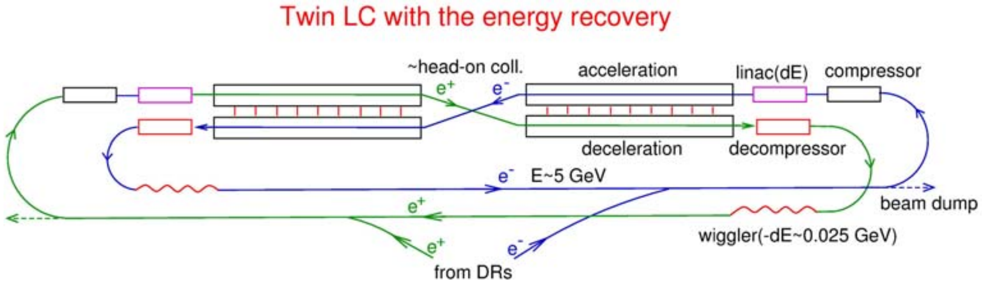


ERLC:

a high luminosity SC e+e- twin linear collider with energy recovery and multiple use of bunches

Valery Telnov

Budker INP and Novosibirsk State Univ.

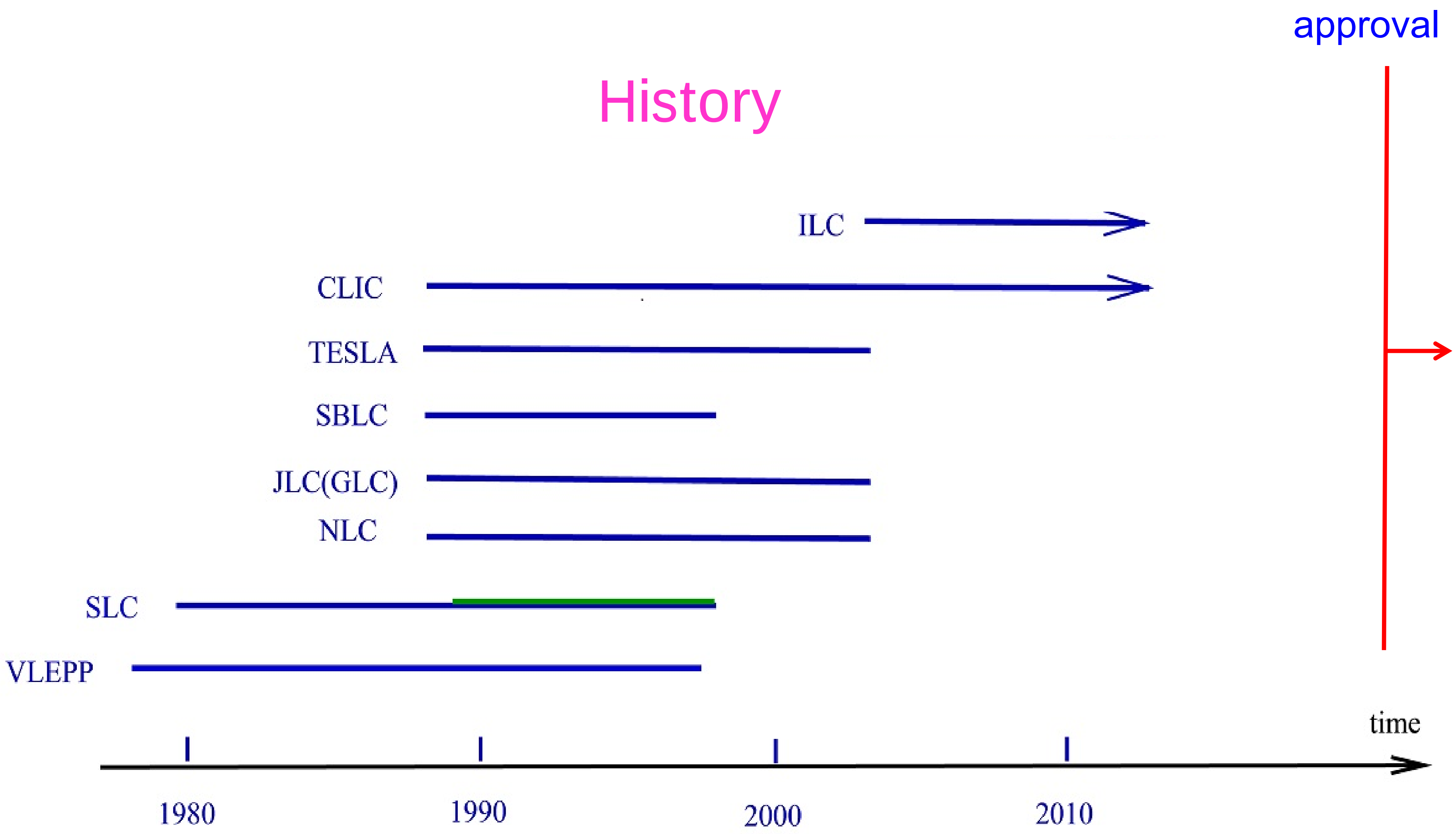
July 14, 2021, ERL sup-panel meeting

Contents

- Introduction, projects of linear e^+e^- colliders
- SC LC with the energy recovery (ER) (history)
- Problems of SC LC with ER
- A proposal of SC twin LC with ER
- Possible parameters
- Conclusion

Linear colliders

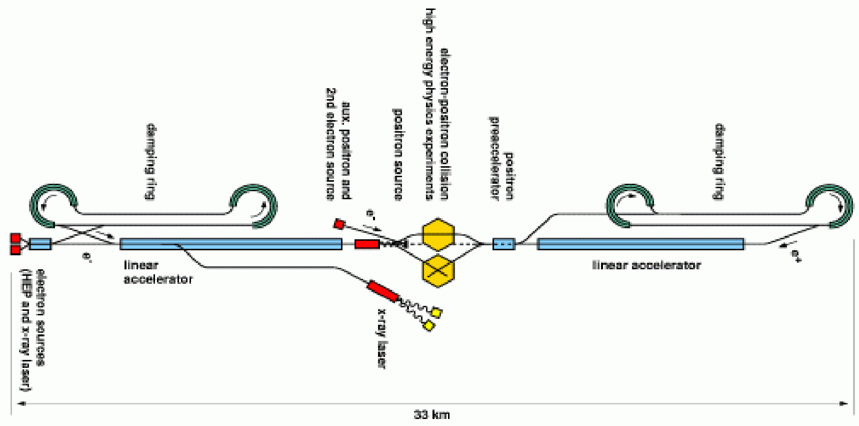
History



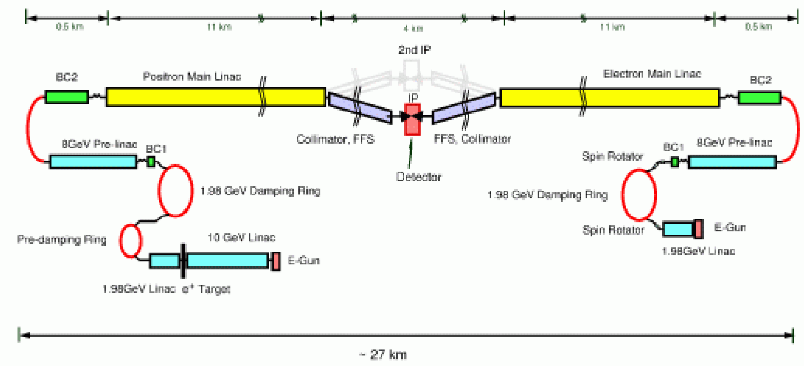
Approval is always on the “Horizon”

Линейные e^+e^- коллайдеры (проекты)

