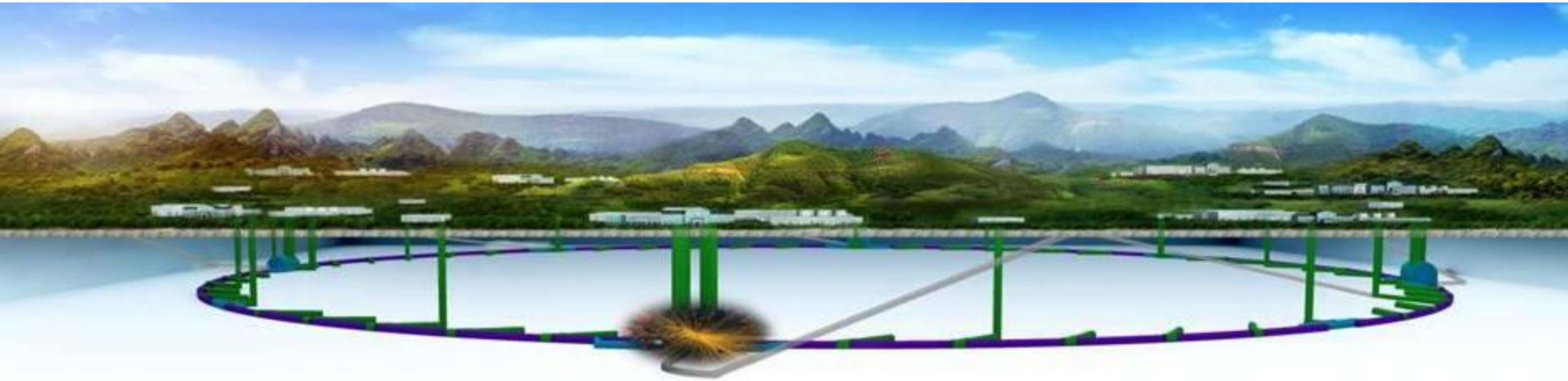
AFAD 2021

Circular Electron-Positron Collider
Status and Progress

XinChou Lou

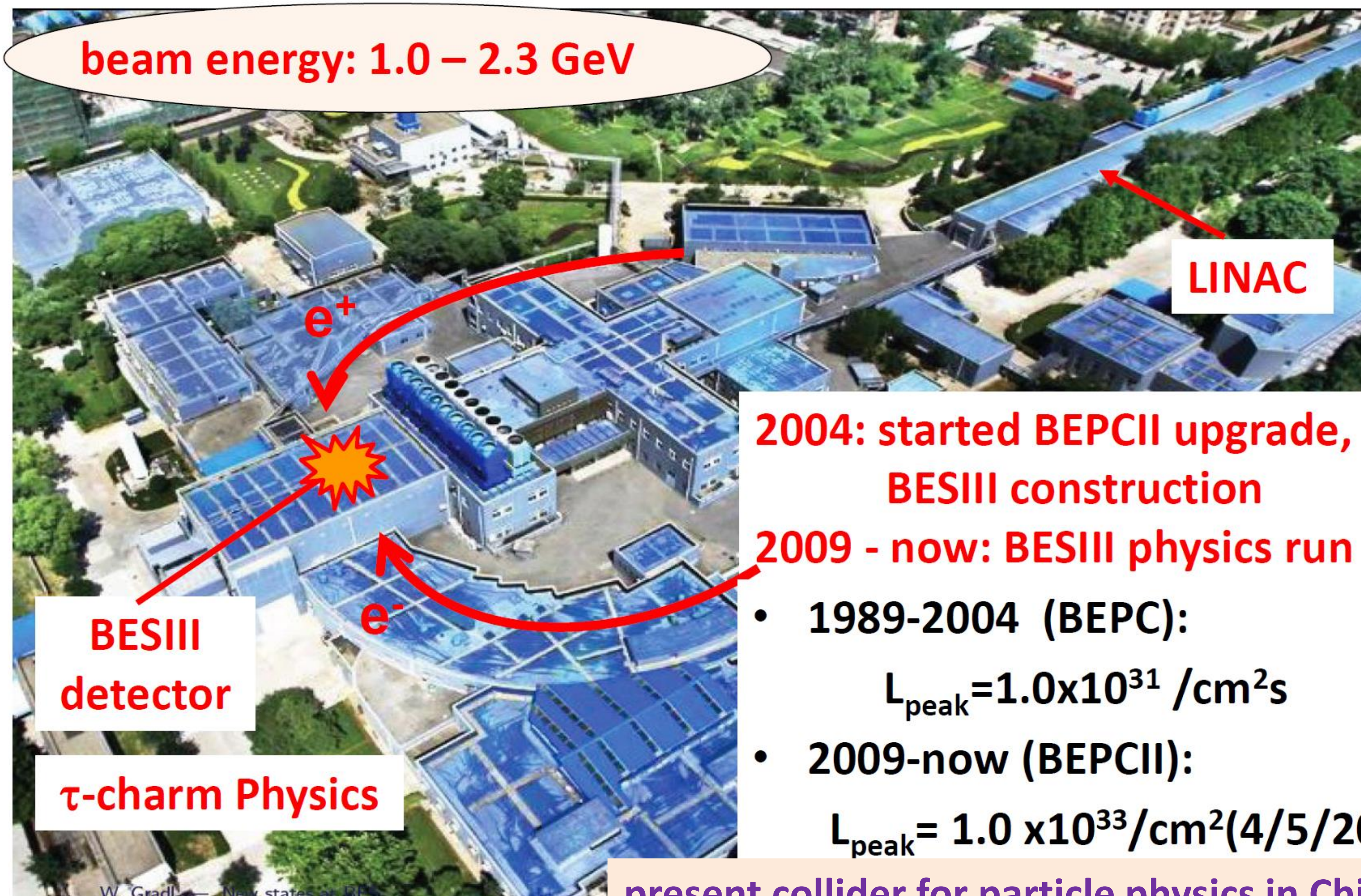
Institute of High Energy Physics, Beijing



Outline

- Reminder & introduction
- CEPC accelerator design improvement
- CEPC accelerator R&D highlights
- Detector, software and simulation study
- Site investigation
- Summary

Beijing Electron Positron Collider (BEPC)



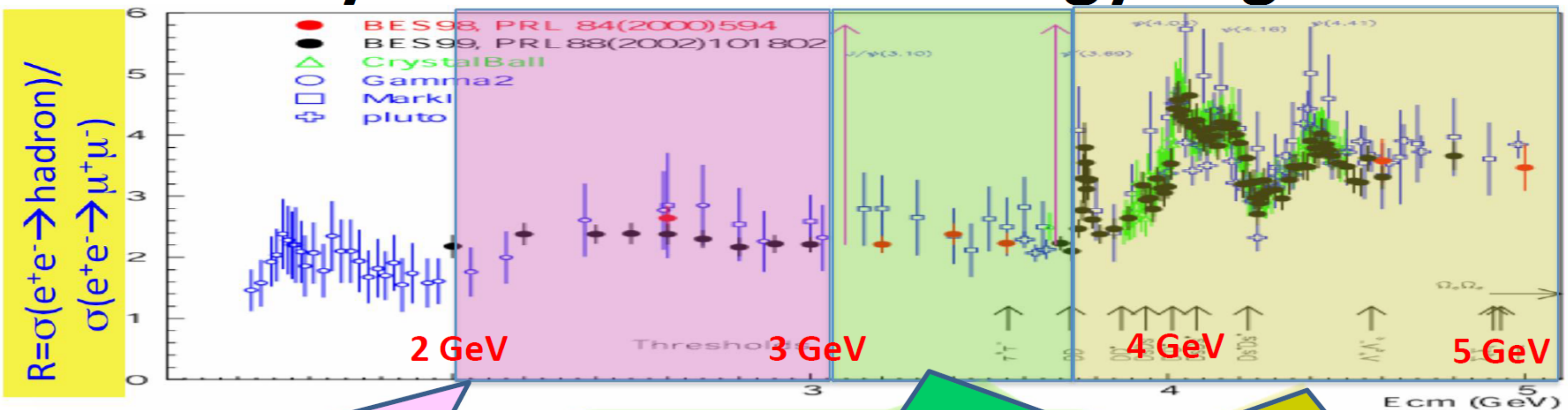
2004: started BEPCII upgrade,
BESIII construction
2009 - now: BESIII physics run

- 1989-2004 (BEPC):
  L_{peak}=1.0x10^{31} /cm^{2}s
- 2009-now (BEPCII):
  L_{peak}= 1.0 x10^{33}/cm^2(4/5/2016)

present collider for particle physics in China
upgrade in lumi. & energy under discussion

Xiaoyan Shen
IHEP

Physics at τ - charm Energy Region



- Hadron form factors
- Y(2175)
- Zs states ?
- QCD test

- Light hadron spectroscopy
- Glueballs, hybrids, multi-quark states
- Rare decays
- Tau physics

- XYZ
- D and Ds physics (f_D and f_{Ds}, mixing, ~~CP~~)
- Charmed baryons

- Rich of resonances: charmonia, charmed mesons, charmed baryons
- Threshold characteristics (pairs of τ, D, D_s, …) -- low BG at threshold, high X-section -- indirect probe of NP
- Transition between pQCD and non-pQCD
- Energy location of the new forms of hadrons

BESIII physics whitepaper
Program may extend to ~2029

What's next?
China is considering the next accelerator beyond the BEPCIII

Xiaoyan Shen
IHEP

Reminder about the CEPC-SppC

e^+e^- Higgs (Z) factory **Initially team set up the minimum goals**

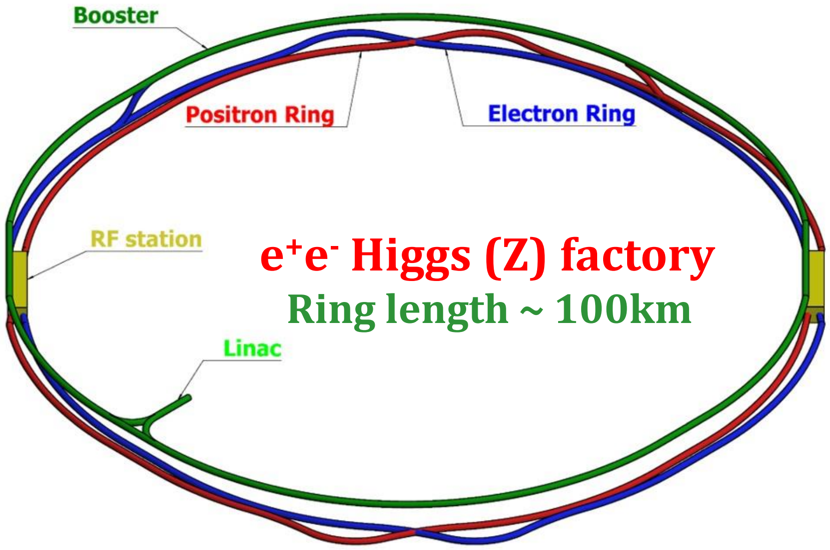
$E_{cm} \approx 240$GeV, luminosity $\sim 2\times10^{34}$ $cm^{-2}s^{-1}$, 2IP, 1M H in 10 years
at the Z-pole 10^{10}Z bosons/yr

