## FCC-ee and alignment issues

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Content:

- Introduction over FCC
- Some accelerator concepts
- Results of preliminary studies of effect of misalignments on:
- vertical emittance
- polarization
- Conclusions

CERN, March 2017, Final PACMAN Workshop
ifm $1 / 35 \quad 00000000000$

## FCC: an introduction

CERN is planning its future at the energy frontier after the completion of the LHC program.

Following 2013 recommendations of the Council on European Strategy for Particle Physics, CERN has launched a 5 years international design study for a Future Circular Collider (FCC).


A $\boldsymbol{p} \boldsymbol{p}$ circular collider with a center of mass energy of about 100 TeV is believed to have the necessary discovery potential.


(N. Arkani-Hamed, Geneva 2014 Kick-off meeting)

The c.m. energy reachable by re-placing LHC dipoles with 20 T dipoles is 33 TeV .

- For 100 TeV a new tunnel is needed.
- It could first host a $e^{ \pm}$collider.
- Further options: ions, ep collider.
- Site: Geneva, it would use existing accelerators as injectors and exploit existing technical and administrative infrastructures.

(F. Bordry, Kick-off meeting)

The Standard Model has successfully described the observed phenomena for over 40 years. However it does not have space for some phenomena as neutrinos mass or for dark matter and dark energy which existence has been postulated for explaining recent observations.

The physics case for a $e^{ \pm}$:

- Energy Upgrade: from 45 GeV to 175 GeV beam energy
- Large luminosity
- Precise energy knowledge of the c.m. energy through resonant depolarization allow for precise measurements and thus for discovery of new physics. Complimentary and synergetic to the $\boldsymbol{p} \boldsymbol{p}$-collider.


First milestone: Conceptual Design Report by end 2018!

## lepton collider parameters

| parameter | FCC-ee (400 MHz) |  |  |  |  | CEPC | LEP2 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Physics working point | Z |  | WW | ZH | $\mathrm{tt}_{\text {bar }}$ | H |  |
| energy/beam [GeV] | 45.6 |  | 80 | 120 | 175 | 120 | 105 |
| bunches/beam | 30180 | 91500 | 5260 | 780 | 81 | 50 | 4 |
| bunch spacing [ns] | 7.5 | 2.5 | 50 | 400 | 4000 | 3600 | 22000 |
| bunch population [10 ${ }^{11}$ ] | 1.0 | 0.33 | 0.6 | 0.8 | 1.7 | 3.8 | 4.2 |
| beam current [mA] | 1450 | 1450 | 152 | 30 | 6.6 | 16.6 | 3 |
| luminosity/IP $\times 10^{\mathbf{3 4}} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$ | 210 | 90 | 19 | 5.1 | 1.3 | 2.0 | 0.0012 |
| energy loss/turn [GeV] | 0.03 | 0.03 | 0.33 | 1.67 | 7.55 | 3.1 | 3.34 |
| synchrotron power [MW] | 100 |  |  |  |  | 103 | 22 |
| RF voltage [GV] | 0.4 | 0.2 | 0.8 | 3.0 | 10 | 6.9 | 3.5 |

identical FCC-ee baseline optics for all energies FCC-ee: 2 separate rings CEPC, LEP: single beam pipe

Schematic FCC layout

K. Oide et al, PRAB 19, 111005 (2016)

## Civil engineering

- Cooperation with Swiss and French geological national institutions to set up a 3D model of the Geneva ground.
- Cooperation with commercial providers to develop a unique Building Information Modeling (BIM) Tunnel Optimisation Tool (TOT), to be used for optimizing depth and site of the tunnel.
- First spin-off: ILC tunnel optimisation in KEK (Japan)

J. Osborne

FCC Infr.\&Operation Meet.
Oct 1, 2014

- Lifts and cranes for up to 400 m deep shaft...
- Removal of $10000000 \mathrm{~m}^{3}$ of debris...

Plenty of technical challenges but no show stoppers so far!

## The Reference System



Figure 1: Mad Reference System

From B. Goddard et al., LHC Project Report 719
The coordinates $\{x, y\}$ used by accelerator physicists are the beam position wrt the design orbit at a given longitudinal position, $s$, along that orbit.

## Collider Luminosity

Luminosity is one measure of the potential of a collider. It is defined as the counting rate for a process of unit cross section.

