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R&D for the International Linear Collider

Report by the R&D Board

April 2007

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1 Introduction

The document addresses high priority R&D items for the ILC. The document reflects the status of knowledge and understanding of ILC R&D in April 2007 when the information was gathered for the meeting of the Machine Advisory Committee for the ILC.

The items included are considered to have a major impact on the performance or the cost of the ILC. The implementation of emerging solutions may affect the layout of the ILC. Such changes may be absorbed in the engineering plans for the ILC if they are announced sufficiently early. When the time to achieve the required research results extends beyond the EDR phase ways of risk mitigation are outlined.

The transition to the engineering is outlined when necessary.

The document makes no attempt to list the numerous research activities in general

2 Global R&D strategy

Responsible: B Willis

2.1 *Assumptions on time lines*

Define baseline

2007 – 2009	EDR phase
2010 – 2011	Approval
2012 – 2018	Construction
2019 – 2020	Commissioning

2.2 *Risk mitigation*

2.3 *Treatment of alternative solutions*

We have to define what this is. Is it a fixed delay over the baseline program? When is the delay incurred – most likely during the approval phase? How can this time be used?

3 Report from the task forces

3.1 S0/S1

The S0/S1 Task force implemented by the ILC R&D Board on request of the ILC EC:

- The RDB is asked to set up a Task Force to carry out a closely coordinated global execution of the work leading to the achievement of the accelerating gradient specified in the ILC Baseline.
- A definition of the goals for the cavity performance in terms of gradient and yield and a plan for achieving them should be proposed by this group, which should take account of the global resources available and how they may be used most rapidly and efficiently.
- The accelerating gradient performance and yield should be specified both for an individual 9-cell cavity and for an individual cryomodule, and the plan should cover the demonstration of this performance in both cases.
- The GDE will facilitate the coordination at the global level to achieve this vital goal as soon as possible.

The main assumption of the task force is that the basic recipe for the cavity treatment to achieve highest gradients is known: Electropolishing (EP), High Pressure Water Rinse (HPR) and In-situ Bakeout.

Nonetheless, the results on the cavity gradients are not fully reproducible yet. Field emission is a major problem limiting the cavity performance. Some surface contaminants have been identified e.g. sulphurus which are evidently produced in long EP processes. Thus fine-tuning the surface preparation parameters is needed to specifically remove those contaminants (see single-cell program).

Two other aspects need to be considered defining a inclusive R&D plan: Firstly, new cavity vendors are being sought. Performance limitations due to their learning curve need to be singled out. It is needed separate the surface preparation process from the potential fabrication errors by new vendors. Secondly, a statistically meaningful sample of cavities and RF tests for the overall cavity fabrication and preparation is needed. Therefore, a reasonably large number of cavities from several regions in a production-like mode must be available eventually.

The R&D goals have been defined by the task force:

S0 Ultimate Goal

- The cavity performance is influenced by the fabrication process and surface preparation process.
    - Effort in all the regions to qualify further vendors for cavities
- Preparation process and vertical test yield for 35 MV/m at Q0 = 1010 should be greater than 90% for a sufficiently large number (greater than 100) of preparation and test cycles.
    - There should be a complete description of the preparation and testing processes (reproducibility in other places). The time scale should be commensurate with the completion of the EDR (middle of 2009).
- After a viable cavity process has been determined through a series of preparations and vertical tests on a significant number of cavities, achieve 35 MV/m at Q0 = 1010 in a sufficiently large final sample (greater than 30) of nine-cell cavities in the low-power vertical dewar testing in a production-like operation e.g. all cavities get the same treatment.

    - The yield for the number of successful cavities of the final production batch should be larger than 80% in the first test. After re-processing the 20 % underperforming cavities the yield should go up to 95%. This is consistent with the assumption in the RDR costing exercise.
    - For this ultimate experiment:
        - Only qualified vendors and qualified preparation infrastructure
        - Should take into account further results from parallel R&D effort (single-cell and tight-loop – see below)
        - Will start end 2009 and results would probably be post-EDR
        - Number of cavities should be A x 30 where A is greater or equal to 1

S1 Ultimate goal

- Achieve 31.5 MV/m at a Q0=1010 as operational gradient as specified in the BCD in more than one module of 8 cavities including e.g. fast tuner operation and other features that could affect gradient performance
- All cavities built into modules perform at 31.5 MV/m including enough overhead as described in the BCD. The cavities accepted in the low-power test should achieve 35 MV/m at Q0 = 1010 with a yield as described in the S0 definition (80% after first test, 95% after re-preparation).
- At least three modules should achieve this performance. This could include re-assemblies of cryostats (e.g. exchange of cavities).
- It does not need to be final module design. An operation for a few weeks should be performed.

S1 Intermediate goal

- Achieve 31.5 MV/m average operational accelerating gradient in a single cryomodule as a proof-of- existence. In case of cavities performing below the average, this could be achieved by tweaking the RF distribution accordingly.

3.1.1 Ideal plan

S0 – Cavity Performance in vertical test

Three main activities have been identified which are closely coupled and partially progressing in parallel, which is needed to separate cavity preparation and production issues. In addition, this separation will allow tracking of the progress of the task force plan.

- Single-cell R&D
    - Establishing more reliable final preparation parameters
    - Focus on the final rinse after EP before HPR:
- Candidate processes are Ultrasound, Short EP (or HF rinse), H2O2
    - Most efficient way for comparing preparation recipes.
    - Program is underway (major effort at KEK) with very promising results
- Tight-loop
    - International multi-cell cavity exchange
    - 1st round

        - Comparison of regional differences in preparation and testing
    - 2nd round
        - Use single-cell results and implement on multi-cells
        - Production-like effort
    - Monitor ongoing productions
        - Esp. XFEL preparation
    - Use qualified and new vendors
    - Use improved preparation process for an ultimate batch of cavities

S1 – Module performance

For the demonstration of the module performance first of all the ongoing effort on module production will be monitored. A clear improvement of the average gradient has been demonstrated. The best operational gradient so far is 28.5 MV/m.

The evaluation of a cavity production model and the module production are consistent with both having enough cavities and cryostats available. For the S1 effort re-population of cryostats with improved cavities is an option. This reduces the cost significantly. Generally, the cost for cryostats is contained within the S2 efforts. Nonetheless, there is an issue with conflicting interests of module gradient test (S1) and full beam tests (S2) as modules in accelerator installations cannot frequently exchanged to install improved cavities.

Nonetheless, the lead-time for the module demonstration is long especially because a higher yield will be demonstrated only in 2008/2009. As a demonstration of the proof-of-principle as the intermediate goal is desirable currently a fast-track module with cavities from several regions is being discussed. A new effort in collaboration would be needed to facilitate this.

