Future Circular Collider (FCC) Study

Michael Benedikt,
Frank Zimmermann

Outline

- Motivation & scope
- Parameters & design challenges
- Preparing global FCC collaboration
- Study organization – WBS
- Study Time Line, next steps
- EU FCC design study proposal
- Summary

Summary: European Strategy Update 2013

Design studies and R&D at the energy frontier

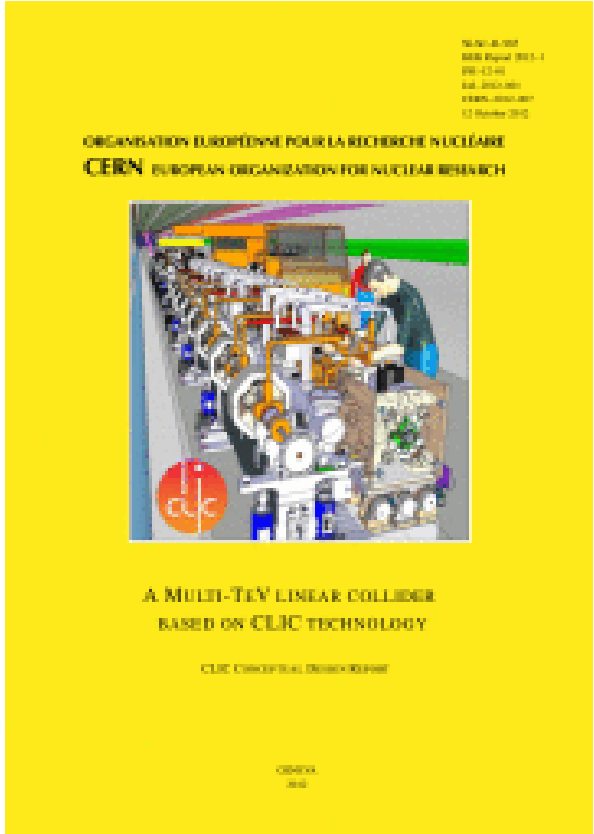
….“to propose an ambitious **post-LHC accelerator project at CERN** by the time of the next Strategy update”:

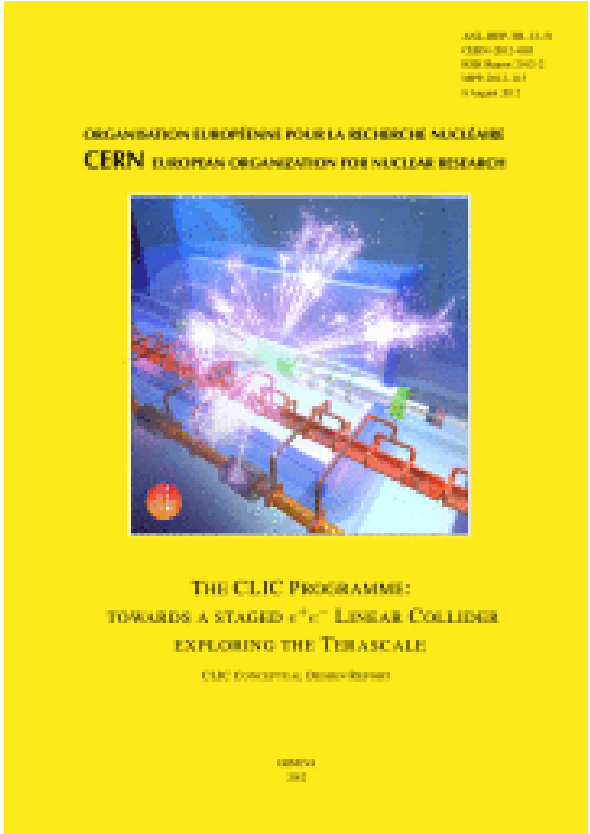
d) ***CERN should undertake design studies for accelerator projects in a global context,***

- *with emphasis on* ***proton-proton and electron-positron high-energy frontier machines****.*
- *These design studies should be coupled to a vigorous accelerator* ***R&D programme, including high-field magnets and high-gradient accelerating structures****,*
- ***in collaboration with national institutes, laboratories and universities worldwide.***

- **http://cds.cern.ch/record/1567258/files/esc-e-106.pdf**

CLIC CDR and cost study (2012)





- **3 volumes CDR: physics & detectors, accelerator complex, strategy, cost & schedule**
- **Collaborative effort: 40+ institutes worldwide**

