ERL option for high-energy high-luminosity FCC e^+e^-

Preliminary studies

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Our approach: ERL with cooling rings

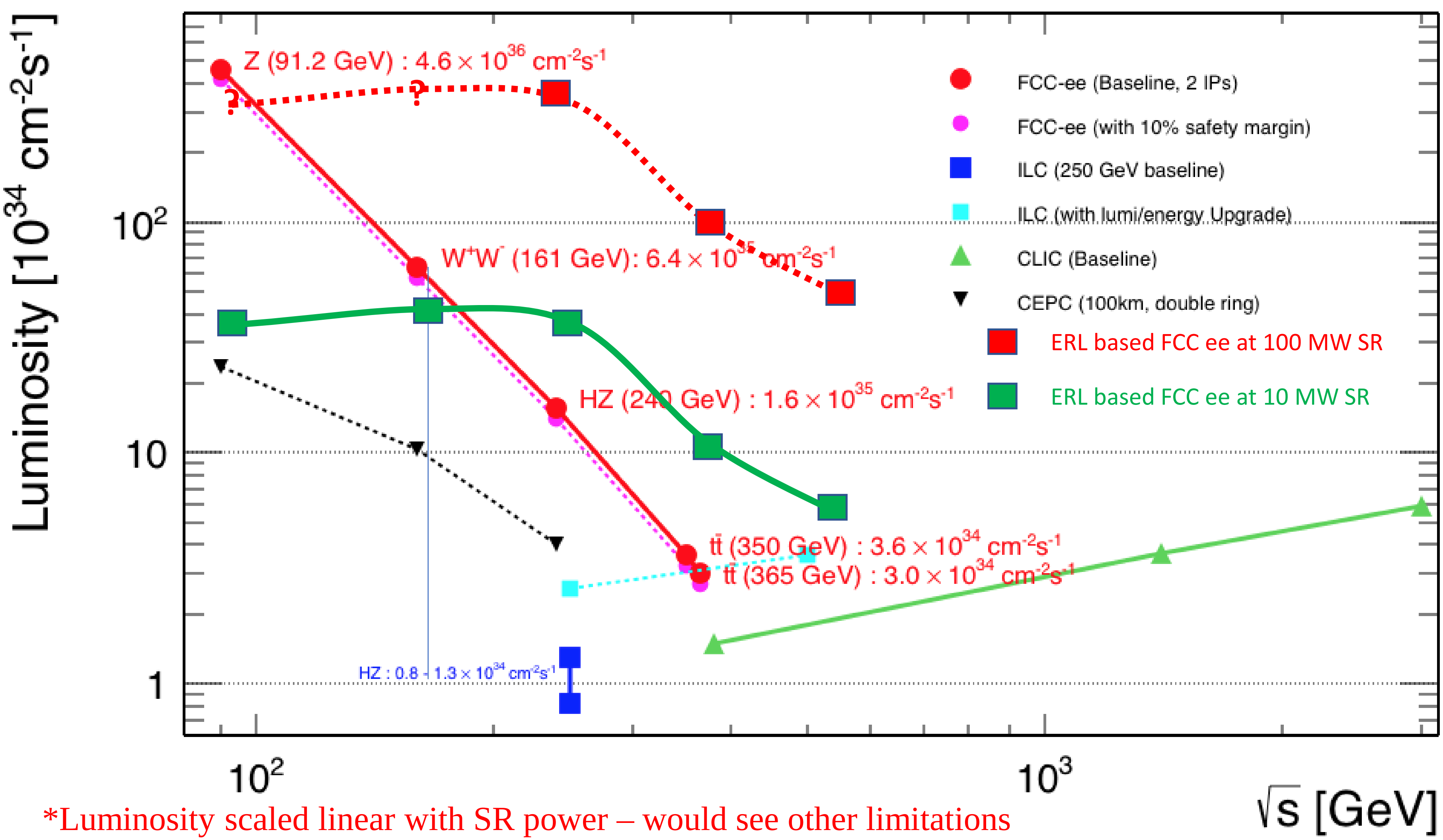
Avoid accesses

The ring-ring FCC ee is power hungry
100 MW SR losses, ~ 200 MW wall plug power

parameter	Z	W	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
arc cell optics	60/60	90/90	90/90	90/90
momentum compaction [10^{-5}]	1.48	0.73	0.73	0.73
horizontal emittance [nm]	0.27	0.28	0.63	1.45
vertical emittance [pm]	1.0	1.0	1.3	2.7
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	2
length of interaction area [mm]	0.42	0.5	0.9	1.99
tunes, half-ring (x, y, s)	(0.569, 0.61, 0.0125)	(0.577, 0.61, 0.0115)	(0.565, 0.60, 0.0180)	(0.553, 0.59, 0.0350)
longitudinal damping time [ms]	414	77	23	6.6
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.10	0.44	2.0	10.93
RF acceptance [%]	1.9	1.9	2.3	4.9
energy acceptance [%]	1.3	1.3	1.5	2.5
energy spread (SR / BS) [%]	0.038 / 0.132	0.066 / 0.153	0.099 / 0.151	0.15 / 0.20
bunch length (SR / BS) [mm]	3.5 / 12.1	3.3 / 7.65	3.15 / 4.9	2.5 / 3.3
Piwinski angle (SR / BS)	8.2 / 28.5	6.6 / 15.3	3.4 / 5.3	1.39 / 1.60
bunch intensity [10^{11}]	1.7	1.5	1.5	2.8
no. of bunches / beam	16640	2000	393	39
beam current [mA]	1390	147	29	5.4
luminosity [10^{34} $cm^{-2}s^{-1}$]	**230**	**32**	**8**	**1.5**
