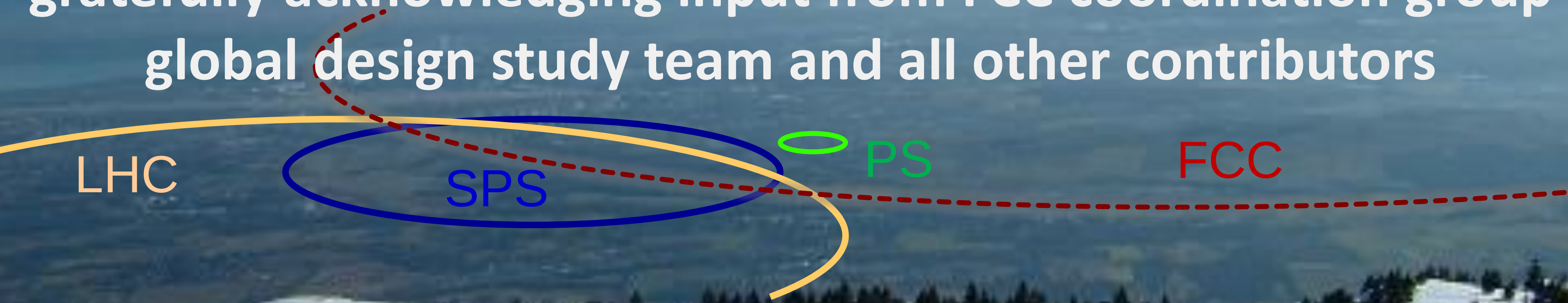
Future Circular Collider Study

Status and Progress

M. Benedikt

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



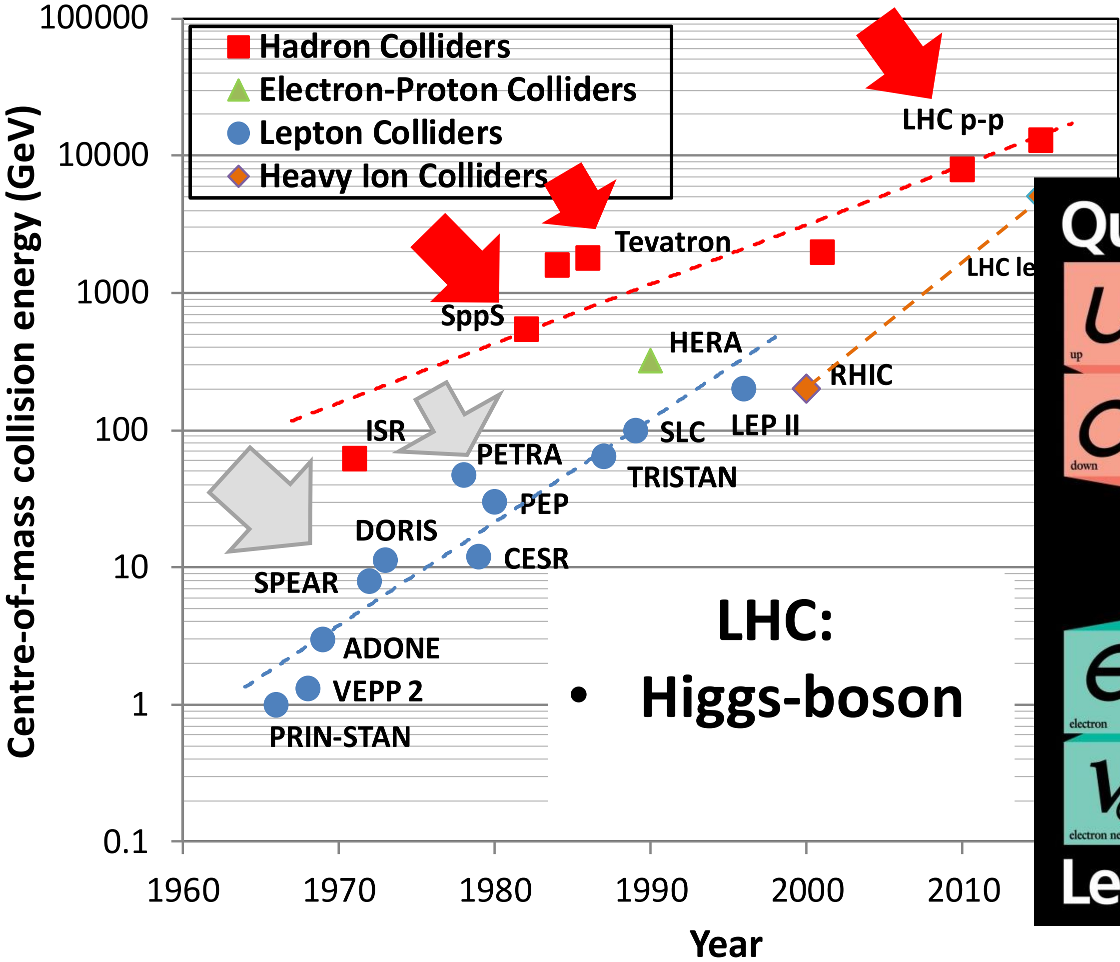
http://cern.ch/fcc

*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
- Detectors & Machine Detector Interface
- Technologies
- FCC Organisation & Collaboration

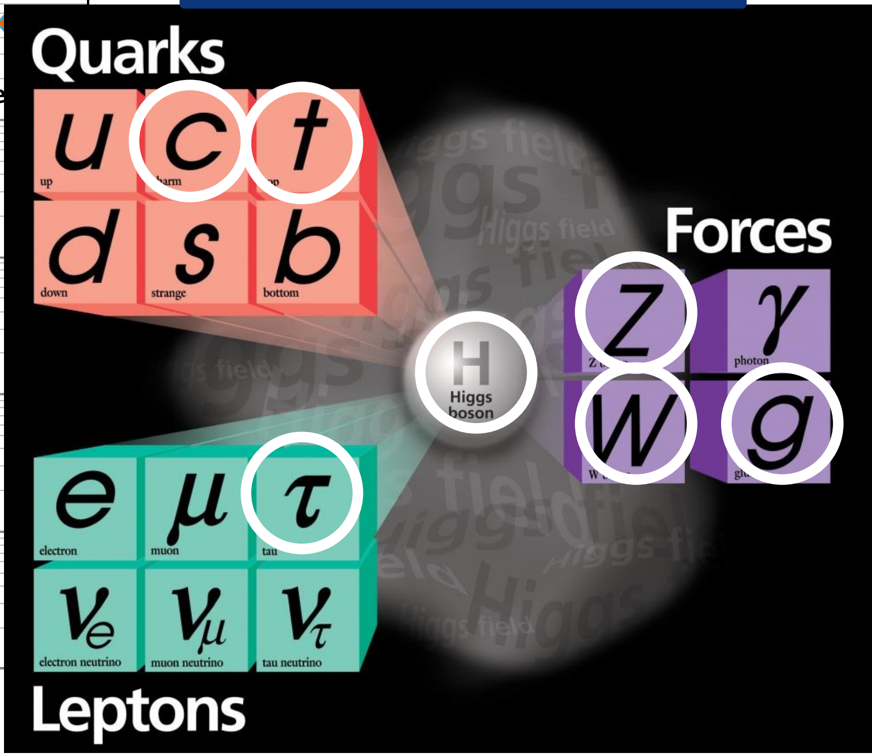
Discoveries by colliders



LHC:

- **Higgs-boson**

Standard Model Particles and forces



Colliders are powerful instruments in High Energy physics for particle discoveries and precision measurements

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…."

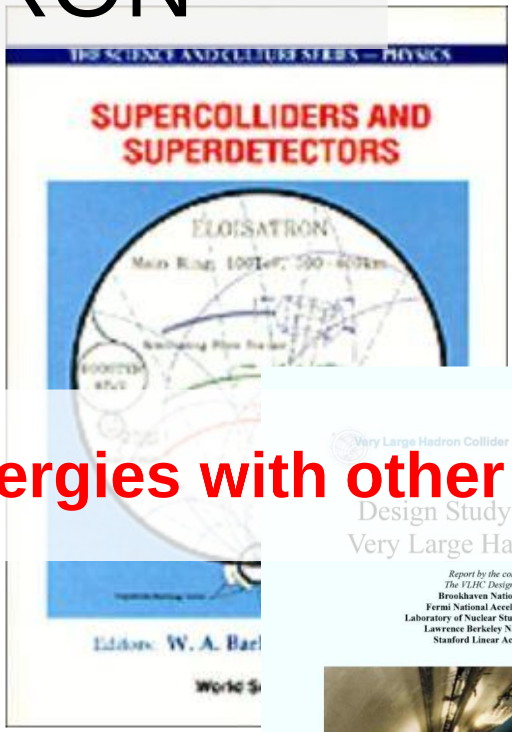
- **International Committee on Future Acceelrators statement 2014:**

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

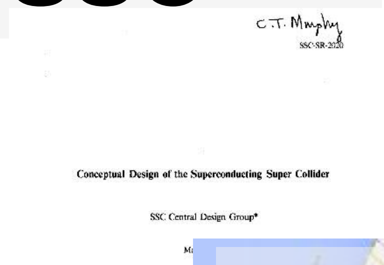
Previous studies in Italy (ELOISATRON 300km), USA (SSC 87km, VLHC 233km), Japan (TRISTAN-II 94km)

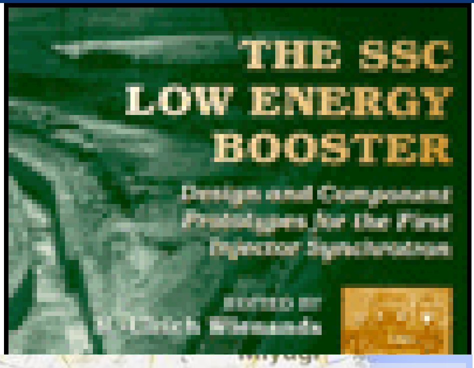
ELOISATRON

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



SSC



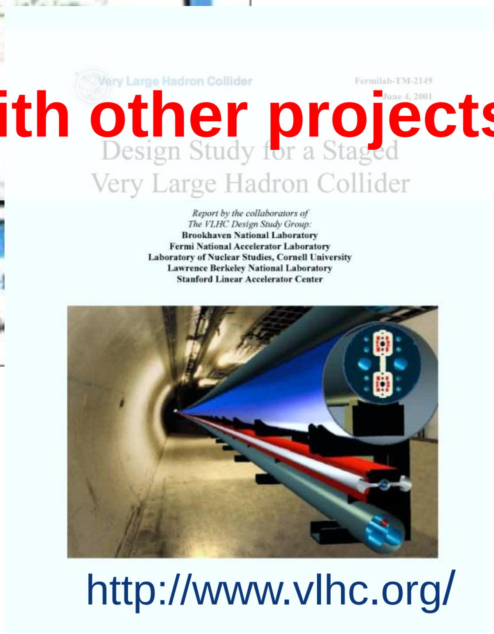


SSC C

→ Exploit synergies with other projects and prev. studies

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/

TRISTAN II

F. Takasaki

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"

