10th Anniversary

J-PARC Symposium 2019

A brief introduction to the Future Circular Collider (FCC) project

K. Oide (CERN)

Many thanks to M. Benedikt, A. Blondel, P. Janot, M. Koratzinos, D. Shatilov, F. Zimmermann, and all FCC-ee collaborators.

Sep. 26, 2019 J-PARC Symposium 2019 @ Tsukuba

Limitation on proton (circular) collider

$$\frac{E}{c} \approx p = eB\rho$$

E: beam energy
c: speed of light
p: momentum
e: charge
B: magnetic field
ρ: bending radius

$$E\ [\mathrm{GeV}] = 0.299792458 \times B\rho\ [\mathrm{Tm}]$$

Collider	LHC	FCC-hh	ratio
E (TeV)	7	50	7.1
Circumference C (km)	26.6	97.8	3.7
ρ (km)	2.8	10.4	3.7
B (T)	8.3	16	1.9
filling factor C / ρ	9.5	9.4	1.0

most crucial subject

Limitation on electron circular collider

$$P_{\mathrm{SR}} = \frac{4\pi}{3} mc^2 r_e \frac{\gamma^4}{\rho} I$$

$$P_{\mathrm{SR}} = 88.5[\mathrm{kW}] \times \frac{E[\mathrm{GeV}]^4}{\rho[m]} I[\mathrm{A}]$$

m: electron mass
c: speed of light
r_e: classical electron radius
γ: Lorentz factor
ρ: bending radius
I: beam current

Collider	LEP2	FCC-ee Z	FCC-ee tt
E (GeV)	104.6	45.6	182.5
Circumference C (km)	26.6	97.8	
ρ (km)	2.6	10.8	
I (mA)	3	1390	5.4
P_{SR} (MW)	12.2	50	

limits the luminosity

Limitation on luminosity

coherent beam-beam 3D flip-flop

beam-beam parameter

$$\mathscr{L} \propto \frac{\xi I}{\beta^*}$$

luminosity

$$\mathscr{L} = \frac{N^2 f}{4\pi\sigma_x^*\sigma_y^*}$$

stored current I

beam dump

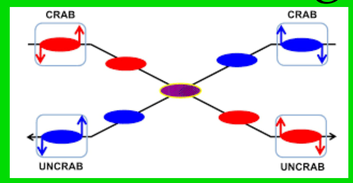
injectors

beamstrahlung

$$\mathscr{L} \approx \frac{I}{2e}\left(\frac{0.1\alpha\eta}{6\pi}\right)^{2/3}\left(\frac{\xi_y}{\gamma r_e^5 \varepsilon_y}\right)^{1/3}$$

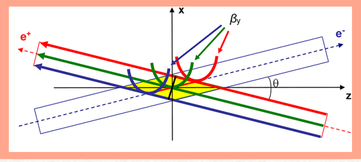
crossing angle

crab-crossing



pile up

crab-waist



parasitic collision

collective effects

beam screen

energy calibration polarization

interaction region

dynamic aperture

beam loss lifetime collimation

e-cloud

high field magnet

low-emittance tuning

machine-detector interface

synchrotron radiation

cryogenics

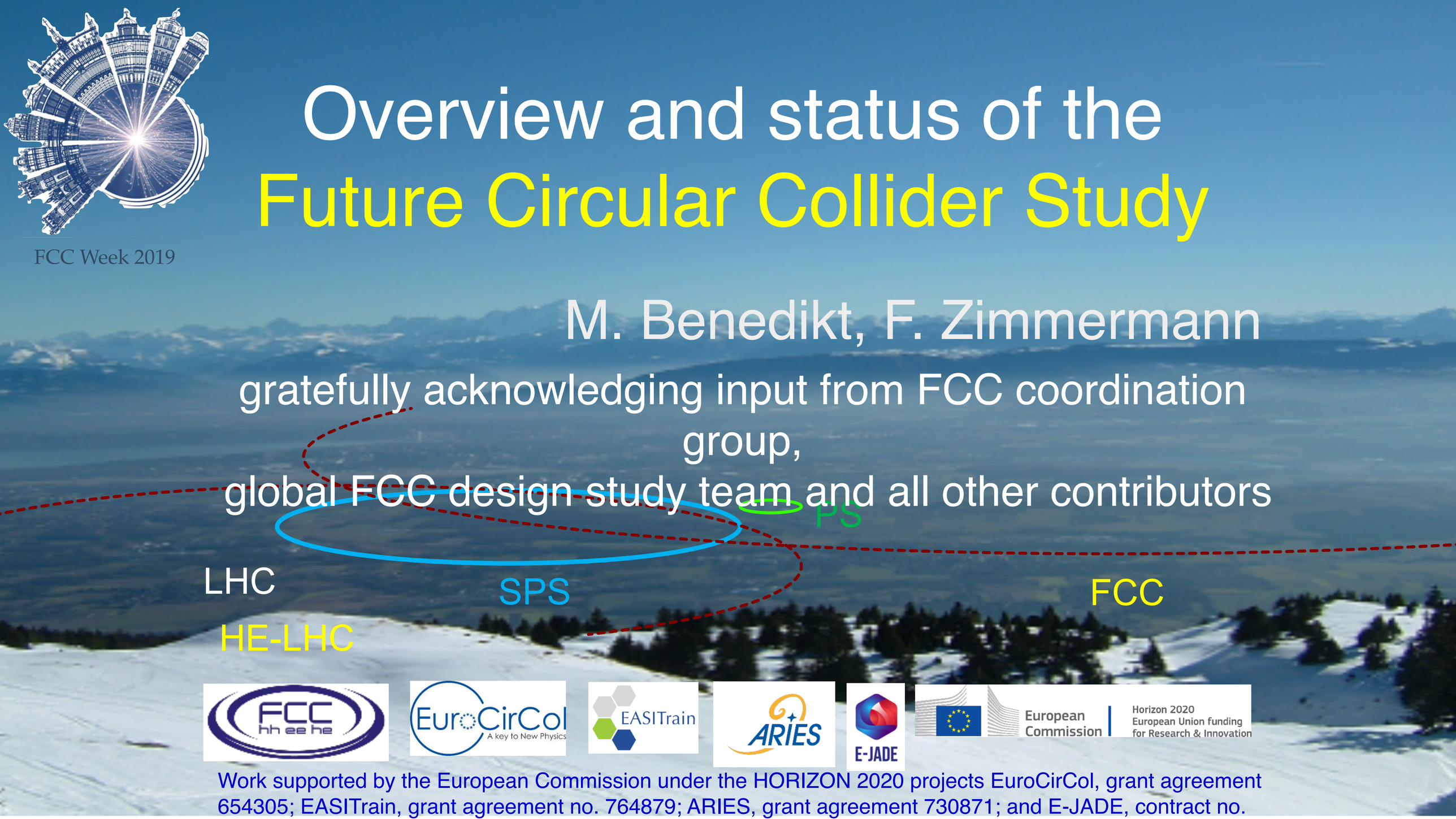
vacuum system

diagnositics

superconducting RF acceleration

…and more!

e+e-
pp
both



FCC Week 2019

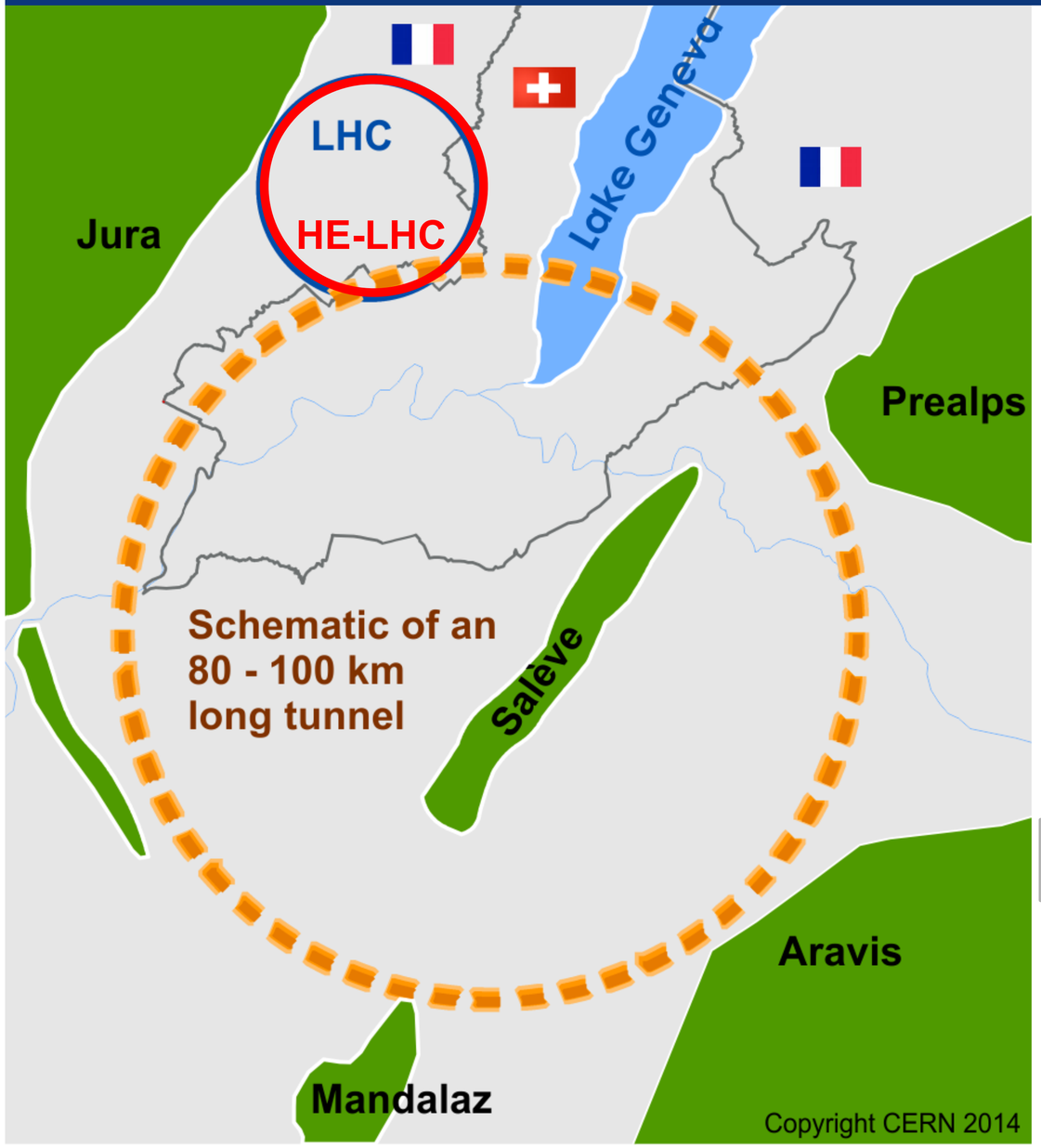
Overview and status of the Future Circular Collider Study

M. Benedikt, F. Zimmermann

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

Work supported by the European Commission under the HORIZON 2020 projects EuroCirCol, grant agreement 654305; EASITrain, grant agreement no. 764879; ARIES, grant agreement 730871; and E-JADE, contract no.

Future Circular Collider Study - Scope



International FCC collaboration with CERN as host lab to study:

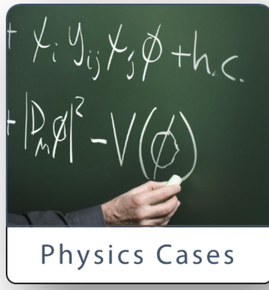
- **~100 km tunnel infrastructure** in Geneva area, linked to CERN
- ***e*⁺*e*⁻ collider (*FCC-ee*),** → potential first step
- ***pp*-collider (*FCC-hh*)** → long-term goal, defining infrastructure requirements

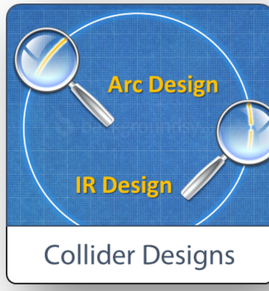
.

