Test Beams

1. Introduction

Given the GDE's accelerator design schedule and the fact that it is ideal to have detector CDR and TDR in synch with the accelerator, the detector R&D efforts will intensify through the end of this decade and early in the next decade. These R&D efforts will then naturally be followed by global detector design and calibration processes. For these reasons, the demand on beam test facilities will grow significantly according to ILC detector time line. More specifically, the next decade or so can be categorized into three different periods:

- Present – ~2010: Detector technology R&D phase
  - Detector technology research and development
  - Global ILC detector concept development and design (there are a total of 4 concepts being developed)
  - Choice of technologies to be used in various ILC detector concepts
  - CDR for ILC detector concepts by 2010, according to GDE schedule
- ~2010 – ~2017: Global ILC detector design and selection phase and the ILC detector construction and calibration phase
  - Remaining performance testing of ILC detector designs
  - Prototype testing of the selected ILC detectors
  - Calibration of the ILC detectors
  - Construction of the detectors
- 2017 and on: ILC Physics Era

Figure 1 shows this rough timeline of the ILC detector development in a graphical manner. Based on the above rough schedule, we anticipate a rich program of detector beam tests for the next 10 – 15 years.

Since the technology choices for ILC global detector concepts must be by the end of this decade, all the detector R&D groups require beams for characterization and

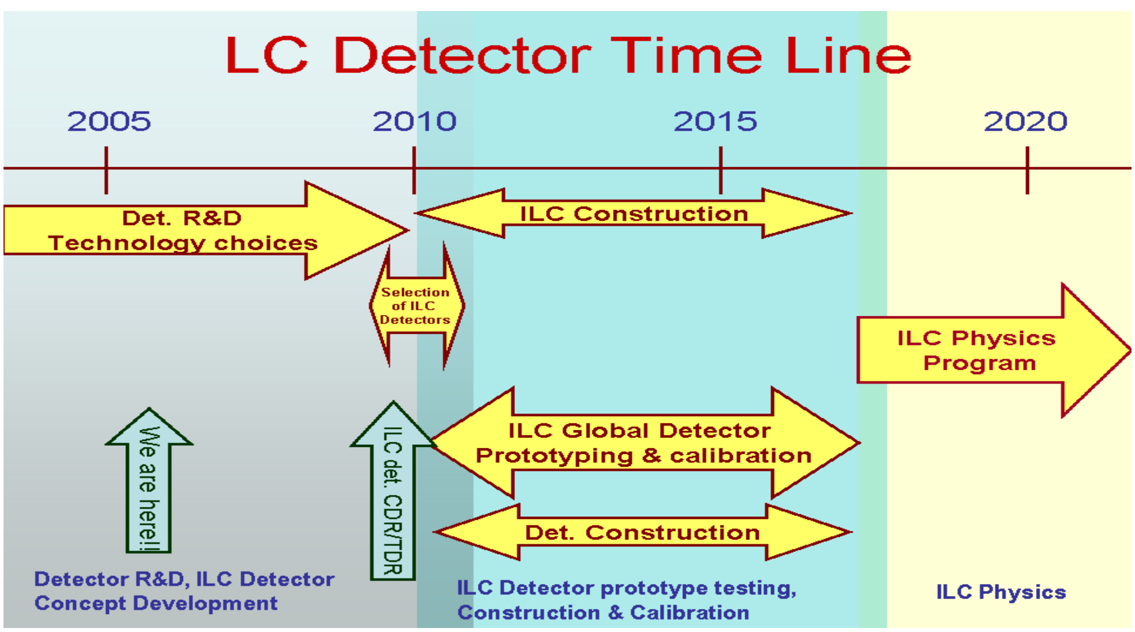

Figure 1 Rough timeline for ILC and its detector development.

performance test of the detectors. These beam tests will have to provide sufficient information to global ILC detector concept groups to complete their CDR and TDR by the end of this decade.

