Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

CERC
Circular Energy Recovery Collider

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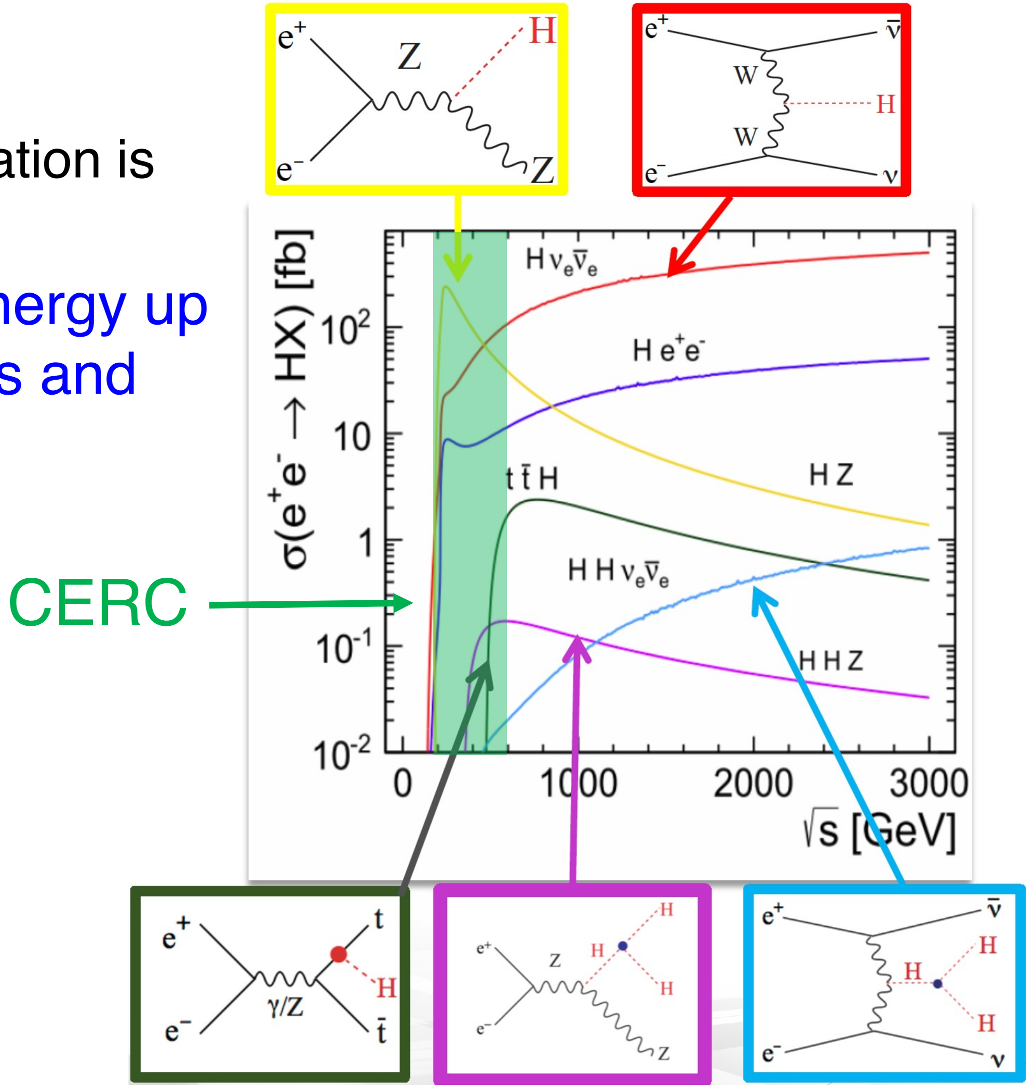
Electron-positron ERL Review Committee

June 16, 2021

Physics Motivation

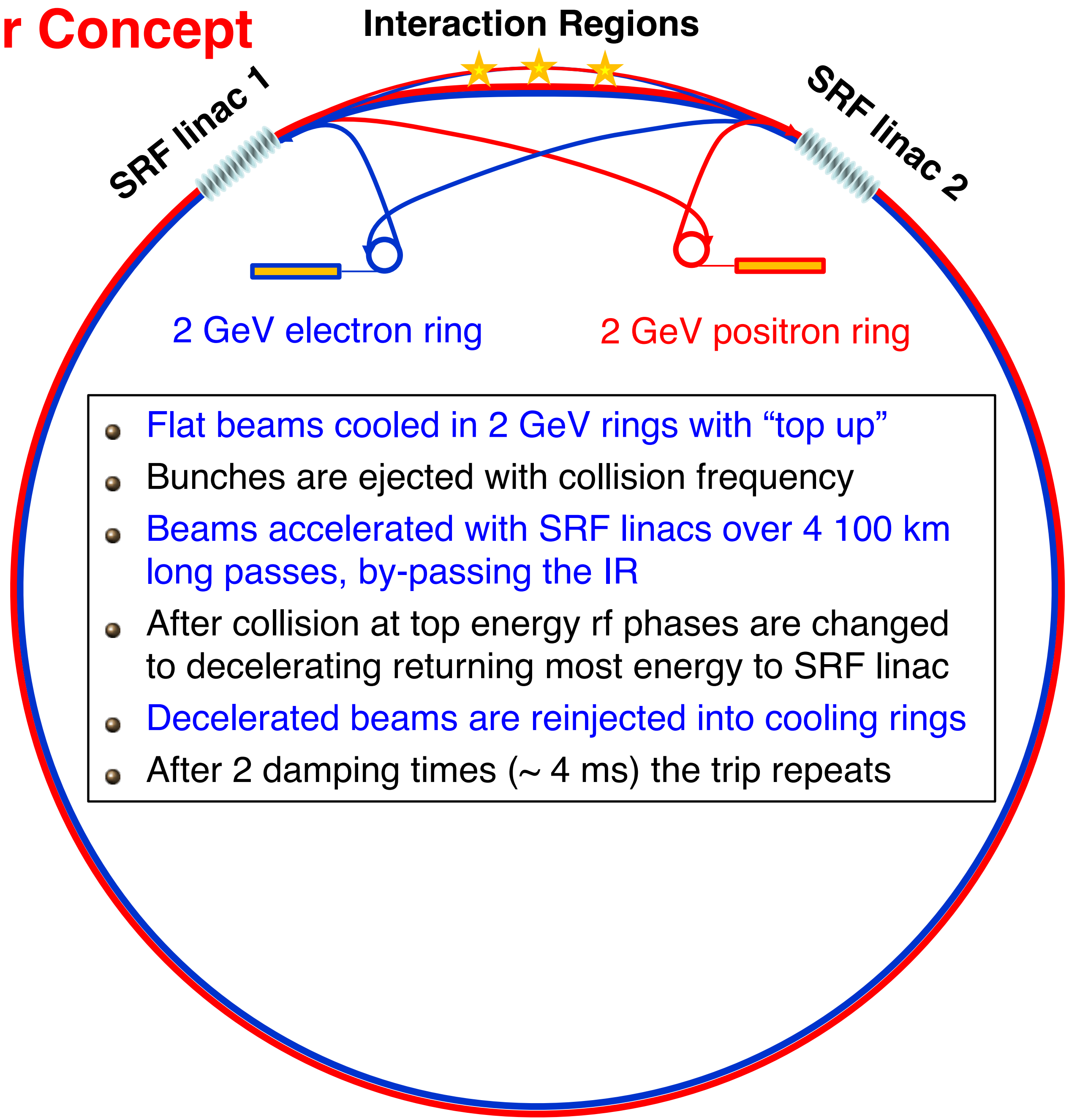
- Precision measurements
- Search for deviations from SM
  - Need high luminosity and high energy, beam polarization is also very useful
- CERC would provide high luminosity and high-energy up to CM energy of 600 GeV to enable double-Higgs and ttbarH production

