Accelerator Studies in China

Qing QIN for the accelerator team in IHEP

Institute of High Energy Physics, CAS

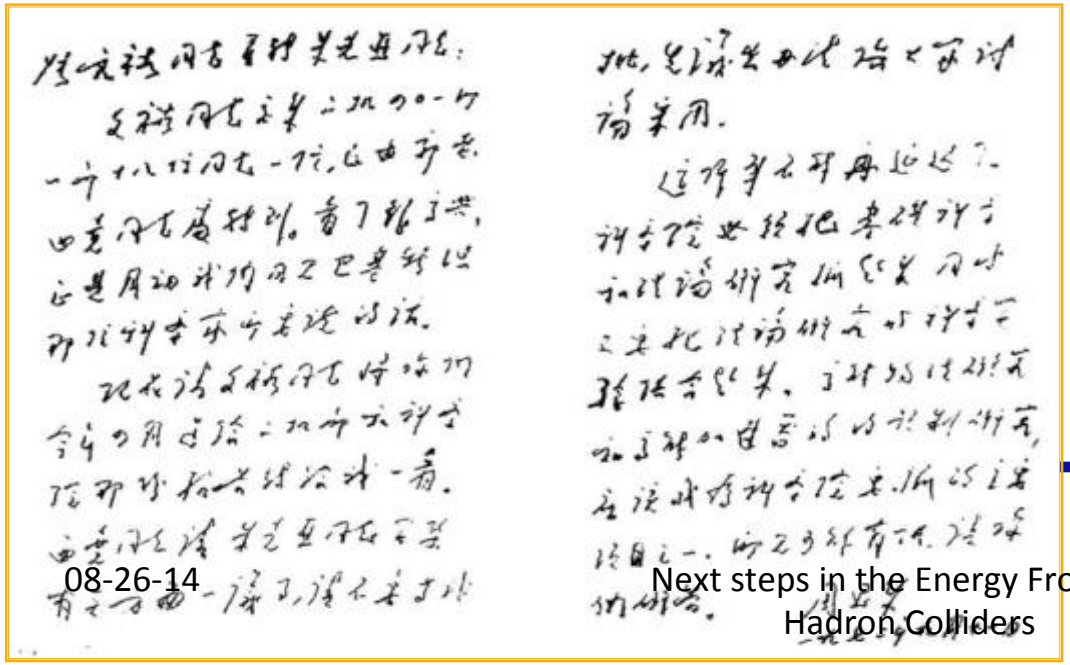
Outlines

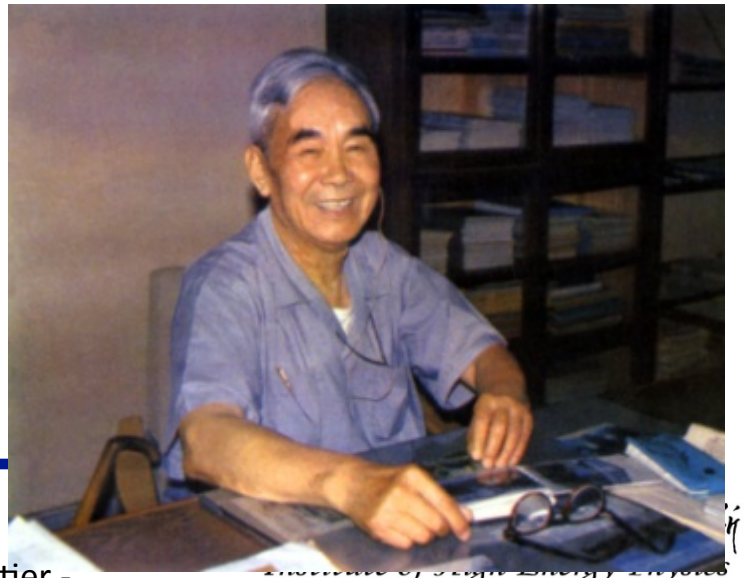
- Introduction
- Plan on CEPC + SppC
- Hadron machine in China
- Key technology for SppC
- Summary

1. Introductoin

- **History of IHEP**

May,1950	Institute of Modern Physics
October,1953	Institute of Physics
July ,1958	Institute of Atomic Energy
February ,1973	**Institute of High Energy Physics**





ZHANG Wenyu

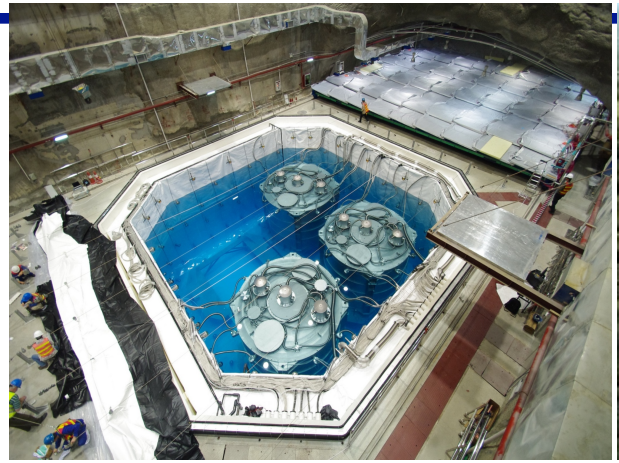
Large science facilities

IHEP serves as the backbone of China's large science facilities

- **In operation**
  - Beijing Electron Positron Collider (BEPCII)
  - Beijing Spectrometer (BESIII)
  - Beijing Synchrotron Radiation Facility (BSRF)
  - Yangbajing Cosmic Ray Observatory: ASg & ARGO
  - Daya Bay Neutrino Experiment
- **Under construction**
  - China Spallation Neutron Source (CSNS)
  - Hard X-ray Modulation Telescope(HXMT)
  - Accelerator-driven Sub-critical System (ADS)
  - Jiangmen Neutrino Underground Observatory (JUNO)
- **Under planning**
  - HEPS, LHAASO, XTP, HERD, …

