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Lecture 6
Part 2

Beam Delivery System and beam-beam effects

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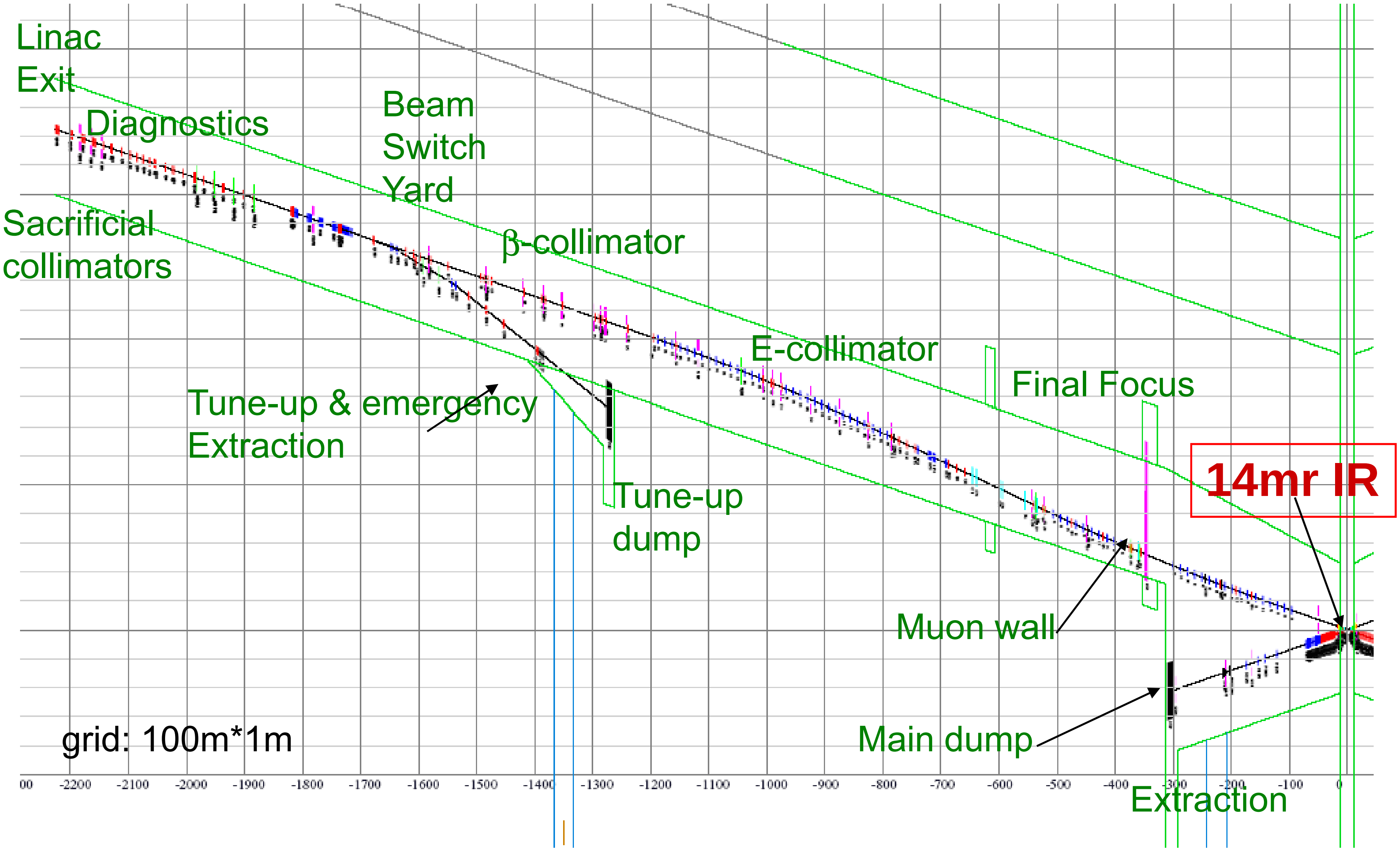
Crossing angle

ILC RDR BDS Layout



Crossing Angle

A crossing angle between the beams can be required :

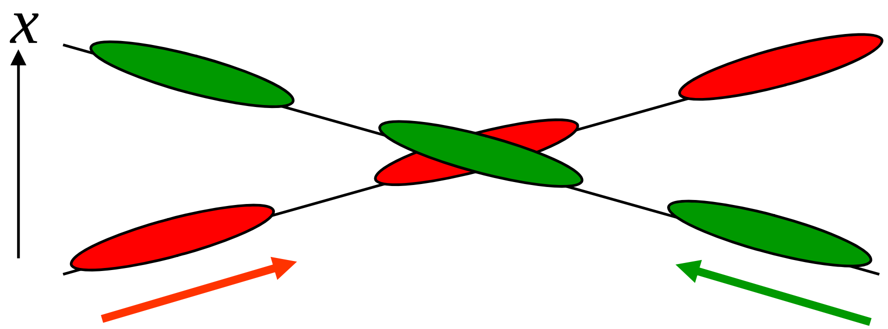
- to avoid parasitic (collisions between bunches away from the IP) bunch interactions.
- to provide geometry which allows to have separate quadrupoles for incoming and outgoing beams and clean extraction.

- In a normal conducting machine, the short bunch spacing requires crossing angle.
- In a superconducting machine, in principle it is possible to avoid a crossing angle.

ILC : 14 mrad crossing angle provides separate channels for extraction. Compact superconducting magnet technology solution.

CLIC : spent beam extraction (including coherent pairs) + space for quadrupoles need 20mrad crossing angle.

Crab Crossing



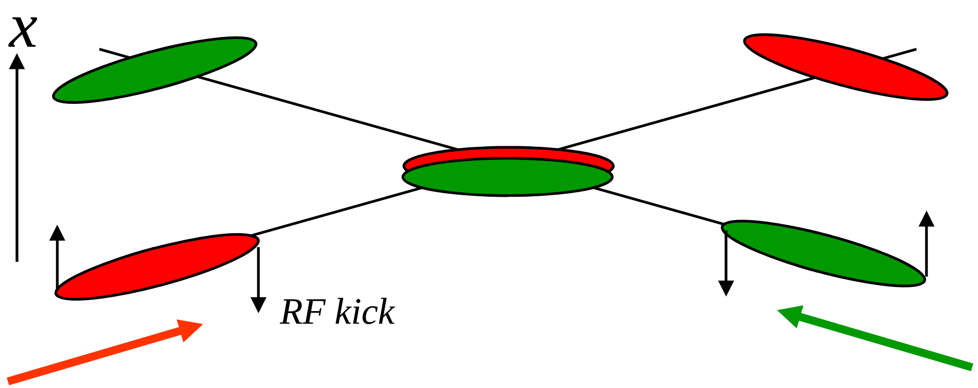
With crossing angle θ_c, the projected horizontal beam size is

$$\approx \sqrt{\sigma_x^2 + \theta_c^2 \sigma_z^2} \approx \theta_c \sigma_z$$

$$\approx 14\ mrad \times 300\ \mu m = 4.2\ \mu m$$ ILC

$$\approx 20\ mrad \times 45\ \mu m = 0.9\ \mu m$$ CLIC

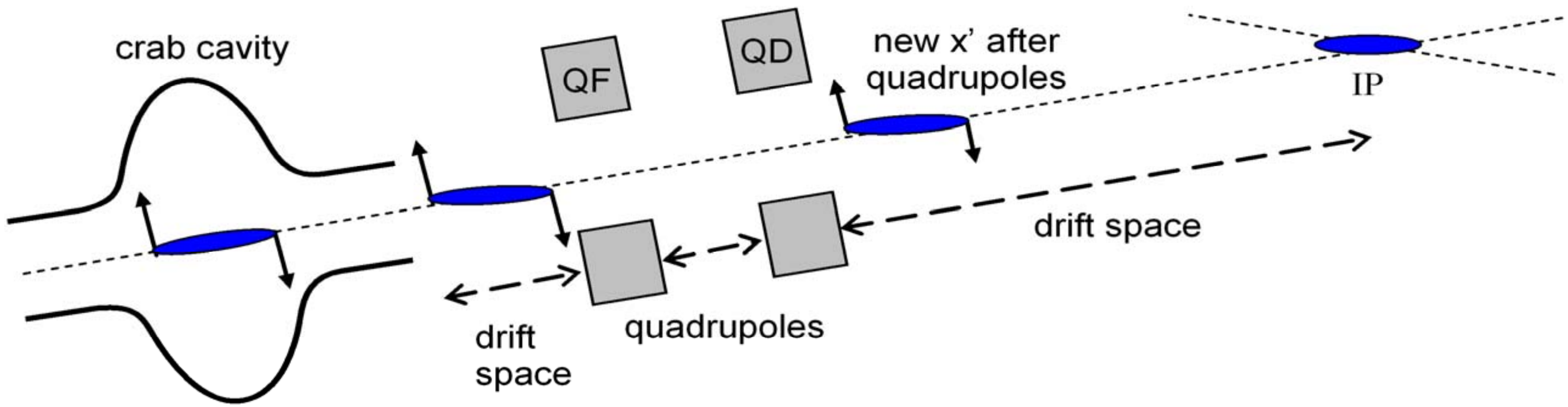
Several time reduction in Luminosity without corrections.



The loss of luminosity for ILC with 14 mrad crossing angle at nominal parameters is 75% (90% for 20 mrad)

Use of transverse (crab) RF cavity to 'tilt' the bunch at IP to collide the bunches head-on.

Location of Crab Cavity



The crab cavity is located just before the final doublet. The momentum kick provided by the final quadrupoles is small and bunch keeps rotating in the same direction.

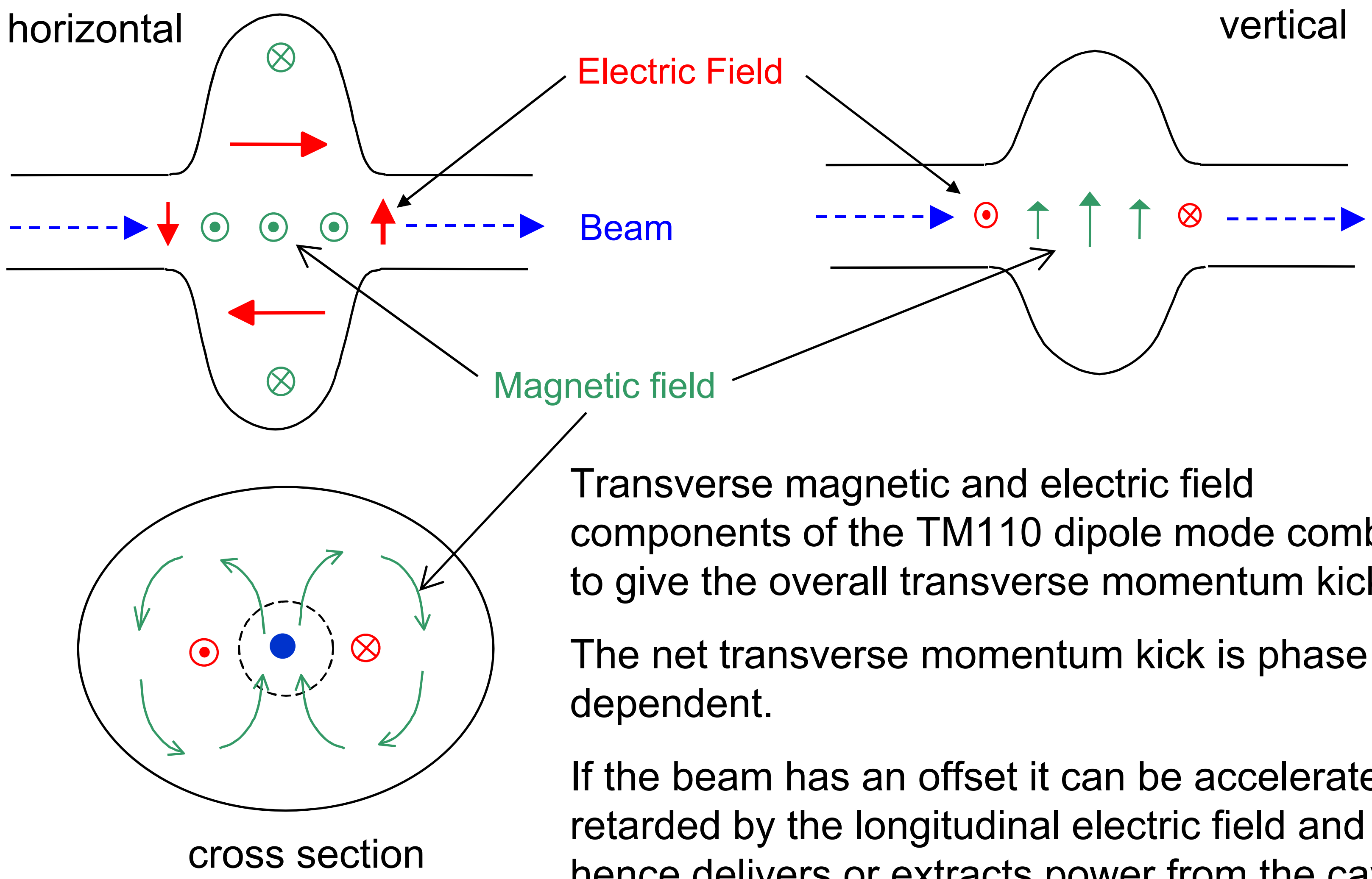
The effect of the final doublet can be expressed in terms of matrix element R12, which determines a transverse displacement at the IP, x_{IP} of a particle at the IP that is on axis at the crab cavity and has a angular direction of x'_{cav}

$$x_{IP} = R_{12} x'_{cav} = R_{12} \frac{V_{\max} \omega \sigma_z}{cE}$$

$$\theta_c = \frac{2 x_{IP}}{\sigma_z} = 2 R_{12} \frac{V_{\max} \omega}{Ec}$$

V_{max}: cavity voltage
ω: angular frequency
E: beam energy

TM110 Dipole Mode Cavity



Transverse magnetic and electric field components of the TM110 dipole mode combine to give the overall transverse momentum kick.

The net transverse momentum kick is phase dependent.

If the beam has an offset it can be accelerated or retarded by the longitudinal electric field and hence delivers or extracts power from the cavity.

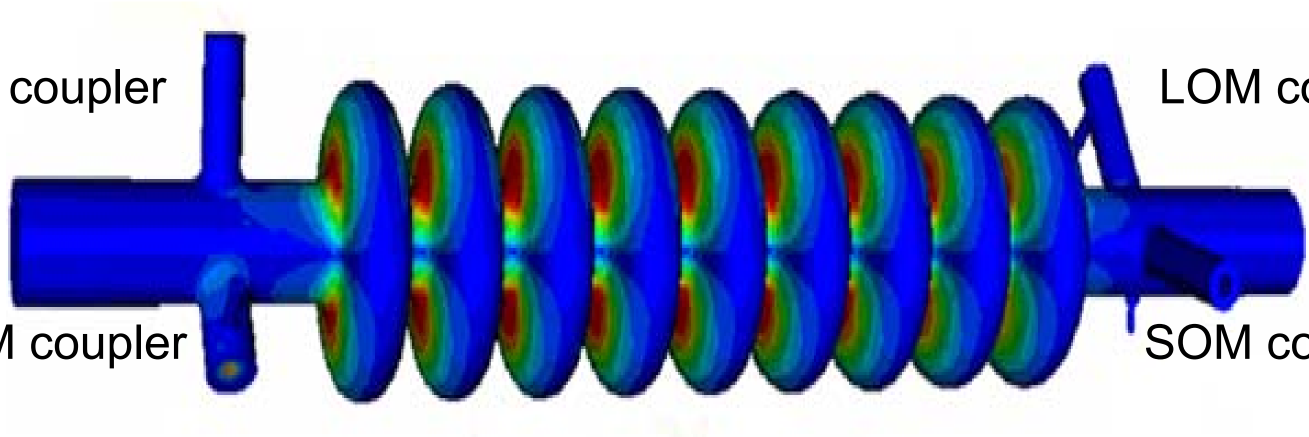
Crab Cavity

Crab cavity for the ILC

Based on FNAL 3.9 GHz CKM cavity

3.9 GHz : compact longitudinally and transversely

3.9GHz cavity achieved 7.5 MV/m (FNAL)

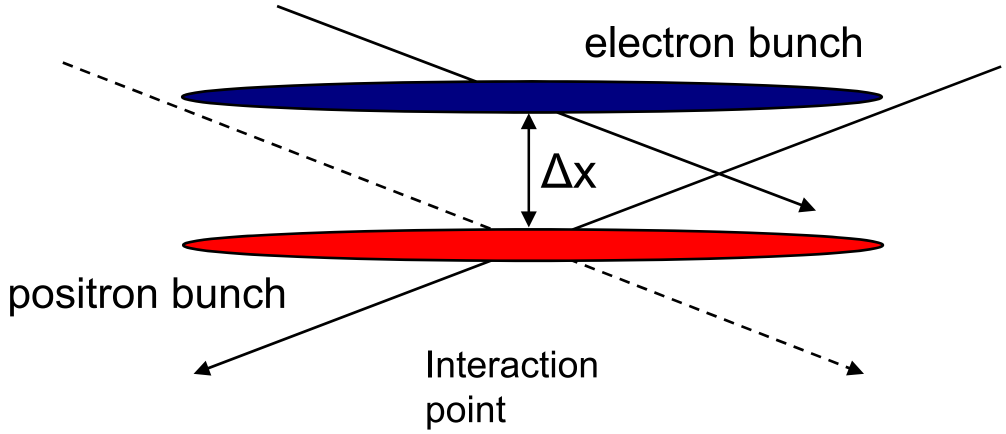


To minimise wakefields, the number of cells must be optimised against overall length.

Crab cavity needs extraction of LOM (avoid unwanted energy spread), SOMs and HOMs.

Crab Cavity Phase Tolerances

Relative phase tolerance between the crab cavities on electron and positron side of the IP is critical as it will cause an horizontal-offset between the beams.



Luminosity reduction factor

$$S = e^{\left(-\frac{\Delta x^2}{4\sigma_x^2}\right)}$$

The allowed timing error

$$\Delta t \approx \frac{2\Delta x}{\theta_c c}$$

Typically set for <2% luminosity loss (S=0.98)

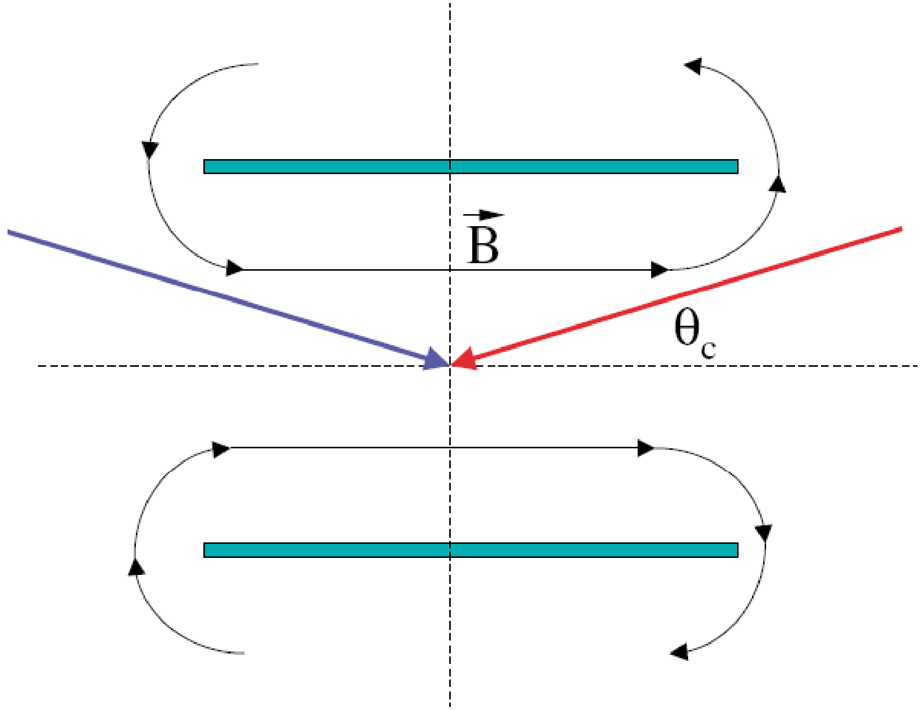
For ILC nominal parameters σ_x=639nm, Δx=181nm, Δt=86 fsec

ILC phase tolerance ~80 fsec, state of the art.

CLIC phase tolerance requirements: harder by a factor?

Beam at Crossing Angle Through Solenoid

- The beam crossing a strong solenoid field at horizontal crossing angle experiences a vertical deflection.
- The deflections can result in a net offset of the beams at the IP, beam size growth due to vertical dispersion and emission of synchrotron radiation.
- The optical effects from the crossing angle (vertical offset and dispersion) vanish at the IP due to the azimuthal symmetry of the detector solenoid. This is due to the fact that the deflections introduced due to solenoid's longitudinal field and its radial fringe field cancel each other.

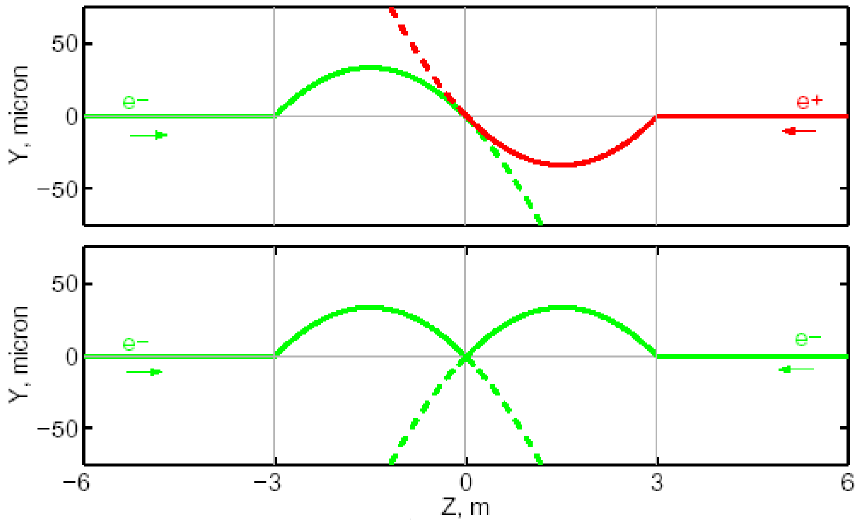


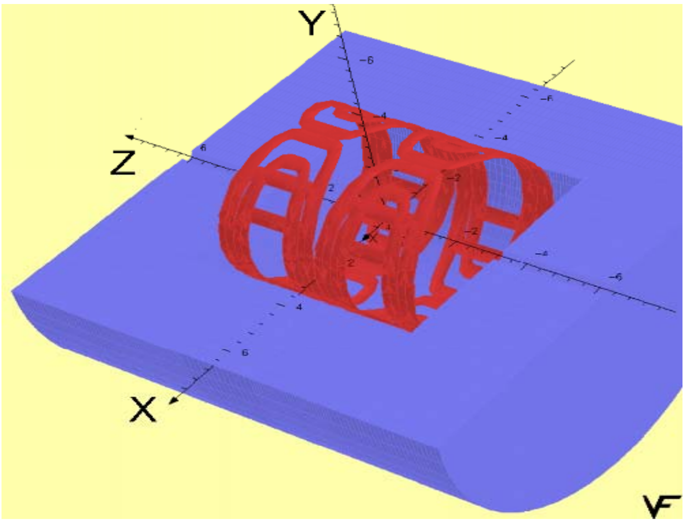
Schematic view of the two beams colliding with a crossing angle in the detector solenoid.

Detector Integrated Dipole

For e+e- the orbit is anti-symmetrical and beams still collide head-on.

If the vertical angle is undesirable (to preserve spin rotation or the e^-e^- luminosity), it can be compensated locally with 'Detector Integrated Dipole' (DID).





DID : Coil wound on the detector solenoid, giving transverse field, such that the combined field from solenoid, DID and QD0 would cancel the vertical angle at the IP.

Correction is local and effective.

But, the post IP field is doubled, giving double crossing angles for outgoing pairs. This increases the background in the detector.