S0/S1: Major Milestones until 2009

- Tight-loop tests
    - Ongoing cavity exchange with first cavities have been identified
- A third of first loop tests will be finished by end of 2007
    - First loop finished by mid 2008
    - Second loop by beginning/mid 2009
- Production-like will have tested
    - ACCEL cavities in the US
- Will have tested the AES cavities also
    - 6 (10) cavities at Japan
- New vendors
    - 15 ACCEL TESLA-short
    - 6th production at DESY
- S1
    - Tests of M7, M8 (FNAL), M9, STF Phase1

  - Acquisition of further modules
- 2 in 2008 (1st US, 1st T4CM)
- 2 in 2009 (2nd and 3rd T4CM)
  - M10 (or one US module) as a dream module

3.1.2 Resources

Impact on total project cost

To put the resources into perspective an estimate of the impact on the whole ILC project could be made. The question is: What is the penalty for taking a cavity performance distribution of today?

The main effect – as long as a variety of gradients can be accommodated in the machine - on the total project cost would be a lower average gradient (following C. Adolphsen):

- Assume a distribution of gradients of a current cavity production with a large spread
  - average 28 MV/m ranging from 22-34 MV/m, flat distribution e.g. DESY 4th production
- tweak power distribution
- reduce overhead a bit
  - due to a small loss in the efficiency of the RF unit
- increases linac length by 12.5 %
- yields 7% increase of total project cost ~500 MILCU

A second effect on the total project cost is associated to width of the cavity gradient distribution. If one calculates the precision on ‚faulty‘ cavities, one gets:

- N= number of cavities in a production-like effort
  - Cavities are from one manufacturer and processed once or twice
- Take delta e = sqrt(e*(1-e)/N) and calculate cost increase for the project
  - if N=100, e=20% then delta e = 4 %
- thus worst case need 4% more cavities
- 30 MILCU
  - if N=60, e=20% then delta e= 5.1 %
- 38 MILCU
  - if N=30, e=20% then delta e= 7,3 %
- 54 MILCU
  - This should be probed by a final batch of N cavities
- Time-line is probably post-EDR
- N is a cost issues

Estimatation of R&D cost

It is acknowledged that the cavity production is an expensive R&D item with significant lead times. Nonetheless, it is mandatory to have a continuing flow of smaller production batches of cavities as this allows to continuously improve processes and quality control measures. In addition, these will be used for estimation of final batch size of the ultimate cavity batch.

For an estimation of the R&D cost the task force developed three scenarios for cavity productions which takes into account existing plans in the regions and makes certain assumptions about the planning due to available resources (funding levels).

Scenarios for Cavity Production

- Pessimistic case
    - EU : ‚only‘ XFEL project preparation and limit (re-)processing to XFEL gradient (~28 MV/m)[1]
    - Flat budgets in US and Japan
- Realistic scenario
    - EU: XFEL as above: 30 additional cavities from EU FP7 with ILC-type processing
    - Japan: Flat budget
    - US: Minor increase in cavity numbers
- Optimistic scenario
    - EU: As above (XFEL + EU), Additional high-gradient program at DESY
    - Japan: flat (+20% increase in cavities)
    - US: roughly double number of cavities in 2009 to 60

For the estimation of the cost of these scenarios the task force calculated the fabrication cost and one process cycle for the production batches. For each processing 30 k$ including labor are taken. A number of re-preparation cycles are included (20%) for the full cost estimate. This assumes the existence of cavity preparation infrastructure, as infrastructure development is not considered as part of S0.

To the production-like effort calculated in Table 1, the process cost for the tight-loop is added. For the roughly 100 processes (81 first loop, 27+ second loop) this amounts to about 3.5 M$. The final major cost item is the batch for the ultimate goal demonstration. Currently 30 cavities with processing are assumed which corresponds to roughly 3 M$.

Table 1: Cost associated with the production efforts in the funding scenarios described in the text.

		KEK			US				EU						
		2007	2008	2009	2006	2007	2008	2009	2007	2008	2009	Sum over 2007-2009	Cost Fabrication	Cost Processing	Cost Sum
S0	pessimistic	6		24	8	8	12	20	30	20	30	158	11850000	6636000	$ 18.486.000,00
	realistic	6		24	8	20	20	30	30	30	60	228	17100000	9576000	$ 26.676.000,00
	optimistic	10		24	8	22	24	60	30	30	60	268	20100000	11256000	$ 31.356.000,00

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[1] Depending on the outcome of the ILC program within the next year XFEL might still change the procedures for preparation. So the distinction XFEL-ILC is somewhat virtual. Impact on schedule and investment need to be considered.

Value Added from these Scenarios

The data which will be available from these scenarios will allow a detailed estimate on average gradient and spread to be compared with DESY's 4th production.

Even in the pessimistic scenario this will improve the estimate by being significantly more precise as roughly 160 cavities will be tested up to 2009 (include 2006 cavities). About 80 will be put through a mature infrastructure for the final preparation step with tight quality control at the vendors. Although this data set might slightly differ from the final ILC preparation process will be partially used for final treatment setup at companies, it is the backbone of the dataset. Certainly, the fabrication yield can be estimated from this data set at least to exclude major fabrication problems.

The other 80 will be partially from qualified vendors and new vendors and be prepared in new infrastructure tailored to the final ILC preparation process.

Thus, this scenario will provide a lower boundary of the average gradient. The minimum expectation is a gradient level of the 4th production at DESY ~27 MV/m with a spread of 4 MV/m.

In the other scenarios more cavities are put through the optimized ILC process assumed to be available by mid 2008. The advantage is a demonstration of a higher average gradient with significantly improved data (although a certain fraction of the cavities will be tested only in 2010):

- Pessimistic: 80 cavities
- Realistic: 120 cavities
  - Have to assume new vendors (~30)
- Optimistic: 150 cavities
  - Have to assume new vendors (~30)
  - Comparable with the number of cavities produced for TTF/FLASH until today

S0/S1 Plan Cost Estimation

Taking the optimistic scenario which provides highest confidence about the gradient distribution with a final batch for the ultimate goal and the tight-loop experiments the cost for the S0S1 plan are roughly 38 M$. As said above S1 cost is contained within S2 cost estimates.

This needs to be compared to a reduction of the average gradient for the ILC by 12.5% (~ 500 MILCU). The risk associated with the width of the gradient distribution

The cost for the full program is roughly half of the final cost impact on the project due to the risk of the gradient spread.

3.2 S2 – String test

The S2 task force was created by the Global R&D board in June 2006 to determine the nature and size of a system test needed to properly test the ILC acceleration technology. Our charge was to set the goals, specifications and a timeline for the system test(s). This section contains our conclusions. There is more detailed information about our deliberations on the S2 Wiki page and the full report is available online .

Our major conclusions are summarized in the following bullets.

