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High luminosity superconducting electron positron colliders¹

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Abstract – This outlines Ugo Amaldi’s contributions to the emergence and development of a new field in particle physics: high-energy linear electron-positron colliders.

Particle accelerators and colliders are fundamental tools for studying the properties of matter. When particles collide, their energy is used to create new particles, allowing for studying their nature, structure and interactions. The energy of accelerated particles is most effectively used when the particles fly toward each other. Such ring accelerators with colliding electron-positron beams appeared in 1965, and by 1975 they had spurred a true revolution in particle physics. At energies of $2E = 3-4$ GeV, psi mesons, charmed quarks, and tau leptons were discovered, and the theory of strong interactions emerged.

The study of weak interactions required colliders with energies of 100 GeV and higher. However, electron-positron colliders have an energy limitation associated with the emission of synchrotron radiation, the power of which is proportional to E^4/R^2 . When, in 1975, discussions began on a circular e^+e^- collider for studying the theoretically predicted Z boson with a mass of approximately 100 GeV, Ugo Amaldi proposed another option: a linear superconducting collider, where the problem of synchrotron colliders is absent. Although this idea was not entirely new, Amaldi’s was the first article published on linear colliders.

In his article “Possible scheme to obtain e^-e^- and e^+e^- collisions at energies of hundreds of GeV”, Amaldi noted that in a superconducting collider particle beams could release energy back into the accelerating structure after a collision at the interaction point, and then be reused after radiation cooling in a damping ring. This process is known as the energy recovery. Since 1978, linear colliders have been actively discussed at many workshops, developed in leading particle physics centers. Ugo Amaldi considered possible physics at linear colliders, compared efficiencies of normal conducting and superconducting colliders, carefully analyzed effects limiting the luminosity. In 1990, the first version of the TESLA superconducting collider design was developed, which included a table of parameters proposed by Ugo Amaldi.

Unfortunately, the beautiful idea of energy recovery was not adopted at that time due to a problem of parasitic collisions between the accelerated and decelerated beams within a linear accelerator. This problem does not exist when only one beam at a time is present in the accelerator, but then the collision rate is low, and the luminosity is even lower than without energy recovery when the beams are used only once. Consequently, only single-pass linear colliders were considered since 1980.

¹ This peer reviewed article originates from contributions to the “Symposium for Ugo’s 90 years” held at CERN (Geneva) on the 4th of April 2025 to celebrate the 90th birthday of Ugo Amaldi, member of the Accademia dei XL since 1992.

In 2021, the author of this article found a way to circumvent the above problem using twin/dual linear accelerators, where the accelerated and decelerated beams travel along parallel lines and do not collide. The luminosity achievable with this scheme could be almost two orders of magnitude higher than that of the ILC collider, the successor to the TESLA project. Thus, Ugo Amaldi's ideas and work continue to inspire and hold great promise for the future.

Keywords: superconducting linear colliders, energy recovery, electron-positron colliders, Higgs factory

Riassunto – Questo articolo descrive i contributi di Ugo Amaldi alla nascita e allo sviluppo di un nuovo campo nella fisica delle particelle: i collisori lineari di elettroni e positroni ad alta energia.

Gli acceleratori di particelle e i collisori sono strumenti fondamentali per lo studio delle proprietà della materia. Quando le particelle si scontrano, la loro energia viene utilizzata per crearne di nuove, consentendo di studiarne la natura, la struttura e le interazioni. L'energia delle particelle accelerate viene utilizzata in modo più efficace quando le particelle si muovono l'una verso l'altra. Questi acceleratori ad anello con fasci di elettroni e positroni in collisione apparvero nel 1965 e, nel 1975, diedero il via a una vera e propria rivoluzione nella fisica delle particelle. A energie di $2E = 3-4$ GeV, furono scoperti mesoni psi, quark charm e leptoni tau, e nacque la teoria delle interazioni forti.

Lo studio delle interazioni deboli richiedeva acceleratori con energie di 100 GeV e superiori. Tuttavia, gli acceleratori elettroni-positroni presentano una limitazione energetica associata all'emissione di radiazione di sincrotrone, la cui potenza è proporzionale a E^4/R^2 . Quando, nel 1975, iniziarono le discussioni su un acceleratore circolare e^+e^- per studiare il bosone Z, teoricamente previsto con una massa di circa 100 GeV, Ugo Amaldi propose un'altra opzione: un acceleratore lineare superconduttore a fasci incrociati, in cui il problema della perdita di energia per radiazione di sincrotrone fosse assente. Sebbene questa idea non fosse del tutto nuova, quello di Amaldi fu il primo articolo pubblicato sugli acceleratori lineari di questo tipo.