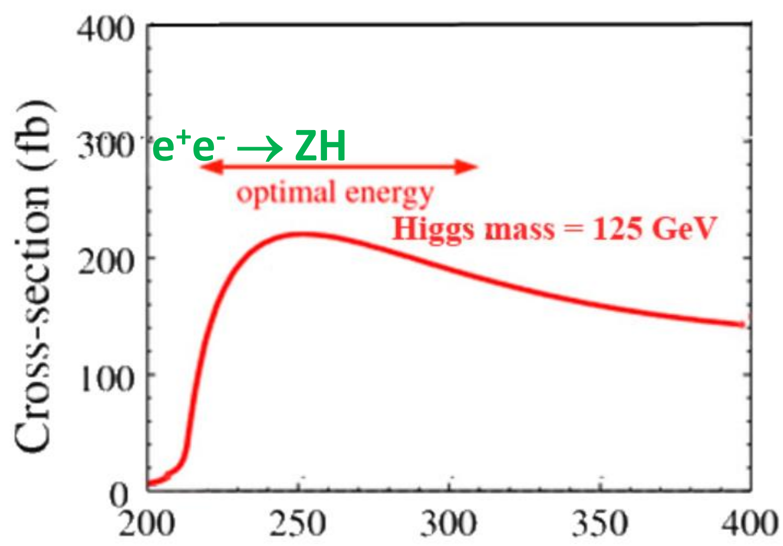
Precision measurement of the Higgs boson (and the Z boson)

Higgs precision 1% or better

Upgradable to pp collision with $E_{cm} \approx$ 50-100 TeV (with ep, HI options)

A discovery machine for BSM new physics





BEPCII → BEPCIII, will likely complete its mission ~2029;
CEPC – possible accelerator based particle physics program in China after BIII

Reminder about the CEPC-SppC

e^+e^- Higgs (Z) factory

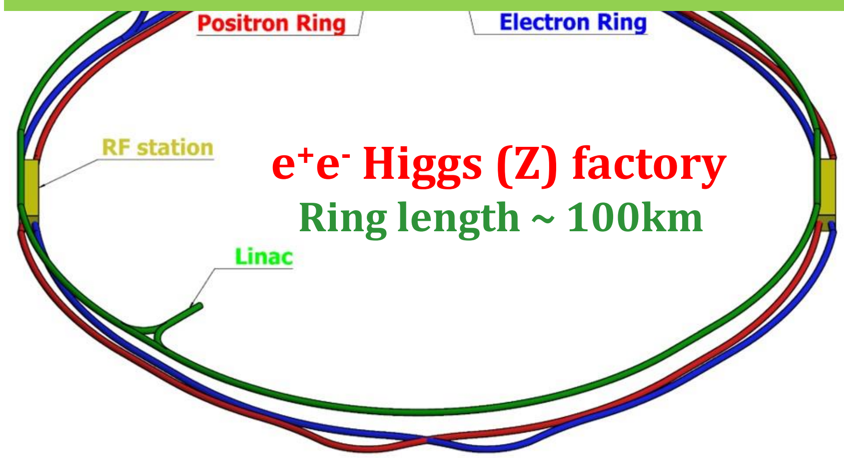
Initially team set up the minimum goals

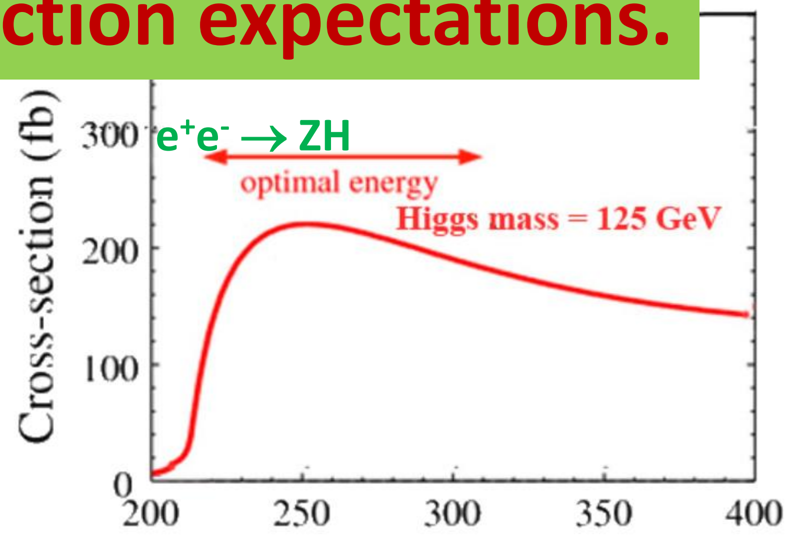
$E_{cm} \approx 240$GeV, luminosity ~2×10^{34} $cm^{-2}s^{-1}$, 2IP, 1M H in 10 years
at the Z-pole 10^{10}Z bosons/yr

Higgs precision
1% or better

Upg

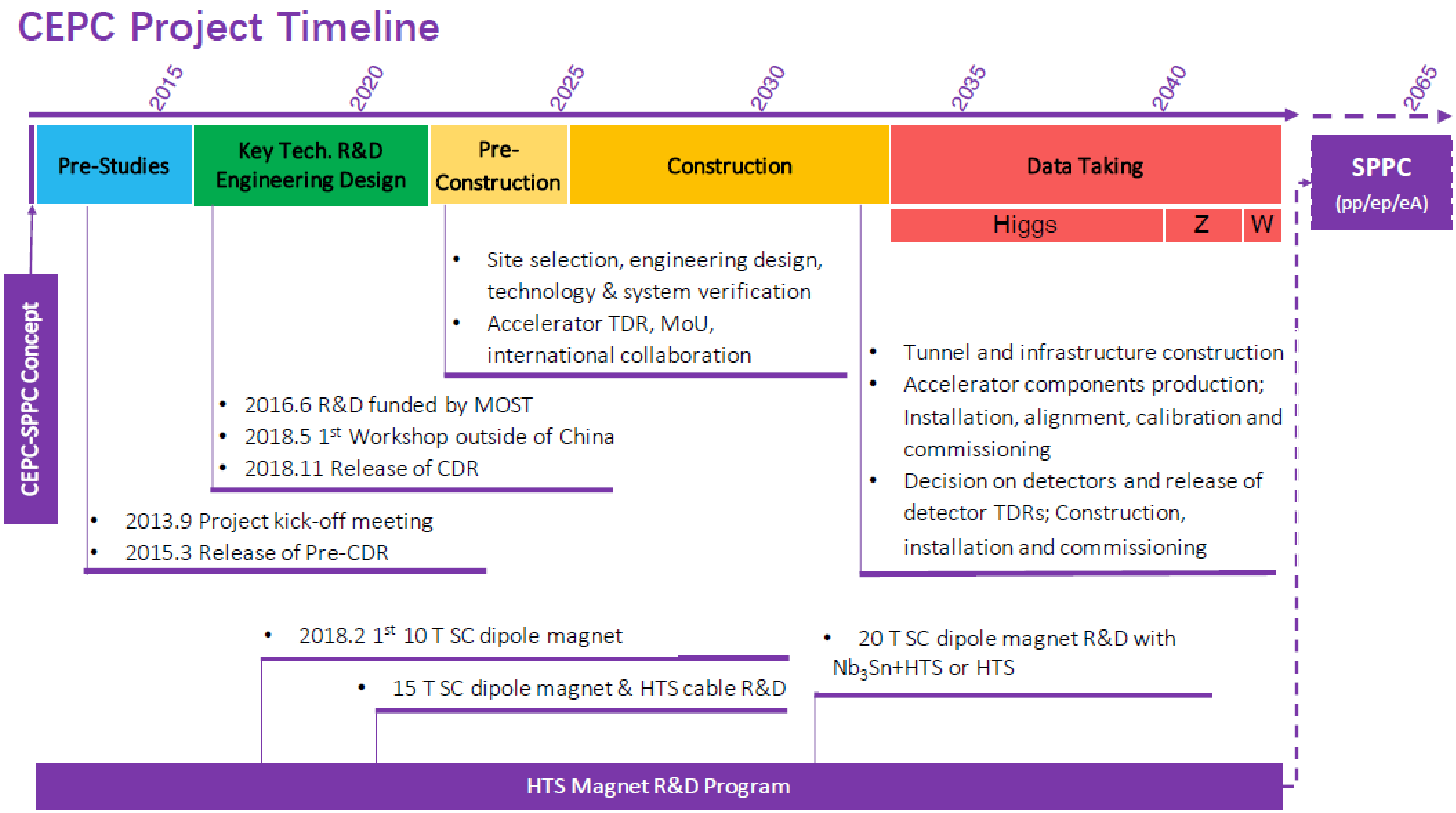
CDR and post CDR design improvement exceeds these minimum requirement on the Higgs and Z in production expectations.