beam-beam parameter (x / y)	0.004 / 0.133	0.0065 / 0.118	0.016 / 0.108	0.094 / 0.150
luminosity lifetime [min]	70	50	42	44
time between injections [sec]	122	44	31	32
allowable asymmetry [%]	±5	±3	±3	±3
required lifetime by BS [min]	29	16	11	10
actual lifetime by BS ("weak") [min]	> 200	20	20	25

What ERL can offer:
Green FCC ee with 10% of R-R power consumption

Note that 100 MW SR power is not what we are proposing*



*Luminosity scaled linear with SR power – would see other limitations

Comparison of ERL and Ring-Ring

$$L = f_c \frac{N_{e-} N_{e+}}{4\pi\sqrt{\beta_x^* \varepsilon_x}\sqrt{\beta_y^* \varepsilon_y}} = \frac{I_{e-} I_{e+}}{4\pi\sqrt{\beta_x^* \varepsilon_x}\sqrt{\beta_y^* \varepsilon_y} \times f_c \times e^2}$$

$$P_{SR} = V_{SRe-} I_{e-} + V_{SRe+} I_{e+}$$

The way to reduce SR power is to reduce beam currents in both electron and positron beam.
To keep luminosity high, one would need to reduce one, two or all in

$$\beta^* \times \varepsilon \times f_c$$

In storage rings there are additional limitations: maximum allowable beam-beam tuned shift and IP chromaticity (e.g. how small is β*)

$$\xi_{x,y} = \frac{N \cdot r_o \cdot \beta^*_{x,y}}{2\pi\gamma\sigma_{x,y}(\sigma_x + \sigma_y)} < 0.1\text{-}0.15$$

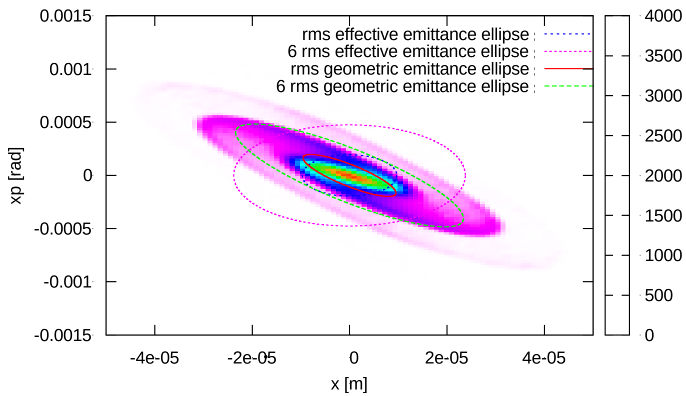
which favors high beam currents, large emittance and high collision frequencies.

