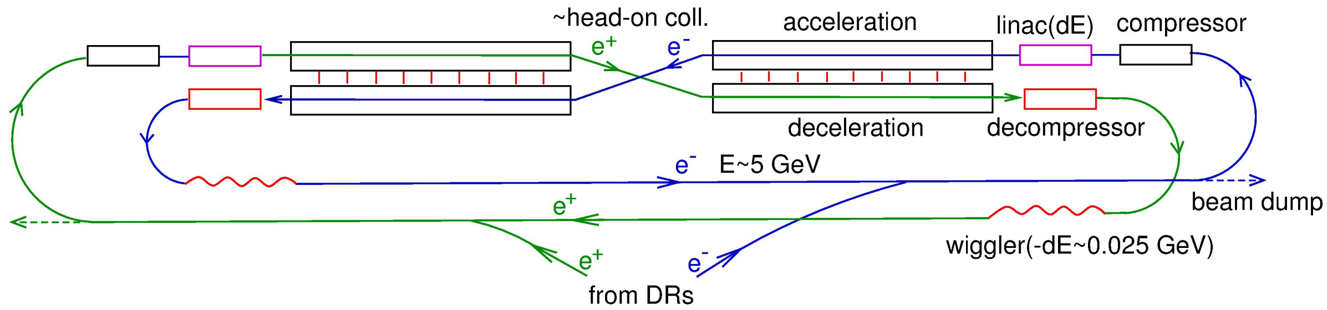
Twin LC with the energy recovery



LHC, ILC and ERLC:

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

Valery Telnov

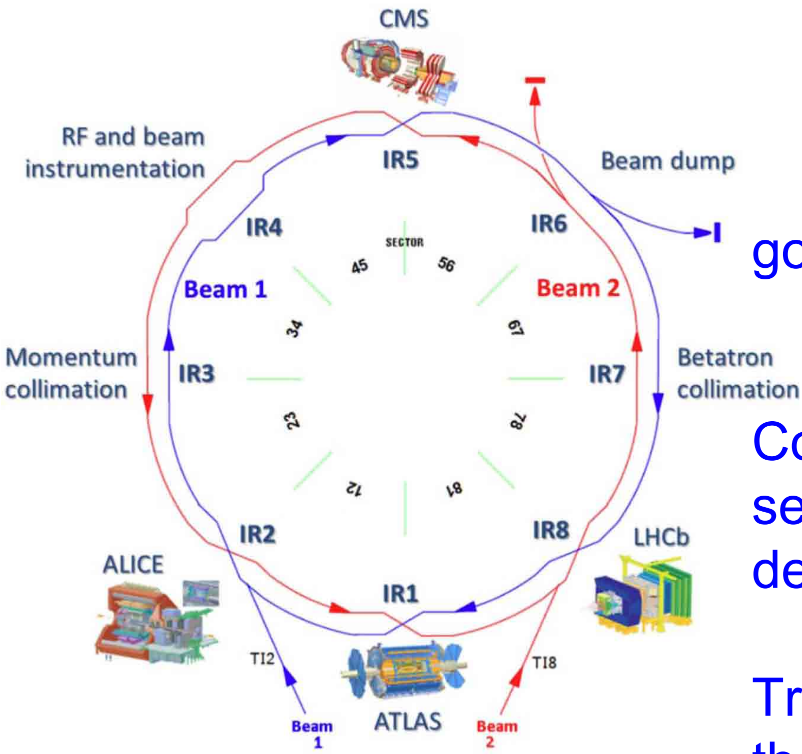
Budker INP and Novosibirsk State Univ.

Sept 27, 2021, RUPAC-2021

Contents

- Introduction, status of LHC,
- Projects of linear e^+e^- colliders, status of the ILC
- 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

LHC



Present: long shutdown 2
2019-2020 →2021

goals –upgrade of the LHC injectors
- preparation for E=7 TeV

Cooldown started in Oct.2020
several short circuit etc, requiring warm-up,
delay > 4 month

Training to 7 TeV takes time,
there is risk, 6.8 as target is discussed

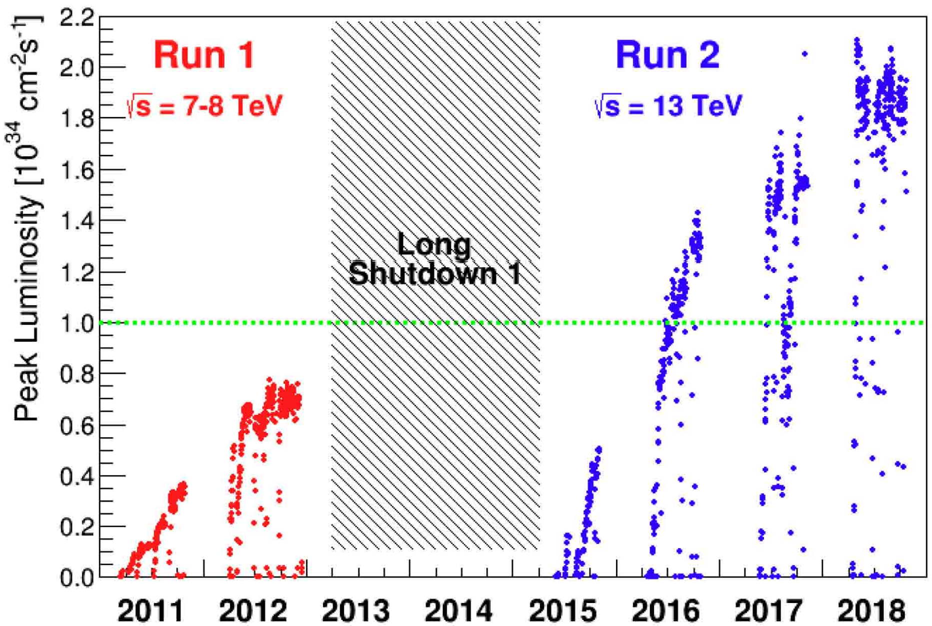
The start of Run 3   March 2022

LHC

Run 2 summary

performance in 2011-2018

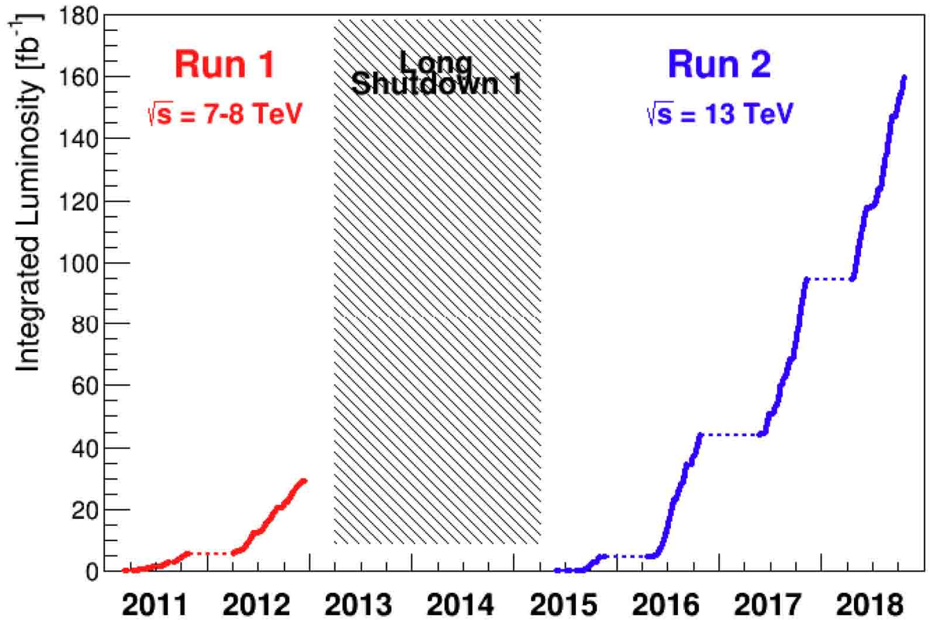
L_{max}~2 x10^{34} (design 1x10^{34})



Total integrated luminosity

30 fb-1 Run 1, E=3.5-4 TeV

160 fb-1 Run 2, E=6.5 TeV



more stability, β*=25 cm, optimized crossing angle

LHC

Run 3 -plans

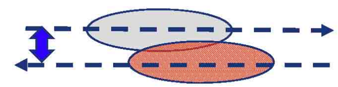
$N=1.15\times10^{11}$ → $N=2\times10^{11}$

ε =3.5 μm → ε =2.1 μm

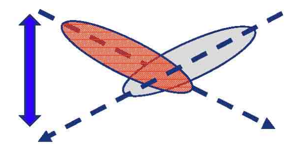
$L_{peak}(10^{34})$ ~2 → 4.5

The luminosity is too high (pile up), will be lavelled dynamically:

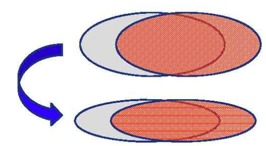
1) offset (2011)



2) crossing angle (2017)



3) β*(at the IP)



In Run 3 levelled $L=2\times10^{34}$ up to 12 hours

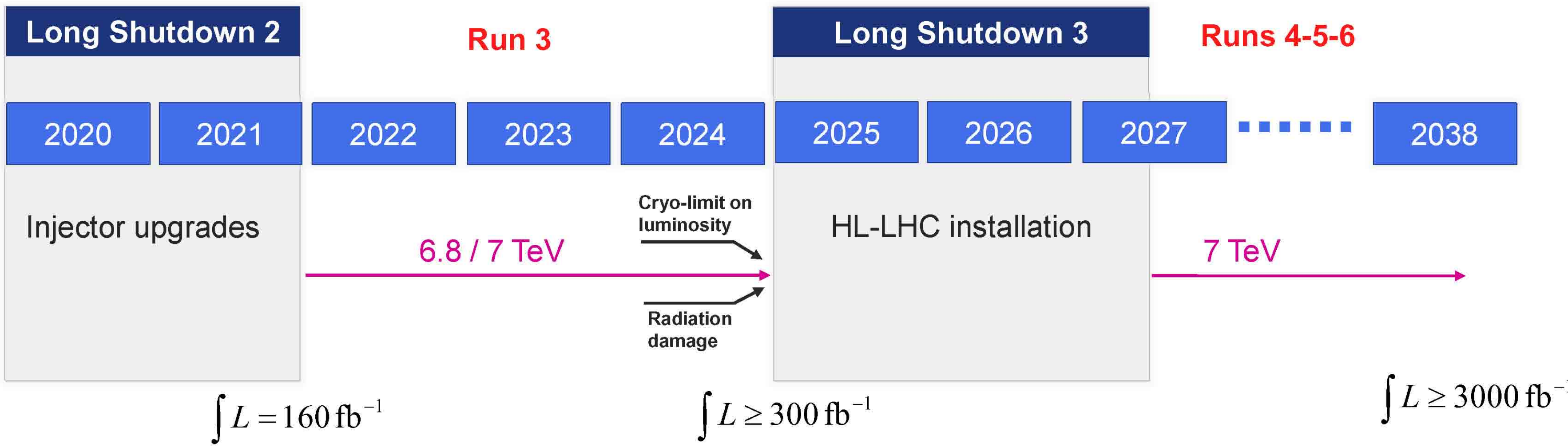
In 2022 ∫Ldt ~ 30-40 fb^{-1} (reduced length 2022 run)

2022-2024 70-80 fb^{-1}/year

Total 2022-2024 160-200 fb^{-1} –doubled (Run-1+Run-2)

HL-LHC

Long term plan



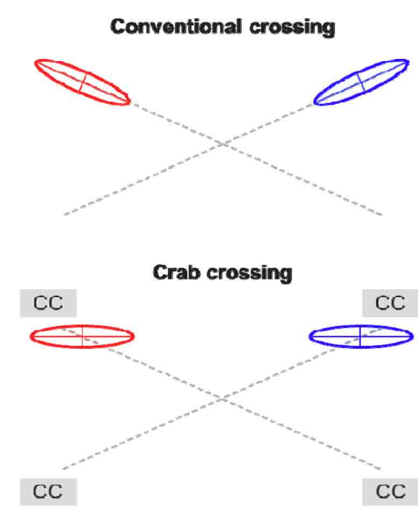
Goal: ~250 fb^{-1}/year in ATLAS and CMS

3000 fb^{-1} ~2038-2040

$N_H \sim 2\times10^8$

Methods:

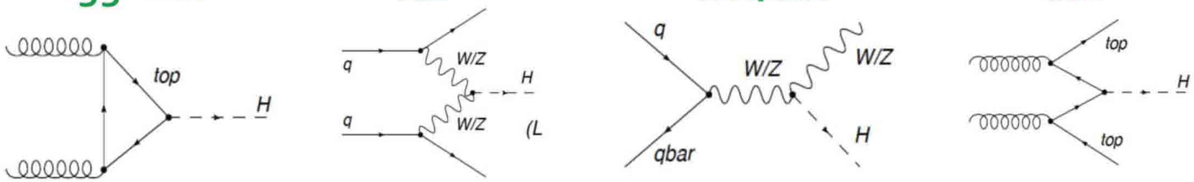
N, β*, ε + crab crossing



Situation in 2022 and with lum. upgrade (2035)

The approved LHC programme will be completed

- With 300 fb^{-1} @ 13 TeV, CMS and ATLAS will measure five production modes
  - $gg \rightarrow H$ VBF WH, ZH ttH



  - … and six decay modes : $\gamma\gamma$, ZZ, WW, $\tau\tau$, bb, $\mu\mu$

Approved LHC 300 fb^{-1} at 14 TeV:

- Higgs mass at 100 MeV
- Disentangle Spin 0 vs Spin 2 and main CP component in ZZ*
- Coupling rel. precision/Exper.
  - Z, W, b, τ 10-15%
  - t, μ 3-2 σ observation
  - $\gamma\gamma$ and gg 5-11%

HL-LHC 3000 fb^{-1} at 14 TeV:

Higgs mass at 50 MeV

More precise studies of Higgs CP sector

Couplings rel. precision/Exper.

