A high luminosity SC e+e- twin linear collider with energy recovery

Valery Telnov

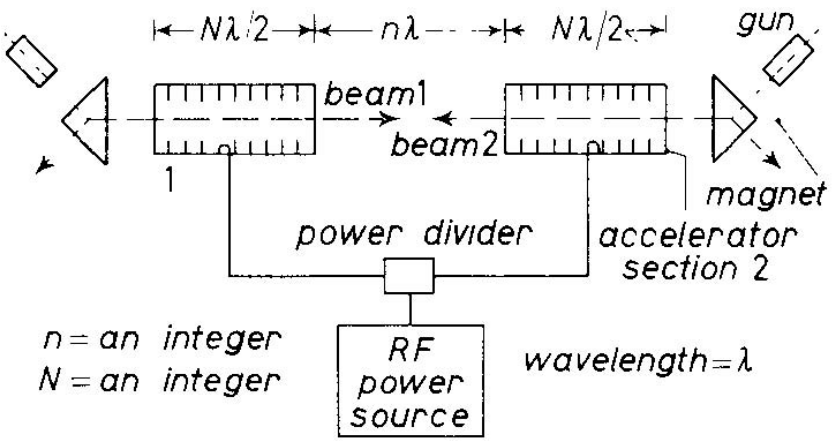
Budker INP and Novosibirsk State Univ.

LCWS 2021

The main advantage of LC – no synch. radiation → higher accessible energies
Main disadvantage of LC – beams are used only once → inefficient use of electricity

M.Tigner (1965) Nuovo Cim. 37, 1228 (1965):

«A possible apparatus for electron clashing-beam experiments»

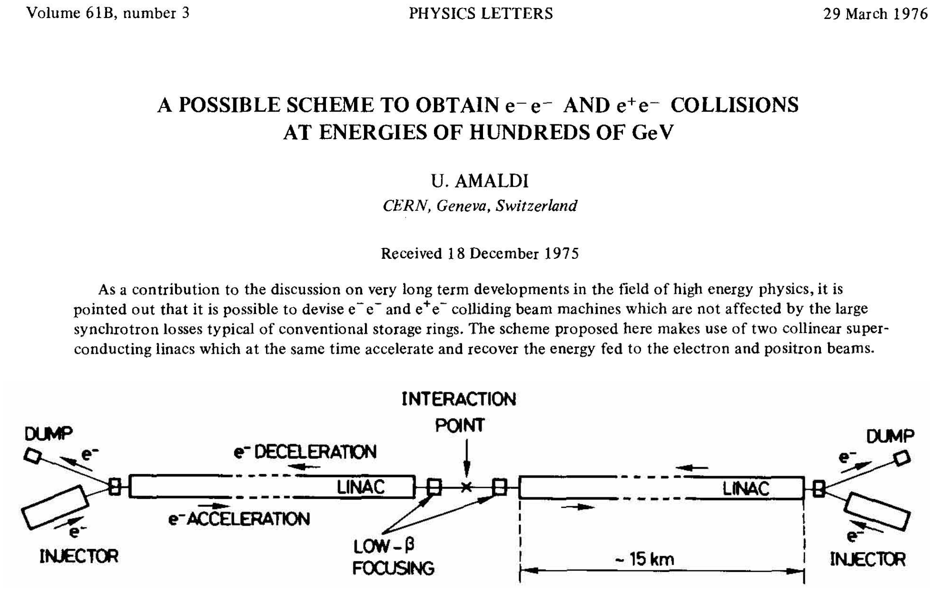


...by the introduction of super-conducting accelerator sections one may avoid the high power necessary to establish the accelerating field

….it can be arranged that electrons leaving accelerator 1 arrive at acce-lerator 2 at just the right phase to be decelerated in accelerator 2, thus giving back their energy to the field.

