FCC e^+e^- ERL option for low RF power and high-energy

Preliminary studies

Vladimir N Litvinenko, Thomas Roser and
Maria Chamizo Llatas

Stony Brook University

CASE Center for Accelerator Science and Education

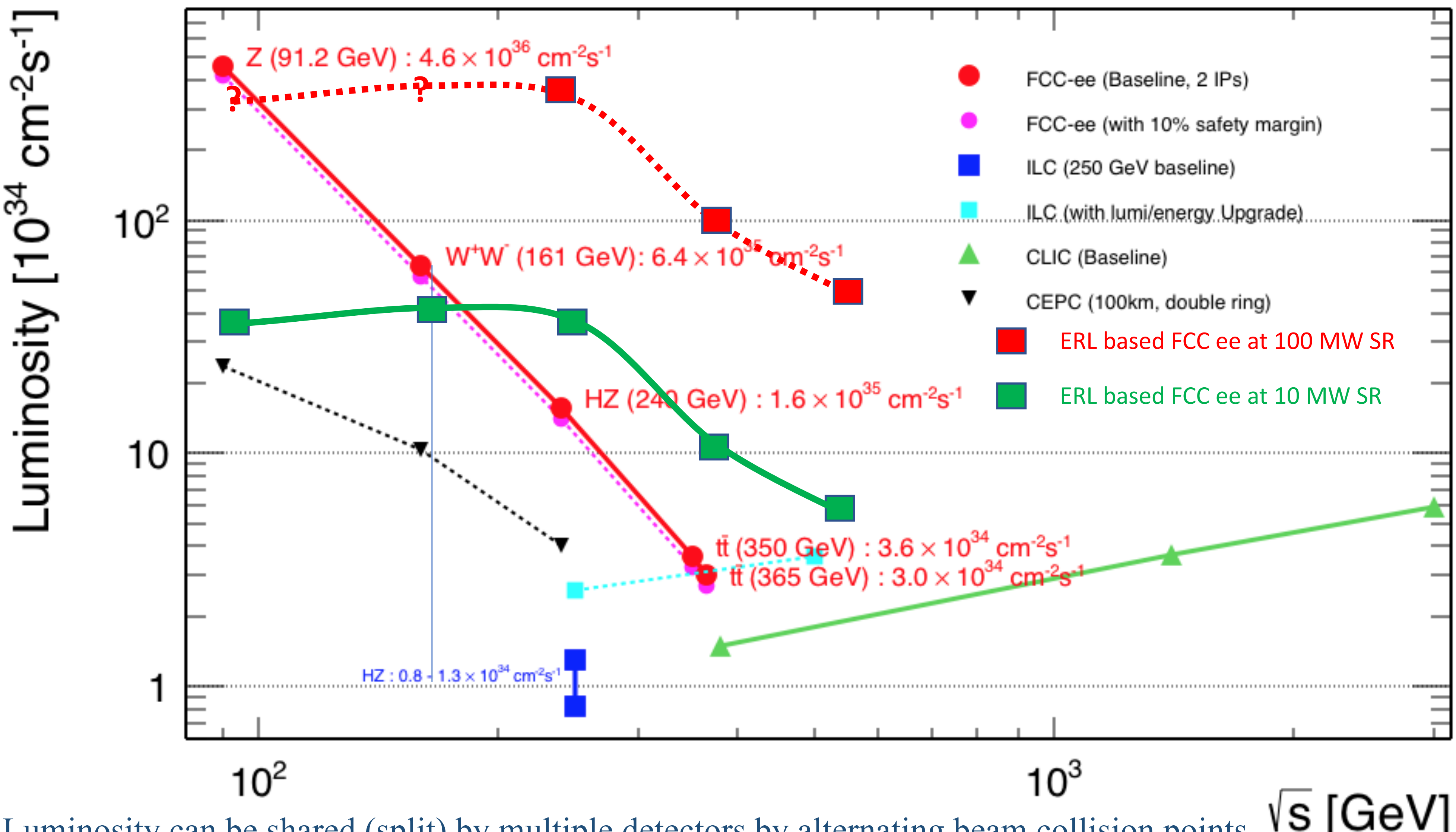
BROOKHAVEN NATIONAL LABORATORY

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

Luminosity scales linear with SR power – would see other limitations – but 100 MW SR power is not what we are proposing.



