A High Energy ERL-based Electron-Positron Collider

Vladimir N Litvinenko, Thomas Roser, Maria Chamizo Llatas
Physics Department Colloquium
November 26, 2019

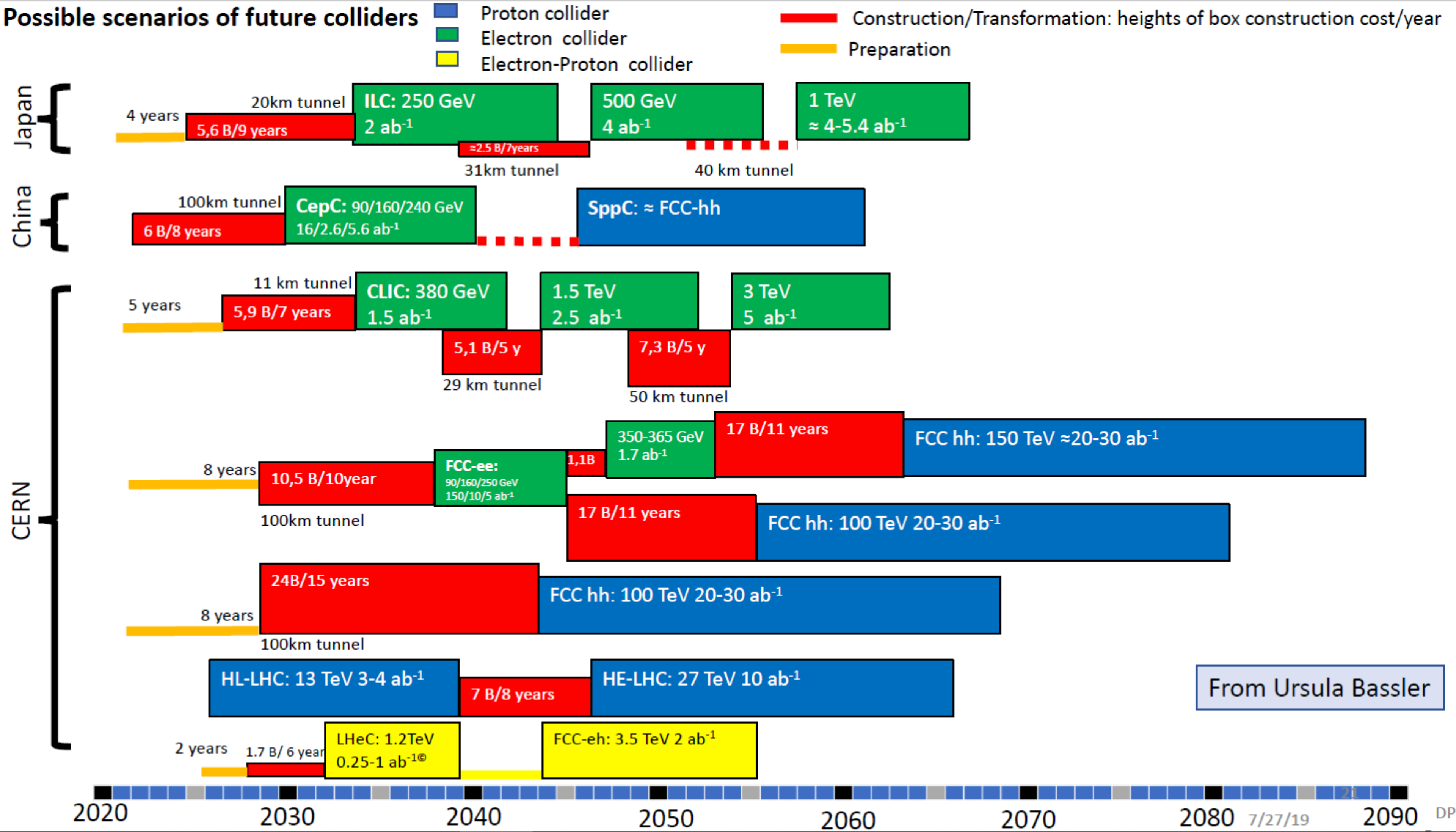
BROOKHAVEN NATIONAL LABORATORY
U.S. DEPARTMENT OF ENERGY

Outline

- Electron Positron collider physics
- Existing electron positron collider concepts
- ERL collider – what are the advantages
- Multi-pass ERL; CBETA and ER@CBAF
- ERL collider concept details
- Conclusions

Future High Energy Collider Timeline

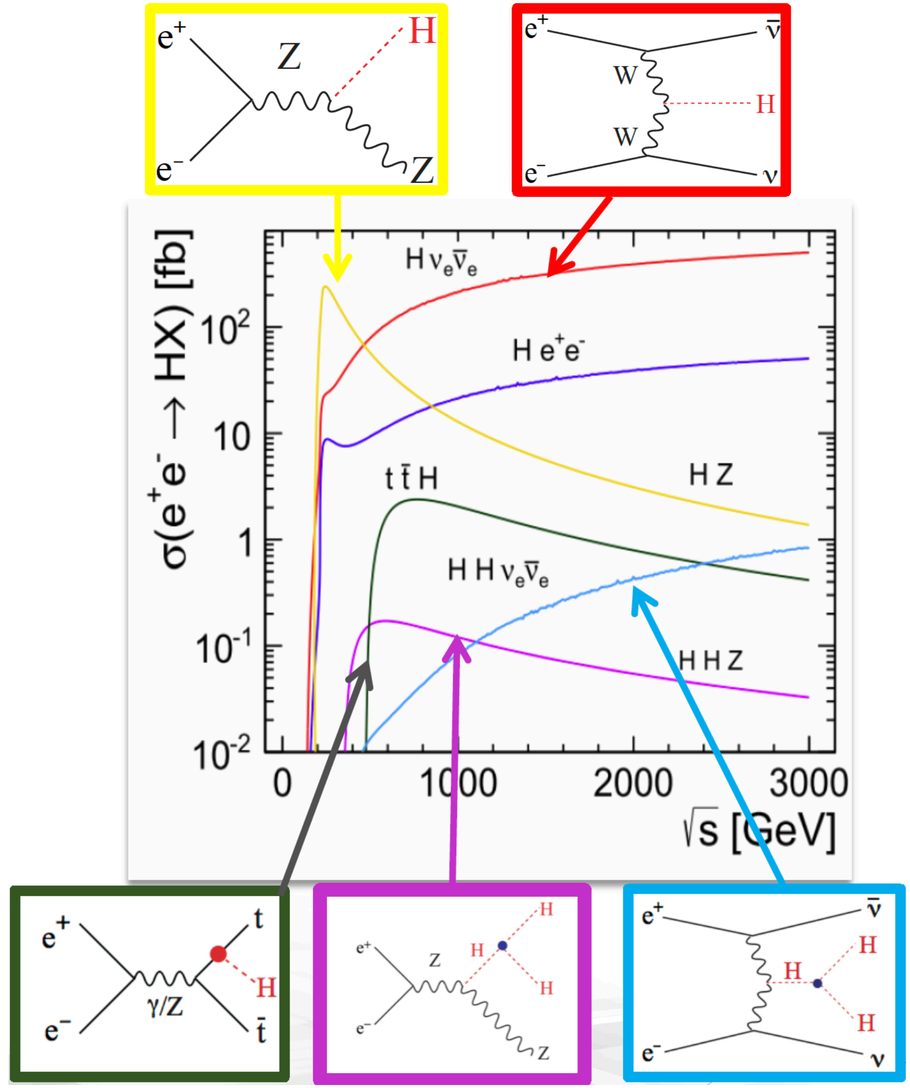
View of CERN Council President Ursula Bassler



