Accelerator prospects for high energy physics

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This talk is an attempt to present the current accelerator field status and assured prospects for elementary particle physics. The discussed subject is so rich that many interesting and important components of the picture are inevitably missing.

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1. Introduction

Accelerators are the principal research tool for high energy physics, and any major new step in accelerator development brings new prospects for elementary particle physics and for fundamental nuclear physics.

Let us mention briefly reasonable recent achievements and inventions in accelerator "technology" and particle dynamics, which gave, are giving and will give in the foreseeable future background for the flowering of the accelerator based High Energy Physics and applications:

- Intensive use of "sophisticated" colliding beams (including "single pass" and linear colliders).
- Application of superconductivity (mainly of II kind, but now H_{Tc} superconductors, also) for magnets and RF structures.
- Development and wide use of beam cooling methods (radiative, stochastic and electron cooling methods; in some cases, laser cooling of not fully stripped ions is useful for fundamental nuclear physics as well).
- Wider and wider use of polarized beams, especially in colliders, including longitudinal polarization in interaction regions.
- Progress in understanding of importance of impedance hygiene, and in corresponding design and technology that allows operation with short and intense bunches.
- Progress in ultra-high vacuum technology and vacuum chambers structures is productive and important to operate with higher and higher currents. Part of this progress is related to "electron cloud" instability and finding ways to suppress it.
- Development of digital bunch-by-bunch feedbacks is also useful to suppress high current instabilities.
- Development of practical energy recovery linacs and recyclers.
- High power targetry, which is so important for use of intense beams, is still at the start.
- Development of ionization cooling of muon beams – so important for future neutrino factories and muon colliders – proposed and understood, in principle, long ago, is approaching now experimental stage.
- Plasma (wake-field and/or laser) accelerators are still in infancy – but promises are high: to achieve 1 GeV/m and even much higher accelerating gradients.

Let us consider now the status and near prospects for accelerator field.

2. The modern proton/hadron accelerators and colliders.

The main p and pbar-p facility for about 20 years remains the TEVATRON complex at Fermilab (Figure 1). The main accomplishment made using this collider was the discovery of t-quark – the last quark of the Standard Model. Very productive were also other fields of research, especially the study of electroweak interactions, neutrino experiments (see below) and direct search for Physics beyond the Standard Model.

The upgraded complex is now in its final run. To improve the collider luminosity, the antiproton recycler was constructed, which for the first time uses permanent magnets for such a high energy ring (8 GeV) – to inject into it antiprotons, to cool them using electron cooling (4 MeV electrons!) and to add and cool a new portion before the injection to the collider ring. The EColing of antiprotons was achieved very recently. The major goal for this Run II is the discovery of the Higgs boson. But to achieve this goal the integrated luminosity of the two running experiments at the collider (D0 and CDF) should be at least more than $10 fb^{-1}$.

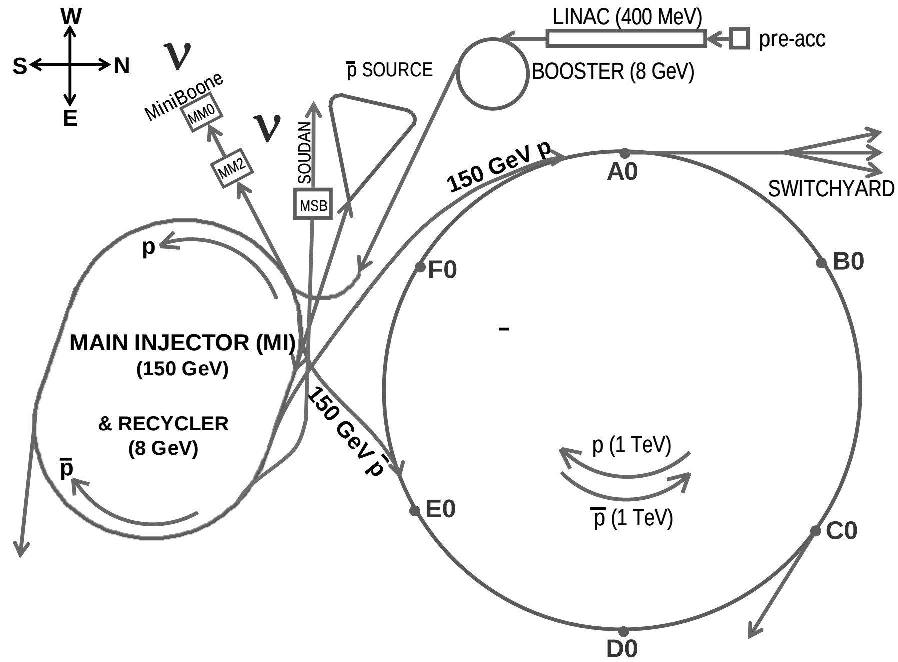


Figure 1. The TEVATRON complex – where the t-quark was discovered!

Unfortunately, the complex will be running in full scale for a few more years only. Then, the collider operation will be stopped. And the experimental activity will be focused mainly on long baseline neutrino experiments, maybe, with some improvements (multi-Megawatt proton injector linac, plus corresponding improvements in targetry) (Figure 2). Some other options for FNAL are under consideration – see below.

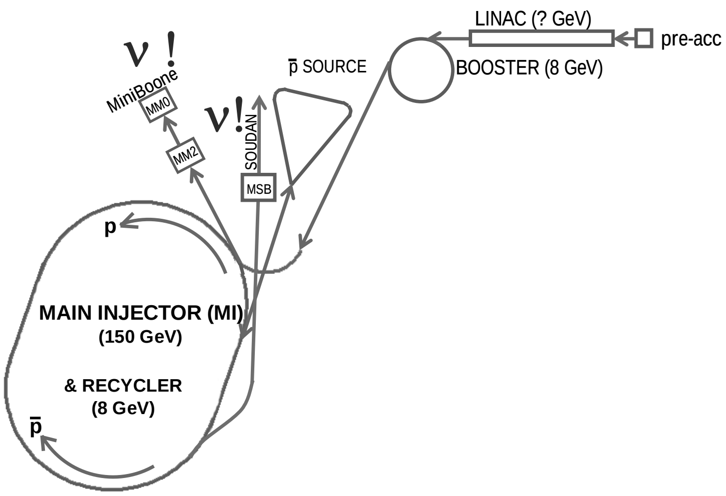


Figure 2. Possible future layout of the FNAL proton-neutrino complex.

Another ultimate – and also famous – facility, which uses the proton collisions, in this case with electrons and positrons, is the HERA collider at DESY Laboratory (Figure 3). It is still the only operating (not planned only) lepton-hadron collider. Apparently, the main achievements of this complex were: in accelerator field – the first high energy superconducting (proton) storage ring, the first operation with longitudinally polarized (in interaction regions) high energy electron (positron) storage ring; in elementary particle physics – precise study of proton structure functions at ultimately high energies and momentum transfers, including their spin-dependence.

But this complex will be also stopped in the near future.

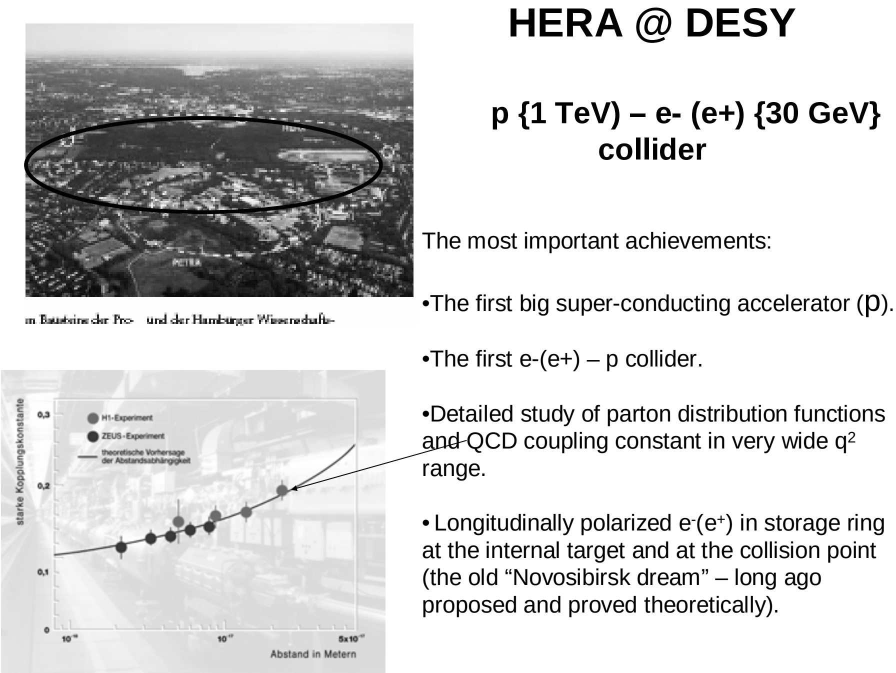


Figure 3. The HERA collider at DESY

For several years now, the Relativistic Heavy Ion Collider (RHIC) (Figure 4) at Brookhaven National Laboratory has been providing experiments with colliding beams of heavy nuclei at ultrarelativistic energies as high as 100GeV per nucleon. The purpose of this accelerator is to search for and explore new high energy forms of matter to understand the nature and origins of matter at its most basic level. The first measurements of head-on collisions at RHIC with nuclei as heavy as gold have already taken us a step toward the long sought Quark-Gluon Plasma.