- The TTF facility at DESY has provided valuable system tests of many elements of the ILC technology. More tests can and should be performed there. Further testing activities for the XFEL, as well as the complete XFEL, will continue to provide valuable experience.

- However several important changes to the TTF design are being planned for the ILC. These include a higher gradient, relocation of the quad to the center of the cryomodule, shortening of the cavity end-group, and a new tuner design. Also under discussion are different modulators, klystrons, and cavity shapes among other developments. These design changes are numerous and major enough that a further system test is warranted.

- The basic building block of the ILC linac is one RF unit containing three cryomodules with full RF power controlled as in the final linac. The minimum size system test needed to confirm the performance of a new design is a single RF unit with ILC like beam. As many tests are statistical in nature, a longer string test with several RF units or multiple tests with one RF unit would be better. The primary reason beam is needed is to check that higher order modes (HOMs) are coupled out and absorbed so they do not cause a significant heat load at liquid helium temperature.

- All three regions have expressed a desire for command of basic ILC SCRF technology and are preparing to manufacture cryomodules locally. Local test facilities at the scale of 1 RF unit are under construction in Asia and the Americas. Europe is trying to increase its ILC related efforts with a forthcoming proposal to the European Commission (FP7). The proposal will be based on expanding the usage of existing infrastructures.

- As construction of the project starts, a test facility (or facilities) will be needed to qualify manufactured RF unit components of the final consolidated ILC linac system design. These components may be built at industries in different regions. One of the possible scenarios is to build a test string with contributions of a total of several RF units from the three regional teams. There are many factors that will influence the choice of the size of the string and whether the goals can be accomplished instead through several smaller tests or one long string. These factors will be coupled to the future industrialization strategy adopted for ILC main linac components. Therefore we cannot at this stage determine the ideal scale of this second phase of system tests.

- Sections 5 and 6 of the full report list reasons for doing tests and give a rough schedule for doing them in a phased approach. Some of the reasons for tests evolved from the R1 – R4 ranked lists of technology demonstrations called for by the Greg Loew TRC report. Our plan is based on a natural schedule for components to be ready. Therefore some low risk items are tested earlier than some high risk items. The phasing of the plan recognizes development times necessary for the final design of components, as well as the need for a few iterations that may be necessary to reach ILC specifications for the full RF unit, especially if these have to be implemented outside the TTF. There are number of phases to the system tests we propose (starting with 1 cryomodule and ending with several RF units). Phase 1.3 (at least 1 RF unit of near final ILC design) should be successfully tested before more than 1% of the final industrially produced ILC cryomodules are manufactured. This keeps the risk of having to rebuild a large number of cryomodules low while accepting a moderate risk of a schedule delay and having to rebuild 1% of the cryomodules. This risk is moderate because the successful phase 0 and 0.5 tests were done with cryomodules only slightly different than the final design.

Table 2 describes the phases of the system tests and gives rough completion dates.

Figure 1 gives the schedule in graphical form showing its relation to other parts of the project.

Costs are a bit difficult to define as these system tests are done in stages some of which are already completed.

We estimated that at a lab which had a cryoplant and an empty building but virtually nothing else it would cost $86M not including lab labor to build phase 1.3. This included: infrastructure to process and test cavities and assemble cryomodules; purchasing the parts for non-final versions of cavities and cryomodules along with those for the final versions; beam source, buncher, diagnostics, spectrometer, dump; shielding and PPS system; cryogenic lines; klystrons, modulators, LLRF, and RF distribution.

Fermilab has estimated a cost of $32M not including lab labor to build phase 1.3. This does not include the infrastructure or parts costs for building the cryomodules as this is partly done and is accounted in a different part of their budget proposal. They have an injector which they will be moving hence its cost is reduced.

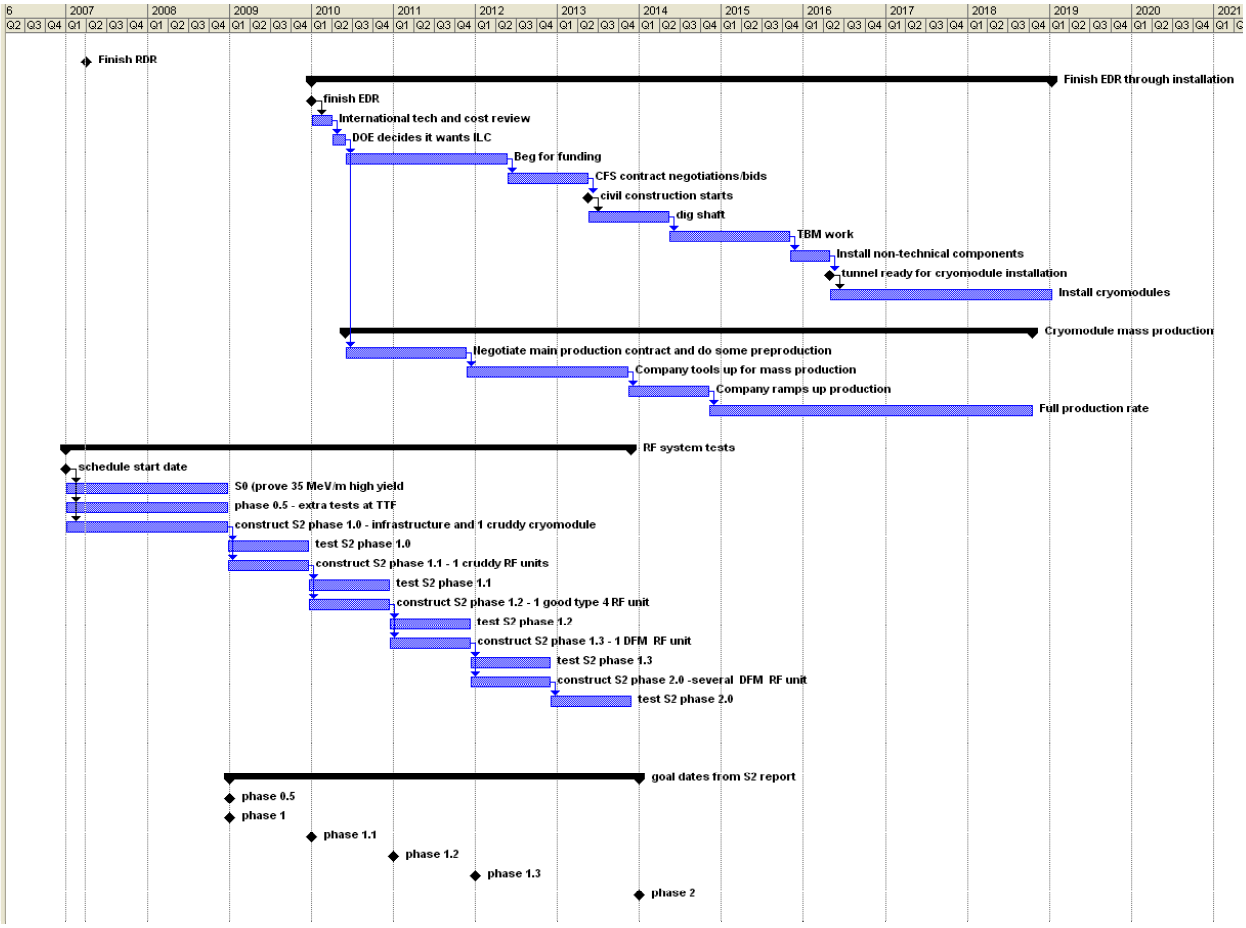
KEK has estimated a cost of 1,579,220 k-yen or about $13M not including lab labor to build phase 1.3. This assumes they have finished an earlier phase which puts beam through a single cryomodule.

