High-luminosity superconducting electron- positron colliders

Valery TELNOV

Budker INP, Novosibirsk

Symposium to celebrate Ugo Amaldi's 90th birthday

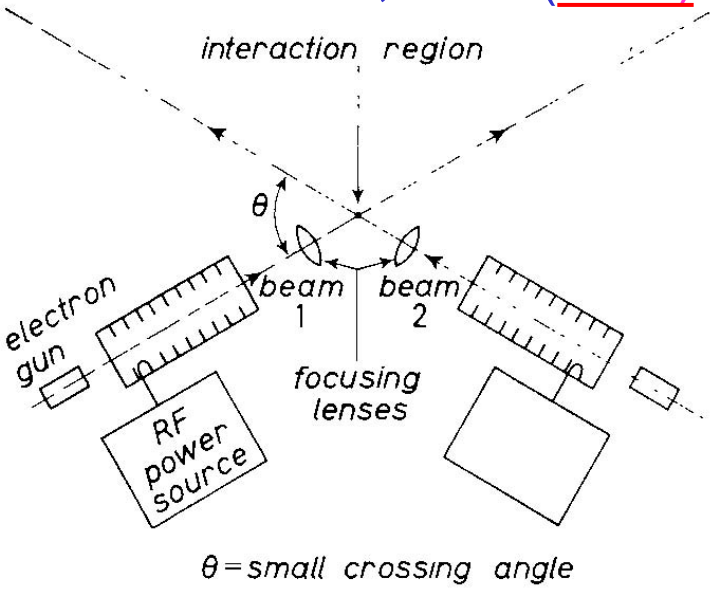
CERN, April 4, 2025

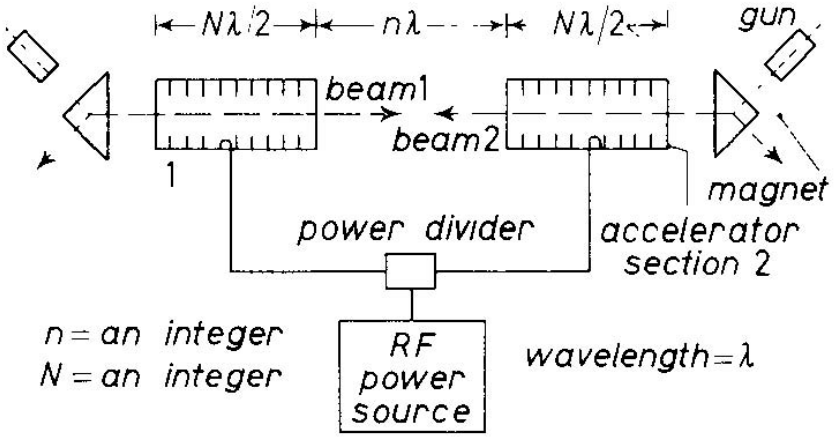
Contents

- LC prehistory (Tigner, Skrinsky, 1965-1971)
- Storage ring energy scaling, motivation proposal of LEP (Richter,1975-76)
- SC linear collider with energy recovery, ”Peloron” (Amaldi, 1976,)
- “Birth” of linear collider at 1978, 1979 ICFA workshops
- Positron production by photons from wiggler (1979)
- Problems of LC with energy recovery (1979)
- SC based projects: charm-tau, beauty, Z, WW, Toponium factories(1987-90)
- TESLA, title and first set of parameters (1990)
- Particle and accelerator physicist, teacher, historian
- Milestones and future of TESLA project
- SC LC with energy recovery “be or not to be”
- The idea of twin SC LC with energy recovery, ERLC (V. Telnov, 2021)
- From PELORON to ERLC: future high luminosity Higgs factory
- Applause for Ugo Amaldi

First SC LC with energy recovery

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.

B. Richter (1987):

In this paper, Tigner talks about a system using colliding linac beams as an alternative to storage rings for studying electron-electron collisions. He talks about the benefits of superconductivity and how to lower the operating power by using energy recovery. He lists the luminosity requirements for low energy machines in the few GeV energy range.

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

First words about high energy linear e+e- colliders

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.

Important motivations

July 1973 – discovery of neutral currents (Gargamelle, CERN), that confirmed Weinberg-Salam model which predicted Z-boson with M_Z~100 GeV.

In 1975-76 B.Richter spent a sabbatical at CERN participating in the experiment on the ISR and worked out the general energy scaling laws for high-energy electron-positron colliding-beam storage rings. As a result the paper was published

B. Richter "Very high energy electron-positron colliding beams for the study of weak interactions", NIM 136 (1976) 47-60,

which opened the way to the construction of LEP.

There were hot discussions (C.Pelegrini, C.Rubbia) on the scaling lows of circular storage rings: Cost = C_0 +kE^2

From U.Amaldi (1992): "Having thought about the advantage of superconducting linear colliders I spoke about it to the friends around the ISR (in particular O. Cocconi, K. Johnsen and B. Montague) and to Richter, who had never heard of such ideas and was immediately interested …the paper A possible scheme to obtain e-e-, e+e- collisions at energies of hundred of GeV was ready by the end of 1975"

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

U. AMALDI
CERN, Geneva, Switzerland

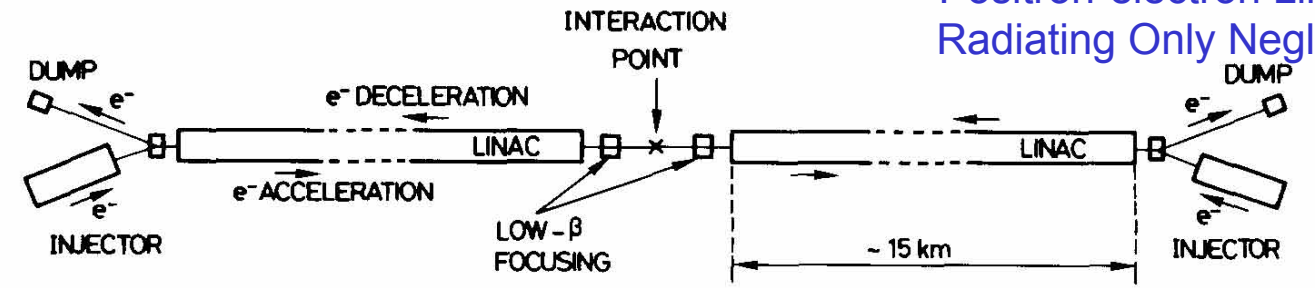
Received 18 December 1975

The very first paper on high energy LCs:

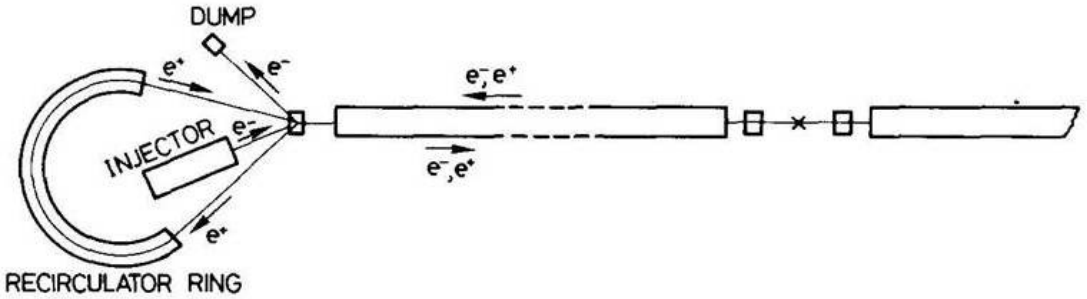
U. Amaldi, Phys. Lett. 61B (1976) 313 (March 29, 1976)
+ report U.Amaldi, H.Lengeler at Serpukhov meeting, May 1976

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.

Ugo called it "Peloron",
"Positron-electron Linear Oscillator Radiating Only Negligibly"



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.

B. Richter (1987): Amaldi in *Physics Letters* in 1976 independently reinvented Tigner's scheme of superconducting electron linacs with energy recovery. He also considered e+e- colliders, but could not find a solution that satisfied him for the production of positrons in a sufficiently small phase space to make high luminosity electron-positron colliders a practicality.