Synchrotron Radiation Effects in Solenoid

Vertical orbit caused by crossing angle would cause emission of synchrotron radiation ⇒ causes growth of energy spread ⇒ beam size increase in vertical plane.

For crossing angle of θ_c and solenoid field 'B' and length 'L', the increase in the beam size is

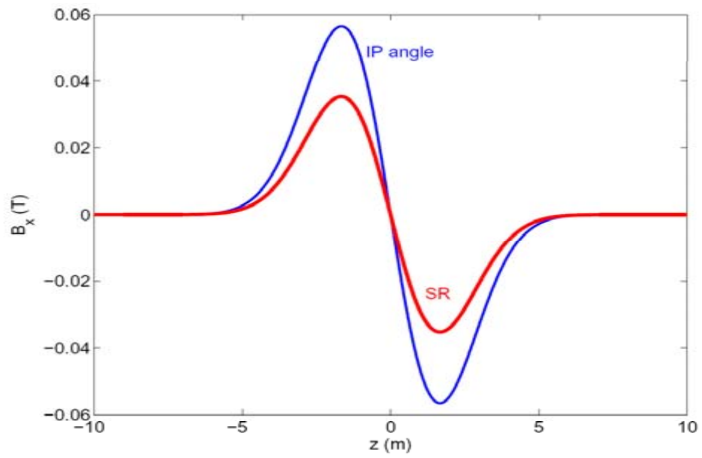
$$\Delta\sigma_{SR} \sim (BL\,\theta_c)^{5/2}$$

The increased vertical beam size is

$$\sigma_y = (\sigma_{y0}^2 + \Delta\sigma_{SR}^2)^{1/2}$$

e.g. for SiD detector solenoid field map and θ_c=20mrad

☟ σ_{SR}= 0.22 nm, σ_{y0}~ 5 nm.



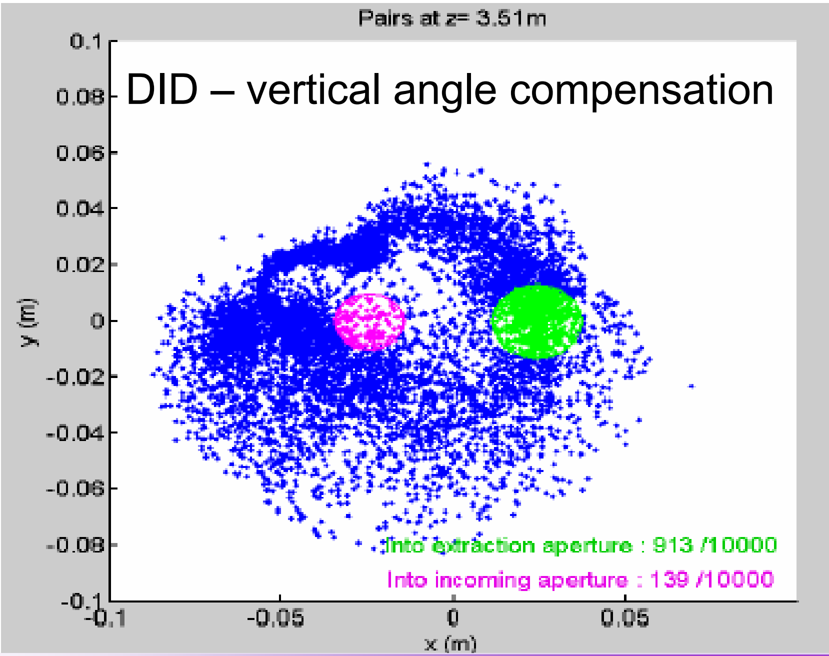
Using DID, it is possible to either flatten the vertical orbit [to eliminate the SR beam growth or to zero the IP angle (for polarisation)]

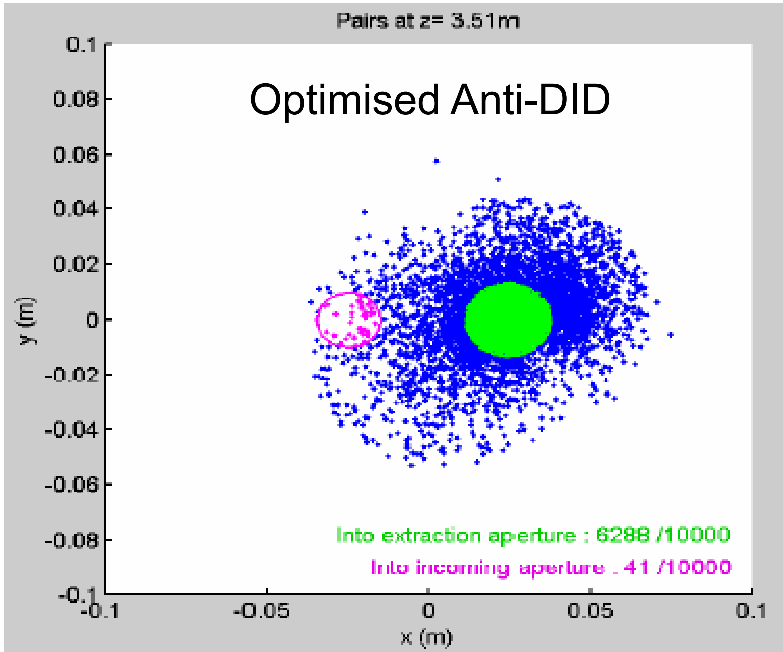
Proposed Anti-DID for ILC

The DID locally compensates the effect of crossing solenoid field for the incoming beam. But doubles the field seen by the outgoing beam (and low energy pairs), which increases the background.

Proposed solution for intermediate crossing angle is to reverse the polarity of DID ⇒ Anti-DID. This will effectively zero the crossing angle for the outgoing beam and pairs. But doubles the angle for the incoming beam.

Increasing this angle will increase the beam size growth due to SR, but this growth ~$(\theta_c)^{5/2}$ and is small for proposed 14mrad crossing angle for the ILC.



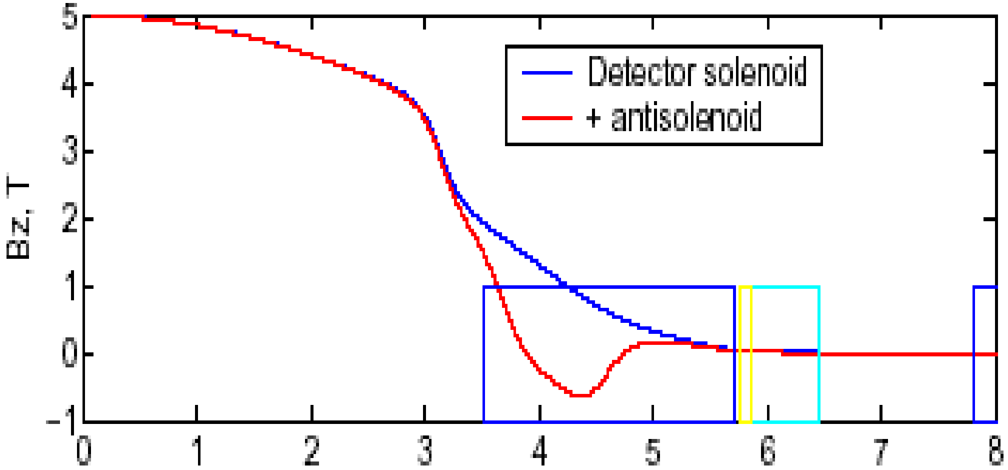


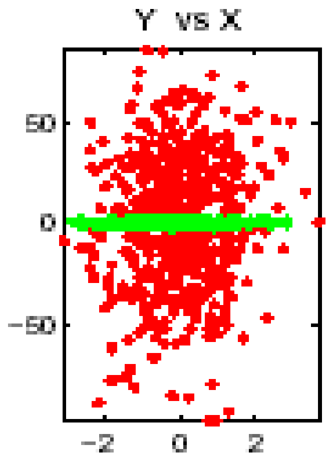
Overlap of Detector Solenoid Field and Final Quadrupole

The detector solenoid field can overlap the final doublet magnets, the degree of this overlap depends upon L* and field map of the detector solenoid.

This causes coupling between y & x' and y & E and can cause large increase in the IP beam size.

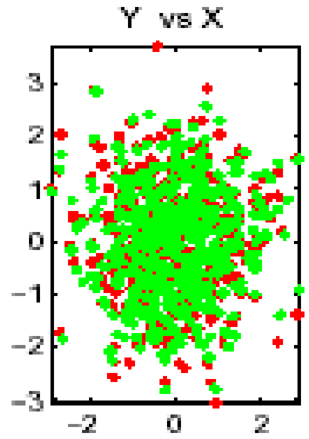
This effect can be corrected using skew quadrupoles but the use of anti-solenoids provide local compensation of the fringe field and correction works over wide range of beam energies.





without compensation

$\sigma_y / \sigma_y(0)=32$



with compensation by antisolenoid

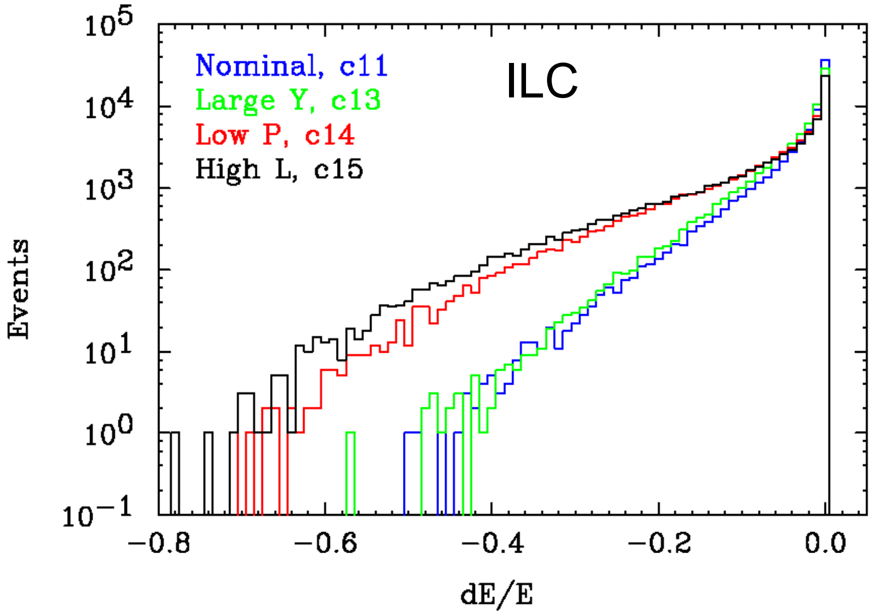
$\sigma_y / \sigma_y(0)<1.01$

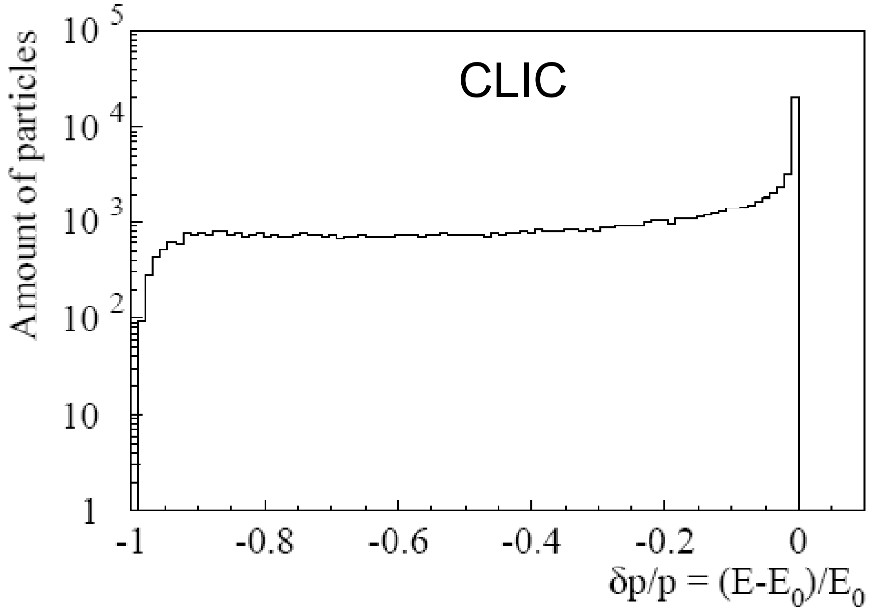
Beam Extraction

Beam Extraction after Collision

Intense e+e- collision creates disrupted beam :

- Huge energy spread and large x,y divergences (emittance) in the outgoing electron beam.
- High power divergent beamstrahlung photon beam going in the same direction with electrons.





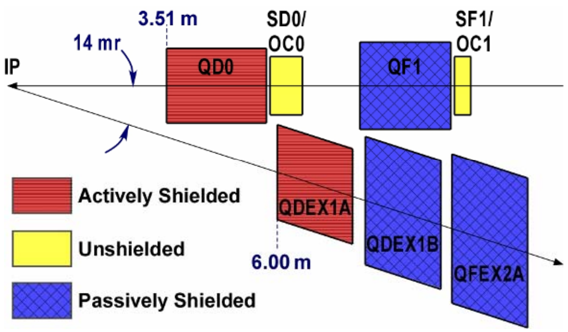
Potential high beam loss in the extraction line due to over-focusing of low energy electrons and divergence of the photon beam.

Beam Extraction after Collision - Design Requirements

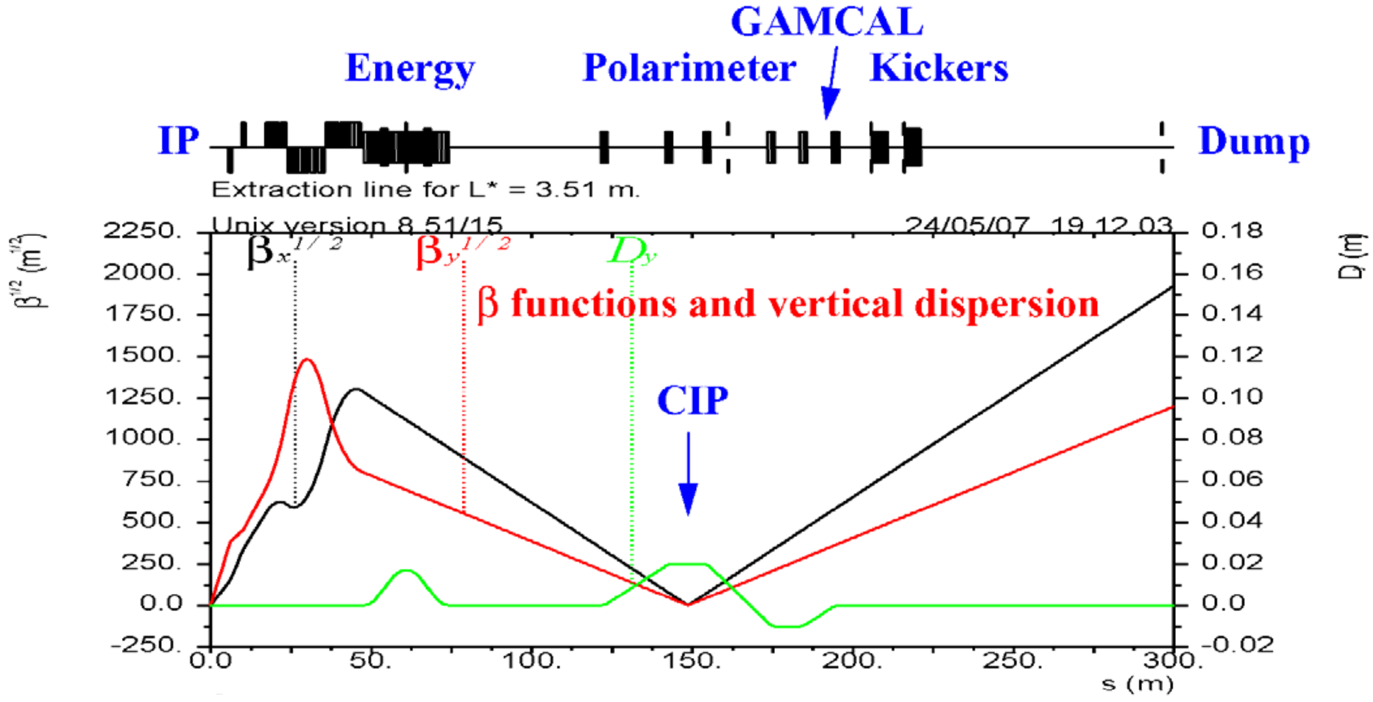
- Safely transport the outgoing e+/e- and (beamstrahlung) photon beams from IP to main dump(s).
- Minimize beam loss from strong overfocusing and dispersion of low energy electrons $\Rightarrow$ requires careful optimization of energy dependent focusing and sufficient aperture.
- Minimize beam loss from the divergent beamstrahlung photons $\Rightarrow$ requires large aperture increasing with distance.
- Provision of downstream diagnostics to measure beam energy and polarization $\Rightarrow$ preferred for physics analysis at collision.
- Protect magnets and post-IP diagnostic devices from unavoidable beam loss and undesirable background.
- Avoid damage to dump window and prevent water boiling in the dump vessel from small undisrupted beam or under abnormal optical conditions (large errors, magnet failures) $\Rightarrow$ requires enlargement of beam size at the dump window by optical means.

ILC Beam Extraction

- 14mrad crossing angle configuration provides separate beam channels for outgoing and incoming beams. The compact superconducting design/technology can be safely pushed to provide this.

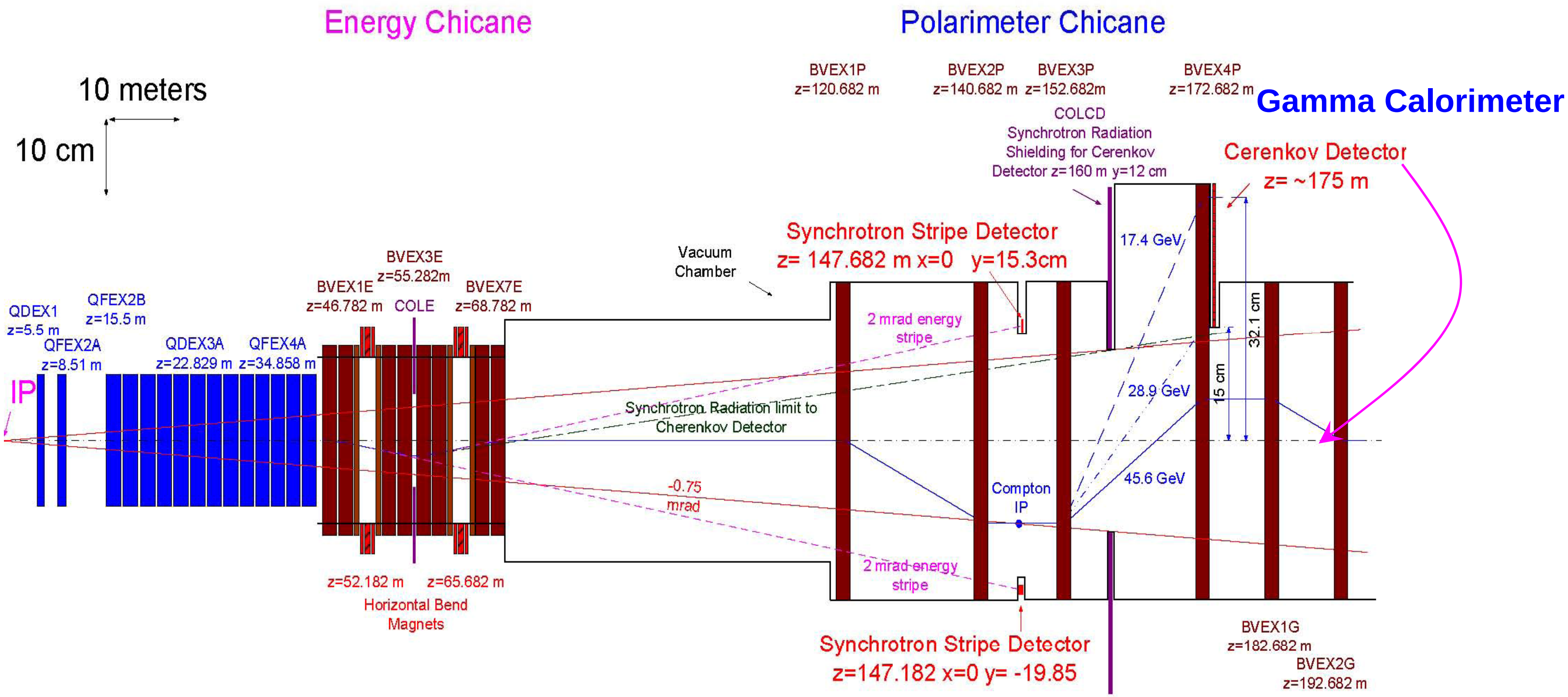


- Beam losses at dedicated collimators, one beam dump for main beam and photons. Dedicated chicanes for polarimetry and energy measurements.



Extraction Diagnostics: 14 mrad

- Energy measurement using synchrotron radiation created in 8-bend vertical chicane with horizontal bump magnets.
- Polarization measurement using laser to produce Compton-scattered electrons at extraction focal point in the 4-bend chicane.
- Luminosity diagnostic using GamCal between 2 vertical bends.

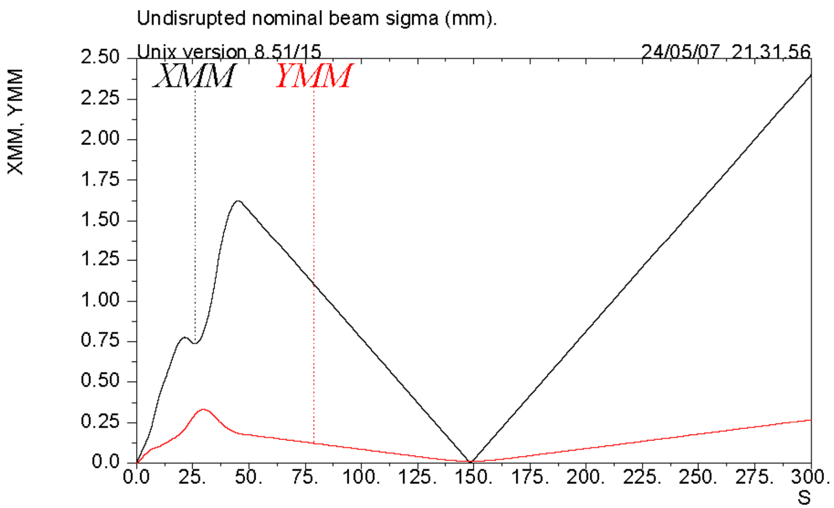


Fast Sweeping System

- System of fast (1 kHz) X-Y kickers is included to sweep bunches of each train in one turn on 3 cm circle at the dump window.

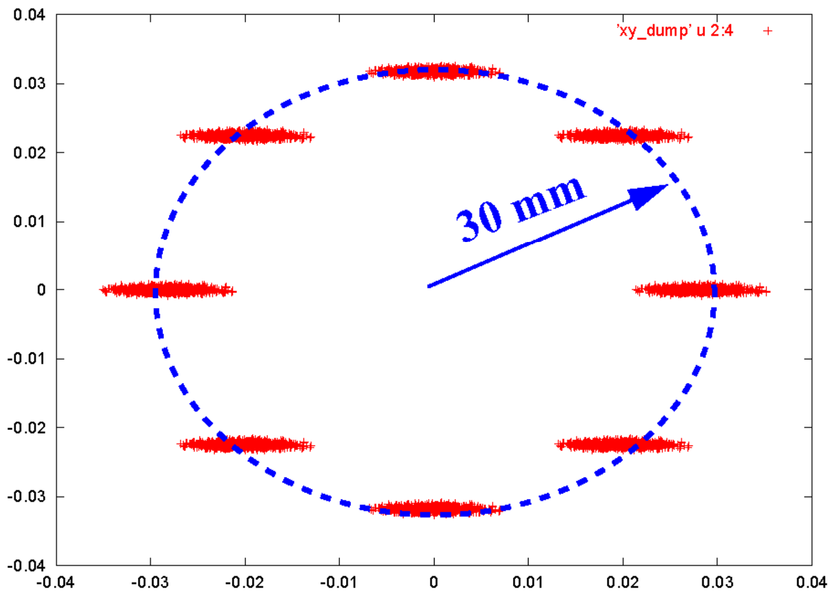
- It enlarges the beam area to protect from window damage and water boiling caused by very small beam size in cases of undisrupted beam or under certain abnormal optics conditions (large errors, magnet failures).

