Future Circular Electron Positron Colliders: CEPC and FCC-ee

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Institute of High Energy Physics

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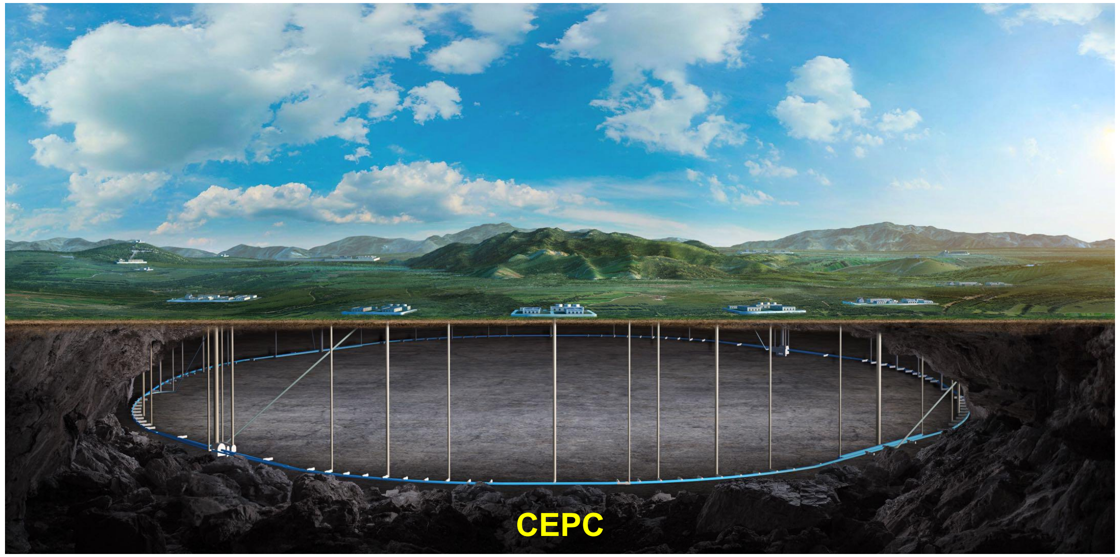
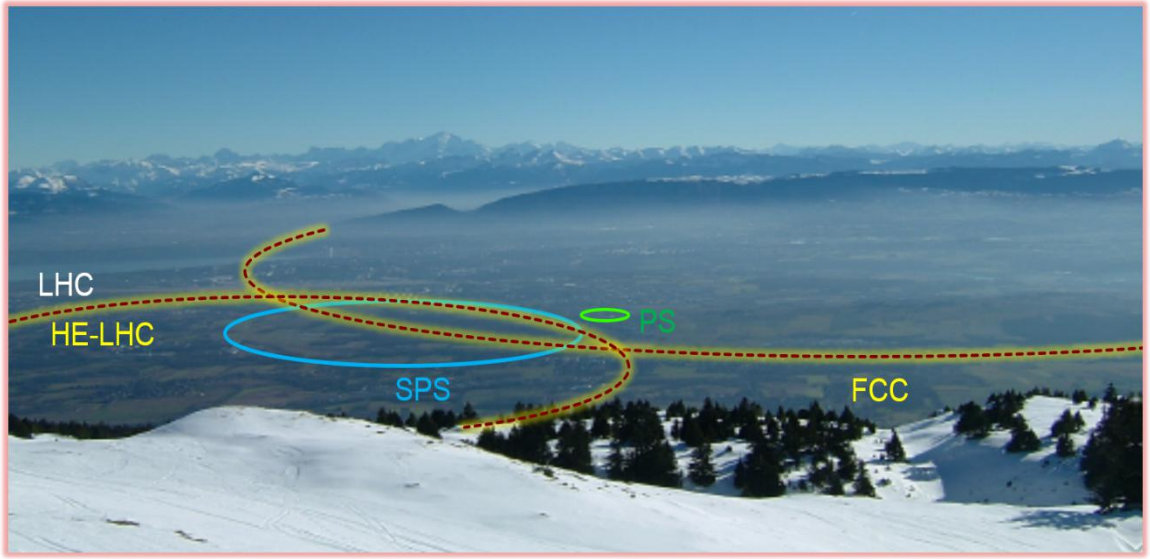
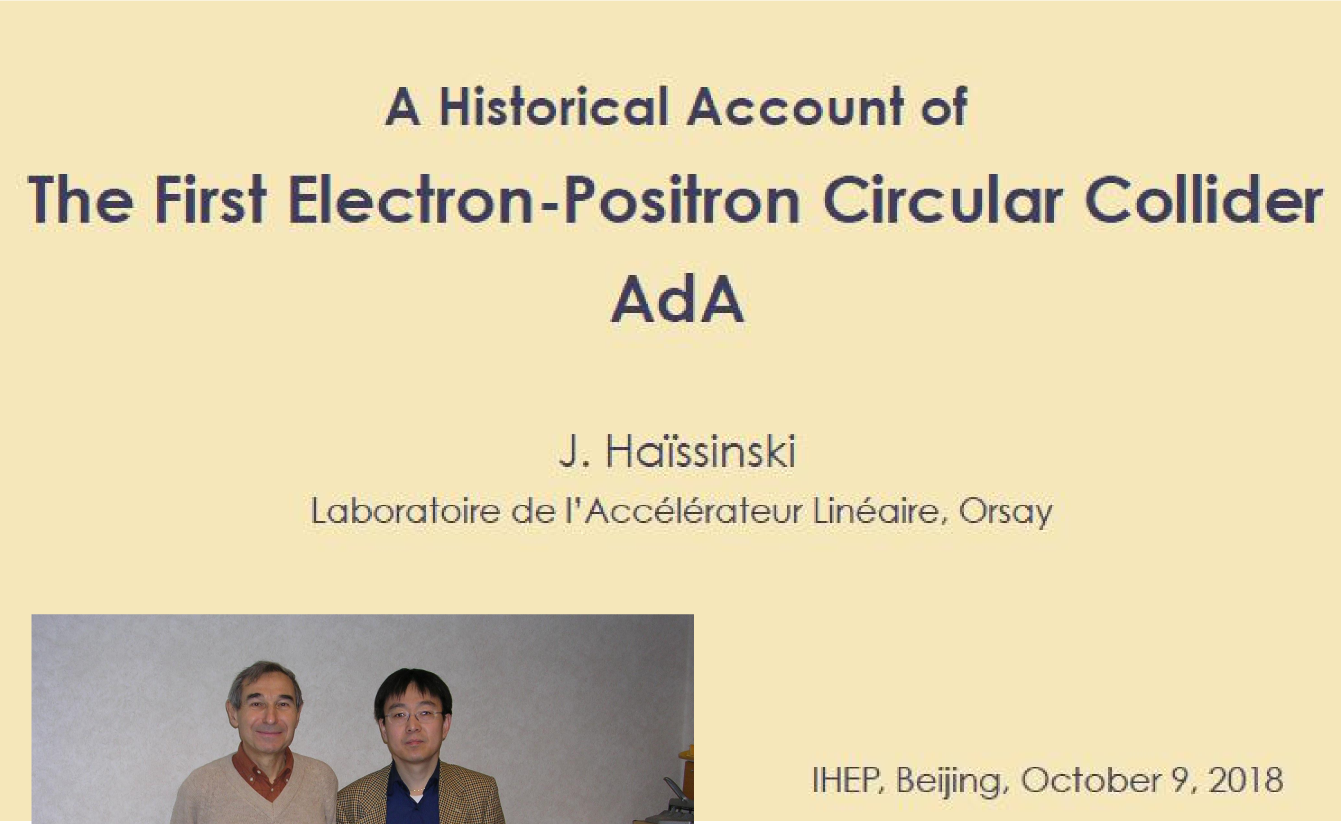