Physics of electron positron colliders

- Precision measurements
- Search for deviations from SM
  - Need high luminosity and high energy, beam polarization is also very useful

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



Present electron-positron collider options

CERN

Future Circular Colliders (FCC)

	√s	Ring(km)
FCC-ee	90-365 GeV	100
FCC-hh	100 TeV	100

Integrated FCC program: FCC-ee as a first step, then FCC-hh

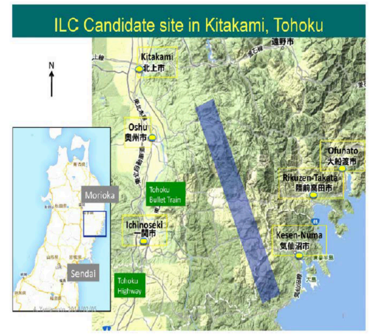
Options		
FCC-eh	3.5 TeV	Needs FCC-hh
HE-LHC	27 TeV	LHC tunnel
LE-FCC	37.5 TeV	100km

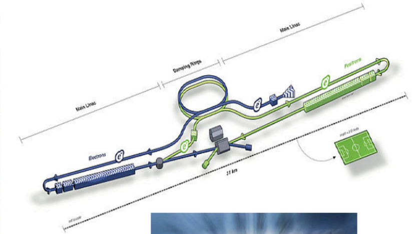
Conceptual Design Report in 2018

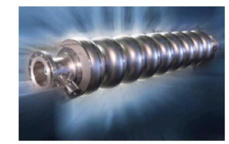
Common layout for FCC ee and hh

Japan

International Linear Collider

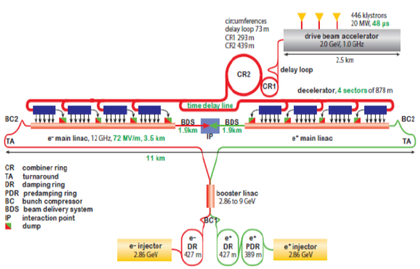


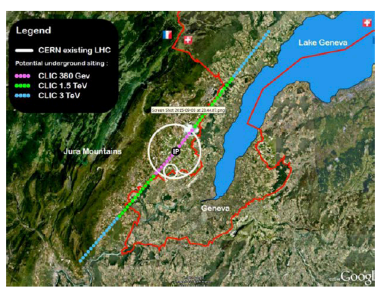




- ILC or International Linear Collider is e⁺e⁻ linear collider with the following main parameters
  - Center of mass energy 250 GeV (upgradeable to higher energies)
  - Luminosity >10^{34} cm^{-2}s^{-1}
- No synchrotron radiation, but long tunnel to accelerate to ~ 125 GeV/beam
  - Excellent Higgs factory with many Higgs production and decay channels accessible

CLIC Collider at CERN





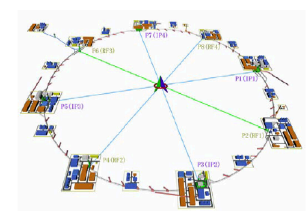
Parameter	Unit	380 GeV	3 TeV
Centre-of-mass energy	TeV	0.38	3
Total luminosity	10^{34}cm^{-2}s^{-1}	1.5	5.9
Luminosity above 99% of √s	10^{34}cm^{-2}s^{-1}	0.9	2.0
Repetition frequency	Hz	50	50
Number of bunches per train		352	312
Bunch separation	ns	0.5	0.5
Acceleration gradient	MV/m	72	100
Site length	km	11	50

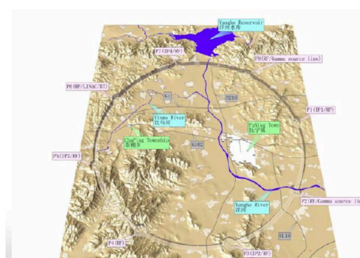
- CLIC is a linear e⁺e⁻ collider based on "warm" RF technology with 70+ MV/m acceleration
  - The only way to get to multi-TeV e⁺e⁻
- 11km long for 380 GeV in the center of mass
- Under active design development

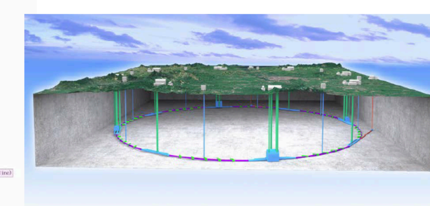
China

Proposals for Colliders in China: CepC and SppC

- CepC – Circular Electron Positron Collider
  - ~100 km long ring
  - 90-250 GeV in the center of mass
  - Z boson and Higgs factory
- SppC – Super Proton Collider
  - In the same ring as CepC
  - ~100 TeV with 16 T magnets



