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# Lepton Colliders at the Energy and Luminosity Frontiers: Linear Colliders & SuperB Factories

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## Abstract

After a brief review of the performance of the various Lepton Colliders presently in operation at the energy and luminosity frontiers, the article describes their possible evolution and the envisaged new projects to improve their performances. Beauty Factories have the potential to extend the present luminosity frontier of Lepton Colliders by two orders of magnitude into the  $10^{36} \text{ cm}^{-2} \text{ sec}^{-1}$  range. Linear Colliders have the potential to extend the present energy frontier of Lepton Colliders by one order of magnitude into the Multi-TeV energy range. The ideas and challenges to boost these frontiers in the next future are described as well as the R&D plans to demonstrate their feasibility and/or to prepare projects proposals through engineering design optimisation and industrialisation. Technically driven schedule for their possible fabrication and installation are presented.

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# 1. Introduction

History of High Energy Physics clearly points out that hadrons and lepton colliders have been very complementary in the success story of the discovery and physics of new particles. The hadrons colliders have demonstrated to be better adapted to the discovery of new particles and the lepton colliders better suited to the precise determination of the properties of these new particles once discovered. Consequently, a worldwide consensus emerged towards a lepton collider as the favoured future facility to complement the LHC, coming on line from 2008, in the same energy range of the constituents. Elementary particle physics in the next decade will be focused on the investigation of electroweak symmetry breaking and the search for extensions of the Standard Model. Colliders at the high energy frontier constitute the ideal tools for the exploration of new Physics domains at the condition of delivering a large enough integrated luminosity. Luminosity is usually required to scale with the square of the colliding beam energy in order to compensate for the reduced particle cross section. As a consequence, the necessary increase of both energy and luminosity makes new projects of colliders at the energy frontier extremely challenging with large beam power and wall plug consumption. Ultra high luminosity at intermediate energies provide another pathway for Physics discoveries by opening other doors to precision physics. Colliders at the energy frontier and colliders at the luminosity frontier are complementary. As displayed on Figure 1, possible new projects of lepton colliders are presently being studied with the objective of an increase of:

- the energy frontier by one order of magnitude with Linear Colliders, namely ILC in the Tera-scale and CLIC in the Multi-TeV energy range
- the luminosity frontier by two orders of magnitude with Beauty Factories, namely Super KEKB and SuperB factory into the  $10^{36} \text{ cm}^{-2} \text{ sec}^{-1}$  luminosity range.

