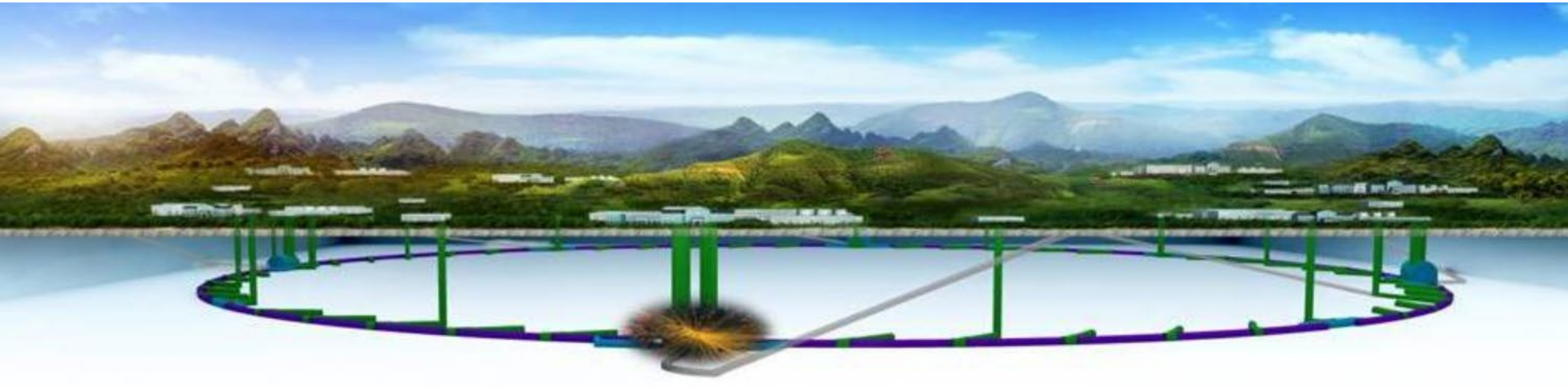
Circular Colliders in China

Yifang Wang， IHEP

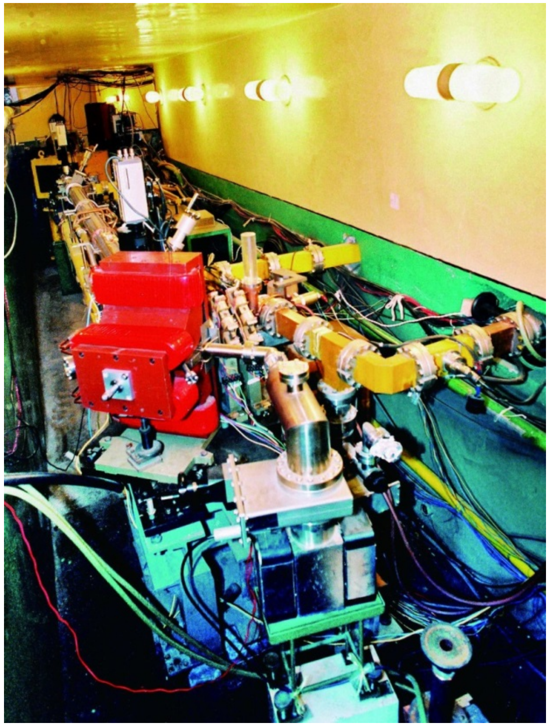
Bruno Touschek 100 Yrs Memorial Symposium

Dec.4, 2021

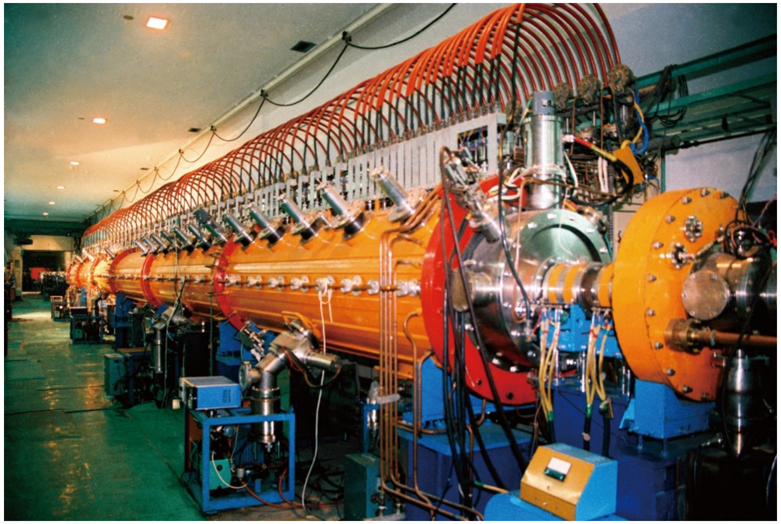


Accelerators in China Since 50's

2.5MeV proton electrostatic accelerator, 50's



30MeV electron LINAC, 60's



30MeV proton LINAC, 80's

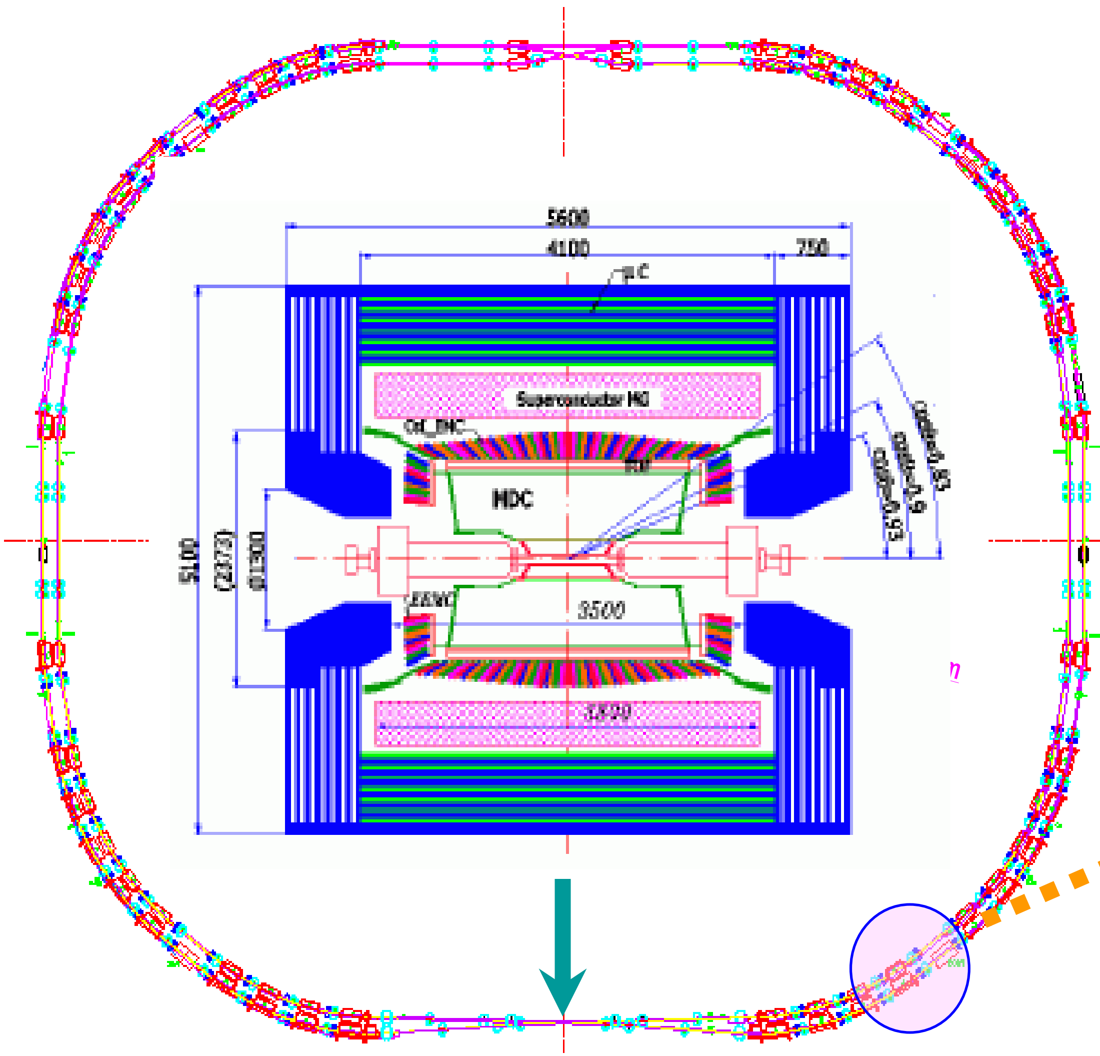
In addition to these small tries, a number of large high energy accelerators were proposed unsuccessfully in 60's - 80's until the real start: **BEPC**

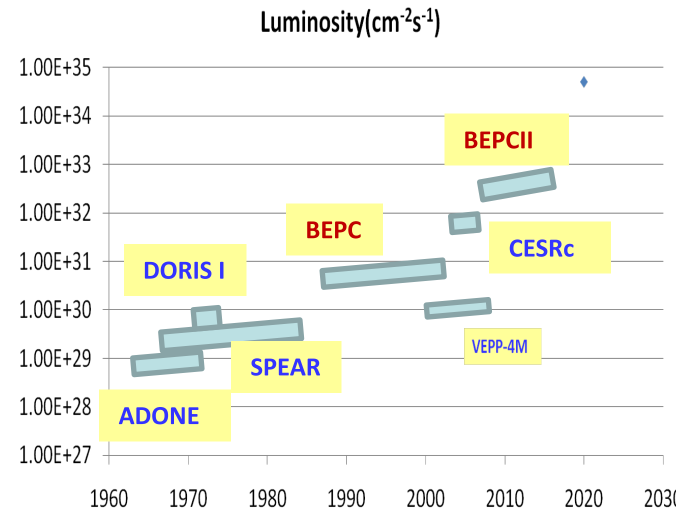
Beijing Electron-Positron Collider(BEPC)
Beijing Spectrometer(BES)
Beijing Synchrotron Radiation Facility(BSRF)

2-5 GeV

1984-1988

BEPCII/BESIII Upgrade: 2004-2008





BESIII Collaboration

Europe (16)

Germany(6): Bochum University, GSI Darmstadt, Helmholtz Institute Mainz, Johannes Gutenberg University of Mainz, Universitaet Giessen, University of Münster

Italy(3): Ferrara University, INFN, University of Turin,

Netherlands(1): KVI/University of Groningen

Russia(2): Budker Institute of Nuclear Physics, Dubna JINR

Sweden(1): Uppsala University

Turkey (1): Turkish Accelerator Center Particle Factory Group

UK(2): University of Manchester, University of Oxford

USA(5)

Carnegie Mellon University
Indiana University
University of Hawaii
University of Minnesota
University of Rochester

Mongolia(1)

Institute of Physics and Technology

Korea(1)

Seoul National University

Japan(1)

Tokyo University

Thailand(1)

Suranaree University of Technology

Pakistan(3)

COMSATS Institute of Information Technology
University of the Punjab,
University of Lahore

India(1)

Indian Institute of Technology madras

China (45)

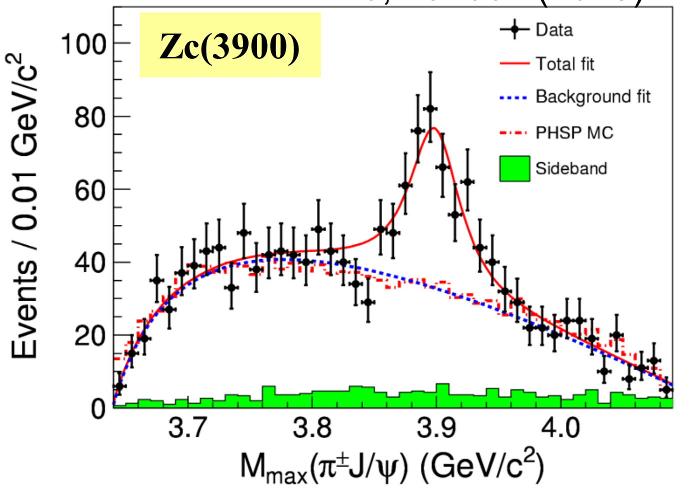
Beijing Institute of Petro-chemical Technology, Beihang University, China Center of Advanced Science and Technology, Fudan University, Guangxi Normal University, Guangxi University, Hangzhou Normal University, Henan Normal University, Henan University of Science and Technology, Huazhong Normal University, Huangshan College, Hunan University, Hunan Normal University, Institute of High Energy Physics, Institute of Modern Physics, Jilin University, Lanzhou University, Liaoning Normal University, Liaoning University, Nanjing Normal University, Nanjing University, Nankai University, North China Electric Power University, Peking University, Qufu Normal University, Shanxi University, Shanxi Normal University, Sichuan University, Shandong Normal University, Shandong University, Shanghai Jiao Tong University, Soochow University, South China Normal University, Southeast University, Sun Yat-sen University, Tsinghua University, University of Chinese Academy of Sciences, University of Jinan, University of Science and Technology of China, University of Science and Technology Liaoning, University of South China, Wuhan University, Xinyang Normal University, Zhejiang University, Zhengzhou University

