Future high energy colliders

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Contents

- LHC, today and prospects (25→300→3000 fb⁻¹)
- Physics motivation for Higgs factories (e+e-(LC,ring), γγ, μ+μ-)
- Linear colliders: ILC, CLIC
- Circular colliders:
  - FCC-ee, FCC-hh - CERN
  - CEPC, SppC - China
  - Muon colliders (briefly)

- Conclusion

Here:
FCC (ee, hh) – Future Circular Collider
CEPC – Circular Electron Positron Collider
SppC – Super proton proton Collider
In July 2012 two detectors ATLAS and CMS working at LHC have discovered the particle with the mass $M \sim 125$ GeV with properties very similar to the predicted Higgs boson and (still) nothing else ... What to do?

The LHC is a Higgs Factory!
1M Higgs already produced – more than any other Higgs factory projects.

15 Higgs bosons/minute – and more to come (gain factor 3 going to 13 TeV)

For nominal LHC

<table>
<thead>
<tr>
<th>HL-LHC</th>
<th>300 fb-1</th>
<th>20 M Higgs bosons</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3000 fb-1</td>
<td>200 M</td>
</tr>
</tbody>
</table>
LHC plans

LHC / HL-LHC Plan

L~7x10^{33} Pile-up~20-35  
LS1  
7 TeV 8 TeV  
splice consolidation button collimators R2E project  
experiment beam pipes  
30 fb^-1  
13-14 TeV  
14 TeV  
L=1.6x10^{34} Pile-up~30-45  
LS2  
experiment upgrade phase 1  
150 fb^-1  
2020  
cryolimit interaction regions  
2 x nominal luminosity  
300 fb^-1  
2021  
LS3  
HL-LHC installation  
3000 fb^-1 luminosity  
2022  
2023  
2024  
2025  
2026  
L=2-3x10^{34} Pile-up~50-80  
L=5x10^{34} Pile-up~130-200  
2026  
2027  
2028  
2029  
2030  
2031  
2032  
2033  
2034  
2035  
30 fb^-1  
75% nominal luminosity  
2035  
L. Rossi
Situation in 2022 and with lum. upgrade (2035)

The approved LHC programme will be completed

- With 300 fb⁻¹ @ 13 TeV, CMS and ATLAS will measure five production modes
  - gg → H
  - VBF
  - WH, ZH
  - ttH
  - ... and six decay modes: γγ, ZZ, WW, ττ, bb, μμ

Approved LHC 300 fb⁻¹ at 14 TeV:
- Higgs mass at 100 MeV
- Disentangle Spin 0 vs Spin 2 and main CP component in ZZ*
- Coupling rel. precision/Exper.
  - Z, W, b, τ 10-15%
  - t, μ 3-2σ observation
  - γγ and gg 5-11%

HL-LHC 3000 fb⁻¹ at 14 TeV:
- Higgs mass at 50 MeV
- More precise studies of Higgs CP sector
- Couplings rel. precision/Exper.
  - Z, W, b, τ, t, μ 2-10%
  - γγ and gg 2-5%
  - H→HH >3σ observation (2 Exper.)

LHC can’t measure Br(cc, invisible) and Γtot.
Precision needed after LHC

- New physics affects the Higgs couplings
  - SUSY \[ \frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left( \frac{1 \text{ TeV}}{m_A} \right)^2 , \text{ for } \tan\beta = 5 \]
  - Composite Higgs \[ \frac{g_{h_{ff}}}{g_{h_{SM}ff}} \simeq \frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 3\% \left( \frac{1 \text{ TeV}}{f} \right)^2 \]
  - Top partners \[ \frac{g_{h_{gg}}}{g_{h_{SM}gg}} \simeq 1 + 2.9\% \left( \frac{1 \text{ TeV}}{m_T} \right)^2 , \quad \frac{g_{h\gamma\gamma}}{g_{h_{SM}\gamma\gamma}} \simeq 1 - 0.8\% \left( \frac{1 \text{ TeV}}{m_T} \right)^2 \]
  - Other models may give up to 5% deviations with respect to the Standard Model

For observation (and some study) of new physics beyond standard Higgs one need precision better than 1%!
Colliders for precision Higgs study

e+e- linear colliders

e+e- circular colliders

Photon colliders

Muon colliders
Higgs factory colliders (discussed at HF2012)

• Linear e+e- collider:
  - ILC
  - CLIC
  - X-band klystron based
• Circular e+e- collider:
  - LEP3
  - TLEP
  - SuperTRISTAN
  - Fermilab site-filler
  - China Higgs Factory (CHF)
  - SLAC/LBNL big ring
• Muon collider
  - Low luminosity
  - High luminosity
• \(\gamma \gamma\) collider:
  - ILC-based
  - CLIC-based
  - Recircul. linac-based SAPHiRE + HERA, Tevatron rings
  - SLC-type
Tagging Z in $e^+e^-\rightarrow ZH$ one can measure all $\text{Br}(H)$, even invisible decays width. One can measure the Higgs total width:

$$\Gamma(H) \sim \frac{\sigma(e^+e^-\rightarrow ZH)}{\text{Br}(H \rightarrow ZZ)} \quad \text{and} \quad \Gamma(H) \sim \frac{\sigma(WW \rightarrow H)}{\text{Br}(H \rightarrow WW)}$$

At linear colliders $L \sim 10^{34}$, $N_H \sim 20000$/year or $10^5$ for life of the experiment;

At circular collider with $C \sim 100$ km and several IP one can have $N_H \sim 10^6$. 

June 19, 2015  V. Telnov
Higgs physics at muon collider

Resonance H production:
\[ \sigma(\mu^+\mu^-\rightarrow H) \approx 40000 \quad \sigma(e^+e^- \rightarrow H) \approx 70 \text{ pb} \]

- The Higgs width is about 4 MeV, the muon collider with \( \delta E/E = 0.003\% \) can measure the Higgs width directly with an accuracy 5% (comparable that in e+e-).
- The Higgs mass can be measured with an accuracy 0.1 MeV, 100 times better than in e+e-.
- Coupling \( H \rightarrow \mu^+\mu^+ \) can be measured with 1.5% accuracy.

