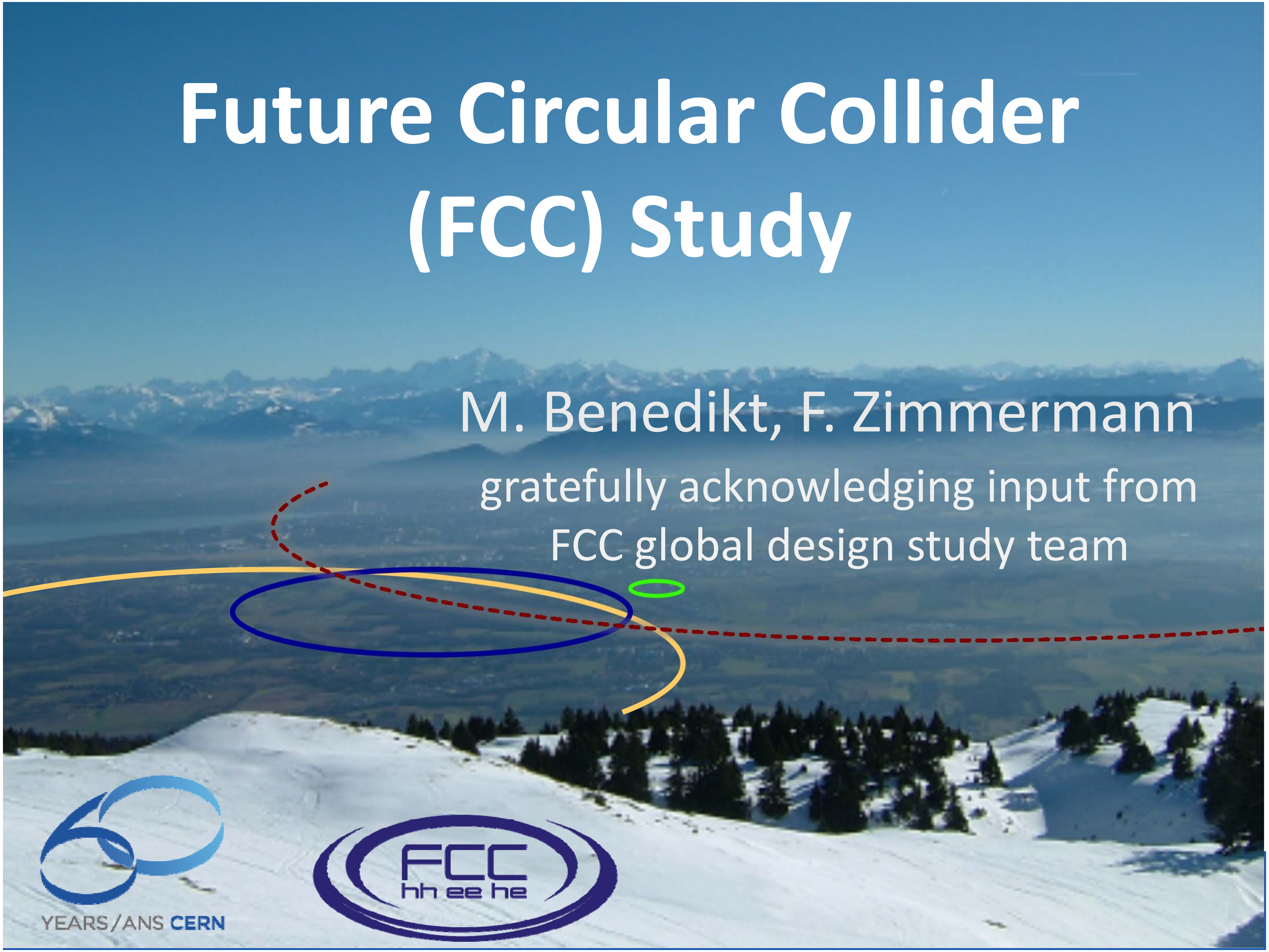
Future Circular Collider (FCC) Study

M. Benedikt, F. Zimmermann

gratefully acknowledging input from
FCC global design study team



YEARS/ANS CERN

FCC
hh ee he

Outline

- Motivation & scope
- Parameters & challenges
- Study organization
- 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**

strategy adopted at Brussels in May 2013, during exceptional session of the CERN Council in presence of the European Commission

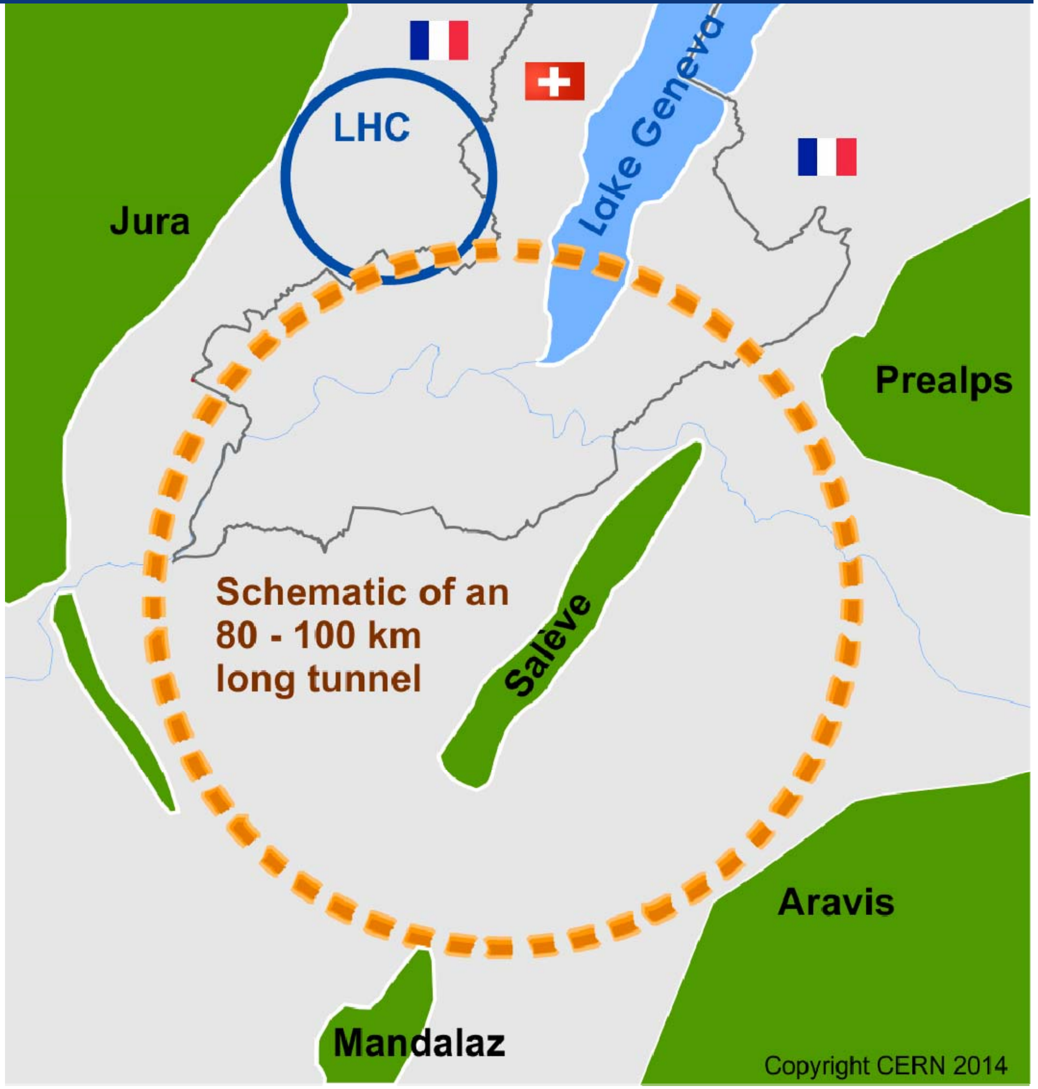
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure

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

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



FCC hadron collider motivation: pushing the energy frontier

hadron collider: presently and for coming decades the only option for exploring energy scale at 10's of TeV

The name of the game of a hadron collider is energy reach

$$\boxed{E \propto B_{dipole} \times \rho_{bending}}$$

Cf. LHC: **→ factor 3.5-4 in radius, → factor 2 in field**

→ factor 7-8 in energy

FCC-hh baseline parameters

parameter	FCC-hh	LHC
energy	**100 TeV c.m.**	14 TeV c.m.
dipole field	**16 T**	8.33 T
# IP	2 main, +2	4
normalized emittance	2.2 μm	3.75 μm
luminosity/$\mathrm{IP}_{\mathrm{main}}$	**5 x 10^{34}** cm^{-2}s^{-1}	1 x 10^{34} cm^{-2}s^{-1}
energy/beam	**8.4 GJ**	0.39 GJ
synchr. rad.	**28.4 W/m/apert.**	0.17 W/m/apert.
bunch spacing	25 ns (5 ns)	25 ns

Preliminary, subject to evolution (several luminosity scenarios)

Preliminary layout

Preliminary layout (different sizes under investigation)

⇒ Collider ring design (lattice/hardware design)

