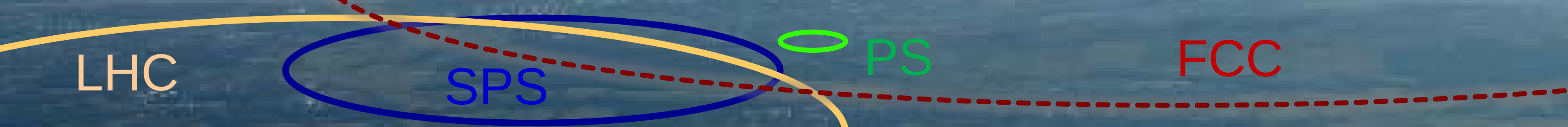
Future Circular Colliders

Michael Benedikt, Frank Zimmermann

gratefully acknowledging input from FCC coordination group, global design study team and all international contributors



The University of Tokyo, 23 May 2016

http://cern.ch/fcc

*Work supported by the **European Commission** under the HORIZON 2020 project EuroCirCol, grant agreement 654305*

Outline

- Motivation for Future Circular Colliders
- FCC Study Scope & Time Line
- Machine Design, Physics, Detectors
- Technologies
- FCC Organisation & Collaboration

FCC 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….coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures,…."

- **U.S. strategy and 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…."

- **ICFA statement 2014:**

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

FCC 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

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}

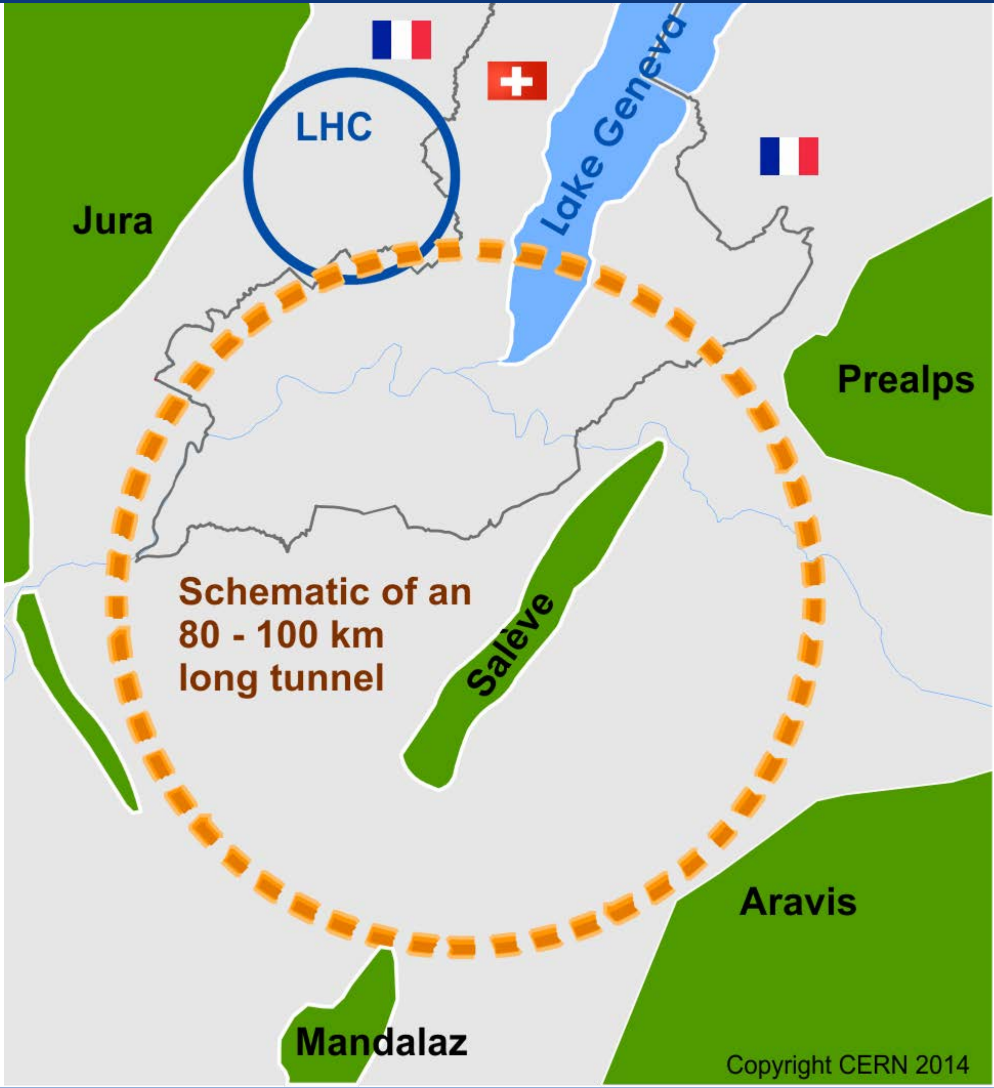
Future Circular Collider Study
GOAL: CDR and cost review for the next ESU (2018)

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

- ***pp*-collider *O(100) TeV* (*FCC-hh*)** → main emphasis, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

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



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

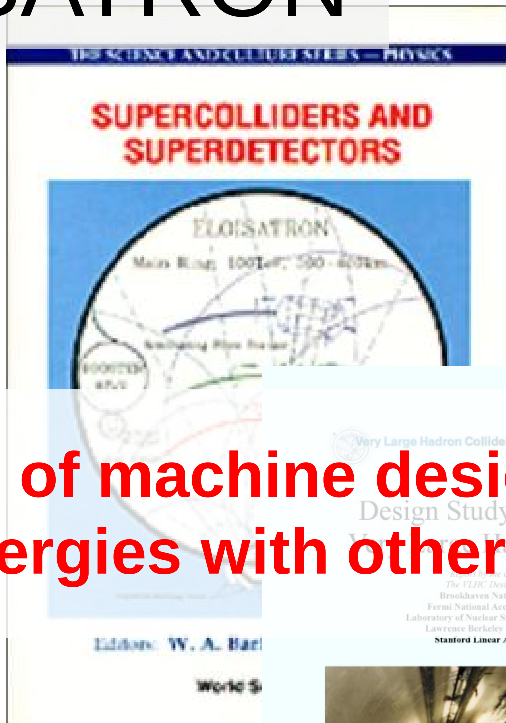
Yifang Wang

"Chinese Toscana"

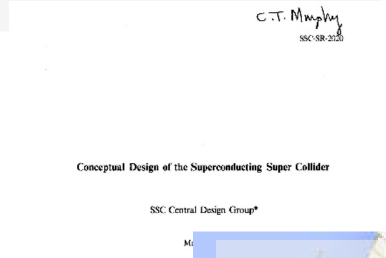
Previous studies in Italy (ELOISATRON 300km), USA (SSC 87km, VLHC 233km), Japan (TRISTAN-II 94km)

ex. ELOISATRON

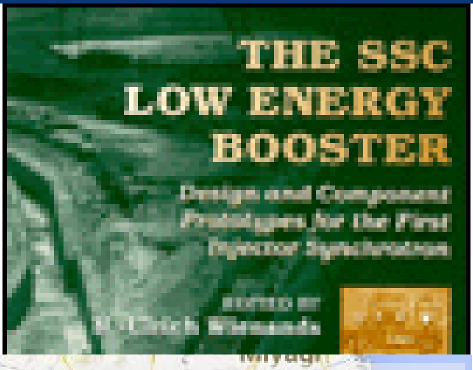
Supercolliders Superdetectors: Proceedings of the 19th and 25th Workshops of the INFN Eloisatron Project



ex. SSC



SSC C



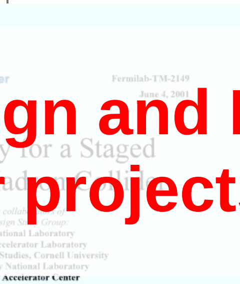
ex. TRISTAN II

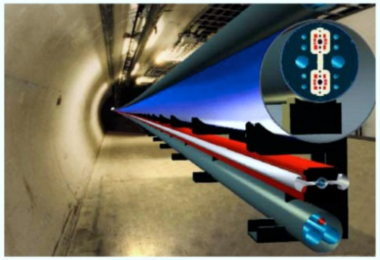
F. Takasaki

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



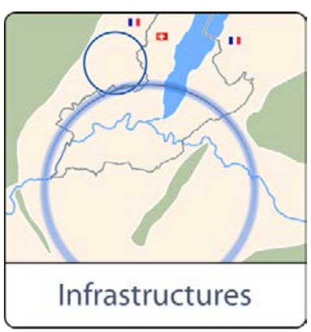


http://www.vlhc.org/

FCC Scope: Accelerator and Infrastructure

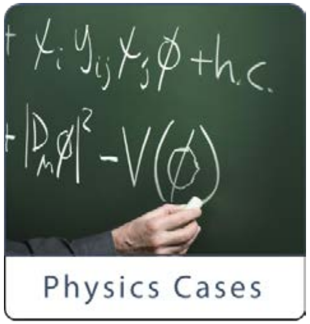
FCC-hh: **100 TeV pp collider as long-term goal**
→ defines infrastructure needs
FCC-ee: **e^+e^- collider**, potential intermediate step
HE-LHC: **based on FCC-hh technology**

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

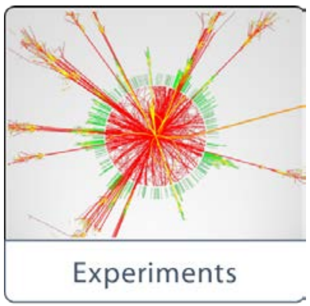


tunnel infrastructure in Geneva area, linked to CERN accelerator complex;
site-specific, as requested by European strategy

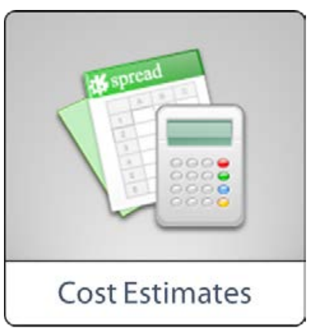
FCC Scope: Physics & Experiments



physics opportunities
discovery potentials

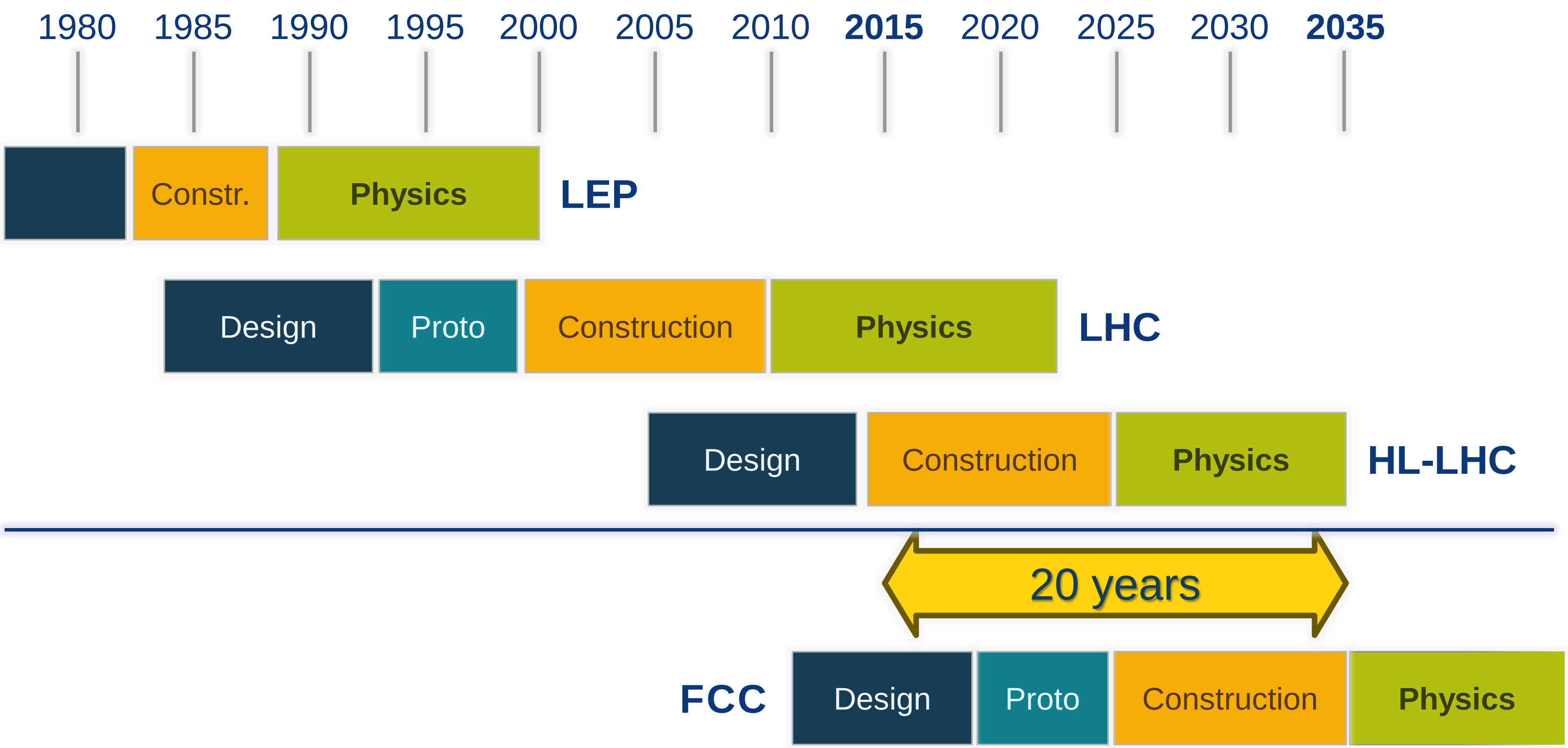


experiment concepts for hh, ee and he
machine Detector Interface studies
concepts for **worldwide data services**



overall cost model ;
cost scenarios for collider options
including infrastructure and injectors ;
implementation and governance models

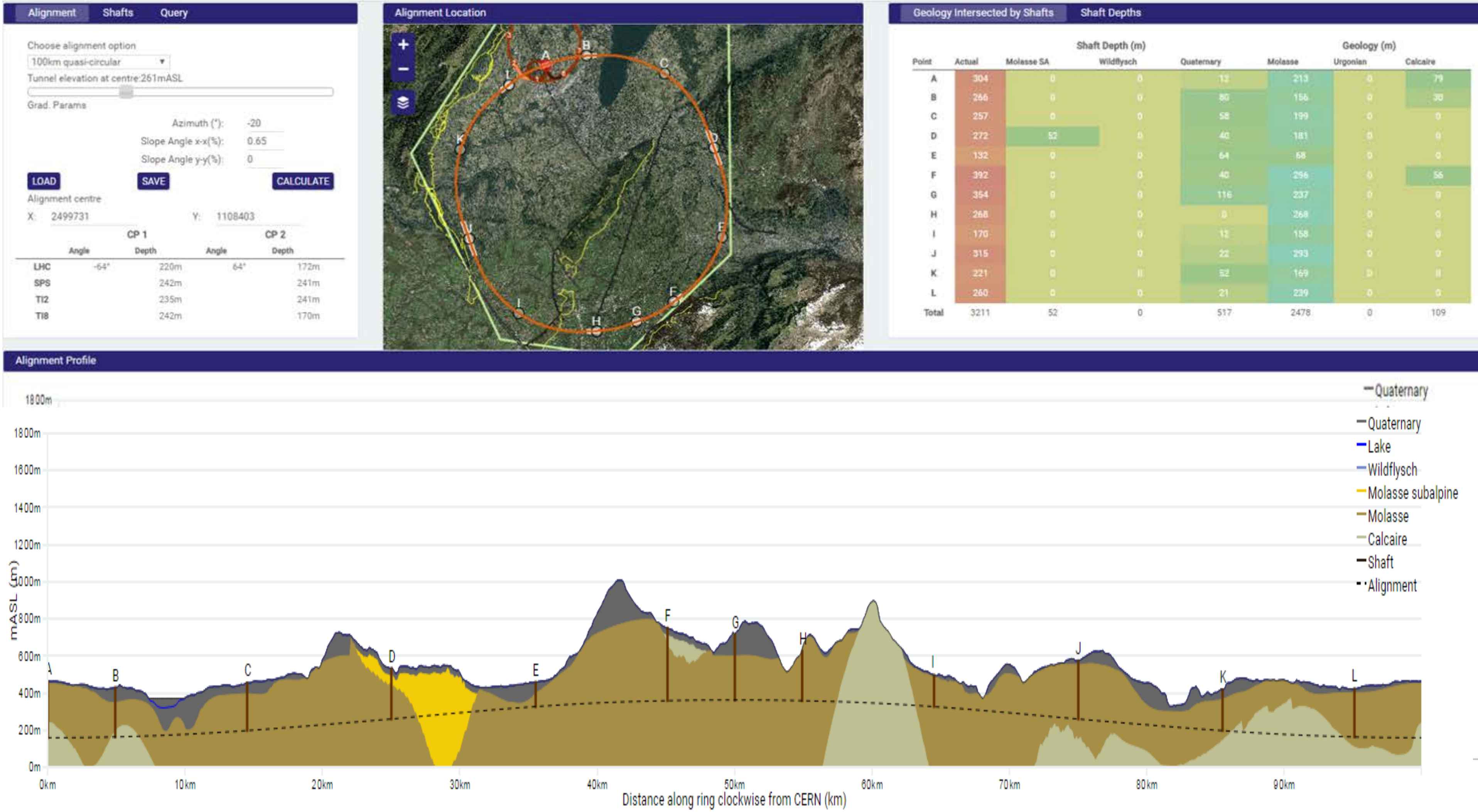
CERN Circular Colliders and FCC



Now is the right time to plan for the period 2035 – 2040

Goal of phase 1: CDR by end 2018 for next update of European Strategy

Progress on site investigations



	Shaft Depth (m)				Geology (m)		
Point	Actual	Molasse SA	Wildflysch	Quaternary	Molasse	Urgonian	Calcaire
A	304	0	0	12	213	0	79
B	266	0	0	80	156	0	30
C	257	0	0	58	199	0	0
D	272	52	0	40	181	0	0
E	132	0	0	64	68	0	0
F	392	0	0	40	296	0	56
G	354	0	0	116	237	0	0
H	268	0	0	0	268	0	0
I	170	0	0	12	158	0	0
J	315	0	0	22	293	0	0
K	221	0	0	52	169	0	0
L	260	0	0	21	239	0	0
Total	3211	52	0	517	2478	0	109