Each group has estimated what is appropriate for it given what they already have (or have planned for the near future). As they are estimating different things, it is no surprise the answers are quite different.

Table 2 Rough technically limited schedule for completing the string tests.

Phase	Completion date	Description
0	2005	TTF/FLASH, not final cavity design, type 3 cryomodule, not full gradient, has beam but work is needed to have regular ILC bunch structure, roughly 2 RF units.
0.5	2008	Extra tests at TTF/FLASH with same type cryomodules as phase 0
1	2008	1 cryomodule, not final cavity design, type 3 cryomodule (and/or) STF type cryomodule, not full gradient, no beam
1.1	2009	1 RF unit, not all final cavity design, not all type 4 cryomodules, not full gradient, beam not needed for tests, but should be built so it and the LLRF are debugged for the next step
1.2	2010	1 RF unit (replacing cryomodules of phase 1.1), final cavity design, full gradient, type 4 cryomodules, with beam
1.3	2011	1 RF unit (replacing cryomodules of phase 1.2), final cavity design, full gradient, type DFM cryomodules, with beam
1.4	2011	Tunnel mockup above or below ground. 1 RF unit perhaps built with parts taken from earlier tests. Includes RTML and e+ transport, no beam
2	2013	Several RF units at one site (of the final ILC?) as a system test of final designs from multiple manufacturers. Need for beam depends on design changes made after phase 1.4.
3	2013	XFEL
4	2018	First 2.5 km of ILC

Figure 1: System test schedule in relation to other major project milestones



3.3 S3 – Damping rings

Six issues for the damping rings have been identified as requiring very high priority R&D in the next few years. These issues are:

- electron cloud;
- fast injection and extraction kickers;
- lattice design;
- low-emittance tuning;
- impedance-driven single-bunch instabilities;
- ion effects.

In each case, R&D is required either to validate the baseline configuration laid out in the RDR, or to provide information that will allow further parameter specifications and detailed design work to proceed. In addition to those R&D items identified as “very high priority”, there are many items that are considered “high priority”: these include specification of magnet field quality to ensure good acceptance; specification of requirements for alignment and survey; characterization of multi-bunch instabilities, and specification of the feedback system; development of technical designs for the damping wiggler, vacuum and RF systems; and development of a range of advance instrumentation and diagnostics devices. Attention will first be given to the very high priority R&D items, with work continuing on the high priority items as resources permit. Below, we briefly describe the status and objectives of R&D for the very high priority items.

3.3.1 e-cloud

Significant effort has been devoted over recent years to understanding the electron cloud effect, and to developing predictive models. However, given the range of phenomena related to electron cloud, and the sensitive dependence of its effects on details of the accelerator environment, there is still significant uncertainty in the impact that electron cloud could have on the performance of the positron damping ring. The best estimates, based on simulations that make significant extrapolations from existing data, suggest that without major improvements in techniques used to suppress build-up of electron cloud, it is likely that electron cloud will prevent the specified beam quality and stability being achieved. It may then be necessary to operate with significantly reduced beam current, or to perform further R&D before implementing (potentially expensive) remediation.

The best data on electron cloud in positron storage rings comes from the B factories, where early problems caused by electron cloud were eventually solved by the use of solenoid windings in the straight sections of the rings. The ILC positron damping rings will operate in a regime different in several respects from the B factories. Although the beam current will be lower, the emittances will be smaller by more than an order of magnitude, making the beam potentially much more sensitive to destabilizing effects. Also, the positron damping ring will include 200 m of wiggler, where solenoid windings will be ineffective at suppressing the cloud.

R&D on electron cloud will focus on two areas: understanding the build-up of electron cloud, and the development of techniques for its suppression; and understanding the interaction between the cloud and the beam, leading to a specification on the maximum tolerable cloud density in the positron damping ring. Both areas will involve experimental and simulation studies. There are several suppression techniques that appear promising, including the use of vacuum chamber coatings having low secondary electron yield, use of grooved chamber surfaces, and use of clearing electrodes. These techniques need to be studied to determine the most effective prescription for the positron damping rings, with the least severe side-effects.

The electron cloud effects is of significant importance for many storage rings (for protons and heavier ions as well as electrons); and, as a result, there are many groups around the world interested in pursuing electron cloud studies that would be of direct benefit for ILC. Potential test facilities include PEP-II, CesrTA, KEKB and DAΦNE.

3.3.2 Fast injection and extraction kickers

The injection and extraction kickers for the damping rings must have rise/fall times less than the bunch separation in the rings; this could be as short as 3 ns in the baseline configuration. To achieve the necessary deflection angles, pulses of many kV are required; furthermore, the kickers must operate reliably at repetition rates of 6 MHz (for bursts of 1 ms), and with pulse-to-pulse stability of better than 0.1%. These parameters are beyond the state-of-the-art in kicker technology.

Possibly the most demanding component of the injection/extraction kickers is the fast, high-power pulser. While there are several possible technologies that approach the parameter specifications for the damping rings – including fast ionization dynistors, drift step recovery diodes, and inductive adders based on mosfet devices – none has yet demonstrated the full parameter specifications for the damping rings. It is possible that further development of any one of these devices may provide an acceptable solution; or some hybrid technology may be needed; or some additional component capable of enhancing the output from a basic pulser (for example, ferrite pulse sharpeners).

As well as the pulser, the stripline electrodes that generate a deflecting field from a high-voltage pulse require careful study. Here, the issues include achieving a sufficiently good impedance match to the pulser and the load, producing a design with sufficient aperture and field quality for the injected beam, and minimizing the beam impedance to avoid instabilities and higher-order mode heating.

The pulser R&D will be primarily experimental, and there are several groups already working on the different candidate technologies. Although much can be achieved using bench tests of prototypes, tests of kickers with beam will be necessary to demonstrate reliable operation meeting all specifications. Possible test facilities include the KEK-ATF and the A0 beamline at FNAL, both of which have already been used for early tests of some devices. The stripline electrodes, though still requiring R&D are relatively conventional; thus, computer modelling and design studies will be appropriate in the near term, but ultimately prototypes will need to be built and tested.

