Future Circular Collider Study

M. Benedikt, F. Zimmermann

gratefully acknowledging input from
FCC global design study team

YEARS / ANS CERN

FCC
hh ee he

Outline

- Motivation
- FCC – Hadron Collider
  - Parameters & challenges
- FCC – Lepton Collider
  - Parameters & challenges
- Status of FCC collaboration

LHC evolution

1983 first LHC proposal, launch of design study

1994 CERN Council: LHC approval

2010 first collisions at 3.5 TeV beam energy

2015 collisions at ~design energy (plan)

now is the time to plan for 2040!

Hadron collider motivation: pushing the energy frontier

- A very large circular hadron collider seems **the only approach to reach 100 TeV c.m. collision energy** in coming decades
- Access to **new particles (direct production) in the few TeV to 30 TeV mass range**, far beyond LHC reach.
- **Much-increased rates for phenomena in the sub-TeV mass range** →increased precision w.r.t. LHC and possibly ILC

M. Mangano

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

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

Cf. LHC: factor ~4 in radius, factor ~2 in field → O(10) in E_{cms}

Strategic Motivation

- **European Strategy for Particle Physics 2013:**

  "…to propose an ambitious post-LHC accelerator project….., CERN should undertake design studies for accelerator projects in a global context,…with emphasis on proton-proton and electron-positron high-energy frontier machines.…."

- **ICFA statement 2014:**

  ".… ICFA supports studies of energy frontier circular colliders and encourages global coordination.…."

- **US P5 recommendation 2014:**

  "….A very high-energy proton-proton collider is the most powerful tool for direct discovery of new particles and interactions under any scenario of physics results that can be acquired in the P5 time window…."

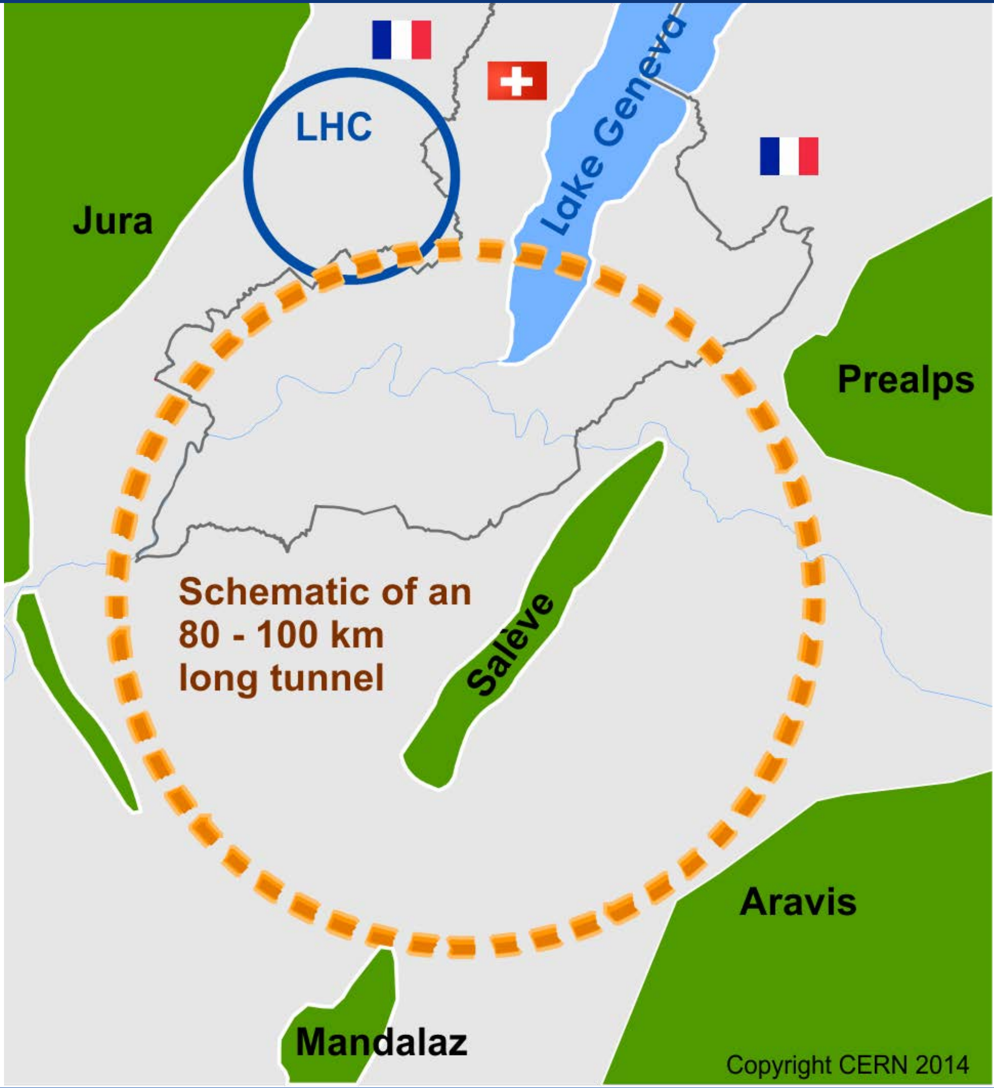
Future Circular Collider Study
GOAL: CDR and cost review for the next ESU (2018)

International FCC collaboration (CERN as host lab) to study:

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

~16 T ⇒ 100 TeV *pp* in 100 km

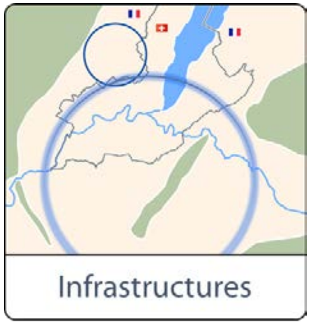
- **80-100 km infrastructure** in Geneva area
- **e^+e^- collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (FCC-he) option**
- **HE-LHC** with FCC-hh technology



FCC Scope: Accelerator and Infrastructure

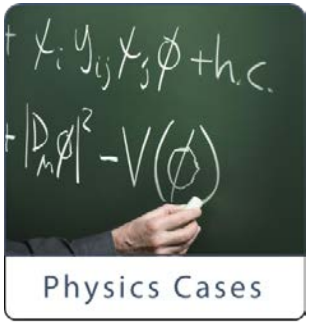
FCC-hh: **100 TeV pp collider as long-term goal**
→ defines infrastructure needs
FCC-ee: **e^+e^- collider**, potential intermediate step
FCC-he: **integration aspects** of pe collisions

Push key technologies
in dedicated R&D programmes e.g.
16 Tesla magnets for **100 TeV** pp in **100 km**
SRF technologies and RF power sources

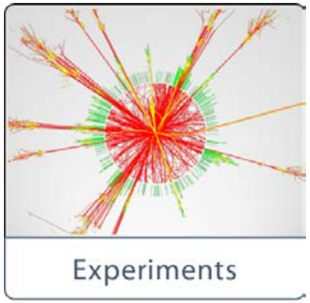


Tunnel infrastructure in Geneva area, linked to CERN accelerator complex
Site-specific, requested by European strategy

Scope: Physics & Experiments



Elaborate and document
- Physics opportunities
- Discovery potentials



Experiment concepts for hh, ee and he
Machine Detector Interface studies
Concepts for worldwide data services

Overall cost model
Cost scenarios for collider options
Including infrastructure and injectors
Implementation and governance models

CepC/SppC study (CAS-IHEP) 54 km (baseline)
e^+e^- collisions ~2028; *pp* collisions ~2042

easy access
300 km east
from Beijing
3 h by car
1 h by train

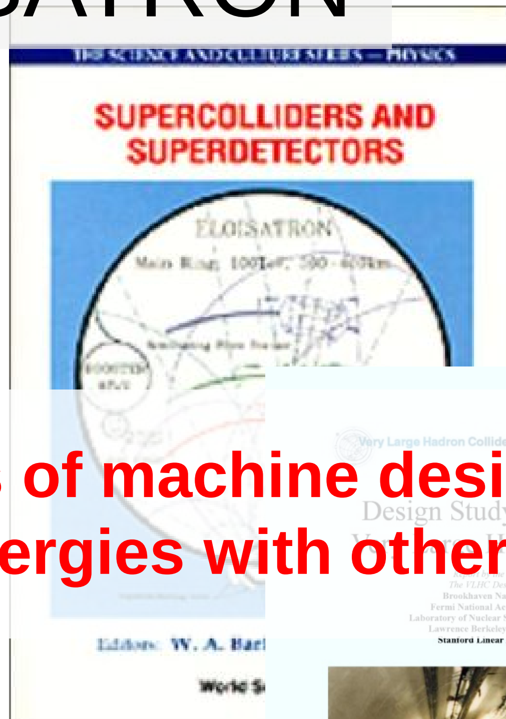
"Chinese Toscana"

Yifang Wang

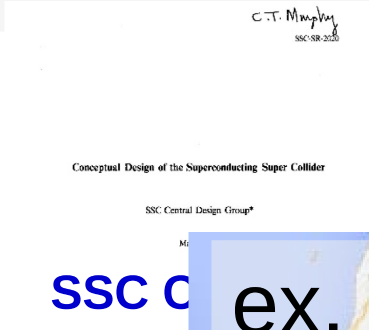
Previous studies in Italy (ELOISATRON 300km), USA (SSC 87km, VLHC 233km), Japan (TRISTAN-II 94km)