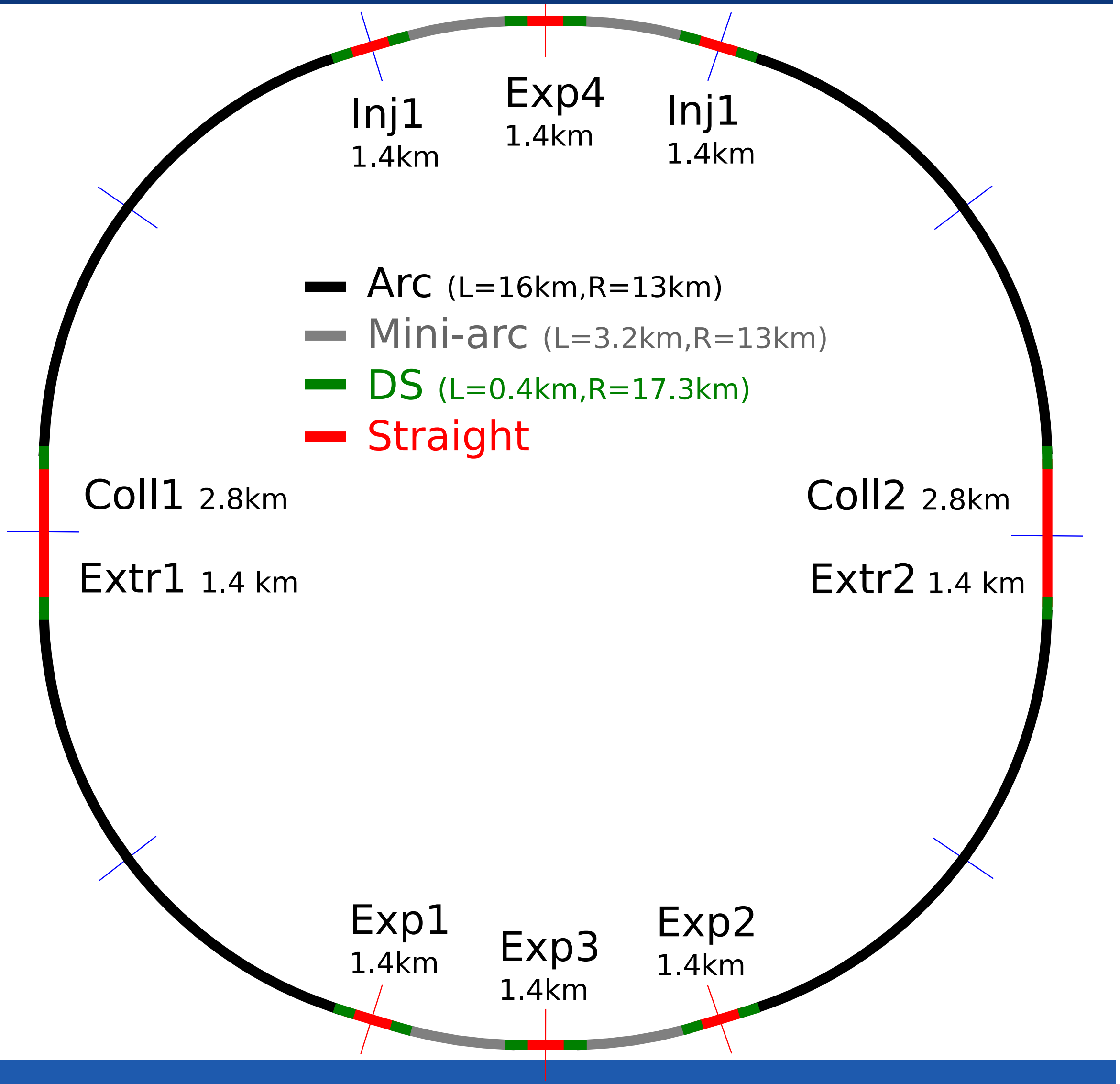
⇒ Site studies

⇒ Injector studies

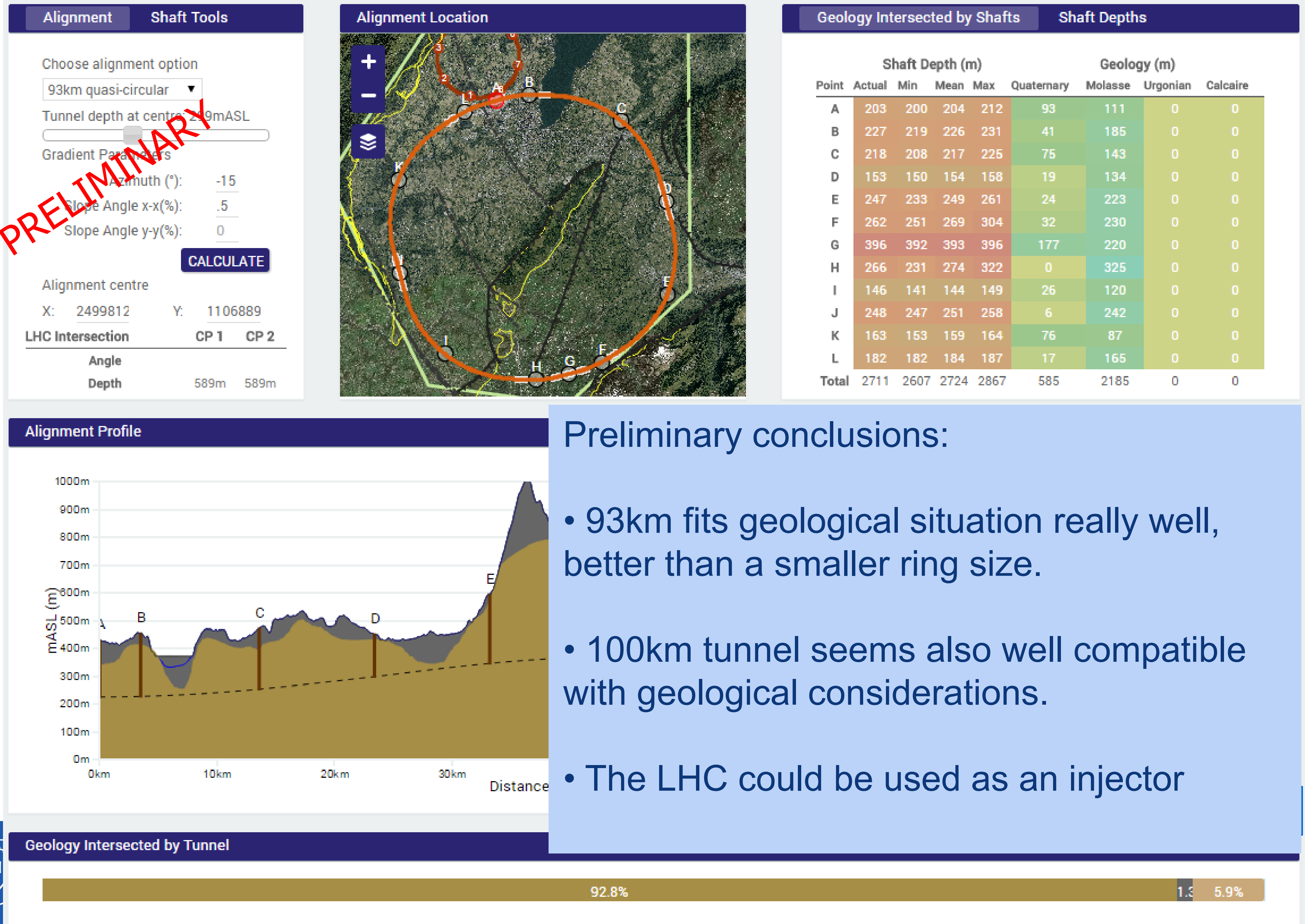
⇒ Machine detector interface

⇒ Input for lepton option

Iterations needed



Site study 93 km example



PRELIMINARY

Alignment | **Shaft Tools**

Choose alignment option: 93km quasi-circular ▼

Tunnel depth at centre: 2[illegible]9mASL

Gradient Parameters

Azimuth (°): -15

Slope Angle x-x(%): .5

Slope Angle y-y(%): 0

CALCULATE

Alignment centre

X: 2499812 Y: 1106889

LHC Intersection	CP 1	CP 2
Angle		
Depth	589m	589m

Alignment Location

Geology Intersected by Shafts | **Shaft Depths**

	Shaft Depth (m)				Geology (m)			
Point	Actual	Min	Mean	Max	Quaternary	Molasse	Urgonian	Calcaire
A	203	200	204	212	93	111	0	0
B	227	219	226	231	41	185	0	0
C	218	208	217	225	75	143	0	0
D	153	150	154	158	19	134	0	0
E	247	233	249	261	24	223	0	0
F	262	251	269	304	32	230	0	0
G	396	392	393	396	177	220	0	0
H	266	231	274	322	0	325	0	0
I	146	141	144	149	26	120	0	0
J	248	247	251	258	6	242	0	0
K	163	153	159	164	76	87	0	0
L	182	182	184	187	17	165	0	0
Total	2711	2607	2724	2867	585	2185	0	0

Alignment Profile

Geology Intersected by Tunnel

Preliminary conclusions:

- 93km fits geological situation really well, better than a smaller ring size.
- 100km tunnel seems also well compatible with geological considerations.
- The LHC could be used as an injector

FCC-hh: high-field magnet R&D

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

Develop Nb_3Sn-based 16 T dipole technology (at 4.2 K?),
- conductor developments
- short models with sufficient aperture (40 – 50 mm) and
- accelerator features (margin, field quality, protect-ability, cycled operation).