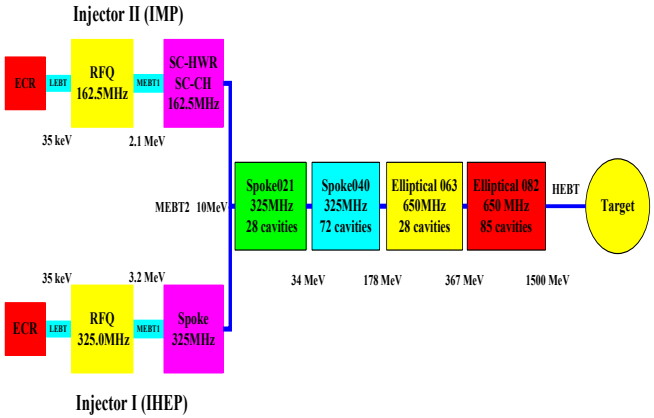
Large science facilities

BEPC



Daya Bay

CSNS

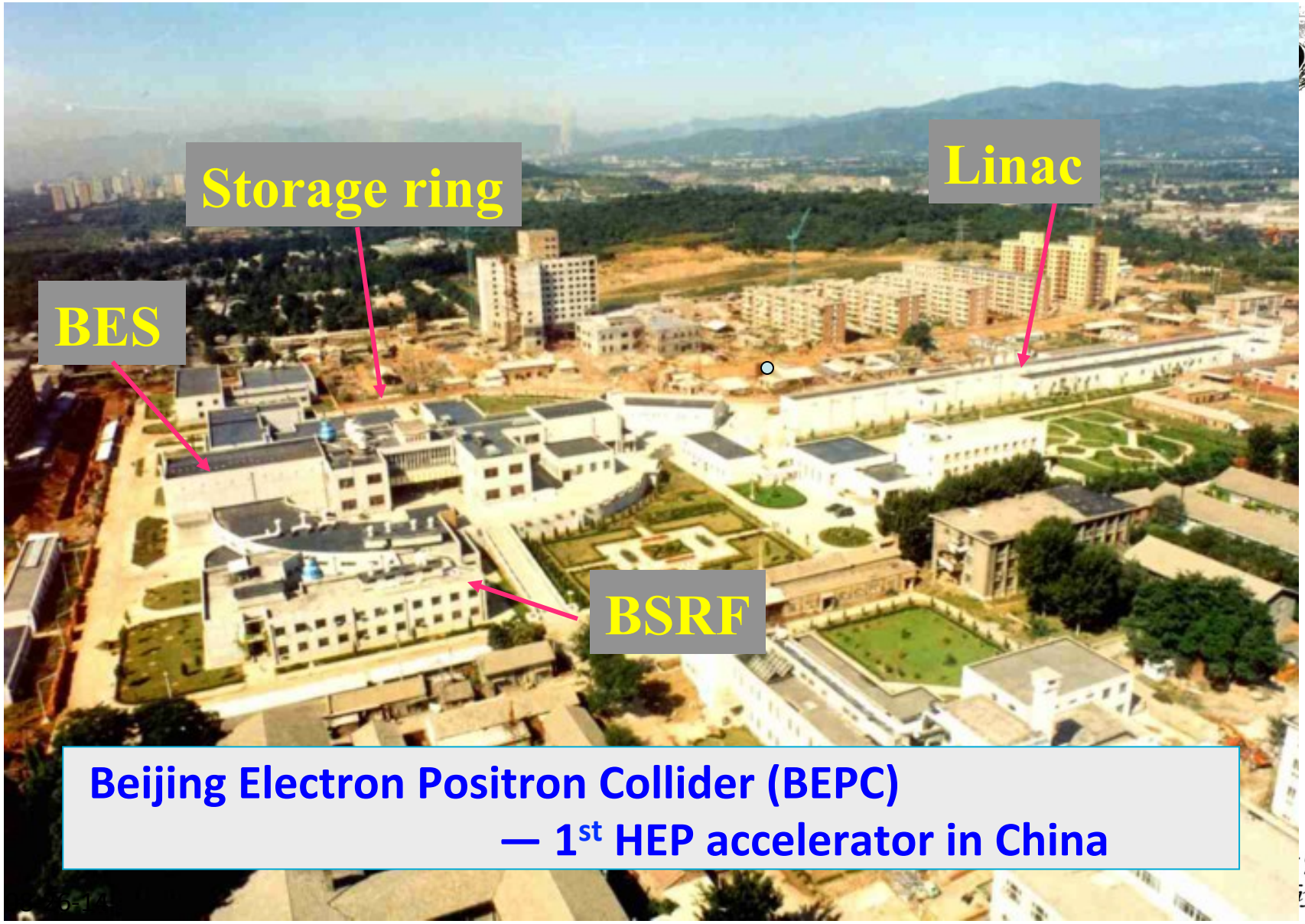


C-ADS

Yangbajing Cosmic Ray observatory

HEPS

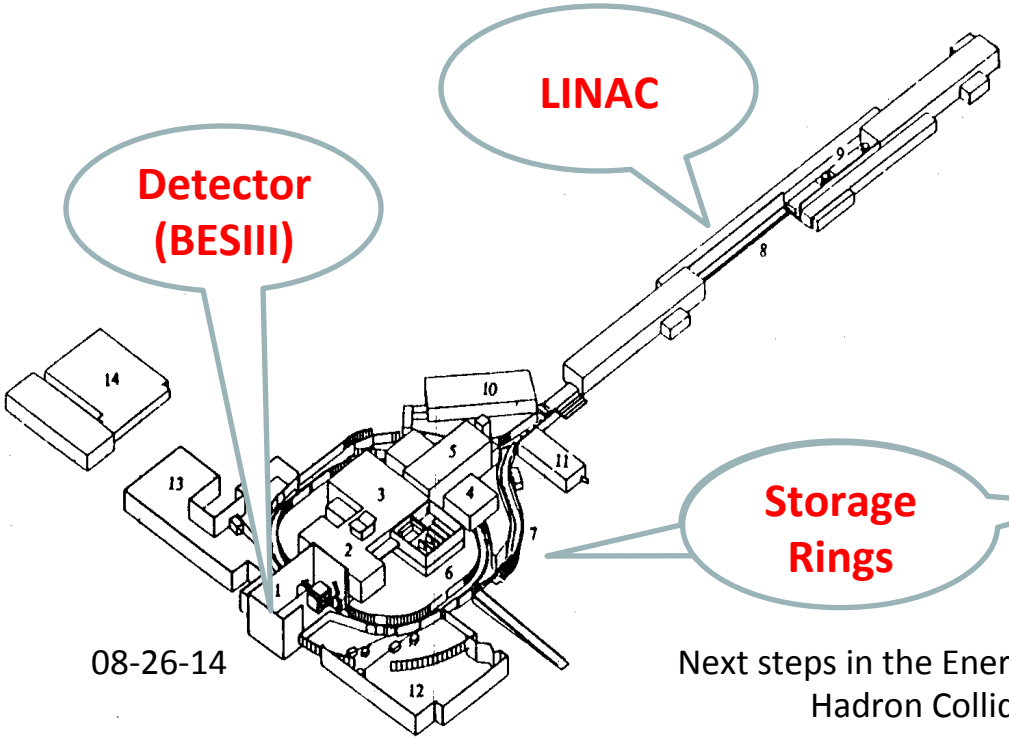
BEPC & BEPCII

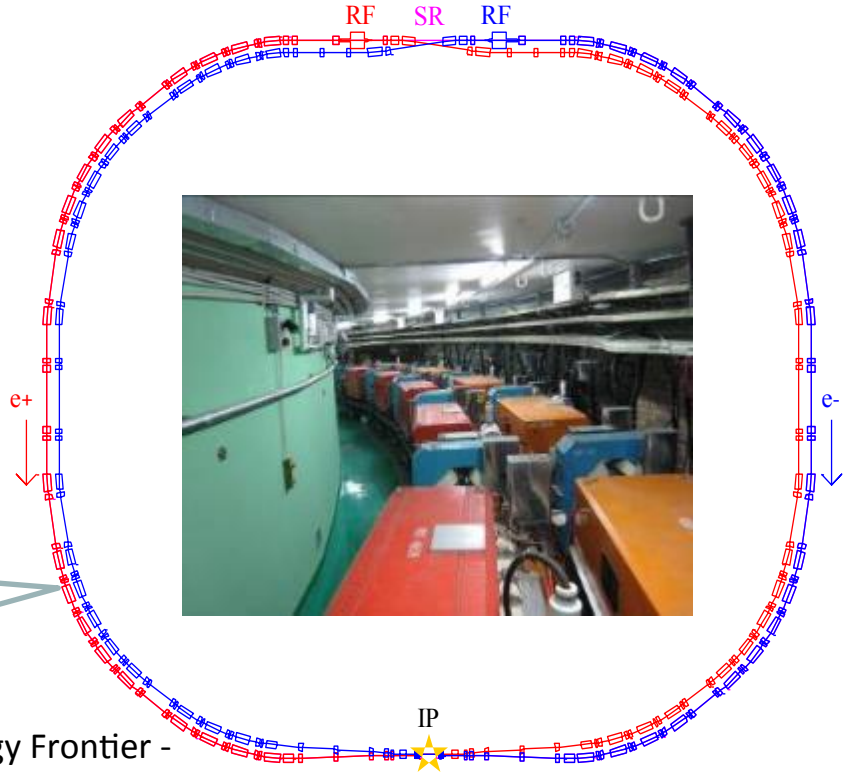


Beijing Electron Positron Collider (BEPC)
— 1st HEP accelerator in China

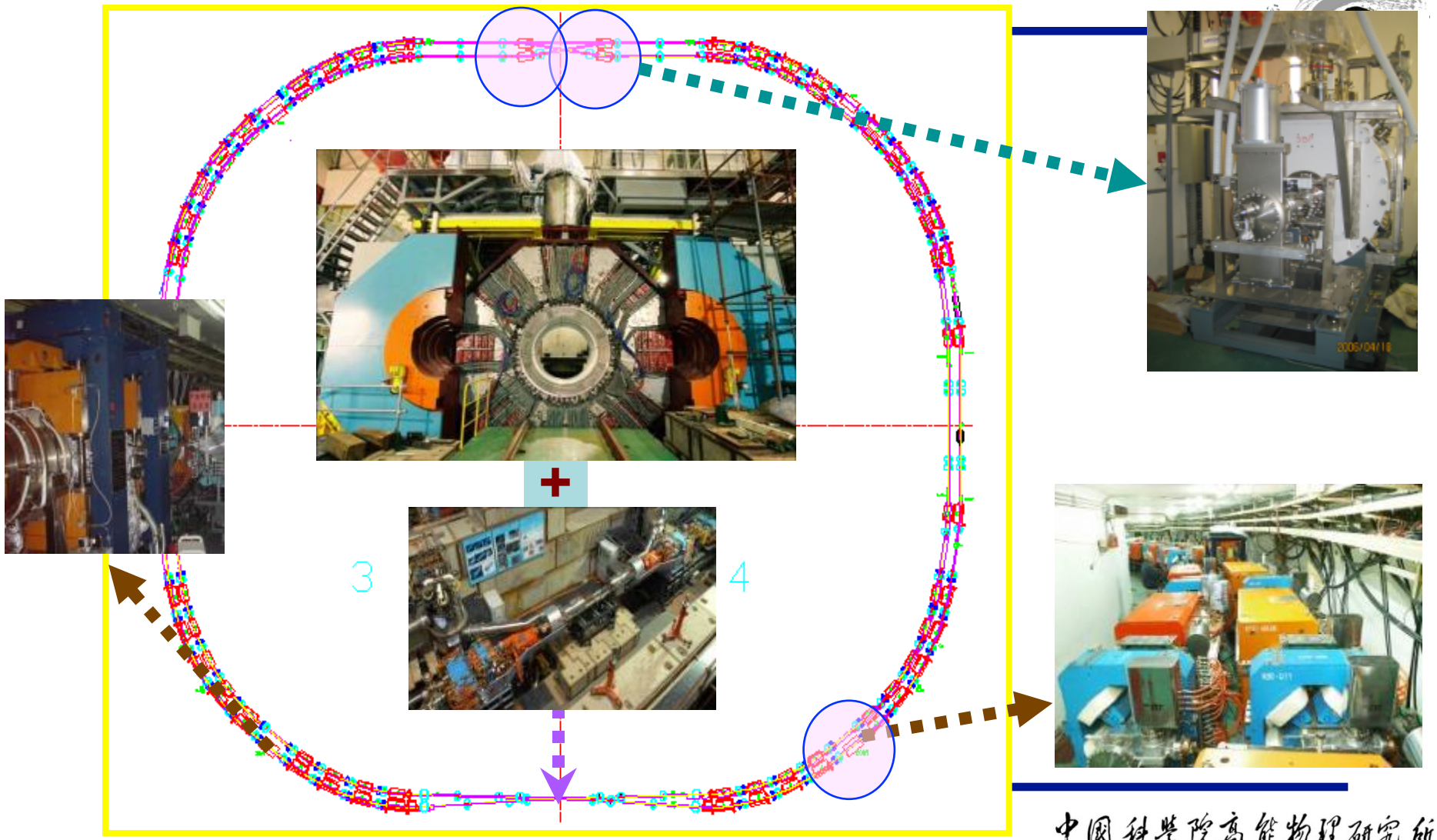
From BEPC to BEPCII

- **BEPCII (Upgrade project of BEPC)**
  - **— a double-ring factory-like machine**
  - **— deliver beams to both HEP & SR**





Accelerator —3-ring structure



中国科学院高能物理研究所
Institute of High Energy Physics

Design Goals of BEPCII

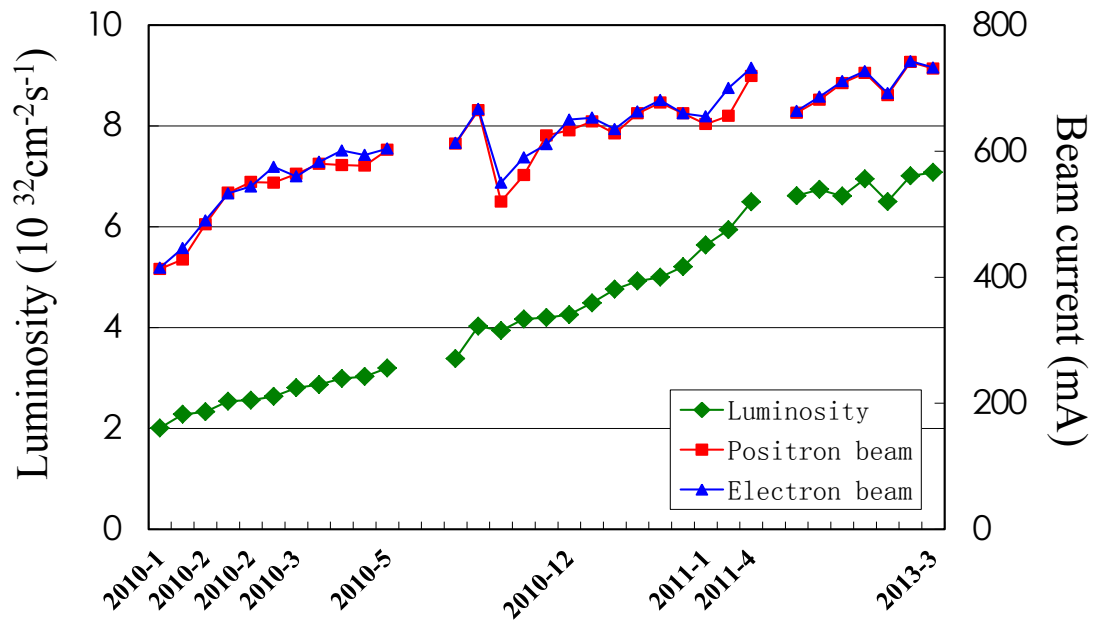
- **Collision Mode**
  - **Beam energy range** — **1-2.1 GeV**
  - **Optimized beam energy** — **1.89 GeV**
  - **Luminosity** — **1×10^{33} $cm^{-2}s^{-1}$ @1.89 GeV**
  - **Full energy injection** — **1-1.89 GeV (2.3/2.5 GeV, e^+/e^-)**
- **SR Mode**
  - **Beam energy** — **2.5 GeV (full energy injection)**
  - **Beam current** — **250 mA**
  - **Keep the present beam lines useable**

Features: One machine, two purposes (HEP, SR), small circumference, big operation energy range

Peak luminosity at different beam energy

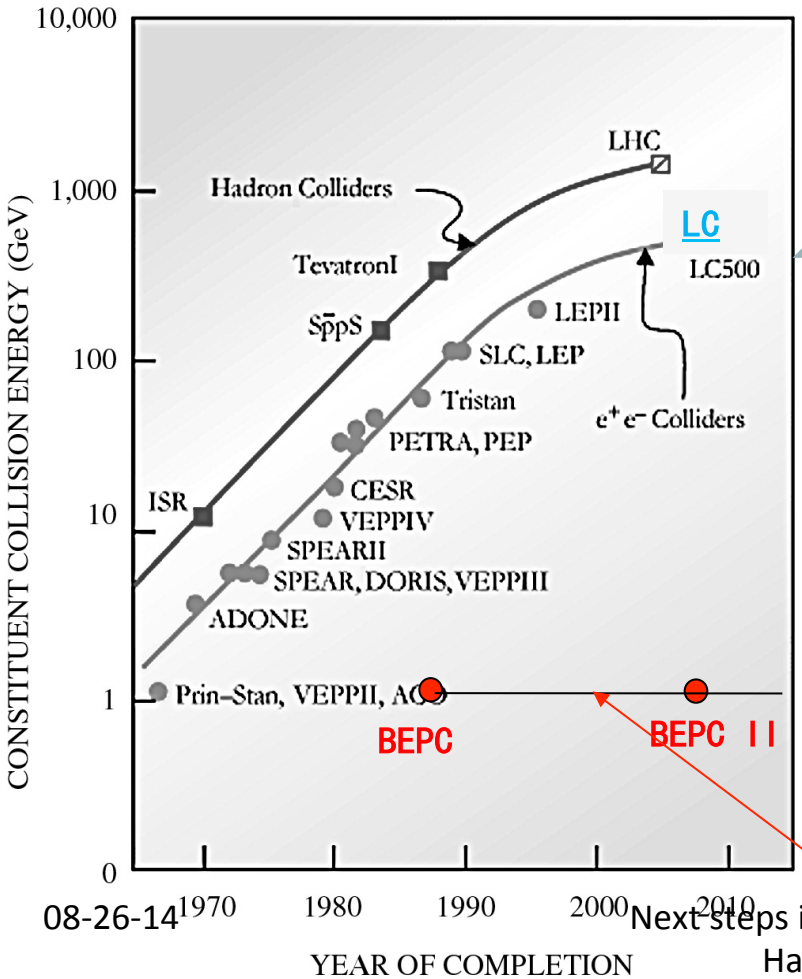
Beam energy	Peak luminosity	Max. beam-beam parameter
1.89 GeV	7.08 E32 /cm^2/s	0.035, 0.042@70mA
1.55 GeV	2.92 E32 /cm^2/s	0.028
1.84 GeV	5.07 E32 /cm^2/s	0.031
2.01 GeV	6.50 E32 /cm^2/s	0.032
2.13 GeV	6.28 E32 /cm^2/s	0.038, 0.04@450mA
2.18 GeV	5.37 E32/cm^2/s	0.037
2.3 GeV	3.0 E32/cm^2/s	0.023

Luminosity evolution at the design energy



2. Plan on CEPC + SppC

- **BEPC to BEPCII, and then to where in the future?**



CEPC+SppC

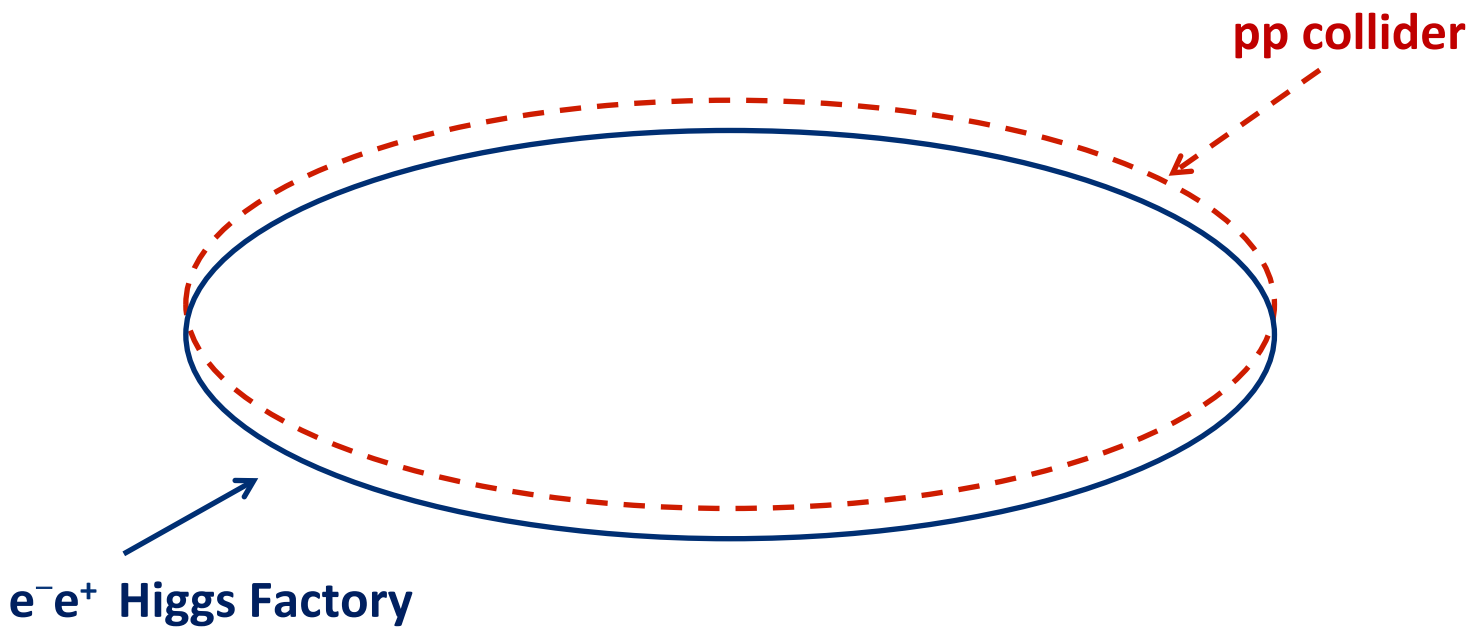
CEPC: Ecm=240GeV e+e- Circular Collider

SppC: Ecm=50-100TeV pp Collider

HIEPAF: High Intensity Electron Positron Accelerator Facility

Evolution of BEPC

- CEPC – Circular e^-/e^+ Collider as a Higgs Factory
- SppC – Super pp Collider in the same tunnel



- CEPC contains a linac, a booster, and a ring.

Main parameters of CEPC

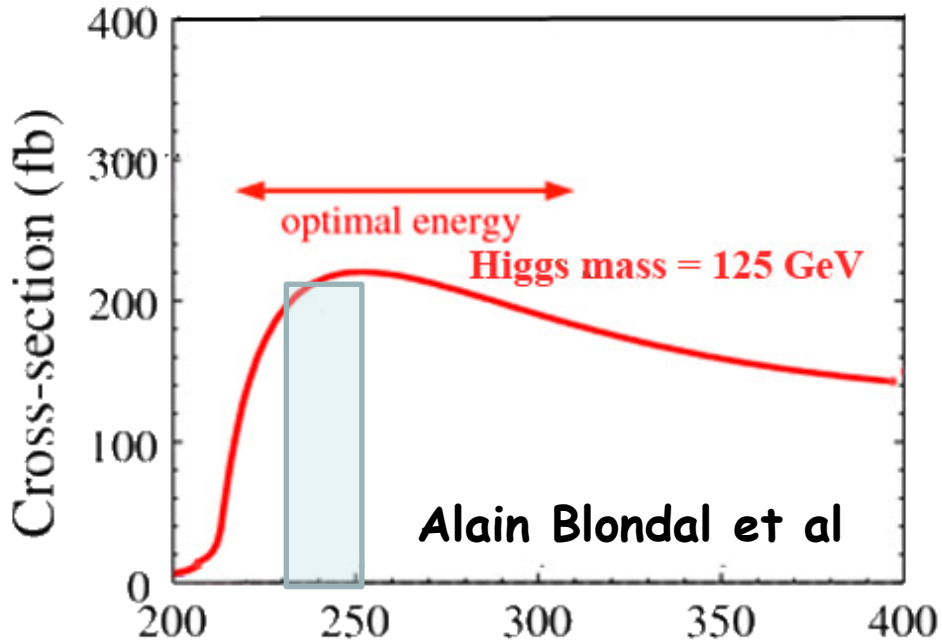
- e beam energy

✓ E_b = 120 – 125 GeV

✓ Beamstrahlung limits luminosity near 125 GeV

✓ E_b = 120 GeV is choosen.