~500 members
From 74 institutions in 15 countries

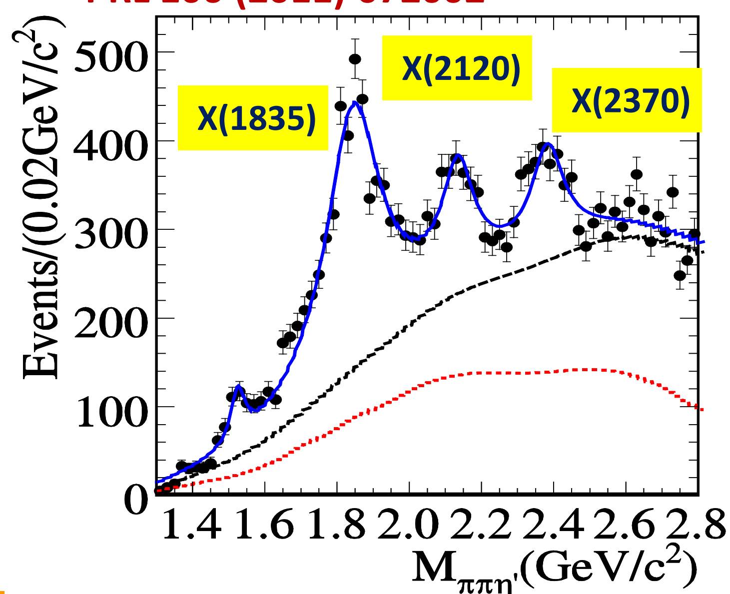
Successful BEPCII/BESIII

- Main Highlights:
  - Discovery of possible 4-quark states: $Z_c^{\pm}(3900)$, $Z_c^{0}(3900)$, $Z_c(4020)$, $Z_{cs}(3985)$, …
  - New decays modes of XYZ and their properties
  - Discovery of exotic light hadrons: X(1835), X(1870), X(2120), …
  - Glueball and hybrid searches…
  - Λ hyperons and its CP
  - Neutron form-factor
  - Tests of the Standard Model by Charmed meson decays
- > 40 papers/year, > 360 papers in total so far

PRL110, 252001 (2013)

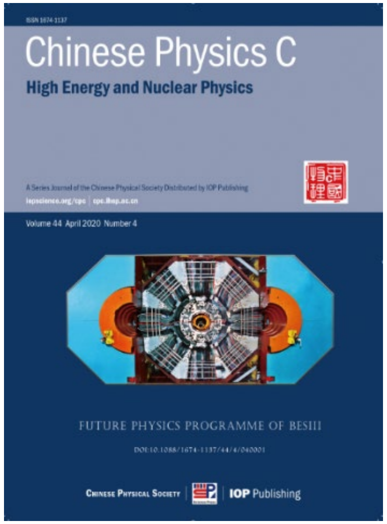


PRL 106 (2011) 072002

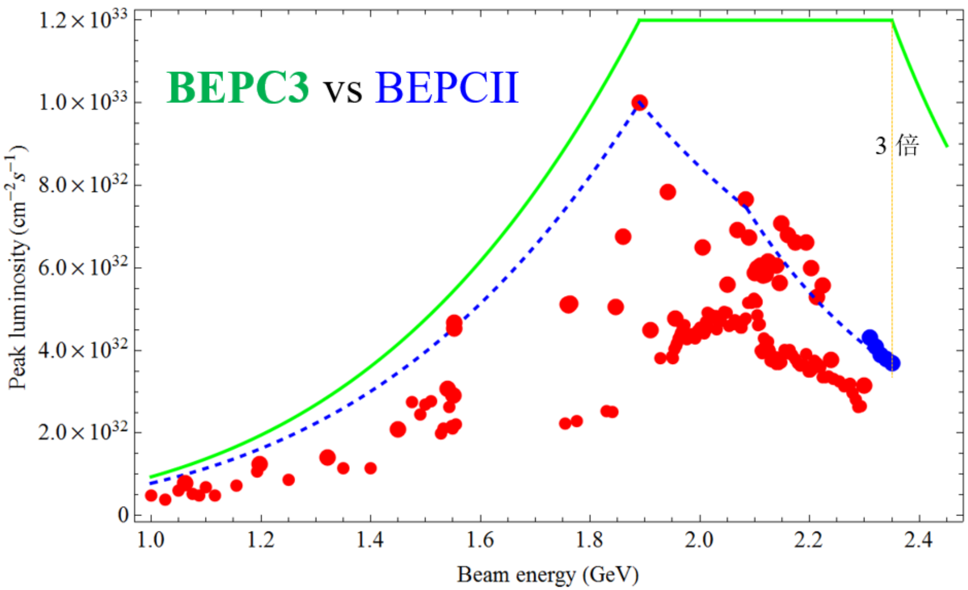


Future Plan

- Rich physics program requiring $> 40\ \text{fb}^{-1}$, corresponding to 15 yrs of data taking at the present luminosity
- Upgrades
  - Luminosity × ~3 ➔ squeeze the beam size by adding a new RF cavity per beam
  - Replace the two SC quadrupole magnets near the IP to increase the maximum beam energy from 2.45 to 2.8 GeV ➔ for charmed baryons
  - Plan to complete in 2024
- Operation will continue until at least 2030



Future physics program of BESIII

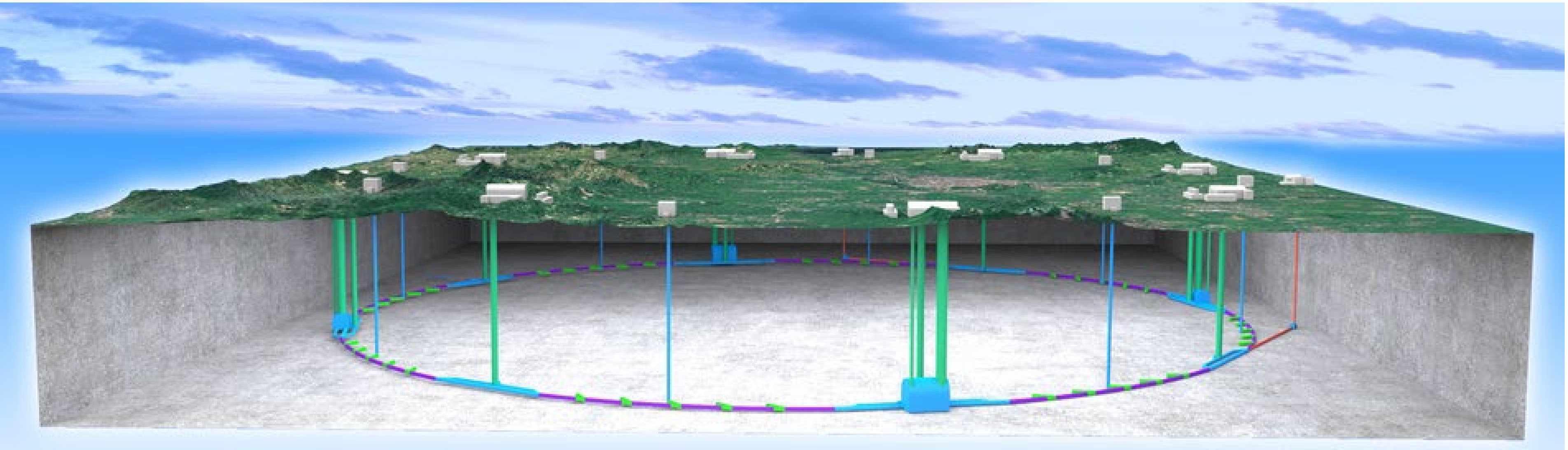


Further Future

- Since 2005, we were discussing what is the future of HEP in China after BEPCII. A new machine in China ? Joining ILC ?
- What could be the future of ILC ? How to get support in China for ILC ?
- Around 2012, we were discussing what is the future of HEP after the Higgs discovery

Answer: CEPC — Higgs Factory

- The idea of a Circular e+e- Collider(CEPC) followed by a possible Super proton-proton collider(SPPC) was proposed in Sep. 2012, and quickly gained the momentum in IHEP and in the world
  - Looking for Hints@e^+e^- Collider ➔ If yes, direct search@PP collider
  - The tunnel can be re-used for pp, AA, ep colliders up to ~ 100 TeV ➔ compatibility study needed now



The idea was firstly reported at the Fermilab Higgs Factory workshop in Oct. 2012

Higgs： the Window to New Physics

- **A very special particle:**
  - The only elementary particle with spin 0
    - Really elementary？
    - Similar to p, Cooper pair？
  - The only elementary particle with non-gauge interactions
    - Self-coupling and Yukawa coupling: anything new？
- **Directly related to physics beyond SM & Cosmology**
  - May interact with dark matter particles
  - Origin of the mass of Higgs？
  - Self-coupling may affect the evolution of the universe
  - Understand the vacuum: why meta-stable？
- **Goal:** By detailed and precise measurement of Higgs properties to understand these issues

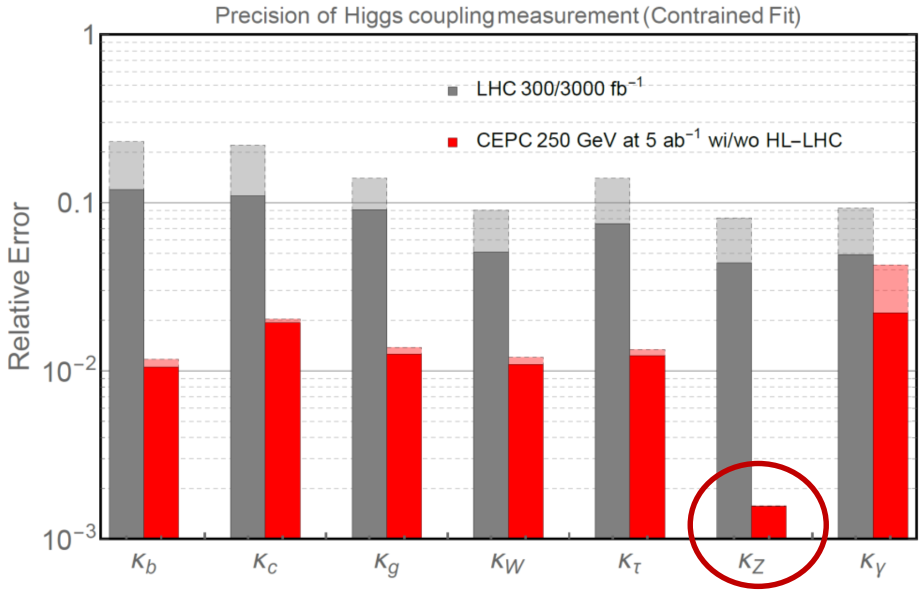
particle	spin
quark: u, d,...	1/2
lepton: e...	1/2
photon	1
W,Z	1
gluon	1
Higgs	0

Detailed study of Higgs can not be skipped

Precision Higgs Physics by CEPC

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{M^2} \mathcal{O}_{6,i}$$

$$\delta \sim c_i \frac{v^2}{M^2}$$



CEPC preCDR Volume 1 (p.9)

At LHC:

Direct searches: M ~ 1 TeV

10% precision: M ~ 1 TeV

At CEPC:

