IPAC 2022, Bangkok

CEPC and FCC-ee

Status of the circular e^+e^- collider projects in Asia and Europe

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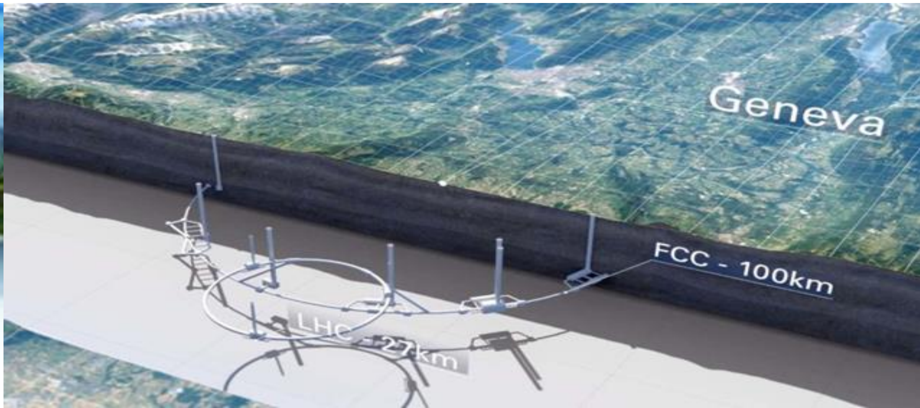


Outline

- Cases for high energy circular e^+e^- colliders
- Status of CEPC and FCC-ee
- R&D progress
- Possible synergies
- Summary

The Cases for High Energy circular e^+e^- colliders

- Physics motivations
- Advantages of an e^+e^- collider over the pp collider
- e^+e^- colliders: circular vs. linear

Cases I: Physics

The Standard Model has been very successful

However it is not a complete theory

facing serious tensions:

naturalness, stability, g-2, W mass, R_K, R_D, R_{D^*}, …

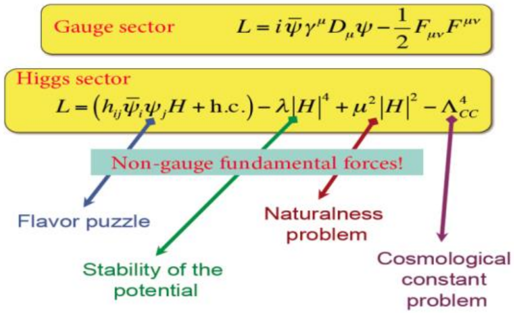
can not explain:

existence & mechanism of dark matter and dark energy,

baryon asymmetry of the Universe,

neutrino masses and oscillations, hierarchy, …

- **The Higgs – only spin-0 elementary particle**
- **Very special:**



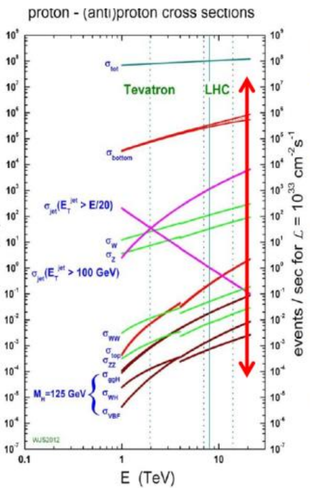
particle	spin
quark: u, d,...	1/2
lepton: e...	1/2
photon	1
W,Z	1
gluon	1
Higgs	0

The Higgs may hold keys to the unknowns

Higgs boson as a portal for new physics

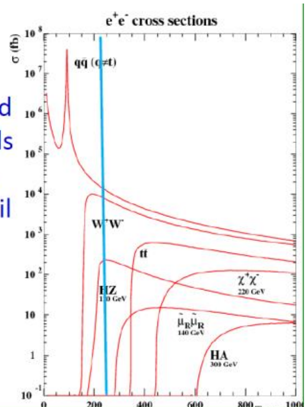
Real opportunities for discovering new physics beyond the SM

Cases II: e^+e^- Higgs Factory

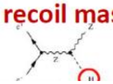


LHC –
- large Higgs cross section
- 150M Higgs per exp.
- dominated by QCD events
- S(H)/B(All) 10^{-10}
- Pile-up and jet overlap
- Not knowing $(\overrightarrow{P_H}, E_H)_{initial}$

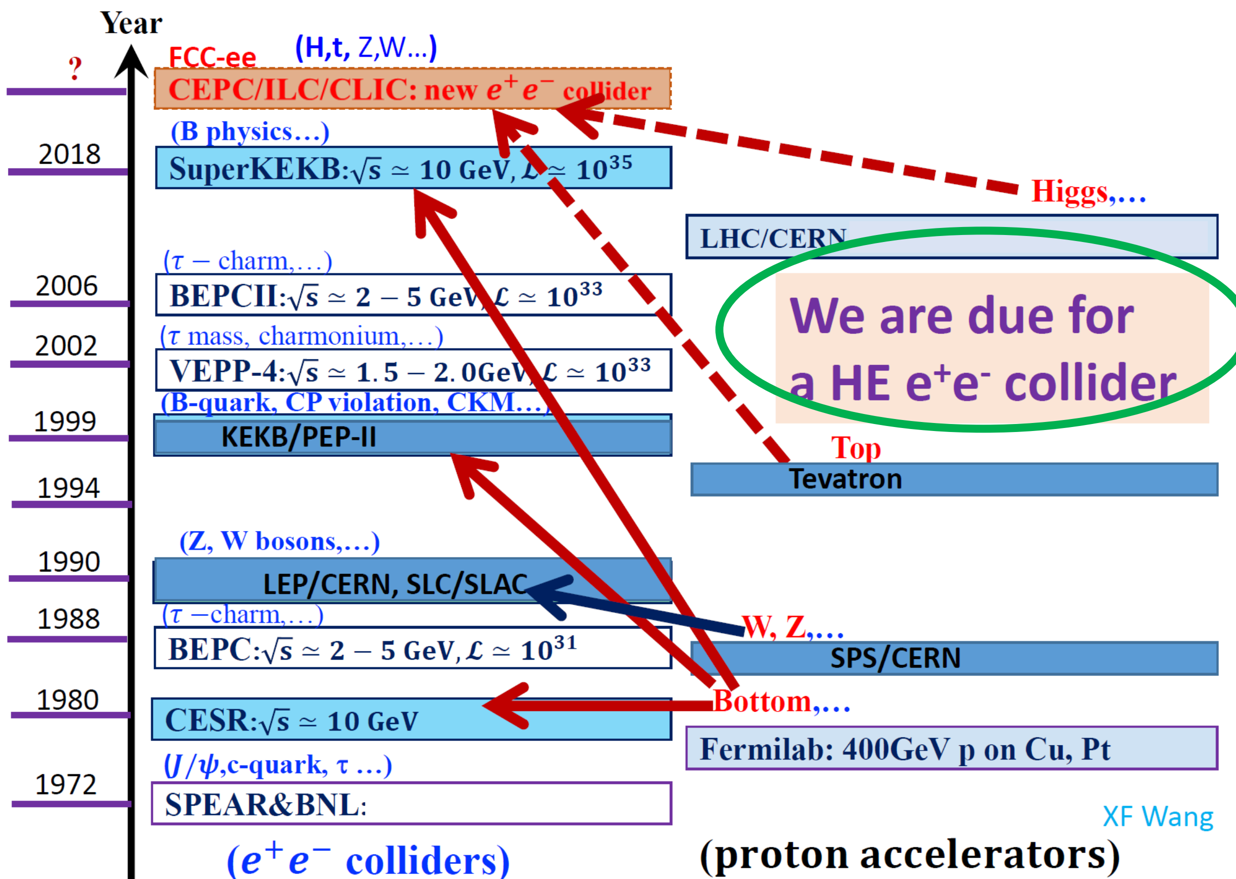
e^+e^- collider –
- Higgs cross section, predicted with (sub)% levels
- Know $(\overrightarrow{P_H}, E_H)_{initial}$ allowing for recoil mass reconst.
- Clean events
- low Higgs cross section