Nel suo articolo «Possible scheme to obtain e^-e^- and e^+e^- collisions at energies of hundreds of GeV», Amaldi osservò che in un collisore superconduttore i fasci di particelle potevano, dopo una collisione nel punto di interazione, rilasciare energia nella struttura in accelerazione, per poi essere riutilizzati dopo un opportuno rallentamento, per emissione di radiazione, in un anello di smorzamento. Questo processo è noto come recupero di energia. Dal 1978, i collisori lineari sono stati oggetto di discussione in numerosi workshop e sviluppati nei principali centri di fisica delle particelle. Ugo Amaldi ha considerato la fisica possibile nei collisori lineari, confrontato l'efficienza dei collisori a conduzione normale e superconduttiva, analizzato attentamente gli effetti che limitano la luminosità. Nel 1990, è stata sviluppata la prima versione del progetto del collisore superconduttore TESLA, che includeva una tabella di parametri proposta da Ugo Amaldi.

Purtroppo, la splendida idea del recupero di energia non è stata adottata all'epoca a causa di un problema di collisioni pa-

rascite tra i fasci accelerati e decelerati all'interno di un collisore lineare. Questo problema non sussiste quando nell'acceleratore è presente un solo fascio alla volta, ma in tal caso il tasso di collisione è basso e la luminosità è ancora inferiore rispetto a quella senza recupero di energia quando i fasci vengono utilizzati una sola volta. Di conseguenza, dal 1980 sono stati presi in considerazione solo i collisori lineari a passaggio singolo.

Nel 2021, l'autore di questo articolo ha trovato un modo per aggirare il problema di cui sopra utilizzando acceleratori lineari gemelli/doppi, in cui i fasci accelerati e decelerati viaggiano lungo linee parallele e non si scontrano. La luminosità ottenibile con questo schema potrebbe essere quasi due ordini di grandezza superiore a quella del collisore ILC, successore del progetto TESLA. Pertanto, le idee e il lavoro di Ugo Amaldi continuano a ispirare e a rappresentare una grande promessa per il futuro.

Parole chiave: collisori lineari superconduttori, recupero di energia, collisori elettroni-positroni, fabbrica di Higgs

1. Introduction. Prehistory of linear colliders

The linear collider scheme was first discussed in an article by Maury Tigner published in *Nuovo Cimento* in 1965 [1]. In this paper, M. Tigner considered a system using colliding beams from linear accelerators as an alternative to storage rings for studying electron-electron collisions. Here, he first discussed the advantages of superconductivity in reducing power consumption through energy recovery. Luminosity requirements for facilities in the GeV energy range were considered.

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

Linear e^+e^- colliders as a tool for achieving high collision energies were first discussed in Novosibirsk by G.I. Budker and A.N. Skrinsky. In 1971, A.N. Skrinsky briefly discussed this at an international seminar on perspectives on high energy physics in Morges, Switzerland. This talk was not published; its main theses were published in the summary talk, see [2]. The talk discussed both conventional colliding linear accelerators with very small transverse dimensions and superconducting ones, where energy recovery is possible.

In July 1973, neutral currents were discovered at CERN, confirming the Weinberg-Salam model of weak interactions, which predicted the Z boson with $M_Z \sim 100$ GeV. In 1975-1976, B. Richter after great discoveries at the e^+e^- storage ring *Spear* at SLAC, spent a sabbatical at CERN participating in the ISR experiment and developing general energy scaling laws for high-energy electron and positron colliding beam storage rings. This resulted in the publication of B. Richter's paper «Ultra-