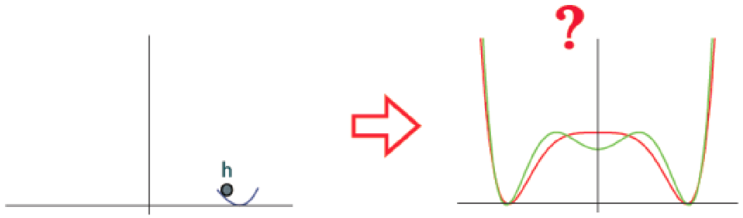
1% precision → M ~10 TeV

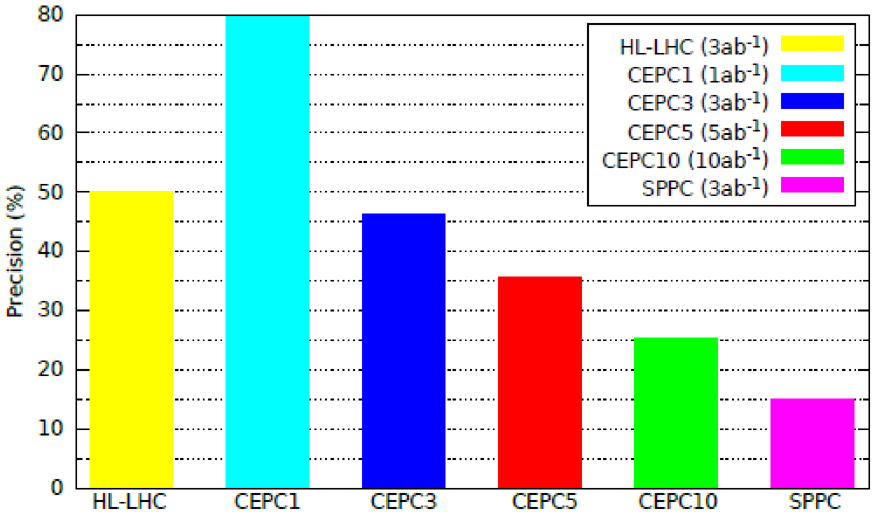
Higgs factory is our first choice if no new physics at LHC

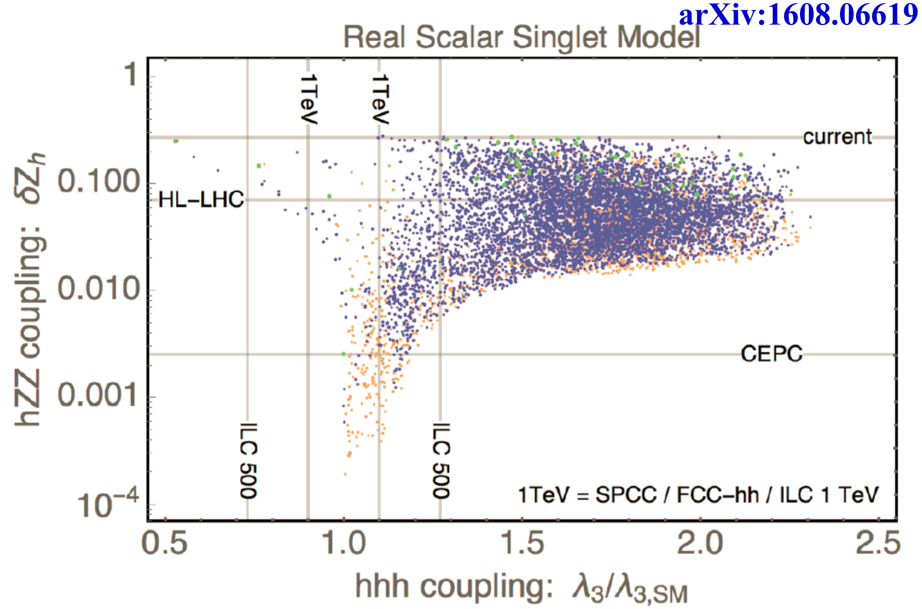
Higgs factory is also a great choice if new physics found at LHC

Nature of EW Phase Transition ?

- 1^{st} or 2^{nd} order ➔ Huge implications
  - O(1) deviations in h^3 coupling
  - O(1%) shift in h-Z coupling
- CEPC can determine it:
  - h^3 coupling at CEPC： 20-30%
  - h-Z coupling at CEPC： < 0.2%





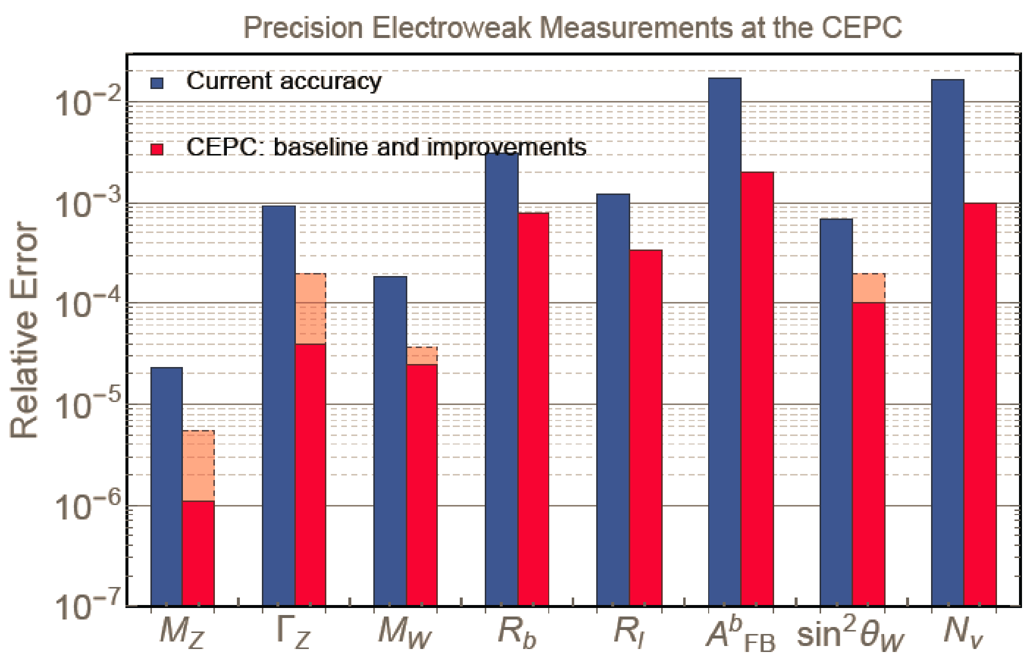


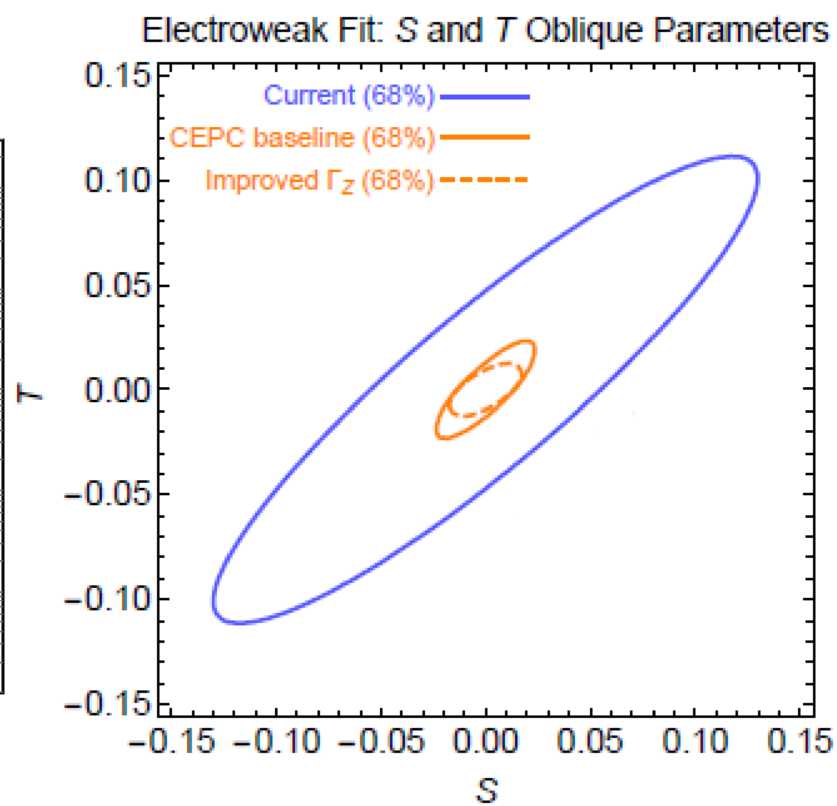
2021/12/8

M. McCullough, PRD 90(2014)015001

Improvement in Electroweak Precision

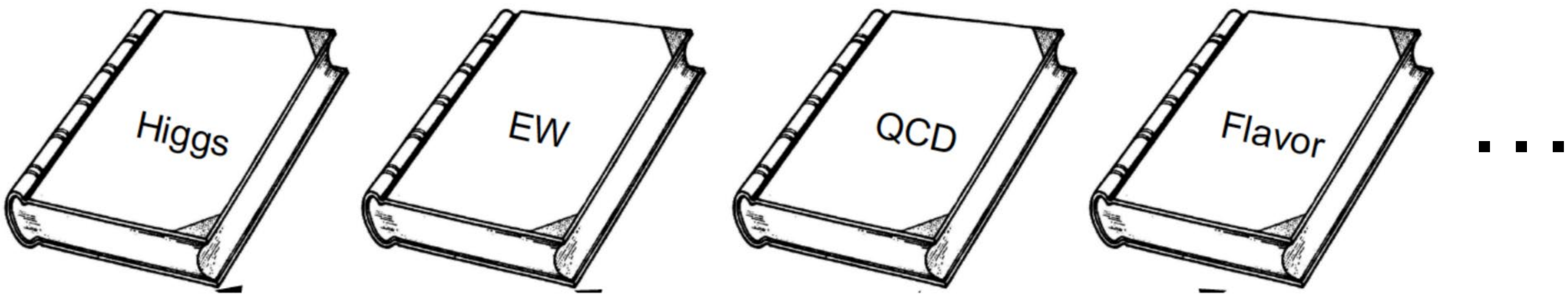
- A total of 10^{12} Z
- **A detailed study of Z & W to look for deviations from the Standard Model**
- **Can probe new physics up to ~ TeV， better than HL-LHC by a factor of 3**





CEPC preCDR Volume 1 (p.10)