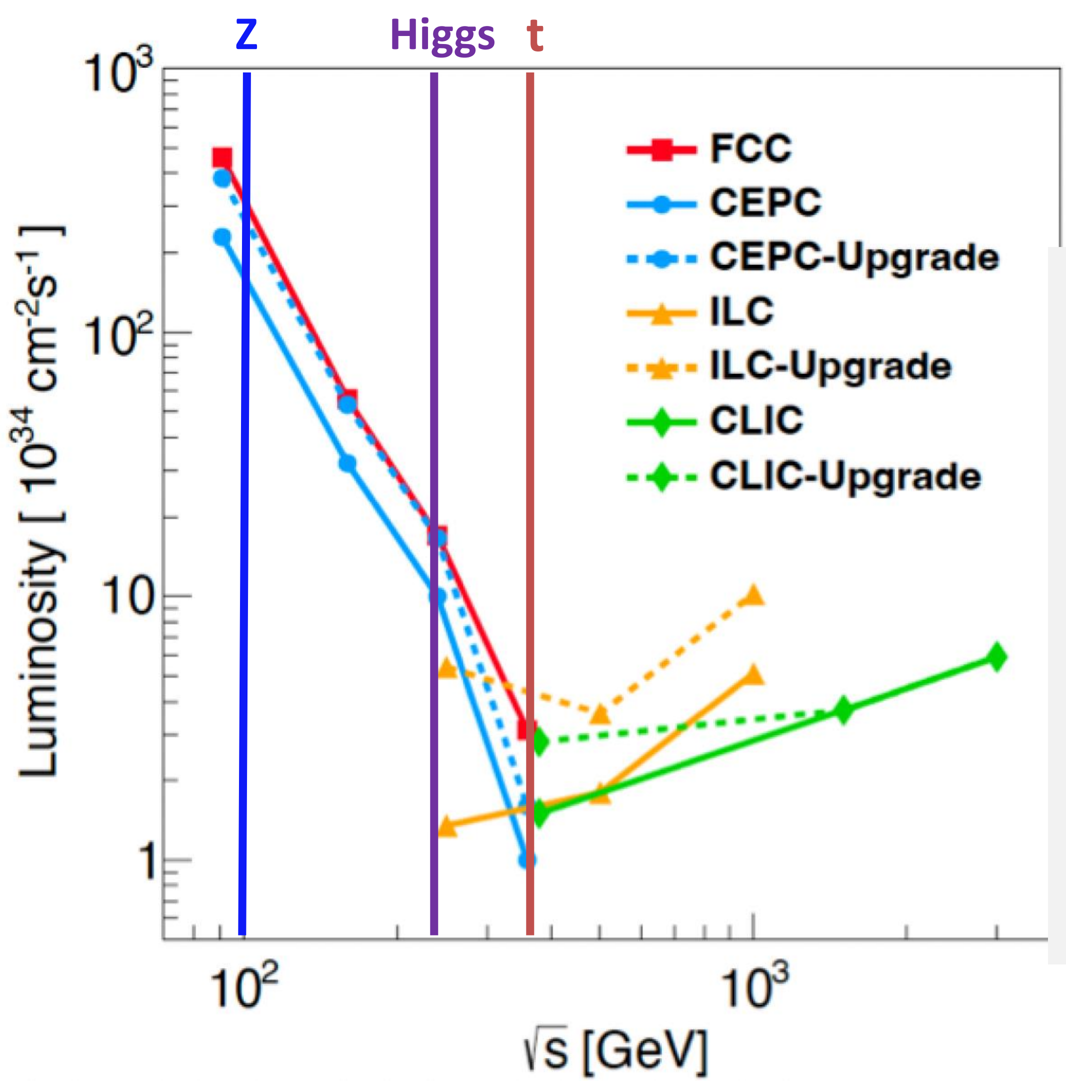
unbiased H sample can be selected by way of recoil mass against the Z boson



$$M^2_{H\to FS} = (\sqrt{S} - E_Z)^2 - |\vec{P}_Z|^2$$



Cases III: HF - Circular vs. Linear



- Circular ee colliders have better luminosity (× **2 IPs**) at **Z**, **Higgs** and **W** (**FCC-ee is considering 4 IPs case**)
- Linear ee colliders advantageous at high energies (**top** quark)
- Circular ee colliders can be replaced by ~100 TeV pp collider to reach high energy frontier

S.C.CHEN based on Snowmass

Status of CEPC and FCC-ee

- Designs and performance
- Organization and plan
- Progress and status

FCC-ee & CEPC

- Two future circular e+e− colliders are being proposed, CEPC on a greenfield site in China; FCC-ee linked to the existing CERN facilities. CM energy 90-360 GeV

- In a subsequent project stage, this same tunnel could later accommodate a high energy hadron collider, such as Super Proton-Proton Collider (SPPC) or FCC-hh, respectively. CM energy ~100 TeV

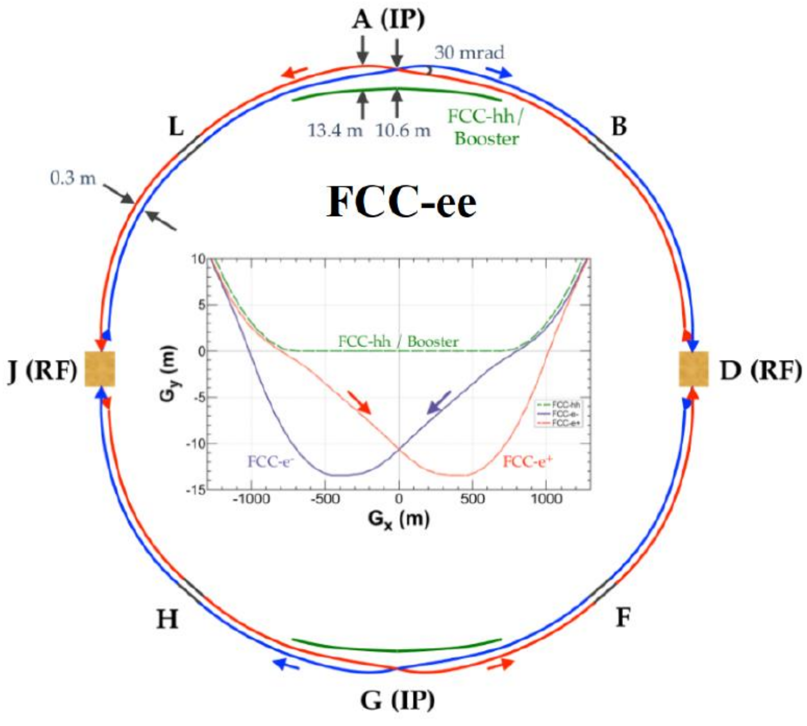
- Common use of RF systems for both beams at highest energy working points, starting from the ZH production mode.

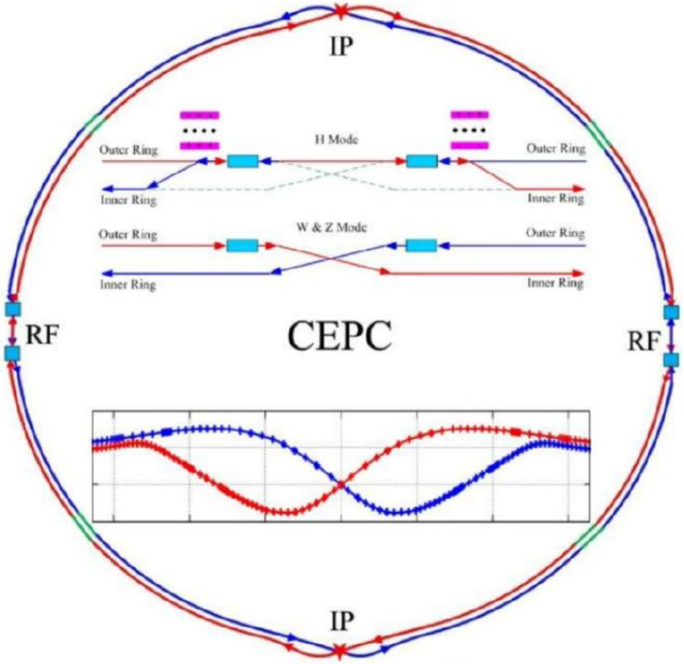
- Both collider designs consider an asymmetric interaction region to limit SR of incoming beams towards detectors and to generate the required large crossing angle.

- Each of the two machines is accompanied by a full-energy top-up booster ring situated in the same large tunnel.

CEPC/FCC-ee Design

Both FCC-ee and CEPC are conceived as double ring colliders, with 4 (or 2) interaction points (IPs), radiofrequency (RF) system straights, and a tapering of the arc magnet strengths to match local energy.





CEPC/FCC-ee Design

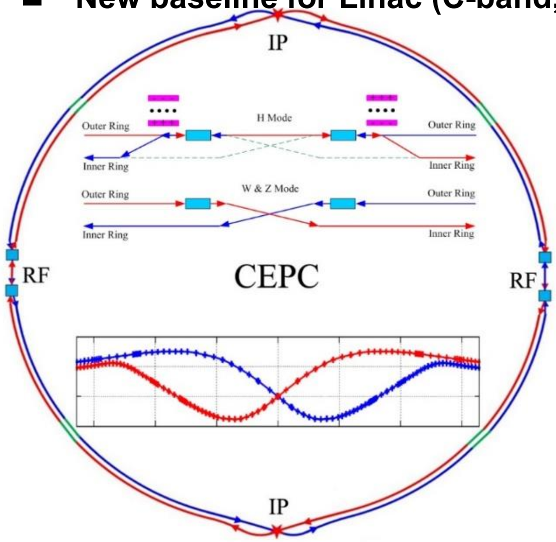
- Preliminary key parameters of FCC-ee (left) and of CEPC (right).
- The beam lifetime due to effect of radiative Bhabha scattering and beamstrahlung.
- For FCC-ee, a scenario with 4 IPs is under study, with ~10-30% lower luminosity per IP, 1.7–1.9× integrated luminosity, and ~1.7 shorter beam lifetime.