Another mode of operation is the polarized proton-proton collisions at energy up to 200GeV+200GeV, extensively using some of Novosibirsk developments. The luminosity achieved in this mode is $1 \cdot 10^{31} cm^{-2} s^{-1}$ with a polarization degree of 45%.

For the future, the plan is to increase the luminosity of ion-ion collisions (the goal is by 10 times) by using very high energy (up to 55 MeV electron energy) electron cooling of both ion beams. The cooling would diminish ion emittances and prevent their growth due to intra-beam scattering.

The next option foreseen is electron (~10 GeV) – ion collisions of high enough luminosity; in this option electron cooling of ions also plays crucial role preventing additional luminosity degradation due to action of electron beam on ion beam.

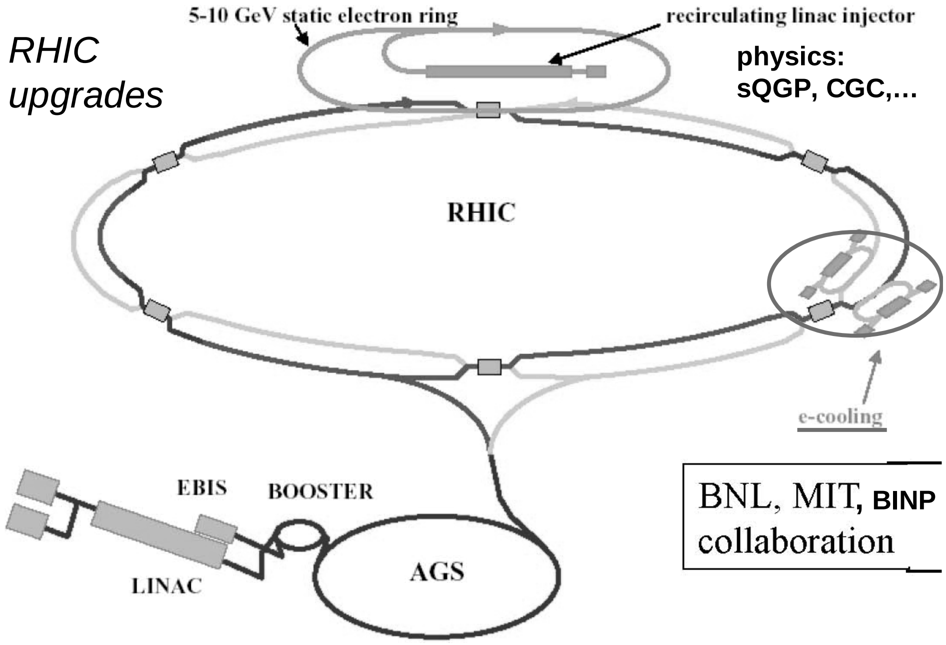


Figure 4. The RHIC collider at BNL.

The next (in energy range) major proton complex operates for several decades in Protvino, Russia (Figure 5). It is still useful for high energy physics.

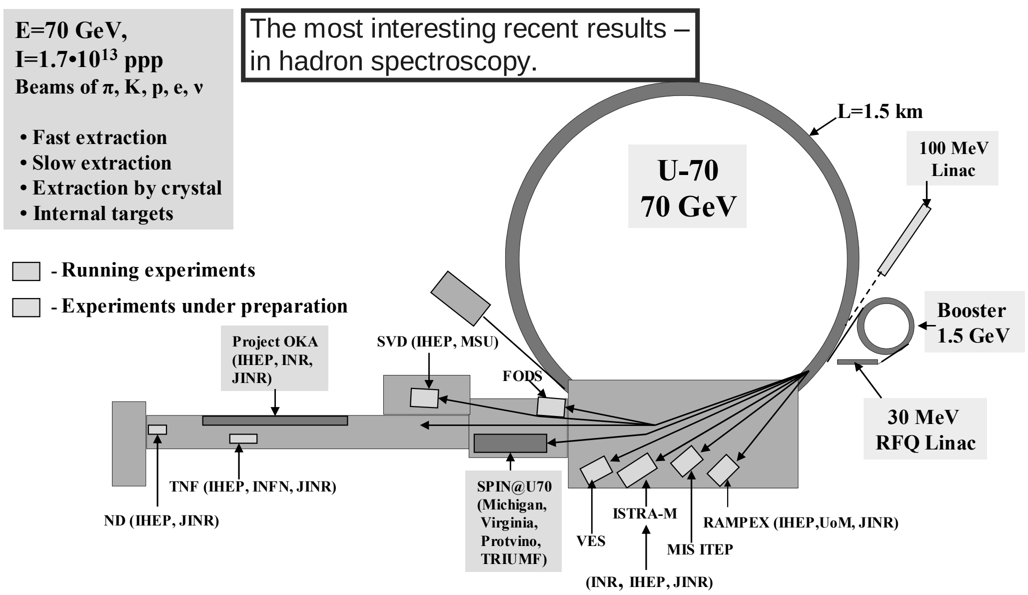


Figure 5. The Protvino complex based on proton accelerator U-70.

The ultimate hadron collider LHC (Figures 6) will come in operation at CERN in 2007. This is the first really Global Project, in design and construction of which (both in accelerator and detector sense) practically all scientifically advanced countries are participating. A search for the Higgs boson is one of the most important tasks of the two multi-purpose experiments ATLAS and CMS, which will be placed at the LHC. Recent studies, which were performed with detailed simulations of the detector geometry and response, pointed out that the LHC detectors have a possibility to cover the whole mass spectrum and detect the Standard Model Higgs boson already in the first years of operation. The LHC has tremendous potential to shed light on the physics of the top quark, understand the nature of Electroweak Symmetry Breaking, and search for signs of physics beyond the Standard Model. The LHC is expected to open new frontiers beyond the Standard Model. This could be supersymmetry or something more exotic, and might even appear in small deviations from Standard Model expectations in rare B-meson decays to be measured at the LHCb experiment.