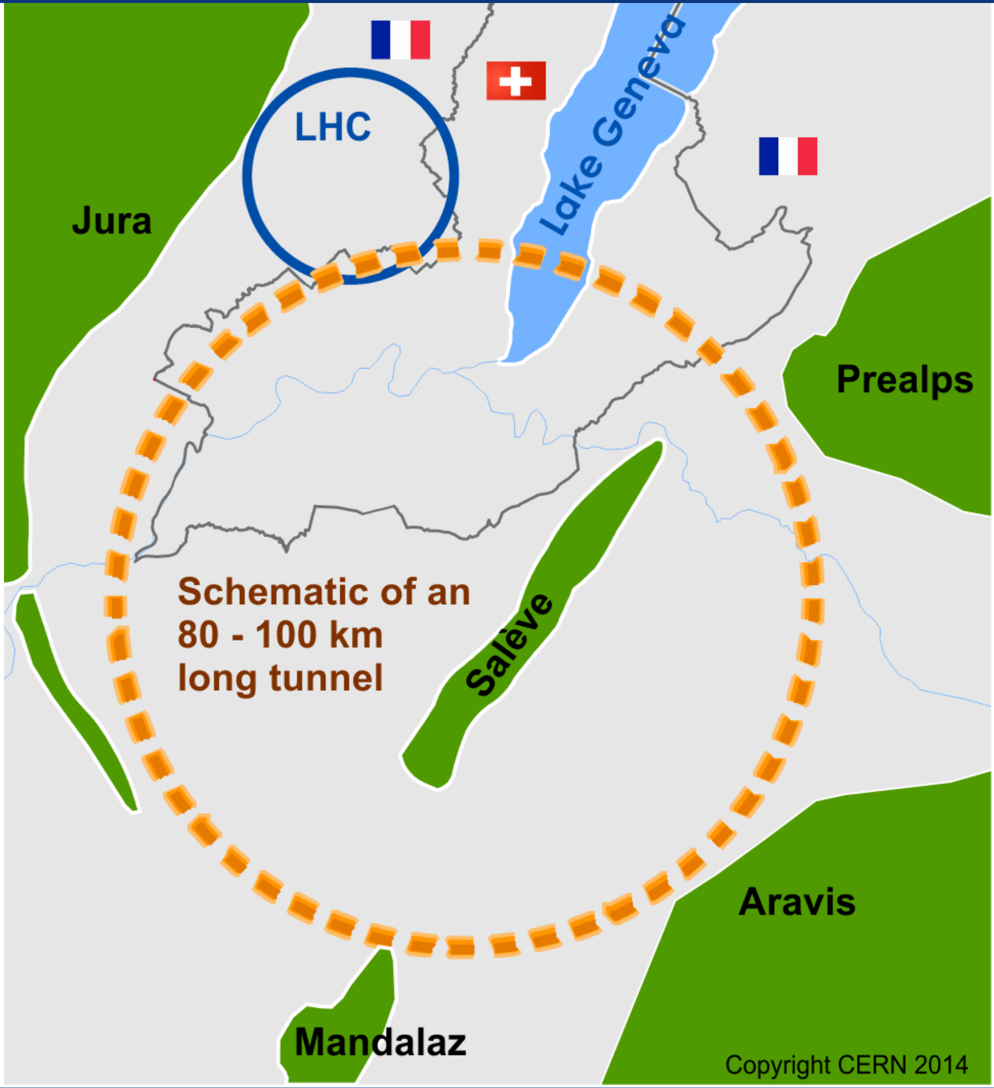
Future Circular Collider Study
GOAL: CDR and cost review for the next ESU (2019)

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

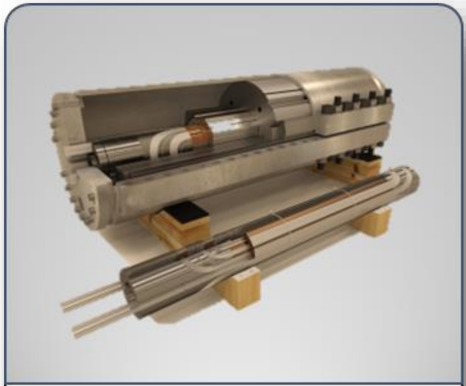
- **80-100 km tunnel infrastructure** in Geneva area, site specific
- ***e⁺e⁻* collider (*FCC-ee*),** as potential first step
- ***p-e* (*FCC-he*) option,** integration one IP, FCC-hh & ERL
- **HE-LHC** with *FCC-hh* technology



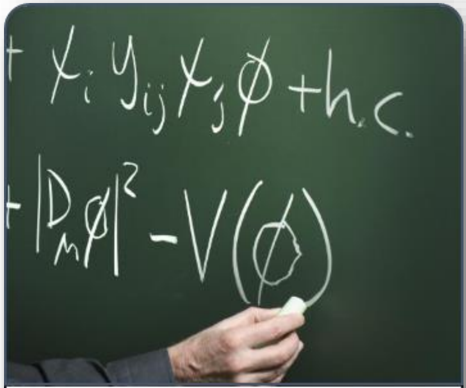
FCC Scope:
Accelerator and Infrastructure

Collider Designs

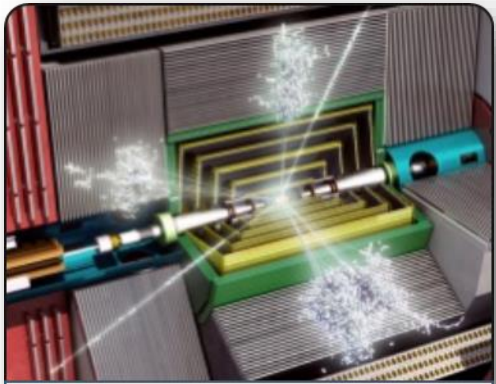
Infrastructures



R&D Programs



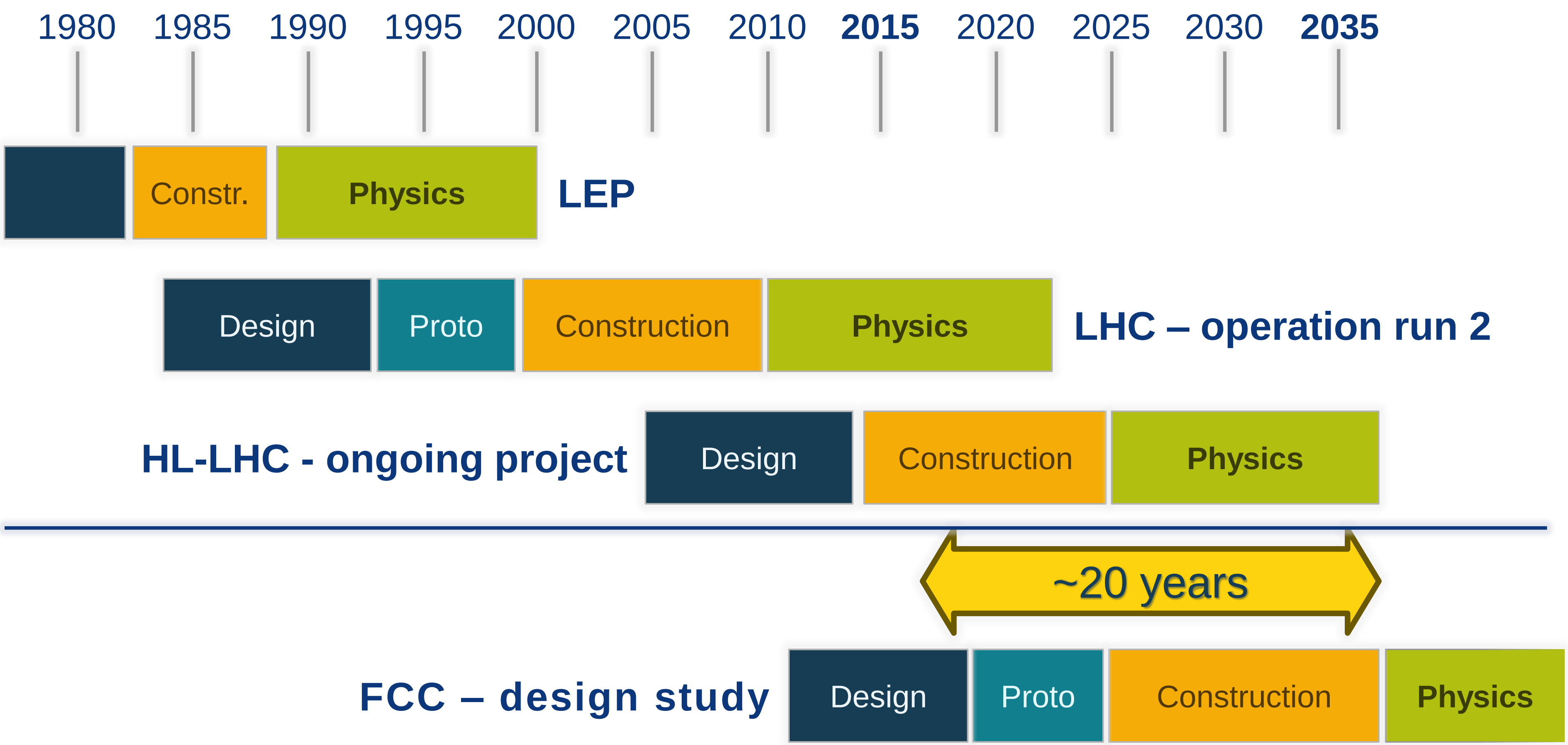
Physics Cases



Experiments

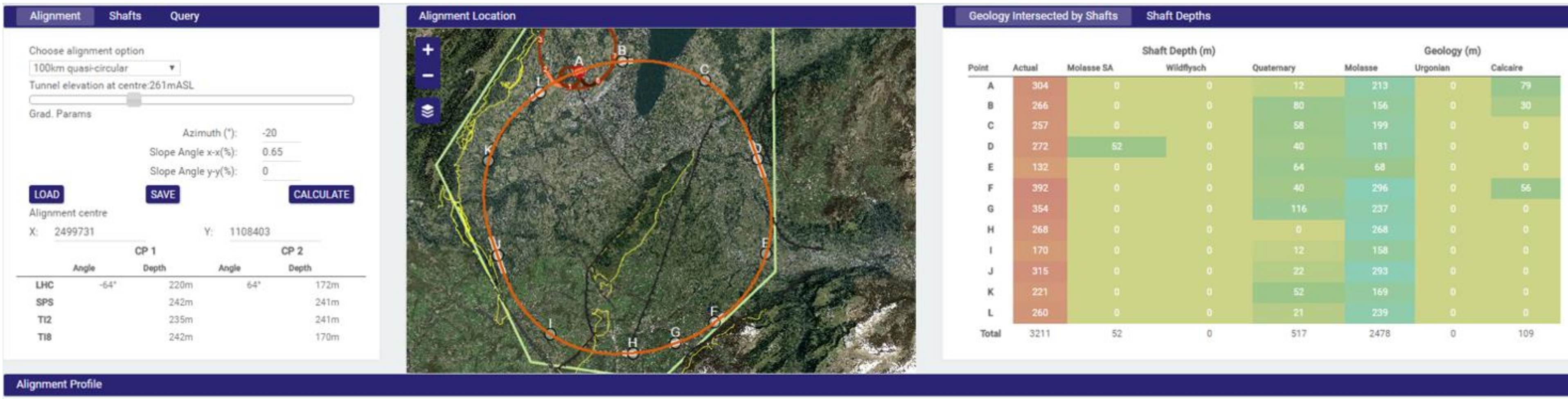
Cost Estimates

CERN Circular Colliders & FCC



Must advance fast now to be ready for the period 2035 – 2040
Goal of phase 1: CDR by end 2018 for next update of European Strategy