Undisrupted σ (mm)



14 mrad ILC beam extraction line

Undisrupted bunches at dump



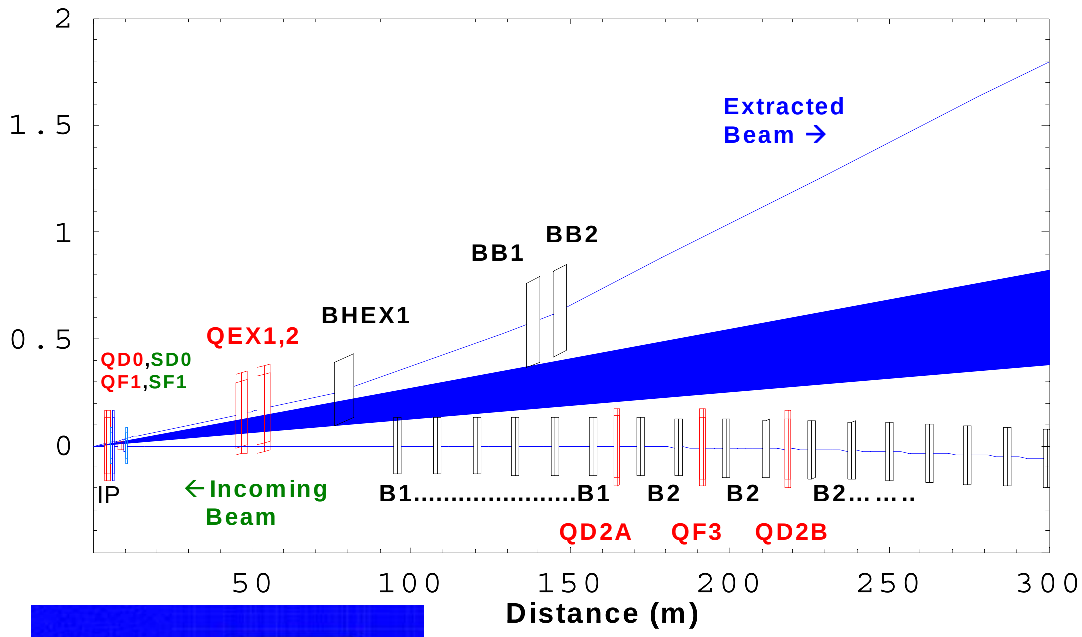
Small/zero Crossing Angle Configurations

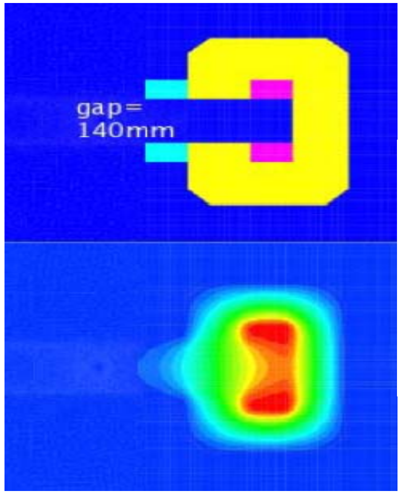
Small crossing angle/head-on designs possible with cold technology.

- Focusing and colliding easier
- No pre-IP constraints
  - Crab-cavity control & tuning
  - Non-axial solenoid + DID / anti-DID ➔ pre / post-IP trajectory bumps
- Physics & detector advantaged
  - Simpler forward geometries
  - Better hermeticity
  - No DID / anti-DID
- Extraction more difficult
  - Dispersion of low energy tails
  - Challenging beam usage and transport to the dump

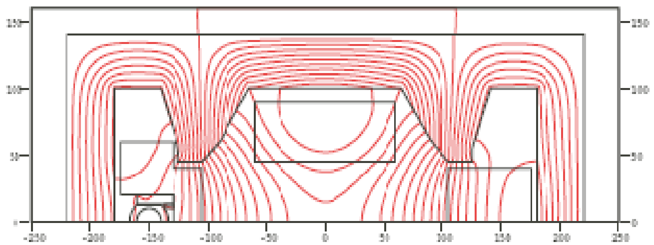
2mrad crossing angle and modified-head on schemes have been proposed for the ILC.

Minimum Extraction Line Solutions for 2 mrad Scheme





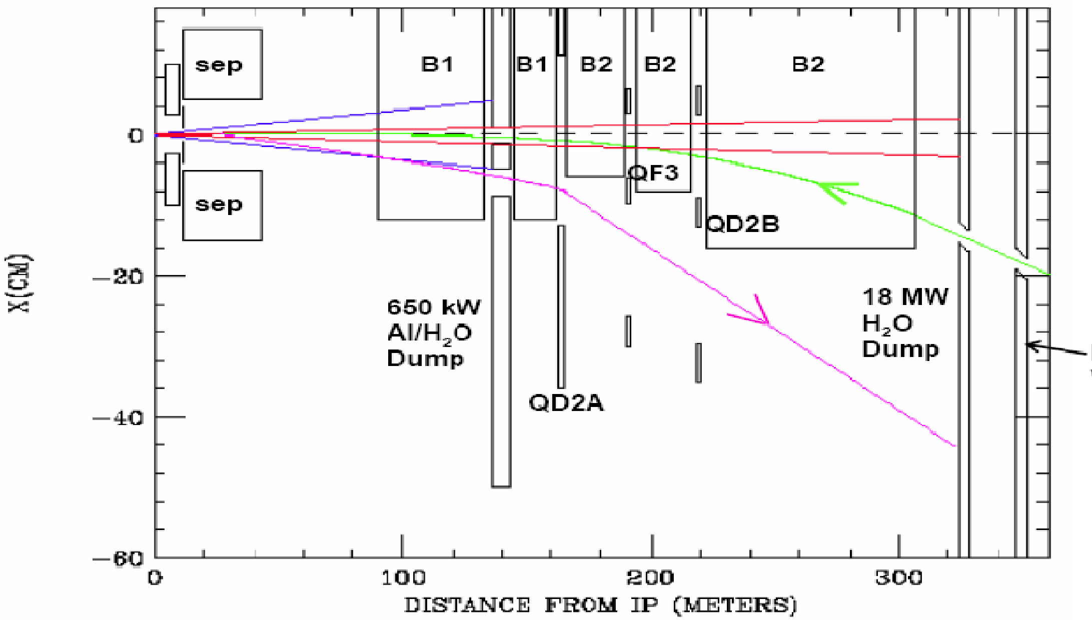
BHEX1

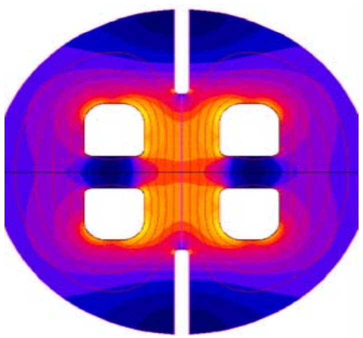


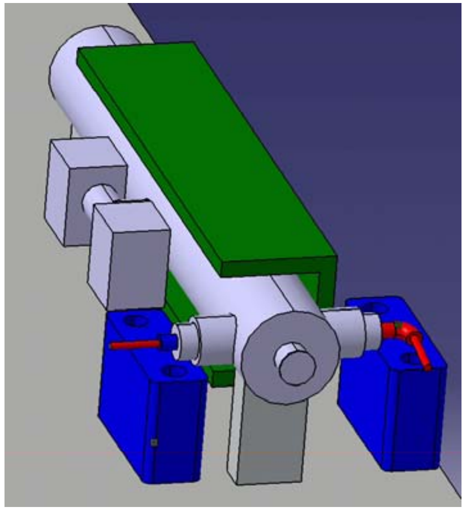
QEX1

- Dipole kick from beam passing through opposite QD0 at 2 mrad for extracted beam.
- Challenging beam optics and magnet designs.
- Final doublet and minimum extraction line optimised to reduce losses near IR and beam losses on dedicated collimators.
- Magnetic fields from extraction line magnets need to be absorbed in the final focus.
- Alternate ideas for measuring energy, polarisation and collision parameters.

Minimum Extraction Line Solutions for Modified Head-on Scheme







Electrostatic separator

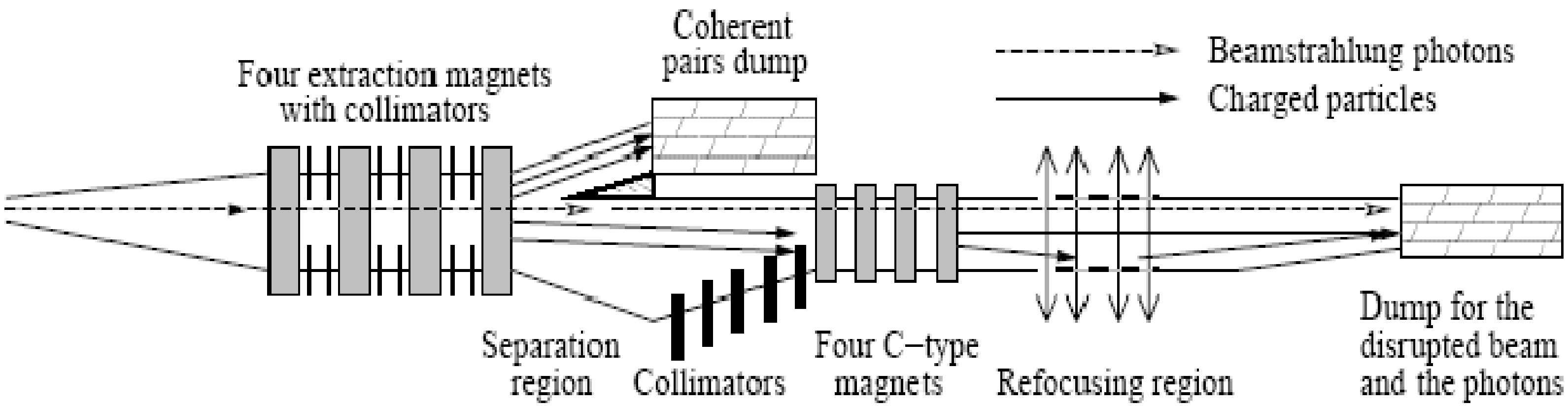
- Electrostatic separators + dipole kick from final focus quadrupole.
- This reduces required kick from electrostatic separators.
- Optimisation of final focus to accommodate the separators.
- Parasitic bunch crossing
- Over-focusing of low energy tail particles increase beam losses ⇒ Intermediate beam dump.
- Alternate ideas for energy and polarisation measurements.

CLIC Beam Extraction Conceptual Design

The design relies on the separation by dipole magnets of the disrupted beams, the beamstrahlung photons and the particles from e+e- pairs with the wrong sign charge. It is followed by a transport to the beam dump in dedicated lines :

- A short one for the wrong-sign charged particles of the coherent pairs, to prevent the transverse beam size from increasing too much.

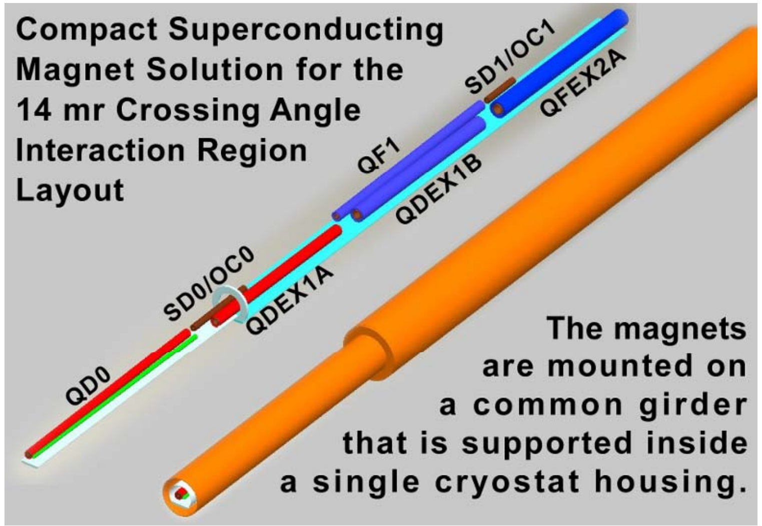
- A much longer one for the disrupted beam and the beamstrahlung photons, to avoid a too small spot size for the undisrupted beam on the beam dump window.

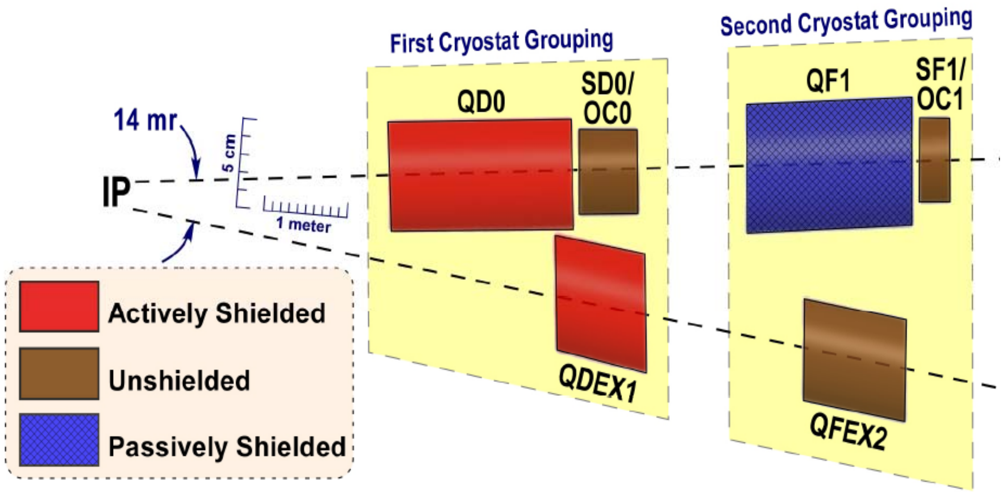


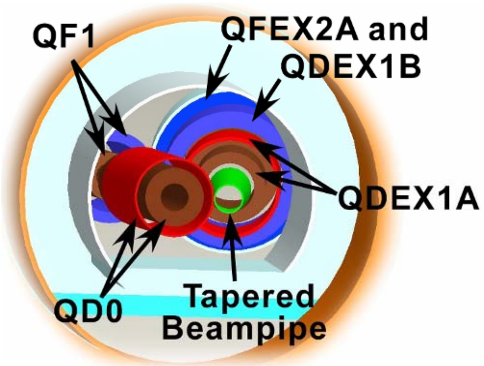
Not to scale

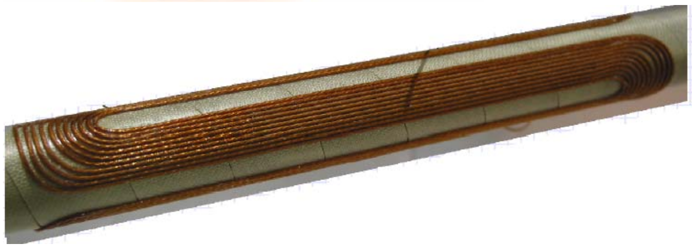
Interaction Region

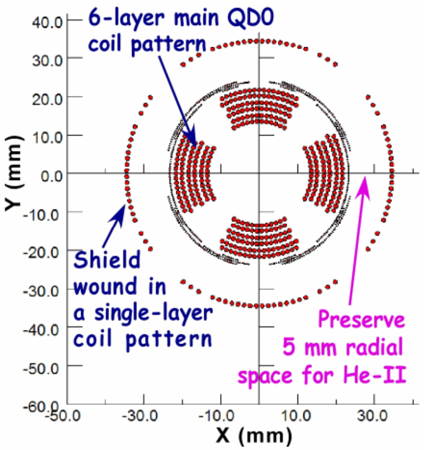
14 mrad Interaction region - ILC

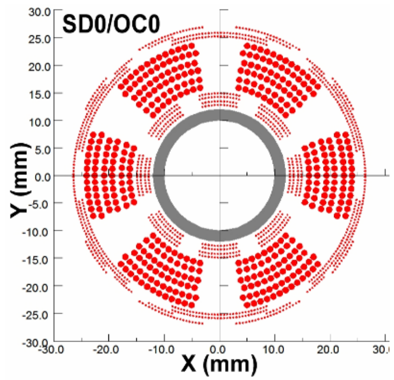




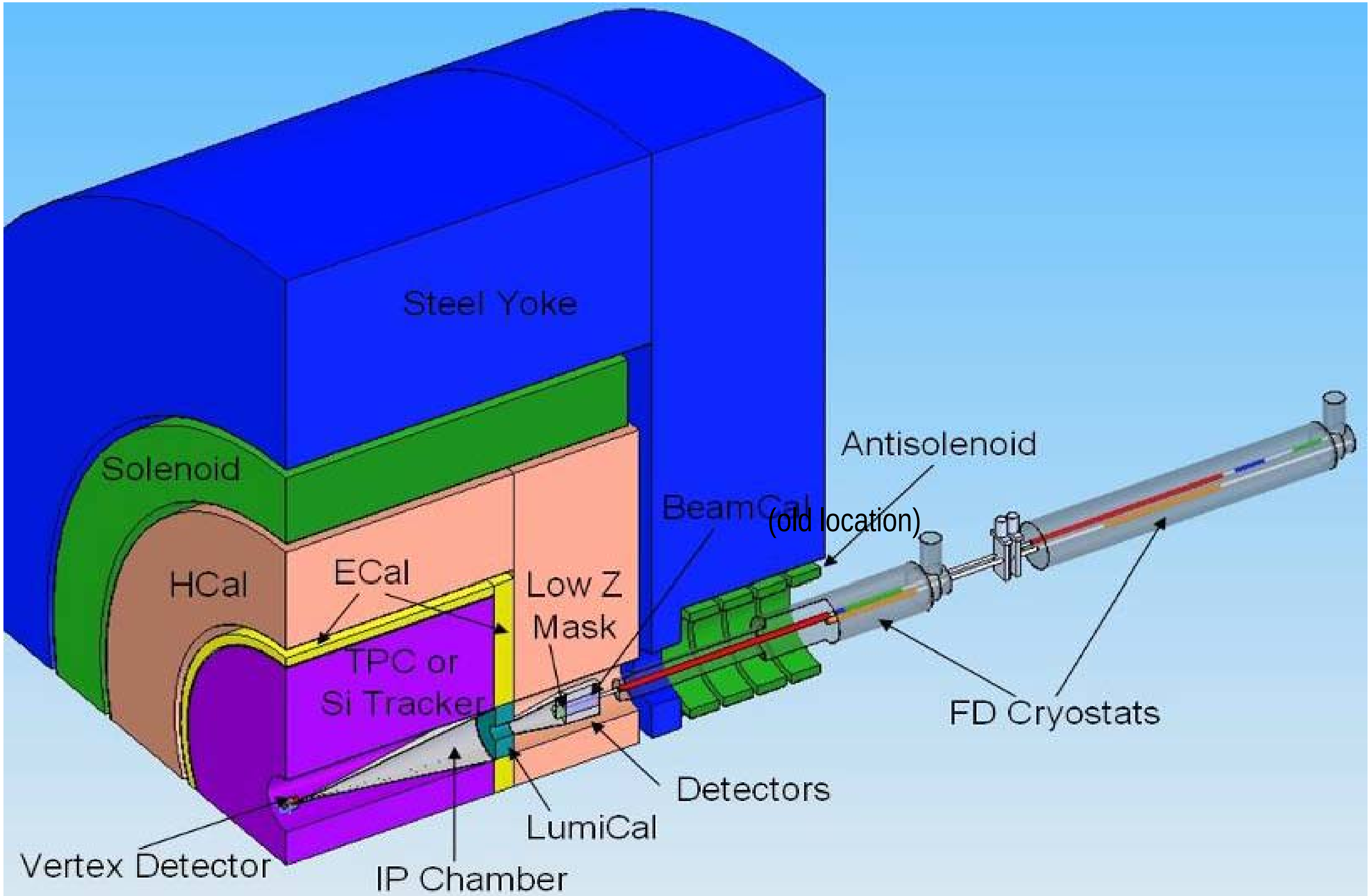








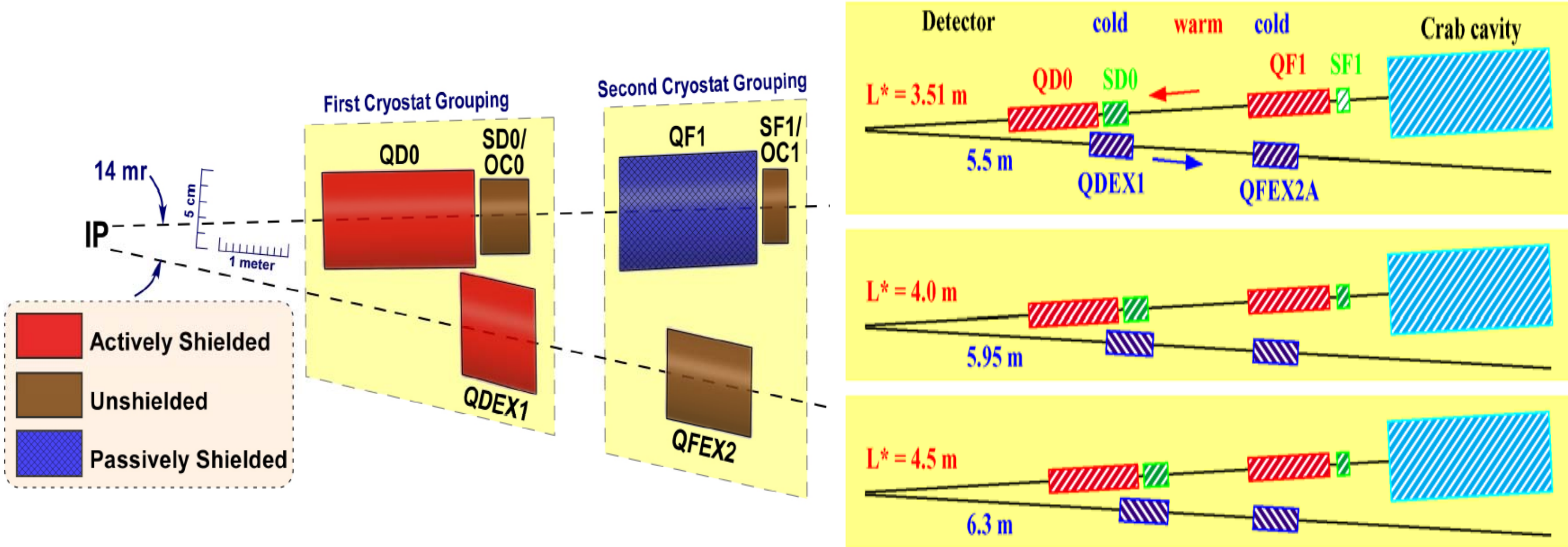
ILC IR integration



Push-pull Configuration

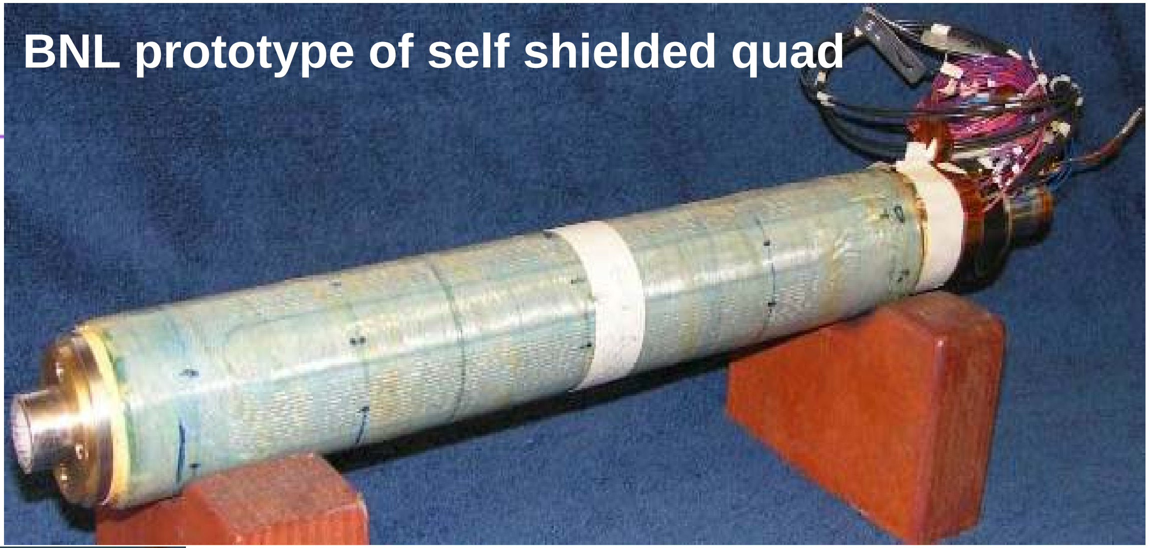
Two complementary detectors in push-pull configuration for ILC (proposed for CLIC as well).