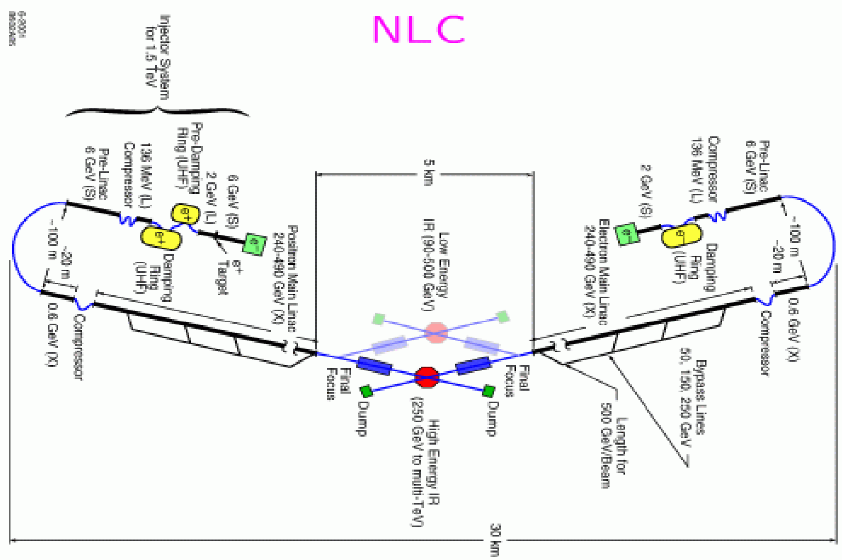
TESLA



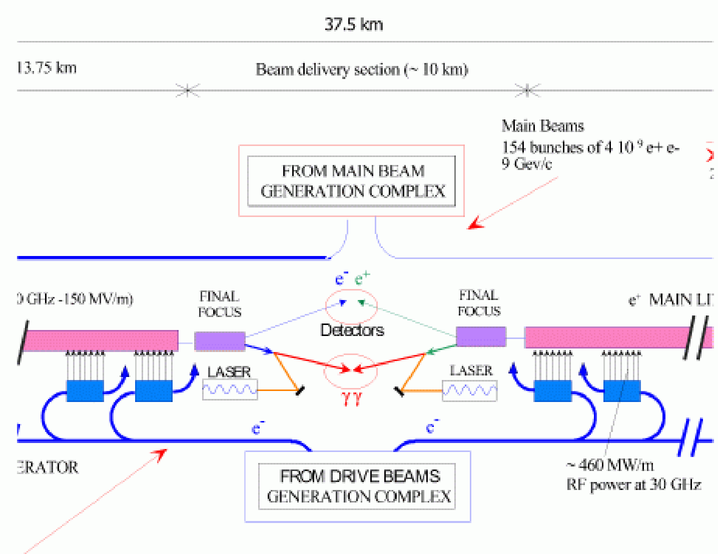
JLC



NLC

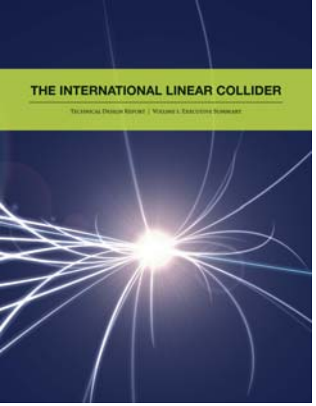


CLIC

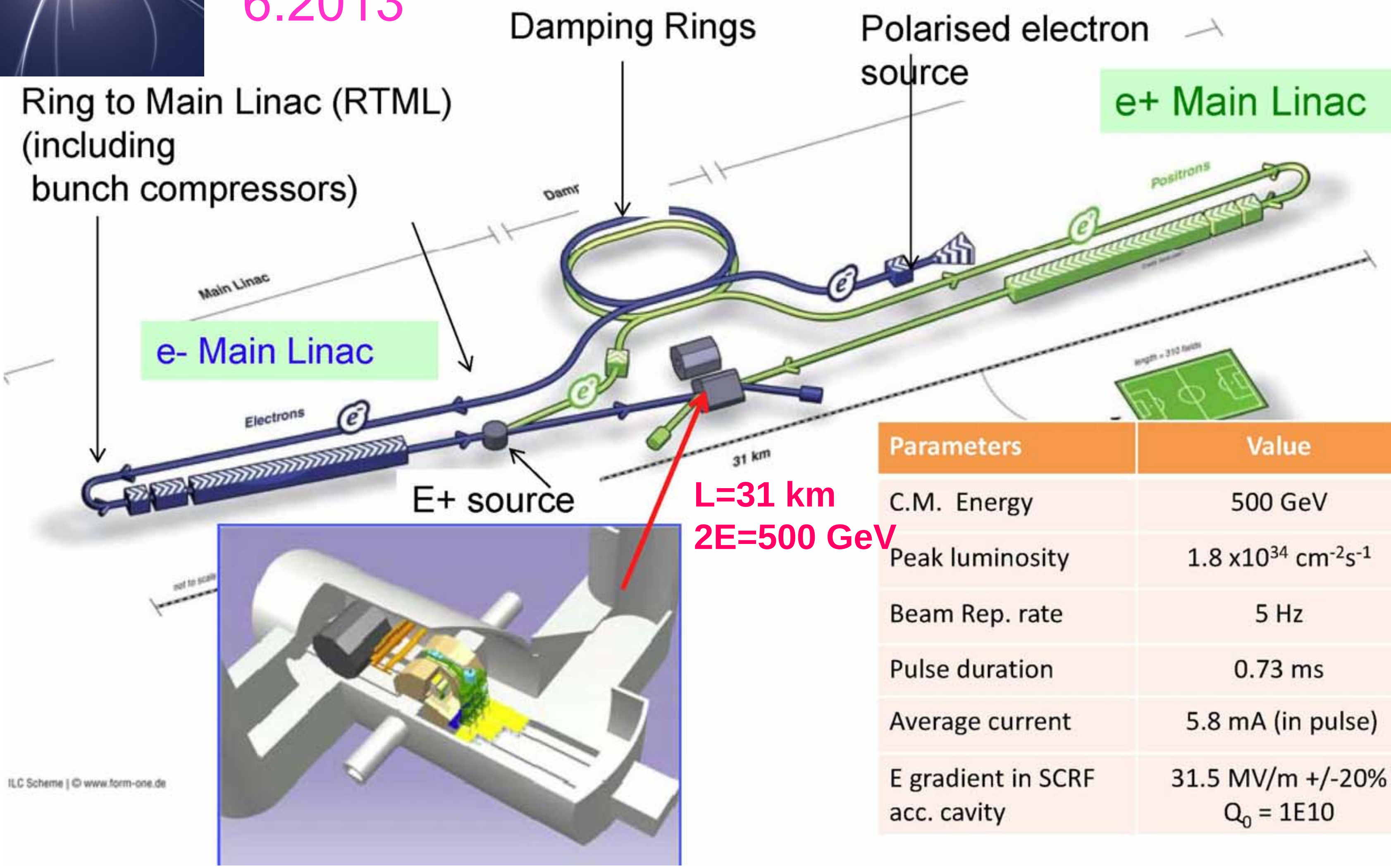


International linear collider (ILC) – since 2004

(based on SC TESLA technology)



ILC TDR
6.2013

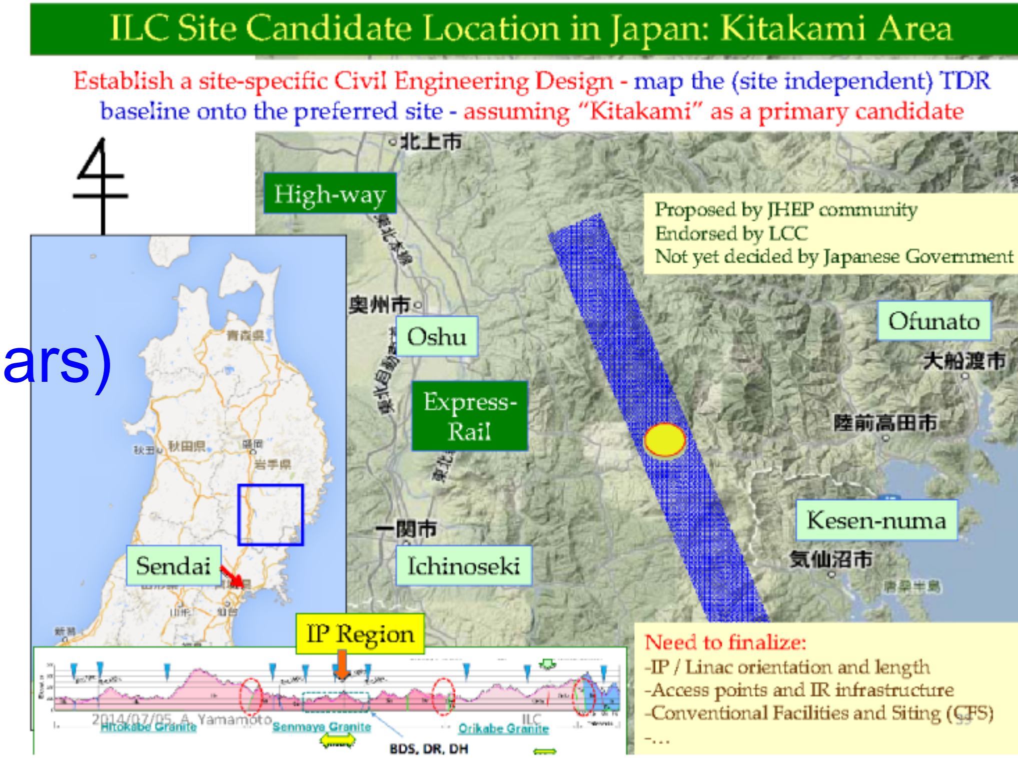


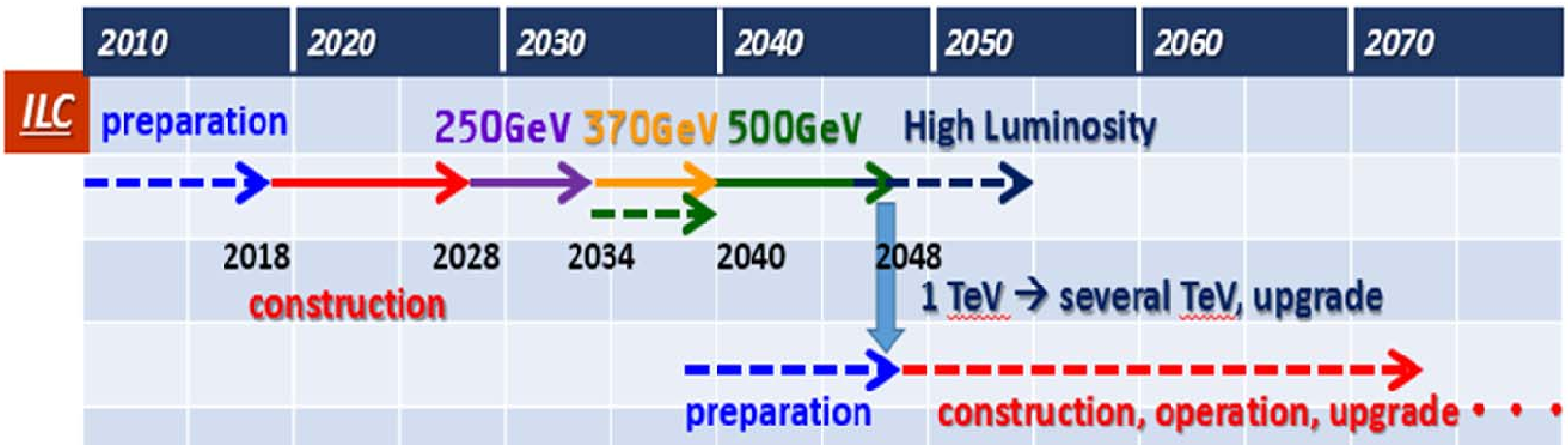
Parameters	Value
C.M. Energy	500 GeV
Peak luminosity	1.8 x10^{34} $cm^{-2}s^{-1}$
Beam Rep. rate	5 Hz
Pulse duration	0.73 ms
Average current	5.8 mA (in pulse)
E gradient in SCRF acc. cavity	31.5 MV/m +/-20% Q_0 = 1E10

2E=250-500 GeV, upgradable to 1000 GeV

Japan is interested to host
-decision ~2018 ???
-construction ~2019?? (~10 years)
-physics ~2030 ???