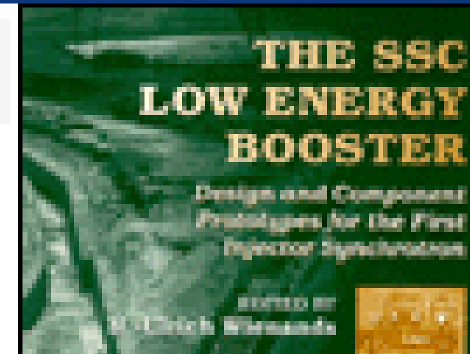
ex. ELOISATRON

Supercolliders Superdetectors: Proceedings of the 19th and 25th Workshops of the INFN Eloisatron Project



ex. SSC





ex. TRISTAN II

F. Takasaki

Tristan-II option 1

Tristan-II option 2

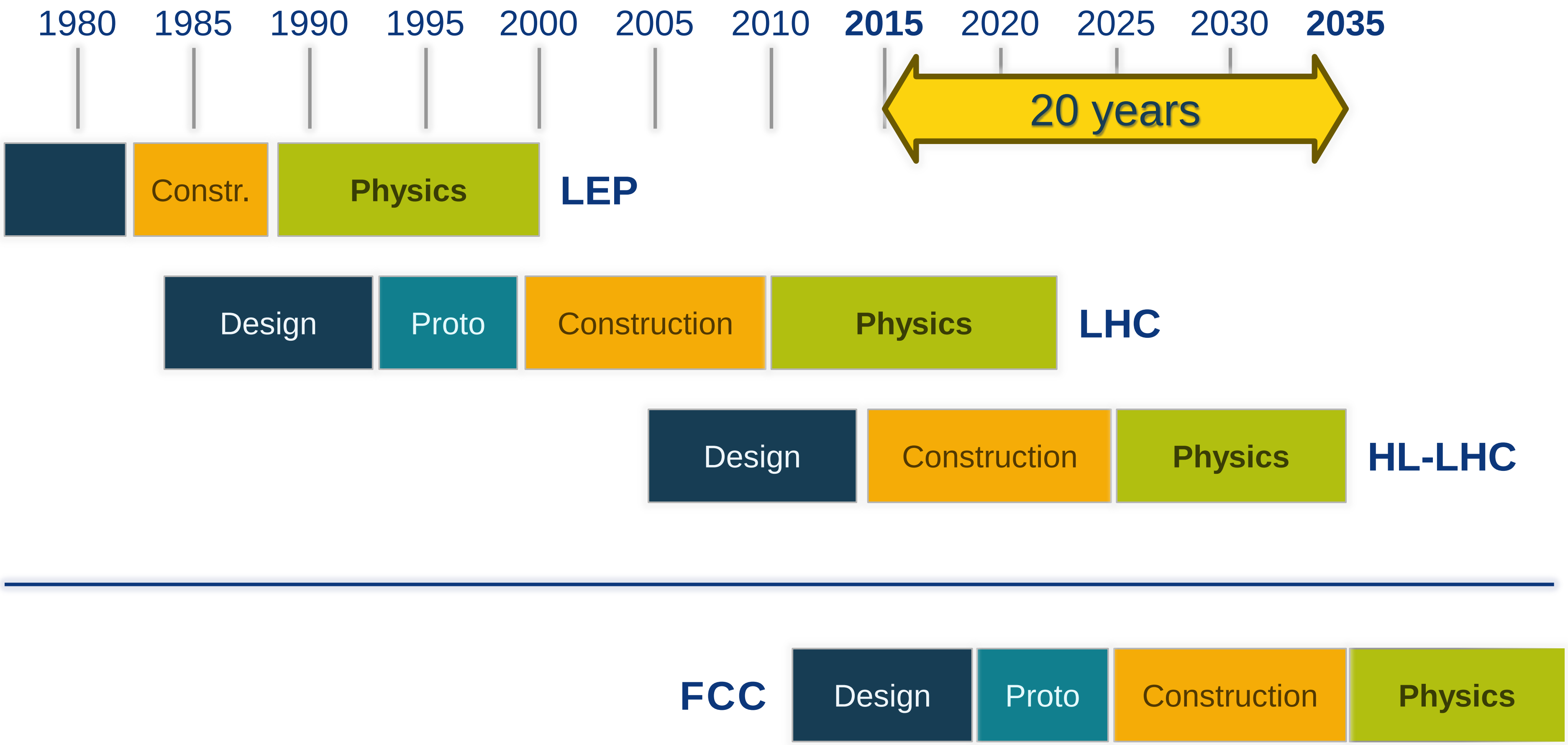
Many aspects of machine design and R&D non-site specific.
→ Exploit synergies with other projects and prev. studies

ex. VLHC

VLHC Design Study Group Collaboration
June 2001. 271 pp.
SLAC-R-591, SLAC-R-0591, SLAC-591, SLAC-0591, FERMILAB-TM-2149

http://www.vlhc.org/

CERN Circular Colliders and FCC



CDR by end 2018 for strategy upade

FCC-hh preliminary layout

100 km layout for FCC-hh (different sizes under investigation)

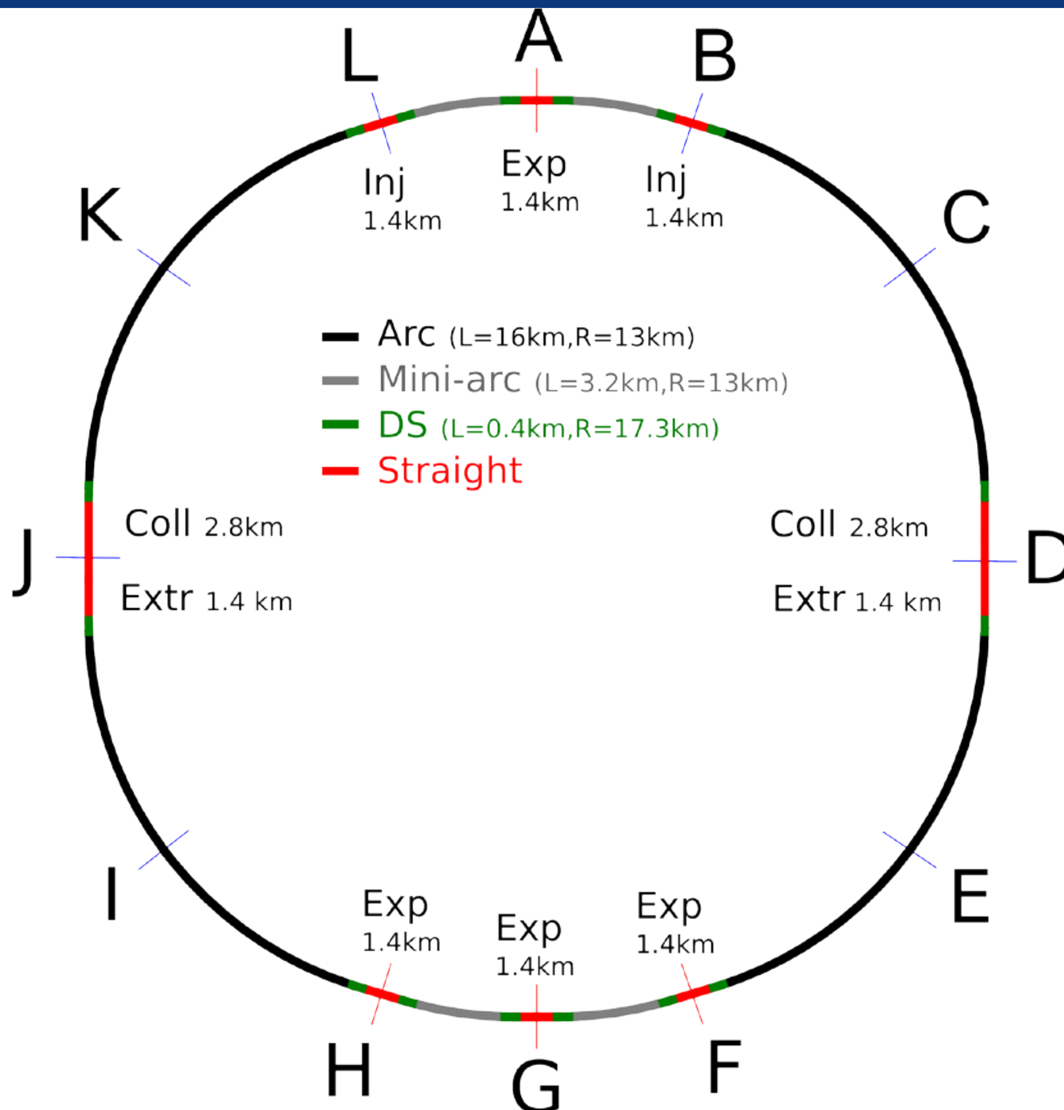
⇒ **Two high-luminosity experiments (A and G)**