The number of Higgs boson is about 2500/year at expected \( L \sim 10^{31} \) (small L due to transverse-longitudinal emittance exchange for obtaining a high monochromaticity).
Higgs study at photon colliders ($\gamma\gamma$, $\gamma e$)

$\Gamma_{\gamma\gamma}$ is determined by contributions of all charge particles (even with $M > 2E_0$), therefore this process is most sensitive to new physics!

In $\gamma\gamma$ collisions the $\Gamma(H \rightarrow \gamma\gamma)$ width can be measured with statistics $\approx$ 90 times higher than in $e^+e^-$ collisions. This is the most important argument for the photon collider.

However, $e^+e^-$ beams are much better for Higgs study (due to $Z$ tagging). Therefore PLC has sense only in combination with $e^+e^-$: parallel work or second stage.
Linear colliders

History

- CLIC
- TESLA
- SBLC
- JLC(GLC)
- NLC
- SLC
- VLEPP

Time:
- 1980
- 1990
- 2000
- 2010

ILC
ILC TDR Layout

- **E+ source**
- **Damping Rings**
- **Polarised electron source**
- **e+ Main Linac**
- **e- Main Linac**

**Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>C.M. Energy</td>
<td>500 GeV</td>
</tr>
<tr>
<td>Peak luminosity</td>
<td>$1.8 \times 10^{34}$ cm$^{-2}$s$^{-1}$</td>
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<tr>
<td>Beam Rep. rate</td>
<td>5 Hz</td>
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<tr>
<td>Pulse duration</td>
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<tr>
<td>Average current</td>
<td>5.8 mA (in pulse)</td>
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<tr>
<td>E gradient in SCRF acc. cavity</td>
<td>$31.5$ MV/m +/−20% $Q_0 = 1E10$</td>
</tr>
</tbody>
</table>

**ILC Scheme**

- **L=31 km**
- **2E=500 GeV**
- **2E=250-500 GeV, upgradable to 1000 GeV**
2 Detector Concepts: **Detailed Baseline Design**

**ILD**
- Large R with TPC tracker
  - 32 countries,
  - 151 institutions,
  - ~700 members
  - $B=3.5T$, TPC + Si trackers
  - ECal: $R=1.8m$

**SiD**
- High B with Si strip tracker
  - 18 countries,
  - 77 institutions,
  - ~240 members
  - $B=5T$, Si only tracker
  - ECal: $R=1.27m$
Japan is interested to host:
- decision ~2018
- construction ~2019 (~10 years)
- physics ~2030
Known physics, ILC stages

- $2E=250\ \text{GeV}$ Higgs boson
- $350$ top quark
- $500$ ZHH –Higgs self coupling
- $500$ and higher ttH - top Yukawa coupling
- $1000$ and higher Beyond
The coupling measurement at HL-LHC in 2-10% range can be reduced at the ILC by an order of magnitude.
Compact Linear Collider (CLIC)

Drive Beam Generation Complex

Main Beam Generation Complex

Legend

- CERN existing LHC
- Potential underground site:
  - CLIC 500 GeV
  - CLIC 1.5 TeV
  - CLIC 3 TeV

0.5 TeV: 8,300 MCHF \( (L \sim 1.4 \times 10^{34}) \)
The feasibility of the CLIC scheme has been established. CLIC proposes a staged approach to reach 3 TeV: Stages with 500 fb-1 at <500 GeV, 1500 fb-1 at 1-2 TeV, 2000 fb-1 at 3 TeV; L = 2.3×10^{34} \text{ cm}^{-2} \text{ s}^{-1} at 500 GeV

Decision: 2018-2019
Preparation stage: ~5 years
Construction could start in 2024-25; commissioning in ~2033.
## ILC and CLIC parameters

<table>
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<th>Parameter</th>
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<th>ILC</th>
<th>CLIC</th>
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<td>$2E_0$</td>
<td>GeV</td>
<td>250</td>
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<td>Pol. $e^-$/Pol. $e^+$</td>
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<td>Bunch distance</td>
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<td>mm-mrad</td>
<td>10</td>
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<td>$\beta_x$ at IP</td>
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<td>11</td>
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<td>$\beta_y$ at IP</td>
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<td>$\sigma_x$ at IP</td>
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<td>$\sigma_y$ at IP</td>
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<td></td>
<td></td>
<td>10.5</td>
<td>28</td>
</tr>
</tbody>
</table>
Circular Higgs e+e- factories

Beginning:
2. K. Oide, Super-Tristan, talk at KEK, Feb. 2012 (crab-waist scheme)
4. A. Blondel...V. Telnov..., LEP3: A High Luminosity e+e- Collider to study the Higgs Boson, arXiv:1208.0504 (Aug. 2012) (Triple-LEP (TLEP) with C=80 km is discussed)

HF2012-First Higgs factory workshop (November, 2012, FNAL) – already 7-8 proposals of Circular e+e- Higgs factories around the world on the energy 2E=230(H)-370(tt) GeV.
Many $e^+e^-$ circular Higgs factories are being studied around the world.
## Circular $e^+e^-$ Collider as a Higgs Factory

### November 2012

- **16 km (Fermilab site-filler)**, **USA**
- **21 km (Protvino)**, **Russia (free tunnel)**
- **27 km (LEP3)**
- **40 km (SuperTRISTAN-40)**, **Japan**
- **50 km (CHF-1)**, **China**
- **70 km (CHF-2)**, **China**
- **80 km (TLEP, SuperTRISTAN-80)**, **Swiss, Japan**
- **233 km (VLLC)**, **USA**

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At present: two projects are very seriously considered

**FCC-ee, FCC-hh (CERN)**, C=100km, $2E_{e^+e^-}=90-350$ GeV, $2E_{pp}=100$ TeV

**CEPC, SppC (China)**, C~54km, $2E_{e^+e^-}=240$ GeV, $2E_{pp}=70$ TeV

**FCC (ee, hh) – Future Circular Collider**
**CEPC – Circular Electron Positron Collider**
**SppC – Super proton proton Collider**

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Main arguments for circular e+e- colliders

During last 25 years linear colliders were considered as best candidates for the next collider for precision study below 1-3 TeV, why ring e+e- colliders again?