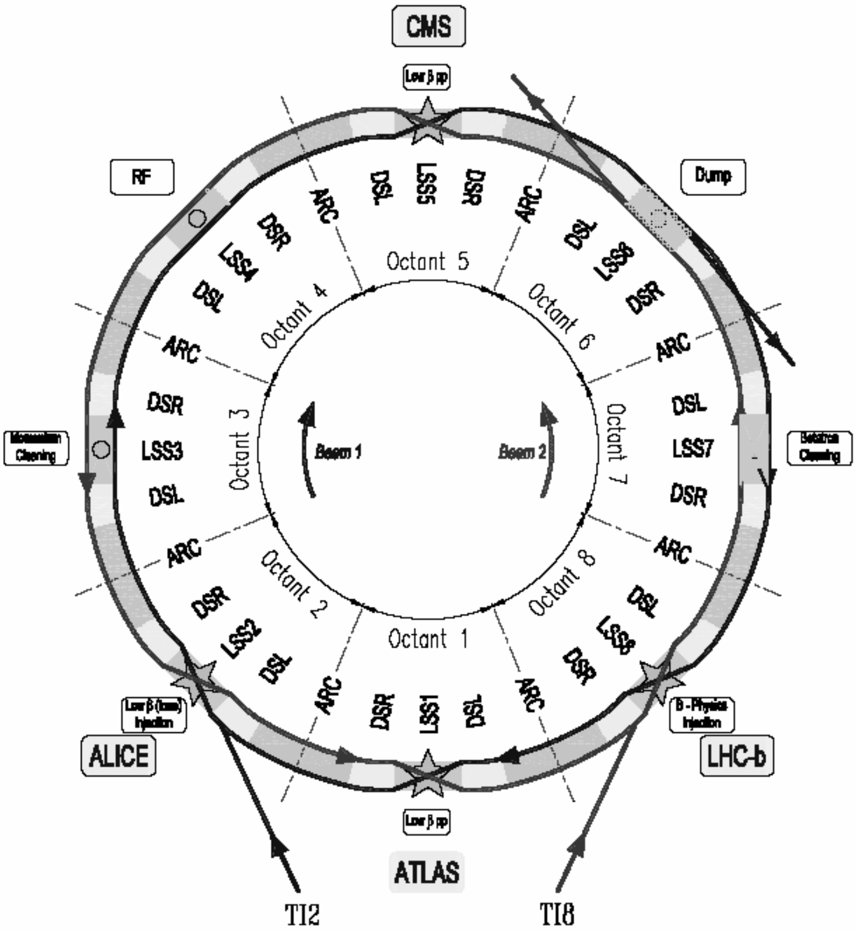
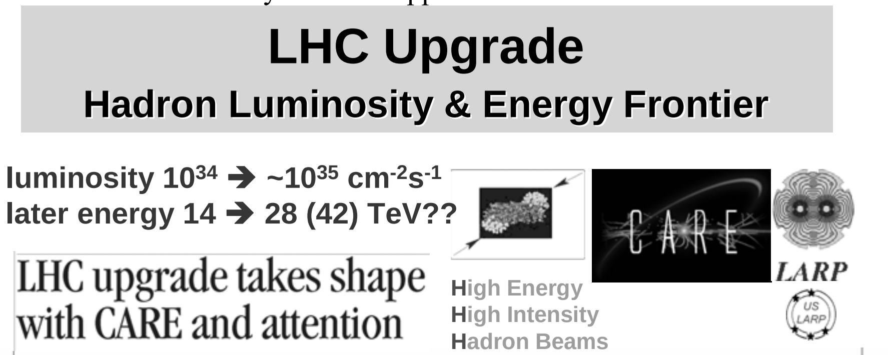


Figure 6. The layout of LHC complex (27 km perimeter; the nominal SC bending magnets field – 8.4 Tesla).

The LHC collider will start its operation in 2007. However, already now there is some activity to ensure its upgrading – in several steps – in not too distant future. At Figure 7 the possible options are presented. Of course, the ultimate energy upgrade up to 42 TeV looks fantastic (magnetic field should exceed 26 Tesla!). But in case of success it would be very important achievement with many different applications.



Parameters for various LHC upgrade options compared with nominal and ultimate values

Parameter	Symbol	Nominal	Ultimate	Shorter bunches	Longer bunches
number of bunches	n_b	2808	2808	4680 7020	936
protons per bunch	N_b (10^{11})	1.15	1.7	1.7	6.0
bunch spacing	Δt_{sep} (ns)	25	25	15 10	75
average current	I (A)	0.58	0.86	1.43 2.15	1.0
longitudinal profile	–	Gaussian	Gaussian	Gaussian	uniform
rms bunch length	σ_z (cm)	7.55	7.55	3.78	14.4
beta at IP1 and IP5	β^* (m)	0.55	0.5	0.25	0.25
crossing angle	θ_c (μrad)	285	315	445	430
Piwinski parameter	$\theta_c\sigma_z/(\sigma^* 2)$	0.64	0.75	0.75	2.8
luminosity	L (10^{34} cm^{-2} s^{-1})	1.0	2.3	7.7 11.5	8.9
events per crossing	–	19	44	88	510

Figure 7. Parameters of LHC upgrade under consideration.

The Japan Hadron Facility (J-PARC) aims to advance many fields of high energy physics by providing various particle beams of high intensity (Figure 8). The accelerator complex consists of 200 MeV linac, 3 GeV and 50 GeV rings which provide proton beams at the mean currents of 200μA and 10 μA, respectively.

At the 50 GeV Proton Synchrotron several types of nuclear physics experiments using kaon, antiproton, pion, hyperon beams and primary beams, including heavy ions, are planned. In addition, experiments on kaon rare decays (for example, K_L->$\pi^0\nu\nu$–bar) and other symmetry tests together with an experiment on neutrino oscillations using Super-Kamiokande as a detector will be carried out.

The facility is under active construction now.

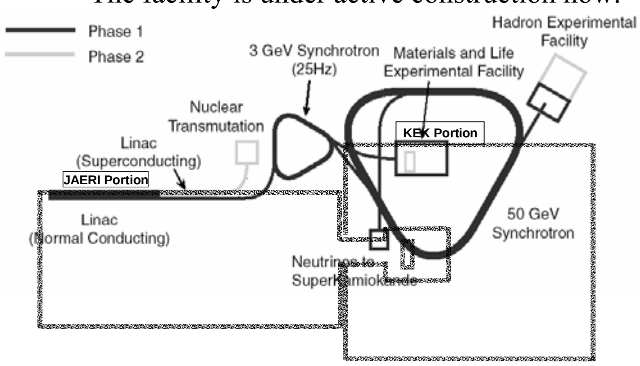


Figure 8. The layout of the KEK-JAERI proton complex.

Another high potential facility is accepted for construction at GSI (Darmstadt, Germany) (Figure 9).

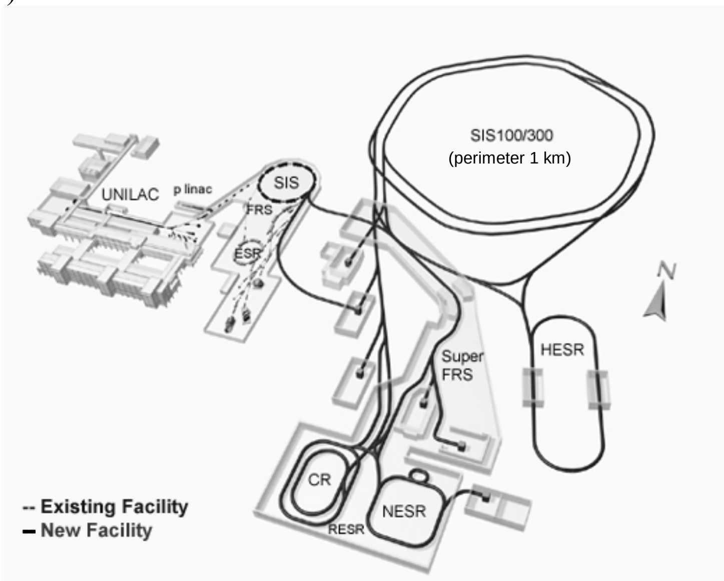


Figure 9. The future **F**acility for **A**ntiproton and **I**on **R**esearch (FAIR) project at GSI (very big collaboration!). SIS 100/300 ➔ 100 GeV/300 GeV.

The principal goal of this new facility is to provide scientific community with a unique and technically innovative accelerator system to perform future forefront research in sciences concerned with the basic structure of matter. The facility will provide an extensive range of particle beams from protons and their antimatter partners, antiprotons, to ion beams of all chemical elements up to the heaviest one, uranium. A key feature of the FAIR will be the generation of intense, high quality secondary (fragment) beams. These include beams of short lived nuclei – often referred to as rare isotope beams. Other characteristics are excellent beam features. This will be achieved through innovating beam handling techniques, many aspects of which have been developed over recent years. They include in particular electron-beam cooling of high energy, high charge ion beams in storage rings.

Research program will include investigations with beams of short-lived radioactive nuclei, addressing important questions concerning nuclei far from stability, areas of astrophysics and nucleosynthesis in different stellar processes. The confinement of quarks and the generation of the hadron masses could be studied at the sub-nuclear level with beams of antiprotons.

Some key concepts and systems of the project were designed with active Novosibirsk participation.

Another facility, which will allow modern heavy ion experiments, is under final stage of construction at Lanzhou (Figure 10).