Toward Physics White Papers



Chinese Physics C Vol. 43, No. 4 (2019) 043002

Precision Higgs physics at the CEPC*

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Contents

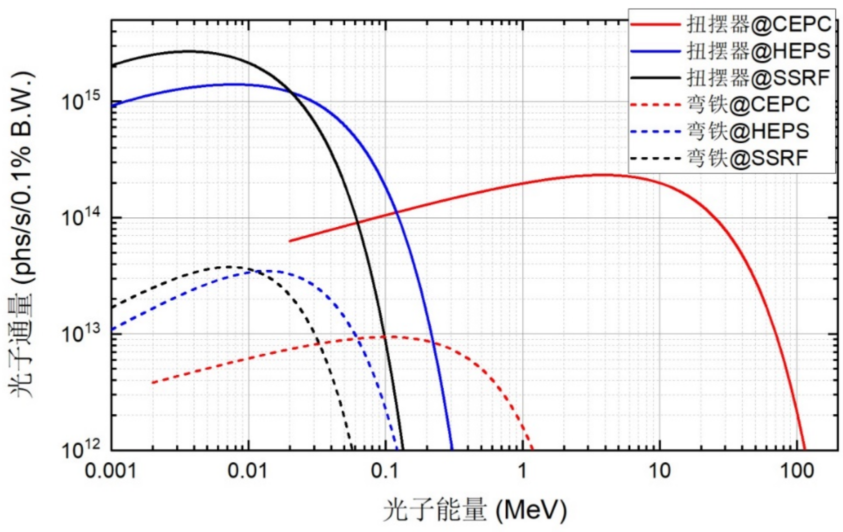
1 Introduction

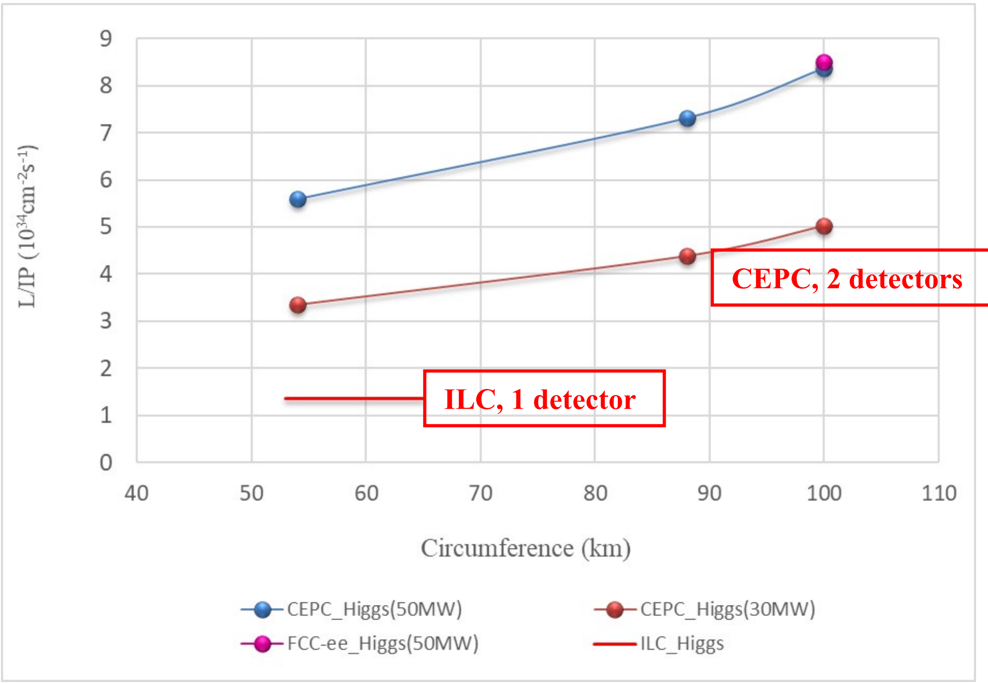
2 Description of CEPC facility

The Circular Electron Positron Collider (CEPC) is a double-ring e^+e^- collider with a 100 km circumference and two interaction points (IP) designed to precisely measure the Higgs boson and related particles. The CEPC Conceptual Design Report [1] includes exquisite details of the CEPC detector system. It operates at $\sqrt{s} \sim 240$ - 250 GeV for Higgs Factory,

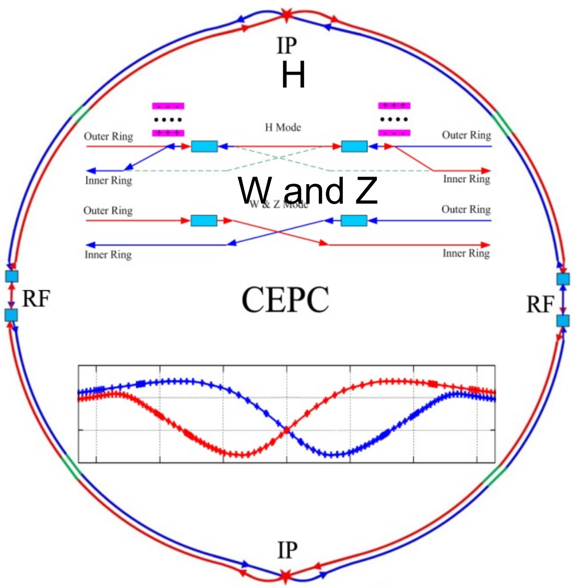
CEPC: High luminosity, multi-purposes, and upgradable

- Very high energy synchrotron radiation photons up to 100MeV
- Unprecedented applications in
  - Nuclear physics, astro-nuclear physics, material science, structural inspection, etc.

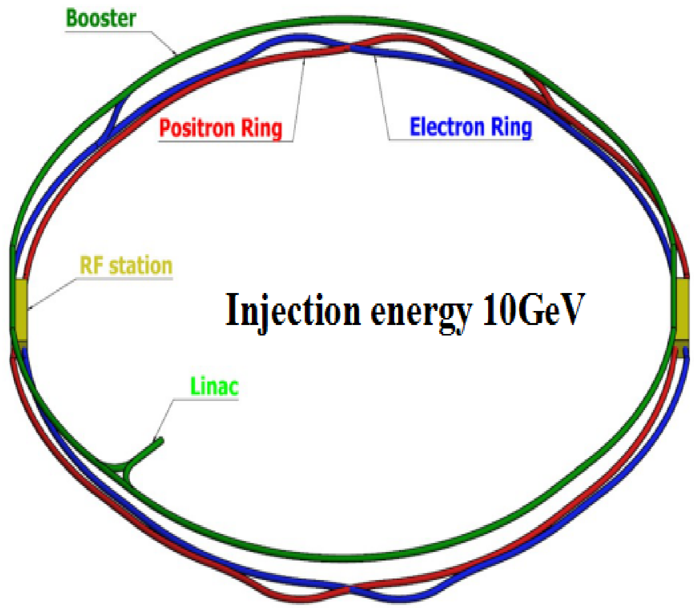




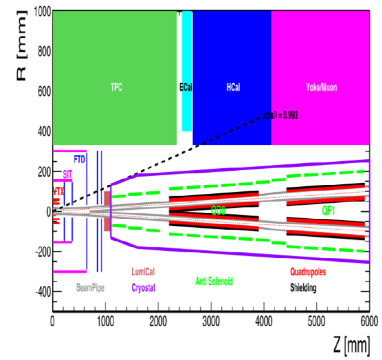
CEPC Layout

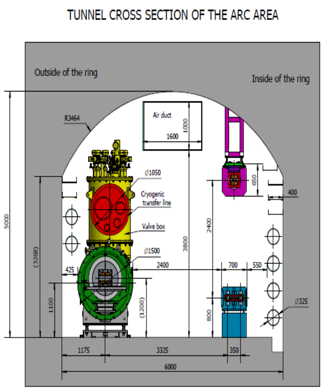


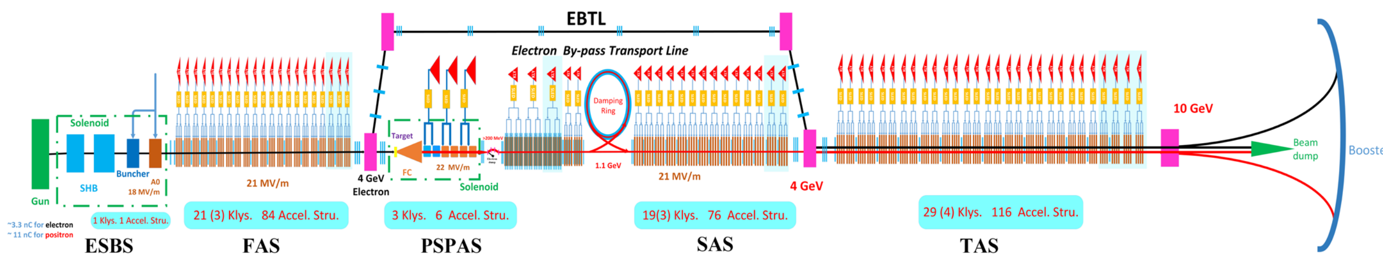
Collider ring (100km)



Booster ring (100km)







Linac injector (1.2km, 10GeV)

Baseline: 100 km, 30 MW; Upgradable to 50 MW, High Lumi Z, ttbar; Compatible to pp collider

Parameters for High Luminosities

	Higgs (high_lum.)	*Z (high_lum.)*
Number of IPs	2	2
Beam energy (GeV)	120	45.5
Circumference (km)	100	100
Synchrotron radiation loss/turn (GeV)	1.8	0.036
Crossing angle at IP (mrad)	16.5	16.5
Piwinski angle	4.87	18.0
Number of particles/bunch N_e (10^{10})	16.3	16.1
Bunch number (bunch spacing)	214 (0.7us)	10870 (27ns)
Beam current (mA)	16.8	841.0
Synchrotron radiation power /beam (MW)	30	**30**
Bending radius (km)	10.2	10.7
Momentum compact (10^{-5})	7.34	2.23
β function at IP β_x^* / β_y^* (m)	0.33/0.001	0.15/0.001
Emittance e_x/e_y (nm)	0.68/0.0014	0.52/0.0016
Beam size at IP σ_x/σ_y (μm)	15.0/0.037	8.8/0.04
Beam-beam parameters ξ_x/ξ_y	0.018/0.115	0.0048/0.129
RF voltage V_{RF} (GV)	2.27	0.13
RF frequency f_{RF} (MHz)	650	650
Natural bunch length σ_z (mm)	2.25	2.93
Bunch length σ_z (mm)	4.42	9.6
Energy spread (%)	0.19	0.12
Energy acceptance requirement (%)	1.7	1.4
Energy acceptance by RF (%)	2.5	1.5
Beamstruhlung lifetime /quantum lifetime (min)	41	-
Lifetime (hour)	21	1.8
Luminosity/IP L ($10^{34}cm^{-2}s^{-1}$)	**5.0**	**101.1**

* High luminosity Z has a lattice same as that of CDR for Higgs. but high luminosity Higgs has a new lattice

R&D and Prototypes

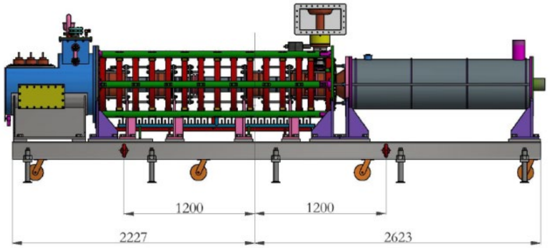
- **Polarized electron gun**
  - ⇨ Super-laIce GaAs photocathode DC-Gun
- **High current positron source**
  - ⇨ bunch charge of ~3nC,
  - ⇨ 6Tesla Flux Concentrator peak magnetic field
- **SCRF system**
  - ⇨ High Q cavity - Max operation Q_0 = 2E10 @ 2 K
  - ⇨ High power coupler - 300kW（Variable）
- **High efficiency CW klystron**
  - ⇨ Efficiency goal > 80%
- **Low field dipole magnet（booster）**
  - ⇨ Lmag=5m, Bmin=30Gs, Errors <5E-4
- **Vacuum system**
  - ⇨ 6m long cooper chamber
  - ⇨ RF shielding bellows
- **Electro-static separator**
  - ⇨ Maximum operating field strength: 20kV/cm
  - ⇨ Maximum deflection: 145 urad
- **Large scale cryogenics**
  - ⇨ 12 kW @4.5K refrigerator, Oversized,
  - ⇨ Custom-made, Site integration
- **HTS magnet**
  - ⇨ Advanced HTS Cable R&D: > 10kA
  - ⇨ Advanced High Field HTS Magnet R&D: main field 12~12T