~16 T ⇒ 100 TeV *pp* in 100 km

technology

- **Ions** and **lepton-hadron** options with hadron colliders





FCC : physics and performance targets

FCC-ee:

- ~20-50 fold improved precision on many EW quantities (equiv. to factor 5-7 in mass) (m_Z, m_W, m_{top} , $\sin^2\theta_w^{eff}$, R_b , $\alpha_{QED}(m_z)$ α_s (m_z m_W m_τ), Higgs and top quark couplings)
- Exploraing 10 - 100 TeV energy scale via couplings with precision measurements

➢ Machine design for highest luminosities at Z, WW, ZH and ttbar working points

FCC-hh:

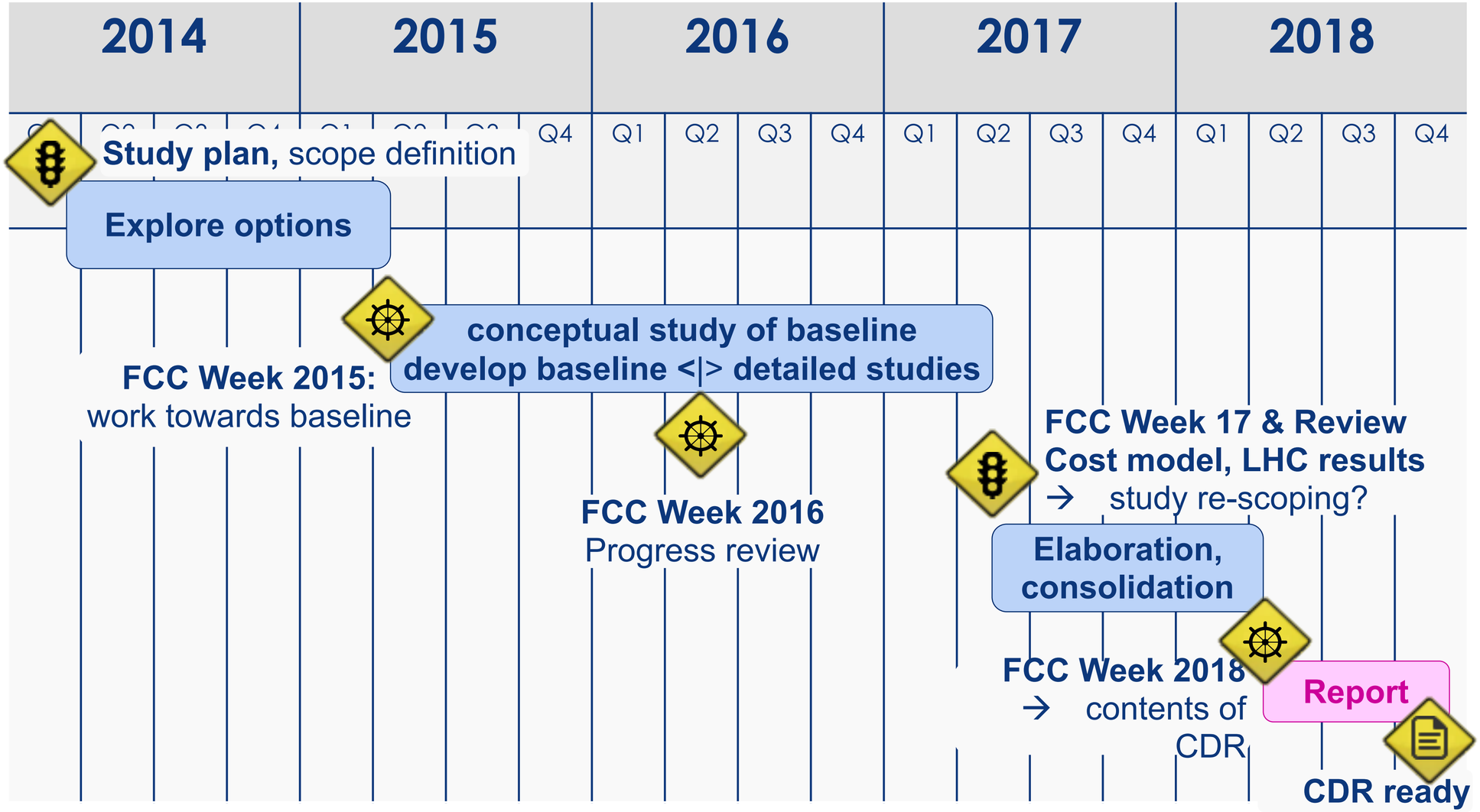
- Highest center of mass energy for direct production up to 20 - 30 TeV
- Huge rates for single and multiple production of SM bosons (H,W,Z) and quarks

➢ Machine design for ~100 TeV c.m. energy & int. luminosity ~ 20ab^{-1} in 25 years

HE-LHC:

- Doubling LHC collision energy with FCC-hh 16 T magnet technology
- c.m. energy ~ 27 TeV = 14 TeV x 16 T/8.33T, target luminosity ≥ 4 x HL-LHC

CDR Study Time Line (from 2014)



Status of global FCC Collaboration

136 Institutes

32 Companies

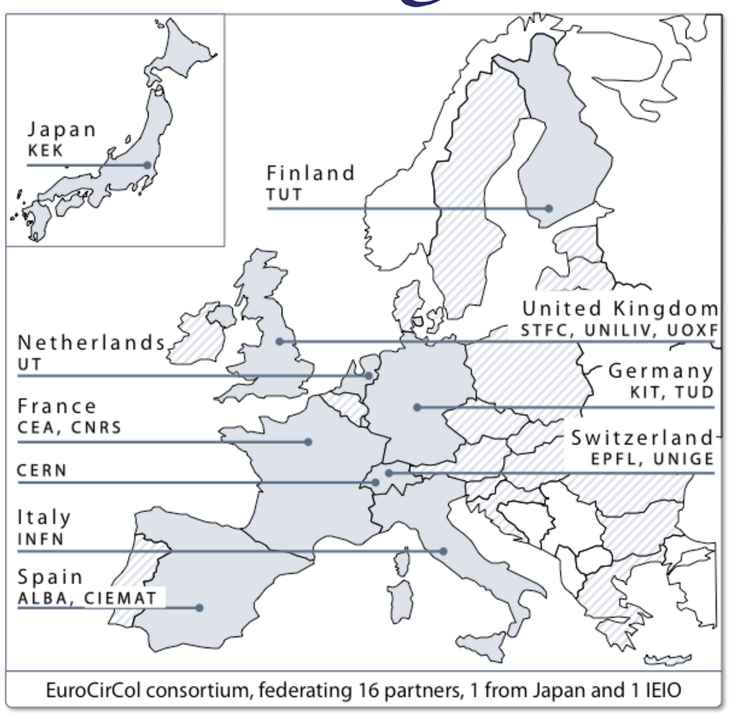
34 Countries

EC H2020

EU H2020 Design Study EuroCirCol

European Union Horizon 2020 program:

- 3 MEURO co-funding
- Started June 2015, ends in Dec 2019
- 15 European beneficiaries & KEK & associated FNAL, BNL, LBL, NHFML

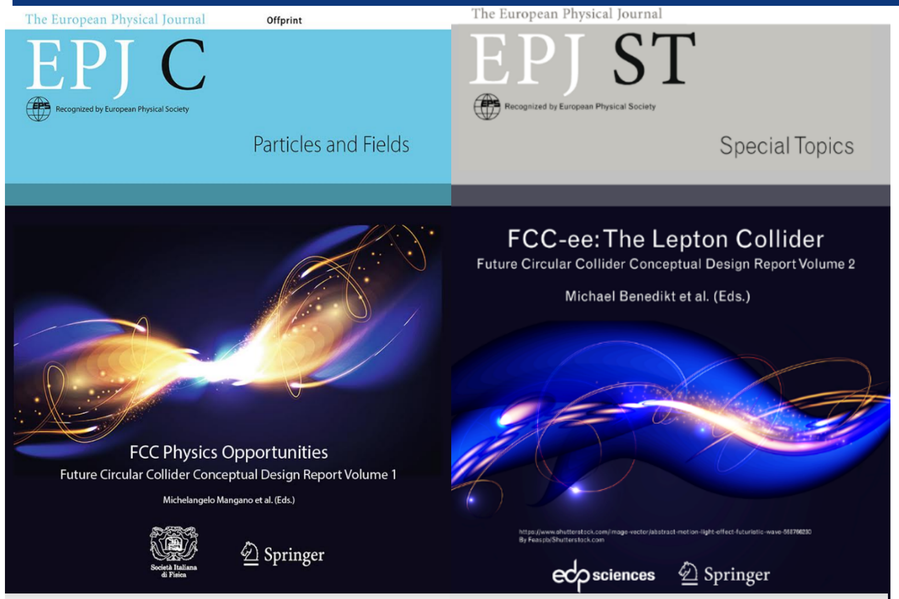


EuroCirCol consortium, federating 16 partners, 1 from Japan and 1 IEIO

Covers FCC-hh key work packages:

- Optics design (arc & IR)
- Cryogenic beam vacuum system design including beam tests at ANKA
- 16 T dipole design, construction folder for demonstrator magnets

Results of FCC Conceptual Design Study



Study Documentation:

4 CDR volumes submitted to EPJ in December 2018.

- FCC Physics Opportunities
- FCC-ee
- FCC-hh
- HE-LHC
- Preprints available since 15 January 2019 http://fcc-cdr.web.cern.ch/

CDR presentation during welcome event this evening.

Paper copies can be requested at

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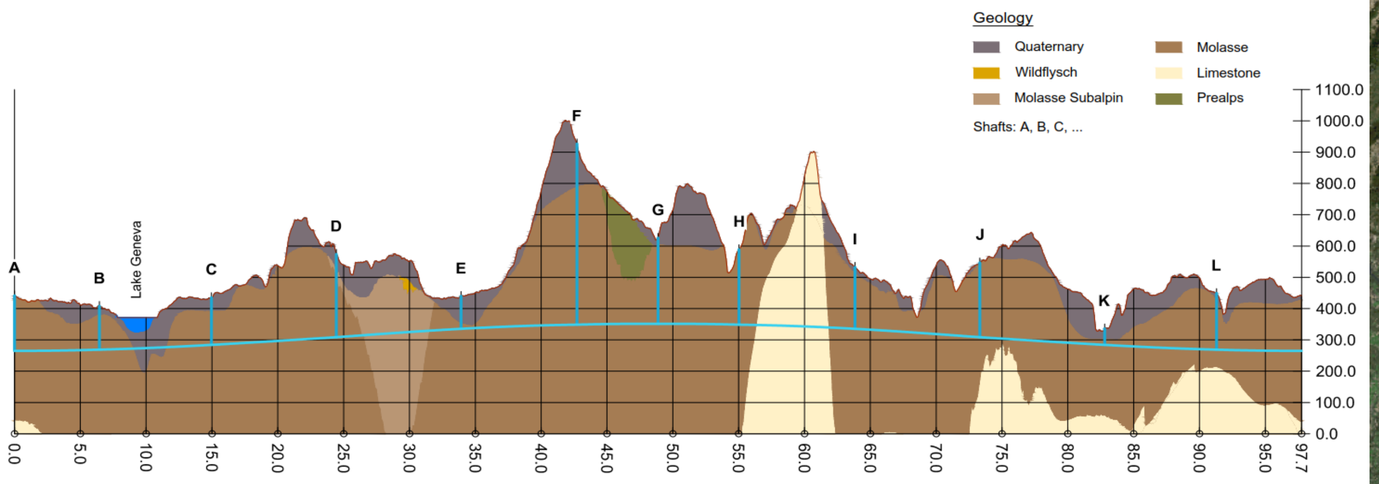
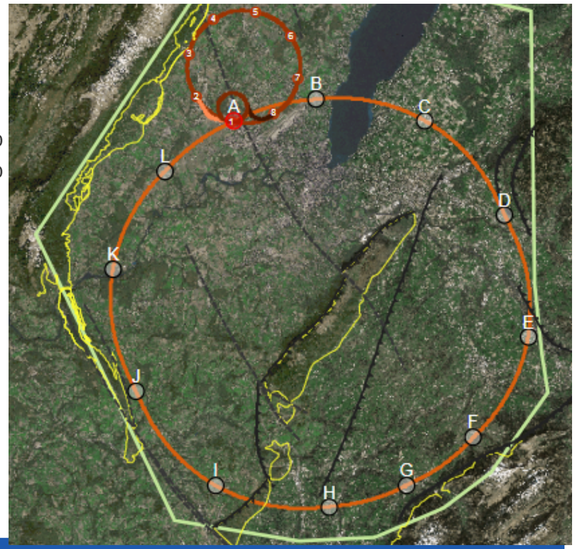
The FCC integral program