Cross-section = 200 fb



- The circumference is determined by that of the SppC.

✓ dipole field *B* = 20 T proton beam energy

✓ 2 schemes are considered: *C* = ~50km & ~70km

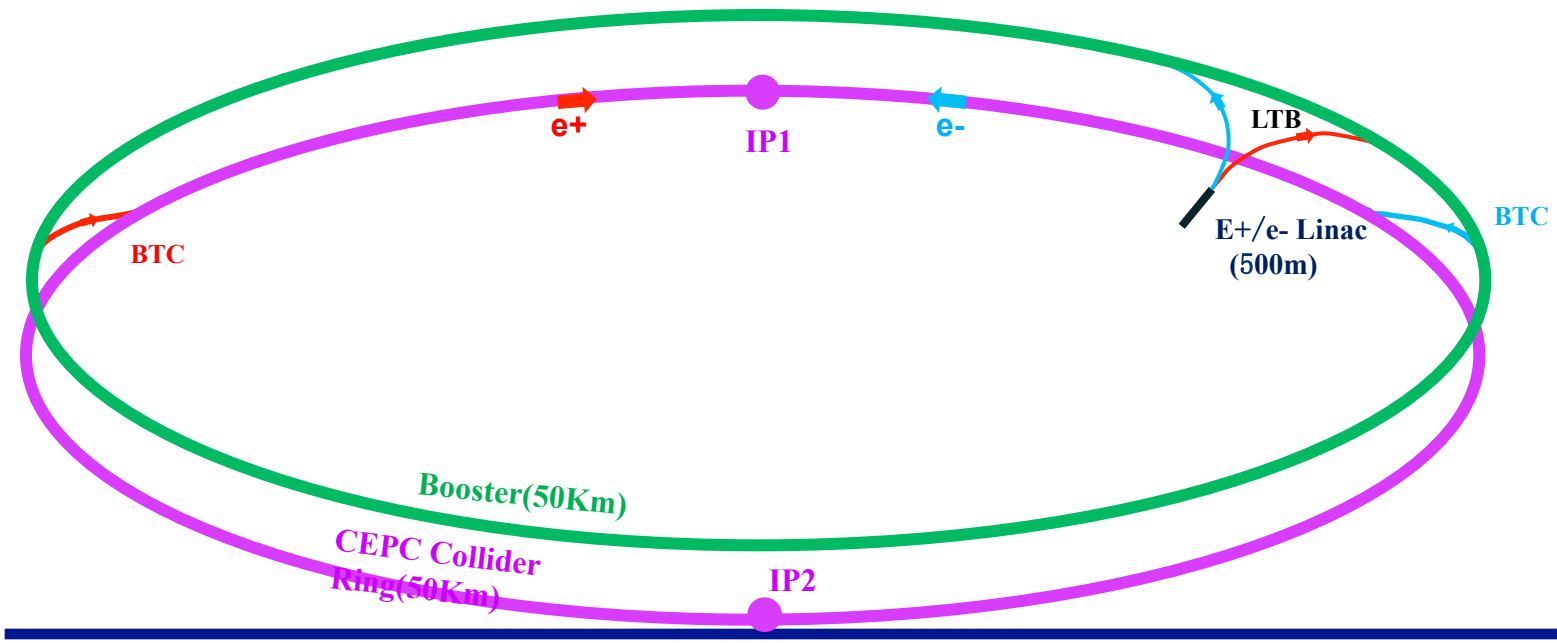
C = 50km (minimum size)

Accelerator Baseline

LINAC to generate and accelerate electrons to 6 GeV

Booster to accelerate electrons to 120 GeV

Main Ring to accumulate electrons to 16.9 mA, FODO lattice, single ring with the Pretzel scheme …



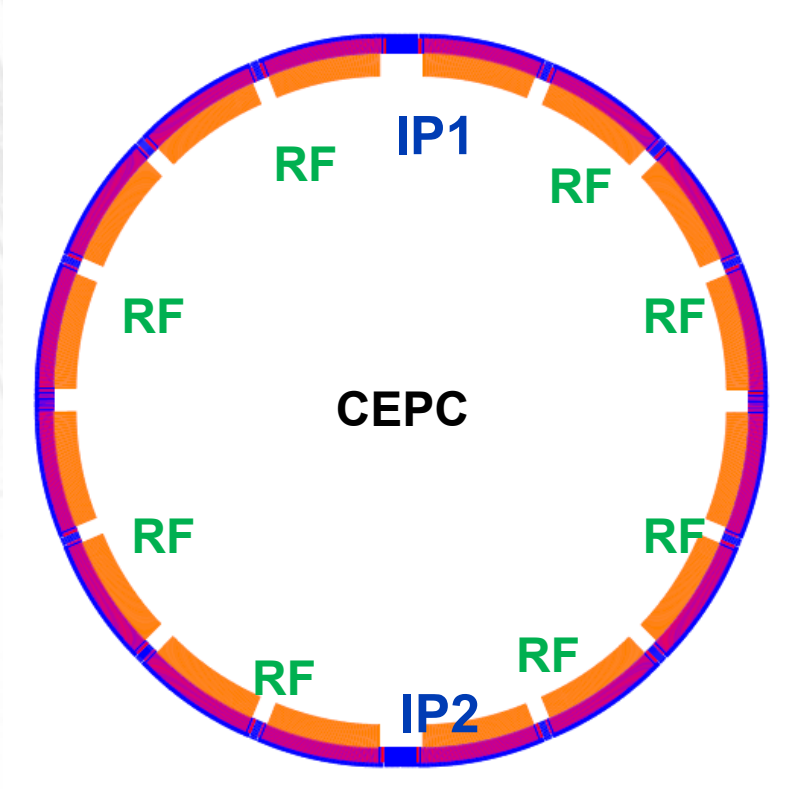
Main parameters of CEPC ring

Parameter	Unit	Value	Parameter	Unit	Value
Energy	GeV	120	Circumference	km	53.6
Number of IP		2	SR loss	(GeV/turn)	3.01
N_e/bunch	1E11	3.71	N_b/beam		50
Beam current	mA	16.6	SR power/beam	MW	50
Partition Je		2	Long. damp. time	ms	6.7
Dipole field	Tesla	0.0658	Bending radius	km	6.094
Emittance (x/y)	nm	6.8/0.0204	β_{IP} (x/y)	mm	800/1.2
Trans. size (x/y)	µm	73.70/0.16	Mom. compaction	1E-4	0.415
$\xi_{x,y}$ /IP		0.104/0.074	Bunch length	mm	2.26
RF voltage V_{rf}	GV	6.87	RF frequency f_{rf}	GHz	0.7
Long. Tune ν_s		0.206	Harmonic number		125208
Hourglass factor		0.687	Energy acceptance	%	2
Lifetime (simu.)	hr	1.5	L /IP (10^{34})	$cm^{-2}s^{-1}$	1.82

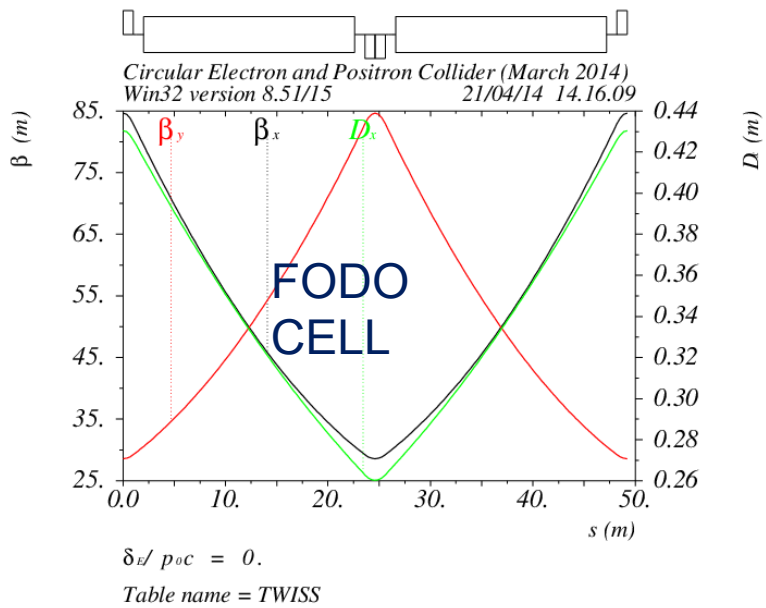
A pre-CDR will be done before the end of 2014.

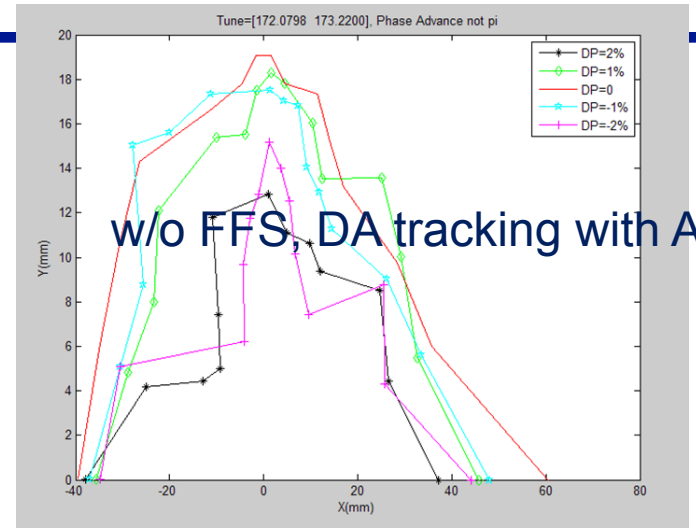
Critical Parameters

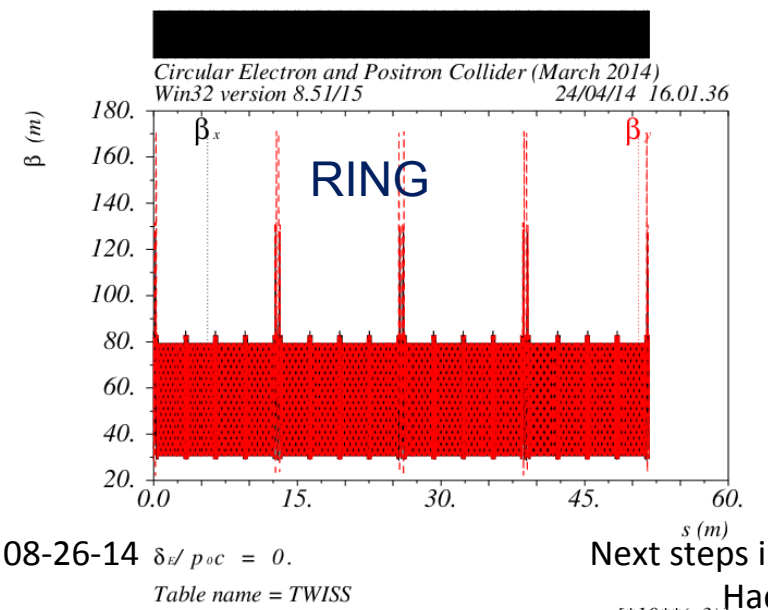
- Circumference: 53.6 km
- SR power: 50 MW/beam
- 16 arcs
- 2 IPs
- 8 RF cavity sections (distributed)
- 6 straight sections (for injection and beam dump)
- Filling factor of the ring: ~80%