⇒ **Two other experiments (F and H) grouped with main experiment in G**

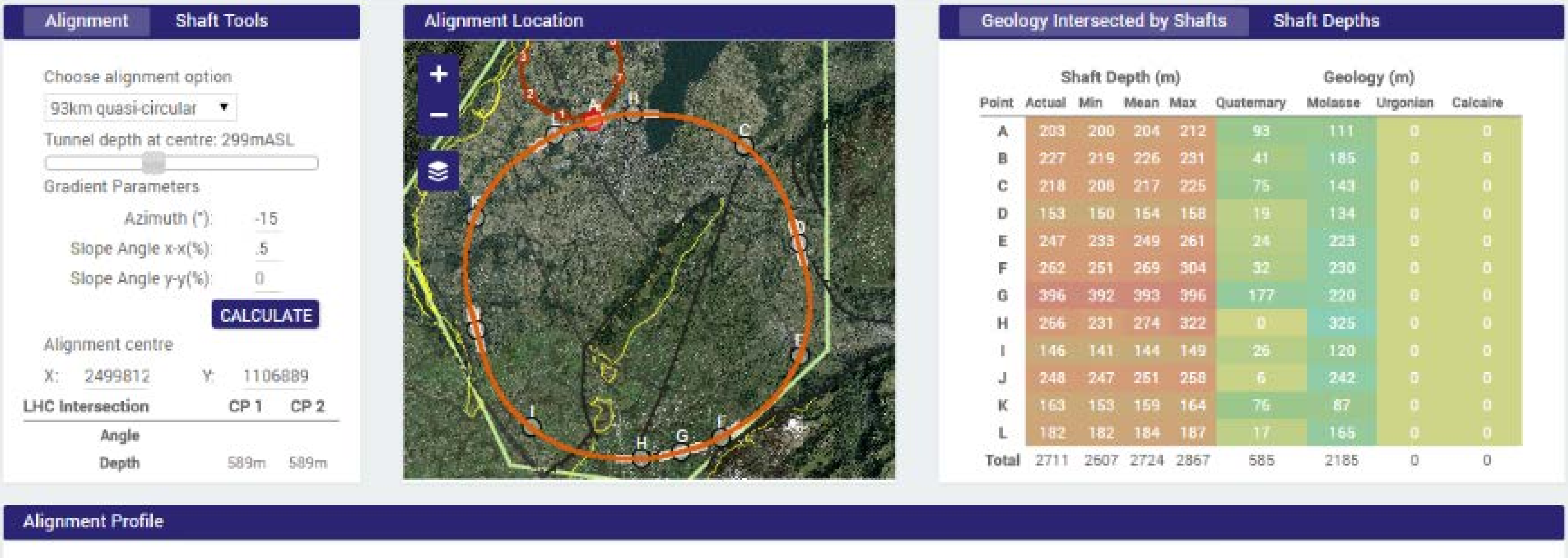
⇒ **Two collimation lines**

⇒ **Two injection and two extraction lines**

Orthogonal functions for each insertion section



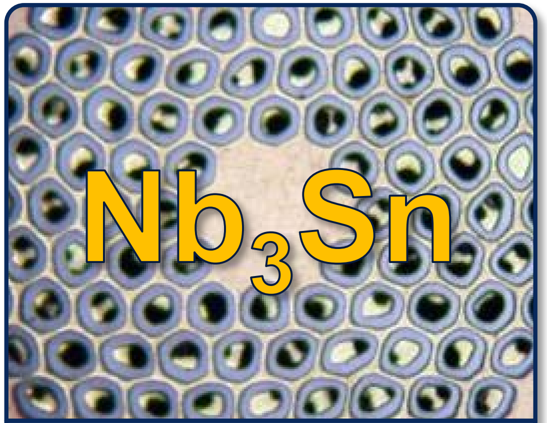
Site investigations



	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

- 90 – 100 km fits geological situation well,
- LHC suitable as potential injector

Key Technology R&D - HFM



Conductor R&D

Magnet Design

- Increase critical current density
- Obtain high quantities at required quality
- Material Processing
- Reduce cost

- Develop 16T short models
- Field quality and aperture
- Optimum coil geometry
- Manufacturing aspects
- Cost optimisation

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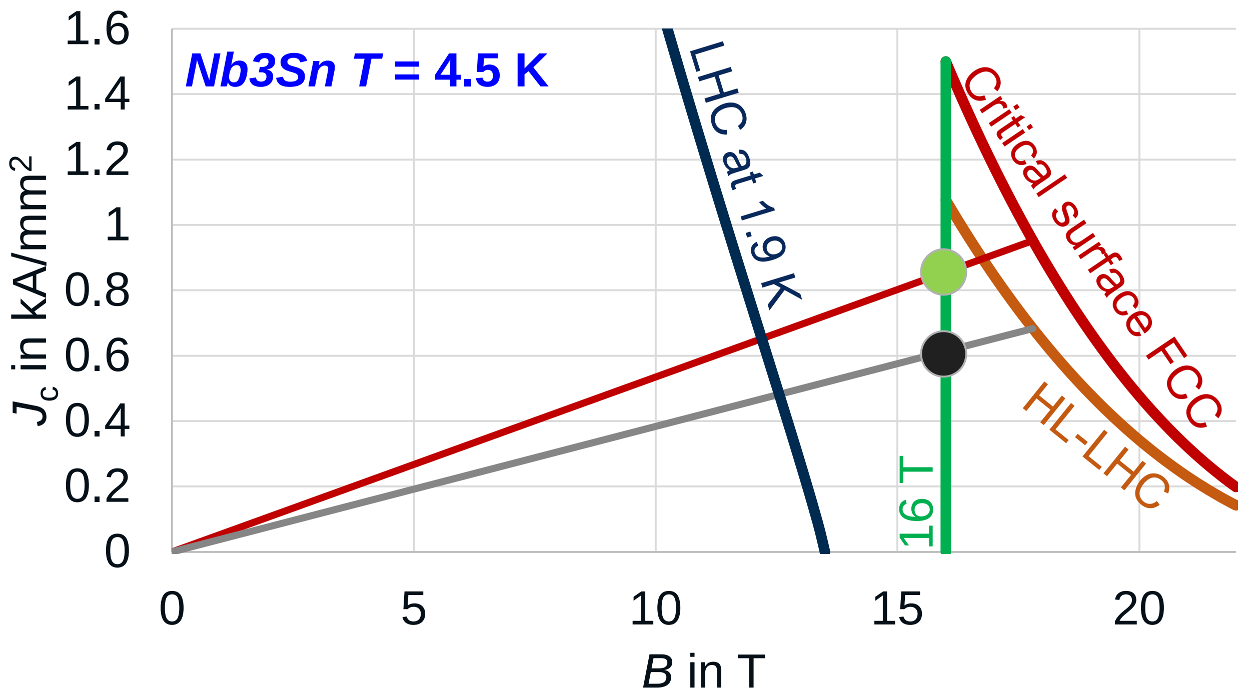
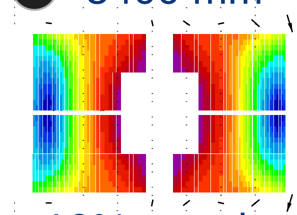
Superconductor performance



Nb-Ti
Not possible

Different technology →

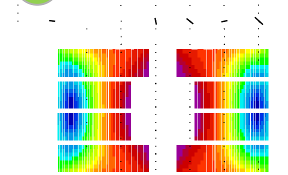
5400 mm²



~10% margin
HL-LHC

~1.7 times less SC →

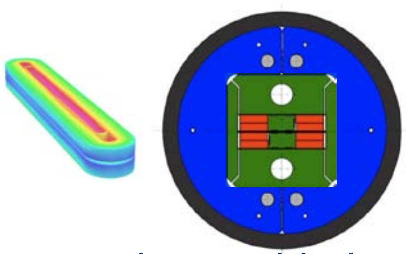
3150 mm²



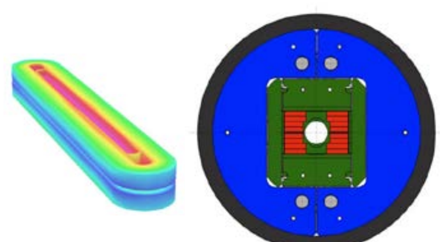
~10% margin
FCC ultimate

FCC magnet technology program

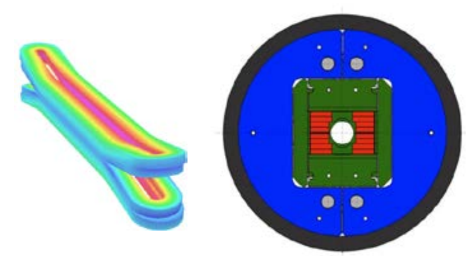
Milestone	Description	15	2016		2017		2018		2019		2020		21
Main Milestones of the FCC Magnets Technologies													
M0	High J_c wire development with industry	■	■	■	■	■	■	■	■	■	■	■	■
M1	Supporting wound conductor test program	■	■	■	■	■	■	■	■	■	■	■	■
M2	Design & manufacture 16T ERMC with existing wire	■	■	■	■								
M3	Design & manufacture 16 T RMM with existing wire		■	■	■	■							
M4	Procurement of 35 km enhanced wire			■	■	■							
M5	Design & manufacture 16T demonstrator magnet			■	■	■	■	■					
M6	Procurement 70 km of enhanced high J_c wire				■	■	■	■	■				
M7	EuroCirCol design 16T accelerator quality model	■	■	■	■	■	■	■	■				
	Manufacture and test of the 16 T EuroCirCol model									■	■	■	■



ERMC (16 T mid-plane field)