BEPCII → BEPCIII, will likely complete its mission ~2029;
CEPC – possible accelerator based particle physics program in China after BIII

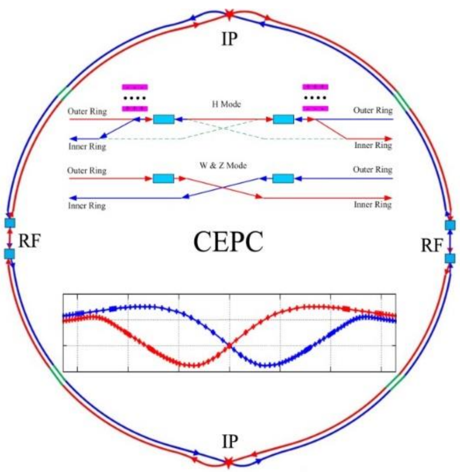
CEPC Roadmap and Schedule (proposed)

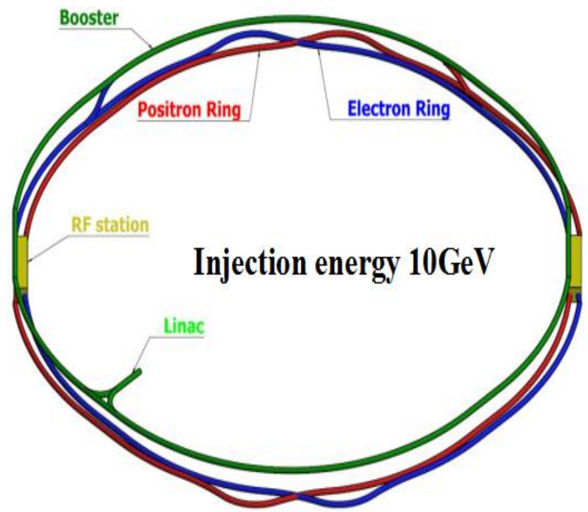


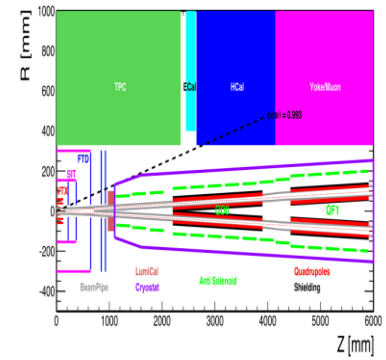
CEPC CDR – Accelerator (2018)

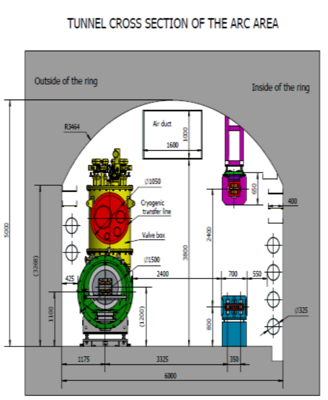
Lumi.	Higgs	W	Z	Z(2T)
$\times10^{34}$	2.93	11.5	16.6	32.1

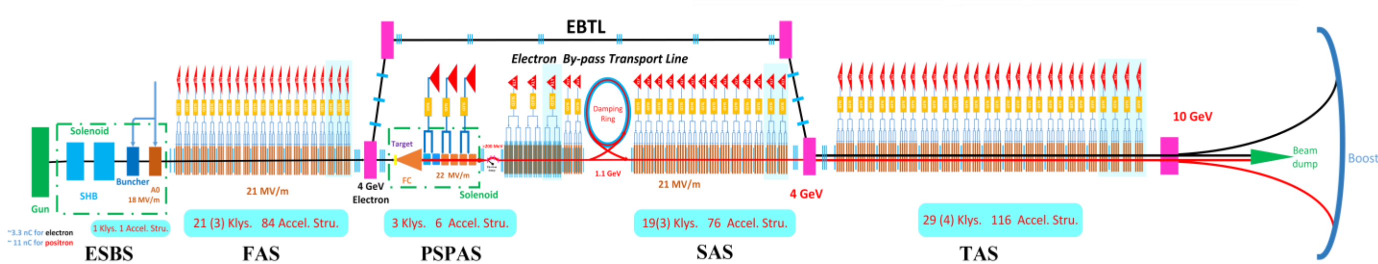
http://cepc.ihep.ac.cn/CEPC_CDR_Vol1_Accelerator.pdf







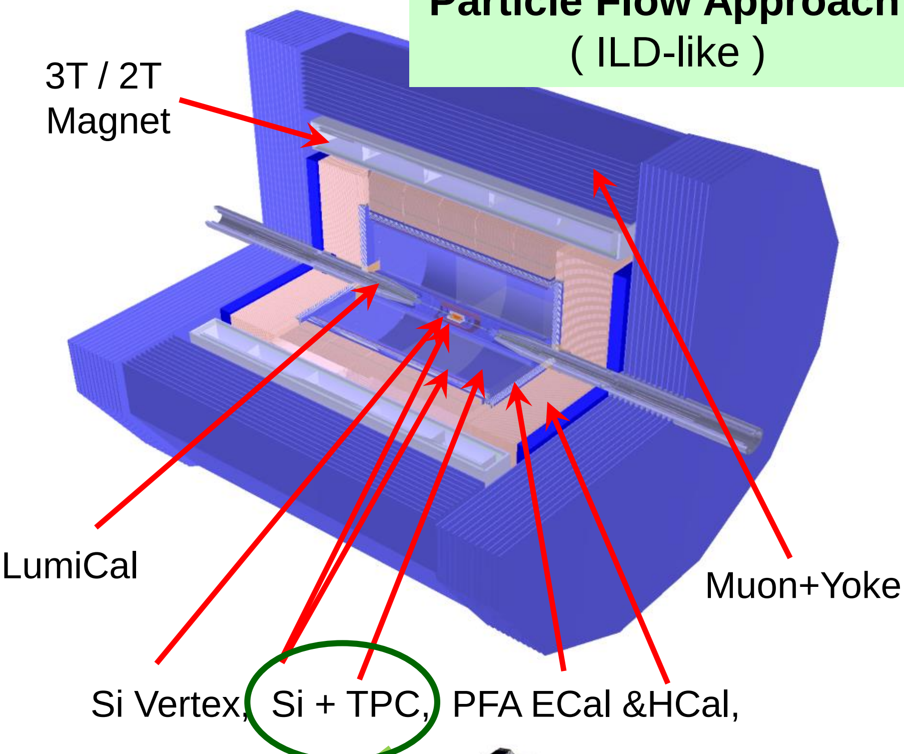




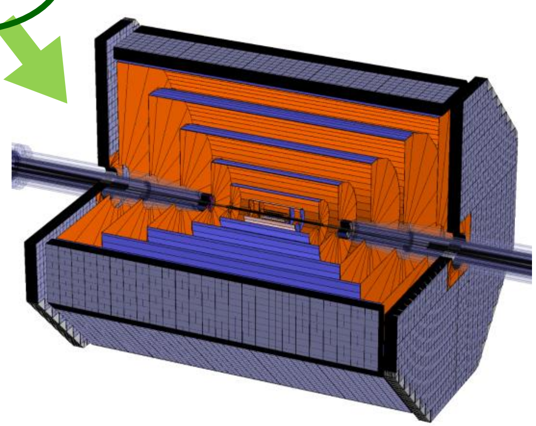
Baseline: 100 km, 30 MW; Upgradable to 50 MW, High Lumi Z, ttbar; Compatible to pp collider

CDR - Detector-Physics (2018)

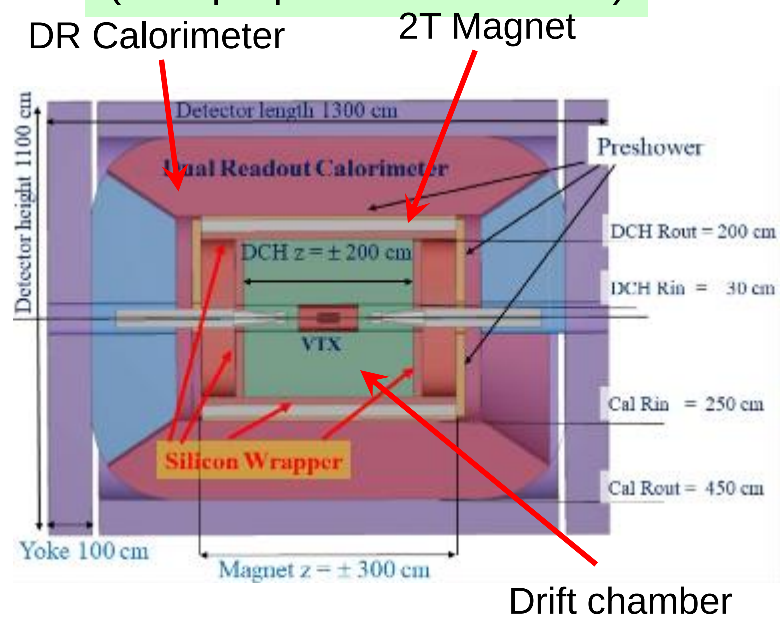
Particle Flow Approach
(ILD-like)



Full Silicon Tracker (FST) concept



IDEA concept
(also proposed for FCC-ee)



- Official international collaborations are to be formed, and to decide the detector design.
- The working group is doing R&D of all sub-systems in the CDR design, and exploring various other technologies.
- The final two detectors likely are mixtures of different options.

http://cepc.ihep.ac.cn/CEPC_CDR_Vol1_Accelerator.pdf

Beyond CDR

design enhancement, R&D, detector-simulation, and infrastructure

CEPC accelerator design improvement

- **High luminosities at Z and H**
  - Optimization of parameters, improving the dynamic aperture(DA) to include errors and more effects, …
  - New lattice for high luminosity at Higgs
  - New RF section layout
  - More detailed study of MDI
  - Optimization of the booster design and its magnets
  - A new alternative design of the LINAC injector
  - A new plasma injector design
  - Injection design
  - ……

- **Accelerator Review Committee** – recommended by the IAC, established and met in November, 2019

CEPC accelerator design improvement

CDR scheme (Higgs)

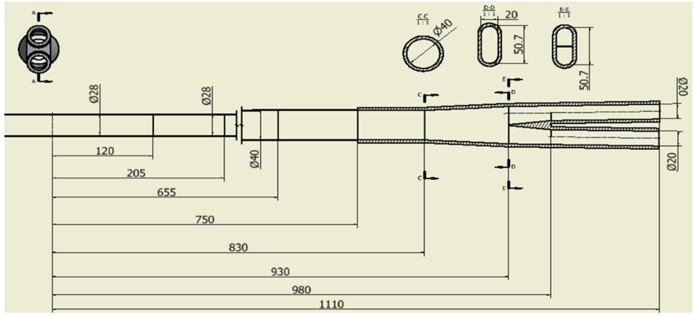
- ✓ **$L^*=2.2m$, $\theta c=33mrad$, $\beta x^*=0.36m$, $\beta y^*=1.5mm$, Emittance=1.2nm**
  - Strength requirements of anti-solenoids (peak field B_z~7.2T)
  - Two-in-one type SC quadrupole coils (Peak field 3.8T & 136T/m)

High luminosity scheme (Higgs)

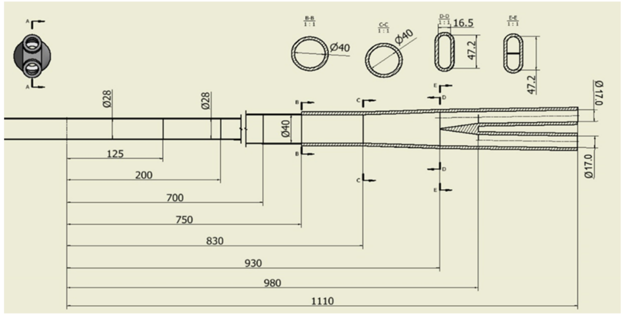
- ✓ **$L^*=1.9m$, $\theta c=33mrad$, $\beta x^*=0.33m$, $\beta y^*=1.0mm$, Emittance=0.68nm**
  - Strength requirements of anti-solenoids (peak field B_z~7.2T)
  - Two-in-one type SC quadrupole coils (Peak field 3.8T & 141T/m) with room temperature vacuum chamber & Iron yoke