“Birth” of linear colliders

G.A. Voss, Collisions of very high energy e+e- beams with the use of linear accelerators, (July 1977, unpublished)

V.Balakin, G. Budker, A.Skrinsky, “Feasibility of creating a superhigh energy colliding electron-positron beams facility”, preprint INP-78-101 11.04.1978, Talk at Intern. Seminar, devoted to 60th anniversary of G.Budker’s, April 1978, presented to ICFA workshop at FNAL 1978

The First ICFA Workshop on "Possibilities and Limitations of Accelerators and Detectors" which was held at Fermilab in October of 1978.

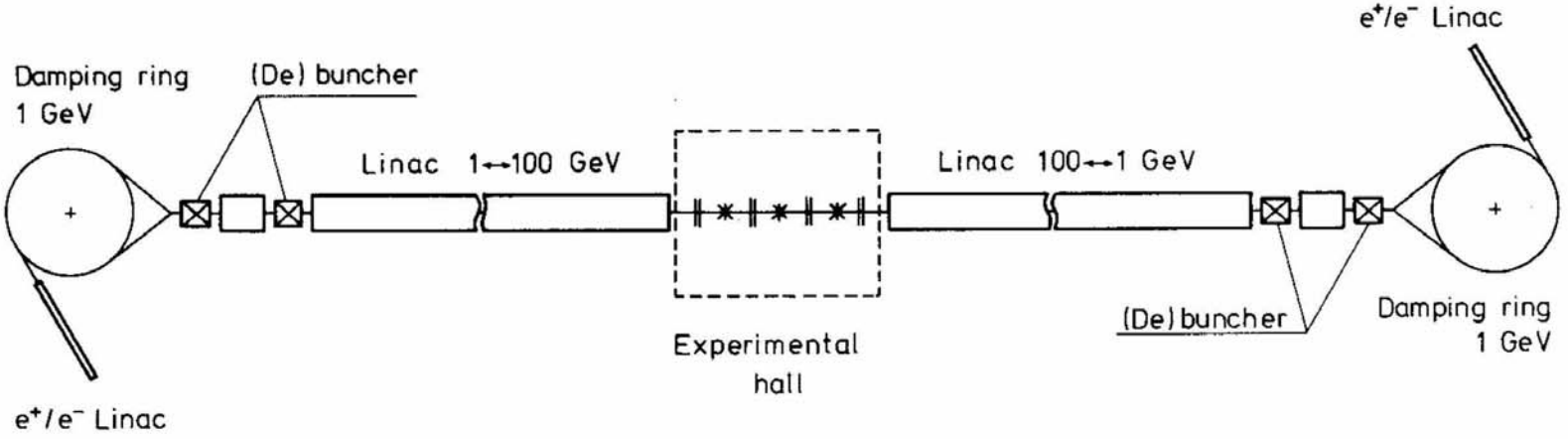
B. Richter SLAC-PUB-4482, (1987):
I believe the seminal event in the birth of the linear collider idea occurred at the ICFA Workshop which was held at Fermilab in October of 1978. We had all been thinking about linear colliders. During the course of the workshop we ..set out all the criteria for linear colliders, including their scaling laws, the effect of synchrotron radiation on the beam-beam collisions, the emittance requirements, etc. ICFA gave birth to linear colliders at that workshop. When I returned to SLAC … we began working on the conceptual design of what became the SLC.

Second ICFA Workshop on "Possibilities and Limitations of Accelerators and Detectors" held at Les Diablerets, Switzerland, 4-10 October of 1978,
where U.Amaldi gave “Forward” talk +“Energy recovery SC colliding linacs without particle recovery” (with C.Pelegrini), coauthor of Report of Group “e+e- colliders”+ the editor of Proceedings

The history of LC before by 1980 was described by U.Amaldi in his talk “Colliding beams” at 9th Int. Symp.on Lepton and Photon Interactions, 1979.

More advanced “Peloron” scheme. Problems

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.

Problems: parasitic collisions in linacs do not allow a high collision rate.
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.

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

(In 1976 paper Ugo assumed “L-band linac with one quarter of the buckets field (f=250 MHz)”, but this is impossible due to parasitic collisions in linacs.)

Energy recovery in superconducting colliding linacs without particle recovery

U. Amaldi, C. Pellegrini, Second ICFA workshop, Oct. 1979, Les Diablerets

Electrons and positrons are produced by synchrotron radiation photons from wigglers. Only <1% of the beam energy is needed for production of new e+ and e-.

ENERGY RECOVERY IN SUPERCONDUCTING COLLIDING LINACS WITHOUT PARTICLE RECOVERY

Ugo Amaldi, CERN, Geneva, Switzerland
Claudio Pellegrini, Brookhaven National Laboratory, Upton, New York

ABSTRACT

A new type of electron-positron collider based on superconducting linacs is proposed. As in other schemes, the bunch energy is recovered by deceleration in the opposite linac, but the spent bunches are dumped after a single pass, thus avoiding many problems connected with their re-use. The needed low energy particles are produced by the monochromatic photons radiated coherently by the high energy bunches in a wiggler magnet before deceleration.

Parameter list of an electron-positron linear collider

Quantity	Symbol	Value
Energy	2E	(350 + 350) GeV
Luminosity	L	10^{33} cm^{-2} s^{-1}
Number of particle/bunch	N	7.1×10^{10}
Bunch/s	f	2.5×10^{4} Hz
Bunch length	d	10 mm
Power in the two beams	P	200 MW
Bunch transverse radius at the interaction point	σ	1.0 μm
Normalized emittance (with $\beta^* = 5$ cm)	ε	1.4×10^{-5} πm

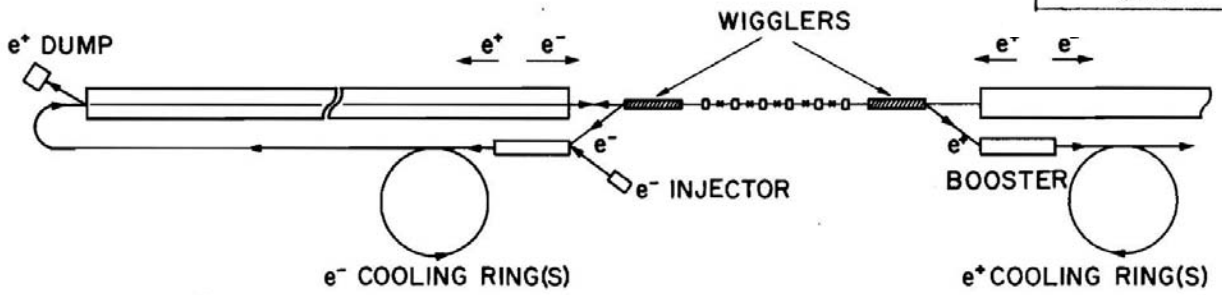


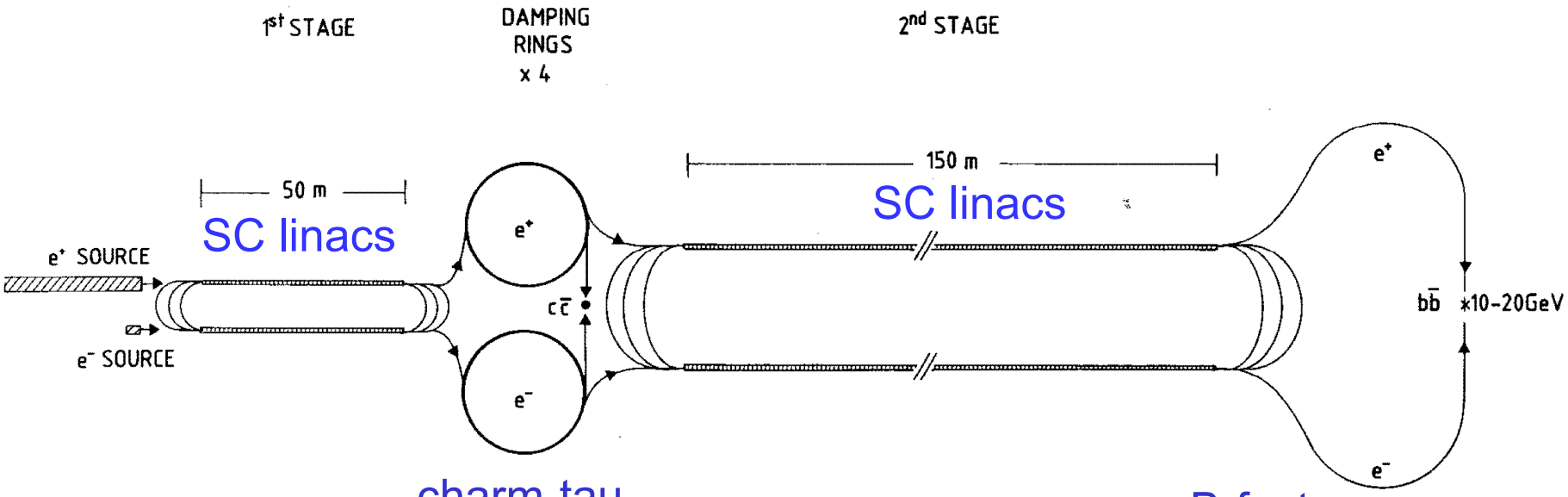
Fig. 2 The principle of the peloron which recovers the energy but not the particles. As discussed in Ref. 1), the many interaction regions have to be served in time sharing because of the emittance increase at an interaction point.