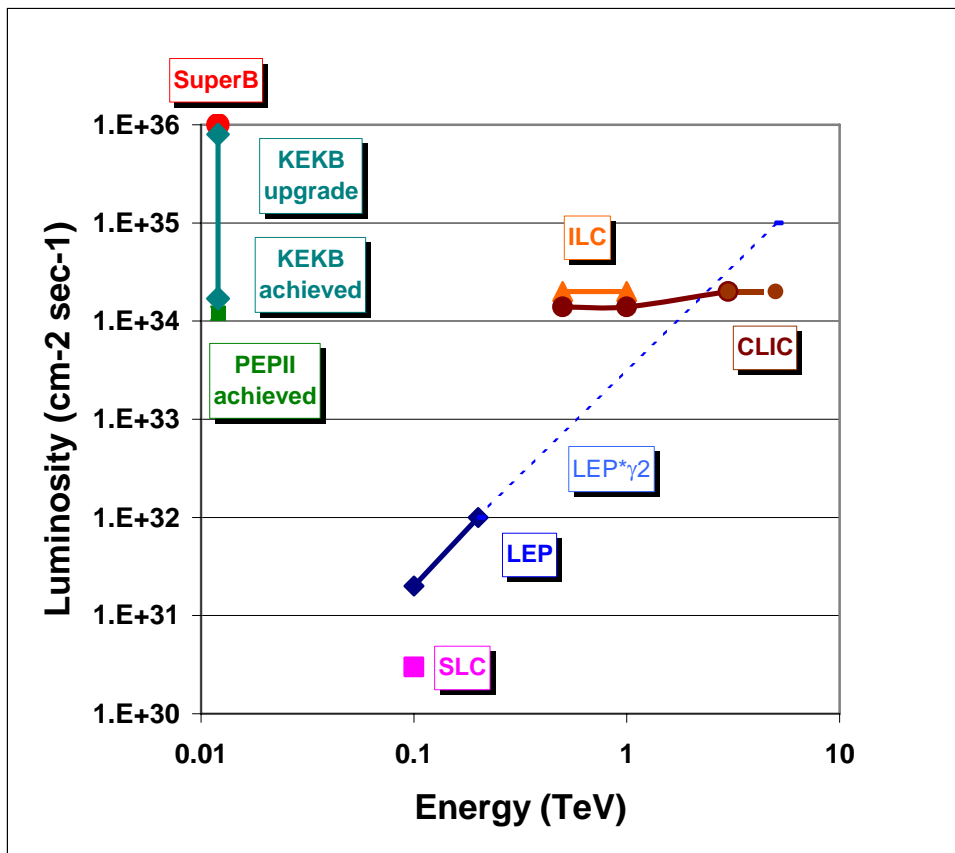


Figure 1: Luminosity versus energy of lepton colliders at the luminosity (KEKB, PEP-II) and energy (SLC, LEP) frontiers presently in operation and possible future projects (ILC, CLIC, KEKB upgrade, SuperB)

## 2. Lepton Colliders at the High Energy Frontier

The present energy frontier of Lepton Colliders has been reached by LEP2 with a colliding beam energy of 200 GeV/c in the centre of mass and a luminosity of  $10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$  range. The LEP2 colliding beam energy was limited by the emission of synchrotron radiation which had to be compensated with energy provided by Super-Conducting RF cavities. A further increase of the colliding beam energy in a circular collider would be extremely expensive since the emission of synchrotron radiation scales with the fourth power of the energy and is inversely proportional to the ring circumference. In order to allow possible increase of lepton colliding beam energies, linear collider technology has been successfully developed and operated with the SLAC Linear Collider (SLC)<sup>1</sup>, providing a luminosity of  $3 \cdot 10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$  at 100 GeV in the centre of mass. The SLC is acknowledged as the proof-of-principle facility for the linear collider concept. Following two decades of world-wide R&D on the various technologies to improve the performance of Linear Colliders and a technical review about their status & the key issues to assess their feasibility, it has been decided in 2004:

- By the International Committee for Future Accelerators (ICFA) to follow the International Technology Recommendation panel (ITRP) and select the Super-Conducting technology developed by the TESLA collaboration<sup>2</sup> for an International Linear Collider (ILC) in the Tera-Scale energy range.
- By the CERN council to support the R&D about the CLIC technology<sup>3</sup> to address by 2010 its feasibility to possibly extend the Linear Collider technology into the Multi-TeV range.

Both decisions have been endorsed in the European Strategy for Particle Physics<sup>4</sup> recommended by the CERN Council Strategy Group.

### 2.1. The International Linear Collider (ILC)<sup>5</sup>

The ILC is based on linacs made of 1.3 GHz Super-Conducting Radio-Frequency (SCRF) accelerating cavities. The many institutes around the world involved in linear collider R&D united in a Global Design Effort (GDE) to define the basic parameters and produce a common ILC design which culminated in 2007 in the completion of the ILC Reference Design Report (RDR)<sup>6</sup> including detailed design work and value estimate. The current ILC baseline assumes an average accelerating gradient of 31.5 MV/m in the cavities to achieve a centre-of-mass energy of 500 GeV. The choice of gradient is a key cost and performance parameter, since it dictates the length of the linacs, while the cavity quality factor (Q0) relates to the required cryogenic cooling power. The achievement of 31.5 MV/m as the baseline average operational accelerating gradient (requiring a minimum performance of 35 MV/m during cavity mass-production acceptance testing) represents the primary challenge to the global ILC R&D. Following the completion of the RDR, the GDE is launching an Engineering Design, closely coupled with a prioritized R&D program. The goal is to produce an Engineering Design Report (EDR) by 2010, presenting the matured technology, design, consolidated cost and construction plan for the ILC, allowing the world High Energy Physics community to seek government-level project approvals. A technically driven schedule shows that first colliding beams could possibly be provided from 2020 following a seven years construction.

#### 2.1.1. The ILC Baseline Design

The overall design has been chosen to realize the physics requirements with a maximum centre of mass energy of 500 GeV and a design luminosity of  $2 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ . Figure 2 shows a schematic view of the overall layout of the ILC with a total footprint of 31 km. The electron source, the damping rings, and the positron auxiliary ('keep-alive') source are centrally located around the interaction region (IR) with two detectors in "push-pull" mode. To upgrade the facility to 1 TeV, the linacs and the beam transport lines from the

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<sup>1</sup> The SLC Design Handbook, SLAC November 1984.