……

N-doping of 650MHz 1-cell cavities

Vertical test of 650MHz 1-cell cavity

High voltage DC Gun

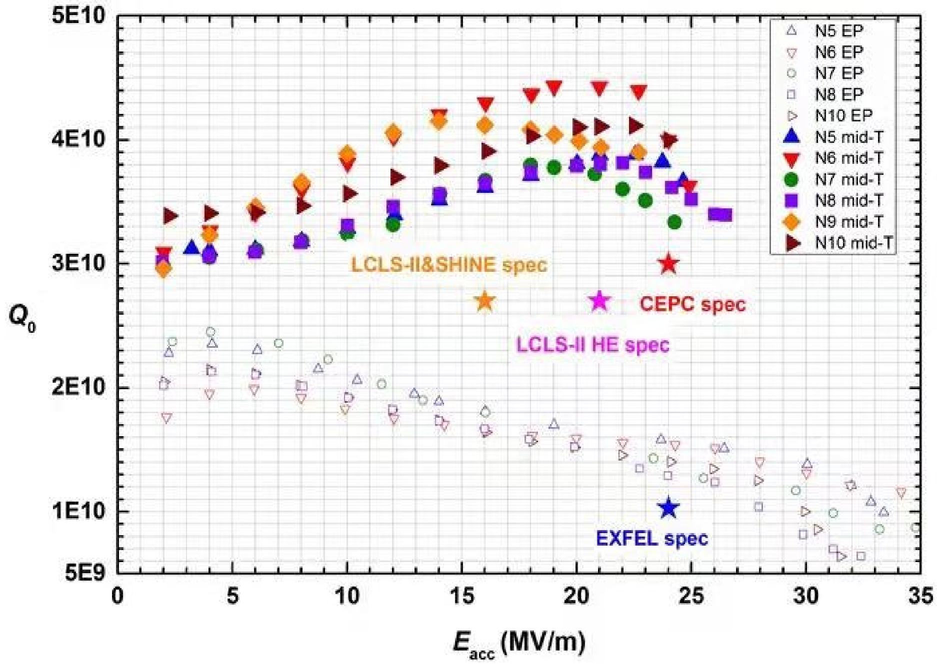


Mechanical design of conventional klystron

R&D：High Q SRF Cavities

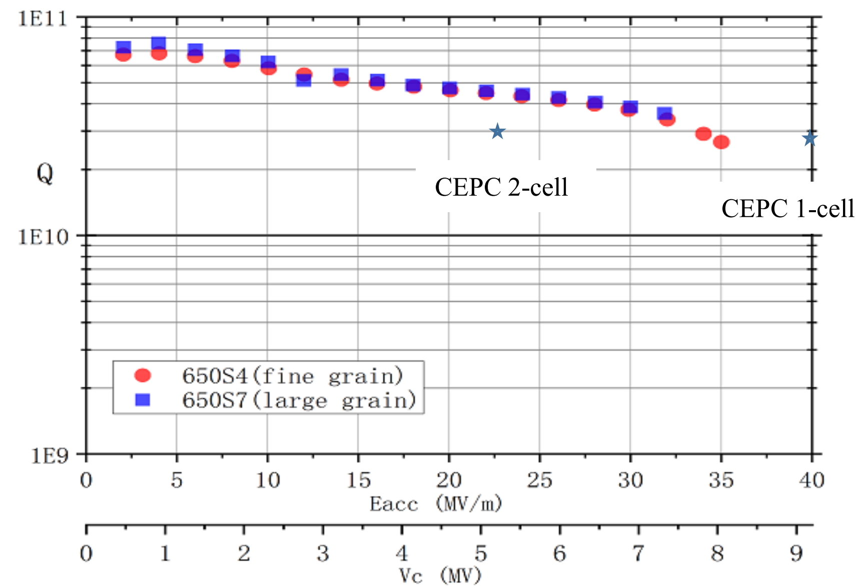
The 650 MHz 2-cell and 1.3 GHz 9-cell cavities have both exceeded the CEPC spec for vertical test, a milestone towards the TDR

Vertical test of 1.3 GHz 9-cell cavity



Medium-temperature (Mid-T) annealing adopted to reach Q= 3.4E10@26.5MV/m

Vertical test of 650 MHz 2-cell cavity



N-infusion adopted to reach Q = 6.0E10@22.0MV/m

A New Recipe: Flexible Polishing

- Friction between flexible medium and the cavity surface through high-speed reciprocating motion: Roughness ~100nm
- By replacing bulk EP, 1.3 GHz 1-cell cavity can reached 46 MV/m
- Advantages: high efficiency, environmental friendly, low cost

Conventional recipe

~~Bulk EP (~150um)~~

Annealing

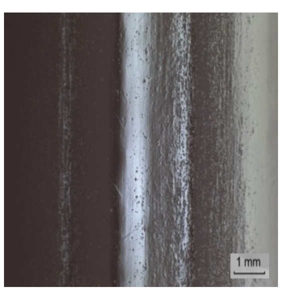
Light EP (~20um)

New recipe

FP (~150um)

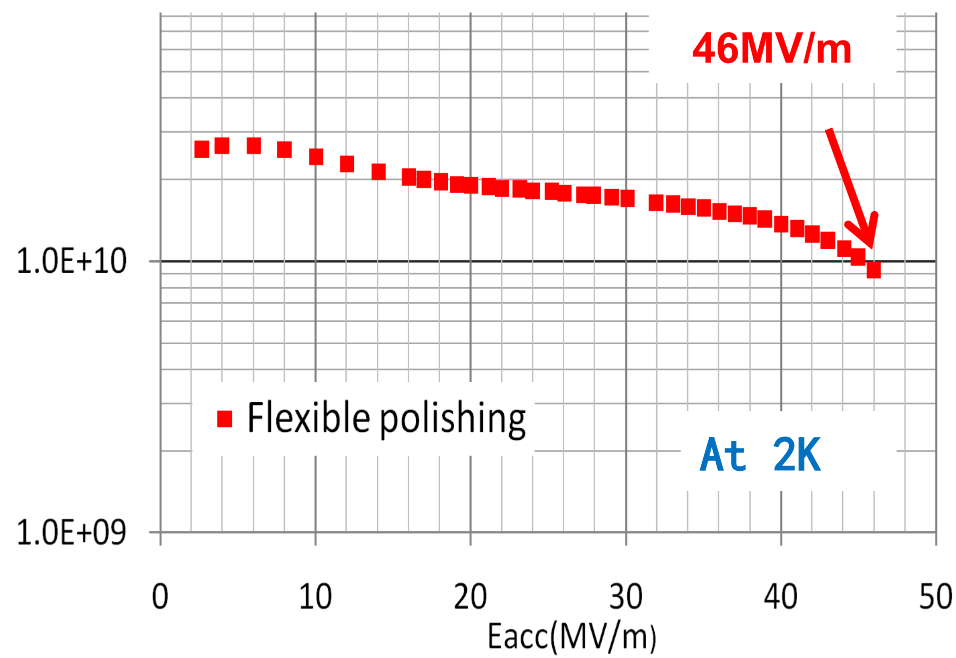
Annealing

Light EP (~40um)



Initial surface

After flexible polishing

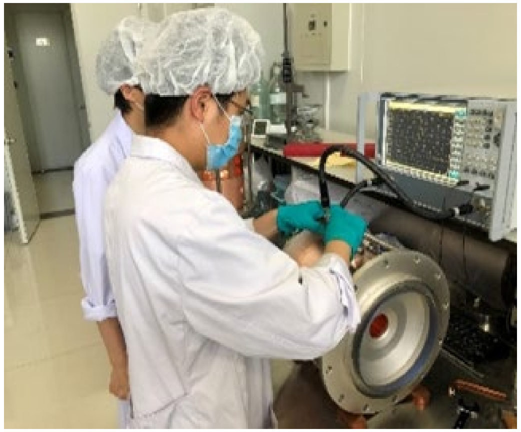


More study in combination with other methods will be performed

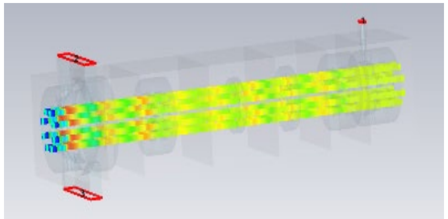
R&D: Towards High Eff. Klystrons

- 1st prototype successfully tested
  - output power reached 400 kW CW and 800 kW pulsed (due to the limitation of the test load)
  - efficiency ~ 62%
  - band width>+-0.5Mhz.
- High efficiency klystron
  - 3D simulation results:
    - 110 kV: 77%
    - multi-beam: 80%
  - Production completed and test underway