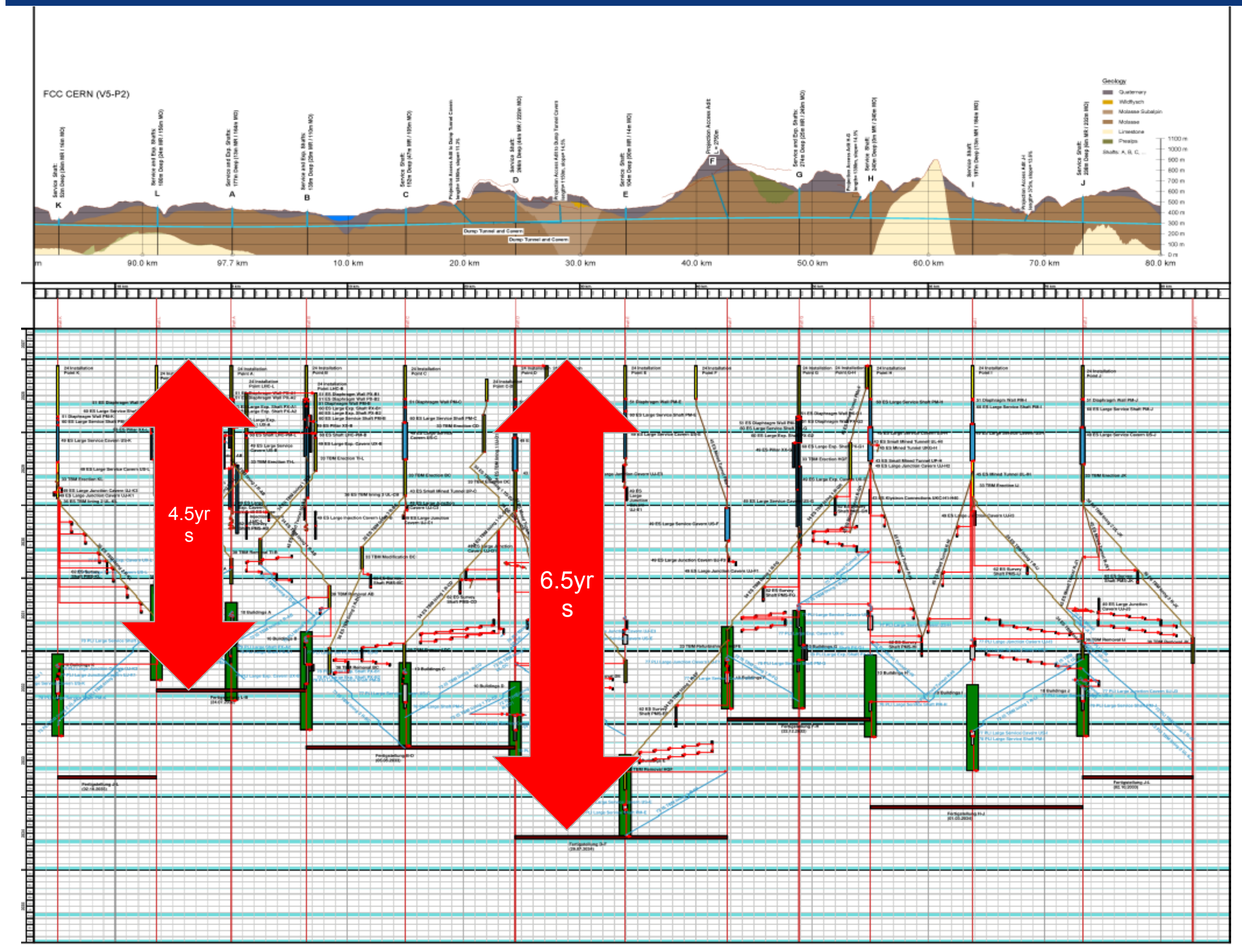
Comprehensive cost-effective program maximizing physics opportunities

- **Stage 1: FCC-ee (Z, W, H, tt) as first generation Higgs factory, EW and top factory at highest luminosities.**
- **Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options.**
- Complementary physics
- Integrating an ambitious high-field magnet R&D program
- Common civil engineering and technical infrastructures
- Building on and reusing CERN's existing infrastructure.
- FCC integrated project plan is fully integrated with HL-LHC exploitation and provides for seamless continuation of HEP in Europe.

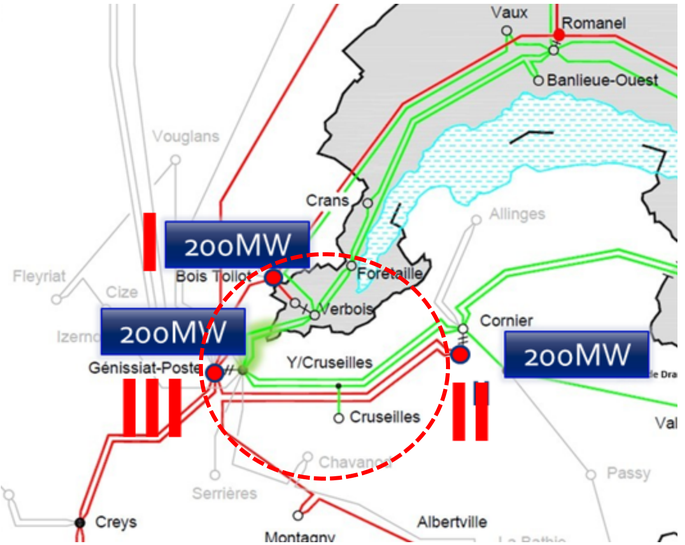




Implementation studies



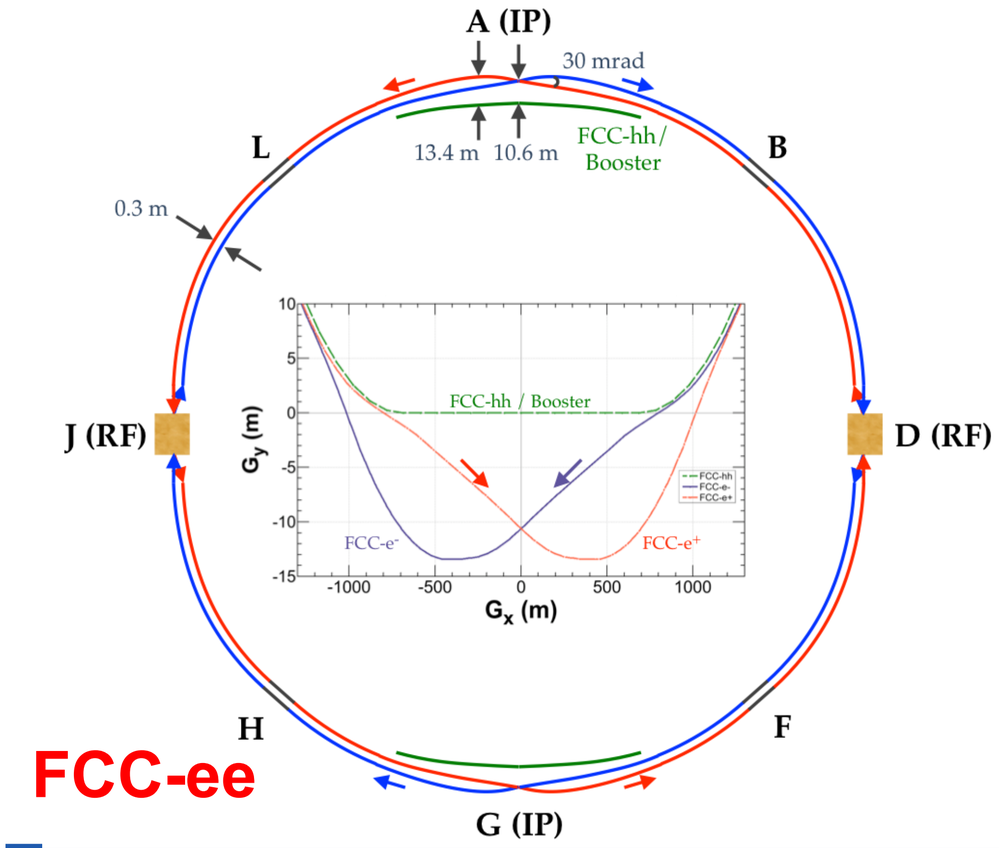
Additional 200 MW available for FCC at each of the three 400 kV sources from European grid

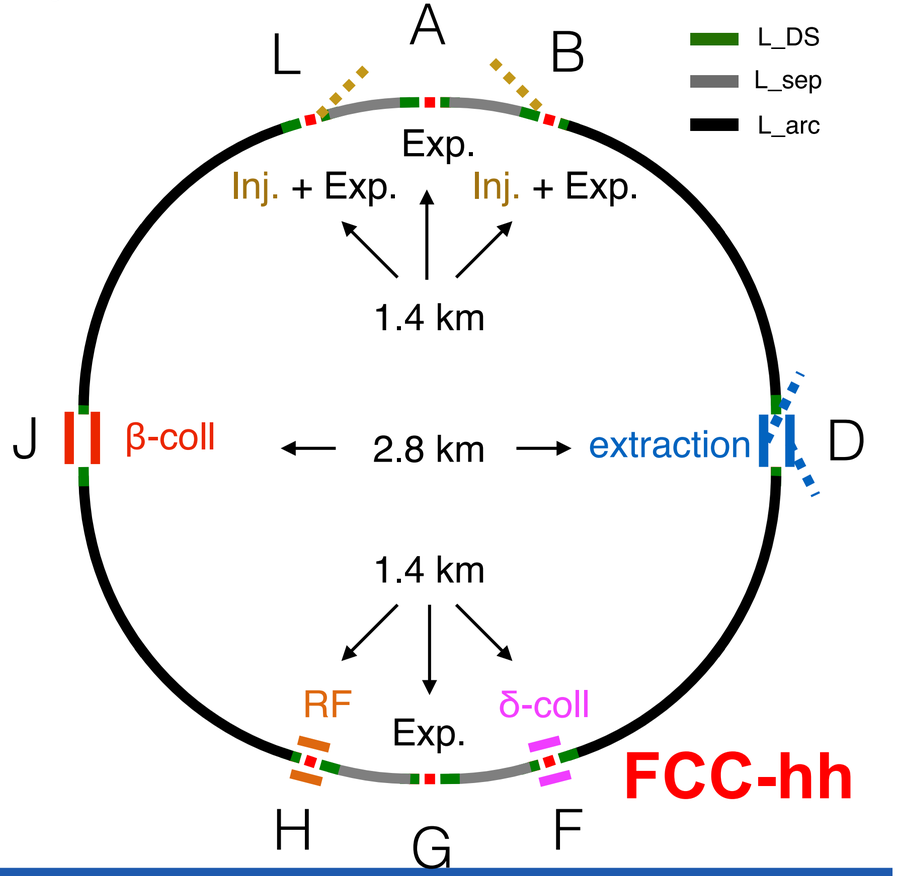


- **Total construction duration 7 years**
- **First sectors ready after 4.5 years**

Common layouts for hh & ee

- **Two main IPs in A, G for both machines.**
- **Common footprint except around IPs.**
- **FCC-ee asymmetric IR layout** to limit synchrotron radiation

