Final Focus Layouts and Stability Considerations

Andrei Seryi
John Adams Institute

CERN Accelerator School
Beam dynamics and technologies for future colliders

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We will focus here on final focus design

As FF most challenging for linear colliders, we will first consider FF of LCs

We will then touch on stability issues of FFs of LCs

And then discuss design of FF in modern hadron or e+e- circular colliders
International Linear Collider (ILC)

ILC $e^+e^-$ Linear Collider

Energy 250 GeV x 250 GeV
Linear Collider – two main challenges

- **Energy** – need to reach at least 250 GeV CM

- **Luminosity** – need to reach $10^{34}$ level
The Luminosity Challenge

- Must jump by a Factor of 10000 in Luminosity !!! (from what is achieved in the only so far linear collider SLC)
- Many improvements, to ensure this: generation of smaller emittances, their better preservation, ...
- Including better focusing, dealing with beam-beam, safely removing beams after collision and better stability
How to get higher Luminosity

• To increase probability of direct $e^+e^-$ collisions (luminosity) and birth of new particles, beam sizes at IP must be very small

• E.g., ILC beam sizes just before collision (500GeV CM): $500 \times 5 \times 300000$ nanometers

Vertical size is smallest

$$L = \frac{f_{rep} n_b N^2}{4\pi \sigma x \sigma y} H_D$$
BDS: from end of linac to IP, to dumps

Beam Delivery System (BDS)
It includes FF, and many other systems
Beam Delivery subsystems

- As we go through the lecture, the purpose of each subsystem should become clear.

Diagnostics

Beam Switch Yard

β-collimator

E-collimator

Final Focus

14mr IR

Sacrificial collimators

Tune-up & emergency

Extraction

Tune-up dump

Muon wall

Main dump

Extraction

grid: 100m*1m
Beam Delivery System tasks

• measure the linac beam and match it into the final focus
• remove any large amplitude particles (beam-halo) from the linac to minimize background in the detectors
• measure and monitor the key physics parameters such as energy and polarization before and after the collisions
• ensure that the extremely small beams collide optimally at the IP
• protect the beamline and detector against mis-steered beams from the main linacs and safely extract them to beam dump
• provide possibility for two detectors to utilize single IP with efficient and rapid switch-over
### Parameters of ILC BDS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (linac exit to IP distance)/side</td>
<td>m</td>
<td>2226</td>
</tr>
<tr>
<td>Length of main (tune-up) extraction line</td>
<td>m</td>
<td>300 (467)</td>
</tr>
<tr>
<td>Max Energy/beam (with more magnets)</td>
<td>GeV</td>
<td>250 (500)</td>
</tr>
<tr>
<td>Distance from IP to first quad, L*</td>
<td>m</td>
<td>3.5-(4.5)</td>
</tr>
<tr>
<td>Crossing angle at the IP</td>
<td>mrad</td>
<td>14</td>
</tr>
<tr>
<td>Nominal beam size at IP, $\sigma^*$, x/y</td>
<td>nm</td>
<td>655/5.7</td>
</tr>
<tr>
<td>Nominal beam divergence at IP, $\theta^*$, x/y</td>
<td>$\mu$m</td>
<td>31/14</td>
</tr>
<tr>
<td>Nominal beta-function at IP, $\beta^*$, x/y</td>
<td>mm</td>
<td>21/0.4</td>
</tr>
<tr>
<td>Nominal bunch length, $\sigma_z$</td>
<td>$\mu$m</td>
<td>300</td>
</tr>
<tr>
<td>Nominal disruption parameters, x/y</td>
<td></td>
<td>0.162/18.5</td>
</tr>
<tr>
<td>Nominal bunch population, N</td>
<td></td>
<td>$2 \times 10^{10}$</td>
</tr>
<tr>
<td>Max beam power at main and tune-up dumps</td>
<td>MW</td>
<td>18</td>
</tr>
<tr>
<td>Preferred entrance train to train jitter</td>
<td>$\sigma$</td>
<td>&lt; 0.5</td>
</tr>
<tr>
<td>Preferred entrance bunch to bunch jitter</td>
<td>$\sigma$</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Typical nominal collimation depth, x/y</td>
<td></td>
<td>8–10/60</td>
</tr>
<tr>
<td>Vacuum pressure level, near/far from IP</td>
<td>nTorr</td>
<td>1/50</td>
</tr>
</tbody>
</table>
Factors driving design of BDS

- **Final Doublet chromaticity**
  - local compensation of chromaticity
- **Beam-beam effects**
  - background, IR and extraction design
- **SR emittance growth in BDS bends**
  - weak and long
- **Halo collimation**
  - survivability of spoilers
- **Beam diagnostics**
  - measurable size at laser wires
- ...
How to focus the beam to a smallest spot?

• If you ever played with a lens trying to burn a picture on a wood under bright sun, then you know that one needs a strong and big lens

  (The emittance $\varepsilon$ is constant, so, to make the IP beam size $(\varepsilon \beta)^{1/2}$ small, you need large beam divergence at the IP $(\varepsilon / \beta)^{1/2}$ i.e. short-focusing lens.)

• It is very similar for electron or positron beams

• But one have to use magnets
Optics building block: telescope

Essential part of final focus is final telescope. It “demagnify” the incoming beam ellipse to a smaller size. Matrix transformation of such telescope is diagonal:

$$R_{X,Y} = \begin{pmatrix} -1/M_{X,Y} & 0 \\ 0 & -M_{X,Y} \end{pmatrix}$$

A minimal number of quadrupoles, to construct a telescope with arbitrary demagnification factors, is four.