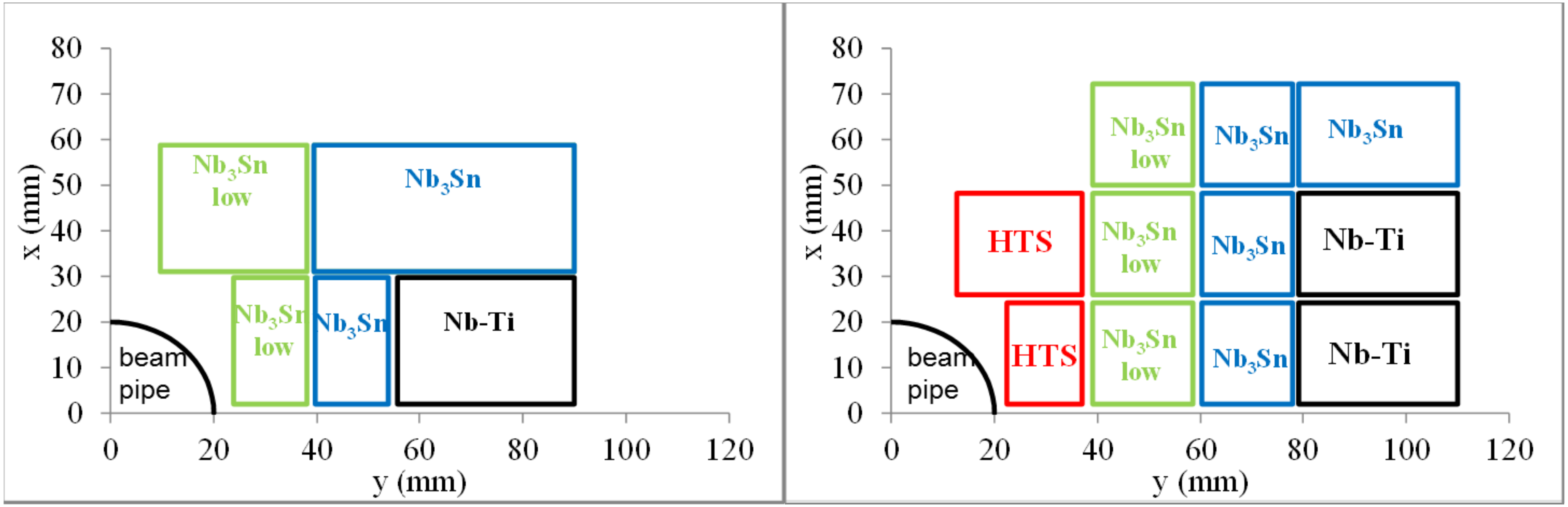
Goal: 16T short dipole models by 2018/19 (America, Asia, Europe)

- **In parallel HTS development targeting 20 T (option and longer term)**

Goal: Demonstrate HTS/LTS 20 T dipole technology:
- 5 T insert (EuCARD2), ~40 mm aperture and accelerator features
- Outsert of large aperture ~100 mm, (FRESCA2 or other)

Key design issue: cost-optimized high-field dipole magnets

Arc magnet system will be the major cost factor for FCC-hh

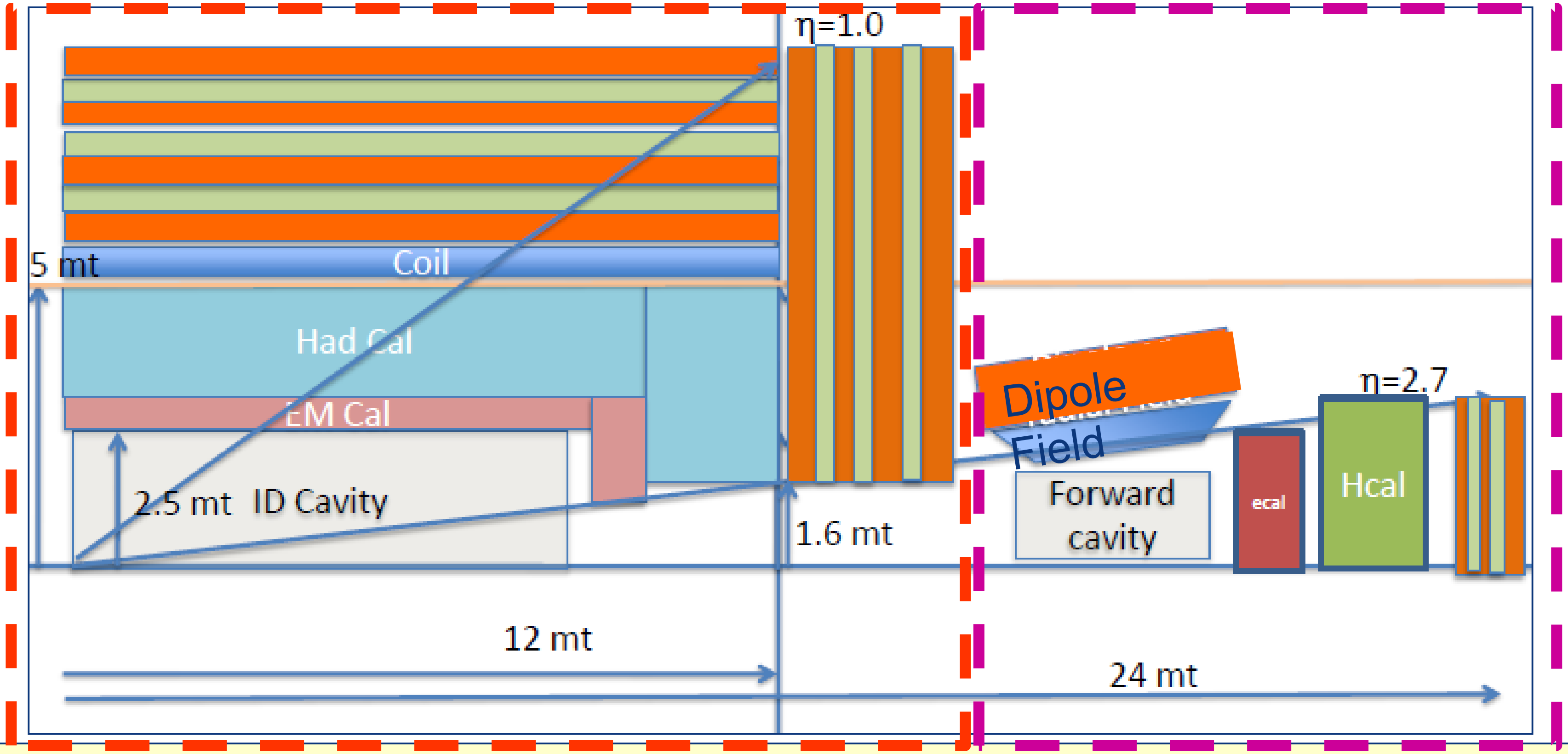


only a quarter is shown

“hybrid magnets”
example block-coil layout

L. Rossi, E. Todesco, P. McIntyre

SC magnets for detectors



- Need BL^2 ~10 x ATLAS/CMS for 10% muon momentum resolution at 10-20 TeV.
- **Solenoid: B=5T, R_{in}=5-6m, L=24m → size is x2 CMS. Stored energy: ~ 50 GJ**
- > 5000 m^3 of Fe in return joke → alternative: thin (twin) lower-B solenoid at larger R to capture return flux of main solenoid
- **Forward dipole à la LHCb: B~10 Tm**

F. Gianotti, H. Ten Kate

FCC-hh: some design challenges

- **Stored beam energy: 8 GJ/beam (0.4 GJ LHC) = 16 GJ total**
  ➔ equivalent to an Airbus A380 (560 t) at full speed (850 km/h)

- ➢ **Collimation, beam loss control, radiation effects: very important**
- ➢ **Injection/dumping/beam transfer: very critical operations**
- ➢ **Magnet/machine protection: to be considered early on**

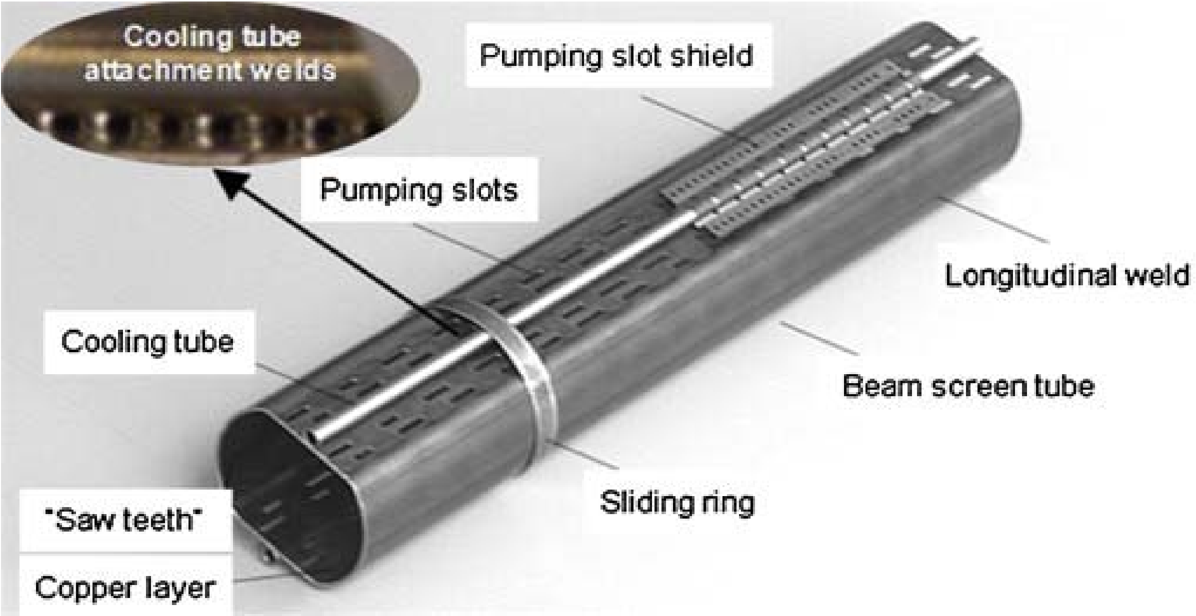
Synchrotron radiation/beam screen

High synchrotron radiation load (SR) of protons @ 50 TeV:

~30 W/m/beam (@16 T)

→ **5 MW total in arcs**

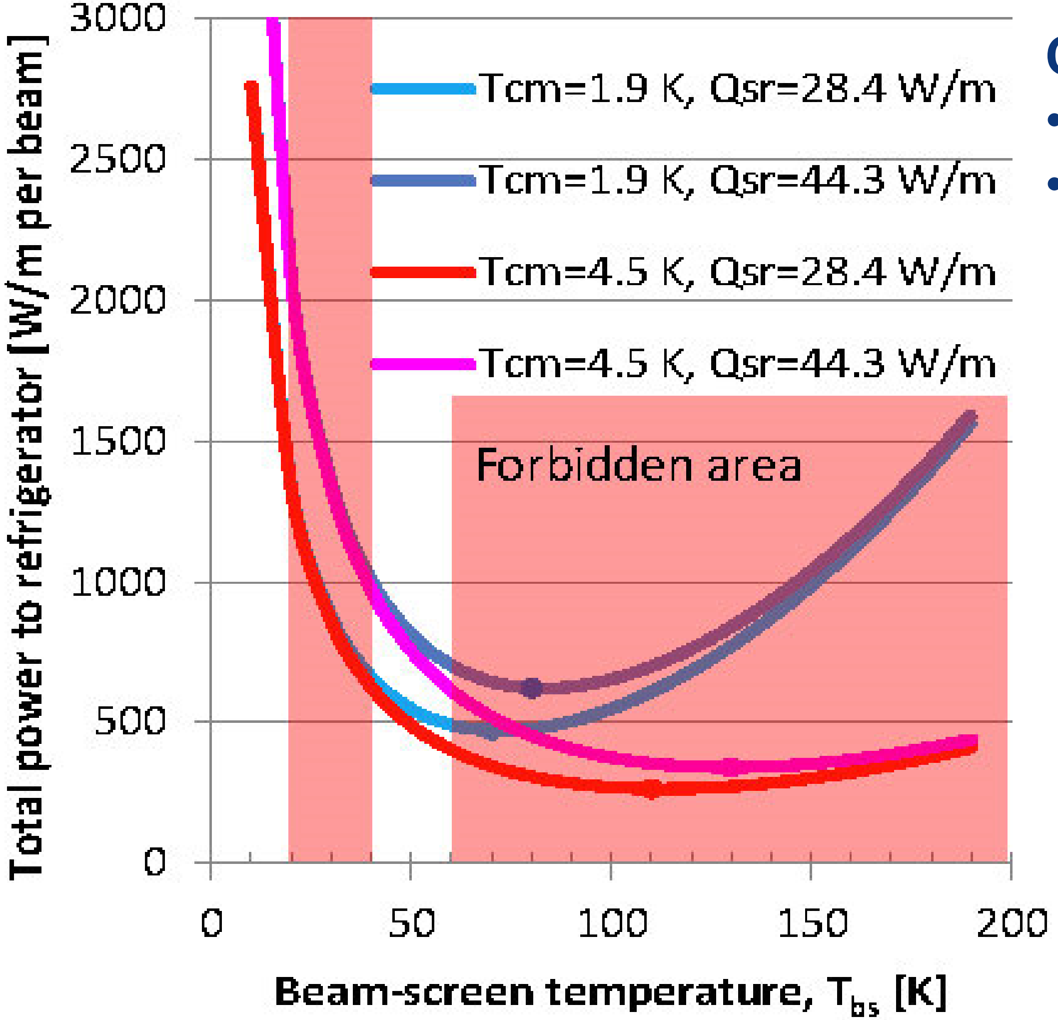
→ (LHC <0.2W/m)



- **Beam screen to capture SR and "protect" cold mass**
- **Power mostly cooled at beam screen temperature;**
- **Only minor part going to magnets at 2 – 4 K**

→ Optimisation of temperature, space, vacuum, impedance, e-cloud, etc.

Cryo power for cooling of SR heat



Contributions to cryo load:

- **beam screen (BS) &**
- **cold bore (BS heat radiation)**

At 1.9 K cm optimum BS temperature range: 50-100 K; But impedance increases with temperature → instabilities

40-60 K favoured by vacuum & impedance considerations

→ 100 MW refrigerator power on cryo plant

P. Lebrun, L. Tavian

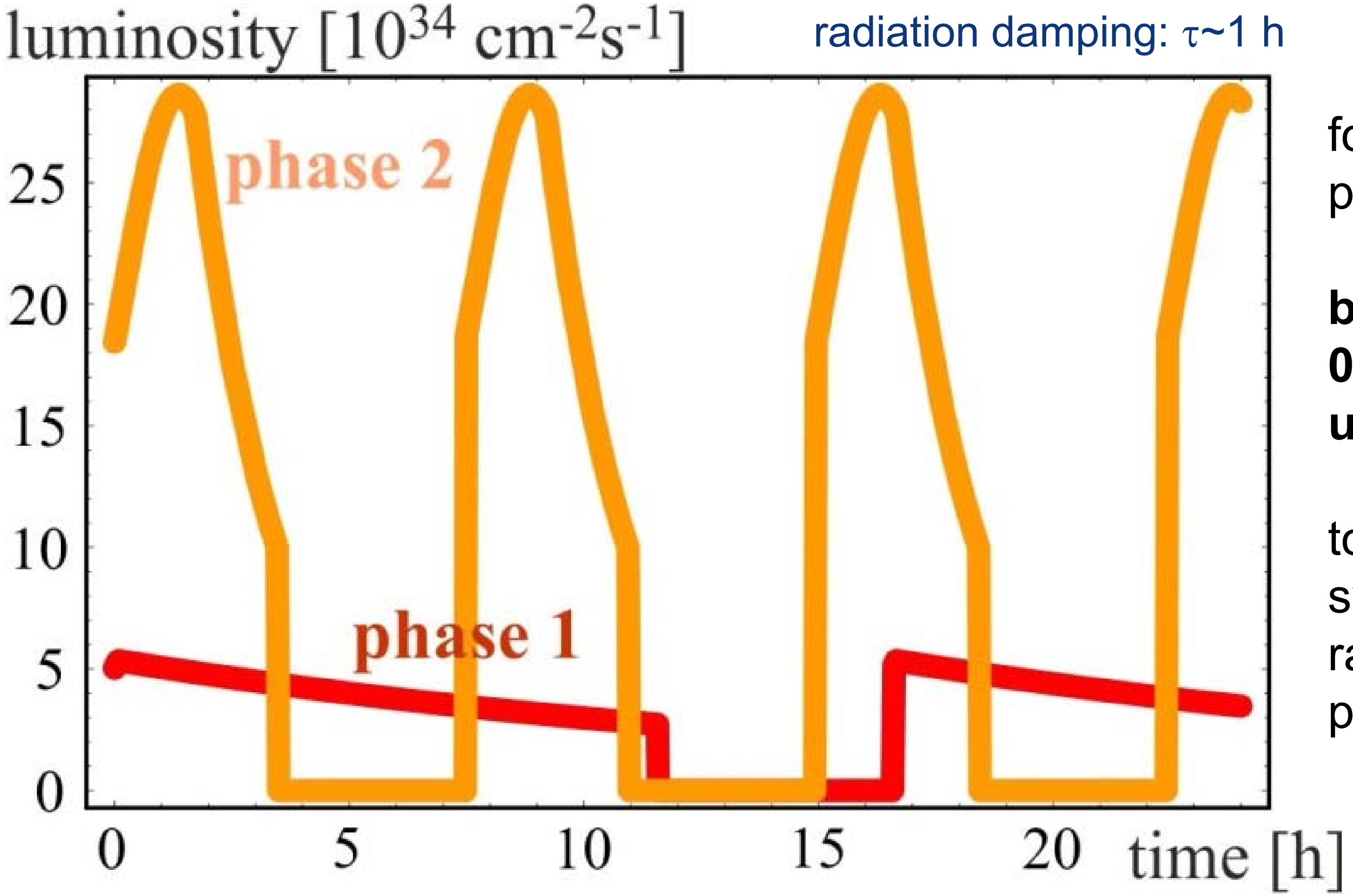
FCC luminosity goals & phases

- **FCC-hh general considerations (assuming operation over 25 years)**
  - **Initial luminosity** should be equal to final HL LHC luminosity
    ➔ **5x10^{34} cm^{-2}s^{-1}** with **~125 days effective operation / year**
  - **Integrated luminosity** (10 years, 125 days eff. operation/y) should be ~ equal to LHC total luminosity ➔ **O(3000 fb^{-1}).**
  - **FCC total luminosity** should be one order higher than LHC total
    ➔ **O(30,000 fb^{-1})**