- Z, W, b, τ, t, μ 2-10%
- $\gamma\gamma$ and gg 2-5%
- H→HH >3 σ observation (2 Exper.)

LHC can't measure Br(cc, invisible) and Γ_{tot}.

Precision needed after LHC

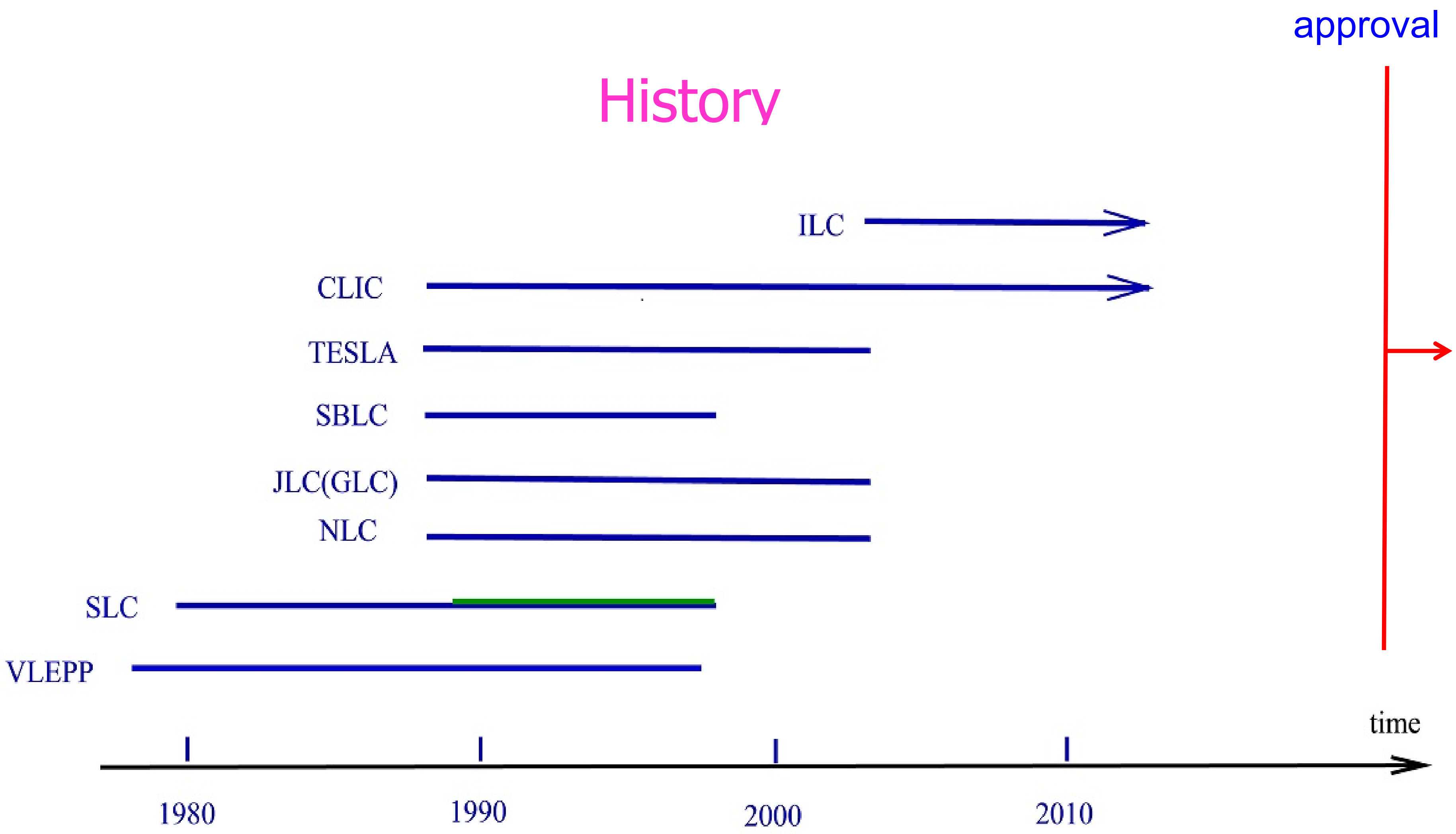
- **New physics affects the Higgs couplings**
  - **SUSY** $\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$ **, for tanβ = 5**
  - **Composite Higgs** $\frac{g_{hff}}{g_{h_{SM}ff}} \simeq \frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 3\% \left(\frac{1\ \mathrm{TeV}}{f}\right)^2$
  - **Top partners** $\frac{g_{hgg}}{g_{h_{SM}gg}} \simeq 1 + 2.9\% \left(\frac{1\ \mathrm{TeV}}{m_T}\right)^2, \quad \frac{g_{h\gamma\gamma}}{g_{h_{SM}\gamma\gamma}} \simeq 1 - 0.8\% \left(\frac{1\ \mathrm{TeV}}{m_T}\right)^2$
  - **Other models may give up to 5% deviations with respect to the Standard Model**

For observation (and some study) of new physics beyond standard Higgs one need precision better than 1%

For that e+e- collider is needed !

Linear colliders

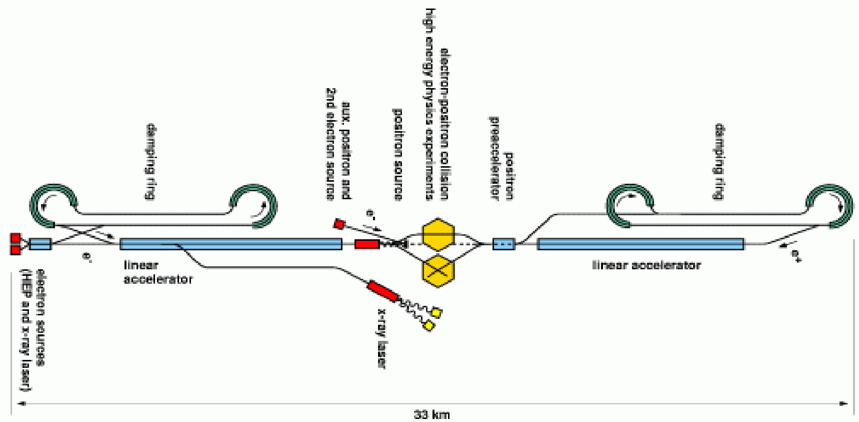
History



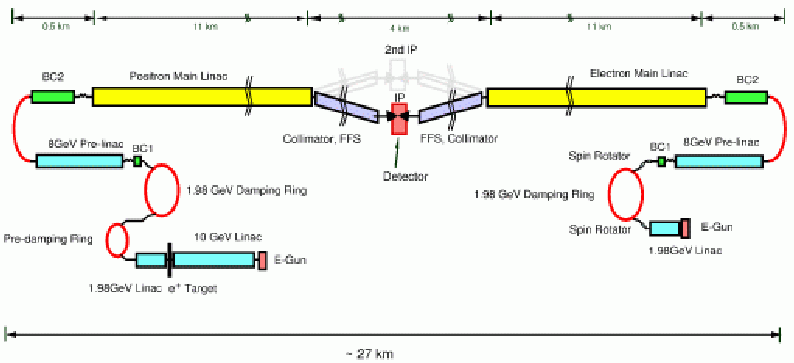
Approval is always on the “Horizon”

Линейные e^+e^- коллайдеры (проекты)