3.3.3 Lattice design

The lattice design provides the basic parameters for many technical subsystems (including the magnets, vacuum system and RF), as well as providing the basis for a wide range of beam dynamics studies. Thus, in order for engineering design work to proceed efficiently, a stable lattice design is required at an early stage. Many of the lattice parameters – such as the damping times and equilibrium emittances – are fairly easily achieved in a lattice conforming to the baseline configuration; but issues such as the acceptance and the sensitivity to errors are very challenging. An acceptance that is insufficient can lead to significant loss of particles from the injected beam, with potentially very serious damage to damping ring components. A lattice that is sensitive to alignment and focusing errors may make it extremely difficult or impossible to meet the specifications on beam quality and stability.

The lattice used as a basis for the RDR meets the principle parameter specifications and shows a promising acceptance. However, as our understanding of the machine requirements and engineering issues evolves, and the potential impact from such effects as electron cloud, impedance and ground motion become better known, it will be possible to optimise the lattice design for performance and cost. Lattice design work requires essentially no experimental studies. There are several groups (including those at ANL and IHEP) intending to explore a range of design options that may be expected to produce alternatives as well as an effective baseline design. While lattice design work generally proceeds iteratively (with modifications made in response to issues raised by development of technical designs of the major components), it is important that process of making design changes is controlled, so that there is a stable basis for studies depending on the lattice design, while allowing flexibility to enable improvements to be made.

3.3.4 Low-emittance tuning

The beam extracted from the damping rings is specified to have a vertical emittance of 2 pm; however, the lowest vertical emittance achieved in any storage ring to date is 4.5 pm (in the KEK-ATF). There is a need for development of more effective procedures for beam-based magnet alignment, orbit and dispersion correction, and compensation of coupling. While simulation studies have an important role in this R&D, experimental work and eventual demonstration of 2 pm vertical emittance will be essential to validate the ILC parameters. Closely connected with these studies will be the development of advanced instrumentation and diagnostics, including tests of high-precision BPM systems, and devices capable of fast beam-size measurements with micron resolution.

It is expected that the KEK-ATF will continue to be an important facility for experimental studies of low-emittance tuning through 2008. However, as the focus of studies shifts to ATF2 and issues relating the beam delivery system, there will be less availability of the damping ring for tuning studies. There is interest at some light sources, including the ALS at LBNL, and the APS at ANL, in developing low-emittance tuning techniques, with the potential of achieving emittances in the range of a few pm. CesrTA could also provide an important facility for such studies.

3.3.5 Impedance-driven single-bunch instabilities

Beam instabilities driven by short-range wake fields were a major operational issue for the SLC damping rings: even small variations in the charge distribution in the beam extracted from the rings had a significant impact in the tuning and operation of downstream systems. This experience makes single-bunch instabilities a concern for the ILC damping rings, particularly since preliminary estimates indicate little margin between the nominal operating parameters and single bunch instability thresholds. However, the present estimates must be based on broad assumptions regarding the impedance of the vacuum chamber. While the assumptions made are thought to be realistic, it is known that the onset and behaviour of single-bunch instabilities can be sensitive to details in the character of the impedance. In order properly to assess the baseline configuration and the developing design, it is therefore necessary to construct an accurate impedance model and study the effect of this impedance on the beam under a range of operational conditions (including variations in bunch charge, bunch length, and momentum compaction factor).

The following is an appropriate outline for the studies into single-bunch impedance-driven instabilities:

- Specify the vacuum system, including quantities and outline parameters of principal components expected to contribute to the chamber impedance.
- Develop technical designs for principal vacuum chamber components.
- Construct an impedance model based on the component designs.
- Assess the impact of the impedance on the beam, under a range of operational conditions.
- Review and improve the designs of the principal components, to mitigate impedance effects as necessary, optimise performance and minimize cost.

The R&D program will require close collaboration and effective coordination between the vacuum technical experts who will specify and provide outline designs for the vacuum system, the engineers who will develop technical designs for the chamber components, and the beam dynamics specialists who will construct the impedance model and determine the effects on the beam.

Initial estimates indicate that the impedance specifications will be demanding, but can be met by careful design work. Experience with existing machines suggests that construction of an accurate and reliable impedance model will be challenging; however, improvements in software tools and computing power in recent years have increased our abilities in this area. There is particular expertise with impedance modelling at SLAC, where there is interest and intent to contribute to this work. The Cockcroft Institute and LBNL can provide technical expertise with vacuum systems and engineering effort for design work. KEK and IHEP have considerable relevant experience, and have expressed interest in being involved in the work. The goal should be to complete at least the first iteration of the program outlined above in time for the EDR.

3.3.6 Ion effects

Ion trapping is a familiar cause of instability in electron storage rings. In existing machines, leaving gaps in the fill pattern is an effective way to clear ions and prevent ion-induced instabilities; however, in machines with very low emittance and moderately high current, there is some evidence that sufficient ions can be accumulated in the course of a few bunches to significantly affect the stability of the beam. Qualitative observations of such a “fast ion instability” have been made at ALS, PLS and ATF. The baseline configuration of the electron damping ring is consistent with the inclusion of frequent gaps that should prevent ions affecting the quality of the beam; however, there remains significant uncertainty in the models, which makes it difficult to predict with any confidence the impact that ions could have on the damping ring. Fast feedback systems may help to counteract ion-induced instabilities, but ultimately a very low residual gas pressure is likely to provide the most effective means of suppression. Development and confirmation of reliable models in the appropriate parameter regime are needed, in order to provide specifications and designs for the vacuum and feedback systems that are optimised for performance and cost.

The need for ultra-low beam emittance to make quantitative measurements presents a challenge for studies of fast ion instability; both because of the difficulty of achieving the required emittance, and the difficulty of making measurements with sufficient precision. However, such studies may be possible at the ATF, CesrTA, and the ALS. A systematic program will require the ability to tune reliably for vertical emittance of a few picometres, and to measure beam size and coherent motion along a train of some number of bunches, under varying conditions of bunch charge and residual gas pressure. The ability to determine the effects of fast feedback systems is also strongly desirable.

If the required facilities are available, the necessary measurements could be completed within two to three years. This will allow development and validation of reliable models, that can be used to predict the impact of fast ion effects on the electron damping ring. It will then be possible to optimise the design of the ring, particularly in regard to the vacuum and feedback systems, and the possible fill patterns during operation.

