Future Circular Colliders and R&D

CERN China Chicago

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Fermilab/IHEP

EPS-HEP Conference

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Outline

- Brief review of the past
- Prospect of the future
  - ee
  - pp
  - μμ
  - γγ
- Summary

Many thanks to CERN, IHEP, Fermilab, SLAC, BNL, LBNL and other colleagues for providing high quality slides.

#1 Question for the World HEP Community

LHC – does it stand for:

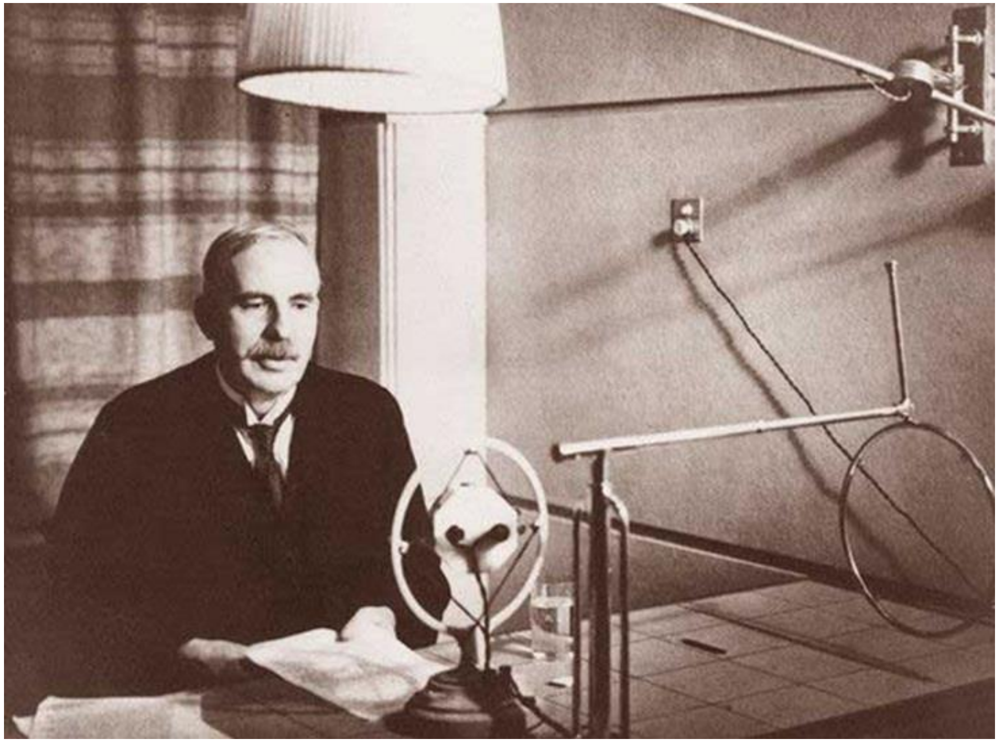
- *Large Hadron Collider*

or

- *<u>Last</u> Hadron Collider?*

This was an old question. It was raised again and again after the demise of the SSC but has not yet had a definite answer.

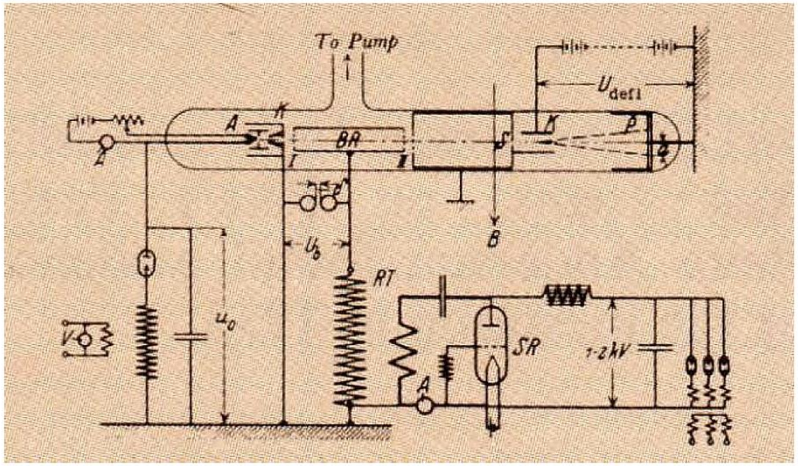
A Brief History



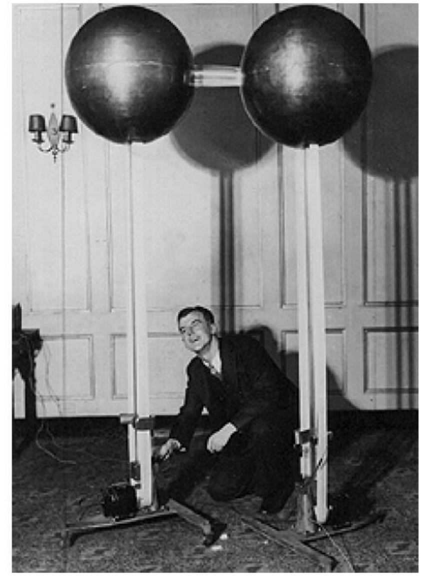
1919: Ernest Rutherford discovered the nuclear disintegration by bombarding nitrogen with alpha particles from natural radioactive substances. Later he **called for "a copious supply" of particles more energetic than those from natural sources.** The particle accelerator era was born.

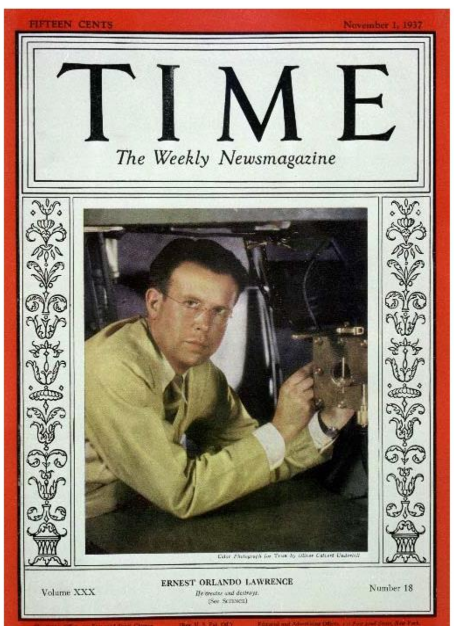
A Brief History (cont'd)

1928: Wideroe, 88-in linac

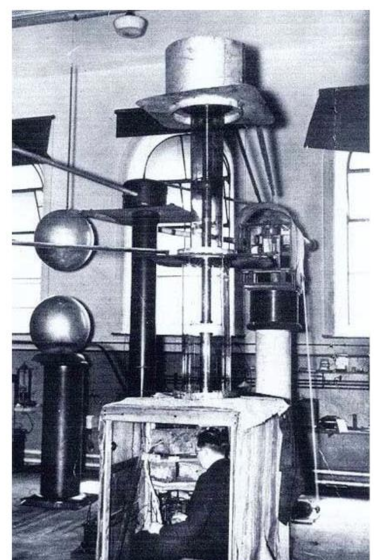


1929: Van de Graaff generator





1930: Lawrence, 4-in cyclotron



1932: Cockcroft-Walton electrostatic accelerator

A Brief History (cont'd)

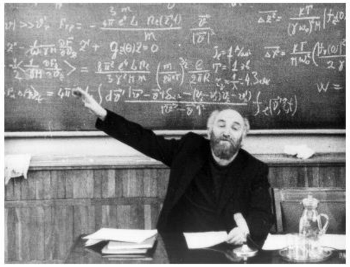
1943: Synchrotron

1944: Phase stability

1952: Strong focusing

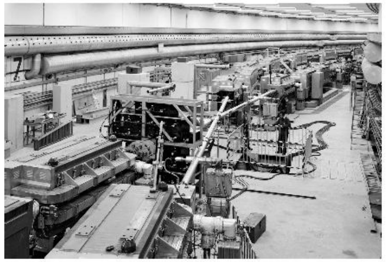
1961: 1st lepton collider

1966: Electron cooling

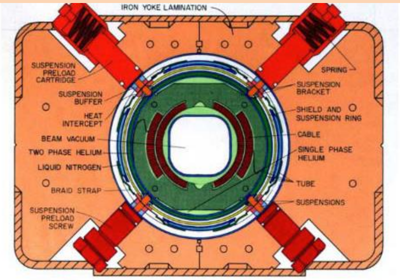


1968: Stochastic cooling

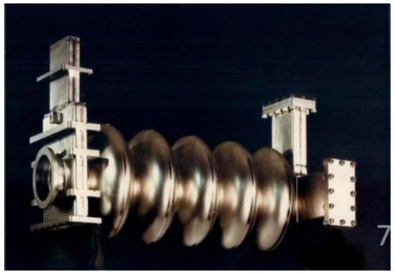
1969: 1st hadron collider



1983: SC magnet



1994: Superconducting RF



25 Nobel Prizes in Physics that had direct contribution from accelerators

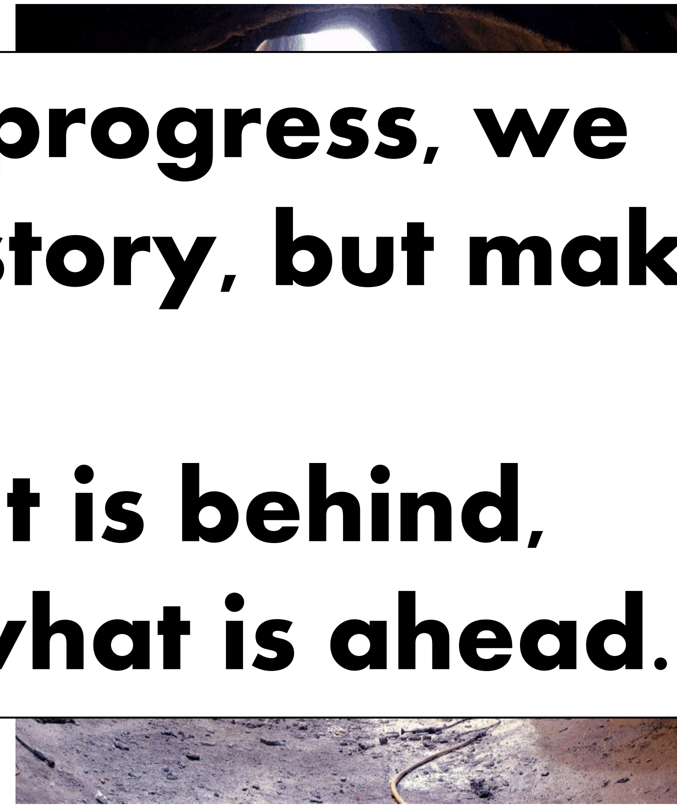
(courtesy: A. Chao)

Year	Name	Accelerator-Science Contribution to Nobel Prize-Winning Research
1939	Ernest O. Lawrence	Lawrence invented the cyclotron at the University of Californian at Berkeley in 1929 [12].
1951	John D. Cockcroft and Ernest T.S. Walton	Cockcroft and Walton invented their eponymous linear positive-ion accelerator at the Cavendish Laboratory in Cambridge, England, in 1932 [13].
1952	Felix Bloch	Bloch used a cyclotron at the Crocker Radiation Laboratory at the University of California at Berkeley in his discovery of the magnetic moment of the neutron in 1940 [14].
1957	Tsung-Dao Lee and Chen Ning Yang	Lee and Yang analyzed data on K mesons (θ and τ) from Bevatron experiments at the Lawrence Radiation Laboratory in 1955 [15], which supported their idea in 1956 that parity is not conserved in weak interactions [16].
1959	Emilio G. Segrè and Owen Chamberlain	Segrè and Chamberlain discovered the antiproton in 1955 using the Bevatron at the Lawrence Radiation Laboratory [17].
1960	Donald A. Glaser	Glaser tested his first experimental six-inch bubble chamber in 1955 with high-energy protons produced by the Brookhaven Cosmotron [18].
1961	Robert Hofstadter	Hofstadter carried out electron-scattering experiments on carbon-12 and oxygen-16 in 1959 using the SLAC linac and thereby made discoveries on the structure of nucleons [19].
1963	Maria Goeppert Mayer	Goeppert Mayer analyzed experiments using neutron beams produced by the University of Chicago cyclotron in 1947 to measure the nuclear binding energies of krypton and xenon [20], which led to her discoveries on high magic numbers in 1948 [21].
1967	Hans A. Bethe	Bethe analyzed nuclear reactions involving accelerated protons and other nuclei whereby he discovered in 1939 how energy is produced in stars [22].
1968	Luis W. Alvarez	Alvarez discovered a large number of resonance states using his fifteen-inch hydrogen bubble chamber and high-energy proton beams from the Bevatron at the Lawrence Radiation Laboratory [23].
1976	Burton Richter and Samuel C.C. Ting	Richter discovered the J/Ψ particle in 1974 using the SPEAR collider at Stanford [24], and Ting discovered the J/Ψ particle independently in 1974 using the Brookhaven Alternating Gradient Synchrotron [25].
1979	Sheldon L. Glashow, Abdus Salam, and Steven Weinberg	Glashow, Salam, and Weinberg cited experiments on the bombardment of nuclei with neutrinos at CERN in 1973 [26] as confirmation of their prediction of weak neutral currents [27].
1980	James W. Cronin and Val L. Fitch	Cronin and Fitch concluded in 1964 that CP (charge-parity) symmetry is violated in the decay of neutral K mesons based upon their experiments using the Brookhaven Alternating Gradient Synchrotron [28].
1981	Kai M. Siegbahn	Siegbahn invented a weak-focusing principle for betatrons in 1944 with which he made significant improvements in high-resolution electron spectroscopy [29].
1983	William A. Fowler	Fowler collaborated on and analyzed accelerator-based experiments in 1958 [30], which he used to support his hypothesis on stellar-fusion processes in 1957 [31].
1984	Carlo Rubbia and Simon van der Meer	Rubbia led a team of physicists who observed the intermediate vector bosons W and Z in 1983 using CERN's proton-antiproton collider [32], and van der Meer developed much of the instrumentation needed for these experiments [33].
1986	Ernst Ruska	Ruska built the first electron microscope in 1933 based upon a magnetic optical system that provided large magnification [34].
1988	Leon M. Lederman, Melvin Schwartz, and Jack Steinberger	Lederman, Schwartz, and Steinberger discovered the muon neutrino in 1962 using Brookhaven's Alternating Gradient Synchrotron [35].
1989	Wolfgang Paul	Paul's idea in the early 1950s of building ion traps grew out of accelerator physics [36].
1990	Jerome I. Friedman, Henry W. Kendall, and Richard E. Taylor	Friedman, Kendall, and Taylor's experiments in 1974 on deep inelastic scattering of electrons on protons and bound neutrons used the SLAC linac [37].
1992	Georges Charpak	Charpak's development of multiwire proportional chambers in 1970 were made possible by accelerator-based testing at CERN [38].
1995	Martin L. Perl	Perl discovered the tau lepton in 1975 using Stanford's SPEAR collider [39].
2004	David J. Gross, Frank Wilczek, and H. David Politzer	Gross, Wilczek, and Politzer discovered asymptotic freedom in the theory of strong interactions in 1973 based upon results from the SLAC linac on electron-proton scattering [40].
2008	Makoto Kobayashi and Toshihide Maskawa	Kobayashi and Maskawa's theory of quark mixing in 1973 was confirmed by results from the KEKB accelerator at KEK in Tsukuba, Ibaraki Prefecture, Japan, and the PEP II at SLAC [41], which showed that quark mixing in the six-quark model is the dominant source of broken symmetry [42].
2013	Francois Englert and Peter W. Higgs	Englert's and Higgs's theory of the Higgs particle in 1960s was confirmed by the ATLAS and CMS experiments at CERN's LHC in 2012.