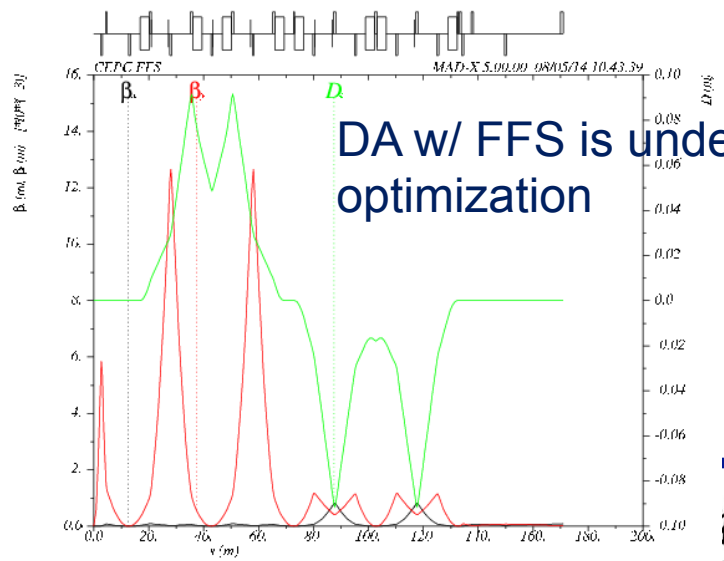


Lattice design for CEPC ring





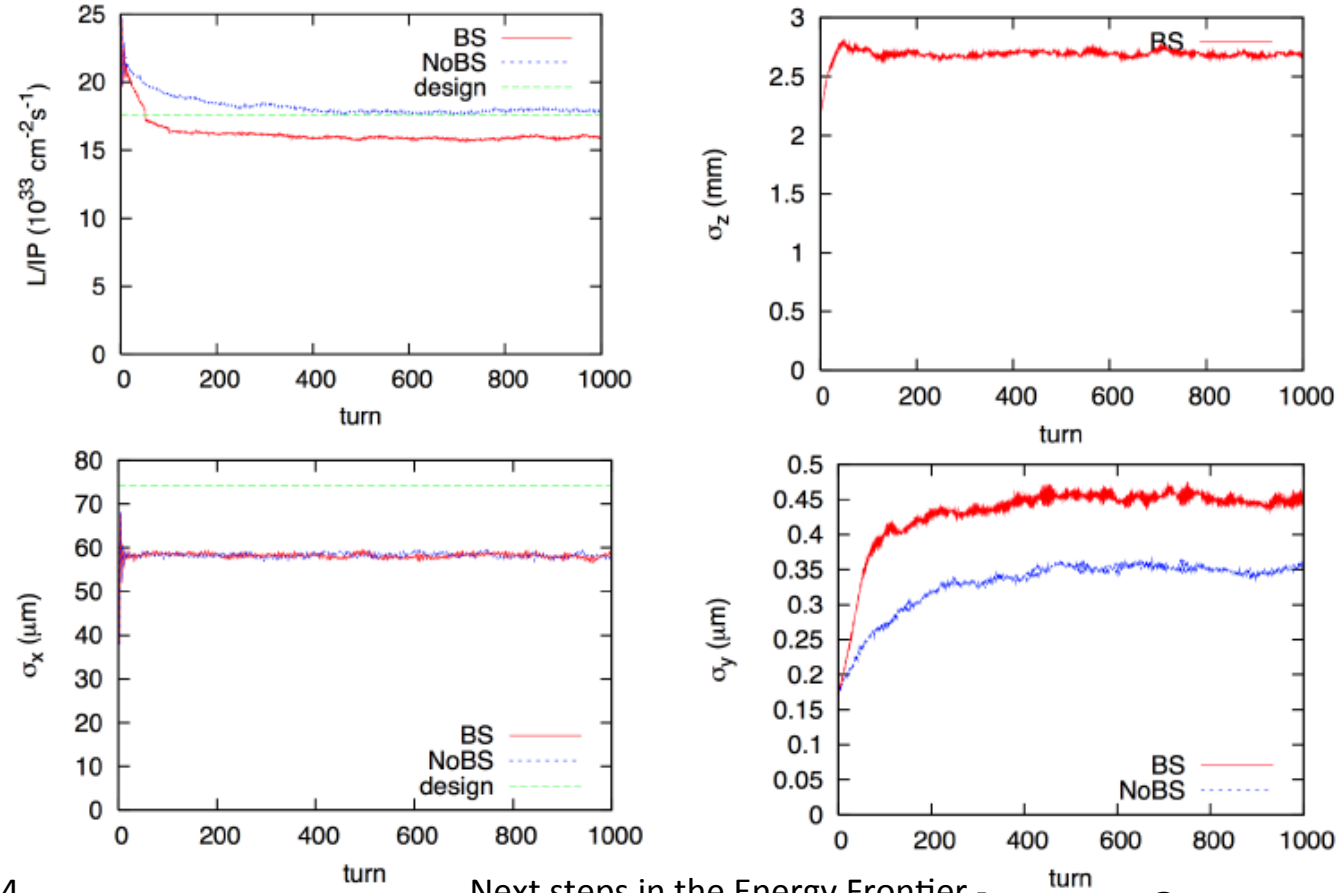




Beam-beam study for CEPC

Weak strong simulation

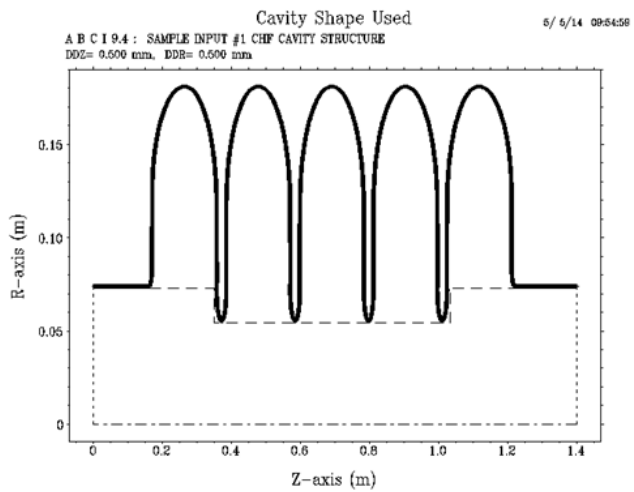
- Self consistent bunch length for beamstrahlung

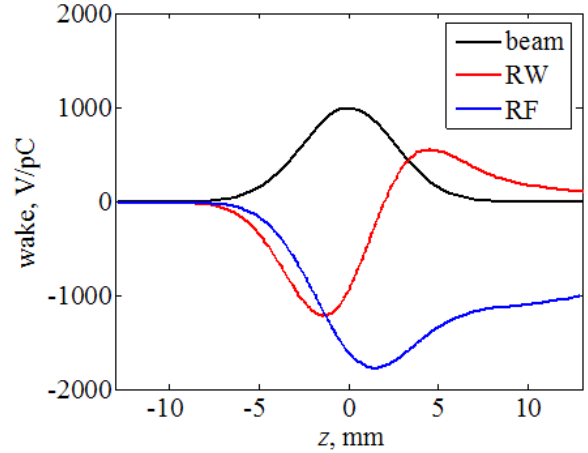


Courtesy of K. Ohmi .

Instability study for CEPC

- RF cavities (Number = 378)





- Impedance and wake

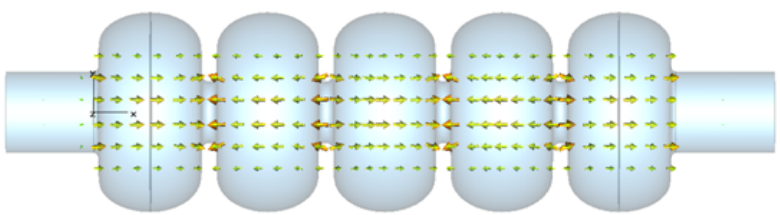
Object	Contributions			
	R [kΩ]	L [nH]	k_{loss} [V/pC]	$\lvert Z_{//}/n \rvert_{eff}$ [Ω]
Resistive wall (Al)	16.8	214.4	552.1	0.0075
RF cavities	40.1	---	1313.6	---
Total	56.9	214.4	1865.7	0.0075

$$W(s) = -Rc\lambda(s) - Lc^2\lambda'(s)$$

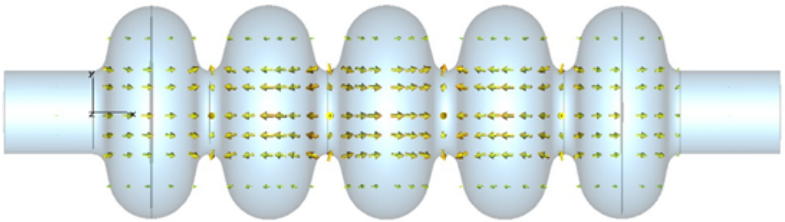
RF cavity design study

Cavity type

- High loss cavity or low loss cavity?



Low loss cavity



High loss cavity

	Low loss	High loss
f(MHz)	704	704
R_{iris}(mm)	55	55
$R/Q(\Omega)$	625.783	579.438
$G(\Omega)$	276.768	251.371
k_l(V/pC)	2.965	1.873

$$\frac{P_{c-low}}{P_{c-high}} = \frac{(R/Q)_{high}}{(R/Q)_{low}} = 92.6\%$$

$$\frac{P_{HOM-low}}{P_{HOM-high}} = \frac{k_{l-low}}{k_{l-high}} = 158.3\%$$

For beam current 5.05mA:

$$P_{HOM-low} / cavity = 2.694kW$$

$$P_{HOM-high} / cavity = 1.702kW$$

High loss cavity better!

From CEPC to SppC

- Use the same CEPC tunnel to build SppC, exploring new physics beyond SM
- Maximize the beam energy to 70-100 TeV range by using 20 T SC magnets
- Keep the e-/e+ rings when add the SppC
- Possible collisions: pp, e-/e+, ep, pA, eA, AA
- Build a new injector chain for SppC (proton and ions)
- Independent physics programs for the accelerators of the injector chain

Accelerator Baseline Design

- **Proton-proton collider luminosity**

$$L_0 = \frac{N_p^2 N_b f_{rep} \gamma}{4\pi\varepsilon_n \beta_{IP}} F \qquad \left(F = \sqrt{1+\left(\frac{\theta_c \sigma_z}{2\sigma_{x,IP}}\right)^2}\right) \qquad \xi = \frac{N_p r_p}{4\pi\varepsilon_n} \le 0.004$$

- **Main constraint: high-field superconducting dipole magnets**
  - **50 km: B_{max} = 12 T, E = 50 TeV**
  - **50 km: B_{max} = 20 T, E = 70 TeV**
  - **70 km: B_{max} = 20 T, E = 90 TeV**

$$B_{\min} = \frac{2\pi(B\rho)}{C_0}$$

Basic Machine Parameters (in progress)

SppC Machine Parameters	Option 1	Option 2
Beam energy [TeV]	25	45
Circumference [km]	50	70
SR loss/turn [keV]	440	4090
Bunch population	1.3×10^{11}	0.98×10^{11}
Bunch numbers	3000	6000
Beam current [mA]	0.5	0.405
SR power/beam (MW)	0.22	1.66
B_0 [T]	12	19.24
Bending radius [km]	6.9	7.8
Momentum compaction factor	3.5×10^{-4}	2.5×10^{-4}
β_{IP} x/y (m)	0.1/0.1	0.1/0.1
Emittance (μm·rad)	4	3
ξ_y/IP	0.004	0.004
Luminosity/IP ($cm^{-2}s^{-1}$)	2.15×10^{35}	2.85×10^{35}

Main features on accelerator physics

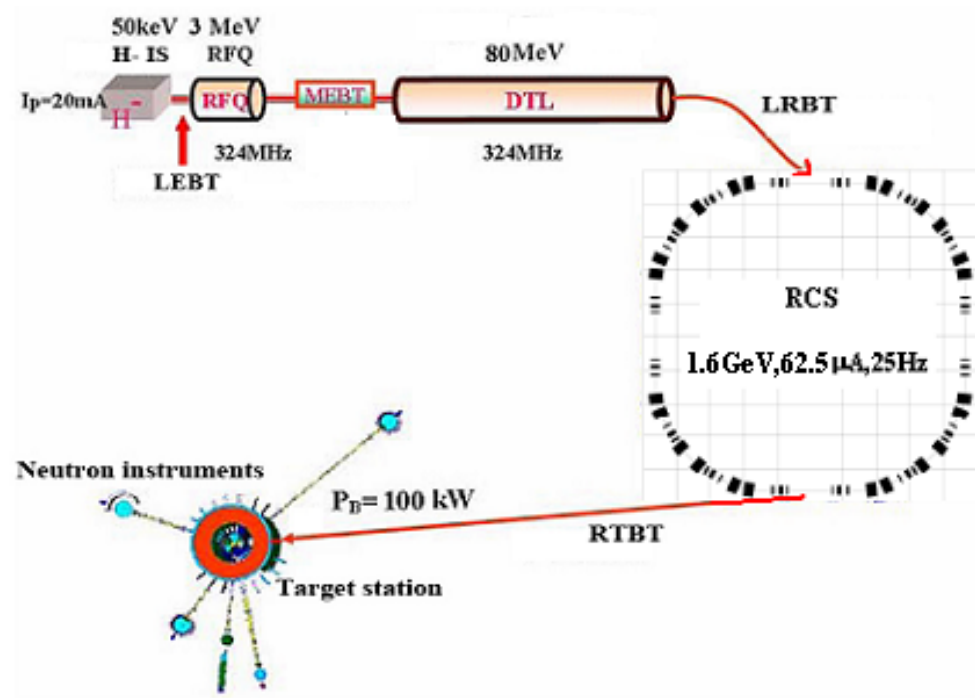
- Very high luminosity: ~3×10^{35} $cm^{-2}s^{-1}$
  - Supported by powerful injector chain and strong focusing at Ips
  - Integrated luminosity enhancement by exploring emittance damping (synchrotron radiation)
- Very high synchrotron radiation power: 56 W/m
  - High circulation current: 1 A (similar to HL-LHC)
- Machine protection by sophisticated collimation system (6.3 GJ per beam; inefficiency: 10^{-7})
- Instability issues
  - Electron cloud, resistive wall (beam screen) etc.
- Challenges in lattice design
  - Insertion lattice (IP, injection, extraction, collimation)
  - Compatible with the existing CEPC rings

3. Hadron machine in China

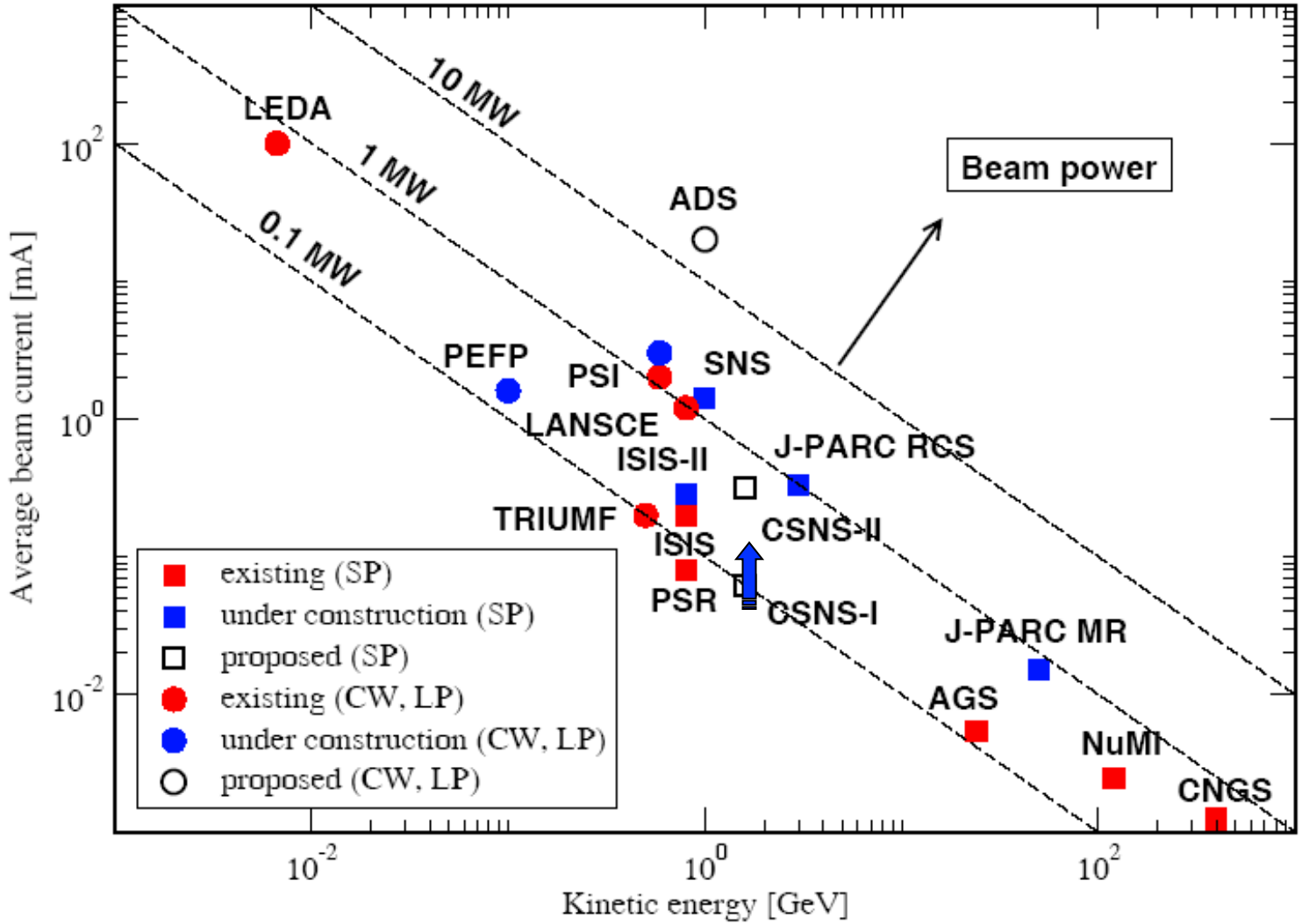
- China Spallation Neutron Source (CSNS)

Beam power (kW)	Repetition rate (Hz)	Beam current (mA)	Energy (GeV)	neutron flux ($n/cm^2/s$)
100	25	63	1.6	2×10^7

Project Phase	I	II
Beam Power on target [kW]	100	500
Proton energy [GeV]	1.6	1.6
Average beam current [μ A]	62.5	312.5
Pulse repetition rate [Hz]	25	25
Linac energy [MeV]	80	250
Linac type	DTL	+Spoke
Linac RF frequency [MHz]	324	324
Macropulse. ave current [mA]	15	40
Macropulse duty factor	1.0	1.7
RCS circumference [m]	228	228
RCS harmonic number	2	2
RCS Acceptance [mm-mrad]	540	540
Target Material	Tungsten	Tungsten