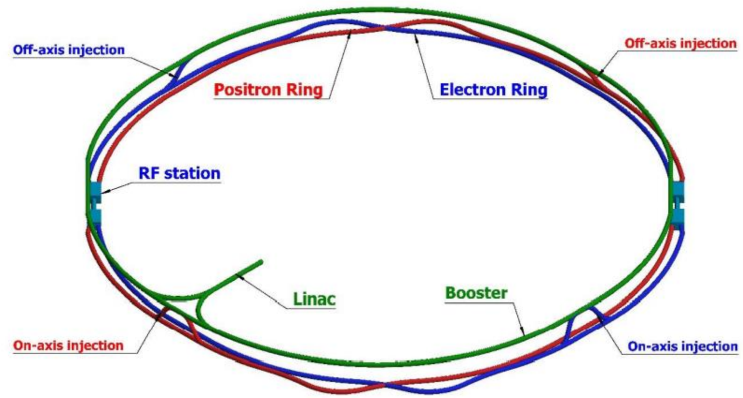
	FCC-ee				CEPC			
Running mode	Z	W	ZH	$t\bar{t}$	Z	W	ZH	$t\bar{t}$
Number of IPs	2				2			
Circumference (km)	91.2				100.0			
Beam energy (GeV)	45.6	80	120	182.5	45	80	120	180
Bunches/beam	12000	880	272	40	11951	1297	249	35
Beam current [mA]	1280	135	26.7	5.0	803.5	84.1	16.7	3.3
Lum. / IP [$10^{34}cm^{-2}s^{-1}$]	193	22.0	7.73	1.31	115	16	5	0.5
Synchr. Rad. Power [MW]	100				60			
Rms b. length (SR) [mm]	4.38	3.55	3.34	2.02	2.5	2.5	2.3	2.2
(+BS) [mm]	12.1	7.06	5.12	2.56	8.7	4.9	3.9	2.9
Rms en. spread (SR) [%]	0.039	0.069	0.103	0.157	0.04	0.07	0.10	0.15
(+BS) [%]	0.108	0.137	0.158	0.198	0.130	0.14	0.17	0.20
Rms hor. emit. ε_x [nm]	0.71	2.17	0.64	1.49	0.27	0.87	0.64	1.4
Rms vert. emit. ε_y [pm]	1.42	4.32	1.29	2.98	1.4	1.7	1.3	4.7
Hor. IP beta β_x^* [mm]	100	200	300	1000	130	210	330	1040
Vert. IP beta β_y^* [mm]	0.8	1.0	1.0	1.6	0.9	1.0	1.0	2.7
Beam lifetime rad. Bhabha & BS [min.]	35	32	9	16	80	55	20	18

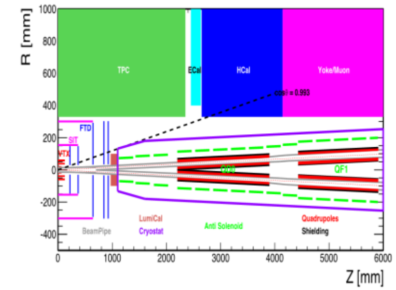
CEPC Status

Design improvement and TDR

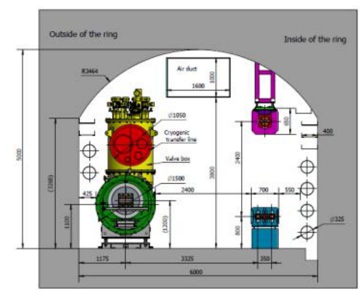
- 100 km double ring design (30 MW SR power, upgradable to 50MW).
- Switchable between H & Z, W modes without hardware change (magnet switch).
- New baseline for Linac (C-band, 20GeV) .



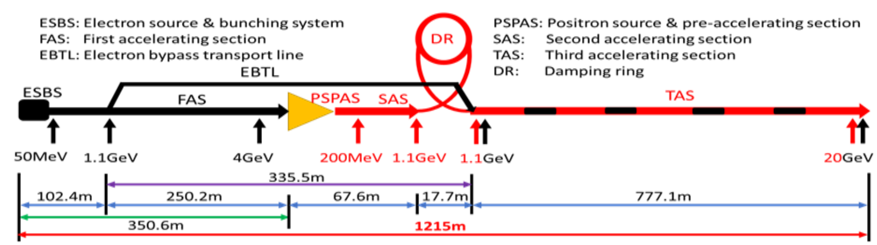




TUNNEL CROSS SECTION OF THE ARC AREA



Operation mode		ZH	Z	W^+W^-	tt
$\sqrt{s}$ [GeV]		~240	~91.2	158-172	~360
L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	CDR (2018)	3	32	10	
	Latest	5.0	115	16	0.5

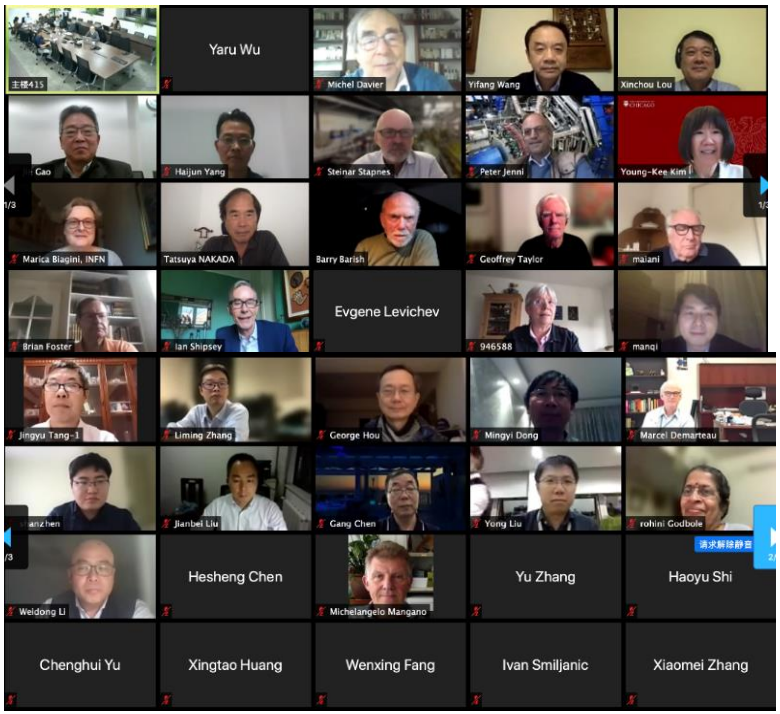


- Injection energy: 10GeV → 20GeV
- Max energy: 120GeV → 180GeV

Future Linac considered: plasma WF, C3

CEPC Status

- The 7th CEPC IAC meeting (online) was held in November, 2021
- The IAC presented an advisory report with many recommendations。



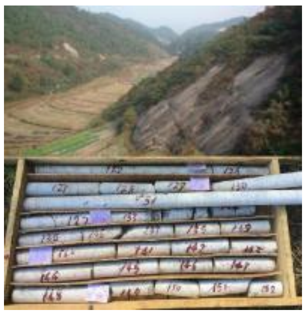
- In 2021, two online International Accelerator Review Committee (IARC) meetings took place,
  - May (11 talks)
  - October (22 talks)
- IARC delivered two dedicated review reports

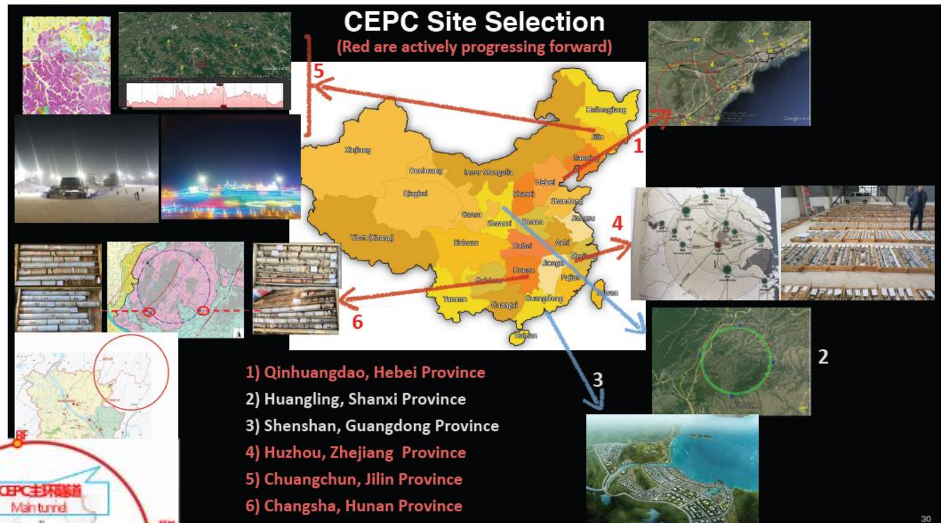
great help and guidance

CEPC Status

Site Investigation

Factors: geology, electricity supply, transportation, international-friendly, local supports …

