Area-System 4: Damping ring

(Ver.3,2021-Mar-23)

Overview:

Damping rings (DRs) are circular accelerators that are placed after the electron and positron sources with the goal of creating high-quality electron and positron beams for the ILC. The dynamic aperture of the circular accelerator is affected by the multipole errors of the magnets, especially for the fringe fields of the bending magnets. The present baseline beam optics for the ILC DR is updated to have a smaller horizontal emittance than that of the ILC TDR in 2017. we will have to carry out the system design of the updated DR optics by considering the multipole errors of the actually designed magnets of the ILC DR during the ILC Pre-Lab period for the ILC EDR.

The ILC DR possesses many collective effects that may affect the beam quality in the DRs. These include impedance-driven instabilities, intrabeam scattering, space-charge effects, electron cloud effects in the positron ring, and ion effects in the electron ring. The largest sources of emittance dilution were found to be the electron cloud (EC) instability in the positron DR and the fast ion instability (FII) in the electron DR. However, because the effects on the old TDR optics were evaluated, but, not for current updated DR optics, we will have to investigate the collective effects on current updated DR optics.

The circumference of the DRs is approximately 3.2 km, and corresponds to approximately 1/90 of the beam pulse length at the electron and positron sources and at the main linac. A fast kicker system compresses and decompresses the beam pulse during injection and extraction, respectively. The system design of the ILC DR injection-extraction system will have to be carried out during the system development at KEK-ATF, including the assurance of the long-term reliability of the injection-extraction system during the ILC Pre-Lab period. Furthermore, because the injection system for the electron-driven position source is different from other ILC injection and extraction kickers, we will have to develop the injection kicker, when we will adopt the electron-driven positron source for the ILC positron source.

The contents of this area system mentioned above need to be described in the EDR (Engineering Design Report).

Area-System Damping ring: Work packages:

Work package	***Items***
WP- 12: System design of ILC damping ring	Optics optimization, simulation of the dynamic aperture with magnet model
	Magnet design : Normal conducting magnet and superconducting wiggler
	Magnet design : Permanent magnet
	Prototyping of permanent magnet
WP- 13: Evaluation of the collective effect in the ILC damping ring	Simulation : Electron cloud instability
	Simulation : Ion-trapping instability
	Simulation : Fast ion instability (FII)
	System design : Fast FB for FII
	Beam test : Fast FB for FII
WP- 14: System design of ILC DR injection/extraction kickers	Fast kicker: System design of DR and LTR/RTL optics optimization
	Fast kicker: Hardware preparation of FID pulsar
	Fast kicker: System design & prototyping of induction kicker
	Fast kicker: Long-term stability test at ATF
	E-driven kicker: System design,including induction kicker development

WP-12: System design of ILC damping ring

(Ver.3,2021-Mar-23)

Technical Preparations Plan:

The basic design of the ILC DR is shown in the document of the Linear Collider Collaboration (LCC); "The International Linear Collider Machine Staging Report 2017". The horizontal emittance is 4.0 μm, while achieving a dynamic aperture of 0.07 m. The dynamic aperture was evaluated by assuming the hardedge ideal magnets, however, the dynamic aperture of the circular accelerator is affected by the multipole errors of the magnets, especially for the fringe fields of the bending magnets. Therefore, magnet design is required for the DR magnets. Then, we will evaluate the DR beam optics by considering the multipole errors of the actually designed magnets of the ILC DR. Once the evaluation of dynamic aperture with the current beam optics is completed, we will also proceed with the DR lattice optimization study to further improve the horizontal emittance while maintaining the dynamic aperture tolerance.

In addition, we investigate the potential for introducing a permanent magnet (PM) in the arc section of the DR. A major advantage of PMs is the reduced operating costs relative to electromagnets; related to this we can also cite lower emissions (even when factoring in those due to mining PM materials), reduced infrastructure (no large power supplies or water pipes) and lower vibrations (no flowing water). The disadvantages can be summarized as follows: PMs are fixed-field, sensitive to small changes in temperature, and susceptible to radiation damage. It is necessary to investigate the magnetic field uniformity, stability, and radiation damage by prototyping several field-adjustable PMs during the ILC Pre-Lab period. Then, we will decide whether to use them for ILC DR. The decision to use PMs will be made carefully, taking into account a wide range of factors, including not only the results of the PM prototyping, but also the experience with PMs used in 4th generation light sources during Pre-Lab period.

Goals of the technical preparation:

System design of the beam optics for the ILC DR. The DR specifications are as follows.

Parameters	***Symbol***	***Unit***	***Design***
Normalized emittance	$\gamma\varepsilon_x/\quad\gamma\varepsilon_y$	μm / nm	4.0 / 20 at N=2E10
Dynamic aperture	$\gamma(A_x + A_y)$	M	0.07 (action variable)
Longitudinal acceptance	$\Delta\delta \times \Delta z$	% × mm	$\pm 0.75 \times \pm 33$

List of items:

Items
Optics optimization, simulation of the dynamic aperture with magnet model
Magnet design : Normal conducting magnet
Magnet design : Permanent magnet (PM)
Prototyping of PM

Status and Prospects:

The ILC DR must provide a low emittance beam as well as a large dynamic aperture to achieve a large acceptance for the positron beam. A DR with a horizontal emittance of 5.5 μm was designed while achieving a large dynamic aperture of 0.07m (action variable) in the ILC TDR published in 2013. Subsequently, DR optics with a lower horizontal emittance was proposed and approved by the LCC in 2017 with the aim of achieving higher luminosity in the ILC250. The LCC document "The International Linear Collider Machine Staging Report 2017" shows the basic design of a DR with a horizontal emittance of 4.0 μm, while achieving the same dynamic aperture of 0.07 m as the TDR design. The dynamic aperture was evaluated by assuming the hardedge ideal magnets; however, the dynamic aperture of the circular accelerator is affected by the multipole errors of the magnets, especially for the fringe fields of the bending magnets. For instance, the simulation results for the SuperKEKB damping ring show that the dynamic aperture is reduced by half when multipole fields of fringe fields are considered. The design of the ILC DR optics should be completed in the Pre-Lab period, considering its influence on the evaluation of the positron source and the corrective effects and so on. In order to achieve this goal, modeling the field distribution of the multi-pole field of the magnets in the ILC DR, including the SC wiggler, will be an important item in the early Pre-Lab period.

PM devices have been used in accelerator facilities for many years. Their primary function is as insertion devices (undulators and wigglers) on synchrotron light sources. The two most prevalent materials used are Sm_2Co_{17} and $Nd_2Fe_{14}B$. The latter has a higher remanent field (meaning it can produce a stronger magnetic field) but a smaller intrinsic coercivity (meaning it is more easily demagnetized by an external field or by radiation). Recent developments include the use of PrFeB and cryogenic PM undulators, both of which aim to enhance the on-axis field. In recent years, many light sources worldwide have embarked upon programs of upgrades, reducing their beam emittance and enhancing their output brightness. The disadvantages of PMs can be summarized as follows: PMs are fixed-field, sensitive to small changes in temperature, and susceptible to radiation damage. However, several groups have produced highly adjustable PM designs using mechanical adjustment. Furthermore, excellent temperature stability can be achieved, even for NdFeB, by adding small amounts of FeNi alloy which has a temperature coefficient with the opposite sign. In terms of radiation damage, synchrotron light sources have employed PM-based insertion devices for many years without significant radiation damage. Maintaining the PMs out of the plane of the circulating beam may be the most important factor in reducing this risk. Some examples of light source facilities that utilizing PMs extensively are:

- ESRF (France): PM longitudinal gradient (LG) dipoles, 128 magnets each consisting of five fixed-field modules, stepping up in the field. Diamond Light Source (UK) has a similar design for its planned upgrade.
- ZEPTO tunable dipole: fixed steel pole with horizontally-moving PM.
- SPring-8 tunable dipole prototype, using a vertically-moving outer plate.
- Sirius (LNLS, Brazil): 'Superbend' dipole/quadrupoles, mechanical adjustment gives ±4%.
- CBETA (USA): fixed-field Halbach combined function magnets providing dipole and quadrupole fields.
- ZEPTO quadrupoles: fixed steel poles with vertically-moving PMs in outer yoke.
- QUAPEVA quadrupole at COXINEL: Halbach array with rotating PM cylinders in outer yoke.