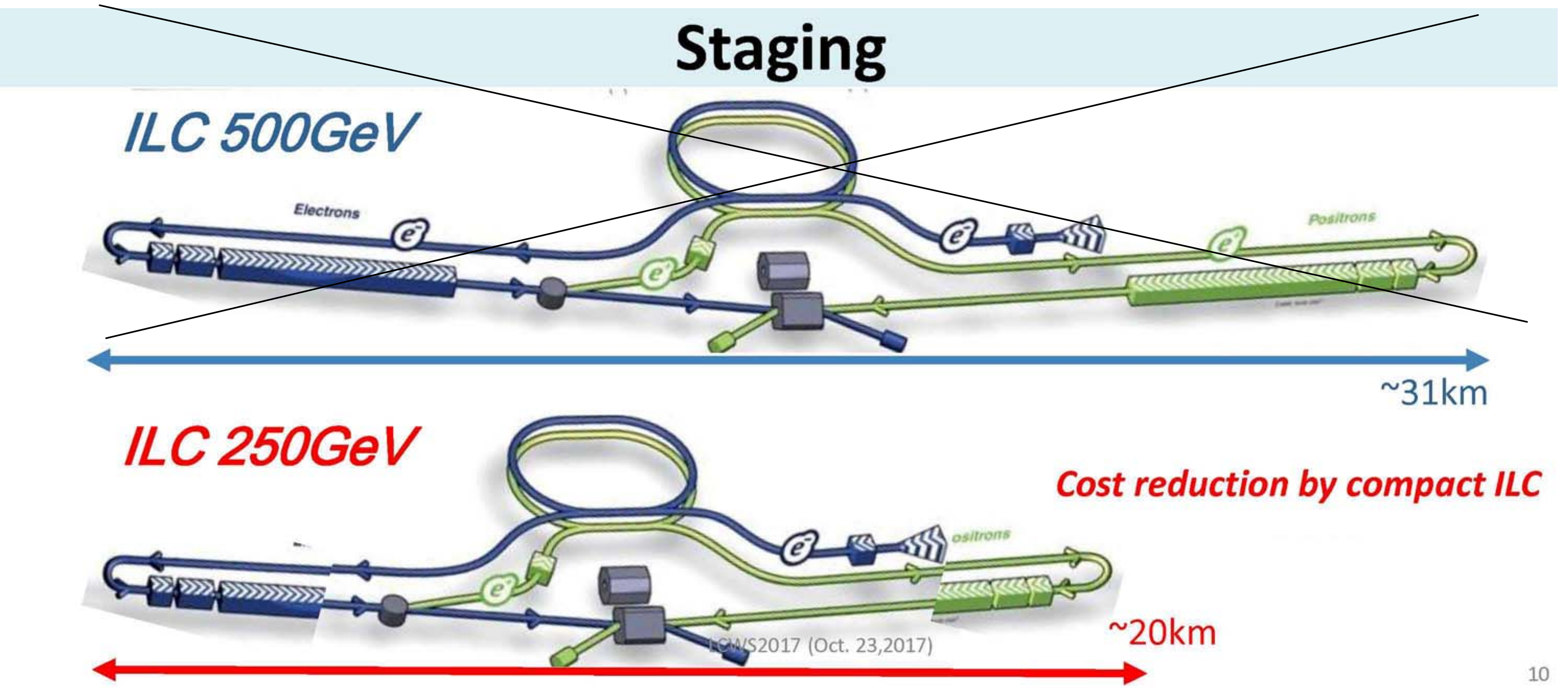
Now 2021, no decisions yet !





ILC, since LCWS 2017

At present Japan consider ILC with 2E=250 GeV, without any words about possible upgrade (but possible). Thus the cost was reduced by 40% compared to 500 GeV.

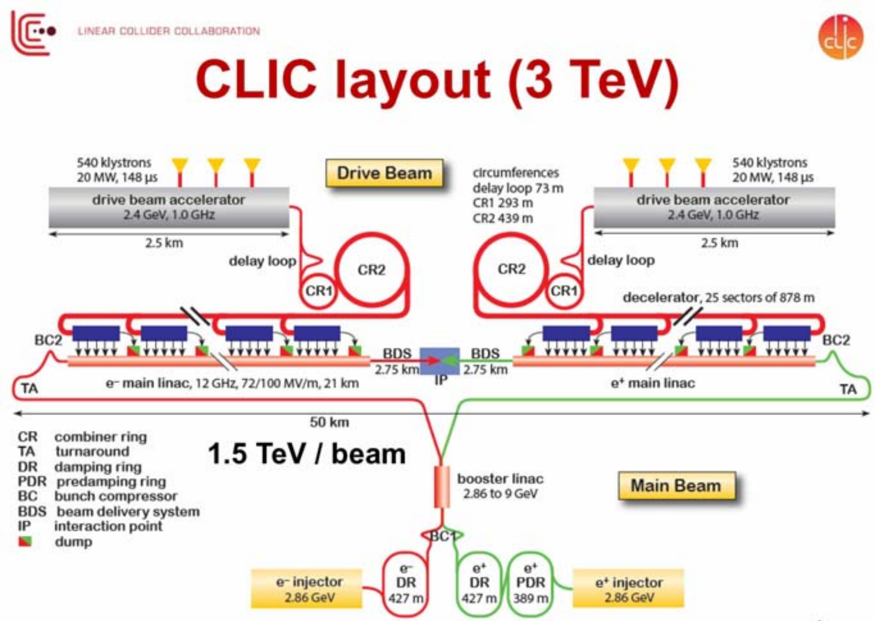


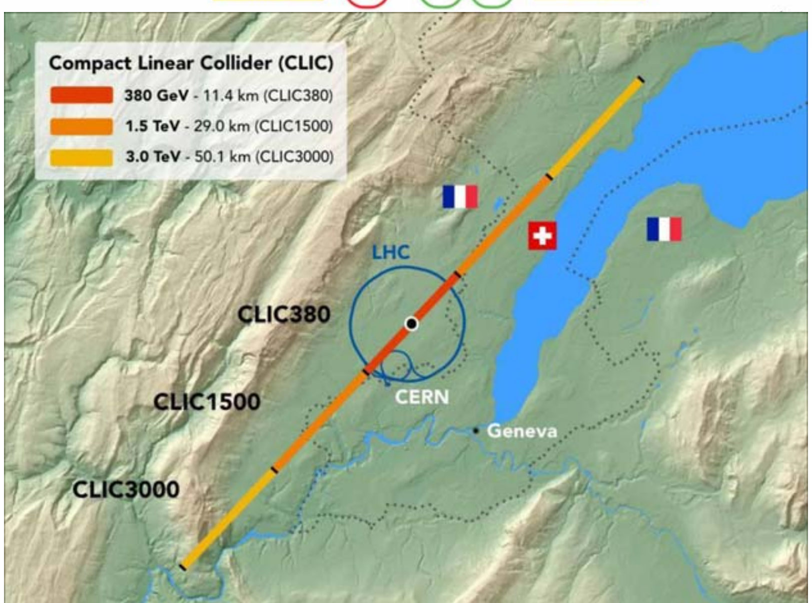
This energy is OK for e+e-→ZH (no tt) and for γγ→H as well

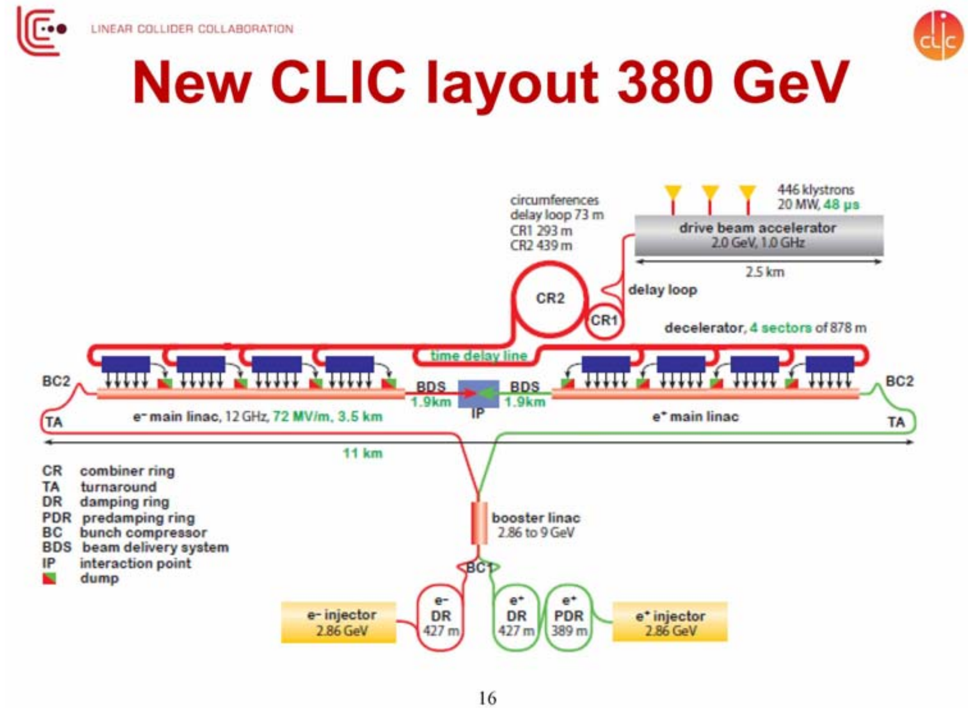
ILC superconducting cavities, ν=1.3 GHz

$Q>10^{10}$ High Gradient (31.5 MV/m→35 MV/m)

CLIC







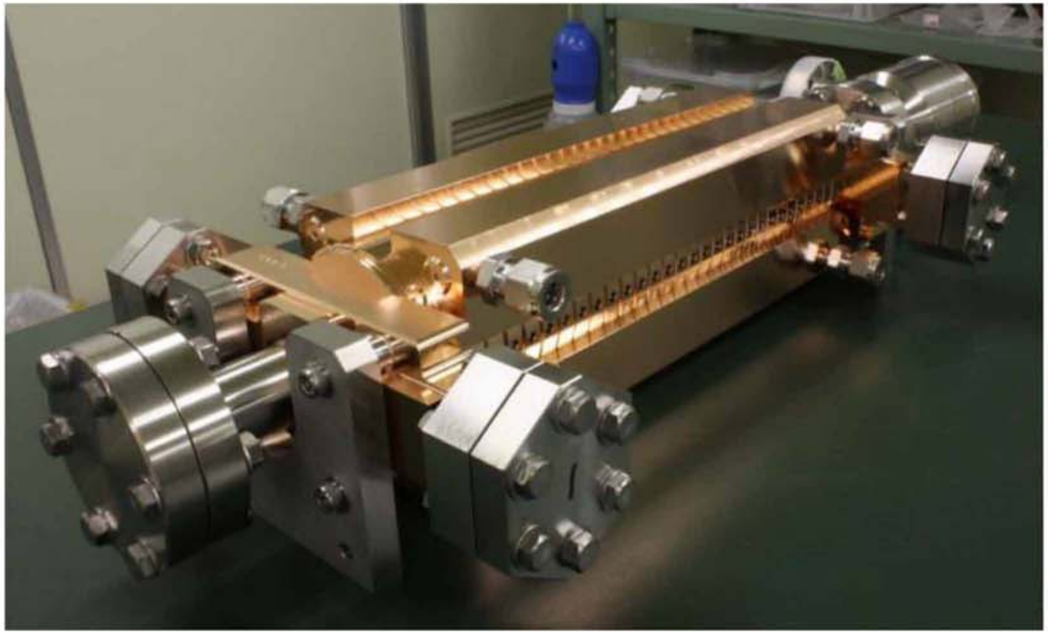
Cost ~6700 SFr

Present plans:

the initial energy 2E=380 GeV (H and top)
2019-20+? – decision
2020-2025+? – preparation phase
2025+? – construction starts
2035+? – first beams