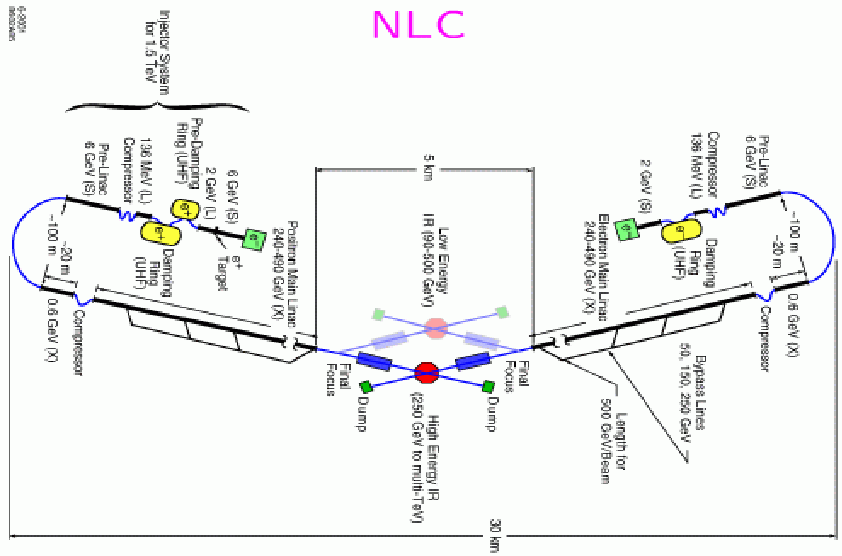
TESLA



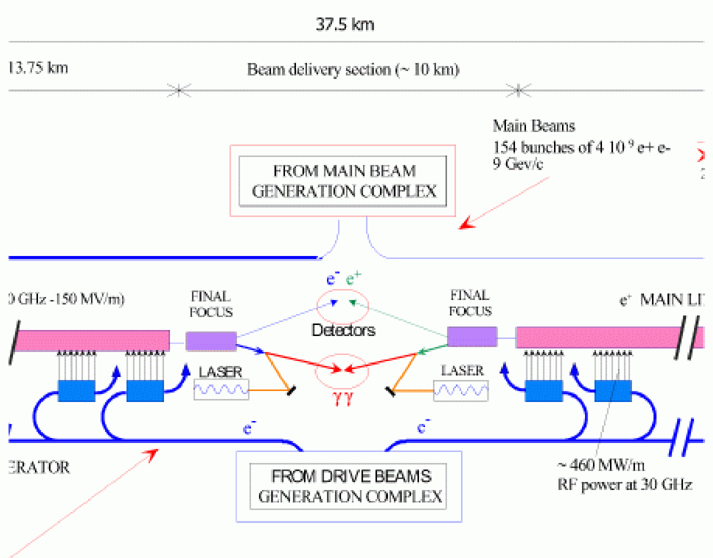
JLC

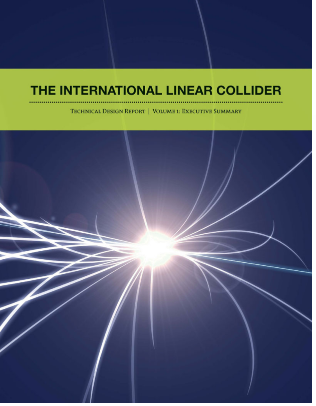


NLC



CLIC

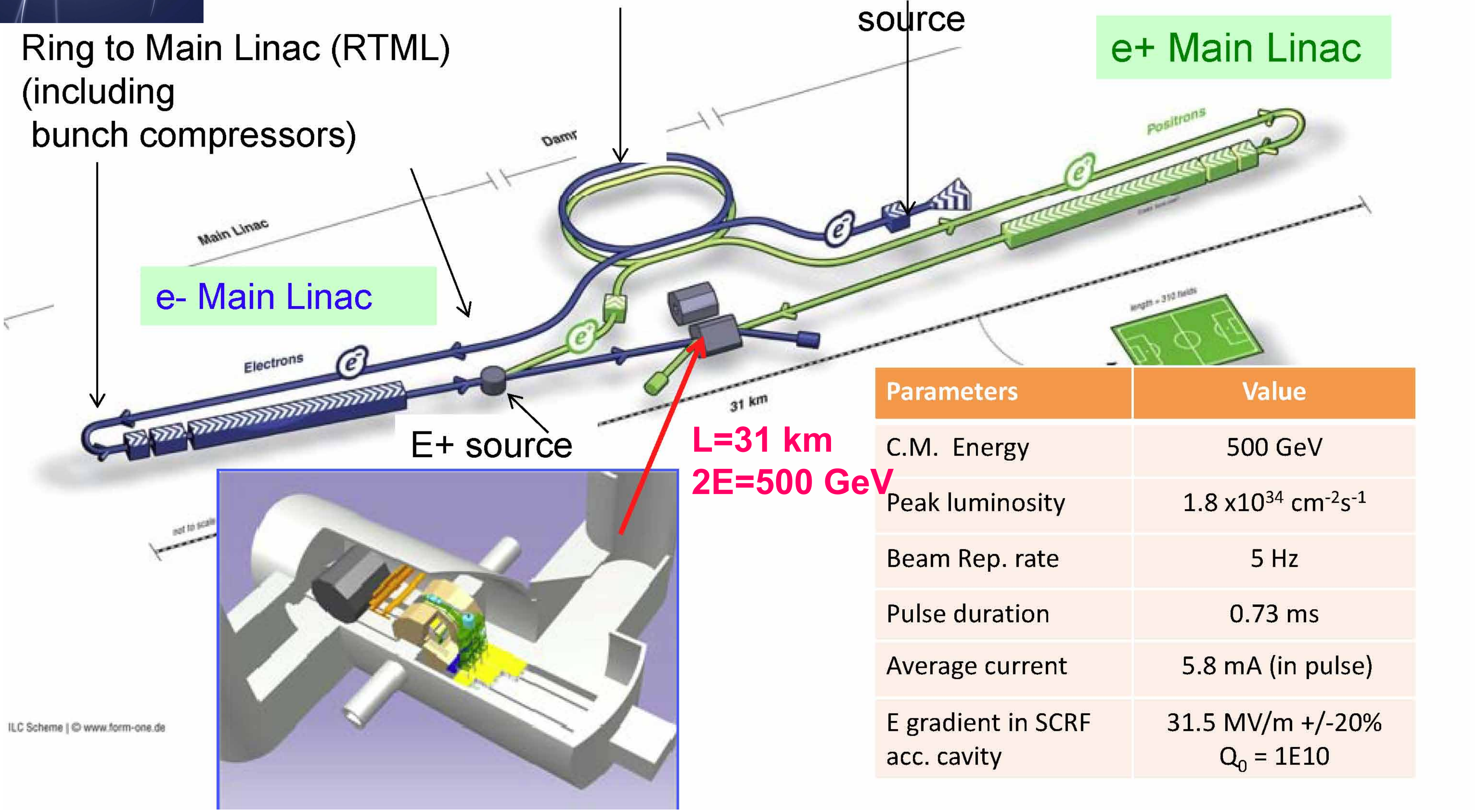




International linear collider (ILC) – since 2004

(based on SC TESLA technology)

ILC TDR
6.2013



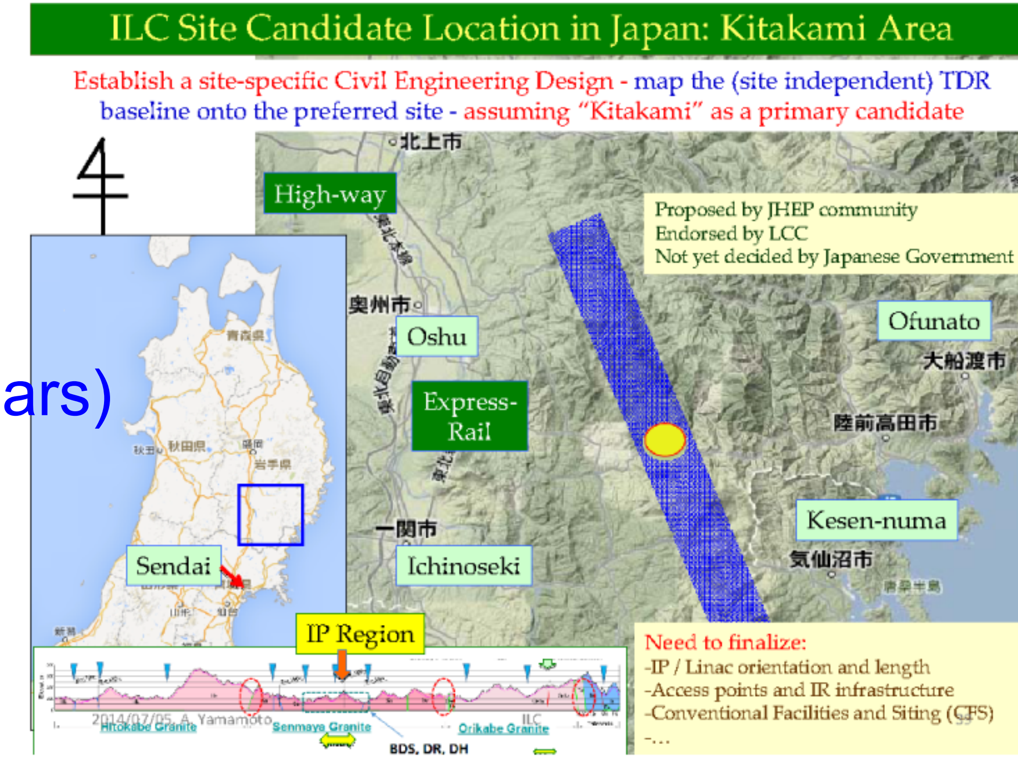
Parameters	Value
C.M. Energy	500 GeV
Peak luminosity	1.8 x10^{34} $cm^{-2}s^{-1}$
Beam Rep. rate	5 Hz
Pulse duration	0.73 ms
Average current	5.8 mA (in pulse)
E gradient in SCRF acc. cavity	31.5 MV/m +/-20% Q_0 = 1E10

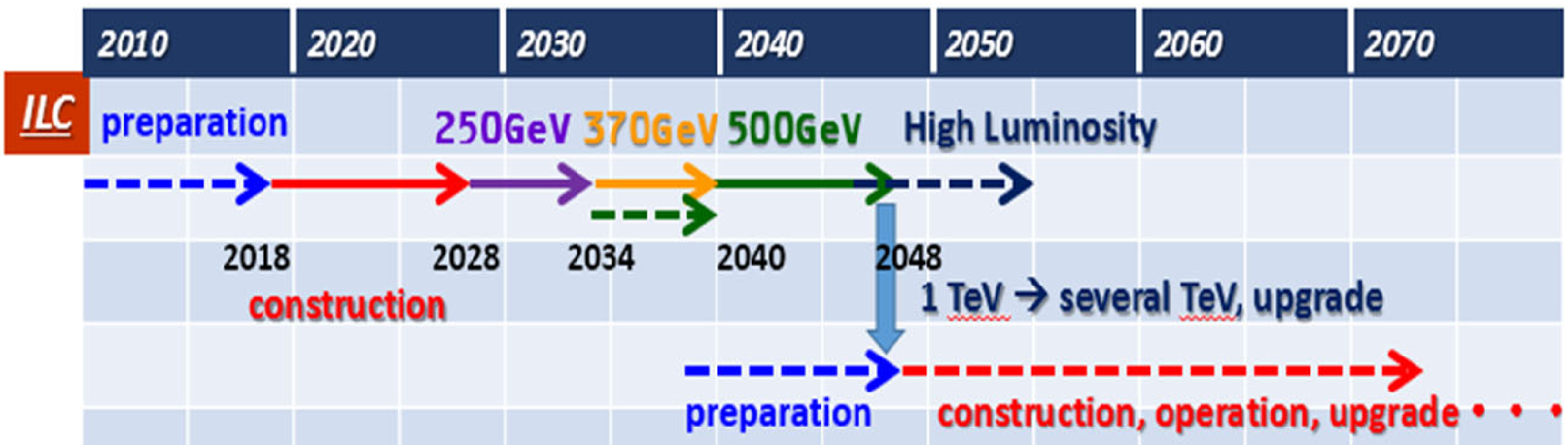
2E=250-500 GeV, upgradable to 1000 GeV

ILC TDR published in 2013

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

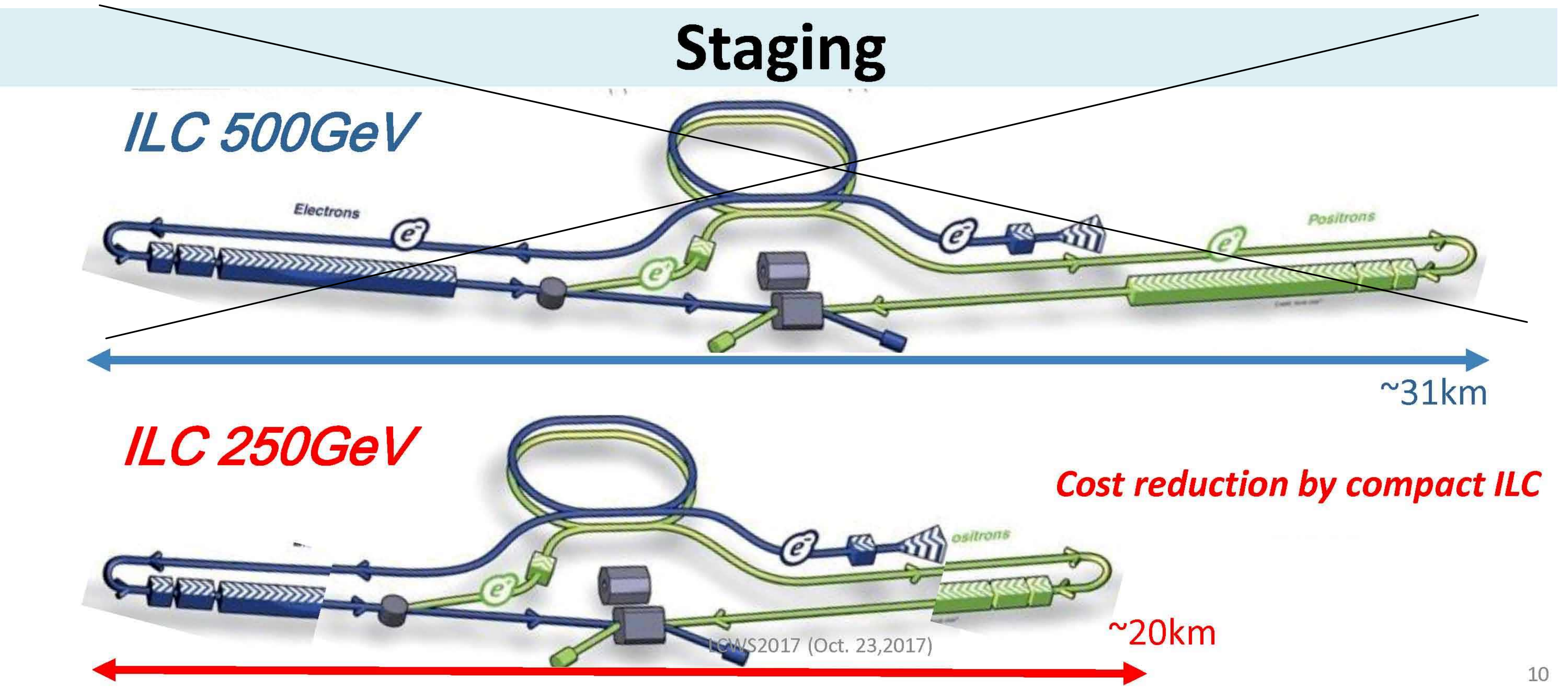
Now 2021, no decisions yet !