- **Present parameter sets for the two operation phases:**
  - **phase 1 (baseline):**
    - **5x10^{34} cm^{-2}s^{-1} (peak),** average 250 fb^{-1}/year (stops incl.)
      ➔ 2500 fb^{-1} within total of 10 years (~HL LHC total luminosity)
  - **phase 2 (ultimate):**
    - **~2.5x10^{35} cm^{-2}s^{-1} (peak),** average 1000 fb^{-1}/year (stops incl.)
      ➔ 15,000 fb^{-1} within 15 years (~6x HL-LHC total luminosity).
  - **yielding total luminosity ~17,500 fb^{-1} over 25 years of operation**

luminosity evolution over 24 h

radiation damping: τ~1 h



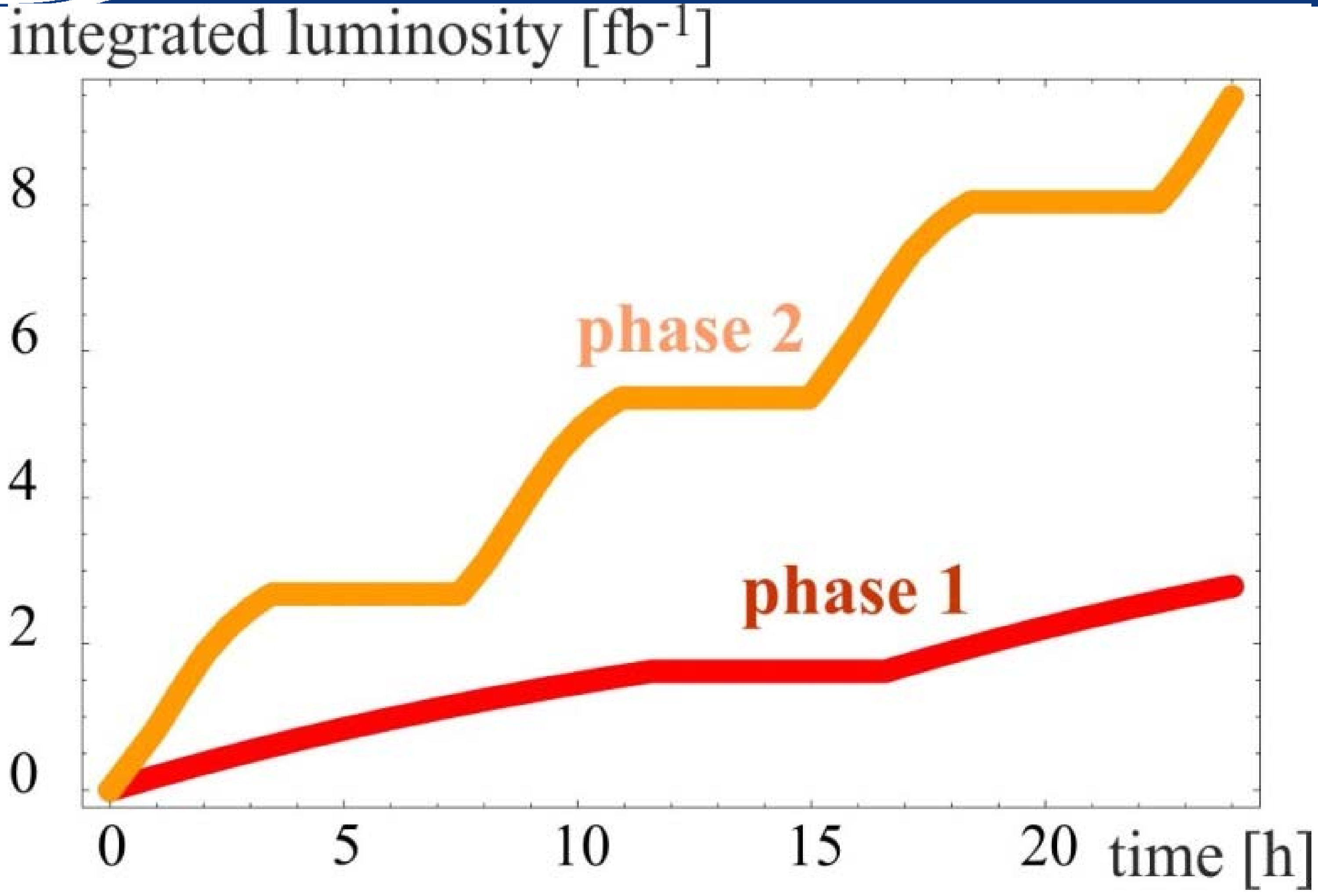
for both phases:

beam current 0.5 A unchanged!

total synchrotron radiation power ~5 MW.

phase 1: β^*=1.1 m, ΔQ_{tot}=0.01, t_{ta}=5 h → phase 2: β^*=0.3 m, ΔQ_{tot}=0.03, t_{ta}=4 h

integrated luminosity / day



phase 1: β^*=1.1 m, ΔQ_{tot}=0.01, t_{ta}=5 h

phase 2: β^*=0.3 m, ΔQ_{tot}=0.03, t_{ta}=4 h

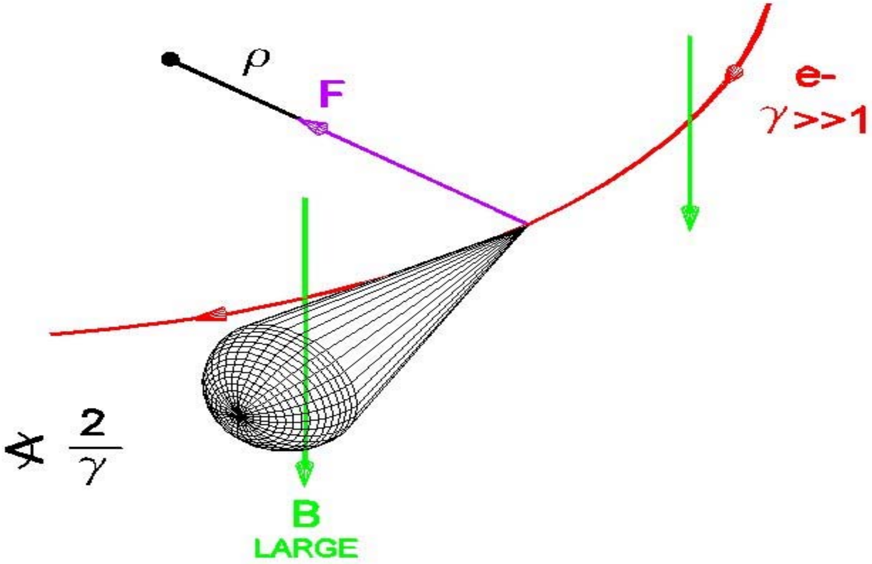
Lepton collider FCC-ee

- Name of the game here - **luminosity: as many collisions as possible → high beam current, small beam size.**

- Energy reach of circular e^+e^- colliders is limited due to synchrotron radiation of charged particles on curved trajectory:

$$\Delta E \propto (E_{kin}/m_0)^4/\rho$$

$$m_{prot} = 2000\ m_{electr}$$



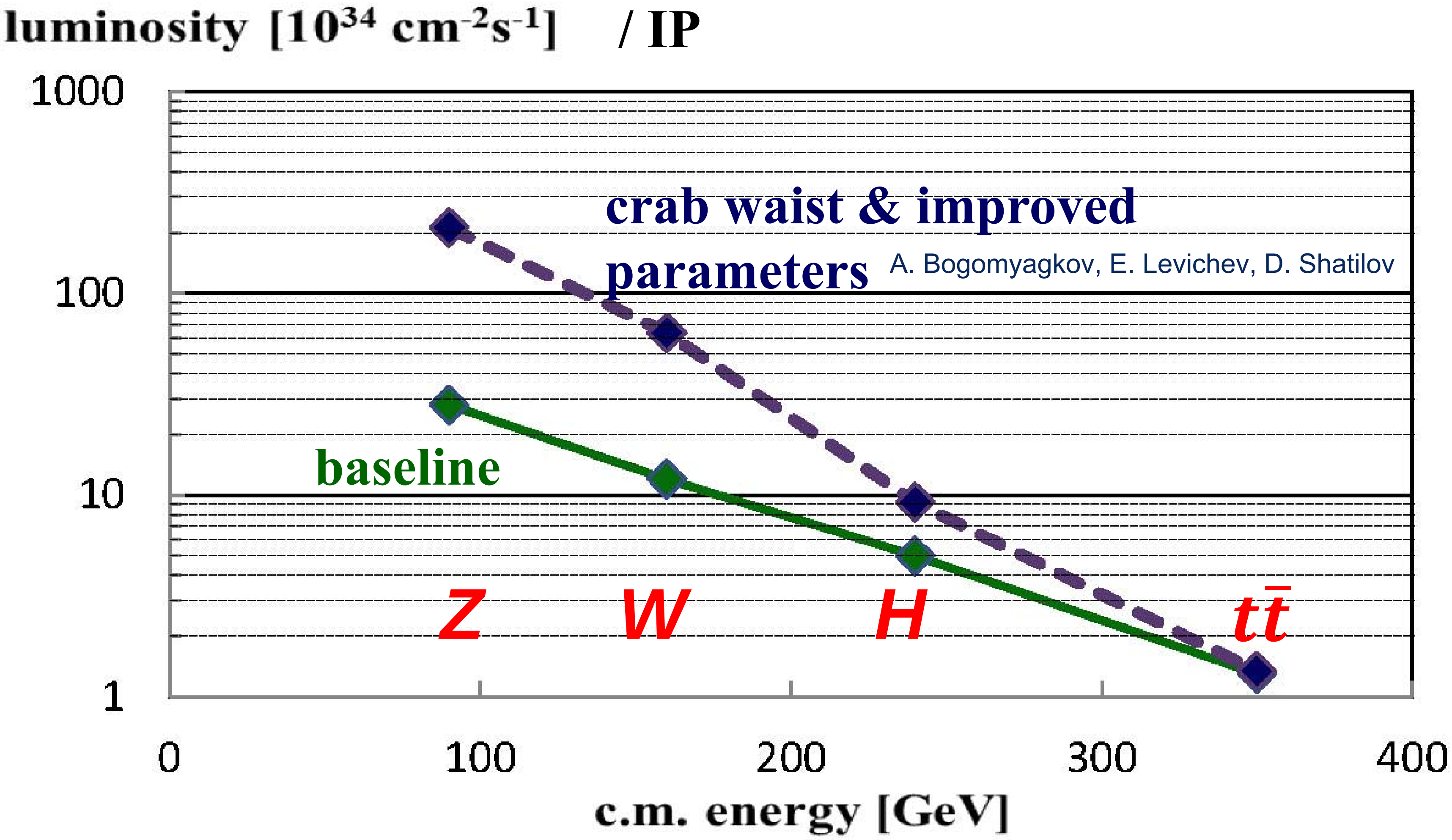
Lepton collider FCC-ee parameters

- **Design choice: max. synchrotron radiation power 50 MW/beam**
  - Defines the max. beam current at each energy
  - 4 Physics working points
  - Optimization at each energy (bunch number & current, etc).