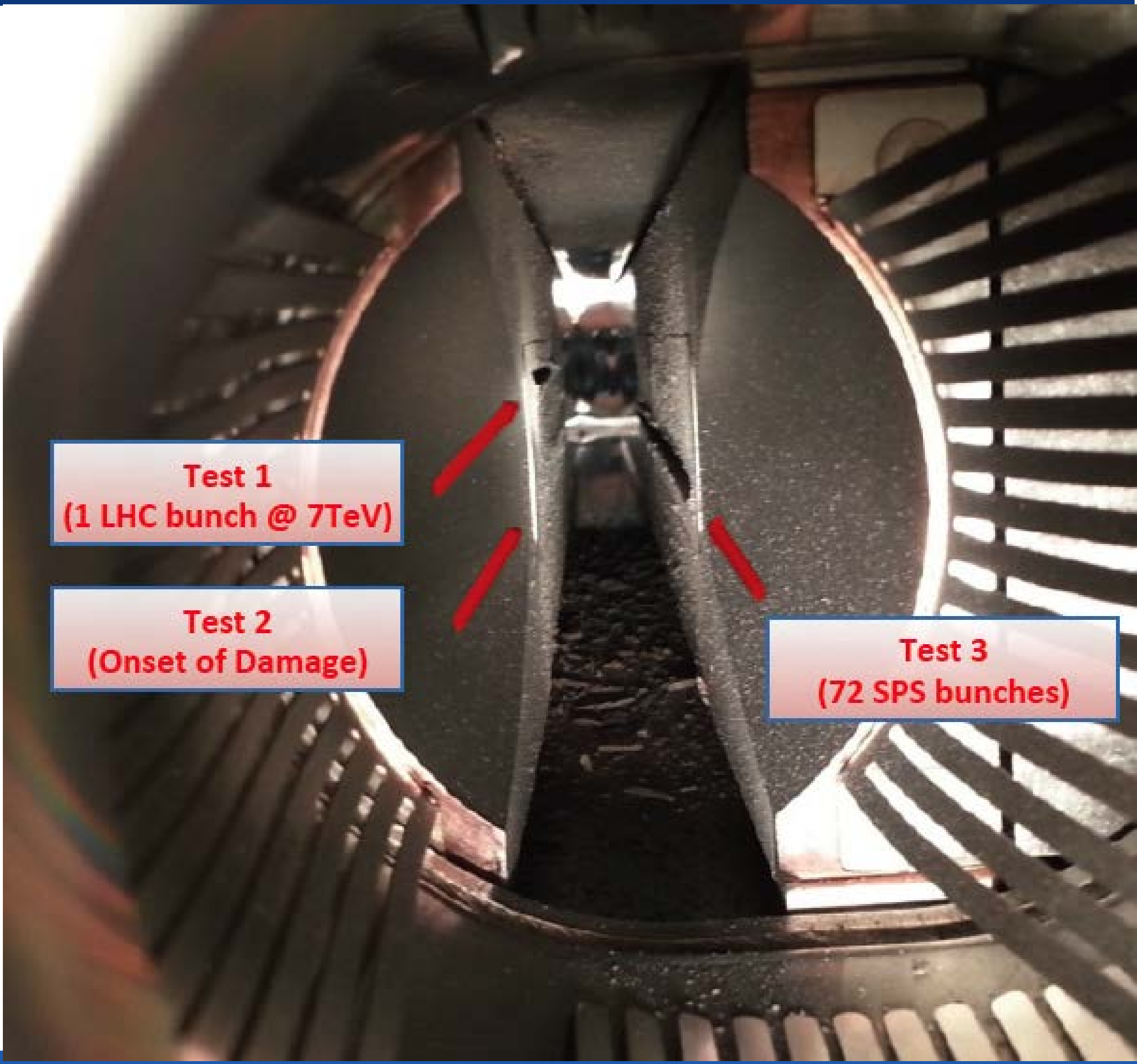
RMM (16 T in 50 mm cavity)



Demonstrator (16 T, 50 mm gap)

Unprecedented beam power

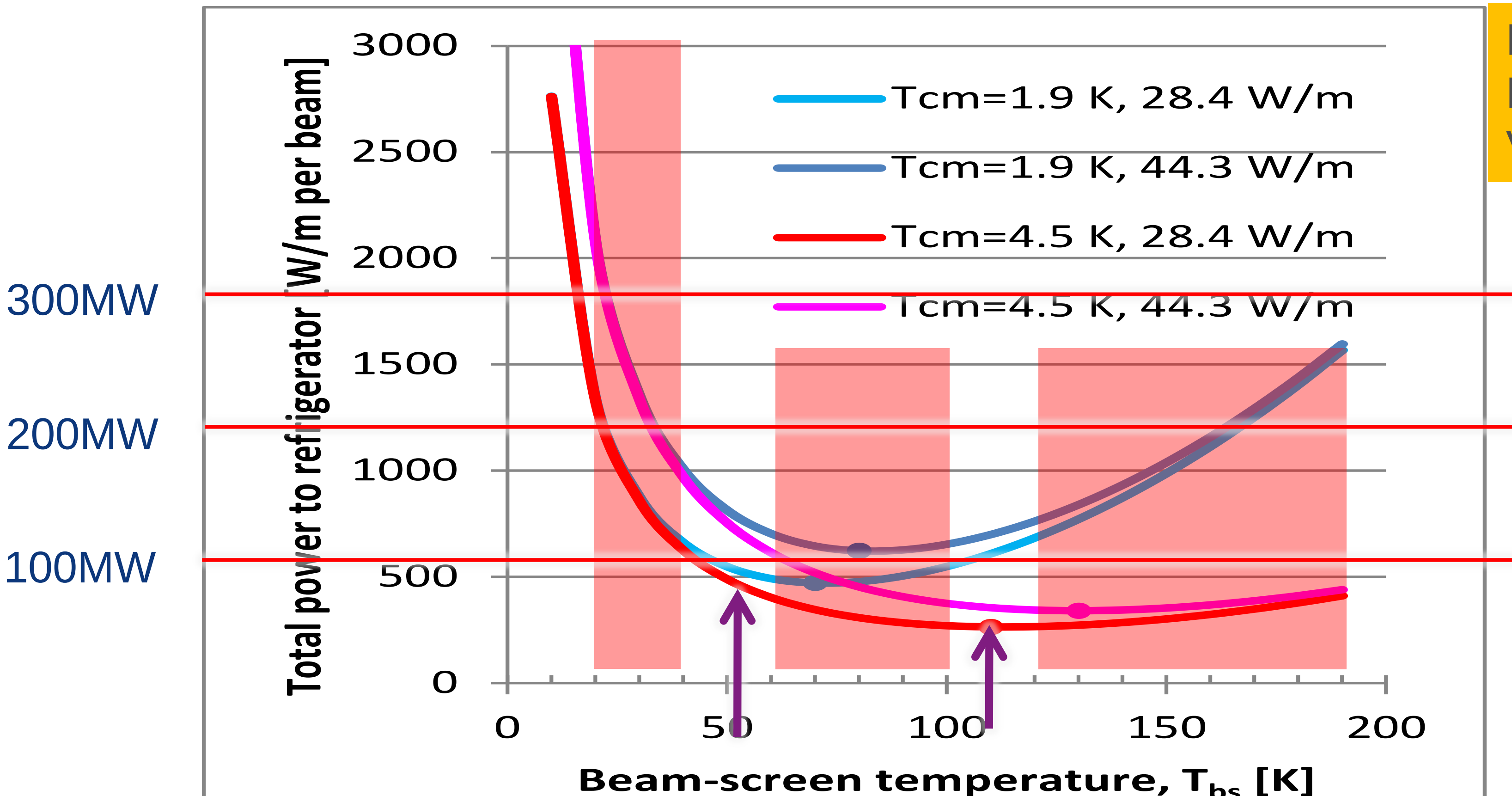
- 8GJ stored energy / beam
  - Airbus A380 at 700km/h
  - 24 times larger than in LHC at 14TeV
  - Can melt 12t of copper
  - Or drill a 300m long hole
  - ⇒ **Machine protection**
  - ⇒ **Beam dumping**
- Any beam loss important
  - E.g. beam-gas scattering, non-linear dynamics
  - Can quench arc magnets
  - Background for the experiments
  - Activation of the machine
  - ⇒ **Collimation system**
  - ⇒ **Transfer and injection**



Cryo power for cooling of SR heat

Overall optimisation of cryo-power, vacuum and impedance
Termperature ranges: <20, 40K-60K, 100K-120K

Ph. Lebrun
L. Tavian
V. Baglin



Multi-bunch instability growth time: 25 turns 9 turns (ΔQ=0.5)

Synchrotron radiation/beam screen

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

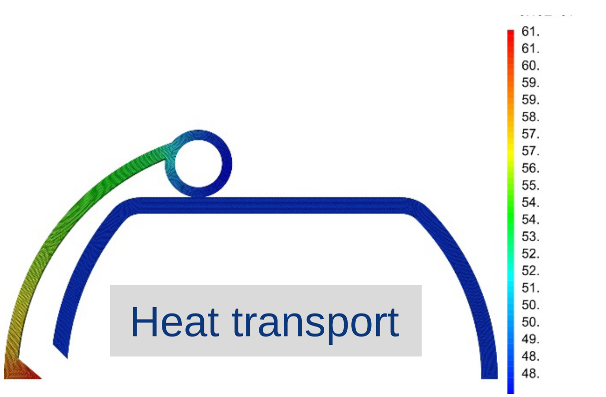
~30 W/m/beam (@16 T)

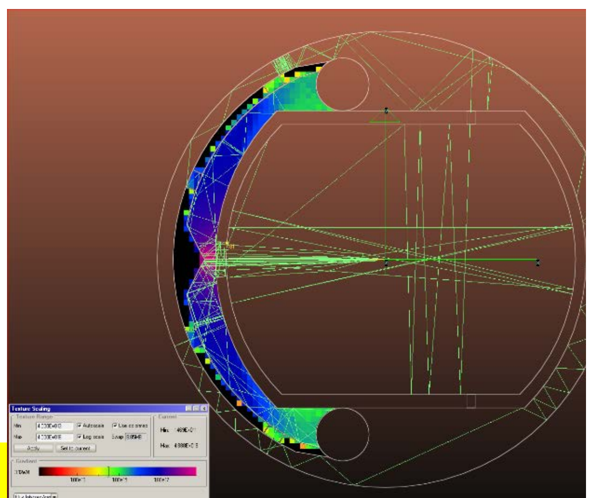
→ **5 MW total in arcs** (LHC <0.2W/m)