This paper did not attract attention, there were no citations until 1979, when U.Amaldi discovered this paper

U. Amaldi (1976) Phys. Lett. 61B, 313



Volume 61B, number 3 PHYSICS LETTERS 29 March 1976

A POSSIBLE SCHEME TO OBTAIN e^-e^- AND e^+e^- COLLISIONS AT ENERGIES OF HUNDREDS OF GeV

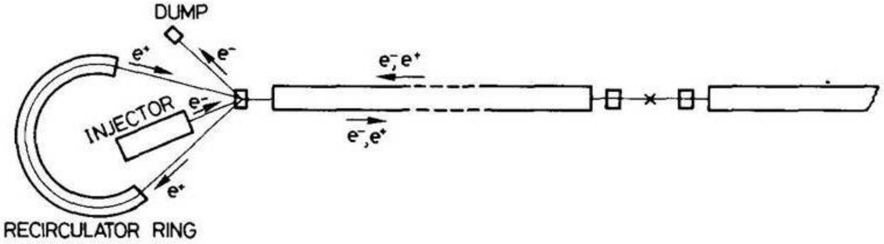
U. AMALDI

CERN, Geneva, Switzerland

Received 18 December 1975

As a contribution to the discussion on very long term developments in the field of high energy physics, it is pointed out that it is possible to devise e^-e^- and e^+e^- colliding beam machines which are not affected by the large synchrotron losses typical of conventional storage rings. The scheme proposed here makes use of two collinear superconducting linacs which at the same time accelerate and recover the energy fed to the electron and positron beams.

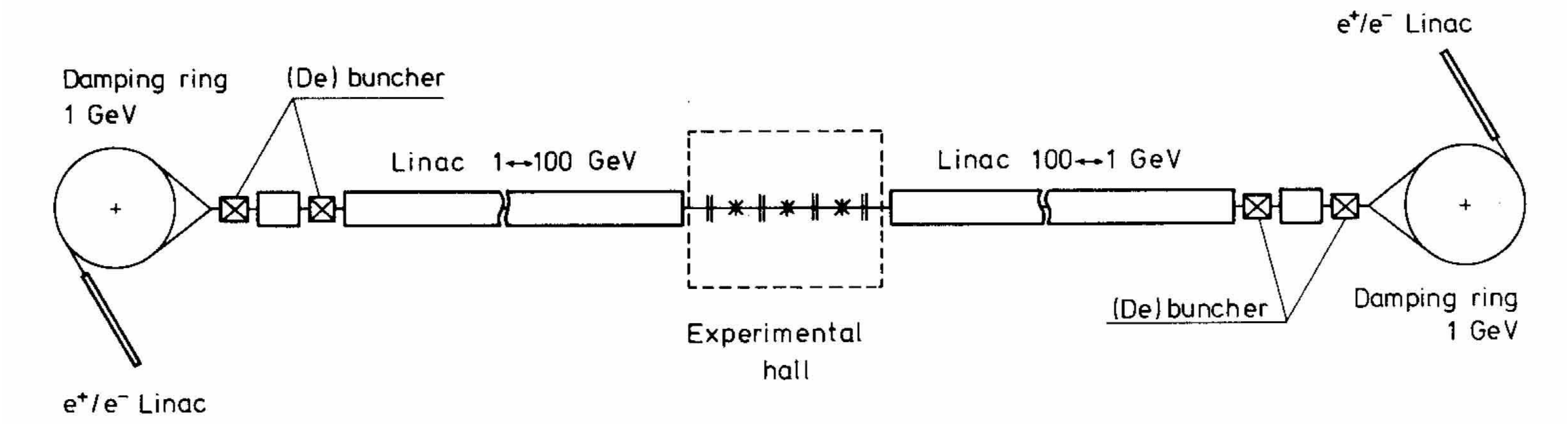
In this scheme the electron and positron bunches are dumped after one-pass energy recovery



In this scheme the electron bunches are dumped after a single traversal while, to save positron current, the positrons are recirculated in a low energy ring.

SC linear collider, working in continues mode (with a duty cicle ~1/30)

H. Gerke and K. Steffen, Note on a 45 - 100 GeV electron swing colliding beam accelerator, DESY-PET 79/06 (1979).



Here bunchers-debanchers reduce the energy spread in damping rings.