<sup>2</sup> Now known as the TESLA Technology Collaboration (TTC); see <http://tesla.desy.de>

<sup>3</sup> <http://clic-study.web.cern.ch/CLIC-Study/>

<sup>4</sup> <http://council-strategygroup.web.cern.ch/council-strategygroup/>

<sup>5</sup> <http://www.linearcollider.org/cms/>

<sup>6</sup> <http://www.linearcollider.org/cms/?pid=1000437>

damping rings would be extended by another 11 km each. The nominal beam parameter set, corresponding to the design luminosity and colliding beam energy of 500 GeV is given in Table 1 below.

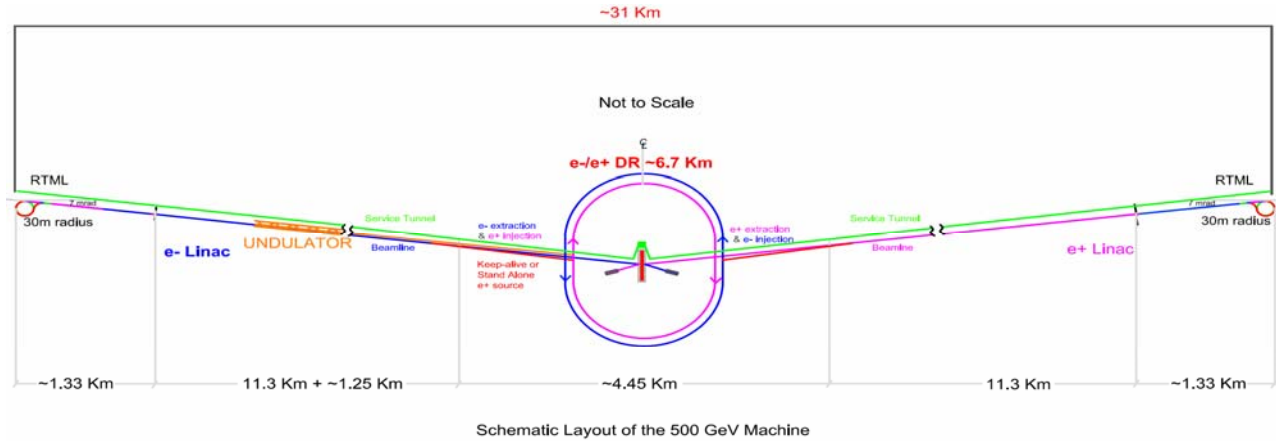


Figure 2: Schematic layout of the ILC complex for 500 GeV center of mass energy

### 2.1.2. Super-Conducting RF

The primary cost drivers of the ILC are the superconducting RF technology used for the Main Linacs, bunch compressors & injector linacs and the Conventional Facilities (including civil engineering). The basic element is a nine-cell 1.3 GHz niobium cavity operated at 2 °K. Eight or nine cavities are mounted together in a string and assembled into a common low-temperature cryostat or cryomodule, the design of which is already in the third generation. The ILC community has set an aggressive goal of routinely achieving 35 MV/m in nine cell cavities, with a minimum production yield of 80%. Approximately 160 of these cavities have been fabricated by industry as part of the on-going R&D program at DESY; some 17,000 are needed for the ILC. Several cavities have already achieved these and higher gradients (Figure 3), demonstrating proof of principle. Records of over 50 MV/m have been achieved in single-cell cavities at KEK and Cornell. However, it is still a challenge to achieve the desired production yield for nine-cell cavities at the mass-production levels required. The key to high-gradient performance is the ultra-clean and defect-free inner surface of the cavity. The best cavities have been achieved using electro-polishing, a common industry practice which was first developed for use with superconducting cavities by CERN and KEK. Building cavities with single grains of raw Niobium could possibly improve the performance and reduce the cost. The focus of the R&D is now to optimize the process to guarantee the required yield.