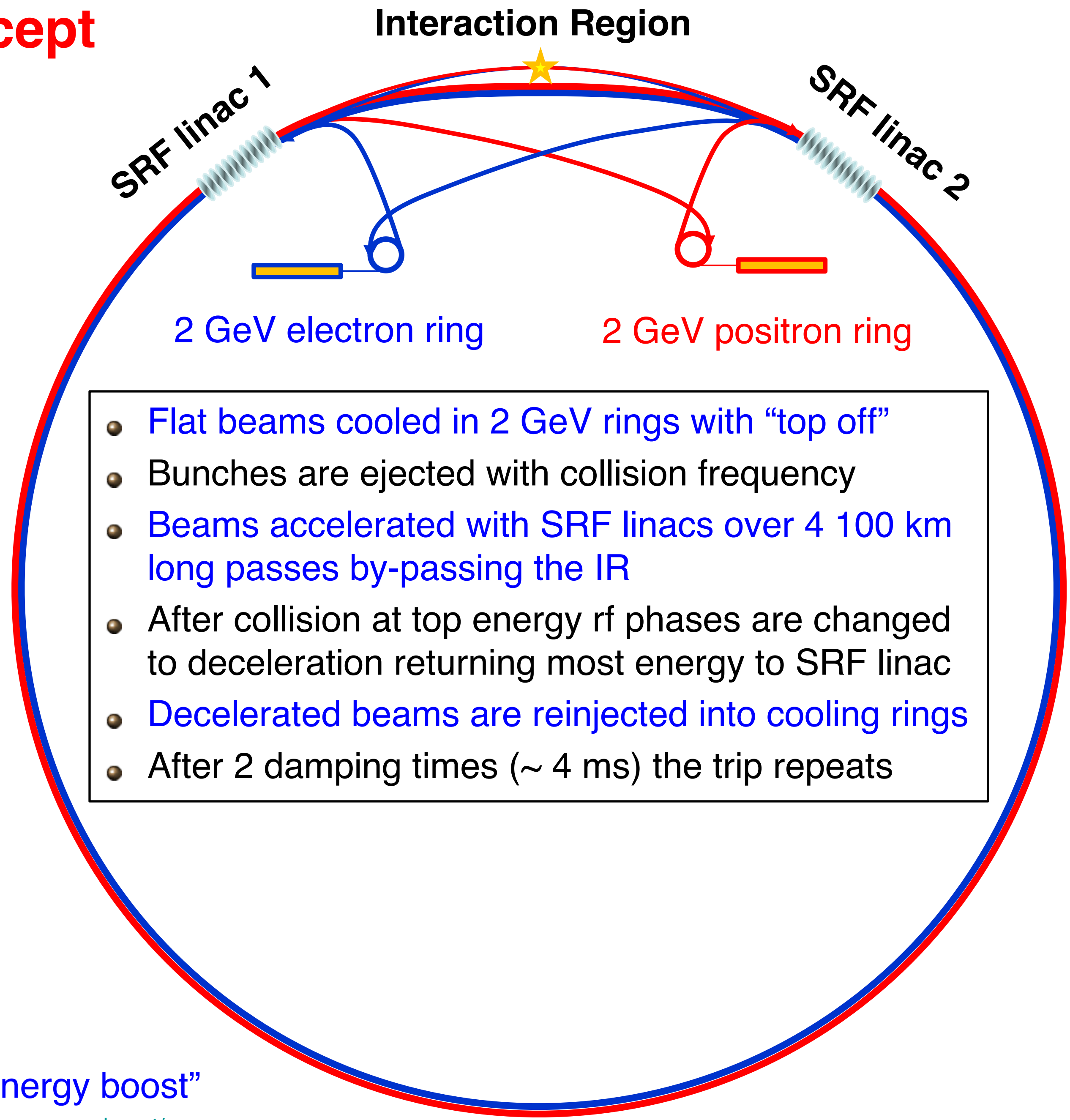




Luminosity dependencies

- Luminosity formula: $$L = f_c \frac{N_{e-}N_{e+}}{4\pi\sqrt{\beta_x^*\varepsilon_x}\sqrt{\beta_y^*\varepsilon_y}} = \frac{I_{e-}I_{e+}}{4\pi\sqrt{\beta_x^*\varepsilon_x}\sqrt{\beta_y^*\varepsilon_y}\cdot f_c \cdot e^2}$$
- Synchrotron radiation power: $P_{SR} = V_{SRe-}I_{e-} + V_{SRe+}I_{e+}$
- Reducing SR power requires lowering electron and positron currents
- To compensate this beta*, emittance or collision frequency must also be lowered: $$\sqrt{\beta_x^*\beta_y^*}\cdot\sqrt{\varepsilon_x\varepsilon_y}\cdot f_c$$
- For storage ring colliders the IR chromaticity limits how small beta* can be and the beam-beam tune spread limits how small the beam emittance can be: $$\xi_{x,y} = \frac{N\cdot r_o\cdot\beta^*_{x,y}}{2\pi\gamma\sigma_{x,y}(\sigma_x+\sigma_y)} < 0.1$$
- For ERL collider (and Linac collider) the beam-beam parameter can be much larger than 1. Better described by disruption parameter.

ERL collider concept



- Flat beams cooled in 2 GeV rings with “top off”
- 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 deceleration returning most energy to SRF linac
- Decelerated beams are reinjected into cooling rings
- After 2 damping times (~ 4 ms) the trip repeats

CERN Courier News:

“US proposal teases FCC-ee energy boost”

https://cerncourier.com/a/us-proposal-teases-fcc-ee-energy-boost/

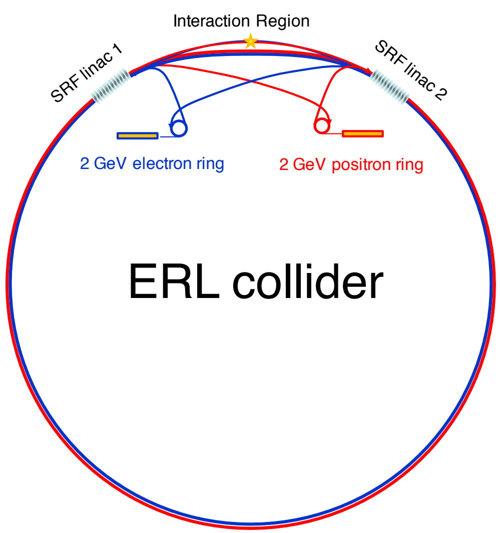
Parameters of ERL-based e^+e^- collider

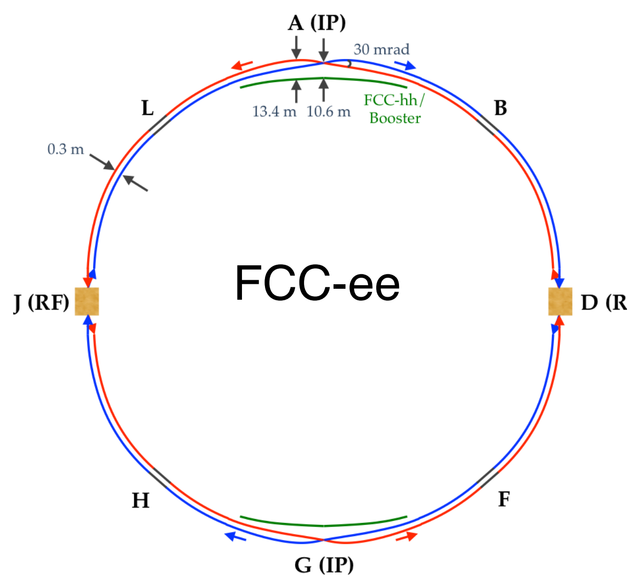
FCC ee (Z, W, HZ, $t\bar{t}$)

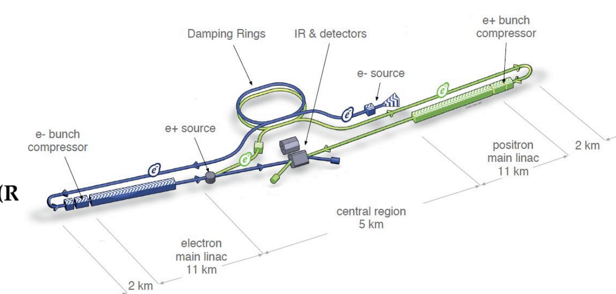
Mode of operation	Z	W	HZ	$t\bar{t}$	HHZ	H$t\bar{t}$
Beam energy, GeV	45.6	80.0	120.0	182.5	250.0	300
Bunch length (rms), mm	0.8	1.0	1.0	2.0	2.0	2.0
Bunch charge, nC	12.5	12.5	25.0	22.5	19.0	19.0
Bunch frequency, kHz	297	270	99	45	18	9
Beam current, mA	3.71	3.37	2.47	1.01	0.35	0.16
Beam emittance $\varepsilon_x/\varepsilon_y$ (norm.), μm rad	4/0.008	4/0.008	6/0.008	8/0.008	8/0.008	8/0.008
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	0.2/121	0.2/121
Energy loss during collision, GeV	0.05	0.16	0.28	0.30	0.55	0.95
Luminosity, 10^{34} cm^{-2} s^{-1}	67.4	86.6	77.8	31.4	13.8	8.6
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	30	30	30	30	30
Total reactive power, MW	338	539	593	369	175	96
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

Why is the power consumption of an ERL collider lower?

- In an ERL collider 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 an ERL all the beam energy is recovered during deceleration except for the radiated synchrotron light. A high energy ERL collider can be much more energy efficient than a linear collider for a large enough circumference, about 100 km for about 300 GeV beam energy.