Luminosity can be shared (split) by multiple detectors by alternating beam collision points.
Potential of increasing total luminosity requires detailed simulations

Comparison of ERL and Ring-Ring

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

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

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

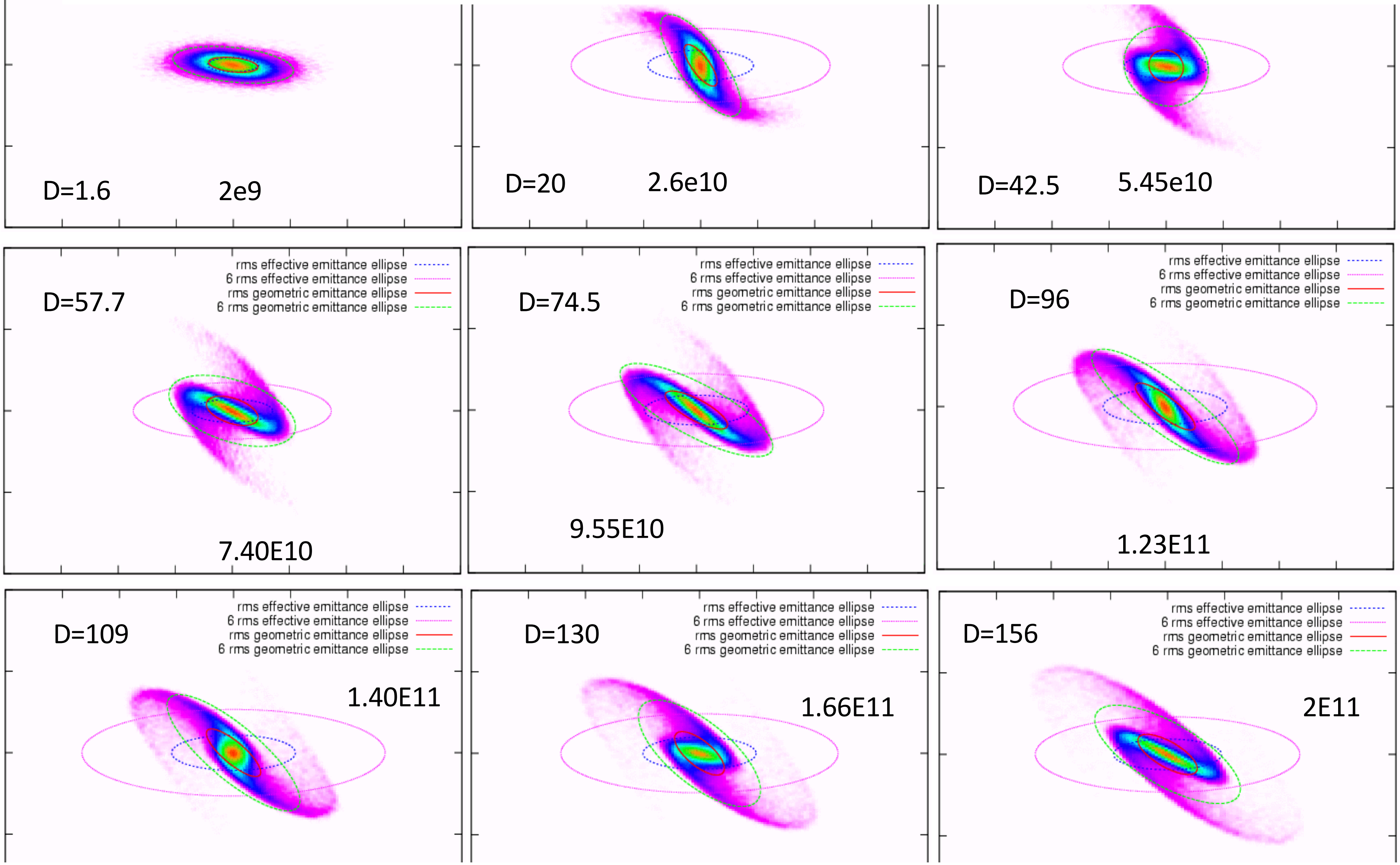
$$\sqrt{\beta_x^* \beta_y^*} \cdot \sqrt{\varepsilon_x \varepsilon_y} \cdot f_c$$