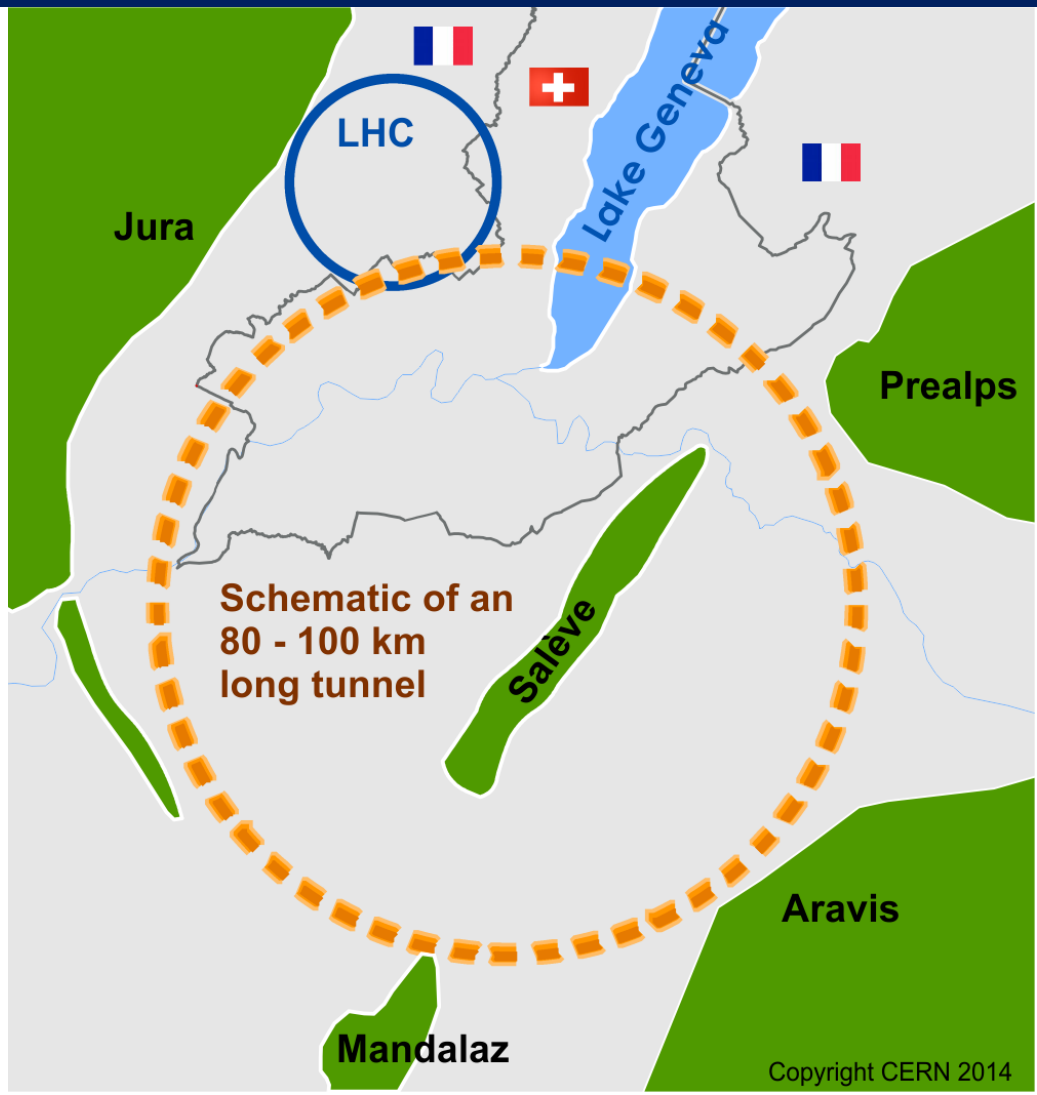
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

- ***pp*-collider (*FCC-hh*)**
  → defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

- **e^+e^- collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**
- **80-100 km infrastructure** in Geneva area



FCC motivation: pushing energy frontier

High-energy hadron collider *FCC-hh* as long-term goal

- **Seems only approach to get to 100 TeV range** in the coming decades
- High energy and luminosity at affordable power consumption
- **Lead time design & construction > 20 years** (LHC study started 1983!)

→ **Must start studying now to be ready for 2035/2040**

Lepton collider *FCC-ee* as potential intermediate step

- Would provide/share **part of infrastructure**
- Important **precision measurements** indicating the energy scale at which new physics is expected
- Search for **new physics in rare decays of *Z, W, H, t*** and rare processes

Lepton-hadron collider *FCC-he* as option

- High precision **deep inelastic scattering and Higgs physics**

Most aspects of collider designs and R&D non-site specific.
Tunnel and site study in Geneva area as ESU requests.