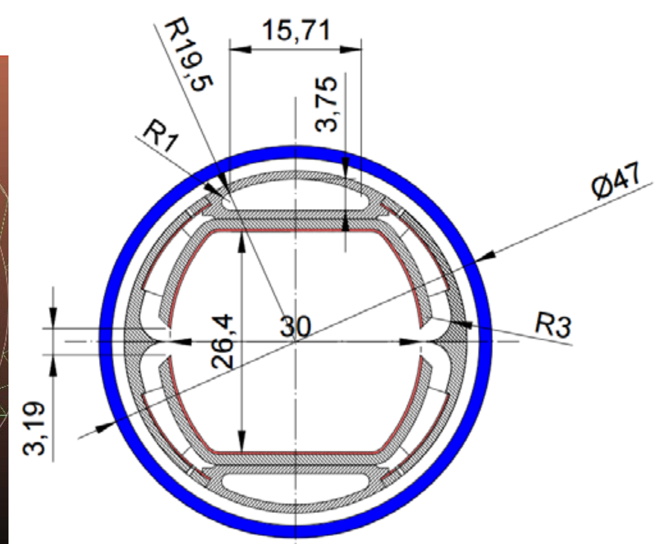
LHC beam screen

New type of ante-chamber

- absorption of synchrotron radiation
- avoids photo-electrons, helps vacuum







R. Kersevan, C. Garion, L. Tavian, et al.

FCC-hh luminosity goals & phases

- **Two parameter sets for two operation phases:**

  - **Phase 1 (baseline): 5 x 10^{34} $cm^{-2}s^{-1}$ (peak),**
    250 fb^{-1}/year (averaged)
    2500 fb^{-1} within 10 years (~HL LHC total luminosity)

  - **Phase 2 (ultimate): ~2.5 x 10^{35} $cm^{-2}s^{-1}$ (peak),**
    1000 fb^{-1}/year (averaged)
    ➔ 15,000 fb^{-1} within 15 years

  - **Yielding total luminosity O(20,000) fb^{-1}**
    over ~25 years of operation

Luminosity goals for a 100-TeV pp collider

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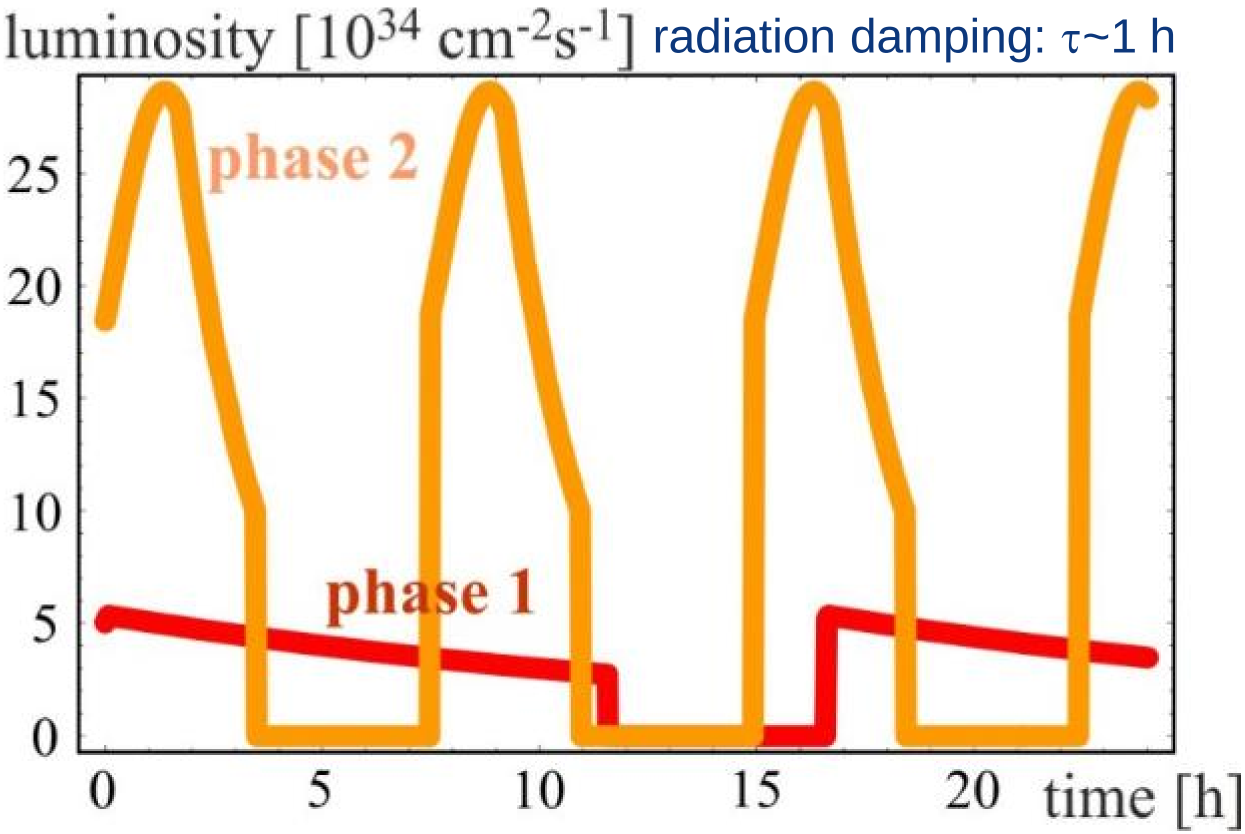
April 24, 2015

Abstract

We consider diverse examples of science goals that provide a framework to assess luminosity goals for a future 100-TeV proton-proton collider.

20 ab^{-1} OK for physics

Luminosity evolution



for both phases:

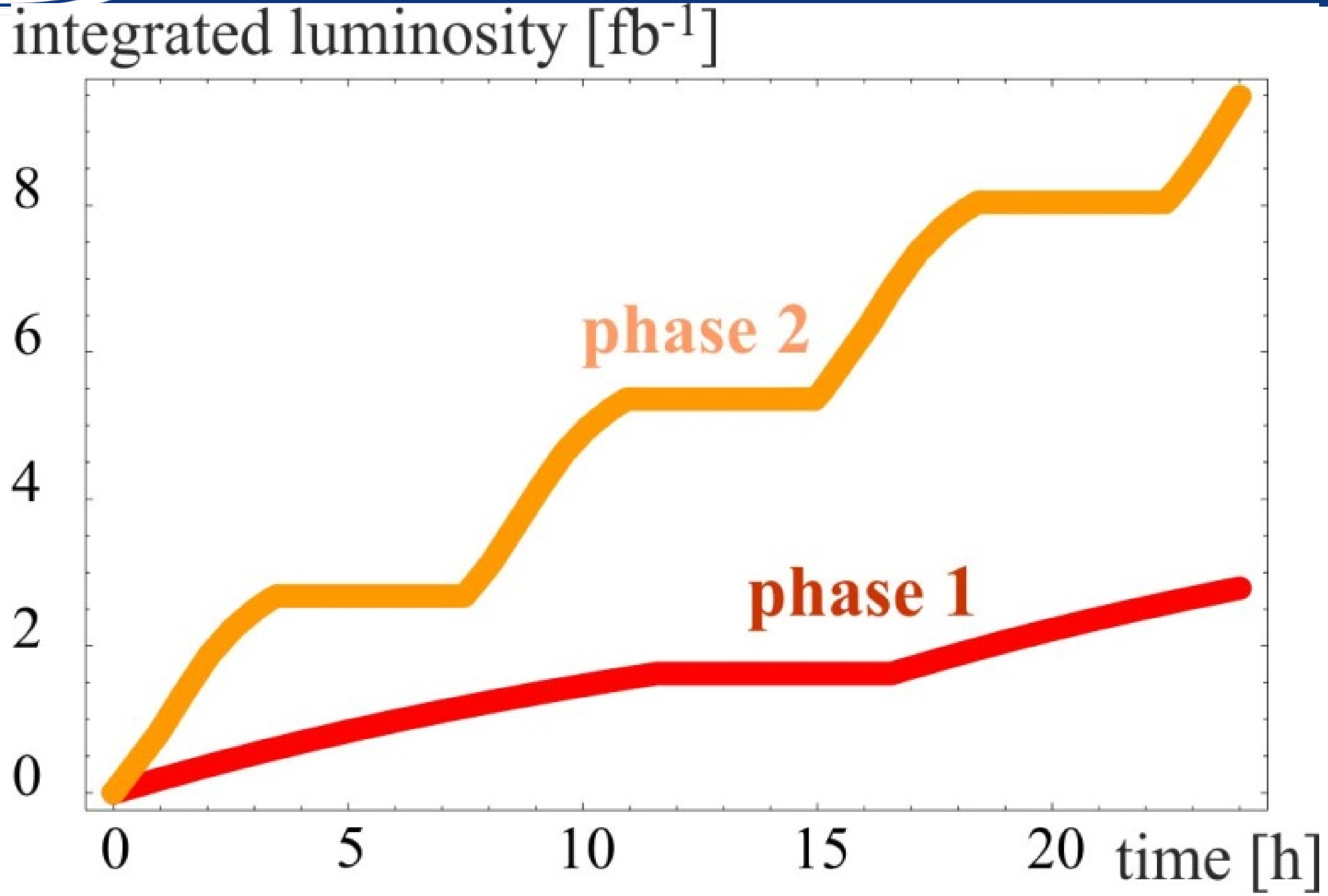
beam current 0.5 A unchanged!