If there would be no energy spread in the beam, a telescope could serve as your final focus (or two telescopes chained together).

Use telescope optics to demagnify beam by factor $$m = f_1/f_2 = f_1/L^*$$

Matrix formalism for beam transport:

$$x_i^{\text{out}} = R_{ij} x_j^{\text{in}}$$
Why nonlinear elements

- As sun **light** contains different colors, **electron beam** has energy spread and get dispersed and distorted => **chromatic aberrations**

- For **light**, one uses lenses made from different materials to compensate chromatic aberrations

- Chromatic compensation for particle beams is done with **nonlinear** magnets
  - Problem: Nonlinear elements create **geometric** aberrations

- The **task** of **Final Focus system** (FF) is to focus the beam to required size and compensate aberrations
How to focus to a smallest size and how big is chromaticity in FF?

- The final lens need to be the strongest
  - (two lenses for both x and y => “Final Doublet” or FD)
- FD determines chromaticity of FF
- Chromatic dilution of the beam size is $\Delta \sigma / \sigma \sim \sigma_E L^*/\beta^*$
  
  Typical:
  - $\sigma_E$ -- energy spread in the beam $\sim 0.002 - 0.01$
  - $L^*$ -- distance from FD to IP $\sim 3 - 5$ m
  - $\beta^*$ -- beta function in IP $\sim 0.4 - 0.1$ mm
- For typical parameters, $\Delta \sigma / \sigma \sim 15 - 500$ too big!
- $\Rightarrow$ Chromaticity of FF need to be compensated

- Size at IP:
  - $L^* (\varepsilon / \beta)^{1/2}$
  - $+ (\varepsilon \beta)^{1/2} \sigma_E$

- Beta at IP:
  - $L^* (\varepsilon / \beta)^{1/2} = (\varepsilon \beta^*)^{1/2}$
  - $\Rightarrow \beta^* = L^*^2 / \beta$

- Chromatic dilution:
  - $(\varepsilon \beta)^{1/2} \sigma_E / (\varepsilon \beta^*)^{1/2}$
  - $= \sigma_E L^*/\beta^*$
Dipoles. They bend trajectory, but also disperse the beam so that $x$ depend on energy offset $\delta$.

Sextupoles. Their kick will contain energy dependent focusing:

$$
\begin{align*}
    x' &\Rightarrow S (x + \delta)^2 \Rightarrow 2S x \delta + .. \\
y' &\Rightarrow -S 2(x + \delta)y \Rightarrow -2S y \delta + .. 
\end{align*}
$$

that can be used to arrange chromatic correction.

Necessity to compensate chromaticity is a major driving factor of FF design.

Terms $x^2$ are geometric aberrations and need to be compensated also.
Final Focus Test Beam – optics with traditional non-local chromaticity compensation

Achieved (in ~1990s) ~70nm vertical beam size
Synchrotron Radiation in FF magnets

- Bends are needed for compensation of chromaticity
- SR causes increase of energy spread which may perturb compensation of chromaticity
- Bends need to be long and weak, especially at high energy
- SR in FD quads is also harmful (Oide effect) and may limit the achievable beam size

Energy spread caused by SR in bends and quads is also a major driving factor of FF design

Field lines

Field left behind

$\nu = c$

$\nu < c$
Synchrotron radiation
on-the-back-of-the envelope – power loss

Energy in the field left behind (radiated!):
\[ W \approx \int E^2 \, dV \]

The field \( E \approx \frac{e}{r^2} \) the volume \( V \approx r^2 \, dS \)

Energy loss per unit length:
\[ \frac{dW}{dS} \approx E^2 \, r^2 \approx \left( \frac{e}{r^2} \right)^2 \, r^2 \]

Substitute \( r \approx \frac{R}{2\gamma^2} \) and get an estimate:
\[ \frac{dW}{dS} \approx \frac{e^2 \gamma^4}{R^2} \]

Compare with exact formula:
\[ \frac{dW}{dS} = \frac{2 \, e^2 \gamma^4}{3 \, R^2} \]
Estimation of characteristic frequency of SR photons

For $\gamma \gg 1$ the emitted photons goes into $1/\gamma$ cone.

During what time $\Delta t$ the observer will see the photons?

Photons emitted during travel along the $2R/\gamma$ arc will be observed.

Photons travel with speed $c$, while particles with $v$.
At point B, separation between photons and particles is

\[ dS \approx \frac{2R}{\gamma} \left( 1 - \frac{v}{c} \right) \]

Therefore, observer will see photons during \( \Delta t \approx \frac{c}{dS} \approx \frac{2R}{c\gamma} (1 - \beta) \approx \frac{R}{c\gamma^3} \)

Estimation of characteristic frequency \( \omega_c \approx \frac{1}{\Delta t} \approx \frac{c\gamma^3}{R} \)

Compare with exact formula: \( \omega_c = \frac{3c\gamma^3}{2R} \)
Estimation of energy spread growth due to SR

We estimated the rate of energy loss: \[
\frac{dW}{dS} \approx \frac{e^2 \gamma^4}{R^2}
\]
And the characteristic frequency \[
\omega_c \approx \frac{c \gamma^3}{R}
\]

The photon energy \[
\varepsilon_c = \eta \omega_c \approx \frac{\gamma^3 \eta c}{R} = \frac{\gamma^3}{R} \lambda_e mc^2
\]
where \[
r_e = \frac{e^2}{mc^2} \quad \alpha = \frac{e^2}{\eta c} \quad \lambda_e = \frac{r_e}{\alpha}
\]