√s, GeV	Science Drivers
90-200	EW precision physics, Z, WW
240	**Single Higgs physics (HZ), $H\nu\nu$**
365	ttbar
500-600	**HHZ, $Ht\bar{t}$, direct access to H self-coupling, top Yukawa couplings**
1000-3000	$HH\nu\nu$, H self couplings



Circular Energy Recovery Collider Concept

- New collider concept using existing accelerator technologies
- Combines advantages of existing collider concepts:
  - Storage ring collider: Recycling of beam energy and particles
  - Linear collider: efficient collisions (collisions per beam particles) using a large disruption parameter

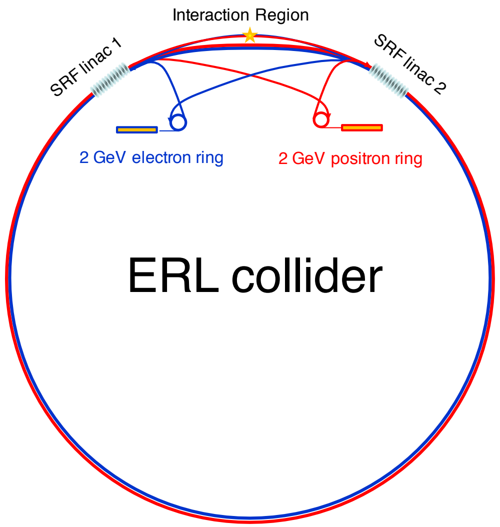


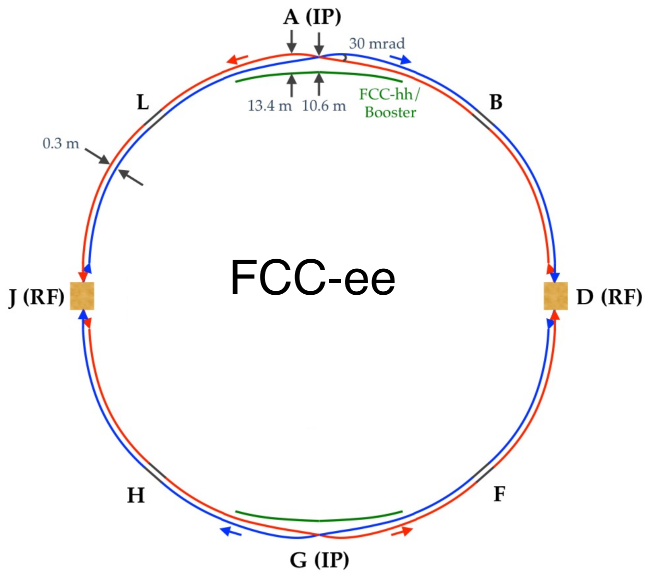
- Flat beams cooled in 2 GeV rings with “top up”
- Bunches are ejected with collision frequency
- Beams accelerated with SRF linacs over 4 100 km long passes, by-passing the IR
- After collision at top energy rf phases are changed to decelerating returning most energy to SRF linac
- Decelerated beams are reinjected into cooling rings
- After 2 damping times (~ 4 ms) the trip repeats

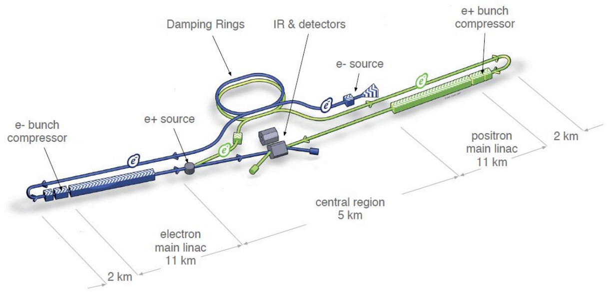
“High-energy high-luminosity e^+e^- collider using energy-recovery linacs”
V.N. Litvinenko, T. Roser, M. Chamizo-Llatas
Physics Letters B 804 (2020) 13594

Why is the power consumption of CERC lower?

- In CERC beam bunches collide only once (like in a linear collider). This allows much larger disruption of the bunches by the beam-beam interaction and therefore much more luminosity for a given bunch intensity. This is a more efficient use of the beam particles.
- This allows to either lower the beam current (and synchrotron radiation power) for the same luminosity or increase the luminosity for same current or some of both.
- A linear collider can make the same efficient use of the beam particles, but the beam is dumped after use and all the beam energy is lost.
- In CERC all the beam energy is recovered during deceleration except for the radiated synchrotron light. It can be much more energy efficient than a linear collider for a large enough circumference, about 100 km for 250 - 300 GeV beam energy.





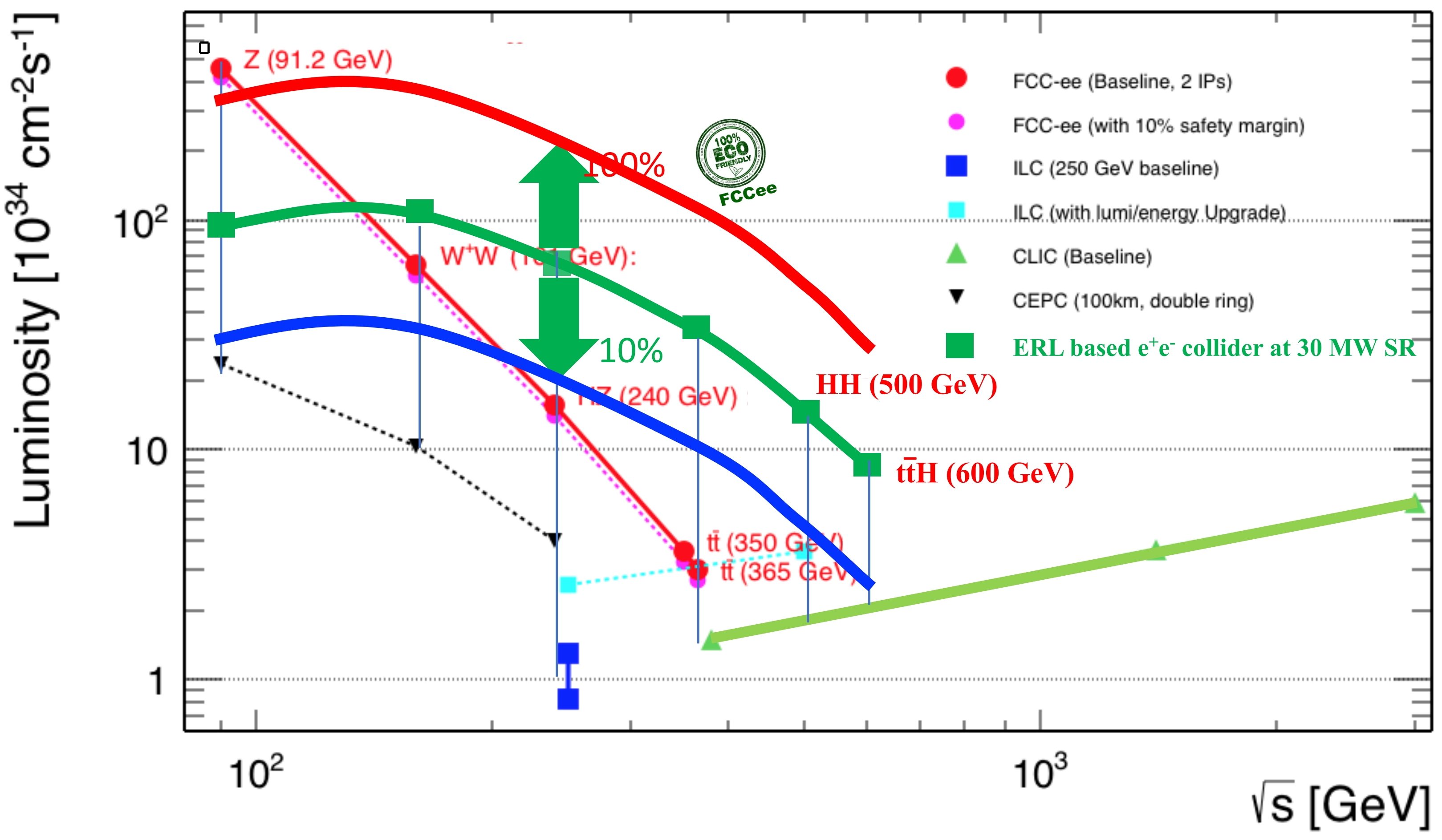


ILC (Japan)

same scale

CERC Luminosity vs Energy

- **CERC luminosity for 30 MW total synchrotron radiation power is shown in green**; luminosity scales linear with SR power
- Luminosity can be shared (split) by multiple detectors by alternating beam collision point
- Potential of increasing total luminosity further with smaller beta*; requires detailed simulations