Only one bunch presents in each moment in the half linac, that restricts the collision rate f~30 kHz. The luminosity, with account of duty cycle 1/30, is low enough.

One remark:
nobody noticed that the same final focus system cannot focus both e+ and e- !
May be it will work, but with additional factor 1/2 in the luminosity (each second collision).

Problems of SC LC with energy recovery

1) Q-factor is not high enough to work continuously with highest accel. field (only with some duty cycle).
2) The FF-system works only for bunches with one charge sign.
3) Parasitic collisions in linac do not allow a high collision rate.

In continuous mode (like circular colliders) the luminosity is restricted by beam-beam strength parameter at the interaction point (IP)

$$\xi_y = \frac{N r_e \beta_y^*}{2\pi\gamma\sigma_x^*\sigma_y^*} \le 0.1$$

At the IP

$$\xi_y^* \propto \frac{\beta_y^*}{\sqrt{\beta_x^*\beta_y^*}} = \sqrt{\frac{\beta_y^*}{\beta_x^*}} \ll 1;$$

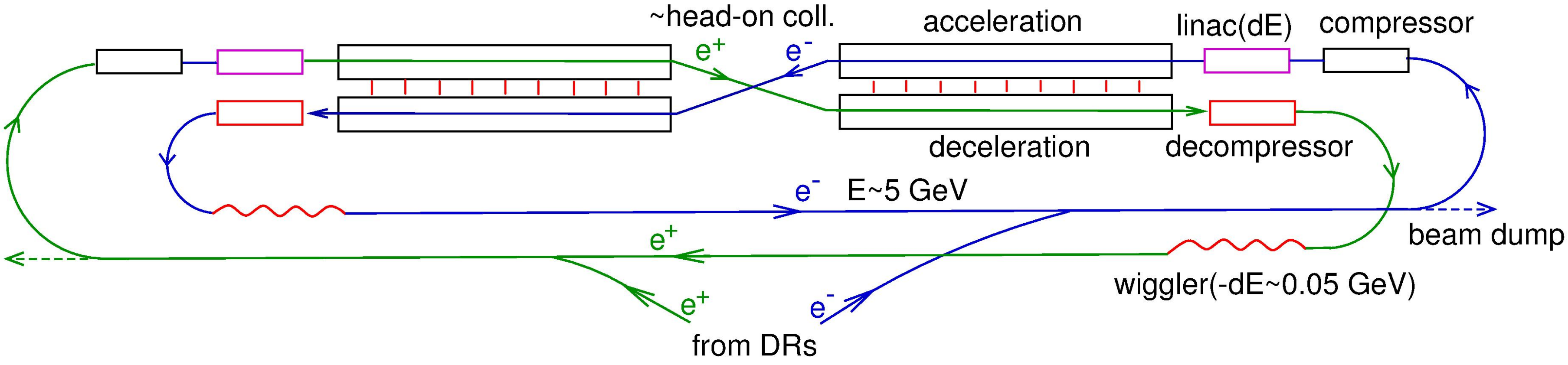
In the linac

$$\xi_y \propto \frac{\beta_y}{\sqrt{\beta_x\beta_y}} = \sqrt{\frac{\beta_y}{\beta_x}} \underline{\approx 1 \gg \xi_y^*}.$$

Collisions inside the linac are more severe for beam stability, therefore should be avoided.

The proposed LC scheme

Twin LC with the energy recovery



1) LC consists of two parallel SC linac connected with each other with rf-coulpers, so that the fields are equal at any time. One line is for acceleration, the other for deceleration.
2) Damping is provided by wigglers (no damping rings) at the “return” energy about E~5 GeV. The energy loss per turn dE/E~1/100. Damping is needed to reduce the energy spread arising from collision of beams.
3) In the presence of a return path, e + and e- are always correctly focused by their own FF.
4) The duration of one cycle (several seconds) is determined by the refrigeration system (rise of temperature on ~0.1 K at 1.8 K).