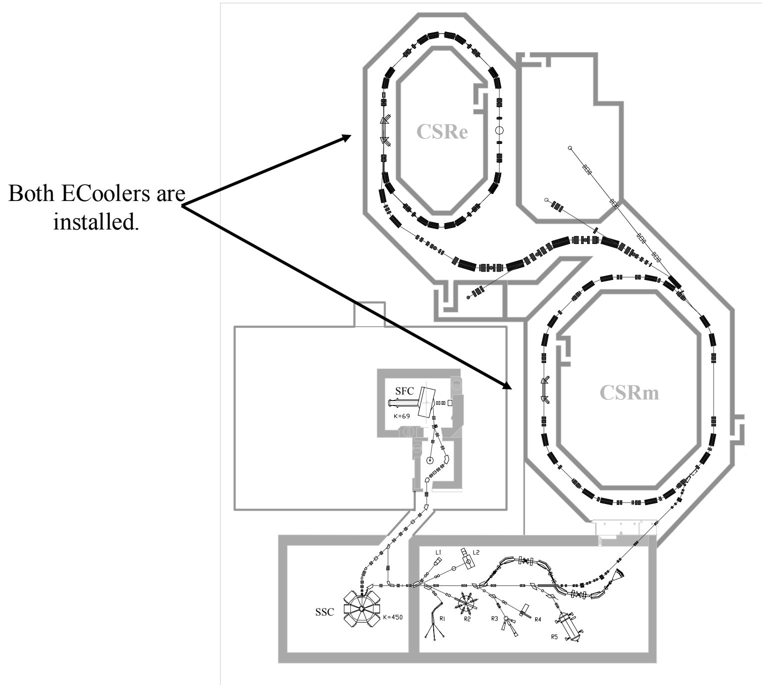


Figure 10. The nuclear facility at the Institute of Modern Physics (Lanzhou, China) – under construction and commissioning (with active D&C&C participation of GSI and BINP!).

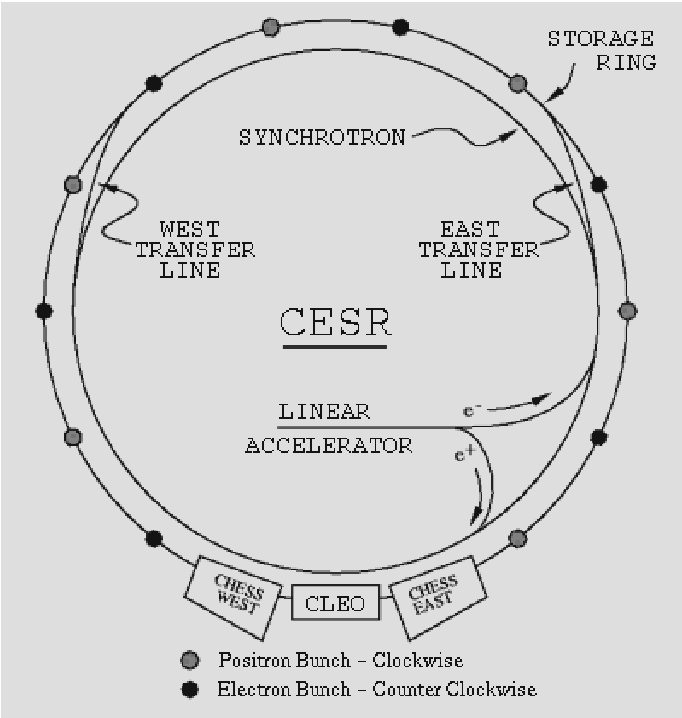
3. Electron-positron colliders (cyclic).

One of the largest samples of the Weak Vector Bosons (Z and W) has been collected at the really ultimate cyclic e+e- collider LEP. LEP has collected about 20 million Z's, and since 1996 up to 2000 has been running at energies above the W-pair production threshold, so that about 40k W-pairs have been detected by LEP experiments. These data allowed a precise determination of the Z and W-bosons parameters and their couplings with fermions. As a result we can now conclude that the number of the fundamental generations in the Standard Model is three.

Moreover, the precise data from LEP and Tevatron played a key role in a Higgs mass estimate from the global electroweak fit, which yielded $m_H = 114^{+69}_{-45}$ GeV. The central fit value of the Higgs mass now coincides with the lower limit from direct searches at LEP, and the hunting for the Higgs at hadron colliders is very much on.

In operation now, there are several cyclic electron-positron colliders – different in scale, but complementary in experimental potential.

The very successful Cornell Electron-positron Storage Ring (CESR) (Figure 11) is providing collisions between electrons and positrons with center-of-mass energies in a range from 3 up to 12 GeV. This collider, armed with powerful detectors CLEO I-III, has been studying the production and decay of beauty and charm quarks and tau leptons. The Collaboration makes some of the most sensitive tests of the Standard Model, including the observation of the B-mesons and their rare decays, measurements of the V_{ub} and V_{cb} elements of the Cabibbo-Kobayashi-Maskawa matrix, precise study of the B^0-anti-B^0 mixing and many other important studies. Some of the innovative approaches in the accelerating technique developed at the CESR (superconducting final focus quadrupoles, multibunch collision scheme in a single ring using 2-dinsional orbit separation, …); some of them were used in the design of the B-factories.



- **Detailed study of B and D meson physics.**
- **Major step to B Factories.**

Figure 11. The electron-positron collider CESR (Cornell).

The asymmetric e+e- B Factories PEP-II (Figure 12) and KEKB (Figure 13), and their associated detectors BABAR and Belle, are in operation since 1999. Both of these projects, realized on the foundation of results from DORIS, CESR and LEP experiments, have been remarkably successful, technically as well as scientifically. The B Factories design peak luminosities ($3x10^{33}cm^{-2}s^{-1}$ for PEP-II and $1x10^{34}cm^{-2}s^{-1}$ for KEKB) were very ambitious, and it is fair to say, were regarded with some skepticism. Both PEP-II and KEKB, however, reached design luminosity in a remarkably short time, and currently operate at even higher luminosity. Such progress was reached due to important accelerator advances – the use of digital "bunch-by-bunch) feedback and suppression of electron cloud instability, what gave possibility to operate at a few ampere currents; the use of micro-beta vertical functions and correspondingly small bunch lengths around 6mm; operation at Q_{vert} value above and very close (few thousandth!) to half-integer resonance for both collider rings; the use of very many bunches and SC Final Focus lenses, ….

The scientific productivity of PEP-II/BABAR and KEKB/Belle has been also remarkable, with wide-ranging studies of CP violation in the B meson system that discovered, for the first time, CP violation in the B meson decays, and demonstrated that the CP-violating phase of the Standard Model with three generations is capable of explaining all CP-violating phenomena thus far observed in the K and B meson systems. BABAR and Belle have each published more than one hundred papers, covering a wide range of CP violation measurements, studies of rare decay phenomena and high precision measurements in B and D meson and τ lepton decays. Their productivity continues to be unabated. The next few years will certainly bring a number of new beautiful results, and, perhaps, even a few surprises. There are already hints of results that disagree with the Standard Model in areas where one might expect measurable New Physics effects, although none of these are as yet of conclusive statistical significance.

After six years of experience, we have excellent understanding of the actual physics performance of BABAR and Belle as well as their ability to elucidate the full range of CP-violating effects in B decays and to make precision measurements of CKM matrix parameters. We have also learned a lot from PEP-II and KEKB operation at high luminosities, including detailed understanding of the backgrounds. This experience gives a solid basis for significant upgrades of these colliders and detectors (Super B Factory), which would open up new scientific opportunities.

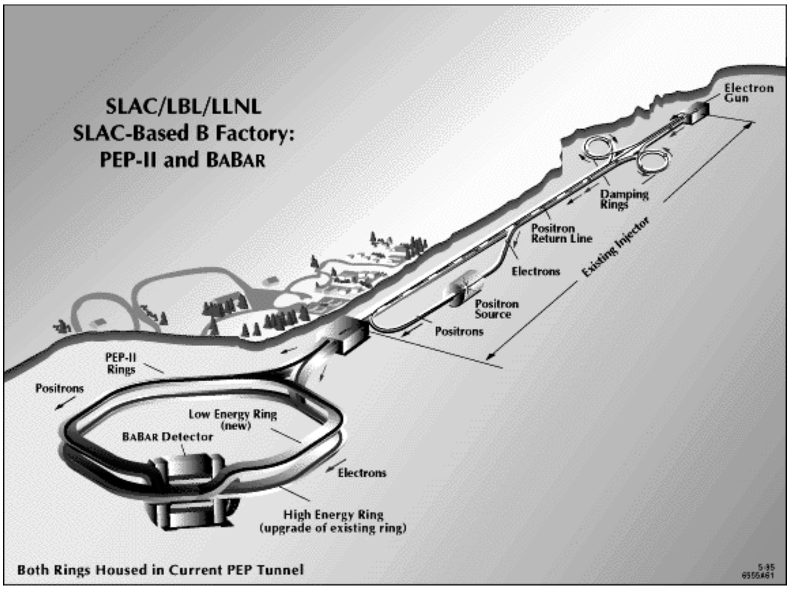


Figure 12. The layout of PEP-II B Factory (Stanford, USA).