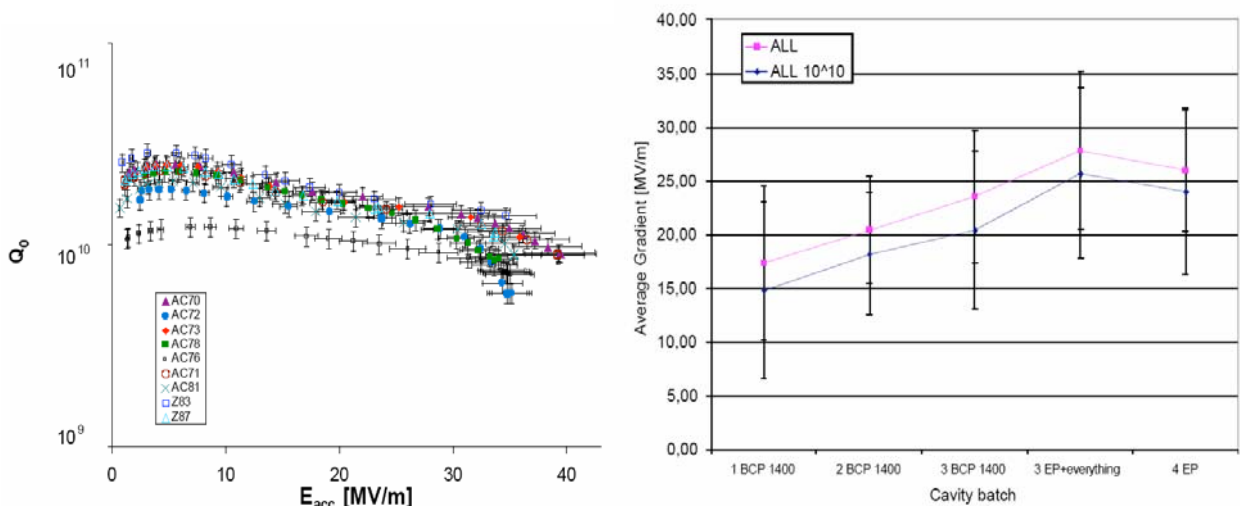


Figure 3: Nine-cell cavities performances: Examples of DESY cavities achieving 35 MV/m (left). Spread of performances for various preparation techniques(right)

## 2.2. The Compact Linear Collider (CLIC)<sup>7</sup>

The aim of the CLIC study is to develop a realistic technology with an affordable cost and power consumption to extend e-/e+ linear colliders into the Multi-TeV energy range, providing high luminosity ( $2.10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ) with a reasonable background over a colliding beam energy range complementary to LHC (0.5 to 3 TeV). The short term objective of the CLIC multi-lateral collaboration<sup>8</sup> is to demonstrate the feasibility, address all critical key issues and document the possible performance of a linear Collider based on the CLIC technology in a Conceptual design Report (CDR) by 2010. An overall layout of a CLIC complex based on a novel Two Beam Acceleration scheme with a nominal centre-of-mass energy of 3 TeV is shown in Fig.4. The main parameters at various colliding beam energies are summarized in table 1. The physics case for such a machine is outlined by the CLIC Physics Study Group<sup>9</sup>. A single tunnel housing the two linacs and the various beam transfer lines, without any active RF system, results in a very simple, cost effective and construction in stages with easily extendable configuration to higher energies without major modifications. Beam acceleration using high frequency (12 GHz) normal-conducting structures operating at high accelerating fields (100 MV/m) significantly reduces the length and, in consequence, the cost of the linac. The overall-length of a 3 TeV collider is about 48 km. In order to achieve the very high design luminosity at high energy, very low emittance beams have to be produced and focused down to very small beam sizes at the interaction point (about 1 nm in the vertical plane) and extremely short time interval (0.5 ns) between bunches.

### 2.2.1. The CLIC RF Power Generating Scheme

The pulsed RF power to feed the accelerating structures is produced by the so-called “Two-Beam Scheme” in which the 12 GHz power is extracted from high-intensity/low-energy electron drive beams running parallel to the main beam by special PETS structures (Power Extraction and Transfer Structures). Each linac has its own drive beam generation complex (Fig.4) which is situated in the central region of the site. The 24 drive beam pulses are produced as one long train with a bunch spacing of 60 cm accelerated up to 2.4 GeV using a fully-loaded normal-conducting linac operating at a low frequency (1 GHz) and an RF to beam transfer efficiency of 97%. The bunch spacing is then reduced in three successive stages in the delay loop and two combiner rings to 2.5 cm (a factor of 24) using funnelling techniques to repetitively interleave 150 ns-long slices of the trains. A particularly attractive feature of the CLIC scheme is that energy upgrading of the collider only requires a change in the pulse length of the modulators which drive the 1 GHz klystrons and not an increase in the number of klystrons. By initially sending this drive beam train in the opposite direction to the main beam, different time pulses in the train are used to power 875m long different sections of the main linac.