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

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

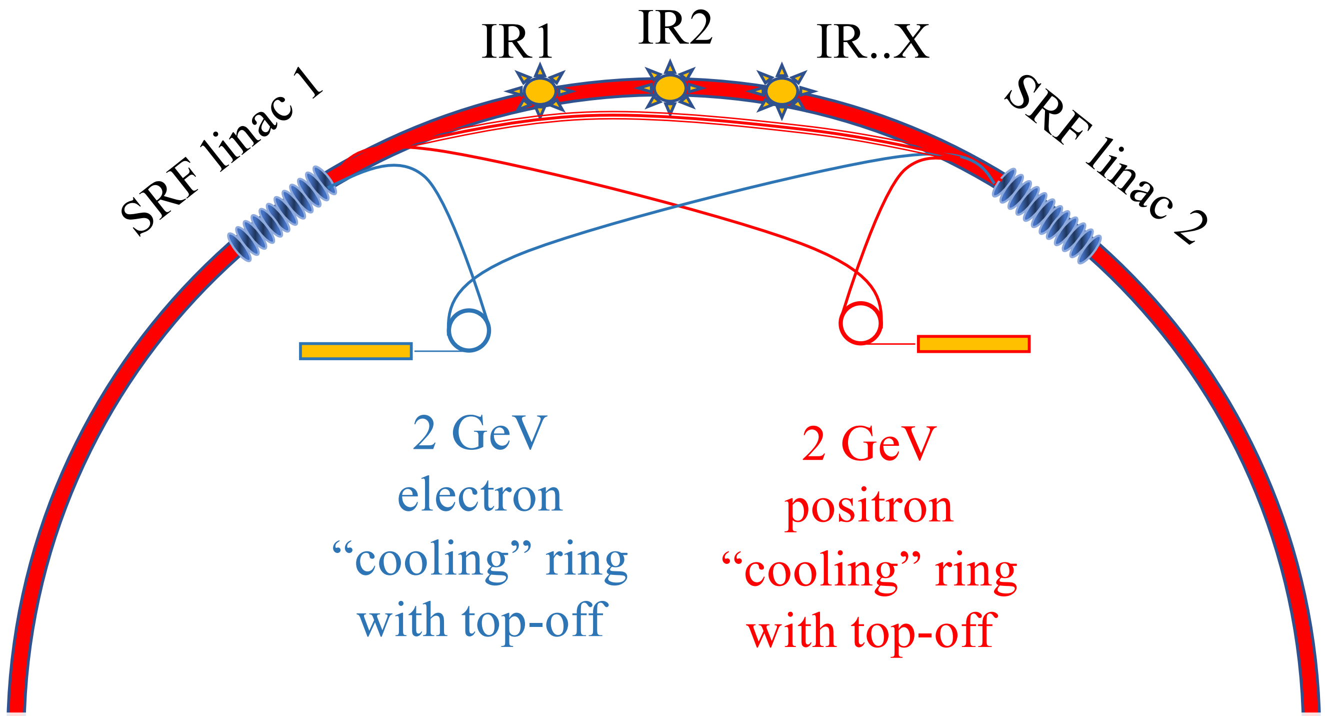
which favors high beam currents, large emittance and high collision frequencies.

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



As part of the ERL-based eRHIC studies it was demonstrated that disruption parameter up to 200 for electron beam colliding with hadron beam can be tolerated : transverse beam emittance will double in a single collision, but the beam than can be comfortably energy recovered.. Important note: this assumption has to be confirmed by direct simulation of colliding electron and position beams.