Simultaneously, in 1979, a similar scheme was proposed by V.Balakin and A.Mikhailichenko for production of polarized e+ and e-.

U.Amaldi and G.Coignet, Nucl. Instrum. Meth. A 260, 7 (1987).

Conceptual Design of a Multipurpose Beauty Factory Based on Superconducting Cavities,

The conceptual design of a high luminosity (10^{33}–10^{34} cm^{-2} s^{-1}) beauty factory ($W = 10$–20 GeV) based on a superconducting linear collider with recirculators and damping rings is discussed in detail. Such an accelerator complex opens not only the possibility of performing interesting experiments in the energy range where $c\bar{c}$ and $b\bar{b}$ quark pairs are abundantly produced, but can be used as continuous linear accelerator for nuclear physics and can support competitive programs in the field of synchrotron light and power FELs. Around it the new techniques needed for future high luminosity TeV linear colliders could be developed and, at a later stage, be used to build a Z factory or a toponium factory (m$_t$ was unknown that time)



charm-tau

B-factory
→ Toponium-factory
→ Z-factory

U. Amaldi, An Asthenon (Z, WW) factory and a top factory on the way to a TeV fully superconducting linear collider," CERN-PPE-90-162, talk at the 1st TESLA workshop, Cornell, 23-26 July,1990

A series of fully SC linear colliders of increasing length and gradients

Z → WW → top factory → 1 TeV

U.Amaldi called it "TESLA" =TeVSCLinearAccelerator

Table 1
Parameter lists of the SC colliders at a frequency $f = 3\ GHz$

Quantity	Symbol (Unit)	Z-factory	W-factory	top-fact narr.band	top-fact wide band	TESLA
Energy	$2E_0$(GeV)	2×50	2×100	2×150	2×150	2×500
Luminosity	$L(10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1})$	3.	5.	1.	6.	4.
Gradient	G(MV/m)	15	25	25	25	40
Active length	$2\ell_G$(km)	2×3.3	2×4.0	2×6.0	2×6.0	2×12.5
Q-value	$Q(10^9)$	3.	6.	6.	6.	10.
Particles/bunch	$N(10^{10})$	4.7	4.7	2.0	5.0	5.0
Vertical emittance	$\varepsilon_y(10^{-6}\mathrm{m})$	1.	1.	1.	1.	1.
Vertical beta	β_y(mm)	1.	2.	3.	3.	10.
Bunch height	σ_y(nm)	**100**	**100**	**100**	**100**	**100**
Bunch length	$\sigma_z(\mu\mathrm{m})$	450	450	1500	600	2500
Aspect ratio σ_x/σ_y	R	10	5	6	5	5
Disruption	D	12.	10.	7.5	10.	12.
Enhancement	H	2.0	2.5	2.3	2.5	2.5
Critical energy	Υ	0.01	0.04	0.006	0.05	0.04
Beamstrahlung	$<\varepsilon>$ (%)	1.0	8.0	0.4	11	11
Av.rep.rate	f_r(kHz)	8.0	6.0	8.0	6.0	4.0
Duty cycle	C (%)	2.4	3.0	1.6	3.0	3.2
Peak rep.rate	$\hat{f}_r$(kHz)	330	200	500	200	125
Beam power	P(MW)	3.0	4.5	3.8	7.2	16.
Total plug power	P_T(MW)	34	53	59	74	174
Overall effic.	η_t(%)	18	17	13	19	18

H.Padamsee (PAC1991)

The purpose of the meeting was to work on an improved parameter list and accelerator physics issues, explore ideas on improving gradients and on developing structures/cryostats suitable for TESLA, review costs, and arrange collaborations for work on TESLA issues. About 70 scientists participated from the laboratories of Argonne, BNL, CEBAF, CERN, Cornell, Darmstadt,DESY, Fermilab, IJXEP Protvino, INFN Frascati, Genova, Milano, KEK, Lawrenc Livermore Los Alamos, Saclay, SLAC, Stony-Brook. *A staged approach for TESLA, suggested by U. Amaldi [6] was adopted (Table 1)* "

Particle and detector physicist, experimenter, accelerator physicist, teacher

U. Amaldi is a real physicist, with a deep understanding of all issues of HEP: particle physics, detectors, accelerators. Analyzing collider scaling he puts into consideration everything that is known on the subject. His lectures and related articles can be used as textbooks on linear colliders.

U. Amaldi, ``Introduction to the Next Generation of Linear Colliders,'' 49 pages

Lecture given at the Joint US-CERN School on Partical Accelerators, Tevas, Oct 23-29,1986,
Lect. Notes Phys. 296, 341 (1988) CERN-EP/87-169.

U.Amaldi, ``Attaining Superhigh Energies with e+e- Collisions," 22 pages

Lecture given at the Advanced Study Institute on Techniques and Concepts of High Energy Physics, Virgin Islands, July 14-25, 1988, NATO Sci. Ser. B 204, 295-316 (1990).

from Amaldi, NIM (1986)