Energy spread in beam collisions

The increase of the beam energy spread in one beam collision $(n_\gamma < 1)$

$$\Delta\sigma_E^2 = n_\gamma \left\langle \varepsilon_\gamma^2 \right\rangle = \frac{\left\langle \varepsilon_\gamma^2 \right\rangle}{\left\langle \varepsilon_\gamma \right\rangle^2} \frac{\left(n_\gamma \left\langle \varepsilon_\gamma \right\rangle \right)^2}{n_\gamma} \sim \frac{5.5(\Delta E)^2}{n_\gamma} \quad \text{where} \quad \frac{\Delta E}{E_0} \approx \frac{0.84 r_e^3 N^2 \gamma}{\sigma_z \sigma_x^2}, \qquad n_\gamma \approx 2.16 \frac{\alpha r_e N}{\sigma_x}$$

ΔE – the average energy loss, n_γ – number of photons per one beam collision

Thus $\dfrac{\Delta\sigma_E^2}{E^2} \approx 1{,}8 \dfrac{N^3 r_e^5 \gamma^2}{\alpha \sigma_x^3 \sigma_z^2}$. The equilibrium is reached at $\dfrac{\Delta\sigma_E^2}{\sigma_E^2} = 2\dfrac{\delta E}{E}$,

where δE is the energy loss in damping wigglers at the energy E~5 GeV.

This gives the requirement to the beams due to beamstrahlung at the IP:

$$\frac{N^3}{\sigma_x^3 \sigma_z^2} < b \approx \frac{8 \cdot 10^{-3}}{r_e^5 \gamma^2} \left(\frac{\sigma_E}{E_0} \right)^2 \frac{\delta E}{E} \qquad (1)$$

The second restriction is due to the tune shift: $\xi_y = \dfrac{N r_e \sigma_z}{2\pi\gamma\sigma_x\sigma_y} \le 0.1 \quad (\text{for } \beta_y \approx \sigma_z) \ \ (2).$

From (1) and (2) we obtain beam sizes

$$\sigma_x \approx 0.7 \frac{N r_e^{9/7}}{\xi^{4/7} \varepsilon_{ny}^{2/7} \left(\sigma_E / E_0 \right)^{2/7} \left(\delta E / E \right)^{1/7}}, \qquad \sigma_z \approx 19.2 \frac{\xi^{6/7} \varepsilon_{ny}^{3/7} r_e^{4/7} \gamma}{\left(\sigma_E / E_0 \right)^{4/7} \left(\delta E / E \right)^{2/7}}.$$

Luminosity

$$L = \frac{N^2 f}{4\pi\sigma_x\sigma_y} = 2.6\cdot10^{-2}\,\frac{Nf\,\xi^{1/7}}{\varepsilon_{ny}^{3/7} r_e^{11/7}}\left(\frac{\sigma_E}{E_0}\right)^{4/7}\left(\frac{\delta E}{E}\right)^{2/7}.$$

does not depend on E_0

For $\xi = 0.1,\ \varepsilon_{ny} = 3\cdot10^{-6}\,\mathrm{cm},\ \sigma_E/E_0 = 2\cdot10^{-3},\ \delta E/E = 10^{-2}$, we get

$$\sigma_x \approx 8.2\left(\frac{N}{10^{10}}\right)\,\mu\mathrm{m}, \qquad \sigma_z = 0.25\,\frac{E[\mathrm{GeV}]}{125},\ \mathrm{mm}.$$

$$\boxed{L \approx 5.3\cdot10^{36}\,\frac{(N/10^{10})}{d[\mathrm{m}]} \approx 1.1\cdot10^{37} I[\mathrm{A}]\ \mathrm{cm}^{-2}\mathrm{s}^{-1}.}$$

For N=10^{10}, d=3 m → $L = 1.75\cdot10^{36}$ at P_{SR}=8 MW/beam
(I=0.16 A)