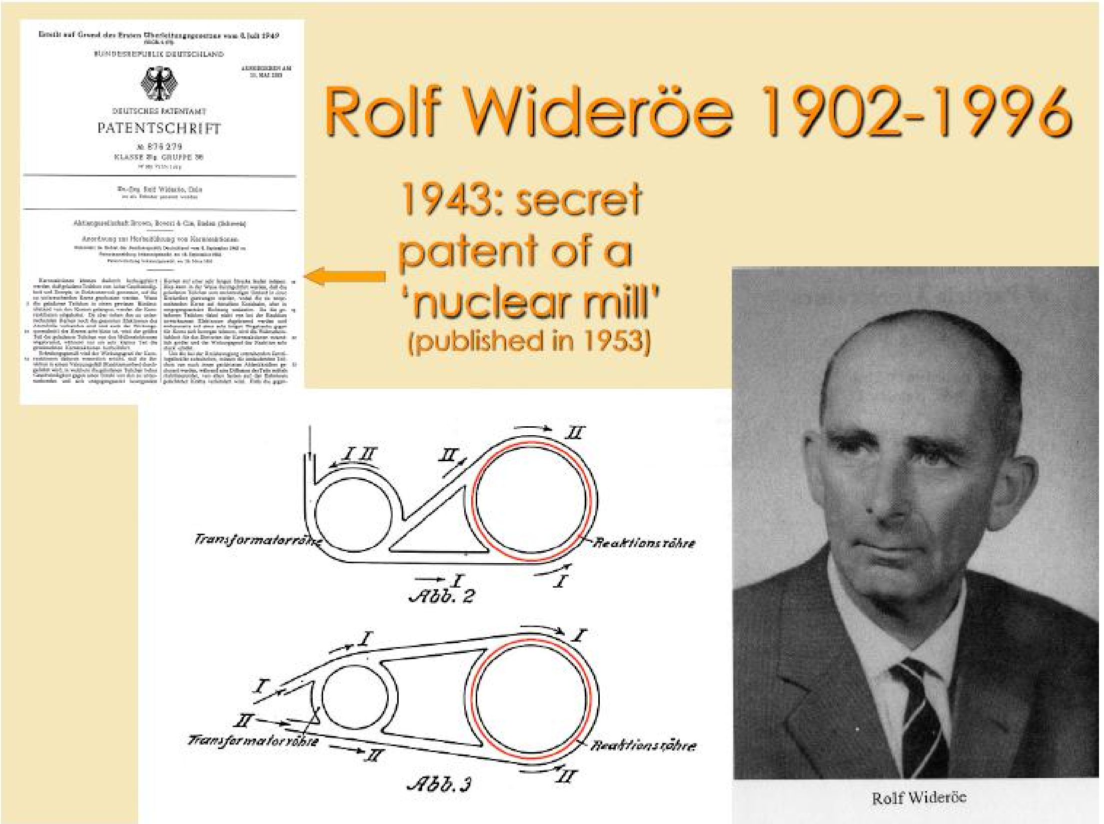
Outline

- Historical review of e+e- circular coliders
- Circular e+e- collider design principles
- FCCee and CEPC status
- Comparison of FCCee and CEPC

Historical Review-1



2004 in the office of
Prof. J. Haissinski,
LAL, Orsay, France



Historical Review-2

Rolf Videröe

was a Norwegian engineer who had given some thoughts to the betatron principle while completing his training in Karlsruhe (1923).

About his circular collider scheme, he wrote:

"...and this is when (1943) I had my idea. If it were possible to store the particles in rings for longer periods, and if these 'stored' particles were made to run in opposite directions, the result would be one opportunity for collision at each revolution..."

Phys. Rev. 102, 590, 15 April 1956 : Attainment of Very High Energy by Means of Intersecting Beams of Particles

D. W. Kerst, F. T. Cole, H. R. Crane, L. W. Jones, L. J. Laslett, T. Ohkawa, A. M. Sessler, K. R. Symon, K. M. Terwilliger, and Nils Vogt Nilsen

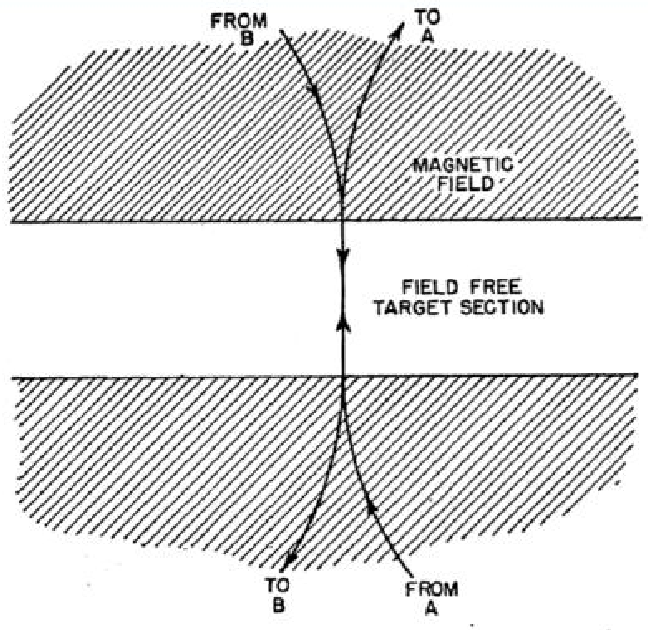


FIG. 1. The target straight section. B and A can be adjacent or concentric fixed-field alternating-gradient accelerators.