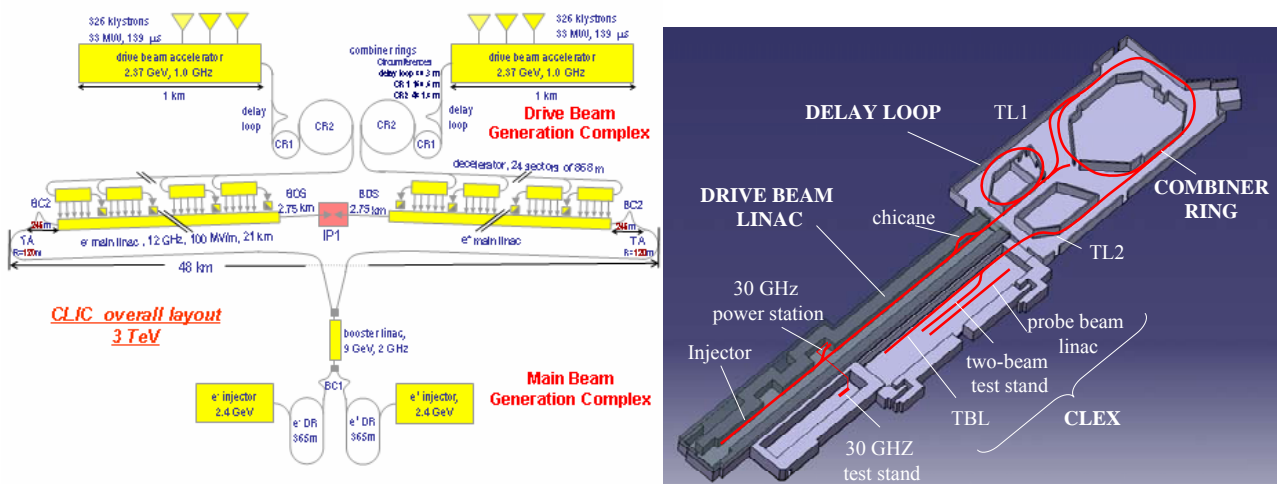


Figure 4: Overall layout of the CLIC complex and of the CLIC Test Facility CTF3.

<sup>7</sup> <http://clic-study.web.cern.ch/CLIC-Study/intro.html>.

<sup>8</sup> [http://clic-meeting.web.cern.ch/clic-meeting/2006/CTF3\\_Coordination\\_Mtg/Table\\_MoU.html](http://clic-meeting.web.cern.ch/clic-meeting/2006/CTF3_Coordination_Mtg/Table_MoU.html)

<sup>9</sup> [http://clic-meeting.web.cern.ch/clic-meeting/CLIC\\_Phy\\_Study\\_Website/default.html](http://clic-meeting.web.cern.ch/clic-meeting/CLIC_Phy_Study_Website/default.html)

### 2.2.2. Major Key Issues addressed in the CLIC Test Facility CTF3

Following demonstration of the principle of the Two Beam scheme in previous test facilities, a new facility CTF3<sup>10</sup> is being built at CERN to demonstrate the technical feasibility of the key concepts of the novel CLIC RF power source albeit on a much smaller scale. This facility is also used to demonstrate the key CLIC-technology-related feasibility as identified by the IL-TRC, namely:

R1.1 Test of damped accelerating structure at design gradient and pulse length

R1.2 Validation of the drive beam generation scheme with a fully loaded linac

R1.3 Design and test of an adequately damped power-extraction structure, with ON&OFF capability

R2.1 Validation of beam stability in drive beam decelerator & design of a machine protection system

R2.2 Test of a relevant linac sub-unit with beam

The facility is built in stages with the linac, delay loop and combiner ring already fully completed and commissioned with beam. The Experimental Area is in preparation to be equipped next year. Excellent performances<sup>11</sup> have already achieved, especially a fully loaded operation with more than 96% RF to beam transfer efficiency, beam combination in the delay loop and the combiner ring. The facility is operated routinely 10 months a year shared between beam commissioning of newly installed equipment and RF power generation for structure tests.

### 2.2.3. The Main Linac Accelerating Structures

A Hybrid Damped Structure (HDS) design had been specially developed including minimisation of the surface field, temperature rise during pulse and hybrid damping by both iris slots and radial waveguides. It allows a simple fabrication in quadrants with potential cost savings in respect with the usual technique based on disks. Tests of such structures based on HDS or disks with iris made of copper or bi-metallic materials have demonstrated high accelerating field up to 150 MV/m and a nominal pulse length but with high breakdown rates. The field has to be significantly reduced to reduce to operational breakdown rate of  $10^{-6}$  as shown on fig 5. A structure derived from the NLC programme recently demonstrated 100 MV/m with  $10^{-6}$  breakdown rate.