Power Map of Proton Accelerators



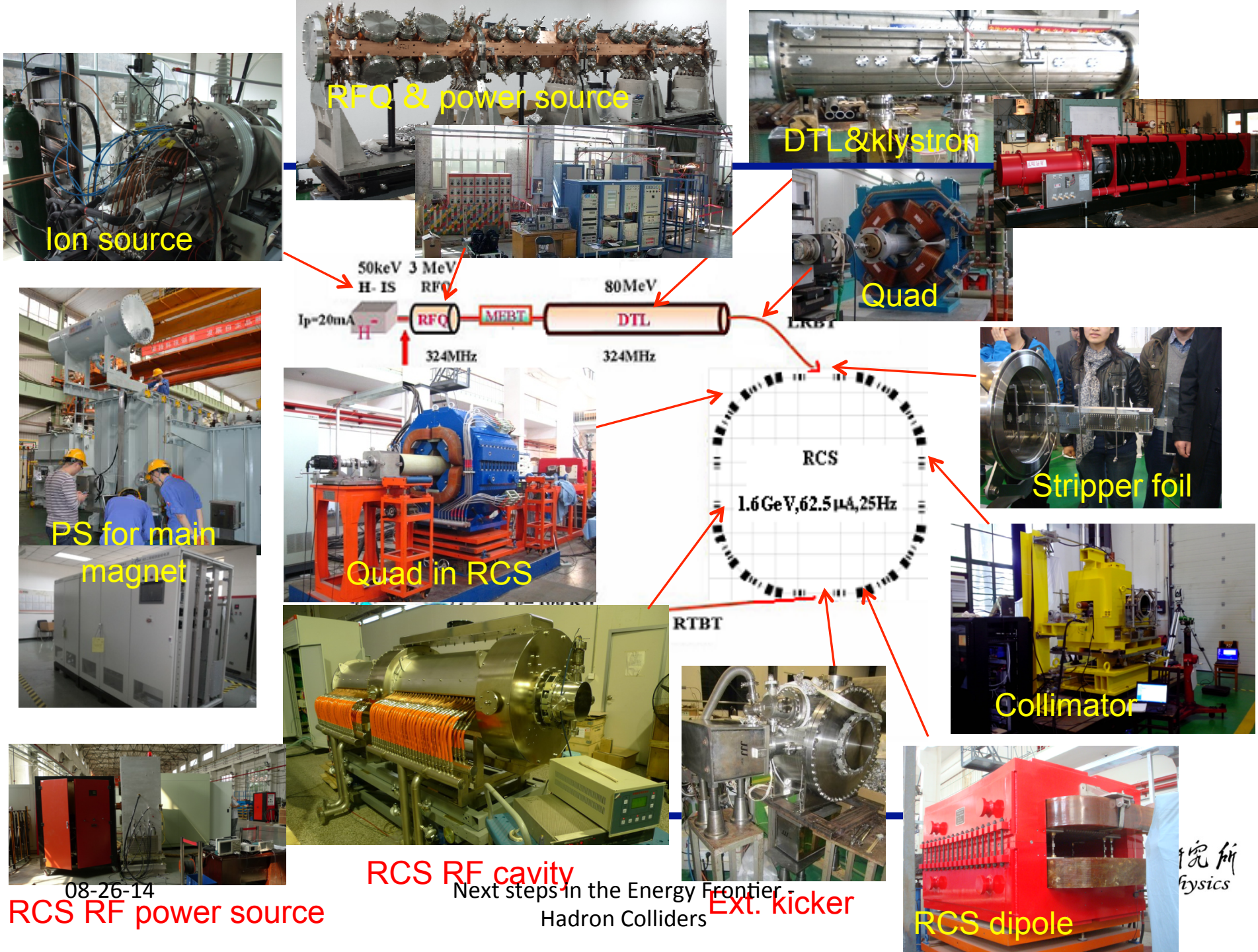
Milestones of CSNS

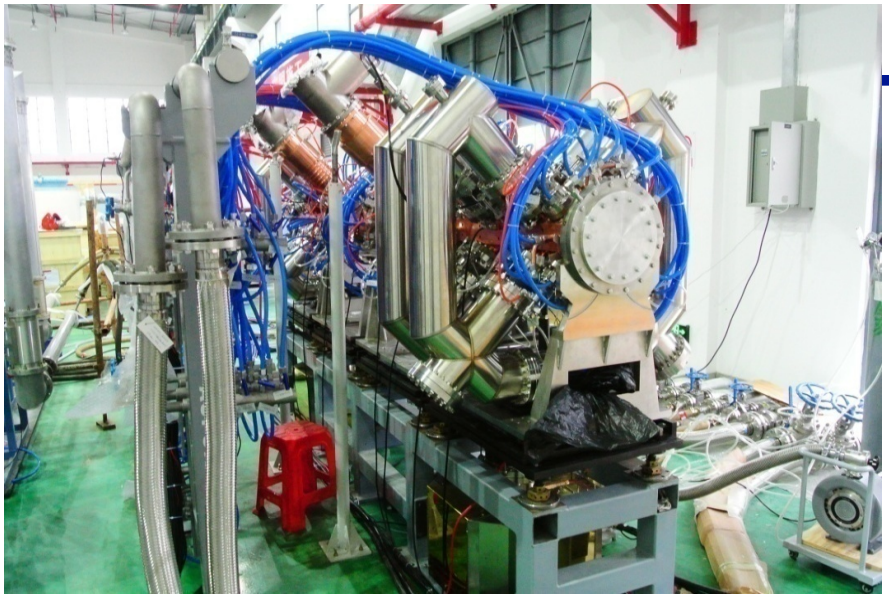
Feb. 2001	idea of CSNS discussed
June 2005	proposal approved in principle by central government
Jan. 2006	CAS funded 30M CNY for R&D I
July 2007	Guangdong funded 40M CNY for R&D II
Dec. 2007	proposal reviewed
Sept. 2008	proposal approved by government
Oct. 2009	feasibility study reviewed
Apr. 2010	site preparation start
Feb. 2011	feasibility study approved
May 2011	preliminary design approved
Sept. 2011	construction started

Site

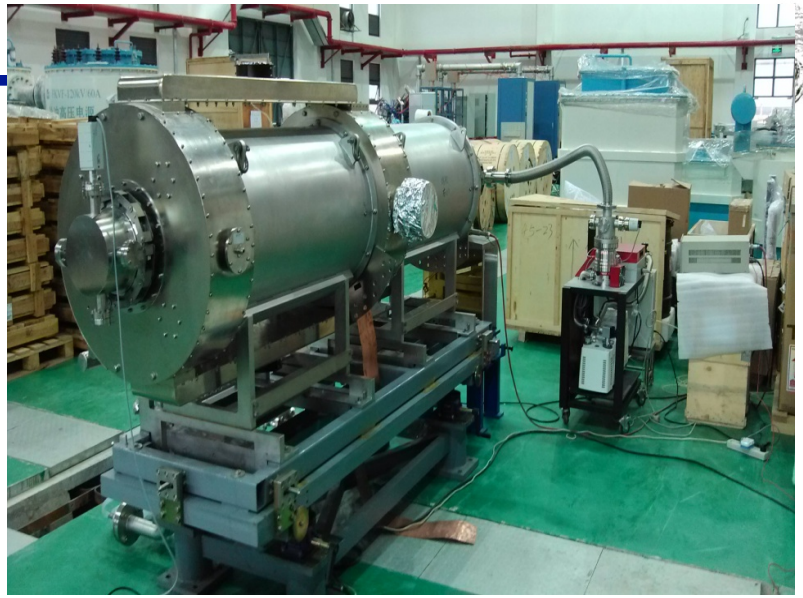
- **CSNS is the first large science facility in southern part of China. It can balance the present uneven distribution of the facility, and promote advanced researches in the economic developed zone of Guangdong-Hong Kong.**
- **The Dongguan local government provided a land of about 0.67 km^2 for CSNS facility. 0.27 km^2 is planned for the phase-I construction.**

Site Preparation & Construction


Ion source
RFQ & power source
DTL&klystron
Quad
50keV
H- IS
3 MeV
RFQ
80MeV
Ip=20mA
H-
RFQ
MEBT
DTL
LRBT
324MHz
324MHz
PS for main magnet
Quad in RCS
RCS
1.6GeV,62.5μA,25Hz
RTBT
Stripper foil
Collimator
RCS RF power source
RCS RF cavity
Ext. kicker
RCS dipole



RFQ & its conditioning



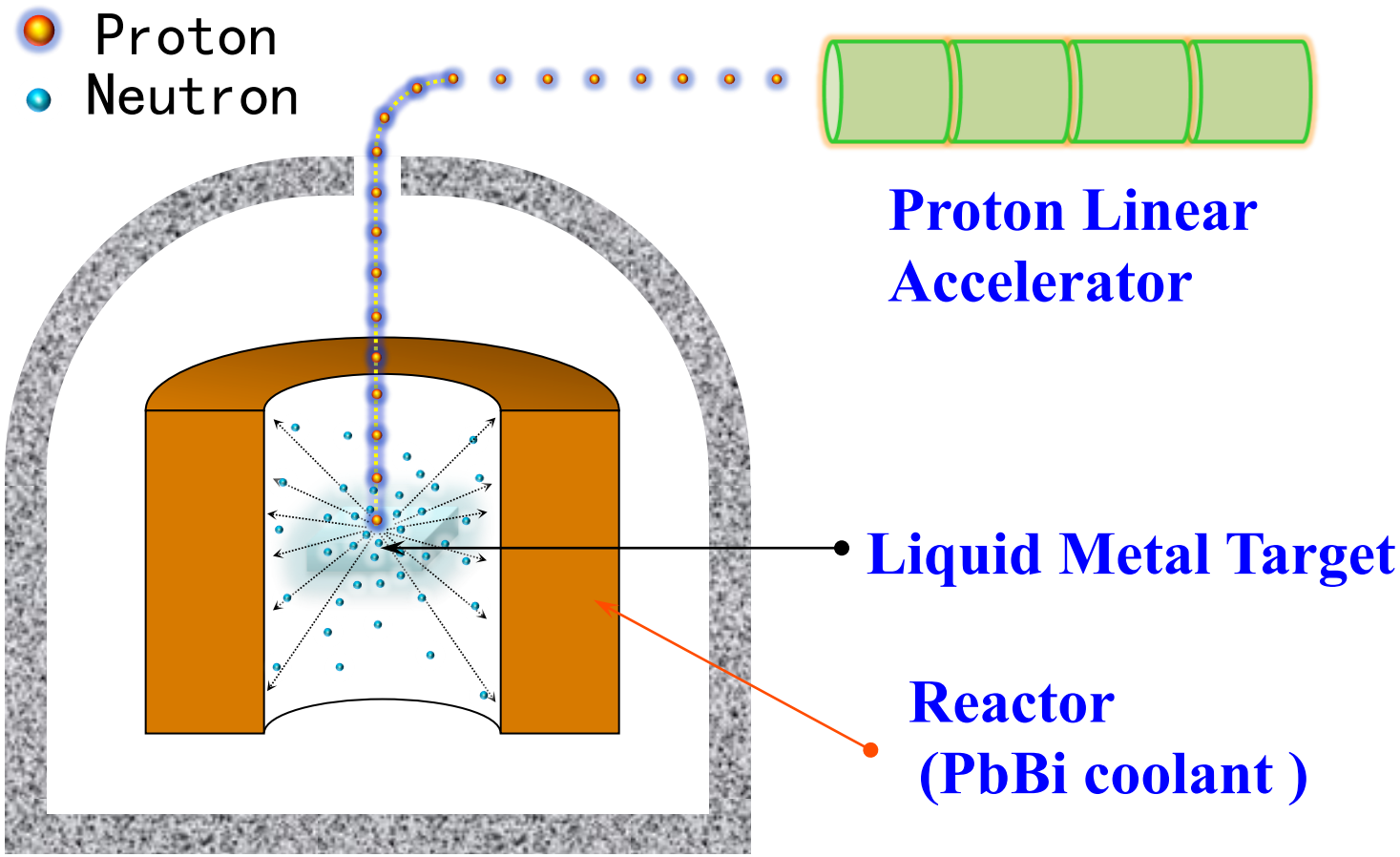
RCS RF cavity & conditioning

RCS dipole in mass production

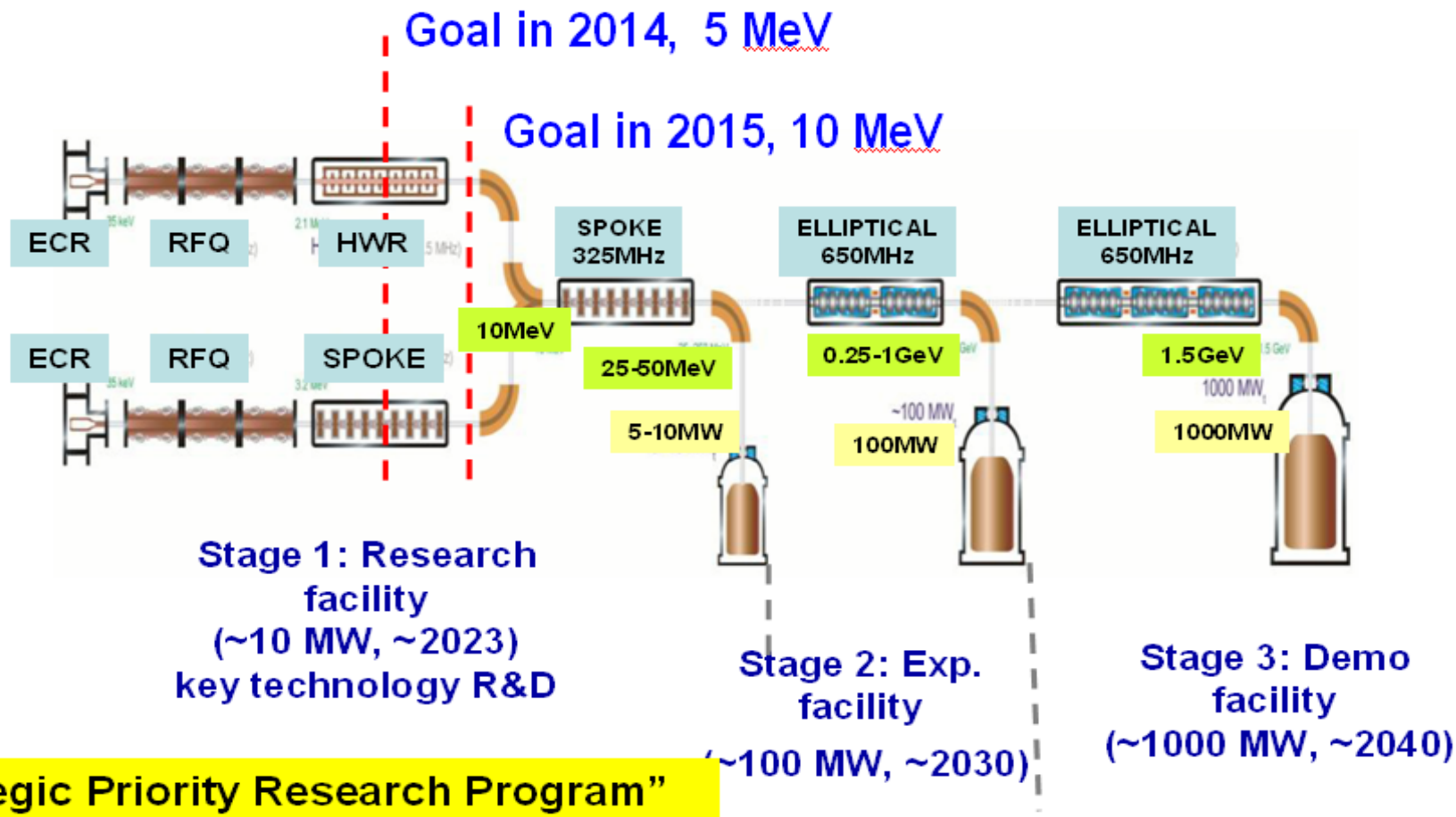
Pulsed PS for LINAC

- **Chinese Accelerator Driven Subcritical System (C-ADS)**
  - **Nuclear waste is a bottleneck for nuclear power development in China.**
  - **ADS has been recognized as a good option for nuclear waste transmutation, but never established for test in the world , many challenges faced.**
  - **As a long-term program, ADS R&D has been supported by CAS.**