Number of photons emitted per unit length \[
\frac{dN}{dS} \approx \frac{1}{\varepsilon_c} \frac{dW}{dS} \approx \frac{\alpha \gamma}{R}
\]
(per angle \(\theta\) : \(N \approx \alpha \gamma \theta\))

The energy spread \(\Delta E/E\) will grow due to statistical fluctuations \((\sqrt{N})\) of the number of emitted photons:

\[
\frac{d\left(\frac{(\Delta E/E)^2}{dS}\right)}{dS} \approx \varepsilon_c^2 \frac{dN}{dS} \frac{1}{\left(\gamma mc^2\right)^2}
\]

Which gives:

\[
\frac{d\left(\frac{(\Delta E/E)^2}{dS}\right)}{dS} \approx \frac{r_e \lambda_e \gamma^5}{R^3}
\]

Compare with exact formula:

\[
\frac{d\left(\frac{(\Delta E/E)^2}{dS}\right)}{dS} = \frac{55}{24\sqrt{3}} \frac{r_e \lambda_e \gamma^5}{R^3}
\]
Estimation of emittance growth rate due to SR

Dispersion function $\eta$ shows how equilibrium orbit shifts when energy changes.

When a photon is emitted, the particle starts to oscillate around new equilibrium orbit.

Amplitude of oscillation is $\Delta x \approx \eta \Delta E/E$.

Compare this with betatron beam size: $\sigma_x = (\varepsilon_x \beta_x)^{1/2}$.

And write emittance growth: $\Delta \varepsilon_x \approx \frac{\Delta x^2}{\beta}$.

Resulting estimation for emittance growth: $\frac{d\varepsilon_x}{dS} \approx \frac{\eta^2}{\beta_x} \frac{d\left((\Delta E/E)^2\right)}{dS} \approx \frac{\eta^2}{\beta_x} \frac{r_e \lambda_e \gamma^5}{R^3}$.

Compare with exact formula (which also takes into account the derivatives):

$$\frac{d\varepsilon_x}{dS} = \frac{ \left( \eta^2 + \left( \beta_x \eta - \beta_x \eta / 2 \right) / \beta_x \right)^2 }{24 \sqrt{3} \frac{r_e \lambda_e \gamma^5}{R^3}}$$
Let’s apply SR formulae to estimate Oide effect (SR in FD)

Final quad

IP divergence: 
\[ \theta^* = \sqrt{\varepsilon/\beta^*} \]

IP size: 
\[ \sigma^* = \sqrt{\varepsilon \beta^*} \]

Energy spread obtained in the quad: 
\[ \left( \frac{\Delta E}{E} \right)^2 \approx \frac{r_e \lambda_e \gamma^5 L}{R^3} \]

Radius of curvature of the trajectory: 
\[ R = \frac{L}{\theta^*} \]

Growth of the IP beam size: 
\[ \sigma^2 \approx \sigma_0^2 + \left( L^* \theta^* \right)^2 \left( \frac{\Delta E}{E} \right)^2 \]

Which gives 
\[ \sigma^2 \approx \varepsilon \beta^* + C_1 \left( \frac{L^*}{L} \right)^2 r_e \lambda_e \gamma^5 \left( \frac{\varepsilon}{\beta^*} \right)^{5/2} \]  
( where \( C_1 \) is \( \approx 7 \) (depend on FD params.))

This achieve minimum possible value: 
\[ \sigma_{\min} \approx 1.35 C_1^{1/7} \left( \frac{L^*}{L} \right)^{2/7} \left( r_e \lambda_e \right)^{1/7} \left( \gamma \varepsilon \right)^{5/7} \]

When beta* is: 
\[ \beta_{\text{optimal}} \approx 1.29 C_1^{2/7} \left( \frac{L^*}{L} \right)^{4/7} \left( r_e \lambda_e \right)^{2/7} \gamma \left( \gamma \varepsilon \right)^{3/7} \]

Note that beam distribution at IP will be non-Gaussian. Usually need to use tracking to estimate impact on luminosity. Note also that optimal \( \beta \) may be smaller than the \( \sigma_z \) (i.e cannot be used).
TeV FF with non-local chromaticity compensation

- Chromaticity is compensated by sextupoles in dedicated sections
- Geometrical aberrations are canceled by using sextupoles in pairs with $M = -I$

Chromaticity arise at FD but pre-compensated 1000m upstream

Problems:
- Chromaticity not locally compensated
  - Compensation of aberrations is not ideal since $M \neq -I$ for off energy particles
  - Large aberrations for beam tails

Traditional FF
(NLC FF, circa 1999)
$L^* = 2m$, TeV energy reach
FF with local chromatic correction

- Chromaticity is cancelled **locally** by two sextupoles interleaved with FD, a bend upstream generates dispersion across FD
- 2\textsuperscript{nd} order dispersion produced in FD is cancelled locally provided that half of horizontal chromaticity arrive from upstream
- Geometric aberrations of the FD sextupoles are cancelled by two more sextupoles placed in phase with them and upstream of the bend
- Higher order aberrations are cancelled by optimizing transport matrices between sextupoles

P. Raimondi, A. Seryi, PRL, 86, 3779 (2001)
Local chromatic correction

- The value of dispersion in FD is usually chosen so that it does not increase the beam size in FD by more than 10-20% for typical beam energy spread.