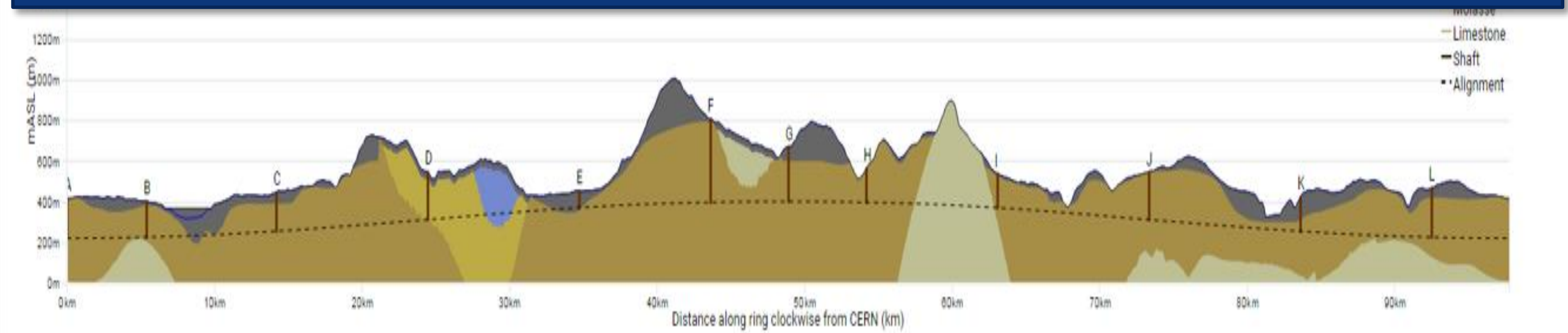
Progress on site investigations



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

	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

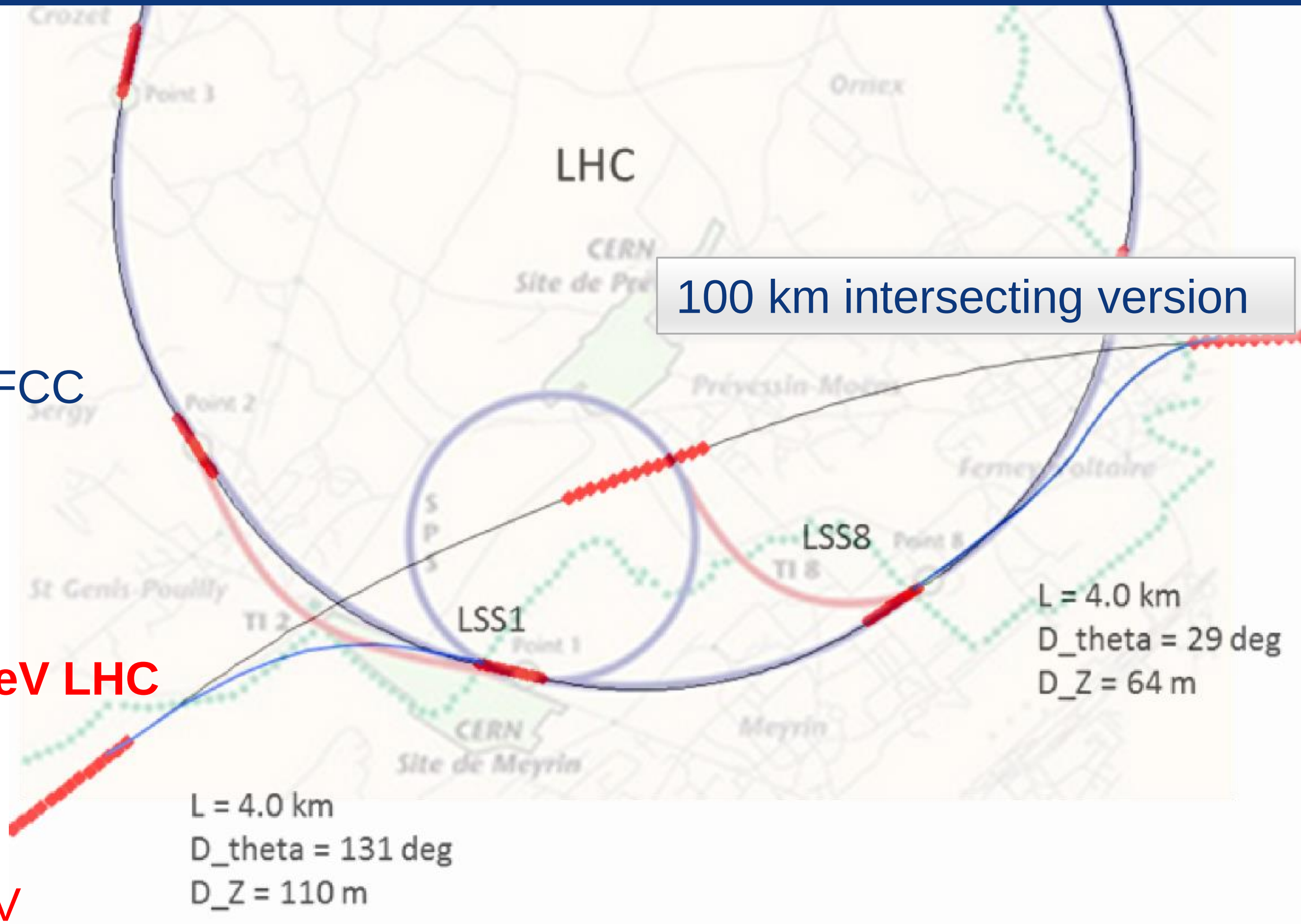
- 90 – 100 km fits geological situation well



FCC-hh injector studies

Injector options:

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



Current baseline:

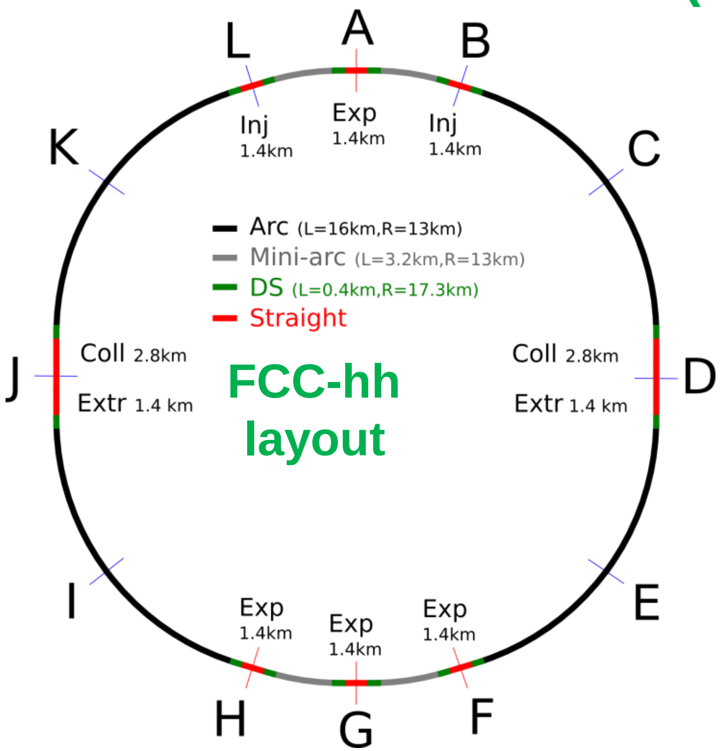
- **injection energy 3.3 TeV LHC**

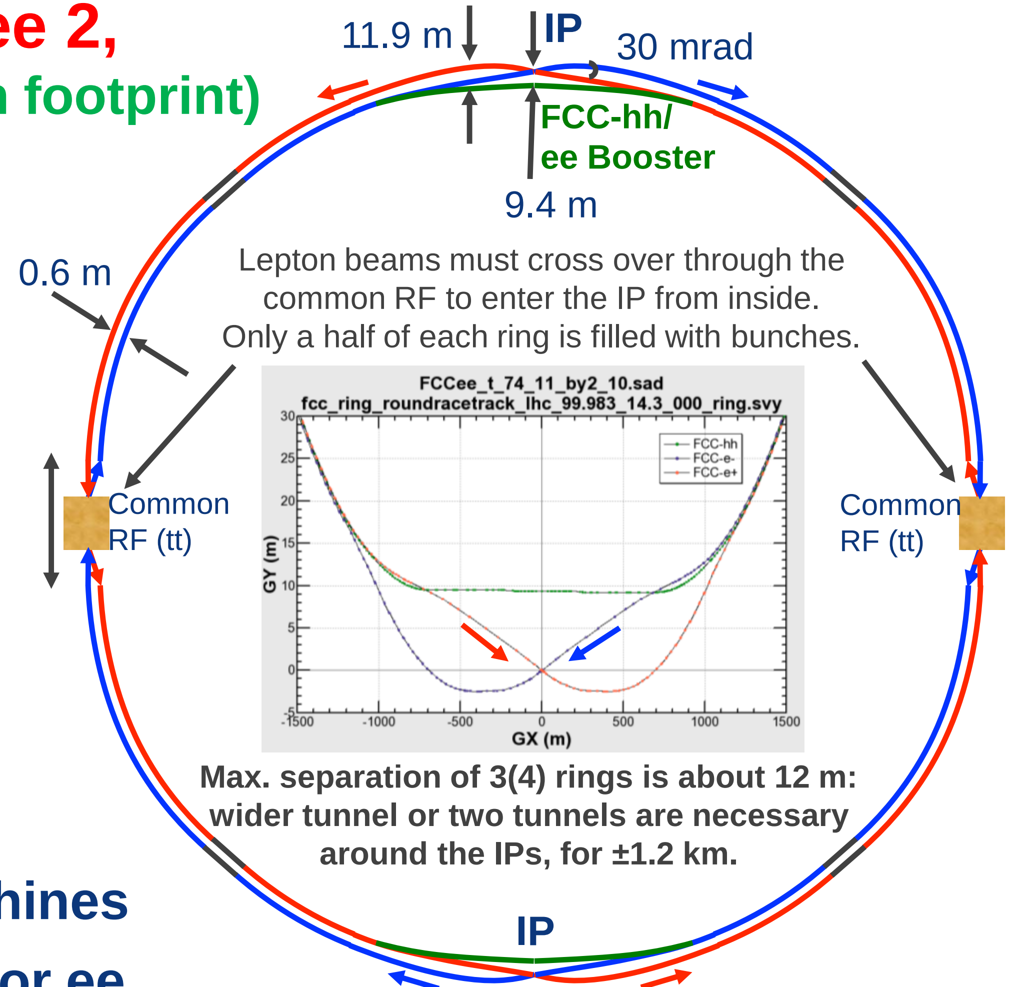
Alternative options:

- Injection around 1.5 TeV
- **compatible with: $SPS_{upgrade}$, LHC, FCC booster**
- **$SPS_{upgrade}$ could be based on fast-cycling SC magnets, 6-7T, ~ 1T/s ramp**

Common layouts for hh & ee

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





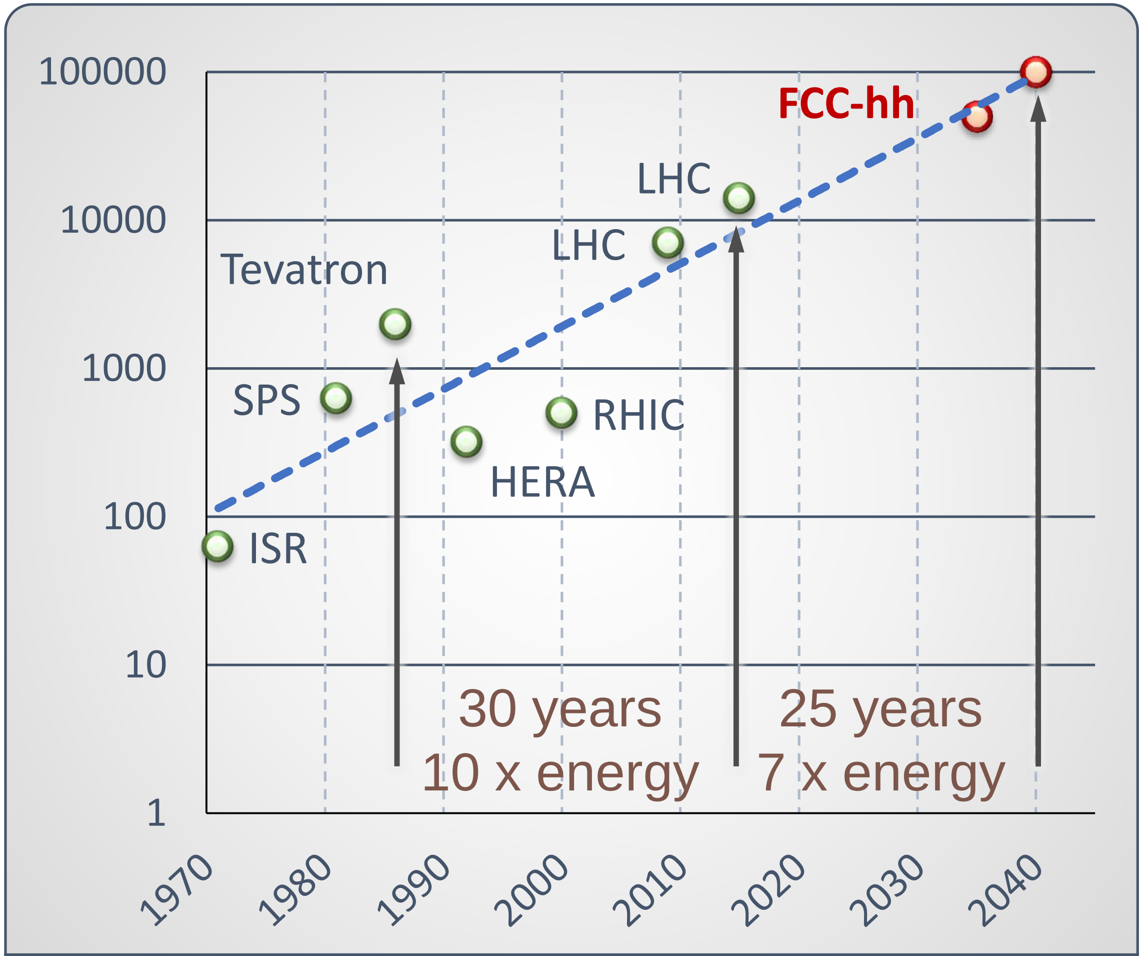
- **2 main IPs in A, G for both machines**
- **asymmetric IR optic/geometry for ee to limit synchrotron radiation to detector**

Hadron collider parameters

parameter	FCC-hh		SPPC	HE-LHC*	(HL) LHC
collision energy cms [TeV]	100		71.2	>25	14
dipole field [T]	16		20	16	8.3
circumference [km]	100		54	27	27
# IP	2 main & 2		2	2 & 2	2 & 2
beam current [A]	0.5		1.0	1.12	(1.12) 0.58
bunch intensity [10^{11}]	1	1 (0.2)	2	2.2	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25	25	25
beta* [m]	1.1	0.3	0.75	0.25	(0.15) 0.55
luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	5	20 - 30	12	>25	(5) 1
events/bunch crossing	170	<1020 (204)	400	850	(135) 27
stored energy/beam [GJ]	8.4		6.6	1.2	(0.7) 0.36
synchrotr. rad. [W/m/beam]	30		58	3.6	(0.35) 0.18

*tentative

Energy evolution



Hadron collider energy evolution [GeV vs. year]

Physics prospects

Physics at the FCC-hh

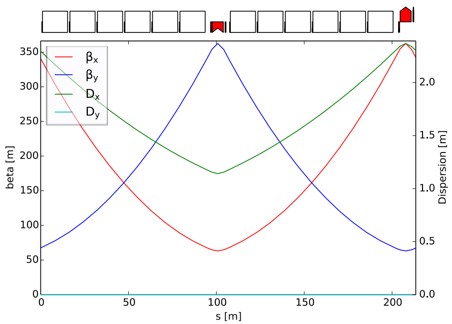
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider

- **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)

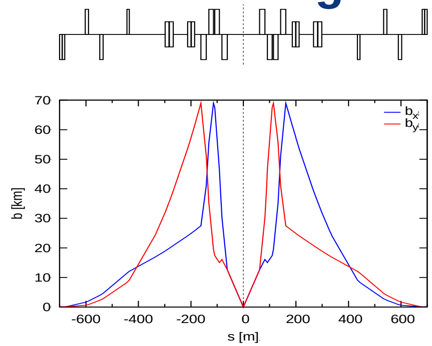
- **Being published as CERN yellow report**

FCC-hh full-ring optics design

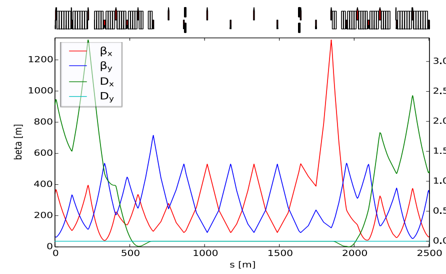
Regular arc cell



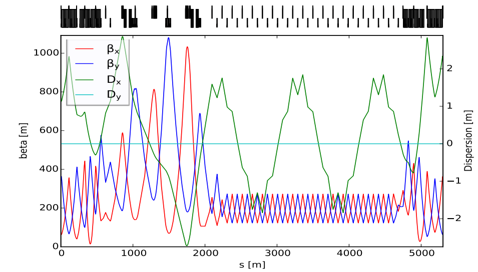
Interaction region



Injection with RF

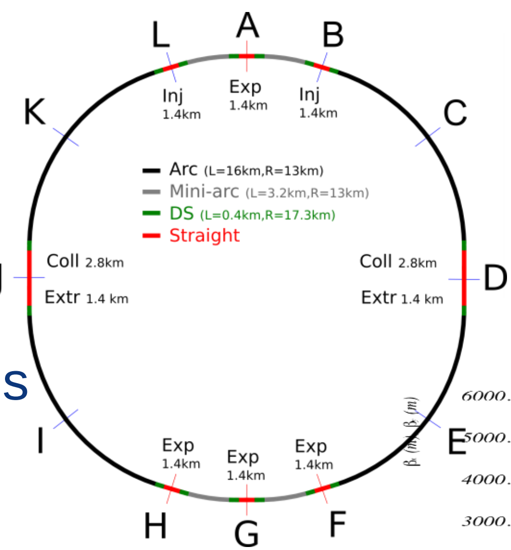


Momentum collim.

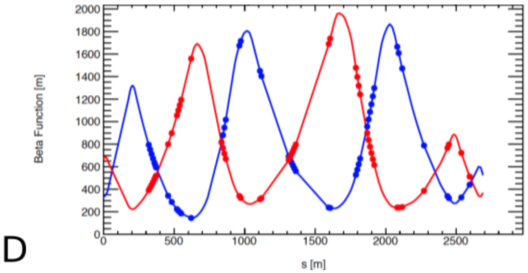


Full ring optics design available as basis for:

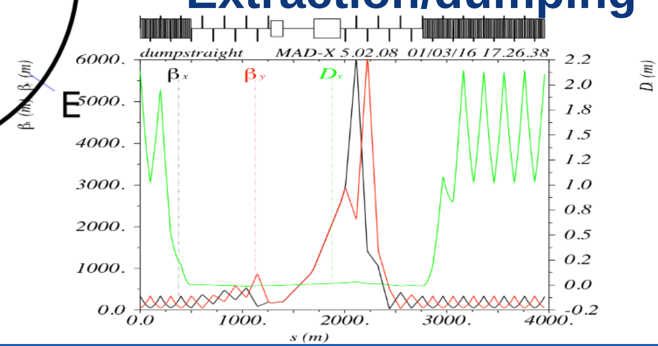
- beam dynamics studies
- optimisation of each insertion
- definition of system specifications (apertures, etc.)
- improvement of baseline optics and layout
- collimation efficiency study & optimisation