The rate of events for any other process is therefore $\mathcal{R}=\mathcal{L} \times \sigma$
For gaussian beams colliding head-on it is

$$
\mathcal{L}=\frac{N_{1} N_{2}}{4 A} n_{b} f_{\text {rev }} \quad[t]^{-1}[\ell]^{-2}
$$

with
$\boldsymbol{N}_{1,2} \equiv \#$ of particles/bunch in beam 1 and 2
$\boldsymbol{n}_{\boldsymbol{b}} \equiv \#$ of colliding bunches

$$
f_{r e v} \equiv \text { revolution frequency } \quad A \equiv \pi \sigma_{x} \sigma_{y}
$$

## Beam Emittance

The size of a beam in a given point of an accelerator depends on the beam emittance, $\boldsymbol{\epsilon}$, and on the value of the $\boldsymbol{\beta}$ and dispersion functions at that point

$$
\sigma_{z}=\sqrt{\epsilon_{z} \beta_{z}+\left[D_{z}\left(\frac{\Delta p}{p}\right)_{r m s}\right]^{2}} \quad z \equiv x, y
$$

The emittance is the area in 6D phase space occupied by the beam. This area is preserved in a system described by a Hamiltonian. If the 3 degrees of freedom are uncoupled, the invariance applies to each of the 3 planes separately.


The emittance may depend on the "beam history".

The dispersion, $D_{z}(s)$, describes the dependence of the particle orbit upon its energy. It originates from the bending magnets.


In a ring where particles radiate in the bending magnets, as it is for relativistic $e^{ \pm}$, the beam has no memory and the equilibrium emittance is the result of two counteracting processes: excitation, due to photon emission, and RF damping.

Horizontal equilibrium emittance

$$
\epsilon_{x}=C_{q} \gamma^{2} \frac{\mathcal{I}_{5}}{J_{x} \mathcal{I}_{2}}
$$

with

$$
\mathcal{I}_{2} \equiv \oint d s \frac{1}{\rho^{2}} \quad \mathcal{I}_{5} \equiv \oint d s \frac{\beta_{x} D_{x}^{\prime 2}+2 \alpha_{x} D_{x} D_{x}^{\prime}+\gamma_{x} D_{x}^{2}}{|\rho|^{3}}
$$

In a "flat" designed machine dipoles are lying on a plane, namely the horizontal one, where the design orbit lyes. In such a machine nominally it is $D_{y}(s)=0$ : vertical emittance originates only from the cone of photon emission, which sets the lower limit for $\boldsymbol{\epsilon}_{\boldsymbol{y}}$, negligibly small, especially for large rings.

In a real machine however vertical emittance originates from

- magnet misalignments
- vertical displacement of quadrupoles
- roll of horizontal bending magnets
- roll of quadrupoles
* through $D_{y}$ if $\boldsymbol{D}_{\boldsymbol{x}} \neq 0$ at the quadrupole
* through betatron motion coupling
- vertical misalignment of sextupoles (used for correcting chromatic effects)

FCC- $e^{ \pm}$design relies on ultra-flat beams (from http://tlep.web.cern.ch/)

|  | $\boldsymbol{Z}$ |  | $\boldsymbol{W} \boldsymbol{W}$ | $\boldsymbol{H}$ | $\boldsymbol{t} \overline{\boldsymbol{t}}$ |
| :---: | :---: | :---: | :---: | :---: | :---: |
| Beam energy $[\mathrm{GeV}]$ | 45.6 |  | 80 | 120 | 175 |
| $\boldsymbol{\epsilon}_{\boldsymbol{x}}[\mathrm{nm}]$ | 0.2 | 0.09 | 0.26 | 0.61 | 1.3 |
| $\boldsymbol{\epsilon}_{\boldsymbol{y}}[\mathrm{pm}]$ | 1 | 1 | 1 | 1.2 | 2.5 |
| $\boldsymbol{\beta}_{\boldsymbol{x}}^{*}[\mathrm{~m}]$ | 0.5 | 1 | 1 | 1 | 1 |
| $\boldsymbol{\beta}_{\boldsymbol{y}}^{*}[\mathrm{~mm}]$ | 1.0 | 2 | 2 | 2 | 2 |
| $\boldsymbol{\sigma}_{\boldsymbol{x}}^{*}[\boldsymbol{\mu \mathrm { m }}]$ | 10 | 9.5 | 16 | 25 | 36 |
| $\boldsymbol{\sigma}_{\boldsymbol{y}}^{*}[\mathrm{~nm}]$ | 32 | 45 | 45 | 49 | 70 |

## $\boldsymbol{\beta}$-function in a "drift" (magnet free) region

$$
\beta_{z}(s)=\beta_{z}(0)-2 \alpha_{z}(0) s+\gamma_{z}(0) s^{2}
$$

with

$$
\alpha_{z} \equiv-\frac{1}{2} \frac{d \beta_{z}}{d s} \quad \gamma_{z} \equiv \frac{1+\alpha_{z}^{2}}{\beta_{z}}
$$



$$
\text { FCC-ee IP }\left(\beta_{y}^{*}=2 \mathrm{~mm}\right)
$$


K. Oide et al, PRAB 19, 111005 (2016)
$\mathrm{A} \pm 2.2 \mathrm{~m}$ long drift is provided for the experiment solenoid and anti-solenoids.