A Tale of Two Cities

Geneva, Switzerland

Waxahachie, Texas, USA



If we are to make progress, we must not repeat history, but make new history.

Forgetting what is behind,
Straining toward what is ahead.

It was the best of times, It was the age of wisdom, It was the spring of hope,	It was the worst of times. It was the age of foolishness. It was the winter of despair.

What is ahead?

Linear collider (Andrei Seryi's talk)

Circular collider

- A turning point was the discovery of the Higgs. As its mass is low, a circular *e+e-* collider of 240 GeV can be a Higgs factory, an energy only 15% higher than the LEP2 (209 GeV). The new big ring will be ideal to host a future *pp* collider.
- China saw this opportunity and quickly launched the **CEPC-SPPC** study.
- CERN, having secured its world leader position with HL-LHC, decided to take up a post-LHC machine – the **FCC**.
- US also wanted to seize the opportunity – the P5 report recommended:

  "Participate in global conceptual design studies and critical path R&D for future very high-energy proton-proton colliders."

ICFA Statements

February, 2014 at DESY

ICFA encouraged the two studies (FCC and CEPC-SPPC) to work as close together as possible, with the following statement:

ICFA supports studies of energy frontier circular colliders and encourages global coordination.

July, 2014 at Valencia

ICFA endorses the particle physics strategic plans produced in Europe, Asia and the United States and the globally aligned priorities contained therein. Here, ICFA reaffirms its support of the ILC, which is in a mature state of technical development and offers unprecedented opportunities for precision studies of the newly discovered Higgs boson. In addition, ICFA continues to encourage international studies of circular colliders, with an ultimate goal of proton-proton collisions at energies much higher than those of the LHC.

CEPC-SPPC Timeline (preliminary)

2nd Milestone: R&D funding in the government's new 5-year plan (2016-2020)

CEPC

2015 | 2020 | 2025 | 2030 | 2035

Pre-studies (2013-2015)	R&D Engineering Design (2016-2020)	Construction (2021-2027)	Data taking (2028-2035)

1st Milestone: Pre-CDR (by the end of 2014)

SPPC

2020 | 2030 | 2040

R&D (2014-2030)	Engineering Design (2030-2035)	Construction (2035-2042)	Data taking (2042-2055)

CEPC-SPPC Pre-CDR (March 2015)

IHEP-CEPC-DR-2015-01

IHEP-EP-2015-01

IHEP-TH-2015-01

CEPC-SPPC

Preliminary Conceptual Design Report

Volume I - Physics & Detector

403 pages, 480 authors

The CEPC-SPPC Study Group

March 2015

IHEP-CEPC-DR-2015-01

IHEP-AC-2015-01

CEPC-SPPC

Preliminary Conceptual Design Report

Volume II - Accelerator

328 pages, 300 authors

The CEPC-SPPC Study Group

March 2015

CEPC Design – Top Level Parameters

Parameter	Design Goal
Particles	e+, e-
Center of mass energy	240 GeV
Integrated luminosity (per IP per year)	250 fb^{-1}
No. of IPs	2

⇒ one million Higgs from 2 IPs in 10 years

SPPC Design – Top Level Parameters

Parameter	Design Goal
Particles	p, p
Center of mass energy	70 TeV
Integrated luminosity (per IP per year)	(TBD)
No. of IPs	2

CEPC – Site Investigation

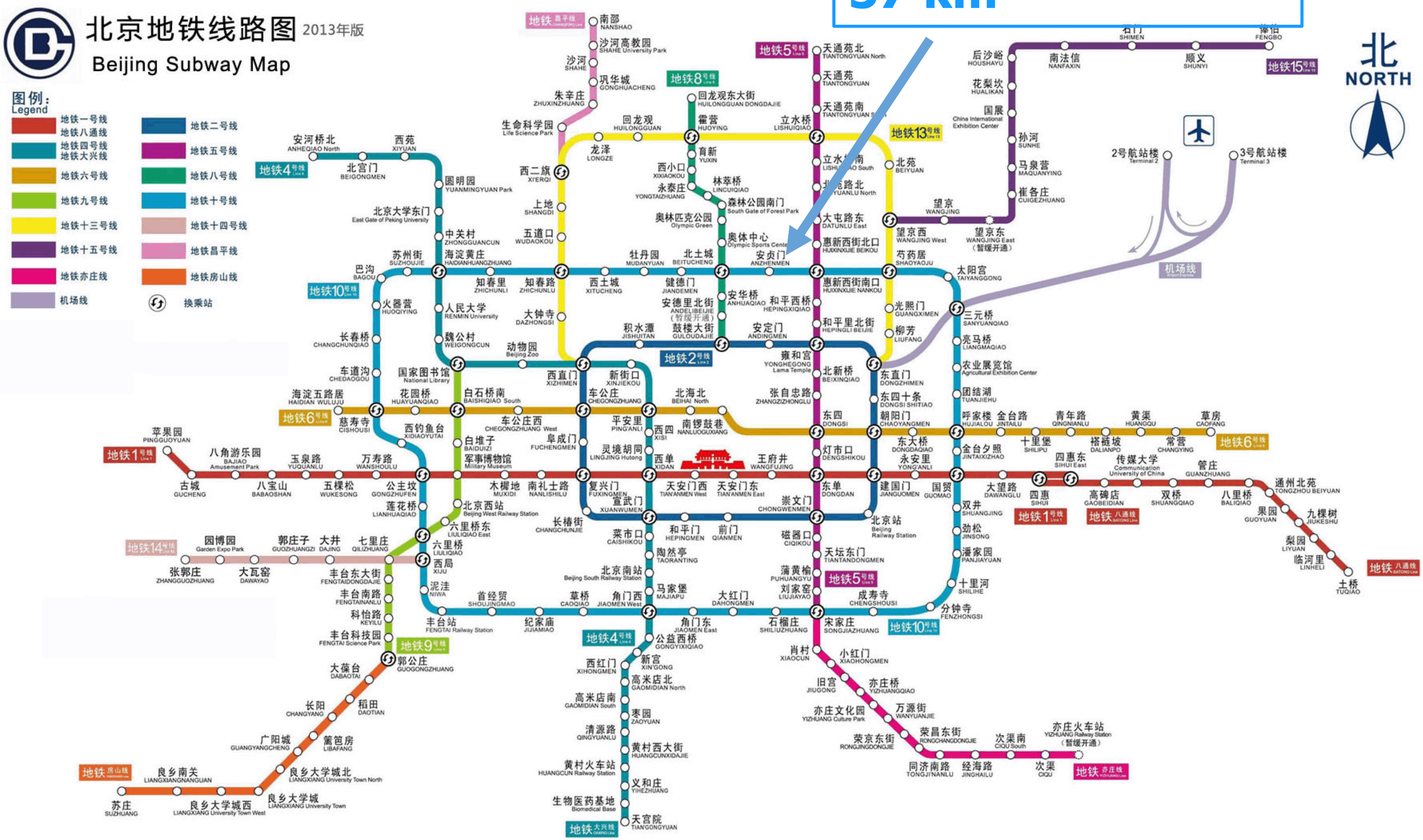
A good example is 秦皇岛:

300 km from Beijing

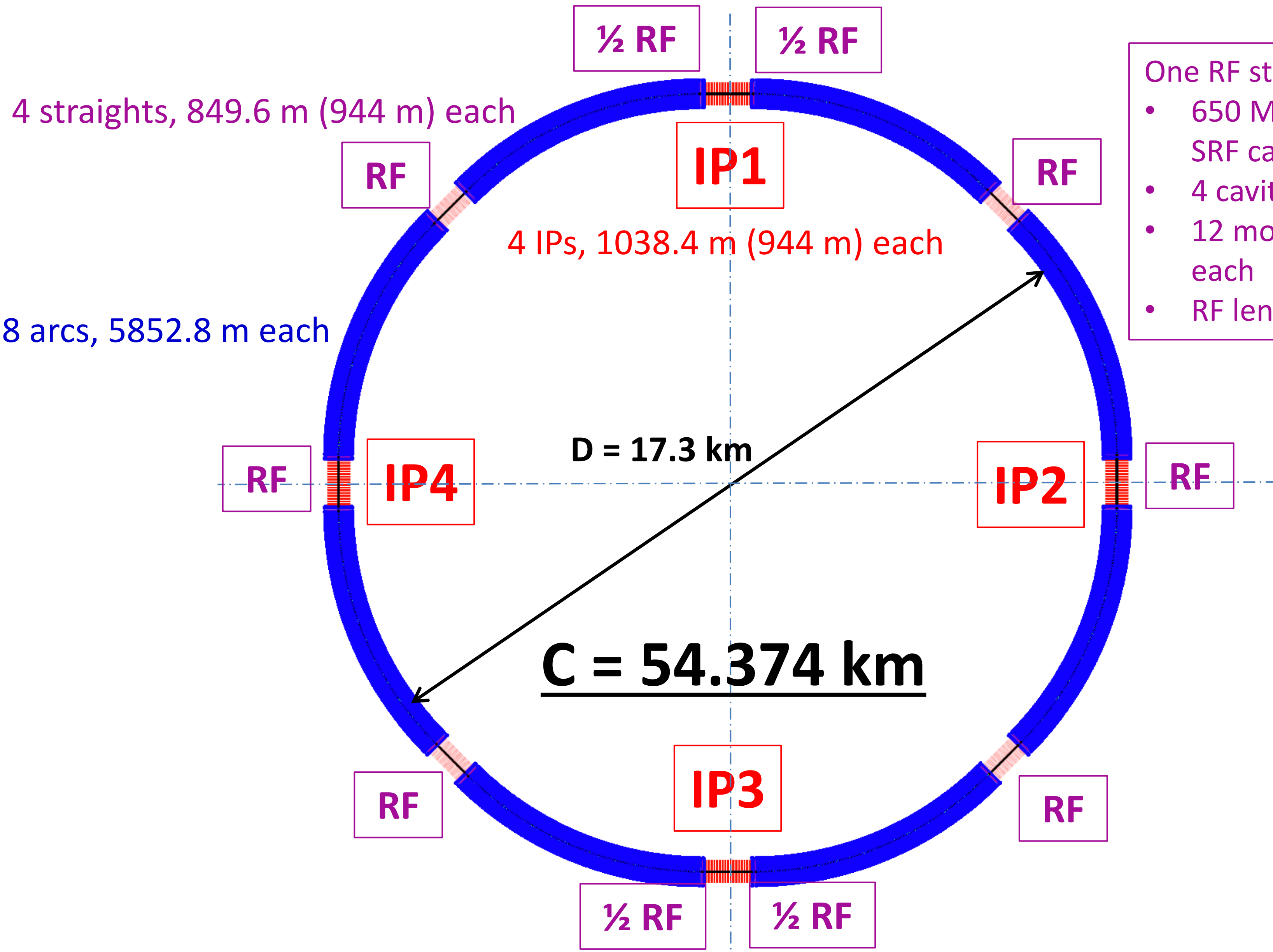
3 hours by car; 1 hours by high speed train

Y. F. Wang

Subway line #10, 57 km



CEPC Lattice Layout (September 24, 2014)

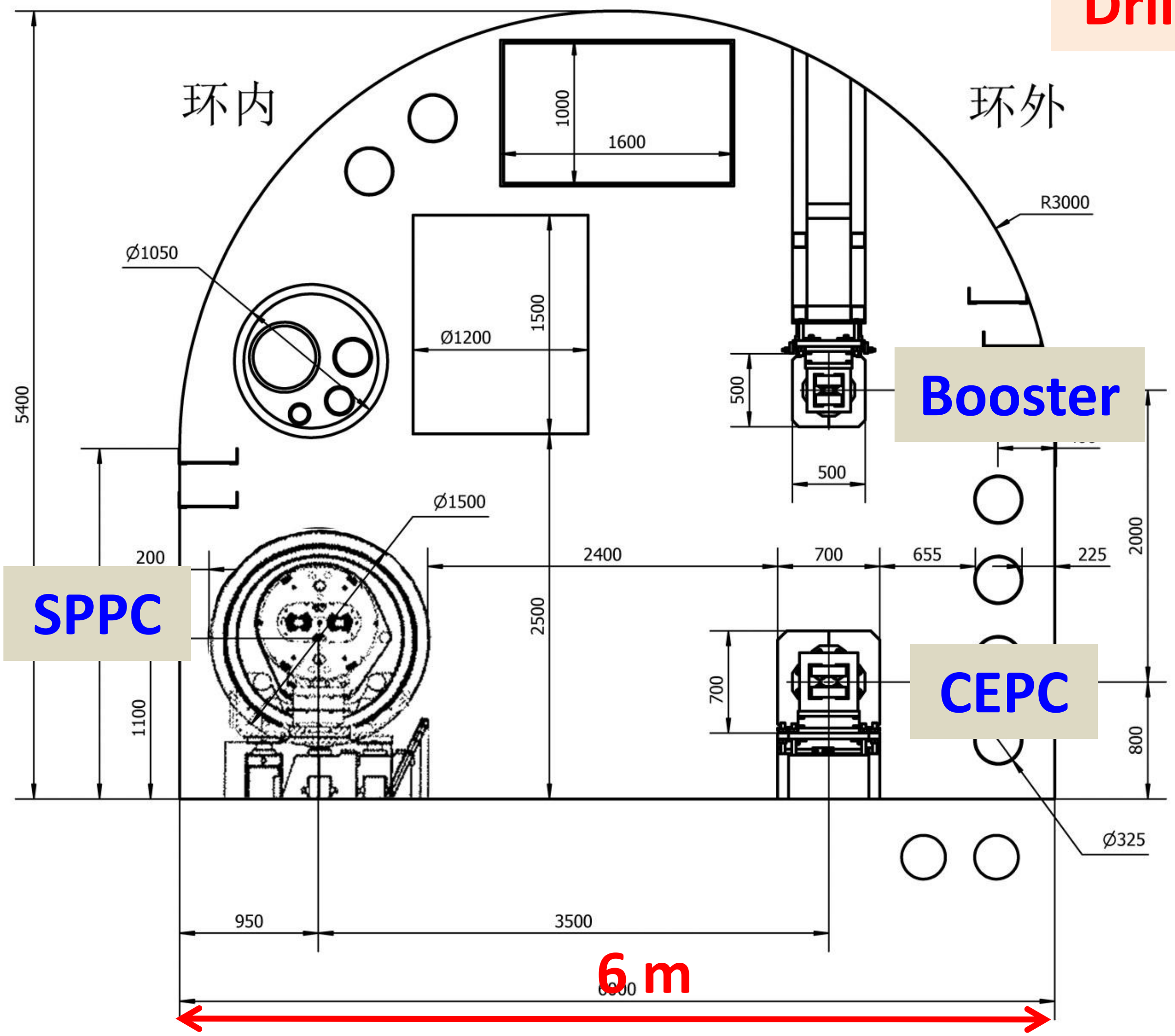


One RF station:

- 650 MHz five-cell SRF cavities;
- 4 cavities/module
- 12 modules, 10 m each
- RF length 120 m

Tunnel Cross Section – SPPC + CEPC Magnets

Drill/Blast Method



LHC Tunnel – Magnet Section

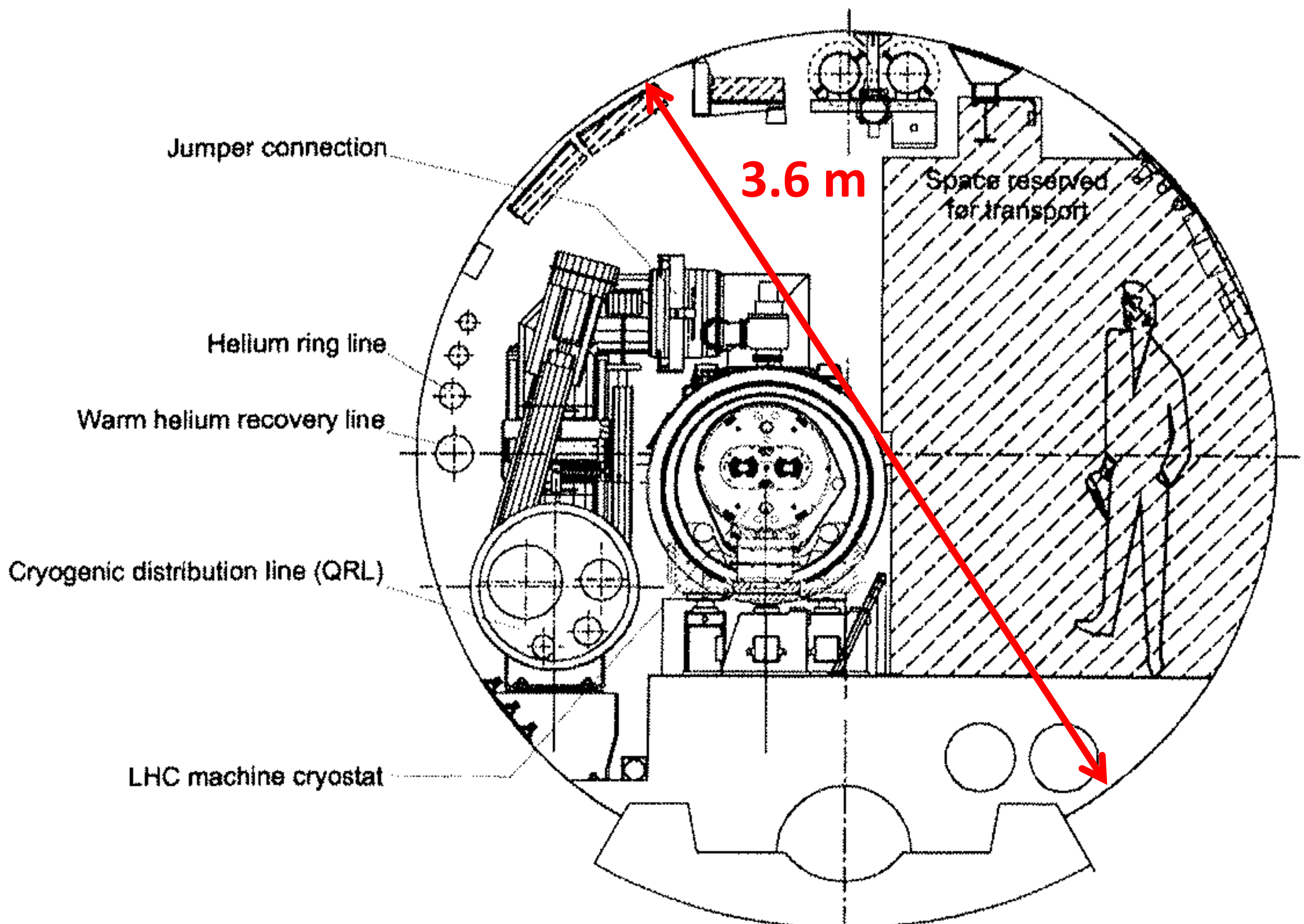
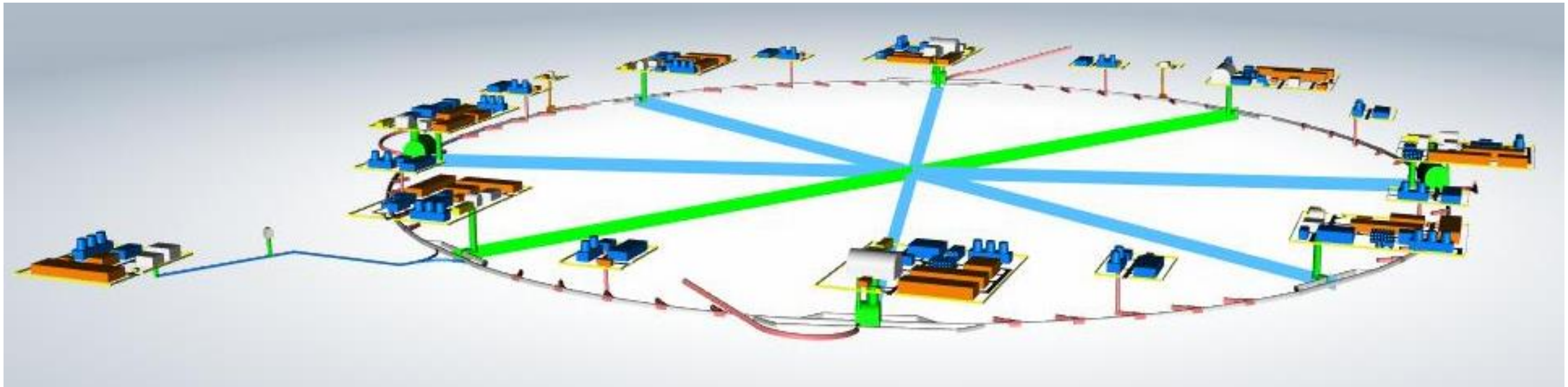
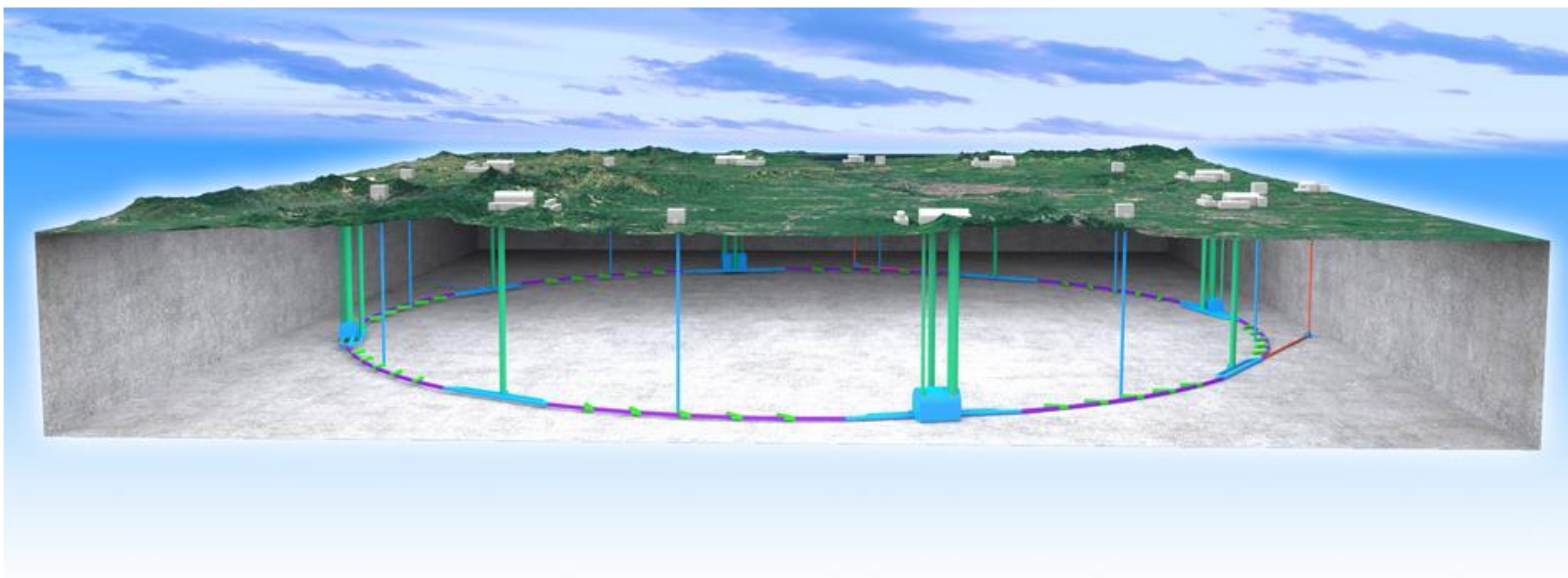


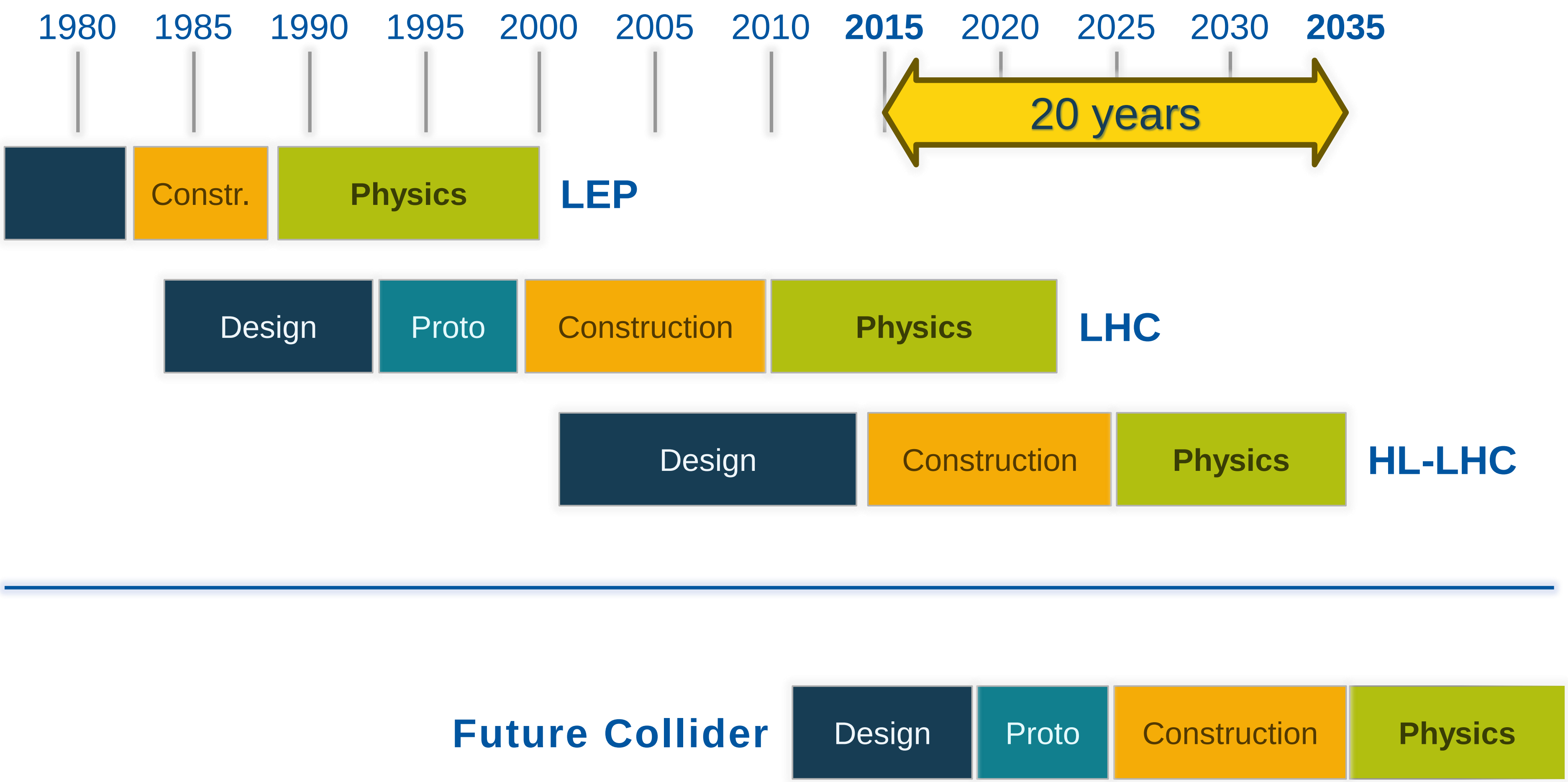
Figure 11.1: Transverse cross-section of the LHC tunnel

Civil Construction Design

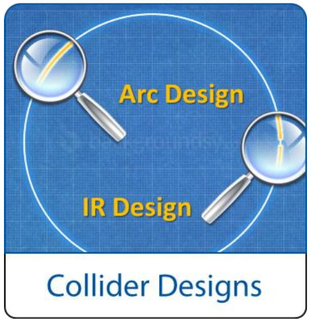




CERN Circular Colliders + FCC

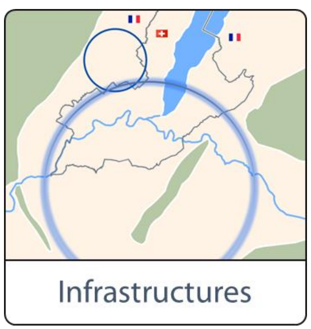


Scope: Accelerator & Infrastructure



FCC-hh: **100 TeV *pp* collider as long-term goal**
→ defines infrastructure needs
FCC-ee: ***e⁺e⁻* collider**, potential intermediate step
FCC-he: **integration aspects** of pe collisions

Push key technologies
in dedicated R&D programmes e.g.
16 Tesla magnets for **100 TeV** pp in **100 km**
SRF technologies and RF power sources