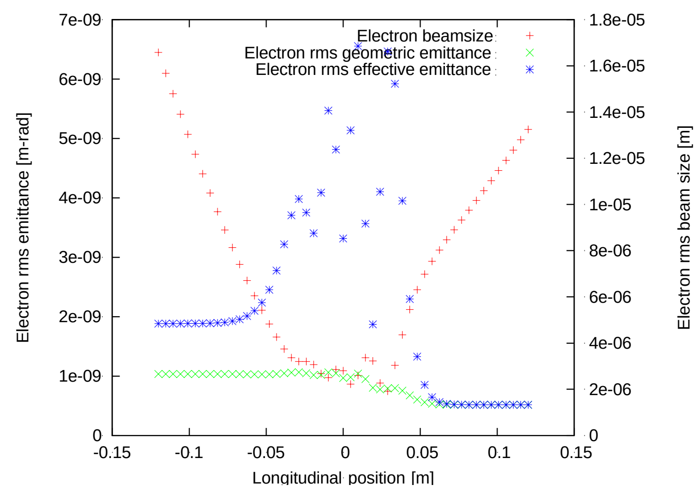
Comparison of ERL and Ring-Ring

In ERL-ERL collider the beams are used only once in collisions and beam-beam tune shift is no longer relevant. The relevant number is the disruption parameter:

$$D_{x,y} = \frac{N_e}{g_e} \frac{2r_e}{\left(s_x + s_y\right) s_{x,y}} s_z ; s_{x,y} = \sqrt{b_{x,y} e_{x,y}}$$

where σ_z is RMS bunch length. As part of the ERL-based eRHIC studies we demonstrated that disruption parameter up to 200 can be tolerated in the following sense in ERL scheme: transverse beam emittance will double in a single collision, but the beam than can be comfortably energy recovered. Here is a sample of electron beam colliding with proton beam with disruption parameter d=156 : electrons execute 2 full oscillation in the opposing beam. Tails are formed due to the nonlinearity and beam emittance doubles.





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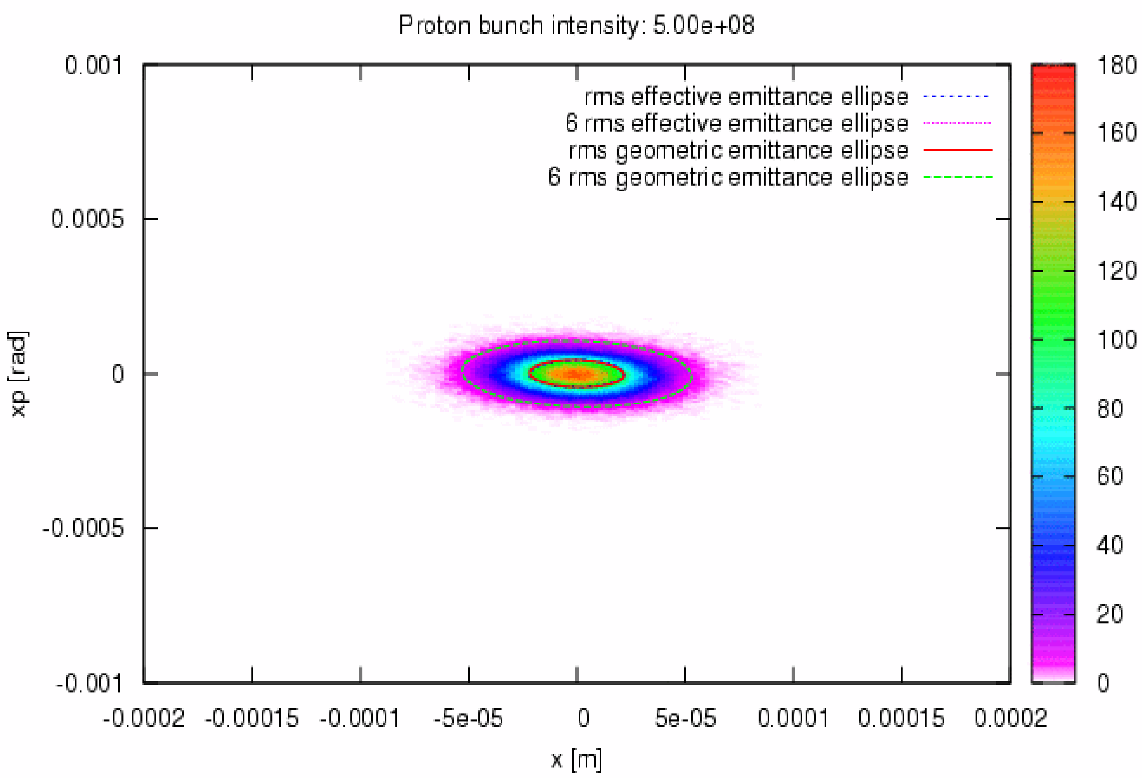
Effect of electron disruption in the energy recovery linac based electron ion collider