Vertex, tracking and muon detector groups are gearing up their preparation for beam test in the next 2 – 3 years which would meet the schedule for global ILC community of detector selection time line in 2010 as shown in Fig. 1. The current status, requirements and plans presented in this section are based on the latest information obtained at the ALCPG workshop held in July 2006 at the University of British Columbia and through the recent e–mail communication with WWS sub-detector working group contact persons.

In this spirit, this section provides the requirements for each detector subsystem, the current activities and the plans for beam tests through the year 2010, at which time significant decisions in detector technologies are expected.

1. Beam Instrumentation and Machine-Detector Interface System

Luminosity and energy reach are the key parameters for the ILC. The ILC's capability for precision measurements, though, distinguishes it from the LHC. The ILC physics program requires precise IP Beam Instrumentation for measurements of i) luminosity and the luminosity spectrum, ii) beam energy and beam energy spread, iii) beam polarization, and iv) electron id at small polar angles.[1 – 3] The luminosity will be measured using Bhabha events. A precise and compact calorimeter, LUMICAL, in the very forward direction at polar angles of 40-120mrad will be used for this.

At smaller polar angles of 5-40 mrad, excellent electron identification is required in the BEAMCAL detector to veto copious 2-photon events that present a serious background to SUSY searches. BEAMCAL resides in a difficult radiation environment and is hit by a large flux of low energy e^+e^- pairs, depositing 10's of TeV per bunch crossing in the detector that can be used for fast luminosity tuning. The determination of particle masses, e.g. for the Higgs boson or top-quark, requires a precise determination of the beam energy to 100 parts-per-million (ppm).

Beam energy spectrometers utilizing precise beam position monitors (BPMs) and synchrotron stripe detectors are being designed to achieve this. The synchrotron stripe detectors also have capability to measure the beam energy spread. Very precise parity-violating asymmetry measurements at the ILC allow sensitive probes for new physics, and require polarimetry measurements to better than 0.25%. Compton polarimeters are being designed to achieve this.

There is a large community actively engaged in R&D for IP Beam Instrumentation. This includes both detailed design and test beam activities, which are vital to validate the designs. An overview of IPBI test beam activities follows.

The FCAL collaboration [4] is leading the effort on very forward region calorimetry for the LUMICAL and BEAMCAL detectors. Recent test beam activities have focused on radiation damage studies for potential BEAMCAL sensors, such as silicon or diamond, at the DALINAC accelerator at the TU Darmstadt. DALINAC provides a 10 MeV electron beam for these studies, similar to the average energy of shower electrons in BEAMCAL. These radiation damage and sensor studies are continuing. Future BEAMCAL test beam studies should also include measurements of electron id efficiency and shower fluctuations for high energy multi-GeV electrons.

At SLAC's End Station A a program [5] to test components for the Beam Delivery System and Interaction Region has started. The ESA beam energy is 28.5 GeV and has similar bunch charge, bunch length, and bunch energy spread as planned for ILC. Of particular interest are prototype energy spectrometers. BPM and Synchrotron Stripe energy spectrometers are both being studied in a common 4-magnet chicane. The ESA program should continue through FY08. Beyond FY08, it is uncertain whether the ESA facility will be available for continued energy spectrometer studies. Another test facility at SLAC, SABER, should become available after 2008 with similar beam parameter capabilities as currently available in ESA. SABER could be useful for a number of ILC beam tests, but accommodating energy spectrometer prototypes will be difficult due to the limited space and infrastructure available.

A wide research program for beam instrumentation is carried out at the ATF [6] at KEK. The ATF delivers an electron beam of 1.3 GeV and micron-sized bunches. Three bunches with 150 ns or two bunches with 300 ns between bunches can be delivered as a train. High resolution nano-BPMs are being tested there that will be important for the BPM energy spectrometer. Laser wire diagnostics are also being tested and have potential use for beam energy spread measurements. The ATF2 project will extend the extraction beamline of ATF to a final focus beamline prototype for the ILC. The goal is to achieve a beam size of 35 nm and nanometer stability simultaneously. Development of nano-BPMs and laserwires will continue at ATF2 in 2008 and beyond. Laserwires are also in use at PETRA and will be further developed there for PETRA III after 2008.