Progress on site investigations

Alignment | Shafts | Query

Choose alignment option: 100km quasi-circular

Tunnel elevation at centre:261mASL

Grad. Params

Azimuth (°): -20

Slope Angle x-x(%): 0.65

Slope Angle y-y(%): 0

LOAD | SAVE | CALCULATE

Alignment centre

X: 2499731 Y: 1108403

	CP 1		CP 2	
	Angle	Depth	Angle	Depth
LHC	-64°	220m	64°	172m
SPS		242m		241m
TI2		235m		241m
TI8		242m		170m

Alignment Location

Geology Intersected by Shafts | Shaft Depths

	Shaft Depth (m)	Geology (m)					
Point	Actual	Molasse SA	Wildflysch	Quaternary	Molasse	Urgonian	Calcaire
A	304	0	0	12	213	0	79
B	266	0	0	80	156	0	30
C	257	0	0	58	199	0	0
D	272	52	0	40	181	0	0
E	132	0	0	64	68	0	0
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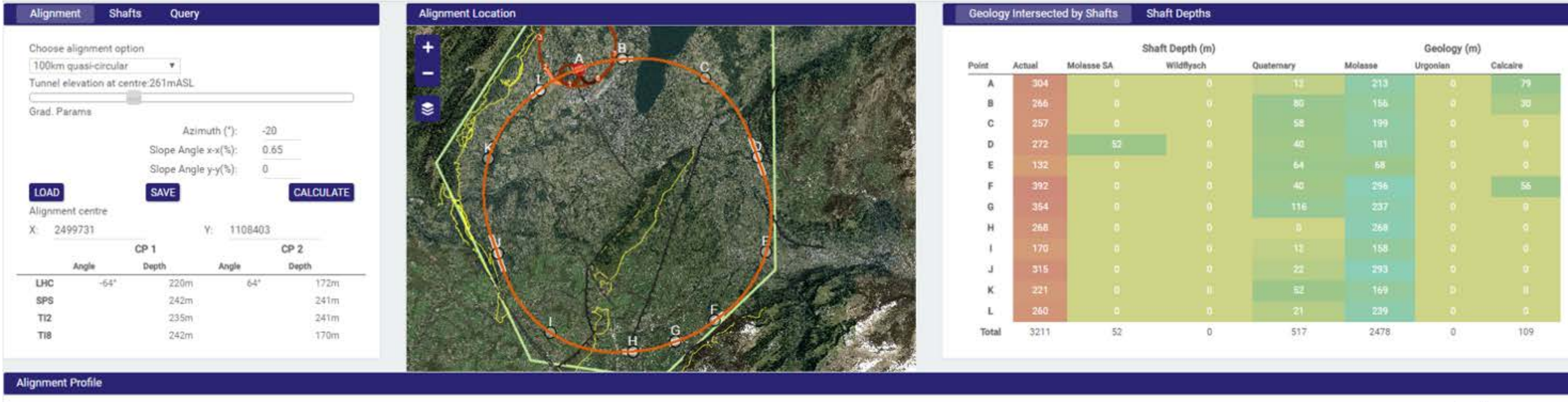
L	260	0	0	21	239	0	0
Total	3211	52	0	517	2478	0	109

Alignment Profile

- 90 – 100 km fits geological situation well
- LHC suitable as potential injector
- The 100 km version, intersecting LHC, is now being studied in more detail

Progress on site investigations



Point	Shaft Depth (m) Actual	Molasse SA	Wildflysch	Quaternary	Geology (m) Molasse	Urgonian	Calcaire
A	304	0	0	12	213	0	79
B	266	0	0	80	156	0	30
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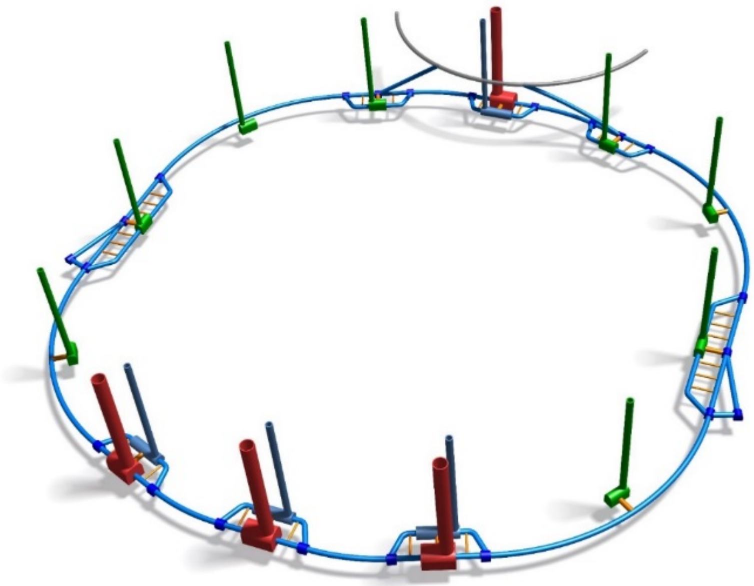
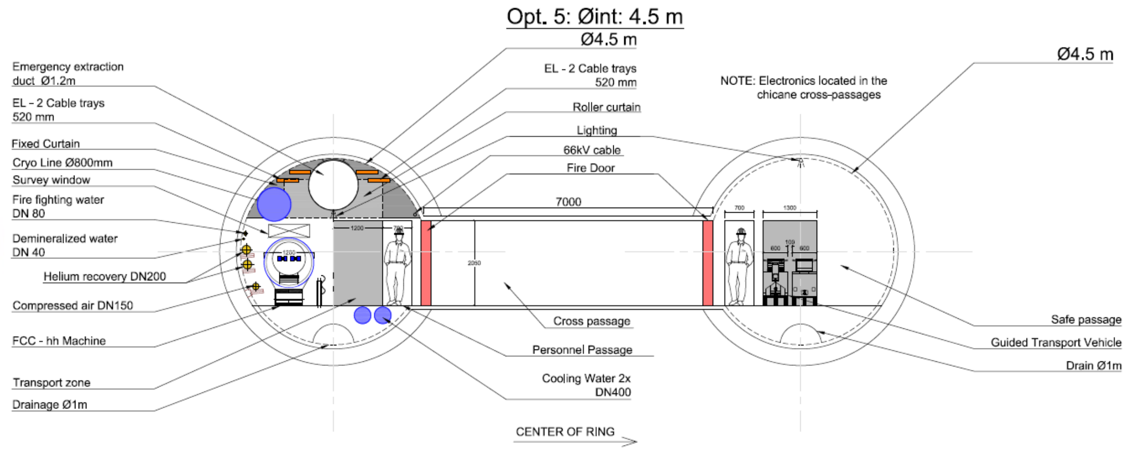
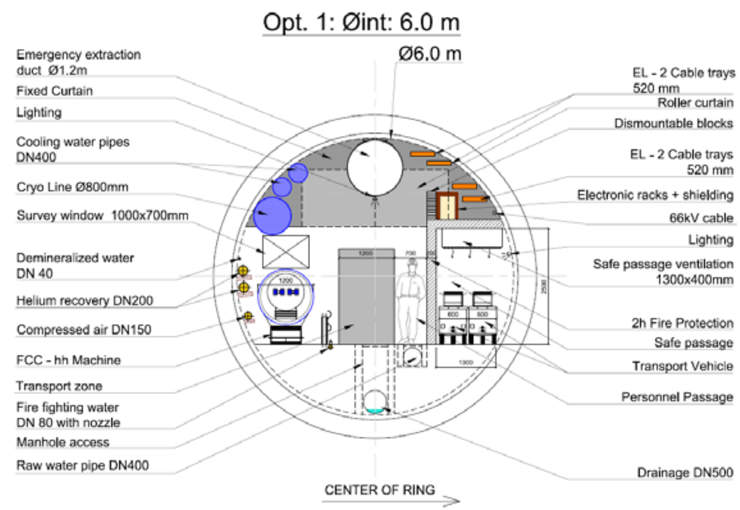
I	170	0	0	12	158	0	0
J	315	0	0	22	293	0	0
K	221	0	0	52	169	0	0
L	260	0	0	21	239	0	0
Total	3211	52	0	517	2478	0	109

- Tunnel optimization tool developed by FCC with industry.
- Now also used for ILC site studies.
- Excellent example for synergy between the projects.

Further CE and TI optimisation







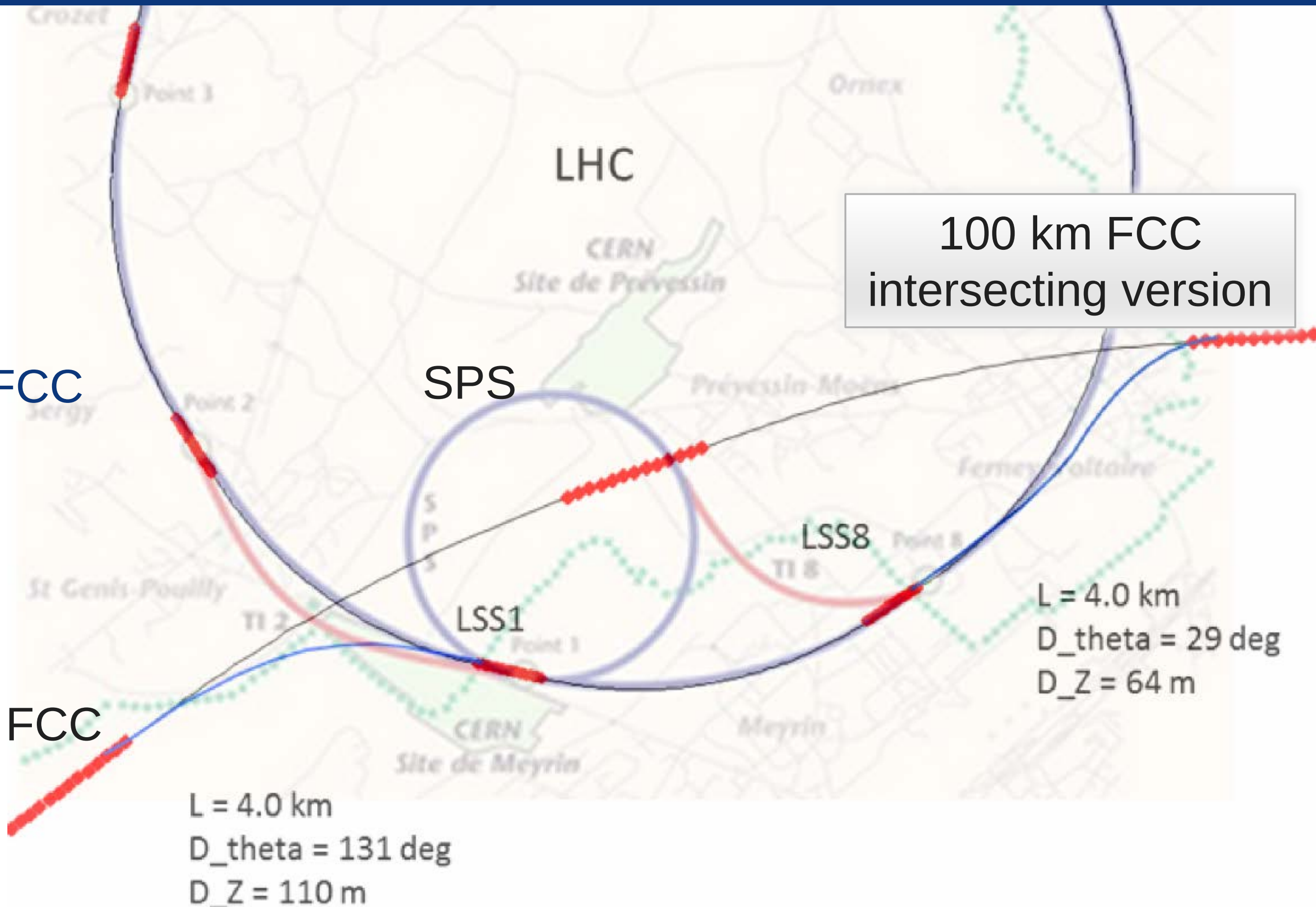
More detailed studies launched on

- CE: single vs. double tunnels
- CE: caverns, shafts, underground layout
- technical infrastructures
- safety, access
- transport, integration, installation
- operation aspects

FCC-hh injector studies

Injector options:

- **SPS → LHC → FCC**
- SPS/$SPS_{upgrade}$ → FCC
- SPS -> FCC booster → FCC



Current baseline is to fully re-use the existing CERN accelerator complex

- **injection energy 3.3 TeV from LHC**

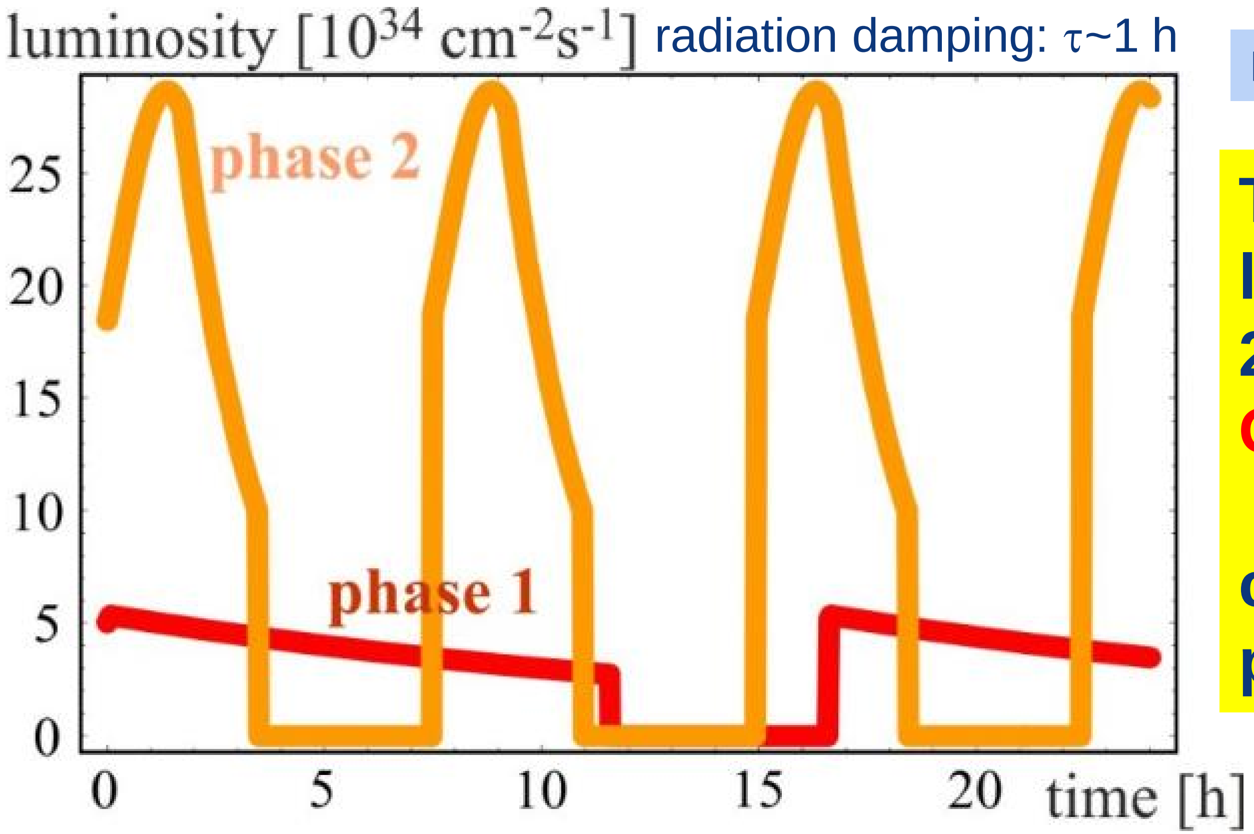
Hadron collider parameters

parameter	FCC-hh		HE-LHC* *tentative	(HL) LHC
collision energy cms [TeV]	100		>25	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
# IP	2 main & 2		2 & 2	2 & 2
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25	25
beta* [m]	1.1	0.3	0.25	(0.15) 0.55
luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	5	20 - 30	>25	(5) 1
events/bunch crossing	170	<1020 (204)	850	(135) 27
stored energy/beam [GJ]	8.4		1.2	(0.7) 0.36
synchrotron rad. [W/m/beam]	30		3.6	(0.35) 0.18

FCC-hh luminosity phases

phase 1: β^*=1.1 m, ΔQ_{tot}=0.01, t_{ta}=5 h, 250 fb^{-1} / year

phase 2: β^*=0.3 m, ΔQ_{tot}=0.03, t_{ta}=4 h, 1 ab^{-1} / year



PRST-AB 18, 101002 (2015)

Total integrated luminosity over 25 years operation O(20) ab^{-1}

consistent with physics goals

Physics prospects

Physics at the FCC-hh

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider

- **Volume 1: SM processes** (238 pages)
- **Volume 2: Higgs and EW symmetry breaking studies** (175 pages)
- **Volume 3: beyond the Standard Model phenomena** (189 pages)
- **Volume 4: physics with heavy ions** (56 pages)
- **Volume 5: physics opportunities with the FCC-hh injectors** (14 pages)