Advantages
1) No new physics is found up to now by LHC for exception of low mass Higgs boson. The energy $2E=230$ GeV needed for study H in e+e- collision can be reached by circular e+e- colliders.

2) Ring colliders are easier and luminosity can be higher than at linear colliders at $2E=230$ GeV (and much higher at Z), can provide higher accuracy needed for observation of new physics (in Higgs and Z decays). Top threshold $2E=350$ GeV can be reached.

3) Ring tunnels (C~100 km) can be used further for highest energy pp (or muon) colliders. It is a very attractive long-term strategy.

Disadvantage: Presence of new physics in the region $2E=350-3000$ is still not excluded, this region can be covered only by linear colliders.
Beam lifetime due to beamstrahlung

The electron loses the beam after emission of beamstrahlung photon with an energy greater than the threshold energy $E_{th} = \eta E_0$, where a ring energy acceptance $\eta \sim 0.01-0.02$.

The beam lifetime due to beamstrahlung (V. Telnov)

$$
\tau \approx 6 \frac{2\pi R \sqrt{6\pi} \gamma u^{3/2} e^{1.225u}}{c \alpha^2 \eta \sigma_z}
$$

$$
u = \eta \frac{\alpha \sigma_x \sigma_z}{3 \gamma r_e^2 N}, \quad \alpha = \frac{e^2}{\hbar c}
$$

The requirement of the lifetime 30 min imposes a new restriction on the beam parameters

$$
\frac{N}{\sigma_x \sigma_z} < 0.1 \eta \frac{\alpha}{3 \gamma r_e^2}
$$
Head-on and “crab-waist” collision schemes

Below we consider two collision schemes: head-on and crab-waist. In the crab-waist scheme the beams collide at an angle \( \theta \gg \sigma_x/\sigma_z \). This scheme allows a higher luminosity, if it is determined by the tune shift (beam-beam strength parameter characterizing instabilities).

For head-on collisions the tune shift (\( \xi_y \approx 0.1 - 0.15 \)) and the luminosity

\[
(1) \quad \xi_y = \frac{N r_e \beta_y}{2 \pi \gamma \sigma_x \sigma_y} \approx \frac{N r_e \sigma_z}{2 \pi \gamma \sigma_x \sigma_y} \quad \text{for} \quad \beta_y \approx \sigma_z, \quad \mathcal{L} \approx \frac{N^2 f}{4 \pi \sigma_x \sigma_y} \approx \frac{N f \gamma \xi_y}{2 r_e \sigma_z}
\]

For the crab-waist scheme

\[
(2) \quad \xi_y = \frac{N r_e \beta_y}{\pi \gamma \sigma_x \sigma_y \sigma_z} \quad \text{for} \quad \beta_y \approx \sigma_x/\theta \quad \mathcal{L} \approx \frac{N^2 f}{2 \pi \sigma_y \sigma_z \theta} \approx \frac{N^2 \beta_y f}{2 \pi \sigma_x \sigma_y \sigma_z} \approx \frac{N f \gamma \xi_y}{2 r_e \beta_y}
\]

In the crab-waist scheme one can make \( \beta_y \sim \sigma_y/\theta \ll \sigma_z \), therefore the luminosity can be higher (>10 times)/ Nf is determined by SR power. The only free parameters in \( \mathcal{L} \) are \( \sigma_z \) (for head-on) and \( \beta_v \) (crab-waist), they are constrained by beamstrahlung condition

\[
(3) \quad \frac{N}{\sigma_x \sigma_z} < 0.1 \eta \frac{\alpha}{3 \gamma r_e^2}
\]
Comparing (1),(2),(3) one can find the minimum beam energy when beamstrahlung becomes important.

For head-on collisions

\[ \gamma_{\text{min}} = \left( \frac{0.1 \eta \alpha \sigma_z^2}{6 \pi r_e \xi_y \sigma_y} \right)^{1/2} \propto \frac{\sigma_z^{3/4}}{\xi_y^{1/2} \varepsilon_y^{1/4}} \]

For “crab-waist” collisions

\[ \gamma_{\text{min}} = \left( \frac{0.1 \eta \alpha \beta_y^2}{3 \pi r_e \xi_y \sigma_y} \right)^{1/2} \propto \frac{2^{1/2} \beta_y^{3/4}}{\xi_y^{1/2} \varepsilon_y^{1/4}} \]

In the crab-waist scheme the beamstrahlung becomes important at much low energies because \( \beta_y << \sigma_z \). For typical values of parameters (for \( \eta = 0.01 \)) \( E_{\text{min}} > 70 \text{ GeV} \) for head-on collisions and \( E_{\text{min}} > 20 \text{ GeV} \) for “crab-waist”.

For considered colliders with \( 2E_0 > 240 \text{ GeV} \) beamstrahlung is important in both schemes.
Luminosities with account of beamstrahlung

It turns out that with account of beamstrahlung luminosities for head-on collisions and crab-waist collisions are practically equal

\[ \mathcal{L} \approx \frac{N f}{4\pi} \left( \frac{0.1\eta\alpha}{3} \right)^{2/3} \left( \frac{2\pi\xi_y}{\gamma r_e^5\xi_y} \right)^{1/3} \]

\[ \sigma_{z,\text{opt}} = \varepsilon^{1/3} \left( \frac{6\pi\gamma^2 r_e \xi_y}{0.1\eta\alpha} \right)^{2/3} \] for head-on

\[ \beta_{y,\text{opt}} = \varepsilon^{1/3} \left( \frac{3\pi\gamma^2 r_e \xi_y}{0.1\eta\alpha} \right)^{2/3} \] for crab-waist
Nf = n_bc/2πR is determined by the SR power in rings

\[ P = 2 \delta E \frac{cNn_b}{2\pi R} = \frac{4e^2\gamma^4 cNn_b}{3RR_b} \]