3.4 S4 Beam Delivery System

3.4.1 Preamble

Starting from the second half of 2006, the BDS area leaders were focusing on developing the internationally coordinated plans for EDR phase and beyond. Since November 2006, the GDE S4 task force was coordinating these planning efforts [1]. The S4 developed the overall assumption about EDR goals, in application to Beam Delivery System, and, via series of expanded meetings with leaders of particular work packages or collaboration leaders, the list of R&D to be focused on during EDR phase as well as the detailed schedules and milestones for critical areas. The results of such deliberations are summarized below. The projected budget situation was taken into account and in certain cases, when limited resources were identified to have caused delays with respect to the desired pace of progress, the GDE and regional leaders were notified [2] (the budget issues are not discussed below, as this is understood to be beyond the scope of the R&D section of the RDR document). The ongoing BDS cost risk analysis was also taken into account inasmuch as it was relevant for EDR planning.

3.4.2 Main contents

In planning the EDR efforts, the S4 assumed that the EDR, till the end of 2009, will follow by two years of approval period, till the end of 2011, after that construction would start, in the beginning of 2012. Although a longer schedule was mentioned, the optimistic schedule was chosen for planning, which may be possible provided that the LHC would give exciting results, the yield of SRF cavities production will be steadily and predictably improving, the process of site selection and approval will be expedited, the commitment to invest in ILC will form in all three regions, and the cost uncertainty will be reduced.

Taking into account the above described schedule and that one of the overall goals should be striving for the early start of the ILC construction, the following defining principles of BDS planning for EDR were adopted:

- the efforts should focus on reduction of cost uncertainty, which means designing systems to appropriate level; and verification of performance via developments and tests of critical prototypes;
- one should not plan to complete all the BDS work at the end of EDR, instead, need to plan to continue optimization and final design after EDR and during earlier years of construction;
- if some development could have high political visibility, in addition to scientific impact, and could tip the balance for early start of ILC construction, this should be taken into account in planning

Several high priority areas of development were identified, in BDS area, where the novelty of design and technical challenges are such that focused efforts are needed in the EDR phase, to verify the performance, reduce risk and cost uncertainty, and develop optimized technical solutions. These areas, which will become the basis or form part of corresponding work package, are (italic font indicate hardware to be built in EDR):

- Integrated design of IR, development of IR superconducting magnets, build engineering prototype of FD magnets, design study to ensure IR mechanical stability, design of push-pull arrangements
- development of crab cavity systems, test phase control system with two single cell cavities, build single multi-cell cavity
- design, construction, commissioning and operation of ATF2 test facility
- development of laser wires for beam diagnostics, prototype laser wires at ATF2
- development of intra-train feedback, prototype at ATF2
- development of beam dump design and study of beam dump window survivability
- development of collimator design, verification of collimation wake-fields with measurements and verification of collimation beam damage
- development and tests of MDI type hardware such as energy spectrometers, IP feedback BPMs, BeamCals, etc.
- and the design work, which does not involve hardware development but use results of the above listed work.

Following the guiding principles, and having identified the areas of focused efforts in EDR phase, the overall schedule for BDS in EDR and beyond was developed, which is shown at the end of the document. Examples of detailed schedules for several systems are also shown below, however, in some cases these schedules were limited by presently known level of funding, and their adjustment and mitigation is under discussion.

For several critical systems the design features, challenges and the corresponding EDR goals are described below in some details.

The integrated design of the Interaction Region is centered around the superconducting Final Doublet, which design and developed is led by BNL. In EDR, an engineering prototype of the QD0 cryostat, containing self-shielding QD0 quad with corrector coils, the sextupole-octupole SD0/OC0 magnet, the antisolenoid, and a dummy first extraction quad, will be built. This engineering prototype is to verify the design, which relies on compact direct wound magnets to provide the independent incoming and outgoing apertures separated by mere 49mm defined by 14mrad crossing angle over the L* distance of 3.5m.

The prototype is also aimed for studies of mechanical stability of the magnets, when integrated into cryostats, and connected to cryogenic system. The FD stability requirements are in the 100-200nm range (the luminosity reduction is 1-2%, 5%, 15-20% for rms FD vibration of 100nm, 200nm and 500nm, correspondingly). Very rough estimation, comparing with existing cryo magnets of completely different design which show 0.3-1micron level vibration, tell that the needed improvement is about a factor of three to five. Vibration studies will be performed after the prototype is built, and in meantime the methods to measure mechanical stability of the cold mass and of the magnetic center, will be developed.

The integrated design of IR, in a wider sense, includes all the systems such as cryogenics, supports of the FD, shielding of beamlines, the interface parts of the detector, lifting equipment in the IR hall and alignment systems, and so on. The single IR push-pull scheme sets specific new challenges for the design. For example, one of design constraints of the cryogenic system is that disconnection of cryo-line are not allowed during push-pull operation, and that the cryo-lines should be placed so that they would not interfere with detector door opening on the beamline. Engineering integrated design of IR will be a major focus of EDR work.

Development of the crab cavity system is led by UK-US (Cockcroft Institute, FNAL and SLAC) collaboration. Crab cavity design challenges include phase stability of about 67fs (or 0.094deg of 3.9GHz), which corresponds to <2% luminosity loss (quadratic dependence of dL on dt); couplers that should provide adequate level of damping of unwanted modes; cryostat with appropriate level of microphonic rejection, etc.

The EDR plans take into account the synergy with developments of other ILC cavities (e.g. 3rd harmonic XFEL cavity) and with developments at non-ILC projects (e.g. LLRF for Energy Recovery Linac or XFEL). The EDR plans would include design of cavity and couplers, fabrication of one cavity and its low power tests, in an adjusted CKM cryostat, developments of RF system and tests of phase stability with two single cell cavities, conceptual design of the integrated system and of the cryostat. This EDR work will follow by tests of single cavity with beam at ILCTA around 2010, and later by design and construction of an optimized cryostat and of the second cavity, their integration and beam tests of two cavities.

The ATF2 facility is being constructed in ILC-like manner, when hardware is provided by in-kind contributions from all three regions, while Japan, as the host country, contributes also the civil construction and most of operation expenses. The ATF2 will prototype the ILC Final Focus system, help in development of tuning methods and instrumentation (laser wires, fast feedback, submicron resolution BPMs), help to learn achieving reliably the nanometer level beam size and beam stability, and potentially able to test stability of FD magnetic center. ATF2 is one of central elements of BDS EDR work, as it will address a large fraction of BDS technical cost risk.

The beam operation of ATF2 is scheduled to start in October 2008 and commissioning may take up to about a year. Studies will first focus on investigation of the small beam size while studies of nanometer beam stability rely on further development of hardware and will take place at the next stage. In addition to the technical challenges of ATF2, the collaboration would need to address the organizational challenge to perform coordinated integration and commissioning of ATF2, likely giving relevant experience for ILC.

The work on beam dumps during EDR would focus on engineering design of the dump and the radiation water system, including considerations of tritium containment, window replacement, removal of dump and access for service. The accompanying prototype and beam test work would include studies of window irradiation (the place is to be defined, the BLIP facility is a candidate) and possibly prototyping the front-end of the mechanism of remote window replacement. These EDR activities would produce a design of the beam dump that could be submitted for pre-approval to environmental agencies.