CLIC accelerating structure

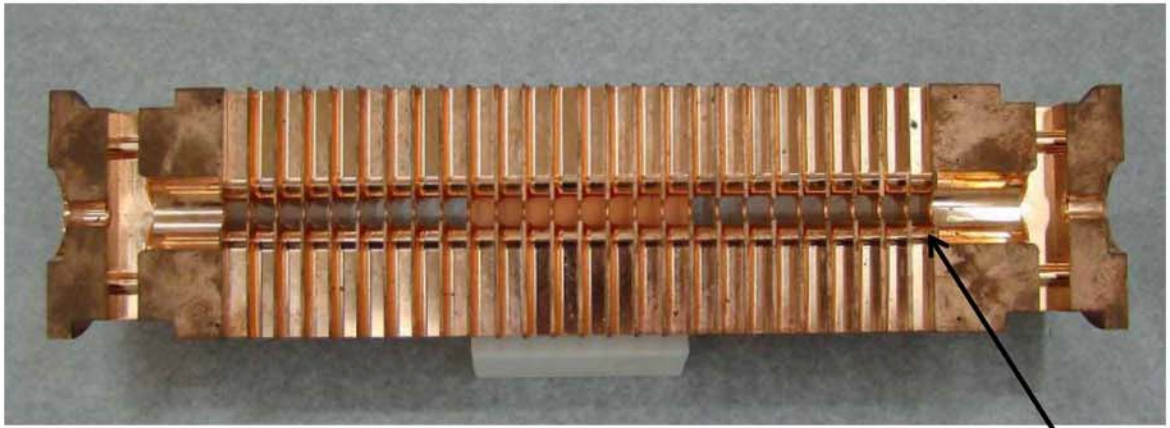
Outside



11.994 GHz X-band
100 MV/m
Input power ≈50 MW
Pulse length ≈200 ns
Repetition rate 50 Hz

HOM damping waveguide

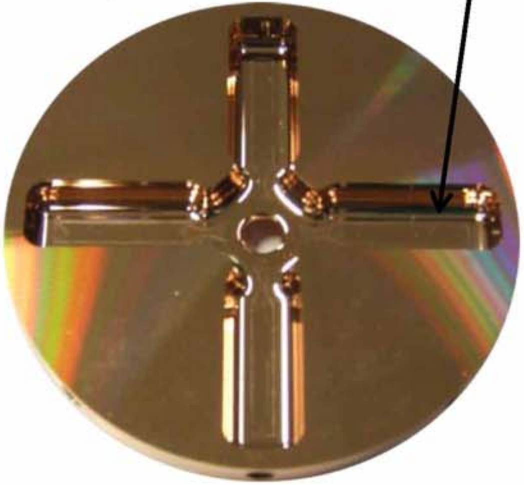
Inside



25 cm

6 mm diameter beam aperture

Micron–precision disk



ILC and CLIC parameters

upgrage to (3-4)10^{34} is possible

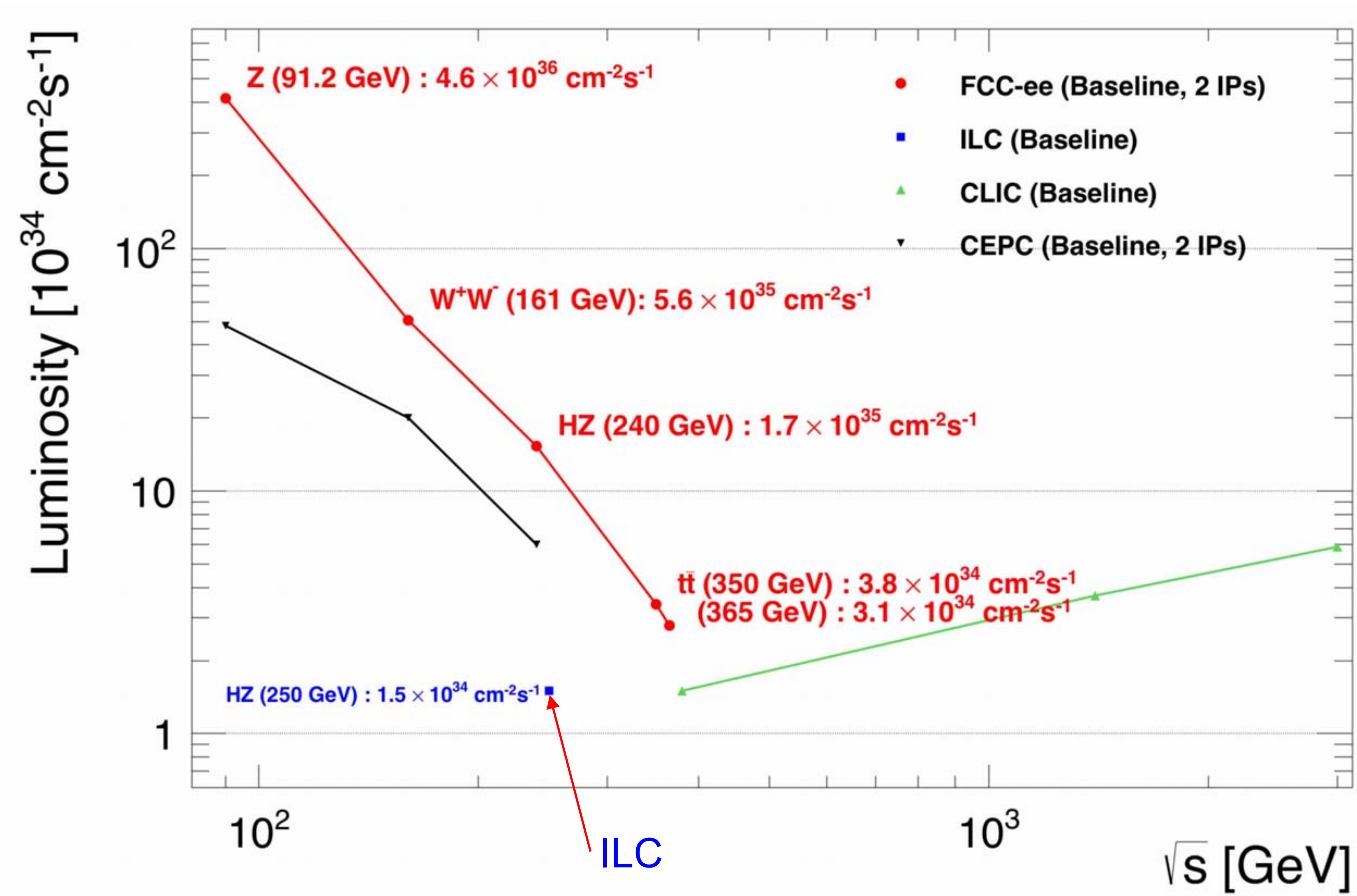
	unit	ILC			CLIC		
$2E_0$	GeV	250	500	1000	250	500	3000
L_{tot}	$10^{34}\,cm^{-2}s^{-1}$	0.75	1.8	4.9	1.37	2.3	5.9
L_{geom}	$10^{34}\,cm^{-2}s^{-1}$	0.37	0.75	2.61	0.82	1.42	4.29
No. Higgs/yr(10^7 s)	1000	23	49	–	34	44	446
Length	km	21	31	48	13.2	13.2	48.3
P (wall)	MW	128	162	301	225	272	589
Pol. e^-/Pol. e^+	%	80/30	80/30	80/30	80/0	80/0	80/0
Accel. gradient	MV/m	31.5	31.5	31.5/45	40	80	100
N per bunch	10^{10}	2	2	1.74	0.34	0.68	0.372
Bunches per pulse		1312	1312	2450	842	354	312
Bunch distance	ns	554	554	366	0.5	0.5	0.5
Rep. rate	Hz	5	5	4	50	50	50
Norm. emit. $\varepsilon_{x,n}$	mm-mrad	10	10	10	0.66	2.4	0.66
Norm. emit. $\varepsilon_{y,n}$	mm-mrad	0.035	0.035	0.03	0.025	0.025	0.02
β_x at IP	mm	13	11	11	8	8	4
β_y at IP	mm	0.41	0.48	0.23	0.1	0.1	0.07
σ_x at IP	nm	729	474	335	150	200	40
σ_y at IP	nm	7.66	5.9	2.7	3.2	2.3	1
σ_z at IP	mm	0.3	0.3	0.225	0.072	0.072	0.044
Ener. loss. $\delta E/E$	%	0.95	4.5	10.5	1.5	7	28

Pulse structure of the ILC and CLIC.

	ILC	CLIC
$2E_0$, GeV	250	250
bunches/train, n_b	1312	354
bunch spacing, ns/m	554/165	0.5/0.15
train length, μs/km	720/220	0.177/0.053
rep. rate, Hz	5	50
collision rate, kHz	6.56	17.7
power (wall plug), MW	128	225
luminosity, $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	0.75	1.37

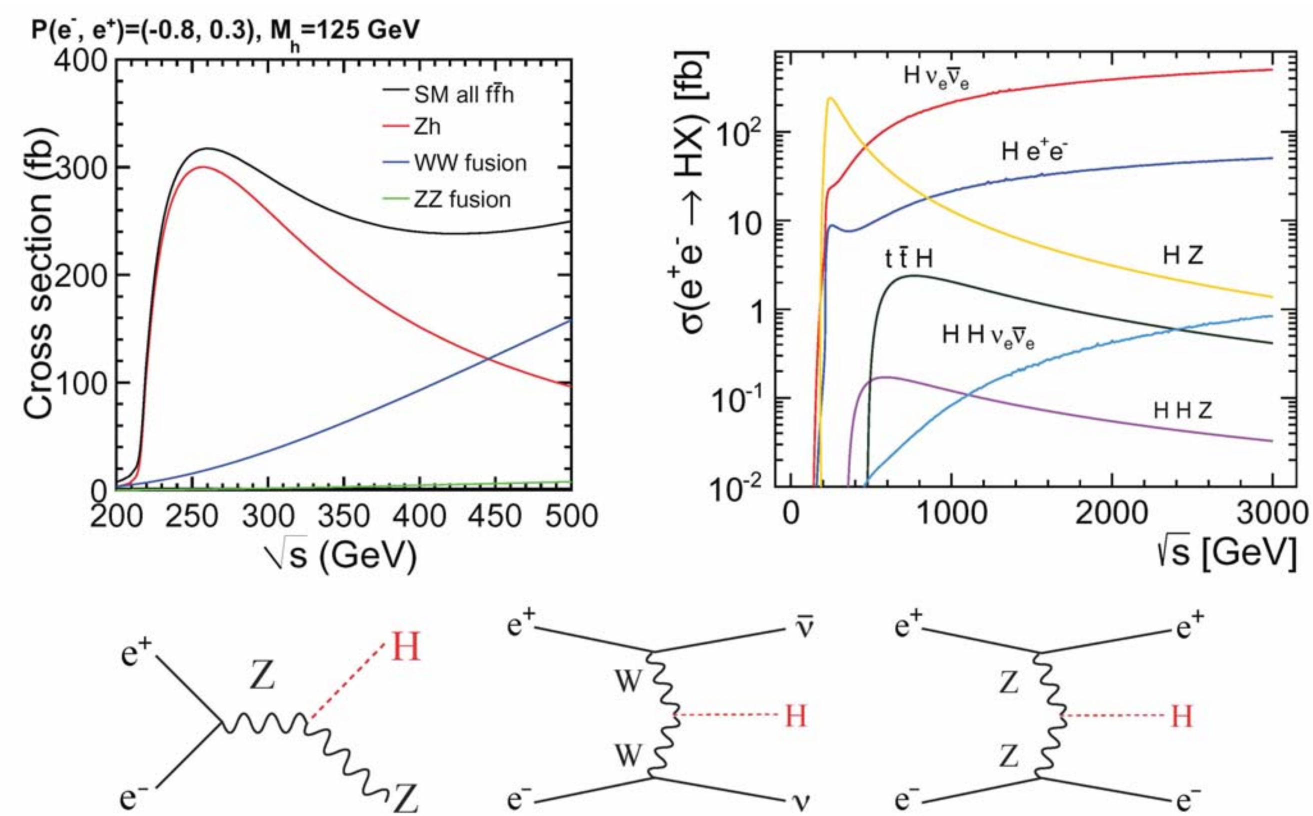
Both LC have L~10^{34}, collision rate ~10 kHz, difference only in distance between bunches

Circular 100 km e+e- collider (FCC-ee, CEPC) vs ILC and CLIC



The luminosity at the Higgs energy 2E=250 GeV is higher at FCC-ee by one order of magnitude

Higgs physics in e+e- collisions



Tagging Z in e+e-→ZH one can measure all Br(H), even invisible decays width.