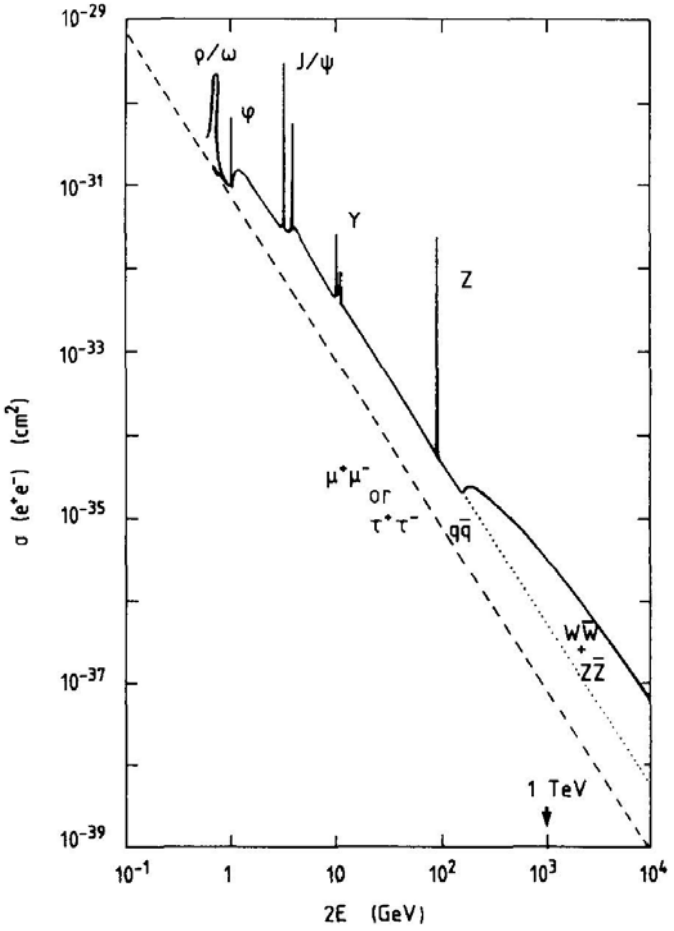


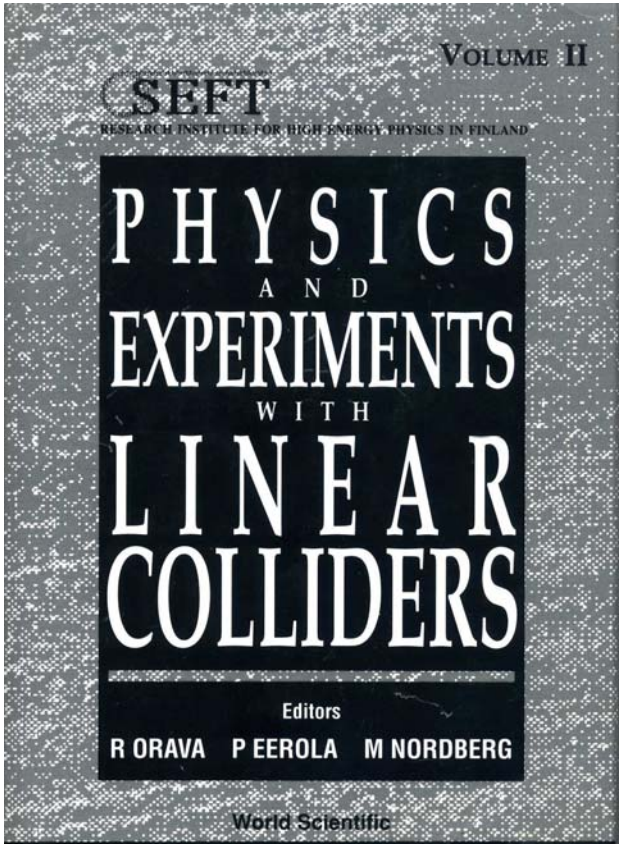
Fig. 1. The e^+e^- cross-section as a function of the center-of-mass energy. In drawing the peaks it was assume that the

$\sigma \sim 10^{-37}/(Ecm[TeV])^2$

In order to have 10000 event for 10^7 s one need $L \sim 10^{34}$ cm^{-2}s^{-1}

U.Amaldi, "Evolution of Concepts and Goals of Linear Colliders"

talk at the (first) Workshop on Physics and Experiments with Linear Colliders, Saariselka, Lapland, 0-14 September 1991, CERN-PPE-92-020



With this historical review, Ugo Amaldi completed his work on linear colliders, and many hundreds of people from all over the world continued his work!

Regular linear collider workshops started in 1988, many projects, hundreds of participants, fruitful atmosphere

TRC/1995 Report (Greg Loew-chair)

Table 1.1
Linear Colliders: Overall and Final Focus Parameters
500 GeV (c.m.)

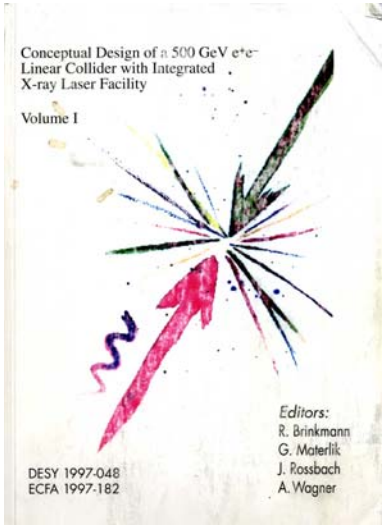
	TESLA	SBLC	JLC (S)	JLC (C)	JLC (X)	NLC	VLEPP	CLIC
Initial energy (c.of .m.) (GeV)	500	500	500	500	500	500	500	500
RF frequency of main linac (GHz)	1.3	3	2.8	5.7	11.4	11.4	14	30
Nominal Luminosity (10^{33} cm^{-2}s^{-2})†	2.6	2.2	5.2	10.9	5.1	5.3	12.3	0.7-3.4
Actual luminosity (10^{33} cm^{-2}s^{-2})†	6.1	3.75	4.3	9.1	5.2	7.1	9.3	1.07-4.8
Linac repetition rate (Hz)	10	50	50	150	150	180	300	2530-1210
No. of particles/bunch at IP (10^{10})	5.15	2.9	1.44	1.0	.63	.65	20	.8
No. of bunches/pulse	800	125	50	72	85	90	1	1-10
Bunch separation (nsec)	1000	16.0	5.6	2.8	1.4	1.4	–	.67
Beam power/beam (MW)	16.5	7.26	1.3	4.3	3.2	4.2	2.4	.8-3.9
Damping ring energy (GeV)	4.0	3.15	2.0	2.0	2.0	2.0	3.0	2.15
Main linac gradient, unloaded/loaded (MV/m)	25/25	21/17	31/25	40/29	73/53	50/37	100/91	80/78
Total two-linac length (km)	29	33	22.1	18.8	10.4	15.6	7	8.8
Total beam delivery length (km)	3	3	3.6	3.6	3.6	4.4	3	2.4
$\gamma\epsilon_x/\gamma\epsilon_y$ (m-$rad \times 10^{-8}$)	2000/100	1000/50	330/4.8	330/4.8	330/4.8	500/5	2000/7.5	300/15
β^*_x/β^*_y (mm)	25/2	22/0.8	10/0.1	10/0.1	10/0.1	10/0.1	100/0.1	10/0.18
σ^*_x/σ^*_y (nm) before pinch	1000/64	670/28	260/3.0	260/3.0	260/3.0	320/3.2	2000/4	247/7.4
σ^*_z (μm)	1000	500	120	120	90	100	750	200
Crossing Angle at IP (m-rad)	0	3	6.4	6.0	6.1	20	6	1
Disruptions D_x/D_y	0.56/8.7	.36/8.5	.29/25	.20/18	.096/8.3	.07/7.3	.4/215	0.29/9.8
H_D	2.3	1.8	1.6	1.4	1.4	1.34	2.0	1.42
Upsilon sub-zero	.02	.037	.20	.14	.12	.089	.059	0.07
Upsilon effective	.03	.042	.22	.144	.12	.090	.074	.075
δ_B (%)	3.3	3.2	12.7	6.5	3.5	2.4	13.3	3.6
n_γ (no. of γ's per e)	2.7	1.9	2.2	1.5	.94	.8	5.0	1.35
N_{pairs}(p_T^{min}=20 MeV/c,θ_{min}=0.15)	19.0	8.8	31.6	10.3	2.9	2.0	1700	3.0
$N_{hadrons}$/crossing	0.17	0.10	0.98	0.23	0.05	0.03	45.9	0.05
$N_{jets} \times 10^{-2}$ (p_T^{min}=3.2 GeV/c)	0.16	0.14	3.4	0.66	0.14	0.08	56.4	0.10

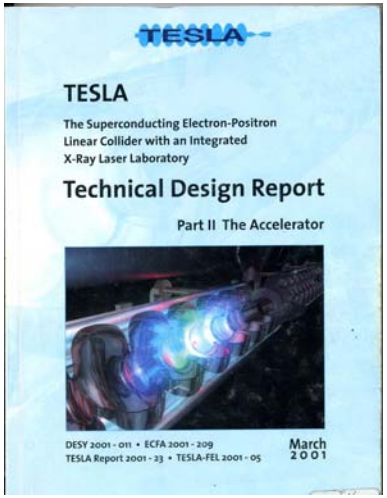
† For the sake of uniformity, the nominal luminosity is simply defined as $N^2/4\pi\,\sigma^*_x\,\sigma^*_y$ times the number of crossings per second, and in all cases sumes head-on collisions, no hour-glass effect and no pinch. The actual luminosity incorporates all these effects, including crossing angle where plicable. NLC calculations assume crab-crossing.