Historical Review-3

Phys. Rev. 102, 1418, June 1956: Storage-Ring Synchrotron: Device for High-Energy Physics Research, Gerard K. O'Neill

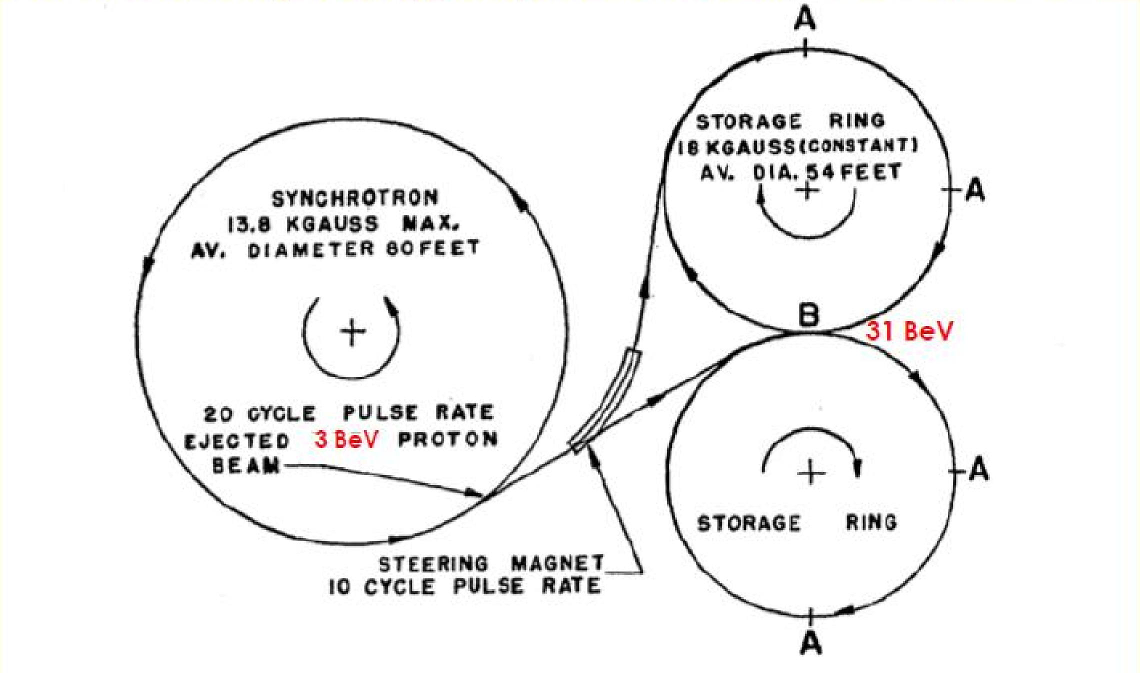


FIG. 1. Plan view of particle orbits in a hypothetical arrangement of storage rings at a 3-Bev proton synchrotron.

HEPL Report, RX-1486, 1958: A Proposed Experiment on the Limits of Quantum Electrodynamics,
Barber, B. Richter, W. K.H. Panofsky, G. K. O'Neill,
Stanford University Internal,

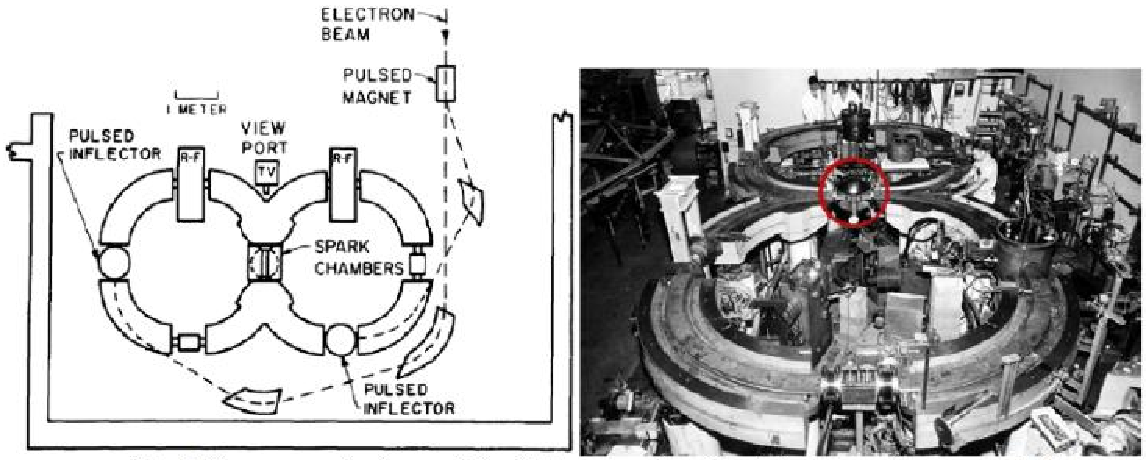


Fig.3: Layout and photo of the Princeton-Stanford electron-electron collider.