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



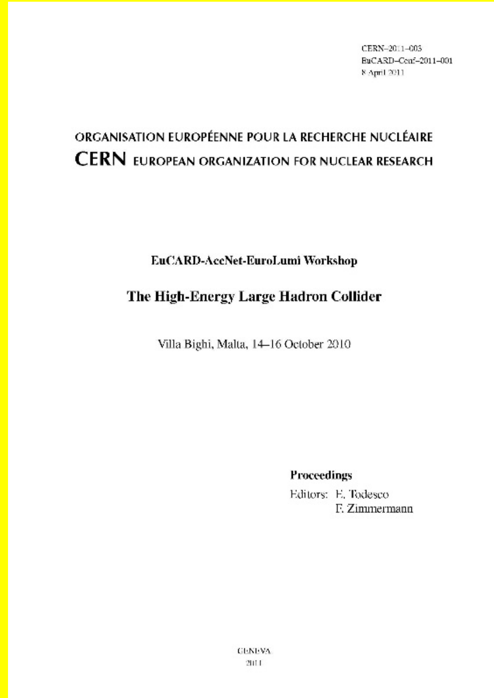
phase 1: β^*=1.1 m, ΔQ_{tot}=0.01, t_{ta}=5 h

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

High-Energy LHC

FCC study continues effort on **high-field collider in LHC tunnel**

2010 EuCARD Workshop Malta;
Yellow Report CERN-2011-1



CERN–2011–003
EuCARD–Conf–2011–001
8 April 2011

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

EuCARD-AccNet-EuroLumi Workshop

The High-Energy Large Hadron Collider

Villa Bighi, Malta, 14–16 October 2010

Proceedings
Editors: E. Todesco
F. Zimmermann

GENEVA
2011

EuCARD-AccNet-EuroLumi Workshop: The High-Energy Large Hadron Collider - HE-LHC10, E. Todesco and F. Zimmermann (eds.), EuCARD-CON-2011-001; arXiv:1111.7188; CERN-2011-003 (2011)

- based on 16-T dipoles developed for FCC-hh
- extrapolation of other parts from the present (HL-)LHC and from FCC developments

LEP – highest energy e^+e^- collider so far

circumference 27 km
in operation from 1989 to 2000
maximum c.m. energy 209 GeV
maximum synchrotron radiation power 23 MW

Lepton collider physics areas

- highest possible luminosities at all working points
- *beam energy range from 35 GeV to ≈200 GeV*
- **physics programs / energies:**

  Z (45.5 GeV) Z pole, 'TeraZ' and high precision M_Z & Γ_Z

  W (80 GeV) W pair production threshold, high precision M_W

  H (120 GeV) ZH production (maximum rate of H's)

  t (175 GeV): $t\bar{t}$ threshold, H studies
- some polarization up to ≥80 GeV for beam energy calibration
- machine optimized for operation at 120 GeV?! (2nd priority "*Tera-Z*")

A. Blondel, P. Janot, et al.

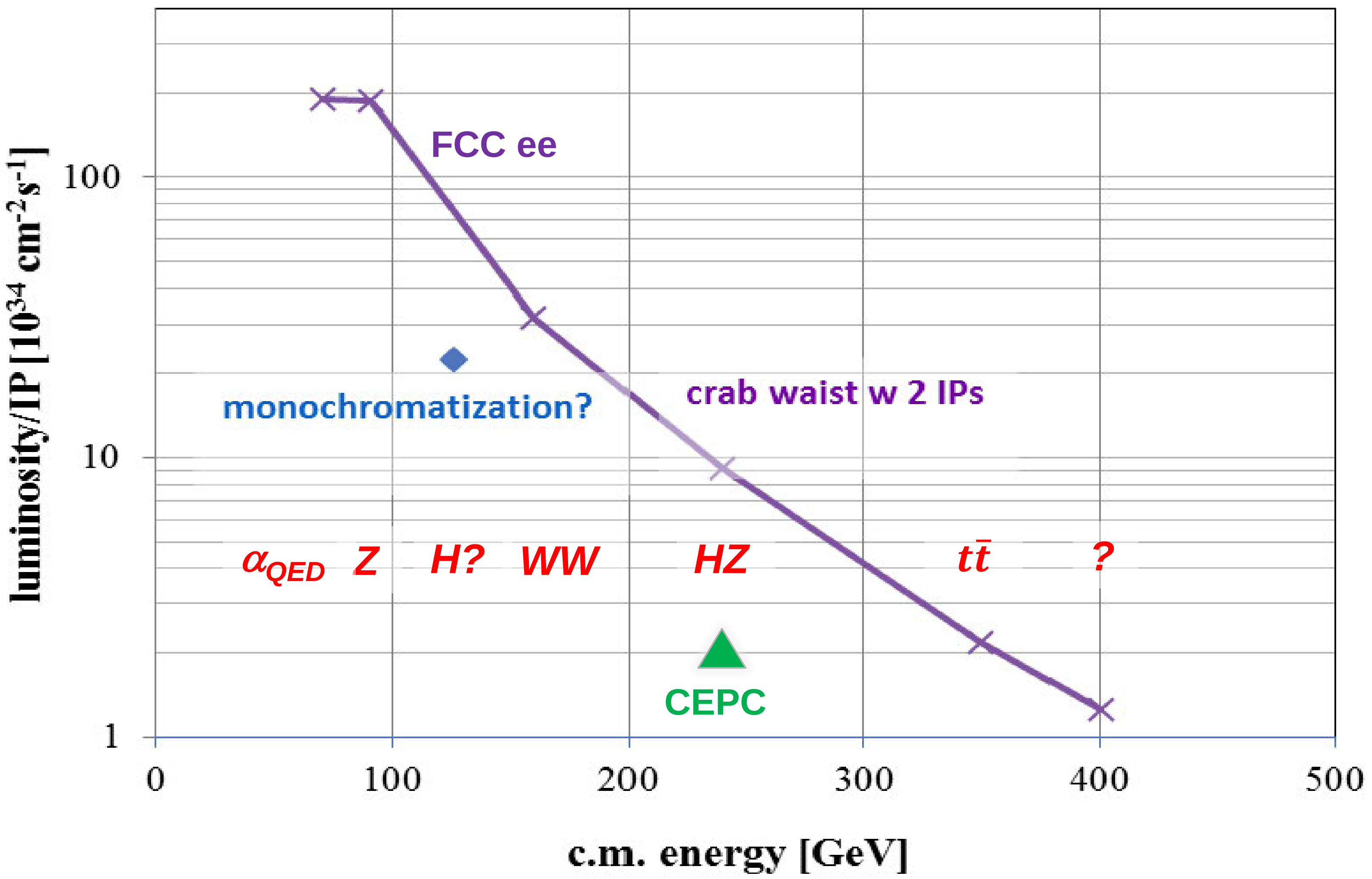
Lepton collider key parameters

parameter	FCC-ee			CEPC	LEP2
energy/beam [GeV]	**45**	**120**	**175**	**120**	105
bunches/beam	13000-60000	500-1400	51- 98	50	4
beam current [mA]	1450	30	6.6	16.6	3
luminosity/IP x 10^{34} $cm^{-2}s^{-1}$	**21 - 280**	**5 - 11**	**1.5 - 2.6**	**2.0**	0.0012
energy loss/turn [GeV]	0.03	1.67	7.55	3.1	3.34
synchrotron power [MW]	100			103	22
RF voltage [GV]	0.2-2.5	3.6-5.5	11	6.9	3.5

FCC-ee: 2 separate rings **CEPC baseline: single beam pipe like LEP**

Dependency FCC-ee: crab-waist vs. baseline optics and 2 vs. 4 IPs

e^+e^- luminosity vs. c.m. energy



FCC-ee SC RF system

RF system requirements are characterized by two regimes:

- *high gradients* ***for H and $t\bar{t}$ – up to ≈11 GV***
- *high beam loading* ***with currents of ≈1.5 A at the Z pole***

LHC cavities (400 MHz)

Main RF frequency of 400 MHz

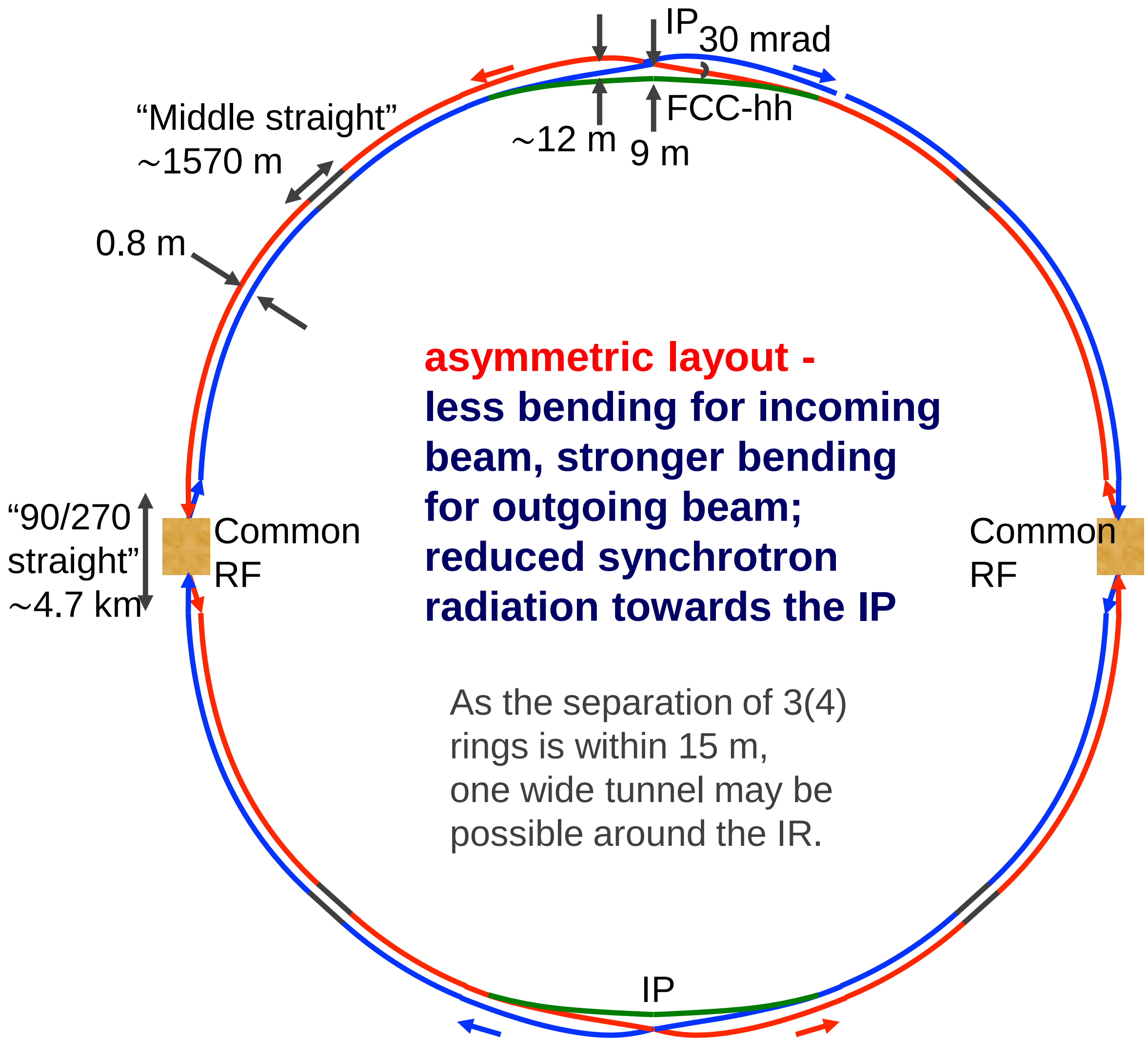
(as for FCC-hh and LHC)

conversion efficiency (wall plug to RF power) is important for power consumption - aiming for 75% or higher → R&D !