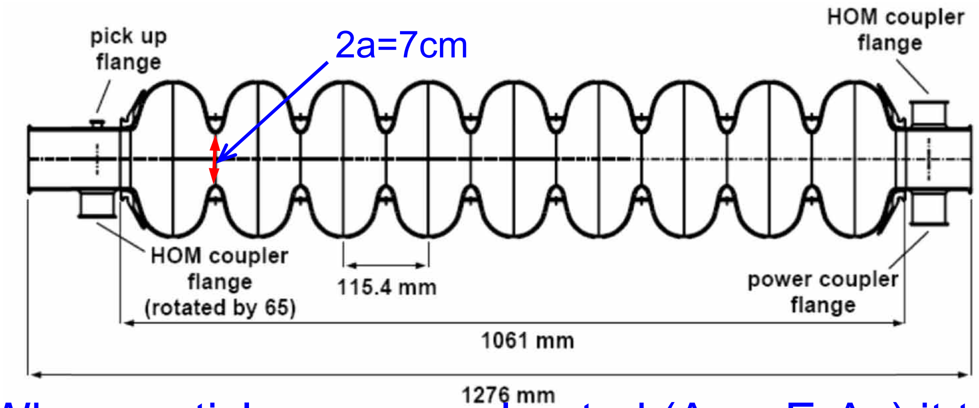
$1.45\cdot10^{36}$ 4 MW

$1.2\cdot10^{36}$ 2 MW

For comparison, at FCC(250) L=$8.5\cdot10^{34}$ at P_{SR}=50 MW/beam

High order mode losses

TESLA-ILC, 1.3 GHz



When particles are accelerated ($\Delta\varepsilon = eE_0\Delta z$) it takes energy from the cavity due to interference of E_0 and the wave E_r, radiated by the bunch to the cavity.

When particles are decelerated ($\Delta\varepsilon = -eE_0\Delta z$) it returns the energy to the cavity back, but only that in fundamental cavity mode.

However, higher radiation modes (longitudinal wake fields ~ bunch charge) lead to energy losses both during acceleration and deceleration → energy recovery not 100%.

The energy loss by one electron per unit length (in the long cavity structure), incl. the main mode $\frac{d\varepsilon}{dz} \sim \frac{2e^2N}{a^2}$, a – iris radius (R.Palmer), very weak dependence on σ_z.

Numerical simulation for TESLA structures gives wakefield energy losses for σ_z=400 μm

$$\frac{d\varepsilon}{dz} \approx 17.5\left(\frac{N}{10^{10}}\right)\frac{\text{keV}}{\text{m}}$$

that is ~0.1% of the acceleration gradient $G \approx (20-30)\frac{\text{MeV}}{\text{m}}$

The efficiency of energy recovery ~99.8%.

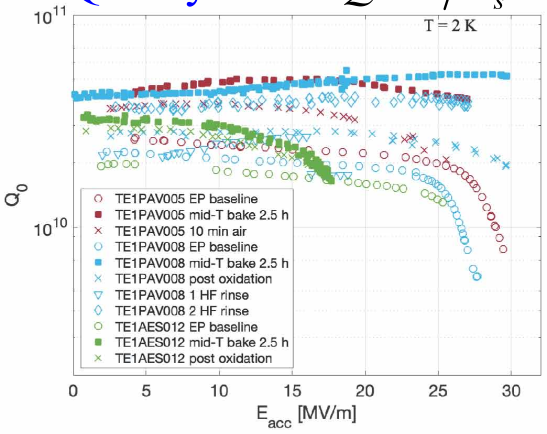
Remark: HOMs do not dissipate in cavities but are removed by special couplers to a high-T region.