Final doublet is grouped into two cryostats, with warm space in between which provides a break point for push-pull.

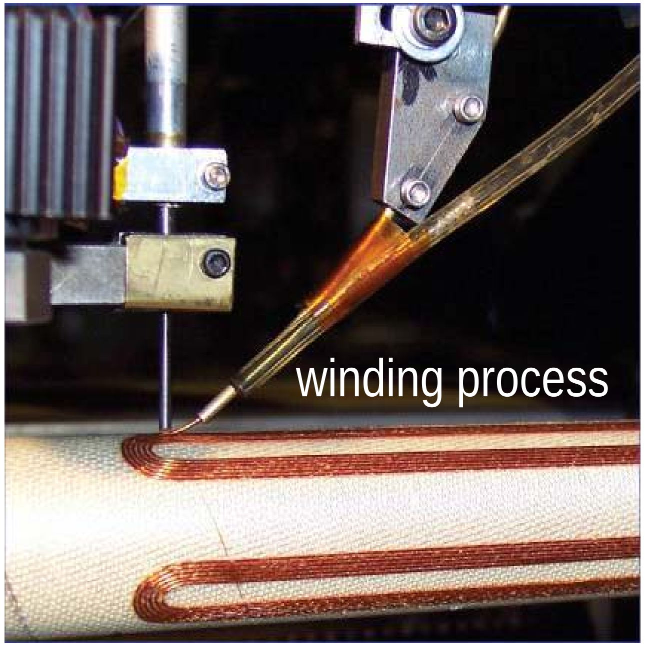


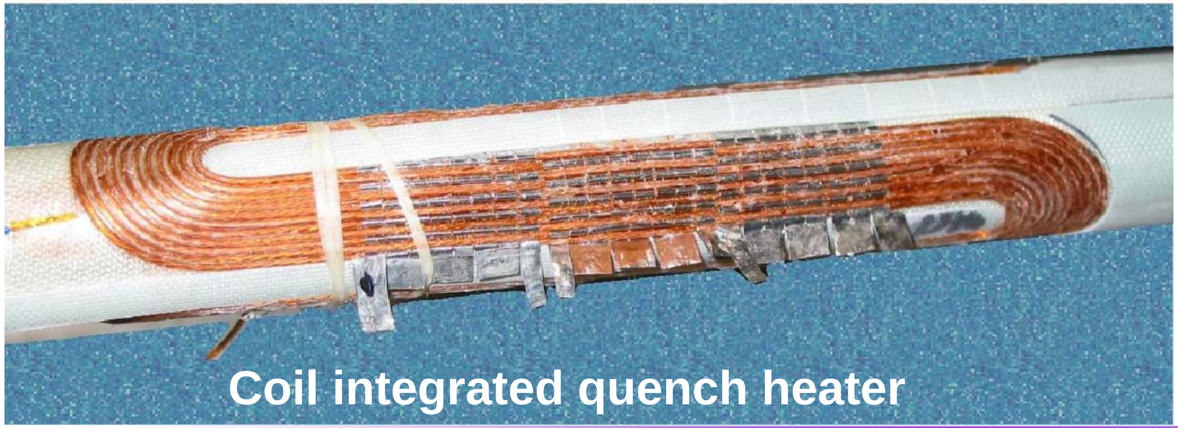
Detector moving in/out of the beamline : time required, moving mechanism, shielding, service cryostat, detector assembly. Need to cater for different detector concepts.

IR Magnets Prototypes



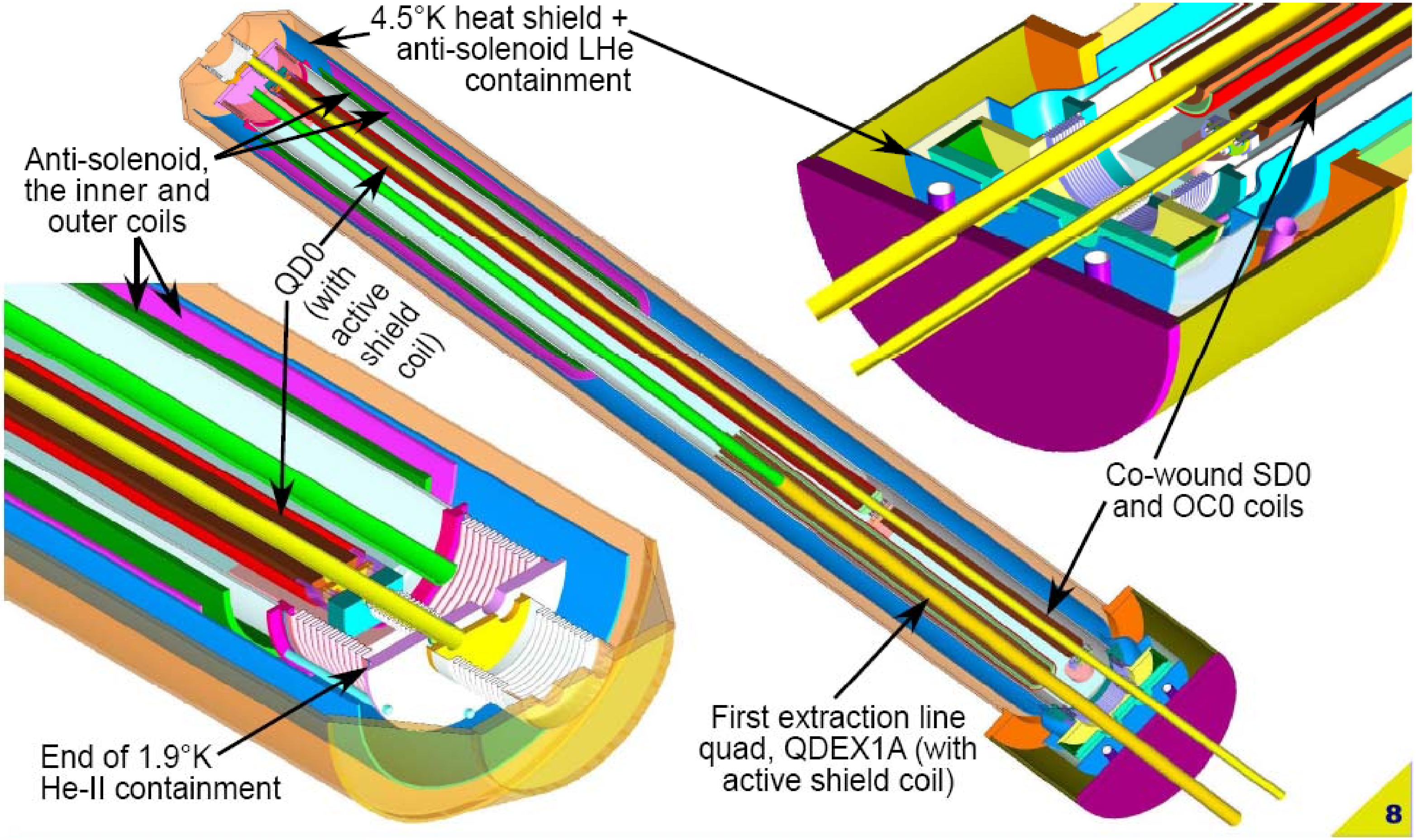
Cancellation of the external field with a shield coil has been successfully demonstrated at BNL

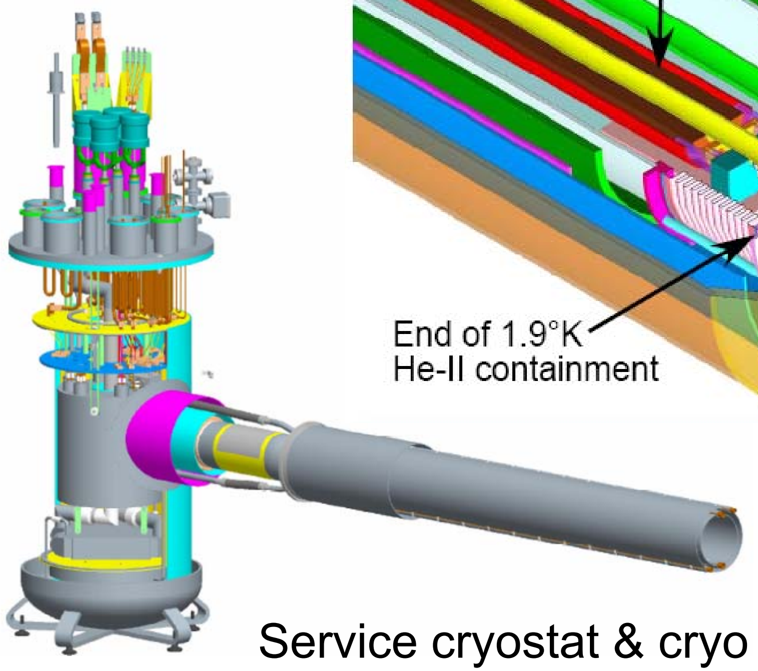




IR Magnets

BNL



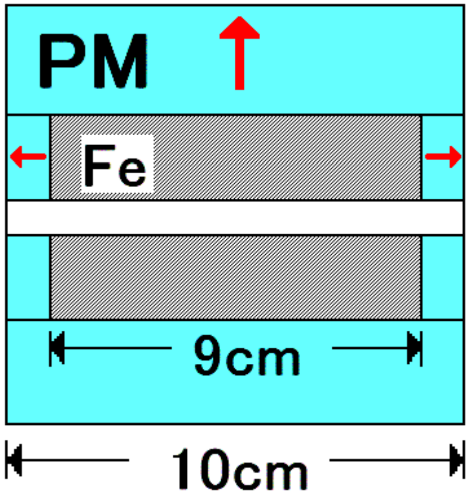


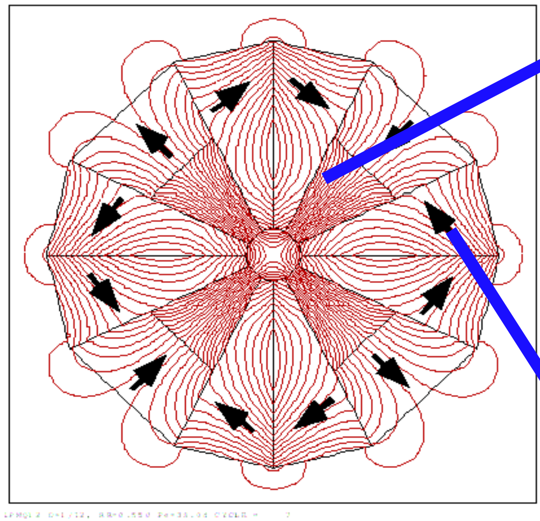
Service cryostat & cryo connections

Permanent Magnet Quadrupole

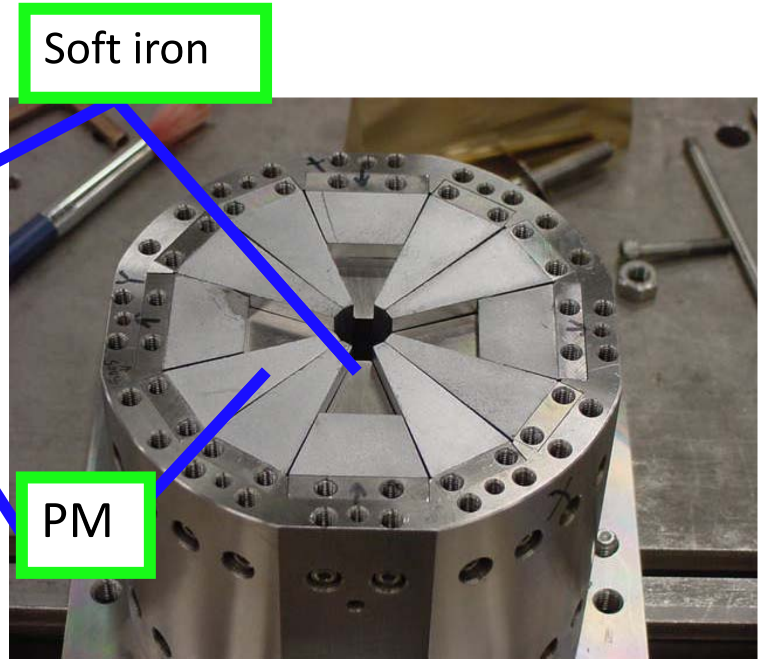
Permanent Magnet Quadrupole – considered for CLIC.
Superconducting option being explored.

Cut plane view





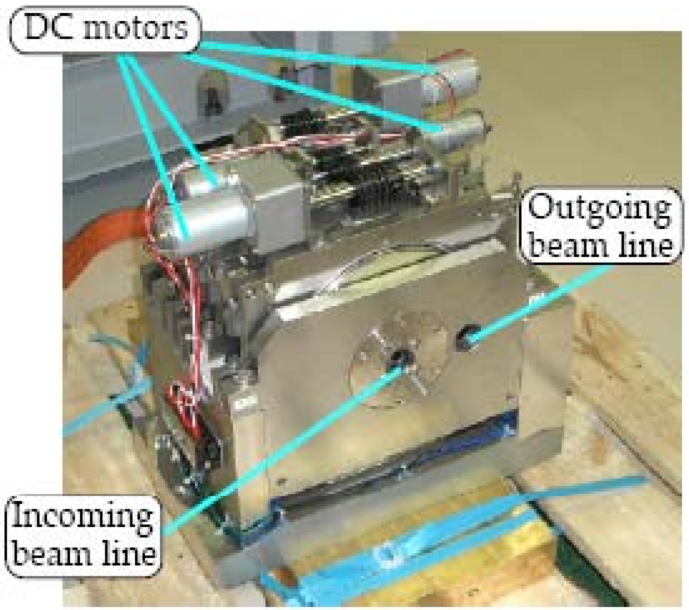
Axial view

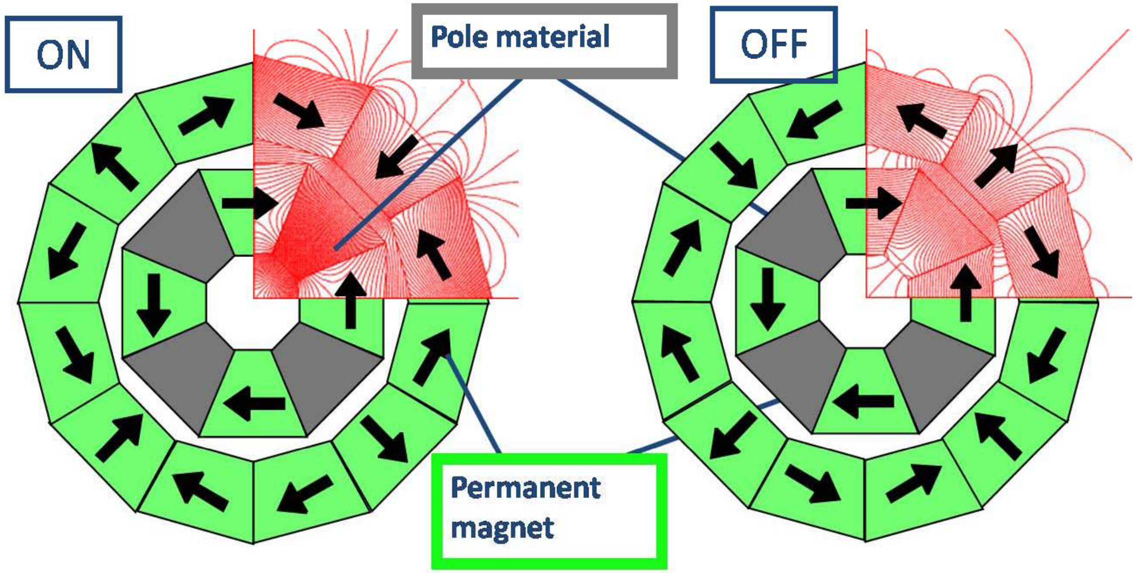


Integrated strength GL=28.5T (29.7T by calc.)
Magnet size. ϕ10cm
Bore ϕ1.4cm
Field gradient is about **300T/m**

$$GL = \int \frac{dB}{dr} dz$$

Double Ring Structure – Adjustable PMQ





The double ring structure

PMQ is split into inner ring and outer ring. Only the outer ring is rotated 90° around the beam axis to vary the focal strength.

Machine Detector Interface (MDI)
and
Background Sources

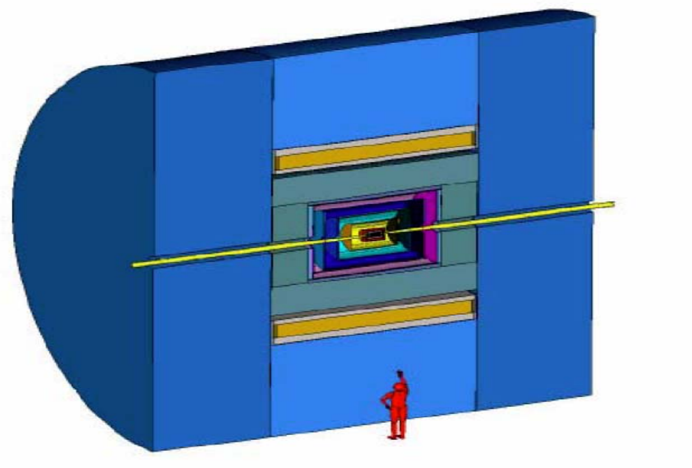
Machine Detector Interface

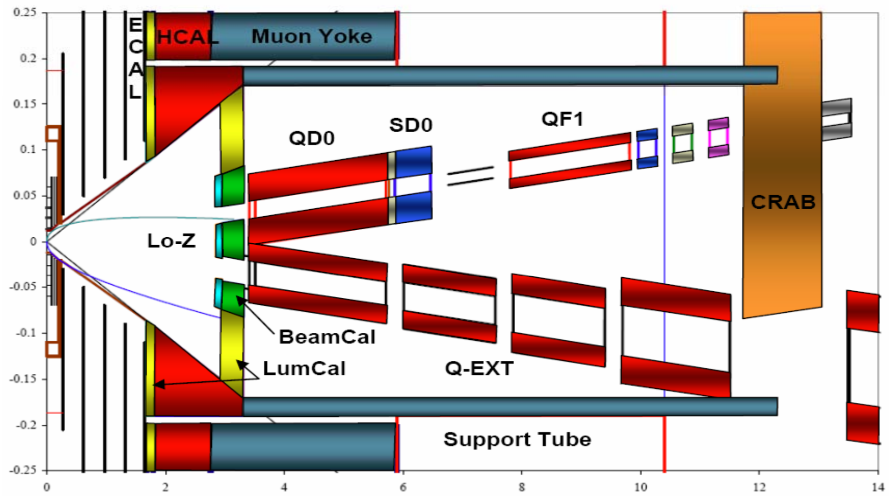
Machine

Luminosity
Backgrounds
Diagnostics
……….

Detector

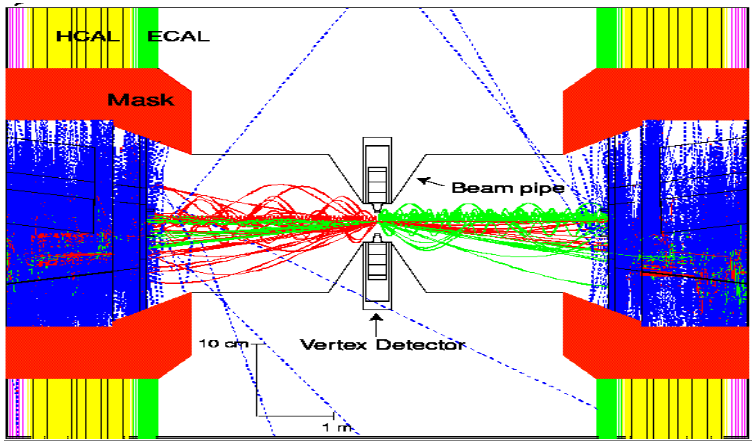
Physics





Background Sources

- Beam-beam background at IP
  - beamstrahlung
  - coherent/incoherent pairs
  - hadron production
  - secondary neutrons
- Machine produced background before IP
  - beam tails from linac
  - synchrotron radiation
  - muons
  - beam-gas scattering
- Spent beam background
  - backscattered particles
  - neutrons (from dumps)



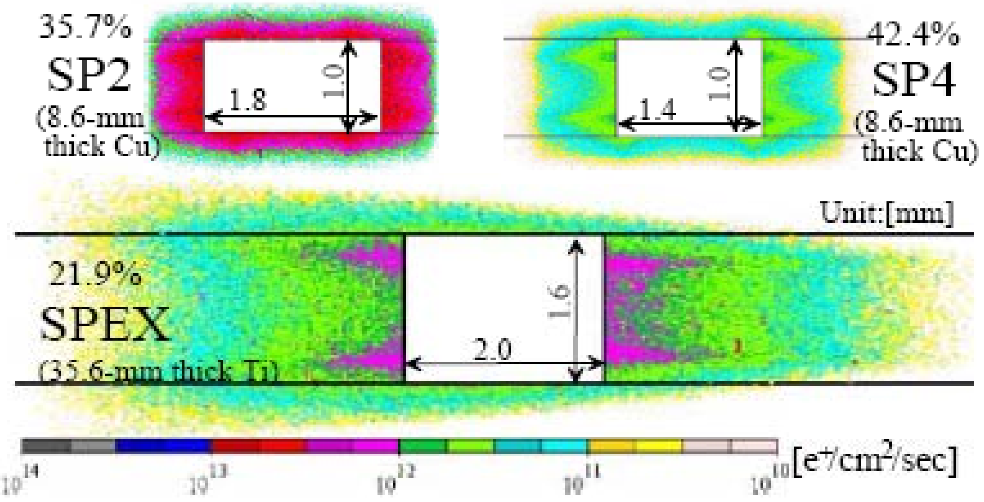
Backgrounds affect linear collider detector performance in three major ways :

- Detector component radiation aging and damage.
- Reconstruction of background objects (e.g. tracks) not related to products of e+e- collisions
- Deterioration of detector resolution (e.g., jets energy resolution due to extra energy from background hits).

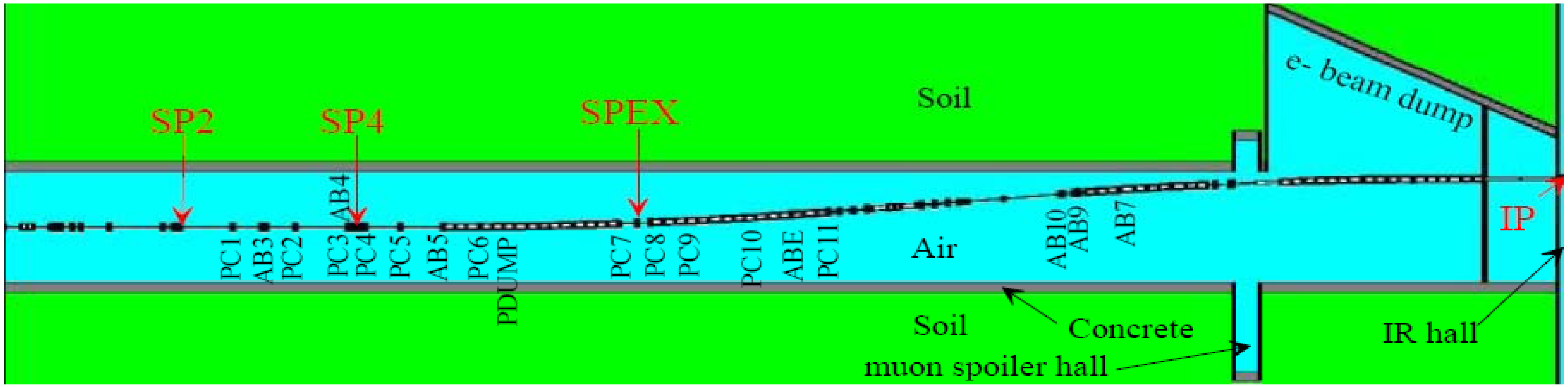
Muons in BDS

Muons are generated when beam halo is collimated at the collimators. The rate depends on assumption of beam halo.