One can measure the Higgs total width:

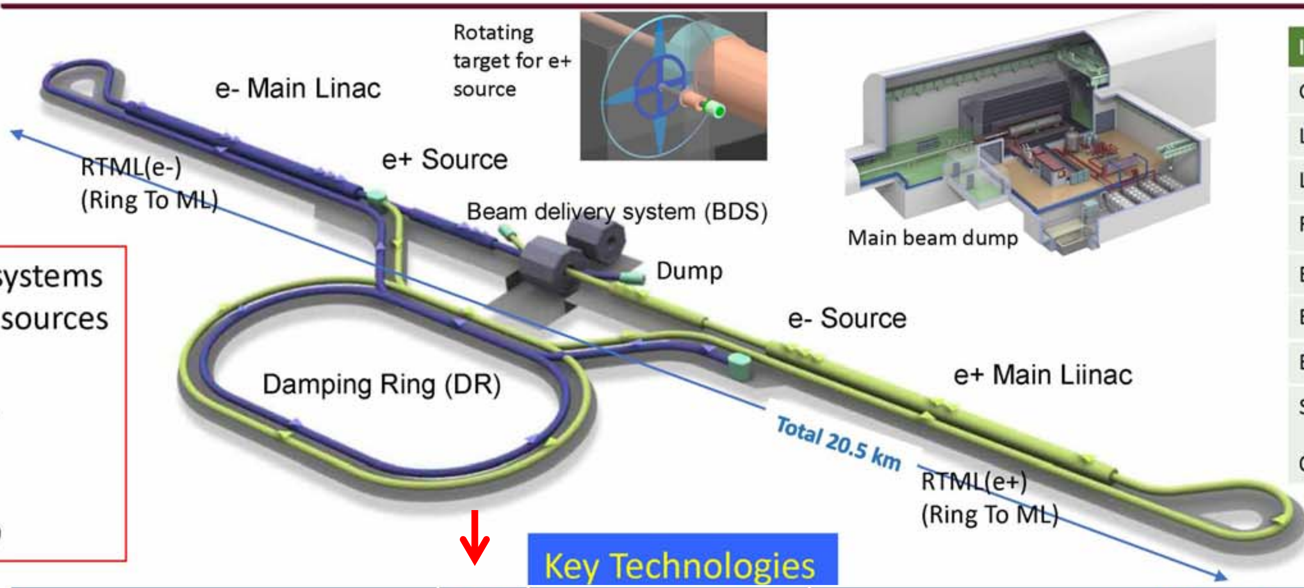
$\Gamma(H) \sim \sigma(e^+e^- \to ZH)/Br(H \to ZZ)$ and $\Gamma(H) \sim \sigma(WW \to H)/Br(H \to WW)$

At linear colliders $L \sim 10^{34}$, $N_H \sim 20000$/year or 10^5 for life of the experiment;

At circular collider with C~100 km and several IP one can have $N_H \sim 10^6$.

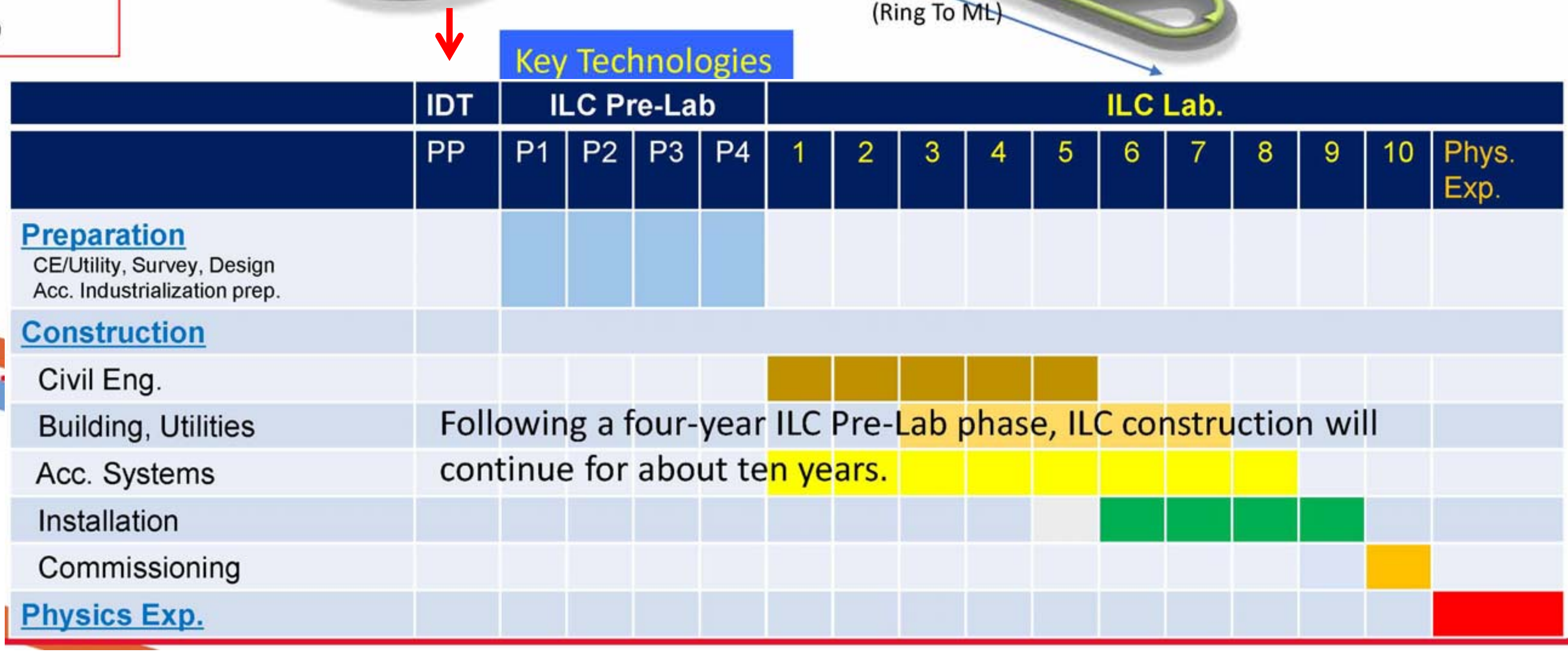
ILC-last news from LCWS 2021

ILC250 accelerator facility



Area systems
e-/e+ sources
DR
RTML
ML
BDS
Dump

Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	1.35 $\times 10^{34}$ $cm^{-2}s^{-1}$
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	7.7 nm@250GeV
SRF Cavity G. Q_0	31.5 MV/m (35 MV/m) $Q_0 = 1 \times 10^{10}$



ILC and CLIC pulse structure

- ILC ~1312 bunch/train (0.72 ms~220 km), Δct~165 m, f=5 Hz
- CLIC 354 bunch/train (177 ns~53 m) Δct~15 cm f=50 Hz

Beams are used only once

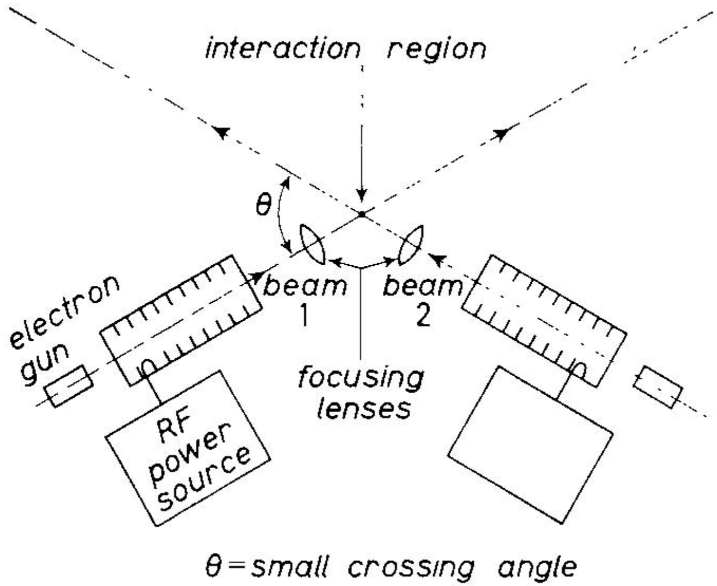
The ILC duty cycle (DC) = 0.00072*5=$3.6\cdot10^{-3}$
CLIC $9\cdot10^{-6}$

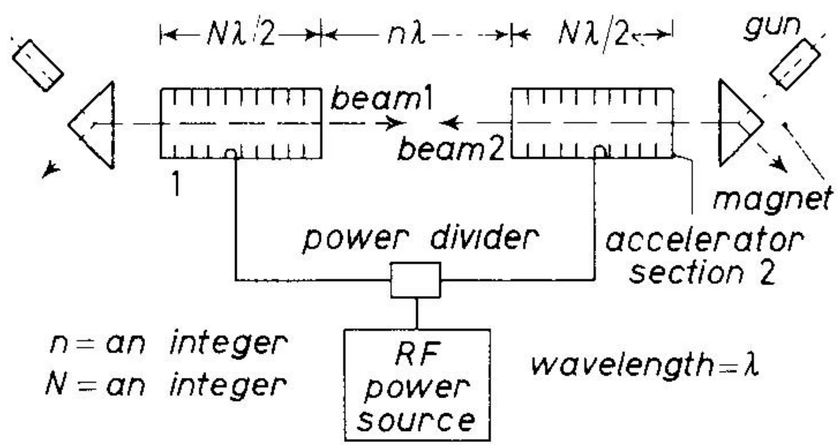
Most of time the colliders do nothing!
(only prepare new beams in damping rings)

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, ``A possible apparatus for electron clashing-beam experiments,'' Nuovo Cim. 37, 1228 (1965).