\[
R = \begin{pmatrix}
m & 0 & 0 & 0 & 0 \\
0 & 1/m & 0 & 0 & 0 \\
0 & 0 & m & 0 & 0 \\
0 & 0 & 0 & 1/m & 0 \\
0 & 0 & 0 & 0 & 1/m \end{pmatrix}
\]
Chromatic correction in FD

Quad: \[ \Delta x' = \frac{K_F}{1 + \delta} (x + \eta \delta) \Rightarrow K_F (-\delta x - \eta \delta^2) \]

Sextupole: \[ \Delta x' = \frac{K_S}{2} (x + \eta \delta)^2 \Rightarrow K_S \eta (\delta x + \frac{\eta \delta^2}{2}) \]

\[ \Delta x' = \frac{K_F}{1 + \delta} (x + \eta \delta) + \frac{K_{\beta\text{-match}}}{1 + \delta} x \Rightarrow 2K_F (-\delta x - \frac{\eta \delta^2}{2}) \]

\[ K_{\beta\text{-match}} = K_F \quad K_S = \frac{2K_F}{\eta} \]

- Straightforward in Y plane
- A bit tricky in X plane:

If we require \( K_S \eta = K_F \) to cancel FD chromaticity, then half of the second order dispersion remains.

Solution:
The \( \beta \)-matching section produces as much X chromaticity as the FD, so the X sextupoles run twice stronger and cancel the second order dispersion as well.
Compare FF designs

FF with local chromaticity compensation with the same performance can be
~300m long, i.e. 6 times shorter

Moreover, its necessary length scales only as $E^{2/5}$ with energy! One can design multi-TeV FF in under a km!
IP bandwidth

Bandwidth of FF with local chromaticity correction can be better than for system with non-local correction.
Aberrations & halo generation in FF

- FF with non-local chr. corr. generate beam tails due to aberrations and it does not preserve betatron phase of halo particles.
- FF with local chr. corr. has much less aberrations and it does not mix phases particles.

Halo beam at the FD entrance.
Incoming beam is ~ 100 times larger than nominal beam.
Beam halo & collimation

- Even if final focus does not generate beam halo itself, the halo may come from upstream and need to be collimated

- Halo must be collimated upstream in such a way that SR $\gamma$ & halo $e^+$ do not touch VX and FD
  - $\Rightarrow$ VX aperture needs to be somewhat larger than FD aperture
  - Exit aperture is larger than FD or VX aperture
  - Beam convergence depend on parameters, the halo convergence is fixed for given geometry
  - $\Rightarrow \theta_{\text{halo}} / \theta_{\text{beam}}$ (collimation depth) becomes tighter with larger $L^*$ or smaller IP beam size
  - Tighter collimation $\Rightarrow$ MPS issues, collimation wake-fields, higher muon flux from collimators, etc.
More details on collimation

- Collimators has to be placed far from IP, to minimize background
- Ratio of beam/halo size at FD and collimator (placed in “FD phase”) remains
- Collimation depth (esp. in x) can be only ~10 or even less
- It is not unlikely that not only halo ($1\times10^{-3} - 1\times10^{-6}$ of the beam) but full errant bunch(s) would hit the collimator
Spoiler-Absorber & spoiler design

Thin spoiler increases beam divergence and size at the thick absorber already sufficiently large. Absorber is away from the beam and contributes much less to wakefields.

Tapered low resistivity surface for wakefields

Need the spoiler thickness increase rapidly, but need that surface to increase gradually, to minimize wakefields. The radiation length for Cu is 1.4cm and for Be is 35cm. So, Be is invisible to beam in terms of losses. Thin one micron coating over Be provides smooth surface for wakes.
FF and Collimation

- Location of spoiler and absorbers is shown
- Collimators were placed both at FD betatron phase and at IP phase
- Two spoilers per FD and IP phase
- Energy collimator is placed in the region with large dispersion
- Secondary clean-up collimators located in FF part
- Tail folding octupoles (see below) are included
- Beam Delivery System Optics, a version with consumable spoilers
ILC FF & Collimation

- Betatron spoilers survive up to two bunches
- E-spoiler survive several bunches
- One spoiler per FD or IP phase

- Beam Delivery System Optics, a version with survivable spoilers
Nonlinear handling of beam tails in ILC BDS

- Can we ameliorate the incoming beam tails to relax the required collimation depth?
- One wants to focus beam tails but not to change the core of the beam
  - use nonlinear elements
- Several nonlinear elements needs to be combined to provide focusing in all directions
  - (analogy with strong focusing by FODO)

- Octupole Doublets (OD) can be used for nonlinear tail folding in ILC FF
Strong focusing by octupoles

- **Two octupoles** of different sign separated by drift provide focusing in all directions for parallel beams:

\[ \Delta \theta = \alpha r^3 e^{-i3\phi} - \left( \alpha r^3 e^{i3\phi} \left(1 + \alpha r^2 Le^{-i4\phi}\right)^3 \right) \]

\[ x + iy = re^{i\phi} \]

\[ \Delta \theta \approx -3\alpha^2 r^5 e^{i\phi} - 3\alpha^3 r^7 L^2 e^{i5\phi} \]

Focusing in all directions

Next nonlinear term focusing – defocusing depends on \( \phi \)

- For this to work, the beam should have small angles, i.e. it should be parallel or diverging

Effect of octupole doublet (Oc,Drift,-Oc) on parallel beam, \( \Delta \Theta(x,y) \).
Tail folding in ILC FF

- Two octupole doublets give tail folding by ~ 4 times in terms of beam size in FD
- This can lead to relaxing collimation requirements by ~ a factor of 4

Tail folding by means of two octupole doublets in the ILC final focus
Input beam has \((x, x', y, y') = (14 \mu m, 1.2 mrad, 0.63 \mu m, 5.2 mrad)\) in IP units (flat distribution, half width) and ±2% energy spread, that corresponds approximately to \(N_\sigma=(65,65,230,230)\) sigmas with respect to the nominal beam
Tail folding
or Origami Zoo
Halo collimation

Assuming 0.001 halo, beam losses along the beamline behave nicely, and SR photon losses occur only on dedicated masks.