Tunnel infrastructure in Geneva area, linked to CERN accelerator complex
Site-specific, requested by European strategy

Key Parameters FCC-hh

Parameter	FCC-hh	LHC
Energy [TeV]	100 c.m.	14 c.m.
Dipole field [T]	16	8.33
# IP	2 main, +2	4
Luminosity/IP_{main} [$cm^{-2}s^{-1}$]	5 - 30 x 10^{34}	1 x 10^{34}
Stored energy/beam [GJ]	8.4	0.39
Synchrotron rad. [W/m/aperture]	28.4	0.17
Bunch spacing [ns]	25 (5)	25

Debate on Luminosity Goal

- B. Richter (RAST, v7, 2014):
  - $L \propto E^2$
  - From HL-LHC to FCC-hh, E x 7 $\rightarrow$ L x 50 ~ 2.5e36
  - Pileup x 50 $\rightarrow$ 7,000 events per collision
- Different opinions expressed at several meetings:
  - Fermilab workshop
  - ICFA Seminar
  - Hong Kong workshop
  - Aspen Winter Conference, etc.
- A recent paper (arXiv:1504.06108) on this by several theorists:

  I. Hinchliffe, A. Kotwal, M. Mangano, C. Quigg, L. Wang

FCC-hh Luminosity Goals

- **Two parameter sets for two operation phases:**

  - **phase 1 (baseline): 5 x 10^{34} $cm^{-2}s^{-1}$ (peak),**
    250 fb^{-1}/year (averaged)
  - **phase 2 (ultimate): ~3.0 x 10^{35} $cm^{-2}s^{-1}$ (peak),**
    1000 fb^{-1}/year (averaged)

➔ total luminosity a few 10's of ab^{-1} over ~25 years of operation

OK for physics

Geology Studies – Example 93 km

Alignment | Shaft Tools

Choose alignment option: 93km quasi-circular

Tunnel depth at centre: 299mASL

Gradient Parameters

Azimuth (°): -15

Slope Angle x-x(%): .5

Slope Angle y-y(%): 0

CALCULATE

Alignment centre

X: 2499812 Y: 1106889

LHC Intersection	CP 1	CP 2
Angle		
Depth	589m	589m

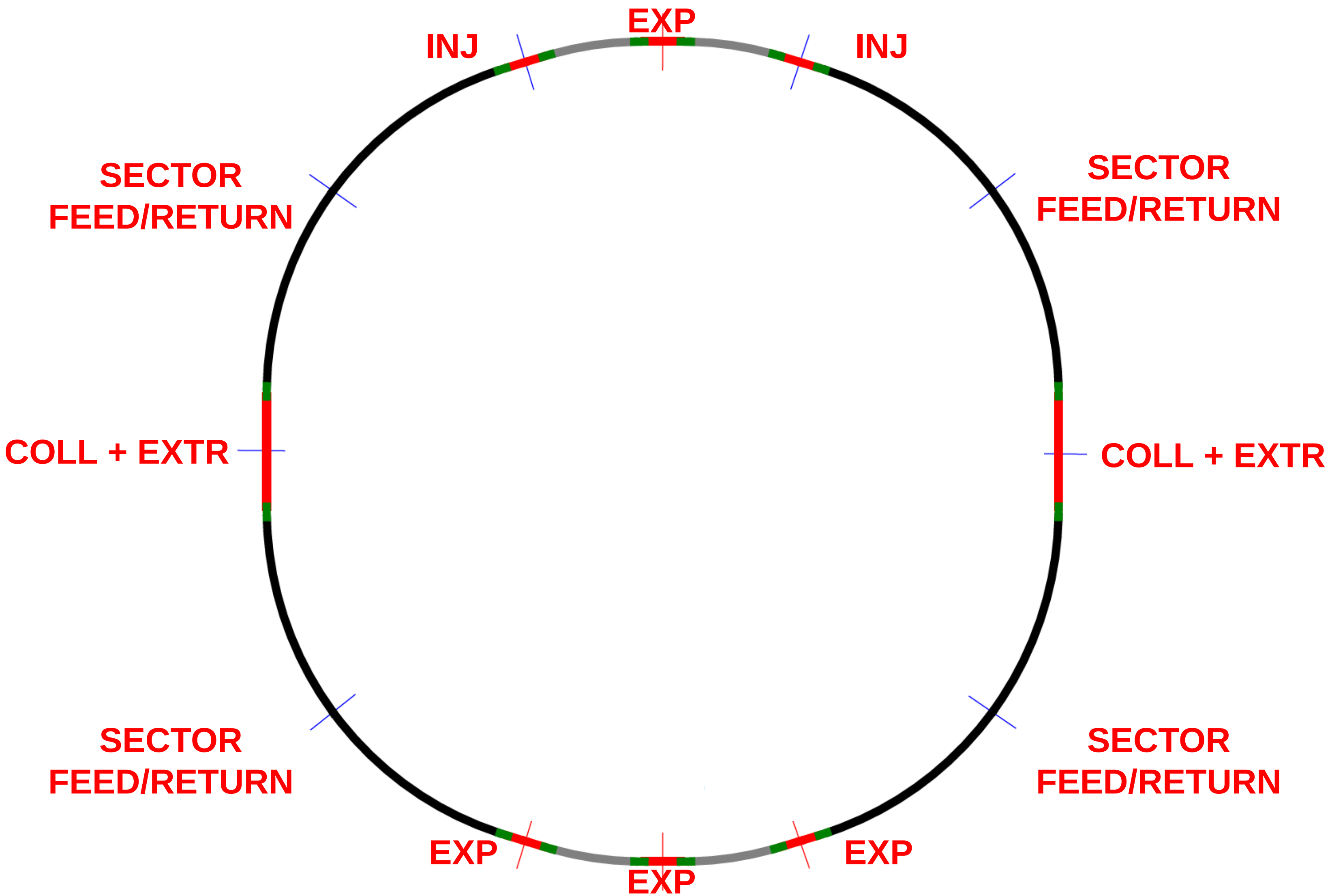
Alignment Location

Geology Intersected by Shafts | Shaft Depths

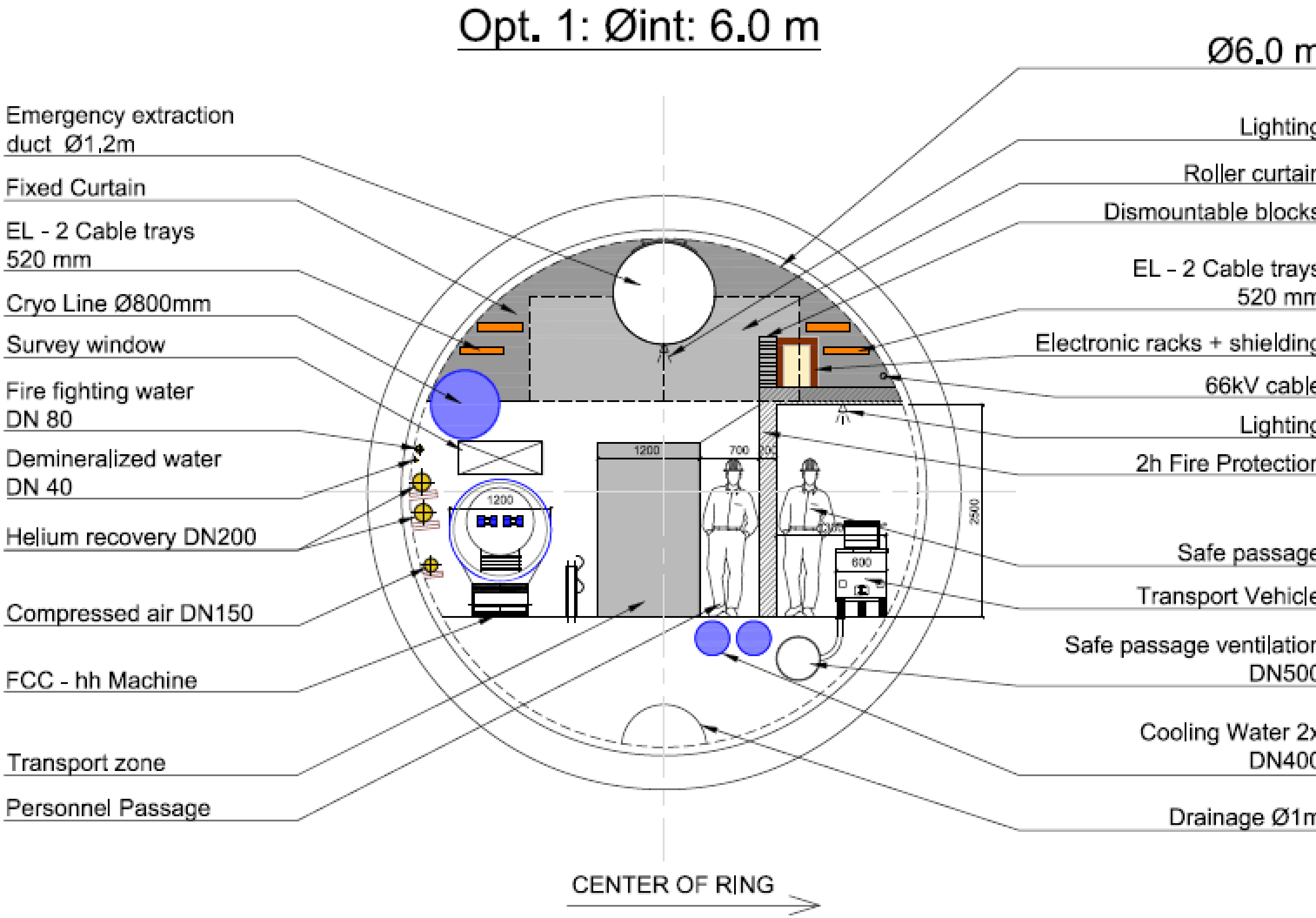
	Shaft Depth (m)				Geology (m)			
Point	Actual	Min	Mean	Max	Quaternary	Molasse	Urgonian	Calcaire
A	203	200	204	212	93	111	0	0
B	227	219	226	231	41	185	0	0
C	218	208	217	225	75	143	0	0
D	153	150	154	158	19	134	0	0
E	247	233	249	261	24	223	0	0
F	262	251	269	304	32	230	0	0
G	396	392	393	396	177	220	0	0
H	266	231	274	322	0	325	0	0
I	146	141	144	149	26	120	0	0
J	248	247	251	258	6	242	0	0
K	163	153	159	164	76	87	0	0
L	182	182	184	187	17	165	0	0
Total	2711	2607	2724	2867	585	2185	0	0

- 90 – 100 km fits geological situation well, better than a smaller ring size
- LHC suitable as potential injector

Allocation of Sectors for FCC-hh



FCC-hh arcs Single tunnel, longitudinal ventilation



FCC Collaboration Status

- 58 institutes
- 22 countries
- EC participation

Top Three R&D Items

- ***e+e-* collider** (CEPC and FCC-ee)
  1. Power consumption
  2. Heat load in the cold region (HOM heating)
  3. Dynamic aperture
- ***pp* collider** (FCC-hh and SPPC):
  1. SC magnet
  2. Heat load in the cold region (SR heating)
  3. Machine protection

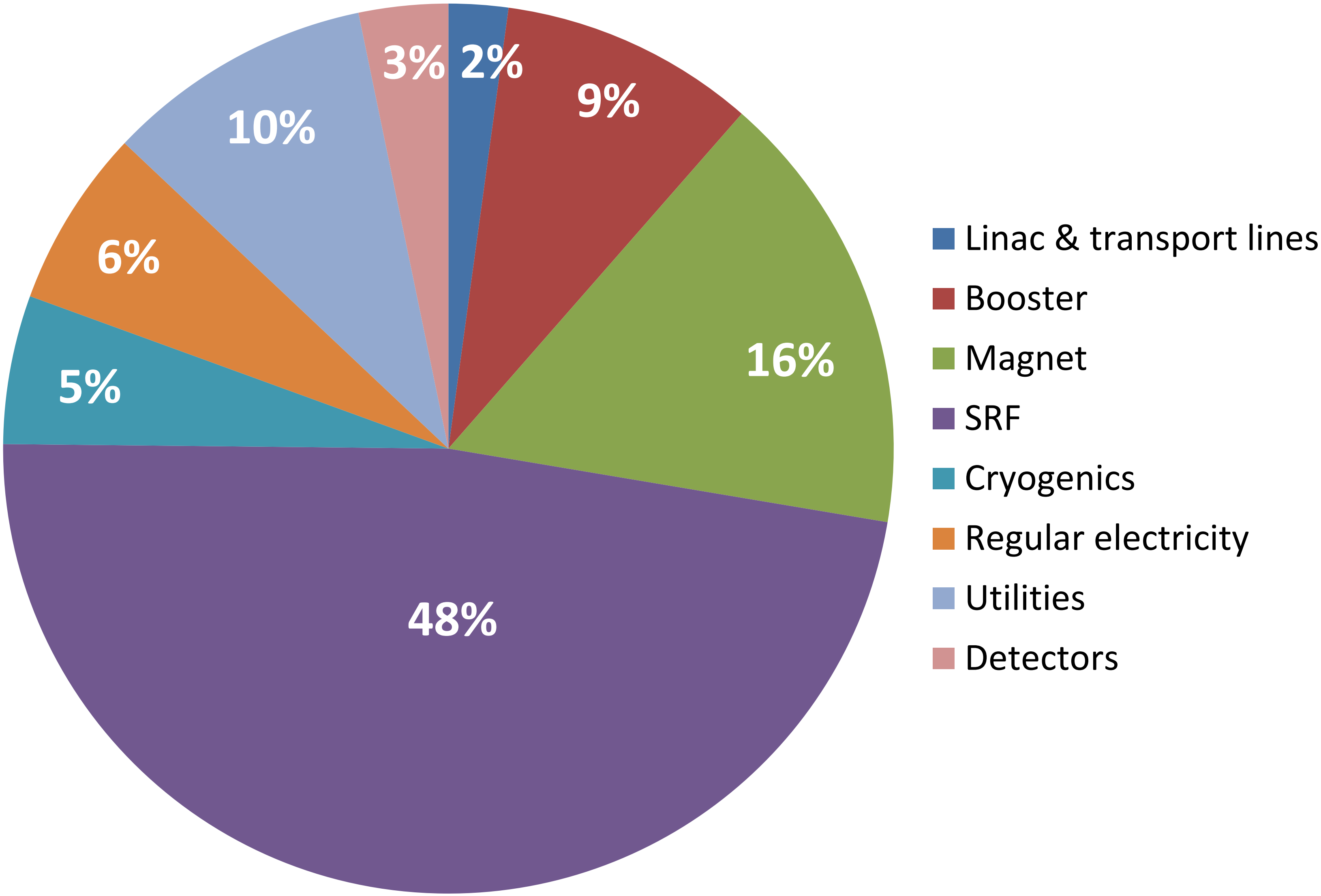
Common concern

e+e- R&D #1 – Power Consumption

system	location and electrical loads(MW)					Total
	ring	Booster	Linac	BT	IP	
power source	230	15	2.1			247.1
cryogenics	16	2			1	19
power converter for magnets	60.5	13.2	1.2	1	1	76.9
experimental devices					14	14
dedicated services	15	5	1	1	2	24
utilities	55	10	2.5	1	2	70.5
general services	15		1	1	1	18
campus						30
Total	391.5	45.2	7.8	4	21	499.5