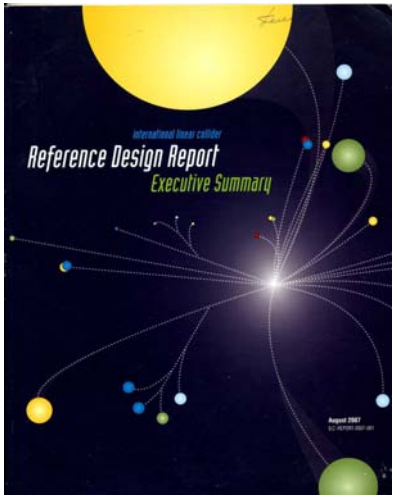
Milestones and future of TESLA project (ILC from 2005)

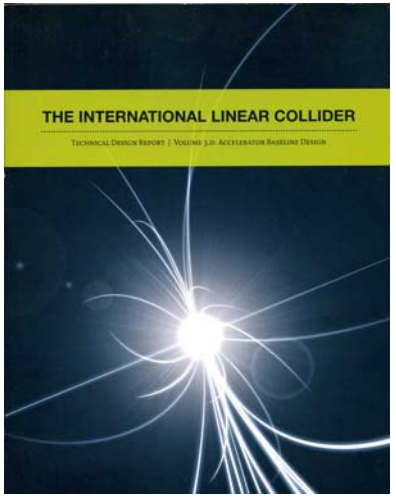
Snowmass 2001

TESLA CDR, 1997 | TESLA TDR, 2001 | ILC RDR, 2007 | ILC TDR, 2013









? Japan ??

Why ?

1. No signals of new Physics in TeV region
2. FCC-ee with 10 times higher L at the Higgs energy (2E=240 GeV)

SC LC with energy recovery “be or not to be”

The U.Amaldi’s idea (1976) of high energy linear colliders with energy recovery turned out to be unattractive due to the too low collision rate (to avoid parasitic collision inside linear accelerators).

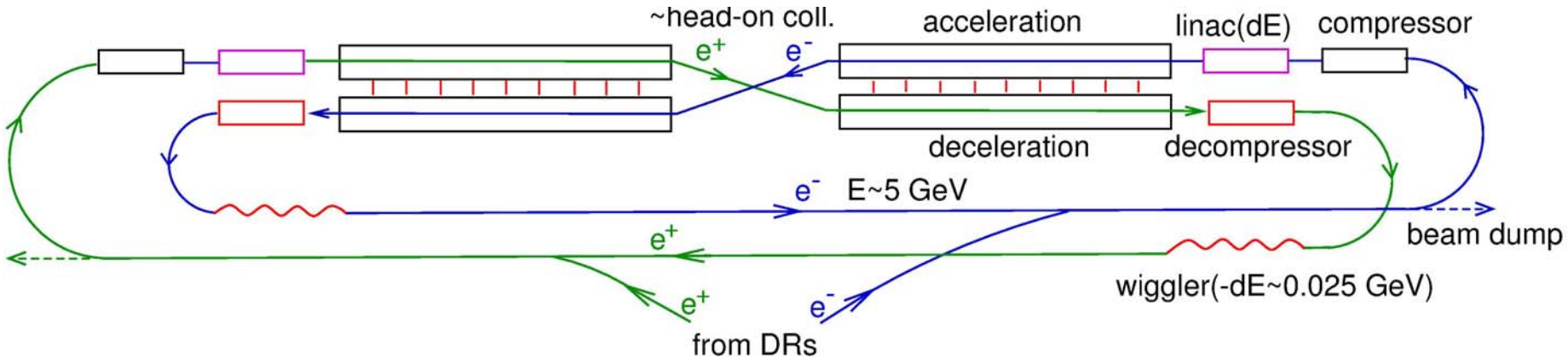
Single-pass linear colliders have proven to be more productive. But single-pass linear colliders have also lost the competition to the FCC-ee in Higgs energy region.

Working on linear colliders since 1980 (photon colliders) and on ring colliders (LEP-3 →FCC-ee) since 2012, I kept thinking about the ultimate possibilities of e+e- colliders. The idea of a radical increase in the luminosity of the linear collider came up in March 2021 and I spoke about at LCWS 2021 (CERN) (remotely).

It was a revival of U. Amaldi's idea

A high-luminosity superconducting twin e+e- linear collider with energy recovery (ERLC)

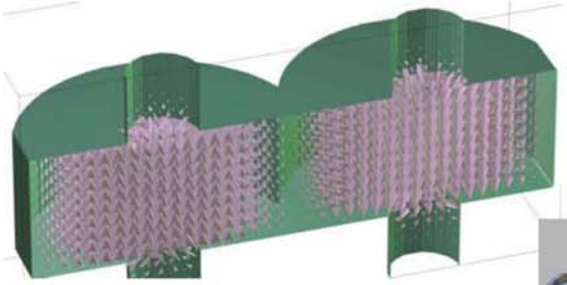
V.I.Telnov, LCWS21
JINST 16 (2021)12, P12025

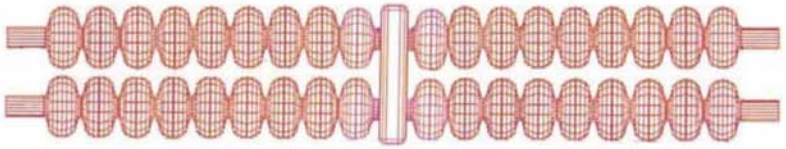


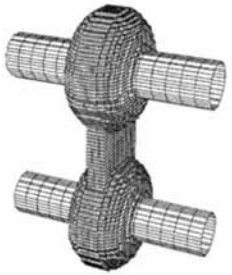
1) LC consists of two parallel SC linacs connected with each other with rf-coulpers, so that the fields are equal at any time. One line is for acceleration, the other for deceleration.
2) Damping is provided by wigglers (no damping rings) at the “return” energy about E~5 GeV. The energy loss per turn dE/E~1/200. Damping is needed to reduce the energy spread arising from collision of beams.
3) It can work with a duty cycle (DC) or in the continuous mode (CW).

The ERLC was reviewed in 2021 by an expert group (led by A. Hutton), found to be realistic, and recommended for further

Dual/Twin cavities (before 2021)







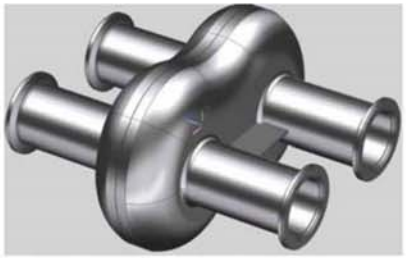


Figure 2: Single cell twin axis cavity.

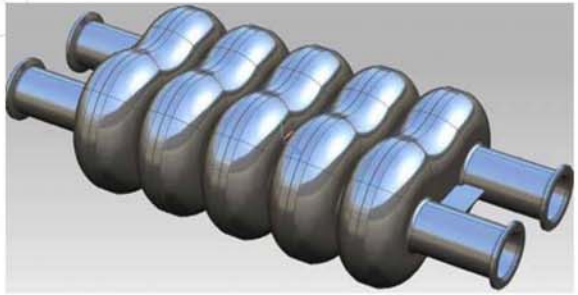
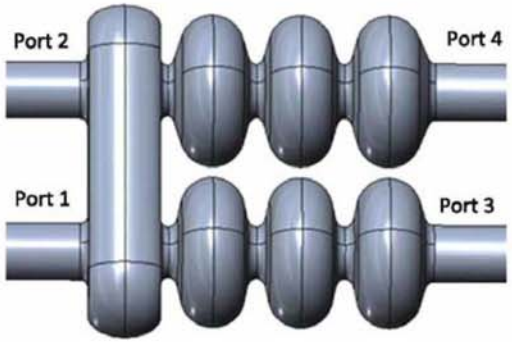
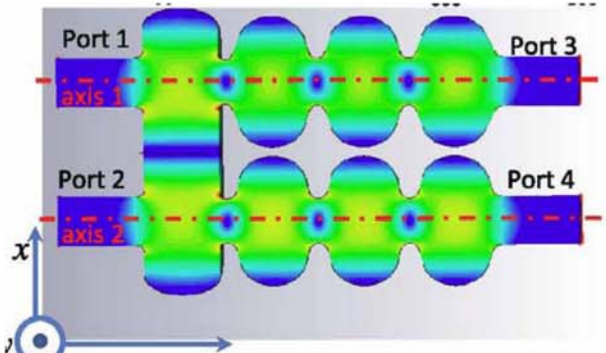