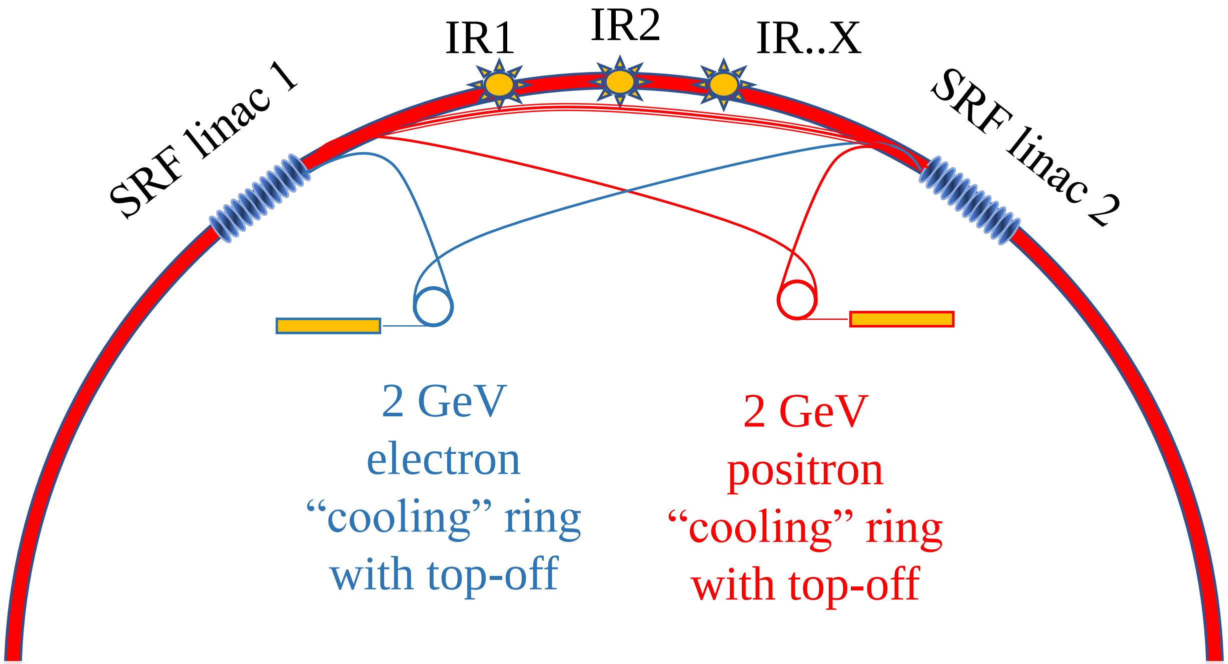
Y. Hao and V. Ptitsyn

Movie of the disruption effect

evolution of the transverse phase space is shown and function of increasing disruption parameter



Courtesy of Y. Hao



Explored layout of the ERL-based FCC ee:

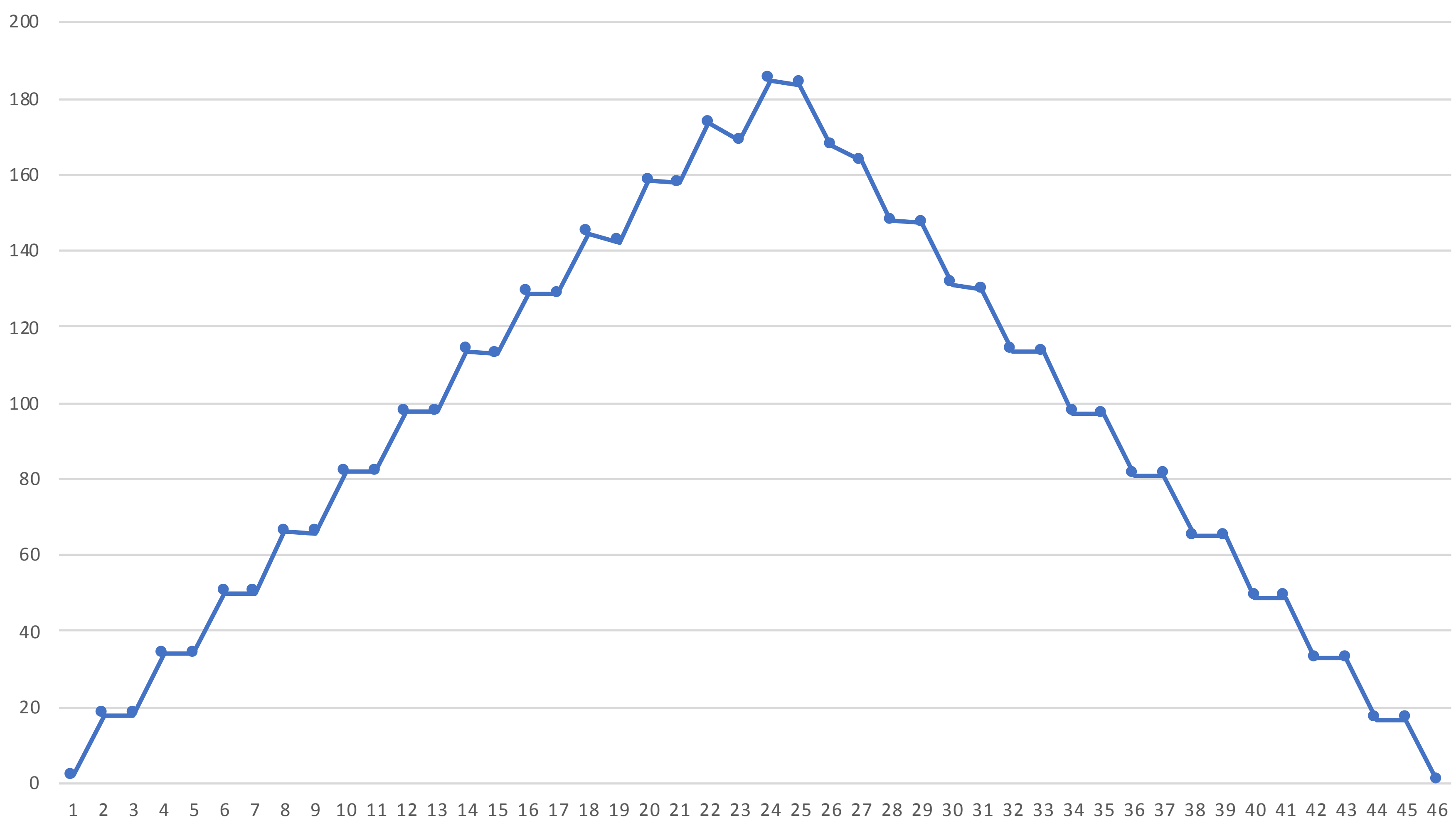
Flat electron and positron beams are cooled in 2 GeV cooling rings with top-off injection to keep intensity constant

Bunches are ejected from the rings with frequency required by the collider – the beams are accelerated to the collision energy in 4 or 6 passes through the super-conducting RF (SRF) linacs bypassing IRs. Each path requires an individual arc.

