideration

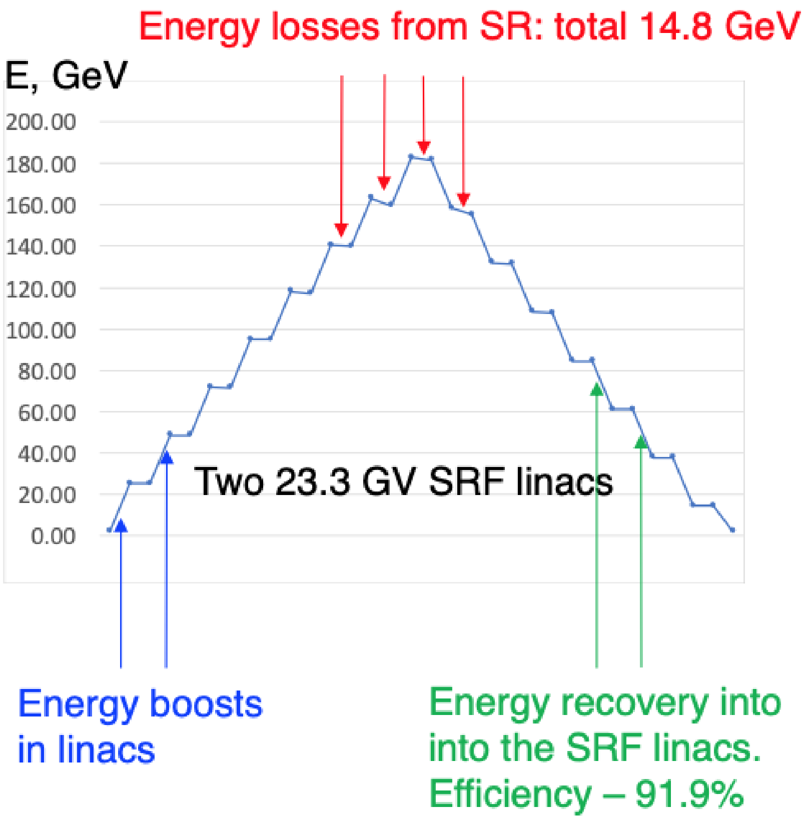
- At high energies the most dangerous effect is beamstrahlung: synchrotron radiation in strong EM field of opposing beam during collision
- It can cause significant amount of energy loss, induce large energy spread and loss of the particles
- Using very flat beams is the main way of mitigating this effect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

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

$$\textit{for}\ \ \sigma_x >> \sigma_y$$

CERC beam energy evolution in 4-pass ERL

E_{beam}= 182.5 GeV



E_{beam}= 250 GeV