Finally, the luminosity

\[ \mathcal{L} \approx h \left( \frac{0.1\eta\alpha}{32\pi^2\gamma^{13/3}r_e^3} \right) \left( \frac{R_b}{R} \right) \left( \frac{6\pi\xi_y r_e}{\varepsilon_y} \right)^{1/3} \]

(here \( h \) is the hourglass loss factor)

In practical units

\[ \frac{\mathcal{L}}{10^{34} \text{ cm}^{-2}\text{s}^{-1}} \approx \frac{100h\eta^{2/3}\xi_y^{1/3}}{(E_0/100 \text{ GeV})^{13/3}(\varepsilon_y/\text{ nm})^{1/3}} \left( \frac{P}{100 \text{ MW}} \right) \left( \frac{2\pi R}{100 \text{ km}} \right) \frac{R_b}{R} \]

In order to increase luminosity one should increase the energy acceptance \( \eta \)

This formula is valid for high energies (for 2E = 230, 350 GeV). For Z factory beamstrahlung is not important.
FCC project (CERN)

FCC-hh hadron collider with 100 TeV proton cms energy

$\sim 16 \, T \Rightarrow 100 \, \text{TeV} \ pp \ in \ 100 \ km$

$\sim 20 \, T \Rightarrow 100 \, \text{TeV} \ pp \ in \ 80 \ km$

FCC-ee a lepton collider as a potential intermediate step

FCC-eh lepton hadron option

International collaboration

Site studies for Geneva area

CDR for EU strategy update in 2018

June 19, 2015
tentative time line and milestones

F. Zimmermann, IPAC14

1990 | 2000 | 2010 | 2020 | 2030 | 2040

LHC
Design, R&D | Proto. | Constr. | Physics

HL-LHC
Design, R&D | Constr. | Physics

FCC-ee
Design, R&D | Constr. | Physics

continued physics program
FCC study milestones

- **LEP**
  - Construct.
  - Physics
  - Upgr

- **LHC**
  - Design, R&D
  - Proto
  - Construct.
  - Physics

- **HL-LHC**
  - Design, R&D
  - Construct.
  - Physics

- **FCC**
  - Study

- **Timeline**
  - 1980
  - 1985
  - 1990
  - 1995
  - 2000
  - 2005
  - 2010
  - 2015
  - 2020
  - 2025
  - 2030
  - 2035

- **Events**
  - Kick-off meeting
    - 12th-14th February 2014
  - CDR and Cost Review 2018
# FCC-hh baseline parameters

<table>
<thead>
<tr>
<th>parameter</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>FCC-hh</th>
</tr>
</thead>
<tbody>
<tr>
<td>c.m. energy [TeV]</td>
<td>14</td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>dipole magnet field [T]</td>
<td>8.33</td>
<td></td>
<td>16 (20)</td>
</tr>
<tr>
<td>circumference [km]</td>
<td>36.7</td>
<td></td>
<td>100 (83)</td>
</tr>
<tr>
<td>luminosity [$10^{34}$ cm$^{-2}$s$^{-1}$]</td>
<td>1</td>
<td>5</td>
<td>5 [→20?]</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>25</td>
<td></td>
<td>25 {5}</td>
</tr>
<tr>
<td>events / bunch crossing</td>
<td>27</td>
<td>135</td>
<td>170 {34}</td>
</tr>
<tr>
<td>bunch population [$10^{11}$]</td>
<td>1.15</td>
<td>2.2</td>
<td>1 {0.2}</td>
</tr>
<tr>
<td>norm. transverse emitt. [μm]</td>
<td>3.75</td>
<td>2.5</td>
<td>2.2 {0.44}</td>
</tr>
<tr>
<td>IP beta-function [m]</td>
<td>0.55</td>
<td>0.15</td>
<td>1.1</td>
</tr>
<tr>
<td>IP beam size [μm]</td>
<td>16.7</td>
<td>7.1</td>
<td>6.8 {3}</td>
</tr>
<tr>
<td>synchrotron rad. [W/m/aperture]</td>
<td>0.17</td>
<td>0.33</td>
<td>28 (44)</td>
</tr>
<tr>
<td>critical energy [keV]</td>
<td></td>
<td>0.044</td>
<td>4.3 (5.5)</td>
</tr>
<tr>
<td>total syn.rad. power [MW]</td>
<td>0.0072</td>
<td>0.0146</td>
<td>4.8 (5.8)</td>
</tr>
<tr>
<td>longitudinal damping time [h]</td>
<td>12.9</td>
<td></td>
<td>0.54 (0.32)</td>
</tr>
</tbody>
</table>
Hadron collider FCC-hh parameters

- **Energy**: 100 TeV c.m.
- **Circumference**: \(\sim 100\) km (baseline) [80 km option]
- **Dipole field (50 TeV)**: \(\sim 16\) T (baseline) [20 T option]
- **Dipole field (3 TeV inject.)**: \(\sim 1\) T (baseline) [1.2 T option]

- **Bunch spacing**: 25 ns [5 ns option]
- **Bunch population (25 ns)**: \(1 \times 10^{11}\) p
- **Emittance normalised**: 2.15x10^{-6} m, normal.
- **#bunches**: 10500
- **Stored beam energy**: 8.2 GJ/beam

- **# Interaction Points**: 2 main experiments
- **\(\beta^*\)**: 1.1 m [baseline]
- **Luminosity**: \(5 \times 10^{34}\) cm^{-2}s^{-1} [baseline]
- **Synchrotron radiation arc**: \(\sim 30\) W/m/aperture (fill. fact. \(\sim 78\%\) in arc)
energy per proton beam

*LHC: 0.4 GJ → FCC-\textit{hh}: 8 GJ (20x more !)*

- kinetic energy of Airbus A380 at 720 km/h
- can melt 12 tons of copper, or drill a 300-m long hole
Increasing luminosity during the FCC-hh fill thanks to SR

Beam-beam tuneshift $\sim 0.07$ !!!