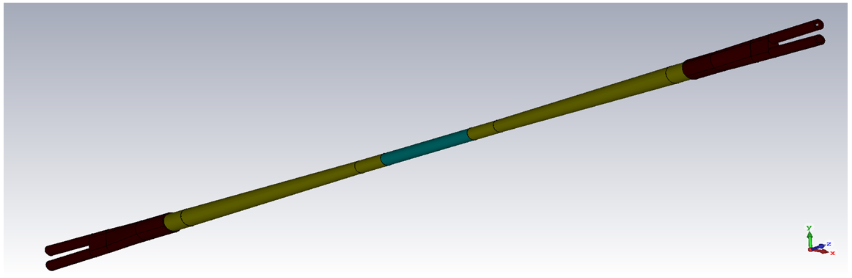
CDR **Change of IP chamber** High luminosity

Be pipe: 28mm, SCQ Beam pipe:20mm



Be pipe: 28mm, Beam pipe:17mm



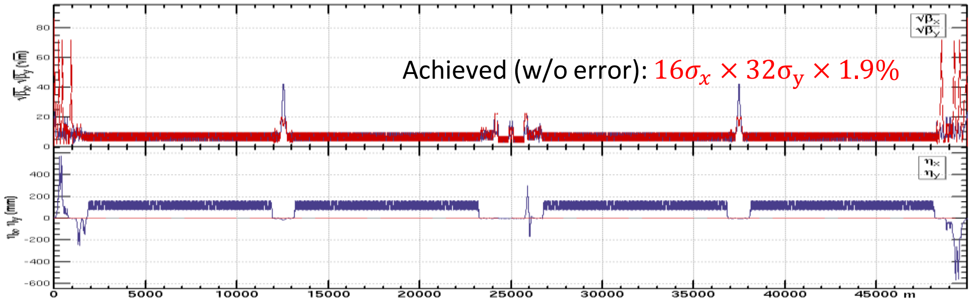


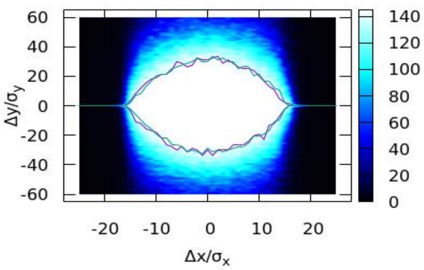
CEPC Higgs High Lumi Lattice and Dynamic Aperture Status

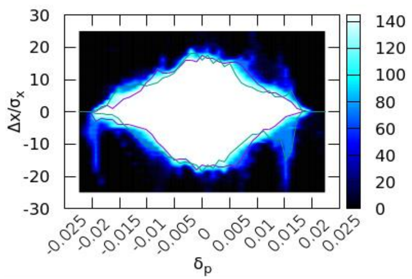
- Fit parameter list with luminosity of $5 \times 10^{34}/\mathrm{cm}^2/\mathrm{s}$
  - Stronger optimization and stricter hardware requirement should be made to get enough dynamic aperture
- Optimization of the quadrupole radiation effect
  - Interaction region: longer QD0/QF1 (2m/1.48m => 3m/2m)
  - ARC region: longer quadrupoles (2m => 3m)
- Reduction of dynamic aperture requirement from injection
  - Straight section region: larger βx at injection point (600m => 1800m)
- Maximization of bend filling factor to minimize the synchrotron radiation loss per turn
  - ARC region: sextupoles in two rings changed from staggered to parallel; The left drifts are used for longer bend.
  - RF region: shorter phase tuning sections

With better correction of energy dependent aberration and shorter L* (without changing the front-end position of the final doublet cryo-module)

Goal (w/ error): $8\sigma_x \times 15\sigma_y \times 1.7\%$







CEPC High Luminosity Parameters beyond CDR

	tt	*Higgs*	*W*	*Z*	
Number of IPs	2	2	2	2	
Energy (GeV)	**180**	**120**	**80**	**45.5**	
Circumference (km)	100	100	100	100	
SR loss/turn (GeV)	8.53	1.73	0.33	0.036	
Half crossing angle (mrad)	16.5	16.5	16.5	16.5	
Piwinski angle	1.16	4.87	9.12	24.9	
N_e/bunch (10^{10})	20.1	16.3	11.6	15.2	
Bunch number (bunch spacing)	37 (4.45μs)	214 (0.7us)	1588 (0.2μs)	3816 (86ns)	11498 (26ns)
Beam current (mA)	3.5	16.8	88.5	278.8	839.9
SR power /beam (MW)	**30**	**30**	**30**	**10**	**30**
Bending radius (km)	10.7	10.7	10.7	10.7	
Phase advance of arc cell	90°/90°	90°/90°	90°/90°	60°/60°	
Momentum compaction (10^{-5})	0.73	0.73	0.73	1.48	
β_{IP} x/y (m)	1.0/0.0027	0.33/0.001	0.33/0.001	0.15/0.001	
Emittance x/y (nm)	1.45/0.0047	0.68/0.0014	0.28/0.00084	0.27/0.00135	
Transverse σ_{IP} (um)	37.9/0.11	15.0/0.037	9.6/0.029	6.36/0.037	
ξ_x/ξ_y/IP	0.076/0.106	0.018/0.115	0.014/0.13	0.0046/0.131	
V_{RF} (GV)	9.52	2.27	0.47	0.1	
f_{RF} (MHz) (harmonic)	650 (216816)	650 (216816)	650 (216816)	650 (216816)	
Nature bunch length σ_z (mm)	2.23	2.25	2.4	2.75	
Bunch length σ_z (mm)	2.66	4.42	5.3	9.6	
HOM power/cavity (kw)	**0.45 (5cell)**	**0.48 (2cell)**	**0.79 (2cell)**	**2.0 (2cell)**	**3.02 (1cell)**
Energy spread (%)	0.17	0.19	0.11	0.12	
Energy acceptance requirement (DA) (%)	2.0	1.7	1.2	1.3	
Energy acceptance by RF (%)	2.61	2.5	1.83	1.48	
Lifetime (hour)	0.59	0.35	1.3	1.7	1.4
L_{max}/IP (10^{34}cm^{-2}s^{-1})	**0.5**	**5.0**	**18.7**	**35.0**	**105.5**

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

CEPC accelerator R&D highlights

CEPC Accelerator TDR, R&D Priority

test facilities are available for many of the tasks

- CEPC 650MHz 800kW klystron: high efficiency (80%), **fabrication will be completed by year end, tests in 2022**
- High precision booster dipole magnets: which are critical for booster operation, **to complete full-size magnet model in 2021**
- CEPC 650MHz SC accelerator system, including SC cavities and cryomodules, **to complete test cryomodule in 2022**
- Collider dual aperture dipole magnets, dual aperture quadrupoles and sextupole magntes: **to complete full-size model in 2022**
- Vacuum chamber system: **to complete fabrication and costing test in 2022**
- SC magnets including cryostats: **to complete short test model in 2022**

16

CEPC Accelerator TDR, R&D Priority,

test facilities are available for many of the tasks

- MDI mechanic system: **vacuum connection removal to be tested in 2022**
- Collimator: **to complete model test in 2022**
- Linac components: **to complete key components test in 2022**
- Civil engineering design: **to complete reference implementation design in 2022**
- Plasma wakefield injector: **to complete the electron accelerator test in 2022**
- 18KW@4.5K cryoplant: **industrial partner**
- ...

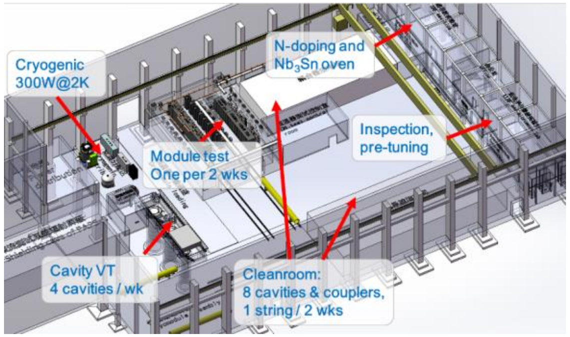
SppC technology R&D

- Ion based supercondcuting materials and high field magnets

17

IHEP New SC Lab under Construction (Status in Nov. 2019)

Facility: CEPC SCRF test facility (lab) is located in IHEP Huairong Area of 4500m^2



New SC Lab Design (4500m^2)

SC New Lab will be available in 2021

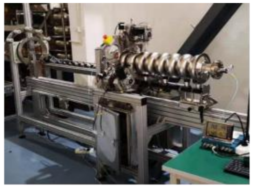
Crygenic system hall in Jan. 16, 2020


Vacuum furnace (doping & annealing)