- ***important item for FCC-ee power budget, ≈65% achieved for LEP2***
- ***recent breakthrough in klystron efficiency (I. Syratchev)***

FCC-ee preliminary layout

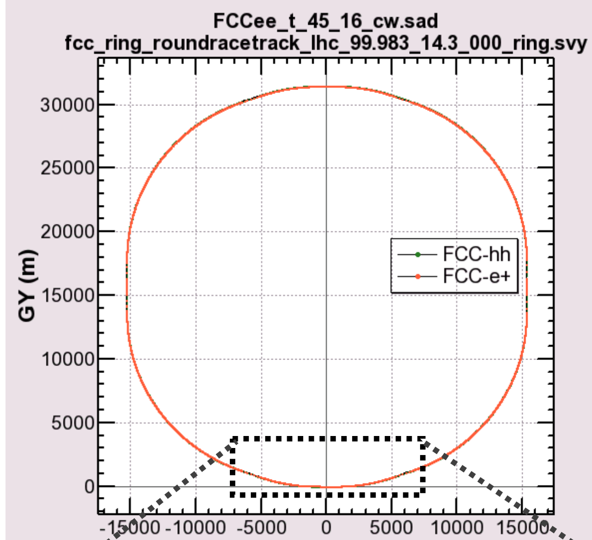
Based on, and compatible with, FCC-hh layout (in green)

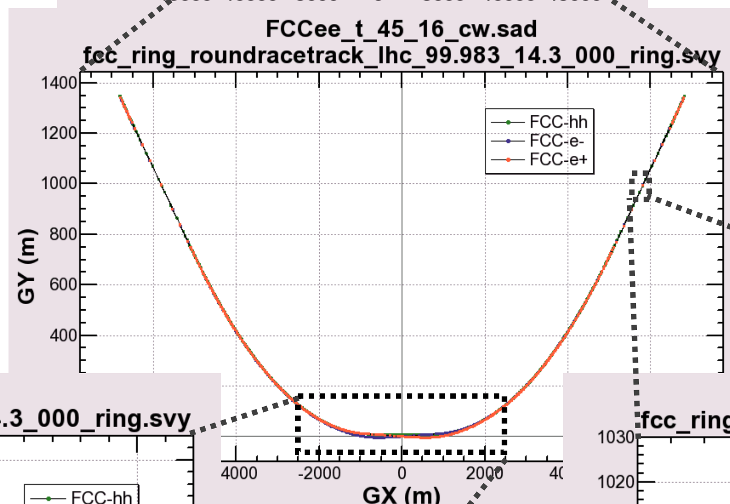


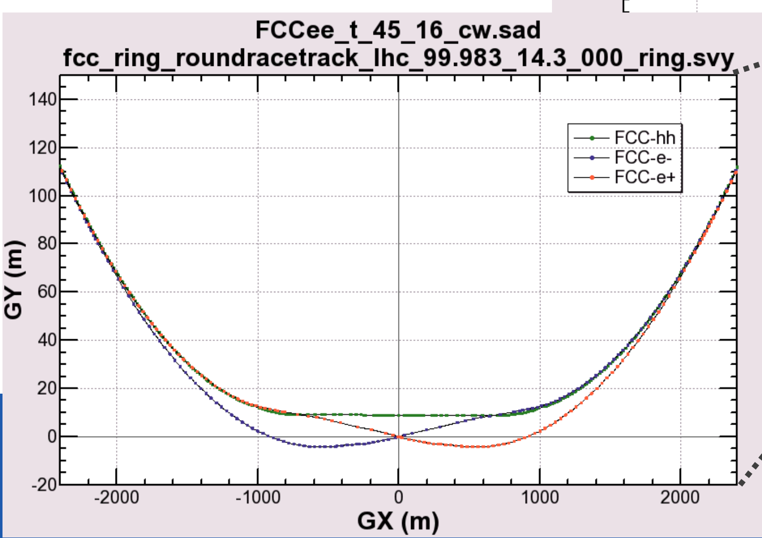
asymmetric layout -
less bending for incoming beam, stronger bending for outgoing beam; reduced synchrotron radiation towards the IP

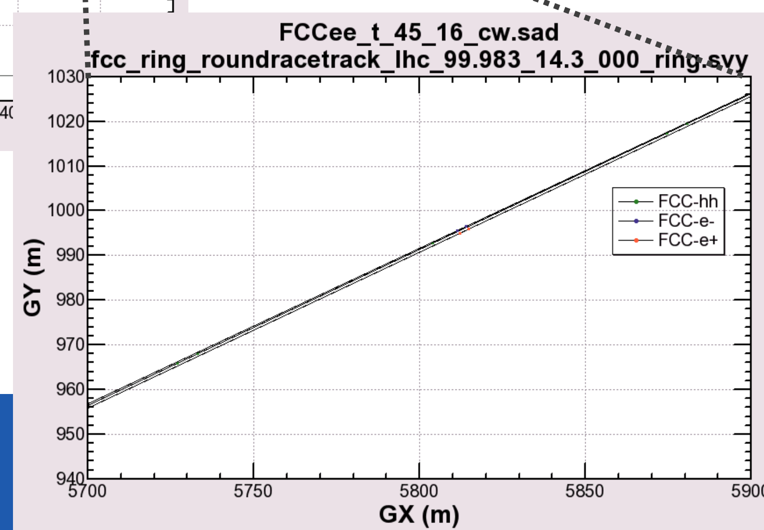
As the separation of 3(4) rings is within 15 m, one wide tunnel may be possible around the IR.

A conceptual layout of FCC-ee



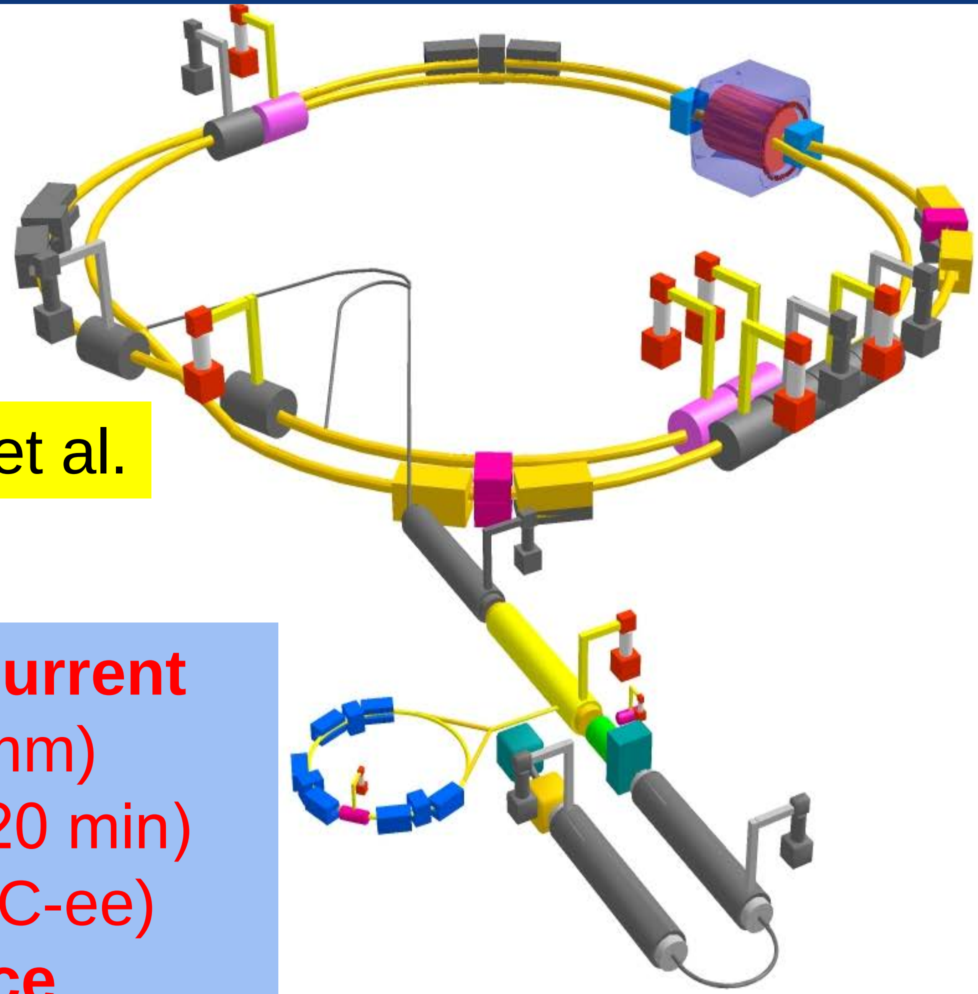






SuperKEKB as demonstrator

beam commissioning will start in 2015



K. Oide et al.

top up injection at high current
β_y^* =300 μm (FCC-ee: 1 mm)
lifetime 5 min (FCC-ee: ≥20 min)
$\varepsilon_y/\varepsilon_x$ =0.25% (similar to FCC-ee)
off momentum acceptance
(±1.5%, similar to FCC-ee)
e^+ production rate (2.5x10^{12}/s,
FCC-ee: <1.5x10^{12}/s (*Z* crab