100% ECO FRIENDLY
FCCee



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

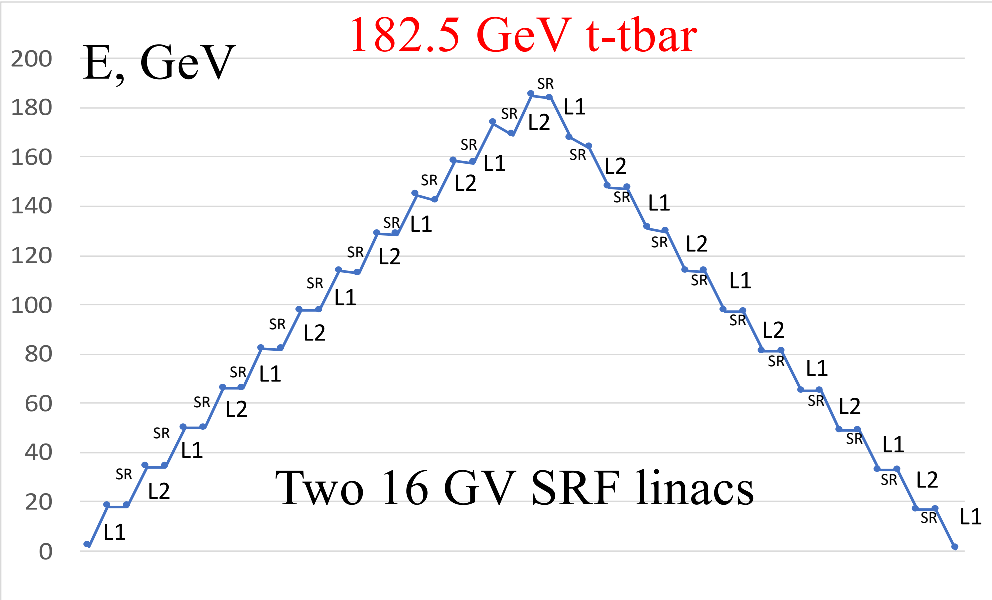
Bunches are ejected from the rings with frequency required by the collider – the beams are accelerated to the collision energy in 4 or 6 passes through the super-conducting RF (SRF) linacs bypassing IRs. Each path requires an individual arc.

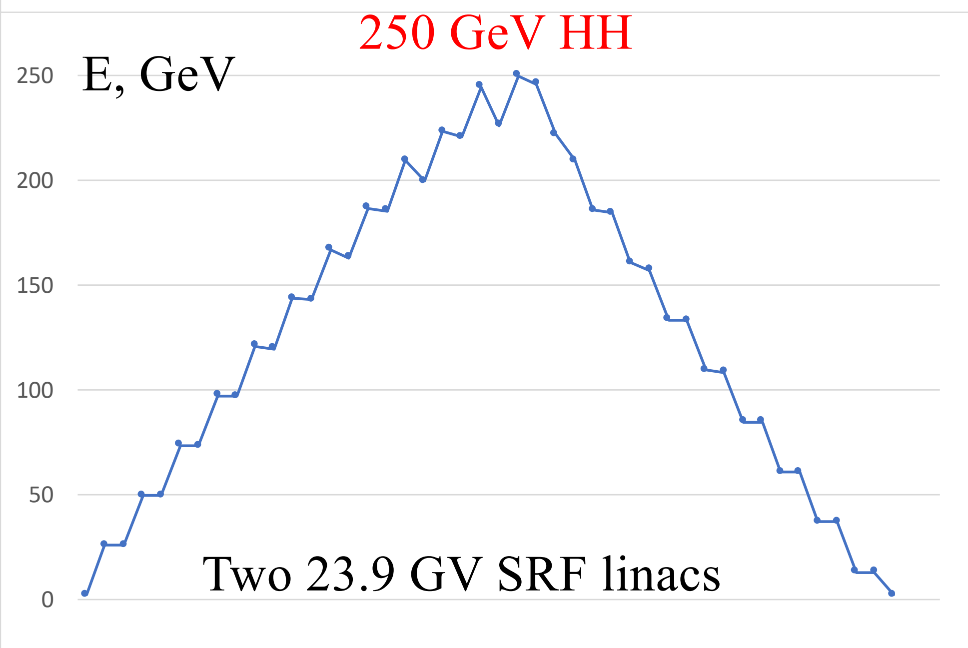
At the top energy beams collide in IR(s), their phases are changed to deceleration and they return most of the energy back into the SRF

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.