Projects are underway for the 4th generation of light sources in the world, and some of these light sources will use PMs. In the Pre-Lab period, we believe that these projects will provide useful information on the temperature dependence and radiation resistance effects of PMs. We consider whether the PMs will be used in the arc section of the ILC DR by taking into account the experience with PMs used in 4th generation light sources during Pre-Lab period.

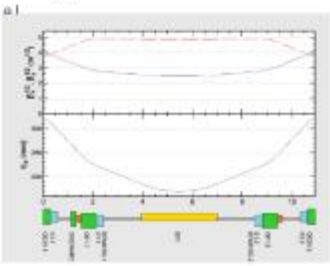
In case we decide to use PMs, the current considered baseline devices of the PMs are the Sirius type for the bending magnets, the ZEPTO type for the quadrupole magnets and the ZEPTO type for sextupole magnets. However, because there are no prototypes of the ZEPTO type of sextupole magnet, we will have to make prototypes for the PM. For other baseline PMs, we do not have to make prototypes only for ILC-optimized magnets, but we should design to be optimized for the ILC. Furthermore, we also consider the use of the CBETA type of bending magnets, and the QUAPEVA type of quadrupole magnets as optional devices for ILC. Using these optional PMs would be more compact and cheaper. However, we should evaluate the field qualities for optional magnets (field uniformity and movement of the magnetic center, when the magnetic field strength is changed, and the effect of radiation damage etc.). Finally, prototyping of the PMs is planned for the following magnets:

- CBETA type bending magnet (i.e. 90cm long with 30 cm segments)
- QUAPEVA type quadrupole magnet
- ZEPTO type sextupole magnet

The prototyping for the PM will be iterated twice each (a total of six prototype magnets) during the ILC Pre-Lab period, and the PM design is determined based on the results of the prototype test. The prototype PMs will also be useful for process making of the PM installation, the test of the radiation damage and the field control by the temperature variation.

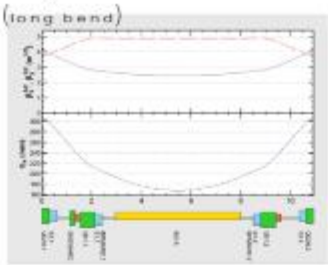
DR optics in TDR

Original



DR optics in ILC-CR-0016

New (long bend)



	Original	New (long bend)
Horizontal normalized Emittance (um)	5.74, 6.27 (IBS)	3.14, 3.97 (IBS)
Tune x/y	48.26/26.76	49.33/26.86
phase adv./cell/2pi x/y	0.21891 /0.08098	0.2250 /0.0808
Damping time x/y/z (ms)	23.9/23.9/11.9	25.5/25.5/12.8

Dynamic aperture: long bend

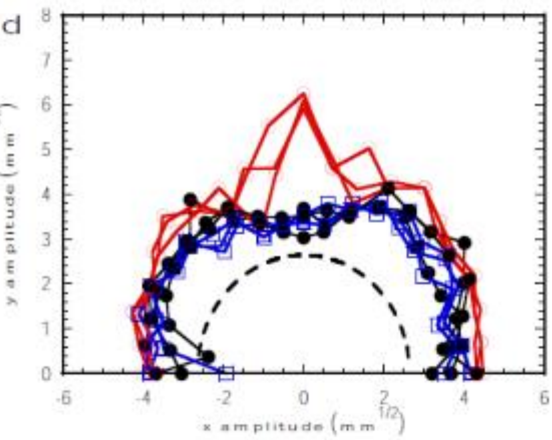
Misalignment + correction

New arc cell: long (5 m) bend

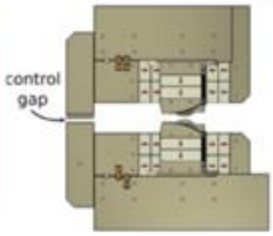
tune/cell: x.225 y.0808

Tune: x49.33 y26.86

Quadrupole & sextupole offset: 50 um
Quadrupole roll: 100 urad
BPM offset: 100 um
BPM roll: 10 mrad
COD & Dispersion correction

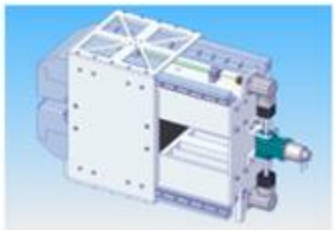


ESRF
Fixed field



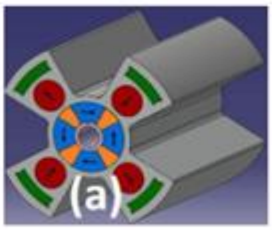
Sirius
Small adjustment (~3%)

CBETA
Fixed field



ZEPTO
Variable field (factor 2)

CBETA
Fixed field



QUAPEVA (Soleil)
Factor of 2 tuning

ZEPTO-Q1
High strength
Factor of 4

ZEPTO-Q2
Lower strength
Very large adjustment range

WP-13: Evaluation of collective effects in ILC damping ring

(Ver.3,2021-Mar-23)

Technical Preparations Plan:

DR optics with a lower horizontal emittance was proposed and approved by the LCC in 2017 with the aim of achieving higher luminosity in the ILC250. Therefore, it is necessary to investigate the collective effects of the present updated DR optics. The largest sources of emittance dilution were found to be the EC instability in the positron DR and the FII in the electron DR. The effect of the ion-trapping instability should also be evaluated by simulations.

MEXT's ILC Advisory Panel expressed technical concerns about the need for a high-resolution fast feedback system. SuperKEKB has a circumference that is close to that of the ILC DR and a feedback system similar to ILC250. System development of the high-resolution fast feedback system for the ILC will be performed based on the experience of the system operation and upgrade development at SuperKEKB. In addition, when there is a need for experience in FII suppression under conditions that exceed the performance of SuperKEKB in evaluation by simulations, etc., additional beam tests should be performed to suppress the FII at other accelerators.