Approximated RF power required for the same luminosity

Parameter	Storage ring	CERC	ILC	CLIC
Beam energy, GeV	182.5	182.5	250	190
Beam current, mA	5.400	1.010	0.021	0.015
Luminosity, 10^{34} cm^{-2} s^{-1}	1.5	31.4	1.8	1.5
Total power loss, MW	100.0	30.0	10.4	5.6
Total power loss for the same luminosity as CERC MW	**2093**	**30.0**	**181.4**	**117.2**

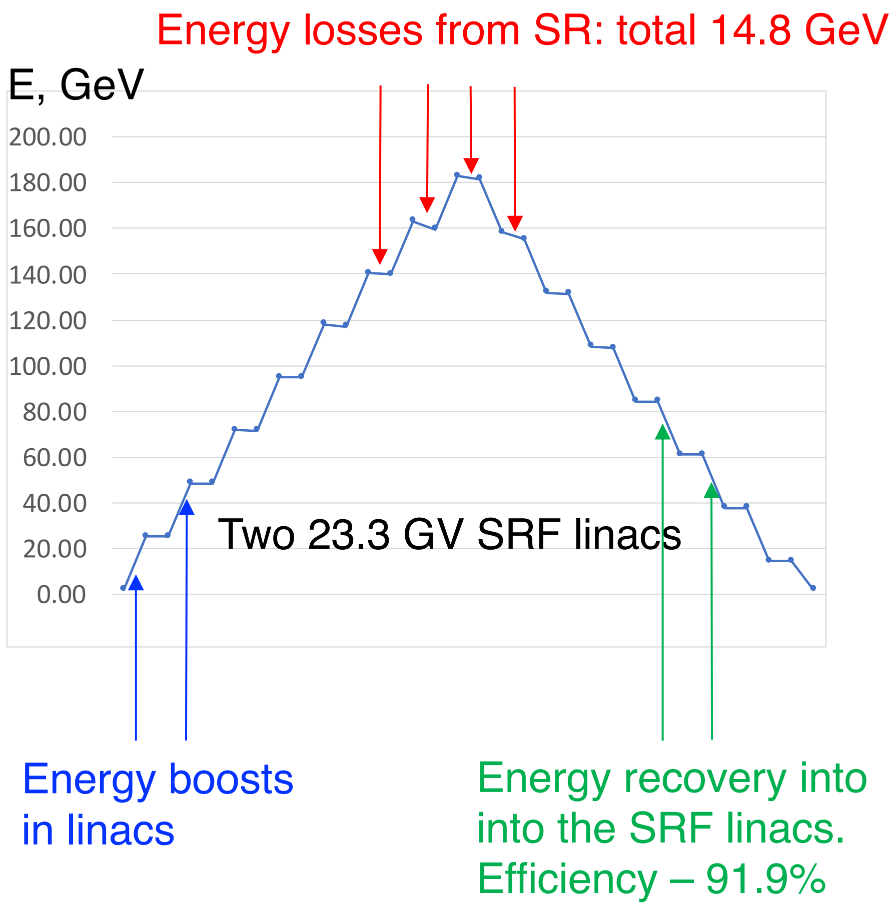
CERC parameters

Table 2
Main parameters of a possible ERL-based electron-positron collider with total synchrotron radiation power of 30 MW.

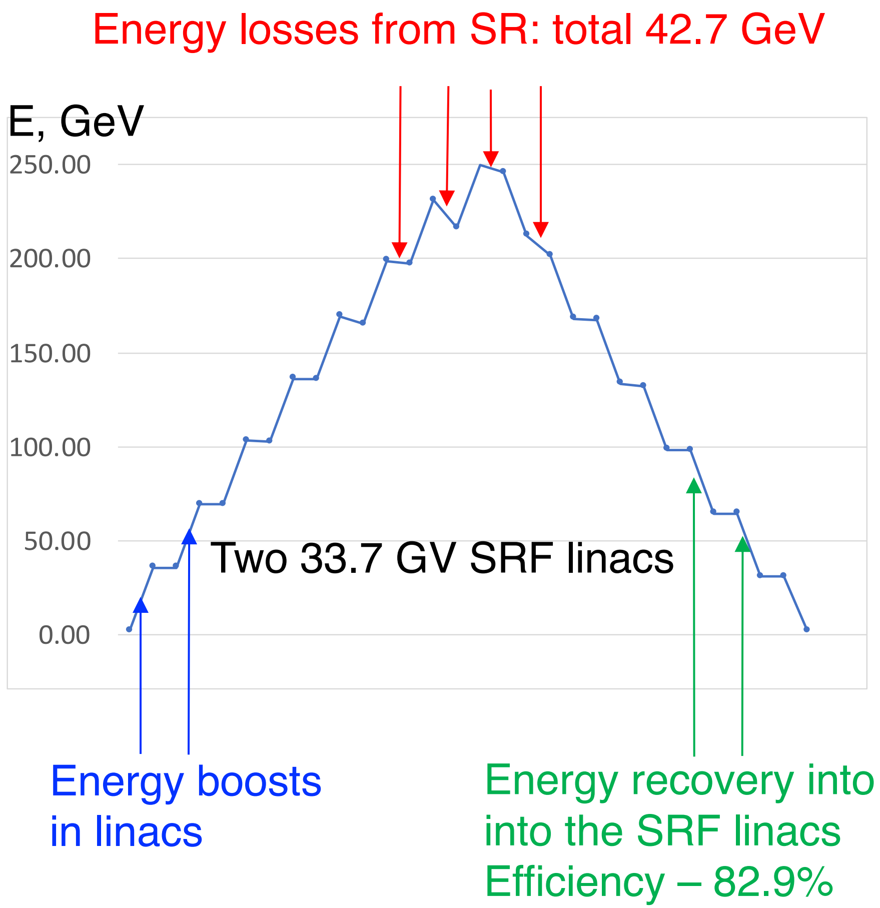
Mode of operation	Z	W	HZ	$t\bar{t}$	HHZ	$Ht\bar{t}$
Beam energy, GeV	45.6	80.0	120.0	182.5	250.0	300
Normalized emittance $\varepsilon_x/\varepsilon_y$, µm rad	4/0.008	4/0.008	6/0.008	8/0.008	8/0.008	8/0.008
RMS bunch length, mm	0.8	1.0	1.0	2.0	2.0	2.0
Bunch charge, nC	12.5	12.5	25.0	22.5	19.0	19.0
Bunch frequency, kHz	297	270	99	45	18	9
Beam current, mA	3.71	3.37	2.47	1.01	0.35	0.16
Luminosity, 10^{34} cm^{-2} s^{-1}	96	118	73	35	13.8	8.3
IP beta function β_x/β_y, cm	15/0.08	20/0.10	100/0.1	100/0.2	100/0.2	100/0.2
Disruption parameter, D_x/D_y	0.6/183	0.6/177	0.1/129	0.2/143	0.2/142	0.2/121
Energy loss during collision, GeV	0.05	0.16	0.28	0.30	0.55	0.95
Damping ring energy, GeV	2	2	2	2	2	2
Damping time, ms	2.0	2.0	2.0	2.0	2.0	2.0
Damping ring current, A	4.858	4.427	3.239	1.325	0.460	0.213
Particle energy loss, GeV	4.0	4.4	6.0	14.8	42.7	92.7
Total radiated power, MW	30.0	29.8	29.8	30.0	30.0	30.0
Total ERL linacs voltage, GV	10.9	19.6	29.8	46.5	67.4	89.1
Efficiency of energy recovery, %	91.1	94.5	95.0	91.9	82.9	69.1