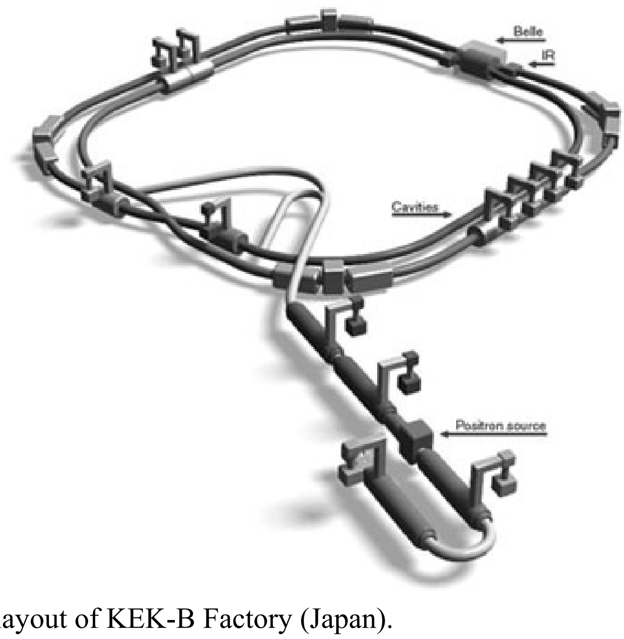


Figure 13. The layout of KEK-B Factory (Japan).

A Super B Factory, an asymmetric e+e- collider with a luminosity of the order of 5-$10 \times 10^{35} cm^{-2} s^{-1}$, would be a uniquely sensitive probe of the flavor couplings of New Physics beyond the Standard Model. The potential of a Super B Factory to explore the effects of New Physics in the flavor sector could be realized by two possible strategies: measuring branching fractions, CP-violating asymmetries in rare B,D and τ decays, in which there are clear potential signatures of New Physics, and pushing the precise predictions of the Standard Model to their limits, by measuring the sides and angles of the unitarity triangle to the ultimate precision warranted by theoretical uncertainties, with an aim to observe a discrepancy with theory. The project is under development at KEK. The concept under consideration is shown at Figure 14.

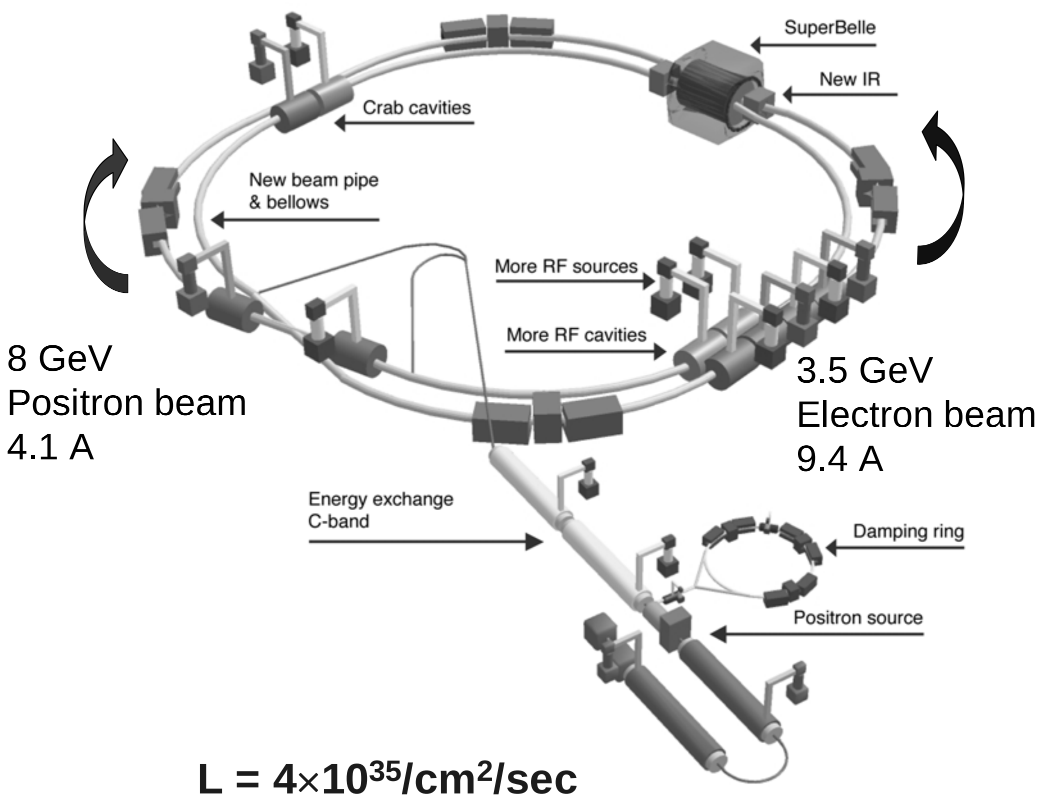


Figure 14. The Super B Factory at KEK (under consideration and design).

High luminosity low energy facilities are still providing valuable information for spectroscopy and dynamics of light hadron interactions as well as for precision measurements of hadron production cross sections. The latter is important to estimate higher-order corrections to the Standard Model calculations. Such electron-positron colliders are now in operation {DAΦNE at Frascati (Figure 15)}, and under construction {VEPP-2000 at Novosibirsk, Charm/Tau Factories at Beijing and Novosibirsk}.

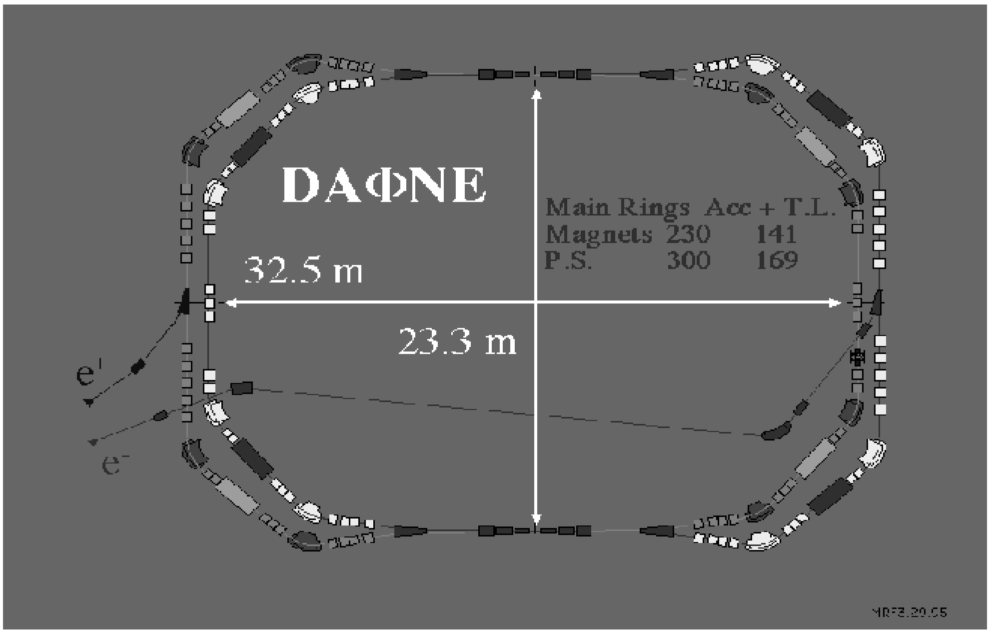


Figure 15. The layout of Frascati collider DAΦNE – operates at phi- meson energy, luminosity around $1{\cdot}10^{32}$ $cm^{-2}s^{-1}$.

The next Novosibirsk collider VEPP-2000 (Figure 16) will very soon start operation, replacing a successful VEPP-2M collider, which for 25 years was the main source of information on electron-positron collisions in the c.m.energy range up to 1.4 GeV. VEPP-2000 will operate in the range from the rho-meson to 2 GeV with luminosity up to 10^{32} $cm^{-2}s^{-1}$. This facility will allow a check of the new concept – high luminosity collisions due to a round-beam scheme.