## Effect of quadrupoles mis-alignment on closed orbit

Orbit sensitivity to quadrupole misalignments

$$
<\boldsymbol{z}_{r m s}>=\boldsymbol{F} \delta z_{r m s}^{Q} \quad \boldsymbol{z}=\boldsymbol{x}, \boldsymbol{y}
$$

with

$$
F \equiv \frac{1}{2 \sqrt{2}\left|\sin \pi Q_{z}\right|} \sqrt{<\beta_{z}>} \sqrt{\Sigma_{i=1}^{N Q} \beta_{z, i}(k \ell)_{i}^{2}}
$$

and $Q_{z} \equiv f_{\beta} / f_{\text {rev }} \quad$ (betatron tune)


With $\operatorname{frac}\left(\boldsymbol{Q}_{y}\right)=0.2$ for FCC-ee it is ${ }^{\text {a }}$

|  | $\boldsymbol{F}$ | $<\boldsymbol{y}_{r m s}>(\mathrm{mm})$ |
| :---: | :---: | :---: |
| for $\delta \boldsymbol{y}_{r m s}^{\boldsymbol{Q}}=200 \boldsymbol{\mu m}$ |  |  |$|$|  |  |  |
| :---: | :---: | :---: |
| all quads | 613 | 123 |
| w/o IPs doublets(*) | 141 | 28 |

$\left.{ }^{*}\right)$ QC1R, QC2R, QC1L, QC2L
Huge effect of vertical misalignments on orbit due to

- large number of quadrupoles
- large contribution of doublet quadrupoles

[^0]
## Effect of quadrupoles mis-alignment on dispersion

Non vanishing vertical closed orbit at quadrupoles introduces radial magnetic fields, $\boldsymbol{B}_{\boldsymbol{x}}=\boldsymbol{K} \boldsymbol{y}_{\boldsymbol{c o}}$, and thus vertical dispersion

$$
\frac{d^{2} D_{y}}{d s^{2}}+K(s) D_{y}=\frac{e}{p} B_{x}
$$

$$
D_{y}(s)=\frac{\sqrt{\beta_{y}(s)}}{2 \sin \pi Q_{y}} \sqrt{\beta_{y}^{q}}(K \ell) \cos \left(\pi Q_{y}-\left|\mu_{y}(s)-\mu_{y}^{q}\right|\right) y_{c o}^{q}
$$

The vertical emittance may become no more negligible!

## The FCC-ee orbit problem

"Tricks" needed for introducing misalignments errors in the simulation (!):

- Move tunes away from integer ("injection" tunes)
$-\boldsymbol{q}_{\boldsymbol{x}}: 0.1 \rightarrow 0.2$
$-\boldsymbol{q}_{y}: 0.2 \rightarrow 0.3$
- Switch sextupoles off
- Add errors to "arc" quads in steps of 5-10 $\mu \mathrm{m}$ (!) and correct by each step with large number (some hundreds) correctors
- Add errors to each doublet quadrupole in steps of $1 \boldsymbol{\mu m}$ (!!) and correct with close by correctors

In the process for each quadrupole the misalignment increment $\Delta \delta^{Q_{i}}$ is kept constant so that at the end it is $\delta y_{r m s}^{Q}=200 \mu \mathrm{~m}$ (or whatever realistic number).

A lengthy procedure not feasible in a real machine. In practice: use "relaxed" optics and one-turn steering through correction dipoles for establishing a closed orbit.

But for many seeds machine became unstable when sextupoles were turned on at the very end!

An example.
Sextupoles off/on but at $45 \%$ for getting a stable machine: vertical orbit is almost unchanged by the sextupoles.