Smallest gaps are ±0.6mm with tail folding Octupoles and ±0.2mm without them.

Assumed halo sizes. Halo population is 0.001 of the main beam.
Dealing with muons in BDS

- Muons are produced during collimation
- Muon walls, installed ~300m from IP, reduce muon background in the detectors
BDS design methods & examples

Example BDS optics; design history; location of design knobs
BDS design methods & examples

Need to take care of very highly nonlinear terms!
Example: $y \sim U (x', y', E^2) -$ FOURTH ORDER
In a practical situation ...

- While **designing** the FF, one has a **total control**
- When the system is built => limited number of observable parameters (measured orbit position, beam size measured in several locations)
- The system, however, may initially have **errors** (errors of strength of the elements, transverse misalignments) and initial aberrations may be large
- **Tuning** of FF is done by optimization of **“knobs”** (strength, position of group of elements) chosen to affect some particular aberrations
- Experience in SLC FF and FFTB, and simulations with new FF give confidence that this is possible
Sextupole knobs for BDS tuning

Second order effect:
\[ x' = x' + S (x^2 - y^2) \]
\[ y' = y' - S 2xy \]

- waist shift
- coupling
- dispersion

Combining offsets of sextupoles (symmetrical or anti-symmetrical in X or Y), one can produce the following corrections at the IP.

To create these knobs, sextupole placed on movers.
**IR coupling compensation**

When detector solenoid overlaps QD0, coupling between $y$ & $x'$ and $y$ & $E$ causes large ($30 - 190$ times) increase of IP size (green=detector solenoid OFF, red=ON)

Even though traditional use of skew quads could reduce the effect, the local compensation of the fringe field (with a little skew tuning) is the most efficient way to ensure correction over wide range of beam energies

\[ \sigma_y' / \sigma_y(0) = 32 \]

with compensation by antisolenoid

\[ \sigma_y' / \sigma_y(0) < 1.01 \]

Y. Nosochkov, A. Seryi, Phys.Rev.ST Accel.Beams 8:021001, 2005
Detector Integrated Dipole

- With a crossing angle, when beams cross solenoid field, vertical orbit arise
- For $e^+e^-$ the orbit is anti-symmetrical and beams still collide head-on
- If the vertical angle is undesirable (to preserve spin orientation or the $e^-e^-$ luminosity), it can be compensated locally with DID
- Alternatively, negative polarity of DID may be useful to reduce angular spread of beam-beam pairs (anti-DID)
The negative polarity of DID is also possible (called anti-DID).

In this case the vertical angle at the IP is somewhat increased, but the background conditions due to low energy pairs (see below) and are improved.

B. Parker, A. Seryi Phys. Rev. ST Accel. Beams 8, 041001, 2005
IR integration

Final doublet magnets are grouped into two cryostats, with warm space in between, to provide break point for push-pull
14 mrad IR

Compact Superconducting Magnet Solution for the 14 mrad Crossing Angle Interaction Region Layout

The magnets are mounted on a common girder that is supported inside a single cryostat housing.
Actively shielded QD0

- Interaction region uses compact self-shielding SC magnets
- Independent adjustment of in- & out-going beamlines
- Force-neutral anti-solenoid for local coupling correction

Intensity of color represents value of magnetic field.
IR magnets prototypes at BNL

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

prototype of sextupole-octupole magnet

winding process

Coil integrated quench heater
- Detailed engineering design of IR magnets and their integration

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Service cryostat & cryo connections
Crab crossing

With crossing angle $\theta_c$, the projected x-size is
$$(\sigma_x^2 + \theta_c^2 \sigma_z^2)^{0.5} \approx \theta_c \sigma_z \sim 4 \mu m$$

$\Rightarrow$ several time reduction in $L$
without corrections

Use transverse (crab) RF cavity to ‘tilt’ the bunch at IP

For a crab cavity the bunch centre is at the cell centre when $E$ is maximum and $B$ is zero.
Beam Delivered...

Beam-beam effects

Beam-beam effects are not discussed in this lecture in detail as I assume you had a dedicated lecture on that.
Incoherent* production of pairs

- Beamstrahlung photons, particles of beams or virtual photons interact, and create $e^+e^-$ pairs

Breit-Wheeler process
$\gamma\gamma \rightarrow e^+e^-$

Bethe-Heitler process
$e\gamma \rightarrow ee^+e^-$

Landau-Lifshitz process
$ee \rightarrow eee^+e^-$

*) Coherent pairs are generated by photon in the field of opposite bunch. It is negligible for ILC parameters.
Deflection of pairs by beam

- Pairs are affected by the beam (focused or defocused)
- Deflection angle and $P_t$ correlate
- Max angle estimated as (where $\epsilon$ is fractional energy):

$$\theta_m = \sqrt{4 \frac{\ln \left( \frac{D}{\epsilon} + 1 \right) D \sigma_x^2}{\sqrt{3} \epsilon \sigma_z^2}}$$