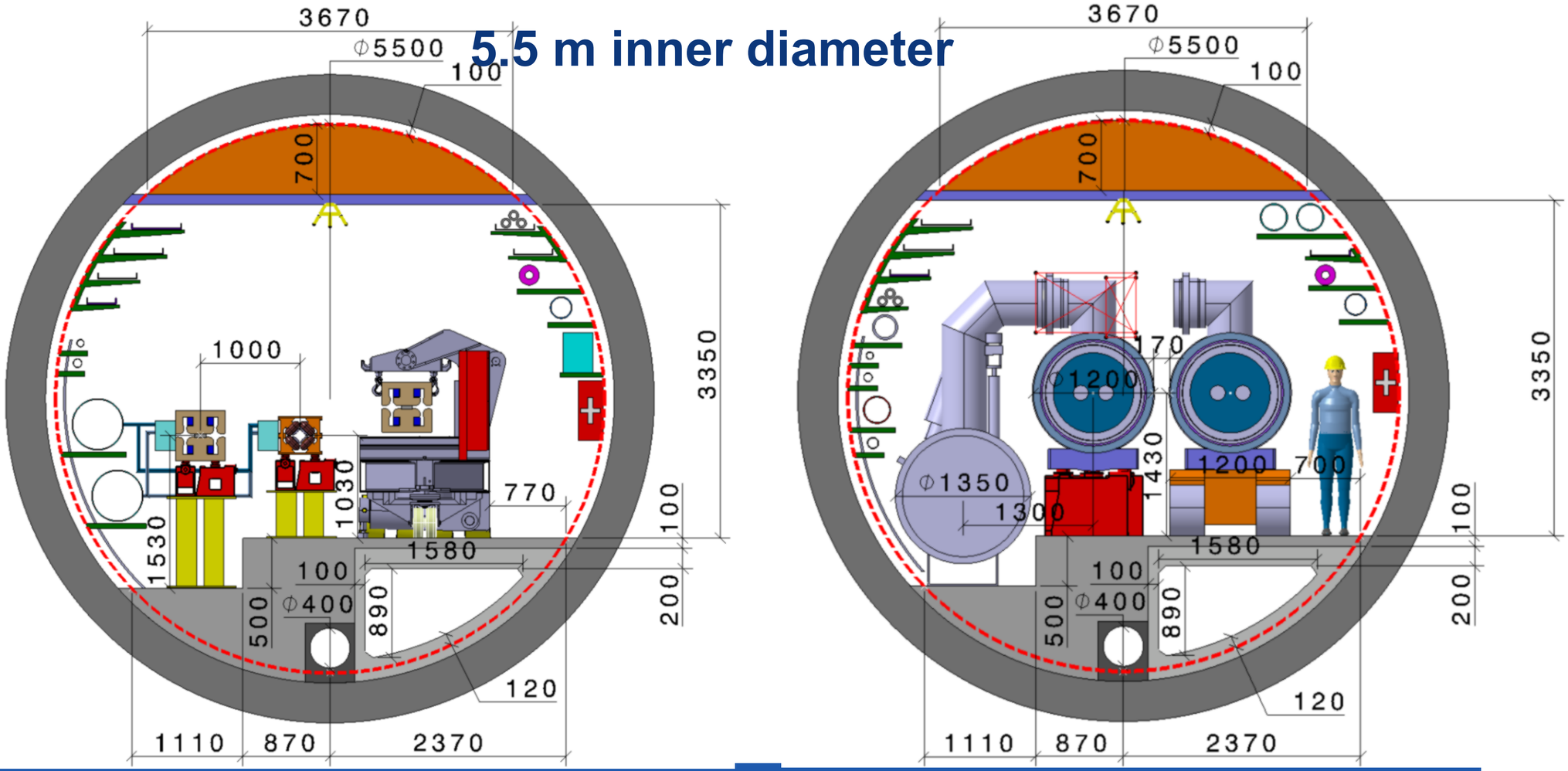




Tunnel integration in arcs

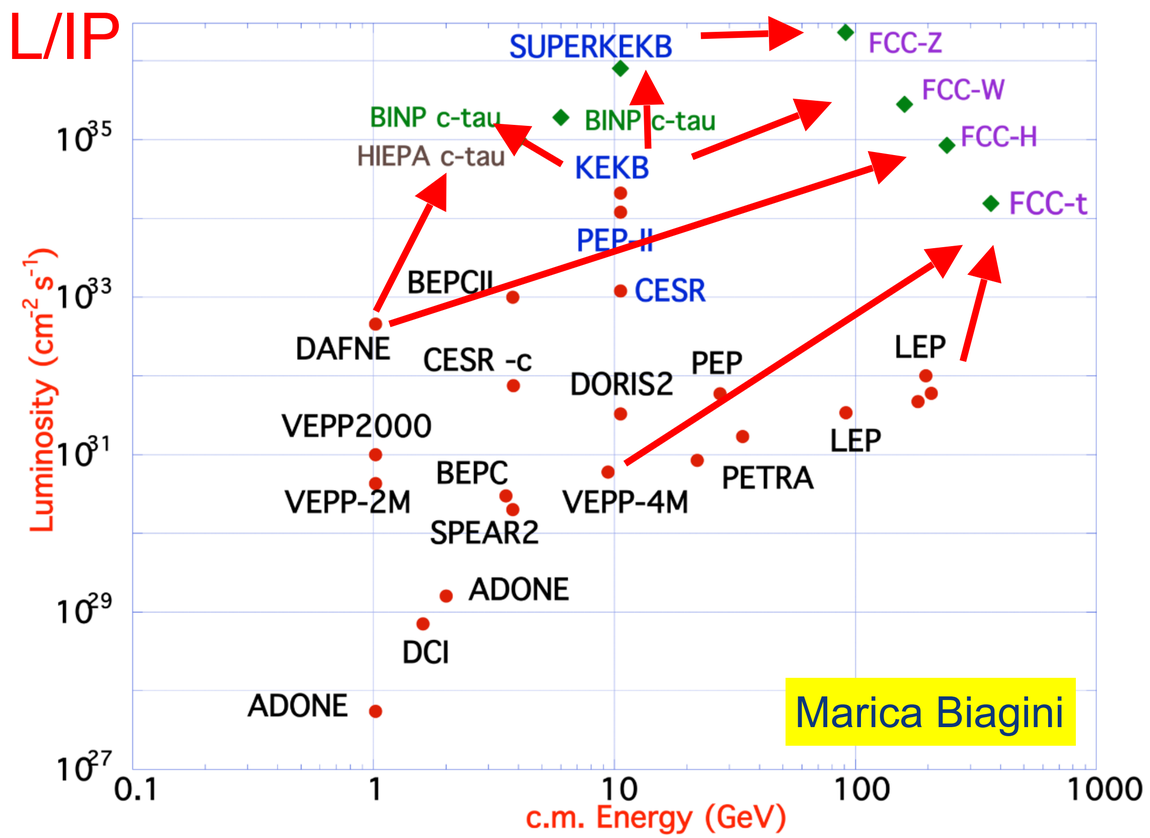
FCC-ee FCC-hh

5.5 m inner diameter



FCC-ee – EW factory: performance

FCC-ee reaches highest luminosities & energies
by combining ingredients and well-proven concepts of several recent colliders:



B-factories: KEKB & PEP-II: double-ring lepton colliders, high beam currents, top-up injection, positron source

DAFNE: crab waist, double ring

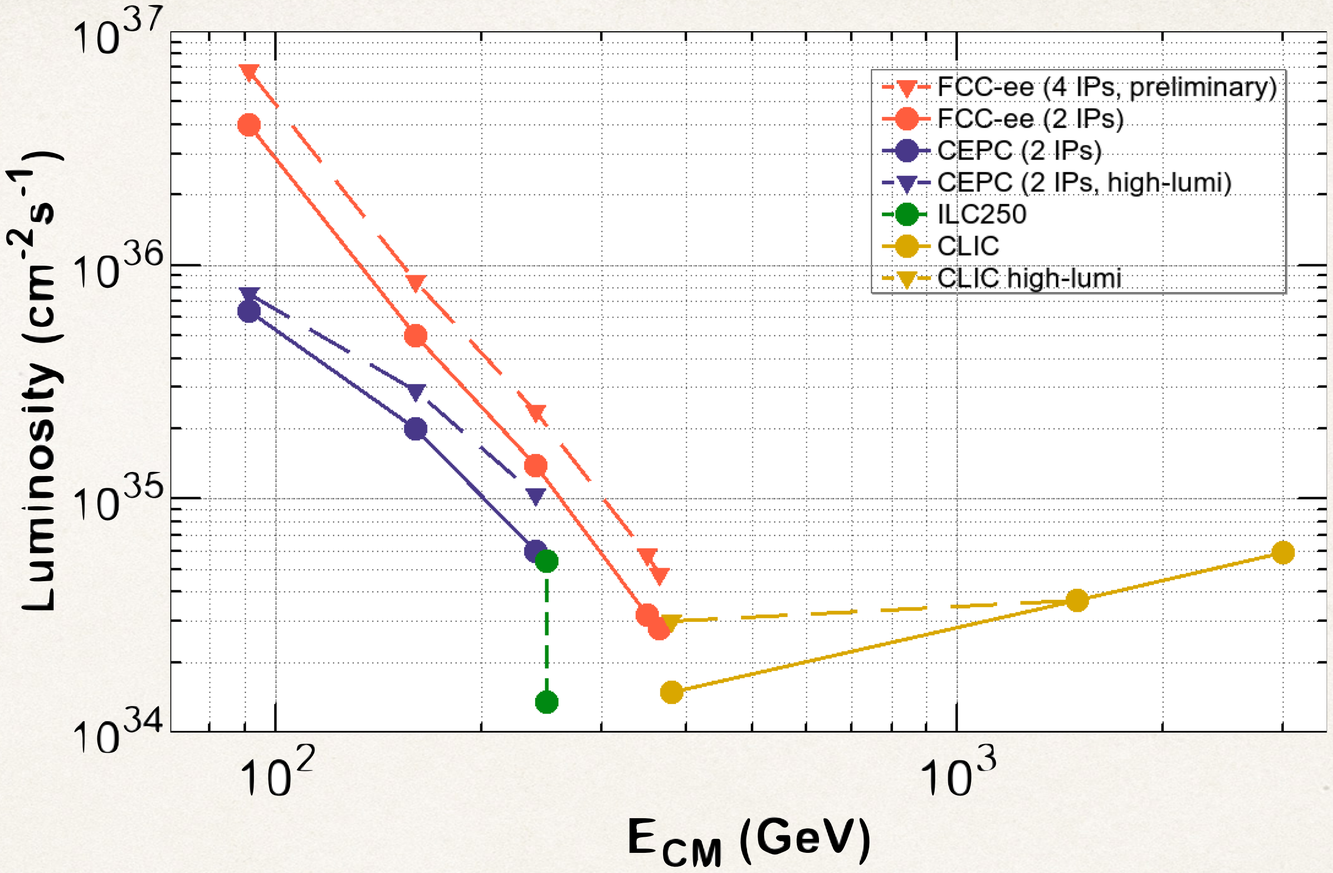
Super B-fact., S-KEKB: low β_y^*

LEP: high energy, SR effects

VEPP-4M, LEP: precision E calibration

KEKB: HERA, LEP, RHIC: spin gymnastics

Highest luminosity up to 365 GeV CM



- In the case of FCC-ee, the luminosity scales by about $E^{-3.6}$, which is slightly better than the scaling by the SR power.
- The cross-over energy for the luminosity between circular and inner collider is around $t\bar{t}$ threshold, assuming 100 MW SR power and C = 100 km.