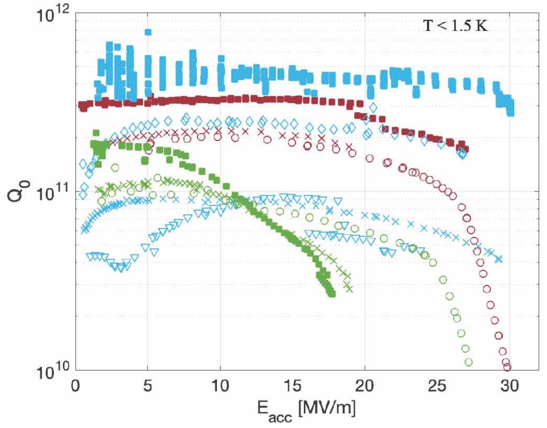
Refrigeration

Surface resistance R_s in ideal case

$$R_{BCS} \propto \frac{f^2}{T}\exp\left(-\frac{16.2}{T}\right)$$

Quality factor $Q \propto 1/R_s$





S. Rosen et al, arxiv 1907.00147

E_{acc} ~20 MV/m:

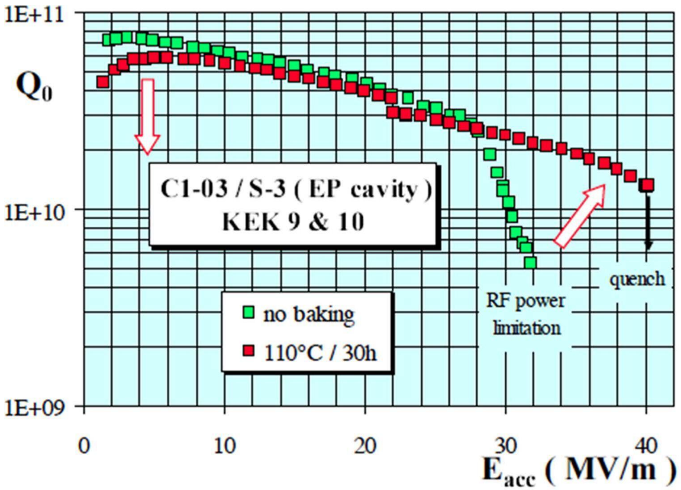
Q_0 of $(3\text{-}4)10^{11}$ at T<1.5 K

Q_0 ~$5\cdot10^{10}$ at 2.0 K.

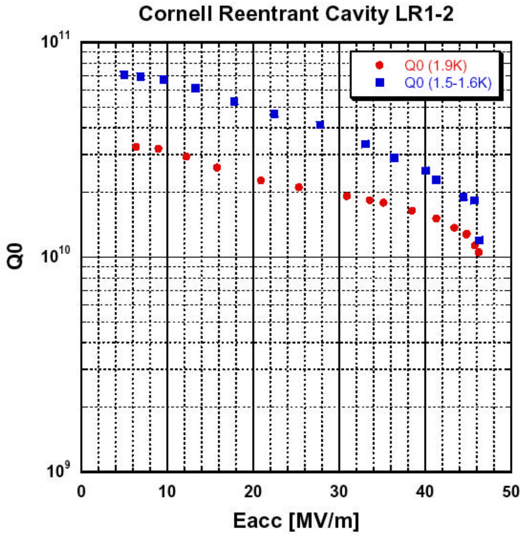
Following LCLS-II assume $Q=3\cdot10^{10}$ at T=1.8 K,
at E=20 MeV/m the heat is about 1 kW/GeV.
The refrigeration efficiency $(1.8/300)\times0.25=1.5\cdot10^{-3}$.
Twin LC(250) in continues mode needs P_{ref}~330 MW.

The duty cycle 1/3 will be sufficient.

H.Padamsee: Q_0 values between $(3–4)\times10^{10}$ at 2 K and 8×10^{10} at 1.8 K can be obtained at 15–20 MV m^{-1}



World Record Eacc= 46.4 MV/m, **CW**



Total power

For $N=10^{10}$, d=3 m , DC=1/3, 2E=250 GeV.

$$L \approx 0.5 \cdot 10^{36}\ \mathrm{cm}^{-2} s^{-1}$$

The number of circulating bunches n_b =2×(30 km/3 m) = 2×10^4 (both beams) .
If bunches are prepared once per >3 s, the average power for beam generation (with ε=10%) will be less than 5 MW.

Radiation in wigglers P_{SR}~5 MW (at ε=50%)

High mode losses P ~ 45 MW (at ε=50%)

Refrigeration power P_{ref} ~110 MW

The total wall plug power ~165 MW (~similar to the ILC)

Remark on the beam injection to LC

RF power in the ILC is designed (sufficient) for distance between bunch d=100 m.