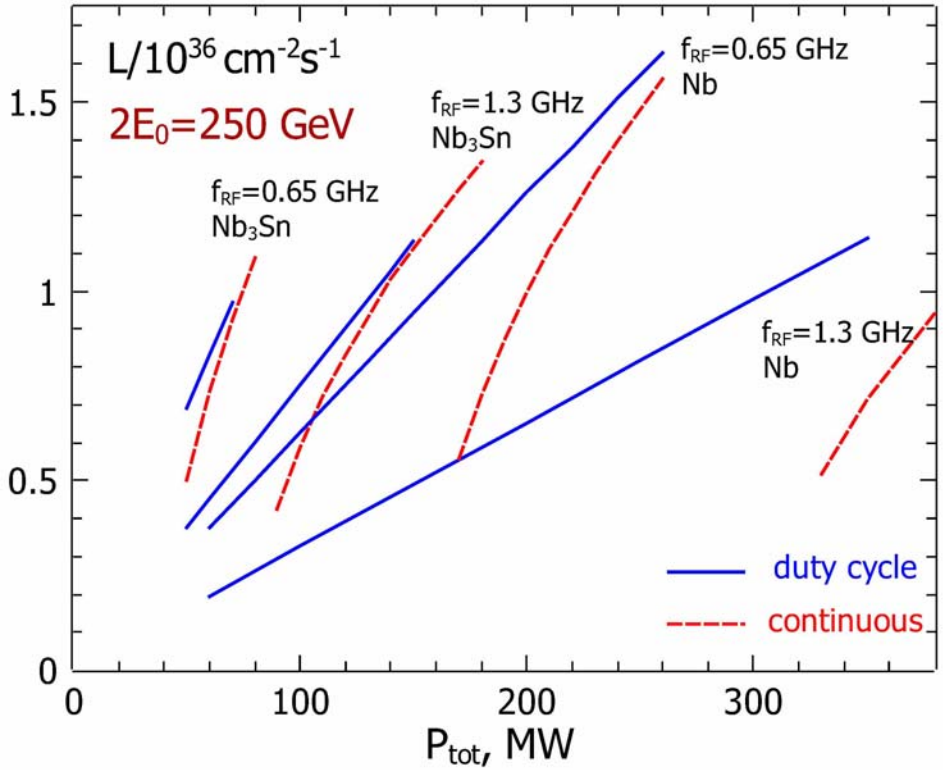
Figure 9: Multicell twin axis cavity.

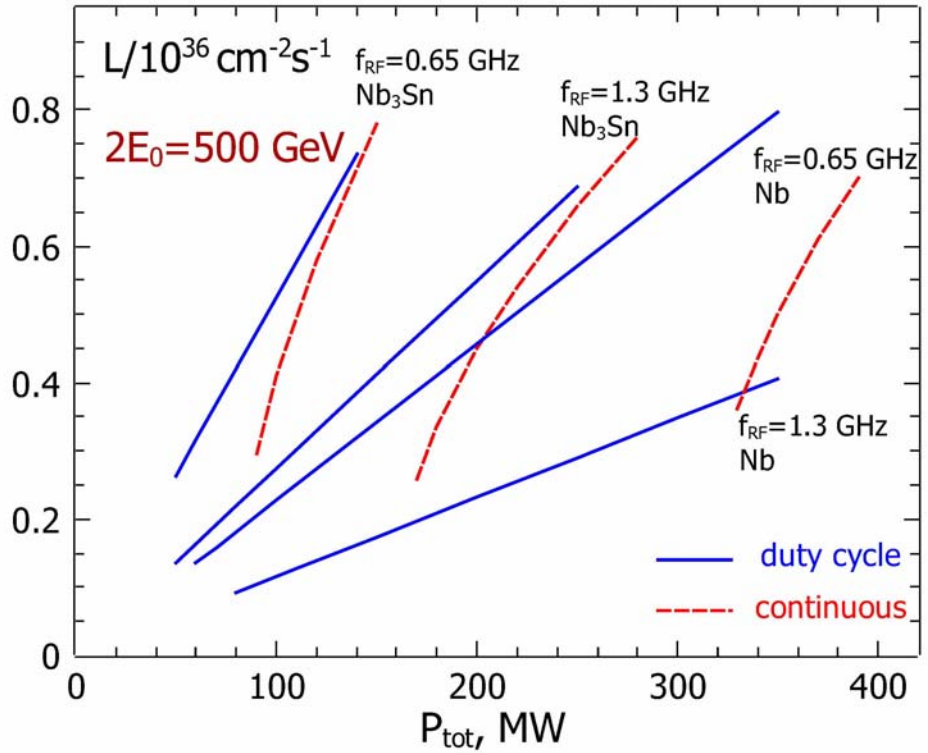




Possible luminosities vs power

V.Telnov, JINST 16 (2021)12, P12025



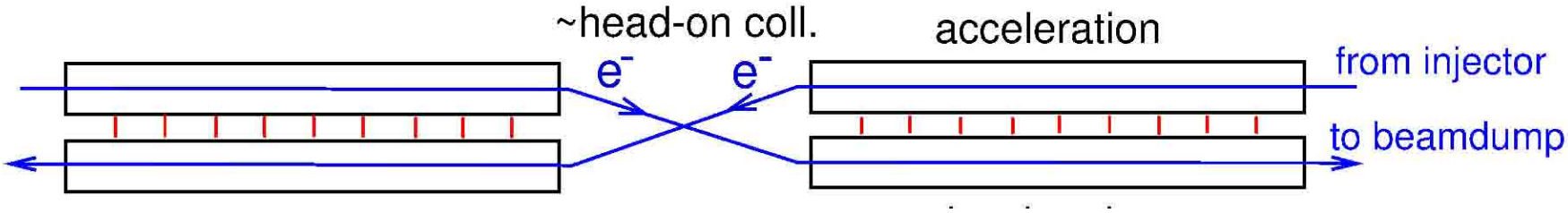


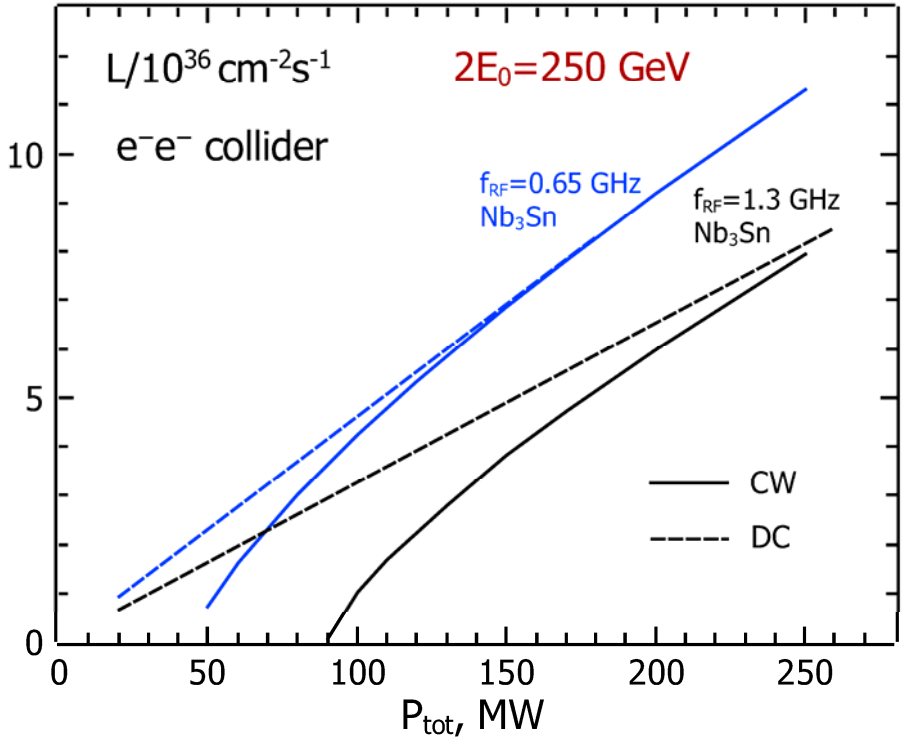
Luminosity can be two order of magnitude higher than at one pass ILC