Suppression of muon background in the interaction region is one of the most important issues for the collider detector performance.



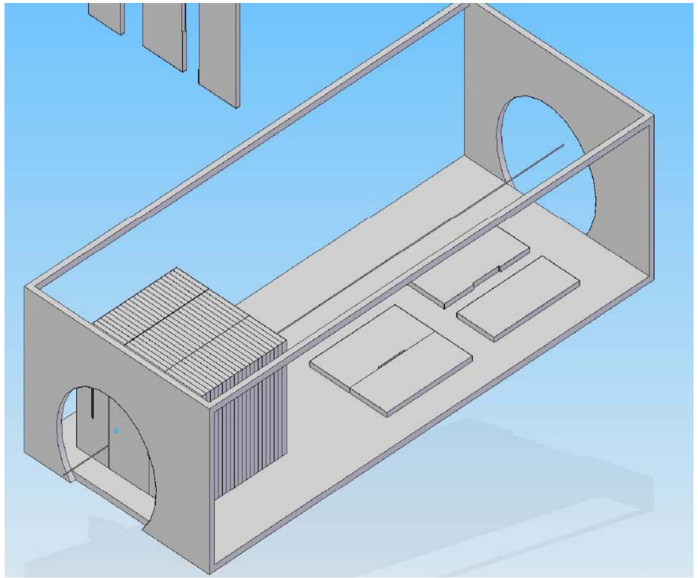
Profiles of the 250 GeV positron beam halo at the three primary collimators in the ILC BDS using STRUCT code (FNAL)



A top view of the BDS tunnel with the entire beam line described in MARS15(FNAL) simulation.

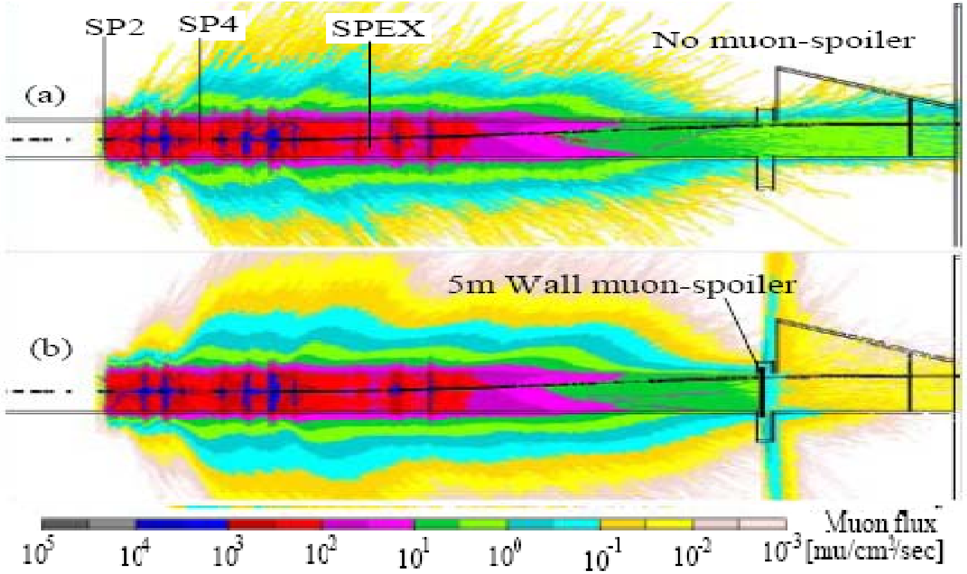
Muons in ILC BDS

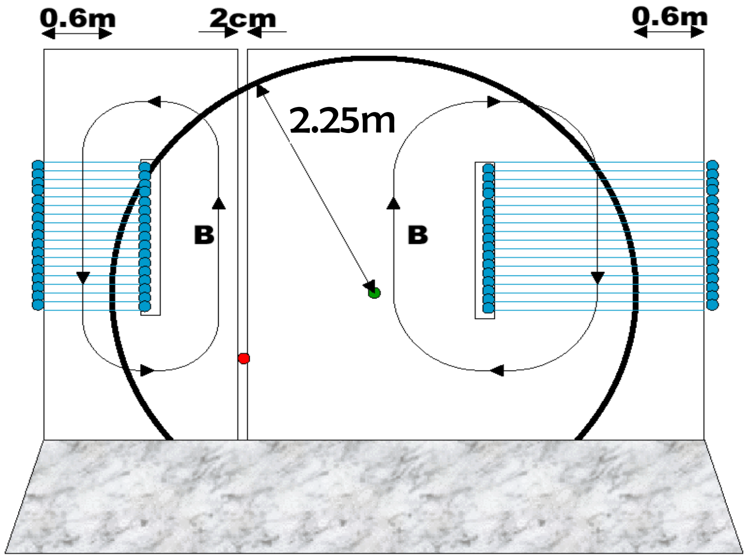
For ILC, thick steel 1.5Tesla magnetic wall sealing the tunnel cross-section, to spray the muons out of the tunnel has been proposed.



The 5m wall is located at ~300m from the IP, which suppresses the muon background by 1/50. Provision to extend this wall to 18m exists.

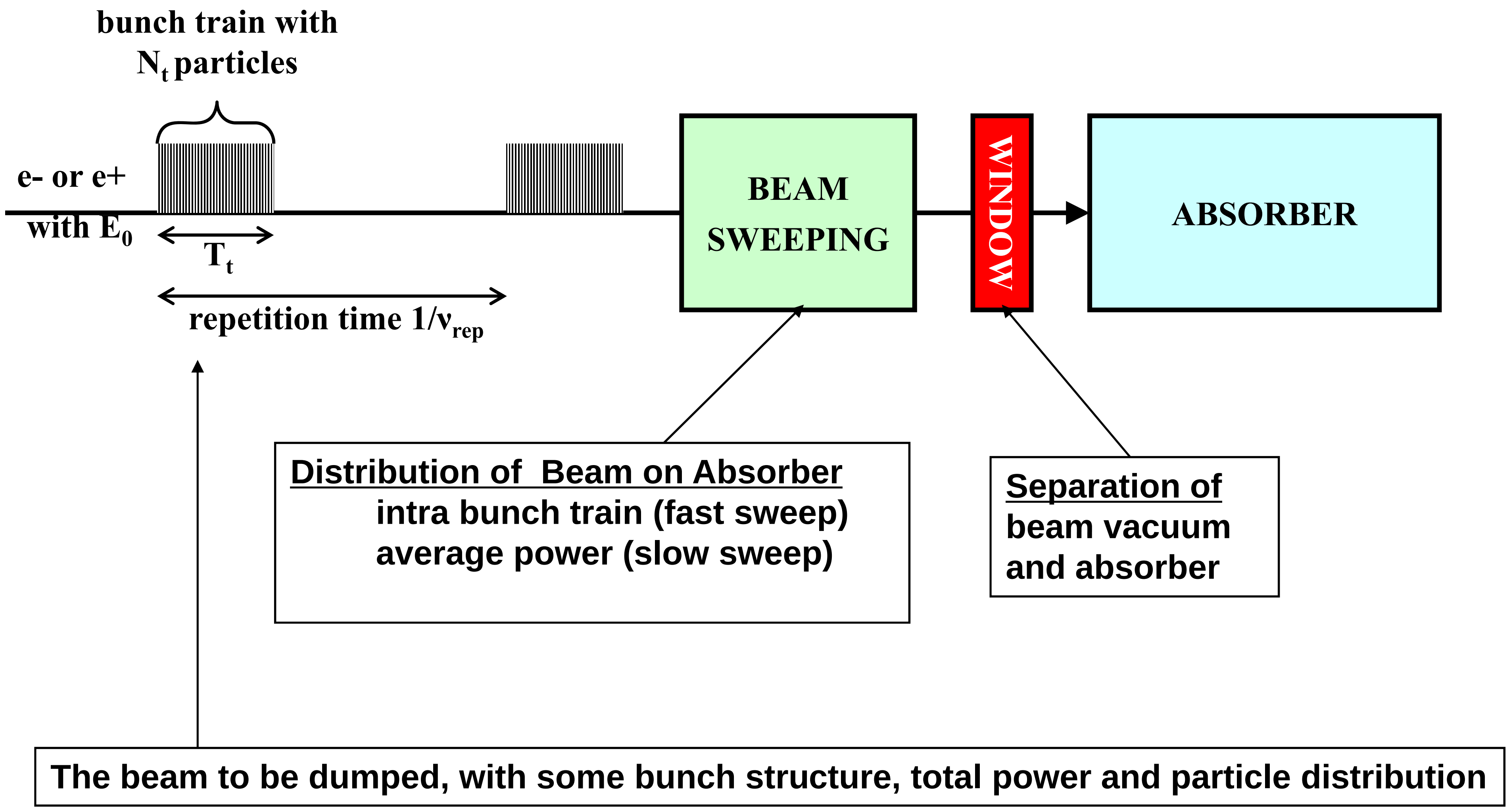
The wall also serves as radiation protection for the collider hall when beam is present in the linac and BDS switchyard.





Beam Dump

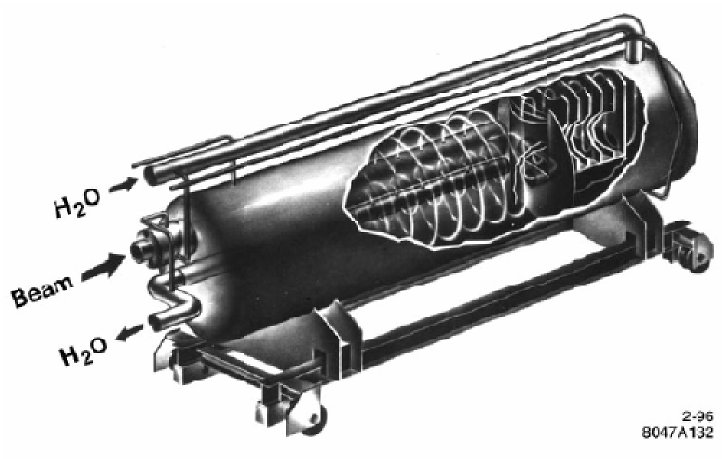
A Generic Beam Dump Layout



Beam Dump

Options for beam dumps

- Solid dump (Graphite based) → Limited by heat extraction (not an option)
- Water based → Most viable, experience at SLAC for 2 MW dump design
- Gas dump → was proposed as an option for TESLA, not pursued



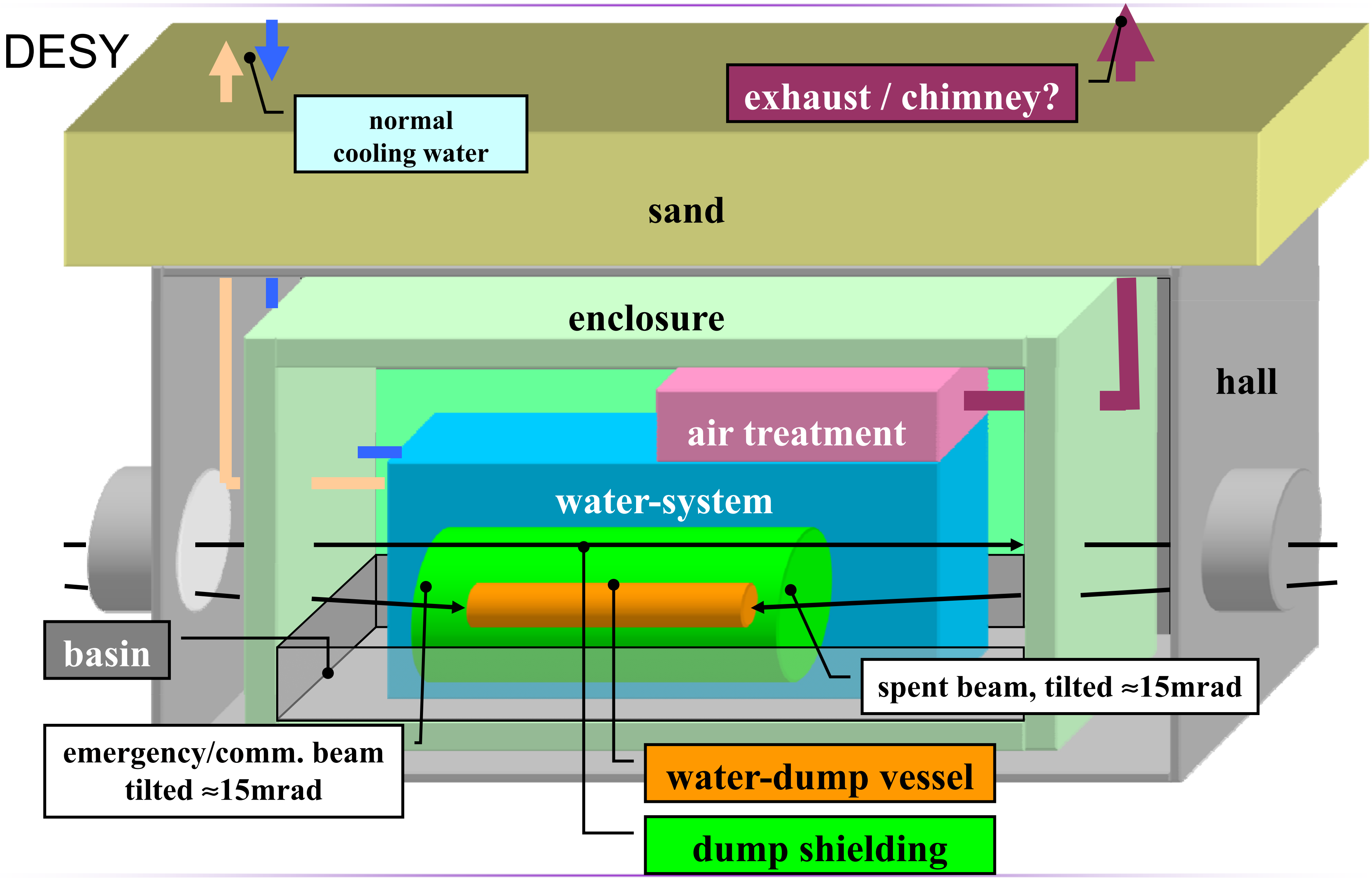
SLAC 2MW beam dumps with water as the primary absorbing medium (1996)

The main issues for the water based dump:

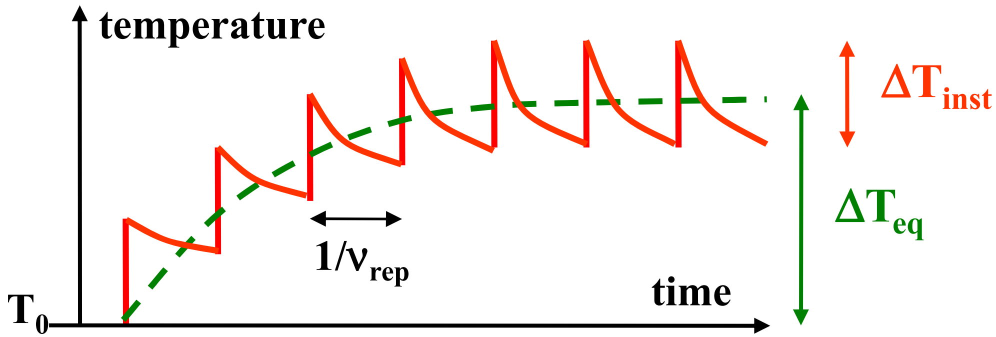
- Mechanical failure of dump or dump window
- Radiation damage to windows
- Management of radionuclides
- Processing of radiologically evolved hydrogen and oxygen
- Containment of activated water

Needs to be reliable, safe and robust in order to sell it!

Beam Dump Design - TESLA

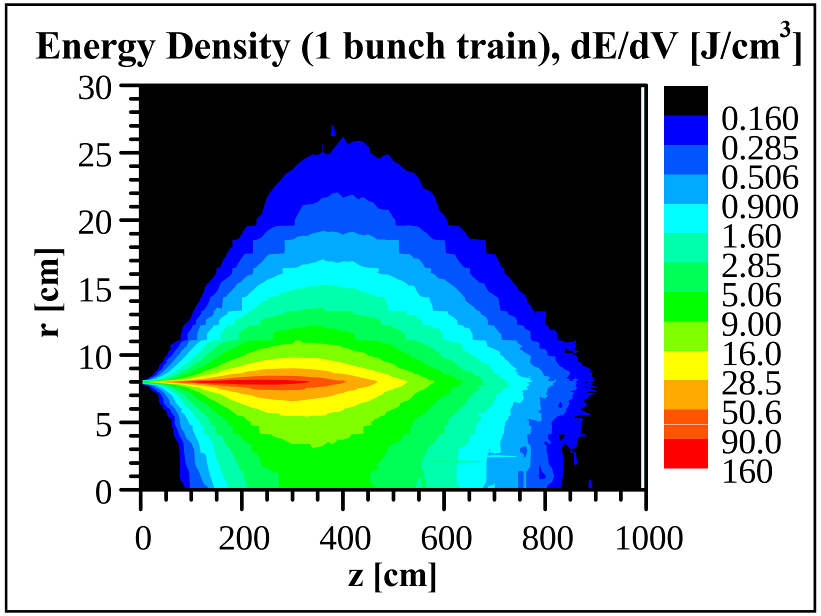


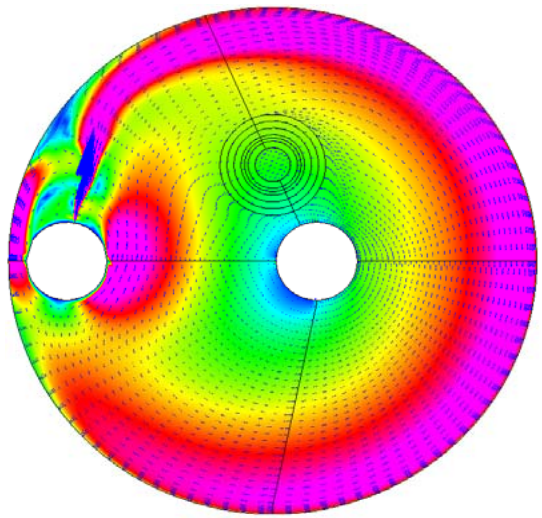
Heat Removal and Water Flow



Temperature rise from bunch train

Goal is to keep ΔT_{eq} below the boiling point of the water, pressurised to 10 atm.





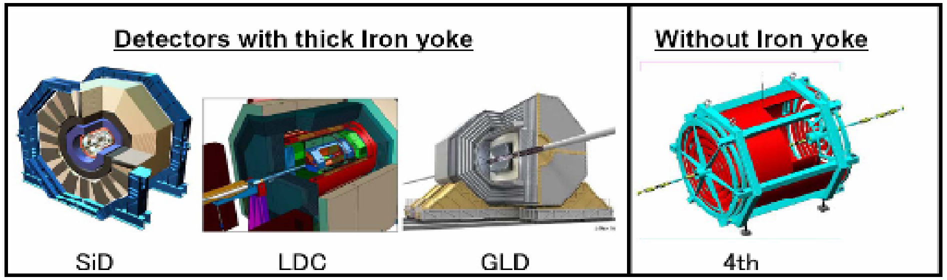
Remove heat through water flow e.g. vortex (Fichtner scheme)

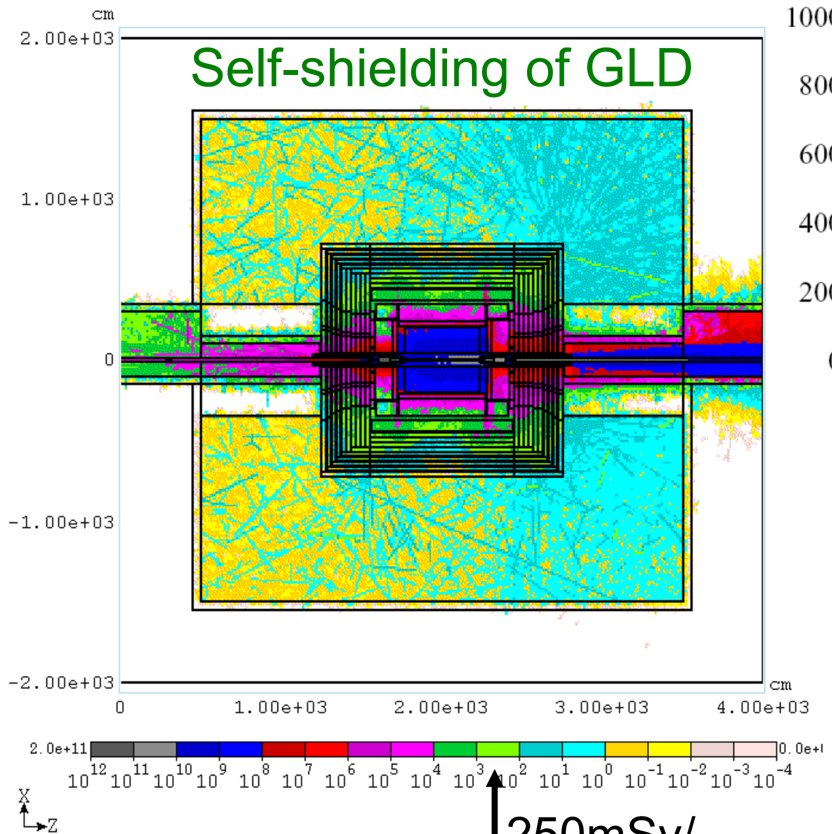
Radiation Shielding

Shielding the IR hall

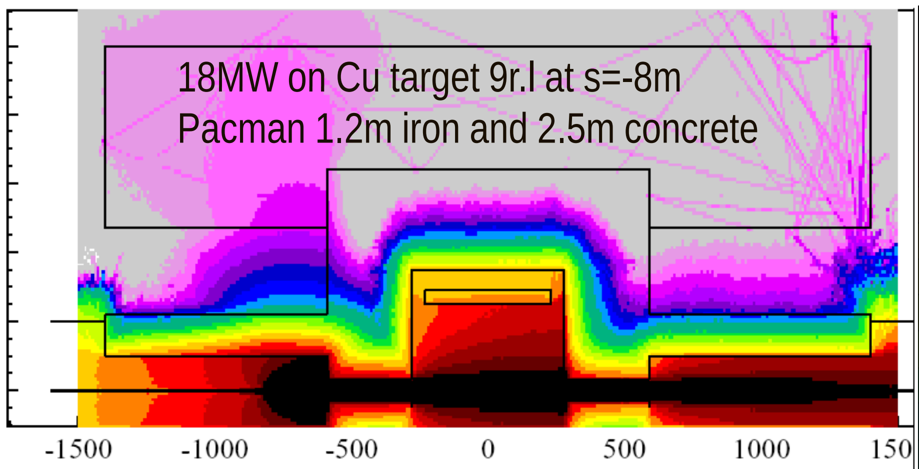
Detector itself is well shielded except for incoming beamlines.

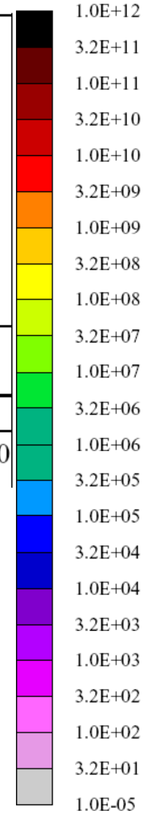
A proper “pacman” can shield the incoming beamlines and remove the need for shielding wall.