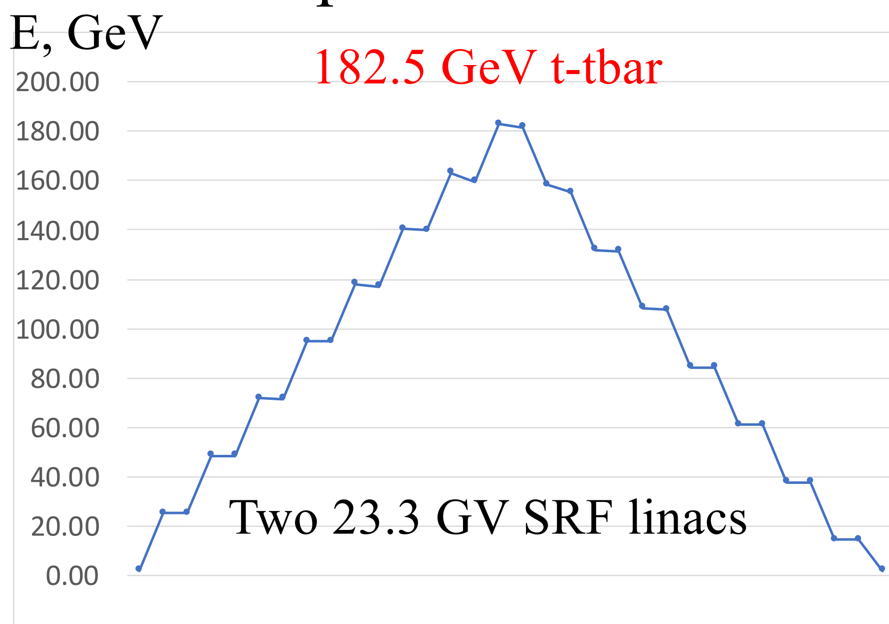
e^- and e^+ beam energy evolutions

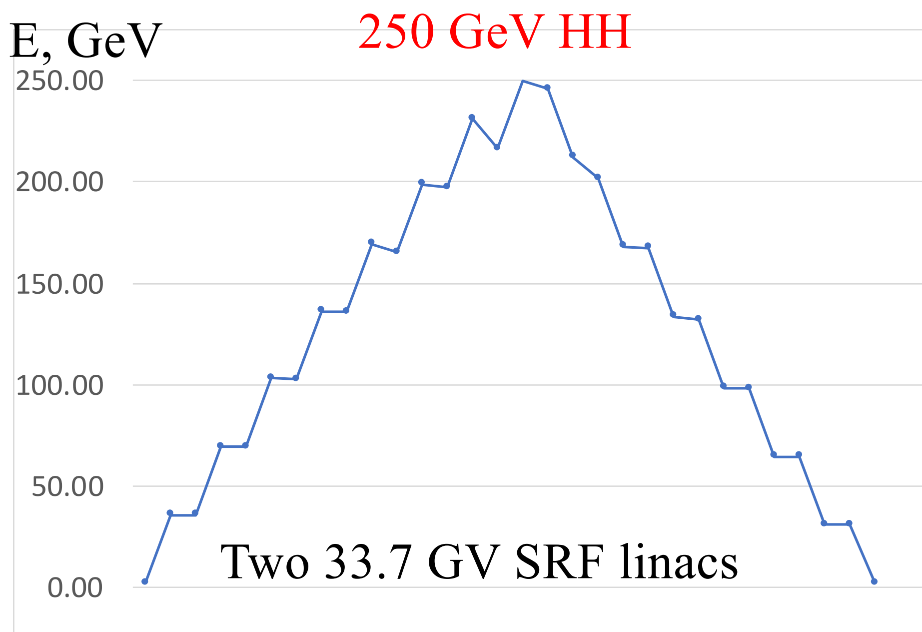
6-pass ERL





4-pass ERL



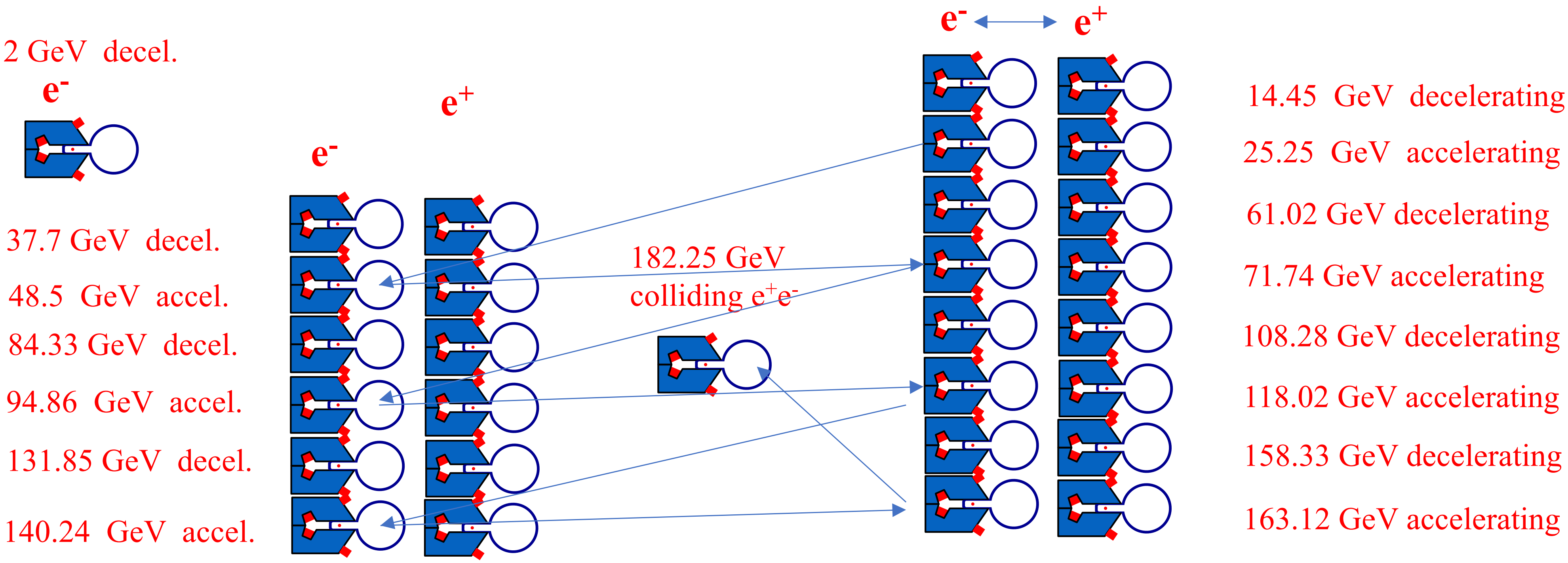


Possible arcs layout for 4-path of 182.5 GeV ERL

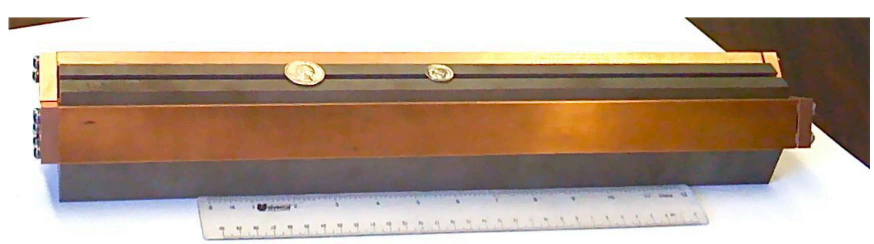
Electrons and positrons alternate the inside and outside passes

IRs side arcs (after linac 2)

Main portion (5/6) of the ring arcs



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



Main table for SR power in both beams

10 MW in 4-path ERL and <15 MW in 6-path ERL

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 norm ε, μm rad	**4**	**4**	**6**	**8**	**8**
Vertical norm ε, nm rad	**8**	**8**	**8**	**8**	**8**
βh, m (same as in FCCee design)	0.15	0.2	1	1	1
βv, mm same as in FCCee design)	0.80	1.00	1.00	2.00	2.00
Bunch length, mm	**0.8**	**1**	**1**	**2**	**2**
Charge per bunch, nC	12.5	12.5	25	22.5	19
Ne per bunch	7.8E+10	7.8E+10	1.6E+11	1.4E+11	1.2E+11
Bunch frequency, kHz	**99**	**90**	**33**	**15**	**6**
Beam current, mA	**1.24**	**1.12**	**0.82**	**0.34**	**0.11**
Luminosity, 10^{34} $cm^{-2}sec^{-1}$	**22.5**	**28.9**	**25.9**	**10.5**	**4.5**