The electron and positron beam energy evolutions in 4-pass ERL

- 2 x 182.5 GeV: 365 GeV CM GeV ttbar



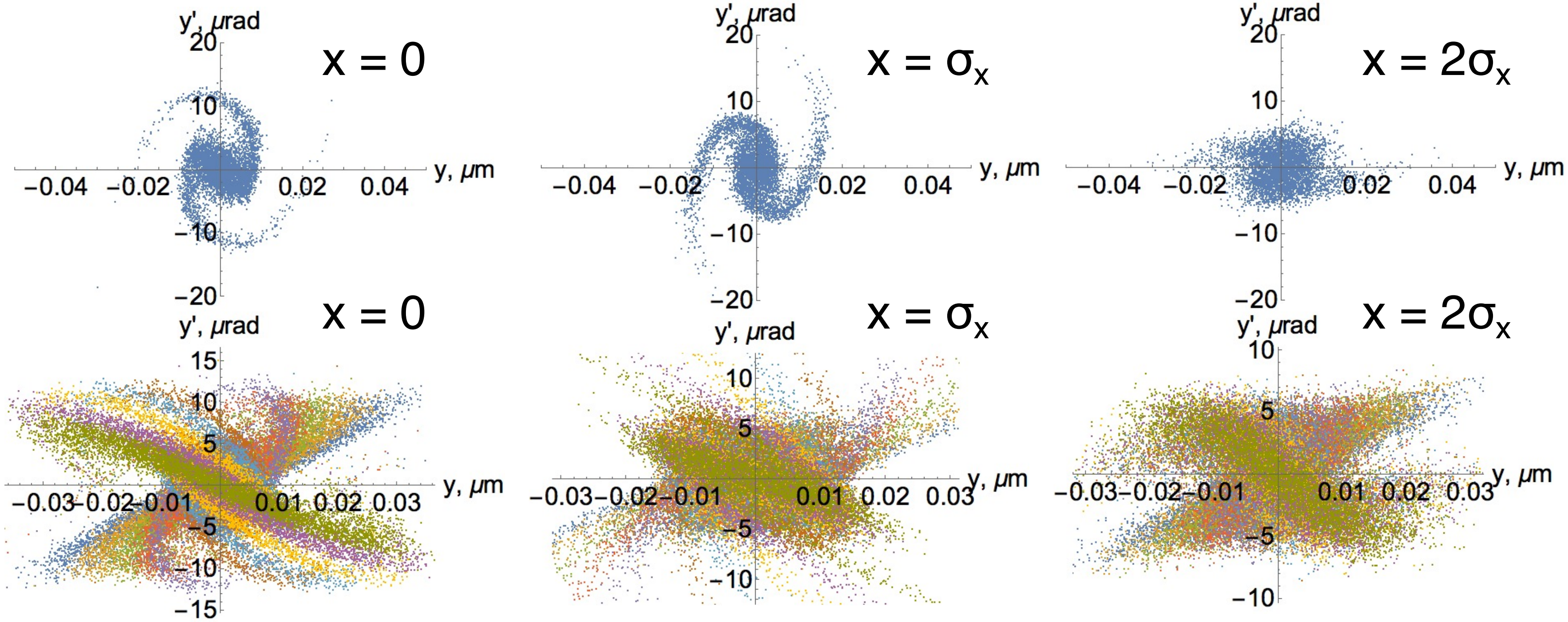
- 2 x 250 GeV: 500 GeV CM HHZ



- 2nd harmonic SRF to compensate SR energy loss

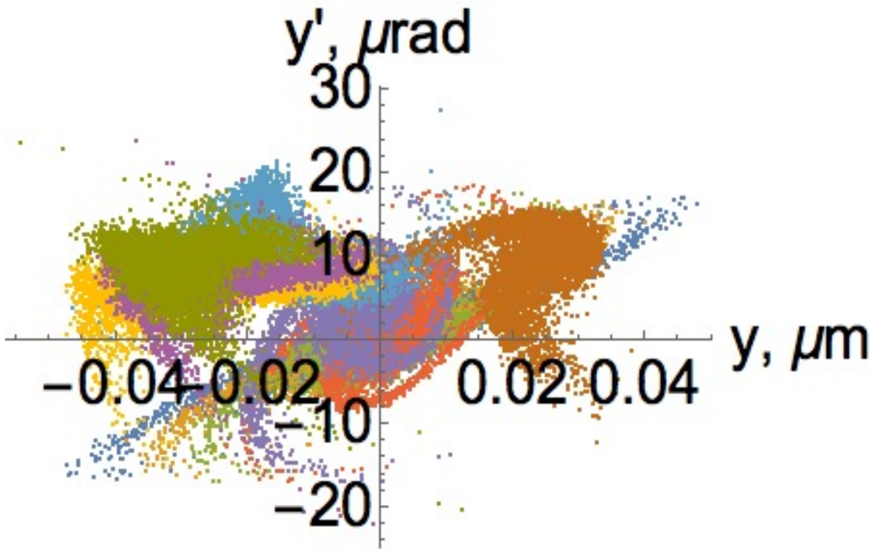
Strong-strong collisions of flat beams

- Using very flat beams minimizes beamstrahlung by minimizing the EM fields, similar to linear colliders. With aspect ratio of sqrt(1000) the energy spread at 300 GeV is about 0.1 - 0.2% after collision. There are, however, long tails in the distribution. See discussion by VL later.
- Flat beams allow for using 2D calculations to estimate beam-beam effects.
- Below is vertical phase space of beam after the collision. Top is for the middle of the bunch; bottom is for 10 slices covering the whole bunch length.
- Vertical emittance grows by about a factor of 5. This is well within acceptance of the deceleration beam line
- There is little disruption and emittance growth in the horizontal direction
- Full 3D simulations, requiring intensive computations, are needed

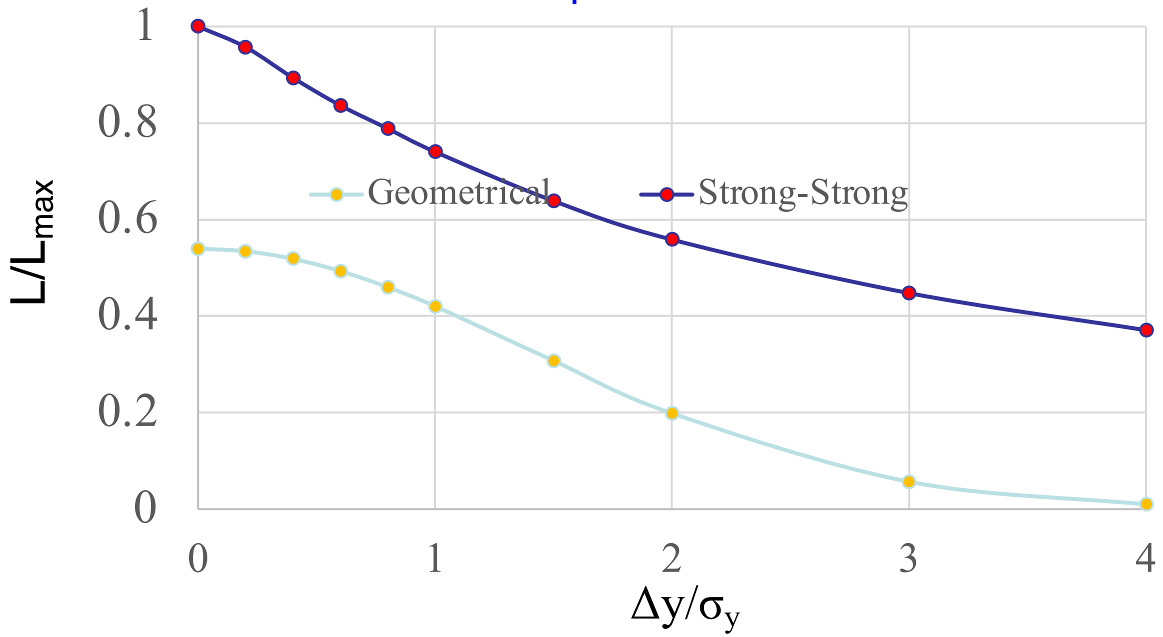


Effects of vertical orbit offsets at IP

- Vertical phase space plot below is for initial beam axis separation is $\Delta y = 1\sigma_y$
- Main effect from offsets: RMS vertical beam emittance increases ~ 10 times after collisions.
- Energy and particles recovery is not affected. May require an increase of the time in the damping rings to three-to-four damping times – this would need to 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