Main areas of FCC design study

Accelerators and infrastructure conceptual designs	Technologies R&D activities planning	Physics experiments detectors
Hadron collider conceptual design	High-field magnets	Hadron coll. physics experiments interface, integration
Lepton collider conceptual design	Superconducting RF systems	$e^+ e^-$ coll. physics experiments interface, integration
Hadron and lepton injectors	Cryogenics	$e^- - p$ physics, experiments, Interface, integration
Safety, operation, energy management environmental aspects	Specific technologies	
Infrastructure	Planning	

FCC-hh parameters – starting point

Energy	**100 TeV c.m.**
Dipole field	**~ 16 T (Nb_3Sn), [20 T option HTS]**
Circumference	**~ 100 km**
#IPs	**2 main (tune shift) + 2**
Luminosity/IP_{main}	**$5x10^{34}$ $cm^{-2}s^{-1}$**
Stored beam energy	**8.2 GJ/beam**
Synchrotron radiation	**26 W/m/aperture** (filling fact. ~78% in arc)
Long. emit damping time	**0.5 h**
Bunch spacing	**25 ns [5 ns option]**
Bunch population (25 ns)	$1x10^{11}$ p
Transverse emittance	2.2 micron normalized
#bunches	10500
Beam-beam tune shift	0.01 (total)
β^*	1.1 m (HL-LHC: 0.15 m)

} already available from SPS for 25 ns

FCC-hh design challenges

Optics and beam dynamics

- IR design, dynamic aperture studies, SC magnet field quality

Impedances, instabilities, feedbacks

- Beam-beam, e-cloud, resistive wall, feedback systems design

Synchrotron radiation damping

- controlled blow up, luminosity levelling, etc…

Energy in beam & magnets → dump, collimation, quench protection

- **Stored beam energy critical: 8 GJ/beam (0.4 GJ LHC)**
- Beam losses, radiation effects → collimation, shielding
- Synergies intensity frontier (**SNS, J-PARC, PSI, PIP, FRIB, ESS, FAIR**)

High synchrotron radiation load on beam pipe

- **Up to 26 W/m/aperture in arcs, total of ~5 MW for FCC-hh**
- (LHC has a total of 1W/m/aperture from different sources)
- Heat extraction: photon stop, beam screen temperature, cryo load,
- Synergies with **SSC,VLHC, LHC, light sources, SppC, …**

High-field magnet R&D targets

***FCC-hh* baseline 16T Nb_3Sn technology for ~100 TeV c.m. in ~100 km**

Develop Nb_3Sn-based 16 T dipole technology,

- with sufficient aperture (~40 mm) and
- accelerator features (field quality, protectability, cycled operation).
- In parallel conductor developments

Possible goal:

- **16T short dipole models by 2018 (America, Asia, Europe)**

In parallel HTS development targeting 20 T:

- HTS insert, generating *O*(5 T) additional field
- in large aperture *O*(100 mm, 15 T)

Possible goal:

demonstrate HTS/LTS 20 T technology in two steps

- a field record attempt to break the 20 T barrier (no aperture), and
- a 5 T insert, with sufficient aperture (40 mm) and accel. features

FCC-ee parameters – starting point

Design choice: max. synchrotron radiation power set to 50 MW/beam

- **Defines the maximum beam current at each energy**
- **4 physics operation points (energies) foreseen *Z, WW, H, ttbar***
- **Optimization at each operation point, mainly via bunch number and arc cell length**

Parameter	***Z***	***WW***	***H***	***ttbar***	***LEP2***
E/beam (GeV)	**45**	**80**	**120**	**175**	**105**
L (10^{34} cm^{-2}s^{-1})/IP	**28.0**	**12.0**	**5.9**	**1.8**	**0.012**
Bunches/beam	**16700**	**4490**	**1330**	**98**	**4**
I (mA)	1450	152	30	6.6	3
Bunch popul. [10^{11}]	1.8	0.7	0.47	1.40	4.2
Cell length [m]	300	100	50	50	79
Tune shift / IP	0.03	0.06	0.09	0.09	0.07

FCC-ee design challenges

Short beam lifetime from high luminosity (radiative Bhabha scattering)

- **Top-up injection** (single injector booster in collider tunnel)

Additional lifetime limit from beamstrahlung at top operation energy

- Flat beams (small vertical emittance, small vertical β^* ~ 1 mm)
- Final focus with large (~2%) energy acceptance to reduce losses