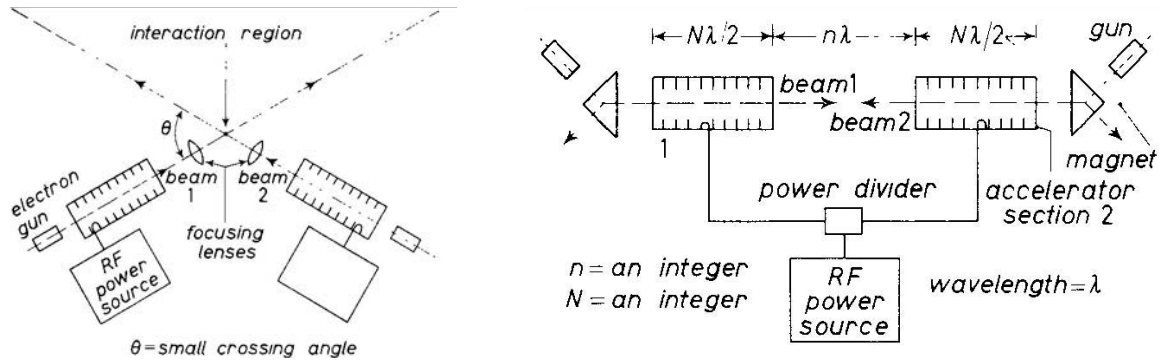


Fig. 1. Figures of linear collider scheme from M. Tigner's [1].

high-Energy Electron and Positron Colliding Beams for the Study of Weak Interactions» [3], paving the way for the creation of LEP. There were hot discussions (B. Richter, C. Pellegrini, C. Rubbia) on the scaling laws of circular storage rings: $\text{Cost} = C_0 + kE^2$.

In his 1992 review paper [2], Amaldi recalls: "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". It was published in Physics Letter B on March 29, 1976 [4]. It was the very first paper, devoted to high energy e^+e^- linear colliders!

2. "A possible scheme to obtain e^-e^- , e^+e^- collisions at energies of hundreds of GeV" by Amaldi

The abstract of the Ugo Amaldi's article is the following: "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 supercon-

ducting linacs which at the same time accelerate and recover the energy fed to the electron and positron beams".

Ugo called this linear collider "Peloron" (Positron-electron Linear Oscillator Radiating Only Negligibly). Its scheme for e^-e^- collisions is shown in Fig. 2. Here the energy is recovered; electron beams are used only once and are prepared anew each time.

In the case of e^+e^- the electron bunches are dumped after a single traversal while, to save positron current, the positrons are recirculated in a low energy ring, see Fig. 3.

B. Richter in 1987 wrote: "U. 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".

In May 1976, U. Amaldi and H. Lengeler presented this proposal at the Serpukhov meeting dedicated to future colliders. This was the only report on linear colliders.

3. "Birth" of linear colliders

The next known reports on linear colliders were by G.A. Voss", Collisions of very high energy e^+e^- beams

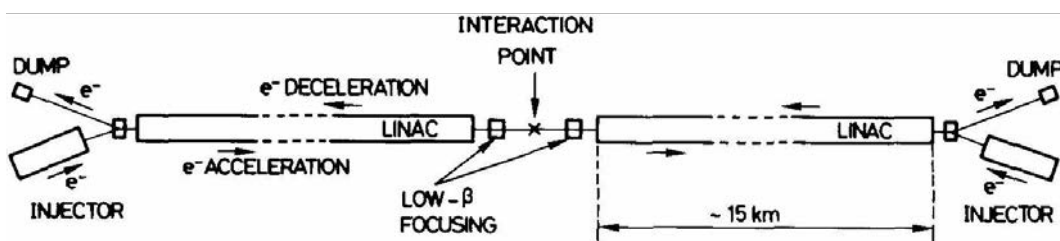


Fig. 2. Schematic drawing of the collinear electron-electron colliding beam.

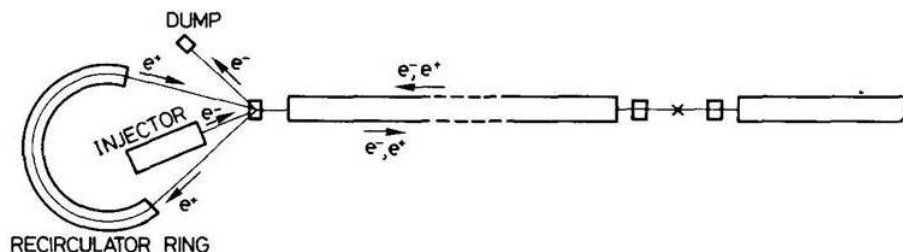


Fig. 3. Electron bunches are dumped after one pass; positrons are recirculated in a low-energy ring to save current [4].

with the use of linear accelerators" (July 1977, unpublished); by V. Balakin, G. Budker and A. Skrinsky "Feasibility of creating a superhigh energy colliding electron-positron beams facility" published in April 1978 [5] and presented to ICFA workshop at FNAL 1978.