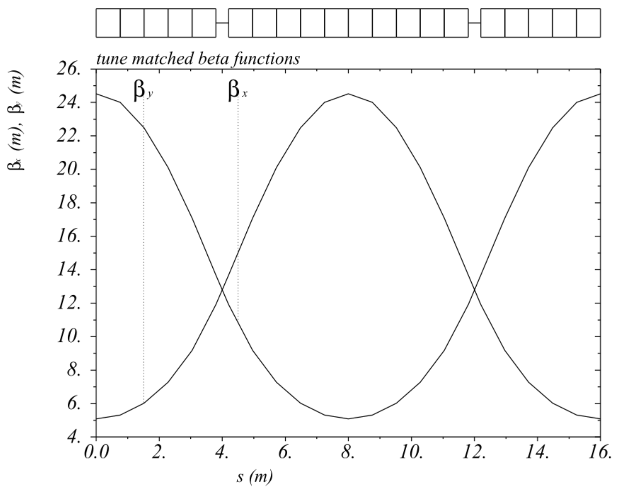


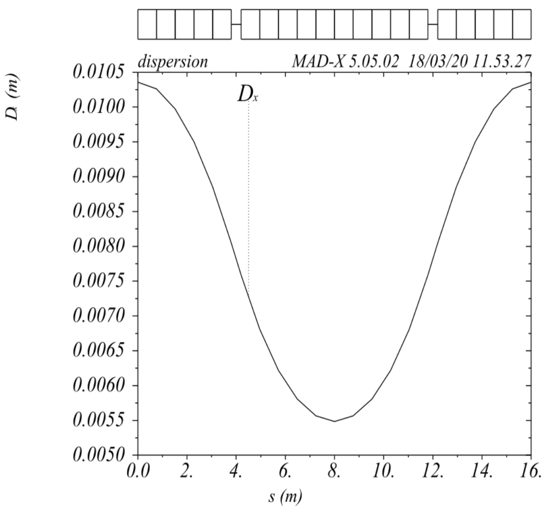
Relative luminosity vs vertical beam separation

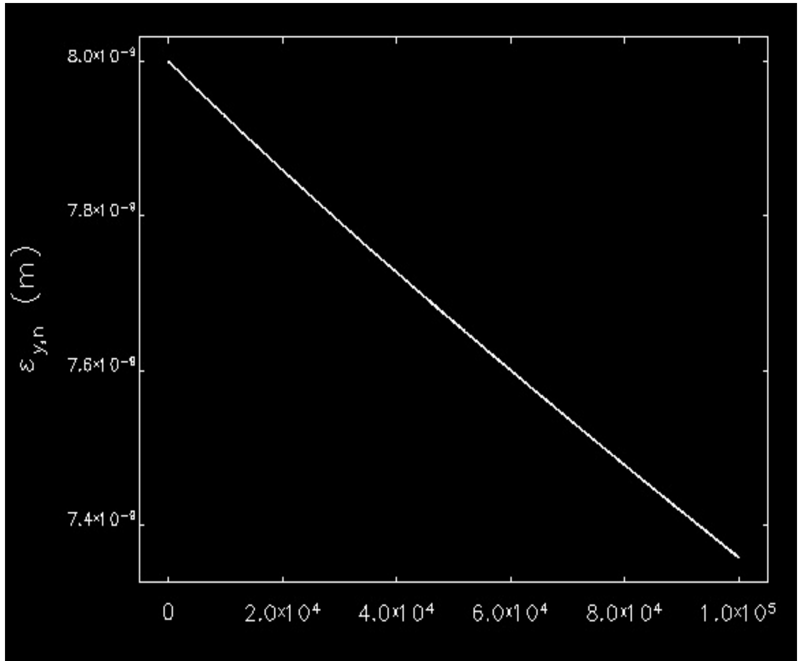


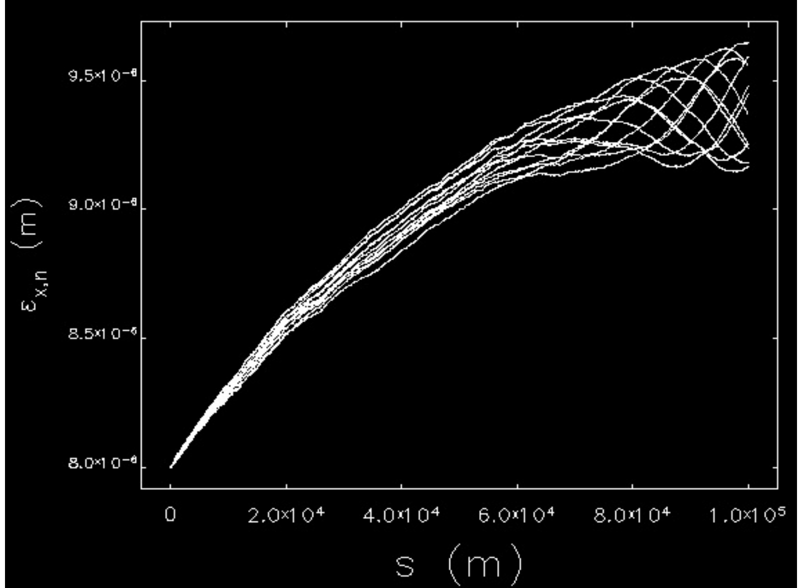
100 km beam transport at 250 GeV

- 6250 FODO cells with combined function (B,G,S) 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); $G_{F,D}$=±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