2. Vertex Detectors

Vertex detector R&D using fine pixel CCDs (FPCCD) is being done in Japan. Study of basic properties (charge spread, signal-to-noise ratio, spatial resolution, etc.) of FPCCD will be done using 3 GeV electron test beam at KEK after 2007. Electron irradiation for the study of radiation damage will be done by 140 MeV electron beam at Laboratory of Nuclear Science at Tohoku University in 2007 - 2009.

Vertex R&D groups from the American region who have expressed interest in vertex detector test beams include those studying 3D and SOI technology (Fermilab, Purdue, Cornell), CMOS and SOI sensors (LBL), Chronopixels (Yale, Oregon) and CAP CMOS sensors (Hawaii, KEK). The American region vertex test beam work will be focused on the Fermilab MTest beam. The Fermilab and CERN test beams are the only high energy beams available for studies where minimizing multiple scattering is important.

The LBL group has submitted an LCRD proposal for a replica of the EUDET telescope to be installed on the Fermilab's Meson Test Beam Facility (MTBF) with a target date of end of 2007 for making it available to users. The LBNL group is currently testing a pilot four-layered CMOS pixel telescope on the LBNL ALS 1.5 GeV beamline. The telescope will be used for systematic studies of the performance of the chips being developed at LBNL and it may be available to outside users on request.

LBL will need approximately one week of beam time at a >50 GeV pion beam to minimize multiple scattering effect in 2007 and probably two periods of one week each in 2008 and 2009. This period will be used to determine the sensor resolution and the cluster characterization for particle tracks in absence of multiple scattering. In 2008 and 2009 they also plan to test full prototype ladders equipped with thinned sensors. They will perform tests with lower energy electrons as well as pair response characterization, proton and neutron irradiation on site at LBNL

Fermilab/Purdue/Cornell group expects to begin test beam work in the spring of 2007, testing 50-100 micron thick, edgeless detectors bonded to BTeV FPIX readout chips. They will study charge collection characteristics, especially near the edges. Testing of 3D chips bonded to the thinned sensors should begin in the summer. Resolution of the thinned, 20 micron pitch sensors as a function of incident angle will be studied. They expect ~3 weeks of beam for each of these phases. This level of activity (3 weeks/quarter) should continue through 2010. Irradiation studies will probably be performed at the Indiana cyclotron.

The CAP program expects 2 one week periods in 2007 and perhaps 1 two week and 1 one weeks period for larger statistics with full scale sensors in 2008 and 2009. The Chronopixel group also plans to utilize the Fermilab's test beam.

The LCFI collaboration plans to test their CCDs in the DESY test beam and may also utilize the Fermilab beam. This is expected to be a continuing program.

It is expected that many of these programs will share much of the infrastructure and electronics associated with the Fermilab beam and detectors and can be organized as facets of an overall vertex test beam effort.

The DEPFET program is in a prototype phase. This group conducted beam test at CERN for two periods of one week in 2006 and will be investigating new structures during 2007 and 2008. The group will focus on detailed charge collection and position resolutions measurements as function of the in-pixel position. This requires a lot of statistics. The program aims to have 2 two week periods of high energy (>100GeV) test beams per year, which is accessible at CERN and accessible only for 120 GeV protons at Fermilab.

Utilizing CERN test beam is at the moment difficult for DEPFET group since the ILC is not a CERN recognized activity, although the CALICE collaboration has been successful in performing their beam tests at CERN. After the completion of the high energy beam program, the group will have short beam tests at DESY. However, due to the low beam energy the precision is not sufficient for their high-precision studies. Starting 2009 the group will have more final prototypes: thinned sensors, full size, final readout electronics, etc. To characterize them fully the group will need two weeks of high energy beams.