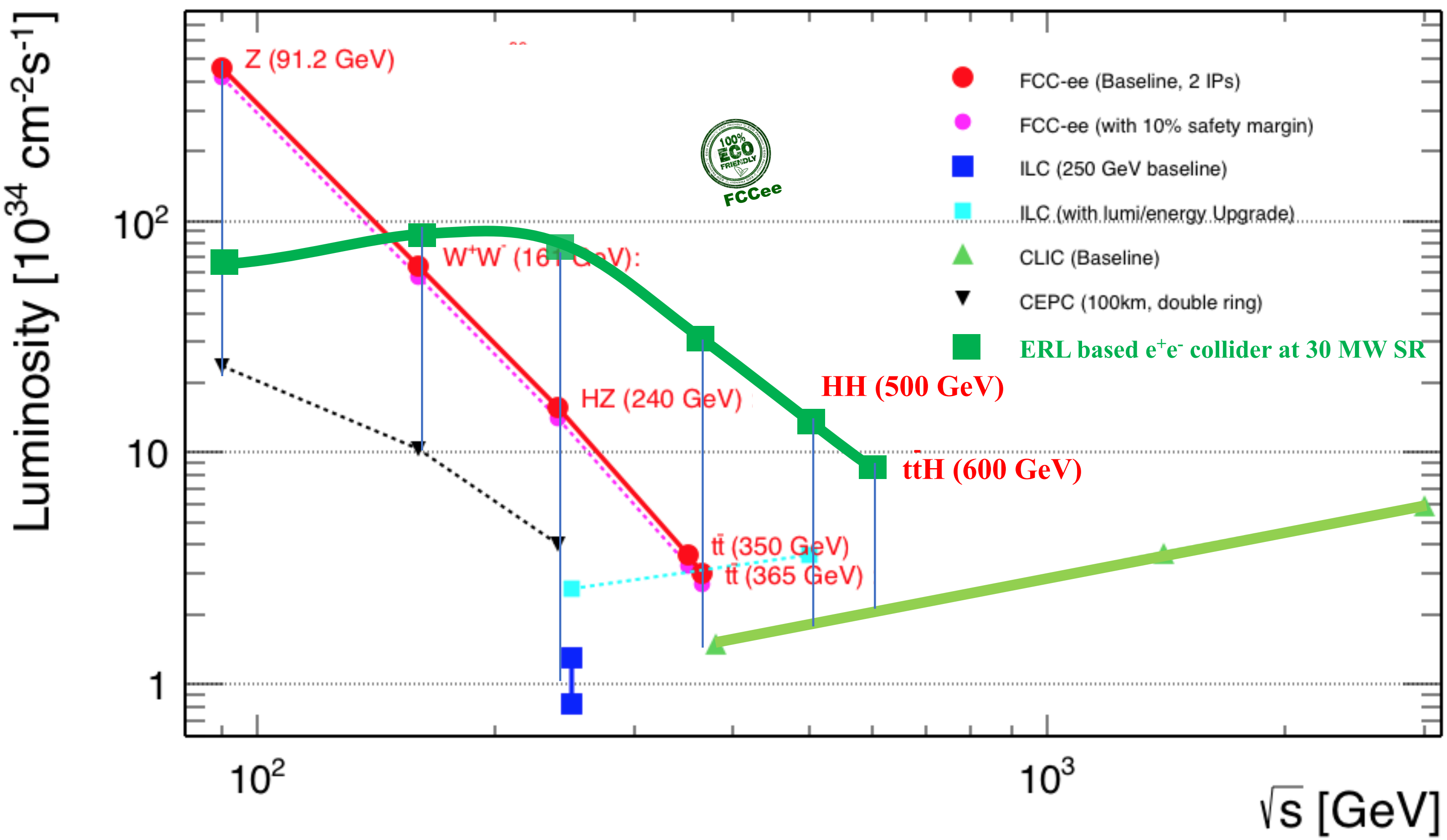




ILC (Japan)

same scale

High Energy e^+e^- Colliders



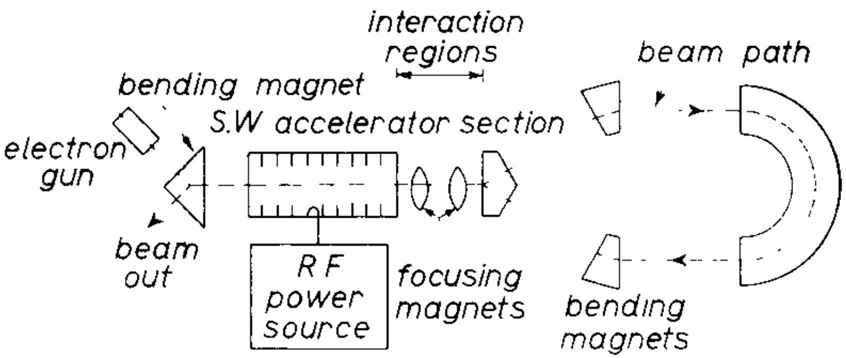
- ERL luminosity for 30 MW SR power; luminosity scales linear with SR power
- Luminosity can be shared (split) by multiple detectors.
- Potential of increasing total luminosity further with smaller beta*; requires detailed simulations

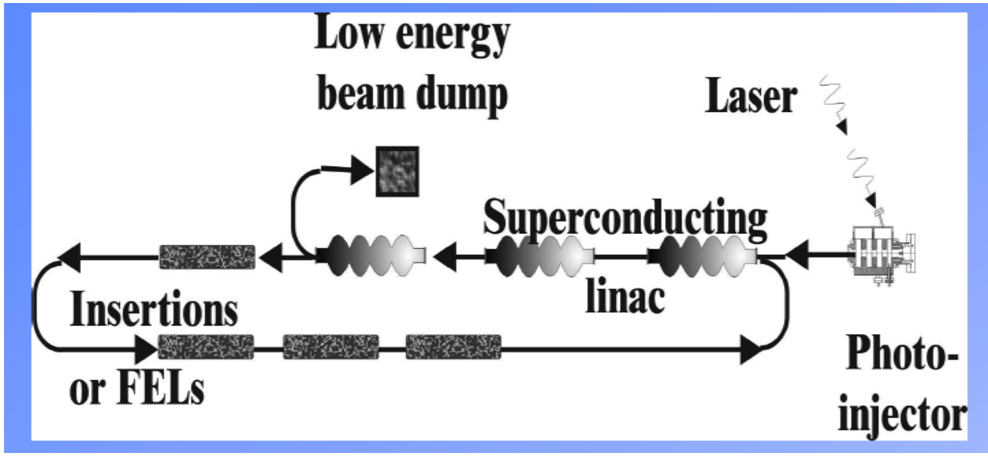
Comparison of Storage Ring, Linac, ERL colliders

Parameter	Storage ring	ERL coll.	ILC	CLIC
Beam energy, GeV	182.5	182.5	250	190
Bunch length (rms), mm	2.00	2.00	0.30	0.07
Bunch charge, nC	46.2	22.5	3.2	0.8
Bunch frequency, kHz	116.9	45	6.5	17.6
Beam current, mA	5.400	1.010	0.021	0.015
Beam emittance $\varepsilon_x/\varepsilon_y$ (norm.), μm rad	518/0.964	8/0.008	10/0.035	1/0.030
IP beta function β_x/β_y, cm	100/0.20	100/0.20	10/0.05	80/0.01
Beam aspect ratio at IP σ_x/σ_y	518	707	239	516
Disruption parameter, D_x/D_y	N/A	0.20/143.0	0.30/24.3	0.24/12.5
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 ERL-ERL Lumi., MW	2093.3	30.0	181.4	117.2
Luminosity per lost power, 10^{34} cm^{-2} s^{-1}/100 MW	1.5	104.7	17.3	26.8

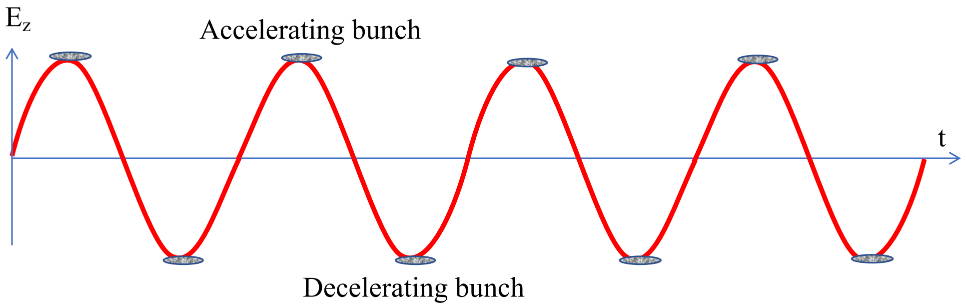
Superconducting RF Energy Recovery Linac