FCC-ee collider parameters

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	230	28	8.5	1.55
beam lifetime rad Bhabha / BS [min]	68 / >200	49 / >1000	38 / 18	40 / 18

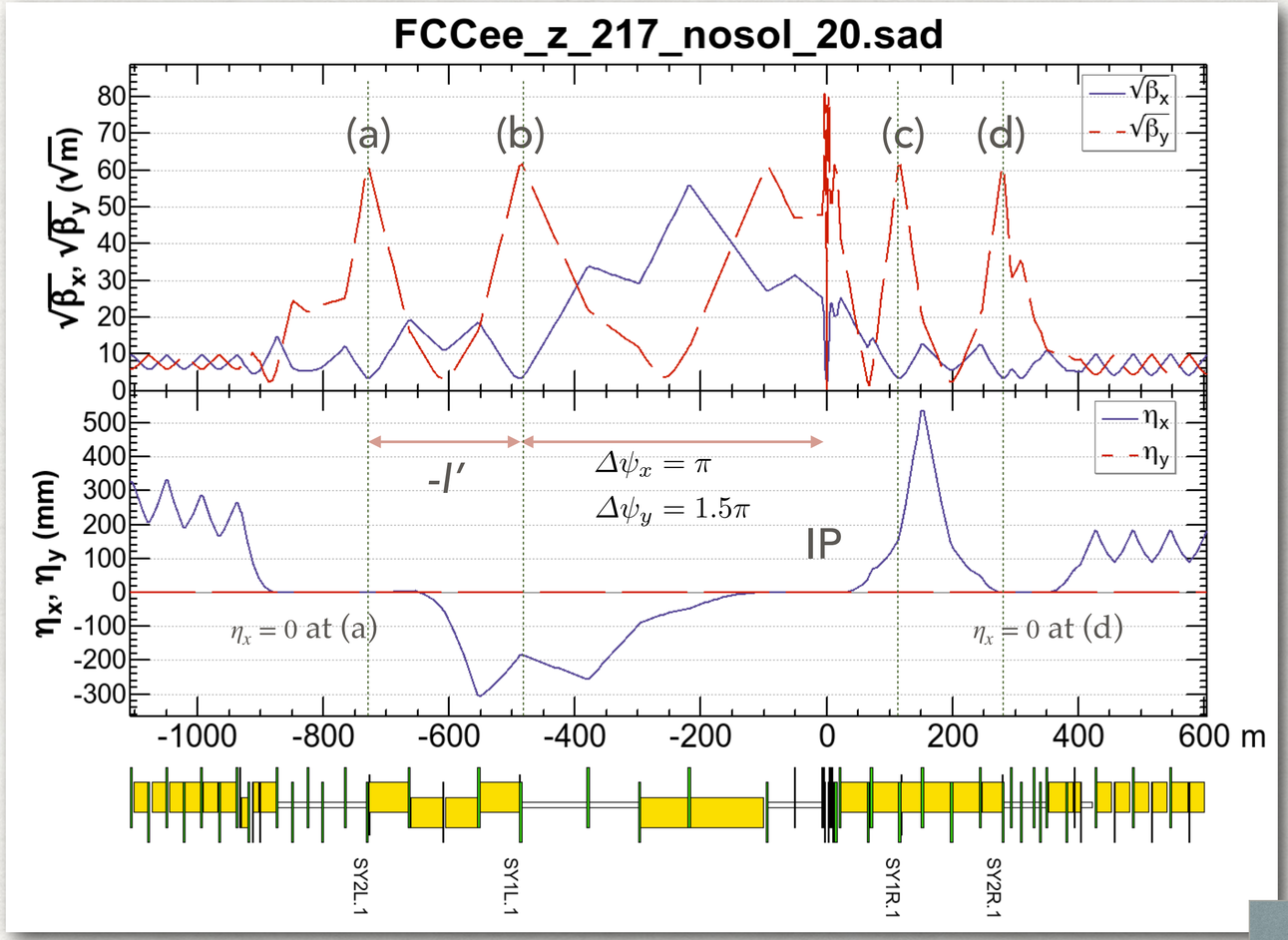
F. Zimmermann

FCC-ee Baseline (CDR) Optics

- A baseline optics* for FCC-ee has been established in Oct. 2016 characterized by:
  - 100 km circumference, 2 IP/ring.
    - Follow the footprint of FCC-hh, except for around the IPs.
  - Common lattice for all energies, except for the detector solenoid (2T).
    - ε_x = 1.45 nm @ 182.5 GeV.
    - $\beta_{x,y}^*$ = (1 m, 1.6 mm) at 175 GeV, (0.15 m, 0.8 mm) at 45.6 GeV
    - 90°/90° (Zh, $t\bar{t}$), 60°/60° (Z, WW) FODO cell in the arc with non-interleaved sextupole pairs.
  - 30 mrad crossing angle at the IP, with the crab-waist scheme.
  - Local chromaticity correction for *y*-plane, incorporated with "virtual" crab sextupoles .
  - Suppress the critical energy of SR toward the IP below 100 keV at 182.5 GeV, up to 450 m upstream.
  - 100 MW total SR power for all energies.
    - Tapering of magnets along the ring to compensate the effects of SR on orbit/optics.
    - Common RF cavities for e+e- at $t\bar{t}$. RF will be installed via staging.
  - Sufficient dynamic aperture considering beamstrahlung and top-up injection.

*Phys.Rev.Accel.Beams 19 (2016) no.11, 111005

Crab-waist optics around the IP (Z)



section	Δψx	Δψy
(a) - (b)	π	π
(b) - IP	π	1.5π
IP - (c)	π	1.5π
(c) - (d)	π	π

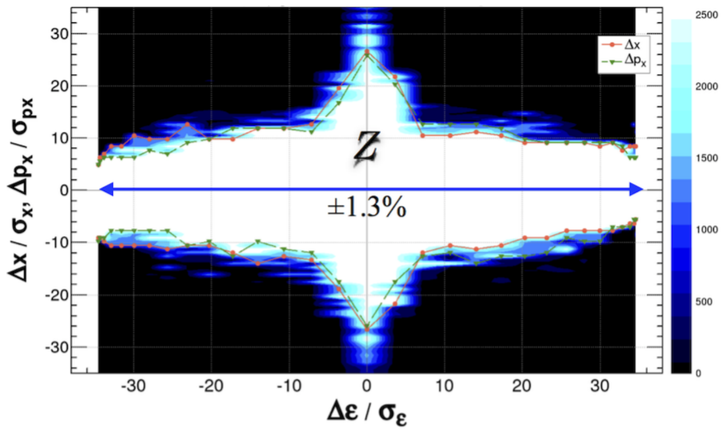
- The outer sexts (a)(d) of the y-CCS work as crab sexts, if phase advances from the IP are chosen as:

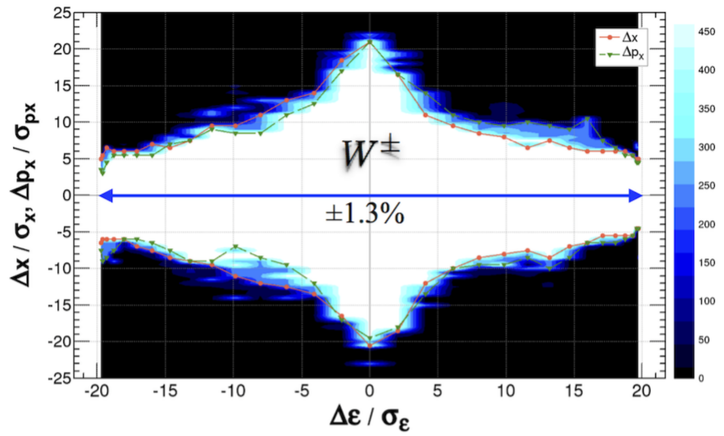
$$\Delta\psi_x = n\pi,\ \ \Delta\psi_y = (m + 1/2)\pi$$

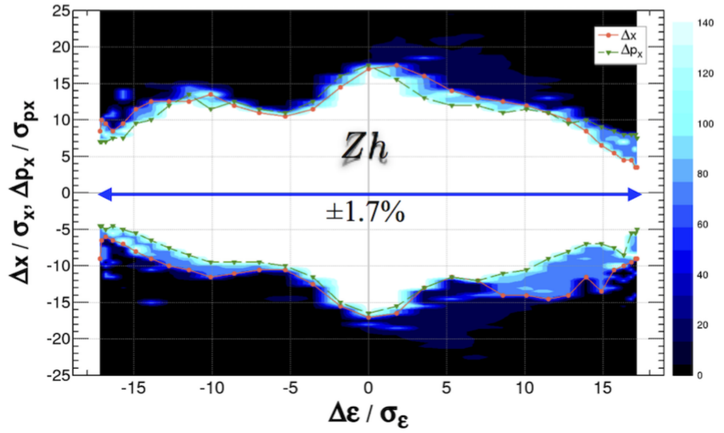
	(a)	(b)	IP	(c)	(d)
β_x	12.1		0.15	12.1	
β_y	3700		0.0008	3700	
k_2	4.53	5.75		-5.82	-4.61

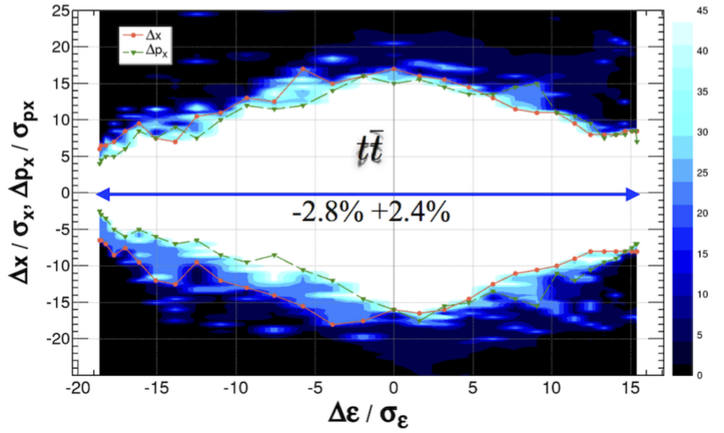
for CW = 97%

off-energy dynamic aperture









Dynamic apertures in *z-x* plane after sextupole optimisation with particle tracking for each energy.

The initial vertical amplitude for the tracking is always set to $J_y/J_x = \varepsilon_y/\varepsilon_x$.

Number of turns ~2 longitudinal damping times.

K. Oide

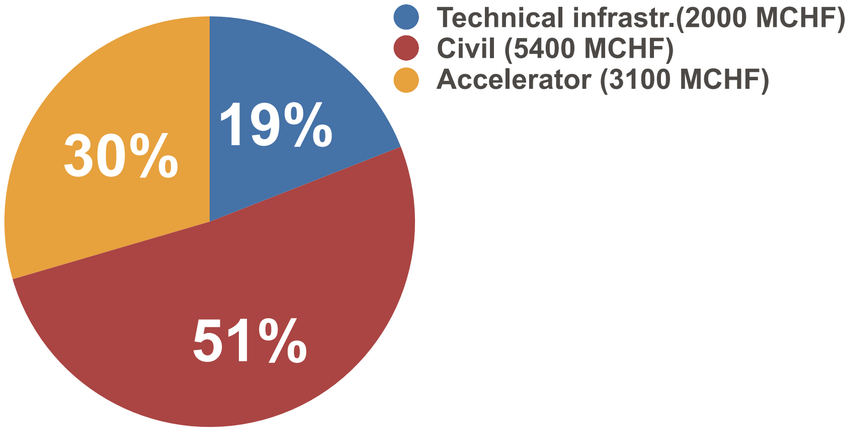
important for top-up injection and for beam lifetime with beamstrahlung

FCC-ee wall-plug power consumption [MW]

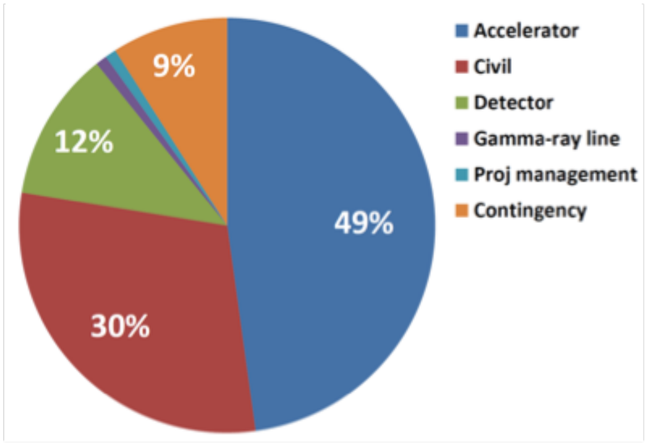
Beam energy (GeV)	45.6 Z	80 W	120 ZH	182.5 ttbar
RF (SR = 100)	163	163	145	145
Collider cryo	1	9	14	46
Collider magnets	4	12	26	60
Booster RF & cryo	3	4	6	8
Booster magnets	0	1	2	5
Pre injector	10	10	10	10
Physics detector	8	8	8	8
Data center	4	4	4	4
Cooling & ventilation	30	31	31	37
General services	36	36	36	36
Total	259	278	282	359