Very important progress was made on linear collider at the First ICFA Workshop on «Possibilities and Limitations of Accelerators and Detectors» which was held at Fermilab in October of 1978. B. Richter recall in SLAC-PUB-4482, (1987): *"I believe the seminal event in the birth of the linear collider idea occurred at the ICFA Workshop. 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"*.

The second important event was the Second ICFA Workshop on «Possibilities and Limitations of Accelerators and Detectors» held at Les Diablerets, Switzerland, 4-10 October of 1979, where U. Amaldi was the key person: he gave the "Forward" talk, presented the paper "Energy recovery SC colliding linacs without particle recovery" (with C. Pellegrini) [6], coauthored the Report of Group "e⁺e⁻ colliders" [7] and was the editor of the Proceedings.

The history of LC by 1980 was described by U. Amaldi in his talk "Colliding beams" at the 9th Int. Symp. on Lepton and Photon Interactions, 1979 [8]. Undoubtedly, Ugo Amaldi was one of the main drivers of the events that led to the birth of linear colliders.

4. Problems of energy recovery

In 1979 H. Gerke and K. Steffen published "Note on a 45-100 GeV electron swing colliding" [9], where they presented a more advanced scheme of superconducting

e⁺e⁻ linear collider with energy recovery. They added bunch compressors-decompressors in order to reduce the beam energy spread of the decelerated beam at the entrance to the damping ring. They also noted that collisions between accelerated and decelerated beams in linear accelerators are unacceptable, so each linear accelerator should only have one beam at a time, which limits the collision frequency to $f \sim 30$ kHz. Taking into account the duty cycle of 1/30, which was feasible for superconducting cavities at the time, the achievable luminosity was only about $L \sim 4 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$. In this case, the luminosity is lower than in a conventional linear collider without energy recovery, where the beams can be focused more tightly because they are used only once.

Thus, the main obstacle for linear colliders with energy recovery is parasitic collisions in linear accelerators! Since 1980, linear colliders with energy recovery have fallen out of favor, as single-pass linear colliders offer higher luminosity, up to $L \sim 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. A sad end of a wonderful idea. However, good ideas never die. The revival and bright prospects of linear colliders with energy recovery are discussed at the end of this article.

5. A great high energy physicist, leader and teacher

In 1980, Ugo Amaldi became the spokesman for the DELPHI detector/experiment for the LEP collider, but his main focus remained on the development and promotion of linear colliders. Linear colliders were a novel area of research, and navigating the complexities required a thorough grasp of all the challenges. Ugo's approach was to master the details himself before communicating them effectively to others. This included the operating principles of each accelerator technology, the choice of optimal parameters, the collision effects that limit luminosity, energy scaling, and, of course, the particle physics for which linear colliders are designed. His papers and lectures could be used as textbooks on linear colliders. That are his lectures «Introduction to the

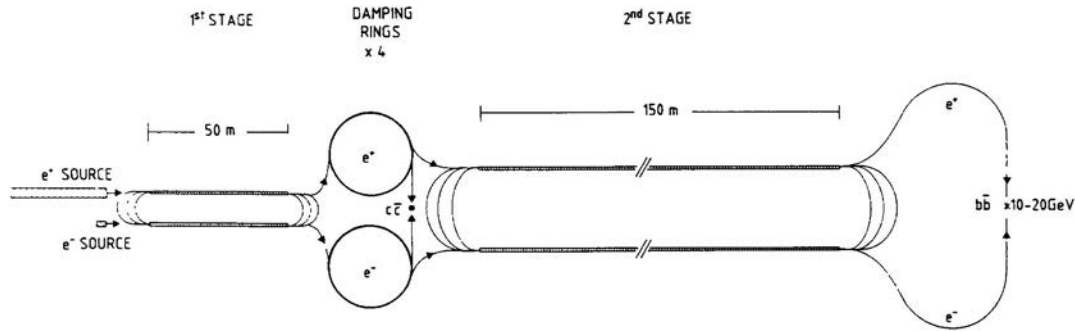


Fig. 4. Schematic drawing of the superconducting beauty factory [14].