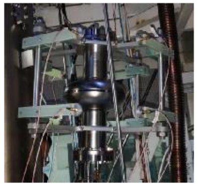

Nb3Sn furnace

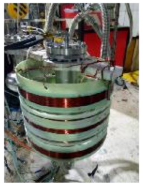

Nb/Cu sputtering device


Cavity inspection camera and grinder


9-cell cavity pre-tuning machine


Temperature & X-ray mapping system


Second sound cavity quench detection system


Helmholtz coil for cavity vertical test

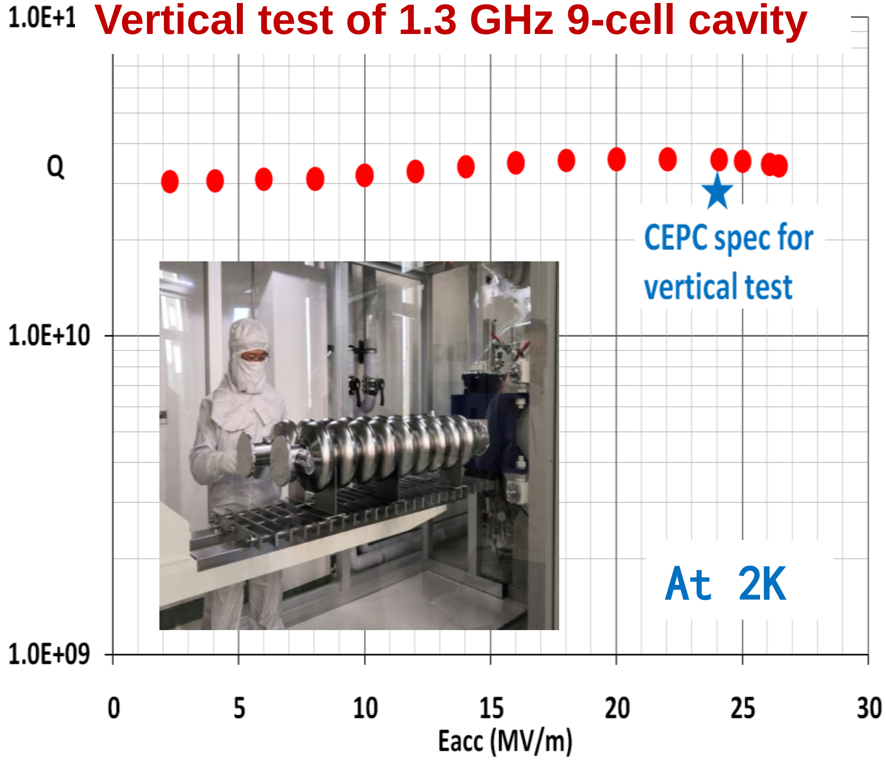

Vertical test dewars


Horizontal test cryostat

R&D：High Q SRF Cavities

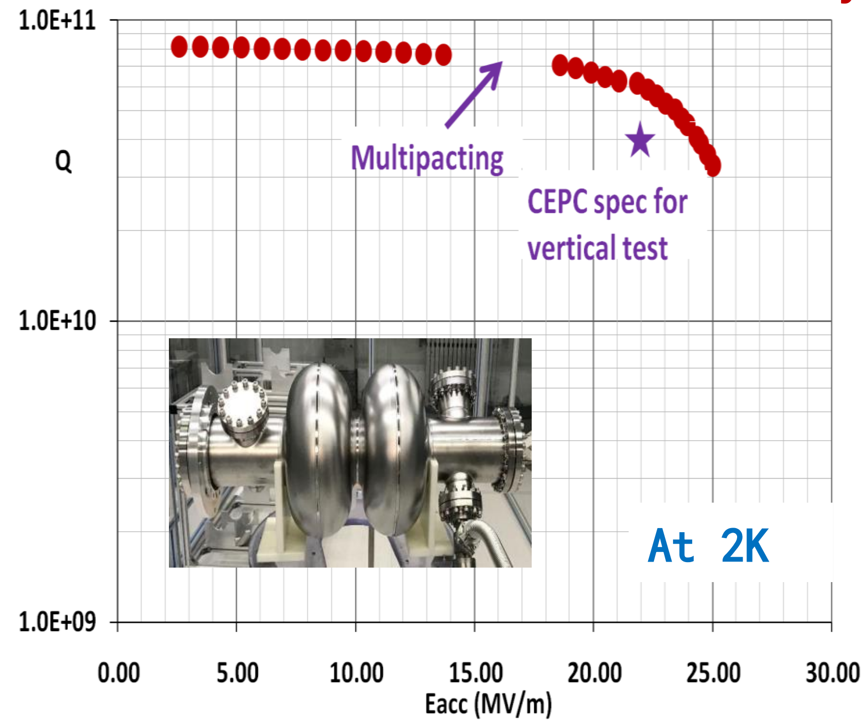
The 650 MHz 2-cell and 1.3 GHz 9-cell cavities have both exceeded the CEPC spec for vertical test, a milestone towards the TDR

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

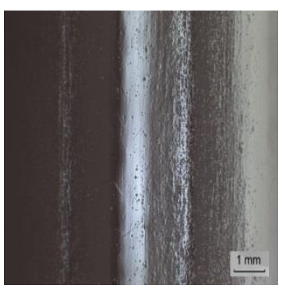
- **Friction between flexible medium and the cavity surface through high-speed reciprocating motion: Roughness ~100nm**
- **By replacing bulk EP, 1.3 GHz 1-cell cavity can reached 46 MV/m**
- **Advantages: high efficiency, environmental friendly, low cost**

Conventional recipe

~~Bulk EP (~150um)~~

Annealing

Light EP (~20um)



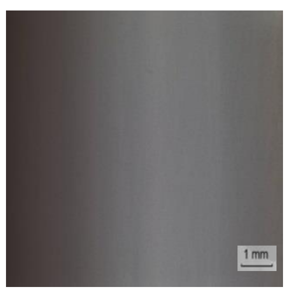
Initial surface

New recipe

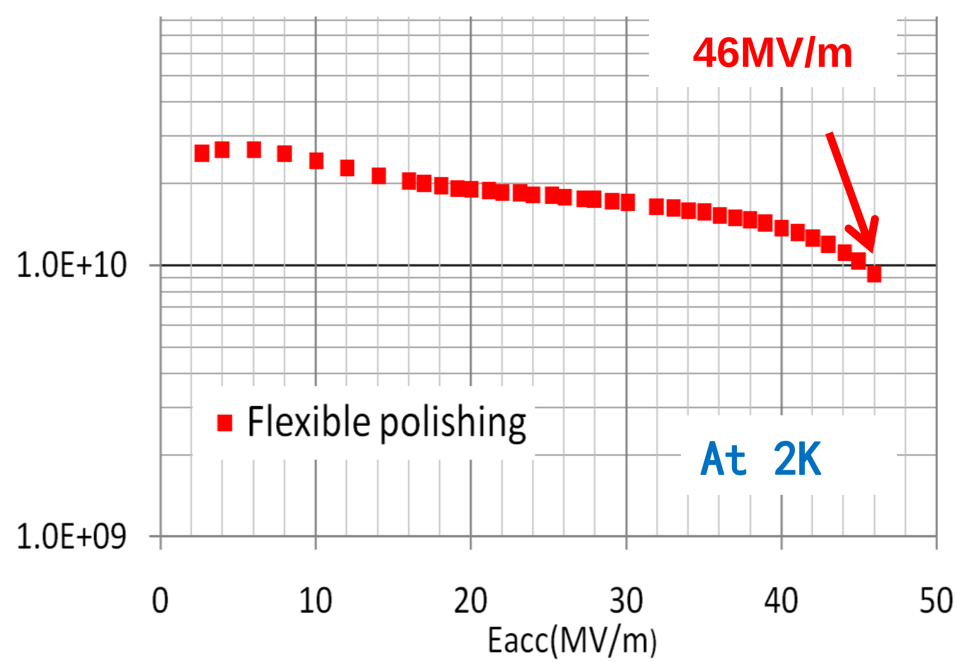
FP (~150um)

Annealing

Light EP (~40um)



After flexible polishing

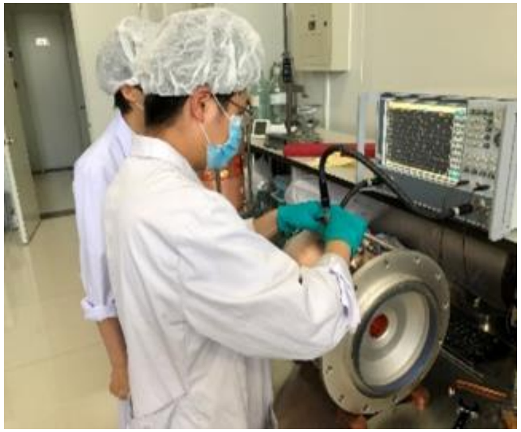


More study in combination with other methods will be performed

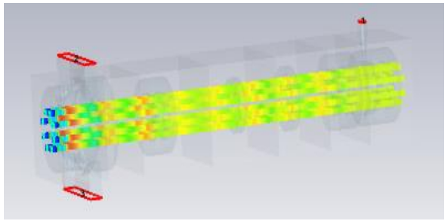
R&D: Towards High Eff. Klystrons

– 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%
  – Design completed and production will start soon

Bake out



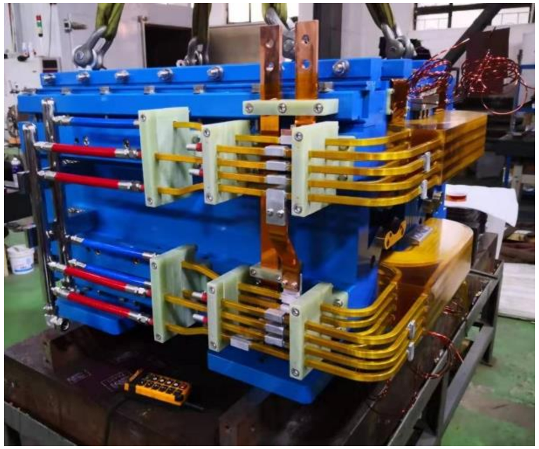
Cold test

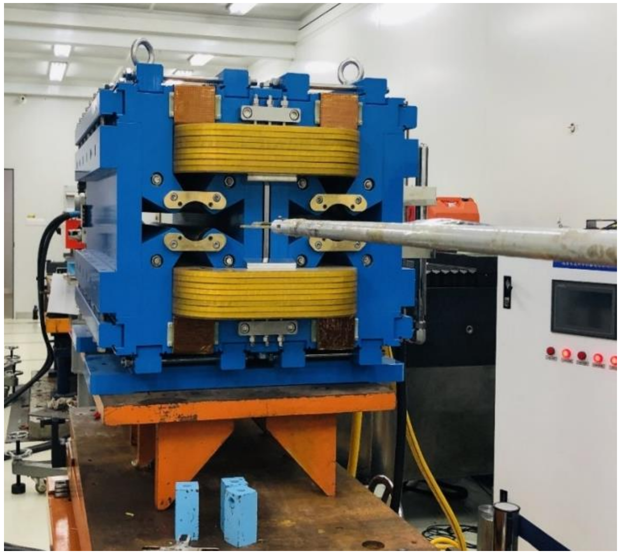


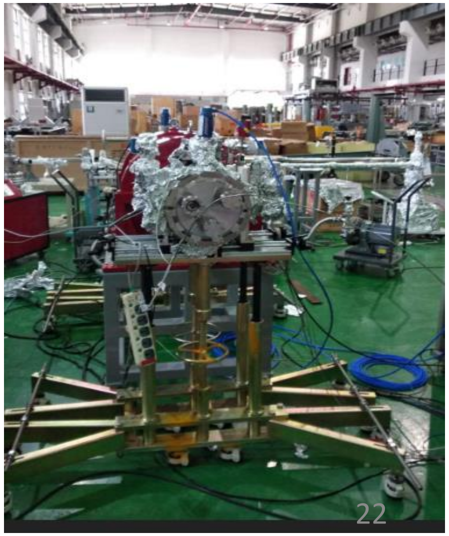
High power test

R&D: Other Prototypes

magnets, EM-separators, vacuum pipes, …



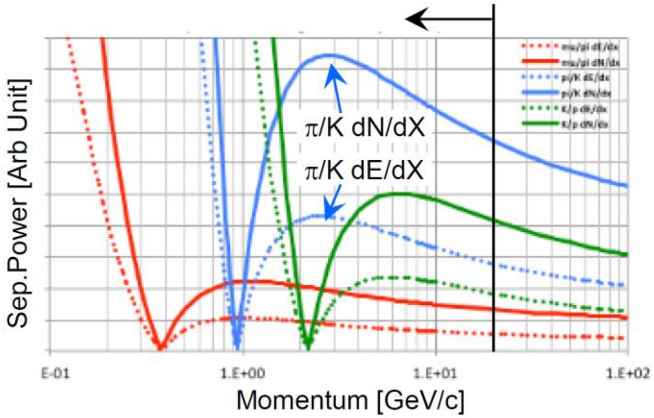


Detector, software and simulation study

- **Detector R&D, software development**
  - Silicon pixel vertex detector: σ(IP)~5μm, 2 lines of ASICs developed, plans to build a full size prototype ladder …
  - Large area silicon tracker: 70-140m^2, investigating HV-CMOS option, aims at a short stave demonstrator based on ATLASPix3
  - TPC: prototype + a laser calibration system built, to correct for ion backflow; exploring pixel TPC with double mesh or micromegas
  - IDEA drift chamber study: mechanical, wire selection, cluster counting electronics, …
  - Built PFA ECAL and HCAL prototypes, …
  - New ideas with crystal ECAL;
  - ……
- **A 4th detector concept – new design based on crystal calorimeter + silicon tracker + ionization PID + thin magnet**
- **Detector R&D Review Committee** – recommended by the IAC, a large committee (~16 members) has been established