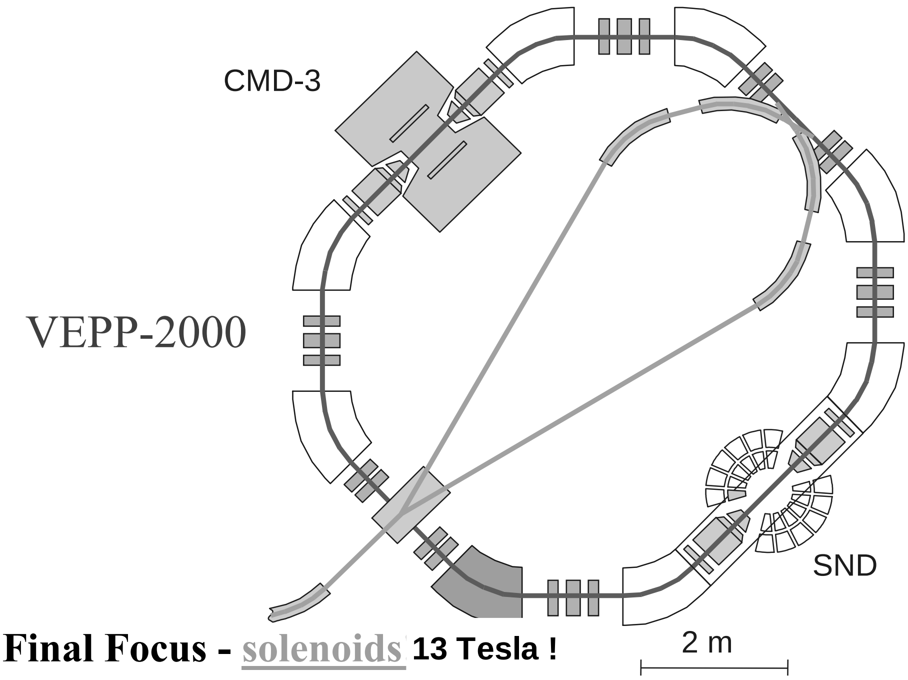


Figure 16. The layout of VEPP-2000 collider (Novosibirsk, Russia) now under final construction. A 13 Tesla field was reached in solenoids.

The electron-positron collider BEPCII (Figure 17) under construction at Beijing will replace the BEPC, successfully operating for more than 15 years since 1989. The peak luminosity at BEPC was 1.2 $\times 10^{31}$ $cm^{-2}s^{-1}$ @ 2x1.89 GeV. Its main achievements included R measurement between 2 and 5 GeV, precise measurement of the tau lepton mass and detailed studies of J//Ψ and Ψ' rare decays. The new facility will allow a significant increase of the samples of charmonia and charmed particles.

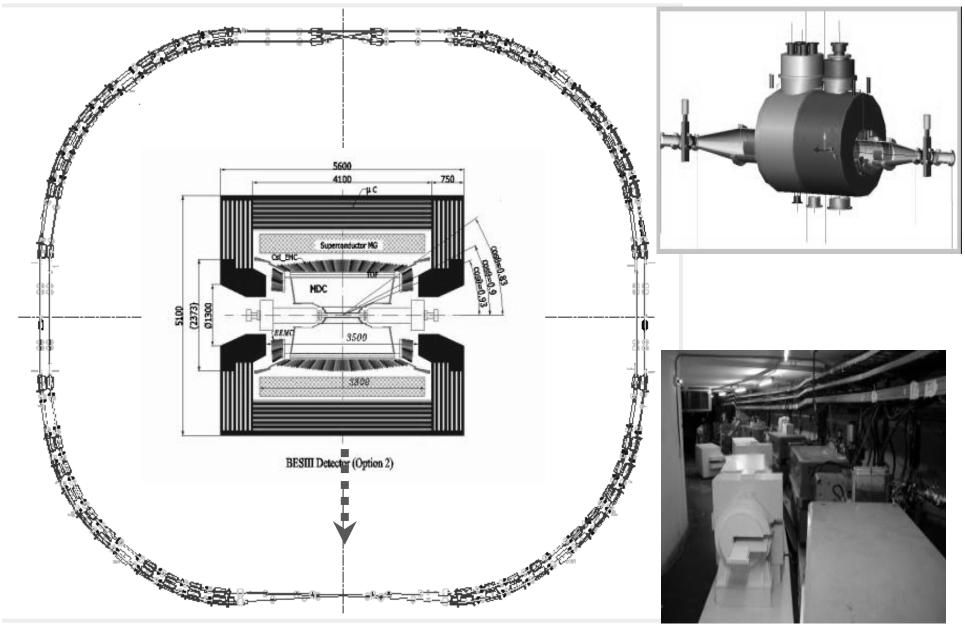


Figure 17. The BEPCII high luminosity double-ring collider (Beijing, China; under construction). Projected luminosity is 10^{33} $cm^{-2}s^{-1}$ at the c.m.energy up to 3.7 GeV.

The tau-charm factory is also considered in Novosibirsk (Fig.18). Construction of the injection complex for this facility is now close to completion. In addition to high luminosity the collider design includes a possibility of experiments with longitudinal polarization and high monochromaticity of the c.m.energy.

There are also facilities, which despite their not very high luminosity offer a possibility of unique sophisticated measurements. An example of such a facility is VEPP-4M (Fig.19), an upgrade of theVEPP-4 collider in Novosibirsk. It continues a series of experiments pioneered at the previous colliders VEPP-2M and VEPP-4 on high precision mass measurements, based on the resonant depolarization method developed in Novosibirsk. As their result, the precise mass scale was established (accuracy close to 10^{-5}) in the range from 1 to 100 GeV/c^2 (the Z boson mass was measured at LEP using the same method). The KEDR detector installed at VEPP-4M continues such measurements at the new accuracy level (M(J/psi) = 3096.917 +- 0.010 +- 0.007 (previous PDG $\Delta M/M = 4\cdot10^{-5}$, now $\Delta M/M = 4\cdot10^{-6}$); M(psi') = 3686.117 +- 0.012 +- 0.015). An experiment on the tau lepton mass measurement is now running aimed at the record accuracy.

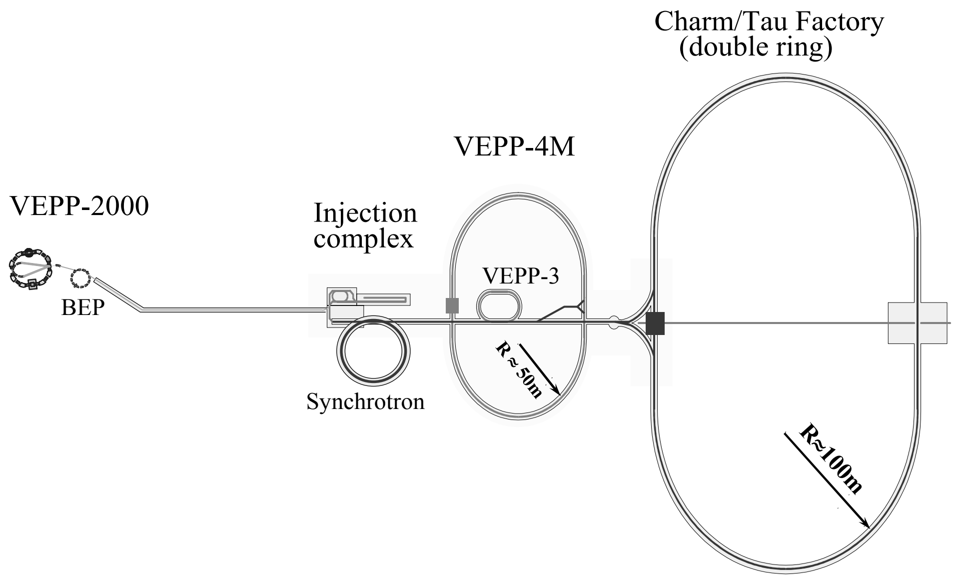


Figure 18. The Tau-Charm “Dream Factory” project (Novosibirsk, Russia).

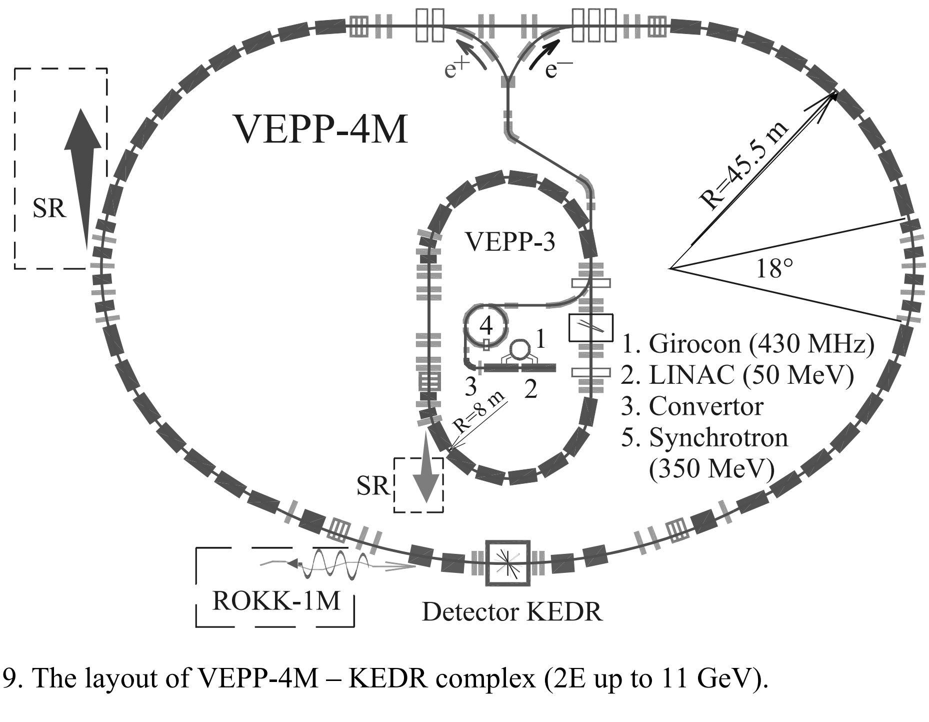


Figure 19. The layout of VEPP-4M – KEDR complex (2E up to 11 GeV).