Goals of the technical preparation:

Evaluation of the collective effect correction in the ILC DR. The beam stabilities in the DR after correction are reduced to be following parameters:

Parameters	*Unit*	*Design*
Bunch population		2E10
Number of bunches in DR	Bunches	1312 / 2625
Beam position fluctuation		$\leq 0.2\sigma_y$

List of items::

Items
Simulation : EC instability
Simulation : Ion-trapping instability
Simulation : FII
System design of fast FB for FII
Beam test of fast FB for FII

Status and Prospects:

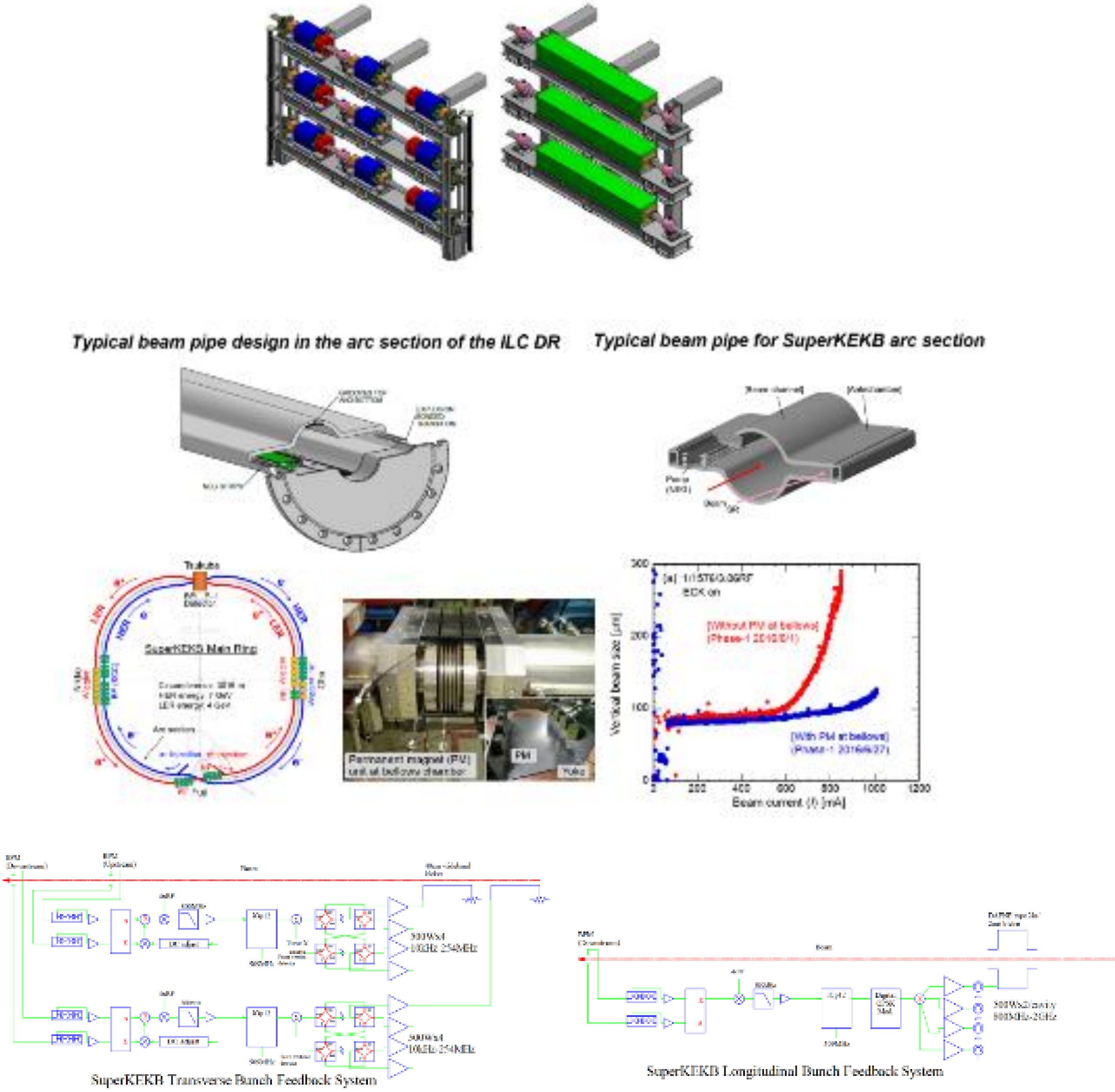
The many collective effects that may affect the beam quality in the DRs were examined in the ILC TDR. These include impedance-driven instabilities, intrabeam scattering, space-charge effects, EC effects in the positron DR and ion effects in the electron DR. The largest sources of emittance dilution were found to be the EC instability in the positron DR and the FII in the electron DR. In contrast to the more familiar ion-trapping effect, where ions oscillate stably for long periods in the potential well of the stored beam, FII is associated with ions that are created in the beam path by interaction with the circulating beam during a single turn. Ions created at the head of the bunch train move slowly, and remain in the beam path, influencing the motion of subsequent bunches. The resultant ion-induced beam instabilities and tune shifts are critical issues owing the ultra-low vertical emittance. The FII create emittance growth, betatron tune shifts, and coherent bunch-by-bunch instabilities. A low base vacuum pressure at the 1×10^{-7} Pa level is essential to reduce the number of ions formed. To mitigate bunch motion, bunch-by-bunch feedback systems with a damping time of 0.1 ms are also employed. The DR optics design with a lower horizontal emittance was approved by the LCC in 2017, and the horizontal emittance was reduced from 5.5 μm to 4.0 μm.

In 2014, SuperKEKB started machine commissioning, and many experiences were obtained for the collective effects. The circumference of the SuperKEKB is comparable to the ILC DR. For the EC of the positron ring, the vacuum chamber designs for the ILC DR and the SuperKEKB low energy ring (LER) are almost the same, except for the chamber diameter (50 mm for the ILC DR, and 90 mm for SuperKEKB). At the first stage commissioning of the SuperKEKB, the beam size growth in the LER (positron ring) was observed by the EC. However, the beam size growth by the EC was cured after the bellows chambers were covered with permanent magnets.

The cloud density of the ILC DR was evaluated to be a factor of about three below the expected single bunch instability threshold in the ILC TDR evaluation for the baseline configuration. However, there is a need for twice the number of bunches to be stored in the DR for high-luminosity upgrade. The doubling of the current in the rings is of particular concern for the positron DR owing the effects of the EC. In the ILC TDR design, allowance was made for the installation of a 2nd positron DR in the same tunnel in the event that the EC mitigations that have been recommended are insufficient to achieve the required performance for this configuration. Based on our experience with EC at SuperKEKB, we will have to investigate the impact of the newly updated ILC DR to examine whether the 2nd positron DR is really needed during the luminosity upgrade.

For the FII of the electron ring, the same concept of the fast FB system was adopted for the SuperKEKB high energy ring (HER) to suppress the coherent bunch-by-bunch instabilities. The design horizontal and vertical emittances for the SuperKEKB HER are roughly one order larger than those for the ILC electron DR, but the design stored beam current of SuperKEKB is 6-7 times higher than that for the ILC DR. The growth times of the coherent bunch-by-bunch instabilities due to FII for the ILC electron DR and those for the SuperKEKB HER are comparable, although the SuperKEKB HER is in the commissioning stage, and the beam current has not yet reached the design value. We expect that they will store a higher beam current operation at the SuperKEKB HER. The reproduction of FII in the SuperKEKB HER by performing simulations is useful for the evaluation of FII in the ILC electron DR.