- Head-on collisions – no crab-crossing and/or crab-focus
- At H and t-tbar energies estimated luminosity exceed that of the ring-ring with 100 MW synchrotron radiation power loss
- Decent luminosity of $4x10^{34}$ $cm^{-2}s^{-1}$ at double Higgs production energy of 2x250 GeV
- Multiple IPs need more detailed considerations.
- Energy recovery definitely beneficial when compared with linac-linac case: 95% at 120 GeV, 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

Four path ERL + Damping ring					
Energy loss per particle, GeV	**4.0**	**4.4**	**6.0**	**14.8**	**42.7**
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	**4.1**	**4.6**	**7.1**	**20.4**	**64.5**
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, dh	0.6	0.6	0.1	0.2	0.2
Disruption, dv	183	177	129	143	121
Energy loss in IP, GeV	0.05	0.16	0.28	0.30	0.55
Tune shift, χ hor	8.9	8.9	11.7	8.0	6.8
Tune shift, χ ver	14.5	14.1	10.2	11.3	9.6
Cooler rings					
Cooler ring energy, GeV	2	2	2	2	2
Damping time, msec	2.0	2.0	2.0	2.0	2.0
Beam current, mA	534	486	356	146	49

Key differences between ring-ring and 4-pass ERL FCC ee

Example: t-tbar case with 182.5 GeV beam energy

	Ring-Ring	ERL-ERL	Ratio
Horizontal norm ε, μm rad	517.85	7.83	66.16
Vertical norm ε, nm rad	964.28	7.83	123.19
Beam collision rate, kHz	116.92	14.99	7.80
Bunch charge, nC	46.19	22.50	2.05
Beam current, mA	5.40	0.34	16.01
Particle energy loss, GeV	9.21	14.80	0.62
SR losses, MW (two beams)	100.00	10.00	10.00
Energy spread in IP, %	0.18	0.16	1.10
Crossing angle	YES	NO	
Crab-focusing	YES	NO	

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%

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

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

Discussion

- In contrast with linear collider, the transverse position jumps/jitter caused by pulsed ejector magnets or vibrations can be corrected when beam path around the FCC – the position and angle can be detected at the arc entrance and corrected at the exit
- Geometric emittances and transverse beam sizes are minuscular - a natural choice for low-cost small gap magnets. Such combined magnets with alternating gradients (bend-quadrupole channel) has extremely high energy acceptance measured in units of energy, not in percent.
- Such combined function magnets with constant bending magnetic field can have 90% packing factor giving ~ 35% savings in the synchrotron radiation power
- As demonstrated by LEP, the synchrotron radiation with MeV photons degrades the surrounding hardware – hence reducing SR power extends the *FCC ee* life-cycle
- Polarized beams can be used if necessary (will need additional studies)
- ERLs can serve as lepton part of future *FCC he*

Preliminary conclusions

- ERL option, in combination with 2 GeV cooler rings, would be advantageous for FCC ee high energy operation
- This option allows significant - 6 to 10 times- 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 no problem with beam stability in ERL: low average current and modern high-order mode (HOM) dumpers sufficient to keep beams stable
- We did not find – so far – any showstoppers for this version of FCC ee. Detailed studies are needed to fully validate the concept