Principle of ADS



Roadmap of ADS Project in China

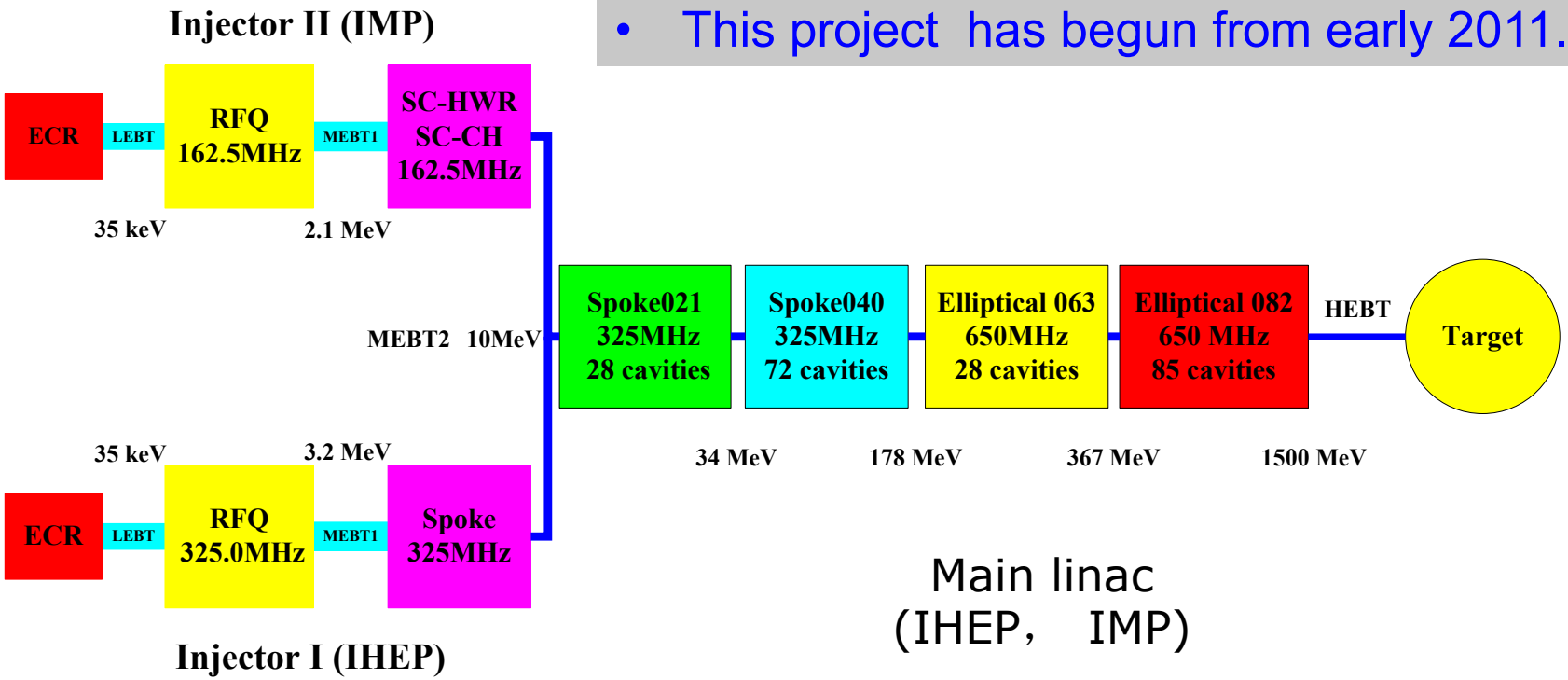


"Strategic Priority Research Program" of the Chinese Academy of Sciences

中国科学院高能物理研究所
Institute of High Energy Physics

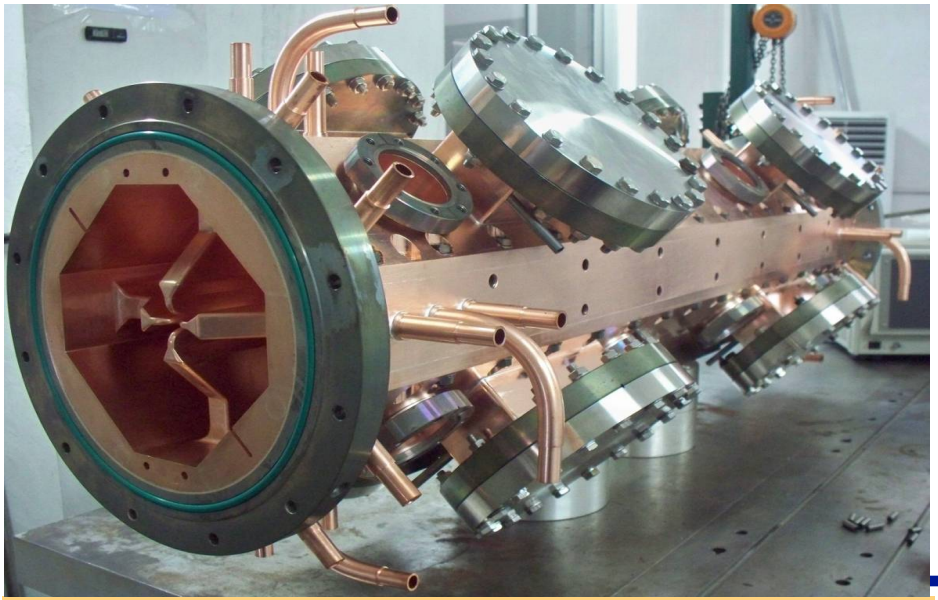
Layout of Accelerator

- The proton accelerator is being built by IHEP and IMP together.
- This project has begun from early 2011.



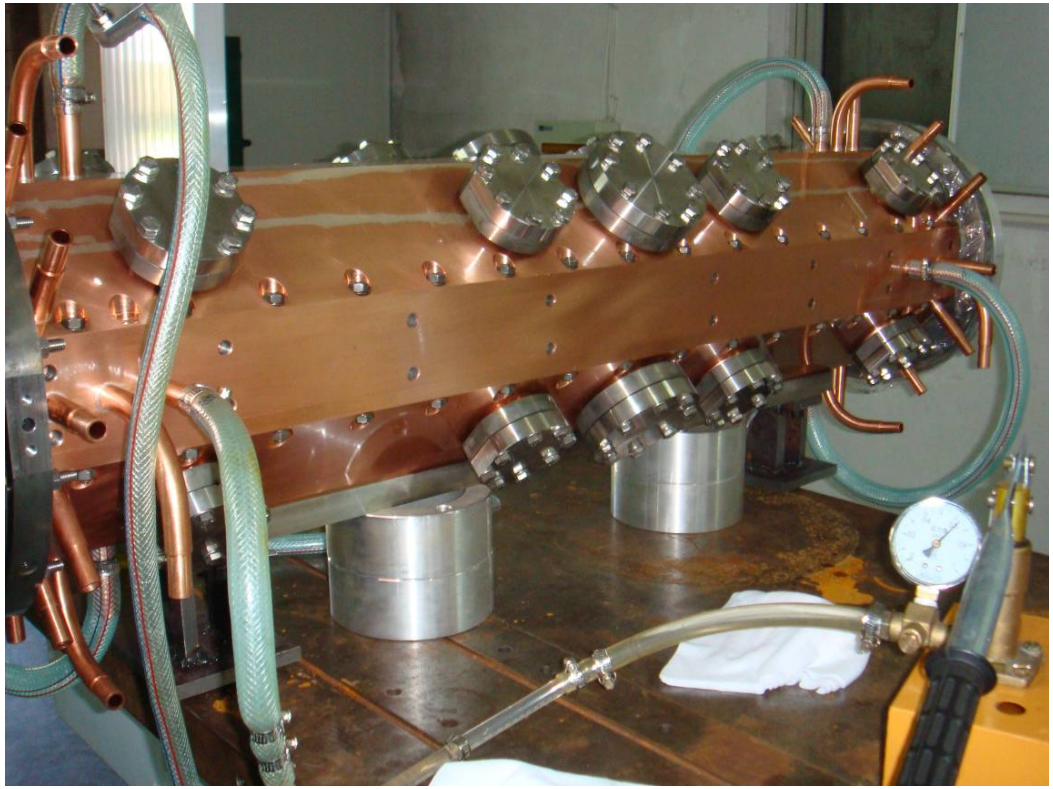
1）RFQ of Injector I

4 technical modules, 64 tuners, 4 RF power couplers, 4 dipole rods on each plate .



The beam transmission is about 98.7%

Parameters	Value
Frequency (MHz)	325
Injection energy (keV)	35
Output energy (MeV)	3.2128
Pulsed beam current (mA)	15
Beam duty factor	100%
Inter-vane voltage V (kV)	55
Beam transmission	98.7%
Average bore radius r_0 (mm)	2.775
Vane tip curvature (mm)	2.775
Maximum surface field (MV/m)	28.88 (1.62Kilp.)
Input norm. rms emittance (x,y,z)(πmm.mrad)	0.2/0.2/0
Output norm. rms emittance(x/y/z) (πmm.mrad/MeV-deg)	0.2/0.2/0.0612
Vane length (cm)	467.75
Accelerator length (cm)	469.95



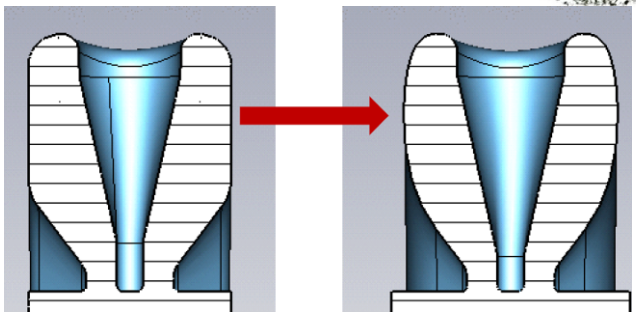
No. 12,3 4 module of RFQ on site

中国科学院高能物理研究所

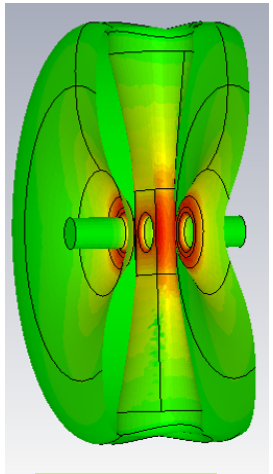
2）Spoke012 Cavity (β=0.12) of Injector I

Main Geometrical parameters	Units	Value
Diameter of cavity	mm	468
Length of cavity	mm	180
Diameter of beam tube	mm	35
RF parameters	Units	Value
E_{peak}/E_{acc}		4.54
B_{peak}/E_{acc}	mT/(MV/m)	6.37
G	Ω	61
Transition Time Factor		0.76
R/Q@β=0.12	Ω	142

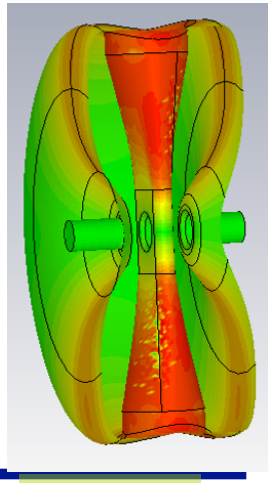
Note: Effective length for Eacc is defined as βλ



The Convex end wall (right) is adopted,which has better mechanical performance than the flat one (left).



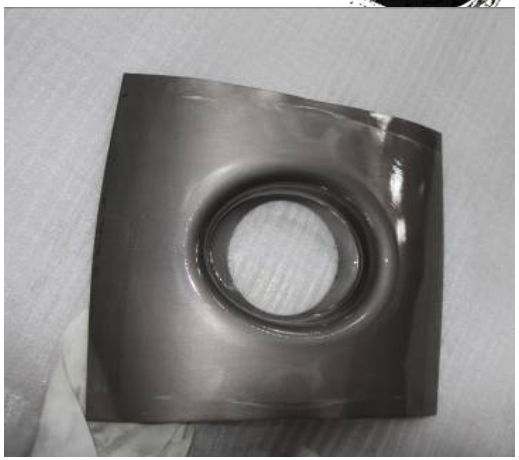
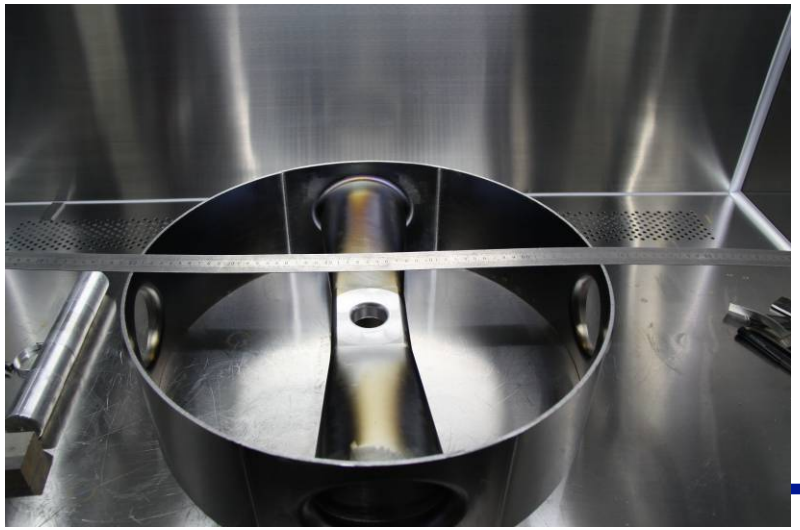
E-field