Next Generation of Linear Colliders» [10], «Energy and luminosity requirements for the next generation of linear colliders» [11], «Achieving Ultrahigh Energies with e^+e^- Collisions» [12]. His plot for the e^+e^- cross-section [13] gave an idea of the expected physics and allowed to estimate the required luminosity.

Following discussions in 1978-79, linear colliders experienced rapid development in all the world's leading laboratories. Without delay, B. Richter oversaw the development of the 90 GeV e^+e^- collider SLC, creatively repurposing the existing linac by adding two rings to it. In April 1989, the first Z boson events were registered there. But this was only a test linear collider with low luminosity and energy. Shortly thereafter, a series of fairly realistic linear collider projects emerged: VLEPP (Novosibirsk, Protvino), NLC (SLAC), TESLA (DESY), JLC (KEK), and CLIC (CERN). Regular international meetings on high-energy and high-luminosity linear colliders began in 1988. Hundreds of accelerator and particle physics experts met in different parts of the world several times a year. There was a wonderful, friendly atmosphere here, where new ideas were born, emerging problems were discussed, people argued over whose project was better, and fought for the right to build a linear collider in their region.

6. Superconducting colliders

Of all the types of linear colliders, Ugo Amaldi clearly favored superconducting colliders. Although the energy recovery approach didn't work out, superconducting colliders still offered benefits, including nearly twice the efficiency and reduced peak power demands on klystrons. In their 1987 article, «Conceptual design of a multi-purpose beauty factory based on superconducting resonators» [14], U. Amaldi and J. Coignet described a flexible superconducting collider design with energy re-

covery. This concept envisioned a single facility that could be used for multiple physics goals, including charm-tau, beauty, Z, and toponium production, with the t-quark still undiscovered at the time. Figure 4 provides a schematic overview of the proposed collider.

U. Amaldi's 1990 article, «An Asthenon-factory and a Top-factory on the way to a TeV fully Superconducting Linear Collider» [15], presented at the TESLA workshop in Cornell, laid out a plan for a staged approach to achieving high-energy collisions using superconducting technology, quoting the abstract «A strategy is proposed to increase the energy of electron-positron collisions above the one reachable with LEP 200. By building a series of fully superconducting linear colliders of increasing length and of increasing gradient, the energies needed for a Z-factory, a W-factory, a top-factory and a 1 TeV collider can be obtained in successive steps....This is possible by using long cryostats, in which the superconducting cavities can be exchanged when techniques for getting higher gradients are developed». The final stage of this project, Ugo Amaldi called «TESLA» (TeV Superconducting Linear Accelerator). In the PAC 1991 proceedings H. Padamsee, the leading expert on superconducting, wrote: «The purpose of the first TESLA meeting was to work on an improved parameter list and accelerator physics issues, to refine the project's parameters, explore ways to improve gradients, develop suitable structures and cryostats, estimate costs and coordinate collaborative efforts. About 70 scientists participated from the laboratories of Argonne, BNL, CERN, Cornell, Darmstadt, DESY, Fermilab, IJXEP Protvino, INFN Frascati, Genova, Milano, KEK, Lawrence Livermore, Los Alamos, Saclay, SLAC, Stony-Brook. A staged approach for TESLA, suggested by U. Amaldi [15] was adopted».

Thus, Ugo Amaldi was undoubtedly one of the Godfathers of the TESLA linear collider project, the technical design of which was ready in 2001. In 2004 the TES-

LA technology was chosen for the International Linear Collider (ILC).

In September of 1991 U. Amaldi gave a talk “Evolution of Concepts and Goals of Linear Colliders” at the (first) Workshop on Physics and Experiments with Linear Colliders, Saariselka, Lapland [2]. With this historical review, Ugo Amaldi completed his work on linear colliders.

7. Linear colliders and scientific politics

At the Snowmass 2001 conference, high-energy physics strategy was discussed by thousands of physicists from around the world. Everyone agreed that the next collider after the LHC should be an e^+e^- collider with an energy of $2E = 500$ GeV. It was decided to join forces, and so the ILC project was born in 2004. The CLIC at CERN stayed, as it has advantages for energies over 1 TeV. Then it was decided to wait for LHC results. In 2012 the Higgs boson was discovered at the LHC with a mass 125 GeV. In 2013 the ILC technical design was published. During the following years of LHC operation, no other new physics was found in the energy range of ILC.