In SuperKEKB, the fast FB is used to suppress coherent bunch-by-bunch instabilities due to FII. The dynamic range of the SuperKEKB fast FB was updated from 8 bits to 12 bits to extend their dynamic range. Because the experience of suppressing FII in the SuperKEKB HER using fast FB is helpful for understanding the suppression of the instability in ILC electron DR, we hope that this experience will provide useful information to ILC. In addition, when there is a need for experience in FII suppression under conditions that exceed the performance of SuperKEKB in evaluation by the simulation, etc., additional beam tests are needed to suppress the FII at other accelerators. When we test FII suppression with other accelerators, it is necessary to prepare the FB system used in SuperKEKB or the FB system that exceeds its performance, and scientists are also required to perform the performance evaluation. Furthermore, in general, since the beam orbit oscillations can be created by cultural noise, working pumps and cryogenic system vibrations etc., we should consider development of the orbit FB to stabilize the beam orbit oscillations in ILC DR down to the required level.



WP-14: System design of ILC DR injection/extraction kickers

(Ver.3,2021-Mar-23)

Technical Preparations Plan:

Fast kicker magnets and fast-pulsed power sources have been developed, and multiple kicker systems have already been operated under beam operation at the Accelerator Test Facility (ATF) at KEK. However, considering the current dynamic aperture of the present design of the ILC DR, the electrode gap of the stripline kicker must be expanded to 50 mm. Then, when using a pulsar tested at the ATF, it is necessary to make minor modifications to the beam optics in the straight section of the ILC DR. Furthermore, when the straight section of the ILC DR is modified, it is necessary to modify the injection and extraction lines for the DR as well.

The remaining task for the ILC kicker system, as reported by MEXT's ILC Advisory Panel is to ensure the stability and reliability over long-term operation. A long-term stability test of the fast kicker system will be performed at the ATF. The kicker pulsar used for the long-term test is basically the FID pulsar used in the ATF, but the power that can be supplied by the FID pulsar is limited and there is no margin when applying it to the ILC. We would like to develop a power source that is considered to be capable of realizing higher voltage simultaneously.

Furthermore, because the injection system for the electron-driven position source is different from other ILC injection and extraction kickers, the injection kicker will need to be developed, when we adopt the electron-driven positron source for the ILC positron source.

Goals of the technical preparation:

System design of the beam injection and extraction for the ILC DR, based on the existing hardware. The specifications of the DR beam injection/extraction are as the follows.

Parameters	*Unit*	*Design*
Number of bunches in DR	Bunches	1312 / 2625 (optional)
Repetition rate	Hz	5

List of items::

Items
Fast kicker: System design of DR and LTR/RTL optics optimization
Fast kicker: Hardware preparation of FID pulsar
Fast kicker: System design & prototyping of induction kicker
Fast kicker: Long-term stability test at ATF
E-driven kicker: System design, include induction kicker development

Status and Prospects:

The electron beam or positron beam is converted into a low emittance beam while circulating the DR. In the ILC, a bunch train of 1312 bunches with a bunch interval of 554 ns is generated by the electron or positron source, and is stored in the DR. These bunches must be stored in the DR by compressing the bunch interval down to 6 ns, which enables a smaller 3.2 km ring compared to that of the uncompressed one. After the bunches become low emittance, they are extracted bunch by bunch from the DR by recovering the bunch interval of 554 ns. These requirements will be changed for the luminosity upgrade option of ILC, that is, a beam consists of 2625 bunches with an interval of 332 ns, and the bunch interval in DR becomes 3 ns. The injection and extraction kickers require high repetition frequencies of 2 MHz, as well as very fast rise/fall times of the kick field of 6 ns and 3 ns for the nominal and luminosity upgrade option, respectively. These parameters cannot be realized by using an ordinary kicker system, which consists of a pulse magnet and a pulse power supply with a thyratron switch. A system using multiple units of stripline kicker and fast high-voltage pulsars is the most promising candidates to realize the parameters.

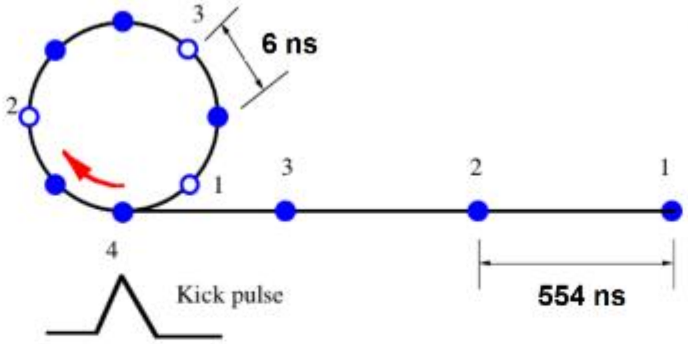
One of the key technologies of the kicker is a high-voltage pulsar to drive the stripline. The pulsar requires over a peak voltage of 5 kV, a 1 ns rise/fall time, a 2 MHz burst pulse with a 1 ms duration, and operation at 5 Hz to realize the ILC parameters. A semiconductor device called a drift step recovery diode (DSRD) has a very fast switching speed and high repetition rate, and the pulsar using DRDS switches (fabricated by FID Technology, Ltd.) meets these parameters. The beam kick test using a single unit of stripline kicker and DSRD pulsar was carried out in the ATF DR.

Successful beam extraction was demonstrated in the beam operation from the ATF DR to the ATF2 beamline. For this experiment, two units of stripline kickers were installed, temporarily replacing the conventional extraction kicker, which has been placed offline. Two pairs of 10 kV pulsars were used to drive the striplines. The stripline kicker produced a 3 mrad kick angle for a 1.3 GeV beam. Owing to geometrical restrictions, the pulse bump orbit and the auxiliary septum magnet were used with the stripline kicker. This 10KV pulsar succeeded in extracting the beam, but could not generate the burst pulse of 1312 bunches required by the ILC.

A long-term stability test of the fast kicker system will be performed at the ATF. The kicker pulsar used for the long-term test is basically the FID pulsar used in the 1st ATF test (5 kV pulsar), which can generate a burst pulse of 1312 bunches. Because the voltage of 5kV is not sufficient for the actual beam extraction from the ATF DR, a long-term test will be performed at the ATF extraction line.

In addition, CERN has been developing an induction-type kicker pulsar for CLIC. By applying this technology, it is expected that a kicker pulsar with a voltage higher than the FID pulsar will be realized. It is hoped that the ILC Pre-Lab period will be able to proceed with the development of an induction type kicker pulsar and perform beam tests using the developed pulsar at the ATF.

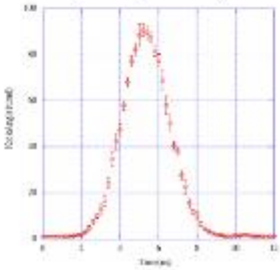
Unlike the kicker used in other ILC kickers, an injection kicker for the electron-driven positron source is required to operate at a rise/fall time of 70 ns, the flat-top of 470 ns, and a repetition rate of 300 Hz. Because the induction-type kicker pulsar may meet this requirement, there is also the need to develop it as an injection kicker for the electron-driven positron source.