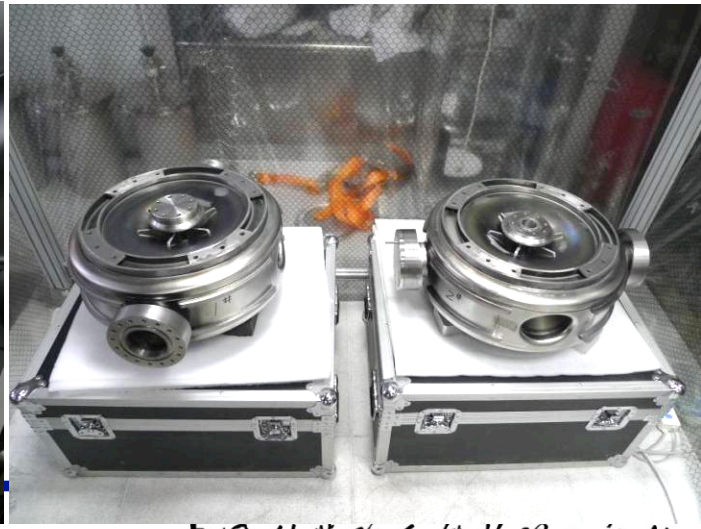


B-field

Fabrication of Spoke012 cavity finished on Nov. 8, 2012

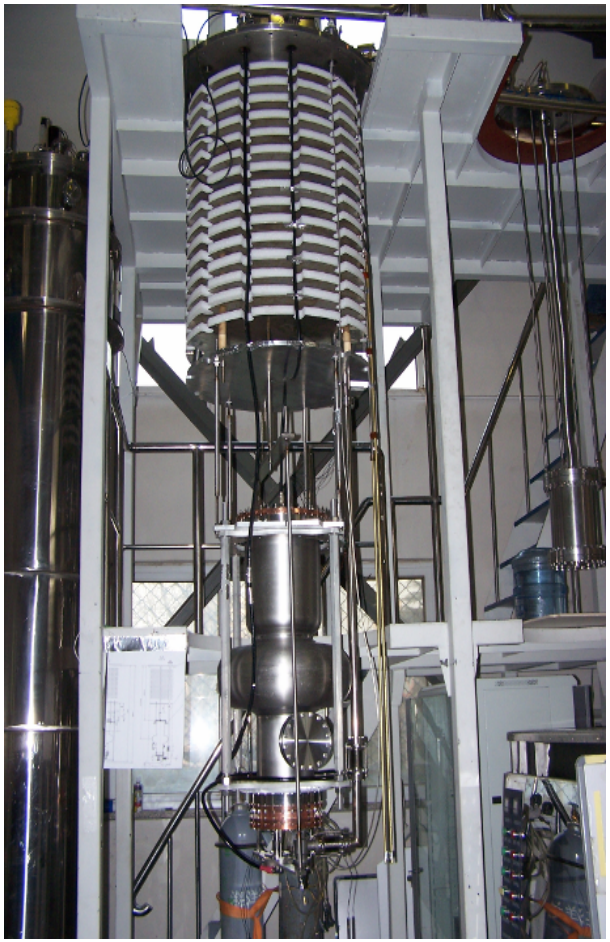


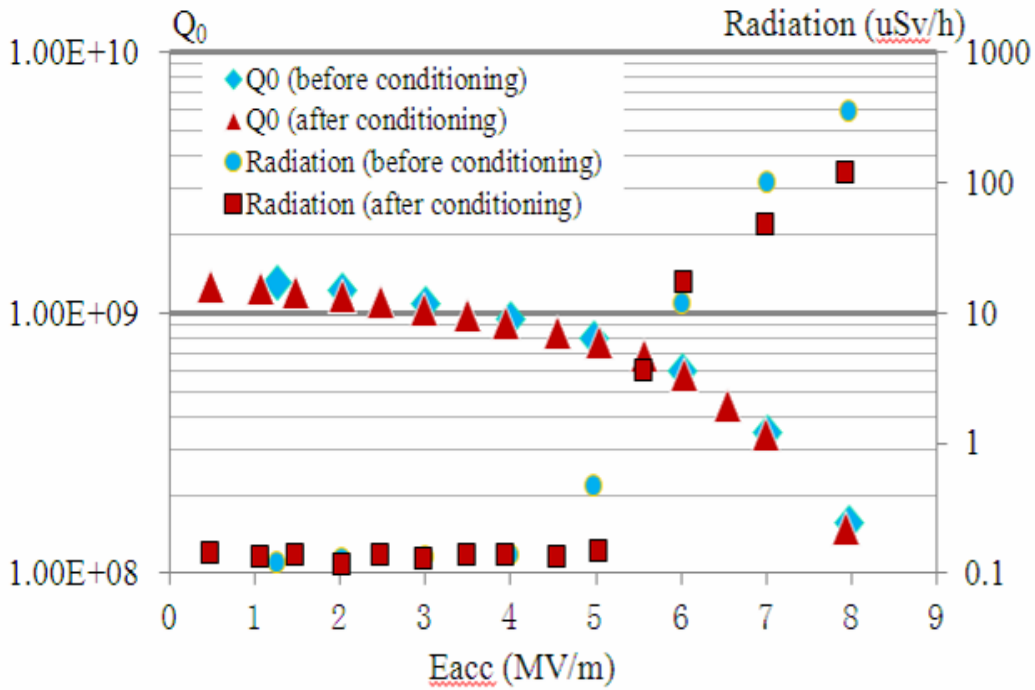





中国科学院高能物理研究所
Institute of High Energy Physics

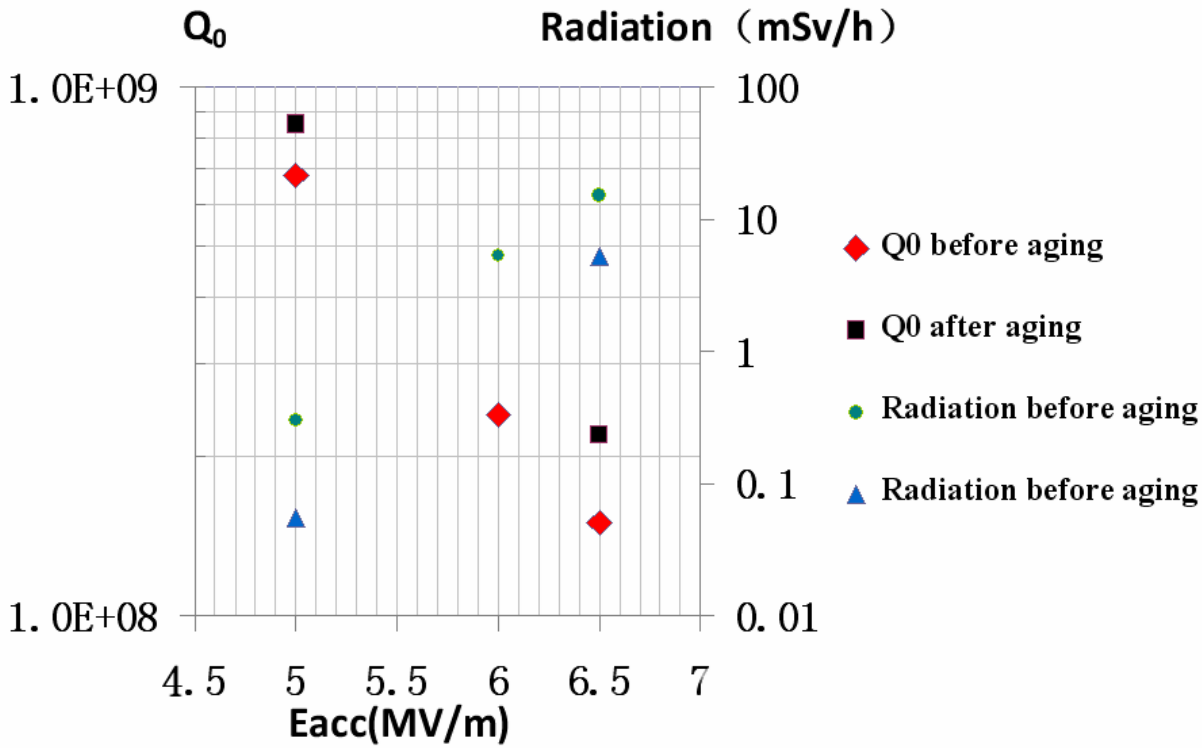
Vertical test of Spoke012 cavity





- ✓ Q_0=5.8x10^8 @6MV/m, 4K;
- ✓ Q_0=3.4x10^8 @7MV/m, 4K

Horizontal test result on Sept. 12, 2013 — the first horizontal test for the low beta proton SC cavity

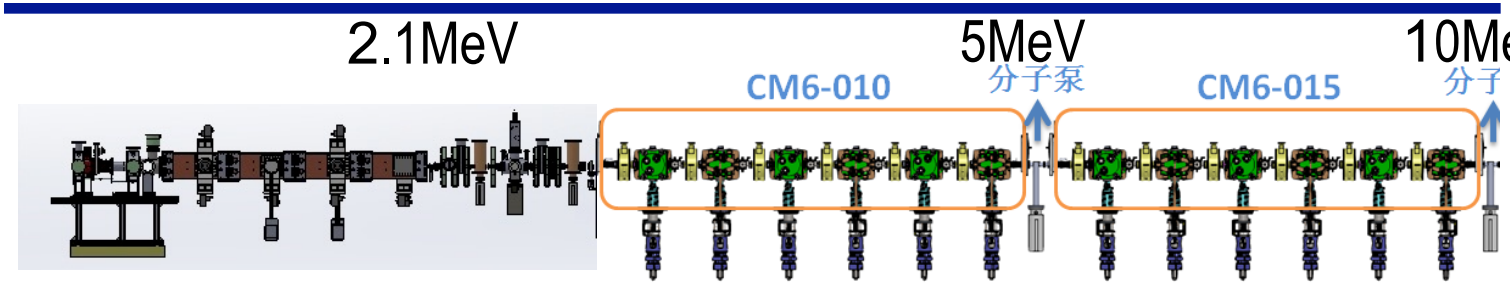


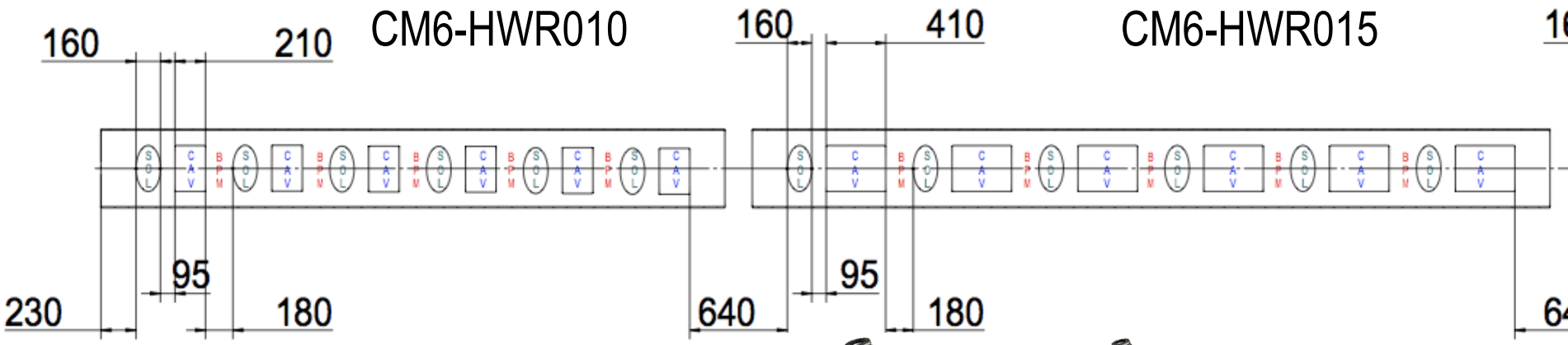
- ✓ Q_0=2.2x10^8 @6.5MV/m, 4K;
- ✓ Q_0=8.5x10^8 @5MV/m, 4K
- ✓ Fit the requirement of ADS.

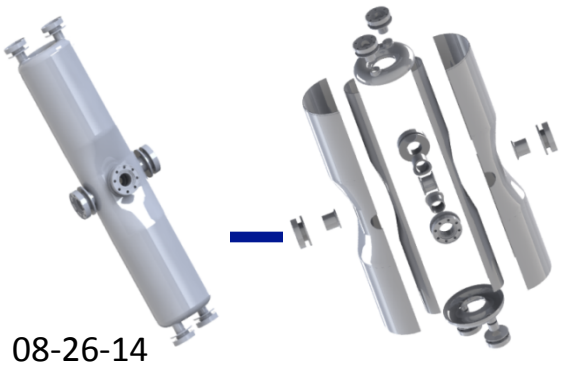
Spoke021 cavity

650MHz(preparing for test)