Since the Higgs boson was found to be quite light, in 2012 a proposal was put forward to study it in a circular collider. The FCC-ee project was born, where the luminosity at an energy of $2E = 250$ GeV, optimal for studying the Higgs boson, is an order of magnitude greater than at the ILC. Looking ahead, a promising strategy could involve constructing a 100 GeV proton-proton collider in the 100-kilometer FCC-ee tunnel. However, the prospects for the International Linear Collider (ILC) in Japan have dimmed, with local scientists and government officials now harboring significant doubts. The lack of signals from new physics has created uncertainty about the next major collider project. As a result, circular e^+e^- and pp colliders, such as FCC/BEPC, and

muon colliders have gained favor, relegating linear e^+e^- colliders, once the top priority for half a century, to a less prominent position.

8. Revival of superconducting linear colliders with energy recovery

The author of this article has been actively involved in the work on linear colliders since 1980, proposed and developed the idea of gamma-gamma collider based on e^+e^- linear colliders, so I was a little disappointed that linear colliders were no longer in favor. Then, in March 2021, a very simple idea for radically increasing the luminosity of linear colliders came to me, and I presented it at the LCWS 2021.

The primary challenge for a linear collider with energy recovery lies in mitigating parasitic collisions within the linacs. To overcome this, a design featuring separate beamlines for accelerated and decelerated beams is necessary to prevent collisions. This concept is illustrated in the twin/dual superconducting e^+e^- linear collider with energy recovery, depicted in Fig. 5, which I’ve referred to as the Energy Recovery Linear Collider (ERLC). A detailed description of this design can be found in the article “A high-luminosity superconducting twin e^+e^- linear collider with energy recovery”, published in JINST in December 2021 [16].

The proposed LC consists of two parallel superconducting linacs with coupled RF systems, so that the fields are equal at any time. One line is used for acceleration, and the other for deceleration. Damping is provided by wiggler magnets at the “return” energy about $E \sim 5$ GeV. Damping is necessary to reduce emittances and the energy spread to the level $\sigma_E/E \sim 2 \cdot 10^{-3}$ which arises from bremsstrahlung at the interaction point. The Linear Collider (LC) can operate in either continuous mode or duty cycle mode. The majority of power consumption is attributed to heat removal from cryogenic

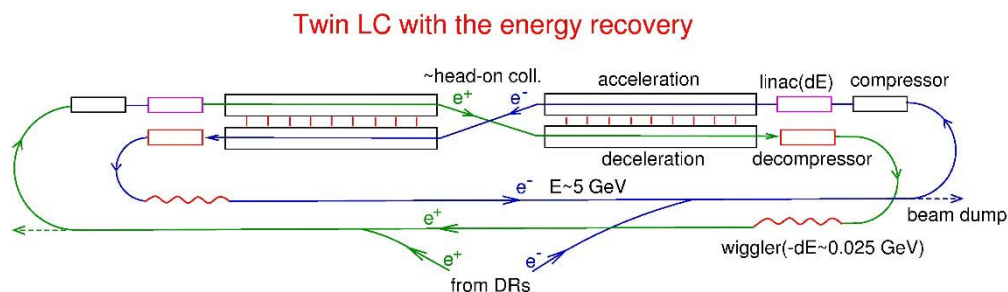


Fig. 5. The layout of the superconducting twin e^+e^- linear collider with energy recovery [16].

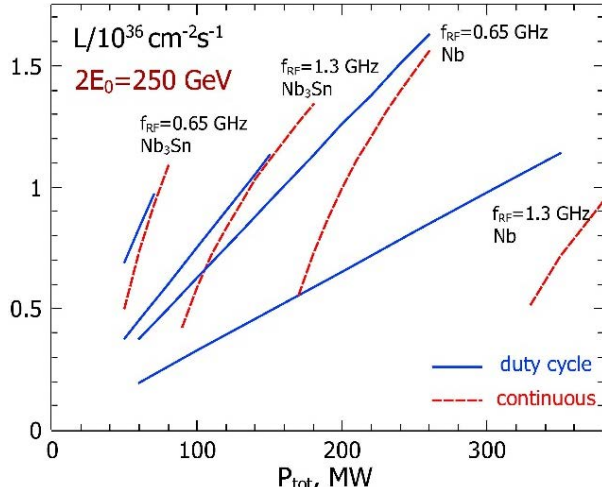


Fig. 6. Dependence of the e^+e^- luminosity on the total power for $2E_0=250$ GeV [16].