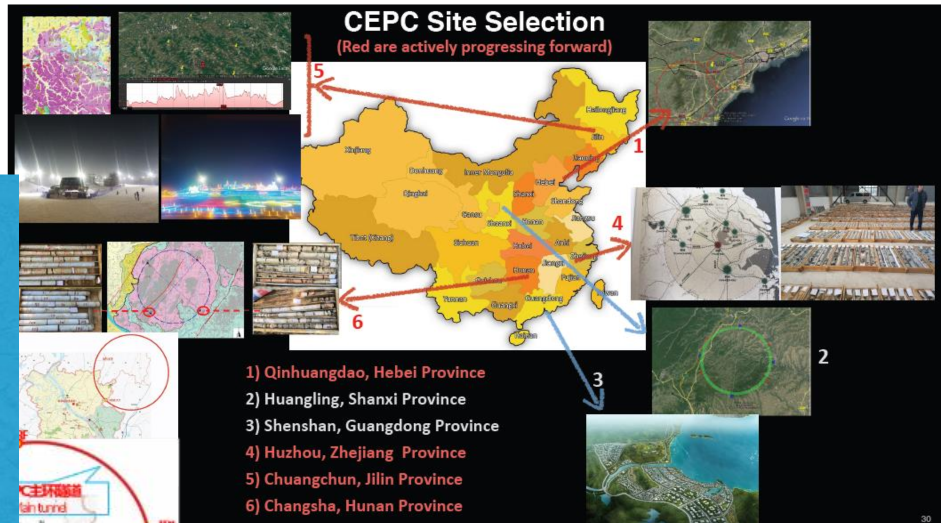




CEPC Status

IPAC 2022, Bangkok

Site Investigation



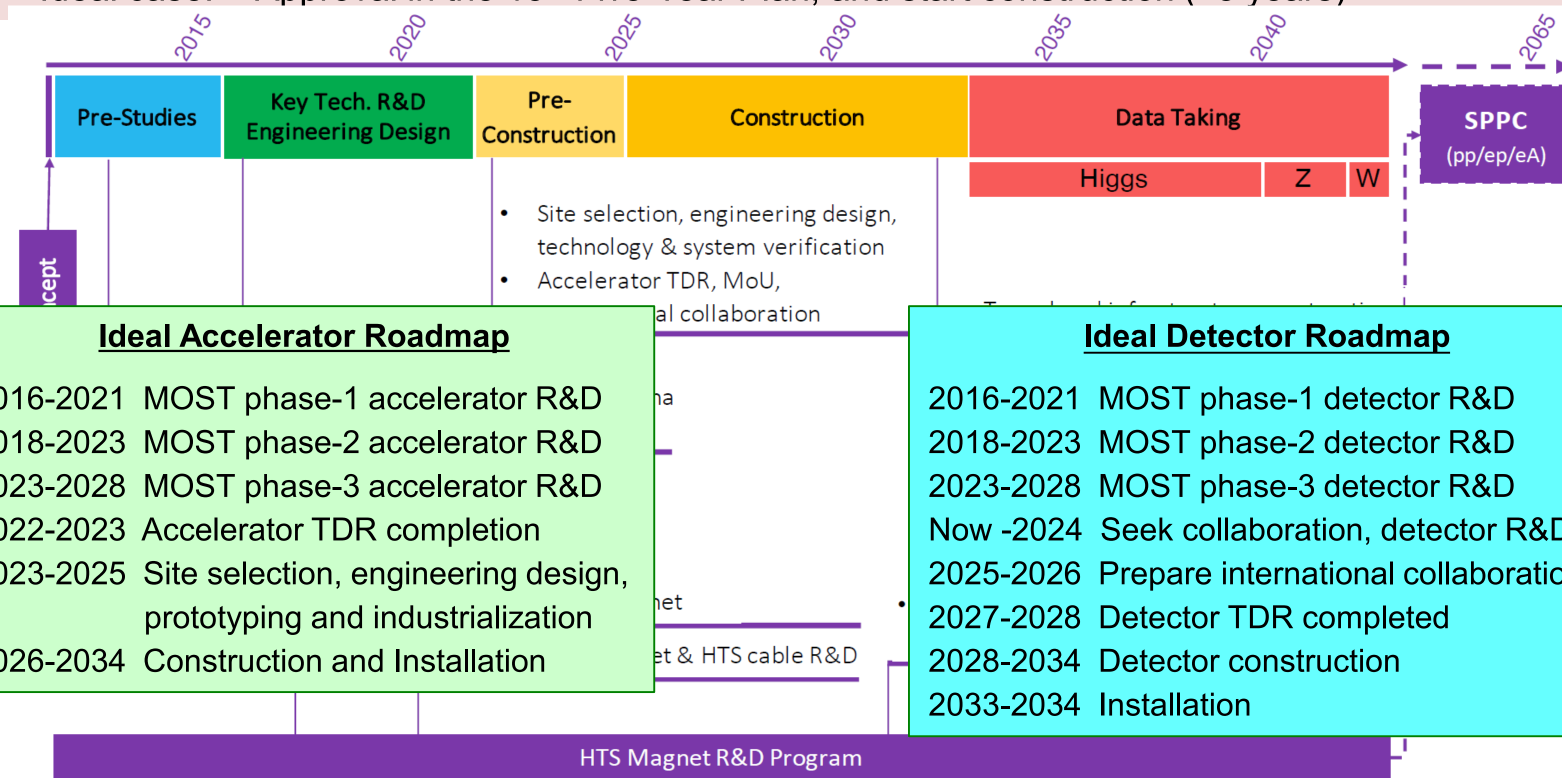
Factors: geology, electricity supply, transportation, international-friendly, local supports …

July 5, 2021: Changsha Bureau of S&T entrusted Hunan U. to conduct a feasibility study.

Sept 4, 2021: Hunan U. organized a review by a committee of experts from multiple disciplines. The committee evaluated scientific potential of CEPC, feasibility of a new science city based on CEPC, and overall impact on Changsha. The overall conclusion is very positive. The local government is interested and very supportive to the CEPC project.

CEPC Status

- 2013-2025: Key technology R&D, from CDR to TDR, site selection, international collaboration etc.
- Ideal case: Approval in the 15th Five-Year Plan, and start construction (~8 years)



Ideal Accelerator Roadmap

2016-2021 MOST phase-1 accelerator R&D
2018-2023 MOST phase-2 accelerator R&D
2023-2028 MOST phase-3 accelerator R&D
2022-2023 Accelerator TDR completion
2023-2025 Site selection, engineering design, prototyping and industrialization
2026-2034 Construction and Installation

Ideal Detector Roadmap

2016-2021 MOST phase-1 detector R&D
2018-2023 MOST phase-2 detector R&D
2023-2028 MOST phase-3 detector R&D
Now -2024 Seek collaboration, detector R&D
2025-2026 Prepare international collaborations
2027-2028 Detector TDR completed
2028-2034 Detector construction
2033-2034 Installation

CEPC Status

CEPC Accelerator TDR

- **Consistent TDR high luminosity parameter design as a Higgs factory**
- **Key components with prototyping, technical feasibility demonstrated, no technical show stopper**
- **Design and R&D technical documentation (data, drawings, etc.)**
- **CEPC accelerator TDR document release planned for 2023**

CEPC Accelerator EDR Plan; ~Jan. 2023-Dec. 2025 preliminary

- CEPC site study will converge to one or two with feasibility studies (tunnel and infrastructures, environment)
- Engineering design of CEPC accelerator systems and components
- Site dependent civil engineering design implementation preparation
- EDR document completed for government's approval of starting construction in 2026 (the starting of the "15th five year plan")
- There will be more discussions on the planning

FCC-ee Status

- A comprehensive Conceptual Design Report (CDR) for the FCC was published in 2019

- Following the 2020 European Strategy Update, in 2021 the CERN Council has launched the FCC Feasibility Study (FS):
  (1) technical aspects of the accelerators,
  (2) feasibility of tunnel construction and technical infrastructures
  (3) possible financing of the proposed future facility.

starts with Z, W, H and then t

	$\sqrt{s}$	L /IP ($cm^{-2} s^{-1}$)	Int. L /IP(ab^{-1})	Comments
e^+e^- FCC-ee	~90 GeV Z 160 WW 240 H ~365 top	230 x10^{34} 28 8.5 1.5	75 5 2.5 0.8	2-4 experiments Total ~ 15 years of operation
pp FCC-hh	100 TeV	5 x 10^{34} 30	20-30	2+2 experiments Total ~ 25 years of operation
PbPb FCC-hh	$\sqrt{s_{NN}}$ = 39TeV	3 x 10^{29}	100 nb^{-1}/run	1 run = 1 month operation
ep Fcc-eh	3.5 TeV	1.5 10^{34}	2 ab^{-1}	60 GeV e- from ERL Concurrent operation with pp for ~ 20 years
e-Pb Fcc-eh	$\sqrt{s_{eN}}$ = 2.2 TeV	0.5 10^{34}	1 fb^{-1}	60 GeV e- from ERL Concurrent operation with PbPb

Realistic timeline matched to HL-LHC:

- ❑ Feasibility Study: 2021-2025
- ❑ If project approved before end of decade → construction can start beginning 2030s
- ❑ FCC-ee operation ~**2045-2060**
- ❑ FCC-hh operation **2070-2090++**

FCC-ee Status

Accelerator Design Status

- New 91 km circumference placement with 8 access points
- Layout with 4 IP's that is consistent with upgrade to FCC-hh
- Optimizing allocation of straight sections
- New FCC-ee optics to optimize beam-beam
- 400 MHz and 800 MHz RF systems
- Starting tunnel integration studies for RF and Arc sections
- Full energy booster that will fit in FCC tunnel for top-up injection
- e+ / e- injector to fill booster 24 / 7

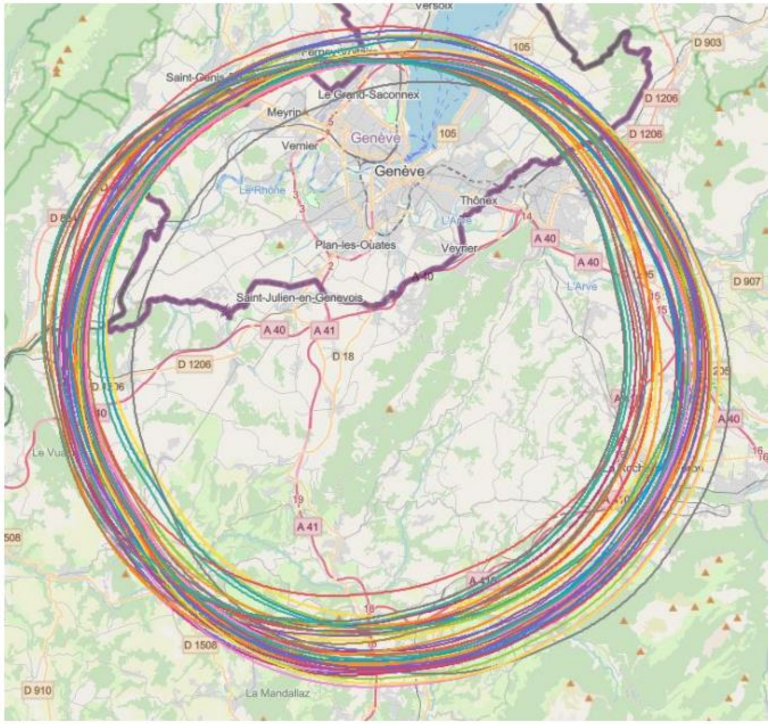
Tor Raubenheimer, FCC Week 2022 (Paris)