Bake out



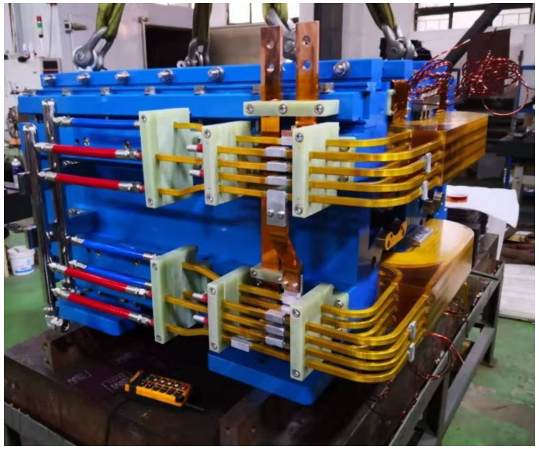
Cold test

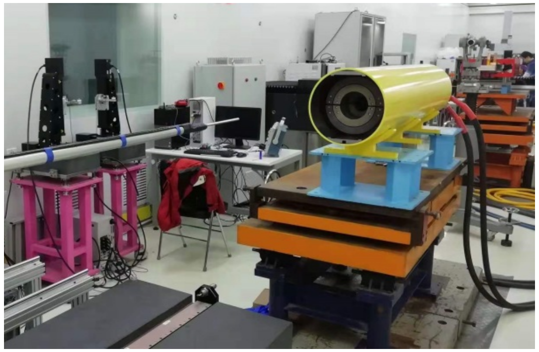


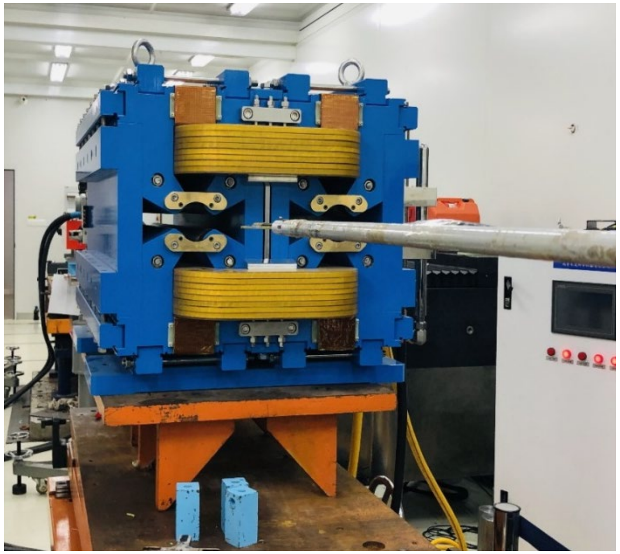
High power test

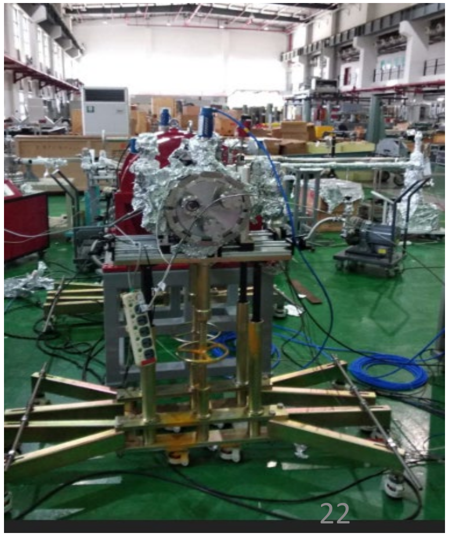
R&D: Other Prototypes

magnets, EM-separators, vacuum pipes, …



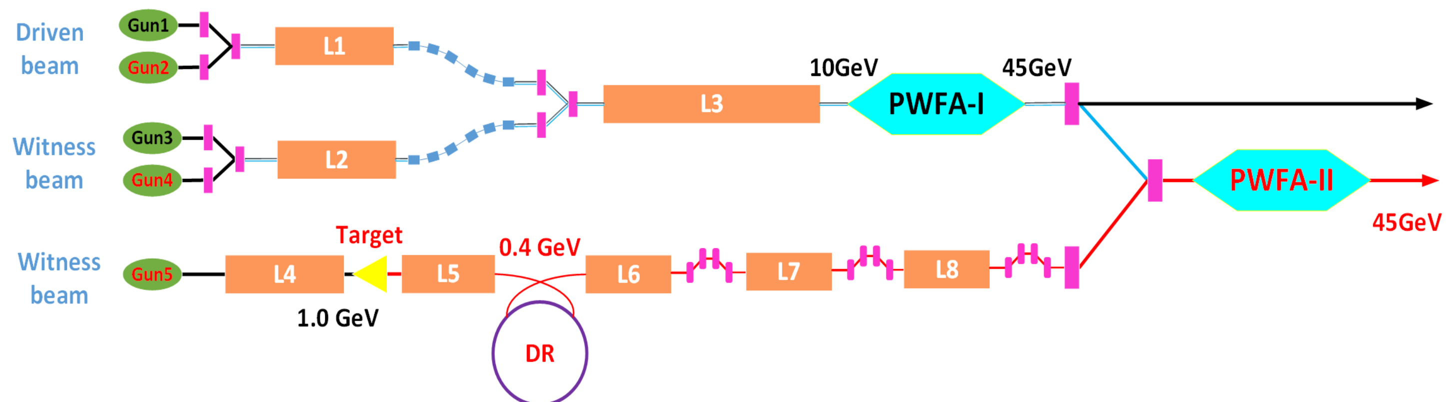




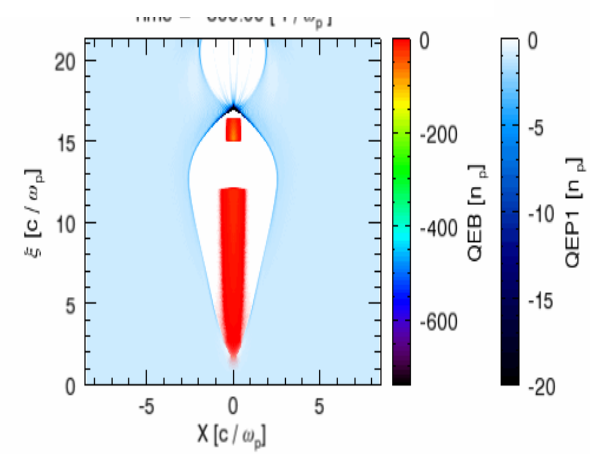


R&D Progress: Plasma Injector

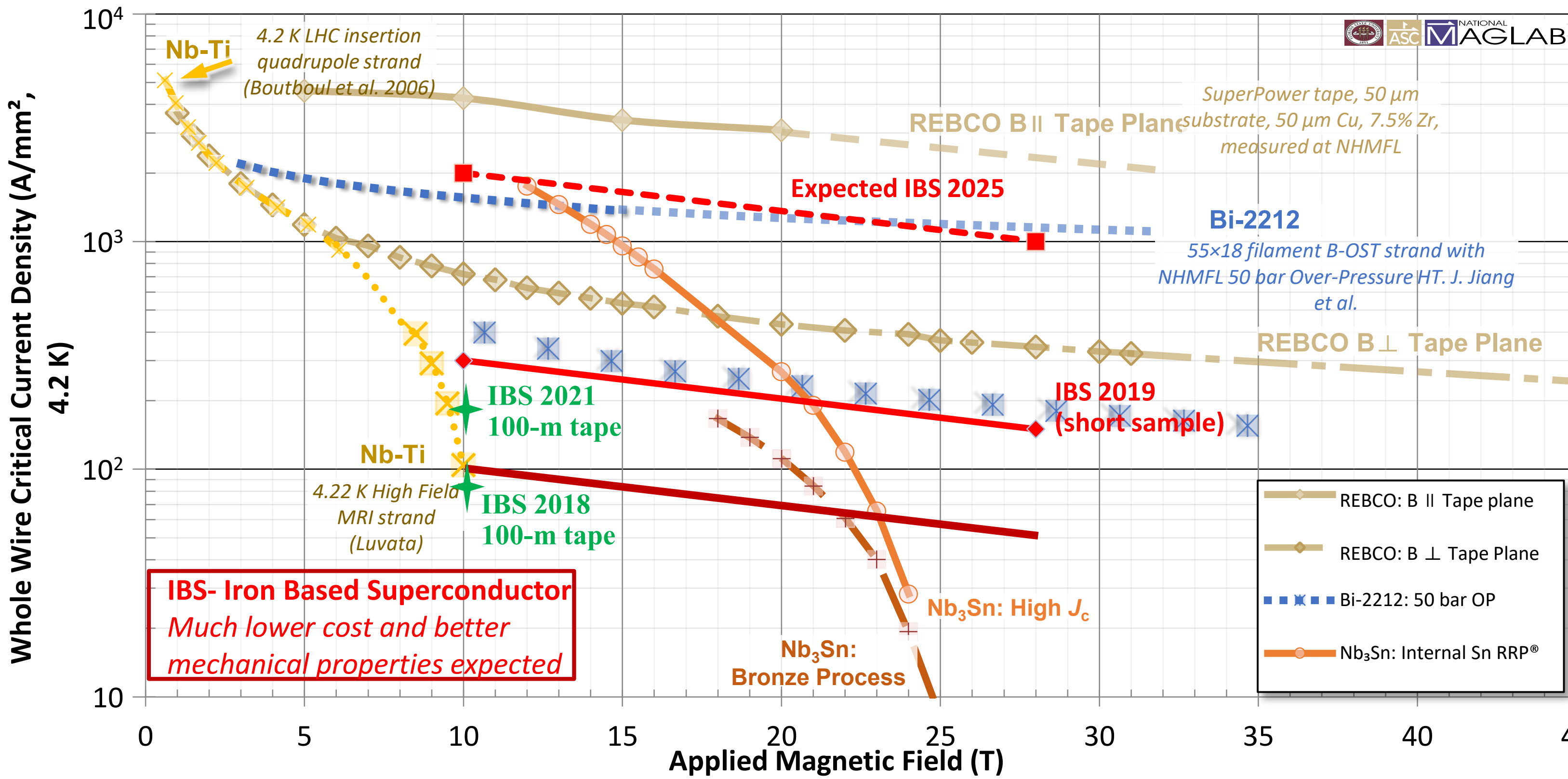
- Technical design reviewed on Aug. 22,2019: Feasible as an injector
- First of its kind to be used for a real accelerator

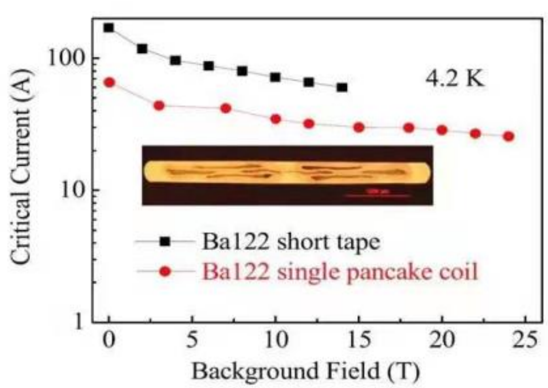


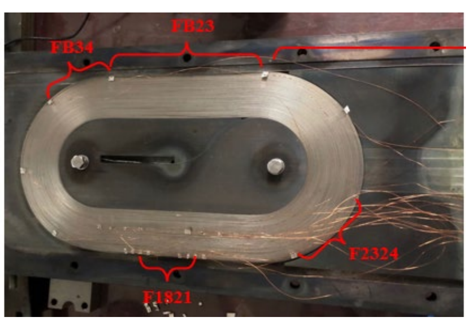
- Plasma acceleration for electrons will be tested at Shanghai's Soft XFEL Facility
- Plasma acceleration for positrons will be tested at FACET-II of SLAC. A new idea was just published at PRL

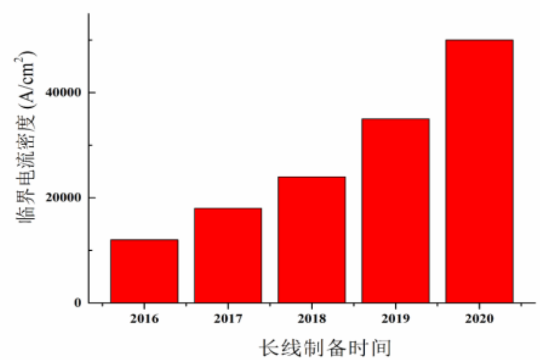


R&D: Iron-based HTC magnets







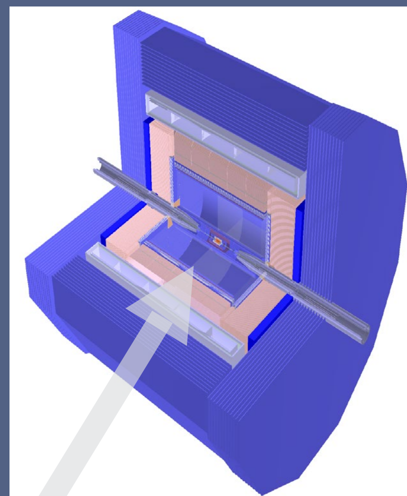


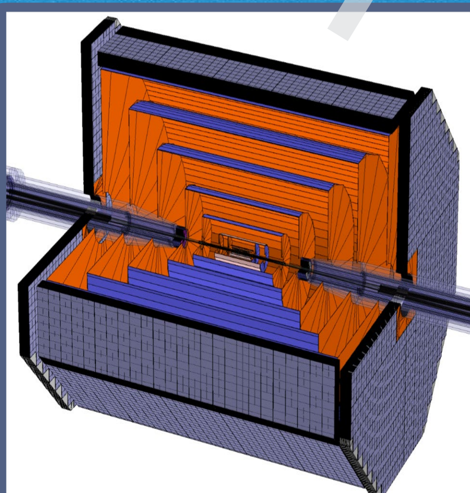
1st Iron-based Superconducting solenoid Coil at 24T

CEPC Detector Concepts Studied

Particle Flow Approach

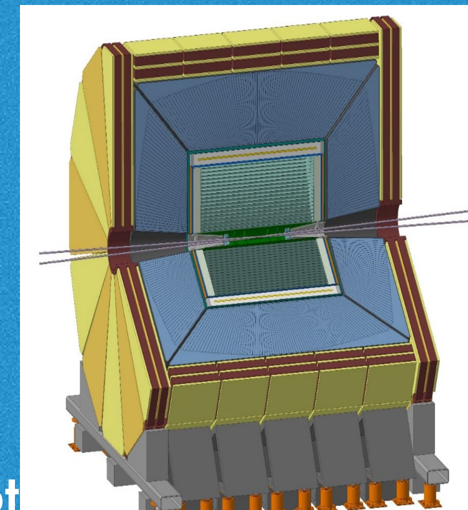
High
magnetic field
concept
(3 Tesla)





Full silicon
tracker
concept

Low
magnetic
field
concept
(2 Tesla)



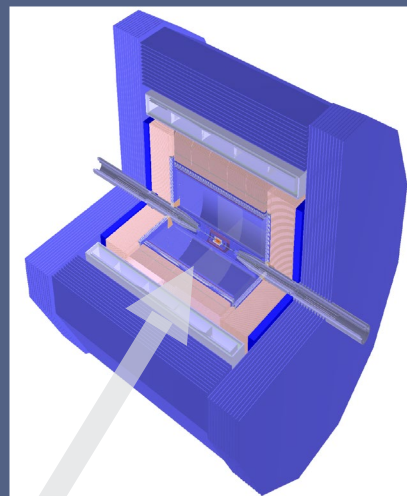
IDEA Concept
also proposed for FCC-ee

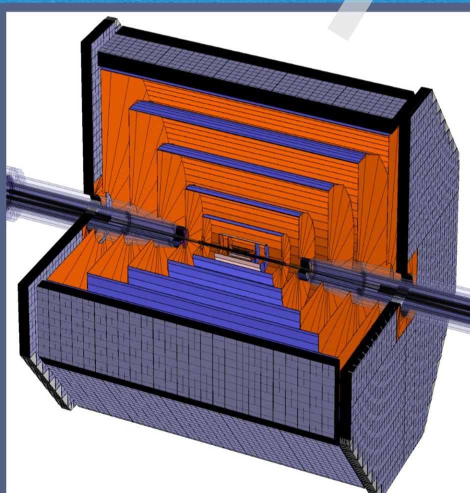
Final two detectors WILL be a mix and match of different options

CEPC Detector Concepts Studied

Particle Flow Approach

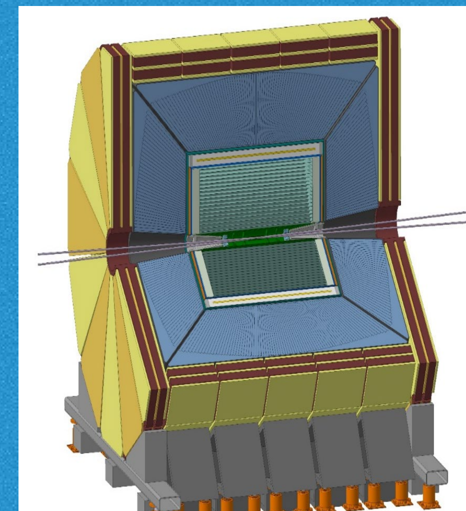
High magnetic field concept (3 Tesla)





Full silicon tracker concept

Low magnetic field concept (2 Tesla)