M.Tigner (1965):

While the storage ring technique for performing clashing-beam experiments [1] is very elegant in concept it seems worth-while at the present juncture to investigate other methods which, while less elegant or superficially more complex may prove more tractable.

energy recovery

...”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 accelerator 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

A. Skrinsky (1971)
Seminar Morges, Switzerland

From U. Amaldi (Saariselka, 1991):

At Novosibirsk, conventional and superconducting linacs were considered, in the same years, as tools for reaching the hundred GeV region by G.I. Budker, A.N. Skrinsky and collaborators. In 1971, at the Morges Seminar, Skrinsky spoke briefly about these ideas and also about the possible use of storage rings for muons. Goldschmidt-Clermont summarized the content of the talk in an unpublished note[7] from which I quote two sentences :

''*The one way to study these [electron-electron and electron-positron] reactions is to build two ordinary linear accelerators with highest possible average power in the beam and to learn the way to compress transversal beam dimensions up to about 10 microns and to achieve the same accuracy in beam control. [With] 10 megawatts in the beams, it should be possible to have* $10^{31} cm^{-2} s^{-1}$ *luminosity.*''

''*Another way will appear after success in superconducting linear accelerators. In this case, it is possible not to have large active power in the beam and then decelerate it in the second half of acceleration and doing the same with opposite beam in the same accelerating structure.*''

Suggestion of high energy linear colliders, but there was no specific scheme in mind at the time. There was no publication.

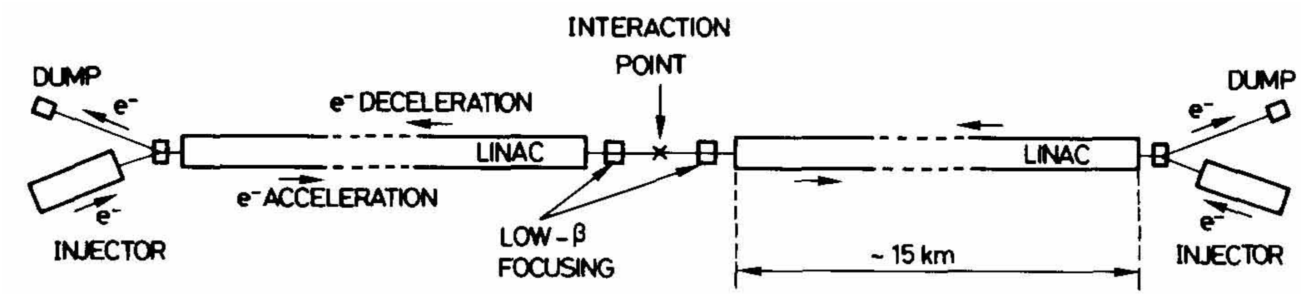
A POSSIBLE SCHEME TO OBTAIN e^-e^- AND e^+e^- COLLISIONS AT ENERGIES OF HUNDREDS OF GeV

U. AMALDI
CERN, Geneva, Switzerland

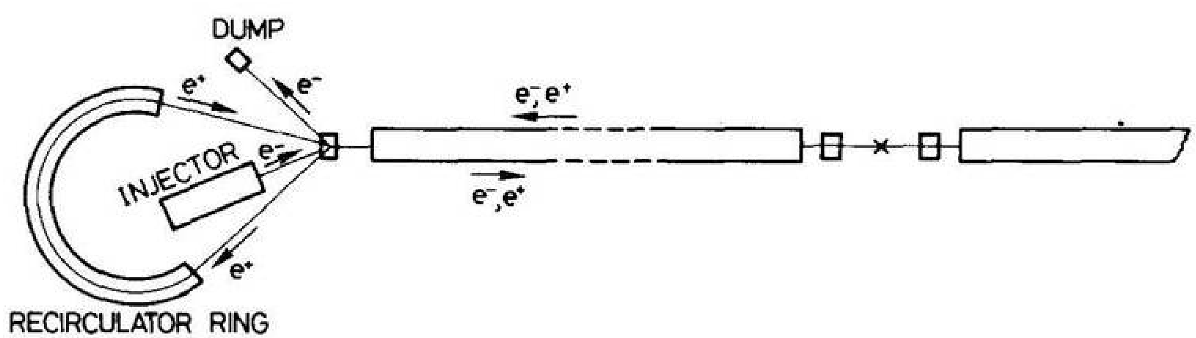
U. Amaldi (1976) Phys. Lett. 61B, 313

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.



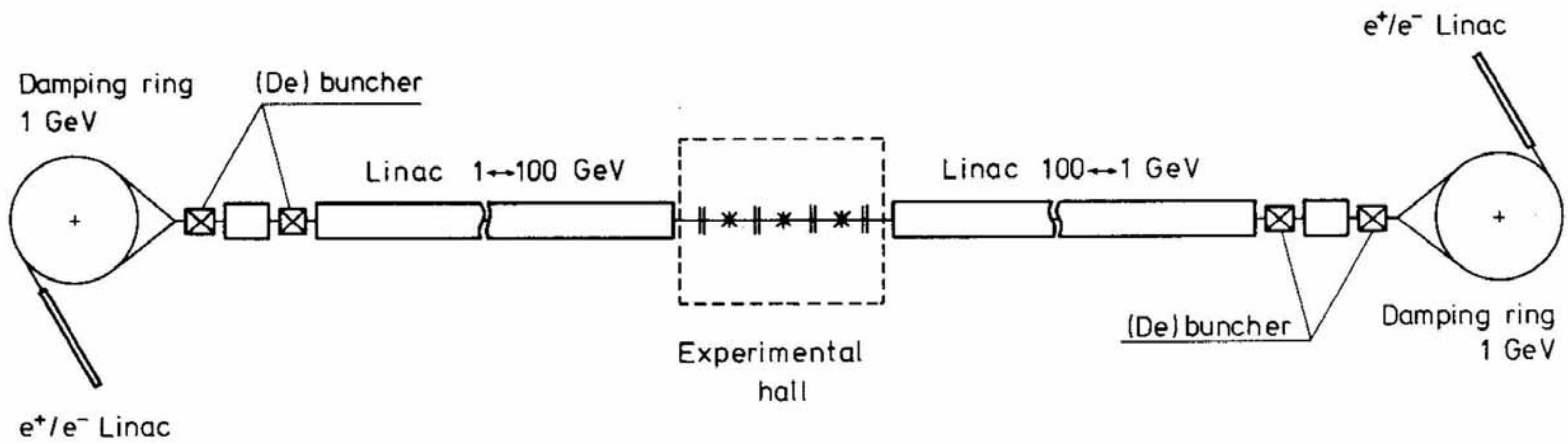
In this scheme the electron and positron bunches are dumped after one-pass energy recovery



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).

$L=3.6\times10^{31}$ - not interesting

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)

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

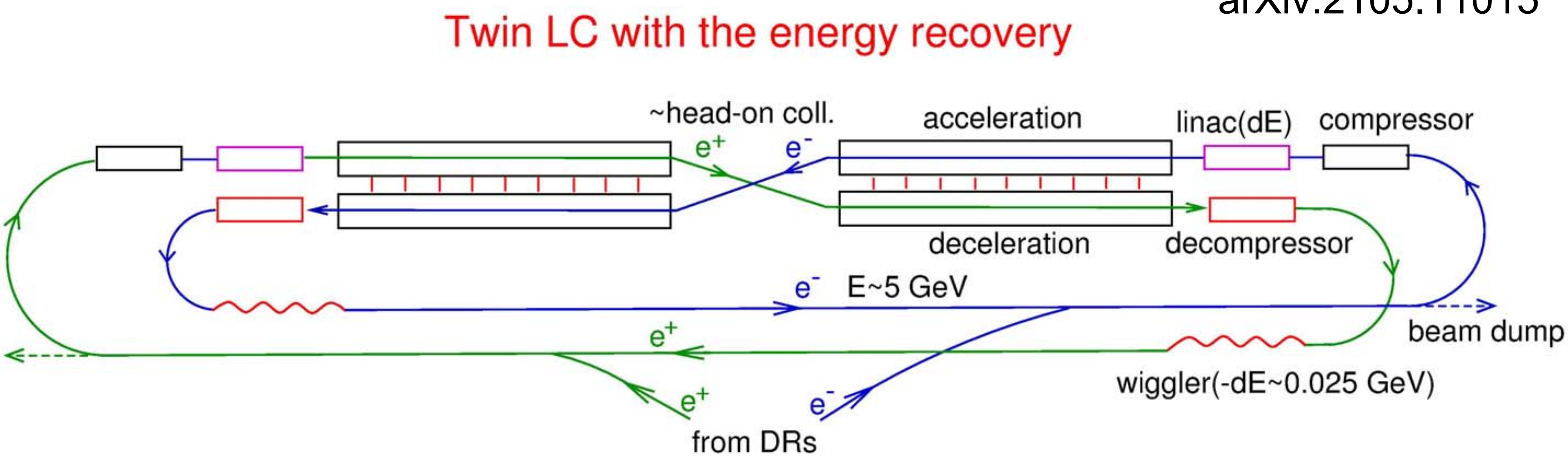
At the IP $\quad \xi_y^* \propto \frac{\beta_y^*}{\sqrt{\beta_x^*\beta_y^*}} = \sqrt{\frac{\beta_y^*}{\beta_x^*}} \ll 1;$

In the linac $\quad \xi_y \propto \frac{\beta_y}{\sqrt{\beta_x\beta_y}} = \sqrt{\frac{\beta_y}{\beta_x}} \approx 1 \gg \xi_y^*.$

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

The proposed LC scheme

Telnov, LCWS21
arXiv:2105.11015



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~1/200. 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).

References on dual/twin cavities (received after my talk at LCWS 2021)

Proceedings of ERL07, Daresbury, UK

DUAL-AXIS ENERGY-RECOVERY LINAC*

Chun-xi Wang†, John Noonan, John W. Lewellen‡
Argonne National Laboratory, Argonne, IL 60439, USA

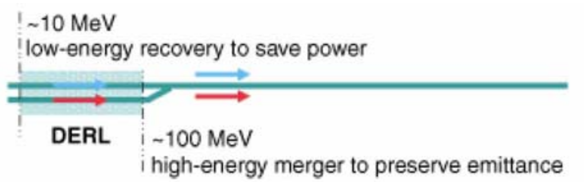
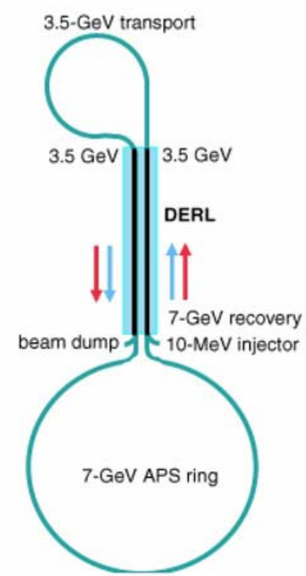
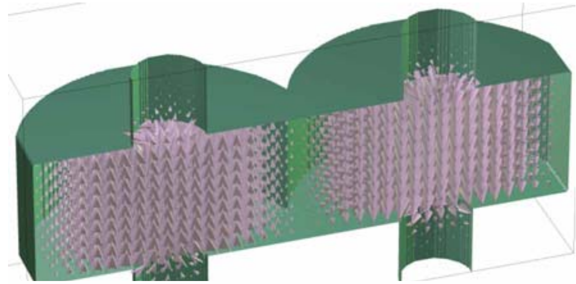
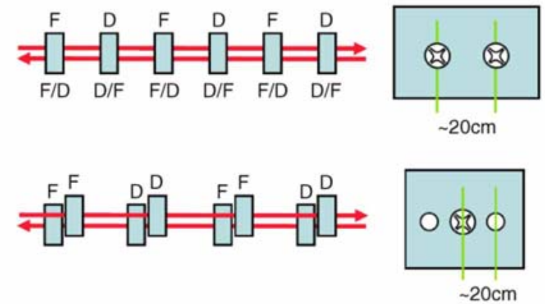


Fig. 2: DERL as a solution for beam merger. The red arrow indicates accelerating beam.