- Half of a nuclear power plant
- Goal: to reduce it by 40% to ~300 MW

Relative Power Consumption



Power Consumption Reduction

- Increase klystron efficiency (from 50% to 80-90%, e.g., the new klystron called collector potential depression or CPD under development in Japan)
- Improve magnet design (smaller aperture, copper conductor)
- Reuse of heat in the cooling water for civil purpose
- This is a common issue for many future accelerators. ICFA is considering to form a new panel to work on it

Request for ICFA Panel of Sustainable Accelerator/Collider

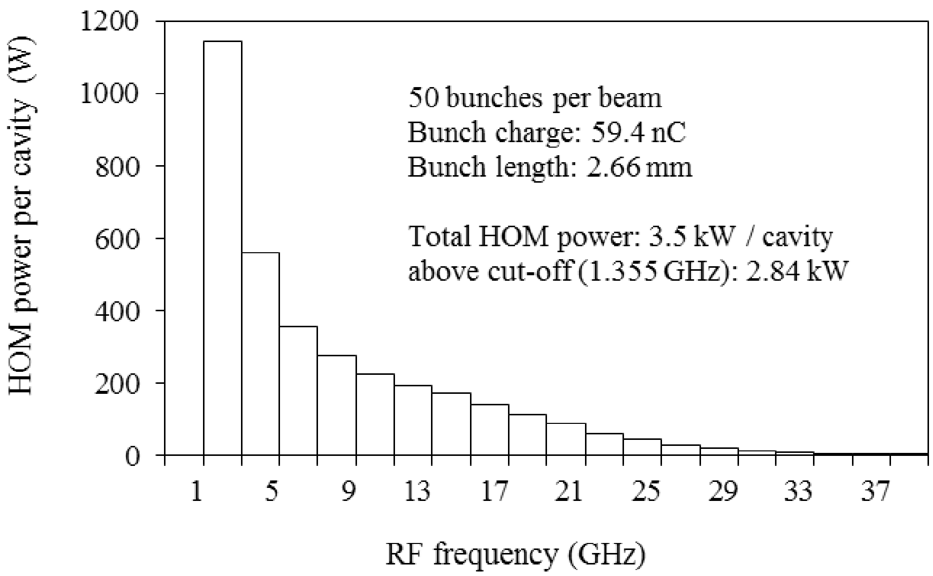
1. **Context**
   - Energy consumption and related running cost are major issues for many on-going and future accelerator/collider projects ranging from the highest energy or most intense fundamental research machines to medical and industrial equipment.
   - The feasibility of HEP future infrastructures is strongly depending on the efficient implementation, both at the design and operation level, of energy saving/recovery/recycling schemes as well as on the injection of sustainable energies in the energy mix.

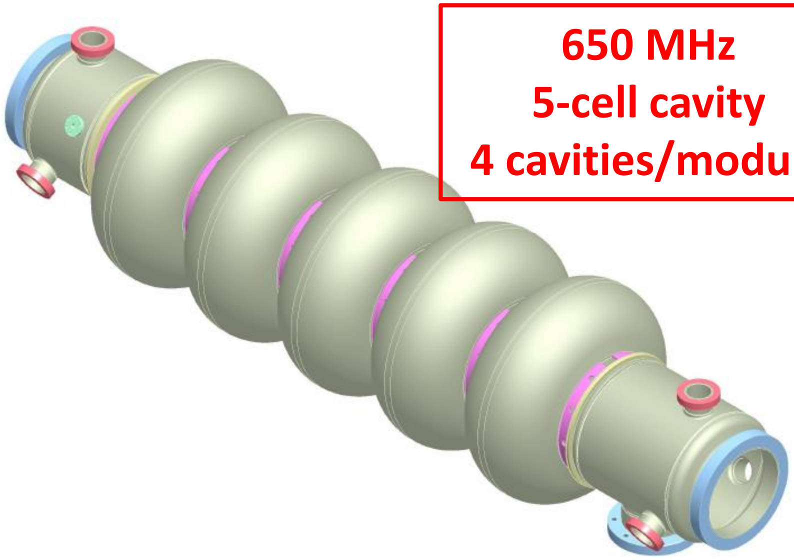
e+e- R&D #2 – HOM Heating

- High average beam current: 2 x 16.6 mA
- High HOM loss: 3.5 kW per cavity

	40 K to 80 K	5 K to 8 K	2K
Efficiency in W/W	16.4	197.9	703.0

	40 K to 80 K	5 K to 8 K	2 K
HOM heat load distribution	18%	1.8%	0.6%



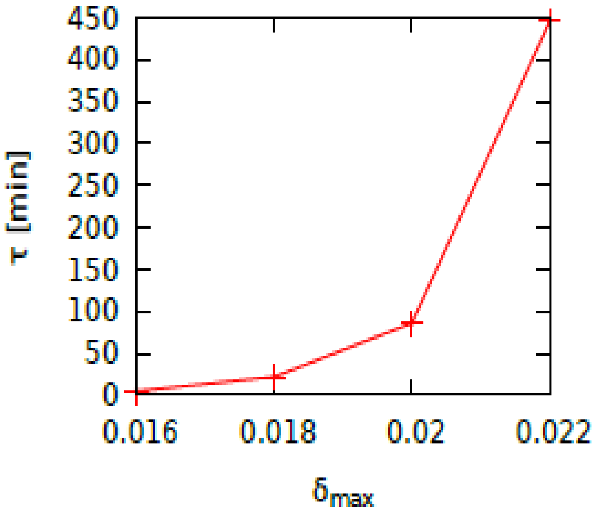


650 MHz
5-cell cavity
4 cavities/module

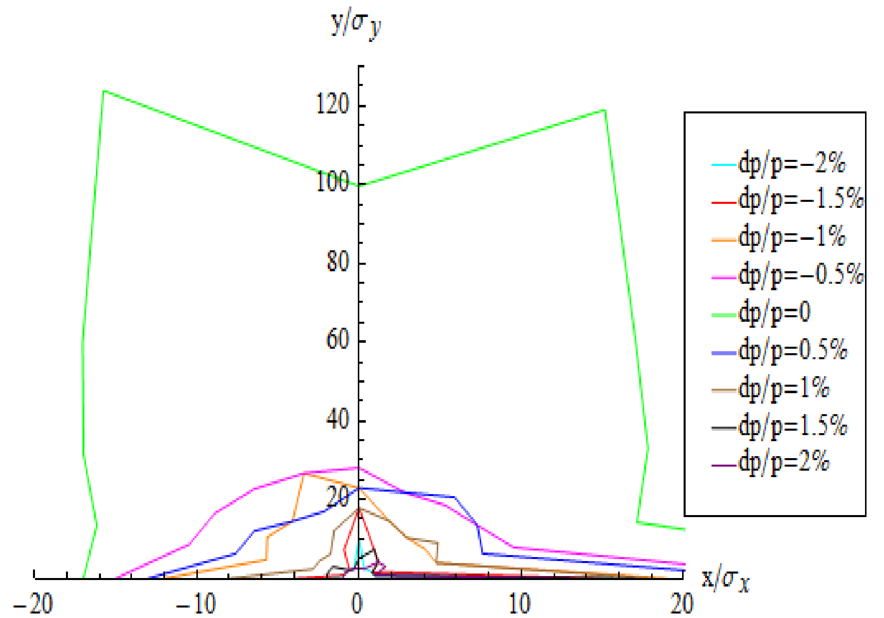
e+e- R&D #3 – Dynamic Aperture

- Strong beamstrahlung → large momentum acceptance (±2%)
- High luminosity → small βy* → strong nonlinearity

Δp/p *vs.* beam lifetime



DA of the entire ring

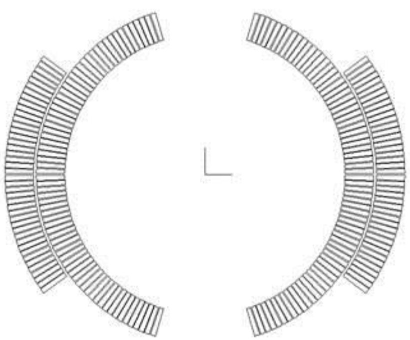


- Decrease L* (from 2.5 m to 1.5 m)
- Increase βy* (from 1.2 mm to 3 mm)
- Iteration in optics design

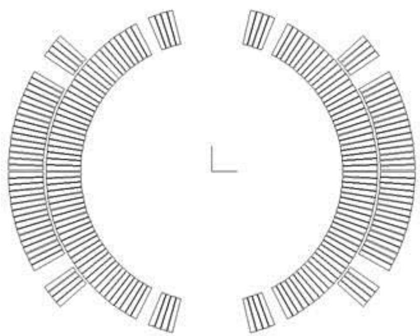
pp R&D #1 – SC Magnets

	E (GeV)	B (T)	Length (m)	First beam
Tevatron	980	4.3	6280	7 1983
HERA	920	5.0	6336	4 1991
RHIC	100/n	3.5	3834	6 2000
LHC	7000	8.3	26659	9 2008

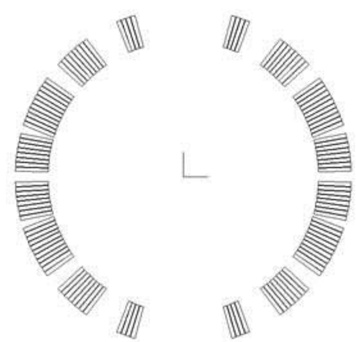
Tevatron (*p-pbar*)



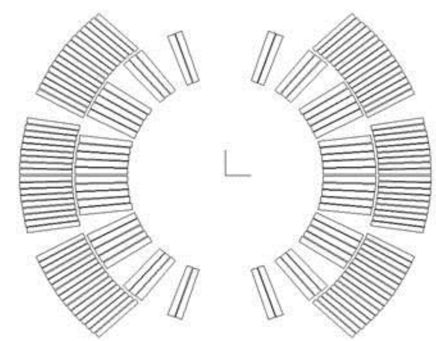
HERA (*p-e*)



RHIC (*ion-ion*)

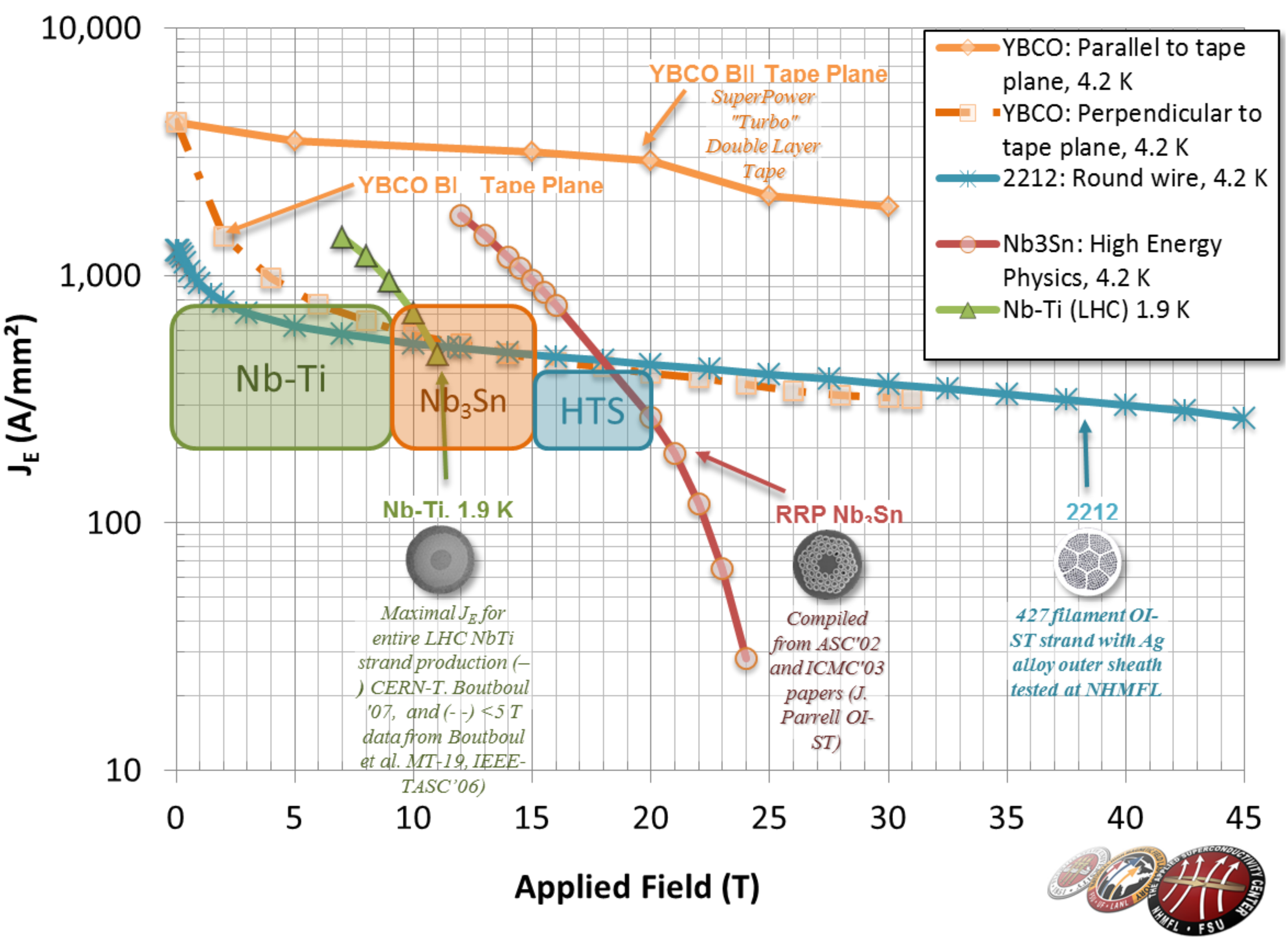


LHC (*p-p*)



All cosine theta, all NbTi

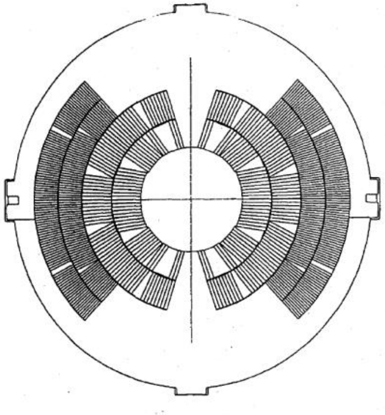
Choice of Superconductors



(courtesy of Peter Lee, Applied SC Center of FSU)

Choice of Magnet Design

Cosine theta (CERN, Fermilab)



Block (LBNL)

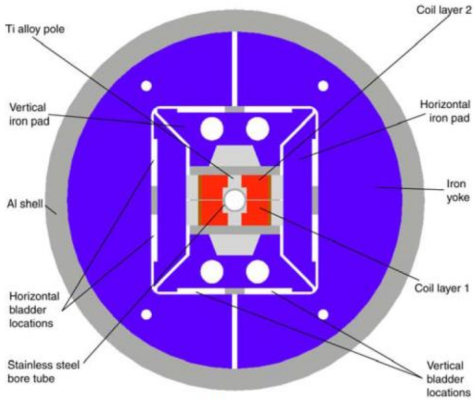
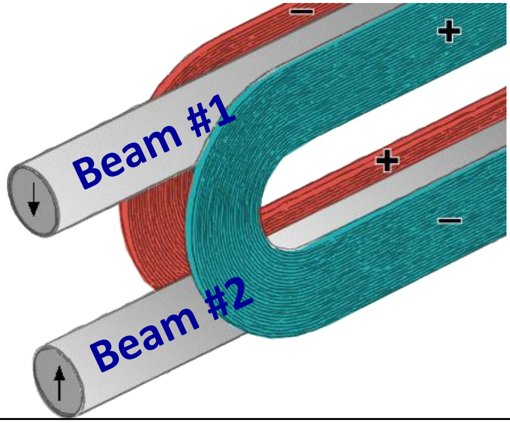
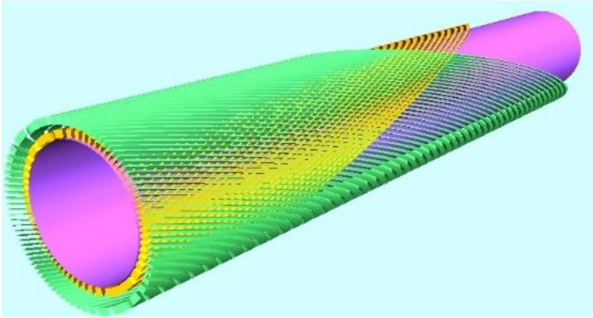


Fig. 2. HD2 cross-section.