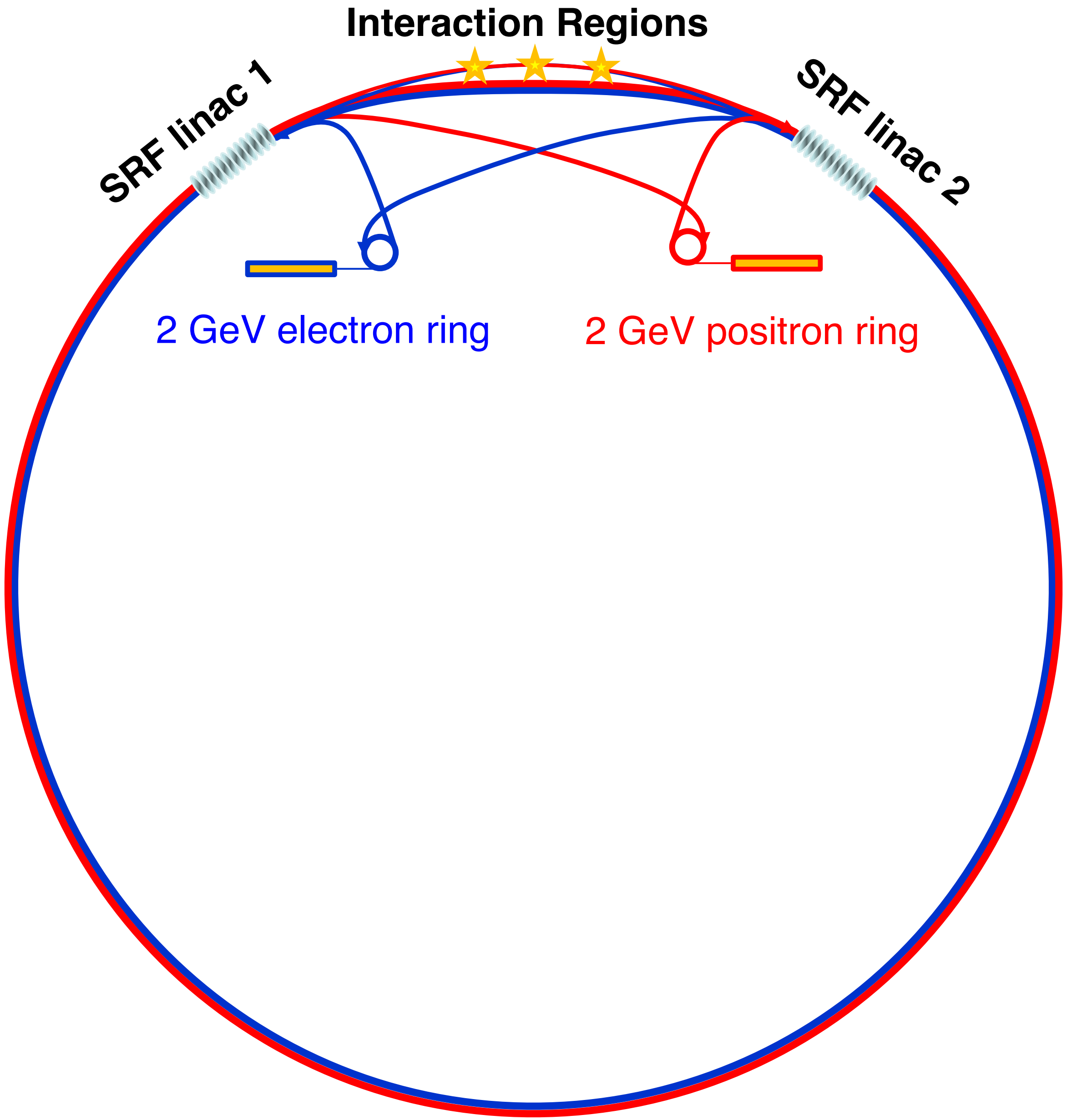






CERC recycles (polarized) electrons and positrons

- 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.
- Depolarization during acceleration, collision, and deceleration is expected to be minimal.
- Simulations by Francois Meot (Zgoubi): no depolarization from 100 km, 220 GeV transport (last turn)
- If this depolarization is less than the polarization build-up during the 4 ms time in the cooling rings, the electron and positron beams will eventually be polarized.



Design challenges and R&D of an ERL collider

- Multi-pass, high energy ERL R&D
- Transport beamline lattice preserving a small vertical emittance with large beam aspect ratio
- Full 3D simulation of electron-positron collisions with flat beams and high disruption parameter
- Using small gap magnets to reduce power consumption and cost of the multiple 100 km beamlines
- Absolute beam energy measuring systems with accuracy $\sim 10^{-5}$ at IRs as pioneered at CEBAF
- High repetition rate extraction and injection kickers for 2 GeV damping rings
- Compressing and de-compressing electron and positron bunches to match energy acceptance of the 2 GeV damping rings

Summary

- The ERL-based high-energy electron-positron collider promises significantly higher luminosities at CM energies above 160 GeV while consuming only 30% of electric power required for a corresponding SR e^+e^- collider design

- The CM energy reach can be extended to 600 GeV for double-Higgs and $Ht\bar{t}$ production

- The ERL collider might be capable of colliding polarized electron and positron beams, which can open a new set of observables for the relevant physics.

- These features of the ERL-based collider are unique in this energy range. It outperforms the ring-ring design - by colliding beams only once - and linear colliders by using energy recovery and recycling of particles

- Extensive detailed studies are needed to fully validate this concept

Q&A and Optimization of Circular Energy Recovery Collider

Vladimir Litvinenko

June 15, 2021

Questions

1. How is the evolution of the longitudinal phase space over a full cycle? It would be interesting how the energy spread generated at high energy develops with anti-damping during deceleration, then de-compression, damping in the ring, and so forth. Is there a full simulation model set up from which the steady-state longitudinal phase space in different sections of the machine can be derived?
2. What is the estimate for the fraction of particles lost per cycle, e.g. due to tails in beamstrahlung or SR or other effects? bunches can be topped-up in the damping rings, but the fresh charge has a much larger emittance (and is injected off-axis), especially for the positrons. That needs many damping times to get to the design values. Is there an issue with possibly loosing part of these partices in the small apertures of the ERL? How does the transverse phase space evolve with time, taking the topping-up process into account?
3. Because of the SR losses the accelerated beam needs to see a higher rf amplitude than the decelerated beam. Is this done by modulating the external rf in power (and phase)
4. **In addition, Valeri Telnov had comments in his presentation at the LCWS2021 that you should address.**
5. I don't understand why electrons and positrons are treated the same. If the requirement is equal current then yes positrons should be damped and recycled, but what is the advantage in doing the same for electrons? I always thought positrons were a precious commodity and electrons two-a-penny.
6. If SR losses are much less than a storage ring, then SR induced energy spread is also much less, does this have advantage in the design of the final focus system as the beam will be less sensitive to chromatic aberrations? So could the FFS of an ERL collider be less demanding than for a storage ring?
7. The beams start at 2 GeV and finish at 2 GeV, and the SR losses are compensated through non-perfect ER. SR losses are very significant e.g. 10-30% of top beam energy according to table 2. This must be done by moving the decelerating beams many degrees away from "on-trough" in phase. Doing this will impart relatively large energy chirp onto the decelerating bunches which may well then fall outwith the energy acceptance of the arcs. Has this been considered?
8. Similarly to the last question, the comments on "RF gymnastics" at the end of section 2. Do you have such a solution as you envisage you will need?
9. Disruption at the IP leads to the "spiral galaxy" plots of figure 3. What are the implications of this in terms of beam losses? I'm thinking that chromatic aberrations will lead these large amplitude tails to be translated to tails in longitudinal phase space, which (in line with my question 3 and 4) may not fit into the energy acceptance of the decelerating transport, especially given the natural adiabatic antidamping of the energy spread. My concern with losses is not just in terms of radiation and replacing lost particles, but of course it further depletes the energy one can recover.

Disclaimer

- There is no way I can answer all nine question in depth required
- In contrast with FCC ee project which was worked upon for about three years by dozen or more world's best accelerator scientist, CERC is a concept developed in time free from main job. This is the reason why we borrowed as many of FCC ee parameters for CERC: for example β^* in IP (minus crabbing) and bunch lengths. They are likely not optimal for ERL-based collider, where beam collide once before being restored to their initial state
- I will answer questions in the following sequence: I'll start from addressing comments by Dr. V. Telnov, which I consider the most important. After that I'll answer as many questions as time allows: again, starting from most impactful (*in my judgement*)

V. Telnov presented the following at LCWS 2021

Mistake in the ERL FCC

Incorrect

$$\sigma_\gamma = \frac{4}{9}\sqrt{\frac{\pi}{3}}N^2\frac{r_e^3}{\sigma_x^2\sigma_z}\gamma^2$$

$$\equiv \frac{\sigma_E}{E_0} \approx 0.54\frac{\Delta E}{E_0}$$

↓

The correct one

$$\frac{\sigma_E}{E_0} \sim \frac{2.3}{\sqrt{n_\gamma}}\frac{\Delta E}{E_0}$$

$$n_\gamma \approx 2.16\frac{\alpha r_e N}{\sigma_x} < 1$$

Main parameters of a possible ERL-based electron-positron collider with total synchrotron radiation power of 30 MW.