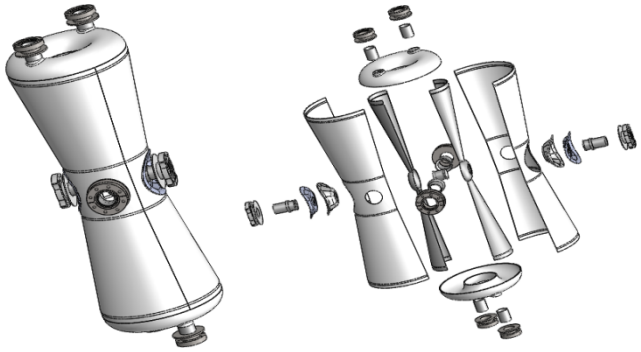
3）HWRs for Injector II





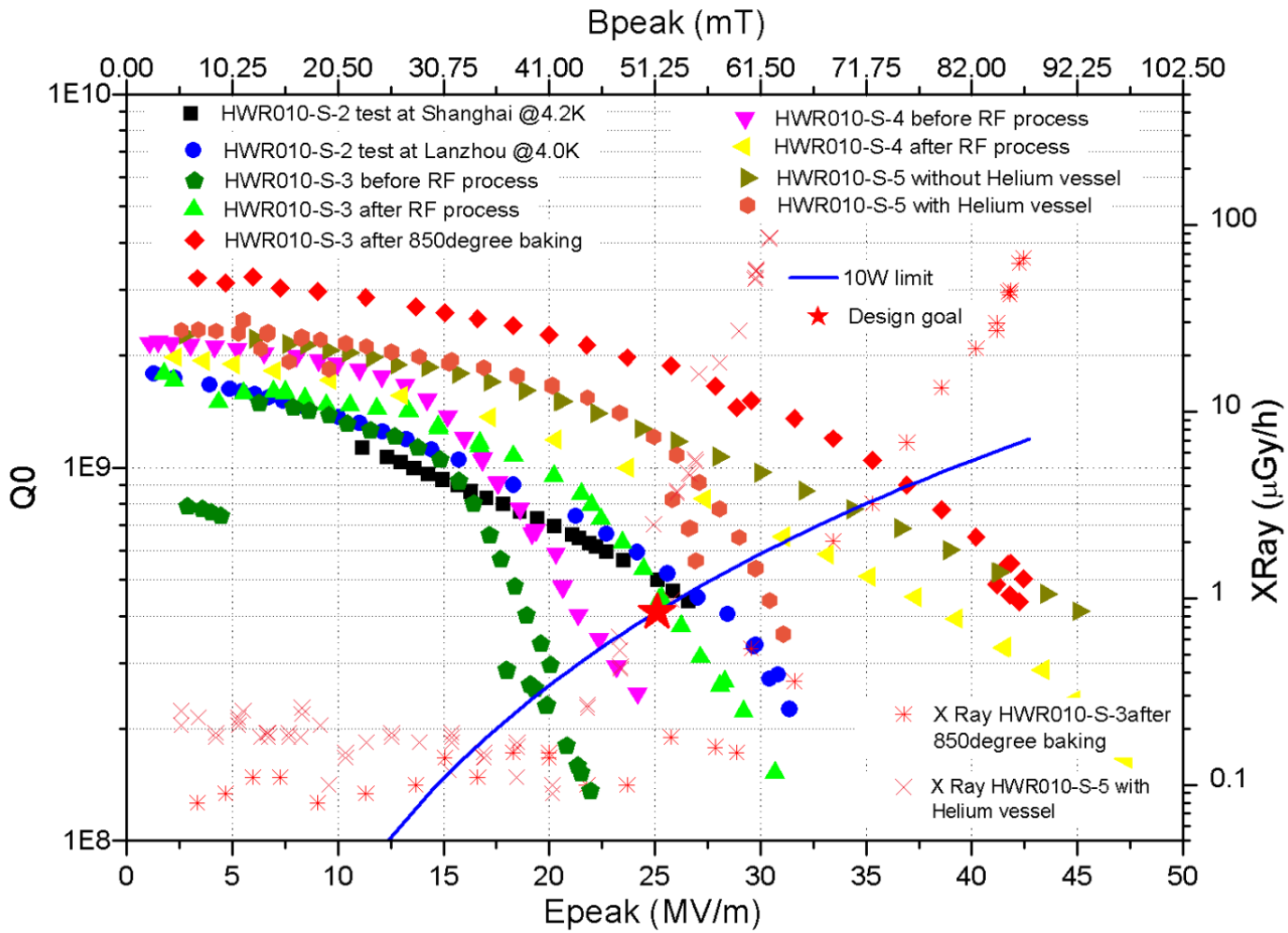


HWR010



HWR015

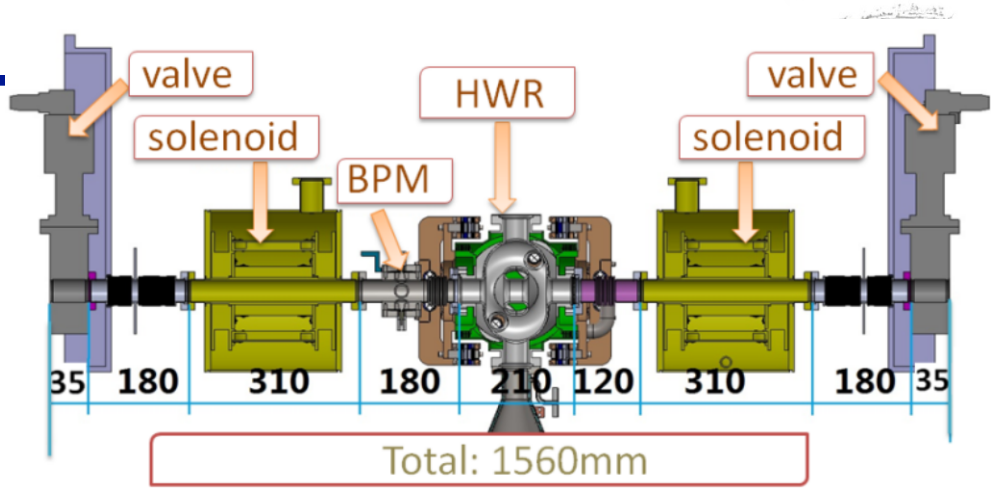
VT results of HWR

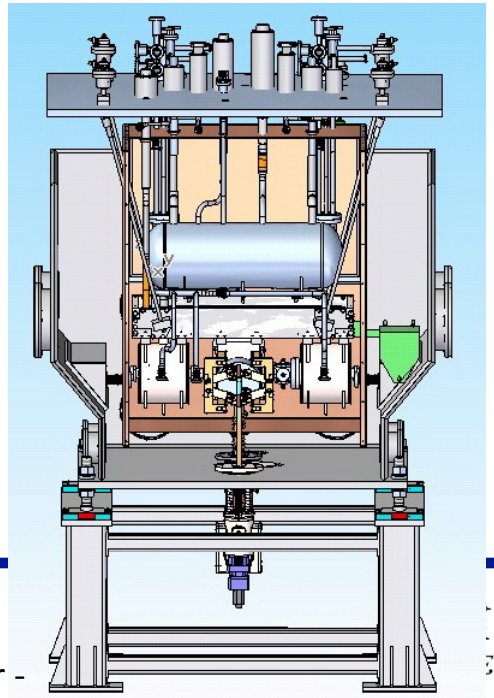


中国科学院高能物理研究所
Institute of High Energy Physics

Horizontal Test of HWR

Op. Temperature	4.4 K
Op. Pressure	1.25 bar
Cooling	bath
Pressure	±1.5 mbar
Dynamic load	10 W
Solenoid storage	27KJ





Solid State Amplifier

162.5 MHz / 40 kW

162.5 MHz / 20 kW

The solid state amplifiers of 162.5 MHz at 20 kW and 40 kW were tested. All requirements for specifications are reached.

4）High Power Input Couplers for Injector I &II

- **Three kinds of couplers have being designed, fabricated and tested for different types of ADS cavities.**

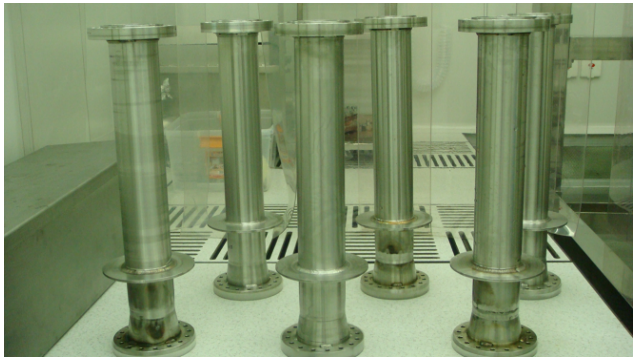
The main parameters of ADS power couplers

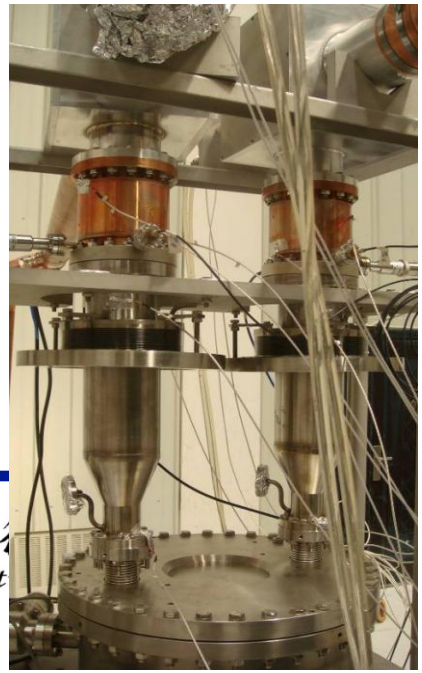
Cavity	Frequency (MHz)	Power (kW)	Qext	Connecting type
SPOKE	325	10,CW,TW	~7.0E5	Coaxial waveguide, $3\frac{1}{8}$'' ,50Ω
HWR	162.5	15,CW,TW	~7.0E5	Coaxial waveguide, YX50-105-1
RFQ	325 &162.5	80,CW,TW	~5670	WR2300

Under high power test;
Power level: 10 kW, CW,TW

Installed in the
Spoke012 Cavity

Operated with cavity;
Power level:10 kW, CW, SW





4. Key technology for SppC

- CSNS & C-ADS will be the solid basis of future SppC
- Key tech:
  - High field magnets: both dipoles (20 T) and quadrupoles (pole tip field: 14-20 T) are technically challenging
  - Beam screen and vacuum: the key issue to solve the problem with very high synchrotron radiation power inside the cold vacuum. Need to develop an effective structure and working temperature to guide out the high heat load when minimizing Second-Electron-Yield, heat leakage to cold mass, impedance in the fast ramping field, vacuum instability etc.
  - Collimation system: requiring unprecedentedly high efficiency, may need some collimators in cold sections.

R&D plan of the 20 T accelerator magnets

(Very Preliminary)

- **2015-2020:** Development of a 12 T operational field Nb_3Sn twin-aperture dipole with common coil configuration and 10^{-4} field quality; Fabrication and test of 2~3 T HTS (Bi-2212 or YBCO) coils in a 12 T background field and basic research on tape superconductors for accelerator magnets (field quality, fabrication method, quench protection).
- **2020-2025:** Development of a 15 T Nb_3Sn twin-aperture dipole and quadrupole with 10^{-4} field uniformity; Fabrication and test of 4~5 T HTS (Bi-2212 or YBCO) coils in a 15 T background field.
- **2025-2030:** 15 T Nb_3Sn coils + HTS coils (or all-HTS) to realize the 20 T dipole and quadrupole with 10^{-4} field uniformity; Development of the prototype SppC dipoles and quadrupoles and infrastructure build-up.

20 T magnet working group in China

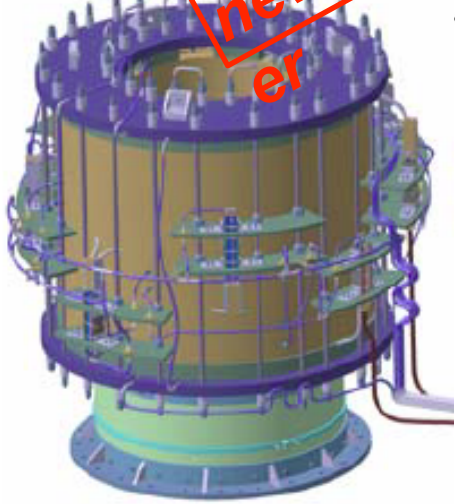
IHEP

CHMFL

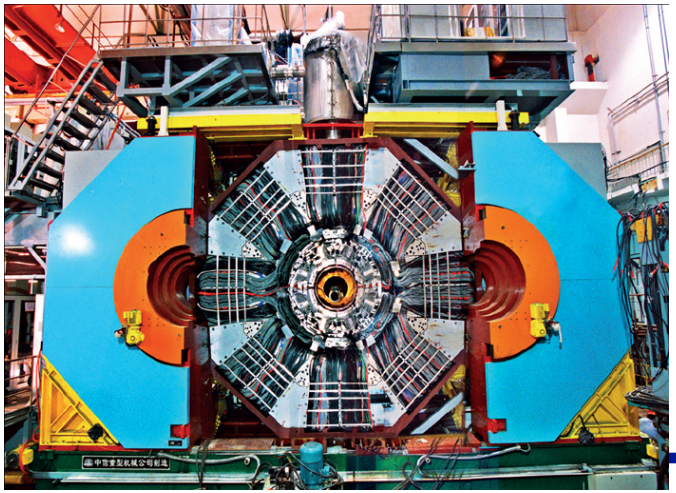
newcomer

Superconducting magnetic separator (2012)

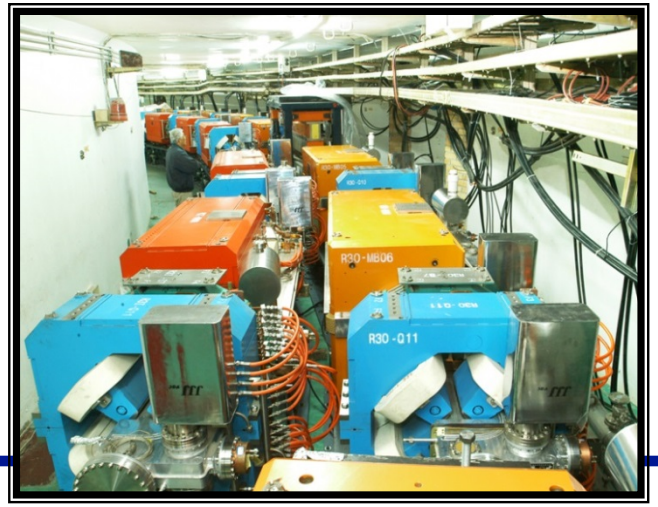
25Hz AC quadruple for CSNS(2013)



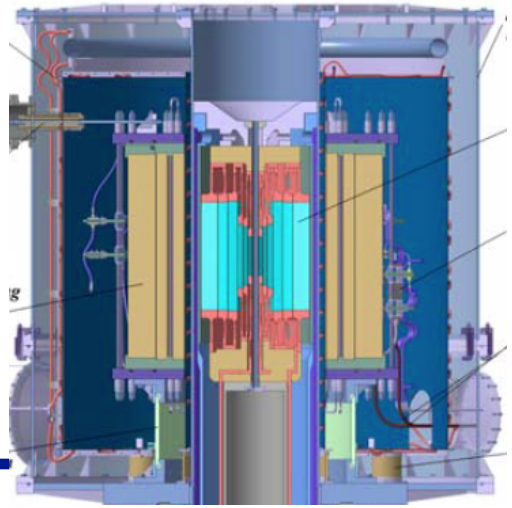
11 T Nb_3Sn solenoid (ongoing)



BESIII Superconducting solenoid (2006)



Conventional magnets for BEPCII (2005)



11 T Nb_3Sn + 29 T Cu insert (ongoing)

5. Summary

- CEPC + SppC preliminary schedule:
  - CPEC
    - Pre-study, R&D and preparation work
      - Pre-study: 2013-15 → Pre-CDR by 2014
      - R&D: 2016-2020
      - Engineering Design: 2015-2020
    - Construction: 2021-2027
    - Data taking: 2030-2036
  - SPPC
    - Pre-study, R&D and preparation work
      - Pre-study: 2013-2020
      - R&D: 2020-2030
      - Engineering Design: 2030-2035
    - Construction: 2036-2042
    - Data taking: 2042 -

Pre-CDR

- **Writing up the preliminary Conceptual Design Report (pre-CDR), covering accelerator, theory, experiment (detector and physics), and civil engineering. → 1st milestone**

Schedule guideline for CEPC pre-CDR

August – December 2014

August 1-15	August 16-31	September 1-15	September 16-30	October 1-15	October 16-31	November 1-15	November 16-30	December 1-15	December 16-31
pre-CDR draft version 0 from each (sub-)group ; (with all required elements, some contents may be missing)									
(1) external reviewers identified and invitations sent out during first period; (2) additions and revisions being worked on; (3) formation of editorial board at SJTU workshop; (4) internal reviews within (sub-)groups.									
(1) revision and finalization of pre-CDR chapters; (2) internal reviews of chapters (theory, detector-simulation, accelerator, site design and civil engineering); (3) draft **Introduction** and **Summary** sections available for comments and revision.									
(1) reviews of chapters (**theory, detector-simulation, accelerator, site design and civil engineering**) by external review committees; (2) revisions of and improvements to the pre-CDR chapters .									
(1) final edition (including **Introduction & Summary**) in English; (2) translation of pre-CDR into Chinese completed and reviewed									
(1) proof; (2) print and release to CAS and public									

Pre-CDR: Accelerator

Table of Contents (Draft, February 10, 2014)

Most chapters ready for internal review

Theory/Detector & Physics chapters in similar status

- High energy accelerators are being developed in China for 30 years.
- CEPC + SppC is the key direction for HEP, and big (HEP) accelerator as well in China.
- We are rather weak in hadron machine, with CSNS and ADS projects just started.
- R&D of key technologies are necessary and crucial to us.
- More international collaboration is foreseen.

Thanks for your attention !