Higgs & EWSB physics at 100 TeV

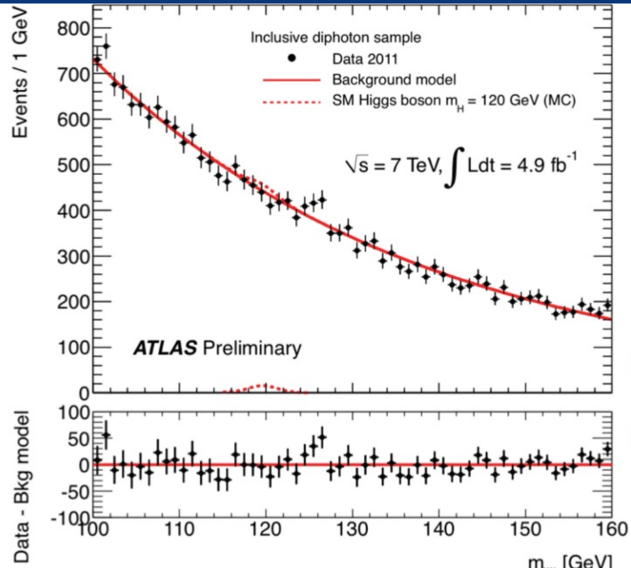
Contino, Lee, Michelangelo, Reuter

	N_{100}	N_{100}/N_8	N_{100}/N_{14}
$gg \to H$	16×10^9	4×10^4	110
VBF	1.6×10^9	5×10^4	120
WH	3.2×10^8	2×10^4	65
ZH	2.2×10^8	3×10^4	85
$t\bar{t}H$	7.6×10^8	3×10^5	420

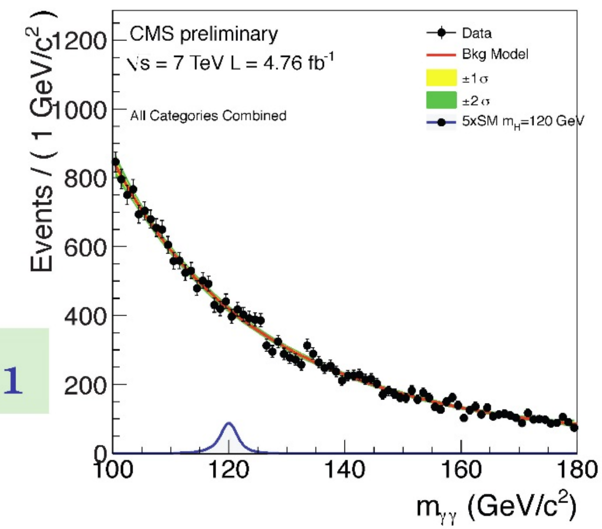
huge production rates at 100 TeV imply:

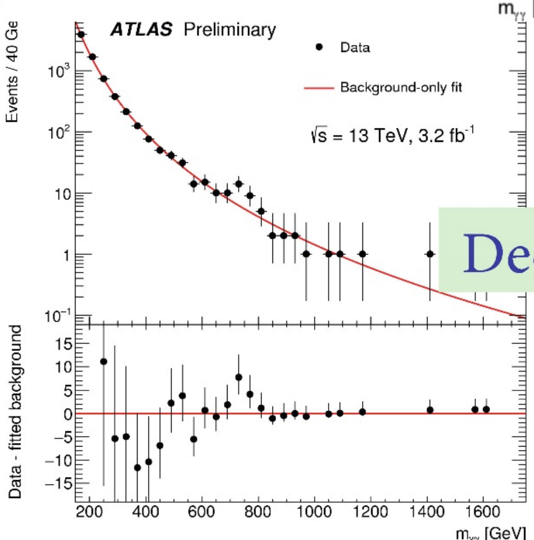
- can afford reducing statistics, with tighter kinematical cuts that reduce backgrounds and systematics
- explore new dynamical regimes, with novel tests of the SM and EWSB

LHC results: need for higher energy

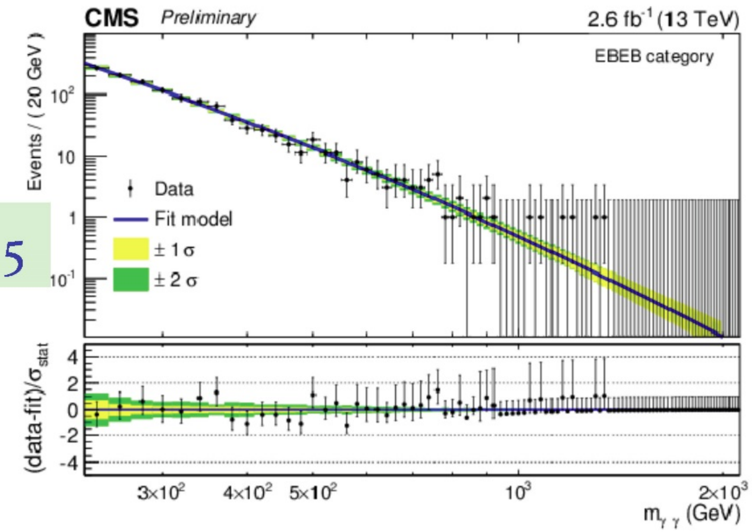


Dec 2011



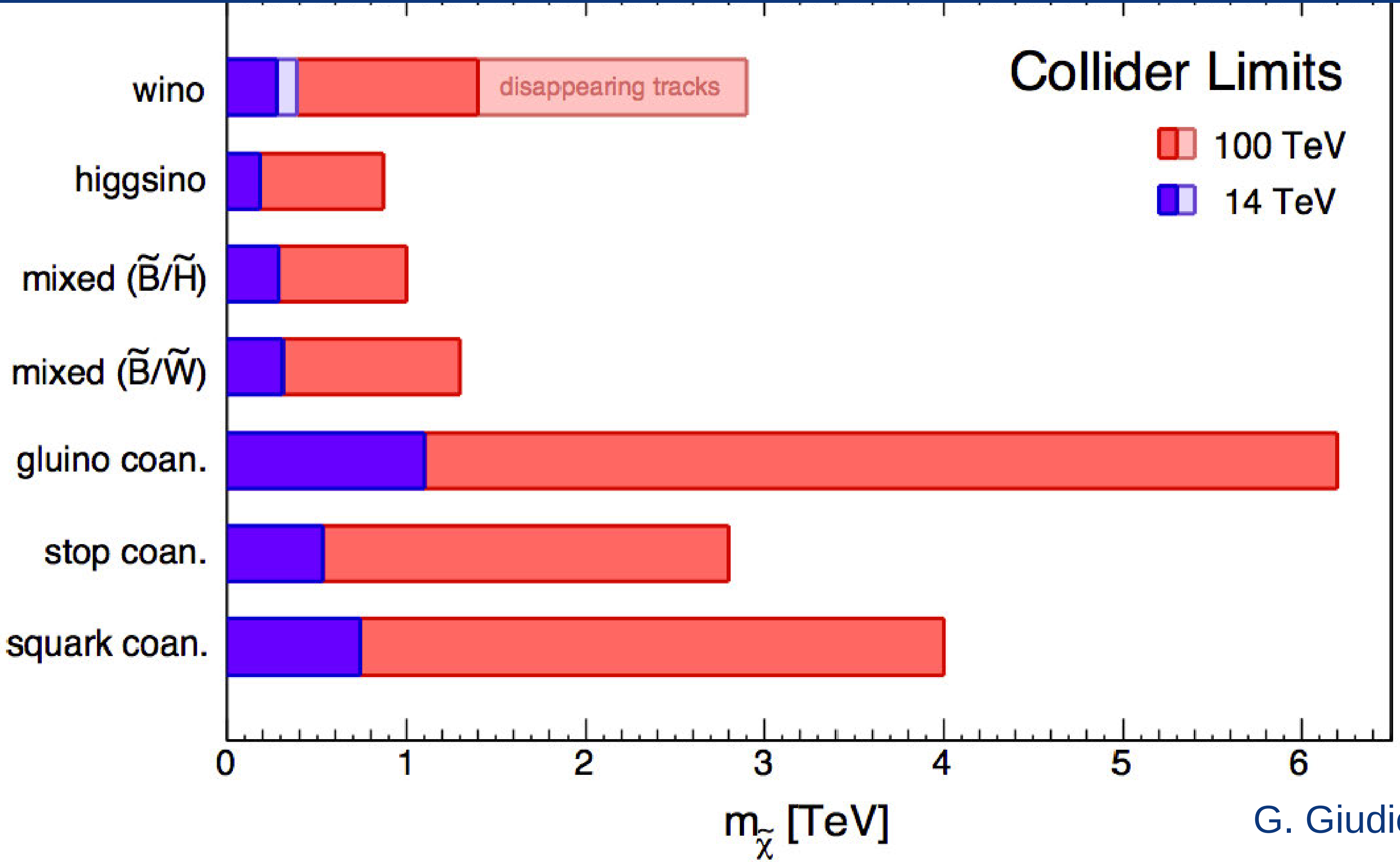


Dec 2015



G. Giudice

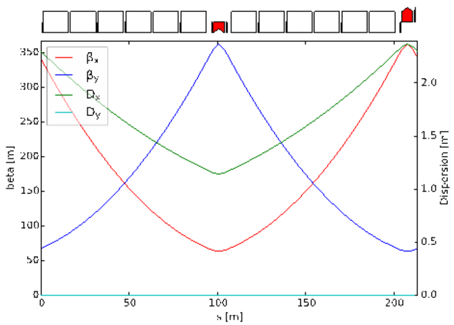
FCC-hh physics perspectives



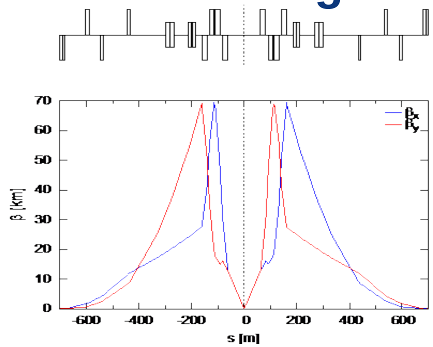
G. Giudice

FCC-hh full-ring optics design

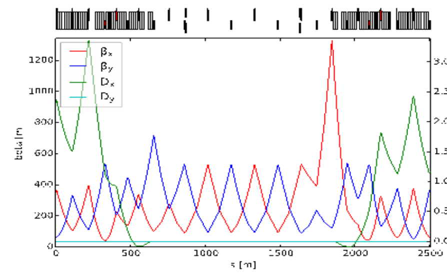
Regular arc cell



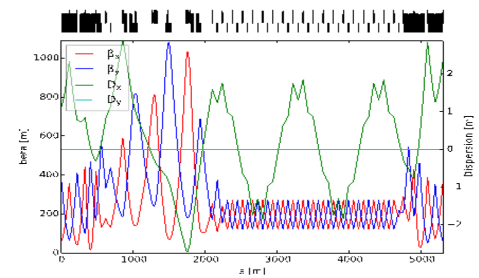
Interaction region

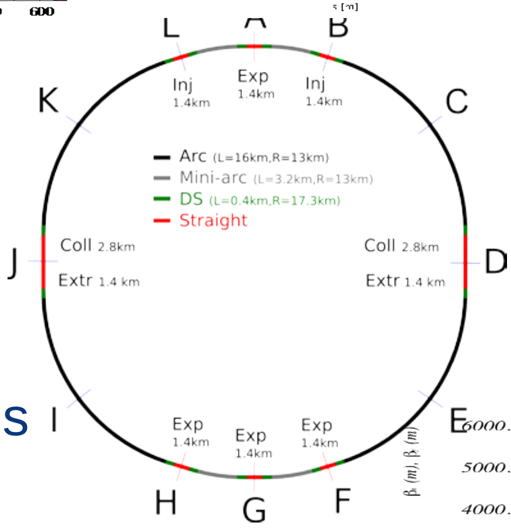


Injection with RF

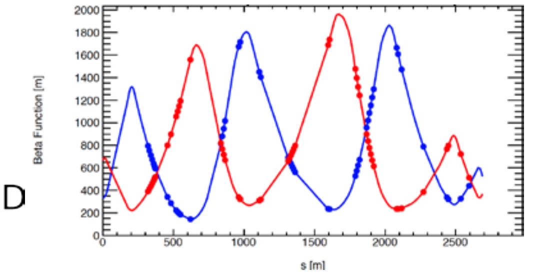


Momentum collim.

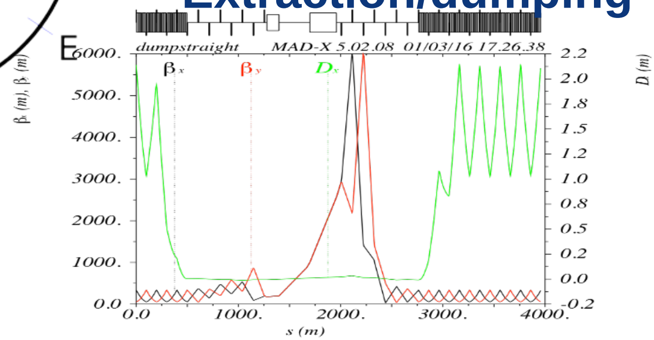




Betatron collimation



Extraction/dumping



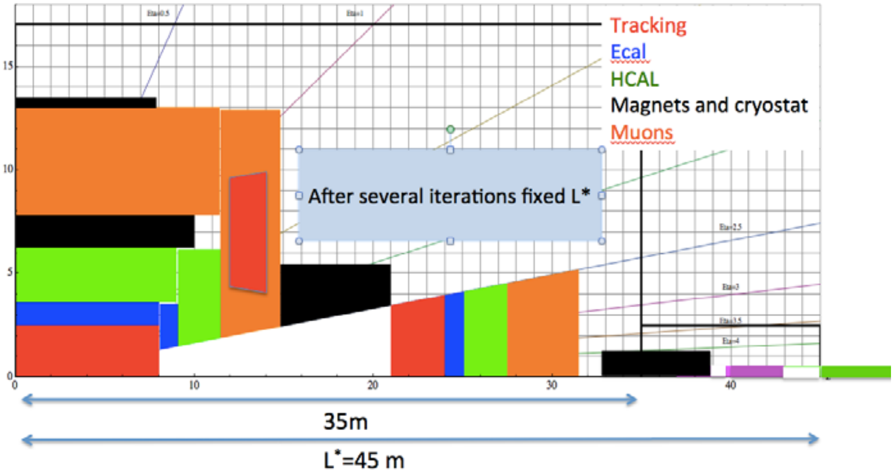
full ring optics design available as basis for:

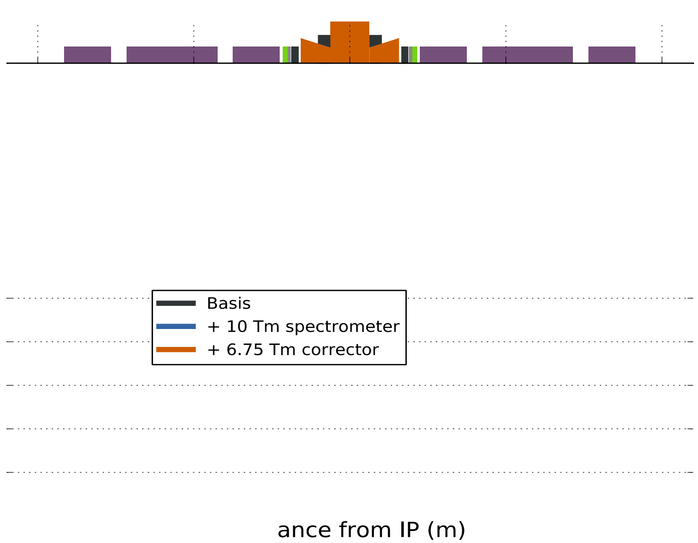
- beam dynamics studies
- optimisation of each insertion
- definition of system specifications (apertures, etc.)
- improvement of baseline optics and layout

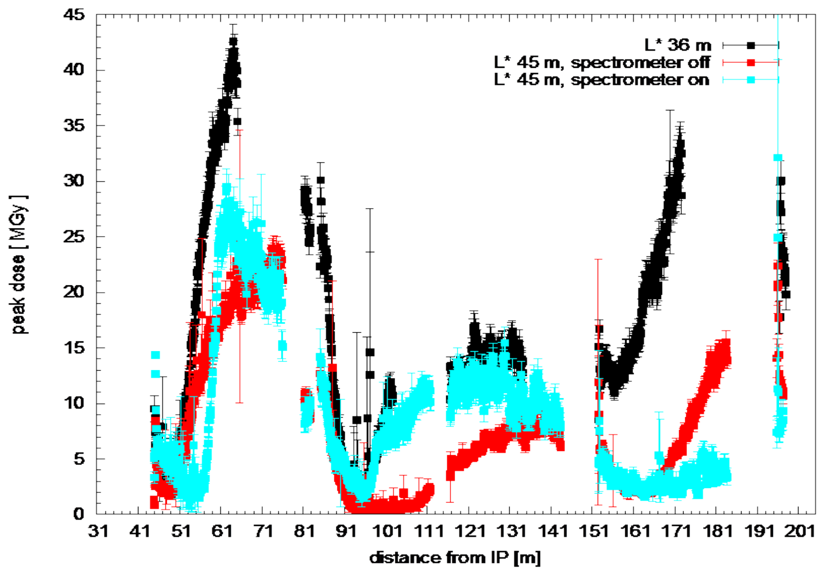
FCC-hh MDI studies

design of interaction region

- consistent for machine and detector
  - L^*=45 m
  - integrated spectrometer and compensation dipoles
- optics with long triplet with large aperture
  - helps distributing collision debris
  - more beam stay clear