SR damping has never been observed in a hadron machine, What to do?
15 T with Nb$_3$Sn and Nb-Ti (preliminary, project goal 16 T)

20 T with HTS and Nb$_3$Sn
Cross sections vs $\sqrt{s}$

$\sigma$ [nb]

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma$ (100 TeV)/$\sigma$ (14 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total pp</td>
<td>1.25</td>
</tr>
<tr>
<td>W</td>
<td>$\sim$7</td>
</tr>
<tr>
<td>Z</td>
<td>$\sim$7</td>
</tr>
<tr>
<td>WW</td>
<td>$\sim$10</td>
</tr>
<tr>
<td>ZZ</td>
<td>$\sim$10</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$\sim$30</td>
</tr>
<tr>
<td>H</td>
<td>$\sim$15 ($t\bar{t}H \sim$60)</td>
</tr>
<tr>
<td>HH</td>
<td>$\sim$40</td>
</tr>
<tr>
<td>stop (m=1 TeV)</td>
<td>$\sim$10$^3$</td>
</tr>
</tbody>
</table>


$\rightarrow$ With 100000/fb at $\sqrt{s}$=100 TeV expect: $10^{12}$ top, $10^{10}$ Higgs bosons, $10^8$ m=1 TeV stop pairs, ...
## FCC-ee baseline parameters

<table>
<thead>
<tr>
<th>parameter</th>
<th>LEP2</th>
<th>FCC-ee</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Z</td>
<td>Z (c.w.)</td>
</tr>
<tr>
<td>$E_{\text{beam}}$ [GeV]</td>
<td>104</td>
<td>45</td>
</tr>
<tr>
<td>circumference [km]</td>
<td>26.7</td>
<td>100</td>
</tr>
<tr>
<td>current [mA]</td>
<td>3.0</td>
<td>1450</td>
</tr>
<tr>
<td>$P_{\text{SR,tot}}$ [MW]</td>
<td>22</td>
<td>100</td>
</tr>
<tr>
<td>no. bunches</td>
<td>4</td>
<td>16700</td>
</tr>
<tr>
<td>$N_\phi$ [$10^{11}$]</td>
<td>4.2</td>
<td>1.8</td>
</tr>
<tr>
<td>$\varepsilon_x$ [nm]</td>
<td>22</td>
<td>29</td>
</tr>
<tr>
<td>$\varepsilon_y$ [pm]</td>
<td>250</td>
<td>60</td>
</tr>
<tr>
<td>$\beta_x^*$ [m]</td>
<td>1.2</td>
<td>0.5</td>
</tr>
<tr>
<td>$\beta_y^*$ [mm]</td>
<td>50</td>
<td>1</td>
</tr>
<tr>
<td>$\sigma_y^*_{\text{SR}}$ [nm]</td>
<td>3500</td>
<td>250</td>
</tr>
<tr>
<td>$\sigma_{\text{SR}}$ [mm]</td>
<td>11.5</td>
<td>1.64</td>
</tr>
<tr>
<td>$\sigma_{\text{SR}}$ [mm] (w beamstr.)</td>
<td>11.5</td>
<td>2.56</td>
</tr>
<tr>
<td>hourglass factor $F_{\text{hg}}$</td>
<td>0.99</td>
<td>0.64</td>
</tr>
<tr>
<td>$L/IP$ [$10^{34} \text{ cm}^{-2}\cdot\text{s}^{-1}$]</td>
<td>0.01</td>
<td>28</td>
</tr>
<tr>
<td>$\tau_{\text{beam}}$ [min]</td>
<td>434</td>
<td>298</td>
</tr>
</tbody>
</table>

$10^5 Z$ per sec
FCC-ee: $e^+e^-$ collider up to 350 (500) GeV

circumference $\approx 100$ km

Top-up injection is the key to extremely high luminosity; requires full-energy injector

Short beam lifetime ($\sim \tau_{\text{LEP2}}/40$) due to high luminosity supported by top-up injection (used at KEKB, PEP-II, SLS,...); top-up also avoids ramping & thermal transients, + eases tuning
Dashed lines: Possible energy and luminosity upgrades
FCC-ee beamstrahlung and IR momentum acceptance

K. Oide & F. Zimmermann, IPAC 2014

- Very strong dependency of lifetime versus momentum acceptance
- Might be OK for Higgs but severe for Top
Physics requirements for FCC-ee

- highest possible luminosity for a wide physics program ranging from the Z pole to the $t\bar{t}$ production threshold
  - *beam energy range from 45 GeV to 175 (250?) GeV*

- main physics programs / energies:
  - $Z$ (45.5 GeV): Z pole, ‘TeraZ’ and high precision $M_Z$ & $\Gamma_Z$,
  - $W$ (80 GeV): W pair production threshold,
  - $H$ (120 GeV): ZH production (maximum rate of H’s),
  - $t$ (175 GeV): $t\bar{t}$ threshold

- some polarization up to $\geq 80$ GeV for beam energy calibration

- optimized for operation at 120 GeV?!
# Accuracy of Higgs coupling for LC and FCC-ee (Snowmass 2013)

Table 1-16. Uncertainties on coupling scaling factors as determined in a completely model-independent fit for different $e^+e^-$ facilities. Precisions reported in a given column include in the fit all measurements at lower energies at the same facility, and note that the model independence requires the measurement of the recoil $HZ$ process at lower energies. †ILC luminosity upgrade assumes an extended running period on top of the low luminosity program and cannot be directly compared to TLEP and CLIC numbers without accounting for the additional running period. ILC numbers include a 0.5% theory uncertainty. For invisible decays of the Higgs, the number quoted is the 95% confidence upper limit on the branching ratio.