FCC-ee Status

FUTURE CIRCULAR COLLIDER

Implementation studies with host states

- layout & placement optimisation across both host states, Switzerland and France;
- following "avoid-reduce-compensate" directive of European & French regulatory frameworks;
- diverse requirements and constraints:
  - **technical feasibility of civil engineering** and subsurface geological constraints
  - **territorial constraints on surface** and subsurface
  - **nature, accessibility**, technical infrastructure, resource needs & constraints
  - **optimum machine performance and efficiency**
  - economic factors including benefits for, and synergies, with the **regional developments**
  - ...
- collaborative effort: FCC technical experts, consulting companies, government-notified bodies



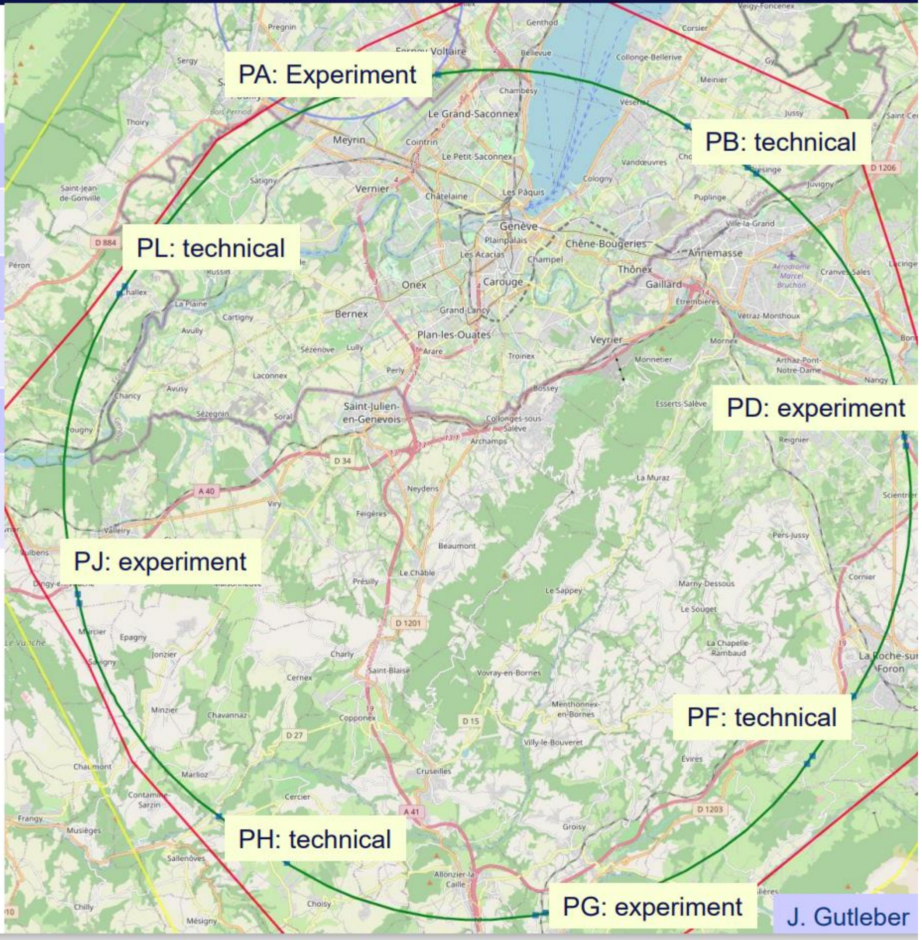
Michael Benedikt, FCC Week 2022 (Paris)

FCC-ee Status

8-site baseline ”PA31”

Number of surface sites	8
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2143 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**91.1 km**

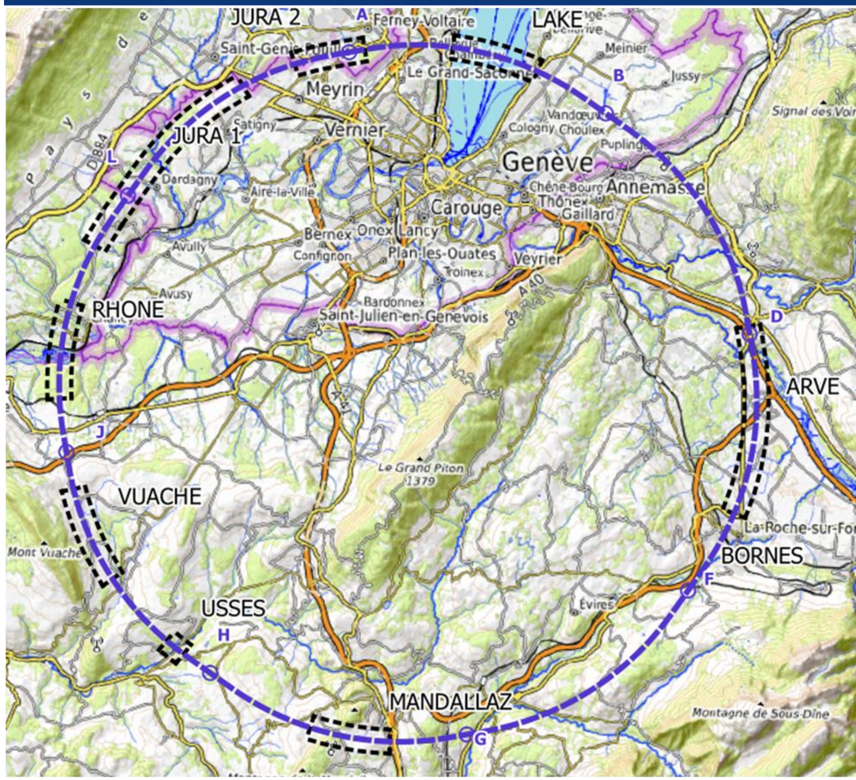
- 8 sites – less use of land, <40 ha instead 62 ha
- Possibility for 4 experiment sites in FCC-ee
- All sites close to road infrastructures (< 5 km of new road constructions for all sites)
- Vicinity of several sites to 400 kV grid lines
- Good road connection of PD, PF, PG, PH suggest operation pole around Annecy/LAPP



FUTURE CIRCULAR COLLIDER

FCC Long Section – PA31-1.0

Plans for high-risk area site investigations



JURA, VUACHE (3 AREAS)
Top of limestone
Karstification and filling-in at the tunnel depth
Water pressure

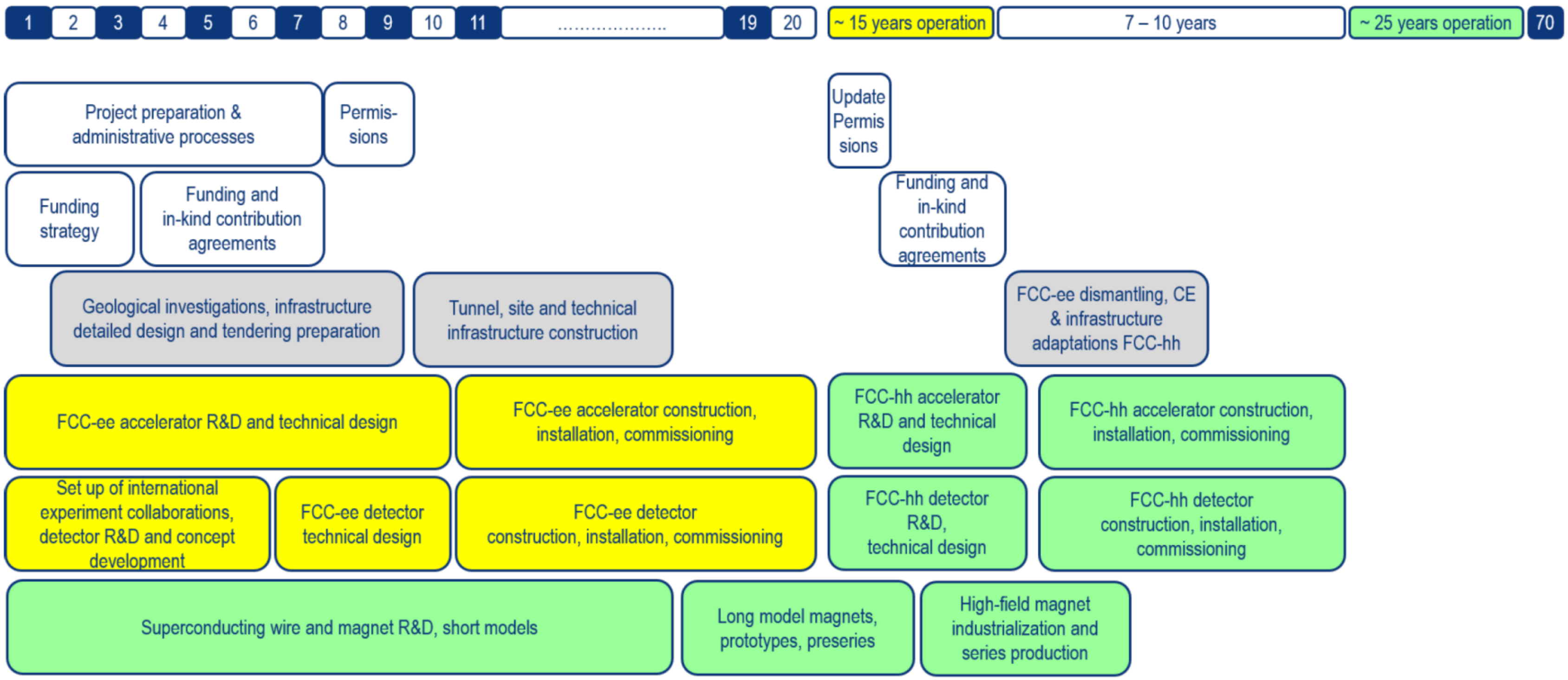
LAKE, RHÔNE, ARVE AND USSES VALLEY (4 AREAS)
Top of the molasse
Quaternary soft grounds, water bearing layers