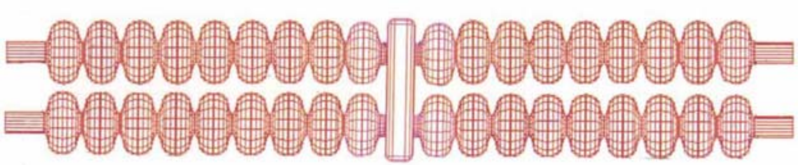


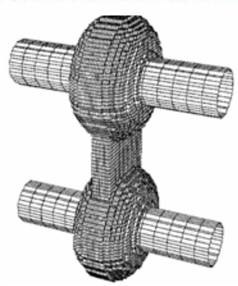


KEK Preprint 2003-130, 11-th Workshop (SRF2003)

MULTI-BEAM ACCELERATING STRUCTURES

Shuichi Noguchi† and Eiji Kako
KEK, High Energy Accelerator Research Organization
1-1 Oho, Tsukuba, Ibaraki, 305-0801, Japan





Proceedings of LINAC2016, East Lansing, MI, USA

DEVELOPMENT OF A SUPERCONDUCTING TWIN AXIS CAVITY*

H. Park†[1], F. Marhauser, A. Hutton, S. U. De Silva[1], J. R. Delayen[1]
Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA

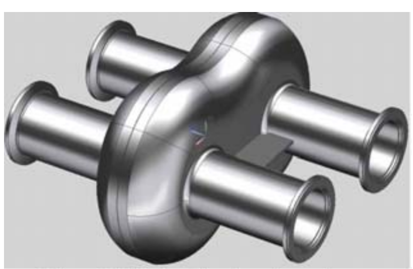


Figure 2: Single cell twin axis cavity.

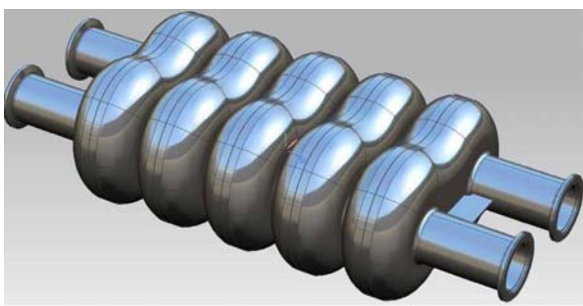


Figure 9: Multicell twin axis cavity.

PHYSICAL REVIEW ACCELERATORS AND BEAMS **20,** 103501 (2017)

Experimental studies of 7-cell dual axis asymmetric cavity for energy recovery linac

I. V. Konoplev,[1,*] K. Metodiev,[1] A. J. Lancaster,[1] G. Burt,[2] R. Ainsworth,[3] and A. Seryi[1]
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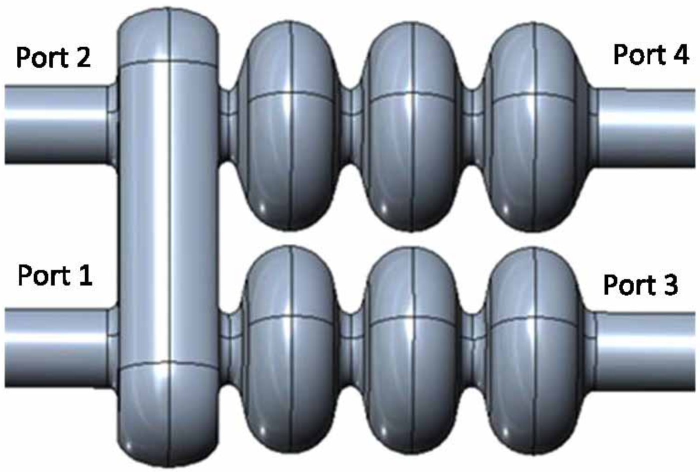
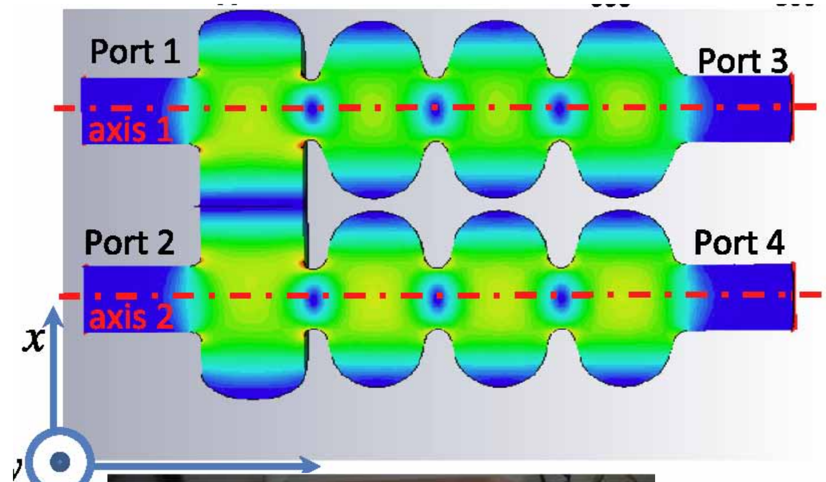
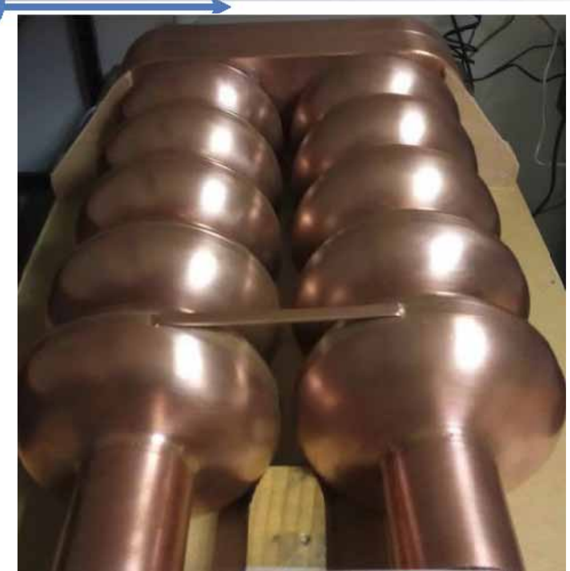
[2]*Cockcroft Institute, Lancaster University, Lancaster LA1 4YW, United Kingdom*
[3]*Fermilab, Batavia, Illinois 60510, USA*
(Received 28 May 2017; published 10 October 2017)







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

$$\sigma_z \approx 19.2 \frac{\xi^{6/7} \varepsilon_{ny}^{3/7} r_e^{4/7} \gamma}{(\sigma_E/E_0)^{4/7} (\delta E/E)^{2/7}}.$$

$$\sigma_x \approx 0.7 \frac{N r_e^{9/7}}{\xi^{4/7} \varepsilon_{ny}^{2/7} (\sigma_E/E_0)^{2/7} (\delta E/E)^{1/7}}, \qquad \sigma_y \approx 4.4 \frac{\xi^{3/7} \varepsilon_{ny}^{5/7} r_e^{2/7}}{(\sigma_E/E_0)^{2/7} (\delta E/E)^{1/7}},$$

Beam lifetime due to tails of beamstrahlumg

This is a third limitation on beam parameters. It is important for FCC.
In ERLC it is important because the beam is decelerated $E_0/5$=10-100 times, and in 5 GeV arcs we require the energy acceptance about 3%.
We require 1-3% loss during 1-3 second active collision cycle (~10^4 collisions), that correspond to beam lifetime n_{col}~10^6 revolutions.

$$\frac{N}{\sigma_x \sigma_z} < \frac{3.6 \times 10^{-3} \eta}{\gamma {r_e}^2 \ln\left(7 \times 10^{-7} \eta \sigma_z n_{\mathrm{col}} / \gamma r_e\right)} \qquad (3)$$

$$n_{\mathrm{col}} = 1.43 \times 10^6 \frac{\gamma r_e}{\eta \sigma_z} \exp\left(\frac{0.0036\, \eta \sigma_x \sigma_z}{N \gamma r_e^2}\right)$$

This requirement (3) differs from (1) on the energy spread at the IP, but in all further practical cases when (1) is fulfilled, then (3) as well, but very close to its limit.

So, we derived previous formulas for beam parameters and luminosity from (1),(2), but (3) should be also checked.

Luminosity

$$L = \frac{N^2 f}{4\pi\sigma_x\sigma_y} = 2.6\cdot 10^{-2}\,\frac{Nf\,\xi^{1/7}}{\varepsilon_{ny}^{3/7} r_e^{11/7}}\left(\frac{\sigma_E}{E_0}\right)^{4/7}\left(\frac{\delta E}{E}\right)^{2/7}.$$

For $2\mathrm{E}_0 = 250$ GeV, $\xi = 0.1$, $\varepsilon_{ny} = 3\cdot 10^{-6}\,\mathrm{cm}$, $\sigma_E/E_0 = 2\cdot 10^{-3}$, $\delta E/E = 0.5\cdot 10^{-2}$

$$\sigma_x \approx 9\left(\frac{N}{10^{10}}\right)\mu\mathrm{m}, \qquad \sigma_y \approx 6.1\ \mathrm{nm}, \qquad \sigma_z = 0.3\frac{E[\mathrm{GeV}]}{125},\ \mathrm{mm}.$$

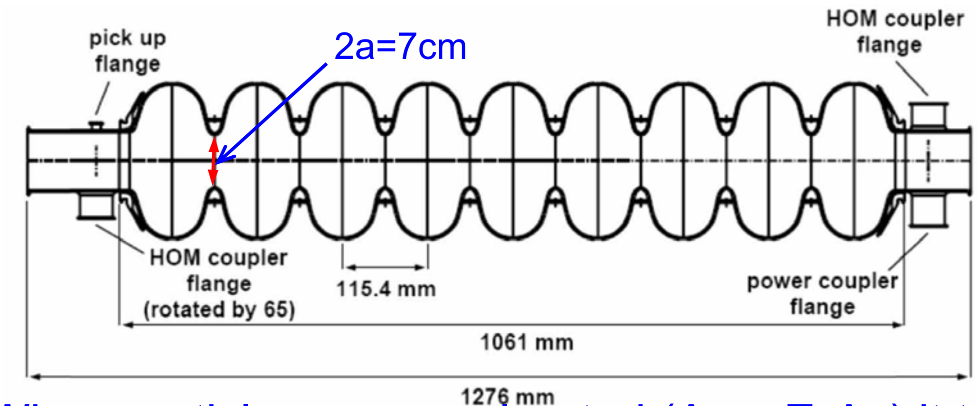
$$L \approx 4.35\cdot 10^{36}\frac{\left(N/10^{10}\right)}{d[\mathrm{m}]} \approx 9\cdot 10^{36} I[\mathrm{A}]\ \mathrm{cm}^{-2}\mathrm{s}^{-1}.$$

For $\mathrm{N}=10^{10}$, d=3 m $\rightarrow$ $L = 1.45\cdot 10^{36}$ at P_{SR}=8 MW
(I=0.16 A)

For comparison, at FCC(250) $L=8.5\cdot 10^{34}$ at P_{SR}=100 MW
P_{SR}/L is 215 times larger

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 $\dfrac{d\varepsilon}{dz} \sim \dfrac{2e^2 N}{a^2}$, a – iris radius (R.Palmer), very weak dependence on σ_z.