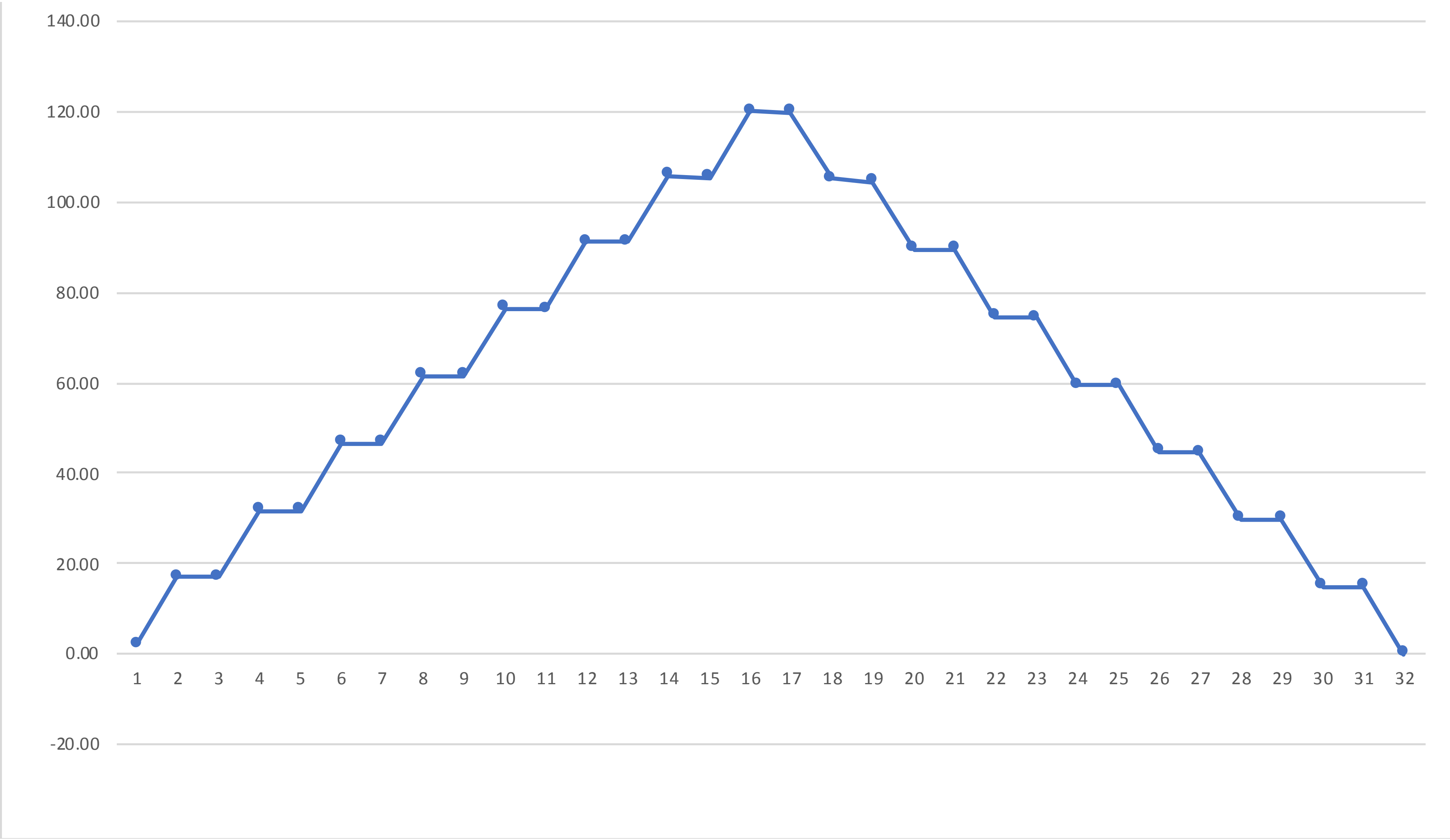
At the top energy beams collide in IR(s), their phases are changed to deceleration and they return most of the energy back into the SRF

Portion of the beam energy is lost in form of synchrotron radiation. Additional energy loss occurs in the cooling ring, where particles circulated for two e-fold damping time to restore the initial emittance. Cooled bunches are extracted for the next trip to the top energy and collision. A very low average current 2-GeV top-off system – common in modern accelerators – will compensate for loss of particles.

e^- and e^+ beam energy evolution in 6-path ERL with two 16 GV SRF linacs (32 GeV boost per turn) and top energy of 182.5 GeV for t-tbar regime



e^- and e^+ beam energy evolution in 4-path ERL with two 14.9 GV SRF linacs (29.8 GeV boost per turn) and top energy of 120 GeV for H(ZH) regime



Cooling rings

- 2 GeV storage ring equipped with damping wigglers will provide for low emittance (1 nm rad horizontal geometrical emittance and 0.2% coupling)
- Bunches will be long to keep IBS under control
- Bunches will be compressed to the design values in the ERL using large R_{56} of low energy arcs
- It is proven technology in 4th generation light sources and cooler rings

Energy	2	GeV
B	1	T
Loss rate	1512	GeV/sec
Filling factor	0.67	
e-cool time	0.002	sec
# of cooling times	2	
Accumulatin time	0.004	sec
Ring circumference	900	m
Revolution frequency	0.33	MHz

Energy	2	GeV
γ	3914	
Emittance, horizontal	1	nm rad
Em. normalized, hor	**4**	µm rad
Em. normalized, vert	**8**	pm rad
Coupling	0.002	

Important considerations

- In addition to disruption, at high energy, there is another dangerous effect - beamstrahlung: synchrotron radiation in strong EM field produced by 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*
- The goal of this exercise was to maintain energy spread in colliding beams at the same level as in ring-ring FCC ee: 0.15-0.2%

- I derived following formula for average change of the beam energy in beam-beam collision

$$\left\langle \mathrm{D}g \right\rangle = \frac{4}{9}\sqrt{\frac{p}{3}}N^2\frac{r_e^3}{s_x^2 s_z}g^2;$$

$$for\ \ s_x >> s_y$$

- This number is included in the table at the next slide

* Using round beams will reduce attainable luminosity by one-to-two orders of magnitude.