4. Linear collider.

Already at the end of the seventies it was understood that further increase of e+e- collider energy can no longer be based on cyclic machines. For the first time, a physically self consistent proposal to reach several hundred GeV energies in a short pulse electron-positron linear collider with a several cm wavelength accelerating structure – the project VLEPP – was presented by the Novosibirsk group in 1978 (Figure 20). A decade later, SLAC reconstructed the existing 3 km linac with a 10 cm accelerating structure to create a single-pass collider with 50 GeV per beam (Figure 20). It was a very important achievement and big progress on the way to linear colliders.

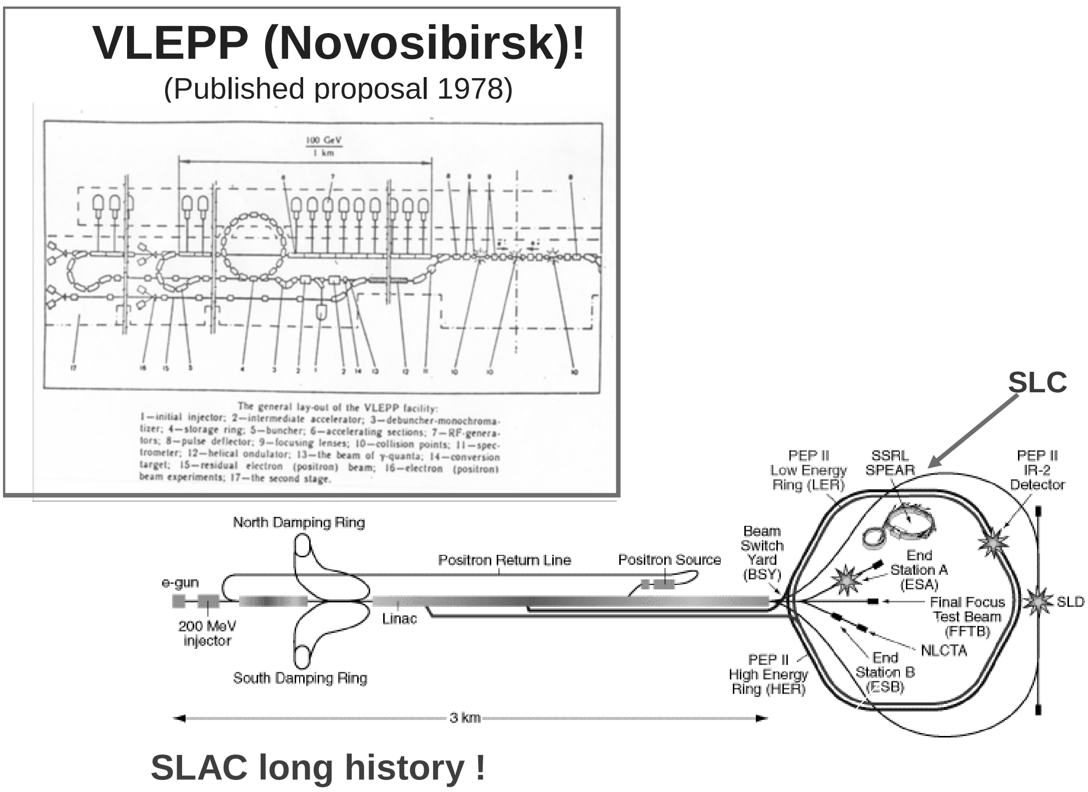


Figure 20. Some historical reminiscences.

Further development of linear colliders took place with the active competition of two approaches: short pulse normal conducting linacs (BINP, SLAC, KEK, …) and super-conducting linacs (mostly DESY). The aim was to reach as high as possible accelerating gradient in as cheap as possible linear accelerators, with preserving very low effective emittances of beams in highly reliable accelerators. All the labs joined their efforts and under guidance of ICFA developed main requirements and performance specification for International Linear Collider (ILC):

– Initial maximum energy of 500 GeV, operable over the range 200-500 GeV for physics running.
– Equivalent (scaled by 500 GeV/√s) integrated luminosity of 500 fb-1 for the first four years after commissioning.
– Ability to perform energy scans with minimal changeover times.
– Beam energy stability and precision of 0.1%.
– Capability of 80% electron beam polarization over the range 200-500 GeV.
– Two interaction regions, at least one of which allows a crossing angle enabling γγ collisions.
– Ability to operate at 90 GeV for calibration running.
– Machine upgradeable to approximately 1 TeV.

Achievements in superconducting RF technology were very impressive (Figure 21).

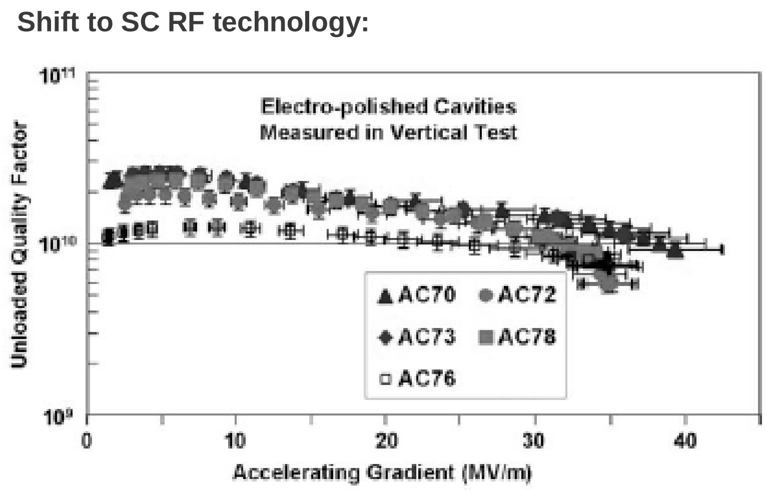


Figure 21. The results in accelerating gradient reached at DESY for multi-cell superconducting structures.

DESY Laboratory, in collaboration with many other laboratories, prepared a rather complete proposal for a linear collider (Figure 22), which included all the main aspects (beam physics, RF technology, cryo-engineering, and even geological studies of the Hamburg region). After several years of comparative studies, it was decided to choose the superconducting structures for ILC. It is the superconducting ILC which is accepted as the next Global Project. In a few years of joint R&D efforts technological details should be fixed, the site project should be chosen, and next the ILC construction will start.

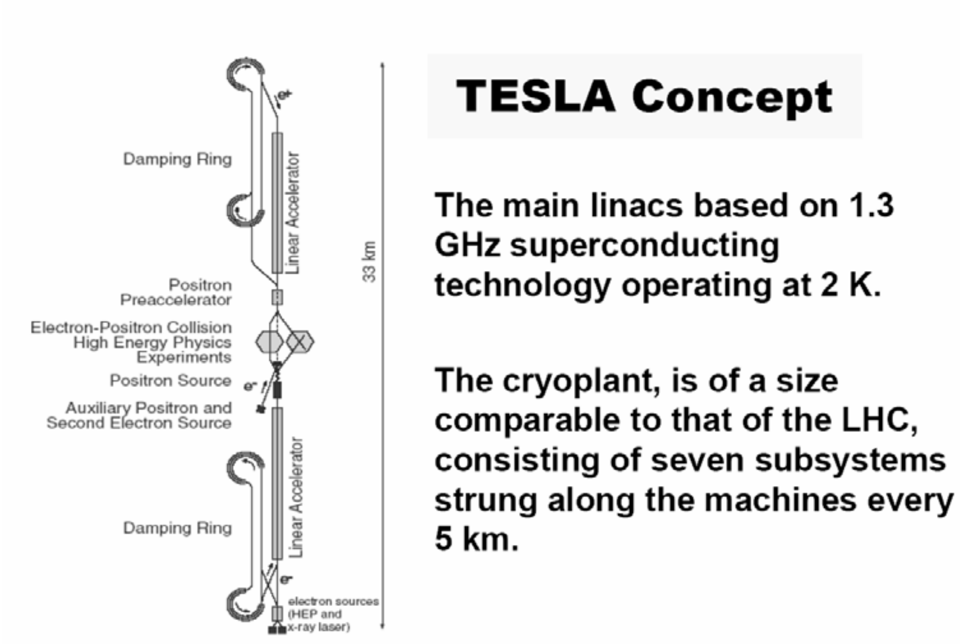


Figure 22. The schematic layout of DESY linear collider project.