250mSv/h



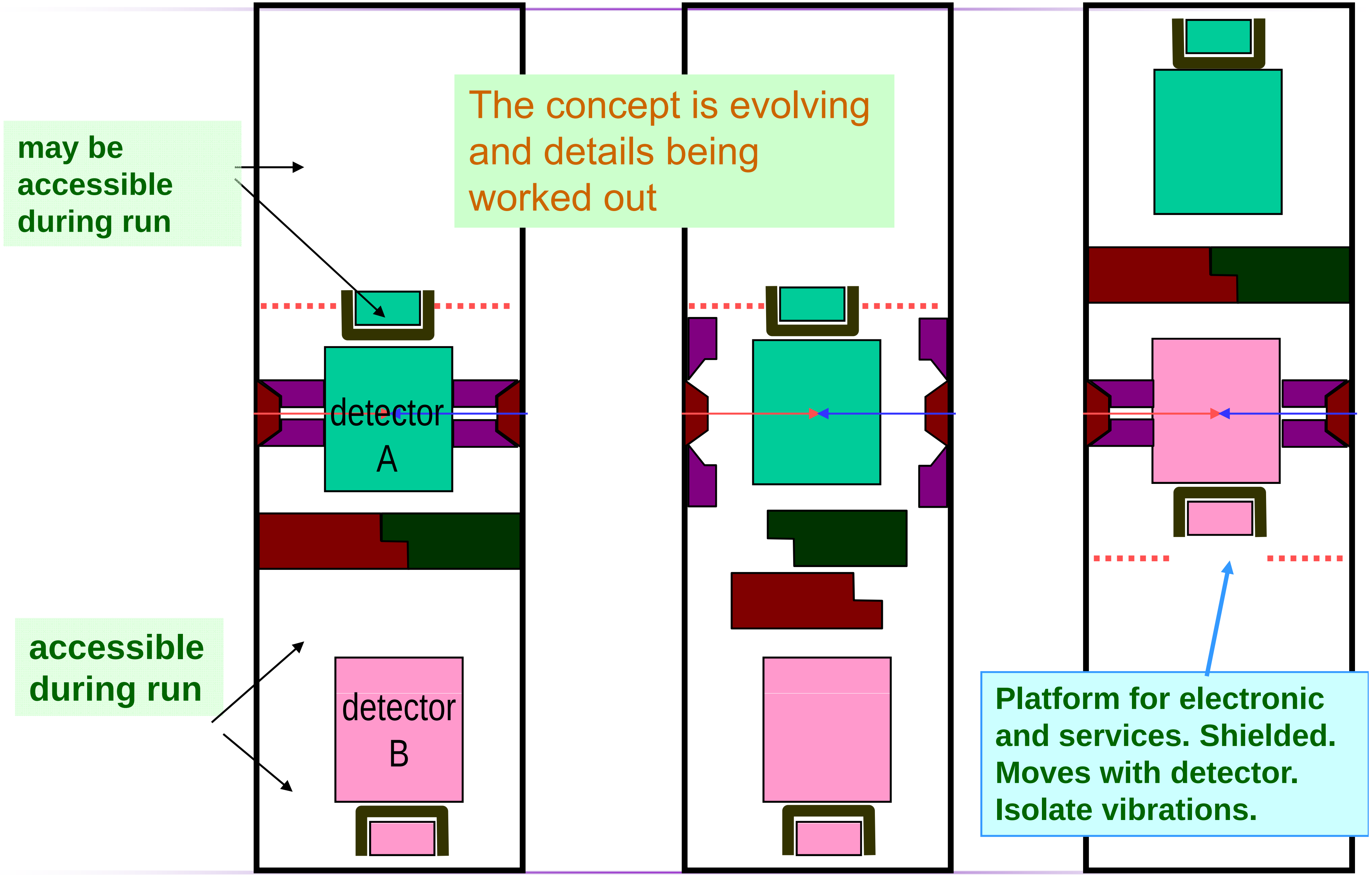


18MW lost at s=-8m.
Pacman has Fe: 1.2m, Concrete: 2.5m

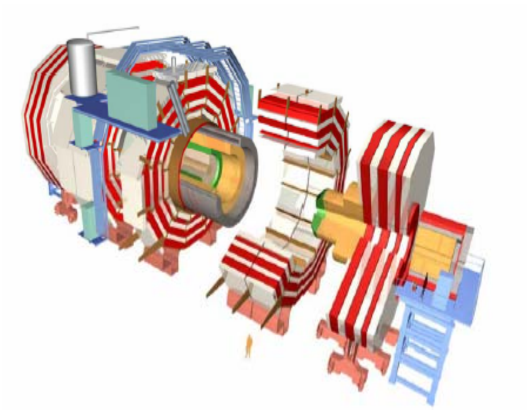
Dose at pacman external wall 0.65rem/hr (r=4.7m)

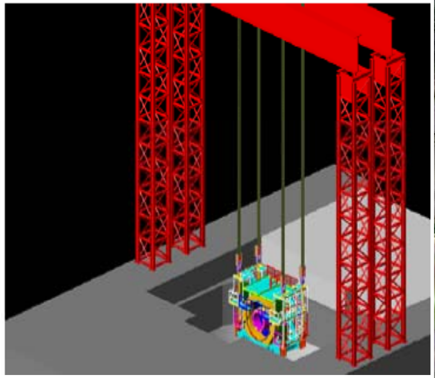
dose at r=7m 0.23rem/hr

Concept of single IR with two detectors



Detector assembly

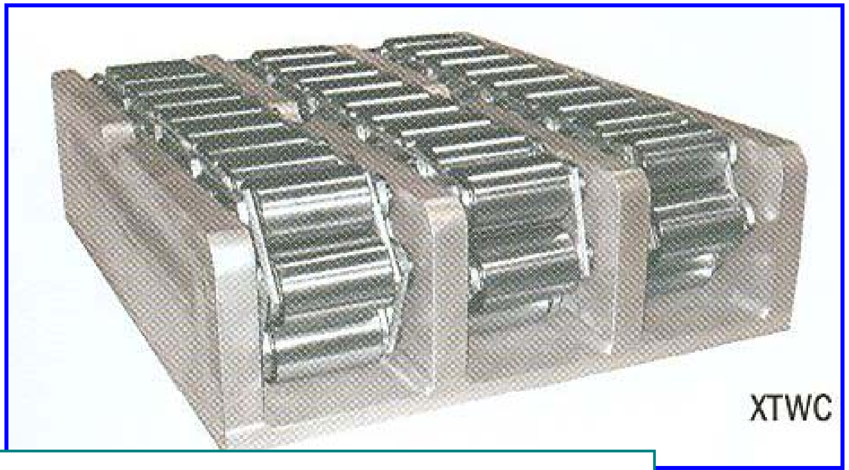




CMS detector assembled on surface in parallel with underground work, lowered down with rented crane.

Adopted this method for ILC, to save 2-2.5 years that allows to fit into 7 years of construction.

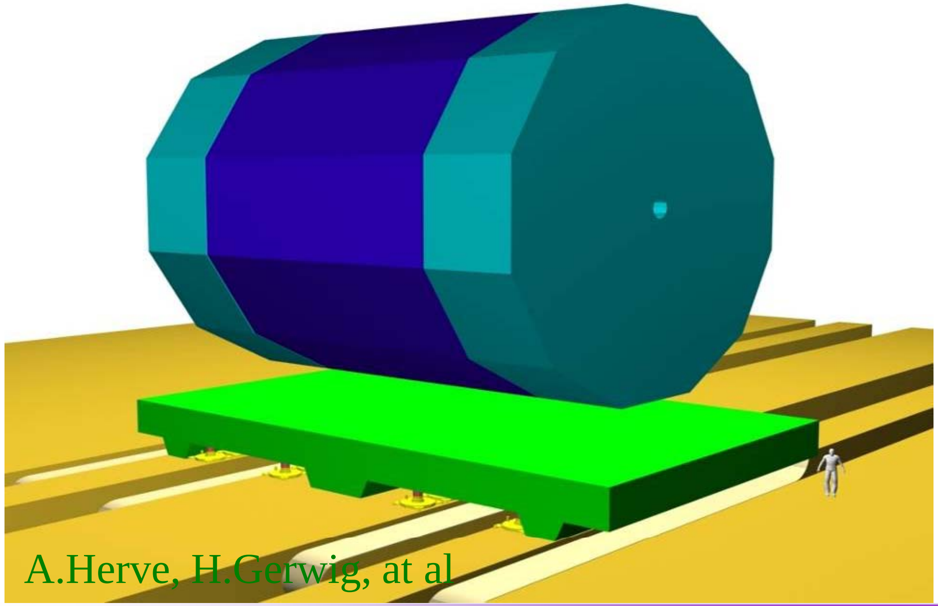
Moving the detector



5000 ton Hilman roller module

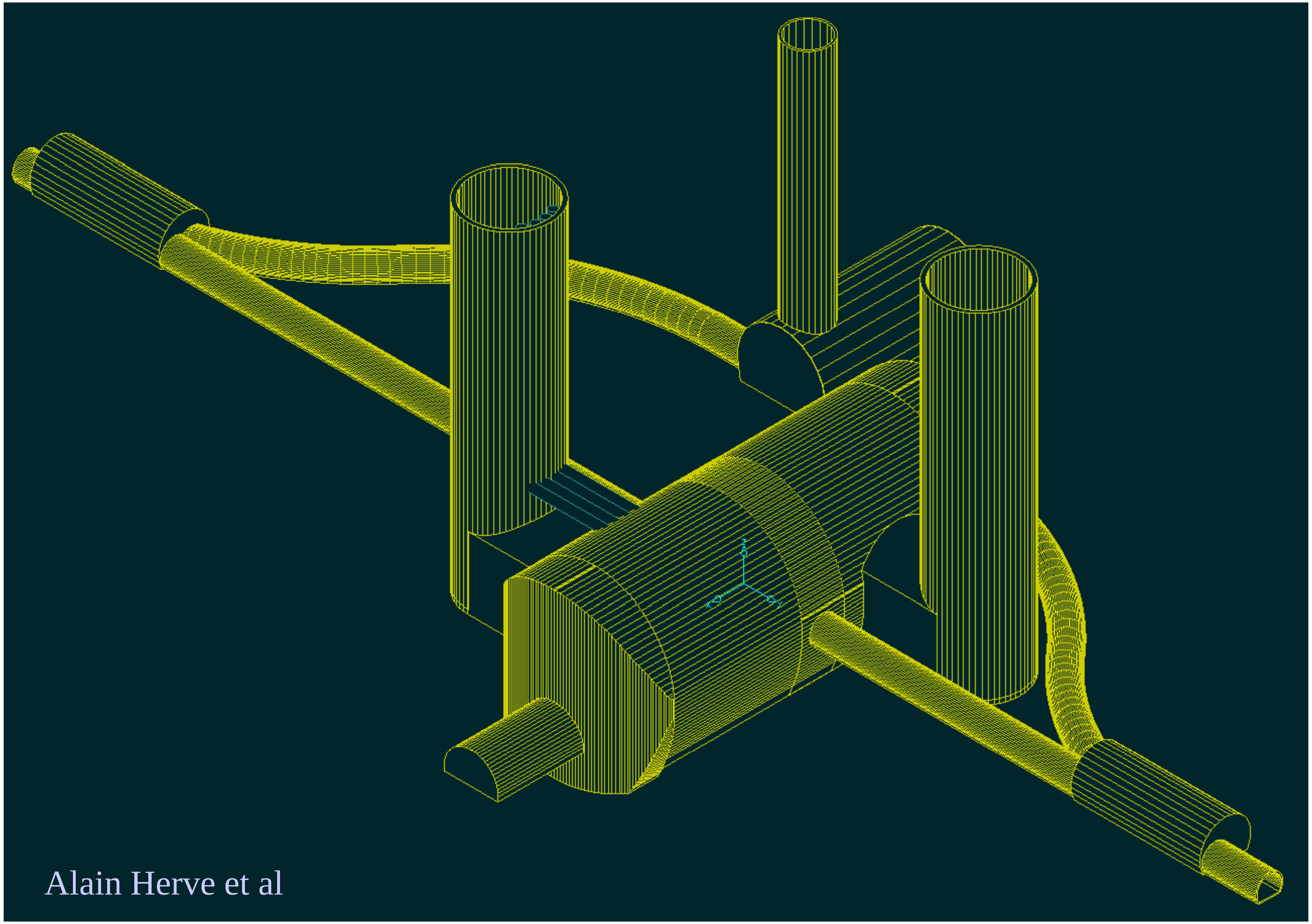
Air-pads at CMS – move 2000k pieces

Is detector (compatible with on-surface assembly) rigid enough itself to avoid distortions during move?

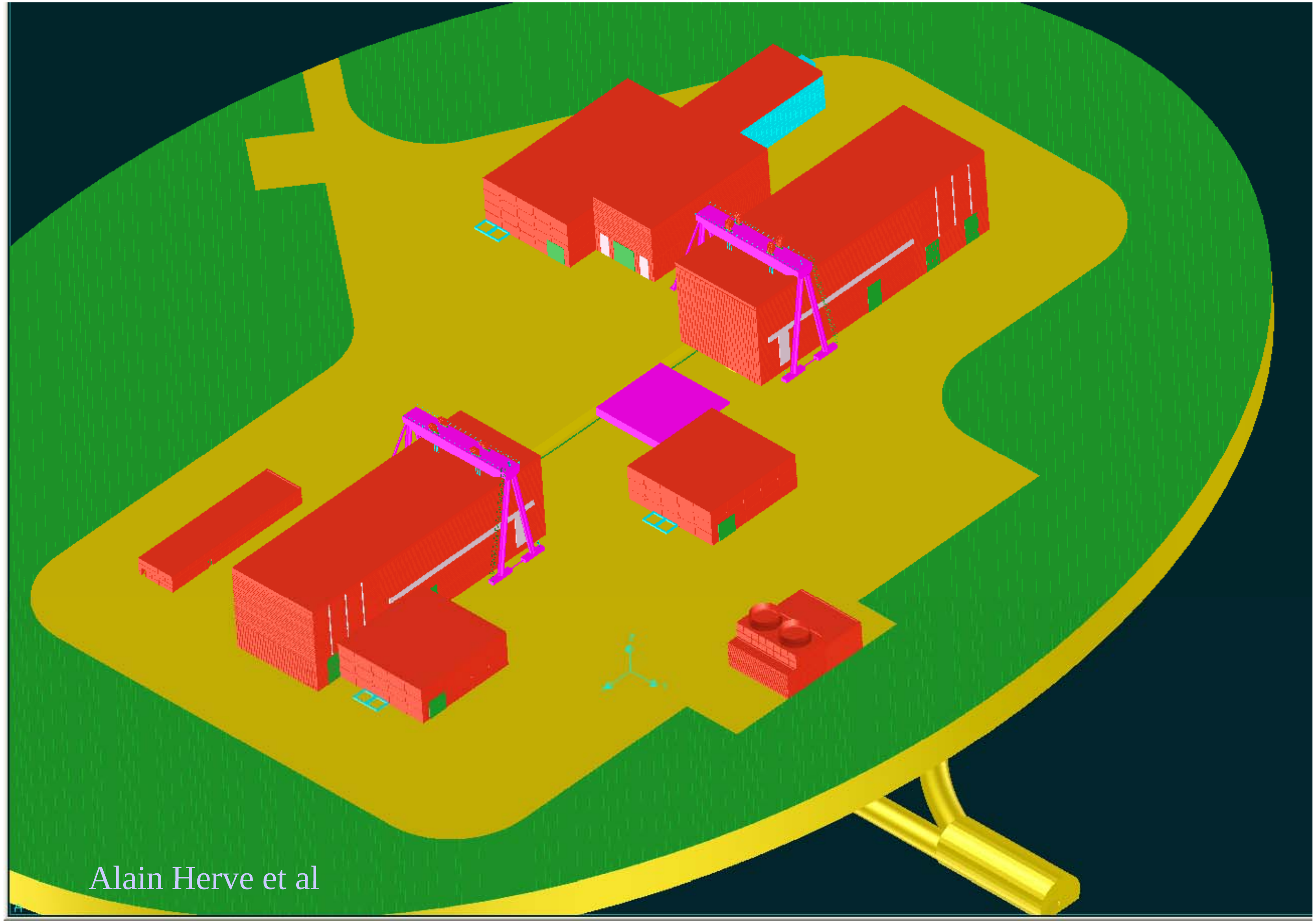


Concept of the platform to move ILC detector.

Configuration of IR tunnels and halls

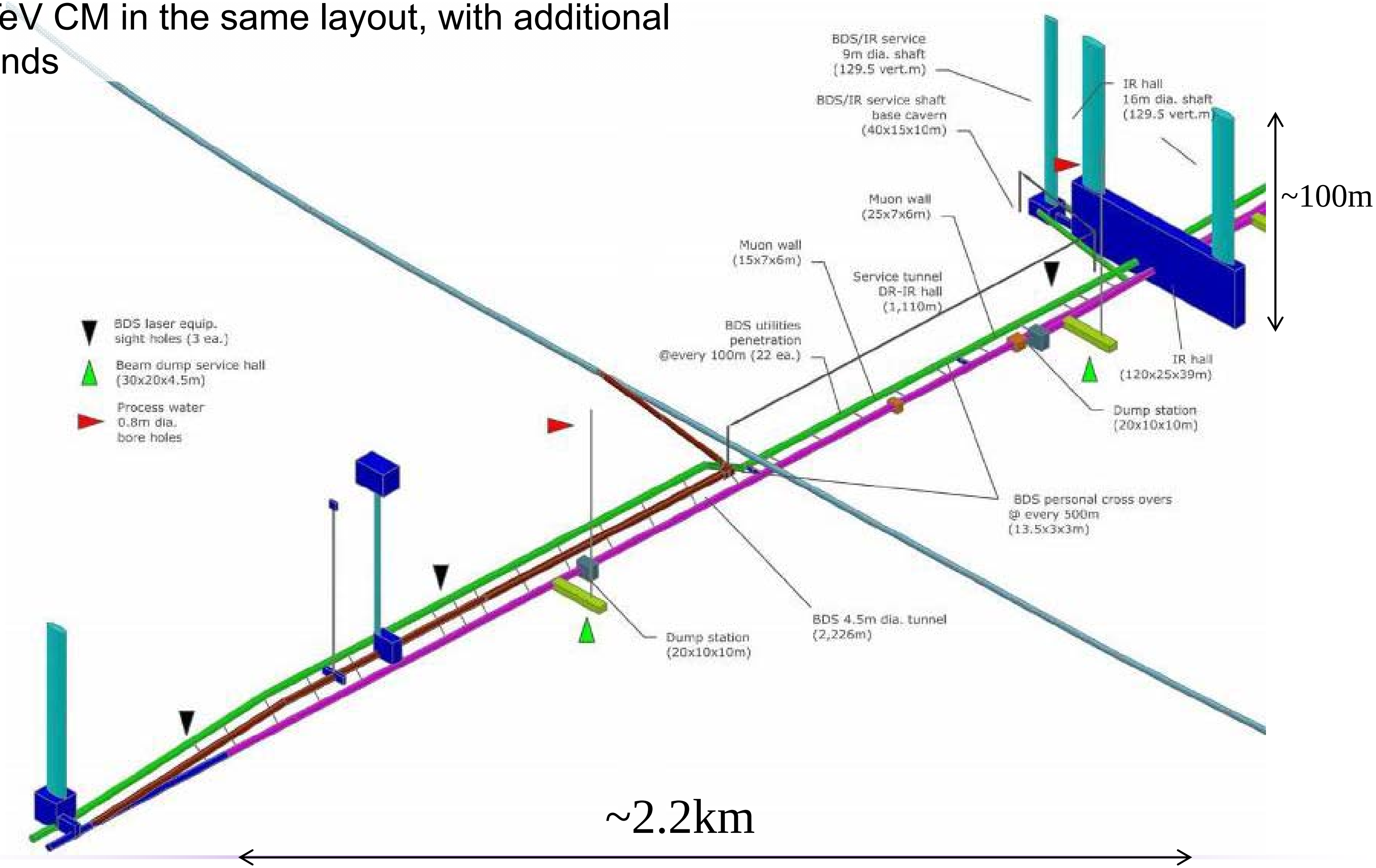


Configuration of surface buildings



Layout of ILC Beam Delivery tunnels

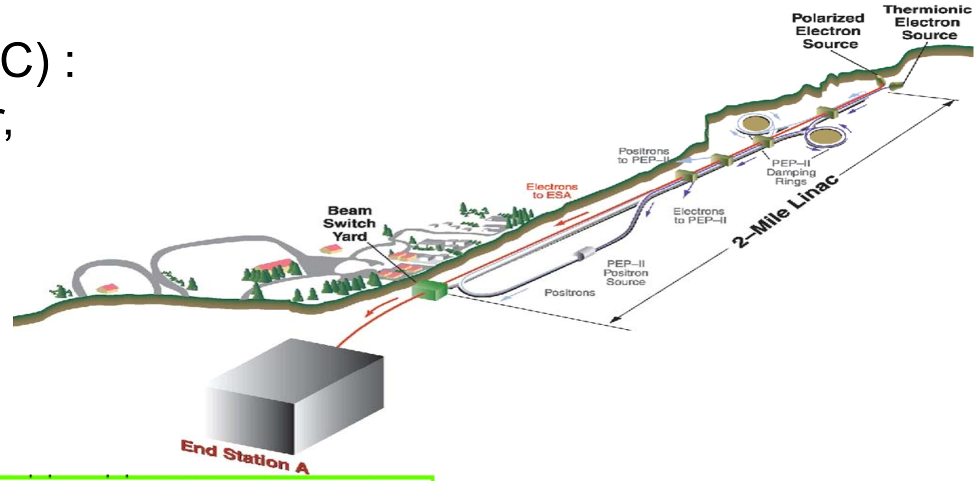
Single IR push-pull BDS, upgradeable to 1TeV CM in the same layout, with additional bends

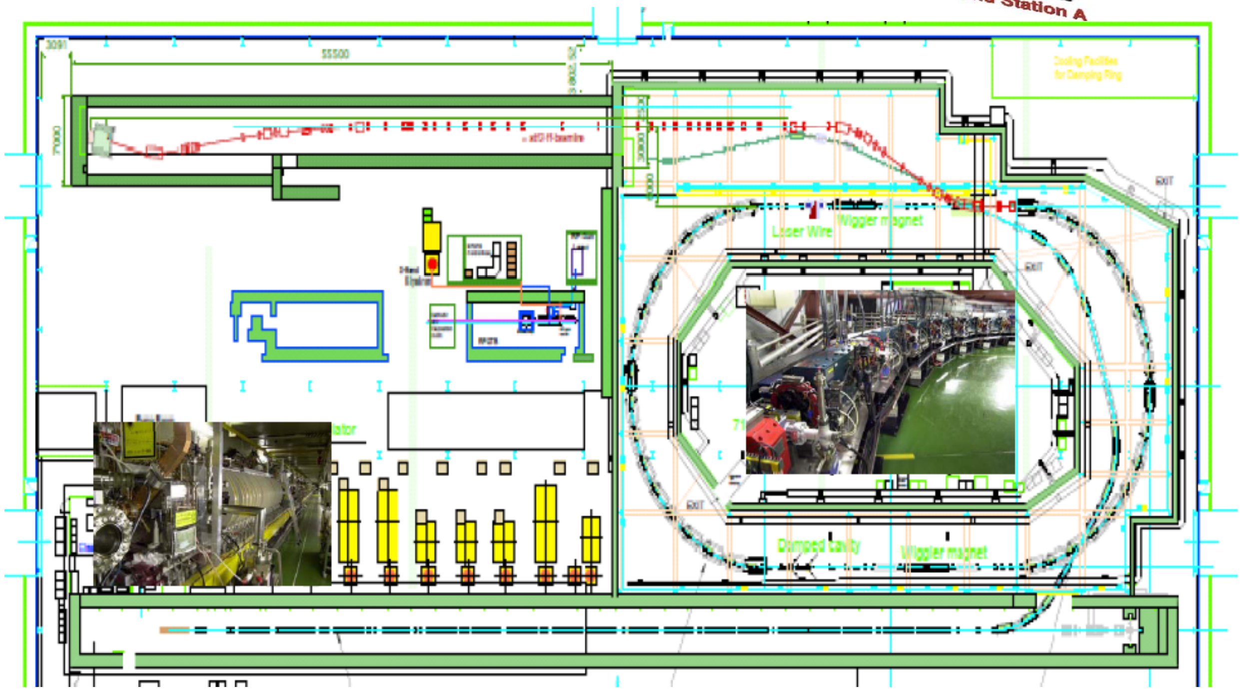


BDS Test Facilities

Test facilities: ESA & ATF2

End Station A (ESA) (SLAC) :
MDI, energy spectrometer,
Collimator wakefields, etc





Accelerator Test Facility (ATF/ATF2) (KEK): Final focus, advanced beam instrumentation, beam damage, etc.