Machine layout for high currents, large #bunches at *Z* pole, *WW*, *H*

- **Two ring layout and configuration of the RF system.**

Polarization for high precision energy calibration at *Z* pole and *WW* with long natural polarization times (*WW*: ~10 hours, *Z*: ~200 hours)

Important expertise available worldwide and potential synergies:

- **IR design, experimental insertions, machine detector interface, (transverse) polarization**

  RHIC, VEPP-2000, BEPC-II, SLC, LEP, *B*- and Super-*B* factories, CEPC, ILC, CLIC

SC-RF main R&D areas

SC cavity R&D

- **Large Q_0 at high gradient and acceptable cryogenic power**
  - Recent results at 4 K with Nb_3Sn coating on Nb at Cornell
  - $800\ ℃ \div 1400\ ℃$ heat treatment at JLAB
  - Beneficial effect of impurities observed at FNAL
- **Relevant for many other accelerator applications**

High efficiency RF power generation from grid to beam

- Power converter technology
- Klystron efficiencies beyond 65%, alternative RF sources as Solid State Power Amplifier or multi-beam IOT (inductive output tube), etc.
- **Relevant for all high power accelerators, intensity frontier (drivers):**

  J-PARC, SNS, νstorm, LBNE, XFEL, μcoll, ESS, MYRRHA, …

Overall RF system reliability → relevant for *FCC-hh* and *FCC-ee*

R&D Goal is optimization of overall efficiency, reliability and cost!

- Power source efficiency, low-loss high-gradient SC cavities, operation temperature vs. cryogenic load, total system cost and dimension.

FCC-he parameters – starting point

- **Design choice: beam parameters as available from *hh* and *ee***
  - Max. $e^{\pm}$ beam current at each energy determined by 50 MW SR limit.
  - **1 physics interaction point, optimization at each energy**

collider parameters	**$e^{\pm}$ scenarios**			**protons**
species	***$e^{\pm}$*** (polarized)	***$e^{\pm}$***	***$e^{\pm}$***	***p***
beam energy [GeV]	**80**	**120**	**175**	**50000**
luminosity [10^{34}cm^{-2}s^{-1}]	**2.3**	**1.2**	**0.15**	
bunch intensity [10^{11}]	0.7	0.46	1.4	1.0
#bunches per beam	4490	1360	98	10600
beam current [mA]	152	30	6.6	500
$\sigma_{x,y}$* [micron]	4.5, 2.3			

FCC-he design challenges

Integration aspects, machine detector interface

- Synchrotron radiation
- Large polar angle acceptance

IR optics & magnets with 3 beams

- Crossing scheme
- Detector integrated dipole, final SC quadrupoles, crab cavities,

Concurrent operation of $e^{\pm}h$ with *hh or/and* $e^{+}e^{-}$ operation?

Relevant expertise available worldwide and potential synergies:

⇔ **HERA, eRHIC, MEIC, HIAF-EIC,…**

Alternative option for *eh* collisions in connection with *FCC-hh*:

- Potential reuse of an **energy recovery linac (ERL)** that is being **studied in the frame of the LHeC study.**

FCC global design study preparation

Following ESU in May 2013, creation of a small preparation group in autumn 2013 to prepare on a short time scale:

- preliminary **draft baseline parameter sets** for all options
- a **possible work breakdown structure** and **study organisation**
- an **international kick-off meeting** (*now*!)

Kick-off event should start process of internat. collaboration

- presenting **preparatory work** as basis for discussion
  → draft parameter sets & WBS documents available
- inviting **feedback and suggestions**
- working towards **formation of a**

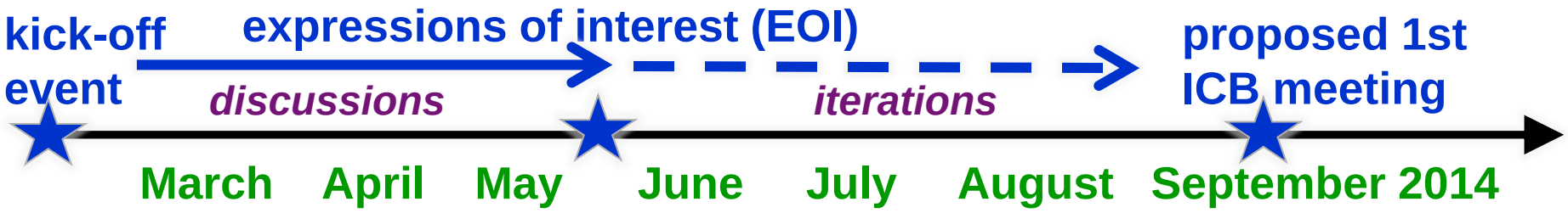
global design study collaboration integrating all aspects of machines, physics and detectors

Reflected in kick-off meeting programme.