SuperKEKB goes beyond *FCC-ee*, testing

FCC International Collaboration

- 61 institutes
- 23 countries + EC

Status: 14 September 2015

FCC Collaboration Status

61 collaboration members & CERN as host institute, September 2015

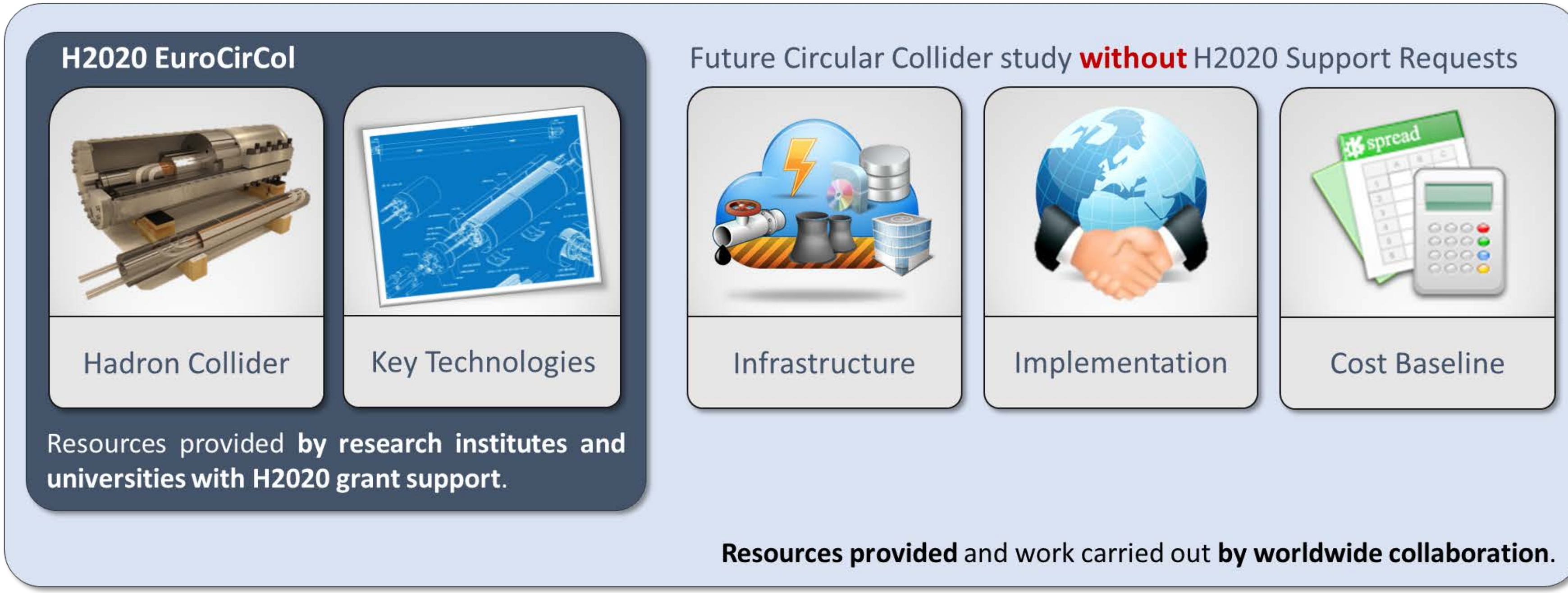
ALBA/CELLS, Spain
Ankara U., Turkey
U Belgrade, Serbia
U Bern, Switzerland
BINP, Russia
CASE (SUNY/BNL), USA
CBPF, Brazil
CEA Grenoble, France
CEA Saclay, France
CIEMAT, Spain
CNRS, France
Cockcroft Institute, UK
U Colima, Mexico
CSIC/IFIC, Spain
TU Darmstadt, Germany
TU Delft, Netherlands
DESY, Germany
TU Dresden, Germany
Duke U, USA
EPFL, Switzerland
GWNU, Korea

U Geneva, Switzerland
Goethe U Frankfurt, Germany
GSI, Germany
Hellenic Open U, Greece
HEPHY, Austria
U Houston, USA
IIT Kanpur, India
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
FZ Jülich, Germany
KAIST, Korea
KEK, Japan
KIAS, Korea

King's College London, UK
KIT Karlsruhe, Germany
Korea U Sejong, Korea
MEPhI, Russia
MIT, USA
NBI, Denmark
Northern Illinois U., USA
NC PHEP Minsk, Belarus
U. Liverpool, UK
U Oxford, UK
PSI, Switzerland
U. Rostock, Germany
Sapienza/Roma, Italy
UC Santa Barbara, USA
U Silesia, Poland
TU Tampere, Finland
TOBB, Turkey
U Twente, Netherlands
TU Vienna, Austria
Wroclaw UT, Poland

EuroCirCol EU Horizon 2020 Grant

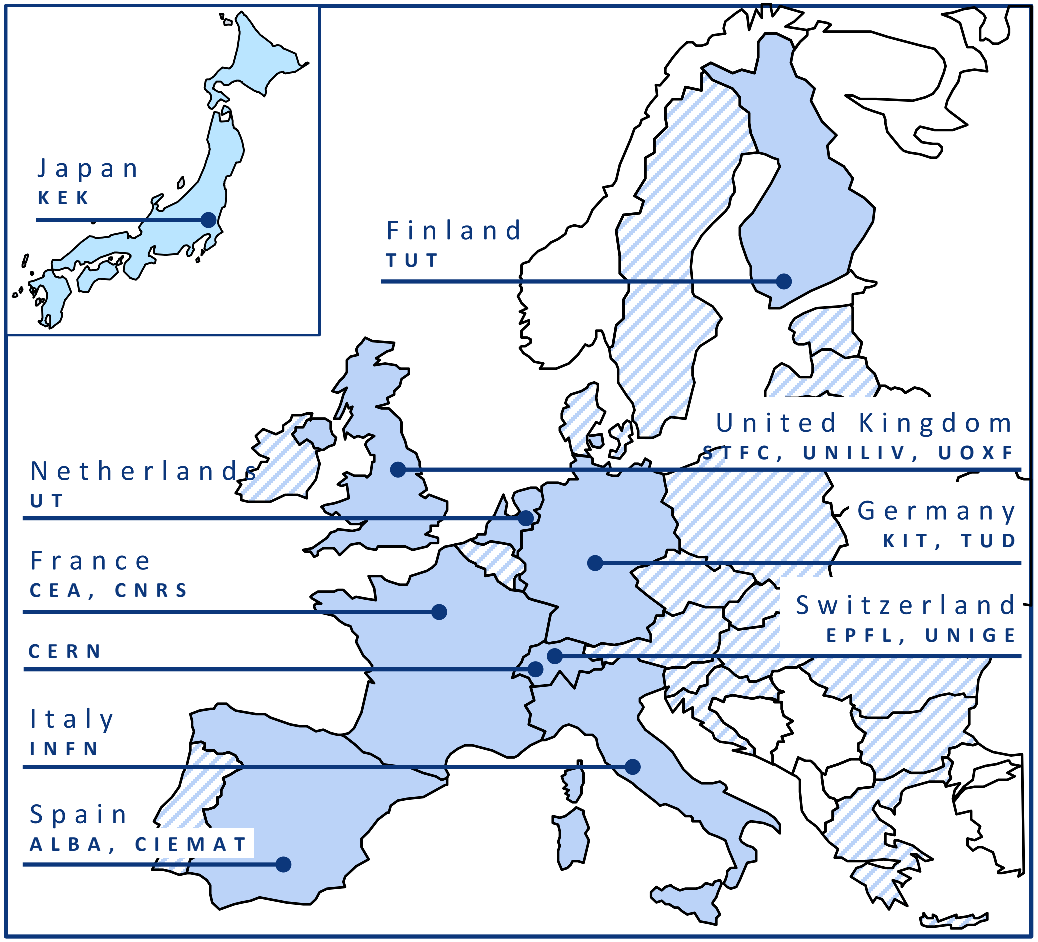
EC contributes with funding to FCC-hh study



- Core aspects of hadron collider design: arc & IR optics design, 16 T magnet program, cryogenic beam vacuum system
- **Recognition of FCC Study by European Commission.**

EuroCirCol Consortium + Associates

CERN	IEIO
TUT	Finland
CEA	France
CNRS	France
KIT	Germany
TUD	Germany
INFN	Italy
UT	Netherlands
ALBA	Spain
CIEMAT	Spain
STFC	United Kingdom
UNILIV	United Kingdom
UOXF	United Kingdom
KEK	Japan
EPFL	Switzerland
UNIGE	Switzerland
NHFML-FSU	USA
BNL	USA
FNAL	USA
LBNL	USA



Consortium Beneficiaries, signing the Grant Agreement

Conclusions

- High energy circular colliders are a powerful option for future accelerator-based HEP!
- We now need to urgently prepare for post-LHC period, and there are strongly rising activities worldwide.
- The design of high energy circular colliders presents many challenging R&D requirements in SC magnets, beam handling, SRF and several other technical areas.
- Global collaboration in physics, experiments and accelerators and the use of all synergies is essential to move forward.

FCC Week 2016

Rome, 11-15 April 2016

SAPIENZA UNIVERSITÀ DI ROMA

INFN Istituto Nazionale di Fisica Nucleare
Sezione di Roma

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