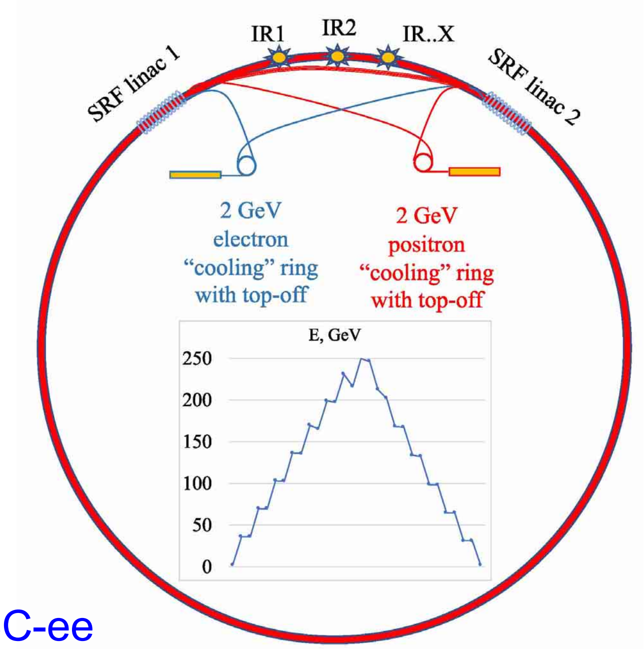
In the case of energy recovery (with much smaller bunch distance) on can have the same RF-power as in ILC (or less) during the entrance and exit of beams and add/remove one bunch every d/c=333 ns (or more time).

In other words, you first inject into the collider bunches with large inter bunch space, and then add (at the next turns) bunches between already circulating bunches. The removal of bunches is done in reverse order.

The required peak RF-power can be several times lower than at the ILC. In order to have the maximum integrated luminosity the accumulation and removal time should be several times less than the operating time in the energy recovery mode (with small inter bunch spacing).

In the energy recovery regime RF is needed only for stabilization of the energy. The average RF-power will be much lower than at the ILC.

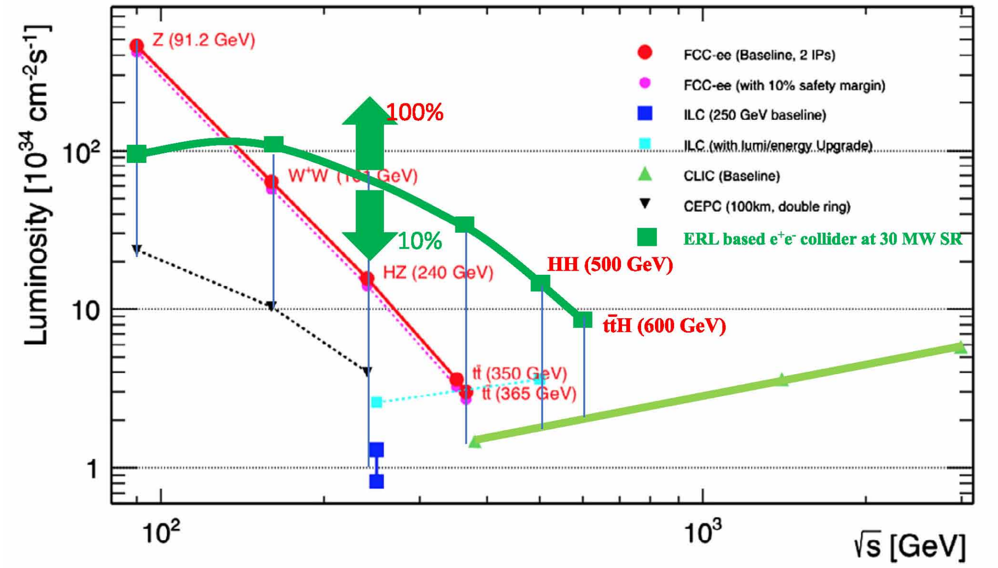
V.Litvinenko, T. Roser, M. Chamizo-Llatas, *High-energy high-luminosity e+e− collider using energy-recovery linacs*, Physics Letters B 804 (2020) 135394