Mode of operation	Z	W	HZ	$t\bar{t}$	HHZ	$Ht\bar{t}$
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Efficiency of energy recovery, %	91.1	94.5	95.0	91.9	82.9	69.1

Even more correct to consider requirement that the particle loss due to energy acceptance is less than about 10^{-3}, which corresponds to the energy loss ~ $4\omega_c$, where (for 2E=240 GeV)

$$\frac{\bar{\omega}_c}{E_0} \sim \frac{1.5 N r_e^2 \gamma}{\alpha\sigma_x\sigma_z}$$

	σ_E/E	ω_c/E
authors	0.0024	
correct	0.0089	0.024 →

$4\omega_c$ give ~ 9.5%!

After deceleration to $E=1/7E_0$, where bunch decompressor is installed, these particles will have $\Delta E/E$~66%! One can increase particle losses by one order taking $2\omega_c$, but in any case it is necessary to decrease N by ~15 times (for 2% acceptance). The luminosity will drop down by $15^2/3$~75 times (3-possible increase the number of bunchers) to L~10^{34} (10 times less than FCC_{ee})

Side comment: this is incorrect scaling. With fixed SR power and fixed average beam current, if bunch intensity is reduced X-fold, the collision frequency would increase X-fold and luminosity is reduced by factor X. **If my memory is correct , 15≠75**

This slide contains multiple statement based on assumption that

$$n_\gamma \approx 2.16\frac{\alpha r_e N}{\sigma_x} < 1$$

and, also, that CERC does not allow further optimization beyond FCCee IP parameters

In fact, n_γ~1.5 > 1 and we optimized length of electron bunches to avoid generating energy tail in the recycled beams

How we calculated energy spread incurred during collisions

- Exact calculations for $n_\gamma \sim 1$
- First, define electric field in the beam

$$\oint \vec{E} d\vec{f} = 4\pi \int \rho\, dV; \rho = \frac{Ne}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z}\exp\left(-\frac{x^2}{2\sigma_x^2}-\frac{y^2}{2\sigma_y^2}-\frac{z^2}{2\sigma_z^2}\right)$$

$$E_y(x,y,z)=\frac{Ne}{\sigma_x\sigma_z}\exp\left(-\frac{x^2}{2\sigma_x^2}-\frac{z^2}{2\sigma_z^2}\right)Erf\left(\frac{y}{\sqrt{2}\sigma_y}\right)$$

- Finding energy loss during collision

$$\Delta E = \frac{2e^4\gamma^2}{3m^2c^3}\int_{-\infty}^{\infty}\left(\vec{\mathbf{E}}+\left[\vec{\beta}\times\vec{\mathbf{H}}\right]\right)^2 dt = \frac{8e^4\gamma^2}{3c^3}\int_{-\infty}^{\infty} E_y^2 dt$$

$$\Delta E(x,y)=\frac{4\sqrt{\pi}e^4\gamma^2\sigma_z}{3m^2c^4}\left(\frac{Ne}{\sigma_x\sigma_z}\right)^2\exp\left(-\frac{x^2}{\sigma_x^2}\right)Erf^2\left(\frac{y}{\sqrt{2}\sigma_y}\right);$$

$$\langle\Delta E\rangle = \int f(x,y)\Delta E(x,y)dxdy = \frac{1}{2\pi\sigma_x\sigma_y}\int \Delta E(x,y)\exp\left(-\frac{x^2}{2\sigma_x^2}-\frac{y^2}{2\sigma_y^2}\right)dxdy;$$

$$\langle\Delta E\rangle = \frac{4}{9}\sqrt{\frac{\pi}{3}}N^2\frac{e^6}{m^2c^4}\frac{1}{\sigma_x^2\sigma_z}\gamma^2$$

- Calculating <Δγ>

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

- RMS energy spread can be estimated by

$$\langle\sigma_\gamma\rangle \propto \frac{\langle\Delta\gamma\rangle}{\sqrt{n_\gamma}} \propto \langle\Delta\gamma\rangle$$

- More accurate calculation will be done using Monte-Carlo simulations

Low energy tail

- Maximum energy loss can occur for particles located at x=0 and large vertical displacements

$$x,z=0;|y|>>\sigma_y \Rightarrow E_{y\max}=\frac{Ne}{\sigma_x\sigma_z};\rho_{\min}=\frac{\gamma mc^2}{2eE_{y\max}}=\frac{\gamma\sigma_x\sigma_z}{2Nr_c};$$

$$\Delta\gamma_{c\max}=\frac{\hbar\omega_{c\max}}{mc^2}=\frac{3}{2}\gamma^3\frac{\lambda\!\!\!^{-}_c}{\rho_{\min}}=3\gamma^2\frac{Nr_c\lambda\!\!\!^{-}_c}{\sigma_x\sigma_z}$$

- It does not affect the RMS energy spread, but it defines necessary acceptance of the lattice, as well as level of quantum losses
- For the range of the proposed c.m. CERC energies from 90 to 600GeV

$$\frac{\Delta\gamma_{c\max}}{\gamma}=(0.2\div 1.2)\cdot 10^{-3}$$

- The later is achieved by using 20x longer electron bunches, crab focusing with $\beta^*=\beta_{sc}$ matched with focusing by the opposite bunch

$$K_y=\left(1+\beta^{-1}\right)\frac{e}{pc}\frac{\partial E_y}{\partial y}\cong\frac{2e}{pc}\frac{\partial E_y}{\partial y};\left\langle K_y\right\rangle=\frac{N_e r_e}{\gamma\sqrt{2\pi}\sigma_x\sigma_y\sigma_z}=\bar{\beta}_{sc}^{-2}\Rightarrow\bar{\beta}_{sc}=\left(\frac{\sqrt{2\pi\gamma\varepsilon_n}\sigma_x\sigma_z}{N_e r_e}\right)^{2/3}$$

Updated CERC parameters

FCC ee with ERLs	**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**
Horizontal ε, nm	0.044	0.025	0.025	0.022	0.016	0.013
Vertical ε, pm	0.088	0.050	0.033	0.022	0.016	0.013
Horizontal norm ε, m rad	3.91E-06	3.91E-06	5.95E-06	7.83E-06	7.83E-06	7.83E-06
Vertical norm ε, m rad	7.83E-09	7.83E-09	7.83E-09	7.83E-09	7.83E-09	7.83E-09
Bend magnet filling factor	0.9	0.9	0.9	0.9	0.9	0.9
βh, m	0.15	0.2	1	1	1	1
βv, m	0.0008	0.001	0.001	0.002	0.002	0.002
Bunch length, mm	30	30	30	50	50	50
Charge per bunch, nC	13	13	25	23	19	19
Ne per bunch	7.80E+10	7.80E+10	1.56E+11	1.40E+11	1.19E+11	1.19E+11
Bunch frequency, kHz	297	270	99	45	18	9
Beam current, mA	3.71	3.37	2.47	1.01	0.35	0.16
Luminosity, $cm^{-2}sec^{-1}$	**6.7E+35**	**8.7E+35**	**7.8E+35**	**3.1E+35**	**1.4E+35**	**8.6E+34**