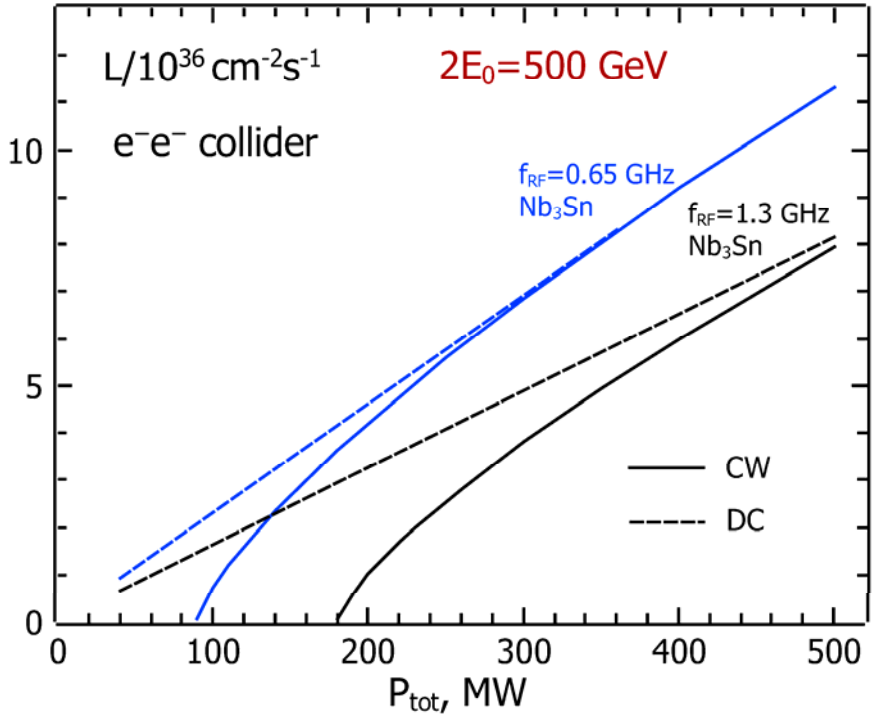
Energy recovery twin linear e+e-, e-e- colliders (ERLC) with high luminosities and acceleration gradients

V.Telnov
arXiv:2302.09758

Twin e^-e^- LC with energy recovery



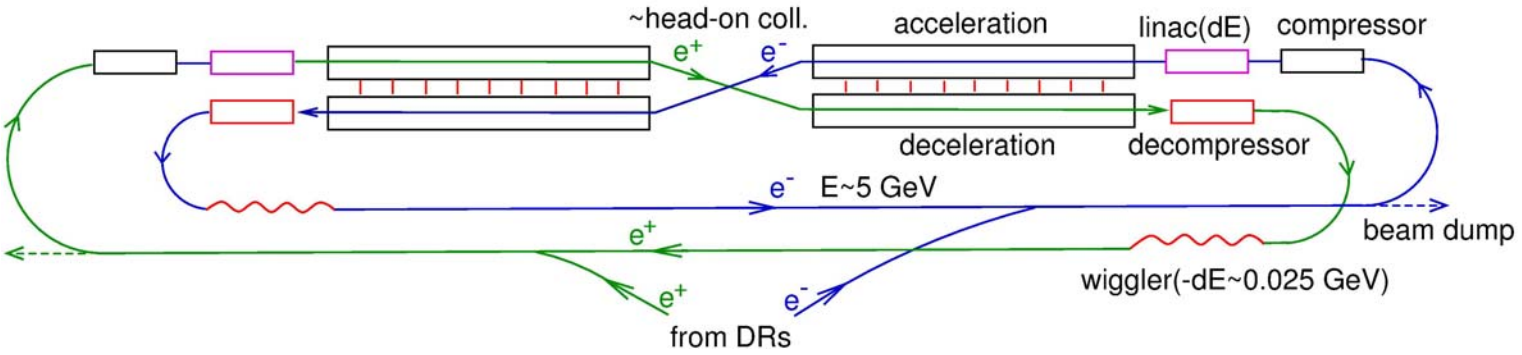


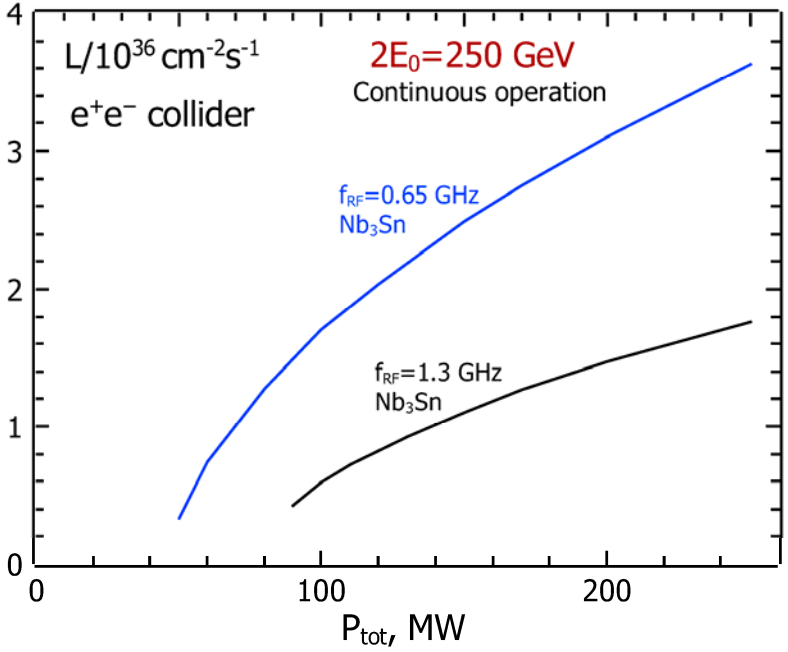


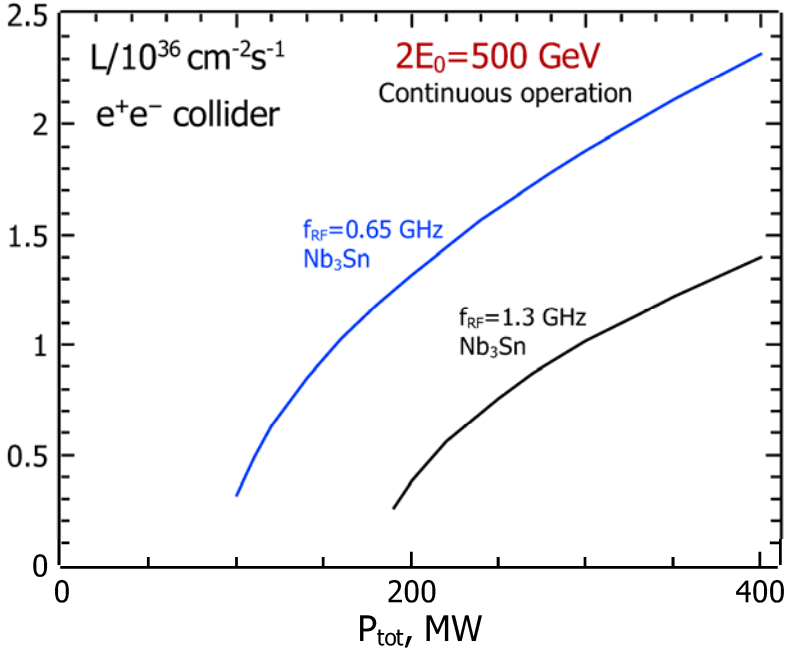
Energy recovery twin linear e+e-, e-e- colliders (ERLC) with high luminosities and acceleration gradients

e+e-, update

V.Telnov
arXiv:2302.09758







A Linear Collider Vision for the Future of Particle Physics

C. Balazs et al., arXiv:2503.19983, 31 March 2025

ERLC

V. Telnov, *A high-luminosity superconducting twin e+e- linear collider with energy recovery*, Journal of Instrumentation **16** (2021) P12025,

Basic idea The idea of ERLC (Energy Recovery Linear Collider) has been proposed by V. Telnov[513]. Fig. 60 shows the concept of ERLC. In the steady state the positron beam goes as follows. It is accelerated in the linac (a) and, after collision with the electron beam, it is decelerated in the linac (b) down to about 5 GeV. After the bunch length is decompressed in (c), the beam looses about 25 MeV of energy in the wiggler section (d). Then the beam is compressed in (e) and again accelerated in (a).