Main table: for 10 MW SR power for 4-path ERL and 15 MW SR power for 6-path ERL (both beams)

- Data is for head-on collisions – no need for crab-crossing and/or crab-focus
- Luminosity exceeds that of ring-ring FCC ee with 100 SR MW power loss at H and t-tbar energies
- It also has a decent luminosity of 4×10^{34} $cm^{-2}s^{-1}$ at double Higgs production energy
- Multiple IRS need more detailed considerations
- By the quick nature of this exercise, all these numbers are not optimized
- Energy recovery definitely beneficial when compared with linac-linac case: 83% of 182.5 GeV and 81% of 250 GeV beam energy is recovered in 4-path ERL scheme.
- Scheme does not have advantage for operating at FCC's lowers energy of 45.6 GeV

FCC with ERLs	**Z**	**W**	**H(HZ)**	**ttbar**	**HH**
Circumference, km	100	100	100	100	100
Beam energy, GeV	**45.6**	**80**	**120**	**182.5**	**250**
Horizontal ε, nm	0.044	0.025	0.025	0.022	0.016
Vertical ε, pm	0.088	0.050	0.033	0.022	0.016
Horizontal norm ε, m rad	3.91E-06	3.91E-06	5.95E-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
Bend magnet filling factor	0.9	0.9	0.9	0.9	0.9
βh, m	0.15	0.2	1	1	1
βv, m	0.0008	0.001	0.001	0.002	0.002
Bunch length, mm	0.8	1	1	2	2
Charge per bunch, nC	13	13	25	23	19
Ne per bunch	7.80E+10	7.80E+10	1.56E+11	1.40E+11	1.19E+11
Bunch frequency, kHz	99	90	33	15	6
Beam current, mA	1.24	1.12	0.82	0.34	0.11
Luminosity, $cm^{-2}sec^{-1}$	**2.2E+35**	**2.9E+35**	**2.6E+35**	**1.0E+35**	**4.5E+34**
Four path ERL + Damping ring					
Energy loss per particle, GeV	4.04	4.41	6.04	14.8	42.67
Radiated power, MW/per beam	**5.0**	**5.0**	**5.0**	**5.0**	**4.9**
ERL linacs voltage, GV	**10.88**	**19.6**	**29.8**	**46.5**	**67.4**
Six path ERL + Damping ring					
Energy loss per particle, GeV	4.07	4.62	7.12	20.43	64.52
Radiated power, MW/per beam	**5.0**	**5.2**	**5.9**	**6.9**	**7.4**
ERL linacs voltage, GV	**7.25**	**13.1**	**20**	**31.6**	**47.7**
Secondary parameters					
Disruption, d_h	0.6	0.6	0.1	0.2	0.2
Disruption, d_v	182.9	177.1	128.7	142.8	120.6
Energy loss in IP, GeV	0.05	0.16	0.28	0.30	0.55
Tune shift, χ hor	8.91	8.91	11.75	8.03	6.78
Tune shift, χ ver	14.53	14.06	10.20	11.32	9.56
Cooler rings					
Cooler ring energy, GeV	2	2	2	2	2
e-fold cooling time, msec	2.0	2.0	2.0	2.0	2.0
number of bunches in the ring	43	39	14	6	3
Beam current, mA	534	486	356	146	49

Discussions

- In contrast with linear collider, the transverse position jumps/jitter caused by pulsed ejector magnets can be corrected at the first arc when beam path around the FCC – the position and angle can be detected at the arc entrance and corrected at its exit. Hence an argument used in “"FCC-ee: Your Questions Answered" about the emittance spoiling is not applicable to ERL scheme;
- Geometric emittance and transverse beam sizes are minuscular, which makes natural using magnets with small gap
- Similarly, in contrast with storage rings, the ERL arcs do not require large dynamic aperture, e.g. one can use a combined function (shifted quads) magnets with constant bending magnetic field and nearly 100% packing factor – while it gives only ~ 35% savings in the radiated power it still an advantage
- Alternating gradient combined magnets (bend quadrupole channel) has extremely high tolerance to energy deviations – it energy acceptance measured in units of energy, not in percent
- As LEP demonstrated, synchrotron radiation with MeV photons degrades the surrounding hardware – hence reducing this power extends the life-cycle of the *FCC ee* and would make it available for future *FCC he*
- **Layout of ERLs**
- Beams are injected at 2 GeV in linacs (e^- in linac 1. e^+ in linac 2) and extracted from the opposite linac at 2 GeV (in e dedicated extraction point)
- Energy of accelerating and decelerating beams are not the same for high energy operation – it is result of the SR losses.
- Beams are combined for propagation through linacs and separated to propagate in individual arcs by magnetic structures which very originally called “combiners” and “separators”