Cost

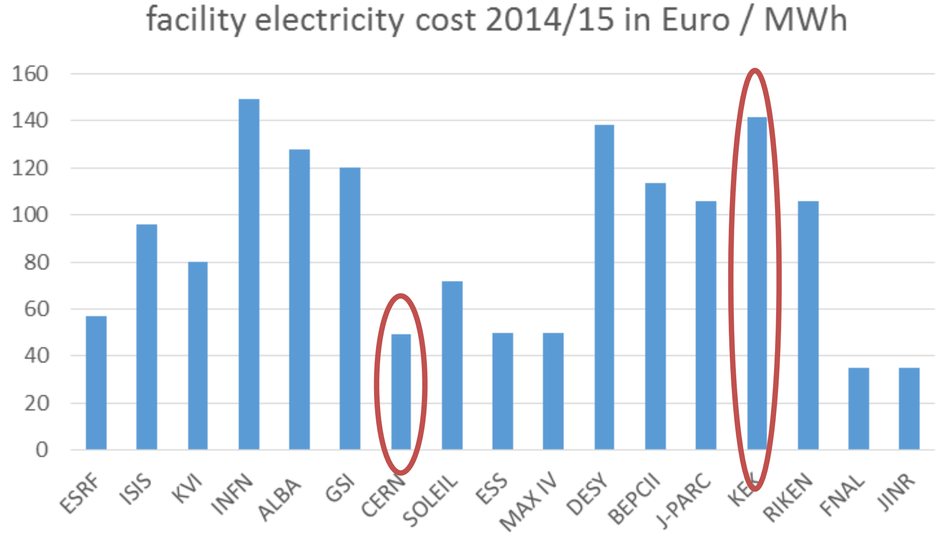
FCC-ee



CEPC



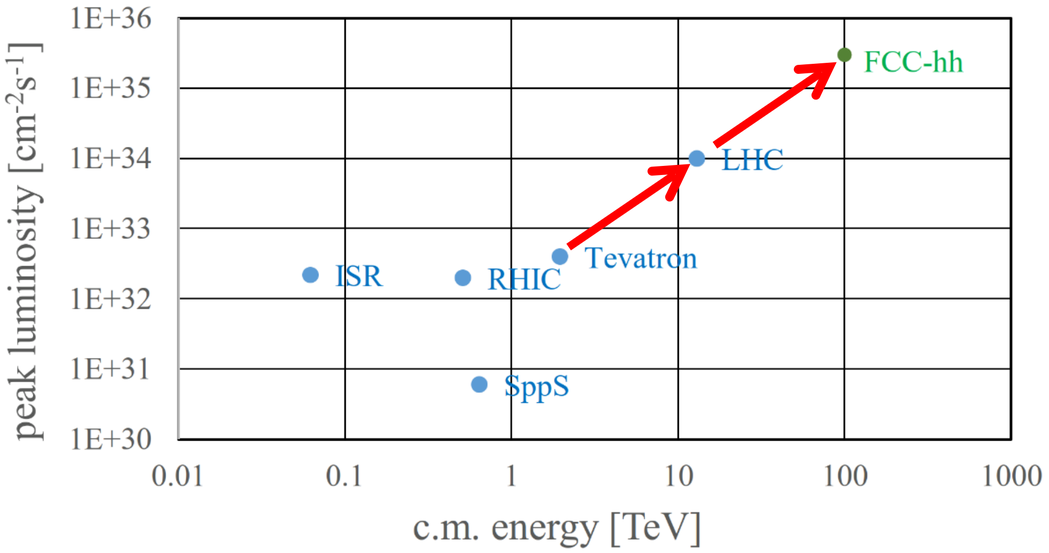
ost of the CEPC project constituents.



Cheaper to build a facility in Asia and operate it in Europe…

M. Koratzinos
@ICNFP 2019

FCC-hh: performance



Aim at **~one order of magnitude performance increase** in both **energy and luminosity w.r.t LHC**

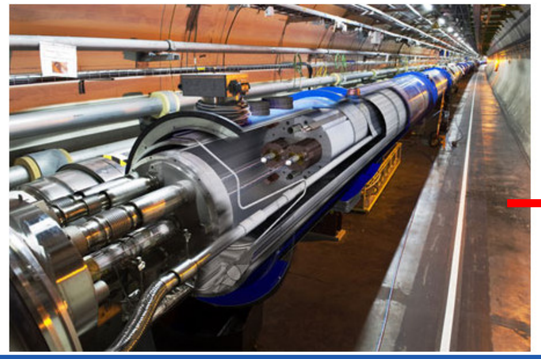
100+ TeV cm collision energy (vs 14 TeV for LHC)

20 ab^{-1} per experiment collected over 25 years of operation time (vs 3 ab^{-1} for LHC).

Similar performance increase as from Tevatron to LHC.

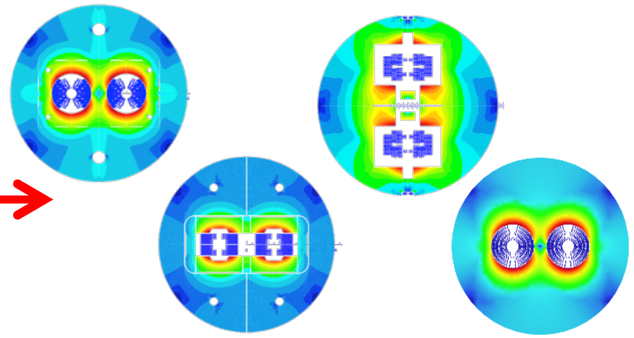
Key technology: High-field magnets

From LHC technology 8.3 T NbTi



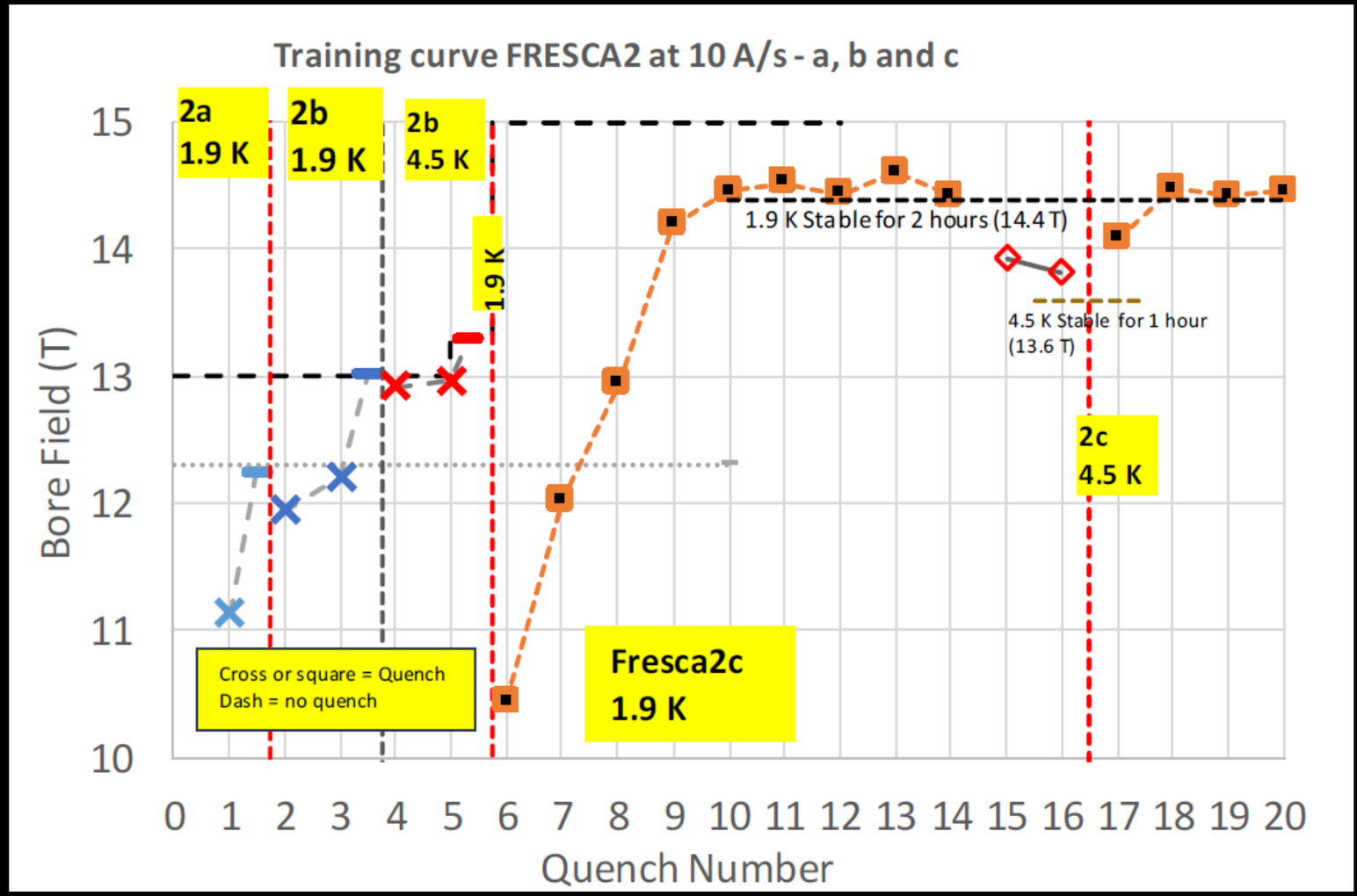
via HL-LHC technology 11 T Nb_3Sn

to 16 T Nb_3Sn EuroCirCol, Chart, US MDP



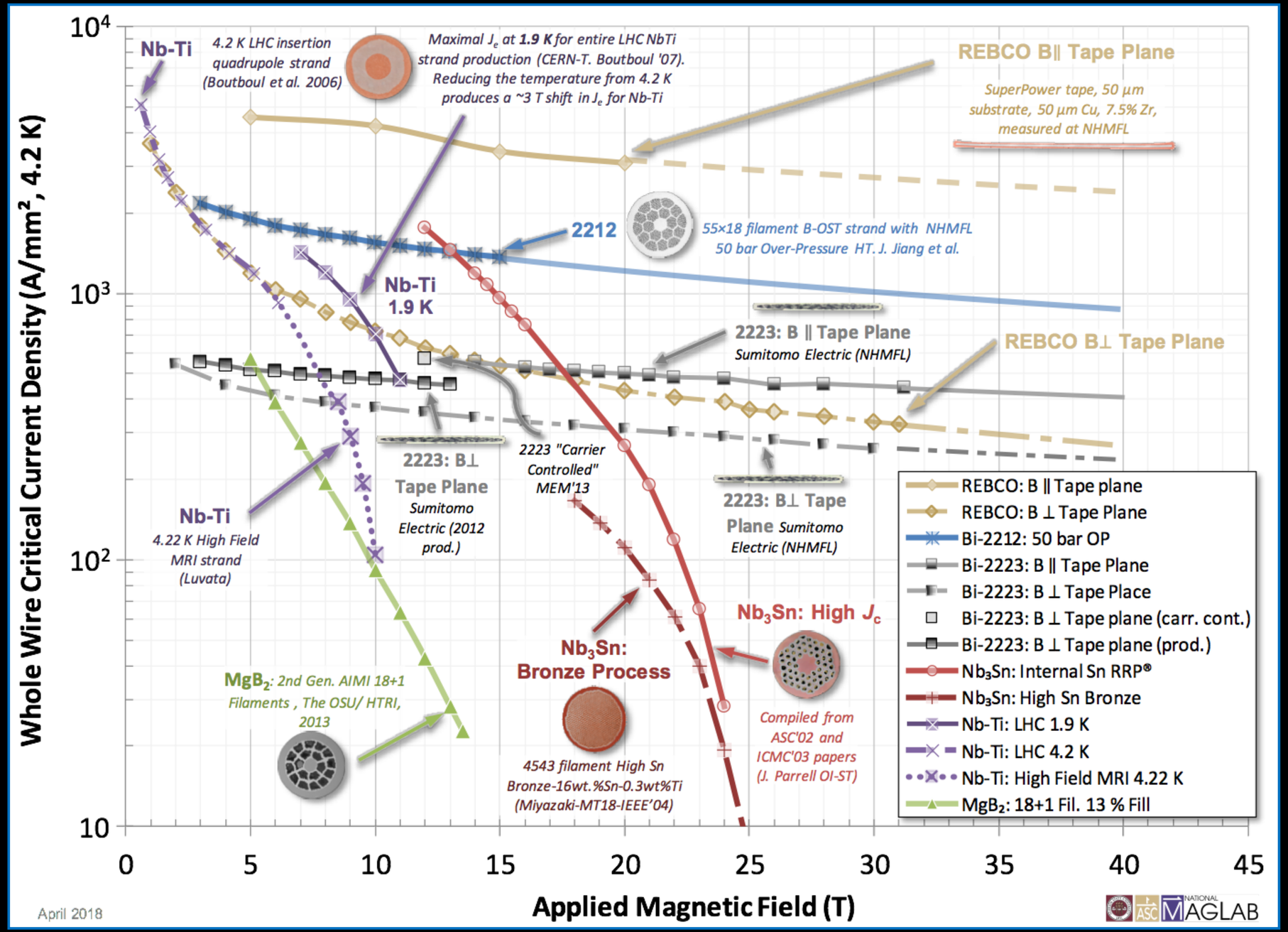
SC Magnet R&D – *16 T magnets would allow to reach much higher pp collision energies*