MANDALLAZ (1 AREAS)
Water pressure at the tunnel level
Karstification

BORNES (1 AREA)
High overburden molasse properties
Thrust zones

Site investigations planned for mid 2023 – mid 2025:
~40-50 drillings, 100 km of seismic lines

FCC Integrated Schedule



Key Technologies & R&D Progress

CEPC Key Technologies and R&D

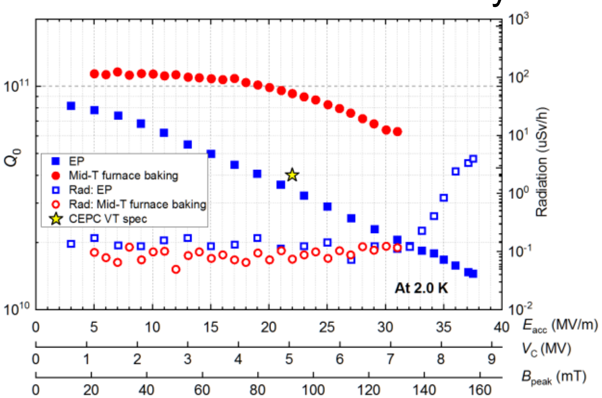
Beijing Huairou (4500m²) **CEPC SCRF Facility & Components**





IHEP PAPS established in July 2021 Horizontal test stand, 1.3GHz 9cell cavities, and couplers...

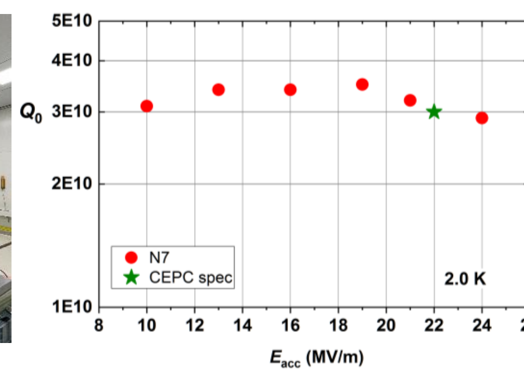
CEPC 650 MHz 1-cell Cavity



P. Sha et al., *Applied Sciences*. 2022; 12(2):546.

The 650Mhz 1-cell cavity's results (6.4E10@30MV/m, 1.5E10@37.5MV/m) have broken China's gradient record of low-frequency (<1 GHz) elliptical cavities. **World record Q** of 650 MHz cavity at 30 MV/m.

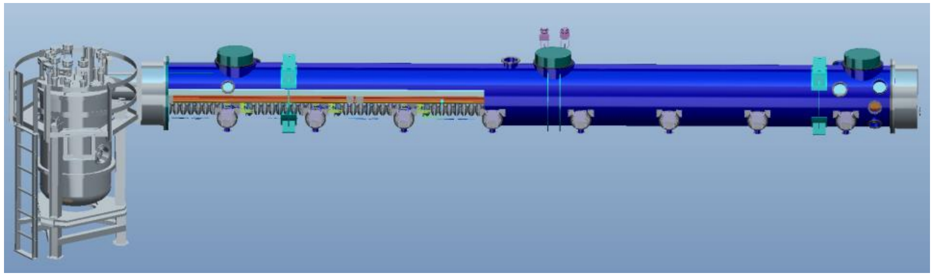
1.3 GHz High Q Mid-T Cavity Horizontal Test

CEPC Key Technologies and R&D

CEPC 650 MHz Test Cryomodule with Beam/ 1.3GHz High Q Cryomodule (8X9cell)

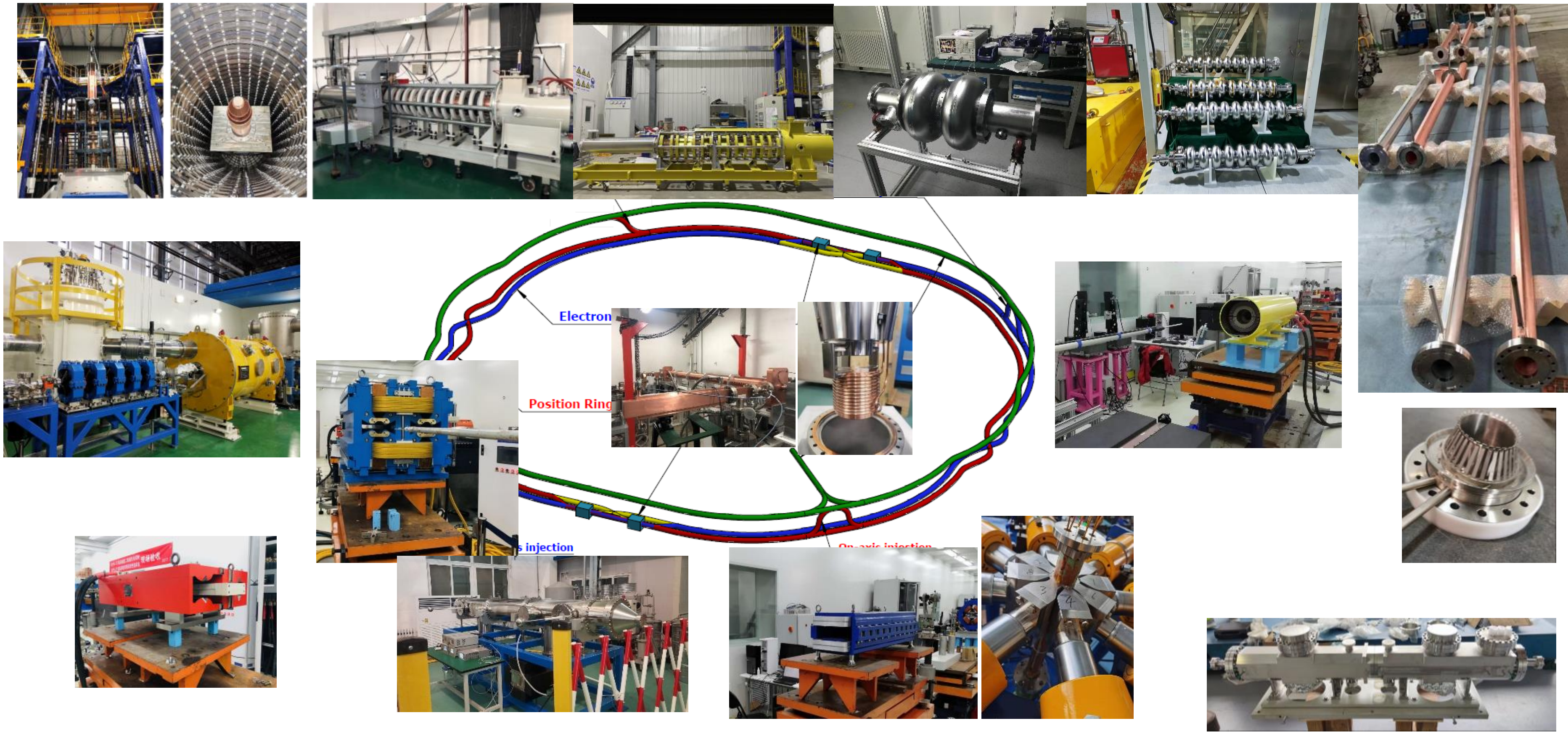
- Cavity string and module assembly in March to May 2021.
- Modul installation in beamline, 2 K cool down test and RT coupler conditioning in May to July.
- IR laser output to 116 W. Photo-cathode QE to 5 %. DC gun vacuum to 1.5E-10 Pa, voltage to 350 kV. Buncher cavity high power tested.