- Bethe-Heitler pairs have hard edge, Landau-Lifshitz pairs are outside
Deflection of pairs by detector solenoid

- Pairs are curled by the solenoid field of detector
- Geometry of vertex detector and vacuum chamber chosen in such a way that most of pairs (B-H) do not hit the apertures
- Only small number (L-L) of pairs would hit the VX apertures
Use of anti-DID to direct pairs

Anti-DID field can be used to direct most of pairs into extraction hole and thus improve somewhat the background conditions.
Beam Delivery & MDI elements

$1\text{TeV CM, single IR, two detectors, push-pull}$

grid: 100m*1m

Diagnostics

Beam Switch Yard

polarimeter

Collimation: $\beta$, $E$

E-spectromter

Final Focus

Muon wall

Main dump

Extraction with downstream diagnostics

Sacrificial collimators

Tune-up & emergency Extraction

Tune-up dump

14mr IR

IR Integration
• Very forward region
• Beam-CAL
• Lumi-Cal
• Vertex

Final Doublet

First Crystal Grouping
• QD0
• SD/OC0

Second Crystal Grouping
• QF1
• SF/OC1

14 mr

IP

Actively Shielded

Unshielded

Passively Shielded
BDS functions and optics

- $\beta_{x}^{1/2}$
- $\beta_{y}^{1/2}$
- $\eta_{x}$
- Matching & spectrometer
- Final transformer
- Final doublet
- Polarimeter & extraction
- Betatron collimation
- Energy collimation
- Coupling & emittance

Linac

IP
Extraction optics need to handle the beam with ~60% energy spread, and provides energy and polarization diagnostics.
Beam dump

- 17MW power (for 1TeV CM)
- Rastering of the beam on 30cm double window
- 6.5m water vessel; ~1m/s flow
- 10atm pressure to prevent boiling
- Three loop water system
- Catalytic $\text{H}_2\text{-O}_2$ recombiner
- Filters for 7Be
- Shielding 0.5m Fe & 1.5m concrete
ATF and ATF2
Accelerator Test Facility, KEK

1997-2008

Energy: 1.28 GeV
Electron bunch: 
2\times10^{10} \text{ e/bunch}
1 \sim 20 \text{ bunches/train}
3 \text{ trains/ring}
1.56 \text{ Hz}

Extraction line: utilization of low emittance beam
beam instrumentation, collimator damage

Cavity BPM
nanometer res.

FONT
fast feedback (ns)

Pulsed Laser Wire Scanner
for beam size monitor (\mu m)

ODR, OTR
single shot meas.

Beam Dynamics

Damping Ring
ultra low emittance beam dynamics -fast ion instability
beam instrumentation (BPM, LW)

Fast kicker
rise time < 3ns

RF Gun
multi-bunch beam

S-band Linac (70m)
multi-bunch acceleration
ATF2: model of ILC beam delivery
goals: ~37nm beam size; nm level beam stability

- Dec 2008: first pilot run; Jan 2009: hardware commissioning
- Feb-Apr 2009: large $\beta$; BSM laser wire mode; tuning tools commissioning
- Oct-Dec 2009: commission interferometer mode of BSM & other hardware
# ATF2 & ILC parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>ATF2</th>
<th>ILC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy, GeV</td>
<td>1.3</td>
<td>250</td>
</tr>
<tr>
<td>(L^*, \text{m})</td>
<td>1</td>
<td>3.5-4.2</td>
</tr>
<tr>
<td>(\gamma \varepsilon_{x/y}, \text{m}^{*}\text{rad})</td>
<td>3E-6 / 3E-8</td>
<td>1E-5 / 4E-8</td>
</tr>
<tr>
<td>IP (\beta_{x/y}, \text{mm})</td>
<td>4 / 0.1</td>
<td>21 / 0.4</td>
</tr>
<tr>
<td>IP (\eta', \text{rad})</td>
<td>0.14</td>
<td>0.094</td>
</tr>
<tr>
<td>(\sigma_E, %)</td>
<td>~0.1</td>
<td>~0.1</td>
</tr>
<tr>
<td>Chromaticity</td>
<td>~1E4</td>
<td>~1E4</td>
</tr>
<tr>
<td>(n_{\text{bunches}})</td>
<td>1-3 (goal A)</td>
<td>~3000</td>
</tr>
<tr>
<td>(n_{\text{bunches}})</td>
<td>3-30 (goal B)</td>
<td>~3000</td>
</tr>
<tr>
<td>(N_{\text{bunch}})</td>
<td>1-2E10</td>
<td>2E10</td>
</tr>
<tr>
<td>IP (\sigma_y, \text{nm})</td>
<td>37</td>
<td>5</td>
</tr>
</tbody>
</table>
ATF collaboration & ATF2 facility

- ATF2 will prototype FF,
- help development tuning methods, instrumentation (laser wires, fast feedback, submicron resolution BPMs),
- help to learn achieving small size & stability reliably,

- ATF2 was constructed as ILC model, with in-kind contribution from partners and host country providing civil construction
ATF International organization is defined by MOU signed by 25 institutions:

MOU: Mission of ATF/ATF2 is three-fold:

- ATF, to establish the technologies associated with producing the electron beams with the quality required for ILC and provide such beams to ATF2 in a stable and reliable manner.
- ATF2, to use the beams extracted from ATF at a test final focus beamline which is similar to what is envisaged at ILC. The goal is to demonstrate the beam focusing technologies that are consistent with ILC requirements. For this purpose, ATF2 aims to focus the beam down to a few tens of nm (rms) with a beam centroid stability within a few nm for a prolonged period of time.
- Both the ATF and ATF2, to serve the mission of providing the young scientists and engineers with training opportunities of participating in R&D programs for advanced accelerator technologies.
ATF2 final doublet

ILC Final Doublet layout
Magnets and Instrumentation at ATF2

22 Quadrupoles(Q), 5 Sextupoles(S), 3 Bends(B) in downstream of QM16

All Q- and S-magnets have cavity-type beam position monitors(QBPM, 100nm).