- Invented by M. Tigner, Nuovo Cimento **37** 1228 (1965)



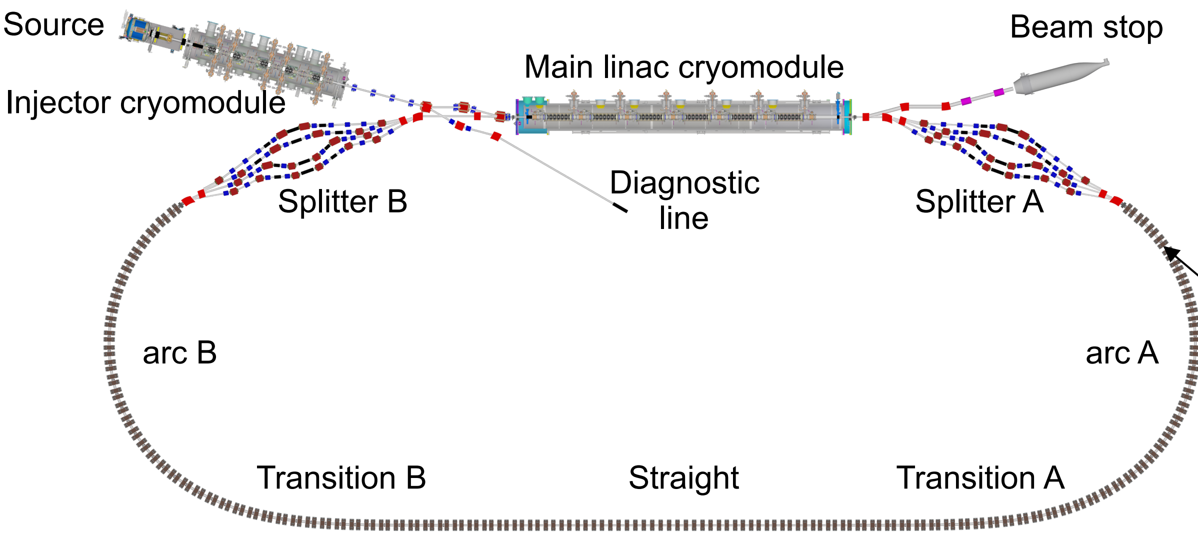


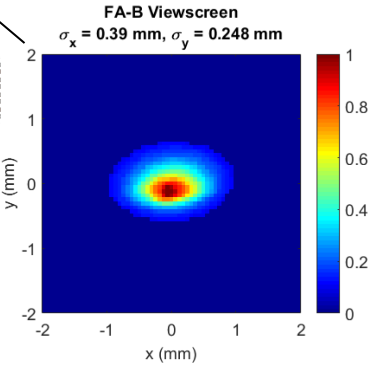
- followed by Stanford, BINP, Jefferson Lab, JAERI, BNL, Cornell, LBNL, Daresbury *and more* ...



CBETA – 150 MeV multi-pass test-ERL
(NY State funded, BNL-Cornell Collaboration)

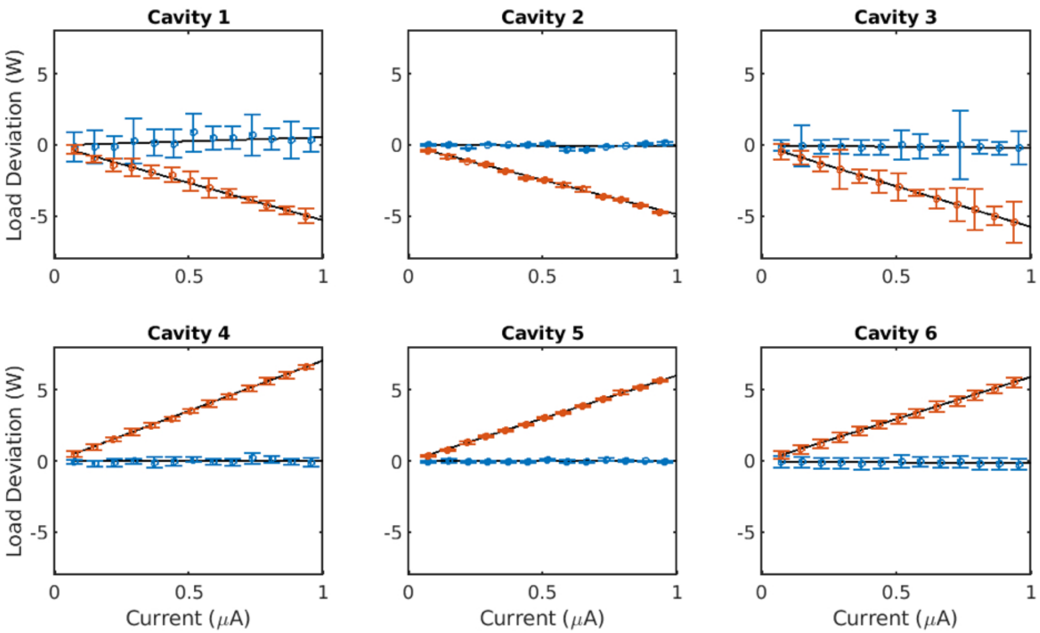
- Uses existing 6 MeV low-emittance and high-current injector and 36 MeV CW 1.3 GHz SRF Linac at Cornell
- Energy Recovery Linac (ERL) with single four-pass recirculation arc with x4 momentum range
- One-pass ERL demonstrated, three-pass RLA demonstrated.
- Four-pass ERL by December 2019
- Active collaboration with JLab, CERN, Orsay (LHeC test accel. PERLE), Berlin-Pro, Mainz, STFC (UK)