Betatron collimation

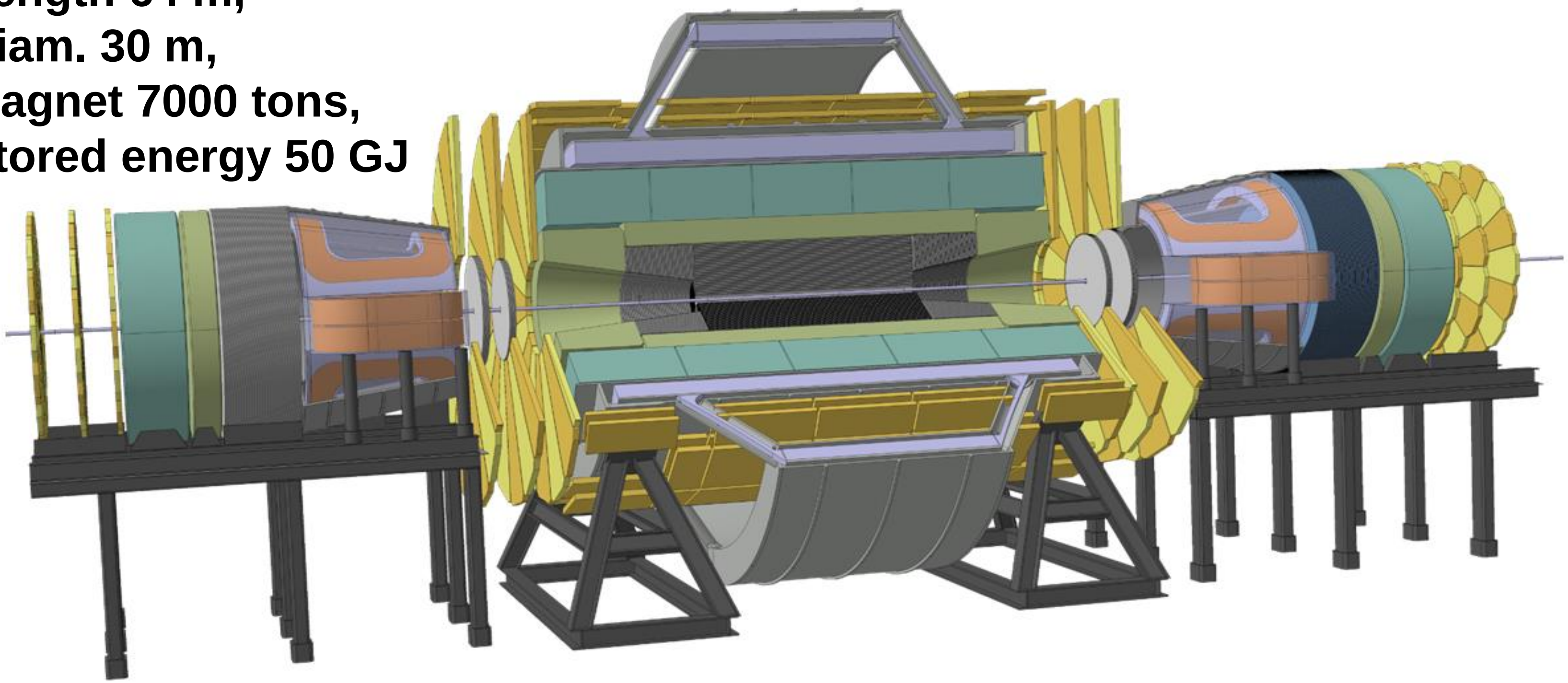


Extraction/dumping



Detector concepts for 100 TeV pp

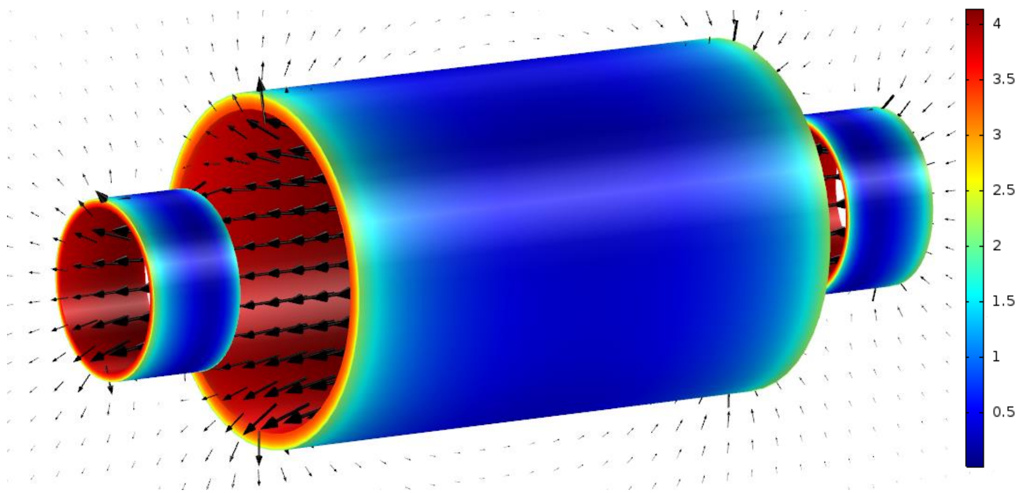
- **A B=6 T, R=6 m solenoid with shielding coil and 2 dipoles has been engineered in detail. Alternative magnet systems are being studied**
  - **Length 64 m,**
  - **Diam. 30 m,**
  - **Magnet 7000 tons,**
  - **Stored energy 50 GJ**



R&D for FCC detectors will be a natural continuation of LHC Phase II upgrade

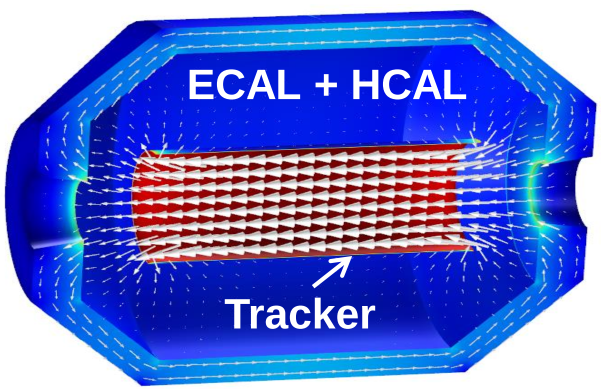
Detector Magnet Studies

Designs for physics-performing and cost-efficient magnet systems



Today's baseline:

4T/10m bore 20m long Main Solenoid
4T Side Solenoids – all unshielded
14 GJ stored energy, 30 kA and
2200 tons system weight



Alternative challenging design:

4T/4m Ultra-thin, high-strength Main Solenoid
allowing positioning inside the e-calorimeter,
280 MPa conductor (side solenoids not shown)
0.9 GJ stored energy, elegant, 25 t only,
but needs R&D!

Beam power and machine protection

Stored energy 8.4 GJ per beam

– At least one order of magnitude higher than for LHC, equivalent to A380 (560 t) at nominal speed (850 km/h).

– **Collimation, control of beam losses and radiation effects (shielding) are of prime importance.**

– **Injection, beam transfer and beam dump all critical.**

Damage of a beam with an energy of 2 MJ

All machine protection issues to be addressed early on!

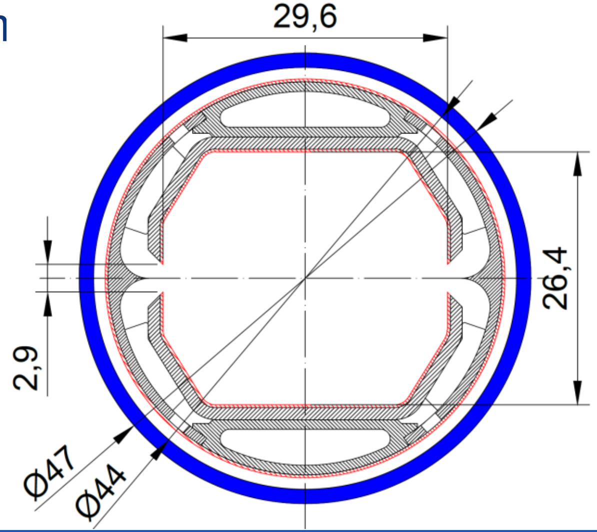
Synchrotron radiation beam screen prototype

High synchrotron radiation load of proton beams @ 50 TeV:

- **~30 W/m/beam (@16 T)** (LHC <0.2W/m)
- **5 MW total in arcs (@1.9 K!!!)**

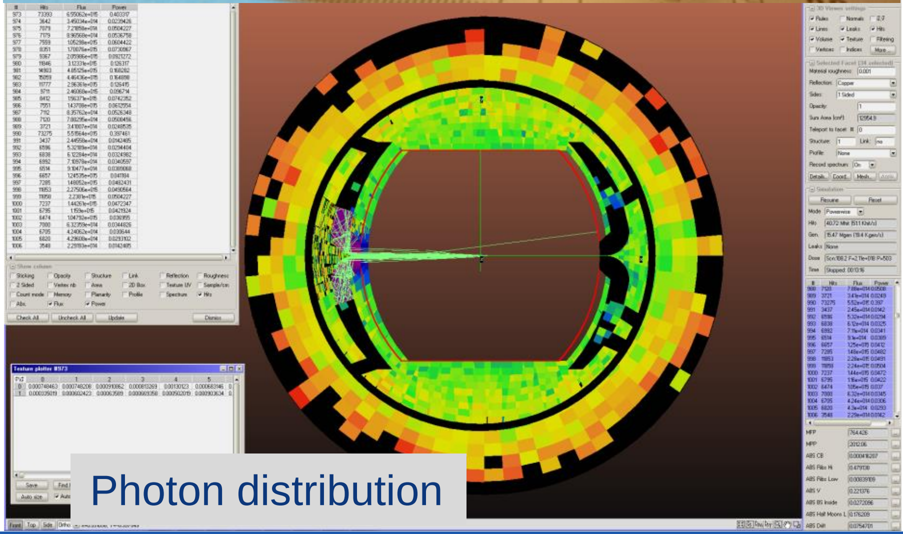
New Beam screen with ante-chamber

- absorption of synchrotron radiation at 50 K to reduce cryogenic power
- factor 50! reduction of power for cryo system