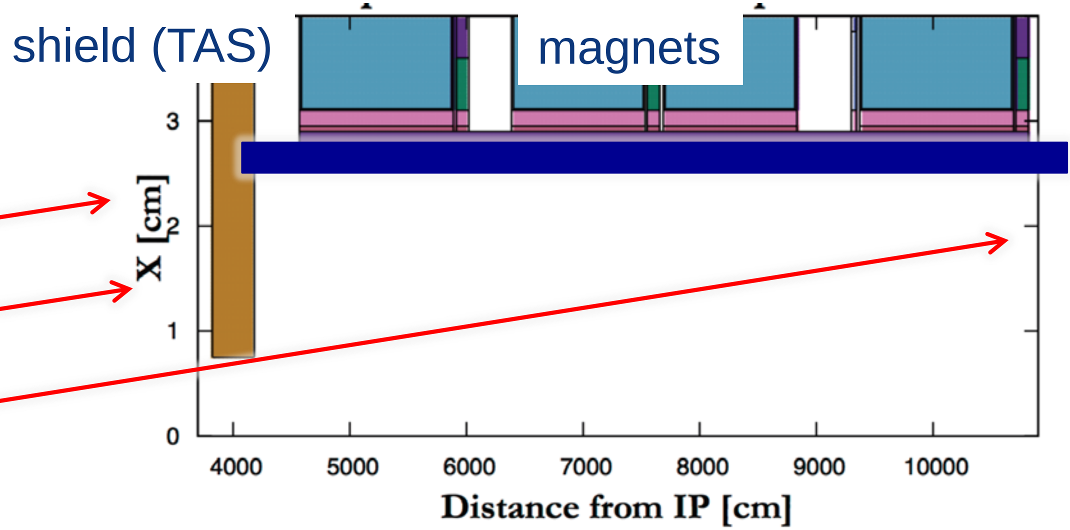
protecting triplet from debris

total power of background events 100-500 kW per experiment

- car or truck engine

already limit in LHC and HL-LHC

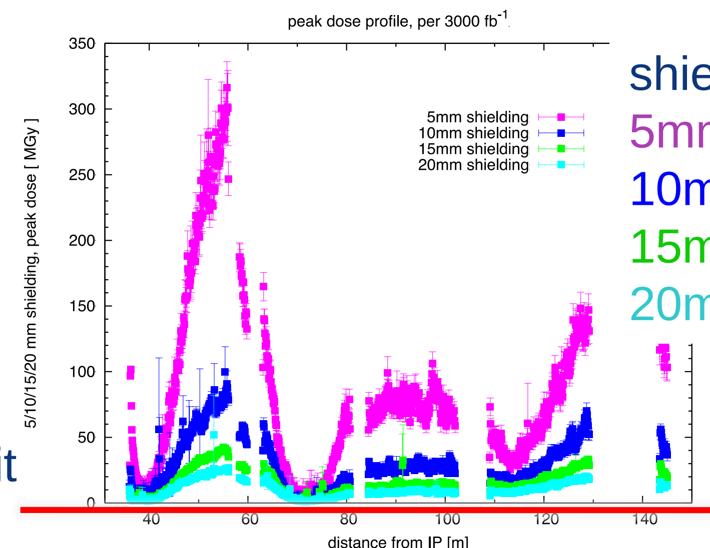
- magnet lifetime, heat load



study of 3000 fb^{-1} in older FCC-hh detector design

dose for 3000 fb^{-1}

30 MGy = present limit



shielding
5mm
10mm
15mm
20mm

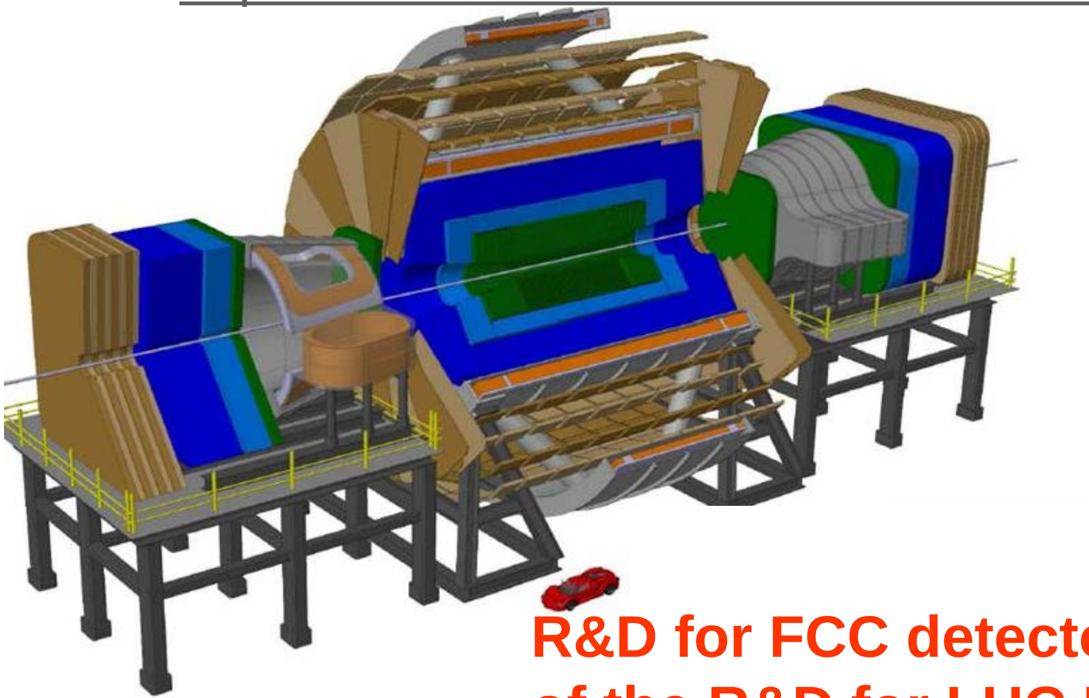
goal: survive at least 5000 fb^{-1}

- one 5-year run

M. I. Besana, F. Cerutti, et al.

detector concepts for 100 TeV pp

- a B=6 T, R=6 m solenoid with shielding coil and 2 dipoles has been engineered in detail. Alternative magnet systems are being studied
- parametrized detector performance model (DELPHES) is available and integrated in FCC software framework for physics simulations
  - https://twiki.cern.ch/twiki/bin/view/FCC/FccPythiaDelphes



some design challenges:

- large η acceptance
- radiation levels of >50 x LHC Phase II
- pileup of ~1000

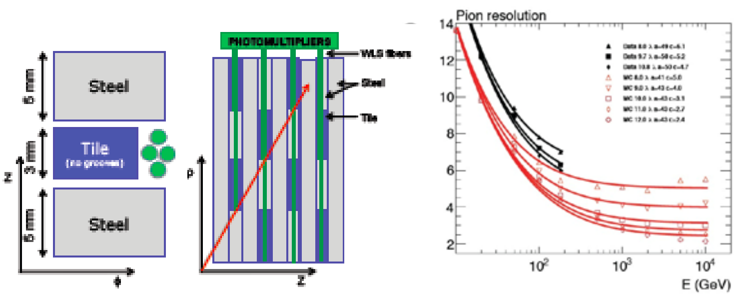
R&D for FCC detectors is a natural continuation of the R&D for LHC Phase II upgrade

physics/detector simulation software

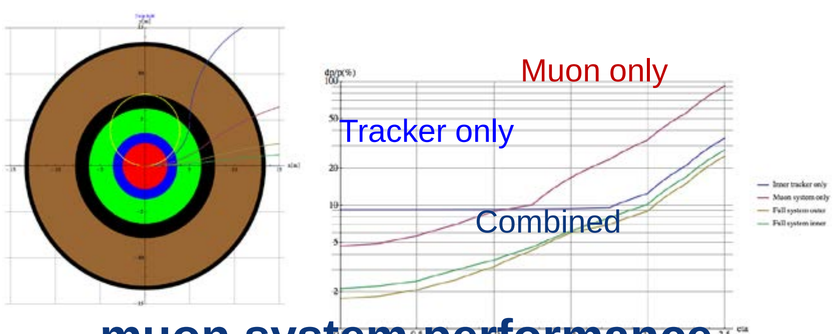
parametrized detector performance (DELPHES) is integrated in the FCC software framework and ready to use.
https://twiki.cern.ch/twiki/bin/view/FCC/FccPythiaDelphes

full simulation functional
reconstruction and fast simulation are very advanced

lots of effort on updating documentation and infrastructure
single entry point for all information: http://fccsw.web.cern.ch/fccsw/



calorimeter resolution, containment studies

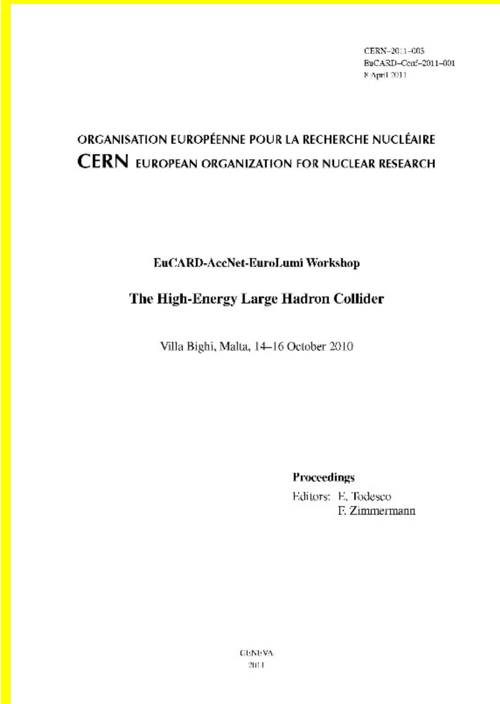


muon system performance studies and requirements

High-Energy LHC (HE-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

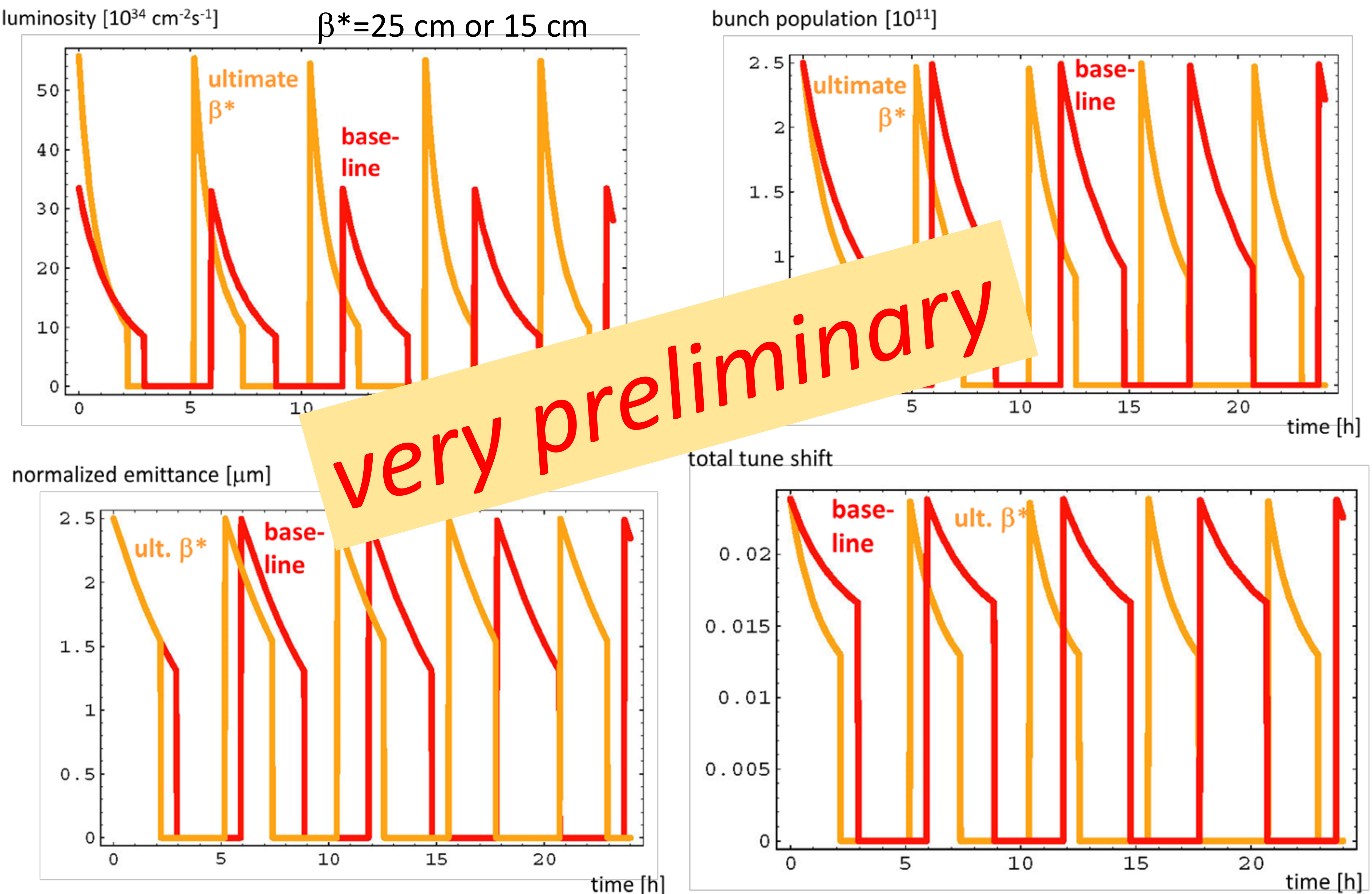
Proceedings
Editors: E. Todesco
F. Zimmermann

GENEVA
2011

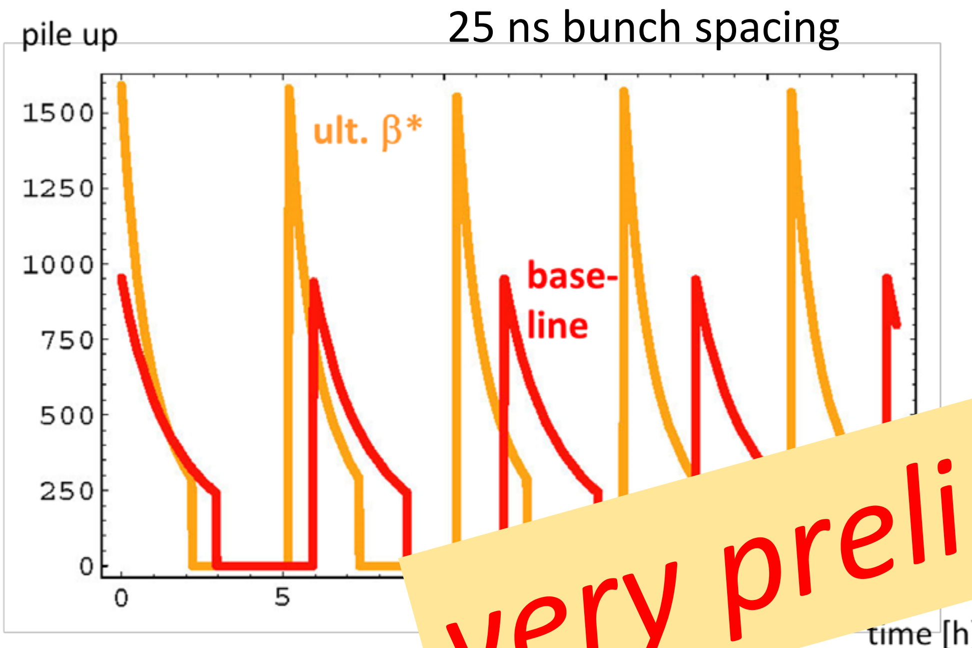
EuCARD-AccNet-EuroLumi Workshop: The High-Energy Large Hadron Collider - HE-LHC10, E. Todesco and F. Zimmermann (eds.), EuCARD-CON-2011-001; arXiv:1111.7188; CERN-2011-003 (2011)

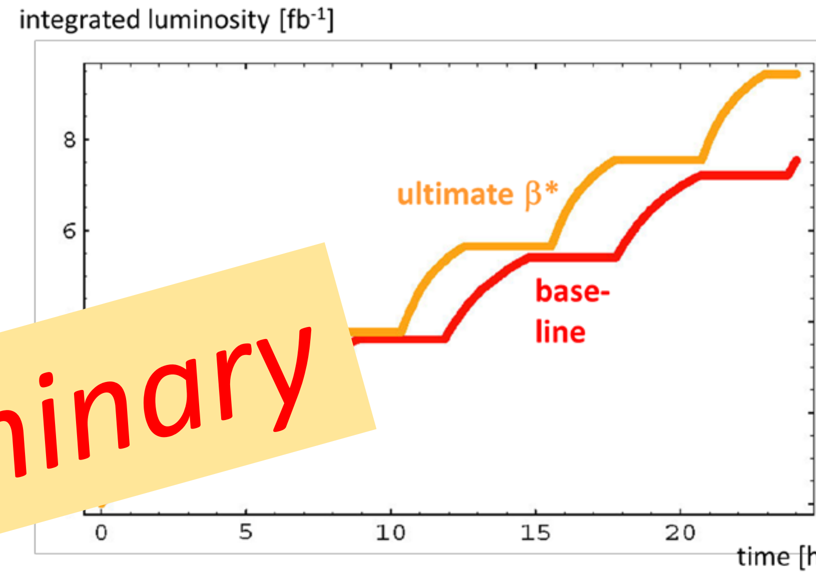
- **based on 16-T dipoles developed for FCC-hh**
- **extrapolation of other parts from the present (HL-)LHC and from FCC developments**

HE-LHC - 25 TeV c.m.



HE-LHC: pile up & performance





very preliminary

with 160 days of physics, 70% availability, 3 h turnaround time

β^*=25 cm: 920 fb^{-1}/year

β^*=15 cm: 1100 fb^{-1}/year

pile up of 1000 or shorter (e.g. 5 ns) bunch spacing – what is easier?