Numerical simulation for TESLA structures gives wakefield energy losses for $\sigma_z = 400$ 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 $G \approx (20-30)\dfrac{\text{MeV}}{\text{m}}$

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.

High order mode losses (continue)

For $2E_0$=250 GeV, G=20 MeV/m

$$P_{\text{HOM}} = \frac{265}{d\,(\text{m})}\left(\frac{N}{10^{10}}\right)^2 \ \text{MW}$$

For N=10^{10}, d=3 m P_{HOM}=88.3 MW (while P_{SR}=8 MW), too much.

Due to quadratic dependence on N, it is profirable to reduce N and d, keeping L=const, our choice N=$0.5\cdot10^{10}$, d=1.5 m, then

$$P_{\text{HOM}} = 45 \times \text{DC}, \quad \text{MW}$$

(DC is a duty cycle)

This power is proportional to the length of the collider

The problem of HOM losses is well known. Removal of this energy from SC cavities to the room temperatures needs special couplers and absorbers. To make easier HOM “photons” removal, the cavities should have larger aperture and smaller length.

Surface resistance R_s in ideal case

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

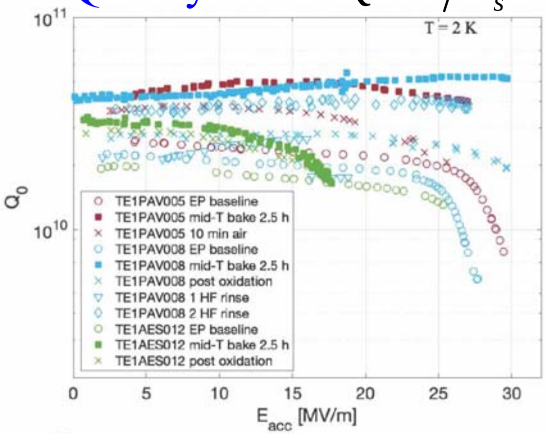
Quality factor $Q \propto 1/R_s$

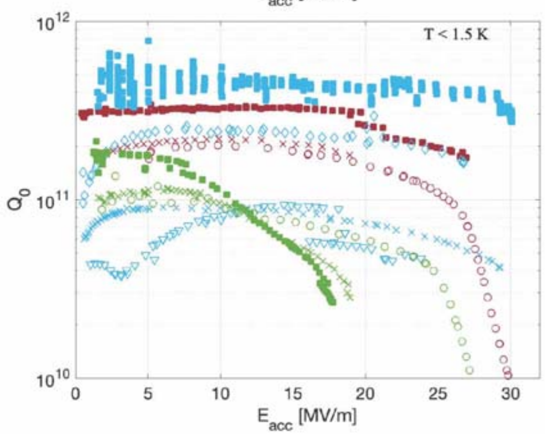
Refrigeration

Following LCLS-II assume $Q=3\cdot10^{10}$ at T=1.8 K,
at E=20 MeV/m the heat is 680 W/GeV ~ 1 kW/GeV.
The refrigeration efficiency (1.8/300)×0.3=1/550.
Twin LC(250) in continues mode needs P_{ref}~275 MW.

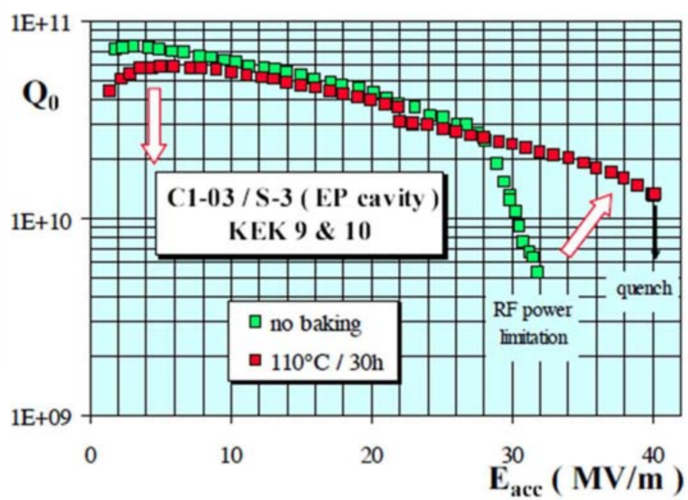
For duty cycle 1/3 P_{ref}~92 MW

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

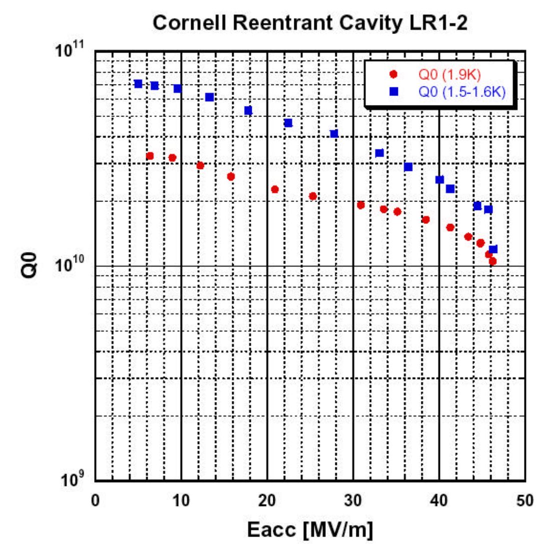




S. Rosen et al, arxiv 1907.00147
E_{acc} ~20 MV/m:
Q_0 of (3-4)10^{11} at T<1.5 K
Q_0 ~5·10^{10} at 2.0 K.



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



Duration of continues operation in the case of working with duty cycle

Duration of continuous operation is determined by the heat capacity of the liquid He that surrounds the cavity and can be estimated as

$$\Delta t = \frac{c_p m \Delta T}{P_{diss}} \sim 12.5\,\mathrm{s}, \tag{7.1}$$

where $c_p(\mathrm{He}) = 2$ J/g at T=1.8 K, m is the mass of liquid He per one TESLA cavity (we take 0.02 m^3 or 2.5 kg), $P_{\mathrm{diss}} \sim 20$ W, $\Delta T \sim 0.05$ K. At 1.5 K, $c_p \approx 1$ J/g. So, we can safely choose the work duration $\Delta t = 2$ s, the break 4 s, the cycle duration 6 s.

Total power

For $N=0.5\cdot 10^{10}$, $d=1.5$ m , $DC=1/3$, $2E=250$ GeV.

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

The number of circulating bunches $n_b = 2\times(40\ \mathrm{km}/1.5\ \mathrm{m}) = 53\times 10^3$ (both beams) . If bunches are prepared once per >6 s, the average power for beam generation (with ε=10%) will be less than 2.5 MW.

Radiation in wigglers $P_{SR} \sim 8\times DC/\varepsilon = 5.3$ MW (at ε=50%)

High mode losses P ~ $15/\varepsilon$ =30 MW (at ε=50%)

Refrigeration power P_{ref} ~92 MW

The total wall plug power ~130 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 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 in linacs is needed only for compensation HOM losses and stabilization of the energy. The average RF-power will be about the same as at the ILC.

Ways to higher energies

In my https://arxiv.org/pdf/2105.11015.pdf the emphasis was on the Higgs energy of 2E=250 GeV. What about higher (and lower) energies?

Main problem are particle losses in 5 GeV arcs (with assumed energy acceptance ~ 3%) due to large energy spread after deceleration and bunch (de)compressor. For 2E=250 GeV I assumed $\sigma_E/E_0=0.002$ at the IP and all was OK, particle losses were at the level 1% after 10000 turns.

To have similar losses at higher energies we take $\sigma_E/E_0=0.002\times(125/E_0)$ at the IP. According to formulas given above in this case the optimum $\sigma_z \sim 0.3\times(E/125)^{11/7}$ mm for E>125 GeV. Due to dependence of the accelerating field on the longitudinal position I put the limit $\sigma_{z,\,max}<2.4$ mm (at $\lambda_{RF}=23$ см, f=1,3 GHz), the energy spread <0.2% is enough for focusing. It is removed back after deceleration. For E<125 GeV I take $\sigma_z=0.3$ mm.

Bunch (de) compressor

It will work at E~5 GeV and should compress by a factor of 10-15.
Main worries about the increase of the horizontal emittance. The first look shows that it is possible (parameters depend on the bunch length in the linac, which varies with E_0).

Horizontal bunch sizes at the IP are about 5-10 μm, therefore the horizontal emittance should not be too small, problem is the coupling between vert. and horizontal directions.

Results

$N=0.5\cdot 10^{10}$, d=1.5 mm

P=140 MW P_{max}=300 MW

2E	σ_x, μm	σ_y, nm	σ_z, mm	L_{cont}, 10^{35}		L, 10^{35}	DC		L, 10^{35}	DC	P, MW
90	7.6	10	0.3	5.2		5.2	1		5.2	1	140
160	5.7	7.6	0.3	9.3		6	0.65		9.3	1	216
250	4.5	6.1	0.3	14.5		5.4	0.37		11.6	0.8	300
360	5.1	6.8	0.54	11.6		3	0.26		6.4	0.56	300
500	5.5	7.4	0.9	9.7		1.85	0.19		4	0.41	300
1000	7.2	8.6	2.4	6.5		0.62	0.096		1.3	0.21	300
1500	12	7	2.4	4.6		0.3	0.065		0.64	0.14	300

Looks very attractive

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!

- Note that the extra Nb does not add the cost, because it can be sold back, possibly at a profit.