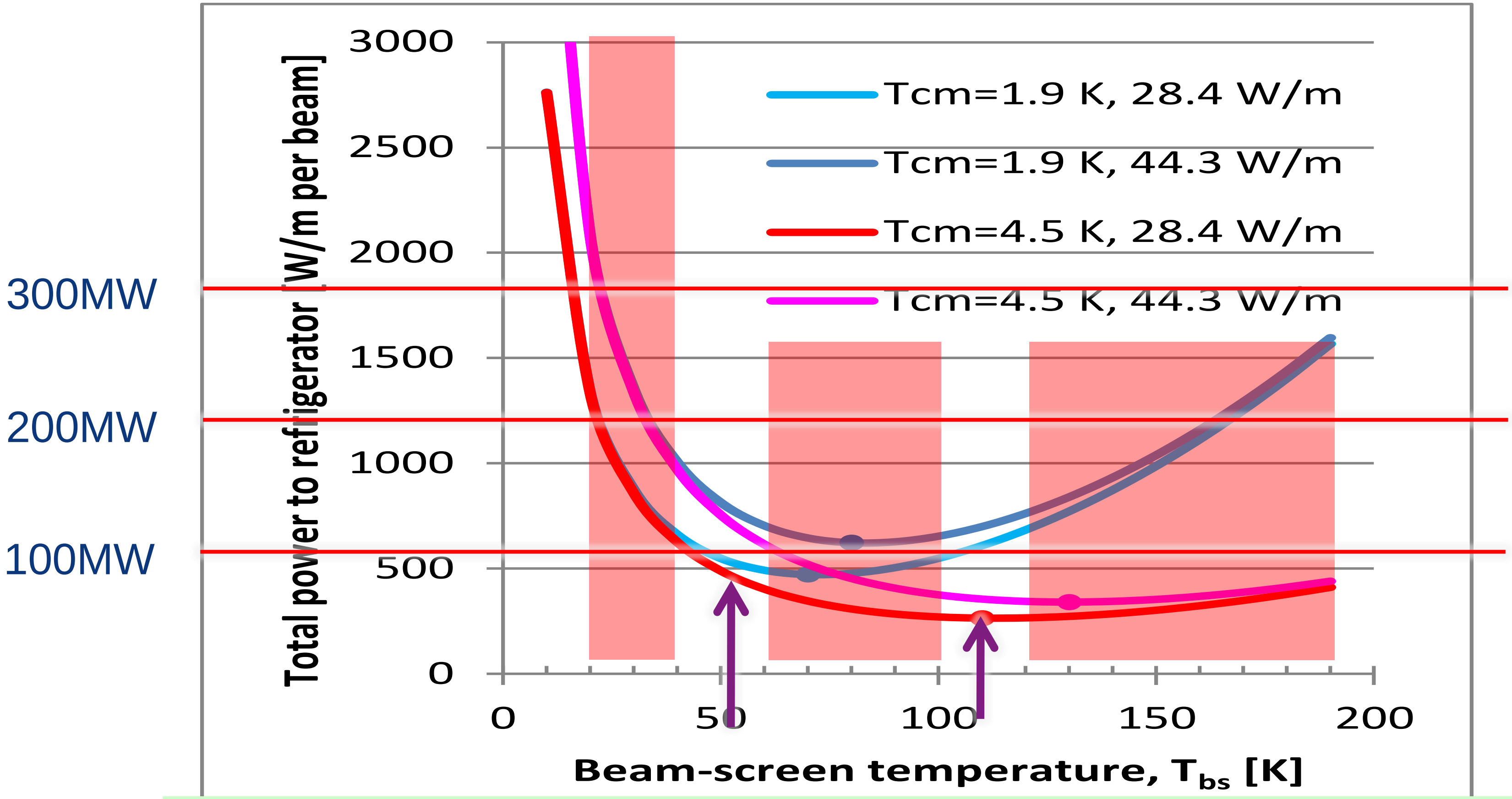
First FCC-hh beam screen prototype

Testing 2017 in ANKA within EuroCirCol



Cryo power for cooling of SR heat

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



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

Main SC Magnet system FCC (16 T) vs LHC (8.3 T)

FCC

Bore diameter: 50 mm

Dipoles: $\mathbf{4578\ \mathit{units}, 14.3\ \mathit{m\ long}, 16\ \mathit{T} \Leftrightarrow \int \mathit{Bdl} \sim 1\ \mathit{MTm}}$

$\mathbf{Stored\ energy \sim 200\ GJ\ (GigaJoule) \sim 44\ MJ/unit}$

Quads: $\mathbf{762\ \mathit{magnets},\ \ 6.6\ \mathit{m\ long}, 375\ \mathit{T/m}}$

LHC

Bore diameter: 56 mm

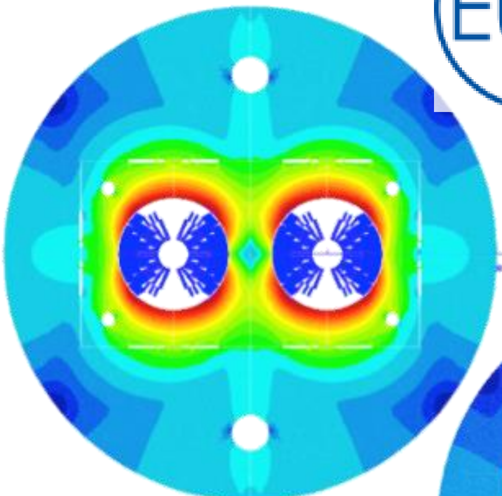
Dipoles: $\mathbf{1232\ \mathit{units}, 14.3\ \mathit{m\ long}, 8.3\ \mathit{T} \Leftrightarrow \int \mathit{Bdl} \sim 0.15\ \mathit{MTm}}$

$\mathbf{Stored\ energy \sim 9\ GJ\ (GigaJoule) \sim 7\ MJ/unit}$

Quads: $\mathbf{392\ \mathit{units},\ 3.15\ \mathit{m\ long}, 233\ \mathit{T/m}}$

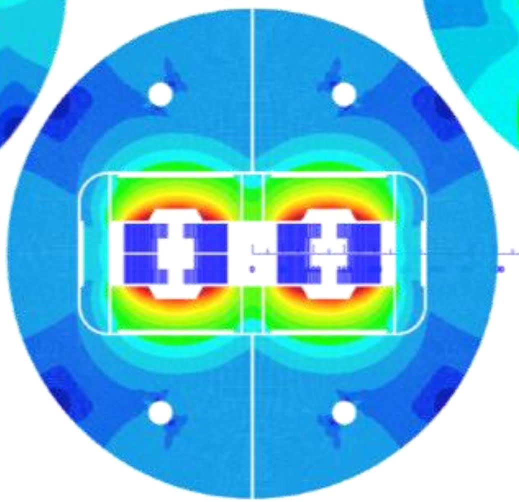
16 T dipole options and plans

Cos-theta

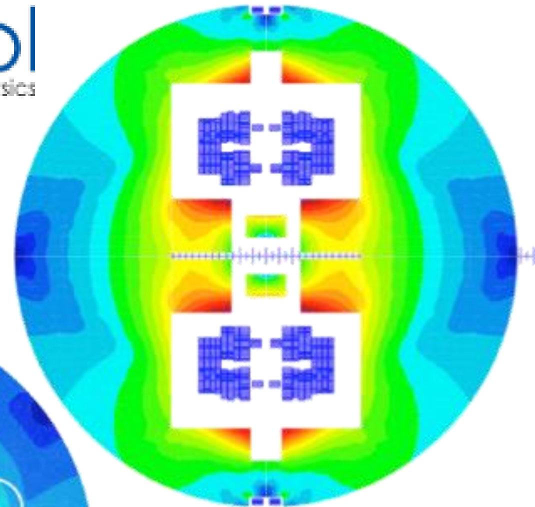


EuroCirCol
A key to New Physics

Blocks

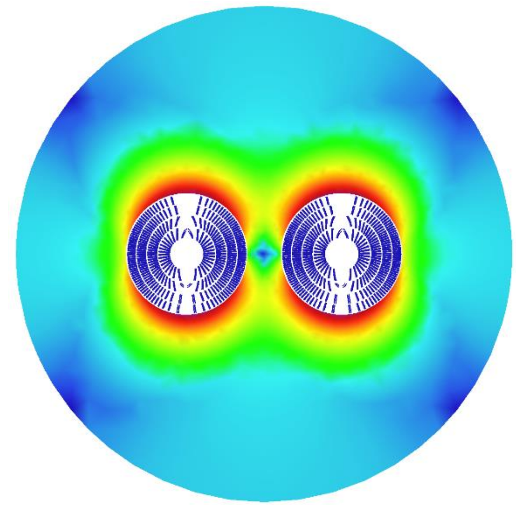


Common coils



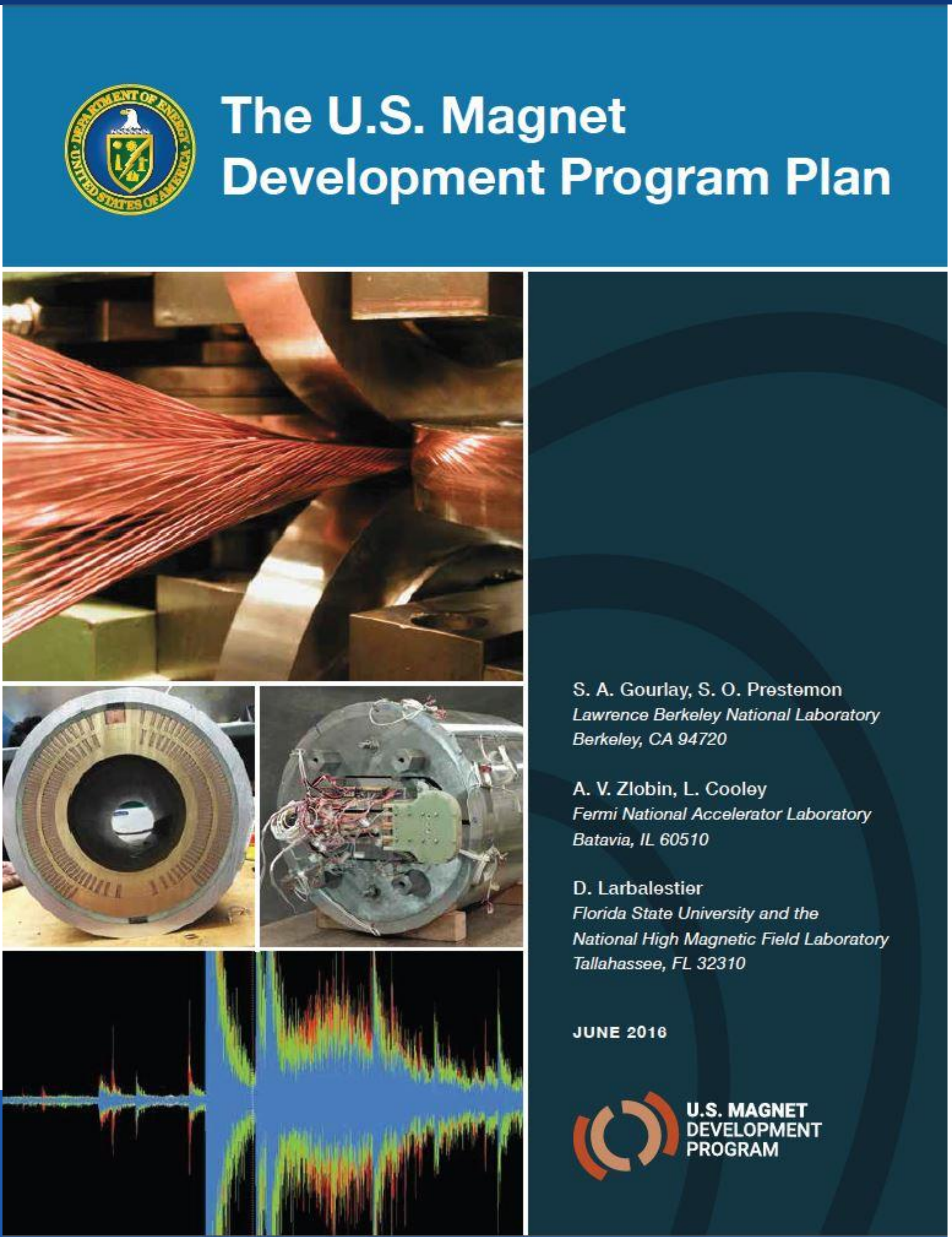
Swiss contribution
via PSI

Canted
Cos-theta



- **Down-selection of options end 2016 for detailed design work**
- **Model production 2018 - 2022**
- **Prototype production 2023 - 2025**

US Magnet Development Program



Program (MDP) Goals:

GOAL 1:

Explore the performance limits of Nb_3Sn accelerator magnets with a focus on minimizing the required operating margin and significantly reducing or eliminating training.