Common coil (BNL, IHEP)



Canted cosine theta (LBNL)



Selection of SC Magnet Technology

- Superconductor:
  - Nb_3Sn
  - 2212
  - 2223
  - YBCO
- Magnet design:
  - Cosine theta
  - Block
  - Common coil
  - Canted cosine theta (CCT)

When and how to down-select the SC magnet technology?

- Situation similar to the linear collider in the 90's
- Shall we follow the path of the linear collider technology selection? (i.e., under ICFA to form a "Wiseman" committee for selection)

pp R&D #2 – Synchrotron Radiation Heating

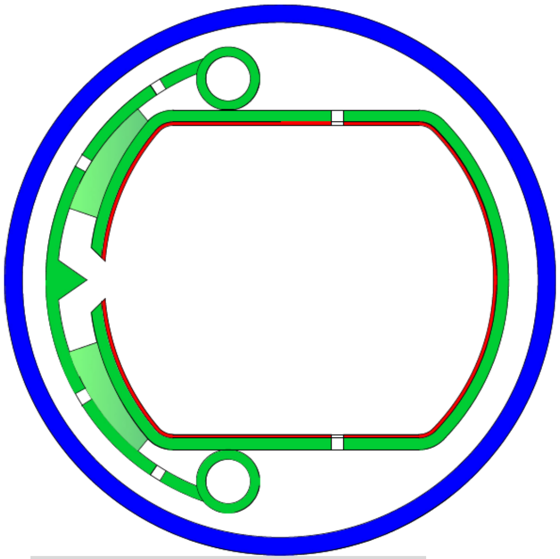
	7TeV(LHC)	16.5TeV(HE-LHC)	50TeV(FCC)	31.7TeV(SPPC)
SR power W/m	0.17w/m	4.35w/m	28.4w/m(100km) 44.3w/m(83km)	45.8w/m(50km)
Critical energy (keV)	0.044	0.575	4.3(100km) 5.5(83km)	2.15

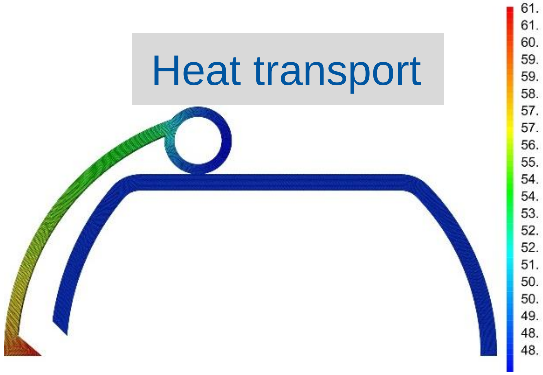
- SR of 100 TeV protons ⇔ 50 GeV electrons

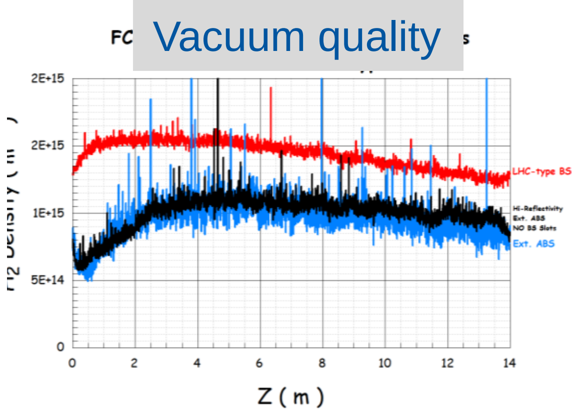
	40 K to 80 K	5 K to 8 K	2K
Efficiency in W/W	16.4	197.9	703.0

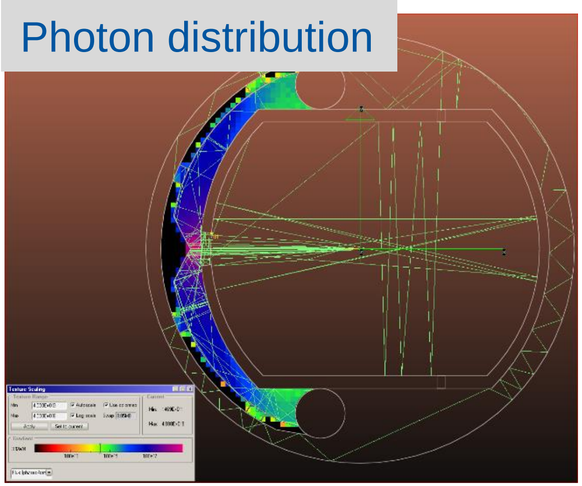
- Plaussible solutions under investigation:
  - Novel beam screen design
  - Open mid-plane magnet
  - Photon stops
  - New ideas

novel beam screen – design example









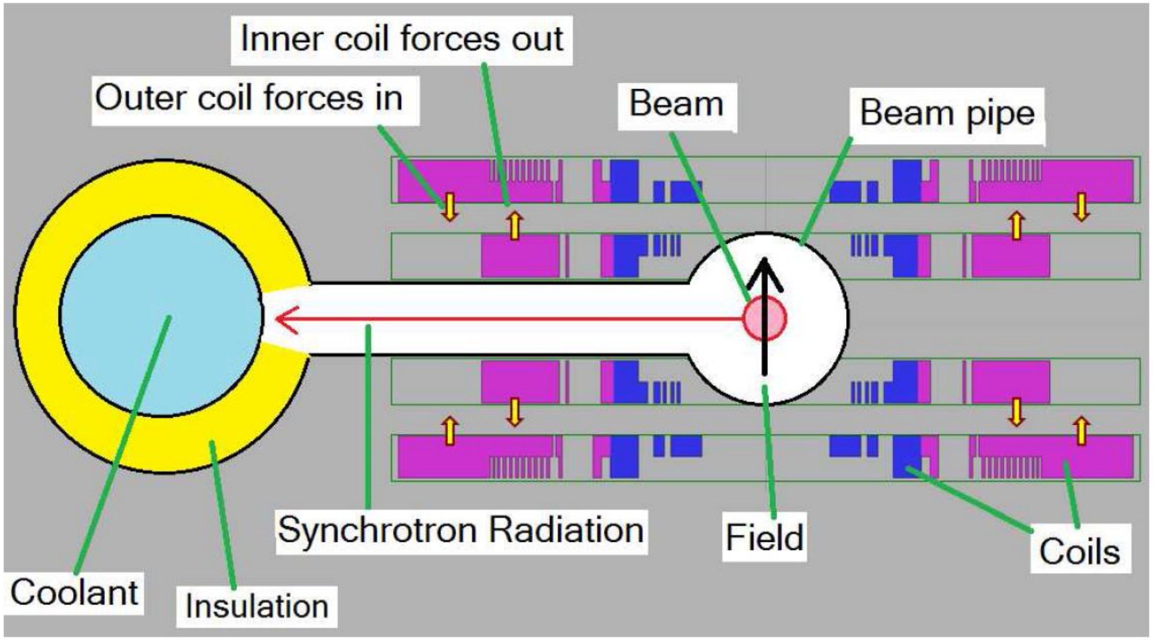
new type of ante-chamber

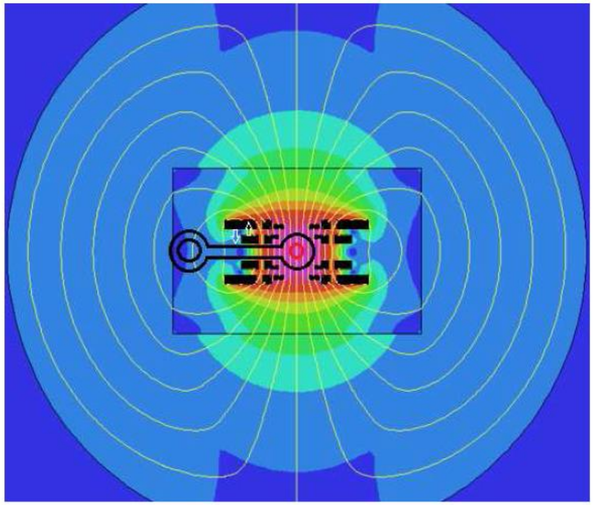
- absorption of synchrotron radiation
- avoids photo-electrons
- helps beam vacuum

R. Kersevan,
C. Garion,
L. Tavian, et a

Open Mid-plane Dipoles

Magnet Division R. Gupta's design[13] for 13.5 T





- Coils shown give very good field uniformity
- The sketched idea of the dump allows cooling at 77 K and space for good thermal insulation to 1.8 K yoke
- The open plane design will be easier at lower dipole fields.

(Bob Palmer, BNL, this workshop)

pp R&D #3 – Machine Protection

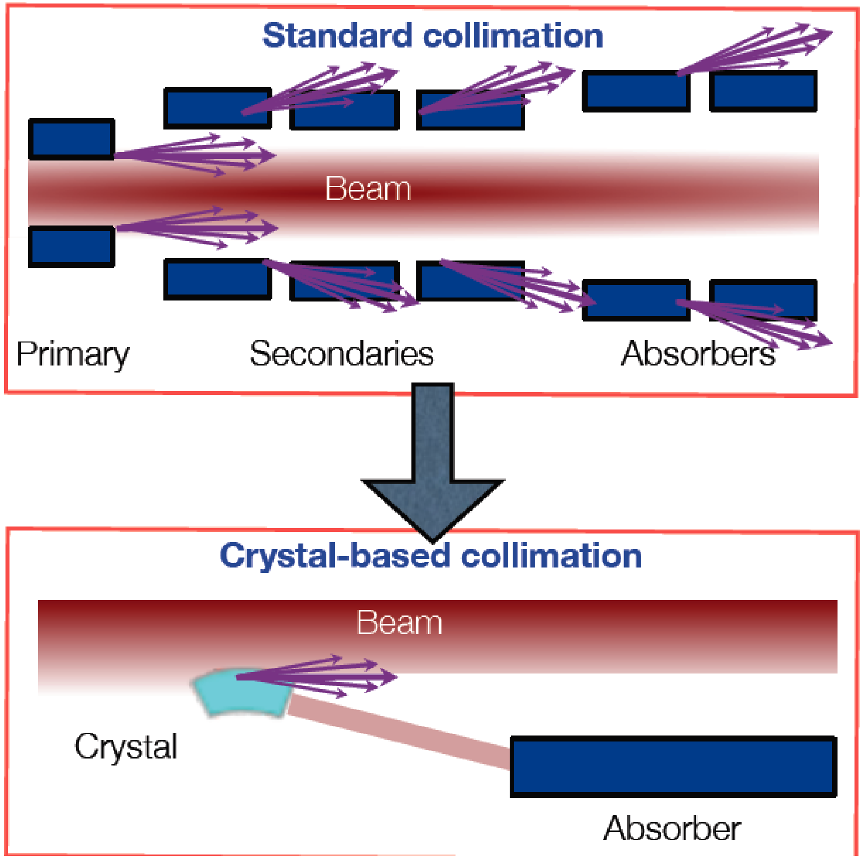
2 tons of TNT

Beam stored enegy:

LHC: 0.4 GJ → *FCC-hh*: 8 GJ (20x more !)