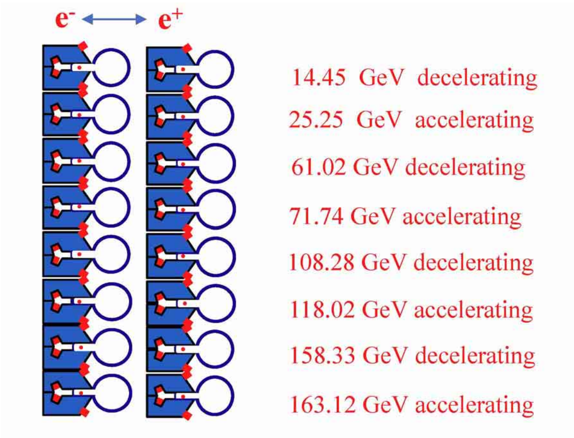


FCC-ee
C=100 km

4-pass ERL

Green curve for P=30 MW





Mistake in the ERL FCC

Incorrect

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

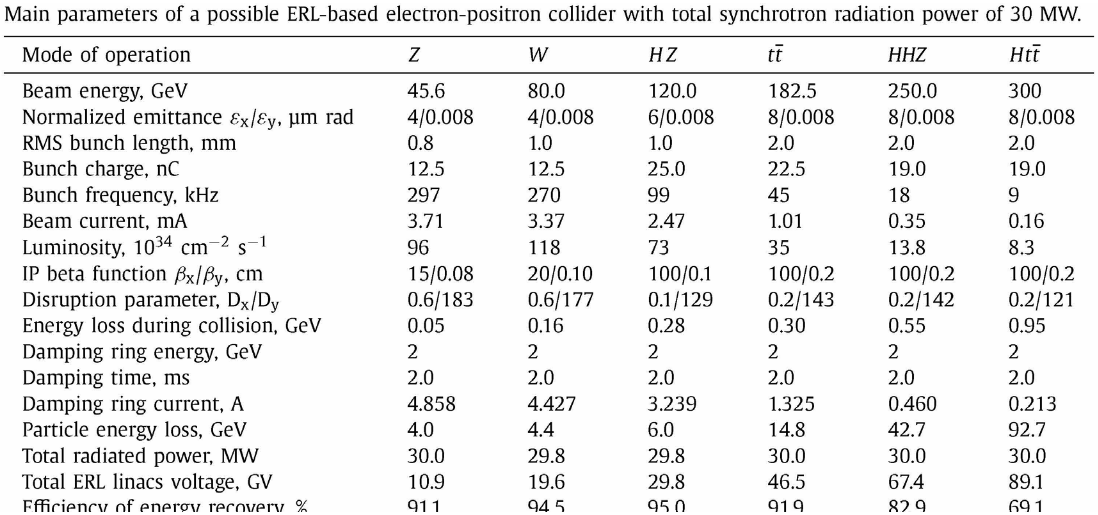
$$\equiv \frac{\sigma_E}{E_0} \approx 0.54\frac{\Delta E}{E_0}$$

↓

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	$Ht\bar{t}$
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

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)

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

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

$$4\omega_c \text{ give} \sim 9.5\%!$$

After deceleration to $E=1/7E_0$, where bunch decompressor is installed, these particles will have ΔE/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})

Conclusion

- At present, the SC ILC design is similar to any room-temperature LC, beams are used only once, superconductivity is not used (only gives some increase of efficiency). This scheme was laid down 40 years ago.

- Since that time there was a big progress in SC cavities, $Q \sim 3 \cdot 10^{10}$ is a reality and $Q \sim 10^{11}$ in reach.

- $L \sim 10^{36}$ is possible (?) already now.

- The proposed “twin” LC scheme opens a way to super high luminosity SC LC!