- 1.3 GHz 8x9-cell high Q cryomodule prototype
- Component fabrication in 2021 to mid 2022
- Assemble and horizontal test in 2022

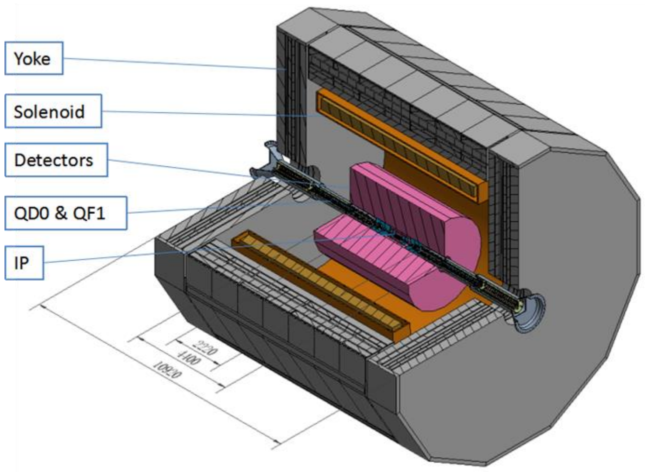
CEPC Key Technologies and R&D

CEPC TDR R&D Status of Key Technologies

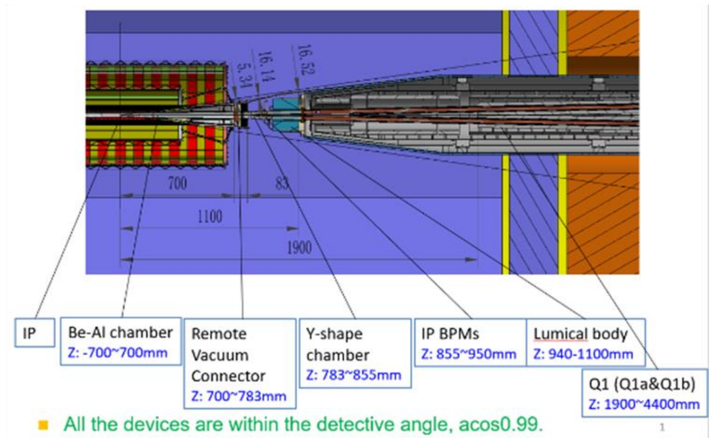


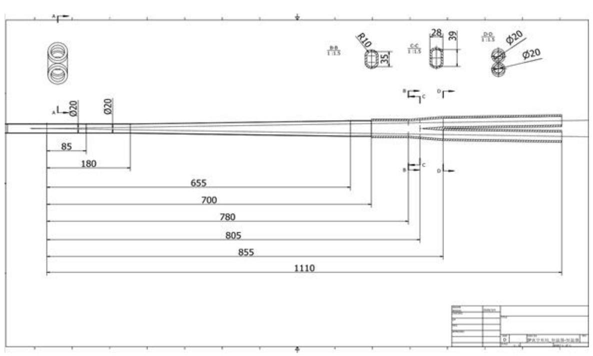
CEPC Key Technologies and R&D

CEPC MDI Study Progresses



- IR Superconducting magnet design
- IR beam pipe
- Synchrotron radiation
- Beam loss background
- Shielding
- Mechanical support
- Full detector simulation

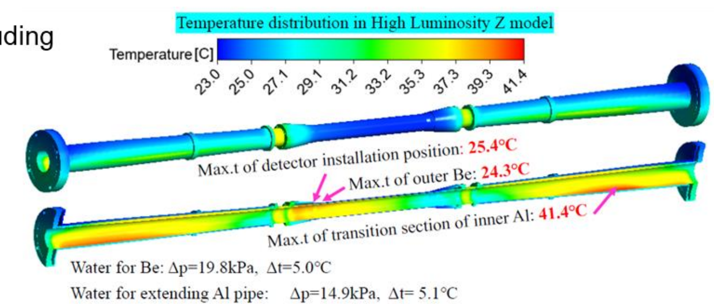




- ✓ HOM in IR region
- ✓ results for MDI 20mm-20mm
- ✓ Transition region: Racetrack (including materials)
- ✓ σ_z=5mm: Two beam in the IR
- ✓ Loss factor Trap in IR @k_trap: 0.032v/pc

P_{trap}: H/W/Z/tt: 24.0w/117.1w/1160.8w/6.67w

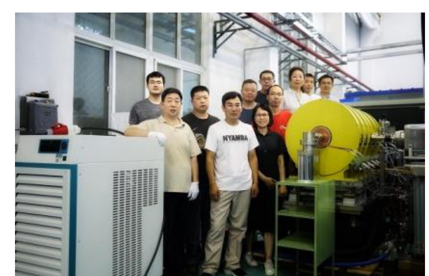
Temperature studies in IR beam pipe



High Energy Light Source under construction

beam energy 6 GeV, 1.36KM, ≤ 0.06nm·rad, 14 beam lines

Carried out by IHEP, to be completed in 2025, great training and preparation for CEPC



FCC-ee Key Technologies and R&D

The FCC-e eR&D aims at developing more efficient, novel technologies, which could decrease costs, lower the energy consumption, and reduce the environmental impact.

Present R&D efforts towards these goals include high-efficiency continuous wave radiofrequency power sources, high-*Q* SC cavities for the 400-800MHz range, and possible applications of HTS magnets.

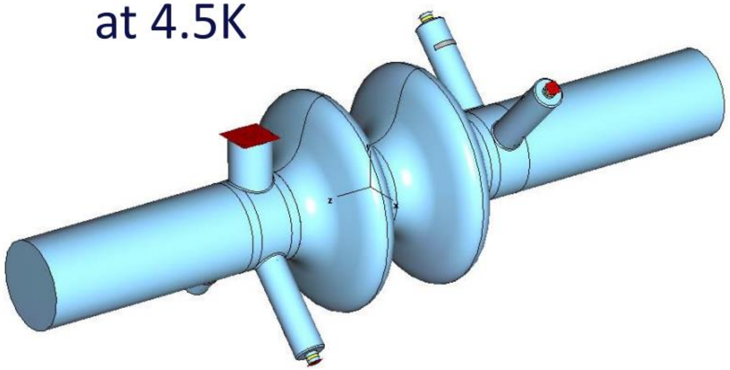
an arc half-cell mock up is foreseen to be constructed by 2025, including girder, a vacuum system with antechamber and pumps, dipole, quadrupole and sextupole magnets, beam position monitors, cooling and alignment systems, and technical Infrastructure interfaces.

Also for the interaction region the construction of a mock up is proposed, consisting of the central beam pipe, first SC quadrupole with its cryostat, support structures, stabilization system, and remotely controlled flanges.

FCC-ee Key Technologies and R&D

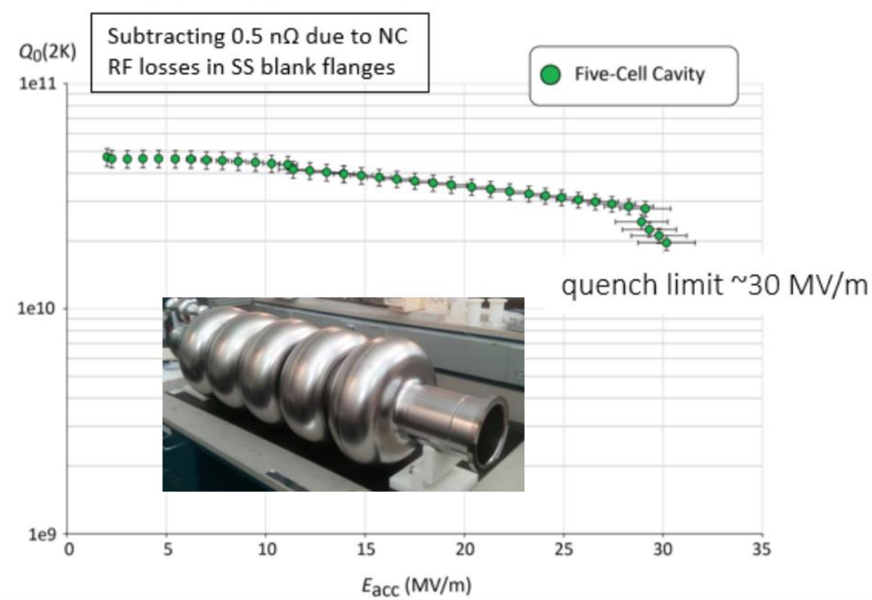
FCC-ee SRF Technology

- **SRF technology building on LHC studies and collaborative R&D**
  - 5-cell 800 MHz cavity without damping built and tested at 2K by Jefferson lab with excellent results
  - 400 MHz cavities based on LHC studies of Cu-coated Nb cavities at 4.5K



Model for 2-cell 400 MHz synergistic with LHC

Jlab test of 5-cell 800 MHz



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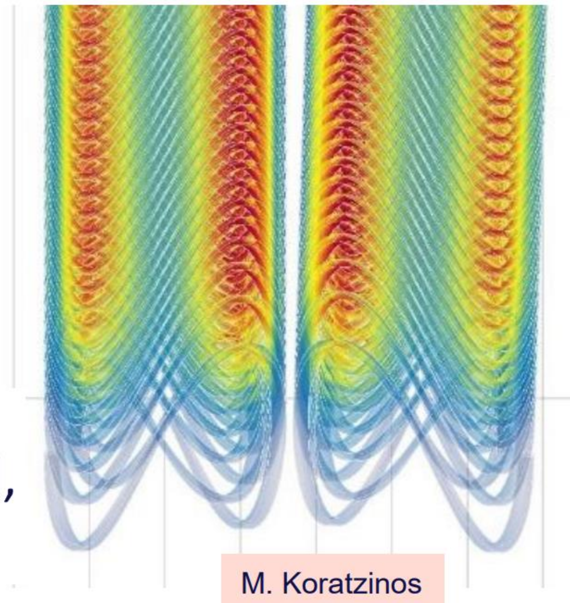
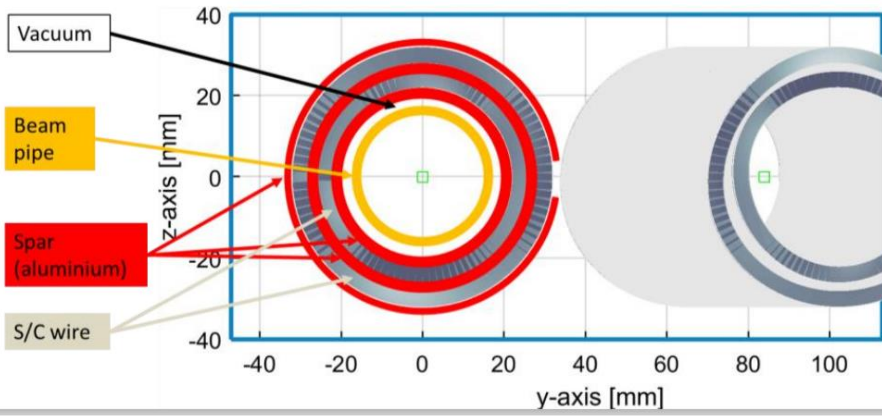
FCC-ee Key Technologies and R&D