M. Benedikt, S. Fartoukh, F. Zimmermann

FCC–ee: physics requirements

- **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*

- **beam energy range from 35 GeV to ≈200 GeV**
- **highest possible luminosities** *at all working points*
- possibly ***H* (63 GeV) direct *s*-channel** production with **monochromatization**
- **some polarization up to ≥80 GeV** for precise beam energy calibration (<100 keV)

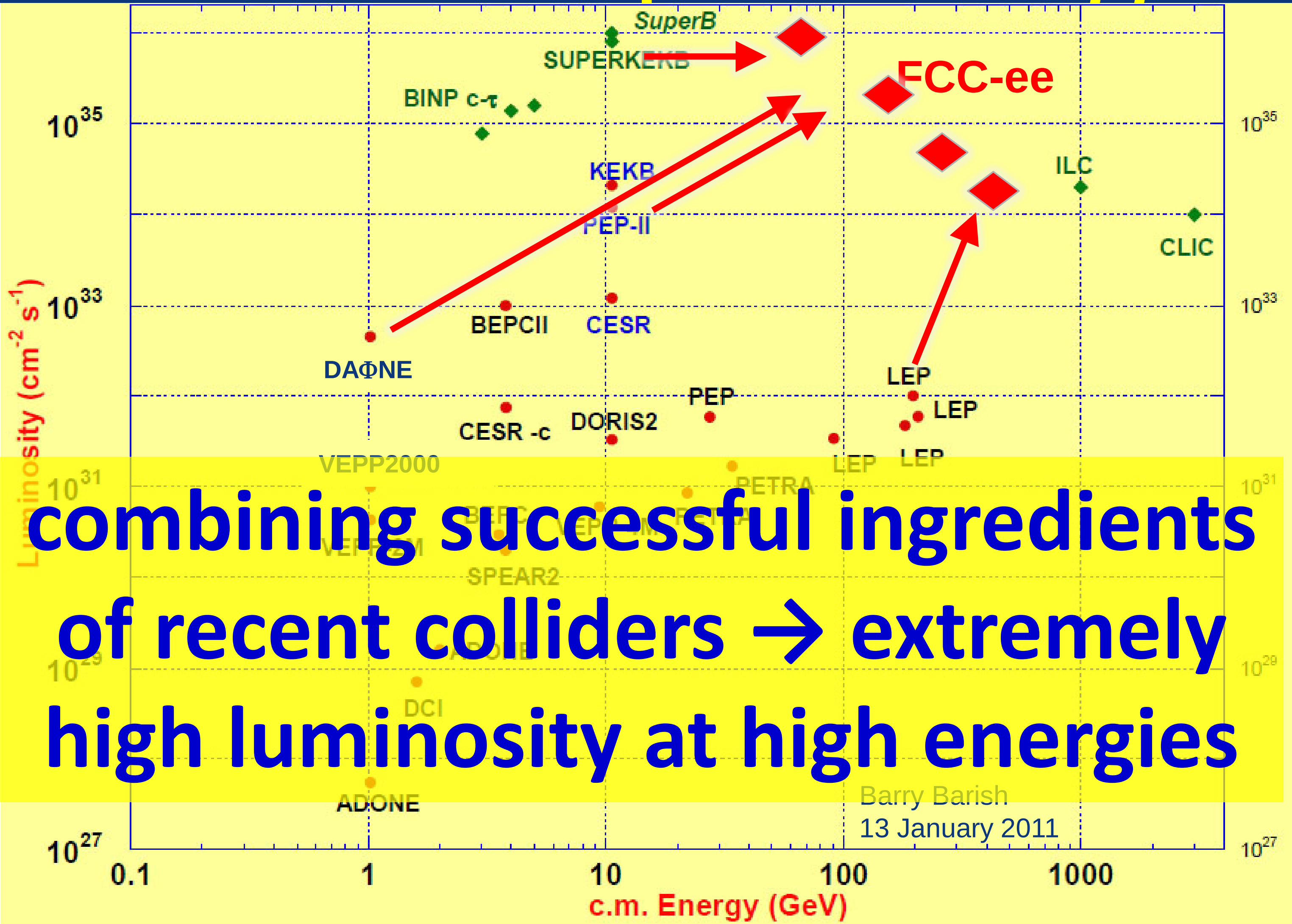
lepton collider parameters

parameter	FCC-ee (400 MHz)					LEP2
Physics working point	**Z**		**WW**	**ZH**	**tt_{bar}**	
energy/beam [GeV]	**45.6**		**80**	**120**	**175**	105
bunches/beam	30180	**91500**	**5260**	**780**	**81**	4
bunch spacing [ns]	7.5	**2.5**	**50**	**400**	**4000**	22000
bunch population [10^{11}]	1.0	**0.33**	**0.6**	**0.8**	**1.7**	4.2
beam current [mA]	1450	**1450**	**152**	**30**	**6.6**	3
luminosity/IP x $10^{34}cm^{-2}s^{-1}$	210	**90**	**19**	**5.1**	**1.3**	0.0012
energy loss/turn [GeV]	0.03	**0.03**	**0.33**	**1.67**	**7.55**	3.34
synchrotron power [MW]	**100**					22
RF voltage [GV]	0.4	**0.2**	**0.8**	**3.0**	**10**	3.5

identical FCC-ee baseline optics for all energies

FCC-ee: 2 separate rings LEP: single beam pipe

FCC-ee exploits lessons & recipes from past e^+e^- and *pp* colliders



combining successful ingredients of recent colliders → extremely high luminosity at high energies

LEP:
high energy
SR effects

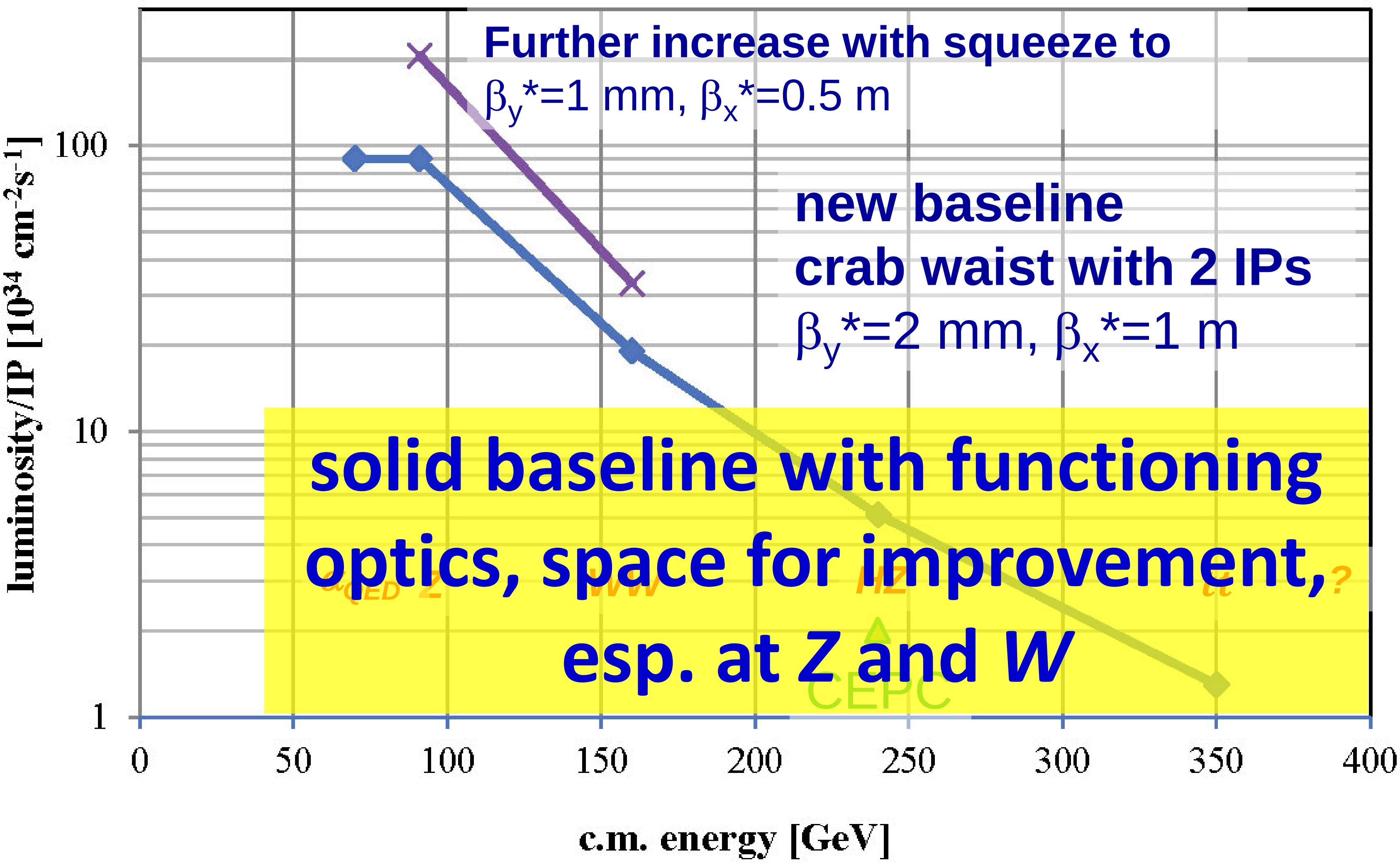
B-factories:
KEKB & PEP-II:
high beam currents
top-up injection
DAFNE: crab waist

Super B-factories
S-KEKB: low β_y^*

KEKB: e^+ source

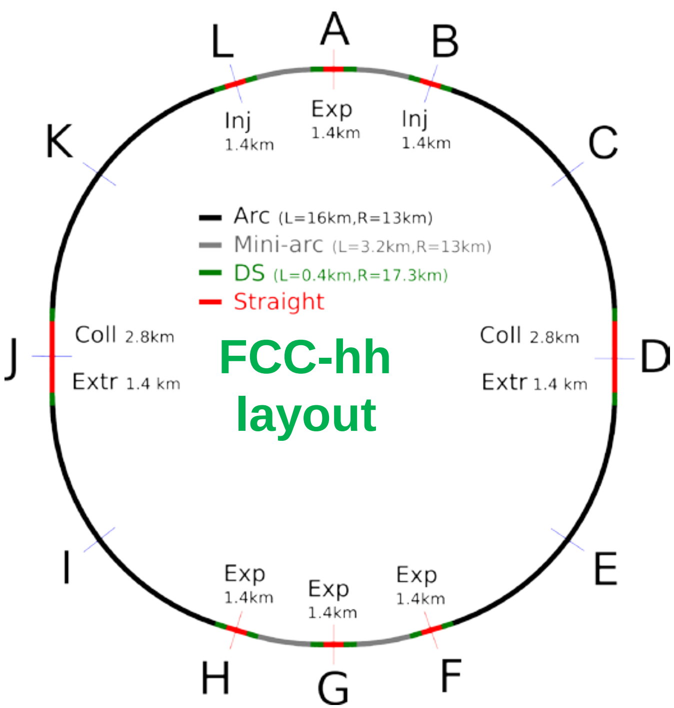
HERA, LEP, RHIC:
spin gymnastics

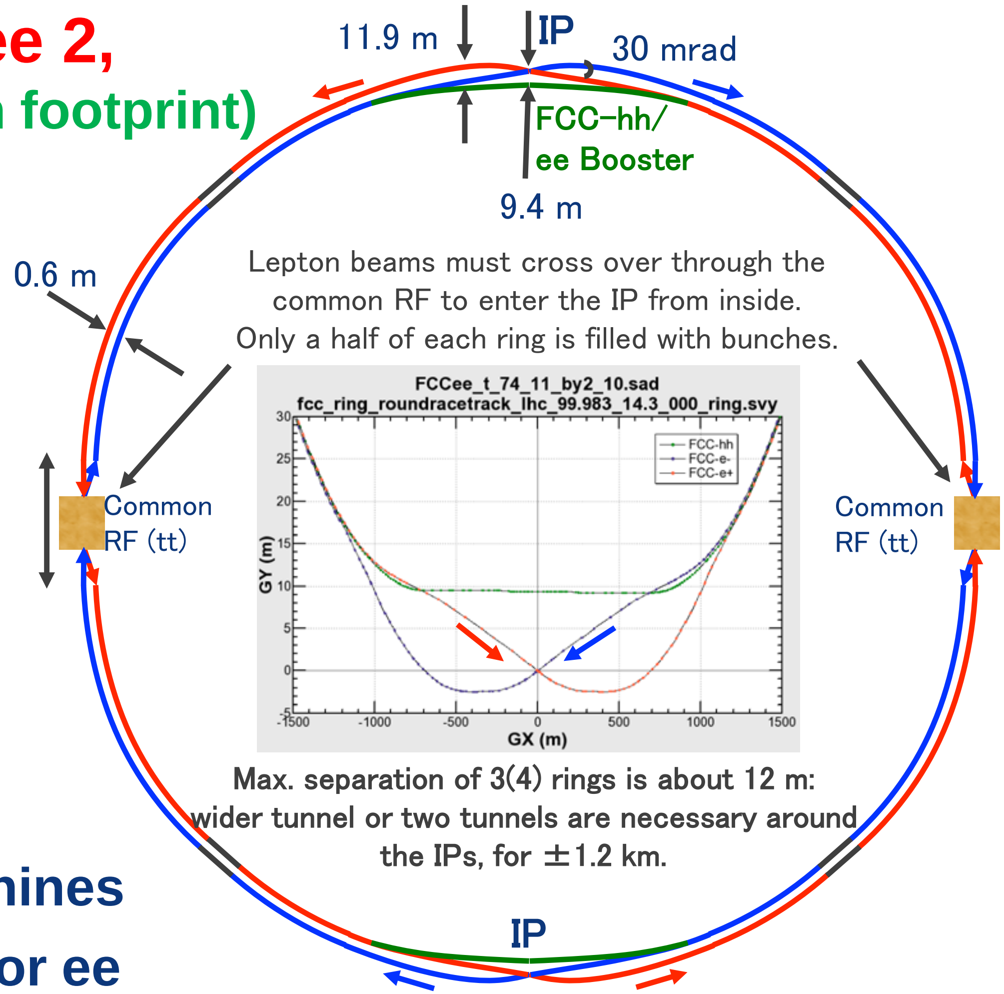
FCC-ee luminosity per IP



common layouts for hh & ee

FCC-ee 1, FCC-ee 2,
FCC-ee booster (FCC-hh footprint)





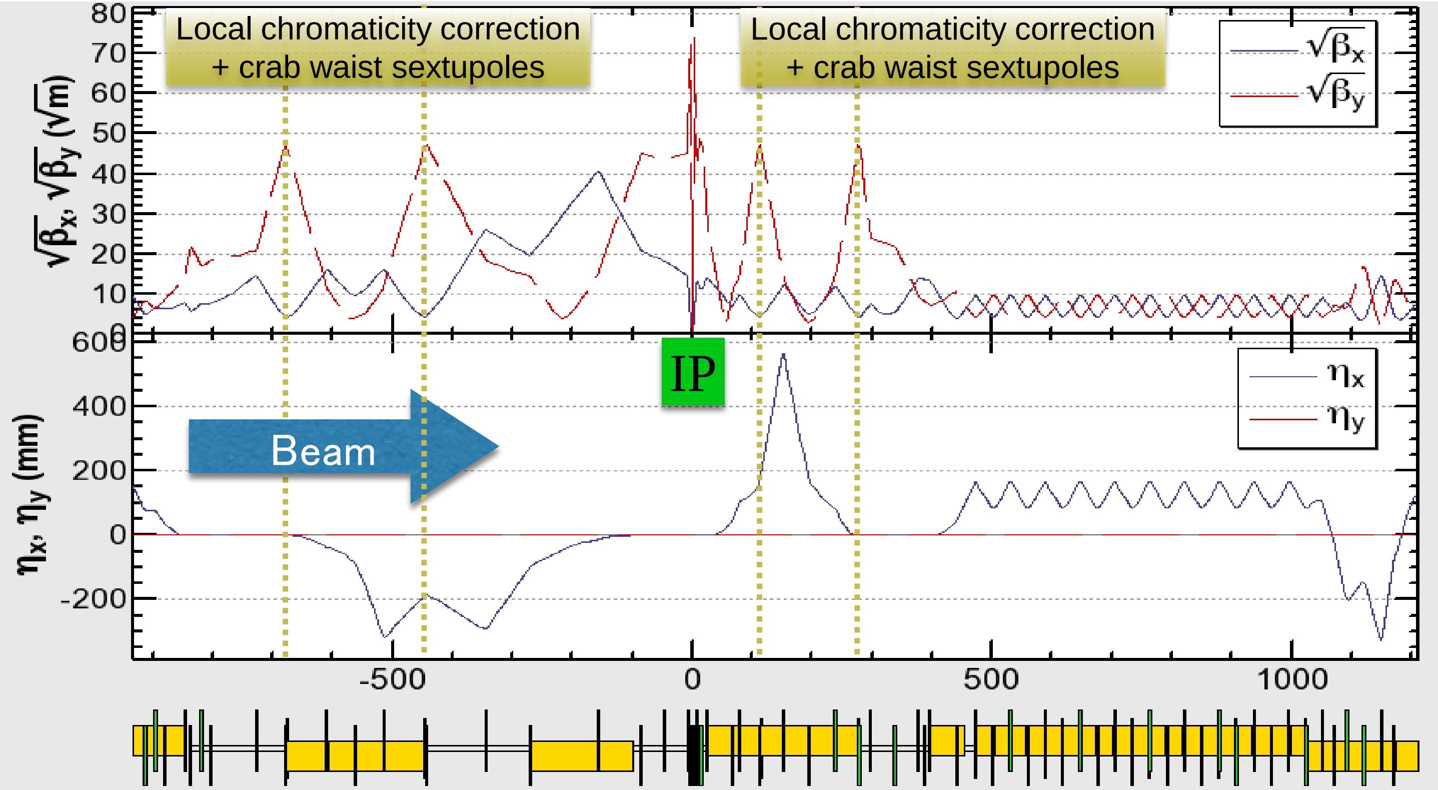
- **2 main IPs in A, G for both machines**
- **asymmetric IR optic/geometry for ee to limit synchrotron radiation to detector**