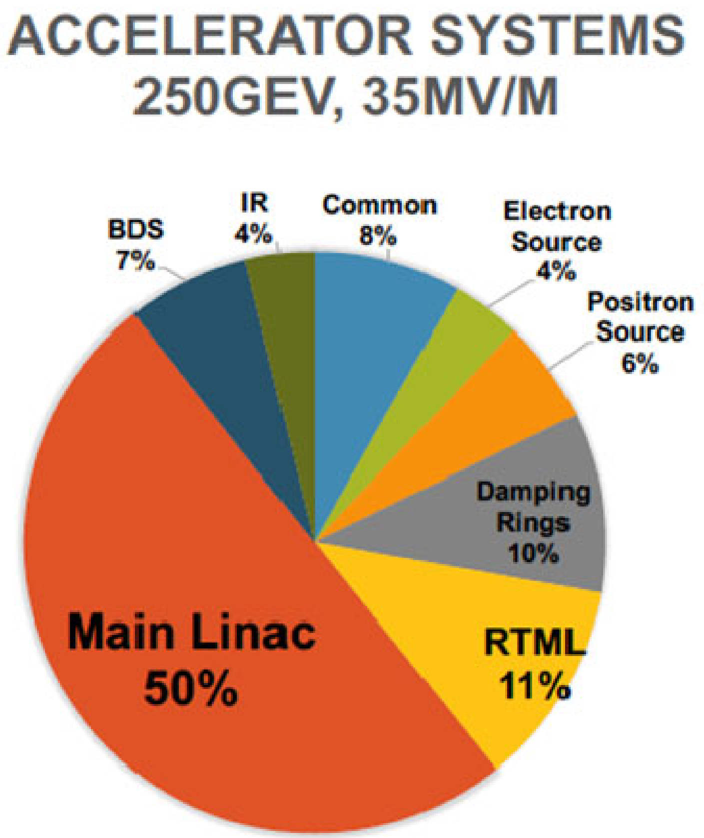
ILC, since LCWS 2017

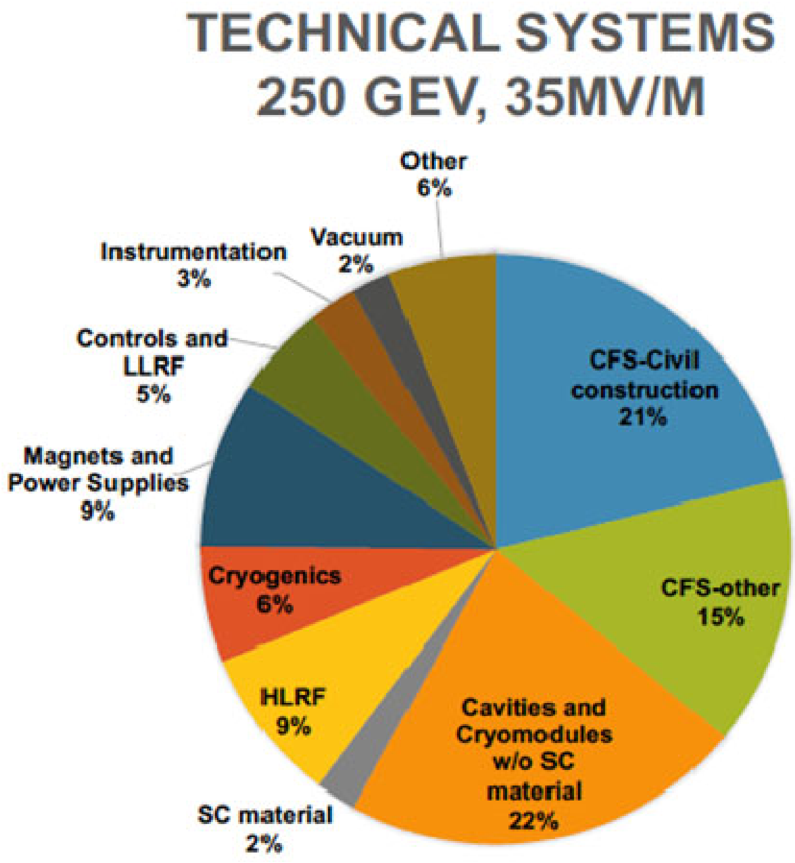
At present Japan consider ILC with 2E=250 GeV, without any words about possible upgrade (but possible). Thus the cost was reduced by 40% compared to 500 GeV.



This energy is OK for e+e-→ZH (no tt) and for $\gamma\gamma \to H$ as well

ILC construction cost = 6.35 -7 G$

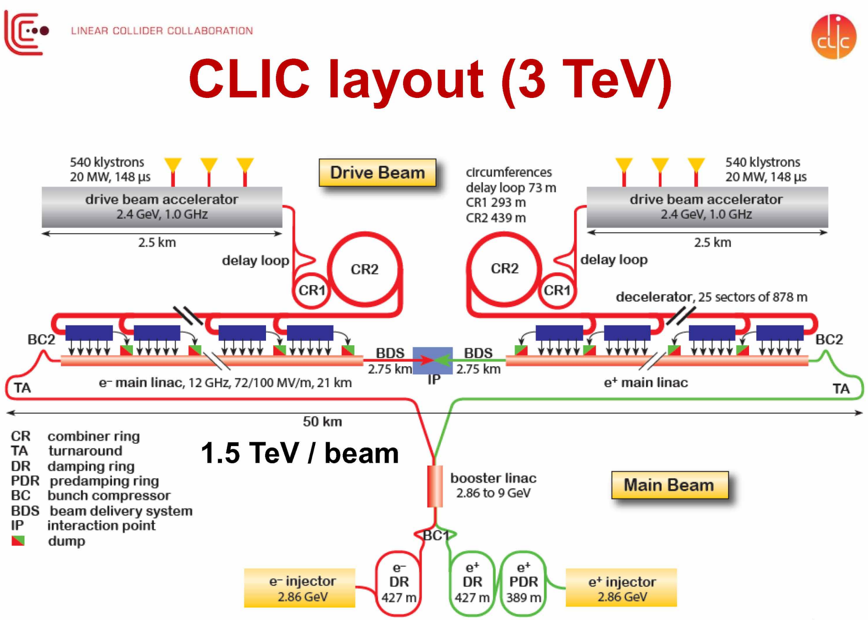


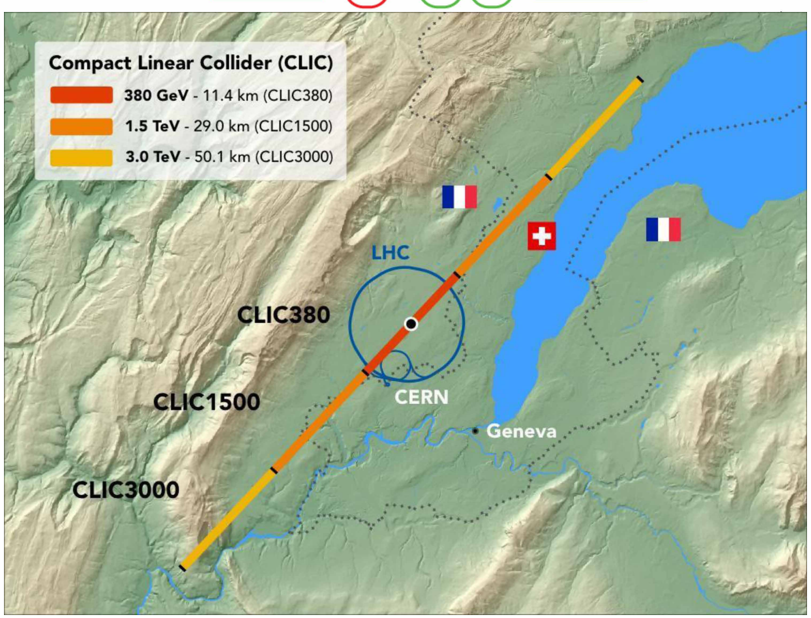


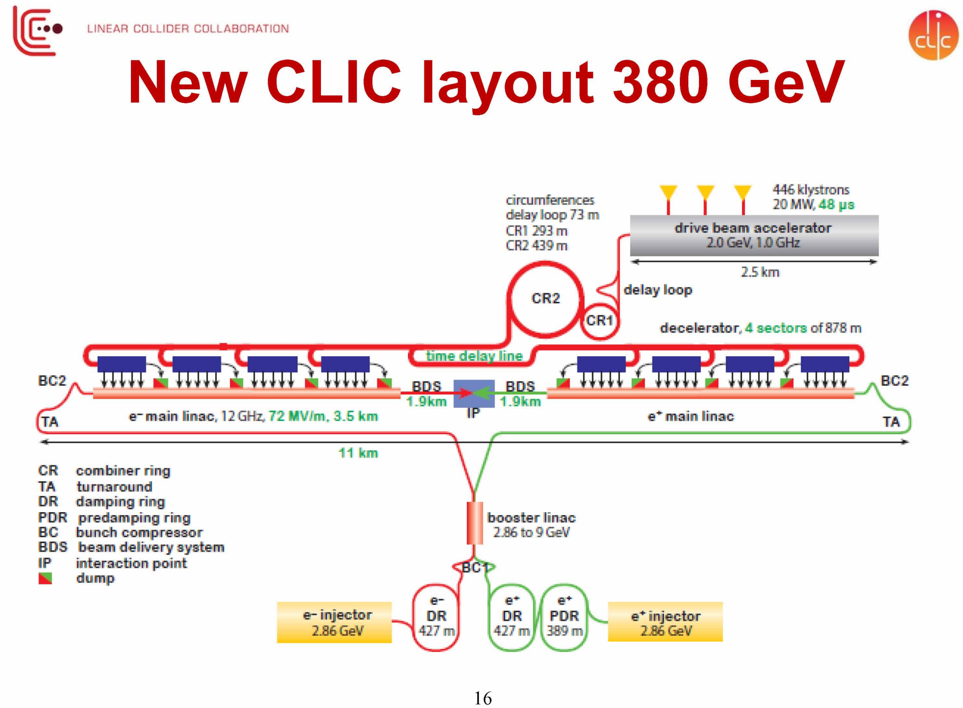
ILC superconducting cavities, ν=1.3 GHz

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

CLIC







Cost ~6700 SFr

Present plans:

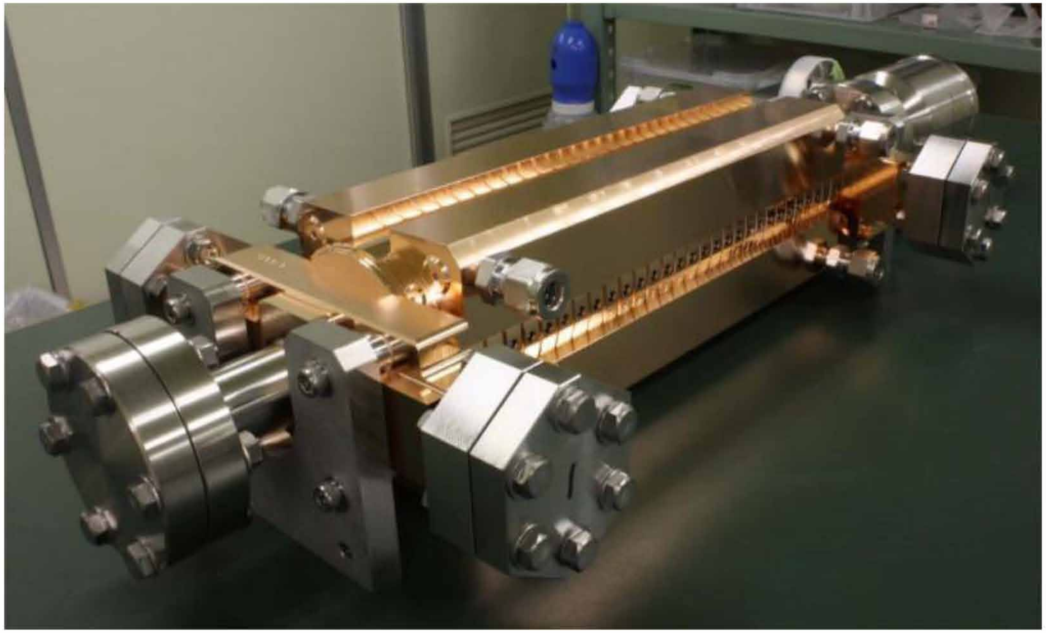
the initial energy 2E=380 GeV (H and top)
2019-20+? – decision
2020-2025+? – preparation phase
2025+? – construction starts