Particle Identifications - Choices

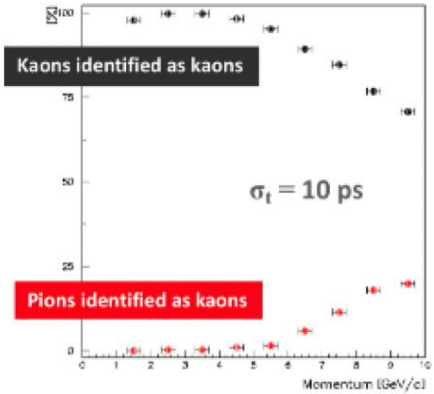
- Charge particle ID is crucial for the flavor physics. Aiming at P < ~ 20 GeV/c.
- Both TPC & DC provide good PID, with dE/dX or dN/dX cluster counting.
- For the FST solution, a supplement PID detector is needed. Combination of different PID detectors is also viable.



① **Drift chamber** between the outer layers of FST. It is promising in a simple simulation. More work in design optimization, and the physics impact.

② **Time of flight** detectors, e.g. LGAD. The resolution ~20-30 ps today (ATLAS/CMS). Sensor by IHEP & NDL reaches 25ps. By the time of CEPC, 10 ps might be possible.

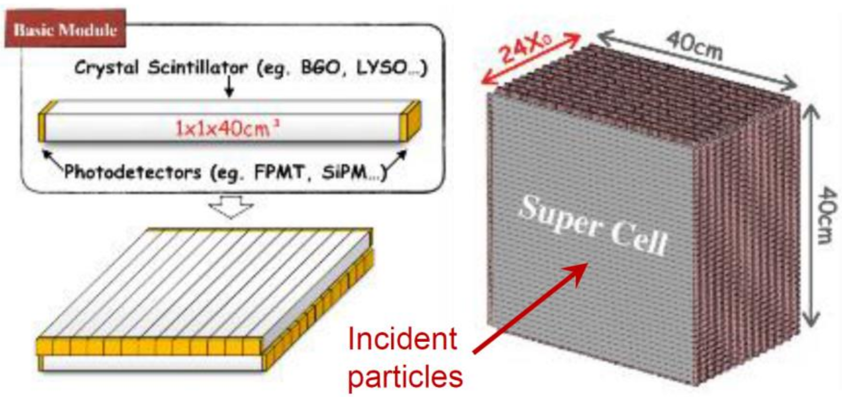
IHEP-NDL LGAD-V2
Pixel size 1.3×1.3 mm^2

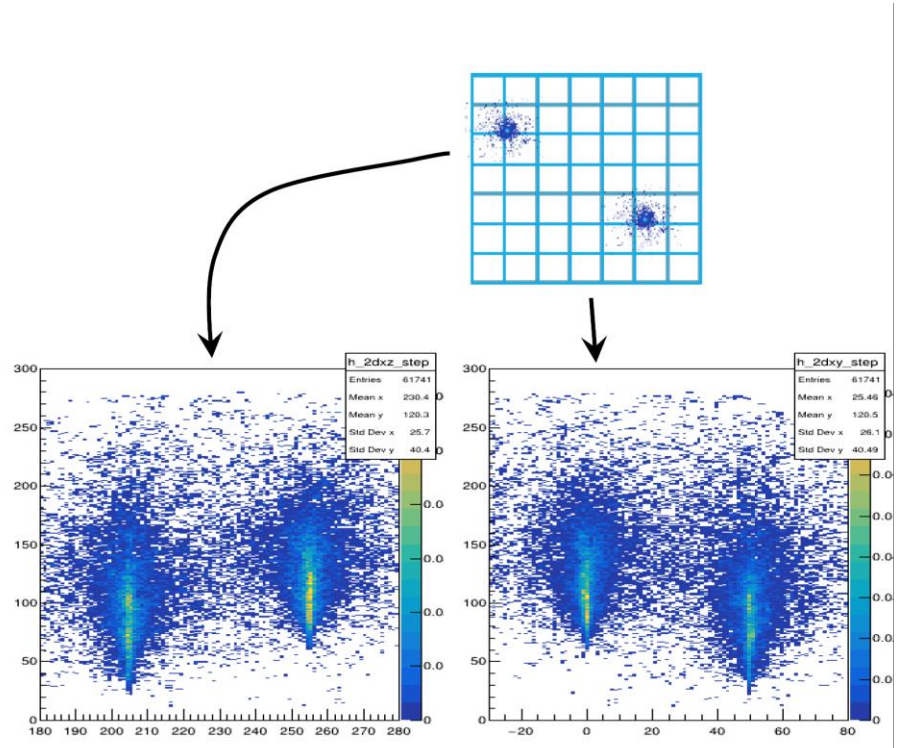


③ A **RICH** of aerogel or gaseous radiators. Space constraint needs to be studied.

- More options and studies are needed.

New Crystal Calorimeter Design





- Crystal bar perpendicular to particles. Significant reduction of number of channels.
- Energy & time matching provide a solution of ambiguity / ghost hits.

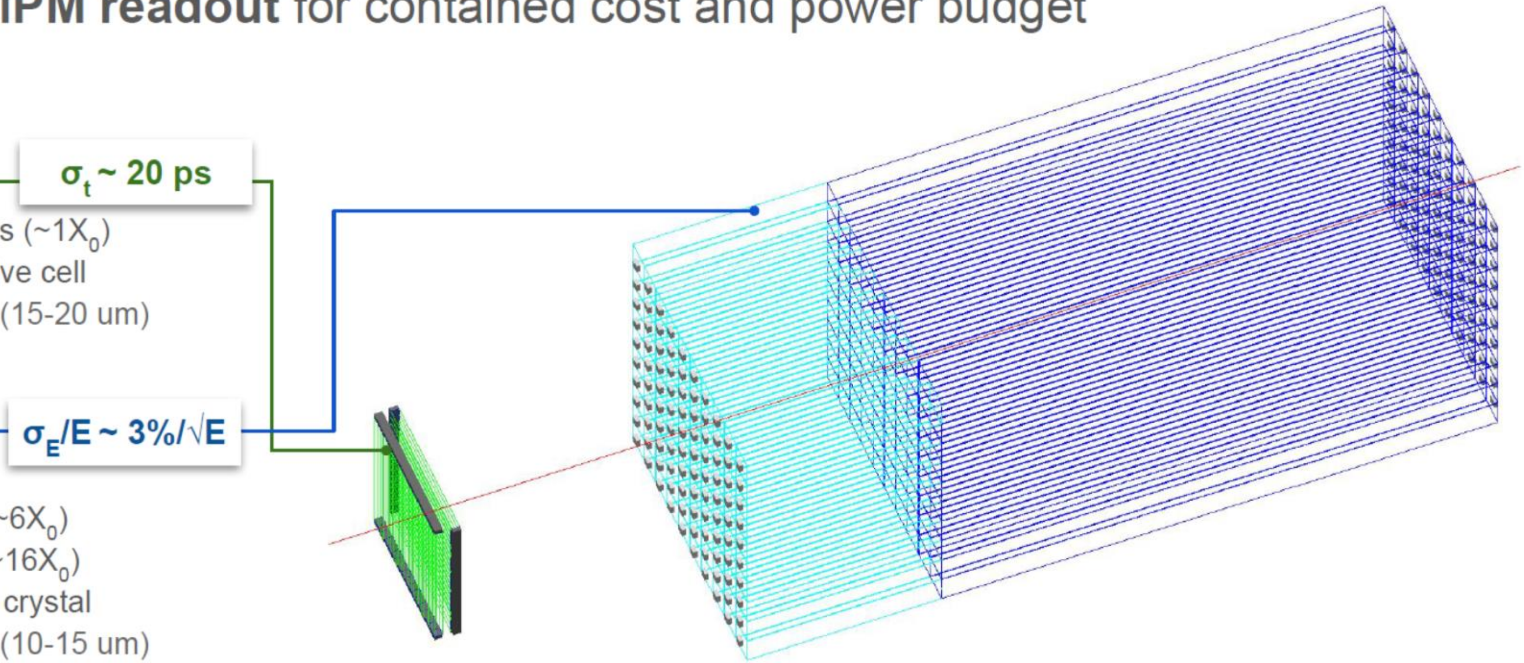
New Crystal Calorimeter Design

Also exploring a design of adding a time layer to the longitudinal solution.