The DEPFET collaboration has a significant presence in the EUDET (European Detector group) program, which aims to build a high precision beam telescope at DESY. As soon as this is operational, they aim to move some of our test beam activities to DESY.

3. Tracking Detectors

At the time of this report, North American groups working on R&D towards the developing of tracking for the ILC are focusing on two general areas: TPC-based gaseous tracking and silicon micro-strips. European and Asian counterparts are similarly focused, and cooperation between regions is increasing, although there is somewhat greater collaboration with the European than with the Asian community.

In the case of R&D towards the development of a high-precision TPC, most of the work is being done in close collaboration with European groups. Most of the anticipated test-beam needs are thus incorporated in the EUDET R&D plans, and are expected to be met at DESY over the next two to four years. There will also be a need for approximately one month of high-energy beam to study two-track separation resolution; current plans are to perform these studies at FNAL within the next two years.

There is a Large Prototpye (LP) TPC R&D program which is being geared up to run at the EUDET facility. In this case, "large" means about 1m in length. Several "small", ca. 30cm, prototypes have been built and tested in the last few years by several groups. The EUDET facility will be located in a 6 GeV electron beam at DESY. For these initial efforts 6 GeV electrons, combined with cosmic ray tests, will be sufficient, but ultimately higher momenta test beams will be needed. The LP is foreseen to start taking data the latter part of 2007, depending on when the fieldcage and electronics are ready and on how fast the endplates can be developed.

Several designs are considered for the endplates: a GEM solution, Micromegas and a SiTPC solution. The testing and data taking of the GEM and Micromegas would last until the end of 2008, at which time some SiTPC prototypes are supposed to be ready. Therefore, DESY will support at least 3 years of LP work. Testing of higher momenta would require a move to Fermilab or CERN. In principle it has been said that the EUDET facility can be transported to Fermilab or CERN, but how practical this would be is unclear at the moment. The requirements for TPC tests at Fermilab would be tagged beams of particles of varying momenta – from 4 GeV or so (to match the DESY results) up to 120 GeV. The TPC tests require a high field, large aperture magnet.

The somewhat smaller silicon micro-strip detector community also envisions collaborative activity with the European and Asian communities, under the umbrella of the SiLC (Silicon for the Linear Collider) group. Over the next three to four years, this group anticipates the use of 1-2 months of high-energy test beam at either or both of FNAL and CERN, as well as some more limited use of test beam time at DESY and SLAC. Independently, the SiD silicon tracker group is planning to perform beam tests for their prototypes starting late 2007 at Fermilab.

4. Calorimeters

As a precision instrument, the ILC detector calorimeter will be used to measure jets from decays of vector bosons and heavy particles, such as top, Higgs, etc. It will be essential to identify the presence of a Z or W vector boson by its hadronic decay mode into two jets. This suggests a di-jet mass resolution of ~3 GeV or, equivalently, a jet energy resolution $\sigma/E \sim 30\%/\sqrt{E}$. None of the existing collider detectors has been able to achieve this level of precision and therefore the testing of alternate possibilities for detector solutions in a test beam is of utmost importance.

Given the critical role of the sub-detector system, the complexity of its development to meet the stringent requirements for ILC physics, and the time required for the development, calorimeter groups dominate the need for beam tests. There are many calorimeter activities currently on–going. Several North American groups, European groups and Asian groups are preparing for beam test experiments in the next 2 – 4 years in the context of the four ILC detector concept studies; SiD, LDC, GLD and the forth concept.

Tests of several concepts for the electromagnetic calorimeter (ECAL), with emphasis on the analog energy measurement of electromagnetic showers, are necessary. Here the challenge is to minimize the lateral extent of showers with a dense ECAL, as required for the optimal use of particle flow algorithms (PFA), while preserving good energy resolution. In addition, novel electronics and schemes for the readout of the active media of these calorimeters need to be tested in a beam environment.