2035+? – first beams

CLIC accelerating structure

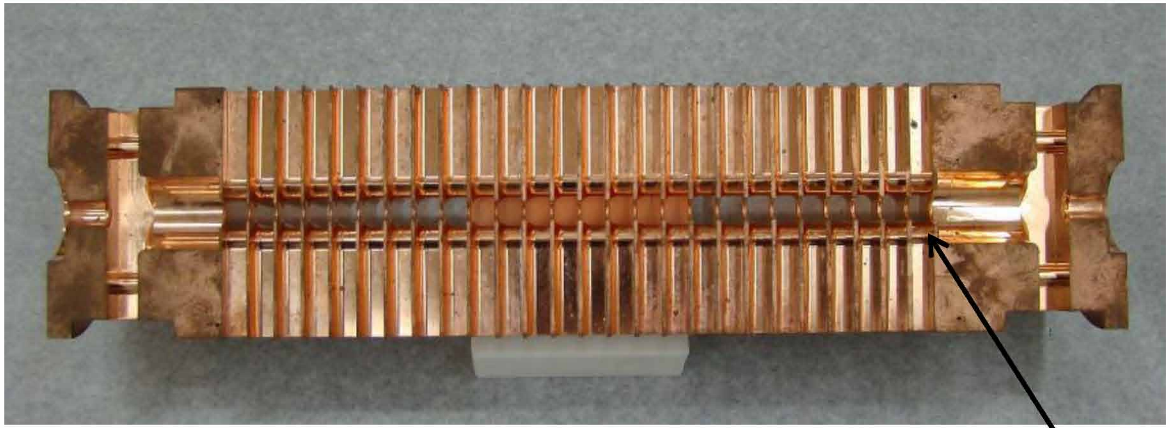
Outside

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

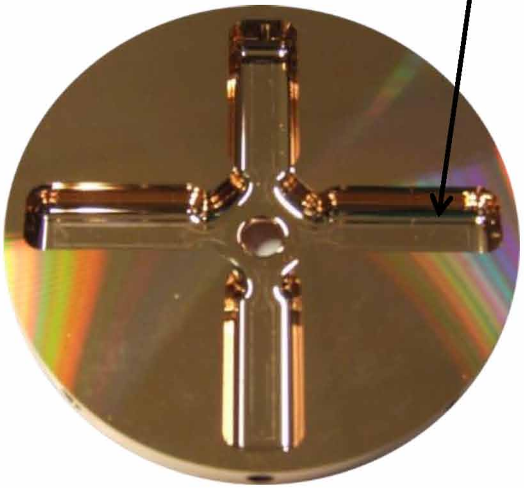


HOM damping waveguide

Inside



Micron–precision disk



25 cm

6 mm diameter beam aperture

ILC and CLIC parameters

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

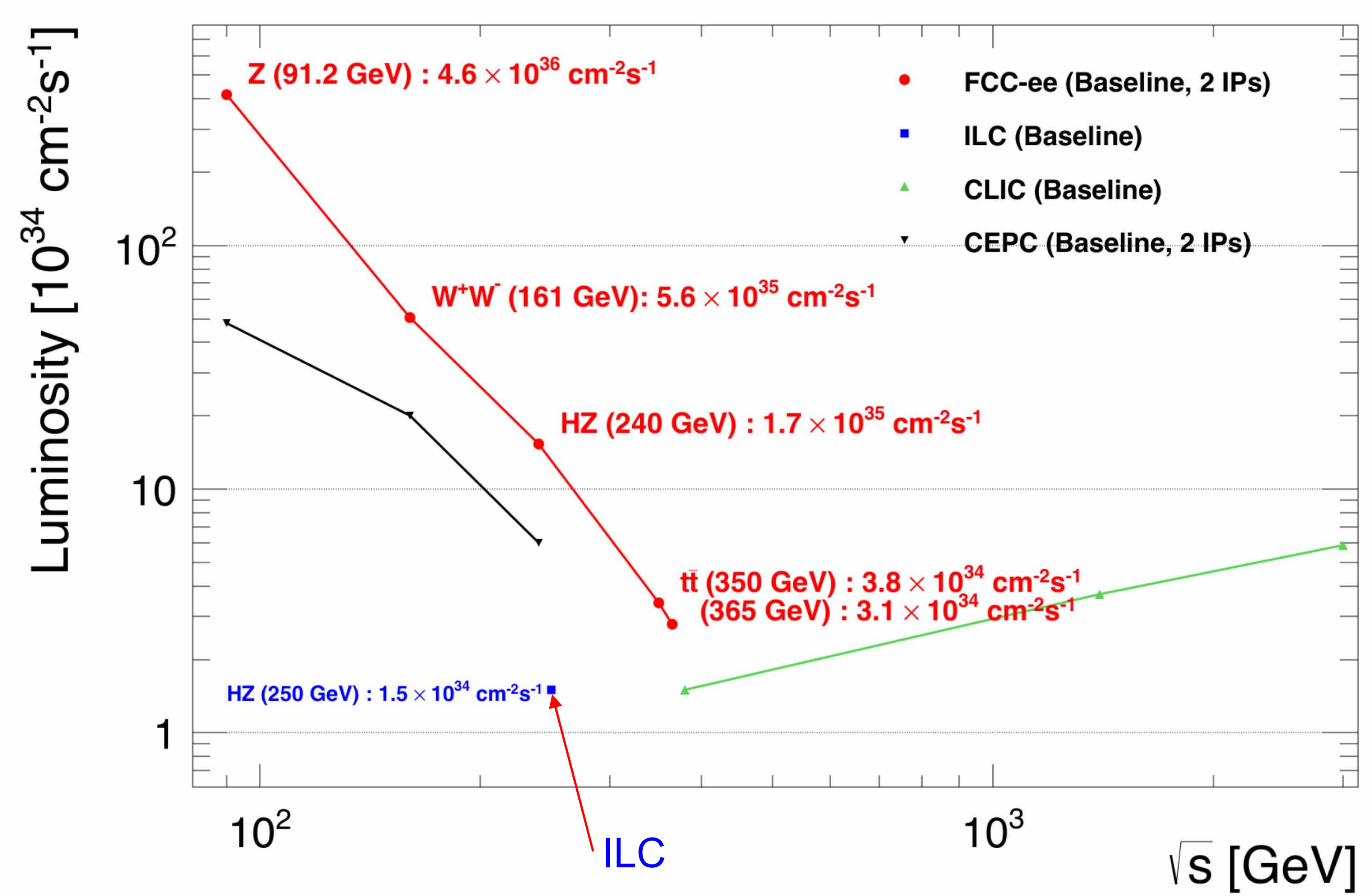
	unit	ILC			CLIC		
$2E_0$	GeV	250	500	1000	250	500	3000
L_{tot}	$10^{34}\,cm^{-2}s^{-1}$	0.75	1.8	4.9	1.37	2.3	5.9
L_{geom}	$10^{34}\,cm^{-2}s^{-1}$	0.37	0.75	2.61	0.82	1.42	4.29
No. Higgs/yr(10^7s)	1000	23	49	–	34	44	446
Length	km	21	31	48	13.2	13.2	48.3
P (wall)	MW	128	162	301	225	272	589
Pol. e^-/Pol. 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} cm^{-2}s^{-1}	0.75	1.37

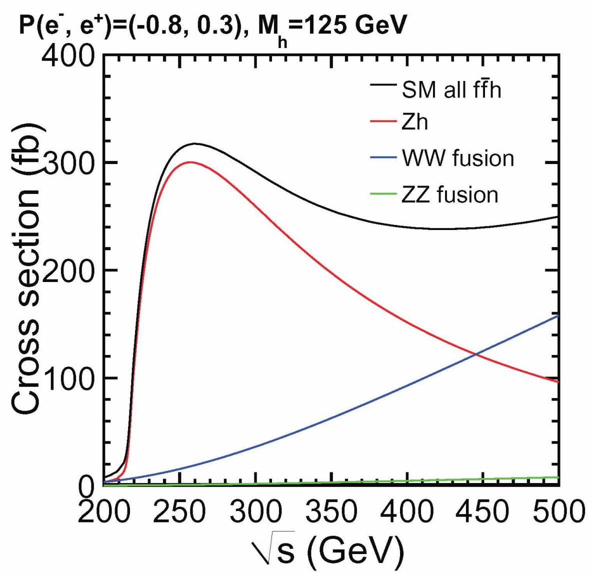
Both LC have $L \sim 10^{34}$, collision rate ~10 kHz, difference only in distance between bunches

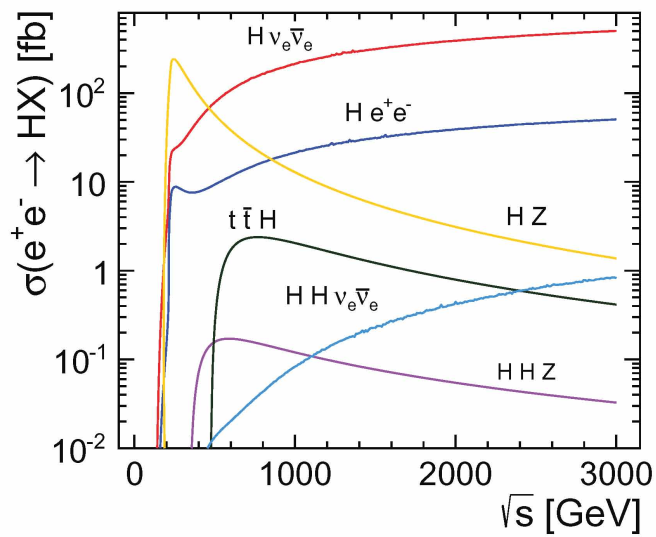
Circular 100 km e+e- collider (FCC-ee, CEPC) vs ILC and CLIC

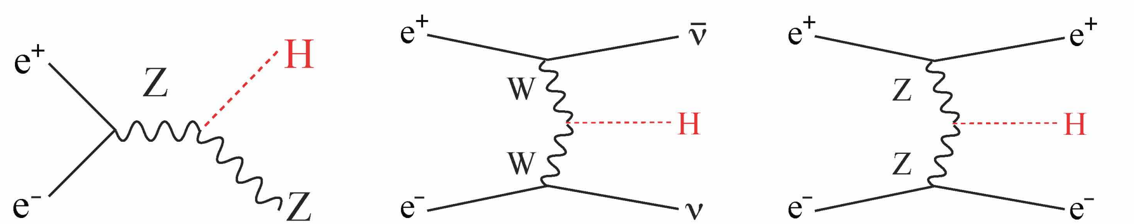


The luminosity at the Higgs energy 2E=250 GeV is higher at FCC-ee by one order of magnitude

Higgs physics in e+e- collisions





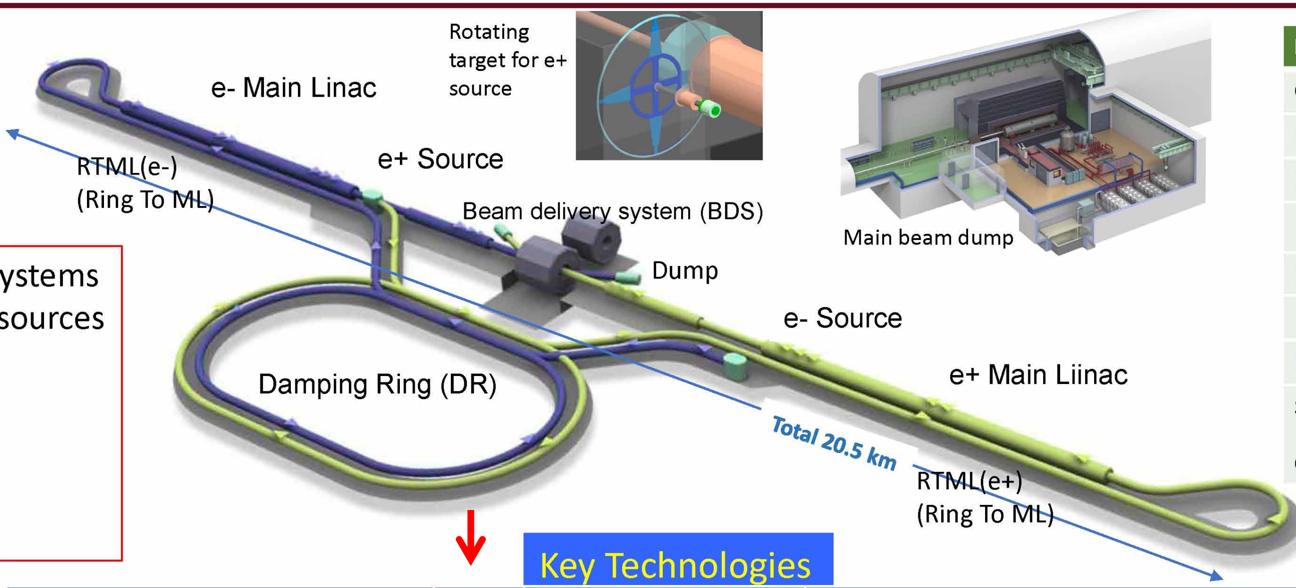


Tagging Z in e+e-→ZH one can measure all Br(H), even invisible decays width.
One can measure the Higgs total width:
$\Gamma(H) \sim \sigma(e^+e^- \to ZH)/Br(H \to ZZ)$ and $\Gamma(H) \sim \sigma(WW \to H)/Br(H \to WW)$

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 x10^{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 = 1x10^{10}

Key Technologies

	IDT	ILC Pre-Lab				ILC Lab.										
	PP	P1	P2	P3	P4	1	2	3	4	5	6	7	8	9	10	Phys. Exp.
Preparation CE/Utility, Survey, Design Acc. Industrialization prep.																
Construction																
Civil Eng.																
Building, Utilities																
Acc. Systems																
Installation																
Commissioning																
Physics Exp.																

Following a four-year ILC Pre-Lab phase, ILC construction will continue for about ten years.

ILC organization

From LCC to the Pre-Lab Proposal

- 2013-Jun 2020: Linear Collider Collaboration LCC under ICFA Mandate, governed by Linear Collider Board LCB
- 2014-2018: MEXT appointed ILC Advisory Panel reviews project, incl. new 250GeV baseline
- Feb-Jun 2020: LCB proposes International Development Team IDT to prepare an ILC-Pre-Lab
- Aug 2020: ICFA establishes IDT and appoints IDT Executive Board (*)
- Goal: establish an ILC Pre-Lab within ~1.5 years
- IDT focusses on ILC realization, KEK provides support (admin., financial)
- June 2021: IDT submits Pre-Lab proposal

Near goal:
International Development team should organize ILC Pre-Lab

Reminder for ICFA mandate for the IDT

- Clarifying the function and organisation of the ILC Pre-Lab based on the KEK International Working Group report,
- Developing a common understanding for the condition to start the ILC Pre-Lab,
- Providing an international framework for the ILC accelerator effort and coordinating further R&D and engineering design work for the ILC in order to sustain the community effort and to guarantee a smooth transition to the ILC Pre-Lab phase,
- Providing an international framework for the ILC physics and detector activities and coordinating physics and detector R&D effort in order to sustain the community effort and guarantee a smooth transition to the ILC Pre-Lab phase,
- Discussing with international partners (e.g. universities, national and regional laboratories) for resources needed for the ILC Pre-Lab, and
- Providing necessary information to the national authorities to support their discussion of the establishment of the ILC Pre-Lab.