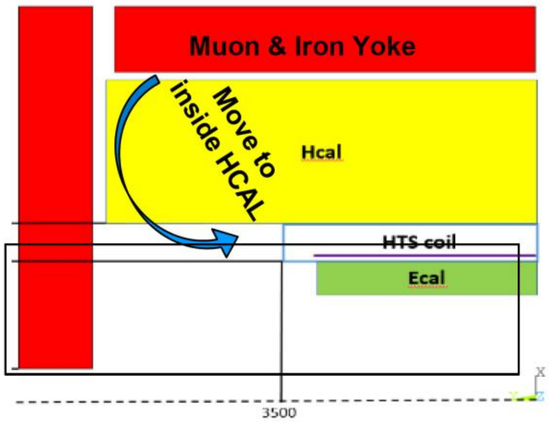
- ***SCEPCAL:*** a **S**egmented **C**rystal **E**lectromagnetic **P**recision **C**alorimeter
- **Transverse and longitudinal segmentations** optimized for particle identification, shower separation and performance/cost
- Exploiting **SiPM readout** for contained cost and power budget

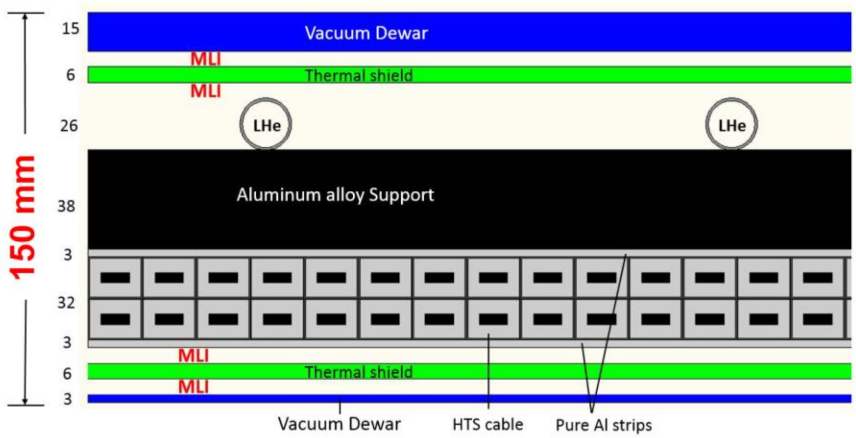
Timing layer
- LYSO:Ce crystals (~1X_0)
- 3x3x54 mm³ active cell
- 3x3 mm² SiPMs (15-20 um)

ECAL layer
- PbWO crystals
- Front segment (~6X_0)
- Rear segment (~16X_0)
- 10x10x200 mm³ crystal
- 5x5 mm² SiPMs (10-15 um)



Detector Solenoid Design

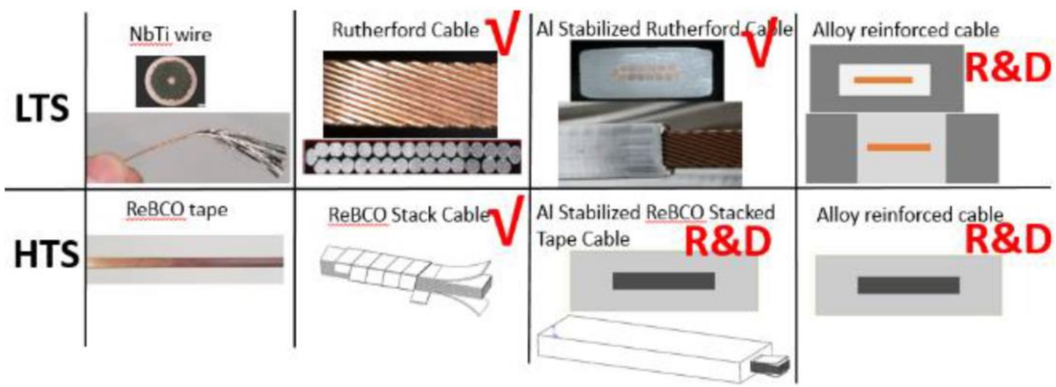




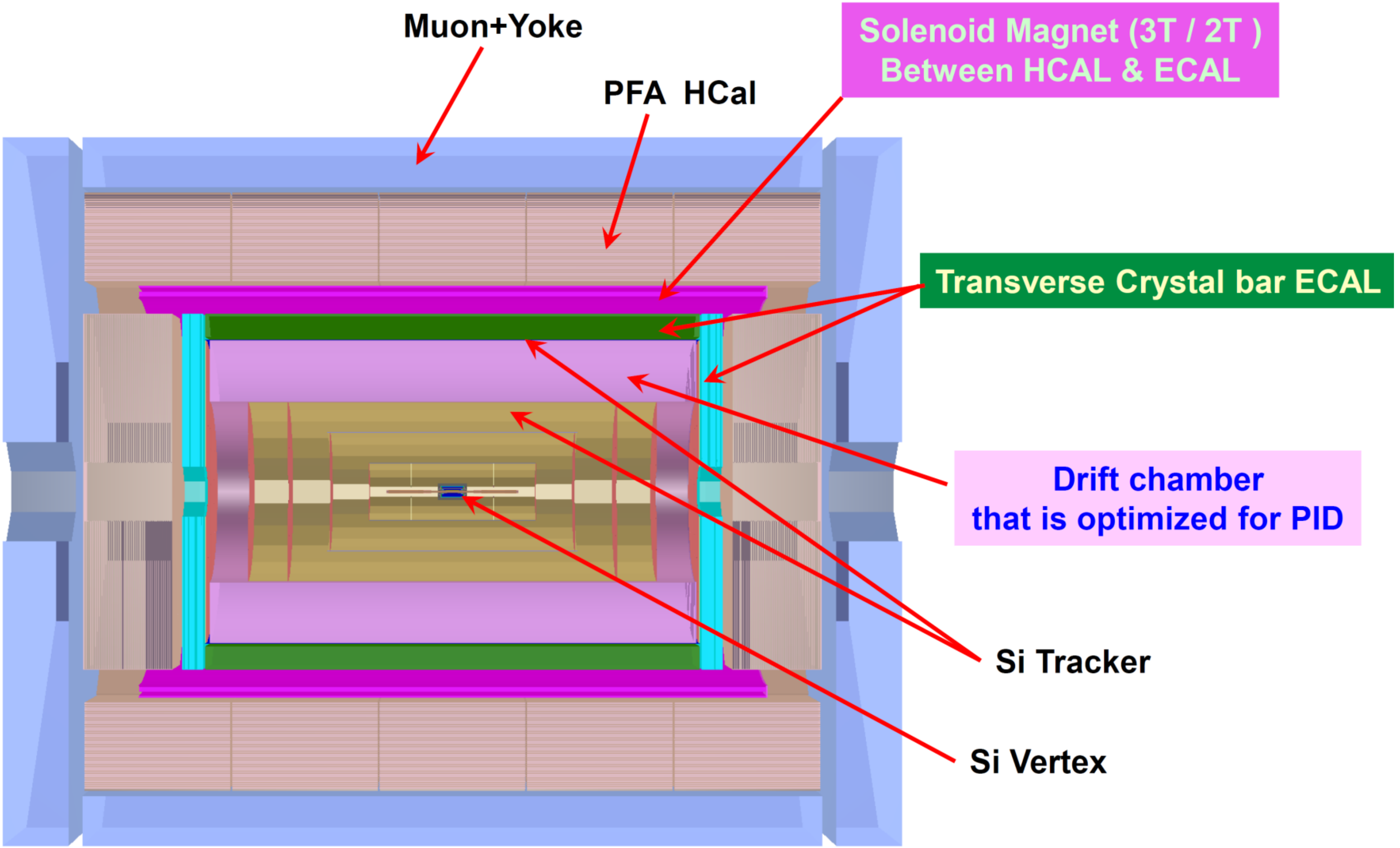
Challenges

Low mass, ultra-thin, high strength cable

LTS solution also possible, but can not be placed inside HCAL

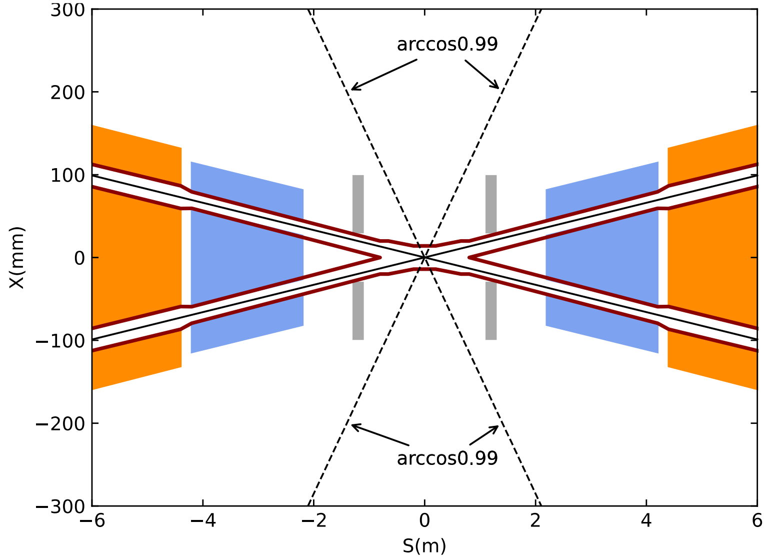


4^{th} Detector Conceptual Design

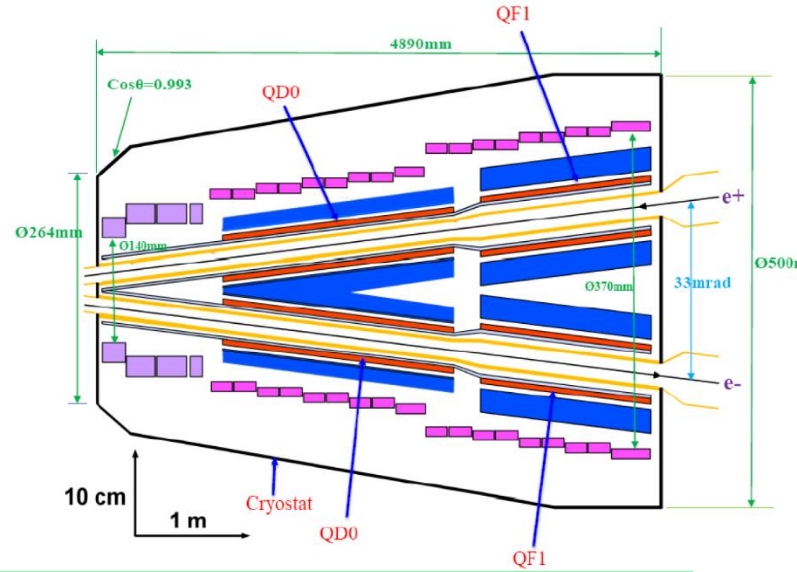


Machine-Detector Interface (MDI)

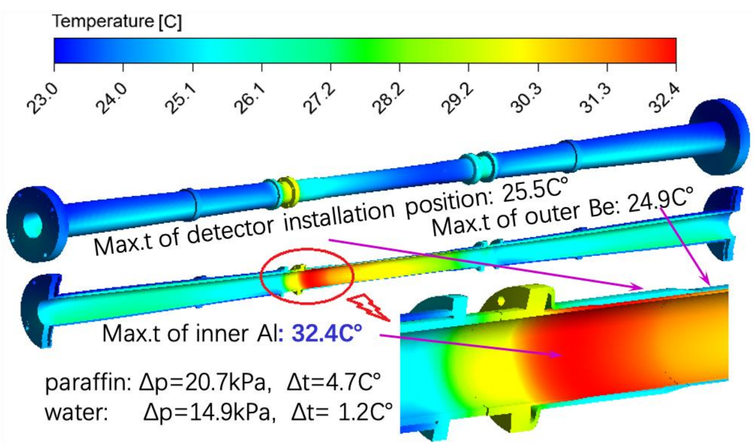
Crossing angle of 33 mrad, focal length of 2.2 m