IDEA Concept

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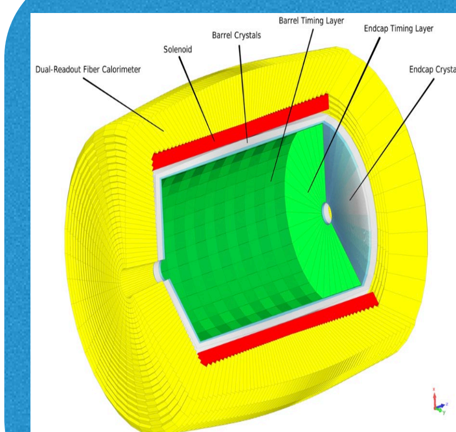


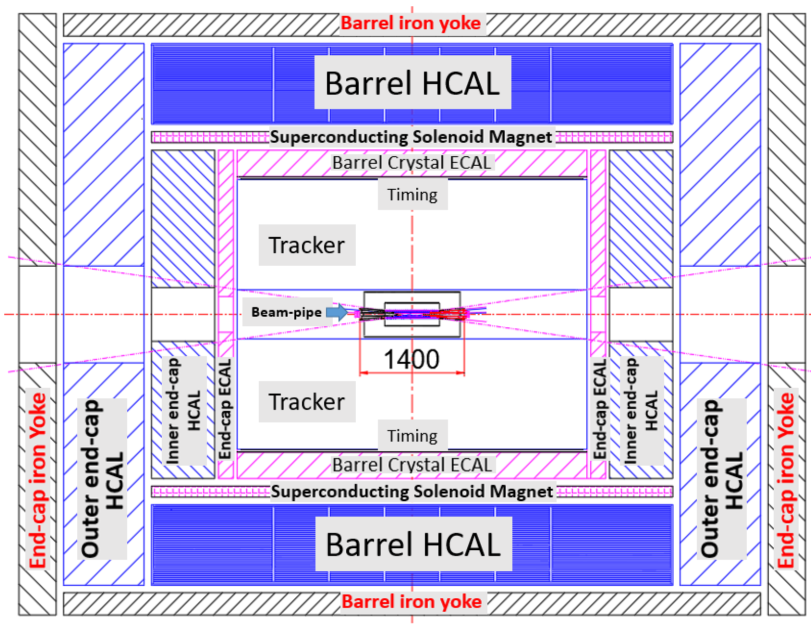
"Fourth concept": Crystal Calorimeter based detector (2-3 Tesla)

Final two detectors WILL be a mix and match of different options

Key Ingredients of the “fourth concept”
(for good jet resolution & flavor physics)

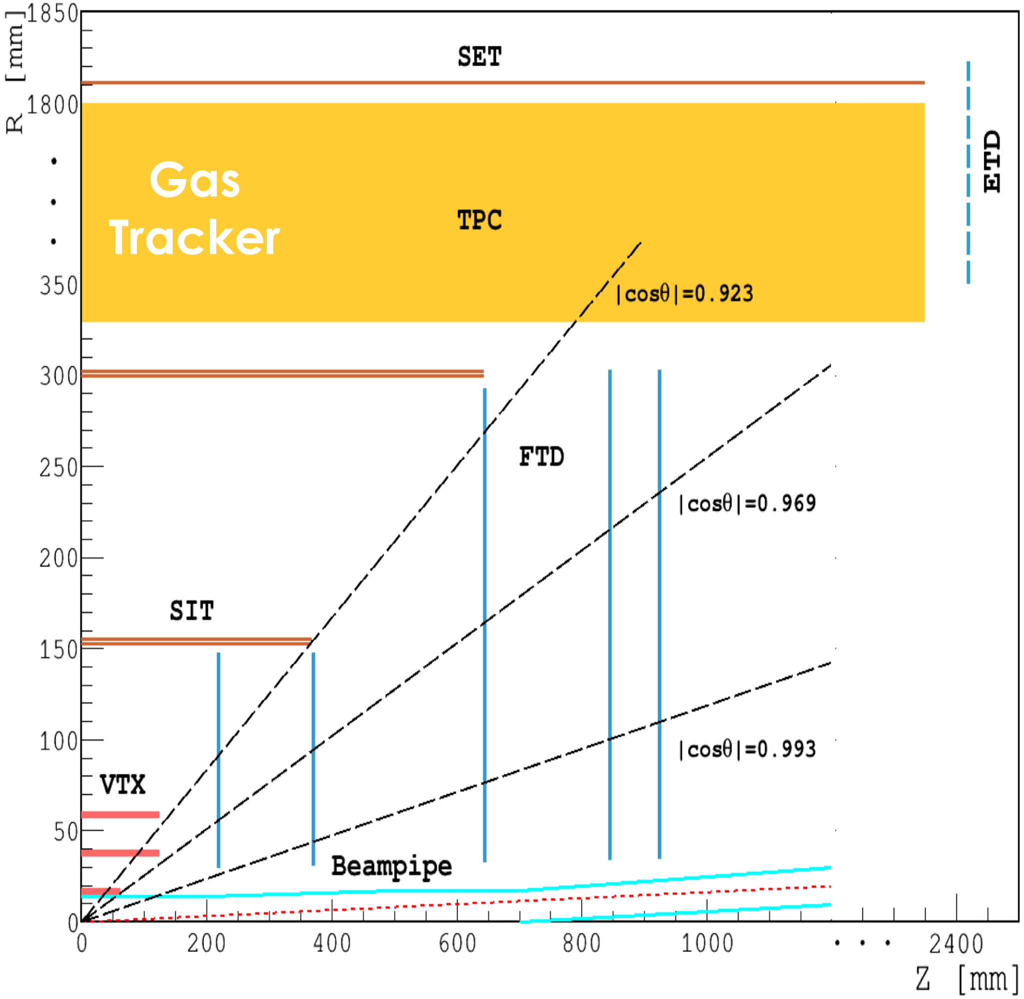
Physics process	Measurands	Detector subsystem	Performance requirement
$ZH, Z \to e^+e^-, \mu^+\mu^-$ $H \to \mu^+\mu^-$	$m_H, \sigma(ZH)$ $\mathrm{BR}(H \to \mu^+\mu^-)$	Tracker	$\Delta(1/p_T) = 2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$
$H \to b\bar{b}/c\bar{c}/gg$	$\mathrm{BR}(H \to b\bar{b}/c\bar{c}/gg)$	Vertex	$\sigma_{r\phi} = 5 \oplus \frac{10}{p(\mathrm{GeV}) \times \sin^{3/2}\theta} (\mu\mathrm{m})$
$H \to q\bar{q}, WW^*, ZZ^*$	$\mathrm{BR}(H \to q\bar{q}, WW^*, ZZ^*)$	ECAL HCAL	3 ~ 4% at 100 GeV
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\Delta E/E = \frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$

$0.03/\sqrt{E} \oplus 0.01$

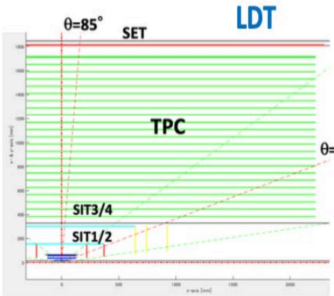


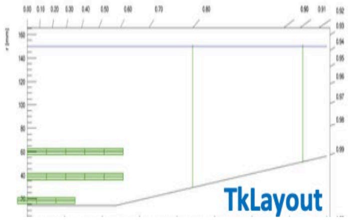
- 3D Crystal EM calorimeter for better energy resolution with PFA capabilities
- Compact silicon tracker in combination with TPC/drift chamber for better tracking and dE/dx(PID)
- Possibly additional PID (Timing or Cerenkov) before EM calorimeter
- Thin solenoid magnet (~ 0.1-0.15λ, equivalent to a HCAL layer) between ECAL and HCAL
- High resolution HCAL using scintillation glass with PFA capabilities (part of return yoke)

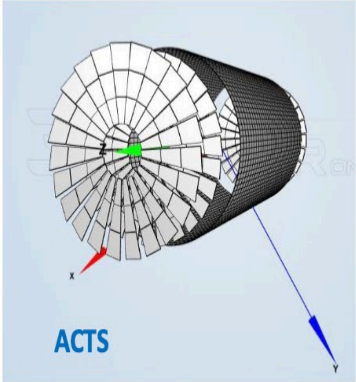
Silicon tracker with TPC/drift chamber



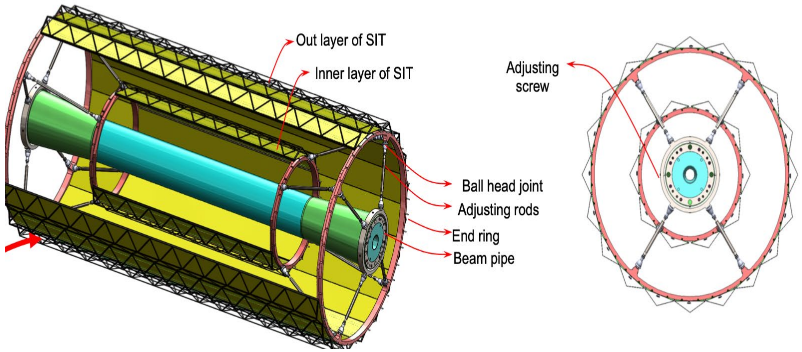
- **LDT** or **TkLayout** to validate basic tracking performance before implementing detailed geometry in **ACTS**



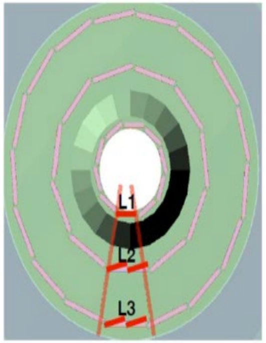




Silicon Tracker



Silicon Pixel Sensors for Vertex detector

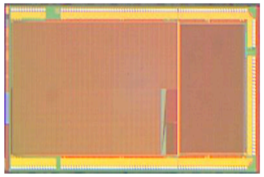


Developed CMOS Pixel Sensor prototypes overview

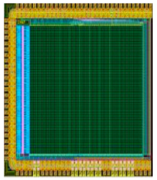
	JadePix1 (2015)	JadePix2 (2017)	MIC4	JadePix3 (2019)
Architecture	Roll. Shutter + Analog output	Roll. Shutter + In pixel discri.	Data-driven r.o. + In pixel discri.	Roll. shutter + end of col. priority encoder
Pitch (μm^2)	33 × 33 /16 × 16	22 × 22	25 × 25	16 × 26 16 × 23.11
Power con. (mW/cm^2)	--	--	150	~ 55*
Integration time (μs)*	--	40-50	~3	~100
Prototype size (mm^2)	3.9 × 7.9 (36 individual r.o)	3 × 3.3	3.1 × 4.6	10.4 × 6.1
Main goals	Sensor optimization	Small binary pixel	Small pixel + Fast readout+ nearly full functional	Smaller pixel + Low power + fully functional

* Assuming a matrix of 512 × 1024 pixels

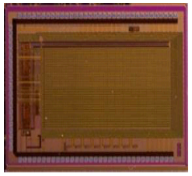
All prototypes in TowerJazz 180 nm process



JadePix1 (IHEP)



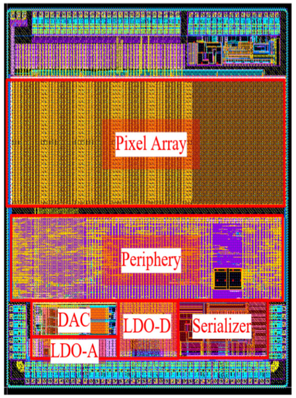
JadePix2 (IHEP)



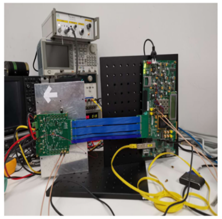
MIC4 (CCNU & IHEP)

JadePix3 (IHEP, CCNU, Dalian Minzu Unv., SDU)

TAICHUPIX-2



- 64 × 192 pixel array with the same dimension as TaichuPix-1
  - 32 double column modified FE-I3 readout, 32 modified ALPIDE readout
  - 6 variations of pixel analog design, each with 16 columns
- New features added to TaichuPix-2
  - Two LDOs for power supplies
  - 8b10b encoder added for Triggerless output and balanced data stream
  - X-chip buses added for multiple chip interconnections