<table>
<thead>
<tr>
<th>Facility</th>
<th>ILC</th>
<th>ILC(LumiUp)</th>
<th>TLEP (4 IP)</th>
<th>CLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s}$ (GeV)</td>
<td>250</td>
<td>1000</td>
<td>240</td>
<td>350</td>
</tr>
<tr>
<td>$\int L dt$ (fb$^{-1}$)</td>
<td>250</td>
<td>+1000</td>
<td>+1000</td>
<td>500</td>
</tr>
<tr>
<td>$P(e^-, e^+)$</td>
<td>(−0.8, +0.3)</td>
<td>(−0.8, +0.2)</td>
<td>(0, 0)</td>
<td>(−0.8, 0)</td>
</tr>
<tr>
<td>$\Gamma_H$</td>
<td>12%</td>
<td>4.6%</td>
<td>1.9%</td>
<td>9.2%</td>
</tr>
<tr>
<td>$\kappa_\gamma$</td>
<td>18%</td>
<td>4.0%</td>
<td>1.7%</td>
<td>5.9%</td>
</tr>
<tr>
<td>$\kappa_\rho$</td>
<td>6.4%</td>
<td>1.6%</td>
<td>1.1%</td>
<td>2.3%</td>
</tr>
<tr>
<td>$\kappa_W$</td>
<td>4.9%</td>
<td>1.2%</td>
<td>0.85%</td>
<td>2.6%</td>
</tr>
<tr>
<td>$\kappa_Z$</td>
<td>1.3%</td>
<td>1.0%</td>
<td>0.16%</td>
<td>2.1%</td>
</tr>
<tr>
<td>$\kappa_\mu$</td>
<td>91%</td>
<td>16%</td>
<td>6.4%</td>
<td>11%</td>
</tr>
<tr>
<td>$\kappa_T$</td>
<td>5.8%</td>
<td>1.8%</td>
<td>0.94%</td>
<td>4.0%</td>
</tr>
<tr>
<td>$\kappa_c$</td>
<td>6.8%</td>
<td>1.8%</td>
<td>1.0%</td>
<td>3.8%</td>
</tr>
<tr>
<td>$\kappa_b$</td>
<td>5.3%</td>
<td>1.3%</td>
<td>0.88%</td>
<td>2.8%</td>
</tr>
<tr>
<td>$\kappa_t$</td>
<td>−</td>
<td>3.2%</td>
<td>−</td>
<td>4.5%</td>
</tr>
<tr>
<td>$BR_{inv}$</td>
<td>0.9%</td>
<td>&lt; 0.9%</td>
<td>0.19%</td>
<td>&lt; 0.19%</td>
</tr>
</tbody>
</table>
Accuracy of Higgs coupling for LHC, LC and FCC-ee (Snowmass 2013)

Table 1-20. Expected precisions on the Higgs couplings and total width from a constrained 7-parameter fit assuming no non-SM production or decay modes. The fit assumes generation universality ($\kappa_u \equiv \kappa_t = \kappa_c, \kappa_d \equiv \kappa_b = \kappa_s,$ and $\kappa_\ell \equiv \kappa_\tau = \kappa_\mu$). The ranges shown for LHC and HL-LHC represent the conservative and optimistic scenarios for systematic and theory uncertainties. ILC numbers assume $(e^-, e^+)$ polarizations of $(-0.8, 0.3)$ at 250 and 500 GeV and $(-0.8, 0.2)$ at 1000 GeV, plus a 0.5% theory uncertainty. CLIC numbers assume polarizations of $(-0.8, 0)$ for energies above 1 TeV. TLEP numbers assume unpolarized beams.

<table>
<thead>
<tr>
<th>Facility</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>ILC500</th>
<th>ILC500-up</th>
<th>ILC1000</th>
<th>ILC1000-up</th>
<th>CLIC</th>
<th>TLEP (4 IPs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s}$ (GeV)</td>
<td>14,000</td>
<td>14,000</td>
<td>250/500</td>
<td>250/500/1000</td>
<td>250/500/1000</td>
<td>350/1400/3000</td>
<td>240/350</td>
<td></td>
</tr>
<tr>
<td>$\int L dt$ (fb$^{-1}$)</td>
<td>300/expt</td>
<td>3000/expt</td>
<td>250+500</td>
<td>1150+1600</td>
<td>250+500+1000</td>
<td>1150+1600+2500</td>
<td>500+1500+2000</td>
<td>10,000+2600</td>
</tr>
<tr>
<td>$\kappa_\gamma$</td>
<td>5 – 7%</td>
<td>2 – 5%</td>
<td>8.3%</td>
<td>4.4%</td>
<td>3.8%</td>
<td>2.3%</td>
<td>$-5.5/-5.5%$</td>
<td>1.45%</td>
</tr>
<tr>
<td>$\kappa_g$</td>
<td>6 – 8%</td>
<td>3 – 5%</td>
<td>2.0%</td>
<td>1.1%</td>
<td>1.1%</td>
<td>0.67%</td>
<td>3.6/0.79/0.56%</td>
<td>0.79%</td>
</tr>
<tr>
<td>$\kappa_W$</td>
<td>4 – 6%</td>
<td>2 – 5%</td>
<td>0.39%</td>
<td>0.21%</td>
<td>0.21%</td>
<td>0.2%</td>
<td>1.5/0.15/0.11%</td>
<td>0.10%</td>
</tr>
<tr>
<td>$\kappa_Z$</td>
<td>4 – 6%</td>
<td>2 – 4%</td>
<td>0.49%</td>
<td>0.24%</td>
<td>0.50%</td>
<td>0.3%</td>
<td>0.49/0.33/0.24%</td>
<td>0.05%</td>
</tr>
<tr>
<td>$\kappa_\ell$</td>
<td>6 – 8%</td>
<td>2 – 5%</td>
<td>1.9%</td>
<td>0.98%</td>
<td>1.3%</td>
<td>0.72%</td>
<td>3.5/1.4/1.3%</td>
<td>0.51%</td>
</tr>
<tr>
<td>$\kappa_d = \kappa_b$</td>
<td>10 – 13%</td>
<td>4 – 7%</td>
<td>0.93%</td>
<td>0.60%</td>
<td>0.51%</td>
<td>0.4%</td>
<td>1.7/0.32/0.19%</td>
<td>0.39%</td>
</tr>
<tr>
<td>$\kappa_u = \kappa_t$</td>
<td>14 – 15%</td>
<td>7 – 10%</td>
<td>2.5%</td>
<td>1.3%</td>
<td>1.3%</td>
<td>0.9%</td>
<td>3.1/1.0/0.7%</td>
<td>0.69%</td>
</tr>
</tbody>
</table>
CEPC-SppC