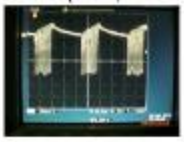
Stripline kicker

Beam extraction test from ATF DR (10kV pulsar)

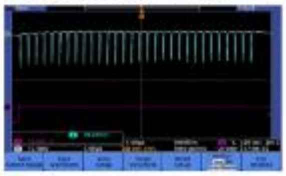
Beam test in ATF DR (5kV pulsar)



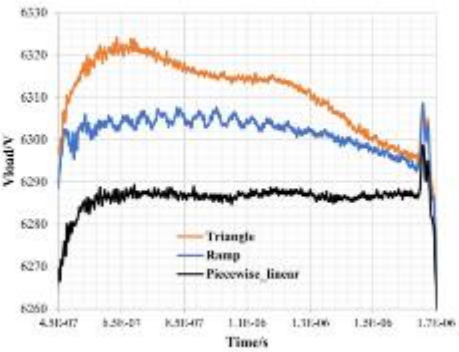
DR bunches(3train, 10bunches, 5.6ns bunch spacing)



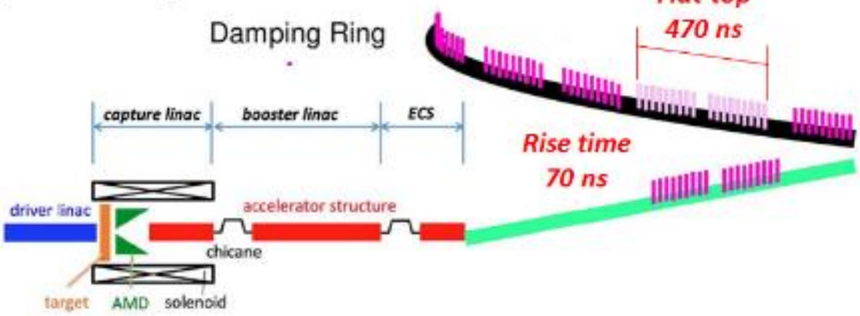
Extracted bunches(308ns bunch spacing, 30 bunches)



Induction kicker pulsar for CLIC DR



Injection system for e-driven PS



Area-System 5: Beam Delivery System

(Ver.3,2021-Mar-23)

Overview:

The ILC beam delivery system (BDS) is responsible for transporting the electron and positron beams from the exit of the main linac (ML), focusing them to the sizes required to satisfy the ILC luminosity goals, causing them to collide, and then transporting the spent beams to the main beam dumps. The ILC BDS was designed to cover a wide range of center of mass energy from 250 GeV to 1 TeV, and the TDR was written mainly for the 500 GeV operation. However, the current concept of ILC is to operate at 250 GeV first and then upgrade to higher energies. BDS should be optimized the design at the Pre-Lab phase for 250 GeV operation and upgradable to higher energies.

The final focus (FF) system is one of the main systems of the BDS. The main purpose of the FF system is to squeeze the electron and positron beams until nanometer level at the interaction point (IP) keeping at the same time a control of the position at the order of nanometer. The ATF2 beamline was designed and constructed by an international collaboration as a facility to validate the design of the ILC FF system. The tuning of the beam to achieve the nanometer beam size level as well as the feedback system to control the position at the IP have been carried out as part of this collaboration. In particular a prototype feedback system for the ILC has been verified to satisfy all ILC requirements, such as time delay, beam position monitor resolution, drive amplifier power, and beam correction dynamic range. A complete validation of the ILC FFS will be continued during the Pre-Lab period in the framework of the ATF international collaboration.

The present ILC design includes a single IP with a 14 mrad beam crossing angle. The 14 mrad geometry provides space for separate extraction lines and requires crab cavities to rotate the bunches horizontally for head-on collisions. There are two detectors in a common interaction region (IR) hall that alternately occupy a single collision point, in a so-called “push-pull” configuration. This approach, which is considerably more exigent for detector assembly and operation than a configuration with two separate interaction regions, has been chosen for budget reasons. The superconducting FD magnet and cryostat package for the ILC were designed by BNL, and the technology for the superconducting FD magnets was demonstrated by a series of short prototype multi-pole coils at the ILC TDR stage. To assess the choice of the most appropriate technology a detailed FD system based on the ILC TDR will be necessary in the ILC pre-Lab period. Furthermore, since the FD package has an impact on the ILC physics detectors, the system design will have to be implemented in coordination with the ILC physics detector groups.

The contents of this area system mentioned above need to be described in the EDR (Engineering Design Report).

Area-System BDS: Work packages:

WP-15: System design of ILC final focus beamline	ILC-FFS system design: Hardware optimization
	ILC-FFS system design: Realistic beam line driven / IP design
	ILC-FFS beam tests: Long-Term stability
	ILC-FFS beam tests: High-order aberrations
	ILC-FFS beam tests: R&D complementary studies

<u>WP-16:</u> Final doublet design optimization	Re-optimization of TDR FF design considering new coil winding technology and IR design advances.
	Assemble QD0 prototype, connect to Service Cryostat and undertake warm/cold vibration stability measurements with a sensitivity of a few nanometers.

WP-15：System design of ILC final focus beamline

(Ver.3,2021-Mar-23)

Technical Preparation Plan:

The beam size at the ATF2 focal point is designed to be 37 nm, which is technically equivalent to a 7 nm beam size for ILC250.　A vertical electron beam size of 41 nm, which essentially satisfies the ATF2 design goal, has been produced at ATF2, with a bunch population of approximately 10% of the nominal value of 10^{10} electrons and with a reduced aberration optics. Recent studies indicate that the vertical beam size growth with the beam intensity owing the effects of wakefields. Furthermore, SCJ expressed technical concerns about the technology of the control and feedback systems and the long-term stability of the beam focus and position for the ATF2 beam experiment.

To overcome these apprehensions, the main objective of this plan is to pursue the necessary R&D to maximize the luminosity potential of ILC. In particular, the ILC final focus system (FFS) design must be assessed from the point of view of beam dynamics, choice of technology and hardware, and long-term stability operation issues. To implement this program based on the outstanding and unique results achieved by the ATF/ATF2 collaboration, an **ATF3 collaboration** is underway with the ATF2 partners and with new possible partners worldwide. The results are expected to provide important information necessary for the system design of the ILC FF beamline. Through these studies, we will optimize the FFS design, which is optimized for the current ILC design of 250 GeV and has energy updatability to higher energies.

Goals of the technical preparation:

System design of beam optics and hardware for the ILC FF beamline, based on the established technologies is necessary. The specification of the ILC FF beamline is designed using the following parameters.

Parameters	***Unit***	***Design***
Beam Energy	GeV	125
Bunch population		2E10
IP beam size (H/V)	μm / nm	0.515 / 7.66
IP position stabilization		$\leq 0.2\sigma_y^*$

List of items::

Tasks
ILC-FFS system design: Hardware optimization
ILC-FFS system design: Realistic beam line driven / IP design
ILC-FFS beam tests: Long-Term stability
ILC-FFS beam tests: High-order aberrations
ILC-FFS beam tests: R&D complementary studies

Status and Prospects:

The FF system is one of the most exigent systems in the ILC. Its function is to provide nanobeam sizes (0.5 μm/7.7 nm) and stabilization at the nanometer level (< 20% of the IP beam size) to achieve the design luminosity of 10^{34} $cm^{-2}s^{-1}$ at $2{\times}10^{10}$ bunch intensity. To achieve the design luminosity of 10^{34} $cm^{-2}s^{-1}$, the ILC requires nanometer-sized electron and positron beams colliding at the IP. To demagnify the beams to the required spot sizes, a novel local chromaticity correction-based FF system was proposed and considered for the baseline ILC designs.

The ATF2 FF system was designed as an energy-scaled version of the ILC FFS, with two main aims: (1) to demonstrate the effectiveness of the local chromaticity correction scheme for achieving an IP vertical beam size as small as 37 nm, and (2) to demonstrate the feasibility of beam orbit stabilization at the nanometer level. The effectiveness of the local chromaticity correction scheme was successfully demonstrated, and the potential or direct beam orbit stabilization at the nanometer level was also demonstrated. To date, an electron vertical beam size as small as 41 nm, essentially satisfying the ATF2 design goal, and stabilization with feedback latency of 133 ns (366 designed) have been achieved.