3 Screen Monitors
Strip-line BPMs

5 Wire Scanners, Laserwires
Correctors for feedback

Shintake Monitor (beam size monitor, BSM with laser interferometer)
MONALISA (nanometer alignment monitor with laser interferometer)
Laserwire (beam size monitor with laser beam for 1 μm beam size, 3 axies)
IP intra-train feedback system with latency of less than 150ns (FONT)
Magnet movers for Beam Based Alignment (BBA)
High Available Power Supply (HA-PS) system for magnets
Advanced beam instrumentation at ATF2

- BSM 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)
IP Beam Size monitor

- **BSM:**
  - refurbished & much improved FFTB Shintake BSM
  - $1064\text{nm}\Rightarrow532\text{nm}$

Jul 2005: BSM after it arrived to Univ. of Tokyo

FFTBB sample: $\sigma_y = 70\text{ nm}$
Nanobeams at ATF2 Final Focus

Operation of Final Focus with local chromatic correction verified successfully

It took long time as we needed to develop instrumentation and tuning procedures

Beam Size 44 nm observed*, (Goal (ideal size): 37 nm corresponding to 6 nm at ILC)

*) Effects (wakefields and magnet nonlinearities) contributing to ATF2 beam size (at 1.2 GeV) would not matter at ILC energy
Some of ATF Collaboration photos
• In the previous lectures we have discussed how to estimate effects of dynamic misalignments on beams

• This can be done analytically, and even taking onto account feedbacks
  – E.g. one-to-one steering in linac
  – Or IP feedforward

• In practice, detailed estimations are performed by end-to-end simulations
  – Or “DR=>IP<=DR” simulations
Ground motion models

- Based on data, build modeling $P(\omega, k)$ spectrum of ground motion which includes:
  - Elastic waves
  - Slow ATL motion
  - Systematic motion
  - Cultural noises

Example of integrated spectra of absolute (solid lines) and relative motion for 50m separation obtained from the models.
Ground motion induced beam offset at IP

$P(\omega, k)$ - 2D spectrum of ground motion

rms beam offset at IP: $\propto \int \int P(\omega, k) \cdot G(k) \cdot F(\omega) \cdot dk \cdot d\omega$

Performance of inter-bunch feedback $F(\omega)$

Spectral response function $G(k)$

Characteristic of Feedback $\sim (F/F_0)^2$
Simulations of feedbacks and Final Focus knobs

IP feedback, orbit feedback and dithering knobs suppress luminosity loss caused by ground motion

- Ground motion with $A=5 \times 10^{-7} \text{ m}^2/\text{m/s}$

- Simulated with MONCHOU
e- source => Interaction Point <= e+ source
integrated simulations

NLC beta-functions, e+ & e- beamlines

1.98GeV
linac

250GeV
bypass

BDS

500GeV CM

250GeV
bypass

1.98GeV
linac

sqrt(beta), m

1/2

0

-15
-10
-5
0
5
10
15
S, km

0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
2300
2400
2500
2600
2700
2800
2900
3000
3100
3200
3300
3400
3500
3600
3700
3800
3900
4000

Intermediate ground motion

Luminosity spectrum

Energy in CM, GeV

Beam position at IP

Y Orbits and ground position

pulsed (@120Hz) = 1

RF misal(x,y) = 75,15 microns, IP feedback

NLC, DR>IP<DR; GM B; RF misal(x,y)=75,15 microns, IP feedback
NLC, DR > IP < DR; GM C; RF misal(x,y) = 75, 15 microns, IP feedback

Luminosity spectrum

Y Orbits and ground position

Beam position at IP
Sub nm offsets at IP cause large well detectable offsets (micron scale) of the beam a few meters downstream.
Beam-Beam orbit feedback

Use strong beam-beam kick to keep beams colliding

Shorten BPM-Kicker path for NLC or CLIC design
Beam offset at the IP of NLC FF for different GM models

Characteristic of Feedback

\( \sim (F/F_0)^2 \)

\( \sim 1 \)

~

Spectral response function

\( G_y^{\text{OFFSET}} \) for NLC FFS

Spectral response function \( k \) (1/m)

rms beam offset at IP:

\( \propto \int \int P(\omega,k) \cdot G(k) \cdot F(\omega) \cdot dk \cdot d\omega \)
Beam-Beam orbit feedback

use strong beam-beam kick to keep beams colliding
ILC intratrain feedback (IP position and angle optimization), simulated with realistic errors in the linac and “banana” bunches.

[Glen White]
To finish up, let's discuss what FF design approaches that we discussed apply to circular colliders.

Circular e+e- colliders – a lot in common:
- Design challenges (chromaticity) similar to linear collider – similar design of FF
- Non-local chromaticity compensation
- Local chromaticity compensation
  - Note possible confusion of terminology: (in circular colliders sometime non-local means chromatic compensation by sextupoles in arcs, while local means by sextupoles in cc sections of FF, but not in final doublet)

Circular hh – not a lot in common
SuperKEKB FF is designed as classic FF with non-local chromaticity compensation. This version is more suitable for circular colliders, due to dynamic aperture performance.