During EDR, development of MDI type hardware would continue to be developed and tested with beam at ESA. This will include BPM based and synchrotron radiation stripe based energy spectrometers and the IP feedback hardware and tests of its resistance to background. Measurements of collimation wake-fields will also be continued at ESA, while the place for the beam damage tests of the collimator spoilers is still to be determined. The ESA facility will be available for BDS tests throughout 2008, while after that it may be unavailable. If additional beam tests, with beams of ESA characteristics, would be needed after 2008, the SABER facility may be used although its starting date is not yet known.

The design work, both accelerator and detector physics design and engineering design, will be a focus of EDR work. This would include design and integration of beamlines, conventional facilities, vacuum system, magnets, instrumentation, collimators, etc. It will also include the optics, background and similar design work for small and zero crossing angle alternative schemes. The design work will also include considerations of new ideas which may improve performance of Beam Delivery subsystems.

Table 3: Activities in the Beam Delivery System

	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	
	EDR			Approval		Construction						
Constraints				LHC physics	total length frozen		tunnel & optics layout frozen		optics details frozen		tunnels ready for install-n	
Beam dumps	beam dump conceptual design and critical tests			pre approval		beam dump final engineering			b.dump design frozen	beam dump construction		bea dur ins
crab cavity	design, build & test of conceptual phase control system; cavity fabrication; conceptual cryostat design; LLRF develop and test with single cells			design of cryostat; cavity integration; beam test of one cavity		beam tests of two cavities		final engineering		production		ins
ATF2	ATF2 construction and installation.		Commissioning	Beam size and optics results	Beam stability results	2nd phase, e.g. SC FD; smaller emittance &		Instrumentation developments and tests at beamline				

	Start of commissioning		beam size				
Final Doublet	Engineering design; full length prototype; stability design study and initial stability tests	Stability tests & design optimization	final design	production	lab tests	installation pre-commiss	
Detectors	Conceptual design; selection of two concepts; continue design	Design optimization	final design and start of production	Construct, assemble and pre-commission on surface			Lo do co
IR integrated	Conceptual eng. design of IR vacuum chambers; supports; pacman and moving shielding; cryogenic; service platform; detector moving system; cranes; etc.	Detailed eng. design of integrated IR with finalized choice of two detectors for final design	final design and start of production	production		installation pre-commiss	
Magnets	Optimization of number of styles; conceptual design of most magnets; definition of interfaces; Detailed design of low field and other special magnets; Vibration -wise design	Design and cost optimization; layouts with real space allocation, and detailed interfaces.	final design & needed prototypes	production		installation pre-commiss	
Collimation	Tests of collimation wakefields and beam damage tests; conceptual eng. design	Detailed eng. design; optimization & integration into beamline	final design & pre-production prototypes	production		installation pre-commiss	
Instrumentation	Develop laser wires; test feedback BPMs with secondary beam; conceptual eng. design	Detailed eng. design; optimization & integration into beamline	final design & pre-production prototypes	production		installation pre-commiss	
Vacuum system	Physics and conceptual eng. design. Detailed design of IR vacuum chamber.	Detailed eng. design; optimization & integration of beamlines	final design	production		installation	

Table 4: Coarse timelines for project activities during engineering and early construction phase

	2007	2008	2009	2010	2011	2012	2013	…
	EDR			Approval		Construction…		
DEVELOP ENG. PROTOTYPE OF FD MAGNETS								
Design & build long coil tooling	▨							
Do long coil winding tests	▨							

Perform coil quench threshold tests (non-ILC funds)	■							
Prototype magnet design	■	■						
Design He heat exchanger / lead assembly	■	■						
Build & vert. cold test prototype QD0/SD0 coil		■						
Design magnet tooling		■						
Buy magnet parts		■	■					
Fabricate/Build magnet tooling			■					
Build insertion region cryostat			■					
Buy He heat exchanger parts			■					
Build He heat exchanger / lead assembly			■					
Buy vibration hardware based on earlier results			■					
Magnet Assembly			■	■				
Perform horizontal cold test				■				
Do vibration msmts on magnet				■				
Update reference design as needed based on results				■				
Final design					■	■	■	
Production								■
DEVELOP CRAB CAVITY SYSTEM								
Design of cavity & couplers	■	■						
Develop conceptual phase control system	■							
Build two single cells for phase control tests	■							
Tests concept. phase control system w.2 single cells	■	■						
Cavity fabrication		■	▨					
Cavity tests in vertical dewar		▨	■					
adjustment of CKM cryostat for crab cavity tests		▨	■					
buld RF power system			■					
cavity integration into cryostat		▨	■					
cavity integration into ILCTA beamline			▨	■				
beam test of one cavity				■				

design of optimized cryostat		▨	■					
build optimized cryostat				■	■			
build second crab cavity				▨	■			
beam test of two cavities						■	■	
final engineering							▨	■
DEVELOP BEAM DUMP								
Window material study & design dump widow	■	■						
Design dump widow remote replacement mechanism	■	■						
Eng. design of beam dump rad water system	■	■	■					
Eng. design of beam dump shielding		■	■					
Eng. design of beam dump vessel		■	■					
Physics design of beam dump	■	■						
Prototyope beam dump window		■						
Irradiation tests of dump window prototype			■					
Pre approval				■	■			
Beam dump final engineering					■	■	■	■
Beam dump construction								■
ATF2 FACILITY								
ATF2 construction and installation	■	■						
Commissioning			■					
Optics and beam size study			▨	■				
Beam stability study					■			
Possibly, SC final doublet						■	■	■
Possibly, smaller DR emittance						■	■	■
Instrumentation developments and tests at beamline						■	■	■

3.5 S5 – Positron Source

The document addresses high priority R&D for the ILC. The items included will have a major impact on the performance or the cost of the ILC and may affect the layout.

3.5.1 Undulator

Short superconducting undulators have been built by both CCLRC and Cornell. These have confirmed that the undulator is feasible in general. A 4m long prototype (active length of 3.5m) is now being constructed by CCLRC and Cornell have also proposed building a long prototype. This is essential to prove that the present design can be scaled up to the level needed by ILC. There is still scope to improve the undulator parameters (period, field, K, bore) to increase the positron yield per metre and efforts in this direction should continue. The complete undulator section (undulator modules, the cryogenic strings, and the room temperature sections with quads, BPMs, photon collimators, pumps, etc) has not been designed yet and this requires further optimisation to achieve the most efficient solution. This optimisation will involve additional wakefield studies, tolerance modelling, vacuum calculations, electron optics, and significant engineering. Furthermore, the undulator itself should move into an industrialisation phase and a fully instrumented, robust, reliable, value engineered design developed.