CEPC is an 240 GeV Circular Electron Positron Collider, proposed to carry out high precision study on Higgs bosons, which can be upgraded to a 70 TeV or higher pp collider SppC, to study the new physics beyond the Standard Model.
CepC/SppC study (CAS-IHEP), CepC CDR end of 2014, $e^+e^-$ collisions $\sim$2028; $pp$ collisions $\sim$2042

Qinhuangdao (秦皇岛)

CepC, SppC

50 km

70 km

easy access

300 km from Beijing

3 h by car

1 h by train

“Chinese Toscana”
CEPC-SppC Project Timeline (dream)

CEPC

2015  2020  2025  2030  2035


1st Milestone: pre-CDR (by the end of 2014) → R&D funding request to Chinese government in 2015 (China’s 13th Five-Year Plan 2016-2020)

SppC

2020  2030  2040

CEPC-SppC Schedule (Preliminary)

- **CPEC**
  - Pre-study, R&D and preparation work
    - Pre-study: 2013-15 ➔ Pre-CDR by 2014
    - R&D: 2016-2020
    - Engineering Design: 2015-2020
  - Construction: 2021-2027
  - Data taking: 2030-2036

- **SPPC**
  - Pre-study, R&D and preparation work
    - Pre-study: 2013-2020
    - R&D: 2020-2030
    - Engineering Design: 2030-2035
  - Construction: 2036-2042
  - Data taking: 2042 -
## CEPC Design – Main Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy [E]</td>
<td>GeV</td>
<td>120</td>
<td>Circumference [C]</td>
<td>m</td>
<td>54752</td>
</tr>
<tr>
<td>Number of IP [N_{IP}]</td>
<td></td>
<td>2</td>
<td>SR loss/turn [U_{0}]</td>
<td>GeV</td>
<td>3.11</td>
</tr>
<tr>
<td>Bunch number/beam [n_{b}]</td>
<td></td>
<td>50</td>
<td>Bunch population [N_{e}]</td>
<td></td>
<td>3.79E+11</td>
</tr>
<tr>
<td>SR power/beam [P]</td>
<td>MW</td>
<td>51.7</td>
<td>Beam current [I]</td>
<td>mA</td>
<td>16.6</td>
</tr>
<tr>
<td>Bending radius [p]</td>
<td>m</td>
<td>6094</td>
<td>3 momentum compaction factor [\alpha_p]</td>
<td></td>
<td>3.36E-05</td>
</tr>
<tr>
<td>Revolution period [T_{0}]</td>
<td>s</td>
<td>1.83E-04</td>
<td>Revolutions frequency [f_{0}]</td>
<td>Hz</td>
<td>5475.46</td>
</tr>
<tr>
<td>emittance (x/y)</td>
<td>nm</td>
<td>6.12/0.018</td>
<td></td>
<td>mm</td>
<td>800/1.2</td>
</tr>
<tr>
<td>Transverse size (x/y)</td>
<td>\mu m</td>
<td>69.97/0.15</td>
<td></td>
<td>\xi_{x,y}/IP</td>
<td>0.118/0.083</td>
</tr>
<tr>
<td>Bunch length SR [\sigma_{\delta,SR}]</td>
<td>mm</td>
<td>2.14</td>
<td>Bunch length total [\sigma_{\delta,tot}]</td>
<td>mm</td>
<td>2.65</td>
</tr>
<tr>
<td>Lifetime due to Beamstrahlung</td>
<td>min</td>
<td>47</td>
<td>lifetime due to radiative Bhabha scattering [\tau_{r}]</td>
<td>min</td>
<td>51</td>
</tr>
<tr>
<td>RF voltage [V_{RF}]</td>
<td>GV</td>
<td>6.87</td>
<td>RF frequency [f_{RF}]</td>
<td>MHz</td>
<td>650</td>
</tr>
<tr>
<td>Harmonic number [h]</td>
<td></td>
<td>118800</td>
<td>Synchrotron oscillation tune [\nu_{s}]</td>
<td></td>
<td>0.18</td>
</tr>
<tr>
<td>Energy acceptance RF [h]</td>
<td>%</td>
<td>5.99</td>
<td>Damping partition number [J_{0}]</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Energy spread SR [\sigma_{\delta,SR}]</td>
<td>%</td>
<td>0.132</td>
<td>Energy spread BS [\sigma_{\delta,BS}]</td>
<td>%</td>
<td>0.096</td>
</tr>
<tr>
<td>Energy spread total [\sigma_{\delta,tot}]</td>
<td>%</td>
<td>0.163</td>
<td>n_{y}</td>
<td></td>
<td>0.23</td>
</tr>
<tr>
<td>Transverse damping time [n_{x}]</td>
<td>turns</td>
<td>78</td>
<td>Longitudinal damping time [n_{e}]</td>
<td>turns</td>
<td>39</td>
</tr>
<tr>
<td>Hourglass factor</td>
<td>Fh</td>
<td>0.68</td>
<td>Luminosity /IP[L]</td>
<td>cm^{-2}s^{-1}</td>
<td>2.04E+34</td>
</tr>
</tbody>
</table>
## SppC Main Parameters (preliminary)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>52</td>
<td>km</td>
</tr>
<tr>
<td>Beam energy</td>
<td>35</td>
<td>TeV</td>
</tr>
<tr>
<td>Dipole field</td>
<td>20</td>
<td>T</td>
</tr>
<tr>
<td>Injection energy</td>
<td>2.1</td>
<td>TeV</td>
</tr>
<tr>
<td>Number of IPs</td>
<td>2 (4)</td>
<td></td>
</tr>
<tr>
<td>Peak luminosity per IP</td>
<td>1.2E+35</td>
<td>cm⁻²s⁻¹</td>
</tr>
<tr>
<td>Beta function at collision</td>
<td>0.75</td>
<td>m</td>
</tr>
<tr>
<td>Circulating beam current</td>
<td>1.0</td>
<td>A</td>
</tr>
<tr>
<td>Max beam-beam tune shift per IP</td>
<td>0.006</td>
<td></td>
</tr>
<tr>
<td>Bunch separation</td>
<td>25</td>
<td>ns</td>
</tr>
<tr>
<td>Bunch population</td>
<td>2.0E+11</td>
<td></td>
</tr>
<tr>
<td>SR heat load @arc dipole (per aperture)</td>
<td>56</td>
<td>W/m</td>
</tr>
</tbody>
</table>
Muon collider as a Higgs factory