FRESCA2 @ CERN

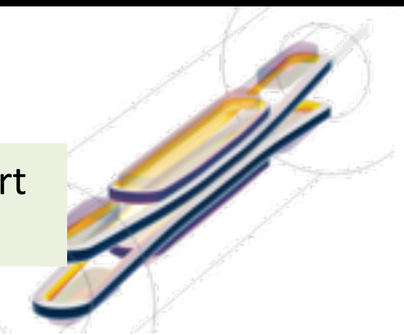


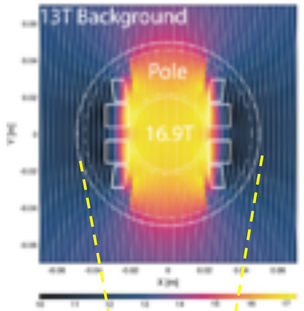
F. Toral @ Plenary ECFA meeting Nov 2018

SC Magnet R&D – *alternative materials for high-J_c at high magnetic field*

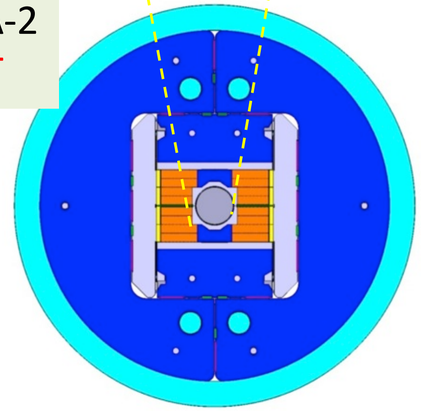


HTS-Insert
3~5 T



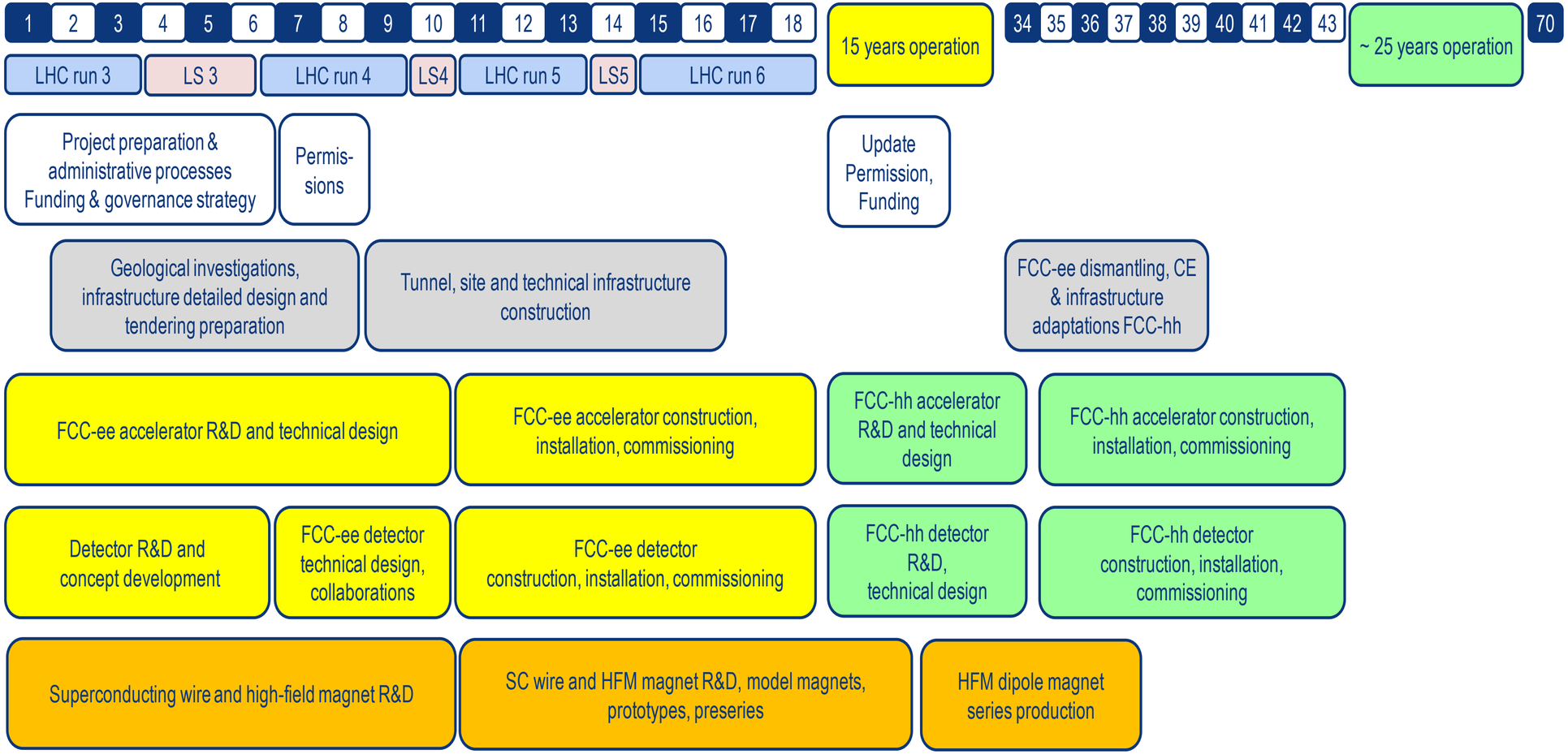


FRESCA-2
13-14 T



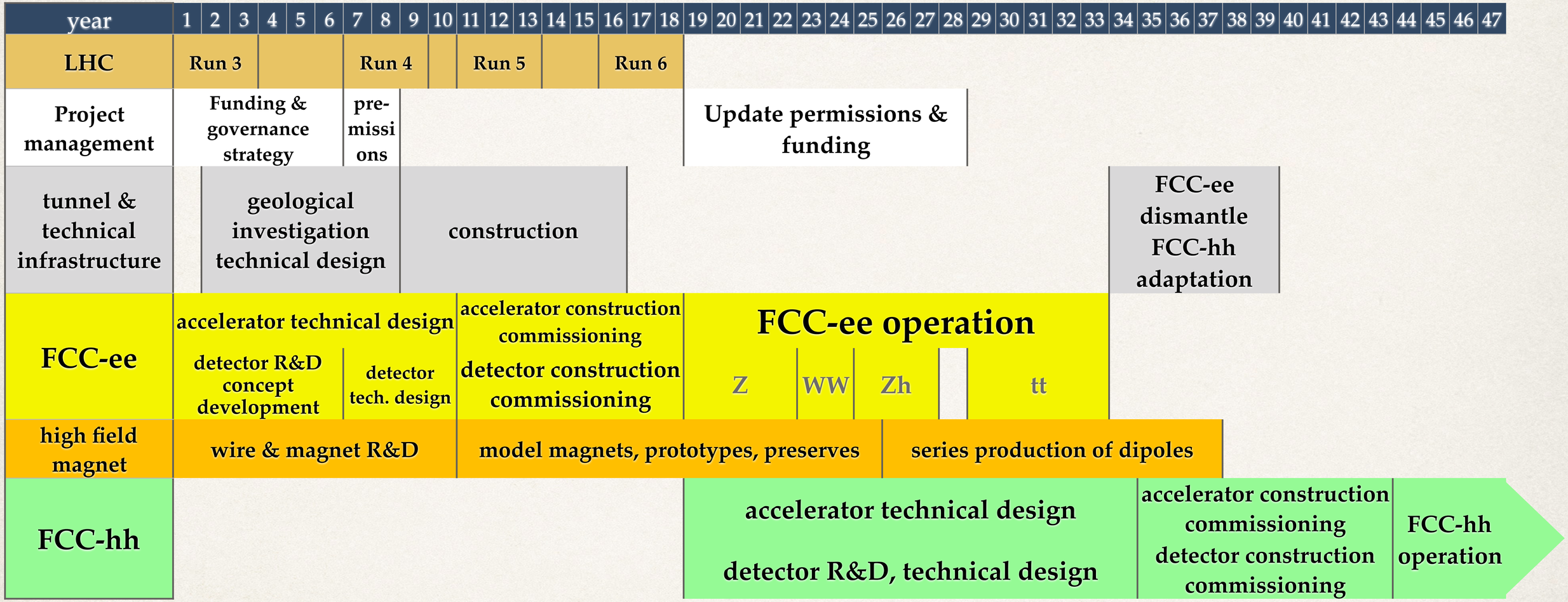
Eucard2: HTS-insert
to be tested in 2019
(3-5) + (13-14)T : > 16 T

FCC integrated project technical schedule



- **FCC integrated project plan is fully integrated with HL-LHC exploitation**
- **provides for seamless further continuation of HEP in Europe.**

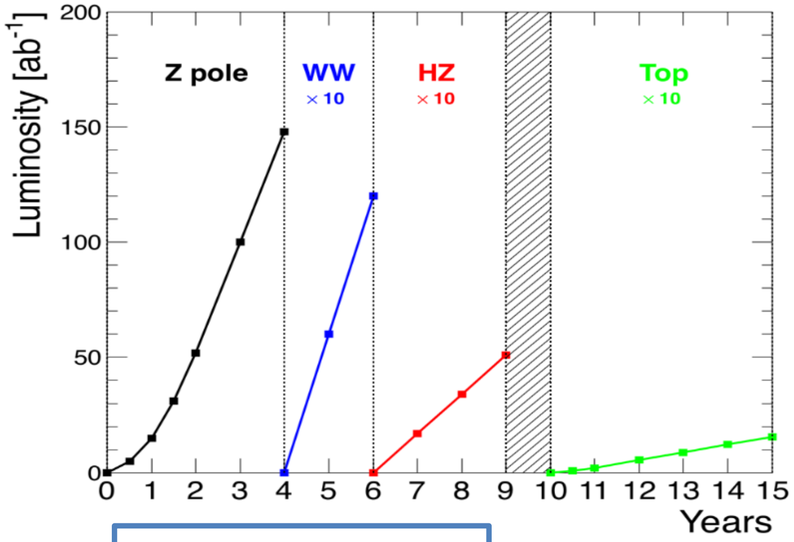
Technical schedule



FCC-ee operation model and statistics

- 185 physics days / year, 75% efficiency, -10% margin on luminosity

Working point	Z, years 1-2	Z, later	WW	HZ	tt threshold and above	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163	240	340 – 350	365
$\sqrt{s}$ precision (MeV)	<0.1		0.3	1	2	
Lumi/IP (10^{34} cm^{-2}s^{-1})	115	230	28	8.5	0.95	1.55
Lumi/year (2 IP, ab^{-1})	24	48	6	1.7	0.2	0.34
Physics goal (ab^{-1})	150 ab-1 (30,90,30 ab^{-1})		10 ab^{-1}	5 ab^{-1}	0.2 ab^{-1}	1.5 ab^{-1}
Run time (year)	2	2	2	3	1	4
Number of events	5×10^{12} Z		10^8 W^+W	10^6 HZ 25k WW→ H	10^6 tt 200k HZ 50k WW→ H	