These are unique and outstanding results; however, the vertical beam size has been demonstrated only a bunch population of approximately 10% of the nominal value of 10^{10} electrons. The extremely large β involved and the presence of non-linear elements make it sensitive to imperfections, such as wakefields, magnet misalignments and jitter. Recent studies indicate that the vertical beam size growth with the beam intensity is generated by wakefield effects. The high content of wakefield sources in ATF2 could be explained by the fact that most of the vacuum chambers are re-used or replicated; hence, there is no dedicated vacuum chamber design. In contrast, to mitigate the impact of aberrations, optics with reduced aberration, i.e., the so-called $10\beta_x^*{\times}\beta_y^*$ optics with an IP horizontal β function thet is 10 times larger than the original design, has be employed in recent operations.

It is recognized that the ATF/ATF2 achievements have already verified the minimum technical feasibility of the ILC FF system. However, to maximize the luminosity potential of the ILC, a further investigation of the effects of the intensity dependence on the IP spot size and optical aberrations especially with smaller β_x^* is crucial. To implement this program and based on the outstanding and unique results achieved by the ATF/ATF2 collaboration, an ATF3 collaboration is underway with the ATF2 partners and with new possible partners worldwide.

To resolve the aforementioned technical issues and establish the design of the ILC FF system beam optics as well as the associated hardware, the ATF3 collaboration to be implemented in the following technical preparation tasks and associated hardware preparations during the ILC Pre-Lab period.

ATF3 ILC-FFS assessment system design

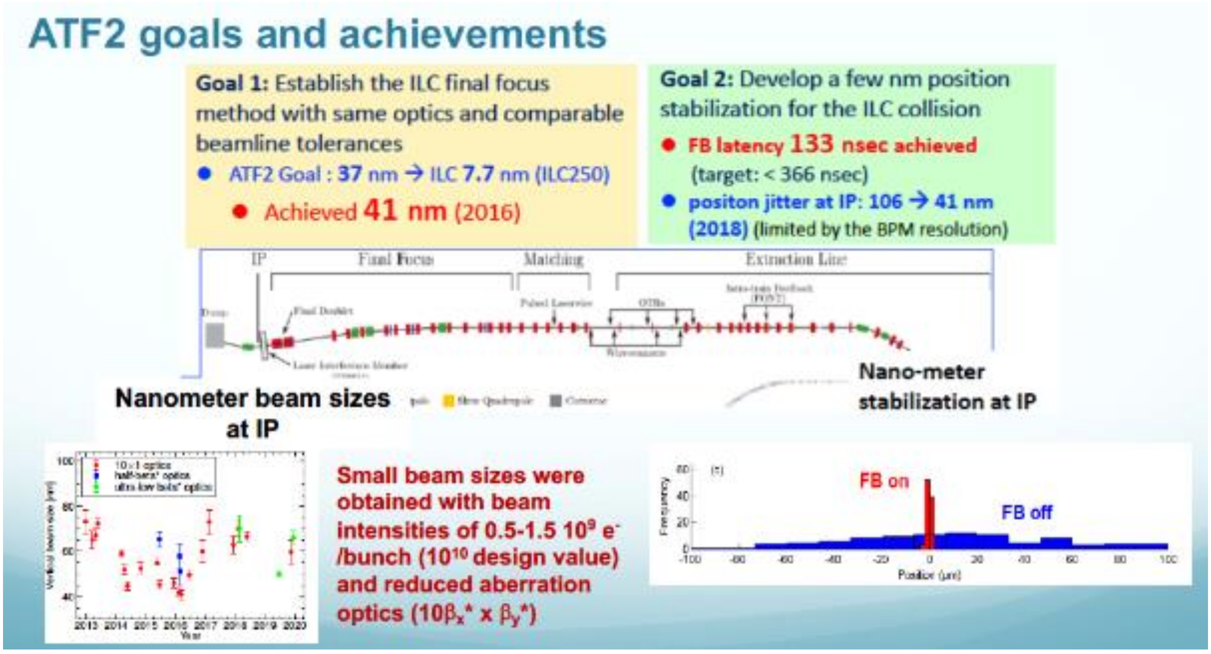
- ✓ Hardware optimization: vacuum chambers, magnets, IP-BSM laser, CBPMs, IP-BPMs
- ✓ Realistic (wakefields, jitter, and magnet error) S2E "beam-dynamics-driven" design and IP optimization

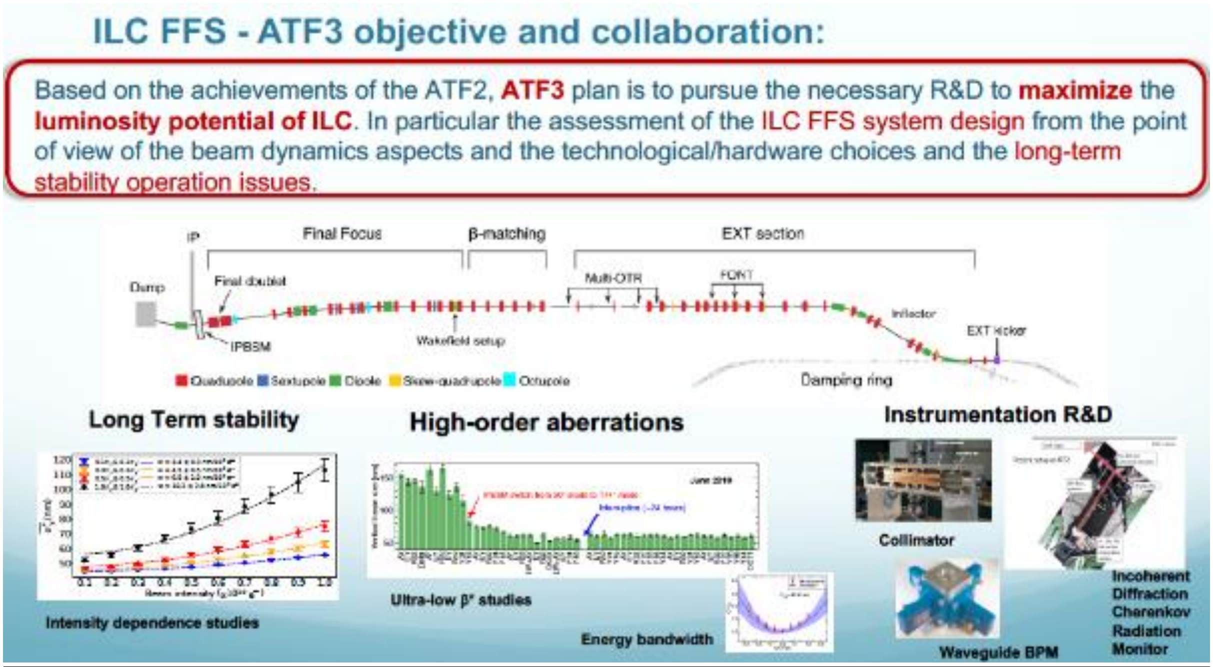
ATF3 ILC-FFS oriented beam tests

- ✓ Long-term stability: nominal ($10\beta_x^*{\times}\beta_y^*$) routine operation assessment, vibration monitoring, intra-train feedback, intensity dependence and beam-based mitigation techniques (orbit and wakefields)

- ✓ High-order aberrations: design optics ($\beta_x^* \times \beta_y^*$), ultra-low β_y^* (octupoles, long L*)
- ✓ Other ILC R&D complementary studies: ILC collimation issues, ILC type CPBMs, new instrumentation, etc.