FCC-ee optics design

optics design for all working points achieving baseline performance

interaction region: asymmetric optics design

- synchrotron radiation from upstream dipoles <100 keV up to 450 m from IP
- dynamic aperture & momentum acceptance requirements fulfilled at all WPs

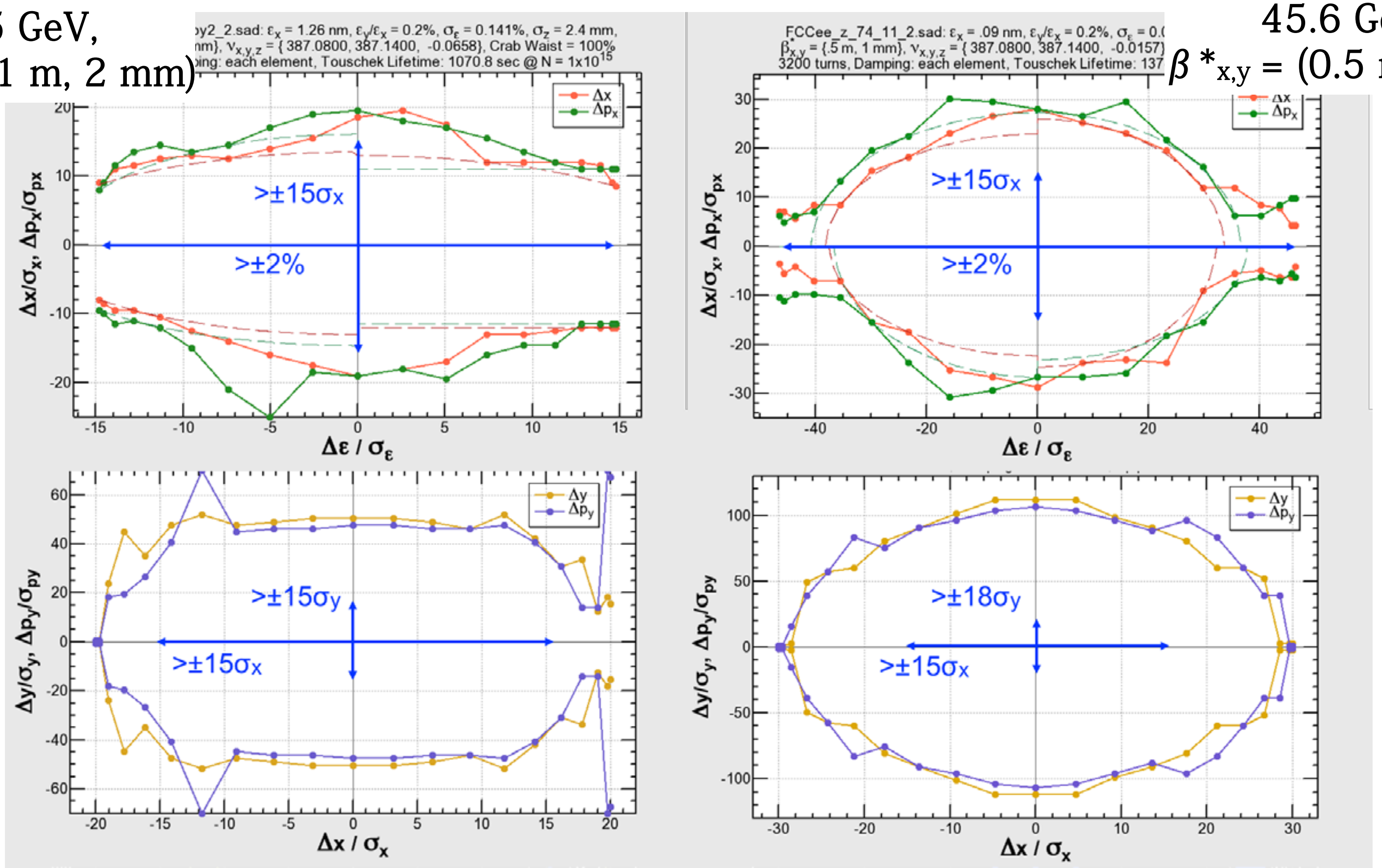


FCC-ee full-ring optics design

dynamic aperture and momentum acceptance requirements fulfilled

175 GeV, $\beta^*_{x,y}$ = (1 m, 2 mm)

45.6 GeV, $\beta^*_{x,y}$ = (0.5 m, 1 mm)



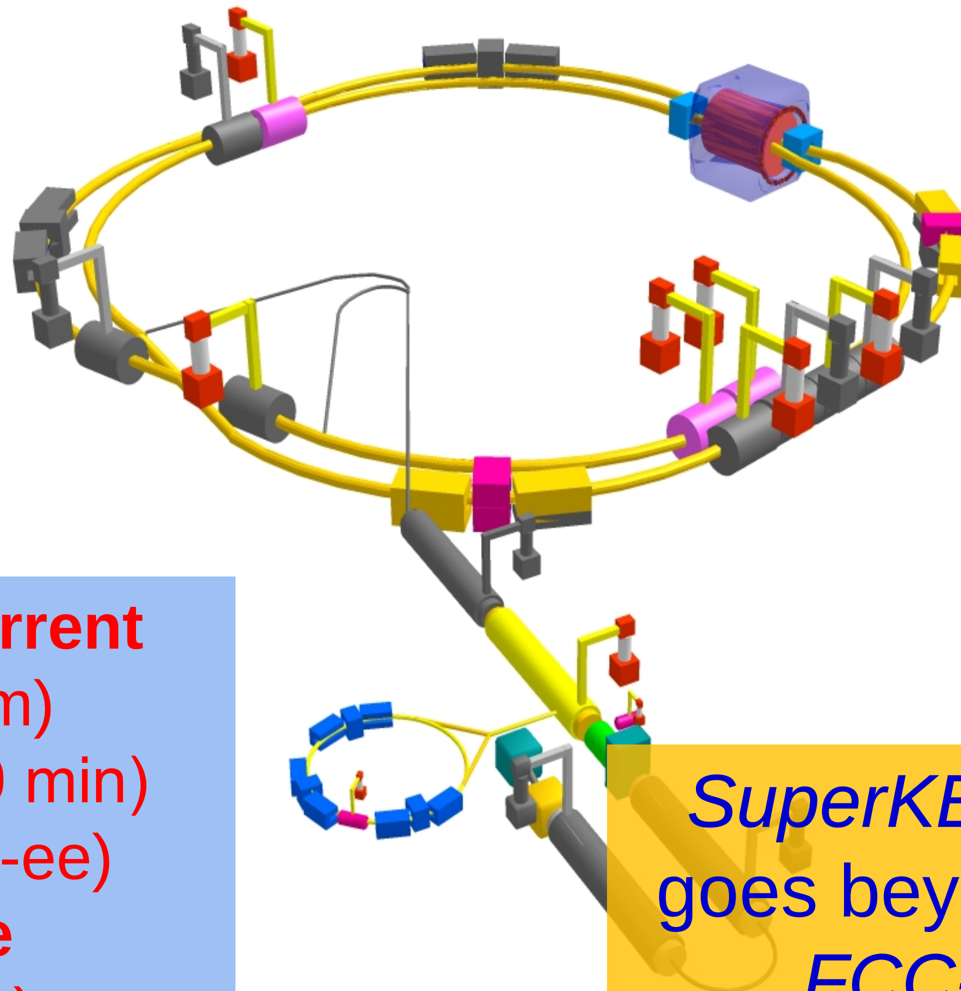
K. Oide

SuperKEKB: FCC-ee demonstrator

I_{e+}=3.6 A, I_{e-}=2.6 A

P_{SR} ~ 13 MW
C = 3 km

beam commissioning started this year



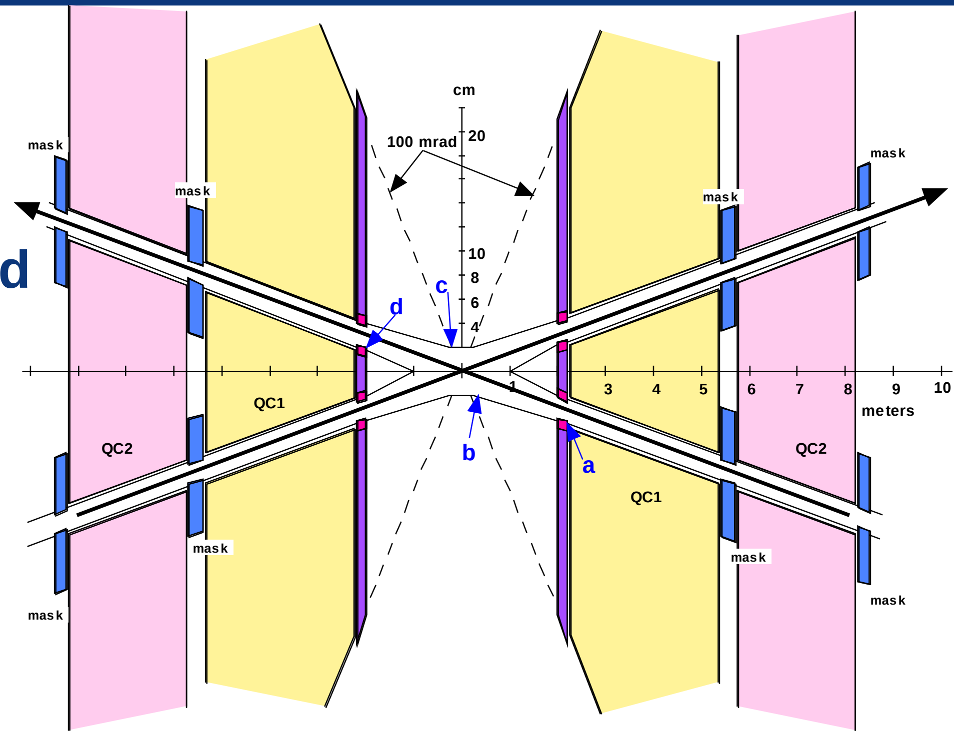
top up injection at high current
β_y^* =300 μm (FCC-ee: 1 mm)
lifetime 5 min (FCC-ee: ≥20 min)
$\varepsilon_y/\varepsilon_x$ =0.25% (similar to FCC-ee)
off momentum acceptance
(±1.5%, similar to FCC-ee)
e^+ production rate (2.5x10^{12}/s,
FCC-ee: <1.5x10^{12}/s (*Z* cr.waist)

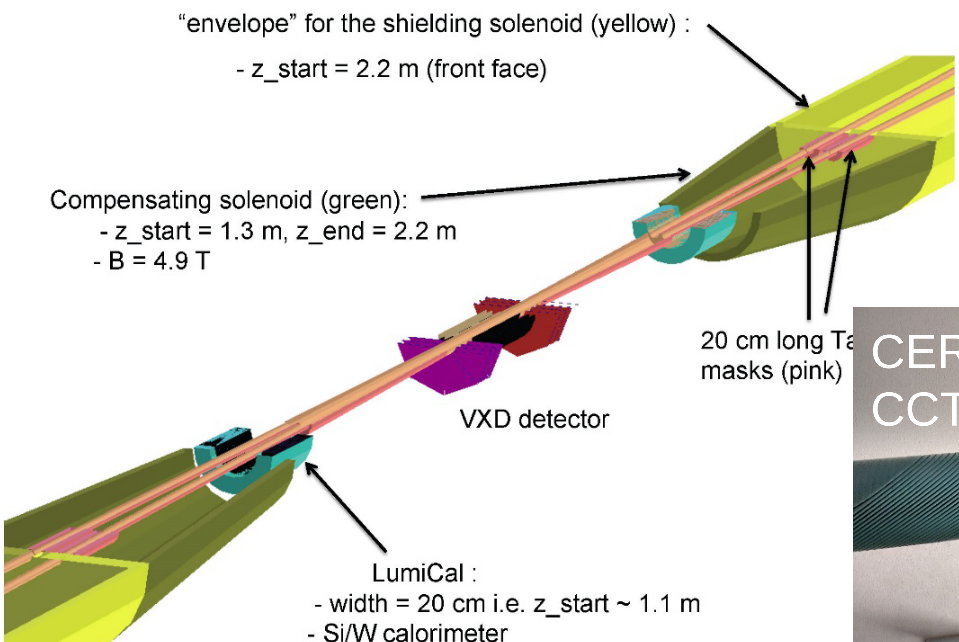
SuperKEKB goes beyond *FCC-ee*, testing all concept

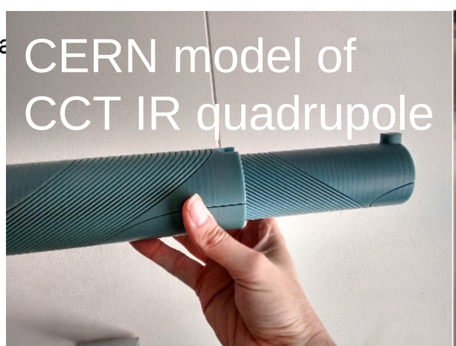
FCC-ee MDI optimisation

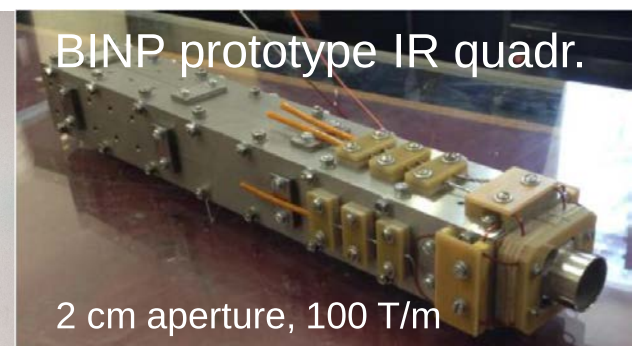
MDI work focused on optimization of

- ***l****, IR quadrupole design**
- **compensation & shielding solenoid**
- **SR masking and chamber layout**









Higgs coupling summary

M. Klute

M. Klute LCWS2015

Uncertainties	HL-LHC*	μ-	CLIC	ILC**	CEPC	FCC-ee	FCC-hh
m_H [MeV]	40	0.06	40	30	5.5	8	
Γ_H [MeV]	-	0.17	0.16	0.16	0.12	0.04	
g_{HZZ} [%]	2.0	-	1.0	0.6	0.25	0.15	
g_{HWW} [%]	2.0	2.2	1.0	0.8	1.2	0.2	
g_{Hbb} [%]	4.0	2.3	1.0	1.5	1.3	0.4	
$g_{H\tau\tau}$ [%]	2.0	5	2.0	1.9	1.4	0.5	
$g_{H\gamma\gamma}$ [%]	2.0	10	6.0	7.8	4.7	1.5	
g_{Hcc} [%]	-	-	2.0	2.7	1.7	0.7	
g_{Hgg} [%]	3.0	-	2.0	2.3	1.5	0.8	
g_{Htt} [%]	4.0	-	4.5	18	-	-	1
$g_{H\mu\mu}$ [%]	4.0	2.1	8.0	20	8.6	6.2	1
g_{HHH} [%]	30	-	24	-	-	-	5

* Estimate for two HL-LHC experiments

** ILC lumi upgrade improves precision by factor 2

For ~10y operation. Lots of "!,*,?"