Final focusing magnets (QD0, QF1) with Segmented Anti-Solenoidal Magnets



Beam pipe design



Temperature distribution under **High Order Mode (HOM) heat**

Central beampipe made with **Beryllium** and located at **r = 14 mm**, beampipe opened up in the forward region and made with aluminum

Structure: Double thin beryllium layers with paraffin (coolant) in the middle, forward beampipe with water cooling

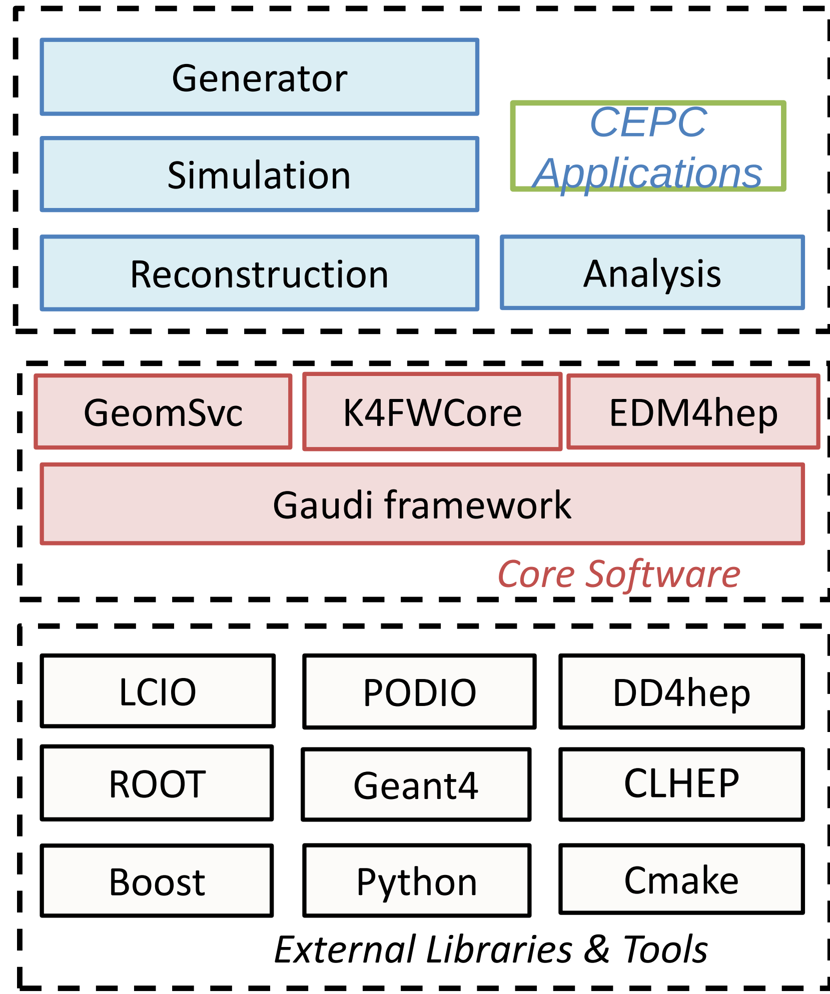
Work in progress with MDI

CEPC Software

- The CEPC software development first started with the iLCSoft
  - Reused most software modules: Marlin, LCIO, MokkaC, Gear
  - Developed its own software components for simulation and reconstruction
  - Massive M.C. data produced for detector and physics potential studies
  - CDR was released in Nov, 2018, based on results from the iLCSoft
- **A new CEPC software, CEPCSW, prototype was proposed at the Oxford workshop in April 2019**
- **The consensus among CEPC, CLIC, FCC, ILC and other future experiments was reached at the Bologna workshop in June 2019**
  - Develop a Common Turnkey Software Stack (Key4hep) for future collider experiments
  - Maximize the sharing of software components among different experiments
- Now CEPCSW, fully integrated with Key4hep, is being developed to facilitate further R&D activities of the experiment

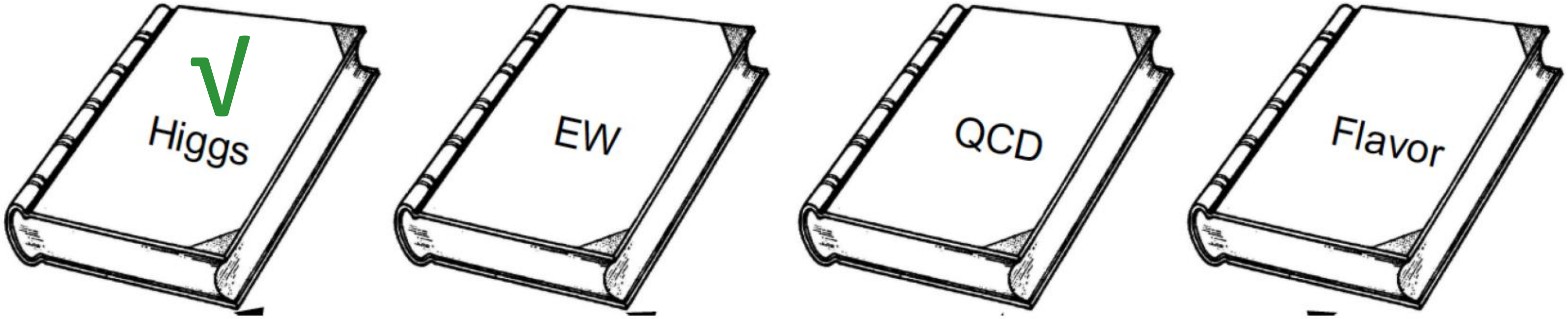
Architecture of the CEPCSW

- The software layout
  - External libraries
  - Core software
  - CEPC applications for simulation, reconstruction and analysis
- Core software
  - Gaudi framework: defines interfaces to all software components and controls their execution
  - EDM4hep: generic event data model for HEP collider experiments
  - K4FWCore :manage event objects defined by EDM4hep
  - GeomSvc :a DD4hep-based geometry service to provide a unified way to access detector geometry data
  - Both K4FWCore and EDM4hep are Key4hep packages



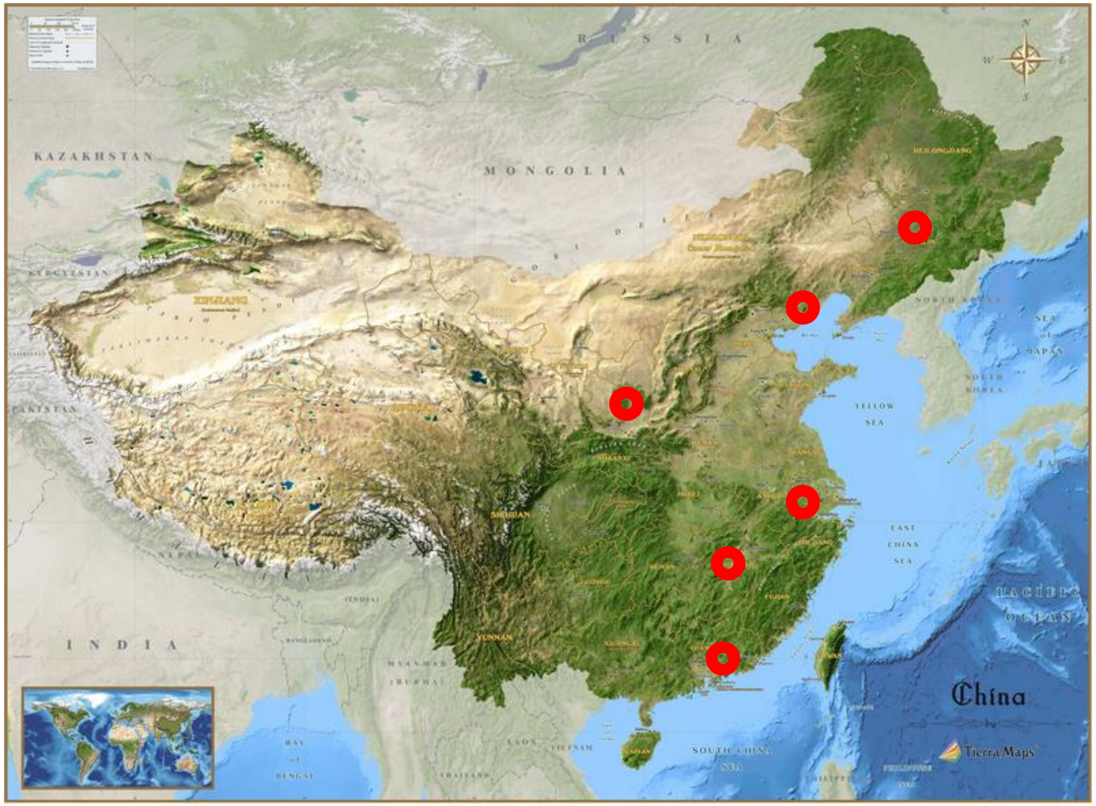
CEPC Simulation Study

White papers



- To promote the physics study at TDR & to converge to the Physics White Papers
- Physics white papers:
  - Physics handbooks for new comers: PostDoc/Student
  - Official references for the physics potential
  - Guideline for future detector design/optimization
- Higgs white paper published in 2019

Site investigation and Civil Design



- Site selection is 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)

Summary

- CEPC accelerator - high luminosity design and TDR moving ahead.
- Guided by IAC and Review committees accelerator/detector R&D making significant progress.
- The CEPC Study Group continues with the site investigation, experimental area design, and the MDI study.
- CEPC is strengthening and broadening the cooperation with industrial partners.
- Build a stronger CEPC team w. intl. collab. & participation, participating in the HEP strategy planning process in Europe and the US.
- Position CEPC to be ready for the government to make the decision; continues to work with funding agencies.

CEPC accelerator design improvement

CEPC CDR Lattice DA with Errors

Achieved DA (with errors)@ Higgs: 10σx/21σy/0.00 (on momentum), 2σx/9σy/0.0135 (off momentum)

Design DA goal (with errors)@Higgs: 8σx/15σy/0.00 (on momentum), 1σx/1σy/0.0135 (off momentum)

Component	Δx (mm)	Δy (mm)	$\Delta\theta_z$ (mrad)	Field error
Dipole	0.10	0.10	0.1	0.01%
Arc Quadrupole	0.10	0.10	0.1	0.02%
IR Quadrupole	0.05	0.05	0.05	
Sextupole	0.10	0.10	0.1	

CDR lattice design with errors reached the DA design goal