Furthermore, since ATF3 seems to be an ideal platform to develop and test machine learning techniques for beam tuning which will benefit ILC, we will also proceed with the development of machine learning techniques in various beam tests at ATF3.





WP-16 : Final doublet design optimization

(Ver.3,2021-Mar-23)

Technical Preparation Plan:

The superconducting coil winding technology has advanced since the TDR was finalized, and later projects have proposed and/or implemented new IR design options. Subsequent to the TDR we recognize that for the 250 GeV CM operation, a significant opportunity exists to raise the luminosity and improve the final doublet (FD) layout to benefit both the experiment and accelerator operation. We will have to reevaluate and reoptimize the FD design by considering these new developments in the ILC Pre-Lab period.

In the TDR baseline, the first QD0 cryostat assembly is supported by and moves with the detector. The 1.9 K superfluid helium supply for QD0 and the interface to external magnet power leads are via the Service Cryostat. The Service Cryostat connects to QD0 via a long He-II cryogenic line that must pass through a labyrinth in the end Pacman radiation shielding to avoid having a direct path for beam line radiation to the presumptively occupied experimental detector hall. The vertical beam fluctuation to QD0 must be stable in the order of 50 nm, to stay within the capture range of the intra-train collision feedback. This requirement is well beyond the experience with existing accelerators and has been considered in the choice of the 1.9 K superfluid He-II cooling for QD0. Therefore, we will have to evaluate the QD0 vibration via the Service Cryostat for the system design of the FD system during the ILC Pre-Lab period.

Since the final doublet design is strongly related to the detector design, the technical preparation will be done in close cooperation with the detector group.

Goals of the technical preparation:

The goal of the present work is to ensure that the 250 GeV ILC FD EDR design yields the best possible luminosity for the experiments and achieves the most cost-effective smooth accelerator operation by accounting for the new magnet winding technology and IR magnet design concepts that are developed after the original ILC TDR is finalized.

List of items::

Items
Re-optimization of TDR FD design considering new coil winding technology and IR design advances.
Assemble QD0 prototype, connect to Service Cryostat and undertake warm/cold vibration stability measurements with a sensitivity of a few nanometers.

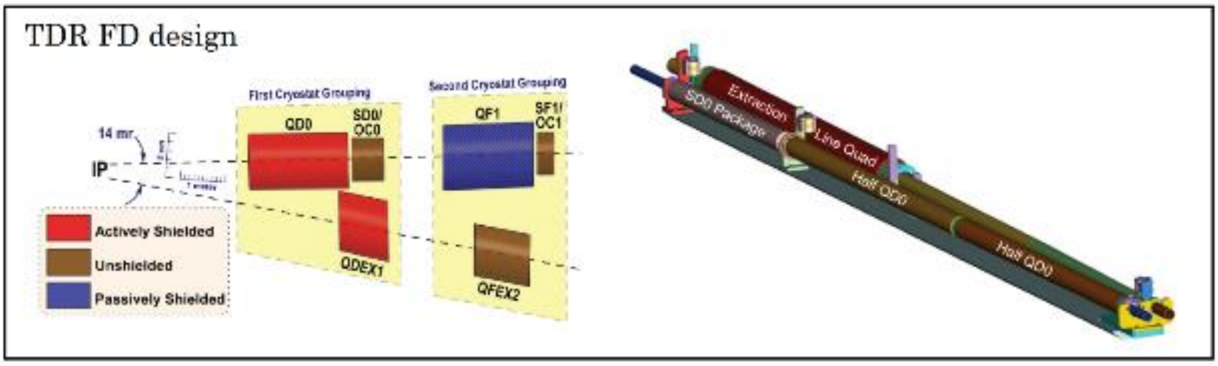
Status and Prospects:

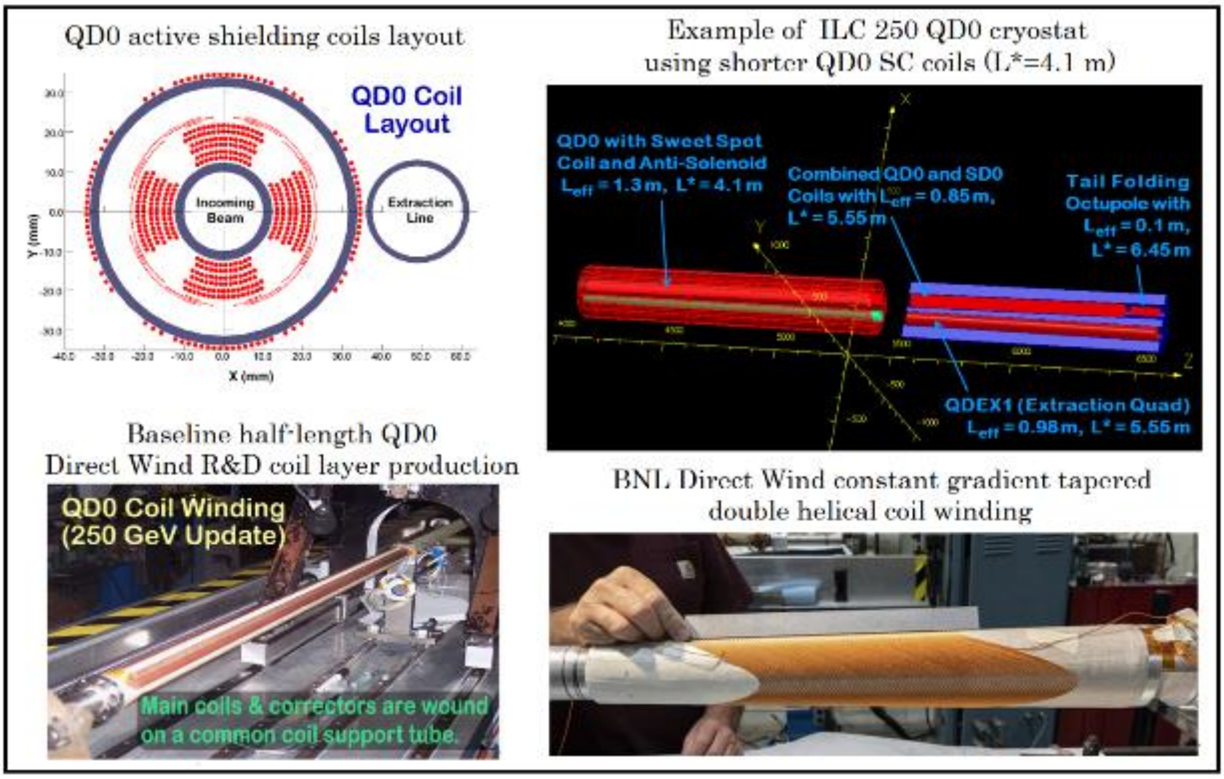
There are four superconducting quadrupole magnets around the ILC IR. QF1 and QD0 are located along the incoming beamline, and QDEX1 and QFEX2 are the superconducting magnets for the extraction beamline. The QD0 and QDEX1 magnets are housed in the QD0 cryostat, whereas QF1 and QFEX2 are housed in the QF1 cryostat, separated only by warm components and vacuum valves. Two sets of the QD0 cryostats are arranged into two physics detectors to facilitate "push-pull" at a shared IP. The QD0 cryostat moves with the detector during switchover, whereas the QF1 cryostat remains fixed on the beamline. The QD0 magnet is inside the detector solenoidal and therefore cannot have magnetic-flux-return yokes. At the closest coil spacing, the magnetic cross-talk between the two beamlines is controlled via actively shielded coil configurations and through the use of local correction coils, dipole, skew-dipole and skew-quadrupole, skew-sextupole, octupole or skew-octupole as appropriate. The QD0 coils can be split into two half-length coils, where both coils are powered for the 500 GeV CM operation. However for the 250 GeV operation, only the first half is powered to reduce the higher order aberrations of beam optics by moving the effective magnetic center of QD0 closer to the IP.