For the hadronic calorimeter (HCAL), the requirement of fine grain segmentation has prompted consideration of digital as well as analog readout schemes for several sensitive gap technology choices. The development of a digital HCAL is fairly new and requires standalone testing to validate the unique (to calorimetry) technologies under consideration. Gas detectors (Resistive Plate Chambers and Gas Electron Multipliers) are being explored as active medium. The proposed analog HCAL utilizes scintillator tiles as small as 3 x 3 cm^2 together with a novel electronic readout device mounted directly on the side of the tile.

4.1 Requirements

To validate Monte Carlo models used to develop the Particle Flow Algorithms (PFAs), the entire calorimeter, consisting of ECAL and HCAL, needs to be tested in a wide variety of test beam configurations. The requirements span the range of particle types (electrons, pions, muons, protons), momenta (1 GeV-120 GeV) and several angles of incidence and wide range of rates. These activities can also benefit from the availability of momentum tagged neutral hadron beams which would provide the means of ultimately testing PFA. In addition, as an alternative to the use of MC models, the test beam data will be used to generate extensive libraries of hadronic showers. Collecting a comprehensive data set with unprecedented granularity will provide a reference for further improvement of hadronic shower modeling that is of paramount importance for the design of a detector for the ILC.

Since there are so many beam particle species that need to be tested to understand calorimetery at the required level, calorimeter R&D effectively determines the specifications of any ILC test beam facility. In addition, even prototype detectors for calorimetry can have over 400,000 readout channels and put a burden on the infrastructure of any test beam facility. The ILC calorimeter and muon detector community has summarized the requirements for test beams in a Fermilab technical document at the URL: http://lss.fnal.gov/archive/test-tm/2000/fermilab-tm-2291.shtml.

4.2 Current Activities and Future Plans

The RPC digital calorimeter (DHCAL) group in the US has performed a chamber characteristics experiment at MTBF (FNAL–T955) in Feb. 2006 before Fermilab Tevatron shutdown for DØ and CDF detector upgrades. They tested 3 RPC chambers with 120GeV/c proton beams. They took a total of six hours of data at the varying trigger rate from 70 – 5000 Hz. This group plans to perform a “Slice test” in spring 2007 after the MTBF upgrade using the close-to-final version of ANL-FNAL joint developed DCAL digital readout chip. This will then be followed by a full scale test using a 40 layer, $1m^3$ prototype in late 2007, as part of the CALICE collaboration beam test effort. While the $1m^3$ prototype test depends heavily on funding, the recent news in the U.S. on additional supplemental funds makes the prospect for the $1m^3$ prototype brighter.

The GEM DHCAL group also has performed a beam exposure experiment using a prototype chamber they built with $30cm \times 30cm$ GEM foils jointly developed with 3M Inc. The group took the chamber to Korea and exposed it to a low energy (10MeV) high intensity, high power electron beam at the Korean Atomic Energy Research Institute irradiation facility. The total exposure to beam was 2×10^{12} electrons per readout pad.

This corresponds to a total accumulated charge of $1.6\times10^{-2}\,\mathrm{mC/mm^2}$. Even though the beam was such a high intensity, no physical or functional damage to the chamber and to the GEM foils have been observed. This group plans to perform a beam test for their chamber characteristic in early 2007 after the upgrade of Fermilab's MTBF. This group is working jointly with the RPC DHCAL group for the slice test with DCAL digital readout chip planned in spring 2007. This will then be followed by another, independent slice test with SLAC's KPix analog readout chip in spring 2007. Both the RPC and GEM DHCAL groups are jointly working on preparing for $1\mathrm{m}^3$ prototype beam tests. The GEM DHCAL group plans to perform its full scale beam test with $1\mathrm{m}^3$ prototype in 2008 as part of the CALICE collaboration's beam test effort.