= kinetic energy of Airbus A380 at 720 km/h

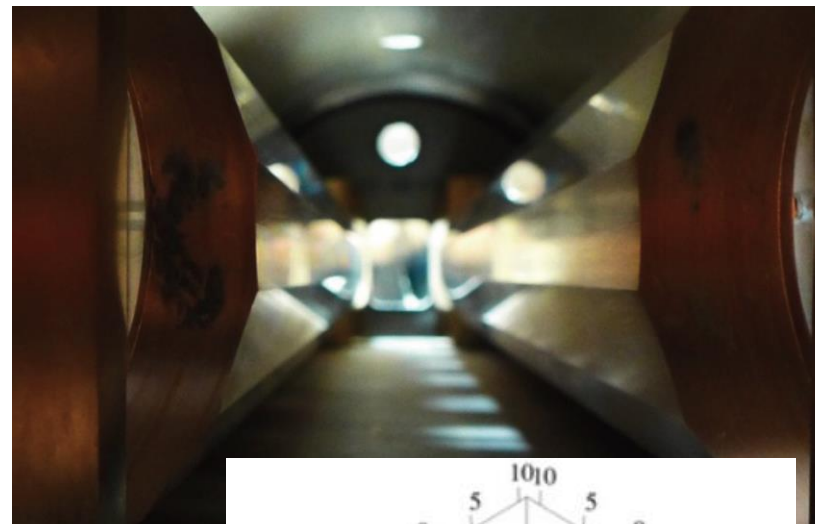
Collimation

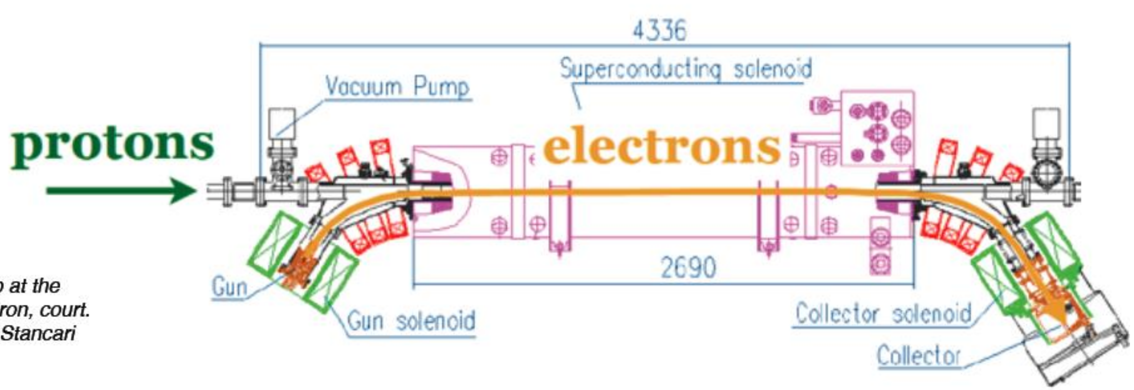


LHC-type solution is baseline, but other approaches should be investigated:

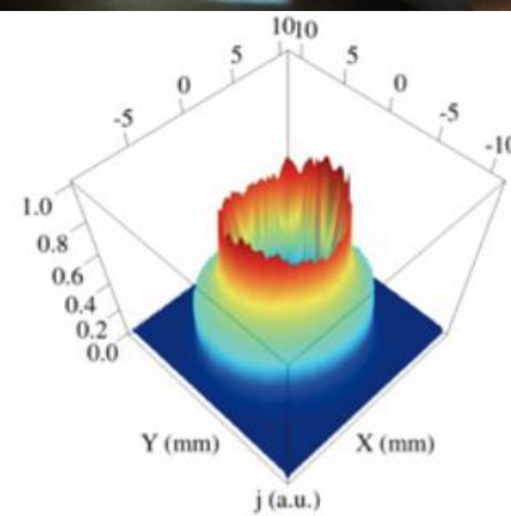
- hollow e^- beam as collimator
- crystals to extract particles
- renewable collimators

D. Schulte,
S. Redaelli

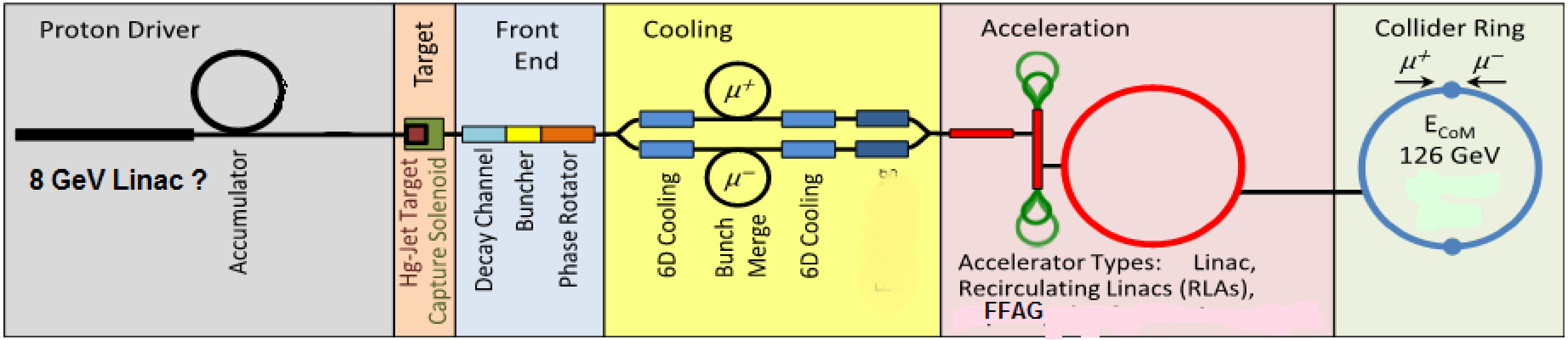


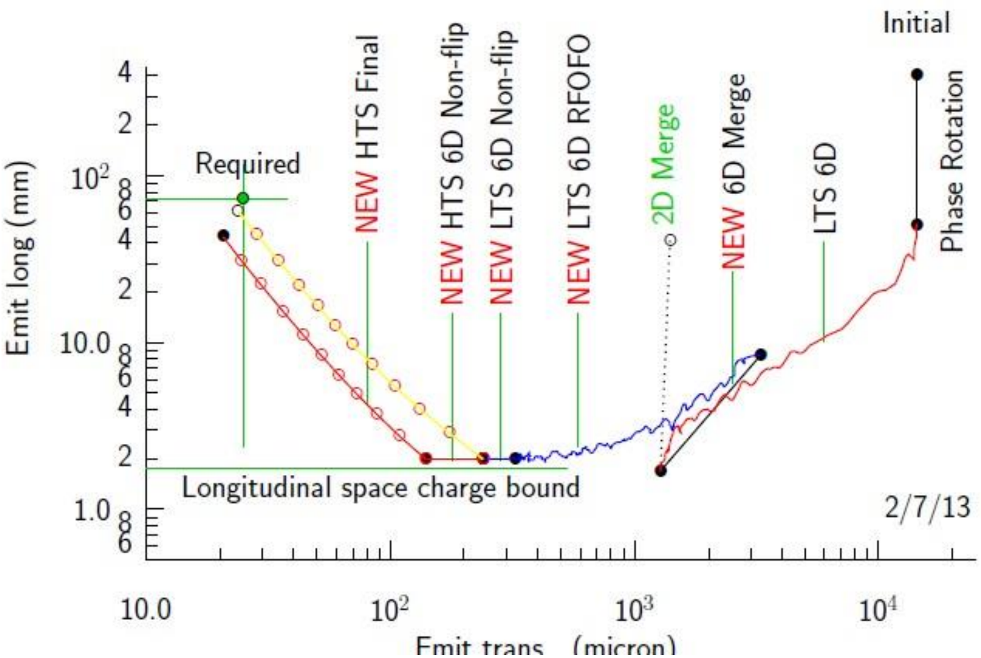


Setup at the Tevatron, court. of G. Stancari



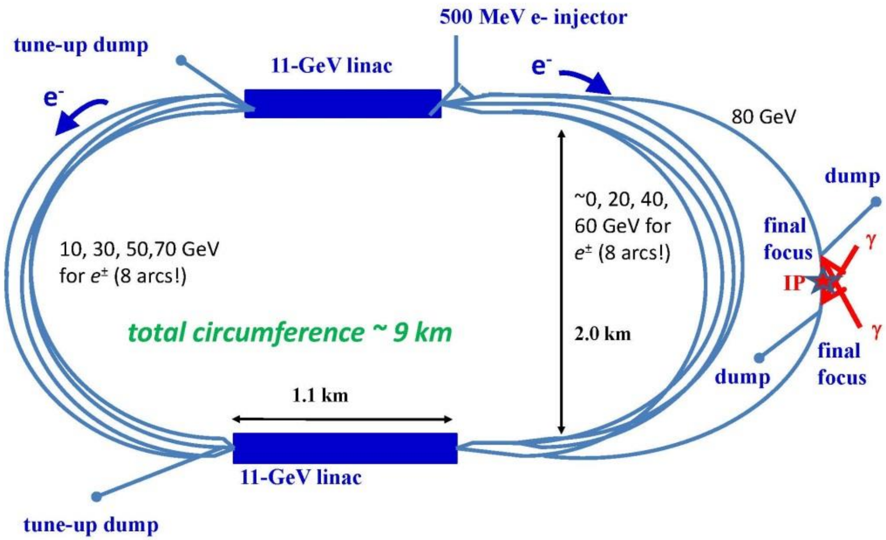
Muon Collider as a Higgs Factory



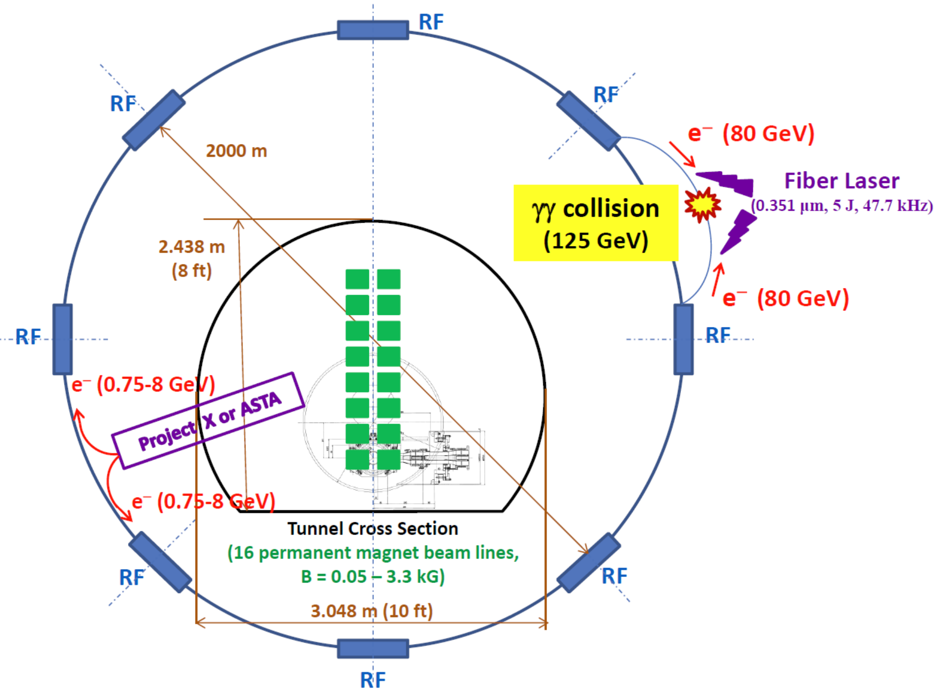


γγ Collider as a Higgs Factory

SAPPHiRE



HFiTT in Tevatron Tunnel



Nature Photonics (G, Mourou et al., v. 7, p. 258, April 2013)

Coherent amplifier network (CAN) based on fiber laser technology would be able to produce 10 J pulse at 10 kHz – meeting the requirement of HFiTT

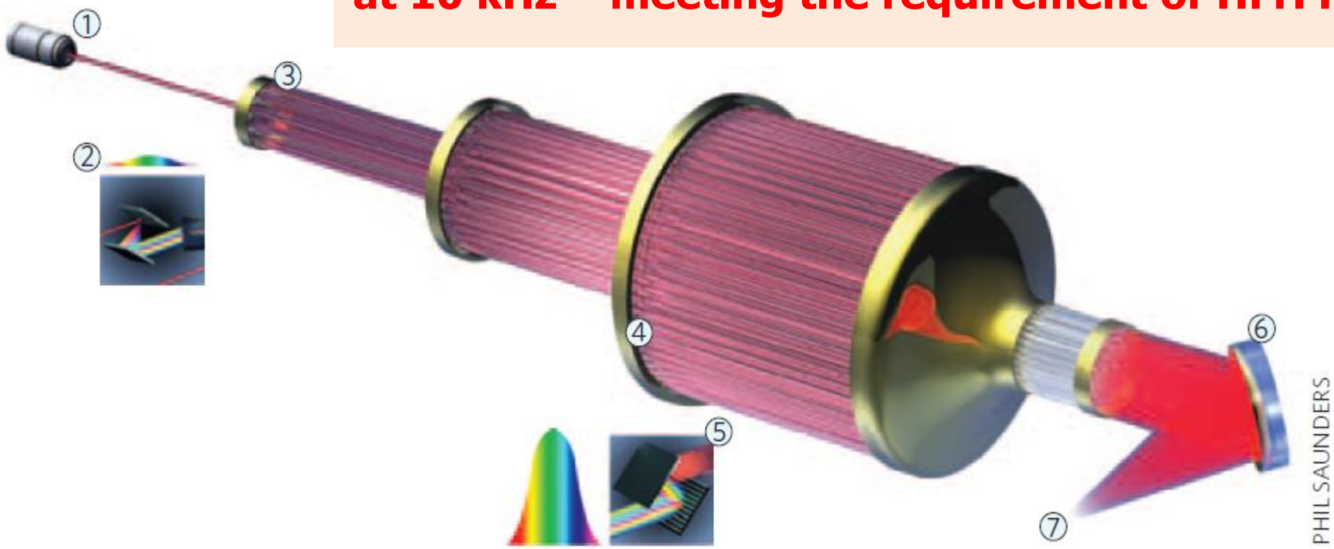
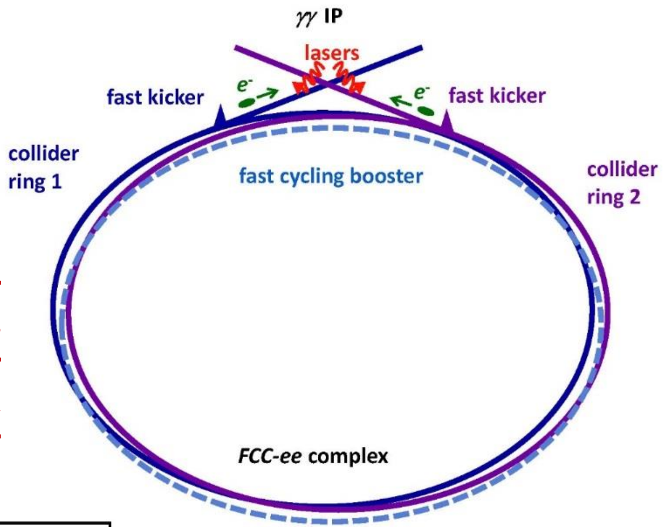


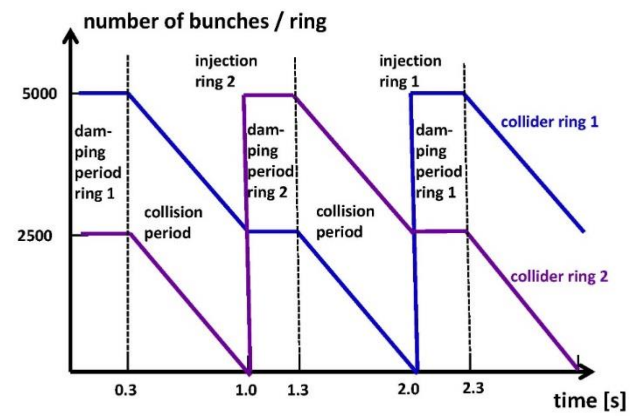
Figure 2: Principle of a coherent amplifier network (CAN) based on fiber laser technology. An initial pulse from a seed laser (1) is stretched (2), and split into many fibre channels (3). Each channel is amplified in several stages, with the final stages producing pulses of ~1 mJ at a high repetition rate (4). All the channels are combined coherently, compressed (5) and focused (6) to produce a pulse with an energy of **>10 J** at a repetition rate of **10 kHz** (7). [5]

CIRCULAR $\gamma\gamma$ HIGGS FACTORY – "FCC-$\gamma\gamma$"

(R. Aleksan, A. Apyan, , Y. Papaphilippou, F. Zimmermann)

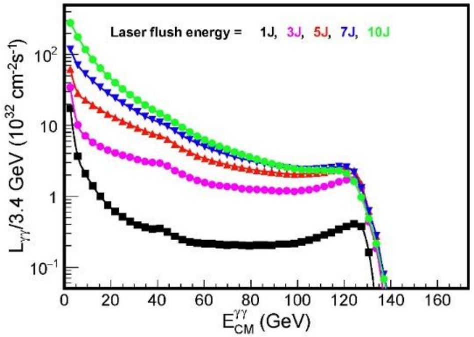
Schematic $\gamma\gamma$ collider based on filling the two FCC-ee collider rings with e^- bunches and extracting one bunch per beam and per turn into a dedicated $\gamma\gamma$ line.