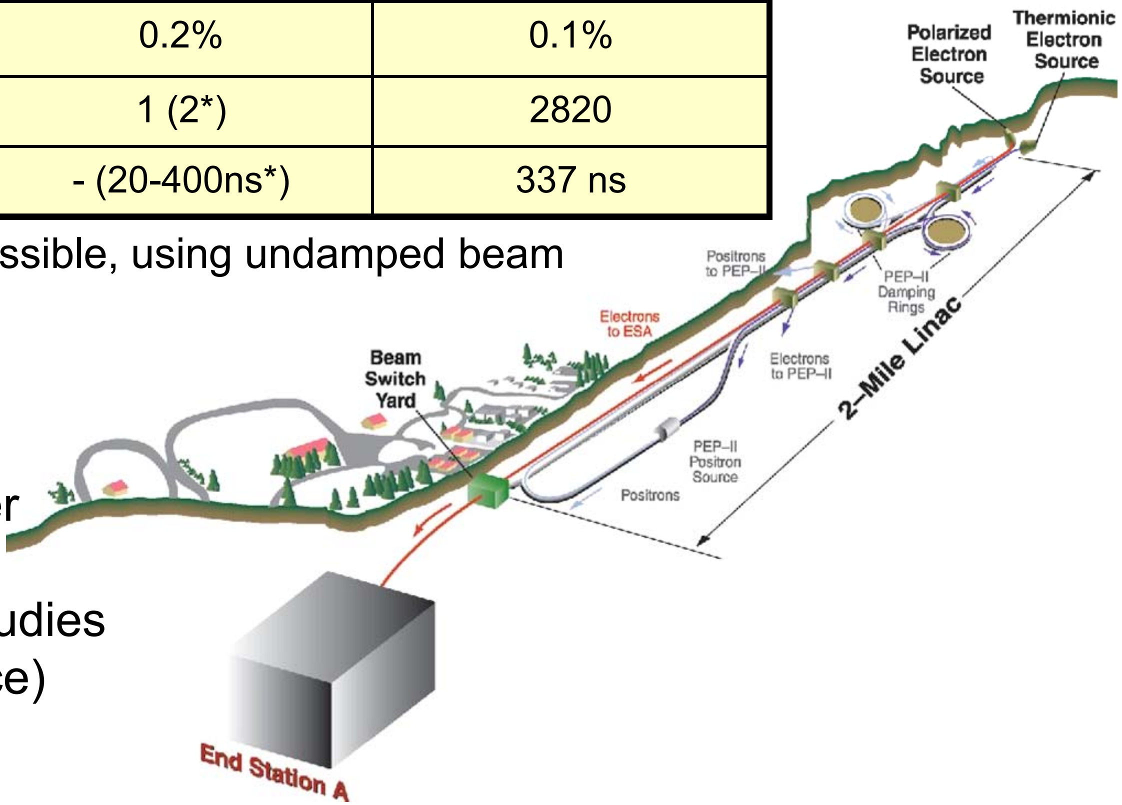
Beam Parameters at SLAC ESA and ILC

Parameter	SLAC ESA	ILC-500
Repetition Rate	10 Hz	5 Hz
Energy	28.5 GeV	250 GeV
Bunch Charge	2.0×10^{10}	2.0×10^{10}
Bunch Length	300 mm	300 mm
Energy Spread	0.2%	0.1%
Bunches per train	1 (2*)	2820
Microbunch spacing	- (20-400ns*)	337 ns

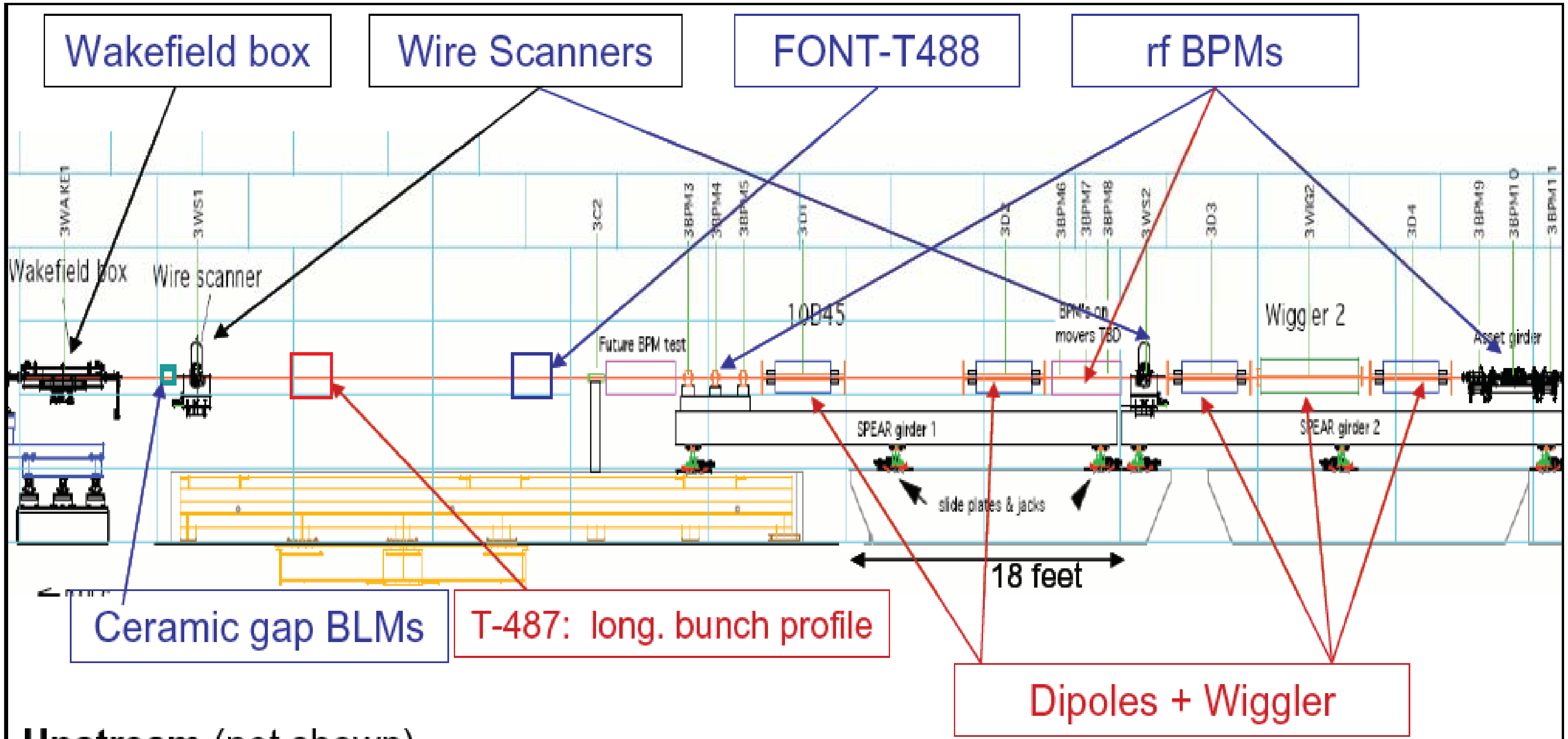
*possible, using undamped beam

Beam tests to study:

- BPM energy spectrometer
- Synch Stripe energy spectrometer
- Collimator design, wakefields
- IP BPMs/kickers—background studies
- EMI (electro-magnetic interference)
- Bunch length diagnostics



BDS beam tests at ESA



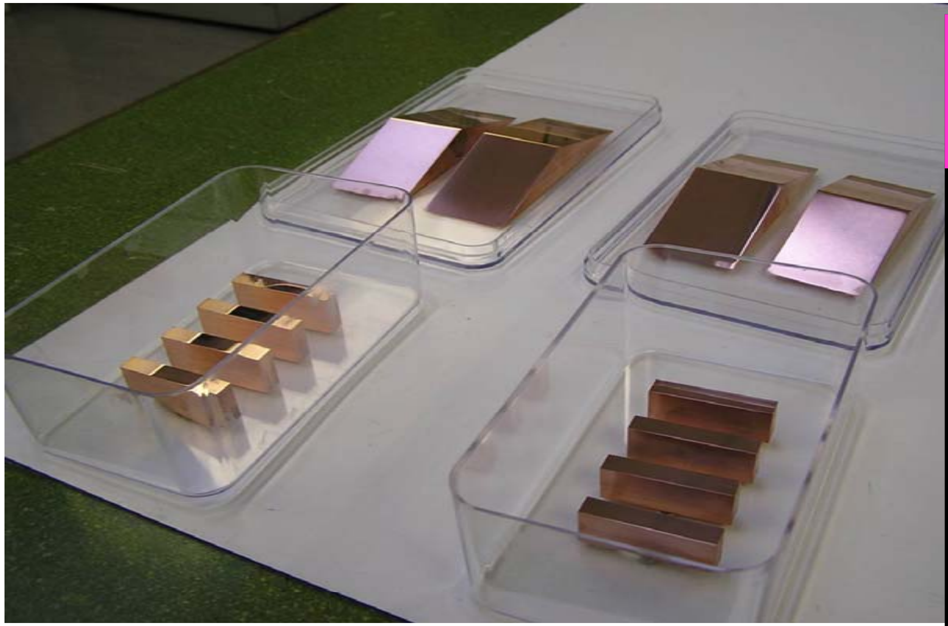
Upstream (not shown)

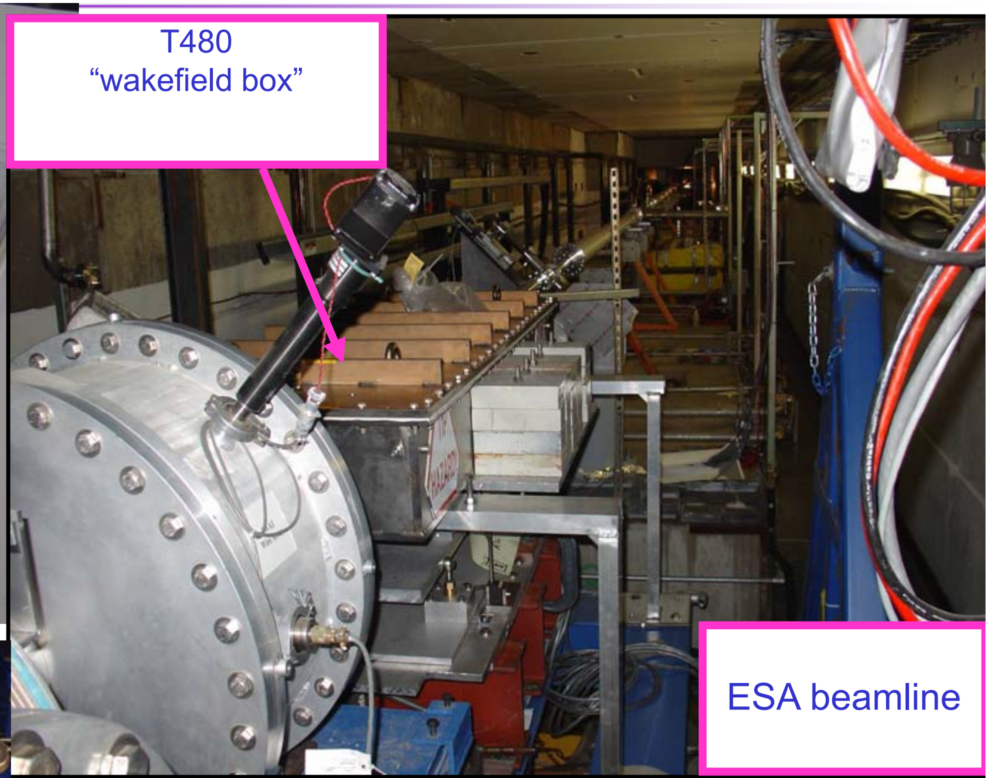
4 rf BPMs for incoming trajectory
Ceramic gap w/ rf diode detectors (16GHz, 23GHz, and 100GHz) and 2 EMI antennas

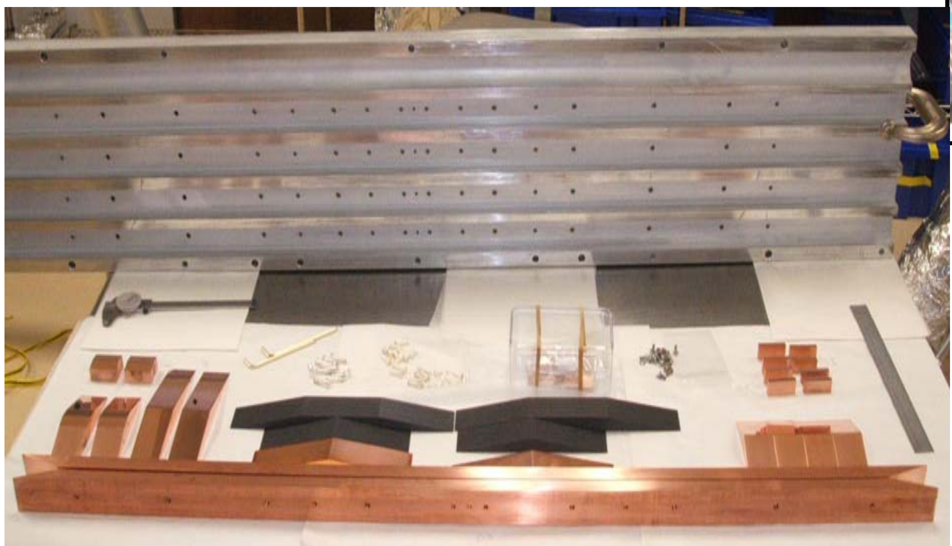
Downstream (not shown)

Ceramic gap for EMI studies
T475 Detector for Wiggler SR stripe

ESA : Collimator wakefields tests

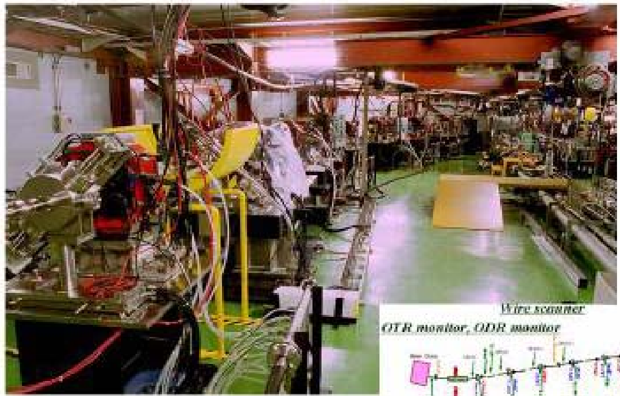


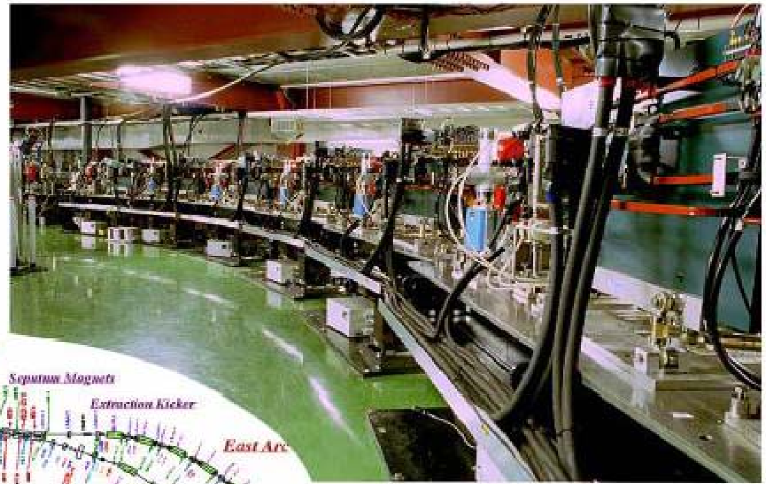


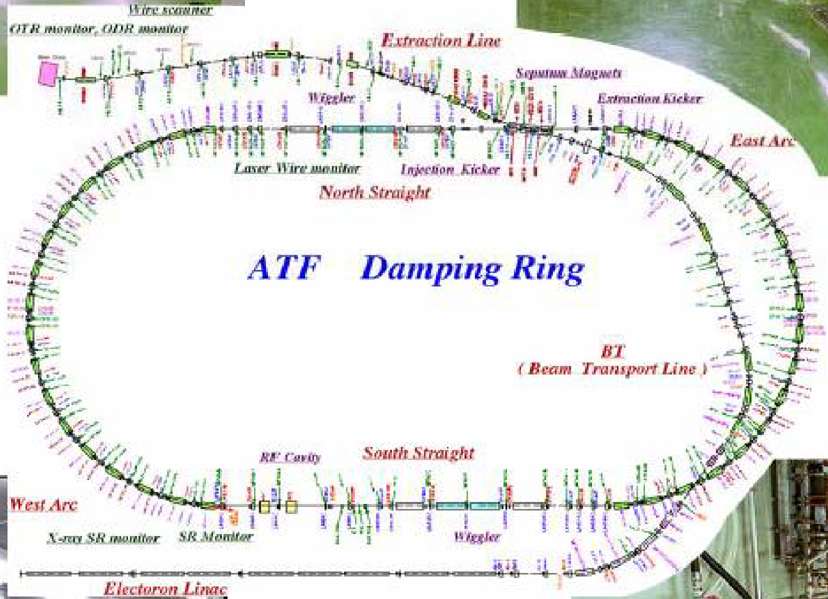


Verify agreement between measured and simulated wakefield kicks.

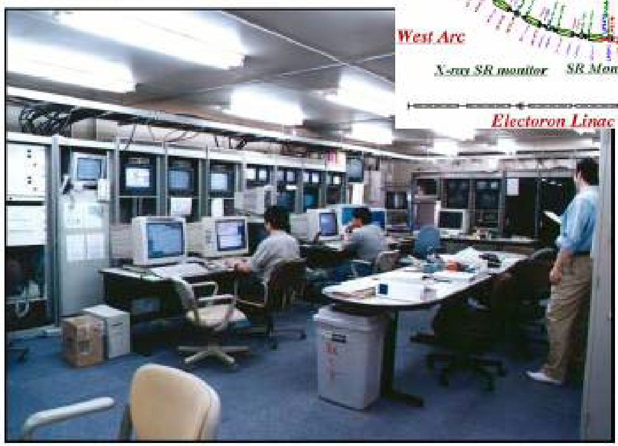
Accelerator Test Facility at KEK





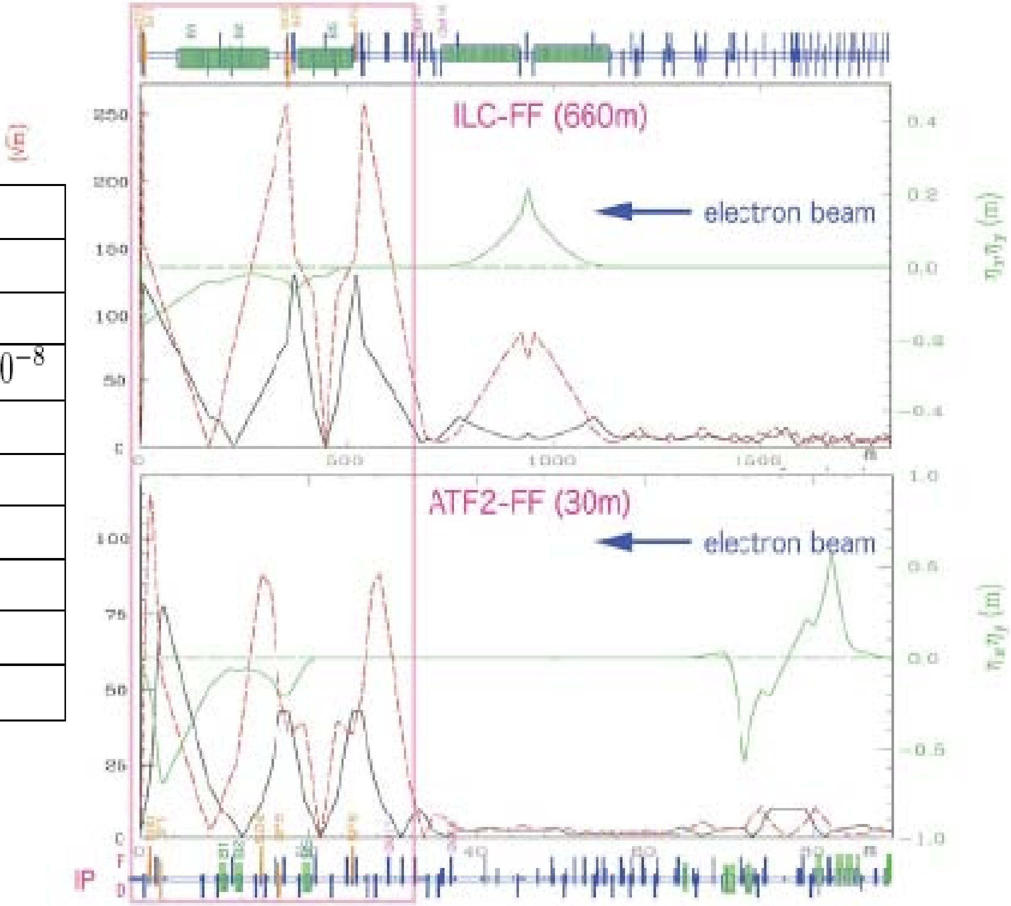


ATF and ATF2



ATF2 : Scaled down version of ILC Final Focus

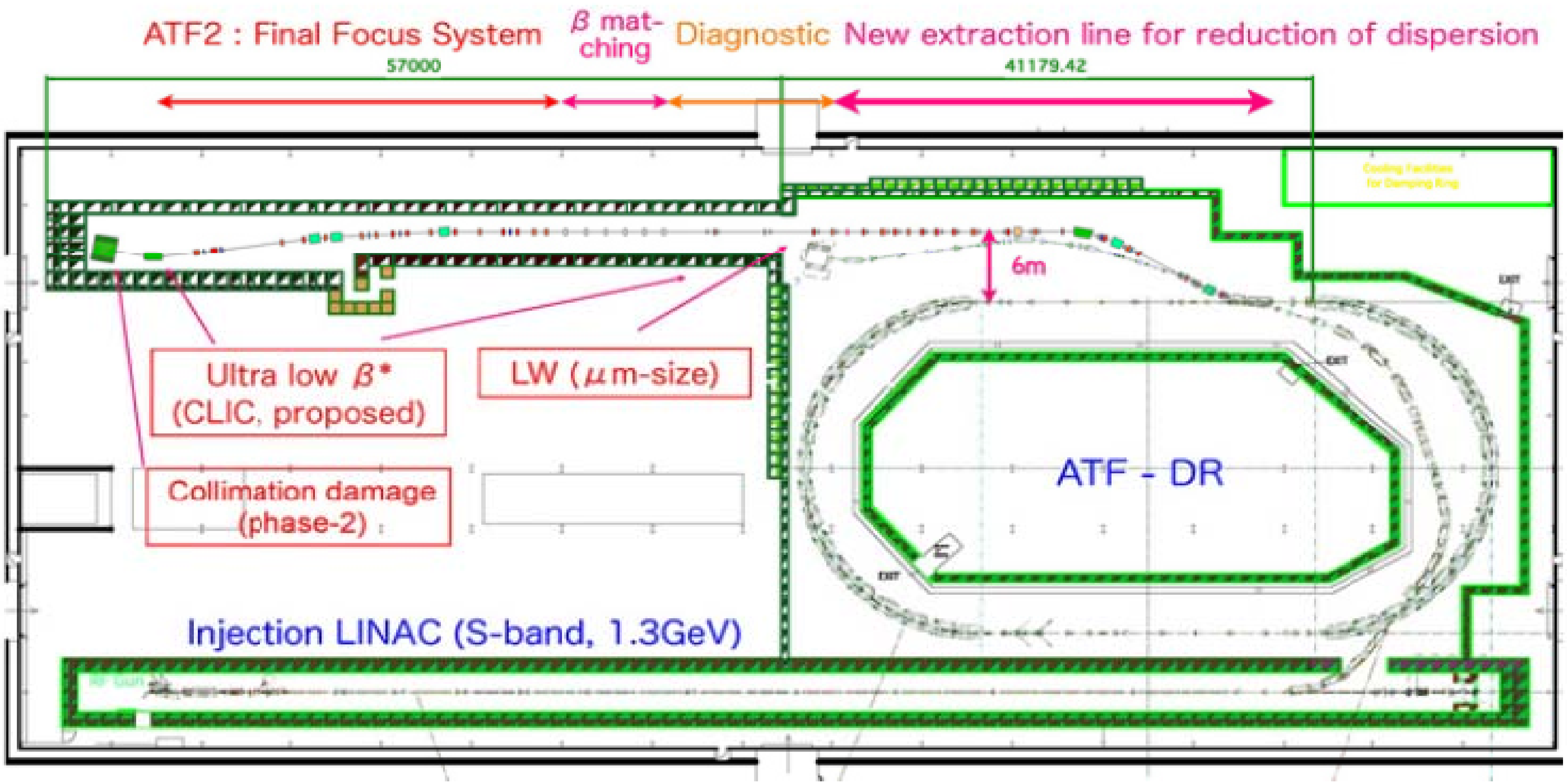
Parameter	ATF2	ILC
Beam energy(GeV)	1.3	250
L^* (m)	1	3.5~4.5
Emittance : $\gamma\epsilon_x/\gamma\epsilon_y$ (m·rad)	$5\cdot10^{-6}/3\cdot10^{-8}$	$1\cdot10^{-5}/4\cdot10^{-8}$
β at IP : β^*_x/β^*_y (mm)	4.0/0.1	21/0.4
η' at IP : η'_x	0.14	0.094
Energy spread:σ_E (%)	~0.1	~0.1
Chromaticity : W_y	$\sim 10^4$	$\sim 10^4$
Beam size at IP : σ^*_x/σ^*_y (μm/nm)	2.8/34	0.66/5.7
Aspect ratio : σ^*_x/σ^*_y	82	115