It has been discussed to test CLIC non-local chr comp FF version at SuperKEKB, P. Thrane et al, LCSW 2017.
## Comparisons of FF

<table>
<thead>
<tr>
<th></th>
<th>$L^*[\text{m}]$</th>
<th>$\beta_y^*[\mu\text{m}]$</th>
<th>$\xi_y \sim (L^<em>/\beta_y^</em>)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLIC</td>
<td>3.5</td>
<td>70</td>
<td>50 000</td>
</tr>
<tr>
<td>ILC</td>
<td>3.5 /4.5</td>
<td>480</td>
<td>7300 /9400</td>
</tr>
<tr>
<td>ATF2</td>
<td>1</td>
<td>100</td>
<td>10 000</td>
</tr>
<tr>
<td>FFTB</td>
<td>0.4</td>
<td>100</td>
<td>4 000</td>
</tr>
<tr>
<td>SuperKEKB LER</td>
<td>0.935</td>
<td>270</td>
<td>3 460</td>
</tr>
<tr>
<td>SuperKEKB HER</td>
<td>1.41</td>
<td>410</td>
<td>3 440</td>
</tr>
</tbody>
</table>
FIG. 7. Optical functions of SuperB HER interaction region with crab waist sextupoles.

PHYS. REV. ACCEL. BEAMS 19, 121005 (2016)
FIG. 12. Optical functions of FCC-ee interaction region variant 2.

PHYS. REV. ACCEL. BEAMS 19, 121005 (2016)
FCC-hh Parameters

We have two parameter sets
• Beam current is the same
• But luminosity differs

\[ \mathcal{L} \propto \frac{N}{\epsilon \beta_y} \frac{1}{N n_b f_r} \]

They have the same current but the ultimate set has more challenging collision parameters

The “baseline” in EuroCirCol should be capable to run with the ultimate parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FCC-hh Baseline</th>
<th>FCC-hh Ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity (L \ [10^{34}\text{cm}^{-2}\text{s}^{-1}])</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>Background events/bx</td>
<td>170 (34)</td>
<td>680 (136)</td>
</tr>
<tr>
<td>Bunch distance (\Delta t \ [\text{ns}])</td>
<td>25 (5)</td>
<td></td>
</tr>
<tr>
<td>Bunch charge (N \ [10^{11}])</td>
<td>1 (0.2)</td>
<td></td>
</tr>
<tr>
<td>Fract. of ring filled (\eta_{\text{fill}} \ [%])</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>Norm. emitt. (\mu\text{m})</td>
<td>2.2(0.44)</td>
<td></td>
</tr>
<tr>
<td>Max (\xi) for 2 IPs</td>
<td>0.01 (0.02)</td>
<td>0.03</td>
</tr>
<tr>
<td>IP beta-function (\beta \ [\mu\text{m}])</td>
<td>1.1</td>
<td>0.3</td>
</tr>
<tr>
<td>IP beam size (\sigma \ [\mu\text{m}])</td>
<td>6.8 (3)</td>
<td>3.5 (1.6)</td>
</tr>
<tr>
<td>RMS bunch length (\sigma_z \ [\text{cm}])</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>Crossing angle (\sigma^{\perp})</td>
<td>14</td>
<td>Crab. Cav.</td>
</tr>
<tr>
<td>Turn-around time [\text{h}]</td>
<td>5</td>
<td>4</td>
</tr>
</tbody>
</table>

Slide from Daniel Schulte
The FCC-hh, housed in a 97.75 km perimeter racetrack tunnel filled with 16 T SC magnets, includes four EIRs -- two for nominal/high luminosity and two for low-luminosity experiments.

Each of the EIR straight sections is 1400 m long, while in low-luminosity EIR sections the experiments are combined with injection sections.
FCC-hh

- FF needs to reach $\beta^*$ around 0.1 m
- From chromatic properties this is not a large challenge
- There is no need for dedicated chromatic correction sections
- Challenges come from other places:
  - Dynamic aperture
  - The need to provide shielding of triplets from collision debris – 15-50mm of shielding may be needed
  - The need to provide good stay-clear for beam tails

### Example of FCC-hh FF triplet layout

<table>
<thead>
<tr>
<th>IP</th>
<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
</tr>
</thead>
<tbody>
<tr>
<td>L*</td>
<td>45m</td>
<td>7m</td>
<td>2m</td>
</tr>
</tbody>
</table>

| Length (m) | 15 | 15 | 15 |
| Shielding (mm) | 15 | 15 | 15 |
| Gradient (T/m) | 44.2 | 33.2 | 24.2 |
| Aperture Ø (mm) | 106 | 111 | 97 |
| Coil Radius (mm) | 86 | 108 | 126 |

*Main EIR inner triplet – inner coil radius, clear aperture, gradient, thickness of shielding and length of individual quadrupole*
FCC-hh triplet FF and Beam Stay Clear

- Triplet aperture still allows for $\beta^*$ below 0.1m at beam stay clear of $15.5\sigma$ and with 15mm thick shielding inside quadrupole apertures.
- Alternative option with thick shielding of 48mm still allows to reach $\beta^* = 0.2m$. 

![Graph showing beam stay clear with various shielding options](image-url)
FCC-hh FF triplet and shielding

Q1
106 T/m
Abs: 4.4 cm

Q2
111 T/m
Abs: 3.3 cm

Q3
97 T/m
Abs: 2.4 cm
• Thank you for your attention!