Every number comes with her own story.

the combination of FCC-ee and FCC-hh is «invincible»

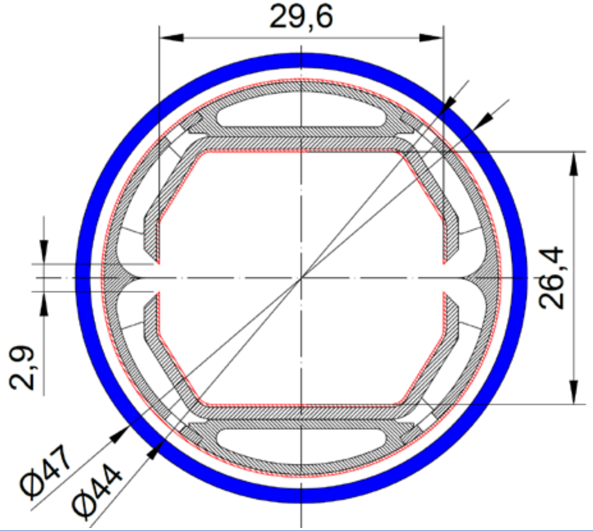
synchrotron radiation/beam screen

handling of high synchrotron radiation load of protons @ 50 TeV:

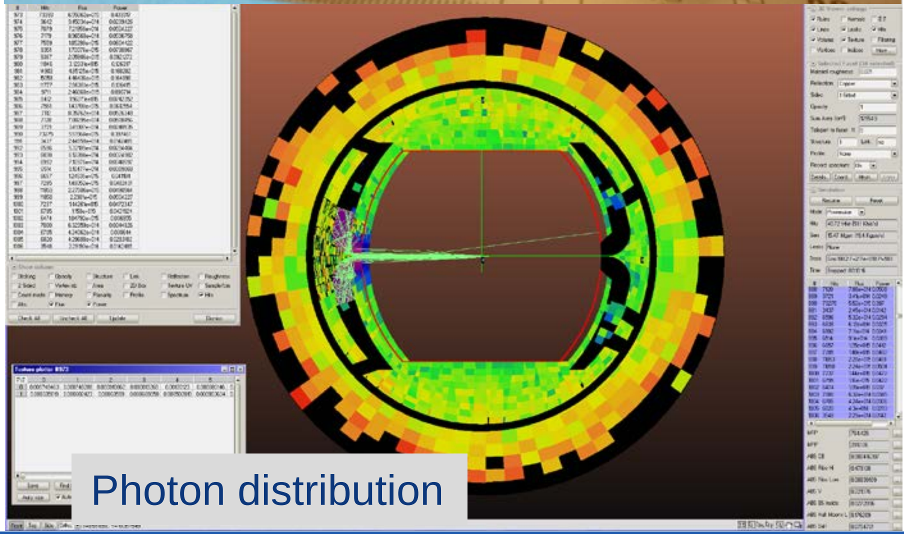
- **~30 W/m/beam (@16 T)** (LHC <0.2W/m)
- **5 MW total in arcs**

new beam screen with ante-chamber

- absorption of synchrotron radiation at 50 K to reduce cryogenic power
- avoids photo-electrons, helps vacuum



first FCC-hh beam screen prototype
testing 2017 at ANKA facility in Germany

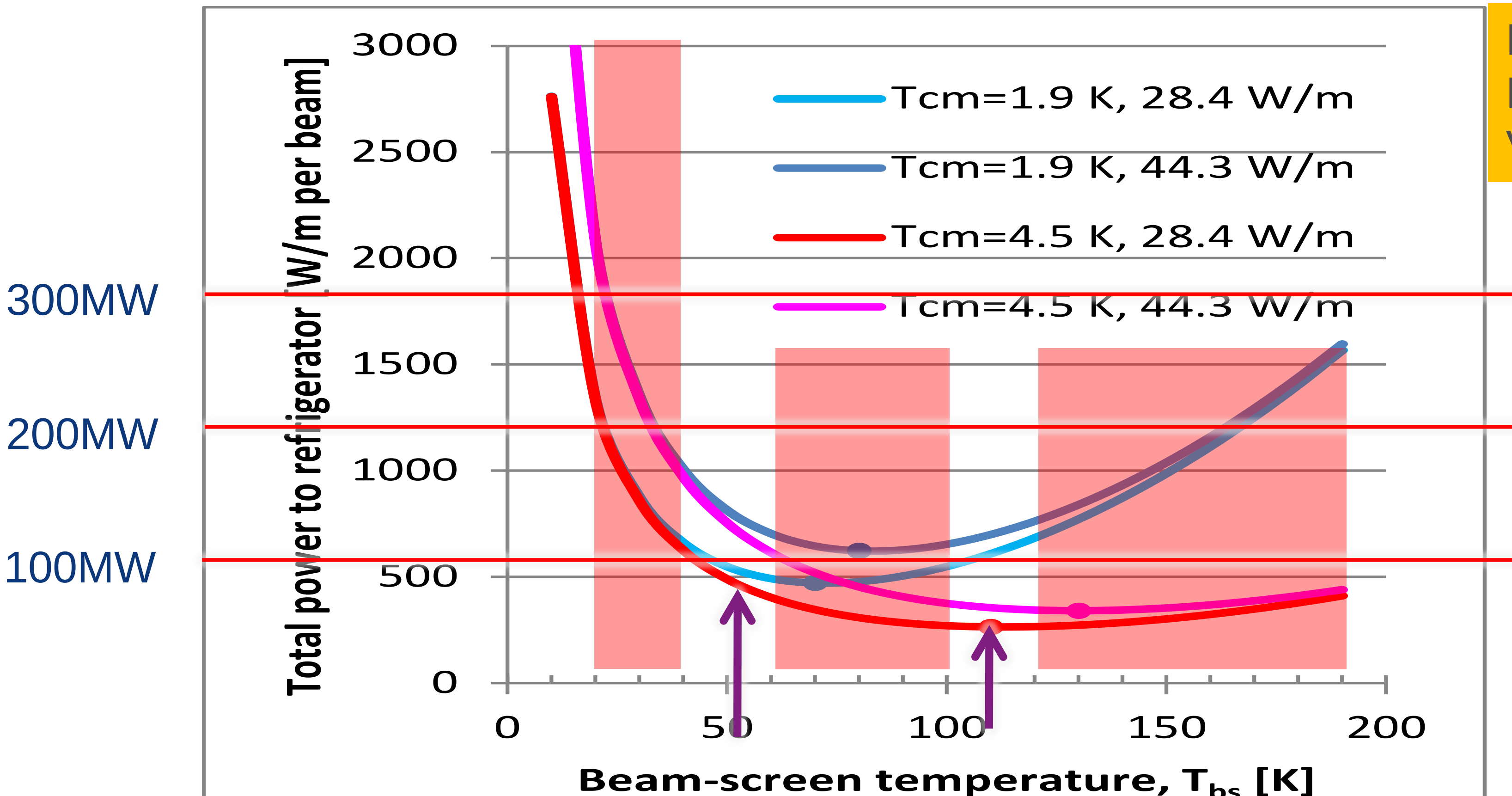


Photon distribution

Cryo power for cooling of SR heat

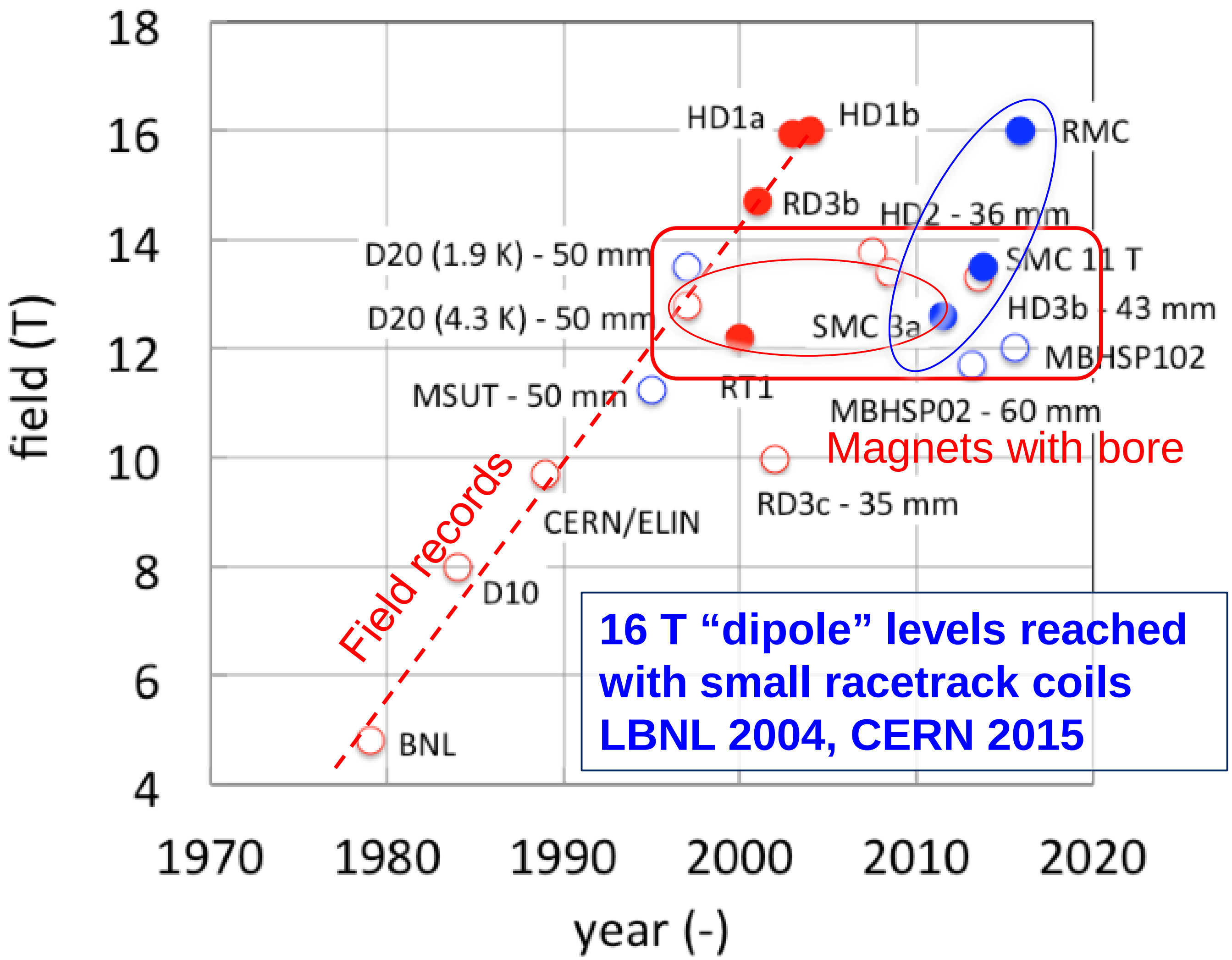
Overall optimisation of cryo-power, vacuum and impedance
Termperature ranges: <20, 40K-60K, 100K-120K

Ph. Lebrun
L. Tavian
V. Baglin

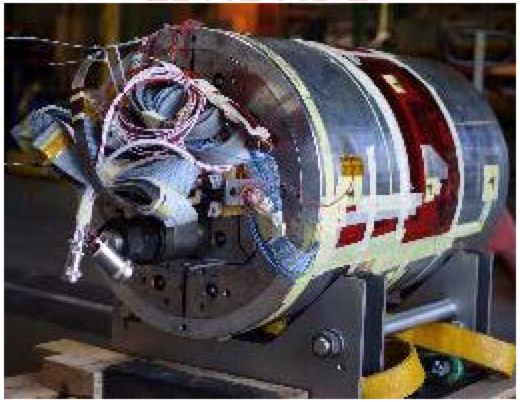


Multi-bunch instability growth time: 25 turns 9 turns (ΔQ=0.5)

CERN & EuroCirCol 16T programs

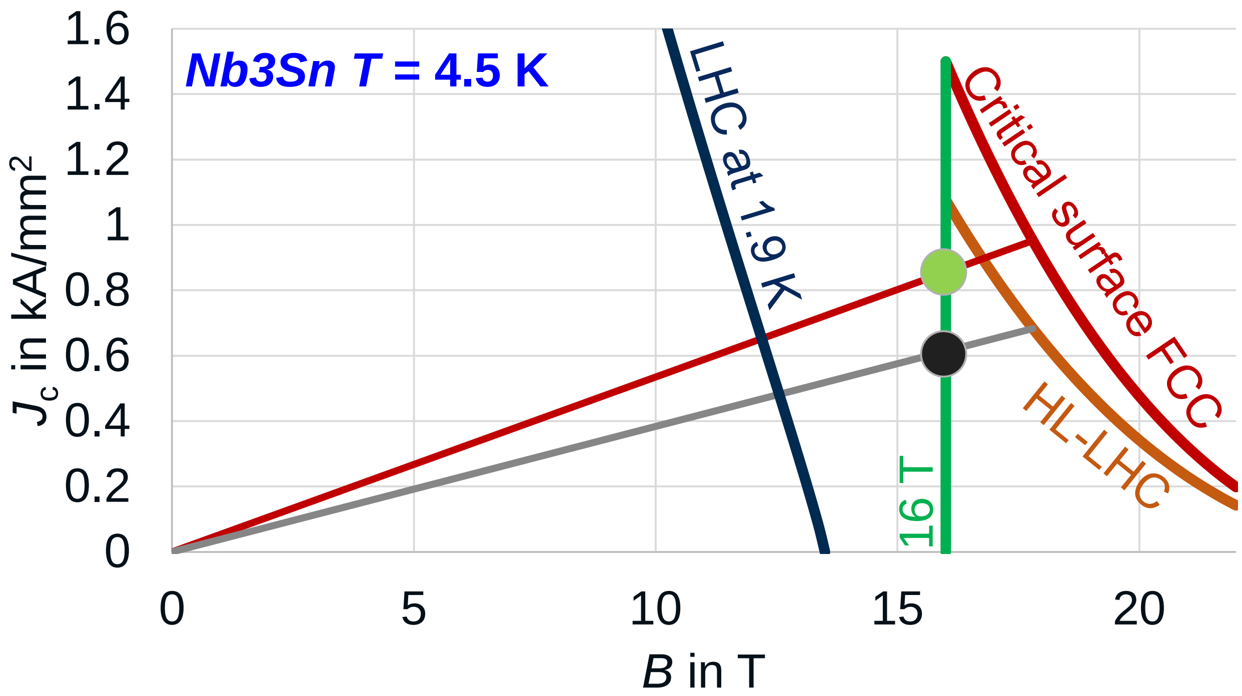


LBNL HD1



CERN RMC

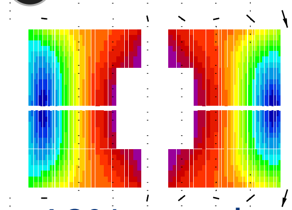
superconductor performance



Nb-Ti
Not possible

Different technology →

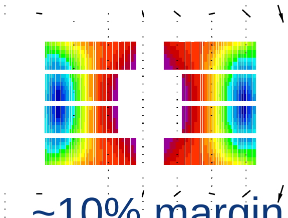
5400 mm²



~10% margin
HL-LHC

~1.7 times less SC →

3150 mm²



~10% margin
FCC ultimate

Nb_3Sn conductor program

Nb_3Sn conductor is one of the major cost and performance factors for FCC-hh and must be given highest attention

- **Goals: J_c increase (16 T, 4.2 K) > 1500 A/mm^2, significant cost reduction**
- **Actions ongoing and planned (in addition to activities at CERN):**
  - Purchase of wires in Europe, US
  - Industrial R&D in Europe
  - **Collaboration agreements with KEK**, Russia, Korea (in preparation), **to stipulate conductor development with regional industry**
  - Collaborations with several European Universities and Research Centres
- **U.S. Magnet Development Program with conductor R&D program and focused on 16 T cos theta dipole model magnet.**

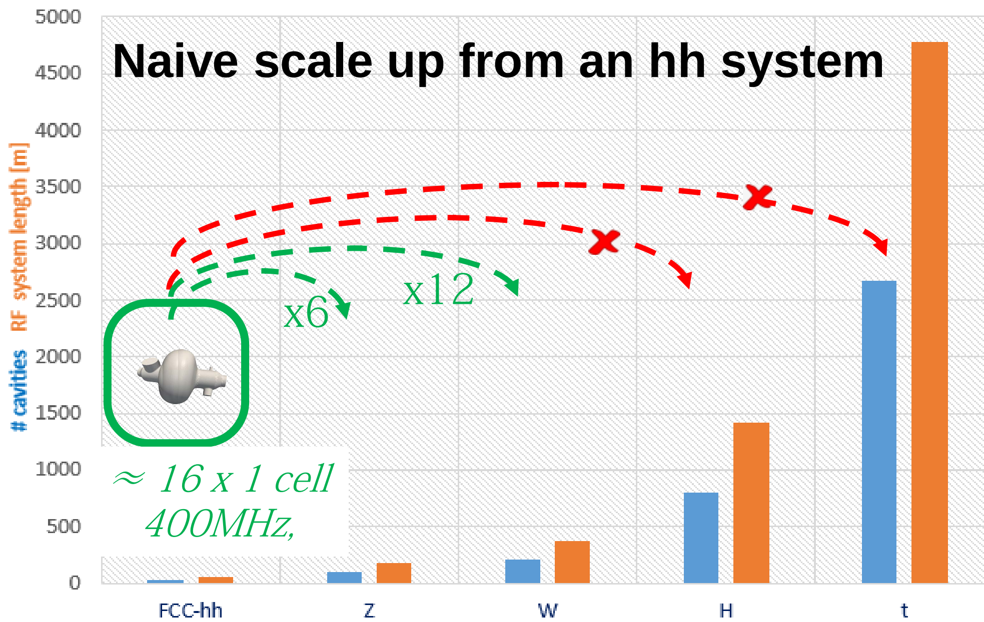
RF system requirements

Very large range of operation parameters

“Ampere-class” machines

	V_{total} GV	$n_{bunches}$	I_{beam} mA	ΔE/turn GeV
hh	0.032		500	
Z	0.4/0.	30000/9000	1450	0.034
W	0.8	5162	152	0.33
H	5.5	770	30	1.67
t	10	78	6.6	7.55

“high gradient” machines

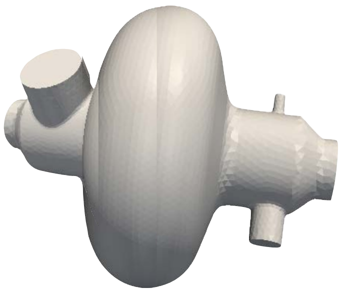


- Voltage and beam current ranges span more than factor > 10^2
- No well-adapted single RF system solution satisfying requirements

RF system R&D lines

400 MHz single-cell cavities preferred for hh and ee-Z (few MeV/m)

- Baseline Nb/Cu @4.5 K, development with synergies to HL-LHC, HE-LHC
- R&D: power coupling 1 MW/cell, HOM power handling (damper, cryomodule)



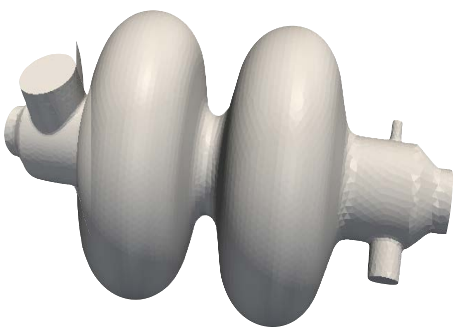
hh — ≈ 16 cells per beam

Z — ≈ 100 per beam (+ 100 for booster ring)

(**W** — ≈ 210 per beam (+ 210 for booster ring))

400 or 800 MHz multi-cell cavities preferred for ee-H, ee-tt and ee-W

- Baseline options 400 MHz Nb/Cu @4.5 K, ◄—► 800 MHz bulk Nb system @2K
- R&D: High Q_0 cavities, coating, long-term: Nb_3Sn like components