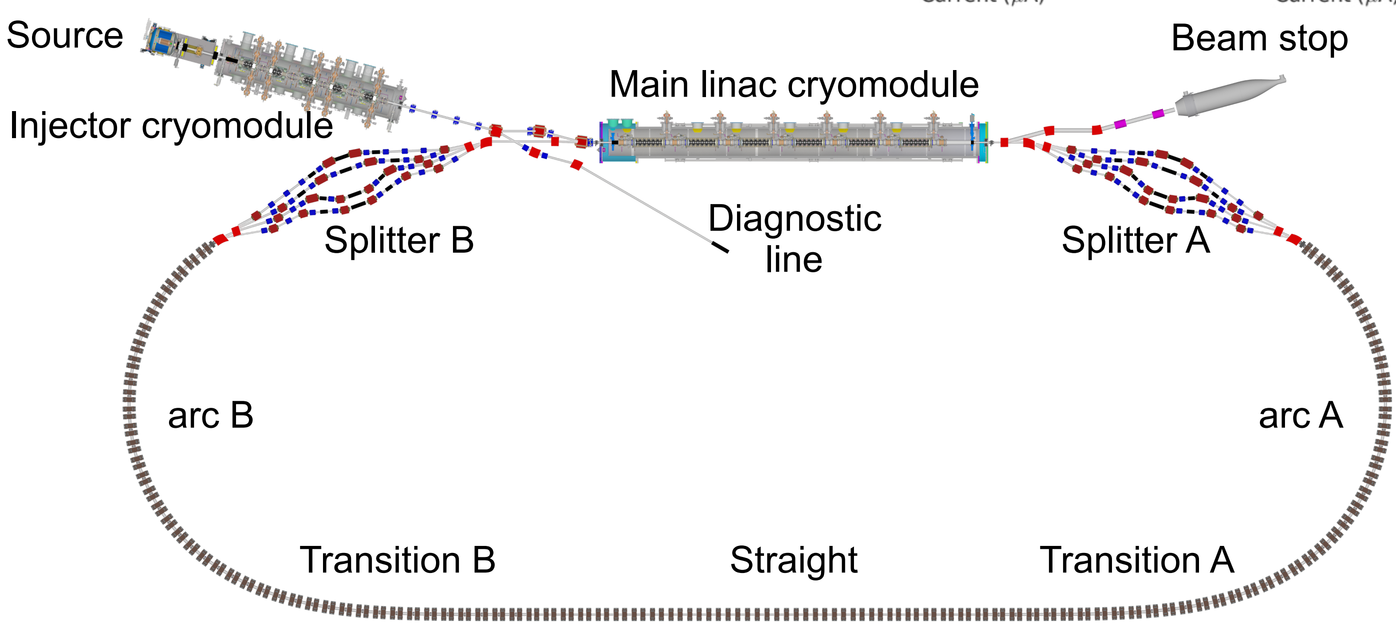




CBETA – single-pass ERL demonstration

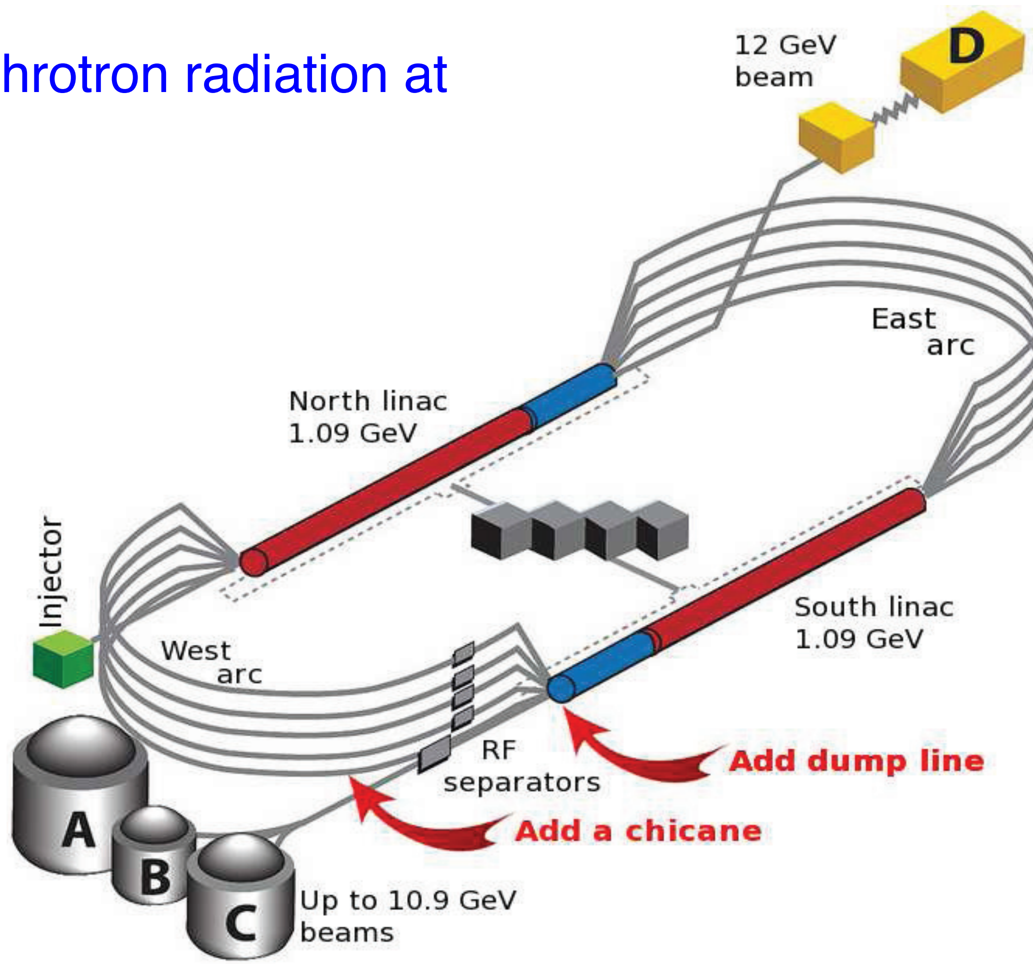
- Measured rf power load in main linac for single pass mode (orange) and energy recovering mode (blue)





ER@CEBAF proposal: 5-pass ERL test using CEBAF RLA

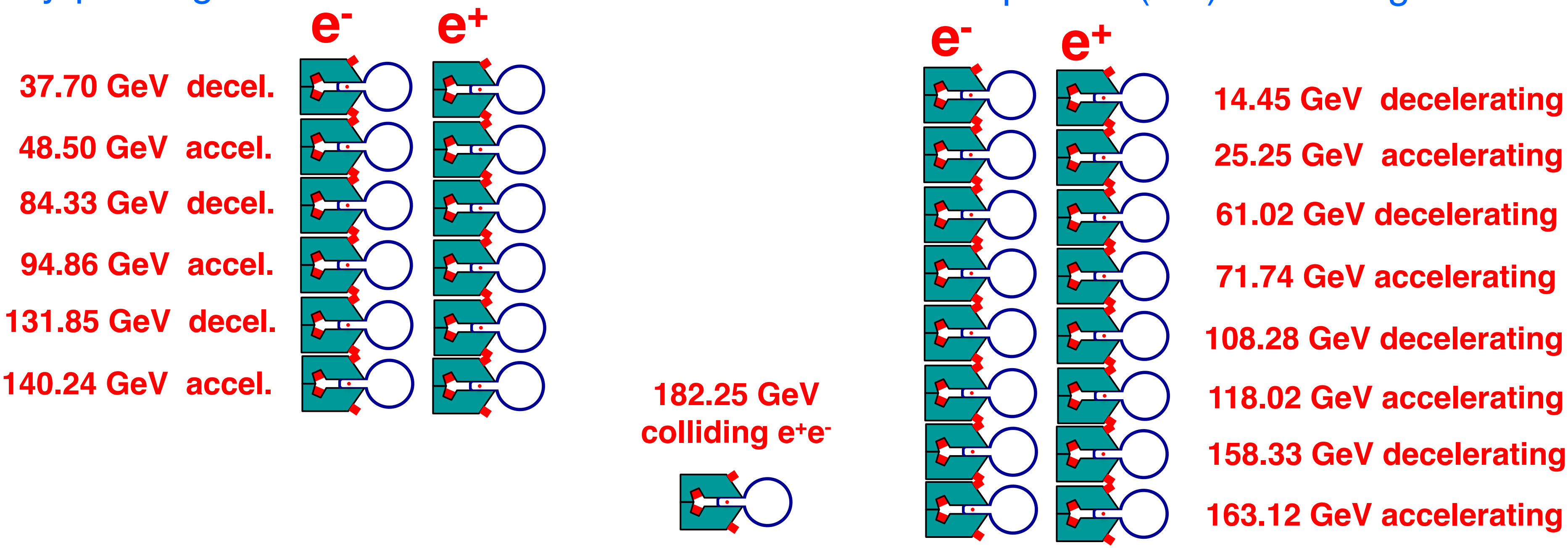
- 5-pass ERL test with top energy of 7 GeV
- Low beam intensity
- First ERL test with synchrotron radiation at high energy passes