GOAL 2:

Develop and demonstrate an HTS accelerator magnet with a self-field of 5 T or greater compatible with operation in a hybrid LTS/HTS magnet for fields beyond 16 T.

GOAL 3:

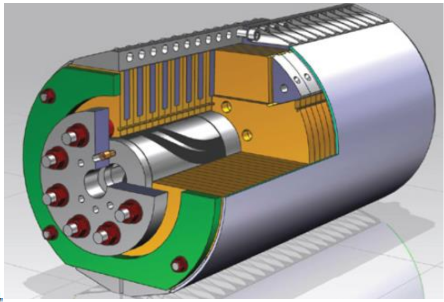
Investigate fundamental aspects of magnet design and technology that can lead to substantial performance improvements and magnet cost reduction.

GOAL 4:

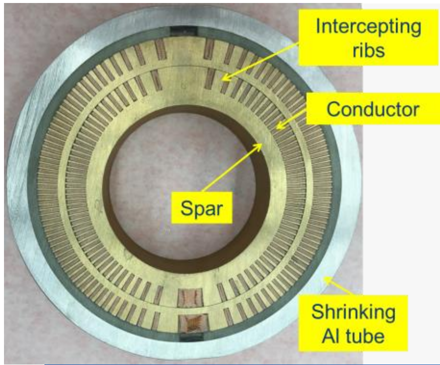
Pursue Nb_3Sn and HTS conductor R&D with clear targets to increase performance and reduce the cost of accelerator magnets.

Under Goal 1:

16 T cos theta dipole design



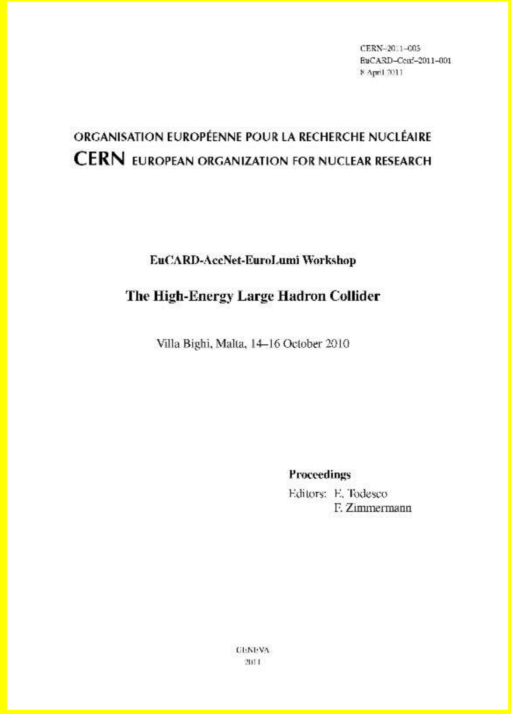
16 T canted cos theta (CCT) design



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
- extraploation from (HL-)LHC and from FCC developments

- **Present focus: optics scaling, infrastructure requirements & integration**

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*
- **some polarization up to ≥80 GeV** for beam energy calibration

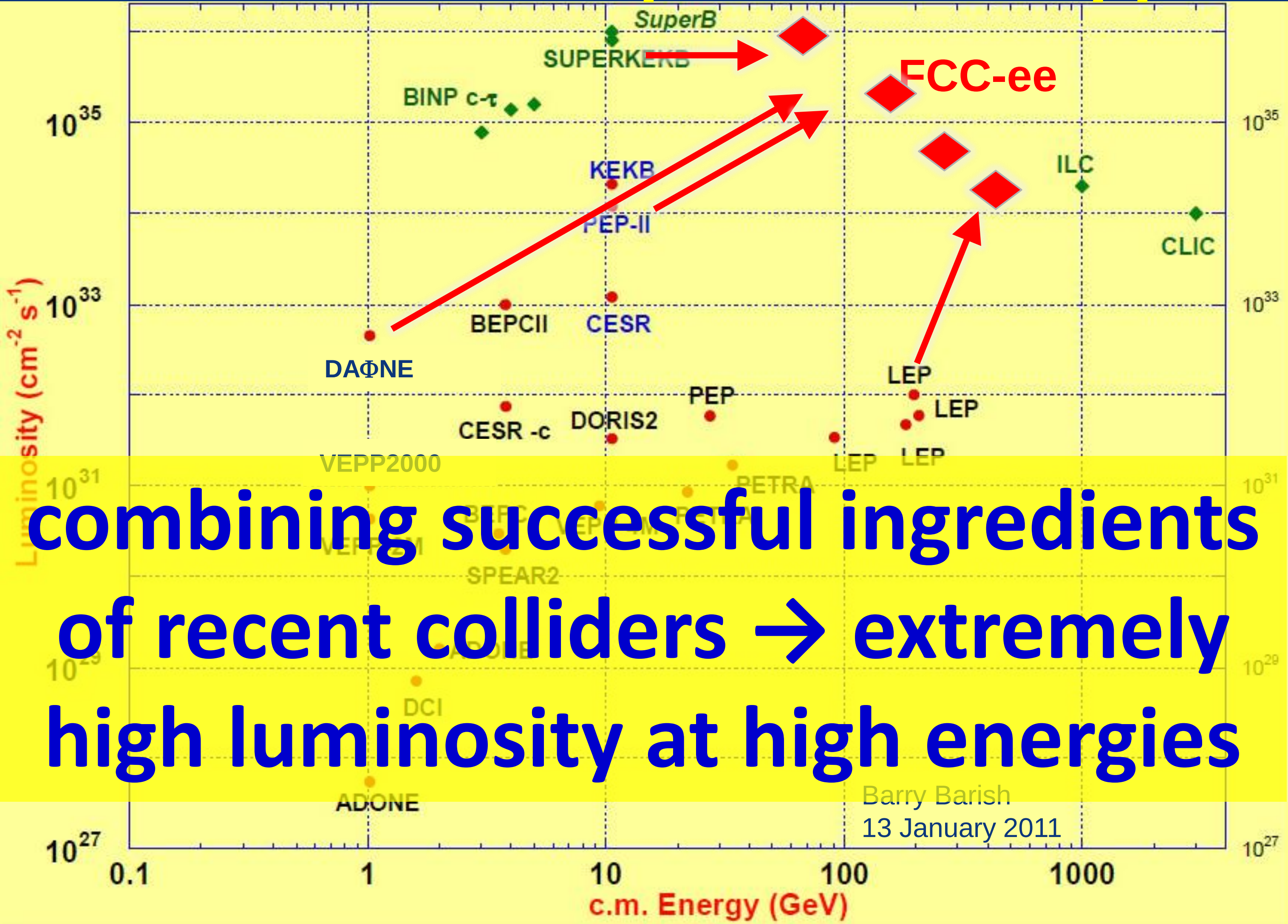
lepton collider parameters

parameter	FCC-ee (400 MHz)					CEPC	LEP2
Physics working point	**Z**		**WW**	**ZH**	**tt_{bar}**	H	
energy/beam [GeV]	**45.6**		**80**	**120**	**175**	120	105
bunches/beam	30180	**91500**	**5260**	**780**	**81**	50	4
bunch spacing [ns]	7.5	**2.5**	**50**	**400**	**4000**	3600	22000
bunch population [10^{11}]	1.0	**0.33**	**0.6**	**0.8**	**1.7**	3.8	4.2
beam current [mA]	1450	**1450**	**152**	**30**	**6.6**	16.6	3
luminosity/IP x $10^{34}cm^{-2}s^{-1}$	210	**90**	**19**	**5.1**	**1.3**	2.0	0.0012
energy loss/turn [GeV]	0.03	**0.03**	**0.33**	**1.67**	**7.55**	3.1	3.34
synchrotron power [MW]	**100**					103	22
RF voltage [GV]	0.4	**0.2**	**0.8**	**3.0**	**10**	6.9	3.5

identical FCC-ee baseline optics for all energies

FCC-ee: 2 separate rings   CEPC, 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