International collaboration process in 2014

Proposal for next steps:

- Suggestions and comments from international community and **discussion on study contents, organisation and resources**
- Invitation of non-committing **expressions of interest for contributions** from worldwide institutes **by end May 2014**
- Prepare for formation of **International Collaboration Board (ICB)**; proposed date first meeting **9-11 September 2014, to start FCC study**



Process can be moderated by preparation group (possibly extended – following EOI) until global collaboration is formed and an international team is put in place to conduct the further study

Process remains open, further joining possible …

FCC Kick-Off & Study Preparation Team

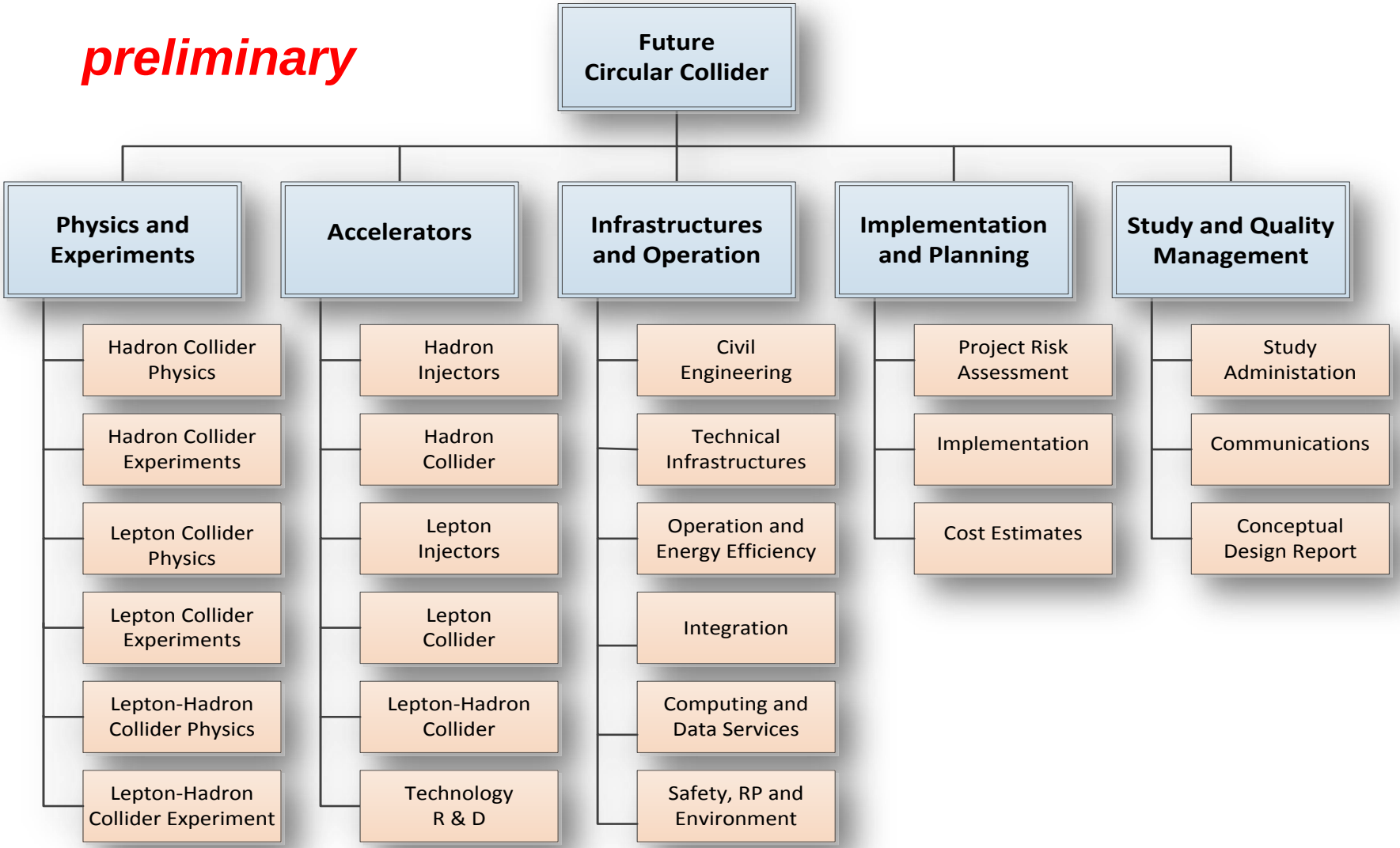
Future Circular Colliders - Conceptual Design Study
Study coordination, **M. Benedikt, F. Zimmermann**