Possible layout of arcs for 4-pass 182.5 GeV ERL

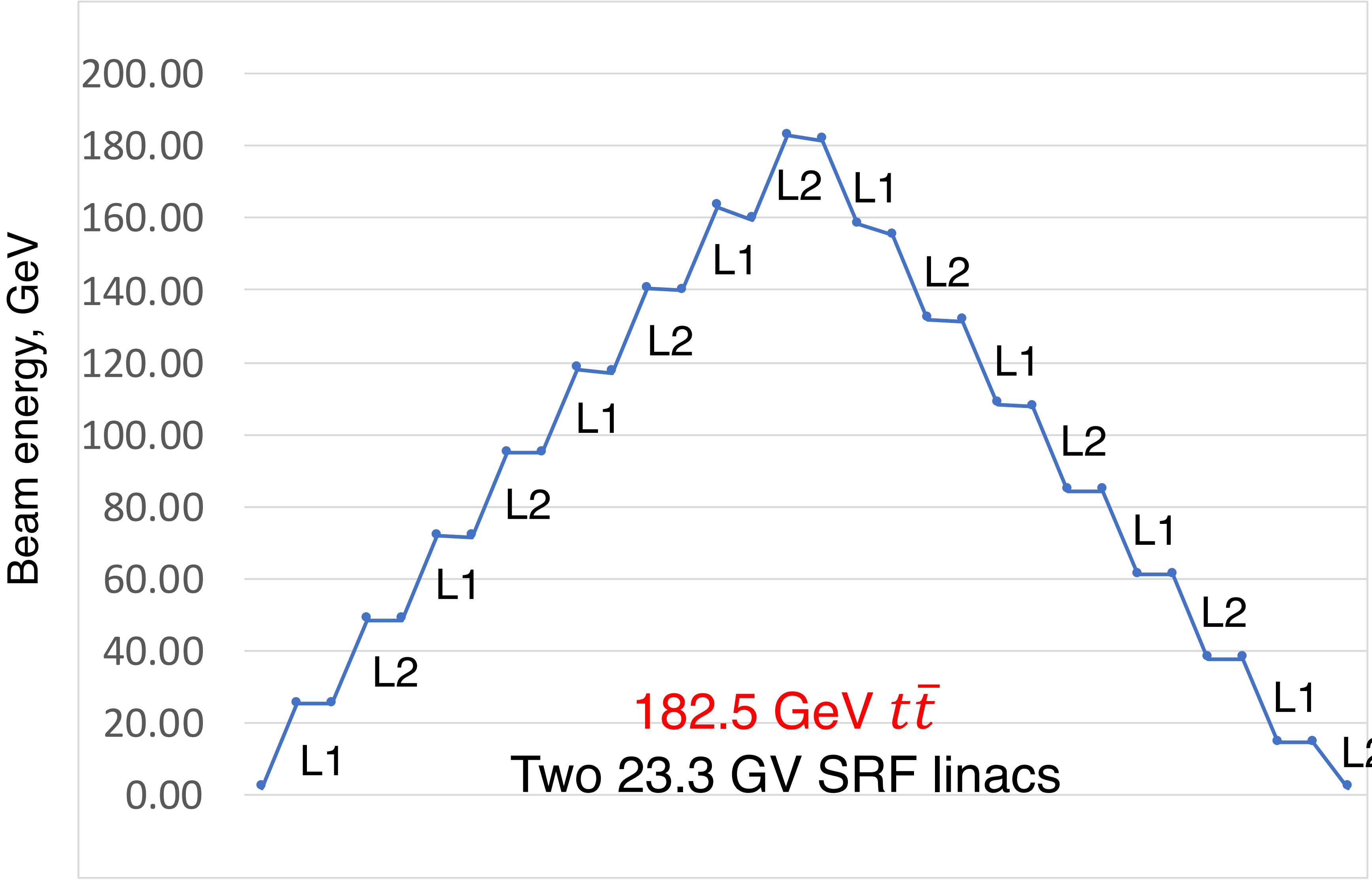
Electrons and positrons alternate the inside and outside passes

By-passing the IR: Main portion (5/6) of the ring arcs:



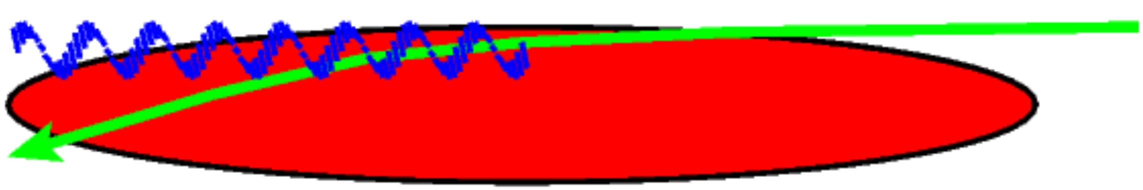
Small gap magnets with 5 mm gap; prototyped for eRHIC at 0.43 T:
ERL collider needs only 0.04 T, e.g. they are very low power consumption magnets

Electron and positron beam energy evolutions



Beamstrahlung

- Beamstrahlung is synchrotron radiation emitted due to the strong EM field of the opposing beam
- Beamstrahlung can cause energy loss resulting in large energy spread and even particle loss.
- Using very flat beams minimizes beamstrahlung by minimizing the EM fields
- The level of beamstrahlung is expressed by the beamstrahlung parameter Υ, the EM field in the particle's rest frame in units of the critical field B_c where nonlinear QED effects start.
- The ERL collider has $\Upsilon = 0.004$, which corresponds to a field of about 50 T and causes an energy spread of about 0.16%.