At the time of writing this report, the EU contingent of the CALICE collaboration is wrapping up the last of the three separate periods of beam tests at CERN's H6 beam line, using full depth (30 layers), half lateral coverage of their Si-W ECAL and 23 layers of scintillator-Steel AHCAL together with the full depth (16 layers) readout scintillator-steel tail-catcher (TCMT).

The Si-W ECAL and the scintillator-steel AHCAL have been exposed to positron beams of momentum up to 6GeV/c at DESY from late 2005 to early 2006, using the full CALICE DAQ system. One sensitive layer of the TCMT was exposed to 3 GeV/c electron beams at DESY in October 2005. The module was then exposed to 16 GeV/c pions and muons as well as 120GeV/c protons at Fermilab's MTBF in early 2006 (FNAL–T957).

The EU contingent of the CALICE collaboration currently plans to request additional two periods of beam for two weeks each at CERN's H6 beam line in summer 2007 for the completion of detector commissioning and high energy hadron beam test runs. The group is planning to move entire detector system to Fermilab in September 2007 for a very low to medium energy hadron and electron beam exposure, long-term detector performance and combined PFA shower shape runs. The group will also exploit the possibility of momentum tagged neutral hadron beams at the Meson Center beam line at Fermilab. This system, including its movable mechanical support, is going to be shared with both the DHCAL groups and the Asian scintillator calorimeter groups for their combined performance tests.

Asian scintillator-W ECAL group will test a prototype at DESY in February-March 2007. The strip length is 4.5 cm, which is much shorter than 20 cm given in the previously submitted planning document, FNAL-TM-2291. No small tile scintillator will be used. The test module will then be upgraded and tested at Femilab in 2007 or 2008. A hadron calorimeter test module will also be constructed with scintillator strips and tiles, probably in collaboration with the CALICE AHCAL group. This prototype module will be tested at Fermilab in 2009 and 2010.

Recently, Korean Silicon Tungsten ECAL group and part of the Asian Scintillator-based calorimeter (GLDCAL) group (Kobe and Shinshu) have joined the CALICE collaboration. In addition, the following universities have joined the GLDCAL: Tsukuba University (S. Kim), Niigata University (H. Miyata) and University of Tokyo (S. Yamashita). More detailed plans for the calorimeter test beam activities in Asia can be found in the presentation: http://atlas.shinshu-u.ac.jp/jlc/conf/calice-sep-06.pdf.

Finally, the crystal-based calorimeter group in the forth detector concept plans a beam test but its timeline is not quite clear yet.

4. Muon Detectors

The FNAL, Indiana University, Wayne State University and the Notre Dame University jointly constructed a layer of scintillation counter and completed its initial beam test run at MTBF (FNAL–T956). The group expects to continue to test strip-scintillator detectors in MTBF when the beam resumes in early 2007 after an upgrade. The group plans to test strip-scintillator detectors equipped with multi-pixel photon detectors, using Minerva electronics. The group's expected use of the beam will consist of a number of two week periods during 2007. In the second half of 2007, the group expects to test some new planes and perhaps one full-scale prototype 2.7m (H) X 5.7m (W). Since the muon counter can concurrently run with the calorimeters, these runs do not necessarily present a conflict with the previously described calorimeter beam tests.

In addition, there may be a desire to test RPC chamber prototypes in MTBF in the future after initial tests are done at SLAC. One of the objectives is to measure their beam rate capability, which might require high intensity beam. However, details of this beam test are not yet well known.

In Asian, it is anticipated that the GLD Muon effort will focus on further tests of MPPCs in Japan and probably with strip scintillator detectors in CERN and DESY in 2007. In 2008 and beyond they may want to use the Fermilab facility. The size or scope of detectors that they would bring to Fermilab for testing was not known as of June 2006.