Explanation of the "mystery": The phase advance between the sextupoles around the IPs being $180^{\circ}$ and their strengths having opposite signs, they produce a coupling wave when the beam offset at those sextupoles are anti-symmetric wrt IP. Indeed moving the betatron tunes closer the sextupole strengths must be further reduced to get a stable machine.
$\leadsto$ The vertical beam position at those sextupoles must be $\lesssim 100 \mu \mathrm{~m}$.

## Beam vertical emittance: one more threat

The roll angle of the quadrupoles around the longitudinal direction introduces coupling between the horizontal and vertical motion

- transfer of the (large) horizontal emittance into the vertical. It can be described by coupling functions, $\boldsymbol{w}^{ \pm}$, which for a single source at $s_{s k i}$, write

$$
w_{ \pm}(\theta)=-\frac{C_{ \pm}^{s k q}}{4 \sin \pi Q_{ \pm}} \mathrm{e}^{-i Q_{ \pm}\left[s-s_{s k q}-\pi \operatorname{sign}\left(s-s_{s k q}\right)\right] / R}
$$

with $Q_{ \pm} \equiv Q_{x} \pm Q_{y}$ and
$\boldsymbol{K}_{s q k}$

$$
C_{ \pm}^{s k q} \equiv \frac{\ell}{2} \sqrt{\boldsymbol{\beta}_{x} \boldsymbol{\beta}_{y}} \frac{e}{p}\left(\frac{\partial B_{x}}{\partial x}-\frac{\partial B_{y}}{\partial y}\right) \mathrm{e}^{i\left(\Phi_{x} \pm \Phi_{y}\right)}
$$

- generation of vertical dispersion if $\boldsymbol{D}_{x} \neq 0$ at the tilted quad

$$
\Delta D_{y}(s)=\frac{1}{2 \pi \sin \pi Q_{y}} D_{x}^{s k q} \sqrt{\beta_{y}^{s k q} \beta_{y}(s)} \cos \left(\pi Q_{y}-\left|\mu_{y}-\mu_{y}^{s k q}\right|\right)(K \ell)_{s k q}
$$

Closed orbit and vertical dispersion are measured by the BPMs.
Coupling functions may be measured by BPMs with Turn-by-Turn capability. Remedies to misalignments

- Accurate closed orbit correction. For FCCee simulations here presented: ${ }^{a}$
- one BPM and a CV next to each IR quadrupole
- one BPM and one CV close to each vertical focusing quad in the arcs
- Dedicated dispersion and betatron coupling correction through skew quadrupoles. Well calibrated BPMs are crucial!

[^1]
## Some results ${ }^{a}$

- $\delta y_{r m s}^{q}=200 \mu \mathrm{~m}$ ( "conservative")
- 0.25 mrad quadrupole roll angle ("conservative")
- 1086 BPMs w/o errors
- orbit corrected with 1086 CV s down to $\boldsymbol{y}_{\text {rms }}=0.05 \mathrm{~mm}$
- coupling/dispersion correction with 289 skew quadrupoles

Coupling functions at BPMs



[^2]

Effect on emittance at 45 GeV (MAD-X)

|  | $\boldsymbol{\epsilon}_{\boldsymbol{x}}(\mathrm{pm})$ | $\boldsymbol{\epsilon}_{\boldsymbol{y}}(\mathrm{pm})$ | ratio |
| :---: | :---: | :---: | :---: |
| design goal | 90 | 1 | 0.011 |
| before orbit correction | - | - | - |
| after orbit correction | 88.1 | 8.4 | 0.095 |
| + coupling/dispersion correction | 88.6 | 0.9 | 0.010 |

## ifm

## 80 GeV

|  | iteration\# | $\boldsymbol{\epsilon}_{\boldsymbol{x}}(\mathrm{pm})$ | $\boldsymbol{\epsilon}_{\boldsymbol{y}}(\mathrm{pm})$ | ratio |
| :---: | :---: | :---: | :---: | :---: |
| design goal | - | 260 | 1 | 0.004 |
| unperturbed | - | 279 | 0 | 0 |
| after orbit correction | - | 270.6 | 31.7 | 0.117 |
| +coupling/dispersion correction | 1 | 279.5 | 2.5 | 0.009 |
|  | 2 | 280.5 | 1.3 | 0.005 |
|  | 3 | 280.2 | 0.8 | 0.003 |

Extrapolating at higher energy:

| Energy $(\mathrm{GeV})$ | $\epsilon_{\boldsymbol{y}}(\mathrm{pm})$ | $\boldsymbol{\epsilon}_{\boldsymbol{y}}$ goal $(\mathrm{pm})$ |
| :---: | :---: | :---: |
| 120 | 1.8 | 1.2 |
| 175 | 3.8 | 2.5 |

Better alignment is required: a $20 \%$ alignment improvement would do it!