Hadron collider **D. Schulte**	**Hadron injectors** **B. Goddard**	**e+ e- collider and injectors** **J. Wenninger**	**Infrastructure, cost estimates** **P. Lebrun**	**Technology**	**Physics and experiments**
				High Field Magnets **L. Bottura**	Hadrons **A. Ball, F. Gianotti, M. Mangano**
				Supercon-ducting RF **E. Jensen**	
e- p option Integration aspects **O. Brüning**				Cryogenics **L. Tavian**	e+ e- **A. Blondel J. Ellis, P. Janot**
Operation aspects, energy efficiency, safety, environment **P. Collier**				Specific Technologies **JM. Jimenez**	e- p **M. Klein**

Planning (Implementation roadmap, financial planning, reporting)
F. Sonnemann, J. Gutleber

Proposal for FCC WBS top level

preliminary



WBS – lower level example: *FCC-ee study*

Draft work packages and units

Lepton injectors

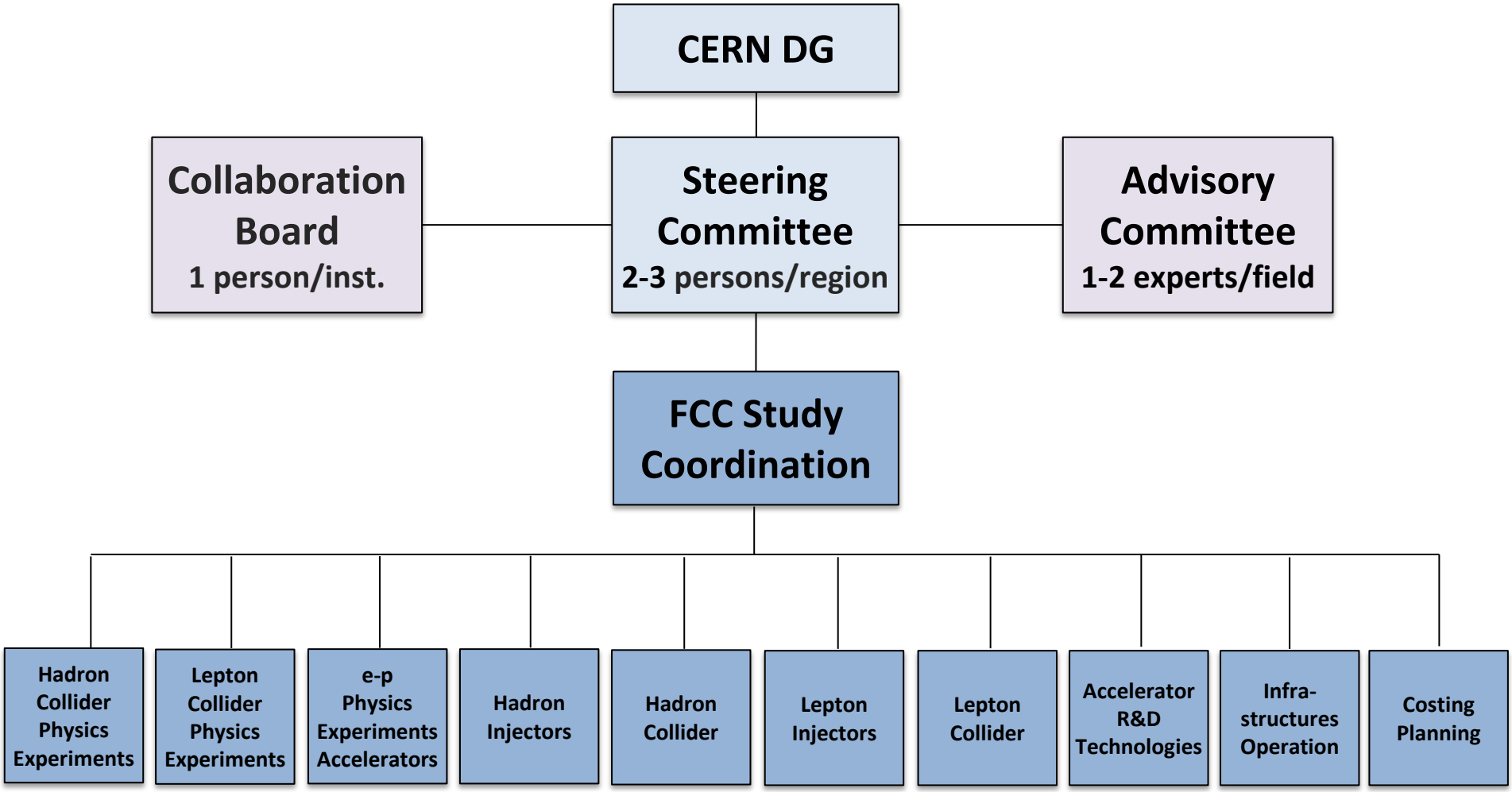
- **Functional machine design**
  - LEP chain performance and gaps
  - LEP chain compatibility with hadron injectors
  - New injector chain baseline
- **Technical systems**
  - Low energy beam transfer lines
  - LIL/EPA re-installation feasibility
  - Existing injectors to be decommissioned for lepton operation
  - Technologies that require R&D
  - SuperKEKB-type injector option
  - CTF3 option usability
  - Planned LHeC test facility usability
  - Electron and positron sources