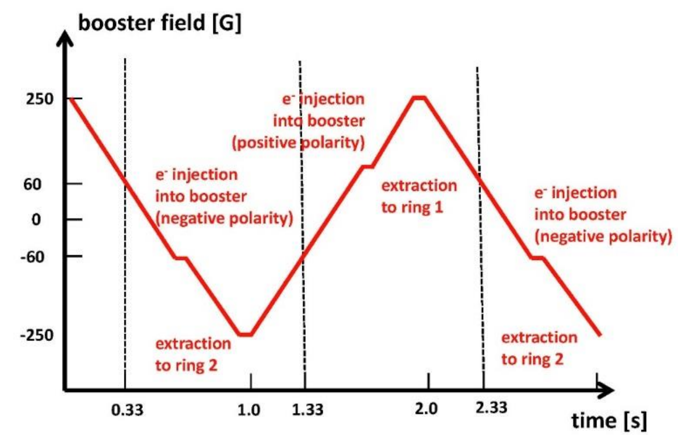


Cycle pattern for the two collider rings

The average laser power required for FCC-$\gamma\gamma$ is more relaxed than for SAPPHiRE. It stays well within the parameter range targeted by ICAN.



The total FCC $\gamma\gamma$ luminosity is 3×10^{34} cm^{-2}s^{-1}. The differential luminosity assumes a local maximum close to the Higgs energy of 2.5×10^{32} cm^{-2}s^{-1} (or 2-3× lower for unpolarised electrons). At FCC-$\gamma\gamma$ about 10000 Higgs bosons are produced in the $\gamma\gamma\rightarrow H$ process for a total effective integrated time of 10^7 s per year.



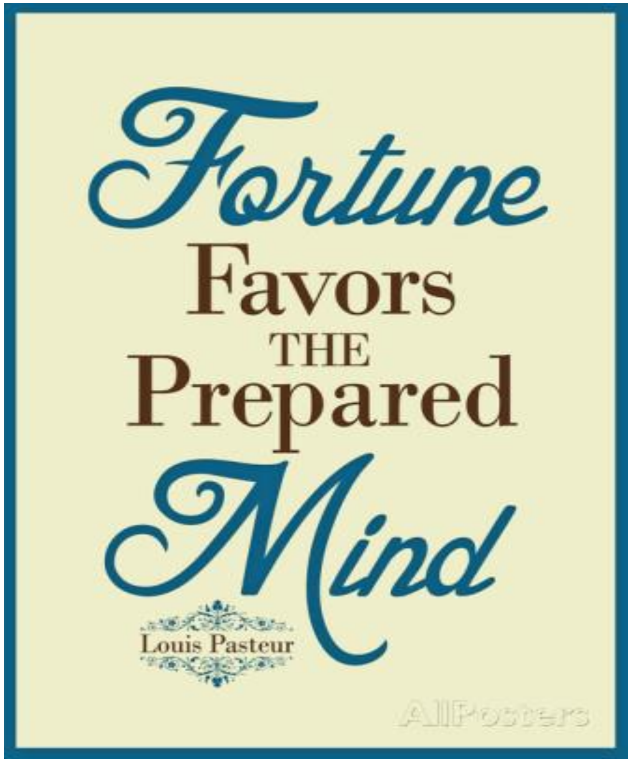
Cycle pattern for the booster (inj. at 20 GeV)

R. Aleksan,; A. Apyan, Y. Papaphilippou, F. Zimmermann, IPAC'15 Richmond

Summary

- FCC and CEPC-SPPC are two exciting and very challenging colliders. They need the best and most dedicated people from our community.
- The goals are set, the challenges are identified, and the plans are in place.
- In order for these machines to be affordable, technology breakthrough will be necessary, in particular for cost efficient Nb_3Sn and HTS material.
    - Cost reduction goal (*ICFA SC magnet mini-workshop 2015 in Shanghai*):
        - **In 15-20 years, to lower the YBCO cost by a factor of 10**
- These are long term projects. Old soldiers never die, but they will fade away. Therefore, the most important planning is <u>to train young generations for these future machines</u>. Existing general purpose schools should be prepared for this. New dedicated schools will be needed (similar to the ILC school).

“The two most important days in your life are the day you are born and the day you find out why.” (Mark Twin)



Concluding Remarks

To imitate J.F. Kennedy's famous speech in 1961 when he announced we will send man to the moon in a decade:

*We choose future circular colliders as our next project, **not because it is easy, but because it is hard**, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend to win.*

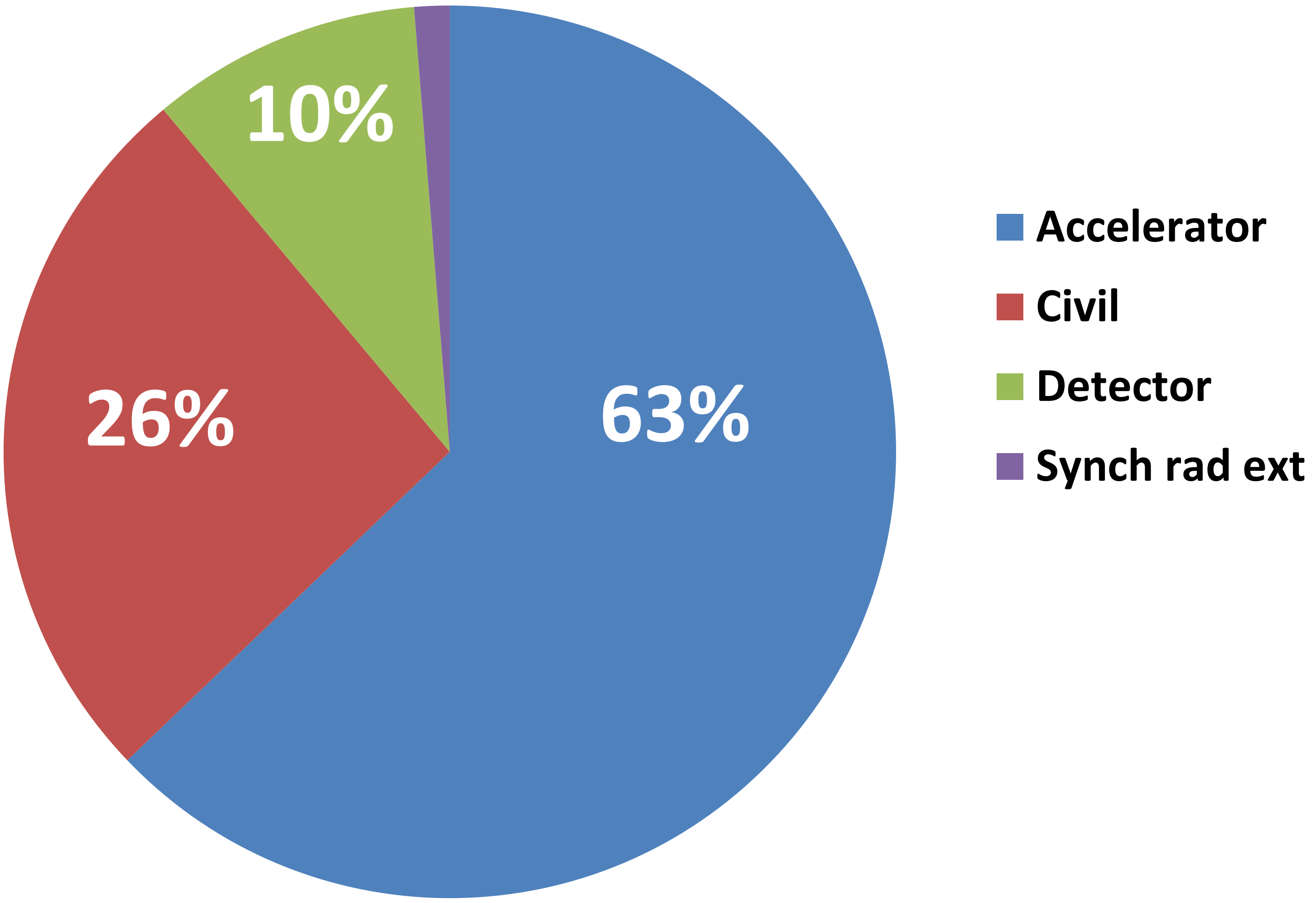
Questions?

Work Breakdown Structure (WBS)

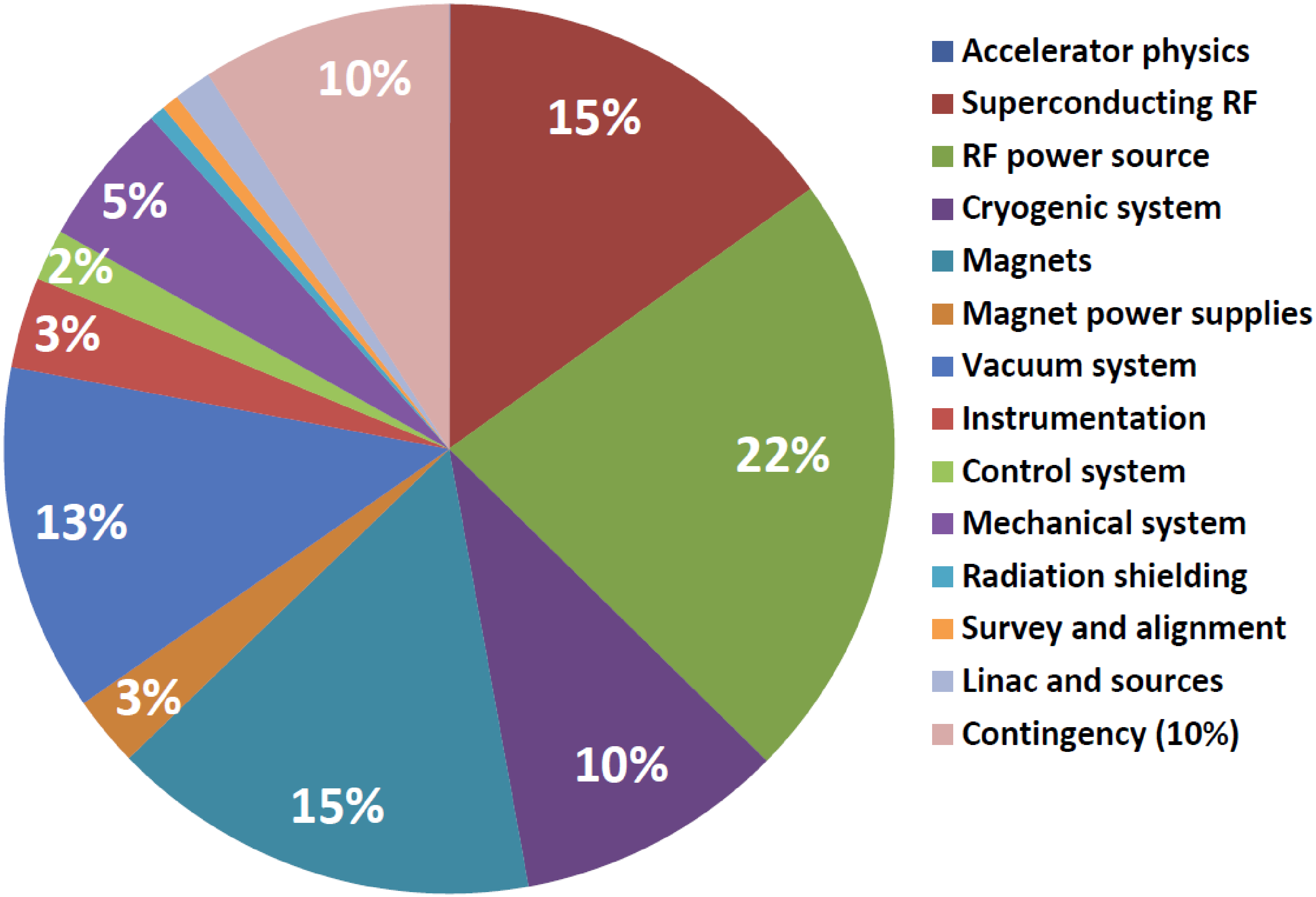
1	合计
2	加速器 Accelerators
2.1	加速器物理
2.2	高频系统
2.3	低温系统
2.4	磁铁系统
2.5	电源系统
2.6	机械系统
2.7	真空系统
2.8	束测系统
2.9	准直
2.10	控制系统
2.11	辐射防护
2.12	直线加速器
2.13	功率源
2.14	增强器
2.15	超导加速器磁铁（SPPC）R&D
2.16	不可预见费10%
3	探测器 Detectors
3.1	径迹探测器（TPC）
3.2	顶点探测器（VTX）
3.3	量能器（电磁+强子）
3.4	Muon探测器
3.5	探测器磁铁
3.6	物理模拟与软件组
3.7	计算资源系统
3.8	触发与数据获取系统
3.9	不可预见费10%

4	同步辐射装置 Light Sources
4.1	光束线站
4.2	不可预见费10%
5	土建 Civil Construction
5.1	地下建筑工程(钻爆法、6.5m)
5.2	地面建筑
5.3	独立费用
5.4	其他费用
5.5	不可预见费10%
6	通用设施 Utilities
6.1	供配电系统
6.2	水冷系统
6.3	通风空调系统
6.4	压缩空气
6.5	独立费用
6.6	其他费用
6.7	不可预见费10%

CEPC Relative Cost



Accelerator Relative Cost



Superconductor Price Comparison

Steve Gourlay – Superconductor price paid by LBNL to the US companies:

NbTi ~ $300/kg
Nb_3Sn ~ $2000/kg
Bi-2212 ~ $20,000/kg

Superconductor price quoted by the Chinese companies:

- Bi-2223: RMB 15,000/kg ⇔ USD 2,400/kg
- YBCO: RMB 20,000/kg ⇔ USD 3,300/kg