The layouts currently considered are presented at Figure 23. Both options include not only e+ e$^-$ collisions, but photon-photon ones also.

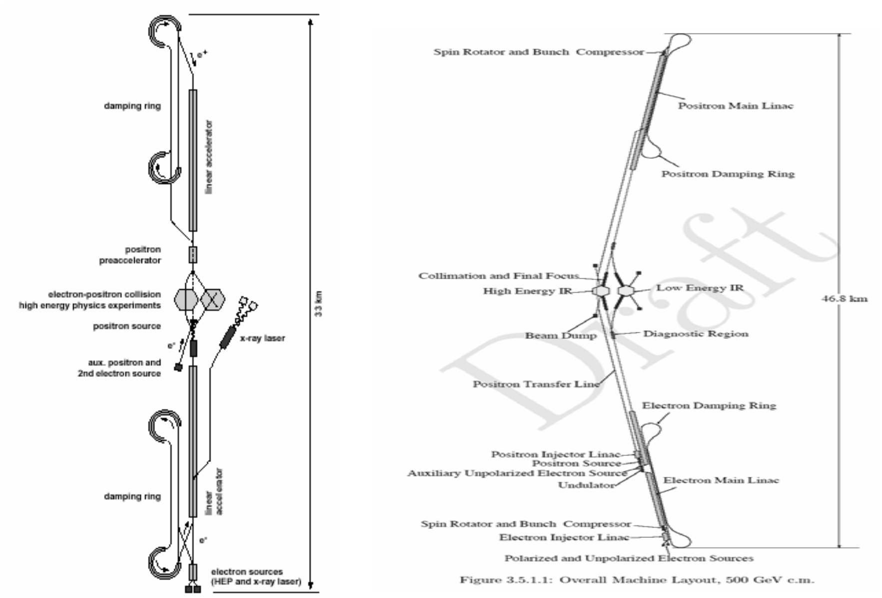


Figure 23. The layout options under consideration for ILC.

Now, more and more labs devote their activity to the ILC project, and construct, for example, different options of accelerating structures (Figures 24, 25).

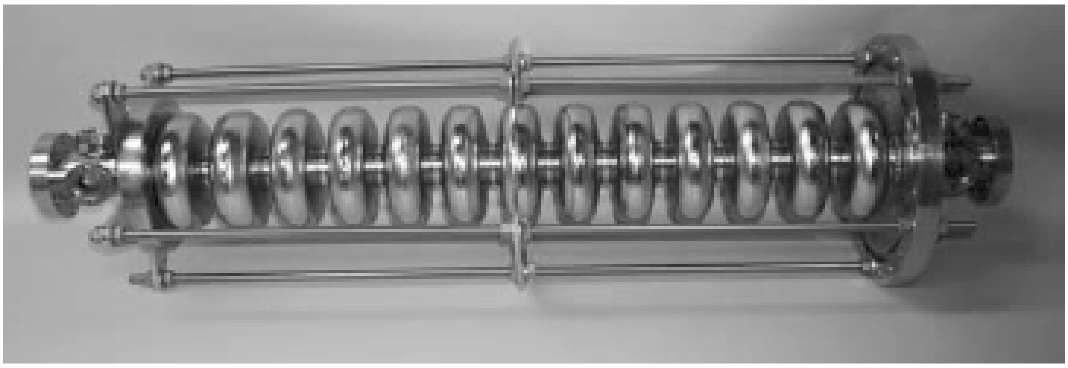


Figure 24. The FNAL SC accelerator structure option for ILC prototype.

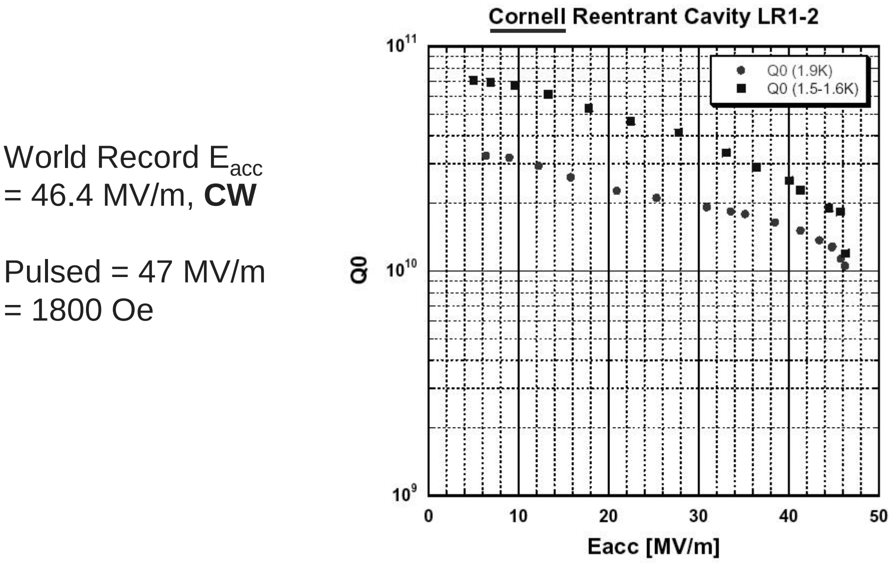


Figure 25. The current record accelerating gradient for ILC prototypes (Cornell).

But there is a lot of work in physics and technology on the way to the optimized ILC project. One example: the “full length” storage “rings” initially foreseen in the DESY proposal are far from optimal – stored beams are space charge limited. Maybe, the better solution would be several storage rings – atop each other in two “columns” – of comparable summary length.

The different approach to a linear collider, which is aimed to a few TeV energy range is under development at CERN (CLIC proposal, Figure 26).

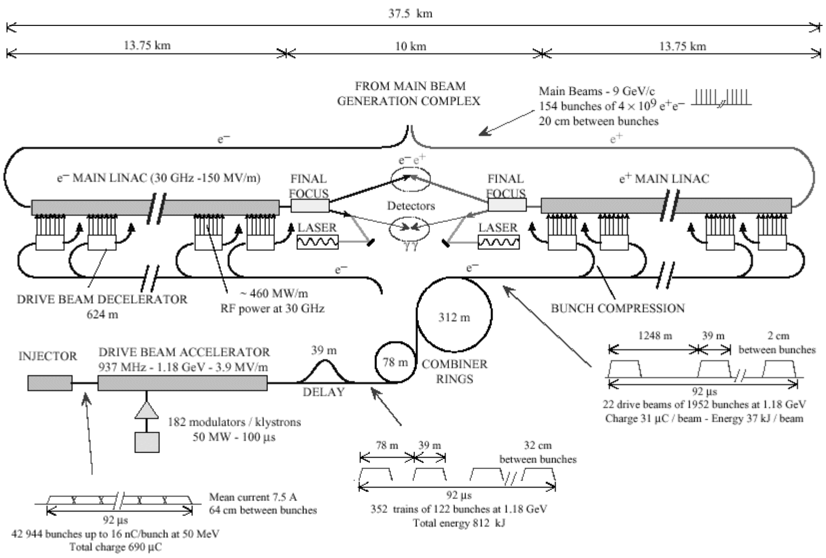


Figure 26. The CLIC collider project schematics (CERN).

4. Conclusion.

It is very unfortunate that I can not present in this brief review many very interesting and important components of the accelerator field activities, like accelerator based neutrino studies (conversion of direct beams, muon neutrino factories), muon collider R&D studies – the muon based prospects are very clear and very bright, and studies of prospects for extremely high gradient plasma linacs (both wake field and laser based).

The other misfortune is impossibility to give fair references even for main contributions in the field. The people interested can address to the appropriate reviews at ICFA Seminars (the last were at CERN in 2002 and in Korea in 2005), and to reviews at main HEP and Accelerator Conferences.