Our approach: ERL with cooling rings

Avoid accesses

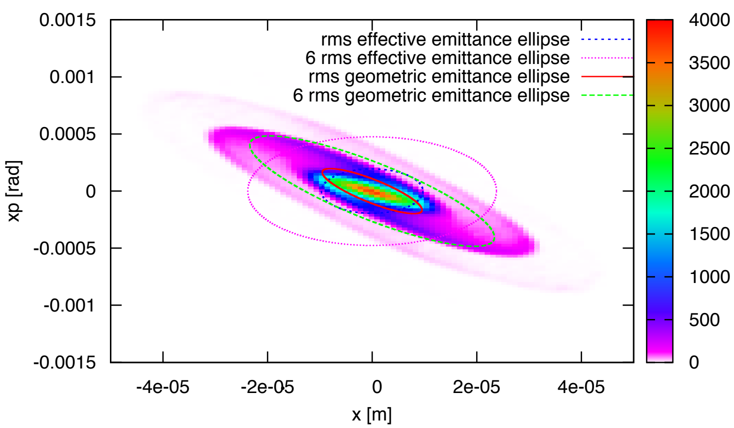
Back-up

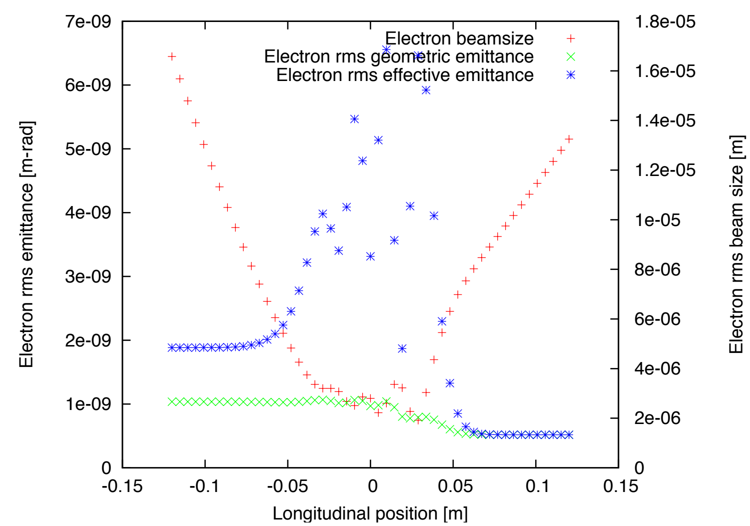
Comparison of ERL and Ring-Ring

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:

$$D_{x,y} = \frac{N_e}{\gamma_e} \frac{2r_e}{\left(\sigma_x + \sigma_y\right)\sigma_{x,y}} \sigma_z ; \sigma_{x,y} = \sqrt{\beta_{x,y}\varepsilon_{x,y}}$$

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.





PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **13**, 071003 (2010)

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

Y. Hao and V. Ptitsyn

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.
- Geometric emittance and transverse beam sizes are minuscular, which makes natural using magnets with small gaps. Alternating gradient combined magnets (bend quadrupole channel) has extremely high energy acceptance measured in units of energy, not in percent
- 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 90% packing factor giving ~ 35% savings in the radiated power
- As LEP demonstrated, synchrotron radiation with MeV photons degrades the surrounding hardware – hence reducing this power extends the life-cycle of the *FCC ee*
- Polarized beams can be used if necessary (will need additional studies)
- ERLs can serve as lepton part *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 synchrotron radiation 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”

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 longitudinal dispersion $R_{56} = ds/d(\ln E)$ in 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**	nm rad
Coupling	0.002	

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

ERL

In-path ERL the radiated power scales with number of turns because in addition to the synchrotron radiation at the top energy, particles loose energy each time they round the ring – both on the way up and way down. For a single linac ERL it is simple formula (*n* number of passes in ERL to reach top energy and)

$$R = \frac{\Delta E_{SR\ ERL}}{\Delta E_{SR\ ring}} = \frac{2\sum_{k=1}^{n} k^4}{n^4} - 1 = \frac{2n(n+1)(2n+1)(3n^2 + 3n - 1)}{30n^4} - 1 \rightarrow \frac{2n}{5}$$

n { 2. 3 **4 5 6** **7** 8 9 10 11 12 }

P_{SR}

R {1.125, 1.41975, **1.766, 2.133, 2.511**, **2.895**, 3.283, 3.674, 4.067, 4.460, 4.855}

Splitting linac in two allows to reduce losses for synchrotron radiation. Energy losses for each ERL structure and each top energy were calculated accurately for each segment of the arc and the totals are included in the table.