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

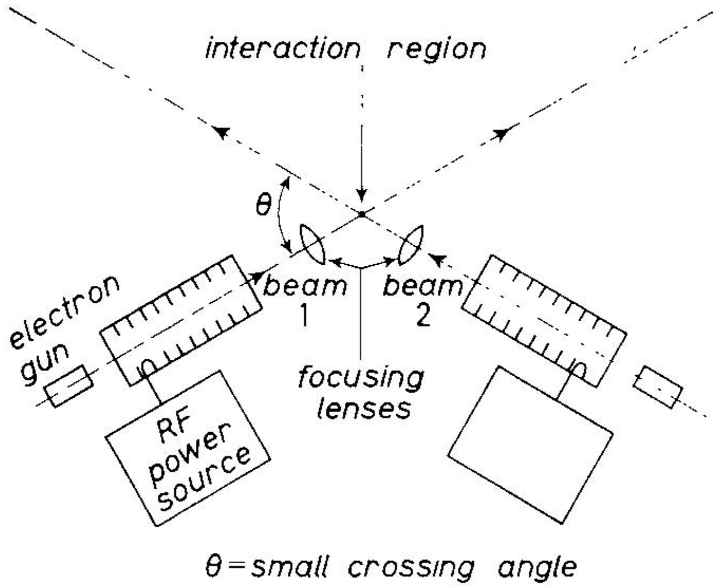
The ILC duty cycle (DC) = 0.00072*5=$3.6\cdot10^{-3}$
CLIC $9\cdot10^{-6}$

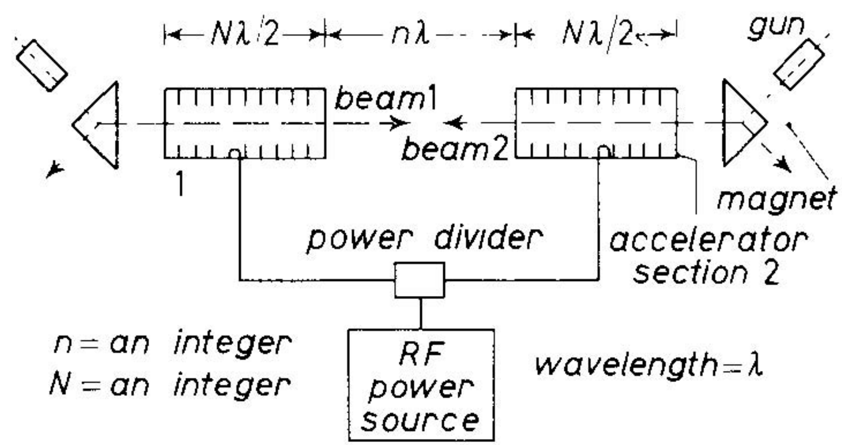
Most of time the colliders do nothing!
(only prepare new beams in damping rings)

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.

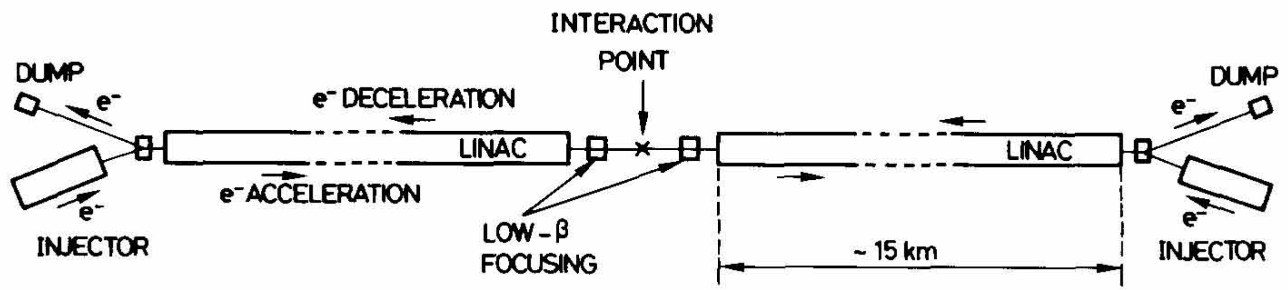
A POSSIBLE SCHEME TO OBTAIN e^-e^- AND e^+e^- COLLISIONS AT ENERGIES OF HUNDREDS OF GeV

U. AMALDI
CERN, Geneva, Switzerland

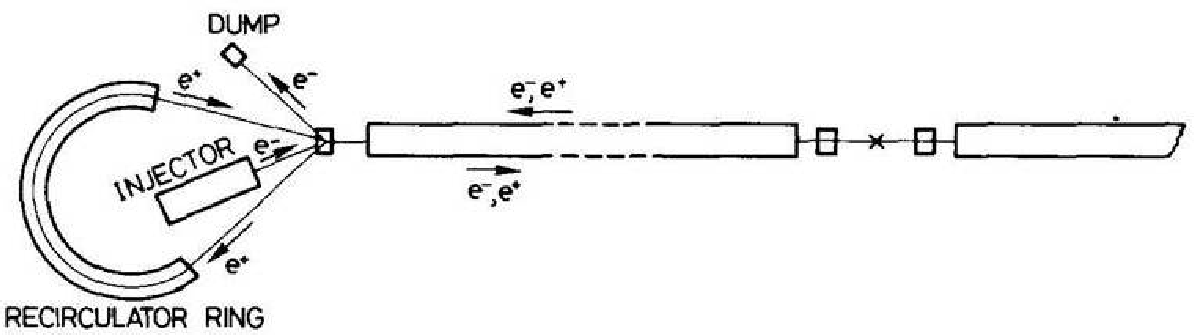
U. Amaldi (1976) Phys. Lett. 61B, 313

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.



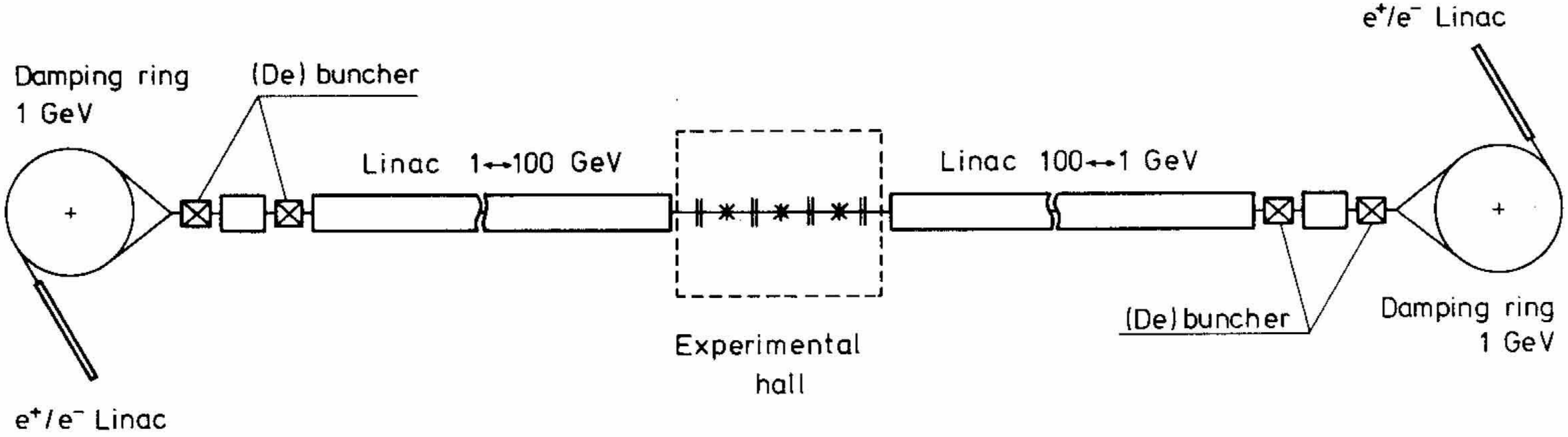
In this scheme the electron and positron bunches are dumped after one-pass energy recovery



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

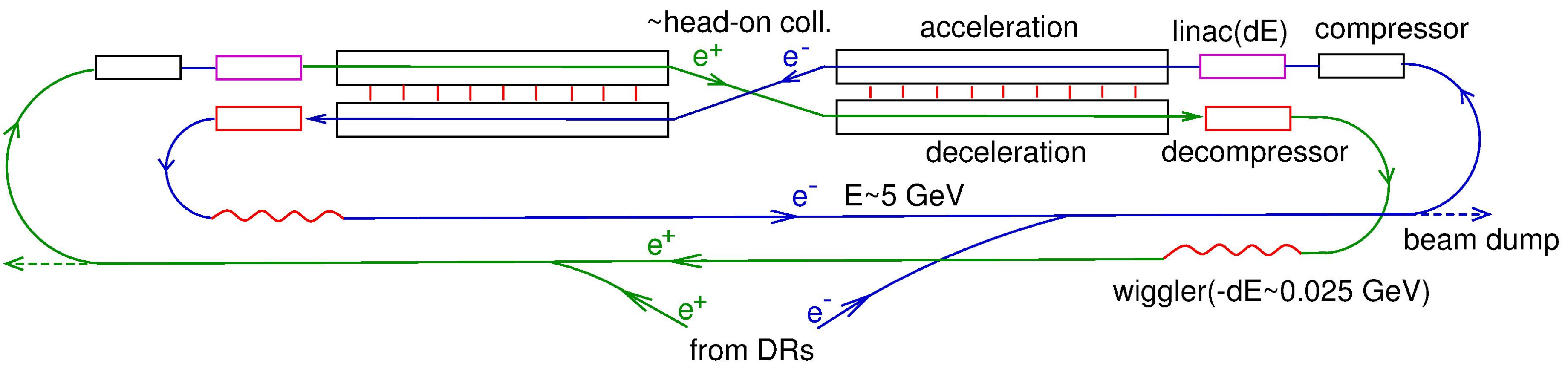
In the linac $$\xi_y \propto \frac{\beta_y}{\sqrt{\beta_x\beta_y}} = \sqrt{\frac{\beta_y}{\beta_x}} \approx 1 \gg \xi_y^*.$$

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

The proposed LC scheme

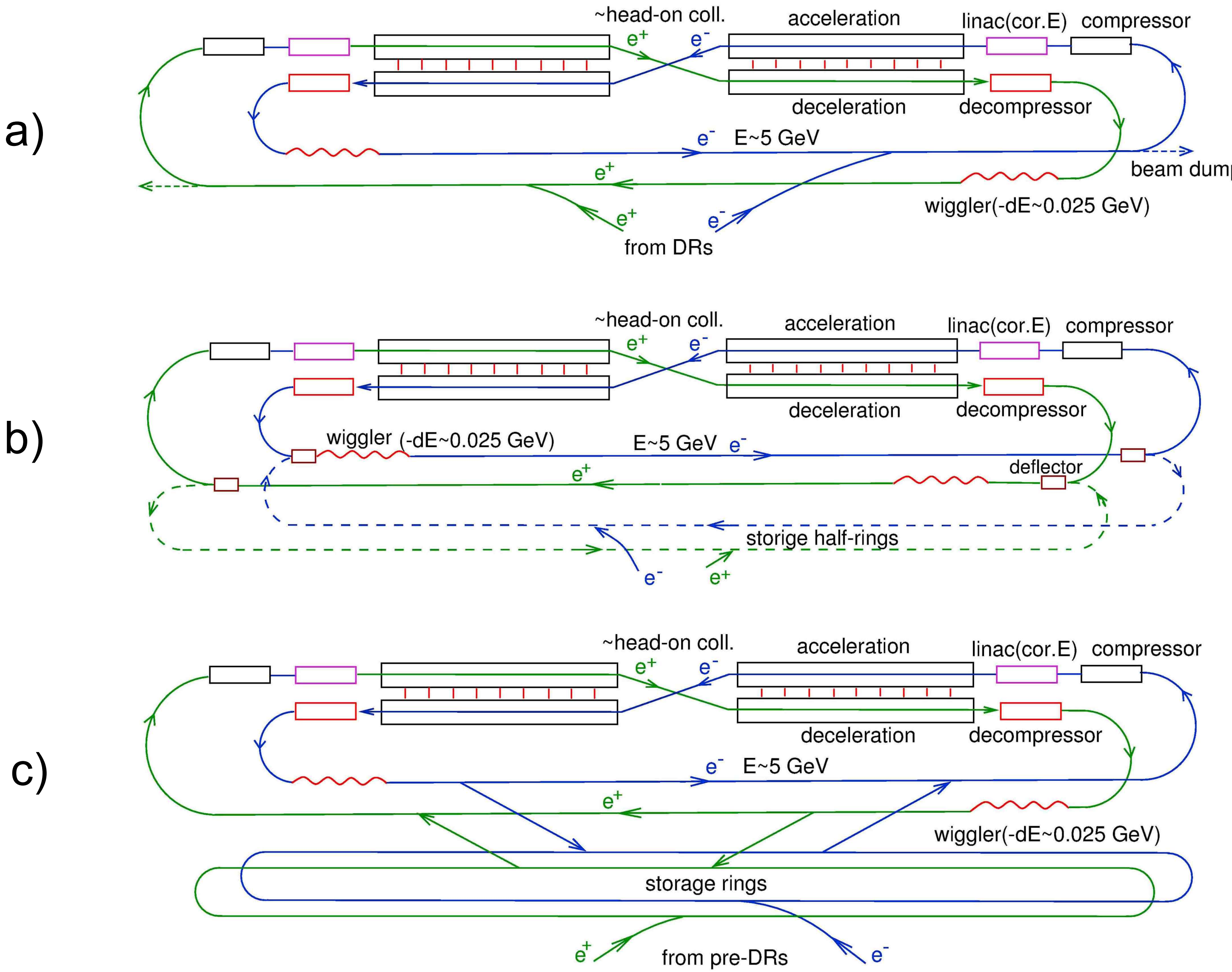
Telnov, LCWS21
arXiv:2105.11015

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~1/200. 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).