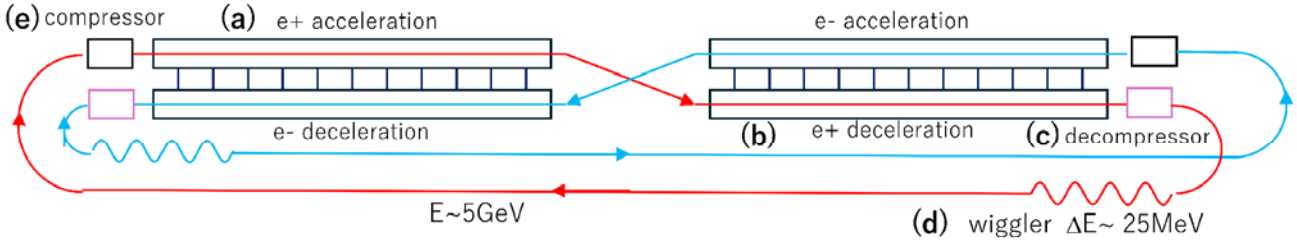
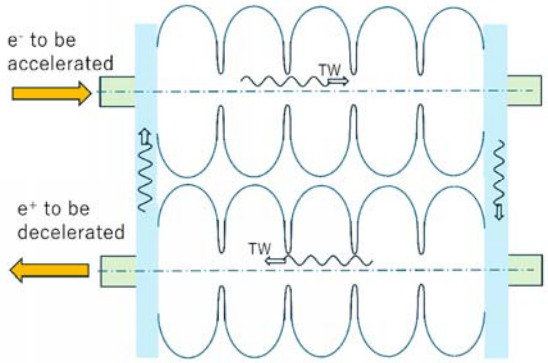


Figure 60: Schematic plot showing the concept of ERLC. Some systems such as injectors, beam dumps, etc. are omitted for simplicity.



K. Yokoya, *ILC Upgrade with Energy Recovery*, EPJ Web Conf. **315** (2024) 02016

Figure 61: Concept of the twin axis cavity of TW type. There exists TW only in the clockwise direction in this figure. The upper cavity accelerates the electron beam going to the right and the lower cavity decelerates the positron beam going to the left.

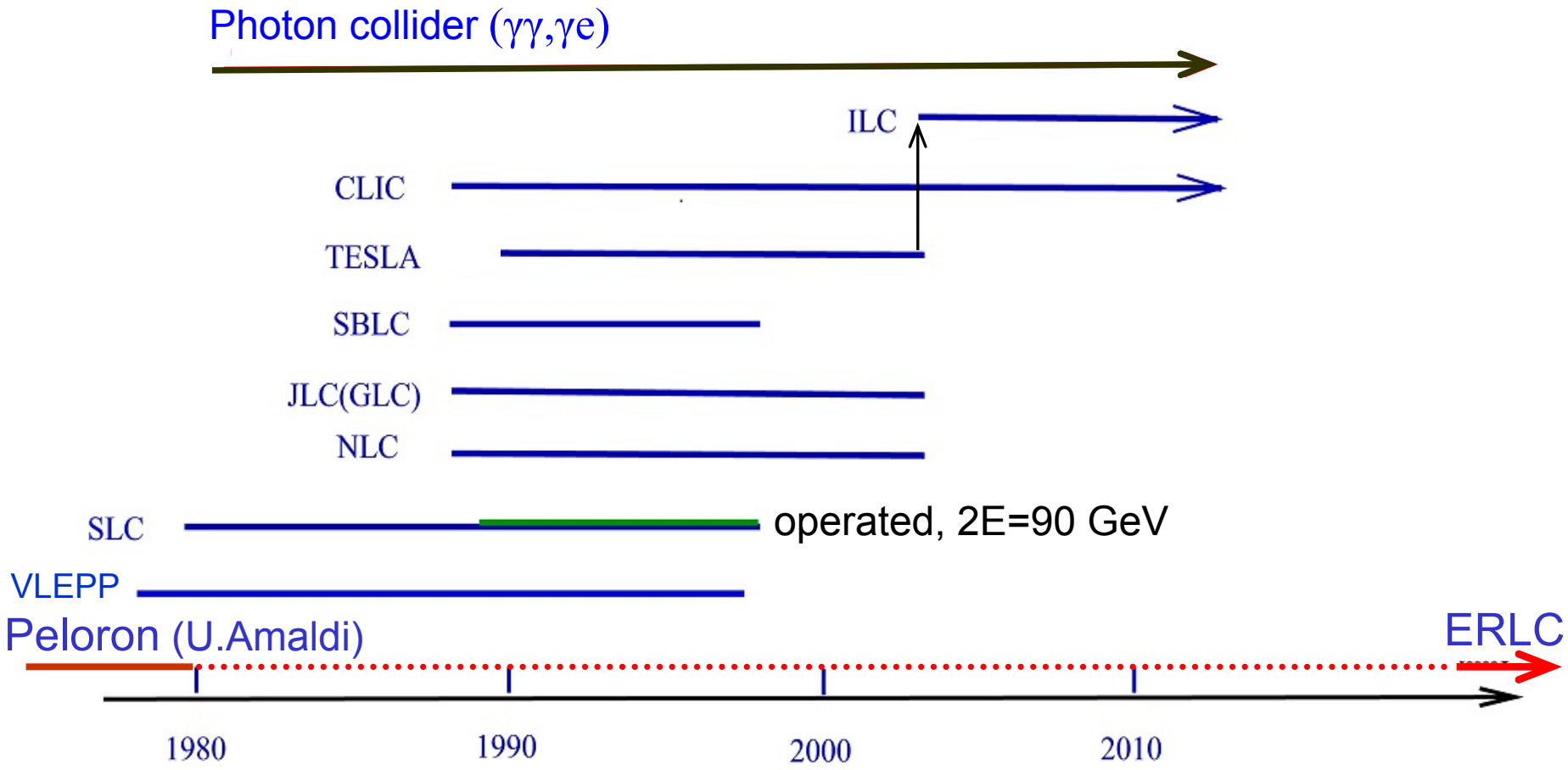
The ERLC is considered now as a high luminosity upgrade of ILC (or instead of ILC?)

Table 20: Tentative Parameters of ERLC for E_{CM} =250 and 500 GeV

	ILC	ERLC	ERLC	
centre-of-mass energy	250	250	500	GeV
Accelerating gradient	31.5	40	40	MV/m
Cavity Q_0	1	3	3	$\times 10^{10}$
Aperture radius	35	35	35	mm
Shunt impedance per unit length	996	1690	1690	Ohm/m
Operating temperature	2	4.5	4.5	K
Bunch population	2	0.075	0.081	$\times 10^{10}$
Bunch distance	166	0.23	0.23	m
Average beam current	0.021	157	169	mA
Beam energy in the return line		5	5	GeV
Total HOM power	0.014	2.9	5.85	MW
Energy acceptance of the return line		3	3	%
Radiation loss in the wiggler		25	25	MeV
Bunch length in main linac and IP	0.3	0.31	0.89	mm
Normalized emittance at IP (x/y)	5/35	10/35	10/35	μm / nm
Beta function at IP(x/y)	13/0.41	12/0.31	40/0.89	mm
Beam size at IP(x/y)	515/7.66	700/6.2	900/7.4	nm
Disruption parameter (x/y)	0.5/34.5	0.011/1.14	0.010/1.14	
Beam-beam tune shift (x/y)		0.033/0.097	0.036/0.098	
Upsilon (max)	0.068	0.00182	0.00106	
Luminosity	1.35	135	102	$10^{34}/\text{cm}^2/\text{s}$
AC power for RF heat cooling	5	91	181	MW
AC power for HOM cooling	1	35	71	MW
Total site power	111	170	320	MW

Linear e+e- colliders

Brief history



Applause

for great physicist and man

Ugo Amaldi !