Lepton collider

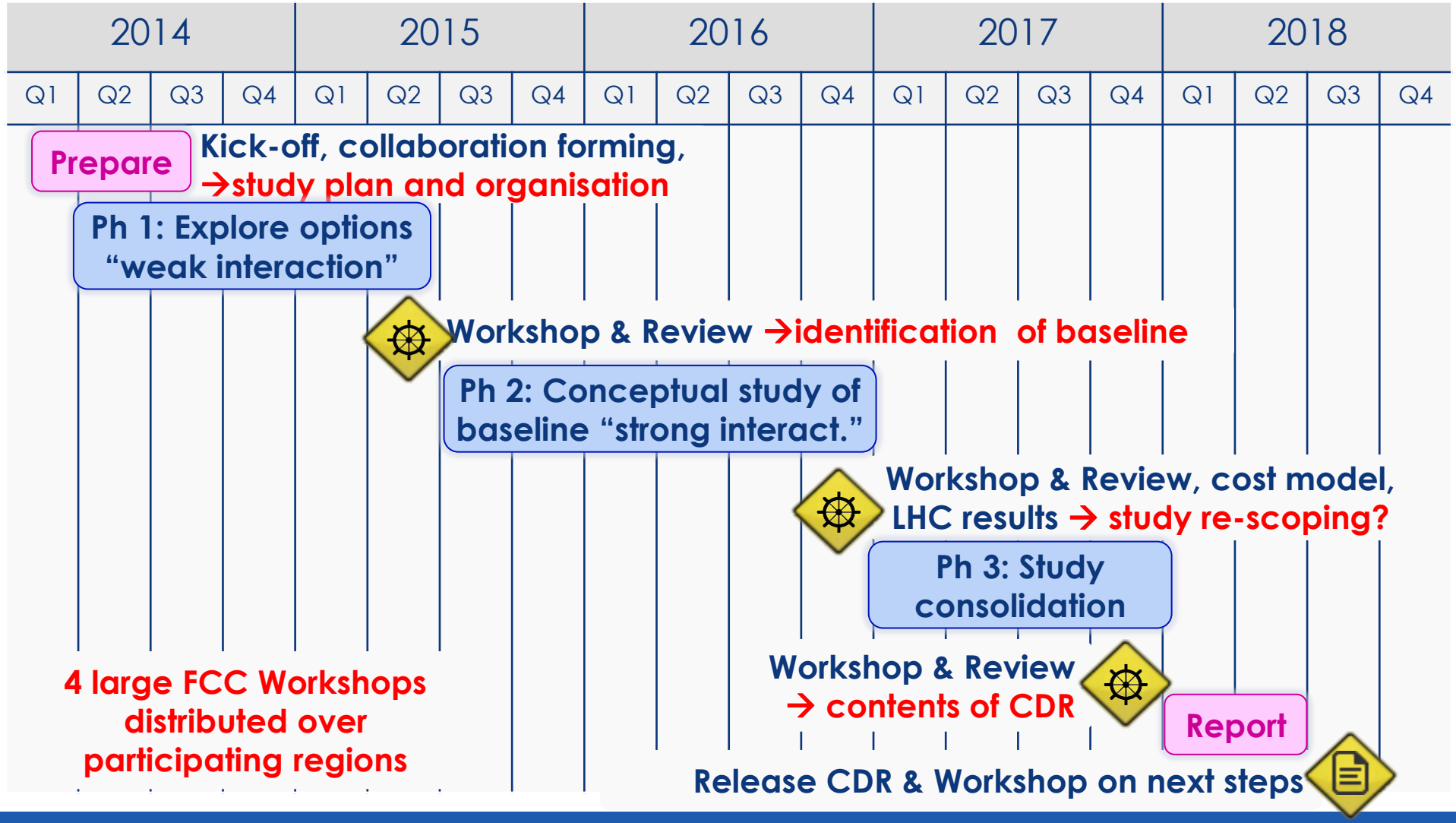
- **Functional machine design**
  - Beam dynamics and collective effects
  - Collimation concepts
  - Injection and extraction concepts and designs
  - Interaction region and final focus design
  - Booster ring conceptual design and integration
  - Lattice design and single particle dynamics
  - Polarization and energy calibration
  - Machine detector interface
  - Machine protection concepts
  - Radiation effects
- **Technical systems**
  - Beam diagnostics requirements and conceptual design
  - Beam transfer elements requirements and conceptual design
  - Collimation systems and absorber requirements and conceptual design
  - Dump and stopper requirements and conceptual design
  - Element support and alignment requirements and conceptual design
  - Machine detector integration
  - Machine protection system requirements and conceptual design
  - Normal magnet requirements and element conceptual design
  - Power converter requirements and conceptual design
  - Quench protection and stored energy management requirements and concepts
  - RF system requirements and conceptual design
  - Superconducting magnet and cryostat requirements and conceptual design
  - Proximity cryogenics for RF and magnets
  - Vacuum system requirements and conceptual design
  - Shielding