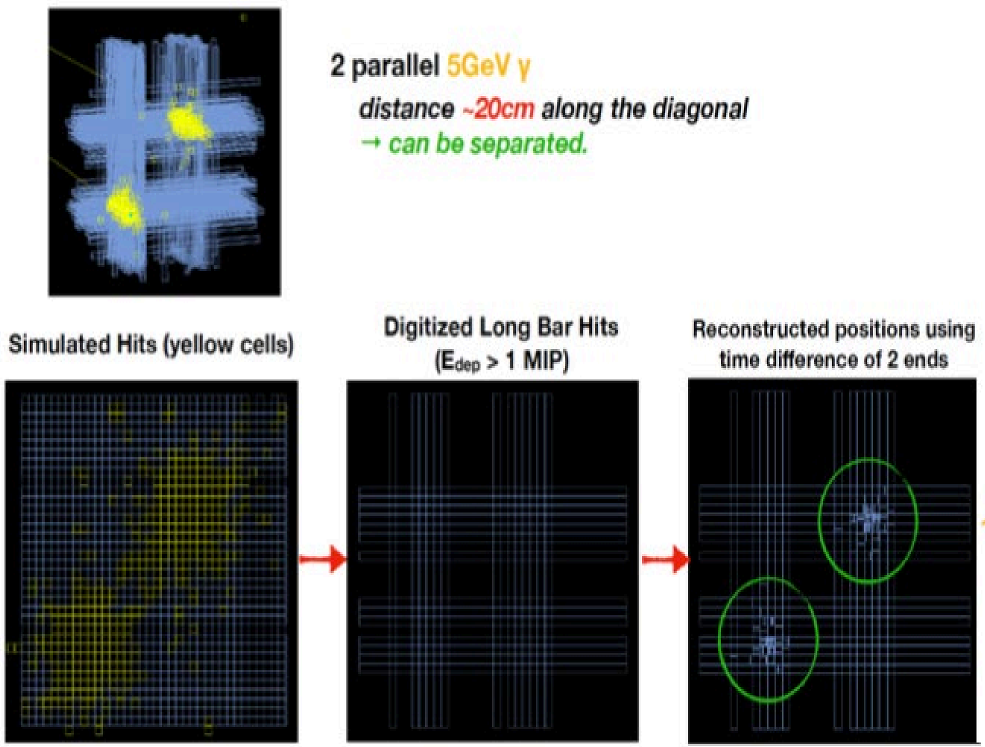


- Test status: functional verification completed (I/O, bandgap, PPL ...), more detailed tests on-going

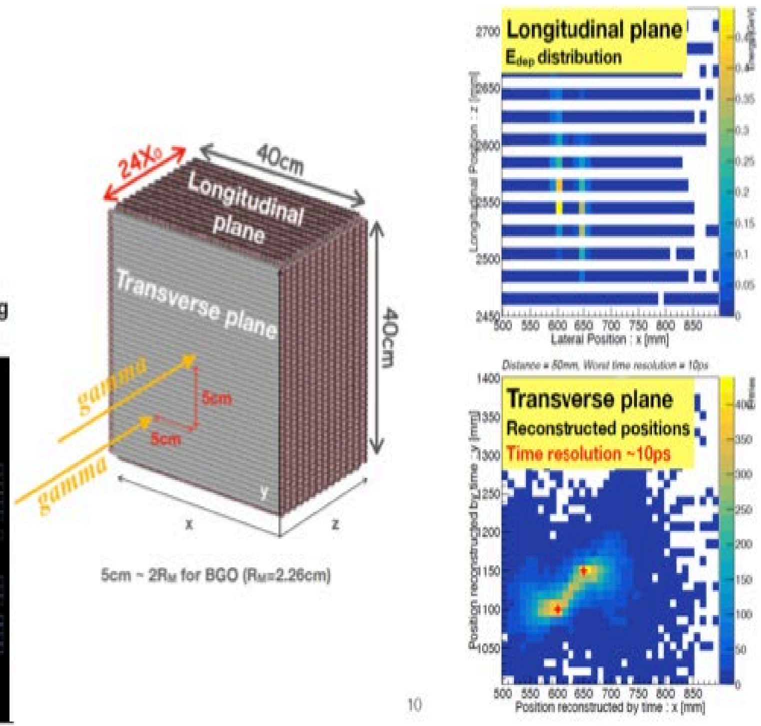
Full size prototype to be built

Can Overlapping ambiguity be resolved ?

Patterns in event display: 2 photons



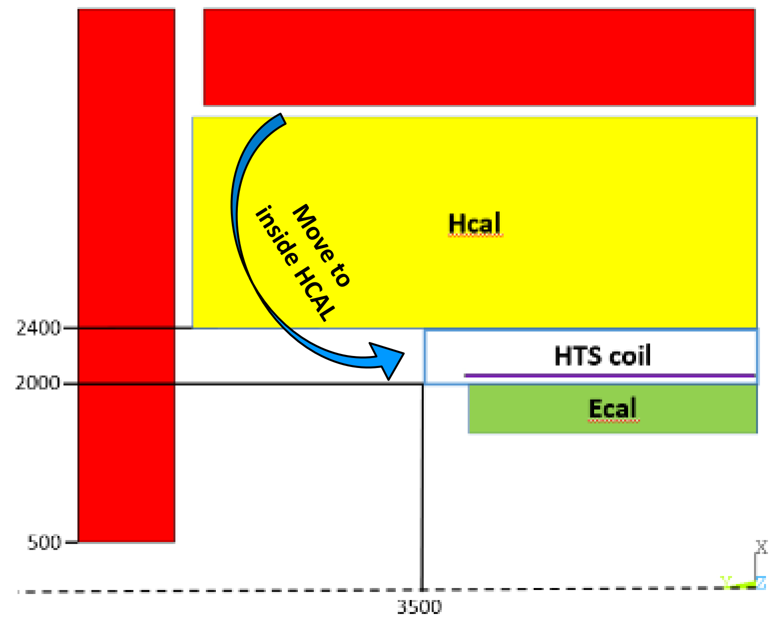
Shower profiles: 2 photons



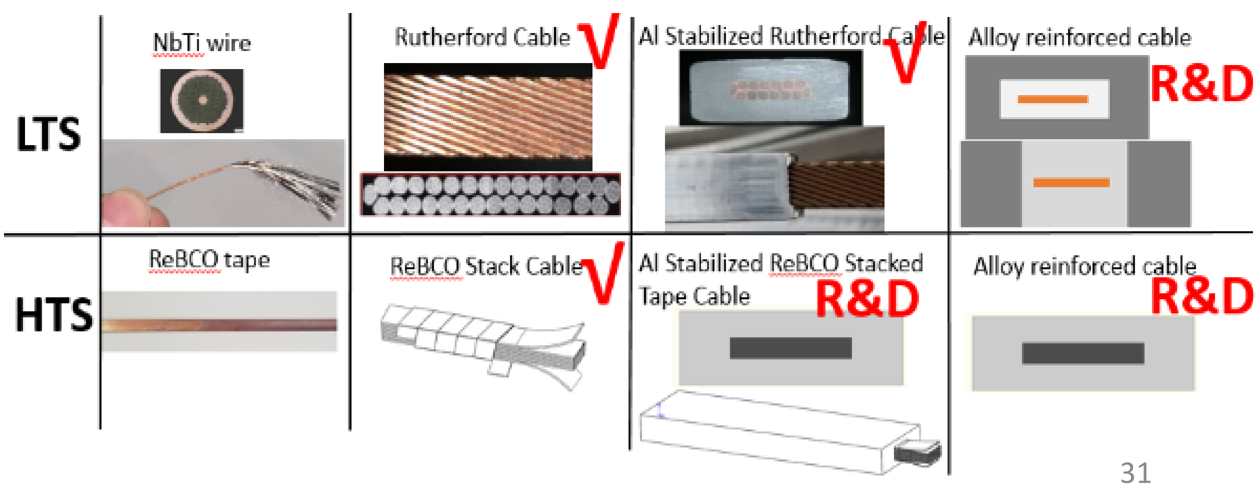
Need more work for complicated cases
Need to demonstrate PFA capabilities

Solenoid Magnet

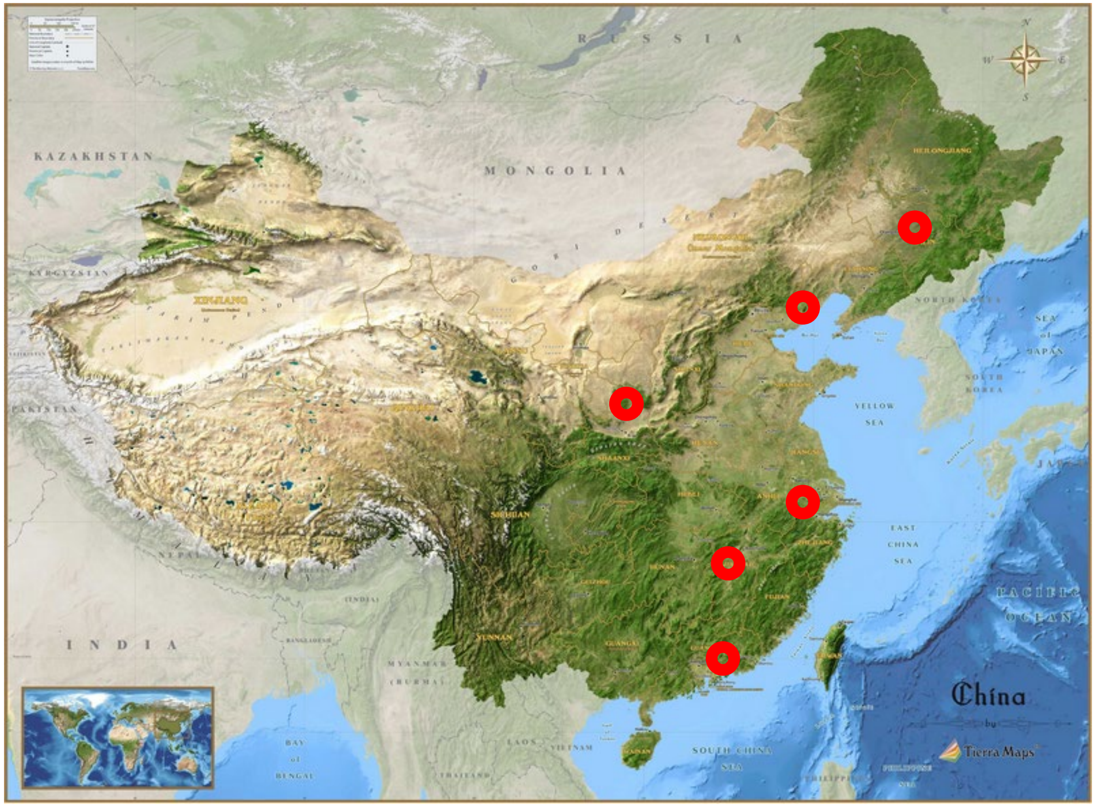
- Requirements: **low mass, ultra-thin, high strength cable**
- Some of the on-going R&D:
  - High strength LTS and HTS cables
  - Large coil winding process
  - Low mass vacuum vessel structure



Magnet Parameters	Value
Central magnetic field	3 T
Inner diameter	4.6 m
Outer diameter	5.3 m
Thickness	0.35 m
Length	7 m



Site investigation and Civil Design



- Site selection based on geology, electricity supply, transportation, environment for foreigners, local support & economy,…
- North are better for running cost
- CDR study is based on Qing-Huang-Dao, which is 300 km from Beijing

- More invitations from local governments: Changsha, Changchun, …
- Recent visit to Shangsha and Changchun: good geology & transportation(~20 km from large city & international airport)

Synergies with FCC-ee

- CEPC and FCC-ee have very similar goals and potentials, even though the two machines are designed somewhat differently, and running plans are not the same
- Technologies required are similar but detailed approaches are sometimes different
    - Collaborative R&D and results may help to cut cost down
- Different detector concepts may converge to similar ones
- CEPC trained a large young team for the relevant physics, machine and detector
- While maintaining scientific collaboration , we should continue to proceed in parallel until one is approved:
    - Competition can enhance the chance for both
    - Higgs factory is too important to miss
- We are happy to collaborate in all front, and in all means

Summary

- CEPC accelerator R&D efforts towards TDR progress well
  - Design optimization, R&D on klystron, SCRF, magnets, vacuum system, etc.
  - Aim to complete TDR at the end of ~2022

- Test facilities for R&D are mostly available

- Detector concepts are still evolving, R&D of all sub-systems are progressing well, international collaboration in detector R&D is expanding.

- Site selection and civil engineering design are in progress

- Continue to work with government agencies