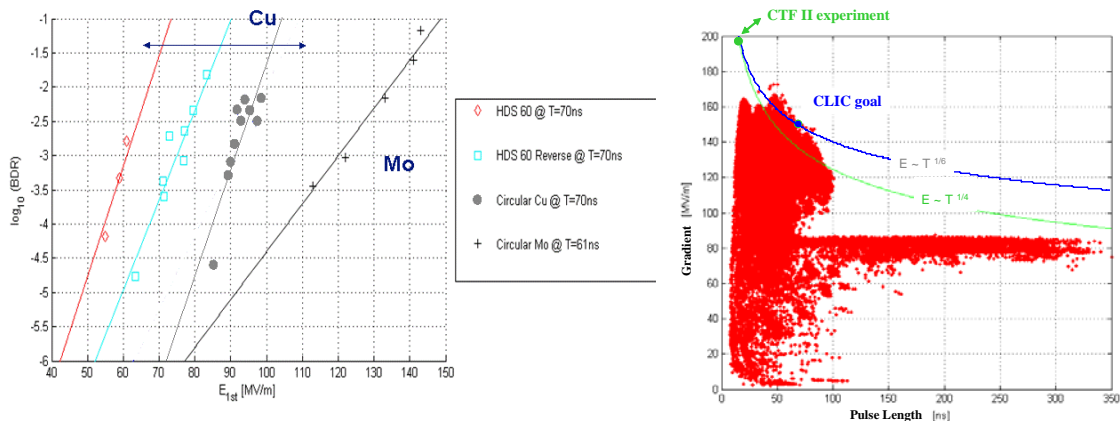


Figure 5: Achieved accelerating field as function of RF pulse length duration (left) and breakdown rates for various materials

<sup>10</sup> CTF3 design report, Editors G. Geschonke, A. Ghigo, CERN-PS-2002-008 (RF).

<sup>11</sup> H.Braun, Results on CLIC proof of principle for CTF3, EPAC06

Parameter	Unit	ILC	CLIC	CLIC	CLIC
Center of mass energy range	GeV/c	500	500	1000	3000
Peak luminosity/(in1% energy)	$10^{34} \text{cm}^{-2} \text{s}^{-1}$	2/2	2.2/1.4	2.2/1.1	5.9/2
RF frequency of main linac	GHz	1.3	12	12	12
Repetition frequency	Hz	5	100	50	50
Particle/bunch	$10^9$	20	3.7	3.7	3.7
# bunches/pulse	-	2625	312	312	312
Bunch separation	ns	369	0.5	0.5	0.5
Normalized emittances at IP (H/V)	mm-mrad	10/0.04	0.66/0.02	0.66/0.02	0.66/0.02
Beam sizes before pinch at IP (H/V)	nm	640/5.7	142/2		40/1
Loaded accelerating gradient	MV/m	31,5	100	100	100
Overall site length	km	31	12	20	48
Beam power per beam	MWatts	10.8	14	4.6	4.6
Wall plug to beam efficiency	%	9.4	6.1	6.1	8.7
Total site AC power	MWatts	230	150	150	322

Table 1 Summary of Linear Colliders main parameters

### 3. Beauty Factories at the High Luminosity Frontier

#### 3.1. Existing facilities: KEKB and PEP-II

In parallel with facilities at the energy frontier, high statistic studies with high luminosity facilities will play a crucial role for complementary High Energy Physics. The success story of the PEP-II<sup>12</sup> and KEKB<sup>13</sup> Beauty Factories in producing luminosity above  $10^{34} \text{cm}^{-2} \text{s}^{-1}$  has validated the design, construction and operation with high performances of  $e^+e^-$  circular colliders in a new parameter regime, especially collisions with asymmetric energies, accelerator physics in the area of high currents, complex interaction regions, high beam-beam tune shifts, high power RF systems, controlled beam instabilities, bunch to bunch feedback with short (4 nsec) bunch distance, rapid injection rates or continuous injections, and reliable uptimes. Their main parameters are summarised in table 2.