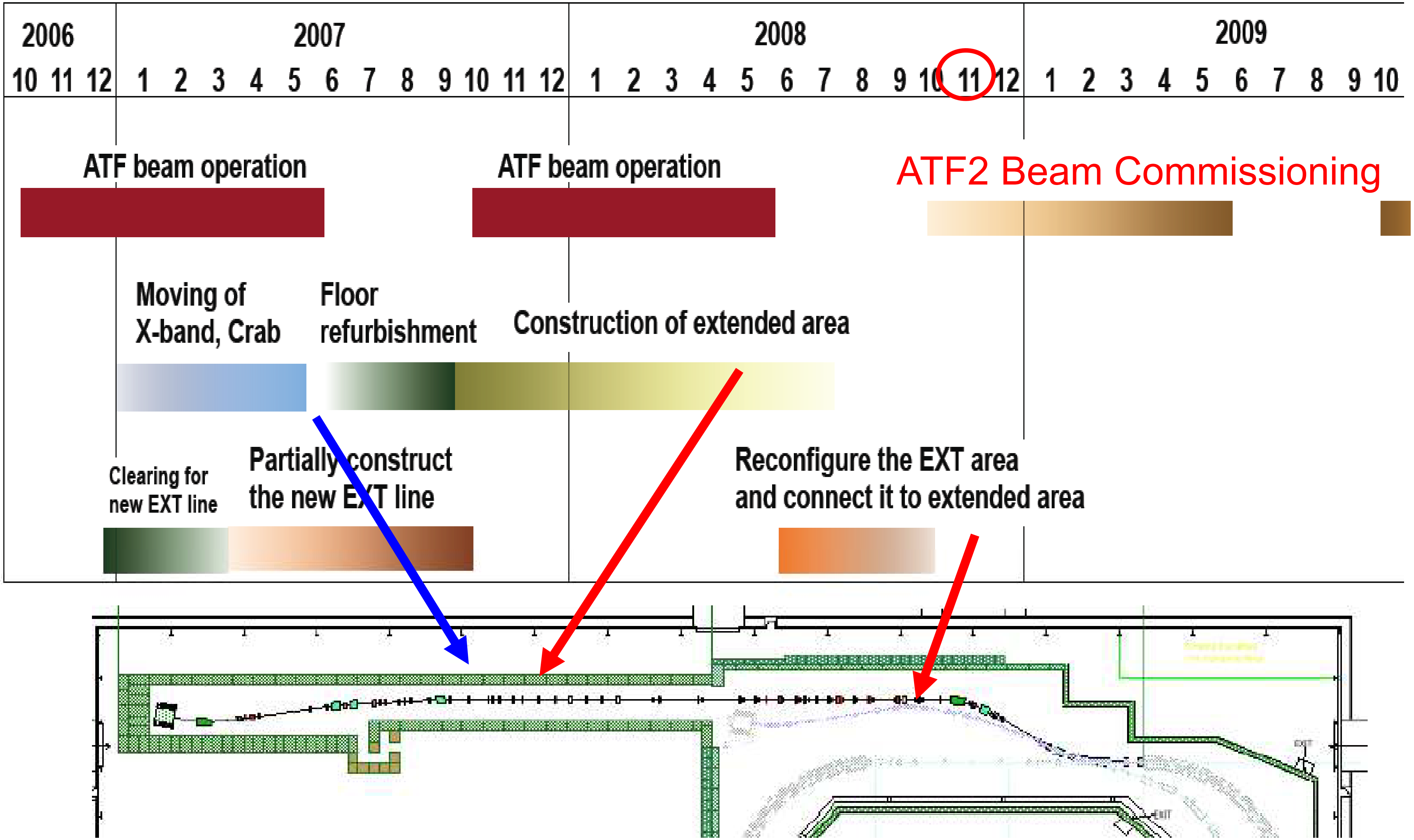
Though the lengths are different by a factor of 20, the optical functions are very similar.

ATF2 goals

1. Verification of local chromaticity corrected final focus to achieve vertical beam size of 35nm at the focal point (IP)
2. Stabilize the focal point at a nanometer level for long period (in order to assure the high luminosity)



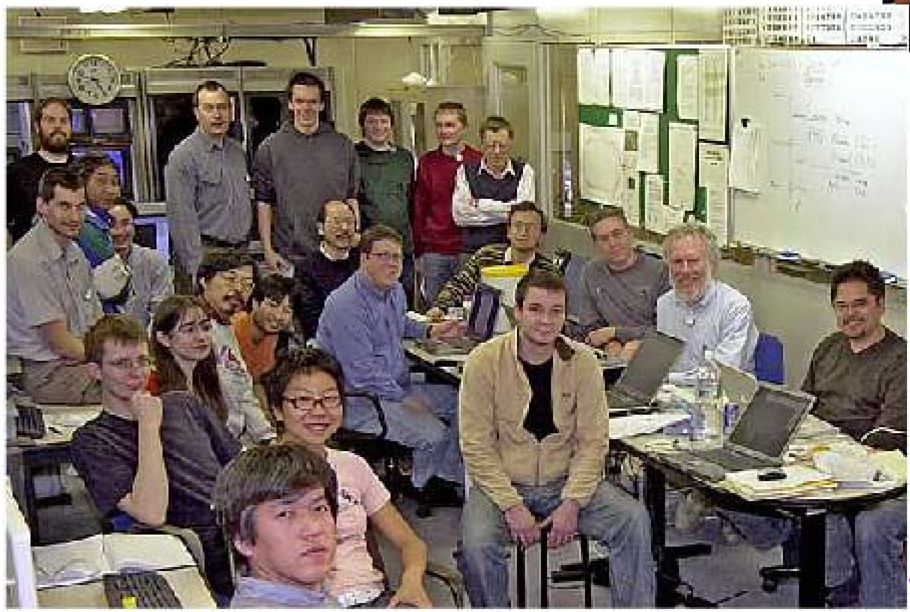
ATF2 Construction Schedule



ATF collaboration & ATF2 facility

In addition to goals 1 and 2, ATF2 will

- help development tuning methods, instrumentation (laser wires, fast feedback, submicron resolution BPMs),
- help to learn achieving small size & stability reliably,
- potentially able to test stability of FD magnetic center.

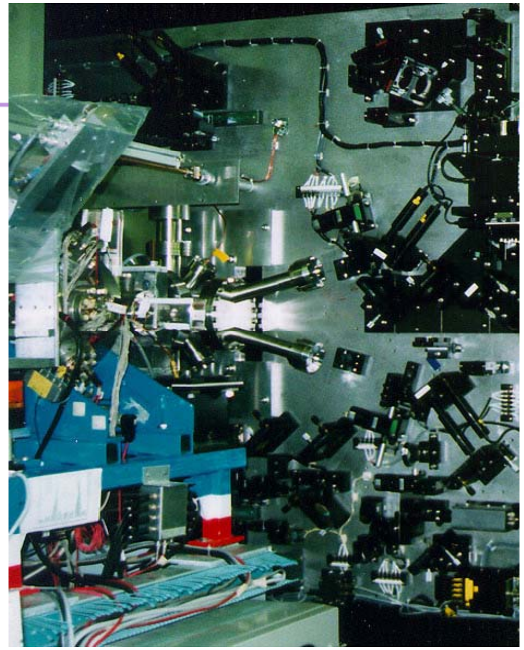


ATF2 is one of central elements of BDS technical design phase work, as it will address a large fraction of BDS technical cost risk.

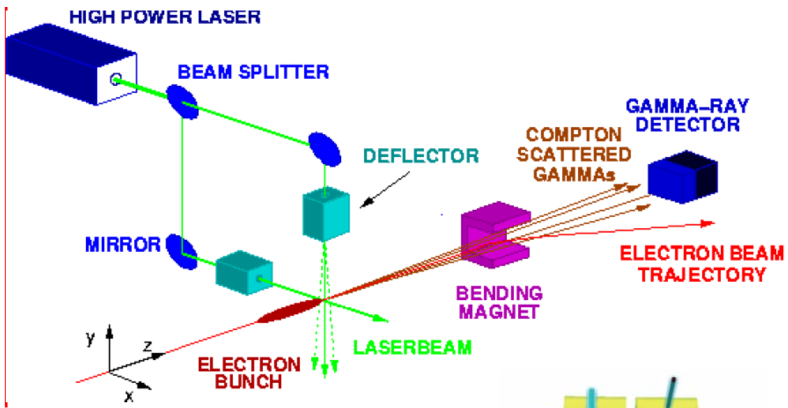
Constructed as ILC model, with in-kind contribution from partners and host country providing civil construction.

Advanced beam instrumentation at ATF2

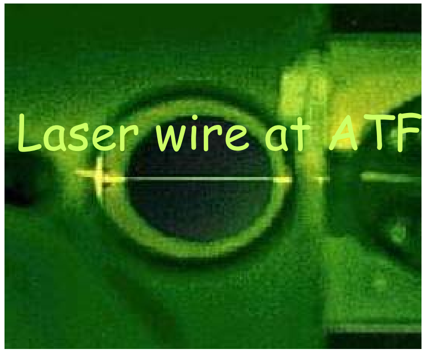
- Beam Size Monitor to confirm 35nm beam size
- nano-BPM at IP to see the nm stability
- Laser-wire to tune the beam
- Cavity BPMs to measure the orbit
- Movers, active stabilization, alignment system
- Intratrain feedback, kickers to produce ILC-like train

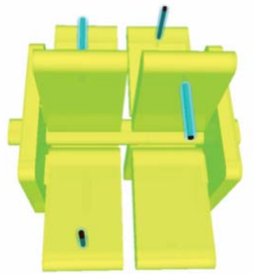


IP Beam-size monitor (BSM) (Tokyo U./KEK, SLAC, UK)

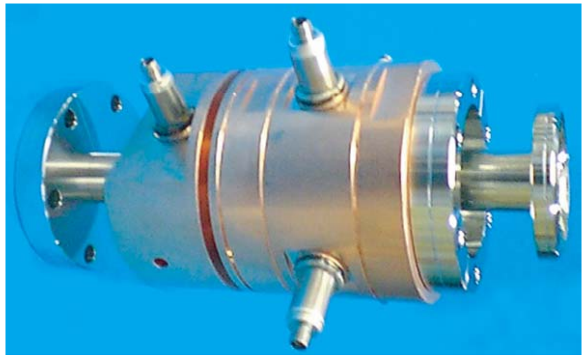


Laser-wire beam-size Monitor (UK group)





Cavity BPMs with 2nm resolution, for use at the IP (KEK)



Cavity BPMs, for use with Q magnets with 100nm resolution (PAL, SLAC, KEK)

ATF2 construction

Photos from ATF2 construction, N.Toge

ATF2 pushed beta optics

Chromaticity

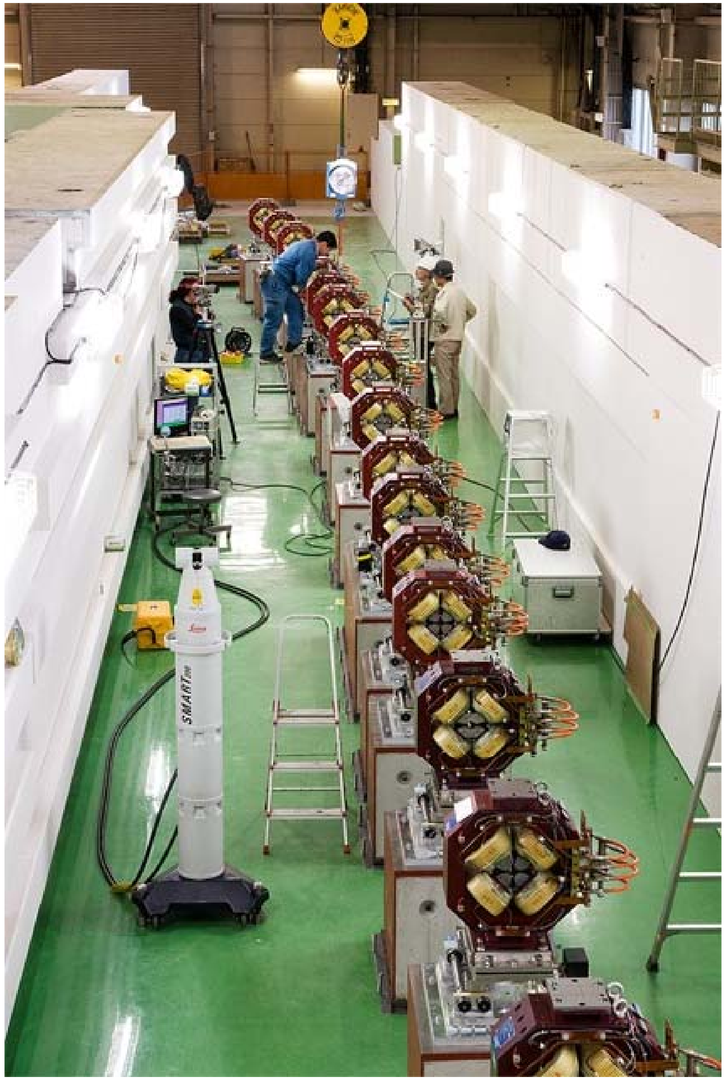
project	status	β_y^* [mm]	L* [m]	L^*/β_y^*	ξ_y
FFTB	design	0.1	0.4	4000	17000
FFTB	measured	0.167	0.4	2400	10000
ATF2	design	0.1	1.0	10000	19000
ATF2 pushed	proposed	0.05	1.0	20000	38000
ATF2 pushed++	proposed	0.025	1.0	40000	76000
CLIC 500 GeV	design	0.2	4.3	21500	35000
CLIC 3 TeV	design	0.09	3.5	39000	63000
ILC	design	0.4	3.5	8750	15000
ILC pushed	design	0.2	3.5	17500	30000

Tuning difficulty

project	status	σ_y^* [nm]
FFTB	measured	70
ATF2	design	37
ATF2 pushed	proposed	<26
ATF2 pushed++	proposed	<20
ILC	design	6
CLIC 500GeV	design	3

- Ultimate challenge at ATF2 will be to achieve ~20nm vertical beam size Tuning algorithms, tuning procedures and hardware requirements are extremely challenging.

ATF2 construction



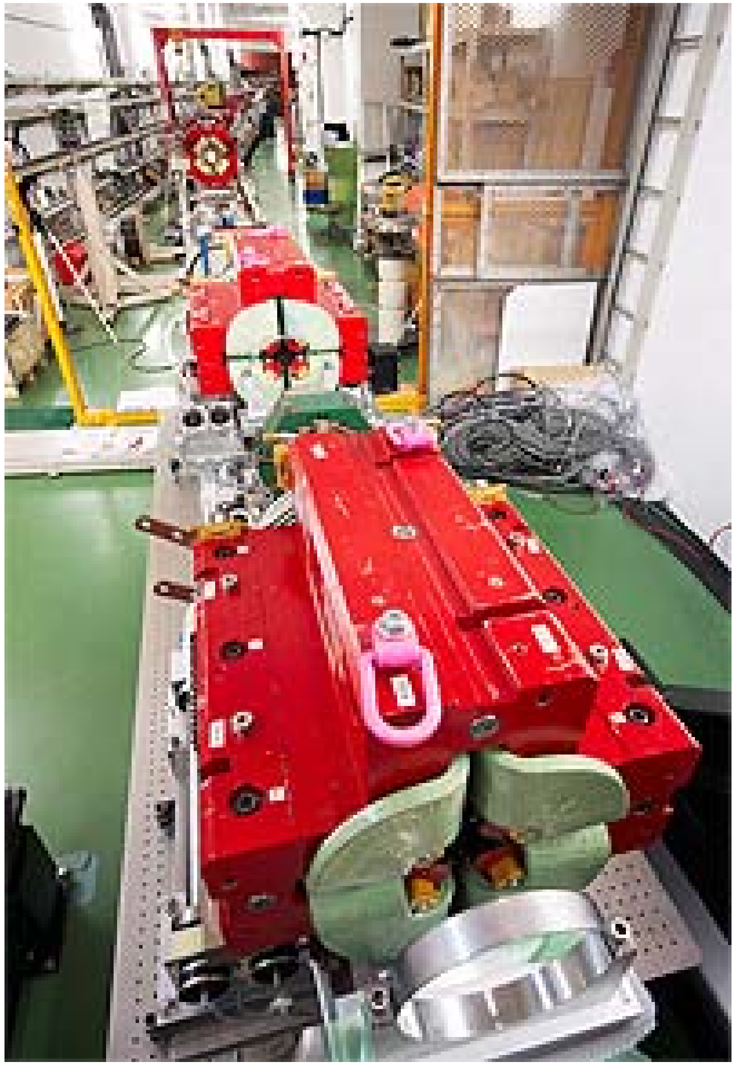
2008/2

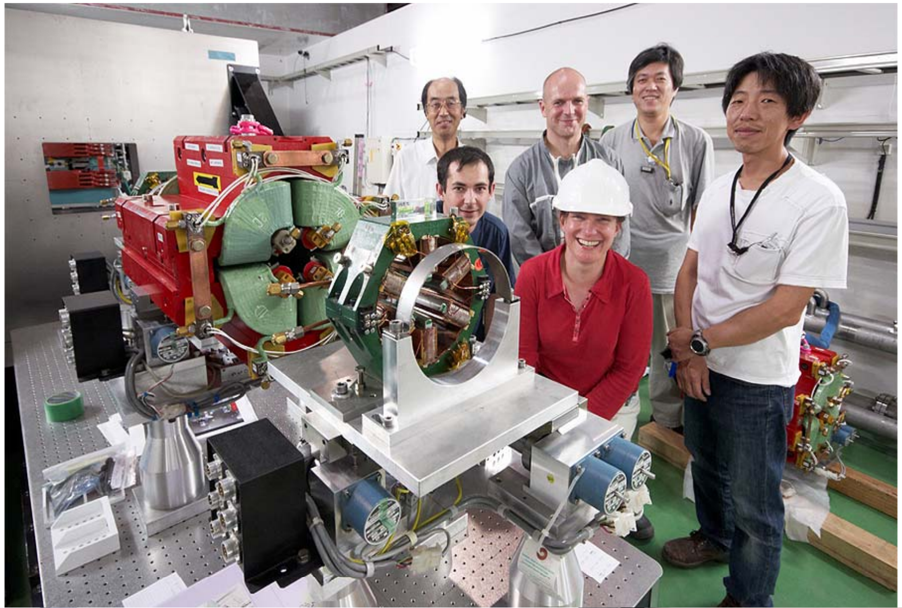
2008/5

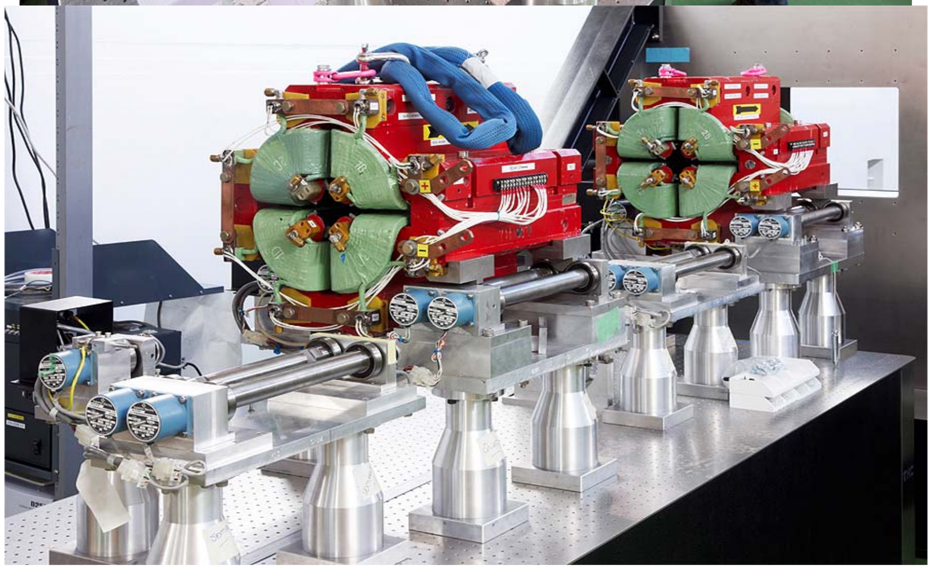
2008/9: new EXT

Photos from ATF2 construction, N.Toge

ATF2 construction : installation of final quadrupole magnets







September'08

Photos from ATF2 construction, N.Toge

Concluding Remarks (1/2)

- BDS design involves optimisation of final focus, collimation, extraction, machine detector interface, physics measurements, tuning and advanced beam instrumentation to achieve the luminosity goal with minimum backgrounds.
- Final focus systems need to provide very strong focusing of the beams
  - correction of chromatic and geometric aberrations is principle design challenge.
- Minimisation of detector background need efficient removal of the ‘beam halo’
  - IR layout defines collimation requirements
  - survivable spoilers can have very small <1mm gaps
  - wake fields and MPS issues important
- Stability tolerances are driven by nm beam sizes to achieve the luminosity
  - need to worry about ground motion and vibration sources
  - need mechanical stabilisation and beam-based feedback
- Beam-beam effects : enhance luminosity, increase background; provide tools for additional beam collision diagnostic; need flat beam to increase the luminosity and reduce the beamstrahlung.

Concluding Remarks (2/2)

- The crossing angle issues include IR layout, magnet choices, crab crossing, DID or (Anti-DID). The extraction line design needs careful transport of highly degraded beam to the beam dump.
- BDS design may need to cover operation at low energies for physics and calibration purposes.
- The physics options need running at e-e- and γ–γ collider (need >25mrad crossing angle option).
- In the immediate future, the BDS activity focus would be to test and demonstrate the local chromaticity correction final focus scheme at ATF2.
- ATF2 will also provide valuable experimental facility for R&D and testing of the advanced beam instrumentation required for the BDS.

References

Many thanks to colleagues whose slides, results and photographs have been used in these two lectures.

In particular, thanks to :

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References given in a separate file “BDS_References.doc”

End of Part 2

Thank you for your attention.