- **Muon Collider Diagram**
  - Proton Driver
  - Accumulator
  - Compressor
  - Hg-Jet Target Capture Solenoid
  - Front End
    - Decay Channel
    - Buncher
    - Phase Rotator
  - Cooling
    - $\mu^+$
    - $\mu^-$
    - 6D Cooling
    - Bunch Merge
    - 6D Cooling
    - 6D Cooling
    - Final Cooling
  - Acceleration
    - $E_{\text{CoM}}$
    - 126 GeV
    - 1.5 TeV
    - 3 TeV
  - Collider Ring
    - C = 300 m
    - ~2000 turns

- **6D Ionization Cooling**

**Source:** June 19, 2015
Parameters of 126 GeV \(\mu^+\mu^-\) Higgs factory

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Low L</th>
<th>High L</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2E_0)</td>
<td>GeV</td>
<td>126</td>
<td>126</td>
</tr>
<tr>
<td>Luminosity per IP</td>
<td>(10^{34}) cm(^{-2}) s(^{-1})</td>
<td>0.001</td>
<td>0.01</td>
</tr>
<tr>
<td>Number of IPs</td>
<td></td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>No. Higgs/yr((10^7) s) per IP</td>
<td></td>
<td>1000</td>
<td>5</td>
</tr>
<tr>
<td>Circumference</td>
<td>km</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>(P) (wall)</td>
<td>MW</td>
<td>100</td>
<td>125</td>
</tr>
<tr>
<td>Pol. (\mu^-) and (\mu^+)</td>
<td>%</td>
<td>10</td>
<td>10-20</td>
</tr>
<tr>
<td>(N) per bunch</td>
<td>(10^{10})</td>
<td>200</td>
<td>500</td>
</tr>
<tr>
<td>Bunches per beam</td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Norm. emit. (\varepsilon_{x,n})</td>
<td>mm-mrad</td>
<td>400</td>
<td>200</td>
</tr>
<tr>
<td>Norm. emit. (\varepsilon_{y,n})</td>
<td>mm-mrad</td>
<td>400</td>
<td>200</td>
</tr>
<tr>
<td>(\beta_x) at IP</td>
<td>mm</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>(\beta_y) at IP</td>
<td>mm</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>(\sigma_x) at IP</td>
<td>(\mu m)</td>
<td>200</td>
<td>120</td>
</tr>
<tr>
<td>(\sigma_y) at IP</td>
<td>(\mu m)</td>
<td>200</td>
<td>120</td>
</tr>
<tr>
<td>(\sigma_z) at IP</td>
<td>mm</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>(\sigma_E/E)</td>
<td>%</td>
<td>0.003</td>
<td>0.003</td>
</tr>
</tbody>
</table>

The luminosity is 2-3 orders of magnitude smaller than at \(e^+e^-\) colliders, but the Higgs production cross section is 200 times larger.
Scale of facility

Proton Ring
Target + π→μ Capture
Cooling line
Linac
Collider Ring
RLA
Similar to radiation damping in an electron storage ring: muon momentum is reduced in all directions by going through liquid hydrogen absorbers, and restored longitudinally by acceleration in RF cavities. Thus transverse emittance is reduced progressively.

Because of a) the production of muons by pion decay and b) the short muon lifetime, ionization cooling is only practical solution to produce high brilliance muon beams.

Emittance exchange involves ionization varying in space which cancels the dispersion of energies in the beam. This can be used to reduce the energy spread and is of particular interest for $\mu^+\mu^- \rightarrow H$(125) since the Higgs is very narrow ($\sim$5MeV).

COOLING -- Principle is straightforward...

Transverse:

\[
\begin{align*}
\frac{dE}{dx} & \quad \text{r.f.} \\
\frac{dE}{dx} & \quad \text{r.f.} \\
\frac{dE}{dx} & \quad \text{r.f.} \\
\frac{dE}{dx} & \quad \text{r.f.}
\end{align*}
\]

Practical realization is not!

MICE cooling channel (4D cooling)

Longitudinal:

Dispersion in magnet
Path length difference in magnet

or

Helical Cooling Channel
Alternating tilted solenoids
Hydrogen absorbers
rf

Snake

6D candidate cooling lattices
Conclusion

- A Higgs factory is needed for precision measurement of the Higgs properties. Possible candidates:

  Linear e+e- Collider (2E=240-350 GeV → 500-1000-3000 GeV)
  Ring e+e- Collider (2E=240-350 GeV)
  Muon collider (2E=126 GeV → 3 -100 TeV)

The choice depends on LHC discoveries:

- If new physics (like SUSY, etc) exists in 200-1000 GeV region, then ILC or CLIC.

- If new physics exist in 1000-3000 GeV region, then CLIC.

- If nothing, except H, is found, then a low energy e+e- Higgs factory, ring or LC. Ring Higgs factory with large R looks very attractive.

- Muon collider is always welcome (as potentially the highest energy collider)