#### 3.2. KEKB upgrade

Because of the success of the B factories and the strong motivation for B Physics, a great activity has recently been developed aiming at luminosity improvement of B factories by a factor 50 to 100 and leading to proposals of PEP-II<sup>14</sup> and KEKB<sup>15</sup> upgrades with luminosities in the  $10^{36} \text{cm}^{-2} \text{s}^{-1}$  range. Their designs are derived from the extrapolation of existing B factories with higher currents (10A), larger number of bunches and reduced Beta functions at collision Point (1.5 to 3 mm). A doubling of luminosity in Super KEKB is provided by “crab crossing” where the bunches are made crossing head-on in spite of a circulating beam crossing angle. This scheme is presently being commissioned and tested on KEKB and has already achieved improved its performances. The PEP-II upgrade is not followed up any more but Super KEKB is still being considered. Main parameters are summarized on Table2.

<sup>12</sup> PEP-II Conceptual Design Report, SLAC 372 and SLAC PUB 12023 (EPAC06)

<sup>13</sup> KEKB Status report PAC 2005 Knoxville, TN and NIM A, 499, 1 (2003).

<sup>14</sup> J.Seeman et al: Design of a  $10^{36}$  SuperB Factory at PEP-II, EPAC04

<sup>15</sup> S.Hashimoto ed., Letter of Intent for KEK SuperB Factory, KEK-REPORT- 2004-4.

Parameters	Unit	PEPII	KEKB	PEPII upgrade	KEKB upgrade	SUPERB
Particle	-	e+/e-	e+/e-	e+/e-	e+/e	e+/e-
Luminosity	1034	1.2	1.7	70	85	100
Energy	GeV	3.1/8.99	3.5/8.0	3.5/8.0	3.5/8.0	4.0/7.0
Circumference	m	2200	3016	2200	3016	2250
Beam current	A	3.0/1.9	1.65/1.3 3	15.5/6.8	9.4/3.5	4.55/2.60
# bunches	-	1730	1389	6900	5000	3466
Crossing Angle	mrad		22		22	34
Bunch length	mm	13.5/12. 5	7/6	1.8	6	6
Horiz. beam at IP	microm		103/116	58	80	5.66
Vert. beam at IP	microm		1.9/1.9	0.7	3	0.035
Horiz emittance	nradm	29/50	18/24	24	18/24	1.6
Vert emittance	nradm	1	0.36	0.28		0.004

Table 2: Beauty Factories main parameters

### 3.3. SuperB Factory

Because of large power consumption of upgrades based on a conventional approach, a new concept<sup>16</sup> of collision scheme, the so-called “crab waist” has been developed. It combines extensions of the design of the current B Factories based on circular colliders with new concepts of low emittance damping rings and strong focusing of final focus developed for linear Colliders and tested in corresponding Test Facilities (FFTB, ATF, ATF2). This new scheme allows SuperB Factory<sup>17</sup> to reach a  $10^{36} \text{ cm}^{-2}\text{s}^{-1}$  luminosity without increasing beam currents, background rates and power consumption.

### 3.4. The Crab Waist collision scheme

In high luminosity colliders, one of the key requirements is very short bunches, since this allows a decreased vertical Beta Function,  $\beta_y$  at the IP, thereby increasing the luminosity. However,  $\beta_y$  cannot be made much smaller than the bunch length without incurring a luminosity reduction by “hourglass” effect. Moreover, high luminosity requires small vertical emittance, together with large horizontal beam size and horizontal emittance, to minimize the beam-beam effect. It is, unfortunately, very difficult to shorten the bunch length  $\sigma_z$  in a ring without reducing the corresponding bunch charge and a corresponding luminosity reduction. The novel “crab waist” scheme allows high luminosity without having to decrease the bunch length, by combining several potentially advantageous ideas:

The first idea is the collision of long bunches with small cross sections and large crossing angle (large Piwinsky parameter) leading to a reduced overlap area of colliding bunches. The vertical  $\beta_y$  function can be made comparable to the overlap area size, leading to high luminosity with reduced vertical tune shift and no vertical synchro-betatron resonances. However, a large Piwinski angle introduces beam-beam resonances and may strongly limit the maximum achievable tune shifts.

The second idea consists in the suppression of betatron (and synchro-betatron) resonances through vertical motion modulation by horizontal beam oscillations. A sketch of the crab waist scheme and correction scheme with two sextupole magnets in phase with the IP in the x plane and at  $\pi/2$  in the y plane, on both sides of the IP, is shown in Fig.6. A “crab waist” scheme is being implemented in the DAPHNE ring of Frascati (LNF/INFN) and will soon be tested with beam.