Twin LC with energy recovery



a) good for continuous mode

b) and c) for DC(duty cycle)<1, beams are saved in storage rings when ERLC is resting

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

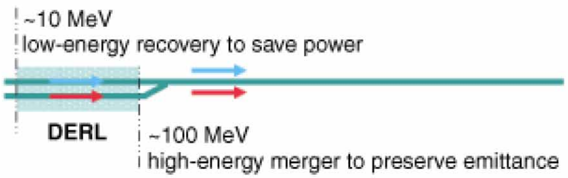
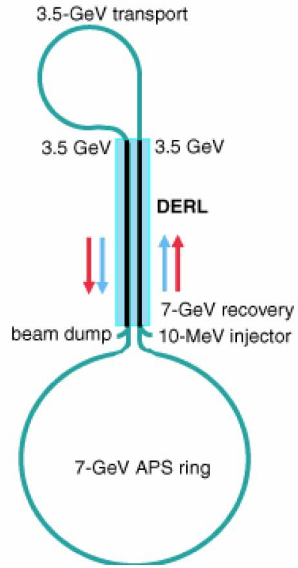
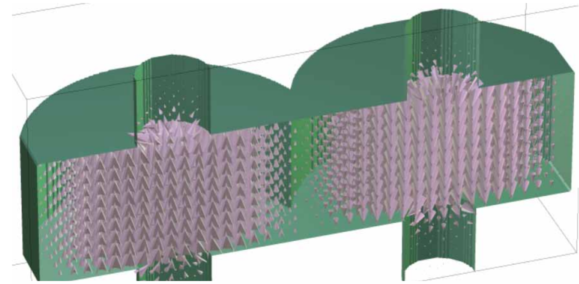
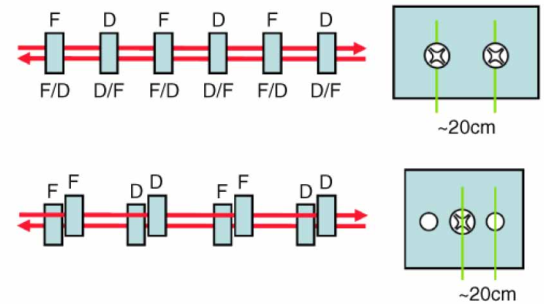


Fig. 2: DERL as a solution for beam merger. The red arrow indicates accelerating beam.







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

MULTI-BEAM ACCELERATING STRUCTURES

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KEK, High Energy Accelerator Research Organization
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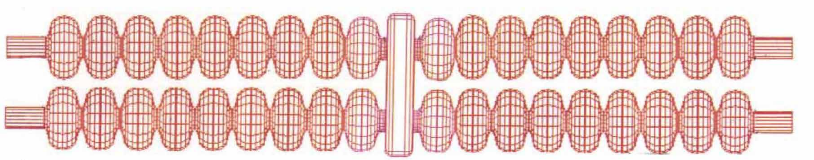

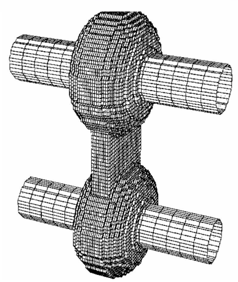

Proceedings of LINAC2016, East Lansing, MI, USA

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

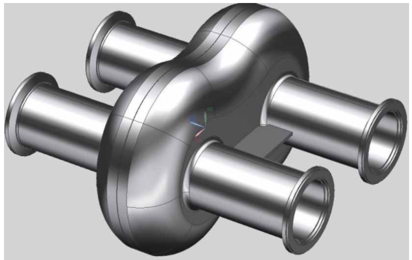

Figure 2: Single cell twin axis cavity.

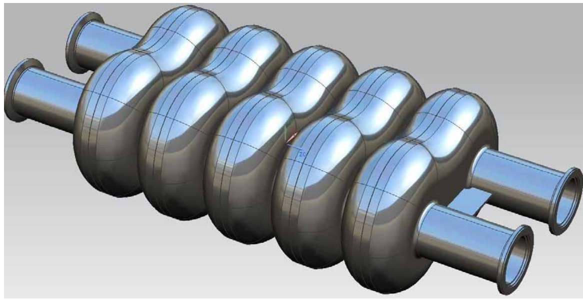

Figure 9: Multicell twin axis cavity.

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

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

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[2]*Cockcroft Institute, Lancaster University, Lancaster LA1 4YW, United Kingdom*
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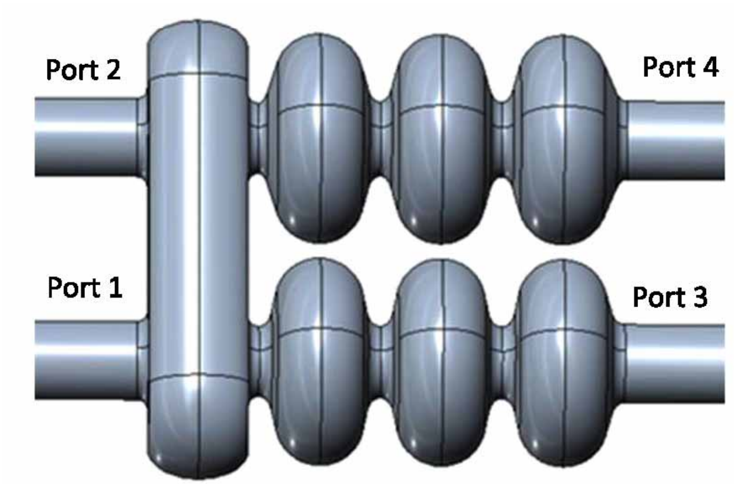
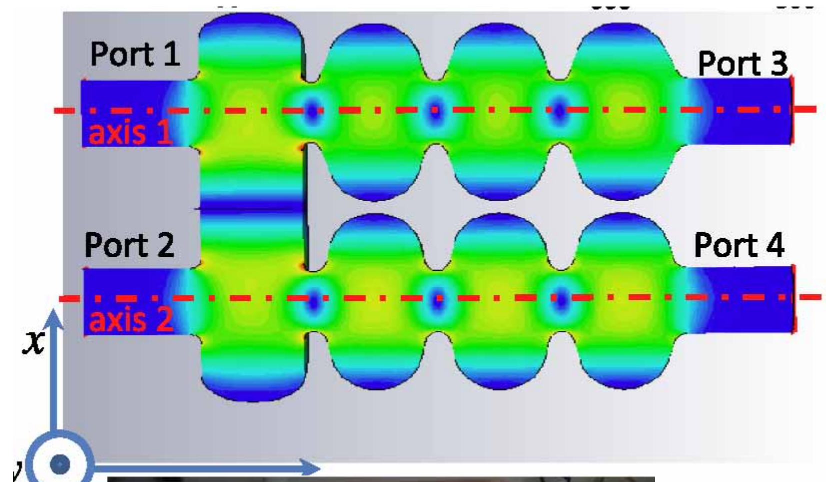
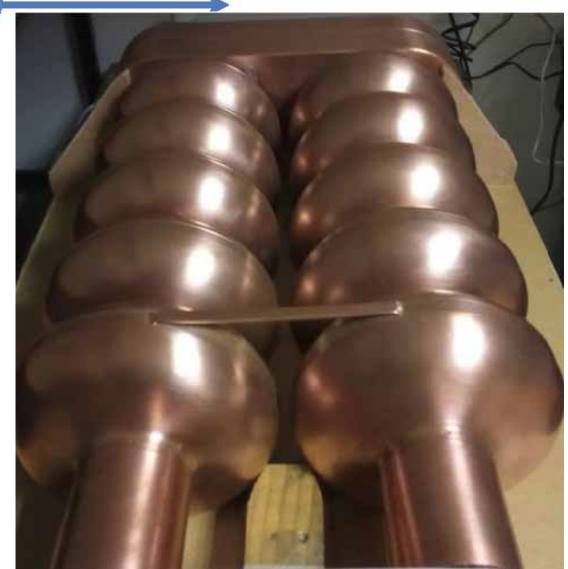
(Received 28 May 2017; published 10 October 2017)







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

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

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

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

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

For $2E_0 = 250$ GeV, $\xi = 0.1$, $\varepsilon_{ny} = 3\cdot10^{-6}\,\mathrm{cm}$, $\sigma_E/E_0 = 2\cdot10^{-3}$, $\delta E/E = 0.5\cdot10^{-2}$

$$\sigma_x \approx 0.9\left(\frac{N}{10^9}\right)\,\mu\mathrm{m}, \qquad \sigma_y \approx 6.1\ \mathrm{nm}, \qquad \sigma_z = 0.3\frac{E[\mathrm{GeV}]}{125},\ \mathrm{mm}.$$

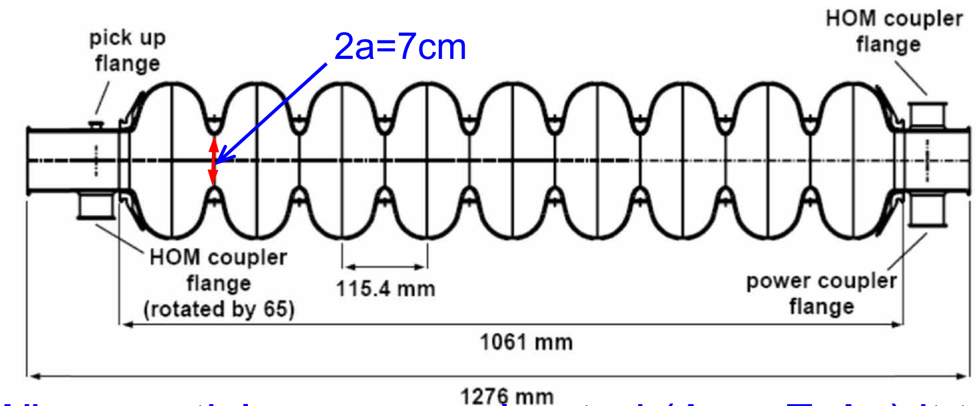
$$L \approx 4.35\cdot10^{35}\frac{\left(N/10^9\right)}{d[\mathrm{m}]} \approx 9\cdot10^{36} I[\mathrm{A}]\ \mathrm{cm}^{-2}\mathrm{s}^{-1}.$$

For $N=10^9$, $d=\lambda_{RF}=0.23$ m $\rightarrow$ $L = 1.9\cdot10^{36}\ \mathrm{cm}^{-2}s^{-1}$ at P_{SR}=10.4 MW (I=0.21 A)

Such L is for continuous operation, should be multiplied by a duty cycle DC, if the power is not sufficient for continuous operation.
$N\sim10^9$ is near to optimum (see below).

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

$$\frac{d\varepsilon}{dz} \approx 2.2\left(\frac{N}{10^9}\right)\frac{\text{keV}}{\text{m}}$$

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

For $N=10^9$ the efficiency of energy recovery ~99.98%.

Remark: small part of HOMs dissipate in cavities but most of it is removed by special couplers and absorbers to a high-T region, that need a lot of refrigeration power.

High order mode losses (continue)

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

$$P_{\mathrm{HOM}} = \frac{2.65}{d(\mathrm{m})}\left(\frac{N}{10^9}\right)^2 \ \mathrm{MW}$$

For $N=10^9$, d=0.23 m P_{HOM}=11.5 MW (while P_{SR}=10.4 MW).

Due to quadratic dependence on N, it is profitable to reduce N and d, keeping L=const, that is why *d* should be small as possible, $d=\lambda_{RF}$.

For compensation beam energy due to HOM losses we need electric power (with efficiency) about $P_{HOM,beam}=2P_{HOM}$. But much more energy is needed for cooling this power, which dissipated mostly at T=77 K, and some at 2K.

At T=77 K, ε~0.3*77/(300-77)~0.1, at 2K ε~0.0018. Assuming that only 1.5% of HOM power is dissipated in SC cavities the total power for removal of HOM losses is about $18\times P_{HOM}$.