Questions related to particles recycling

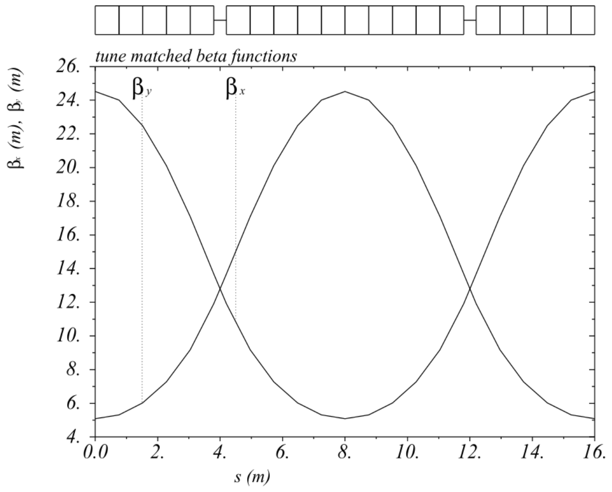
- How is the evolution of the longitudinal phase space over a full cycle? It would be interesting how the energy spread generated at high energy develops with anti-damping during deceleration, then de-compression, damping in the ring, and so forth. Is there a full simulation model set up from which the steady-state longitudinal phase space in different sections of the machine can be derived?
- What is the estimate for the fraction of particles lost per cycle, e.g. due to tails in beamstrahlung or SR or other effects? bunches can be topped-up in the damping rings, but the fresh charge has a much larger emittance (and is injected off-axis), especially for the positrons. That needs many damping times to get to the design values. Is there an issue with possibly loosing part of these partices in the small apertures of the ERL? How does the transverse phase space evolve with time, taking the topping-up process into account?
- I don’t understand why electrons and positrons are treated the same. If the requirement is equal current then yes positrons should be damped and recycled, but what is the advantage in doing the same for electrons? I always thought positrons were a precious commodity and electrons two-a-penny.
- Disruption at the IP leads to the “spiral galaxy” plots of figure 3. What are the implications of this in terms of beam losses? I’m thinking that chromatic aberrations will lead these large amplitude tails to be translated to tails in longitudinal phase space, which (in line with my question 3 and 4) may not fit into the energy acceptance of the decelerating transport, especially given the natural adiabatic antidamping of the energy spread. My concern with losses is not just in terms of radiation and replacing lost particles, but of course it further depletes the energy one can recover.

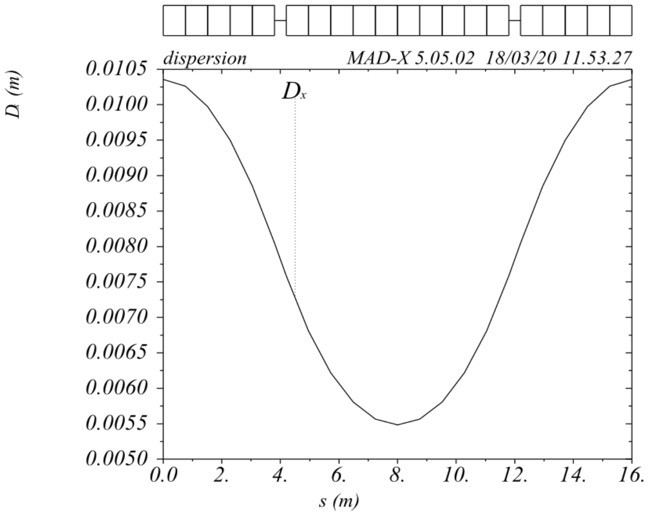
Answers

- Sorry, there is no such thing as anti-damping in Hamiltonian system: the longitudinal phase space volume it preserved. Only relative energy spread is increasing when we decelerate the beam.
- The only possible means to keep it within the energy acceptance of damping ring is to increase the bunch length. We developed the lattice for 4-pass system and one student working part-time on the start-to-end simulations - will be glad to accept help from interested parties. We working on expanding bunch length from up to 10 fold (depending on the CERC energy) and optimize the damping ring energy (between 2 GeV and 8 GeV) and to keep RMS energy spread of recycled beams withing 1%. The most critical is to recover weak but long low energy tail – this could be achieved by intermediate damping ring with acceptance of ±5%.
- Steady state will be achieved by damping beam to natural emittances and energy spread in the damping ring. Exponential nature of damping would mean that we may need to increase circulation time from two (7.4 fold damping) to three (20-fold damping) or four damping times (54-fold damping).
- We are working with the assumption that recirculating beams will have lifetime ~ 1 hour, which corresponds to 1 p.p.m. particle and topping-off bunches every minute. It means that bunch which is topped-off will spend some extra time in the damping ring - ones per 15,000 cycles up and down in the CERC.
- Both horizontal and transverse emittances are so minuscular that even with 10-fold increase of horizontal emittance, the RMS size of the horizontal beam will be less than 300 microns in all arc. Our estimation indicate less than 50% increase of horizontal emittance. Our simulations show that “spiraling galaxy” remains intact after initial “inflation”. Vertical emittance is so small that in all possible scenarios beam RMS size is measured in microns or tens of microns. Lattice of the arcs includes sextupole which zero chromaticity to prevent blow-up of the emittances by unavoidable orbit errors.
- Hence, we do not expect any losses related to the scraping on the vacuum chamber of the ERL with aperture radiusof 15 mm. Exception is the scattering on residual gas - unavoidable in any accelerators.

Answers

- About recycling electrons: maximum average e-beam current for full energy CERC is ~10 mA, which exceeds capacity of current polarized electron beam sources. Our preliminary simulation indicated that polarization can be preserved in CERC. In addition, damping mA scale GeV beam does not bode well with green technology… Only at high energy of CERC average current in in hundreds of microamps.
- The main challenge is to avoid loss of the particles low energy tail, which is the most challenging for the higherest energy of CERC: 2 x 300 GeV. With new beam parameters, maximum critical photon energy (x=0, z=0, y >>σ_y) will be 375 MeV (0.125%) and there will be an exponentially weak tail of higher energy losses. We plan to expand bunch length 10-fold prior to injection into the 8 GeV damping ring with ±5% (0.4 GeV) energy acceptance sufficient to accept energy tail with $10.6\hbar\omega_c$. According to our estimations, losses will be significantly less 1 p.p.m. We plan to do Monte-Carlo simulations to identify exact amount of particles that do not fit in this aperture.





Remaining Questions

1. Because of the SR losses the accelerated beam needs to see a higher rf amplitude than the decelerated beam. Is this done by modulating the external rf in power (and phase)
2. The beams start at 2 GeV and finish at 2 GeV, and the SR losses are compensated through non-perfect ER. SR losses are very significant e.g. 10-30% of top beam energy according to table 2. This must be done by moving the decelerating beams many degrees away from "on-trough" in phase. Doing this will impart relatively large energy chirp onto the decelerating bunches which may well then fall outwith the energy acceptance of the arcs. Has this been considered?
3. Similarly to the last question, the comments on "RF gymnastics" at the end of section 2. Do you have such a solution as you envisage you will need?
4. If SR losses are much less than a storage ring, then SR induced energy spread is also much less, does this have advantage in the design of the final focus system as the beam will be less sensitive to chromatic aberrations? So could the FFS of an ERL collider be less demanding than for a storage ring?

Answers

- The best solution for the question about asymmetric losses and corresponding need to shift "phase vector" was found when we worked on ERL-bases electron-ion collider: use second harmonic cavities to boost energies of both accelerating and decelerating bunches. Since 180-degree change in the phase of the fundamental mode corresponds to 360-degrees for the second harmonic, the concept does is simple and straight forward
- We did not complete strat-to-end simulation of the beam dynamics, including compression and de-compression if the bunches. What become obvious that we will need a relatively low fundamental frequency of the main linac - 500 MHz or less- and use of third harmonic for linearization
- We in full agreement that FFS for ERL-based colliders is much simpler than for the storage ring. One possible scenario for further improvement of the IP is in reduction of the vertical β^*, which either can be used to further boost luminosity or to reduce required beam currents. Unfortunately, we do not have resources to design such new IR.

Summary

- We want to thanks Dr. Telnov for raising questions about low energy tail in collided beams, which indeed could be a problem. We found an elegant solution to this problem by elongating colliding bunches. This arrangement has an additional advantage that vertical β^* of colliding beams matched focusing provided by the opposite bunch.
- The main challenge of recycling all electrons and positrons with losses less than 1 p.p.m. is decompression of the bunches and use proper energy of damping ring (or in perfect world, a chain of two damping rings: one with large energy acceptance and second with small natural emittances).
- We developed a straw-man lattice of the arc and are in the process of developing details of compression and de-compression. This work is done by a part-time student – we welcome anybody to help speeding it up.
- Next step for CERC should be a full-scale design of IR and lattice optimized for maximum luminosity, low loss and preservation of polarization