cavities, resulting from RF and HOM energy losses. The relationship between luminosity and total collider power is illustrated in Fig. 6, for $2E_0=250$ GeV, which demonstrate a luminosity of approximately $10^{36} \text{ cm}^{-2} \text{ s}^{-1}$. Notably, this is two orders of magnitude higher than the luminosity achieved at the ILC!

Similar “twin” approach can be used for the e^-e^- linear collider with the energy recovery [17], whose scheme is shown in Fig. 7. Here recycling is not required, the electron beams can be prepared anew each time. In this case the power is spent also for compensation of bremsstrahlung energy losses at the interaction point which reach tens of MW. The dependence of luminosity on the total power for such e^-e^- linear collider for $2E_0=250$ GeV is shown in Fig. 8. Graphs for $2E_0=500$ GeV can be found in [17]. As one can see, the luminosity is huge. The electron-electron collider also have very interesting physics program. It can produce the Higgs boson in virtual ZZ and $\gamma\gamma$ collisions.

In 2021, a group of experts led by A. Hutton reviewed the ERLC project and found it feasible, recommending its further development. Such collider is con-

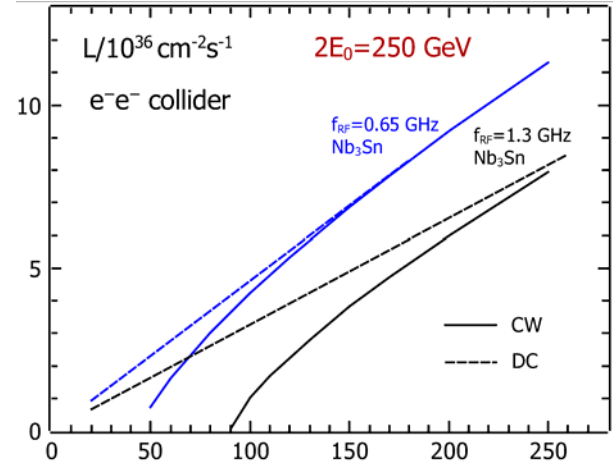


Fig. 8. Dependence of the e^-e^- luminosity on the total power for $2E_0=250$ GeV [17].

sidered now as a second high luminosity stage of the ILC [18] or, may be, this is the project instead of the ILC. This project is still in its early stages, many issues still require detailed study and technical research is required to improve the parameters and reliability of superconducting cavities.

9. Conclusion

It was an honor and a pleasure to contribute to this article highlighting Ugo Amaldi’s pioneering work on high-energy superconducting linear e^+e^- colliders. As the author of the first article on this topic, Ugo’s vision has paved the way for a major direction in high-energy physics. Particle colliders have revolutionized our understanding of matter, and each significant advancement requires substantial effort, resources, and time. Although the collider Ugo proposed 50 years ago remains to be built, and energy recovery poses a challenge, I presented a potential solution to this issue in this article. Today, Ugo’s vision for linear colliders can be fully realized. Happy 90th birthday, Ugo, your legacy continues to inspire!

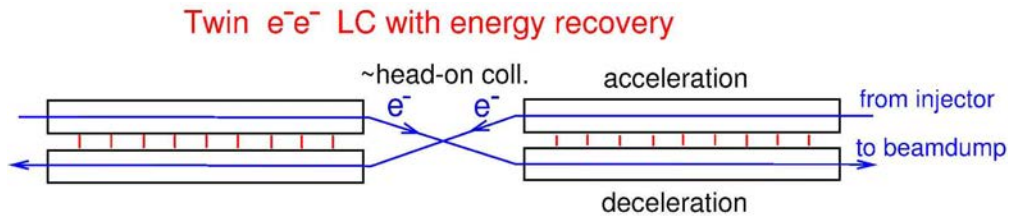


Fig. 7. The layout of the superconducting twin e^-e^- linear collider with energy recovery [17].

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