FCC-ee IR magnets

- **Canted-Cosine-Theta magnets w/ fringe fields fully compensated**
    - Elegant 2-layer design for inner quadrupoles
    - Working to fit within 100 mrad stay-clear cone
    - Integration with supports, solenoids, trim coils, shielding, cryostat, etc needs to be developed
    - Prototype built and warm-tested
    - External review of concept April, 2022





FUTURE CIRCULAR COLLIDER

Pre-engineering design review and roadmap discussion for FCC-ee IR magnets

4 Apr 2022, 14:00 → 5 Apr 2022, 19:00 Europe/Zurich

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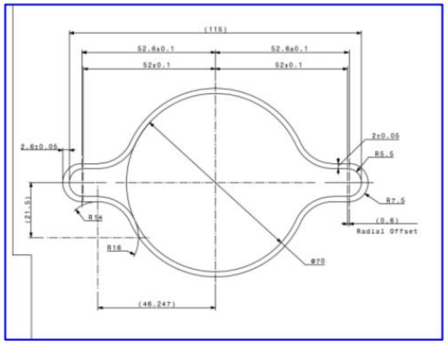
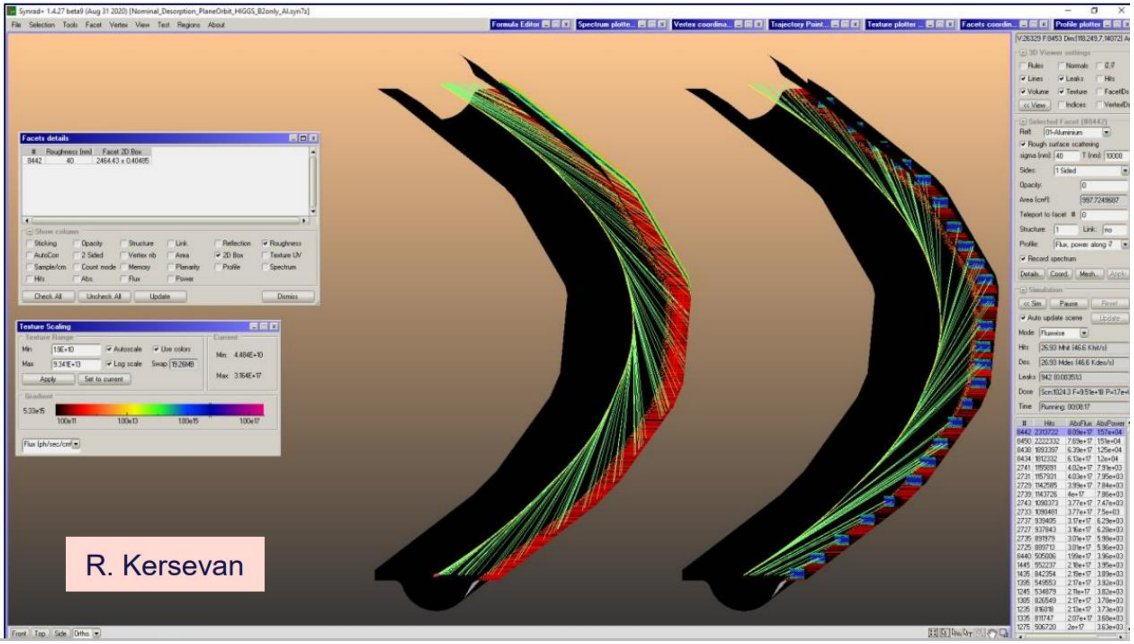
FCC-ee Key Technologies and R&D

FCC-ee Vacuum system

- **Specifying vacuum system**
  - Consider discrete absorbers space every <6 m or continuous absorbers along chamber wall
  - NEG coated Cu vacuum chamber
  - Need shielding to minimize tunnel radiation levels





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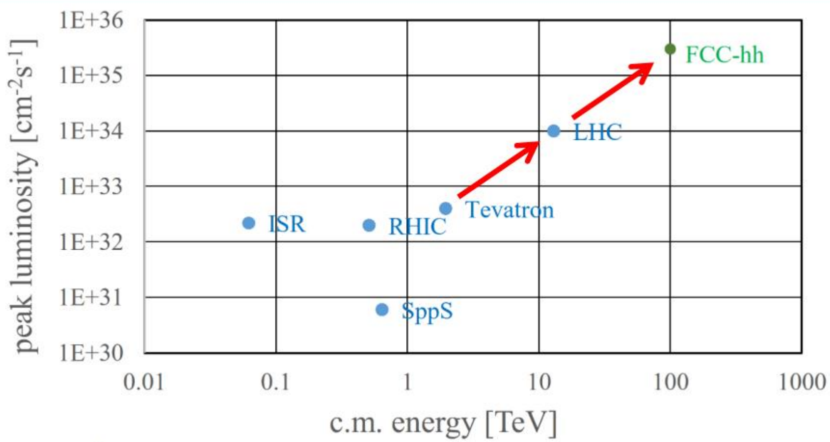
FCC-ee Key Technologies and R&D

FUTURE CIRCULAR COLLIDER

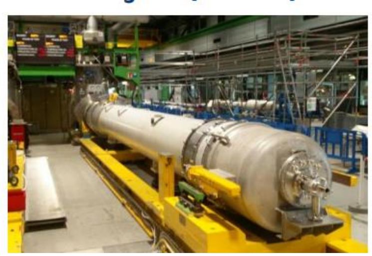
FCC-hh: highest collision energies

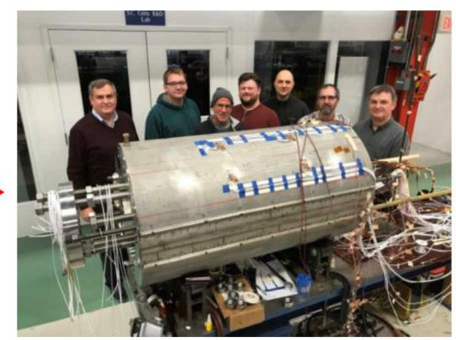


- **order of magnitude performance increase** in both **energy & luminosity**
- **100 TeV cm collision energy** (vs 14 TeV for LHC)
- **20 ab-1 per experiment collected over 25 years** of operation (vs 3 ab^{-1} for LHC)
- similar performance increase as from Tevatron to LHC
- **key technology: high-field magnets**

from
LHC technology
8.3 T NbTi dipole

via
HL-LHC technology
12 T Nb_3Sn quadrupole





FNAL dipole demonstrator
4-layer cosϑ
14.5 T Nb_3Sn
in 2019

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Possible Synergies

Possible Synergies

Ideally

- **Important technical areas for circular ee colliders**
- **Challenging domains for circular ee colliders to achieve the design performance**
- **Prototyping of key hardware components**
- **New and innovative approaches that may bring the collider technology and performance to the next level**
- **Instrumentation enabling physicists to collect & analyze data to reach the limit of the collider data**
- **Independent crosschecks**

Possible Synergies

Technical areas critical to circular ee colliders

design optimization
design reviews
key beam physics studies

large volume components: design, quality, cost (magnets, SRF, installation, ….)

energy saving and cost reduction

prototyping of key hardware components

Possible Synergies

Challenging domains for circular ee colliders to achieve the design performance

machine-detector interface

control system, safety (environment, operation)

management software

experience at previous and present colliders (SuperKEKB,…)

Possible Synergies

New and innovative approaches that may bring the circular collider to the next level

new linac and injection (plasma WF, C3, …)

upgradability (luminosity, easy to operate, energy)

HT superconductor development, lower the cost for the pp collider

high energy gamma synchrotron light and app.

advanced SRF systems with higher gradient (for example, thin Nb_3Sn films on copper)

Possible Synergies

Instrumentation

detector design beyond those of ILC, LEP
6G wireless detector control, data transmission
upgradability (luminosity, easy to operate, energy)

ECFA detector program

collect, store and analyze collision data under the best possible conditions;

Possible Synergies

Cross-checks and mutual support

circular ee collider eco-system
independent crosschecks of design concepts and simulation results

outreach and science education about HEP

……

Summary

Strong physics cases for high energy e^+e^- colliders to study the **Higgs, Z, W bosons and the t quark** with much improved precisions, and possible new physics with input from the LHC and other experiments.

Both FCC-ee and CEPC are compelling options for a future factory for the Higgs, Z, W bosons and top quark, providing great opportunities for discovery in physics.

Either machine can be upgraded towards a future hadron collider (FCC-hh or SPPC), which would become the next high energy frontier machine.

The FCC-ee and CEPC groups are advancing toward the realization of the project, respectively.

Numerous possible synergies exist between the CEPC and FCC-ee designs, and could be exploited for better design, critical technologies, affordability and support for a future high energy circular e^+e^- collider.

Acknowledgement

Special thanks to

The FCC collaboration and CEPC study group.