Possible arcs layout for 4-path of 182.5 GeV ERL

Electrons and positrons alternate the inside and outside passes

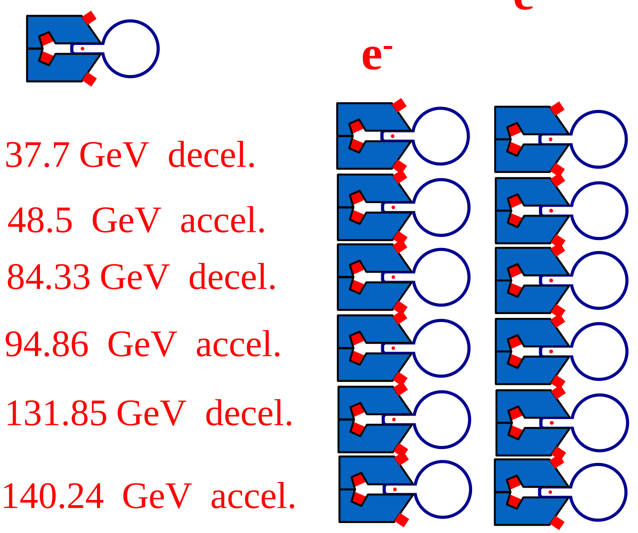
IRs side arcs (after linac 2)

2 GeV decel.

e^-

e^+

e^-



37.7 GeV decel.

48.5 GeV accel.

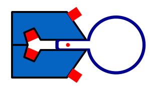
84.33 GeV decel.

94.86 GeV accel.

131.85 GeV decel.

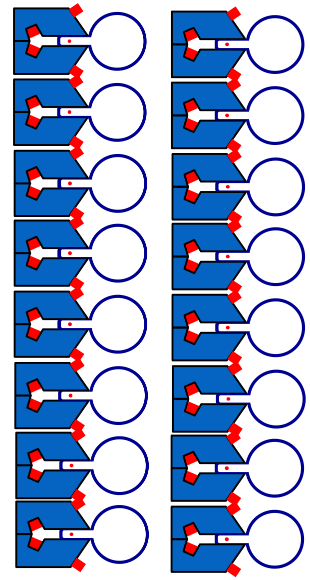
140.24 GeV accel.

182.25 GeV colliding e^+e^-



Main portion (5/6) of the ring arcs

e^- ↔ e^+



14.45 GeV decelerating

25.25 GeV accelerating

61.02 GeV decelerating

71.74 GeV accelerating

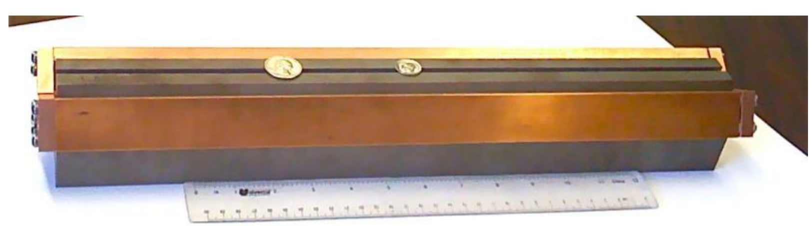
108.28 GeV decelerating

118.02 GeV accelerating

158.33 GeV decelerating

163.12 GeV accelerating

Small gap magnets with 5 mm gap
Prototyped for eRHIC at 0.43 T: FCC ee needs only 0.04 T,
e.g. it is very low power consumption magnet



Preliminary conclusions

- ERL option, in combination with 2 GeV cooler rings, would be advantageous for FCC ee high energy operation
- This option allows both significant (6-fold to 10-fold) reduction in required RF power while delivering higher luminosities at top energies
- This scheme does not have advantages at lowest FCC ee energy of 46.5 GeV
- There is clearly no problem with beam stability in ERL – the average current is very low. Modern HOM dumpers will be sufficient to keep beams stable.
- We did not find – so far – any showstoppers for this version of FCC ee