3.5.2 Target

The baseline target is a 1m diameter, rotating, 5 spoked wheel made of titanium alloy. The wheel rotates at high speed (100m/s at the rim) in a vacuum and has integral water cooling. It will become highly activated and will need to be in a remote handling area. A concept has been developed by LLNL/SLAC and this has been passed to Liverpool/CCLRC who are further refining the design and are generating machine shop drawings. This work continues to be supplemented by LLNL vibrational and thermal studies. The plan (subject to UK funding) is to prototype the target in 3 stages at Daresbury. The first stage will be to build a wheel of the correct material and to spin it at full speed out of vacuum but in a magnetic field. This will confirm mechanical issues such as balancing, performance of the motors and drive shafts etc and also eddy current effects such as magnetic braking, heating and induced vibration. These eddy current effects are being simulated independently by ANL/CCLRC/Cornell. The second stage is to operate the system in a vacuum to prove the vacuum levels required can be achieved and maintained for long periods. This second stage will pass water through the wheel at the required pressure as well. The third prototype stage will be to operate the full system (rotating wheel in a vacuum with the OMD magnetic field) with an external heat source to try to replicate possible thermal problems associated with the target. Target activation studies are being led by DESY with Liverpool/CCLRC also contributing in this area.

In addition to this baseline work alternative materials are being studied for the target wheel (CCLRC) which could perhaps operate with radiative cooling only or might have much lower conductivity and so be able to operate more effectively in a magnetic field. (Furthermore, liquid metal targets are also being advocated by groups at Cornell and BINP.)

3.5.3 Optical Matching Device

Text still missing

3.5.4 Remote Handling

The target and OMD will need to be installed in a remote handling area since they will become highly activated. CCLRC have developed some initial schemes for the area and these include the ability to vertically remove the target system and to replace it with a spare system. Although such changes would naturally be scheduled during shutdowns they would also be required if the target failed during operational time. In that case the changeover time (presently estimated at 53 hours) for the target systems becomes critical. It is important that this time is reduced during the design phase to increase the ILC positron source availability.

3.5.5 Positron Source System

Multivariate optimization studies are needed to refine system and component functional requirements and performance specifications and tolerances. This effort integrates the subsystem R&D into the overall design. The optimization is aimed at developing a robust and reliable positron source given a range of possible undulator parameters, target requirements, and capture expectations. These efforts include the development of a realistic start-to-end simulation of the full ILC positron production, beginning with the high energy photon production and continuing through polarized pair-production, positron capture, collimation, acceleration, and transport to the entrance of the ILC damping ring. The simulation permits optimization and trade-off studies within the large parameter space that includes undulator parameters, target damage issues, field configuration of the capture optics, acceleration gradients, collimation, and spin preservation. This work is conducted in collaboration with the Americas and European regional partners with SLAC taking the lead in coordinating the activities and ANL playing a major role in the developing the overall systems modelling. This work will continue through to commissioning.

3.5.6 Upgrade to Higher Positron Polarization

The baselined configuration produces positrons with an overall polarization of about 30%. Positron polarization in the range of 60% is possible with the addition of more undulator sections and angular collimation of the incident photon flux. The EDR design is required to be fully compatible with the upgraded scenario for higher polarization. A more detailed design is required. These efforts are just being started in earnest amongst the European and Americas regional partners

3.5.7 Alternative Positron Source – The Compton Source

The ILC positron source based on the Compton back-scattering is an advanced alternative because it requires only a few GeV electron beam to produce high energy gamma for the positron generation. It is more than 100 GeV for the case of the Undulator Source. Furthermore, the Compton Source does not make any inter-system dependency between the electron and positron arms in ILC and makes the total system availability better. In addition to the system engineering perception, the positron source based on the Compton back-scattering is more compact and could be demonstrated prior to the construction of the real ILC with equivalent conditions (beam energy, positron intensity, etc). It is practically impossible in the case of the Undulator source and it dramatically relieves the system risk.

The Compton back-scattering can be interpreted as an undulator with a short period corresponding to the laser wave length. That is a big advantage to generate high energy gamma with a reasonable energy of electron beam, but the interaction length (laser pulse length in Compton case, undulator length in Undulator case) is very limited. To obtain enough flux of positron is the biggest issue for the Compton Source.

Fortunately, the technology of the Compton back-scattering is a candidate of a future X-ray source with a compact system and R&D is actively continued around the world. Thanks to the recent development of the laser technology, several kW class high power lasers are even commercially available and can be used for the Compton Source. Important mile-stones are summarized as follows:

1) Develop a conceptual design which is fully compatible to the ILC requirements including expecting technological developments in future.

2) Develop key technologies, e.g. laser, optical cavity and its precise control, target, capture optics, etc. It may be not a direct technological development, but a system integration of the advanced technologies.

3) Demonstrate the positron generation in a level scalable to the real ILC positron source.

We are now in the first stage, i.e. developing the conceptual design. Mainly, three different concepts have been proposed: Linac based, Storage-ring based, and ERL based. They have different pros and cons and the vitality strongly depends on the key components and technologies. In our plan, we will establish a conceptual design (the first mile-stone) within 3 or 4 months from now. PosiPol workshop will be held in Paris in May 2007 and this workshop will be an important phase towards the first milestone. Soon after this workshop, the conceptual design will be established.

Concurrent to the efforts for the first mile-stone, several experimental studies are already started. As a collaboration among many labs and universities, gamma-ray and positron generation with a pulse-stacking optical cavity in an electron storage ring is carried out at KEK-ATF. This experiment is generating positrons with an equivalent concept proposed for the ILC positron source. This experiment contains many aspects listed in the second mile-stone. Another advanced concept for the optical stacking cavity is under development at LAL in France. This optical cavity has 4 mirrors and has 104 – 105 enhancement factor (103 in KEK-ATF). In BNL-ATF, an experiment of the gamma ray generation for the linac based Compton source has been carried out. In their scheme, an extremely high power and high repetition CO2 laser is a key component.

In one or two years, technical feasibility of the Compton Source will be clearer than that at present. If the feasibility as the ILC positron source is proven the baseline of the positron source should be switched from the Undulator Source to the Compton Source because of the less system risk as mentioned before. This period corresponds to the third mile-stone, Demonstration of the ILC positron source; A prototype of the ILC positron source should be constructed and the total performance should be confirmed prior to the real construction. This prototype can be less bunch number (e.g. 100, not 3000 or more), but the bunch intensity should be equivalent to the ILC requirement. Demonstration of the ILC positron source (not including damping ring stacking) is only possible for the Compton source and impossible for the Undulator source.

4 Remaining R&D

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4.1 Definition of critical R&D

4.2 Strategy

5 Conclusions

Not yet.

6 Appendix

This section may contain tables of R&D projects