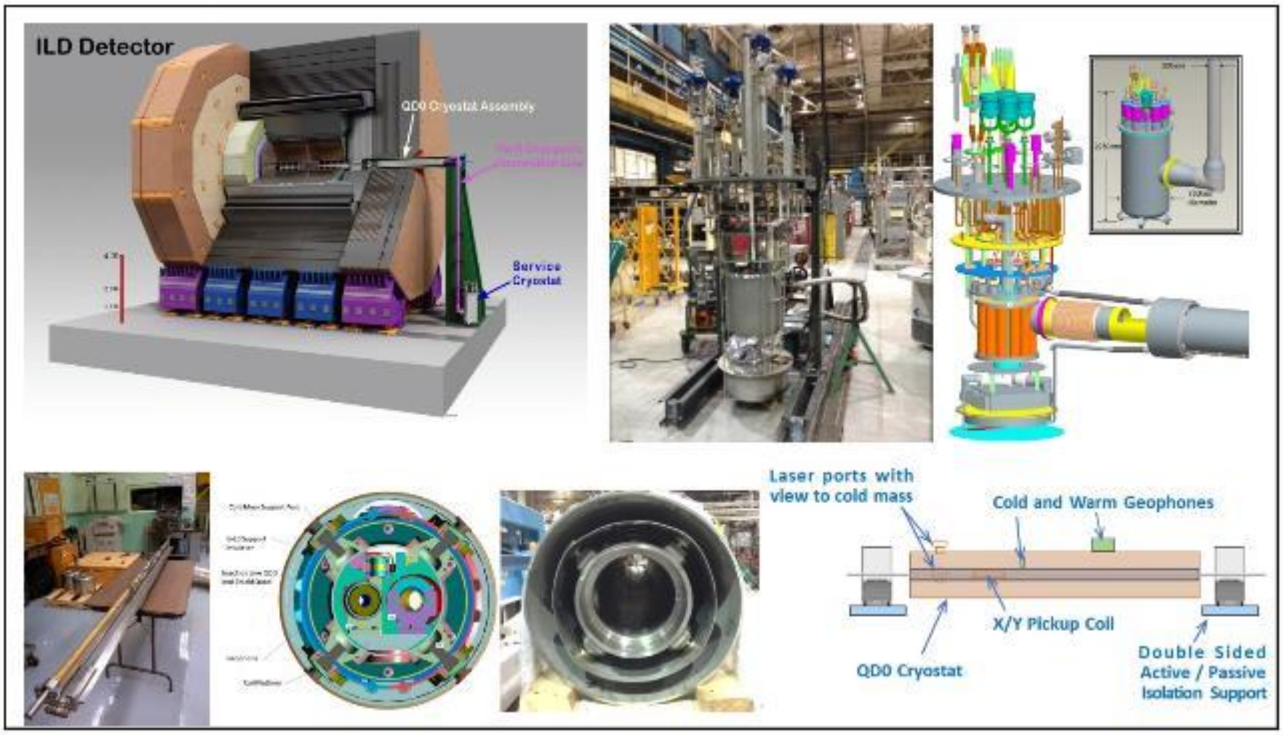
The superconducting coil winding technology has advanced since the TDR was finalized, and later projects have proposed and/or implemented new IR design options. The "sweet spot" coil concept was developed for the BNL Electron Ion Collider (EIC) IR. The sweet spot concept uses a combination of dipole and quadrupole coils that are adjusted to leave a zero net field at the main QD0 beam axis but then provide a tailored field profile to compensate for the main QD0 coil external field at the extraction line. The sweet spot configuration is magnetically more efficient than the baseline active shielding option. Furthermore, the BNL Direct-Wind coil production scheme was demonstrated recently. The BNL Direct-Wind technology is used to produce closely spaced coil layers of superconducting multi-strand cables. The design is extremely compact, and the coils practically touch inside shared cold-mass volumes. Cooling is provided by the superfluid helium at 1.9 K to avoid the risk of exciting vibration in the magnet cryostat and the formation of a long transfer line from the helium heat exchanger in the Service Cryostat. The above options represent a sample of the new magnet winding schemes and coil geometries that should be investigated before we finalized the ILC EDR FD design. The budget proposed for this work represents an investment to ensure that we reach a final mature design for the EDR, yielding the best possible FF optics performance in the most cost-effective manner.

The fluctuation of the vertical beam position at the QD0 magnet must be stable in the order of 50 nm, to stay within the capture range of the intra-train collision feedback. This requirement is well beyond the experience with existing accelerators and is considered in the choice of the 1.9 K superfluid He-II cooling for QD0 cryostat. More specially, the column of He-II maintains the QD0 magnet coils at the same temperature as the heat exchanger in the Service Cryostat without the necessary for mass flow, which carries the risk of becoming a strong vibration source (He-II effectively provides rapid and efficient "conduction cooling"). The effectiveness of this design strategy was partially demonstrated for the TDR during the dedicated R&D for constructing and measuring a full QD0 prototype. However, there was no follow-up to complete this work after the TDR was published (final R&D status: 90% complete). The SuperKEKB probe is designed with a target to demonstrate 2 nm stability and plan is to use a similar probe for QD0 tests. It is important to complete the technical work for this vibration stability measurement using the existing QD0 prototype hardware while also taking advantage of the later experience thet has been gained during the SuperKEKB IR magnet vibration measurement development work.

When the prototype QD0 cryostat is finally connected via the He-II cryogenic connection line (line parts are yet to be fabricated) to the Service Cryostat, we will perform the actual vibration stability measurements using the setup. In the laboratory, we can stabilize a 2000 turn pickup coil inside the QD0 bore from both sides and directly measure the magnetic center motion with a sensitivity of a few nanometers. Previous work has established that it is considerably easier to stabilize a pickup coil from two ends than from a single side support to proceed with in. situ measurement. Note that because the pickup coils are sensitive to the relative motion of the probe with respect to the magnet, it is important to stabilize these pickup coils to ensure that the probe's signal corresponds to the true magnetic center motion. Note that we also have sets of geophones and a contactless laser doppler vibrometer measurement system for comparison with the pickup coil readings. We will first use these other devices to perform baseline room temperature measurements and subsequently acquire pickup coil data when the QD0 magnet is cold and may be powered to its 140 T/m operation gradient.






ILD Detector
QD0 Cryostat Assembly
Service
Cryostat
Laser ports with
view to cold mass
Cold and Warm Geophones
X/Y Pickup Coil
QD0 Cryostat
Double Sided
Active / Passive
Isolation Support

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