In Europe, based on discussions with Marcello Piccolo (INFN/Frascati) and Giovanni Pauletta (INFN Udine/Trieste), there is interest in testing Italian SiPMs with scintillator. Very preliminary results on two SiPMs were obtained during our September running. It is expected that more tests will follow in 2007. Giovanni and Marcello can update this expected use of test beam.

5. Conclusions

Based on what we have learned at the ALCPG workshop and the rough ILC detector timeline laid out earlier in the report, Fig. 2 presents a perspective view of the upcoming beam test activities. As can be seen clearly in the picture, due to the timeline driven by the ILC design and construction, the technology choices for detector concept studies must ideally be made before the end of the decade. Thus, many detector groups are planning their beam tests in late 2007 – 2009. However, the available facilities to meet all the demands are currently limited to Fermilab's MTBF and MC beam lines and CERN's SPS and PS beam lines. Given the fact that the LHC commissioning will be the highest priority at CERN for the next 1 – 2 years, it is not quite clear what beam test facilities will be available at CERN during the critical time period. This not only presents the urgent need for more facilities but also requires better coordination between different detector development projects.

In order to assess these needs for the next several years and provide this information to facility managers, users and to the ILC Worldwide Study for a viable beam test road-map, the WWS Test Beam working group is holding an ILC Detector Test Beam Workshop in January 17 – 19, 2007, hosted by Fermilab.

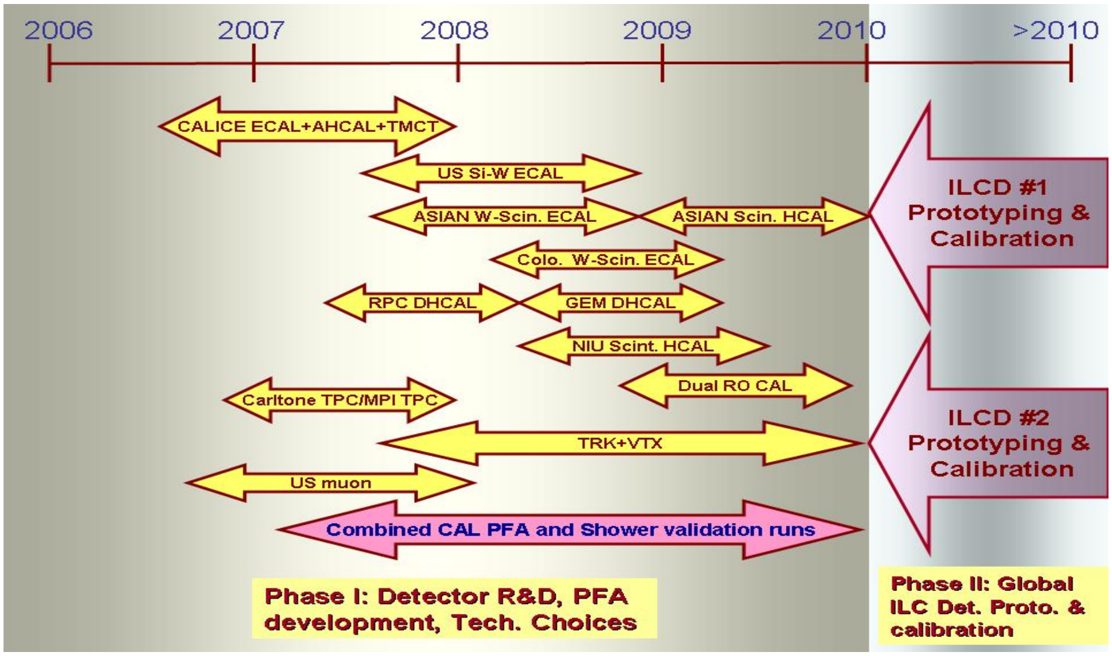

Figure 2 Timeline of expected beam tests activities for ILC detector development

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