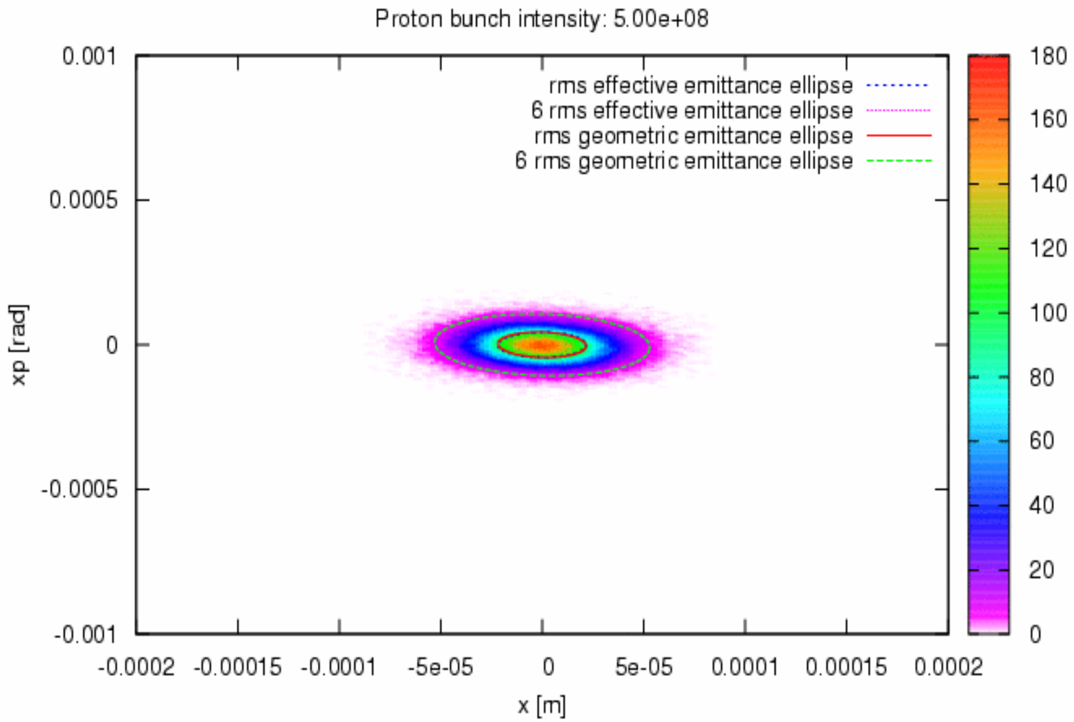


Courtesy of D. Schulte

Colliding beam disruption

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

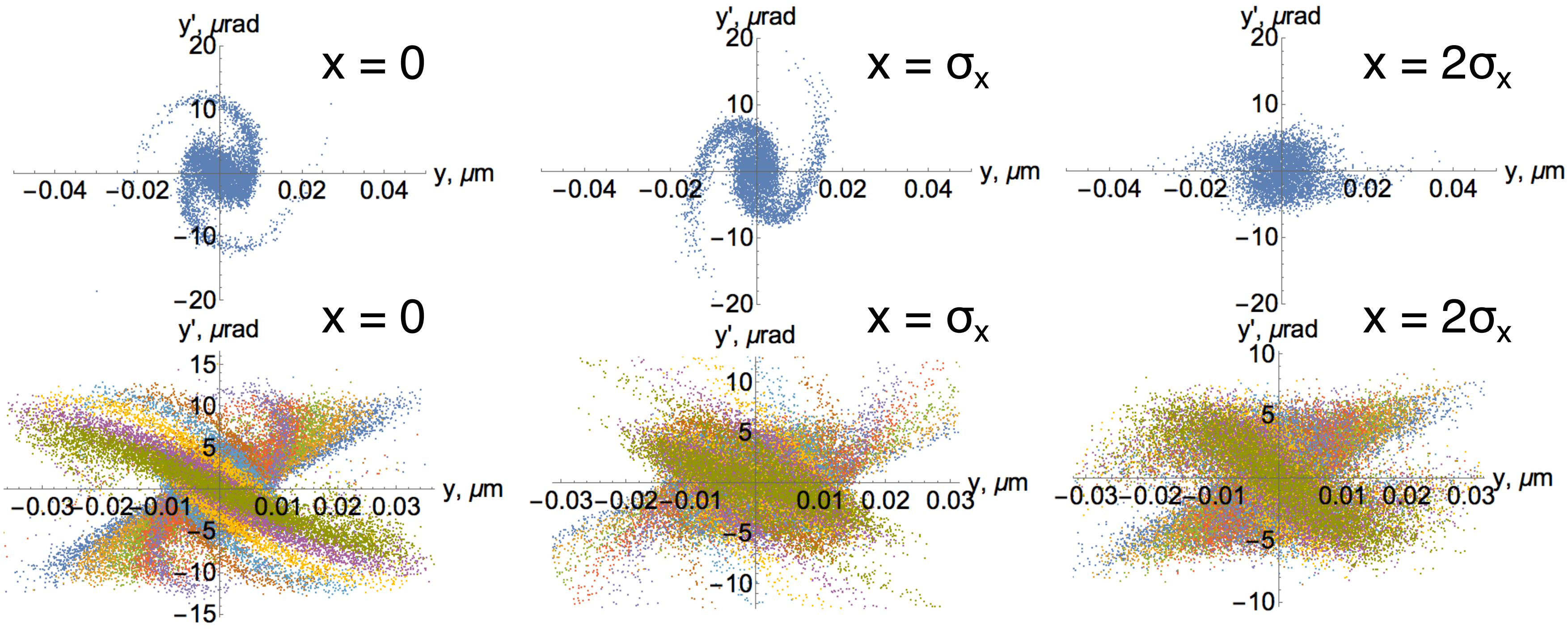
- Electron-proton collisions (Linac-Ring eRHIC) with D=150 leads to a doubling of the emittance:



Courtesy of Y. Hao

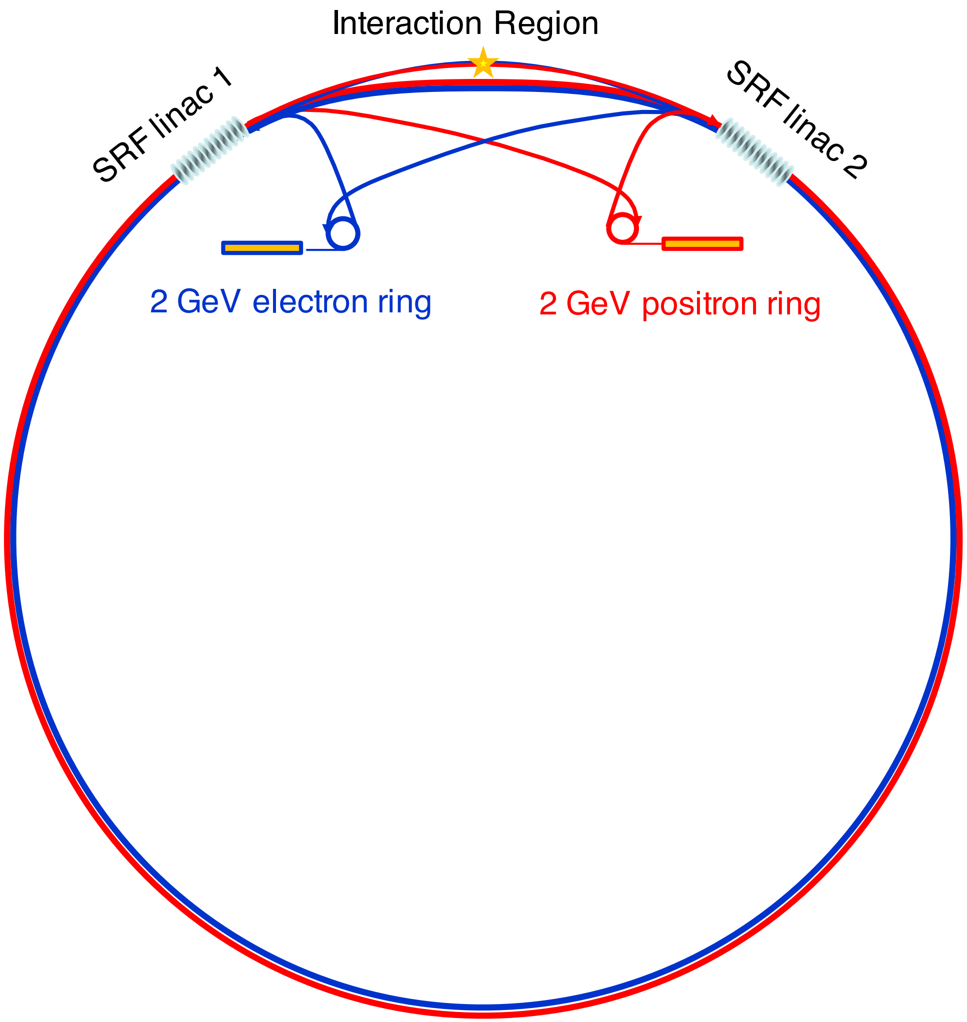
Strong-strong collisions of flat beams

- 2D simulation of strong-strong beam-beam interaction
- Below is vertical phase space of beam after the collision. Top is for slice in the center of the bunch, bottom is for 10 slices covering the whole bunch.
- 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 are needed but are very computation intensive



ERL collider 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. First estimates shows 0.5% polarization loss from collision.
- 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.



Conclusions

- 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 H$t\bar{t}$ 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
- The ERL collider concept is stand alone – it does not need to build on an existing injector complex. Although it would fit well into the planned 100 km FCC tunnel at CERN it could be built anywhere.
- Extensive detailed studies are needed to fully validate the concept