International contributors and convenors needed for technical areas and study organisation

Proposed international organization structure



Proposal for FCC Study Time Line



Possible FCC Study Phases

Phase 1: Explore options, now – spring 2015:

- Investigate **different options** in all technical areas, **taking a broad view**
- **Deliverables: description and comparison of options with relative merits/cost**
- **FCC workshop to converge to common baseline with small number of options**
- **Proposed WS date 23 – 27 March 2015** (presently no known collisions…)
- Followed by review ~2 months later, begin June 2015

Phase 2: Conceptual design: spring 2015 – autumn 2016

- Conceptual study of baseline and remaining options with iterations between all areas
- Deliverable: description of baseline with first cost model, identification of critical areas, cost drivers, performance limitations
- FCC workshop to discuss conceptual design, performance and cost figures
- Proposed date autumn 2016.
- Followed by review 2 months later to take into account LHC results and do re-scoping of study for phase 3

Phase 3: Study consolidation: winter 2016 – winter 2017

- Detailed conceptual design of re-scoped baseline
- Deliverables: description of re-scoped baseline with cost model, identification of critical areas, cost drivers, performance limitations, planning for further R&D activities
- FCC workshop to discuss conceptual design, performance and cost figures and contents for CDR editing.
- Proposed date autumn 2017.
- Followed by review 2 months later to confirm CDR contents

Phase4: Editing conceptual design report: winter 2017 – summer 2018

FCC EU Design Study (DS) Proposal

Horizon2020 call – design study, deadline 02.09.2014

Prepare proposal parallel to FCC collaboration setup

Goals fo EU DS: conceptual design, prototypes, cost estimates, …

From FP7 HiLumi LHC DS → positive experience:

- **5-6 work packages as sub-set of FCC study**
- **~10-15 beneficiaries** (signatories of the contract with EC)

Time line

kick-off event — *discussions* — **input from interested partners, end of May** — **complete draft proposal, end of June** — *iteration, agreements, signatures* — **submission of EU FCC DS proposal, 2 Sept.**

March — April — May — June — July — August — September 2014

Non-EU partners can join as beneficiary – signatory with or w/o EC contribution (**contractual commitment**) **or as associated partner – non-signatory** (in-kind contribution with own funding, no contractual commitment)

FCC Study - Summary

- In line with the **European Strategy**, CERN is launching a **5-year international design study** for **Future Circular Colliders**;
- **Worldwide collaboration in all areas** - physics, experiments and accelerators – is **essential to reach CDR level by 2018**.
- **FCC R&D areas** e.g. **SC high-field magnets** and **SC RF** are **of general interest & relevant for many other applications**.
- **Significant R&D investments have been made** over last decade(s), e.g. in the framework of LHC and HL-LHC; **further continuation will ensure efficient use of past investments**.
- **Goals of kick-off meeting: Introducing FCC study, discussing study scope and organization, preparing and establishing collaboration!** ***Invitation to join!***