<sup>16</sup> P.Raimondi: New developments in SuperB Factory; PAC07

<sup>17</sup> SuperB Factory Design Report: <http://www.pi.infn.it/SuperB/?q=CDR>



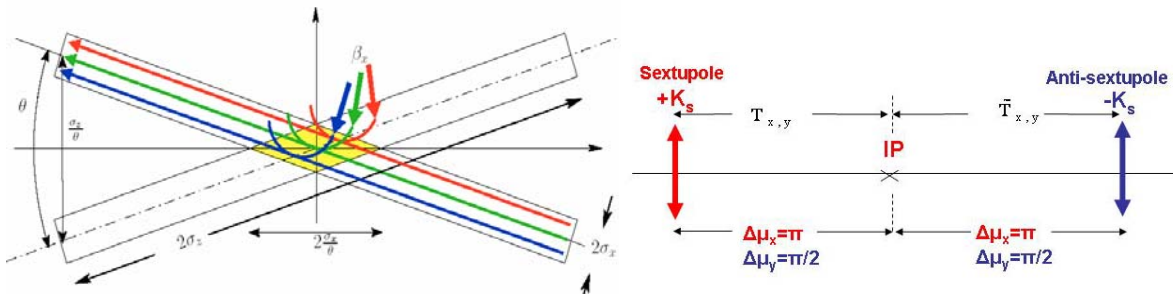


Figure 6: Large Piwinsky angle and crab waist scheme (collision area in yellow)

## 4. Conclusion

Lepton Colliders envision a bright future based on innovative ideas to push further the Luminosity and Energy frontiers. Promising results have already been achieved with the present R&D. Further R&D and Engineering Studies are still needed to transform promising ideas in realistic facilities and make them high performing with a minimum risk and an affordable capital and operational cost.

Ambitious Linear Colliders based on alternative technologies and complementary objectives are being developed to push further the energy frontier:

- The International Linear Collider (ILC) based on a pretty mature Super-Conducting RF technology derived from the TESLA Collaboration for a Linear Collider in the TeV colliding beam energy range. A Reference Design Report including cost estimation has just been published. The R&D is still being pursued by a world-wide collaboration to further improve the performance and reduce the cost. A detailed Engineering Design is in preparation for 2010, taking advantage of a strong synergy with the recently approved X-FEL project at DESY especially concerning the industrialization. It aims to be ready for project approval as soon as interest for Physics in the TeV range will be confirmed by LHC Physics results and the resources for its construction made available.
- The CLIC technology based on a novel Two Beam Acceleration scheme to further extend colliding beam energy reach of Linear Colliders into the Multi-TeV range. It provides promising performances with possible substantial cost savings. The feasibility of this novel scheme based on a challenging technology is being addressed in a Test Facility, CTF3, with results due by 2010. A Conceptual Design of a Linear Collider based on CLIC technology including cost estimate, is in preparation for publication by the same date.
- ILC and CLIC teams are closely collaborating on common issues especially in EU supported activities in the Framework Programs (FP6 and FP7 in the future). Both studies have timely defined milestones for important deliverables when LHC physics results will become available and physics requests will be better defined possibly in 2010.

Ambitious SuperB Factories are being developed to possibly increase the luminosity of Beauty Factories by two orders of magnitude into the  $10^{36}$  cm<sup>-2</sup> s<sup>-1</sup> luminosity range. Their design builds up on the excellent performance of the present B factories, PEP-II and KEKB, and on innovative schemes like “crab waist” taking advantage of the development on Damping Rings and Beam Delivery Systems in the frame of Linear Colliders studies and a strong synergy between Circular and Linear Colliders. The feasibility of this novel scheme is presently being addressed in DAFNE.

Impressive test facilities are being built all over the world as essential features to address the key issues, validate the technologies, improve the performances, reduce the cost and transfer knowledge to industries. They will require substantial (M&P) resources during the next few years.

A major key of success will be the ability of the community to make the necessary R&D and future project preparation in world-wide collaborations,

- taking advantage as much as possible of synergies,

- distributing most efficiently the effort in a complementary and coherent approach,
- joining resources
- fostering new ideas and developments.

New Physics Facilities at the Energy and Luminosity frontiers will be studied, built and operated in the future in World-Wide Collaborations ...or will not be!

## **5. Acknowledgments**

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