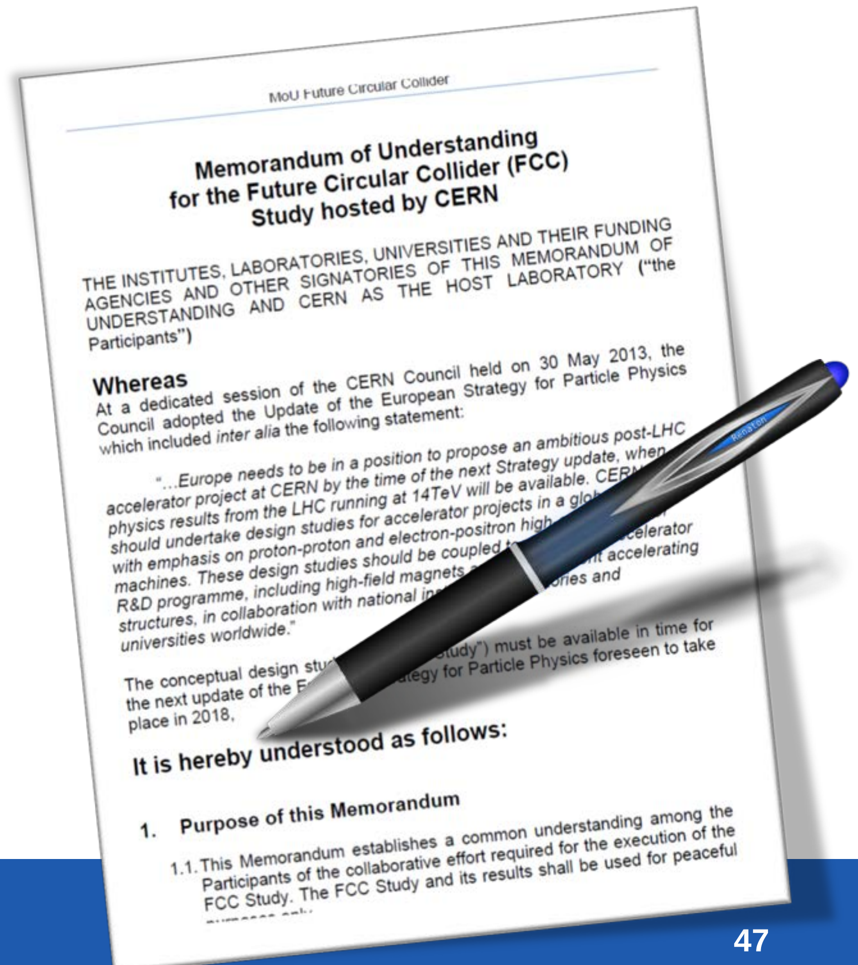
W — ≈ 200 per beam (+ 200 for booster)

H — ≈ 800 per beam (+ 800 for booster)

t — ≈ common 2600 cells for both beams (+ 2600 for booster)

FCC Collaboration

- A **consortium** of partners based on a Memorandum Of Understanding (MoU)
- Working together on a **best effort basis**
- Pursuing the same **common goal**
- **Self governed**
- **Incremental & open** to academia and industry


MoU Future Circular Collider

Memorandum of Understanding for the Future Circular Collider (FCC) Study hosted by CERN

THE INSTITUTES, LABORATORIES, UNIVERSITIES AND THEIR FUNDING AGENCIES AND OTHER SIGNATORIES OF THIS MEMORANDUM OF UNDERSTANDING AND CERN AS THE HOST LABORATORY ("the Participants")

Whereas

At a dedicated session of the CERN Council held on 30 May 2013, the Council adopted the Update of the European Strategy for Particle Physics which included *inter alia* the following statement:

"…Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14TeV will be available. CERN should undertake design studies for accelerator projects in a glob… with emphasis on proton-proton and electron-positron high… machines. These design studies should be coupled… R&D programme, including high-field magnets… structures, in collaboration with national… universities worldwide."

The conceptual design stu… the next update of the E… place in 2018.

It is hereby understood as follows:

1. Purpose of this Memorandum

1.1. This Memorandum establishes a common understanding among the Participants of the collaborative effort required for the execution of the FCC Study. The FCC Study and its results shall be used for peaceful

FCC International Collaboration

- **75 institutes**
- **26 countries + EC**

Status: April, 2016

FCC Collaboration Status

75 collaboration members & CERN as host institute, April 2016

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
Cinvestav, Mexico
CNRS, France
CNR-SPIN, Italy
Cockcroft Institute, UK
U Colima, Mexico
UCPH Copenhagen, Denmark
CSIC/IFIC, Spain
TU Darmstadt, Germany
TU Delft, Netherlands
DESY, Germany
DOE, Washington, USA
ESS, Lund, Sweden
TU Dresden, Germany
Duke U, USA
EPFL, Switzerland

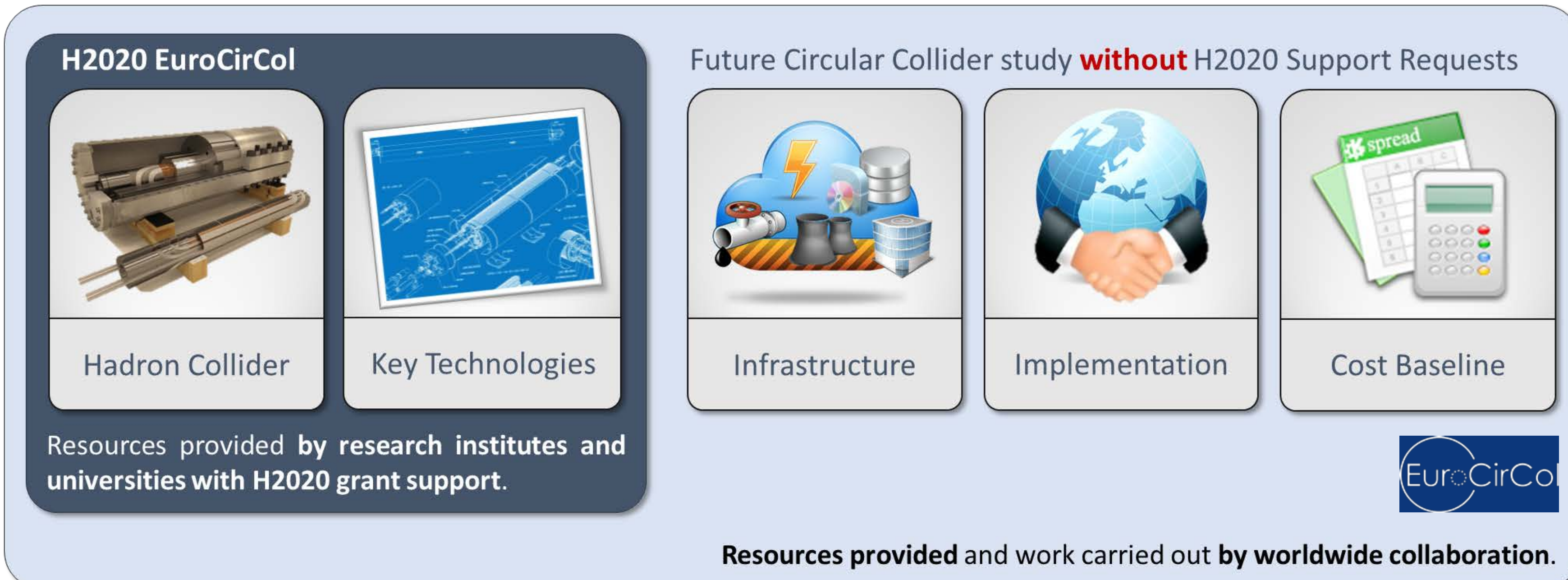
UT Enschede, Netherlands
U Geneva, Switzerland
Goethe U Frankfurt, Germany
GSI, Germany
GWNU, Korea
U. Guanajuato, Mexico
Hellenic Open U, Greece
HEPHY, Austria
U Houston, USA
IIT Kanpur, India
IFJ PAN Krakow, Poland
INFN, Italy
INP Minsk, Belarus
U Iowa, USA
IPM, Iran
UC Irvine, USA
Istanbul Aydin U., Turkey
JAI, UK
JINR Dubna, Russia
Jefferson LAB, USA
FZ Jülich, Germany
KAIST, Korea
KEK, Japan
KIAS, Korea
King's College London, UK

KIT Karlsruhe, Germany
KU, Seoul, Korea
Korea U Sejong, Korea
U. Liverpool, UK
U. Lund, Sweden
MAX IV, Lund, Sweden
MEPhI, Russia
UNIMI, Milan, Italy
MIT, USA
Northern Illinois U, USA
NC PHEP Minsk, Belarus
U Oxford, UK
PSI, Switzerland
U. Rostock, Germany
RTU, Riga, Latvia
UC Santa Barbara, USA
Sapienza/Roma, Italy
U Siegen, Germany
U Silesia, Poland
TU Tampere, Finland
TOBB, Turkey
U Twente, Netherlands
TU Vienna, Austria
Wigner RCP, Budapest, Hungary
Wroclaw UT, Poland

EuroCirCol EU Horizon 2020 Grant

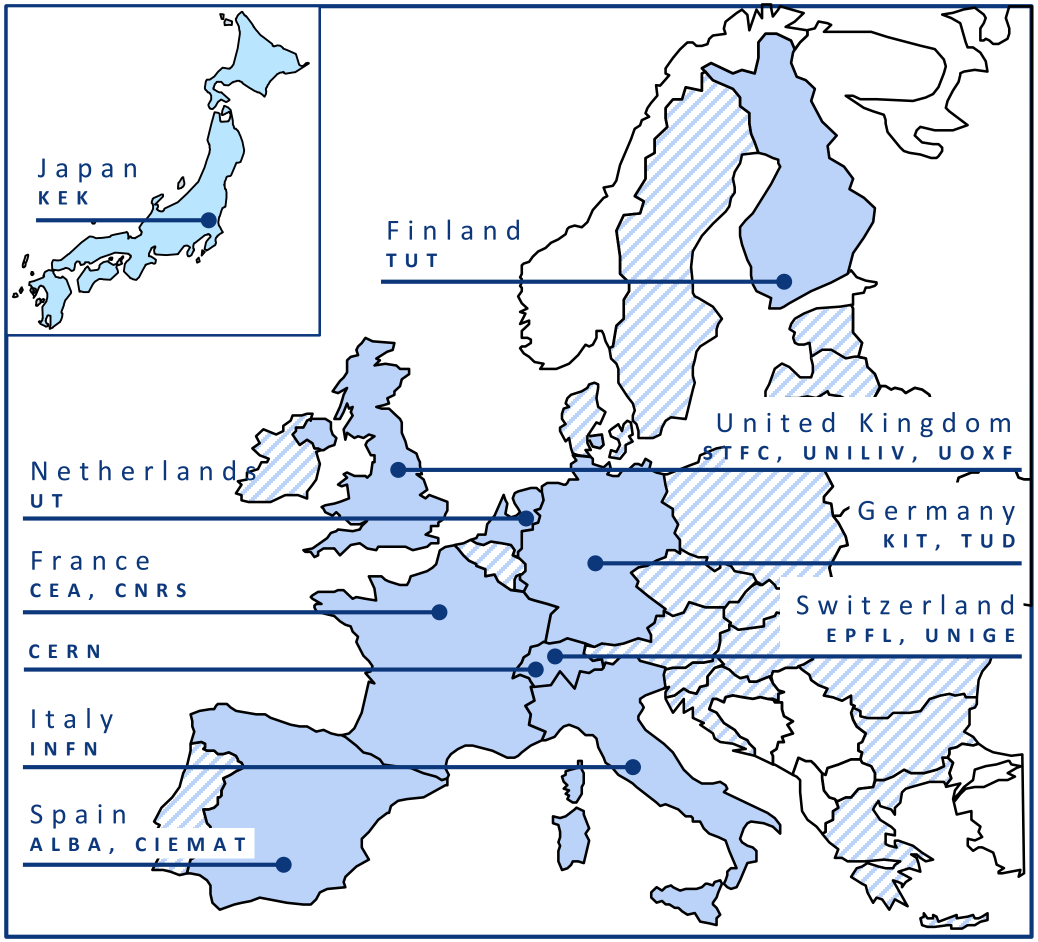
European Union contributes with funding to FCC-hh study

- Supports and makes essential contributions to the FCC-hh work packages:
- **Arc & IR optics design, 16 T dipole design, 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

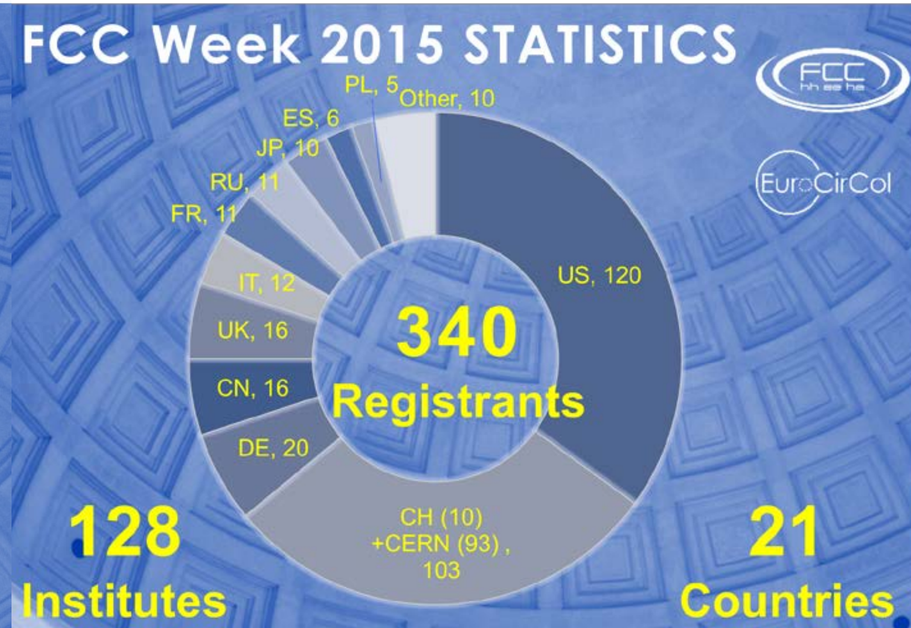


Consortium Beneficiaries, signing the Grant Agreement

First FCC Week Conference

Washington DC
23-27 March 2015

http://cern.ch/fccw2015



“head shots” from Bob Palmer (BNL)

FCCWEEK 2016

International Future Circular Collider Conference

ROME 11-15 APRIL

fccw2016.web.cern.ch

http://cern.ch/fccw2016

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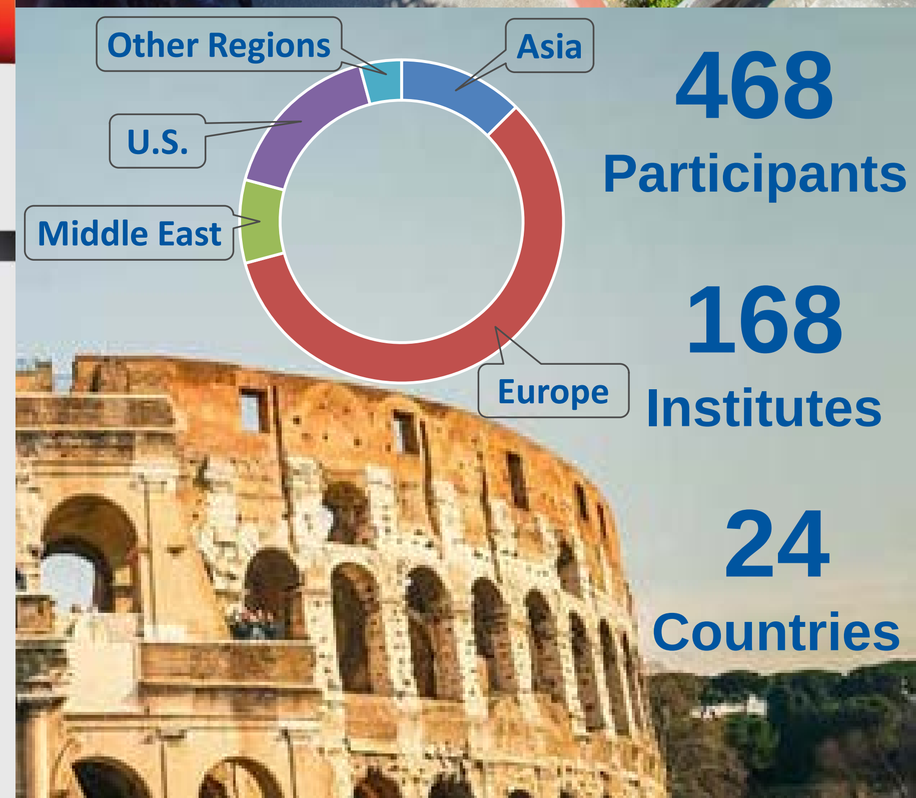
D. Tommasini (CERN)
G. Tonelli (U. Pisa)
P. Vedrine (CEA)
A. Weiler (TU München)
J. Wenninger (CERN)
F. Zimmermann (CERN)
F. Zwirner (U. Padova)



Conclusions

- There is a strong, rising interest in Future Circular Colliders and a community is forming to study these machines
- International collaboration is needed to advance with this study on all of its challenging subjects
- Japanese expertise and participation in accelerators, experiments & physics are essential and most welcome!
- Consolidated parameter sets for both machines FCC-hh and FCC-ee have been established. Work on all areas, accelerator physics, technologies, infrastructures, detectors and physics is advancing well.
- Next milestone is a study review at FCC Week 2017, to define contents of the Conceptual Design Report.

FCC Week 2017

29 May – 2 June 2017
Berlin, Germany