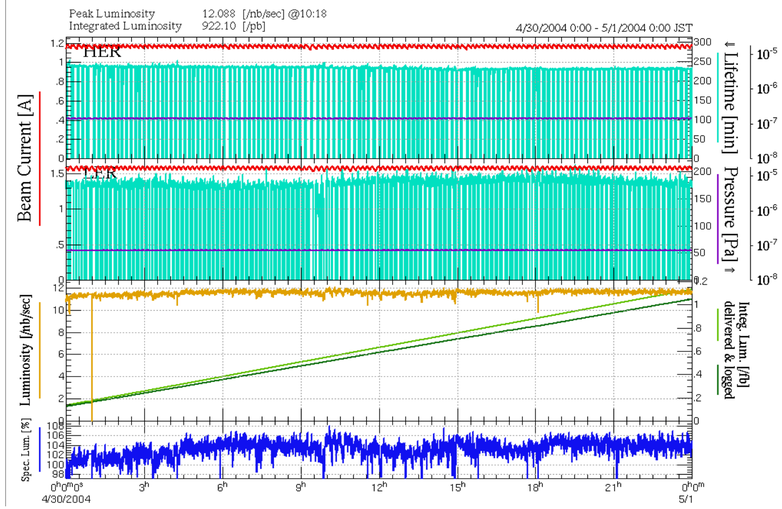


Total : 15 years

Different projects use different definition for a ‘year’:

- 1 ILC year = 1.5 FCC years

M. Koratzinos, ICNFP 2019



KEKB has demonstrated a very high efficiency >80% with top-up (continuous) injection

Jorgen D'Hondt

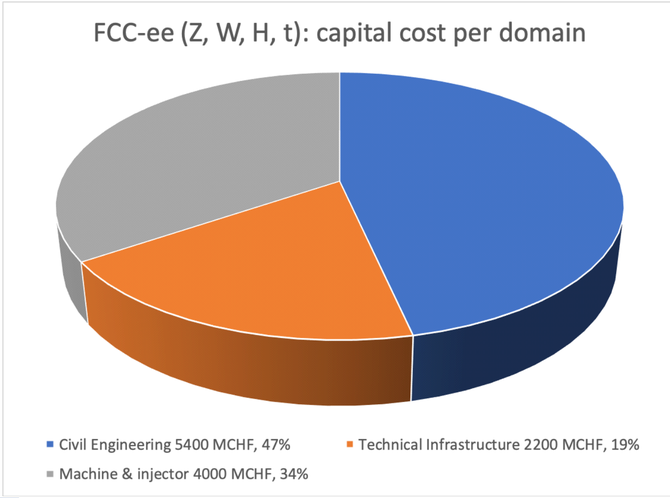
@ICNFP 2019

	2020-2040 *HL-LHC era*	2040-2060 *Z/W/H/top-factory era*	2060-2080 *energy frontier era*
our technology	SCRF ~ 30 MV/m B ~ 11 T	SCRF ~ 50 MV/m B ~ 14 T plasma demo muon demo	SCRF ~ 70 MV/m B > 16 T (HTS?) plasma collider muon collider
other technology	AI for new physics quasi-online analysis digital imaging new transistors	quantum computing self-learning simulation	…
societal threats	eco friendly gases careers at mega-research facilities	energy consumption long-term engagement global vs sustained collaboration	human vs machine

FCC integrated project cost estimate

Construction cost phase1 (FCC-ee) is 11,6 BCHF

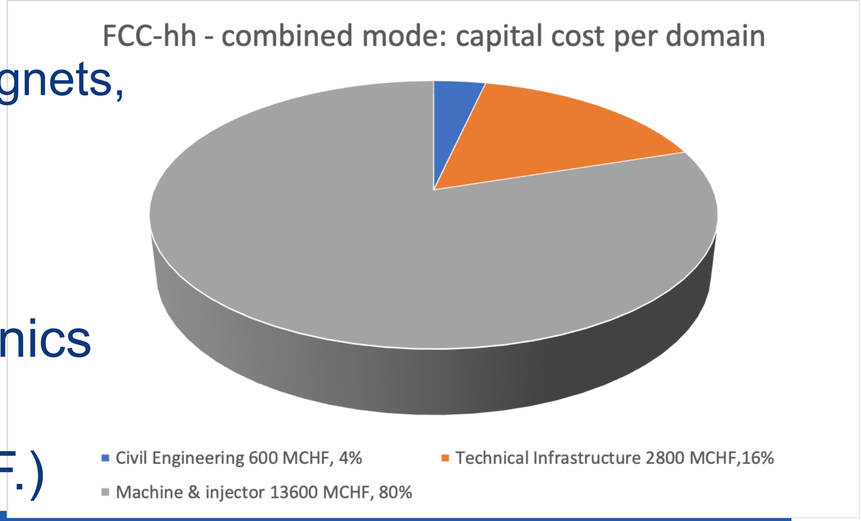
- 5,4 BCHF for civil engineering (47%)
- 2,2 BCHF for technical infrastructure (19%)
- 4,0 BCHF accelerator and injector (34%)



Construction cost phase 2 (FCC-hh) is 17,0 BCHF.

- 13,6 BCHF accelerator and injector (57%)
  - Major part for4,700 Nb_3Sn 16 T main dipole magnets, totalling 9,4 BCHF, targeting 2 MCHF/magnet.
- CE and TI from FCC-ee re-used, 0,6 BCHF for adaptation
- 2,8 BCHF for additional TI, driven by cryogenics

(Cost FCC-hh stand alone would be 24,0 BCHF.)

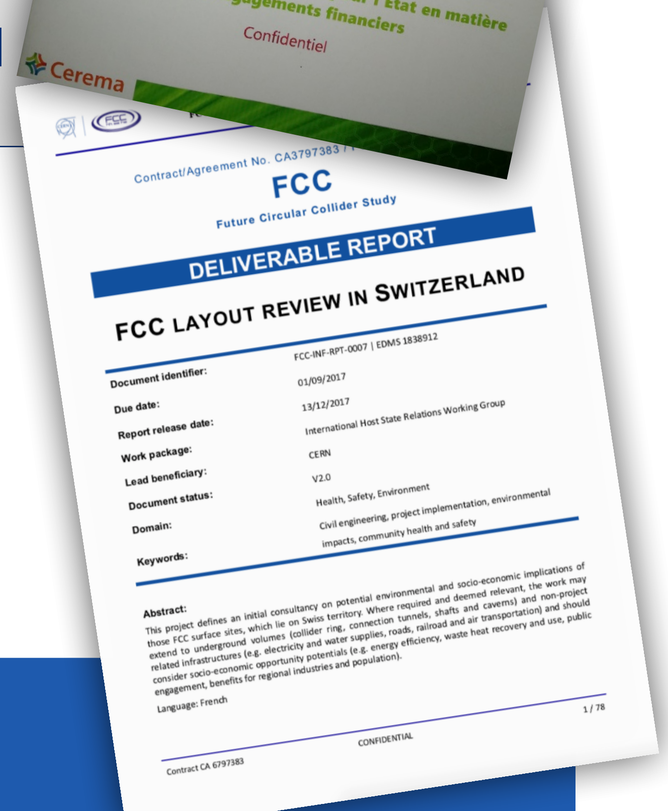


FCC work with host states

General secretariat of the region Auvergne-Rhône-Alpes and notified body “Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement”

Working group with representatives of federation, canton and state of Geneva and representation of Switzerland at the international organisations and consultancy companies

- Administrative processes for project preparatory phase developed.
- Requirements for urbanistic, environmental, economic impact, land acquisition and construction permit related processes defined.
- **Common review of tunnel and surface site placement ongoing.**


Contract/Agreement No. CA3797383

FCC

Future Circular Collider Study

DELIVERABLE REPORT

FCC LAYOUT REVIEW IN SWITZERLAND

Document identifier:	FCC-INF-RPT-0007 | EDMS 1838912
Due date:	01/09/2017
Report release date:	13/12/2017
Work package:	International Host State Relations Working Group
Lead beneficiary:	CERN
Document status:	V2.0
Domain:	Health, Safety, Environment
Keywords:	Civil engineering, project implementation, environmental impacts, community health and safety

Abstract:

This project defines an initial consultancy on potential environmental and socio-economic implications of those FCC surface sites, which lie on Swiss territory. Where required and deemed relevant, the work may extend to underground volumes (collider ring, connection tunnels, shafts and caverns) and non-project related infrastructures (e.g. electricity and water supplies, roads, railroad and air transportation) and should consider socio-economic opportunity potentials (e.g. energy efficiency, waste heat recovery and use, public engagement, benefits for regional industries and population).

Language: French

CONFIDENTIAL

Contract CA 6797383

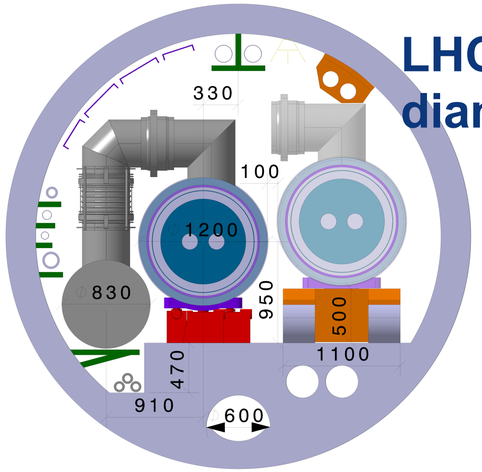
1 / 78

Next steps 2019 - 2020

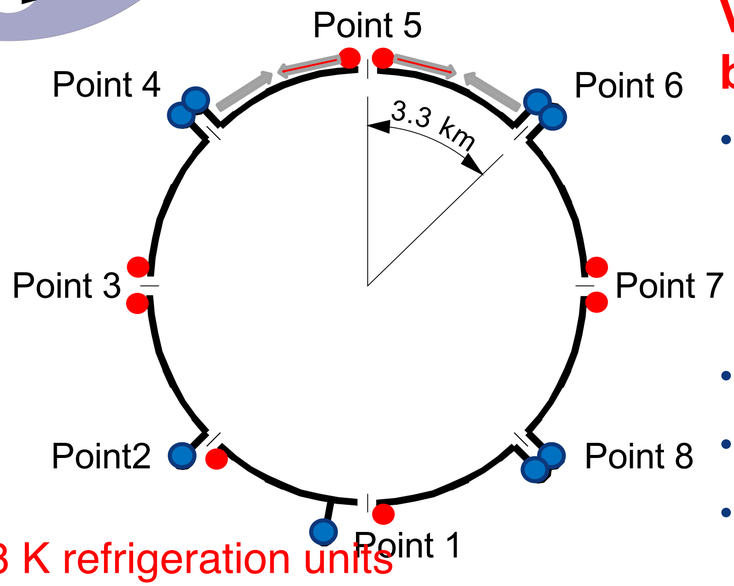
- Iteration of tunnel and surface structures layout and implementation with host states.
- Adaptation of CE, machine designs, etc. according to implementation optimisation.
- Following Integral Project proposal, presently focus on FCC-ee as potential first step (awaiting strategy recommendation).
  - Review and more detailed design for FCC-ee injector concept
  - Detailed design of technical infrastructure for FCC-ee
- Preparation of EU H2020 DS project (INFRADEV call November 2019), focused on preparations for infrastructure implementation.

backups

Conclusions from HE LHC studies



LHC tunnel diameter 3.8 m



8 additional 1.8 K refrigeration units
8 new higher-power 4.5 K cryoplants

Performance

- **26 - 27 TeV cm collision energy**
- **~10 ab^{-1} per experiment collected over 20 years**
- **Key technology: high-field magnets FCC-hh**

Very challenging option due to existing boundary conditions:

- Machine integration due to space limitations (tunnel cross section, straight section length, caverns) of existing underground infrastructures
- Compatibility with safety requirements
- Increased cryogenics requirements
- Injector requirements