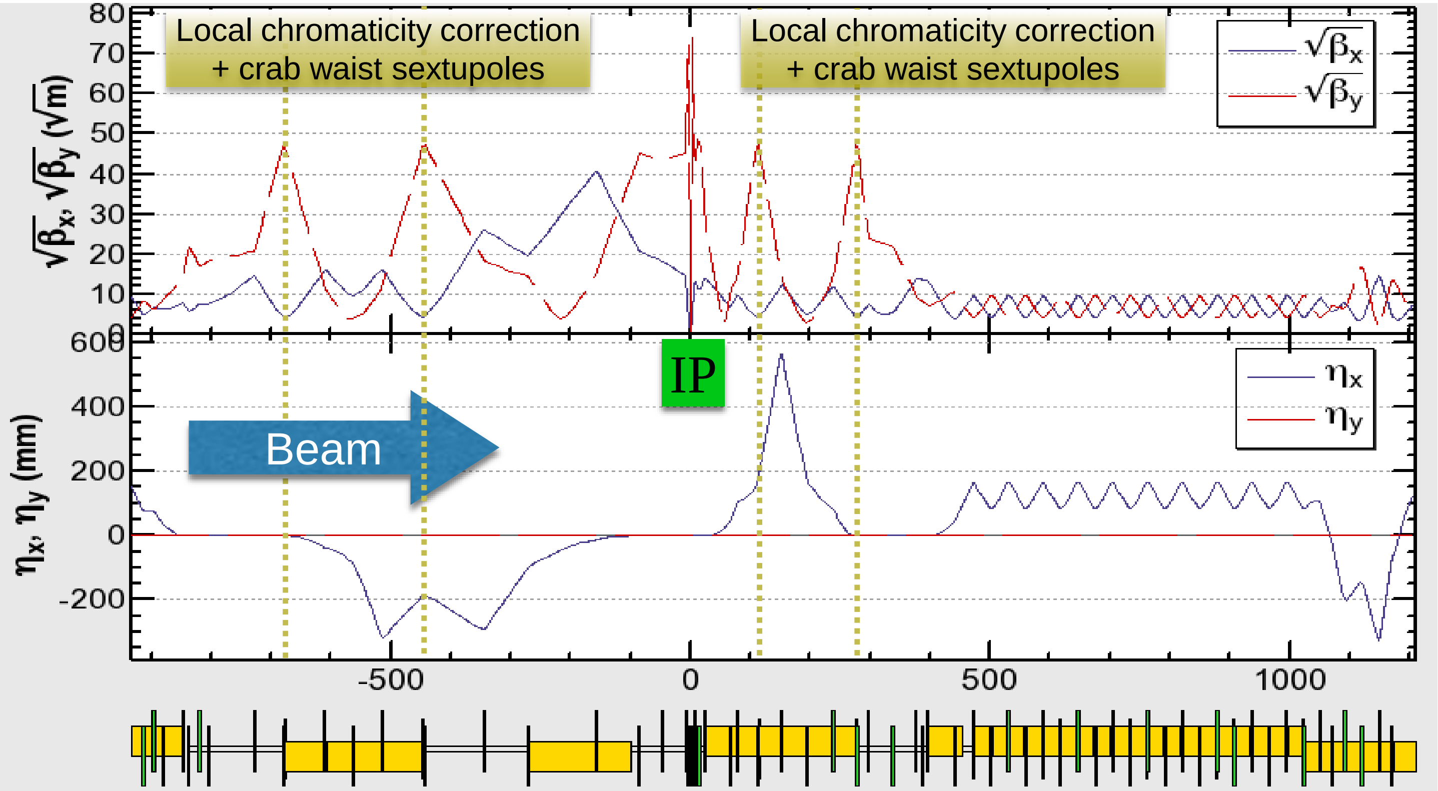
HERA, LEP, RHIC:
- spin gymnastics

FCC-ee optics design

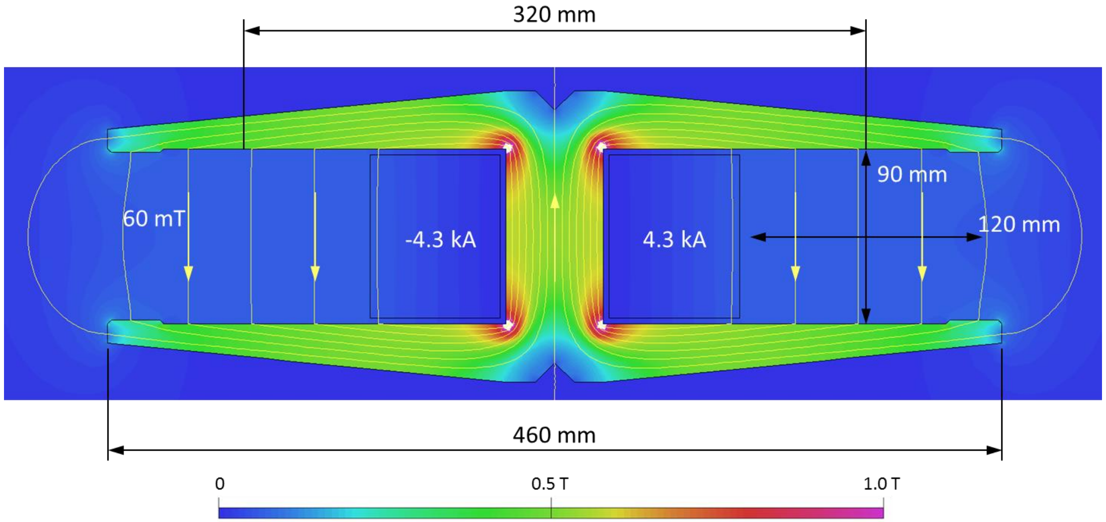
Optics design for all working points achieving baseline performance

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

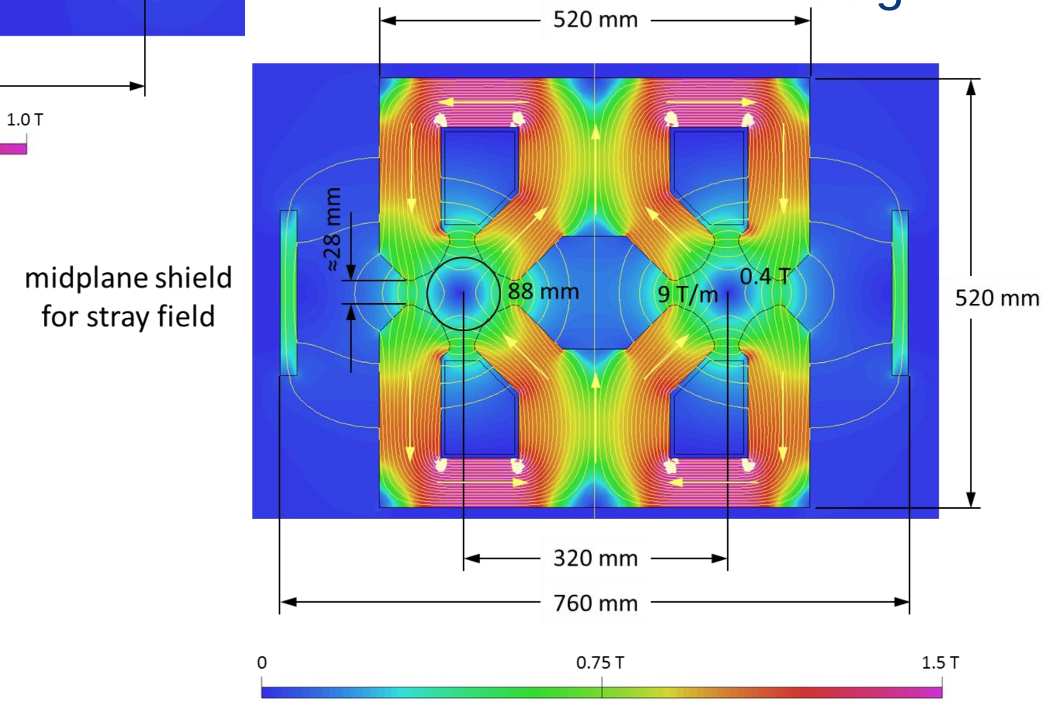


Efficient 2-in-1 FCC-ee arc magnets



Dipole:
twin aperture yoke
single busbars as coils

Quadrupole:
twin 2-in-1 design



- **Novel arrangements allow for considerable savings in Ampere-turns and power consumption**
- **Less units to manufacture, transport, install, align, remove,…**

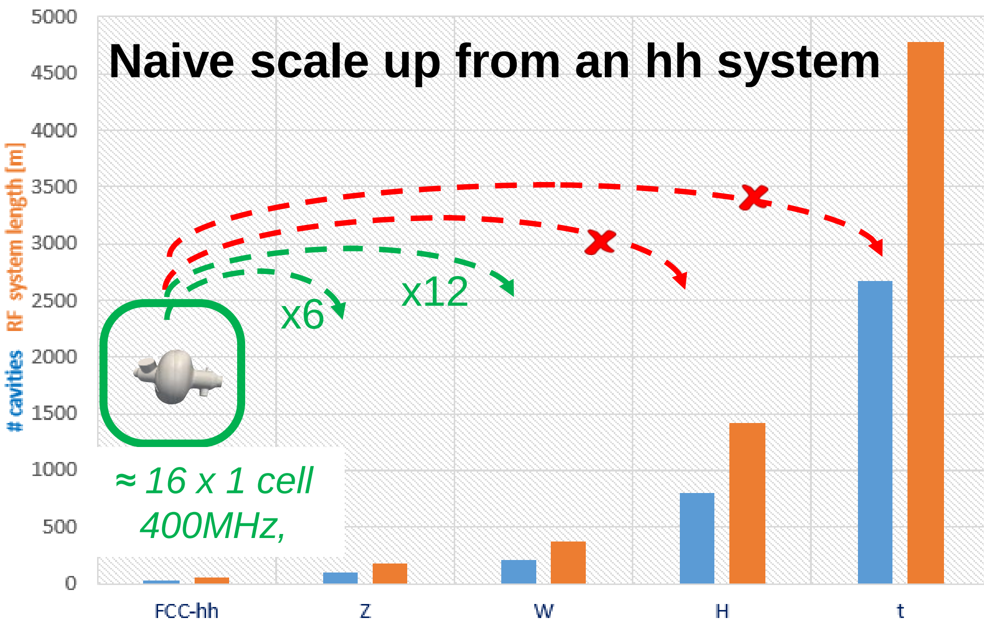
RF system requirements

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	0.4/0.2	30000/90000	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

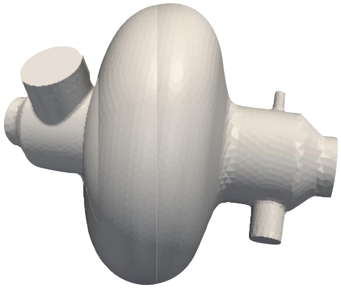


- Voltage and beam current ranges span more than factor > 10^2
- No well-adapted single RF system solution satisfying requirements

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)



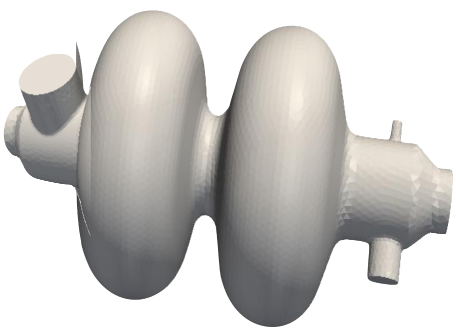
hh — ≈ 16 cells per beam

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-ZH, ee-tt and ee-WW

- 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)

Summary

- FCC study is advancing well towards the CDR for end 2018
- Consolidated parameter sets exists for FCC-hh and FCC-ee machines with complete baseline optics design and beam dynamics compatible with parameter requirements
- First round of geology, civil engineering & infrastructure studies completed
- Superconductivity is the key enabling technology for FCC. Nb3Sn 16T magnets (FCC-hh) and SRF systems (FCC-ee).
- Several other important R&D areas in technology, detectors,...
- **International collaboration is essential to advance on all challenging subjects and the community is warmly invited to join the FCC efforts.**


FCCWEEK2017
Future Circular Collider Conference
BERLIN, GERMANY
29 MAY - 02 JUNE
fccw2017.web.cern.ch