Parameter	**Z**	**WW**	**H**	**tt_{bar}**	**LEP2**
E/beam (GeV)	**45**	**80**	**120**	**175**	**104**
I (mA)	**1450**	**152**	**30**	**6.6**	**3**
Bunches/beam	16700	4490	1360	98	4
Bunch popul. [10^{11}]	1.8	0.7	0.46	1.4	4.2
L/IP ($10^{34}cm^{-2}s^{-1}$)	28.0	12.0	6.0	1.7	0.012

- Large number of bunches at Z and WW and H requires 2 rings.
- High luminosity means short beam lifetime (few mins) and requires continues injection.

FCC-ee luminosity vs energy



FCC-ee key parameters

parameter	**FCC-ee**	LEP2
energy/beam	45 – 175 GeV	105 GeV
bunches/beam	**98 – 16700**	4
beam current	**6.6 – 1450 mA**	3 mA
hor. emittance	**~2 nm**	~22 nm
emittance ratio $\varepsilon_y/\varepsilon_y$	**0.1%**	1%
vert. IP beta function β_y^*	**1 mm**	50 mm
luminosity/IP	**1.8-28** x 10^{34} $cm^{-2}s^{-1}$	0.0012 x 10^{34} $cm^{-2}s^{-1}$
energy loss/turn	0.03-7.55 GeV	3.34 GeV
synchrotron radiation power	**100 MW**	23 MW
RF voltage	2.5 – **11 GV**	3.5 GV

Preliminary, subject to evolution (staging scenarios)

FCC-ee: RF parameters and R&D

- **Synchrotron radiation power: 50 MW per beam**
- **Energy loss per turn: up to 7.5 GeV (at 175 GeV, t)**
- System dimension compared to LEP2::
  - **LEP2: 352 MHz RF freq., 3.5 GV voltage, 22 MW SR power (27 km)**
  - **FCC-ee: 400 MHz RF freq,,12 GV voltage, 100 MW SR power (100 km)**

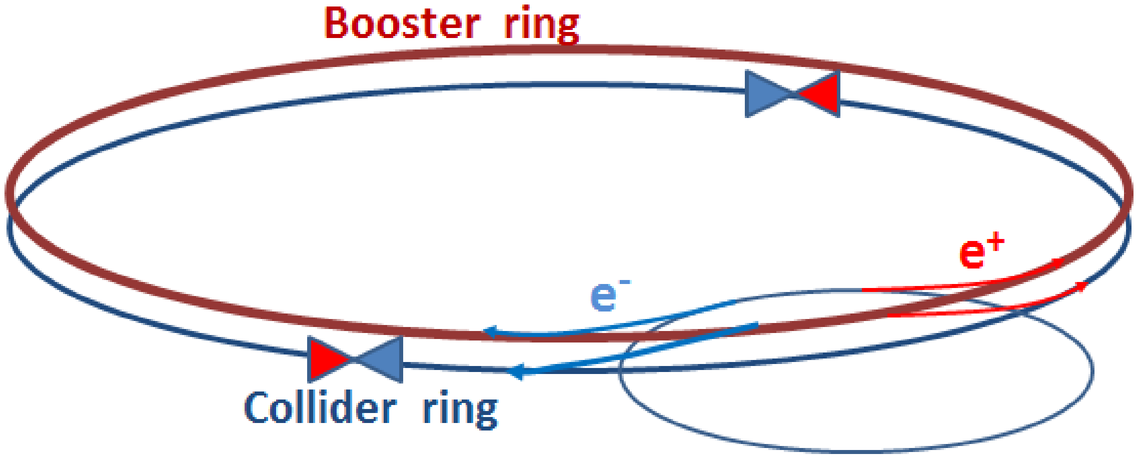
- **R&D Goal is optimization of overall system efficiency and cost!**

1. **SC cavity R&D → large Q_0, high gradient, acceptable cryo power!**
   - Recent promising results at 4 K with Nb3Sn coating on Nb at Cornell,
   - $800\ ^\circ\mathrm{C} \div 1400\ ^\circ\mathrm{C}$ heat treatment JLAB, beneficial effect of impurities FNAL.
2. **High efficiency RF power generation from electrical grid to beam**
   - Amplifier technologies
   - Klystron efficiencies >65%, alternative RF sources as solid state amplifier, etc.
3. **High reliability**

FCC-ee top-up injector

Beside the collider ring(s), a booster of the same size (same tunnel) must provide beams for top-up injection

- **same RF voltage, but low power (~ MW)**
- **top up frequency ~0.1 Hz**
- **booster injection energy ~5-20 GeV**
- **bypass around the experiments**