Full extra power from wall plug due HOMs is

$$P_{HOM,wall\text{-}plug} \sim 20P_{HOM} \sim 230(N/10^9)^2 \ \mathrm{MW}$$

(for continuous operation)

Surface resistance R_s in ideal case

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

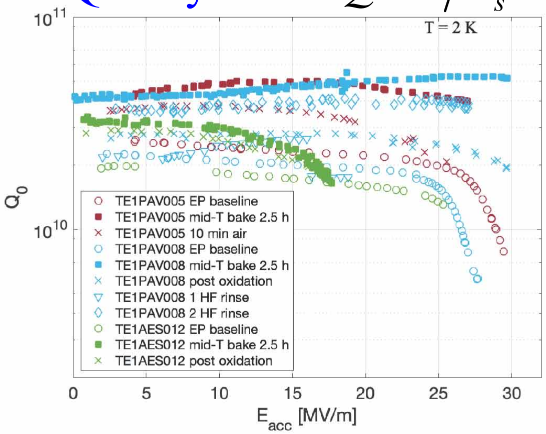
Quality factor $Q \propto 1/R_s$

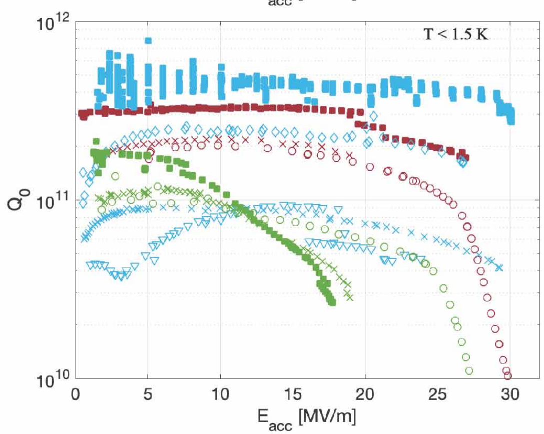
Refrigeration of RF losses

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

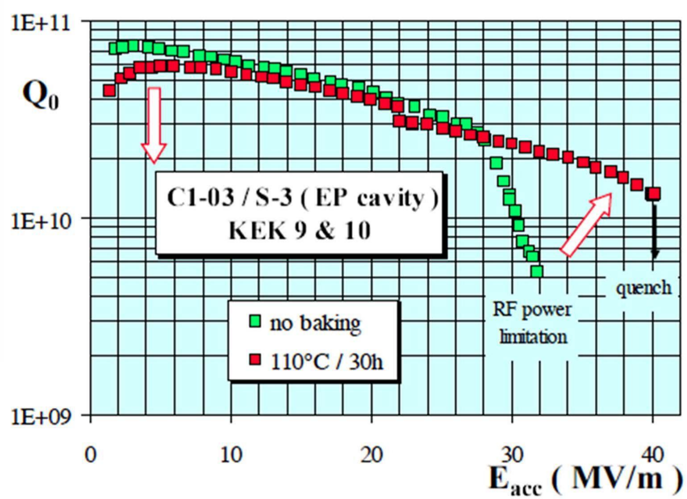
$P_{RF,refr}$~190 MW.

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}

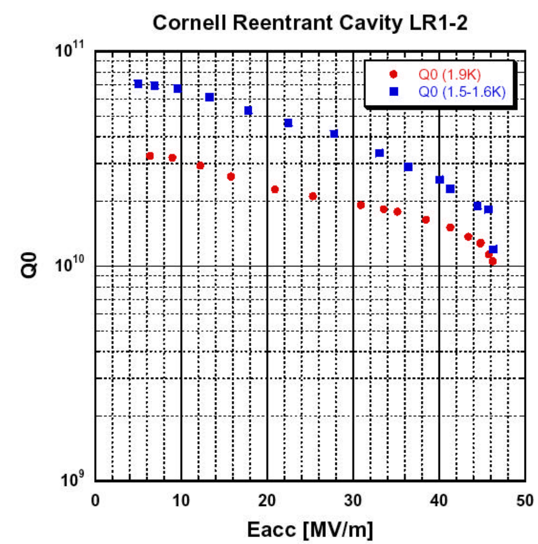




S. Rosen et al, arxiv 1907.00147
E_{acc} ~20 MV/m:
Q_0 of (3-4)10^{11} at T<1.5 K
Q_0 ~5·10^{10} at 2.0 K.



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



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

MW. 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

$$P_{tot} = 20\left(\frac{N}{10^9}\right) + \left(187 + 230\left(\frac{N}{10^9}\right)^2\right) \times DC$$

SR in wigglers

refrig.
RF losses

refrig.
HOM losses

Luminosity (for DC<1)

$$L = 1.9 \times 10^{36} \left(\frac{N}{10^9}\right) DC = 1.9 \times 10^{36} \left(\frac{N}{10^9}\right) \frac{P_{tot} - 20.8(N/10^9)}{187 + 230(N/10^9)^2} \propto \frac{x(P - ax)}{b + cx^2}$$

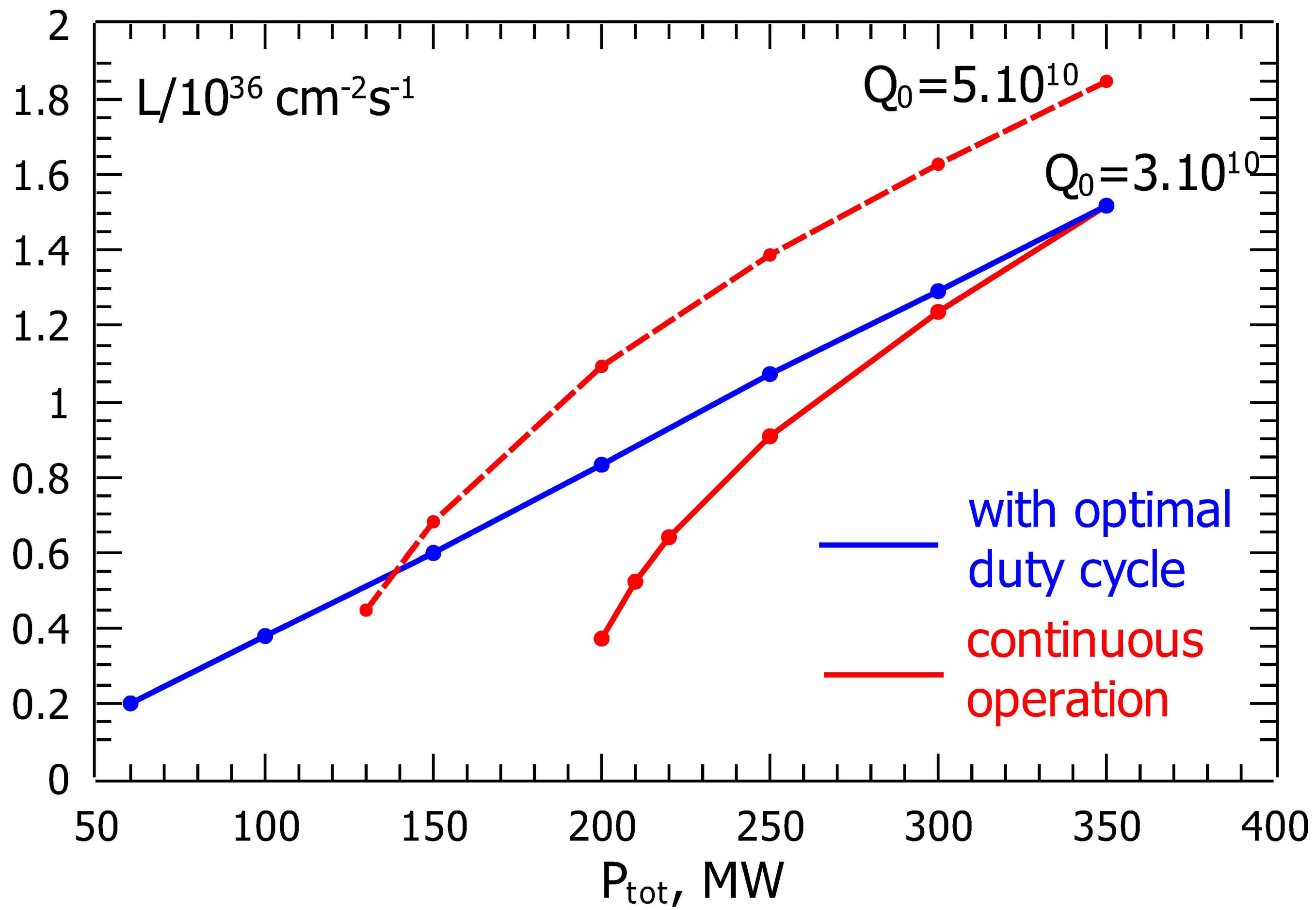
Optimum $N/10^9 \sim 0.8$ for P=130 MW and very weakly depends on P, but DC prop. to P. When working with DC<1

$$L_{DC} = 1.9 \times 10^{36} \times \frac{0.5(P-19)}{\sqrt{bc}} = 1.9 \times 10^{36} \times \frac{0.5(P-19)}{\sqrt{187 \times 230}} = 4.6(P-19)10^{33}\ \mathrm{cm^{-2}s^{-1}}$$

For P=130 MW (as ILC) <u>$L = 0.5 \times 10^{36}\ \mathrm{cm^{-2}s^{-1}}$</u> at $DC_{opt} \sim 0.35$

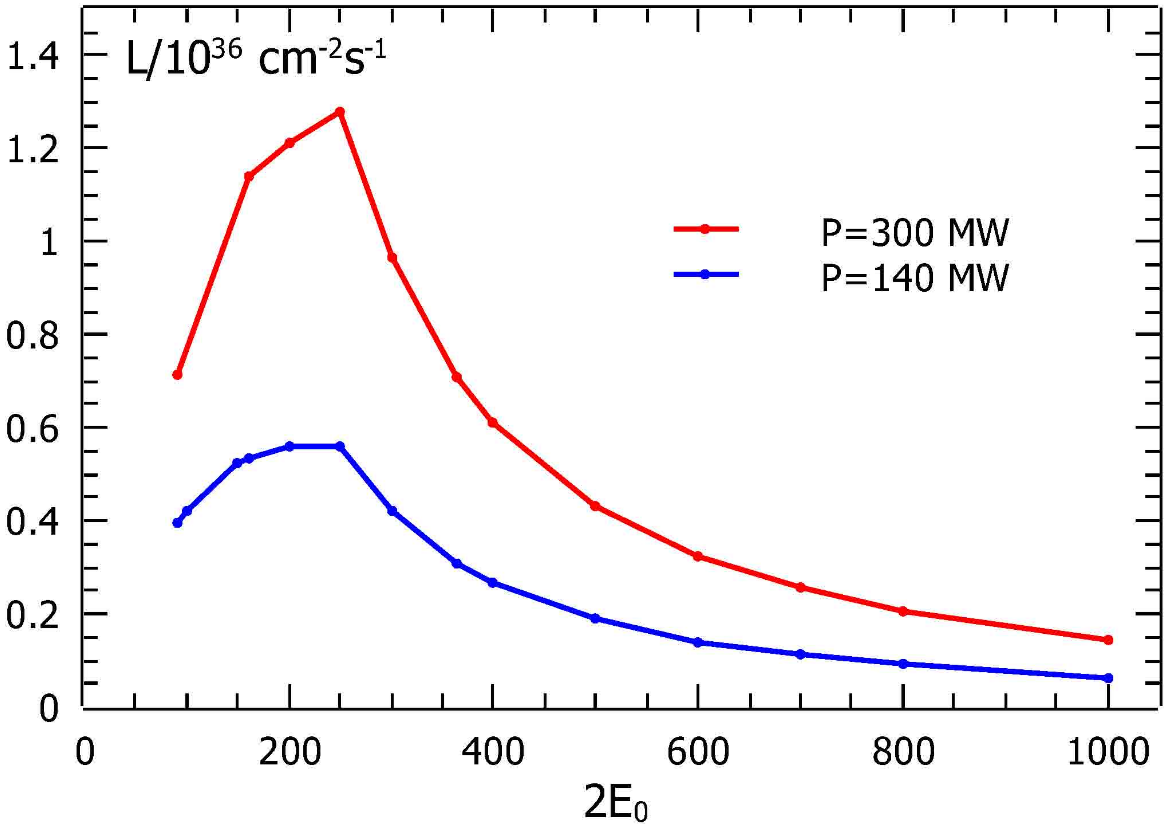
If power is larger than RF dissipation in SC cavities the continuous operation is possible. In this case

$$L_{\rm cont} \approx 1.9\times10^{36}\sqrt{\frac{P-b}{c}} = 1.9\times10^{36}\sqrt{\frac{P-187}{230}}\ \rm cm^{-2}s^{-1}$$



Ways to higher energies

The main problem are particle losses in 5 GeV arcs (with assumed energy acceptance ~ 3%) due to large energy spread after deceleration. For 2E<250 GeV we assumed σ_E/E_0=0.002 at the IP and particle losses at ~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. Add. requirements 0.3mm $<\sigma_z<$2.4 mm.



2E=500 GeV $L\sim0.45\times10^{36}$

2E=1000 GeV $L\sim0.15\times10^{36}$

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 $Q \sim 6 \cdot 10^{10}$ in reach.

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

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

Results

$N=0.8\cdot10^9$, $d=0.23$ m

					P=140 MW			P_{max}=300 MW		
2E	σ_x, µm	σ_y, nm	σ_z, mm		L, 10^{35}	DC		L, 10^{35}	DC	P, MW
90	1.2 1.6	10	0.3		4	0.72		7.1	1	300 $N=1.05\cdot10^9$
160	0.91 1.08	7.6	0.3		5.3	0.55		11.4	1	300 $N=0.95\cdot10^9$
250	0.73	6.1	0.3		5.6	0.37		12.8	0.8	300
360	0.81	6.8	0.54		3.1	0.25		7.1	0.58	300
500	0.88	7.4	0.9		1.9	0.19		4.3	0.43	300
1000	1.1	8.6	2.4		0.63	0.093		1.4	0.21	300
1500	1.9	7	2.4		0.3	0.062		0.68	0.14	300

Looks very attractive