## ifm ${ }^{2 / / 5 s}$ <br> 00000000000

## Polarization

FCC-ee relies on resonant de-polarization for accurate (better than 100 KeV ) beam energy calibration at 45 and 80 GeV beam energy.

Beam polarization is obtained "for free" through Sokolov-Ternov effect. However the effect is in practice restricted to a limited range of values of machine size and beam energy because

- of the build-up rate

$$
\tau_{p}^{-1}=\frac{5 \sqrt{3}}{8} \frac{r_{e} \gamma^{5} \hbar}{m_{0} C} \oint \frac{d s}{|\rho|^{3}} \simeq 250 \mathrm{~h} \text { for FCC-ee at } 45 \mathrm{GeV} \leadsto \text { wigglers }
$$

- it is jeopardized by machine imperfections (spin/orbital motion resonances) which affects the reachable level of polarization in particular at high energy.


## Importance of quads mis-alignment

Resonances are awakened by imperfections! In a perfect ring $\boldsymbol{P}_{\infty}=92 \%$ at all energies!
Question: how perfect the ring must be for keeping resonances "sleeping"? An example for a (much) simplified FCC-ee at 45 GeV ( "toy ring"):


- $\delta y_{r m s}^{q}=200 \mu \mathrm{~m}$
- 1086 BPMs w/o errors
- orbit corrected with 1086 CVs
- $\boldsymbol{y}_{r m s}=0.049 \mathrm{~mm}$
- no $\delta \hat{n}_{0}$ correction

FCCee, $\boldsymbol{\delta} \hat{\boldsymbol{n}}_{\mathbf{0}, \boldsymbol{r m s}}=0.4 \mathrm{mrad}$


Toy ring, $\boldsymbol{\delta} \hat{\boldsymbol{n}}_{\mathbf{0}, \mathrm{rms}}=0.3 \mathrm{mrad}$


- Same error realization as at 45 GeV
- $\delta y_{r m s}^{q}=200 \mu \mathrm{~m}$
- 1086 BPMs w/o errors
- orbit corrected with 1086 CVs
- $\boldsymbol{y}_{\text {rms }}=0.049 \mathrm{~mm}$
- no $\boldsymbol{\delta} \hat{\boldsymbol{n}}_{0}$ correction

FCCee, $\boldsymbol{\delta} \hat{\boldsymbol{n}}_{\mathbf{0}, \boldsymbol{r m s}}=0.4 \mathrm{mrad}$


FCCee, $\boldsymbol{\delta} \hat{\boldsymbol{n}}_{\mathbf{0}, \text { rms }}=2 \mathrm{mrad}$


Aim (for energy calibration): $\boldsymbol{P} \simeq 10 \%$

But if we can reduce the alignment errors...


$$
\begin{aligned}
& \delta x_{r m s}^{Q}=2 \mu m \\
& \leadsto \delta \hat{n}_{0, r m s}=0.02 \mathrm{mrad}
\end{aligned}
$$



## Conclusions

The results here presented are preliminary

- The simulation must be improved: possibility of linking quadrupole and close-by-BPM offsets
- BPMs calibration errors must be included
- BPMs availability
- Further sources of errors must be added: horizontal
 quadrupole displacements, bending magnet roll, sextupoles misalignments....

Tolerances will become tighter when all is taken into account...

Although I did not mention other crucial beam dynamics issues which strongly impact the whole project and the IR design (beam-beam effects, beamstrahlung, chromatic correction, synchrotron radiation..) it is clear that FCC-ee is a quite challenging project and that a machine alignment at nano-meter and nano-radians level and well calibrated BPMs would be of great help for

- bringing the machine into operation
- reaching required machine performance
- making possible polarization also at high energy.

The Washington FCC week (2015) included a supportive opening address by congressman G. W. Foster
"..never be shy in standing up for the unique nature of your field and never be afraid of big numbers."
(from CERN Courier, May 2015)


We can add
"...and never be afraid of small numbers!"
THANKS FOR YOUR ATTENTION!


[^0]:    ${ }^{\text {a }}$ In the following the focus will be on vertical mis-alignments which are the most important

[^1]:    ${ }^{\text {a }}$ quads vertical mis-alignments and roll angle only

[^2]:    ${ }^{\mathrm{a}} \mathrm{nb}$ : in the following horizontal misalignments and BPMs errors have been not included.