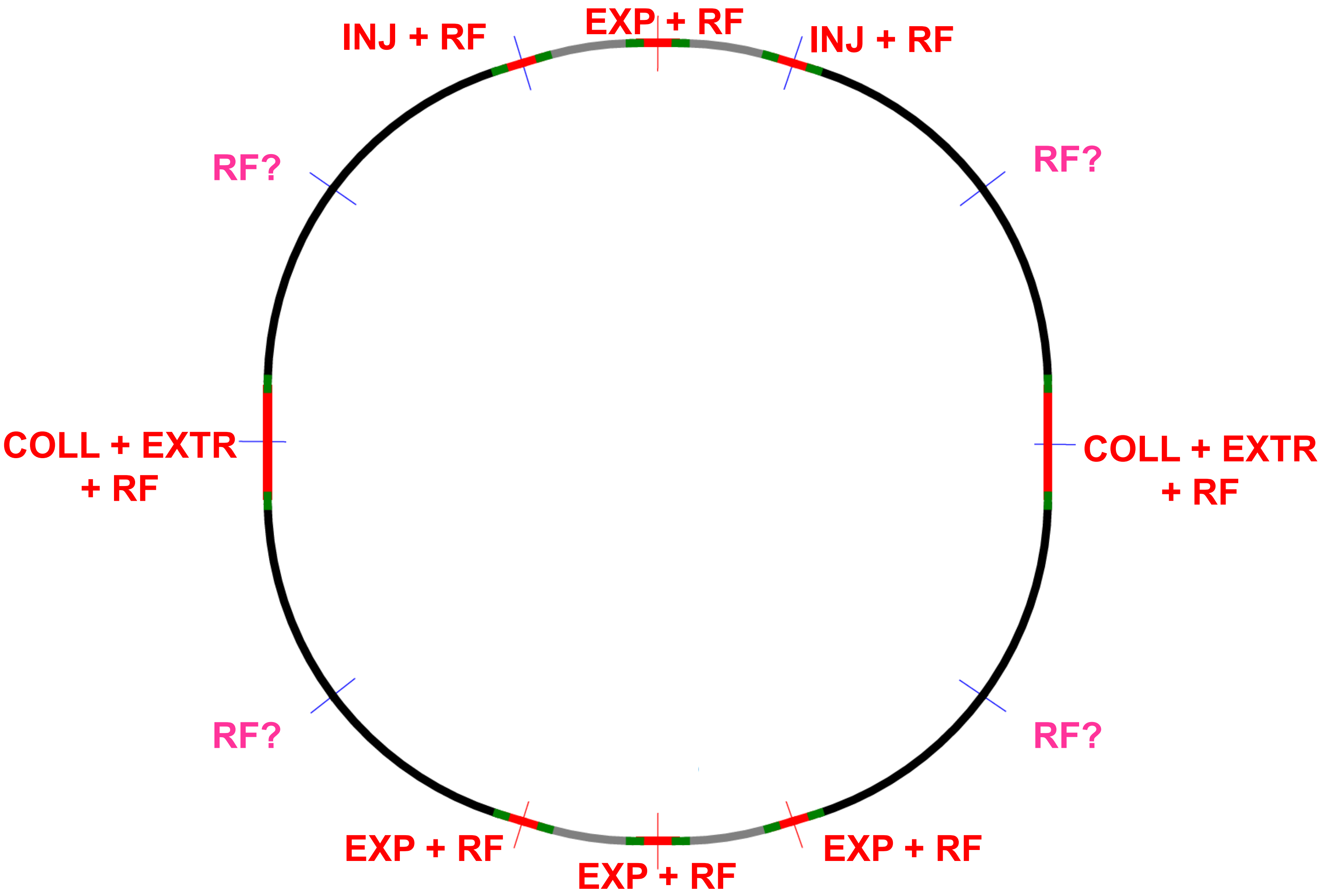


A. Blondel

injector complex for e^+ and e^- beams of 10-20 GeV

- **Super-KEKB injector ~ almost suitable**

FCC-ee preliminary layout



Tentative FCC-he parameters

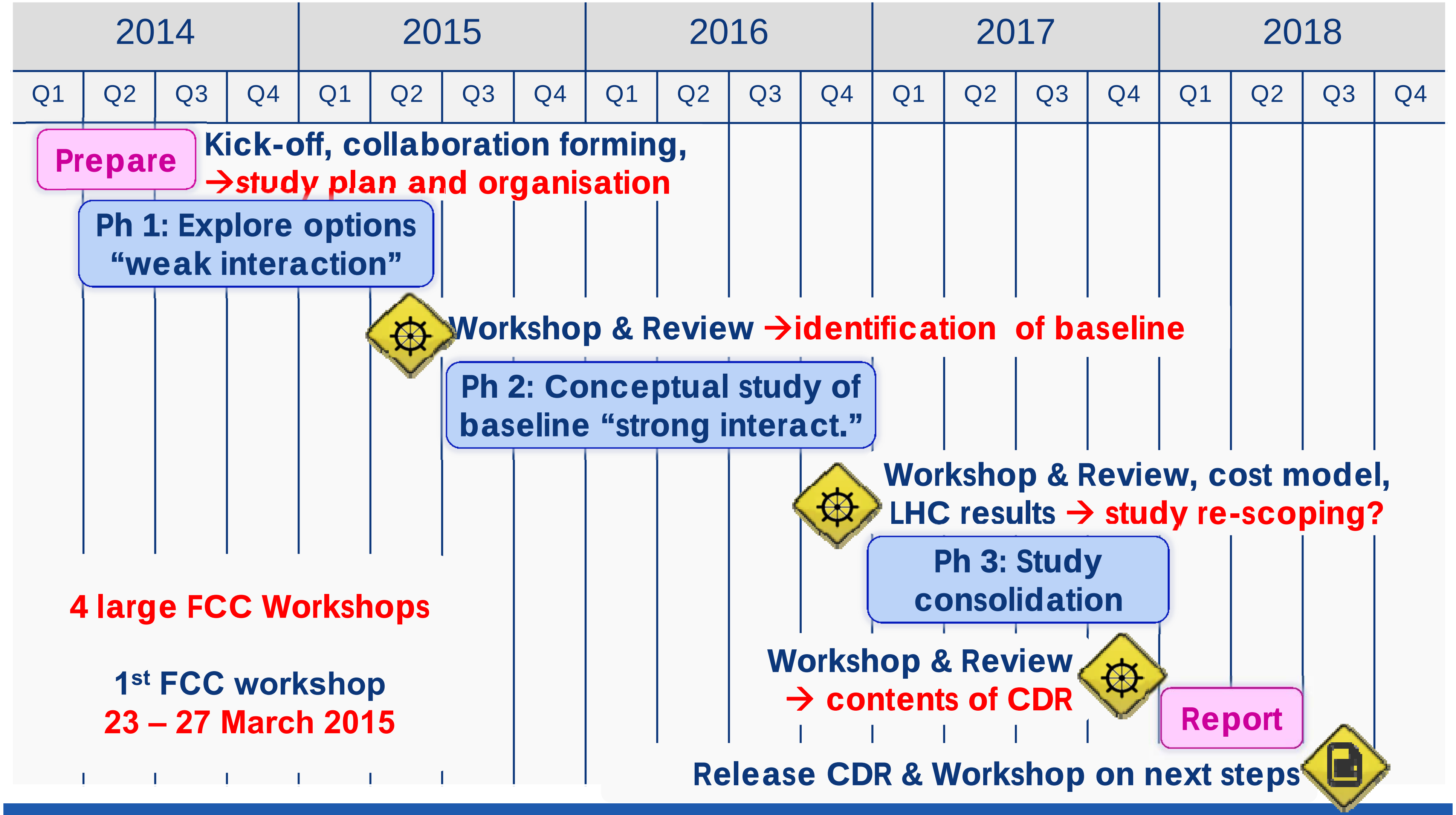
parameter	e^-	p
energy/beam	60 GeV (ERL)	50 TeV
bunches/beam	-	**10600**
bunch intensity	**5×10^9**	**10^{11}**
hor. & vert. emittance	0.17 nm	**0.04 nm**
emittance ratio $\varepsilon_y/\varepsilon_y$	1	**1**
IP beta function $\beta_{x,y}^*$	100 mm	**400 mm**
IP beta function $\sigma_{x,y}^*$	**4 μm**	
luminosity/IP	**1.0×10^{34} cm^{-2}s^{-1}**	
synchrotron power	~50 MW	**2.5 MW**

Preliminary, subject to evolution (staging scenarios)

FCC study status

- Study launched at FCC kick-off meeting in Feb. 2014
- Presently forming a global collaboration based on general MoU between CERN and individual partners. Specific addenda for each participant.
- First international collaboration board meeting on 9. and 10. September 2014 at CERN. Chair Prof. L. Rivkin (PSI/EPFL).
- Design study proposal for EU support in the Horizon 2020 program was submitted, evaluation expected end Jan 2015.
- First FCC Week workshop from 23. to 27. March in Washington DC.

FCC work plan study phase



Prepare Kick-off, collaboration forming,
→study plan and organisation

Ph 1: Explore options "weak interaction"

Workshop & Review →identification of baseline

Ph 2: Conceptual study of baseline "strong interact."

Workshop & Review, cost model,
LHC results → study re-scoping?

Ph 3: Study consolidation

Workshop & Review
→ contents of CDR

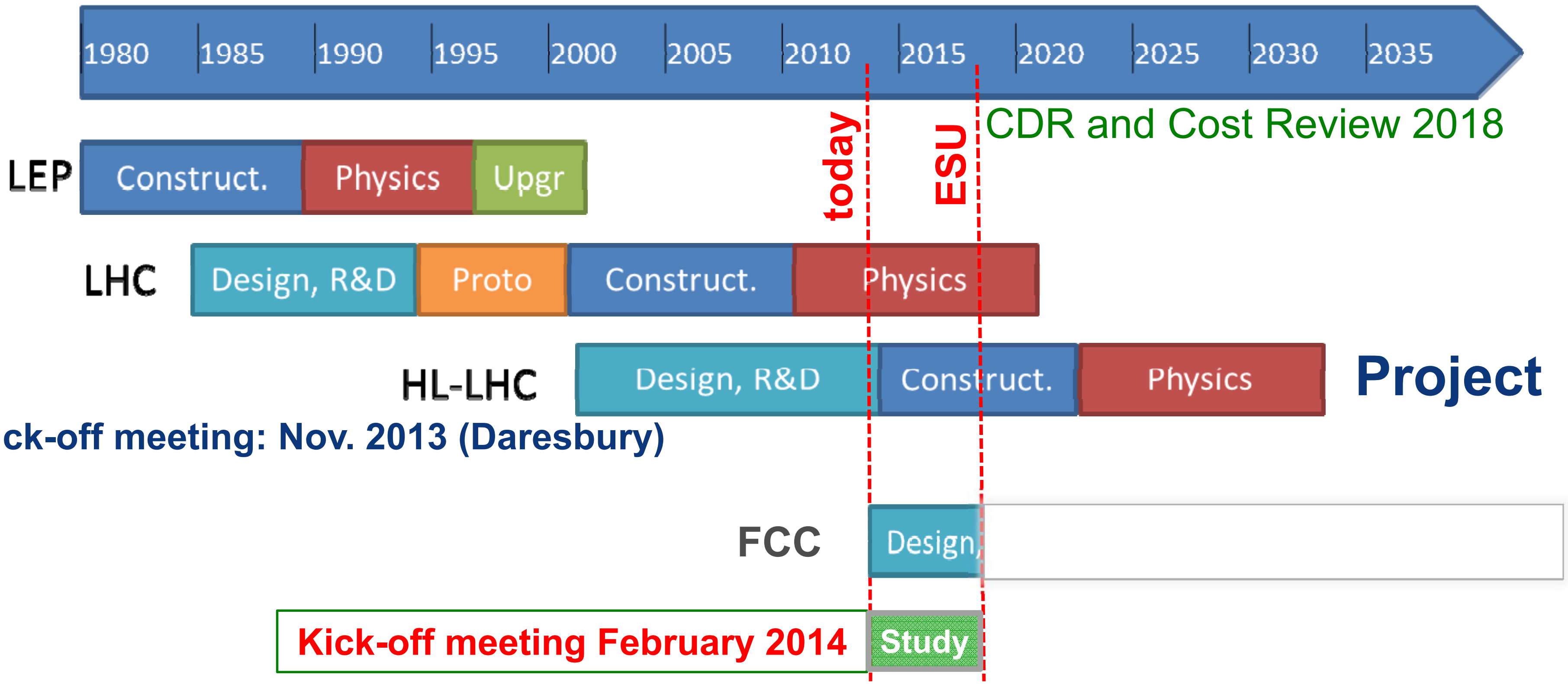
Report

Release CDR & Workshop on next steps

4 large FCC Workshops

1st FCC workshop
23 – 27 March 2015

LHC roadmap and FCC study



CDR and Cost Review 2018

Project

Kick-off meeting: Nov. 2013 (Daresbury)

Kick-off meeting February 2014

CDR and Cost Review for 2018

FCC MoU Status

43 collaboration members & CERN as host institute , 21 Jan. 2015

ALBA/CELLS, Spain
U Bern, Switzerland
BINP, Russia
CASE (SUNY/BNL), USA
CBPF, Brazil
CEA Grenoble, France
CIEMAT, Spain
CNRS, France
Cockcroft Institute, UK
U Colima, Mexico
CSIC/IFIC, Spain
TU Darmstadt, Germany
DESY, Germany
TU Dresden, Germany
Duke U, USA
EPFL, Switzerland
Gangneung-Wonju Nat. U., Korea
U Geneva, Switzerland
Goethe U Frankfurt, Germany
GSI, Germany
Hellenic Open U, Greece
HEPHY, Austria
IFJ PAN Krakow, Poland
INFN, Italy
INP Minsk, Belarus
U Iowa, USA
IPM, Iran
UC Irvine, USA
Istanbul Aydin U., Turkey
JAI/Oxford, UK
JINR Dubna, Russia
KEK, Japan
KIAS, Korea
King’s College London, UK
Korea U Sejong, Korea
MEPhI, Russia
Northern Illinois U., USA
NC PHEP Minsk, Belarus
PSI, Switzerland
Sapienza/Roma, Italy
UC Santa Barbara, USA
U Silesia, Poland
TU Tampere, Finland

FCC Week 2015

IEEE International Future Circular Collider Conference

March 23 - 27, 2015 | Washington DC, USA

Organising & Scientific Program Committee:

- N. Arkani-Hamed (Princeton U.)
- A. Ball (CERN)
- W. Barklow (SLAC)
- T. Barletta (MIT)
- M. Benedikt (CERN)
- A. Blondel (U. Geneva)
- F. Bordry (CERN)
- L. Bottura (CERN)
- O. Bruning (CERN)
- W. Chou (FNAL,IHEP)
- P. Collier (CERN)
- E. Delucinge (CERN)
- M. D'Onofrio (U. Liverpool)
- J. Ellis (King's College)
- F. Gianotti (CERN)
- B. Goddard (CERN)
- S. Gourlay (LBNL)
- C. Grojean (ICREA)
- J. Gutleber (CERN)
- G. Hoffstaetter (Cornell U.)
- J. Incandela (UCSB)
- P. Janot (CERN)
- E. Jensen (CERN)
- J.M. Jimenez (CERN)
- M. Klein (U. Liverpool)
- M. Klute (MIT)
- A. Lankford (UCI)
- D. Larbalestier (NHFML)
- P. Lebrun (CERN)
- L.K. Len (DOE)
- E. Levichev (BINP)
- J. Lykken (FNAL)
- M. Mangano (CERN)
- S. Nagaitsev (FNAL)
- T. Ogitsu (KEK)
- K. Oide (KEK)
- V. Palmieri (INFN LNL)
- A. Patwa (DOE)
- F. Perez (ALBA-CELLS)
- C. Potter (CERN)
- Q. Qin (IHEP)
- R. Rimmer (JLAB)
- T. Roser (BNL)
- L. Rossi (CERN)
- D. Schulte (CERN)
- M. Seidel (PSI)
- A. Seryi (JAI)
- B. Strauss (DOE)
- S. Strauss
- R. Sundrum (U. Maryland)
- S. Su (U. Arizona)
- M. Syphers (MSU)
- L. Tavian (CERN)
- E. Todesco (CERN)
- R. Van Kooten (Indiana U.)
- P. Vedrine (CEA)
- J. Wenninger (CERN)
- U. Wienands (SLAC)
- F. Zimmermann (CERN)

Jamieaddams99

Further information and registration
http://cern.ch/fccw2015

U.S. DEPARTMENT OF **ENERGY** | Office of Science

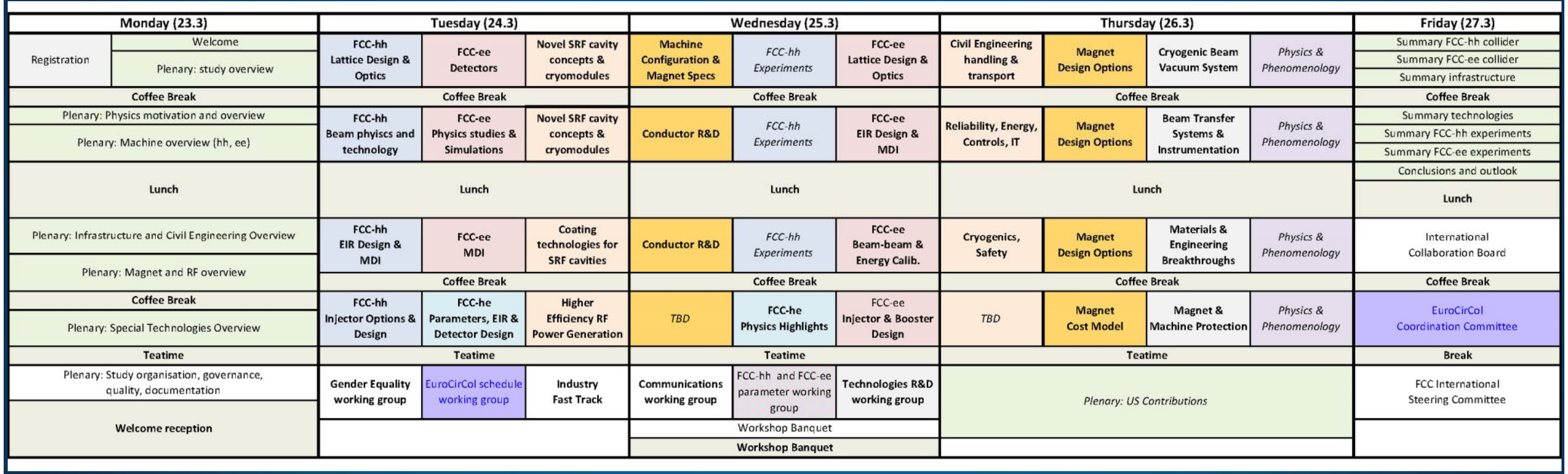
First FCC Week

Conference

Washington DC
23-27 March 2015

http://cern.ch/fccw2015

First FCC Week, Washington DC
23-27 March 2015 – DRAFT SCHEDULE



Monday (23.3)	**Tuesday (24.3)**			**Wednesday (25.3)**			**Thursday (26.3)**				**Friday (27.3)**
Registration Welcome Plenary: study overview	**FCC-hh Lattice Design & Optics**	**FCC-ee Detectors**	**Novel SRF cavity concepts & cryomodules**	**Machine Configuration & Magnet Specs**	*FCC-hh Experiments*	**FCC-ee Lattice Design & Optics**	**Civil Engineering handling & transport**	**Magnet Design Options**	**Cryogenic Beam Vacuum System**	*Physics & Phenomenology*	Summary FCC-hh collider Summary FCC-ee collider Summary infrastructure
Coffee Break	**Coffee Break**			**Coffee Break**			**Coffee Break**				**Coffee Break**
Plenary: Physics motivation and overview Plenary: Machine overview (hh, ee)	**FCC-hh Beam phyiscs and technology**	**FCC-ee Physics studies & Simulations**	**Novel SRF cavity concepts & cryomodules**	**Conductor R&D**	*FCC-hh Experiments*	**FCC-ee EIR Design & MDI**	**Reliability, Energy, Controls, IT**	**Magnet Design Options**	**Beam Transfer Systems & Instrumentation**	*Physics & Phenomenology*	Summary technologies Summary FCC-hh experiments Summary FCC-ee experiments Conclusions and outlook
Lunch	**Lunch**			**Lunch**			**Lunch**				**Lunch**
Plenary: Infrastructure and Civil Engineering Overview Plenary: Magnet and RF overview	**FCC-hh EIR Design & MDI**	**FCC-ee MDI**	**Coating technologies for SRF cavities**	**Conductor R&D**	*FCC-hh Experiments*	**FCC-ee Beam-beam & Energy Calib.**	**Cryogenics, Safety**	**Magnet Design Options**	**Materials & Engineering Breakthroughs**	*Physics & Phenomenology*	International Collaboration Board
Coffee Break	**Coffee Break**			**Coffee Break**			**Coffee Break**				**Coffee Break**
Plenary: Special Technologies Overview	**FCC-hh Injector Options & Design**	**FCC-he Parameters, EIR & Detector Design**	**Higher Efficiency RF Power Generation**	*TBD*	**FCC-he Physics Highlights**	FCC-ee **Injector & Booster Design**	*TBD*	**Magnet Cost Model**	**Magnet & Machine Protection**	*Physics & Phenomenology*	EuroCirCol Coordination Committee
Teatime	**Teatime**			**Teatime**			**Teatime**				**Break**
Plenary: Study organisation, governance, quality, documentation	**Gender Equality working group**	EuroCirCol schedule working group	**Industry Fast Track**	**Communications working group**	FCC-hh and FCC-ee parameter working group	**Technologies R&D working group**	*Plenary: US Contributions*				FCC International Steering Committee
Welcome reception				Workshop Banquet							
				Workshop Banquet							

hoping to see you there!

Conclusions

- There are strongly rising activities in energy-frontier circular colliders worldwide.
- The FCC collaboration is being formed with CERN as host laboratory, to conduct an international study for the design of Future Circular Colliders (FCC).
- FCC presents many challenging R&D requirements in SC magnets, SRF and other technical areas.
- Global collaboration in physics, experiments and accelerators and the use of all synergies is essential to move forward.