IL NUOVO CIMENTO Vol. XVIII, N. 6 16 Dicembre 1960

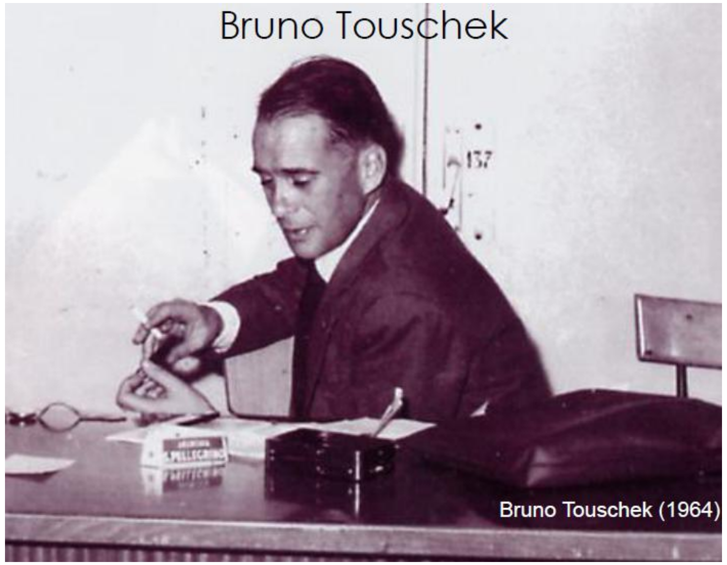
Historical Review-4

The Frascati Storage Ring.

C. Bernardini, G. F. Corazza, G. Ghigo
Laboratori Nazionali del CNEN - Frascati

B. Touschek
Istituto di Fisica dell'Università - Roma
Istituto Nazionale di Fisica Nucleare - Sezione di Roma

(ricevuto il 7 Novembre 1960)



p-p vs e-e- vs e+e- colliders

Each kind of colliders gives access to quite different physics:

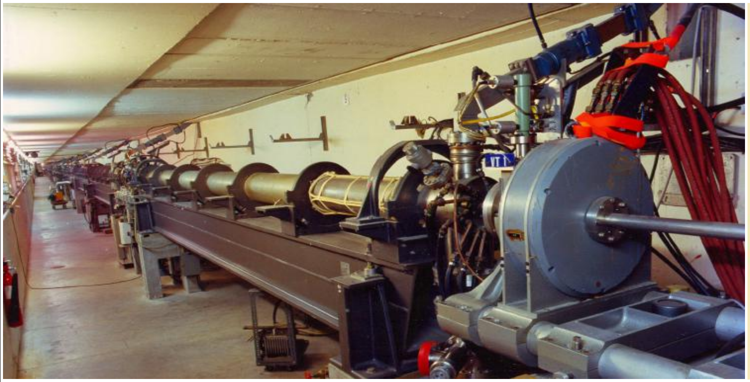
- p-p New particle searches thanks to the high energy reach
- e-e- QED validity limits (electron size, photon propagator)
- e+e- annihilation Adjustable energy deposition in vacuum which allows one to study vacuum excitations → spin-1 boson searches and study.

The technologies involved are quite different too

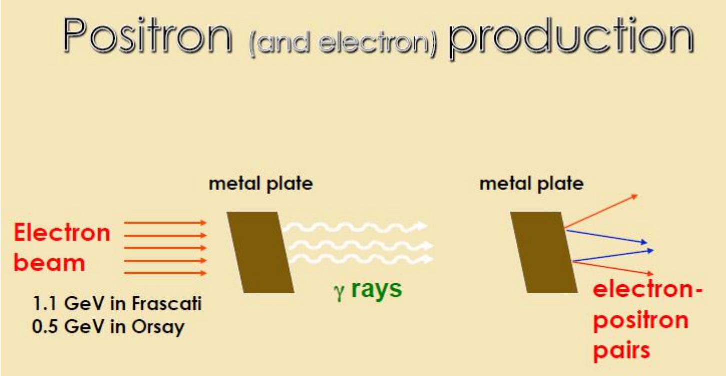
Main parameters of AdA

Parameter	Typical operation value	Units
Energy per beam	200	MeV
Circumference	4	m
Luminosity	$\sim 10^{25}$	$cm^{-2}\ s^{-1}$
Beam current, per beam	0.5	mA
Injector (linac) energy	500	MeV
Max field on the orbit	1.45	T
Field index (dB/B)/(dr/R)	0.54	
Vacuum pressure	1	nTorr
RF peak voltage	5.5	kV

Historical Review-5

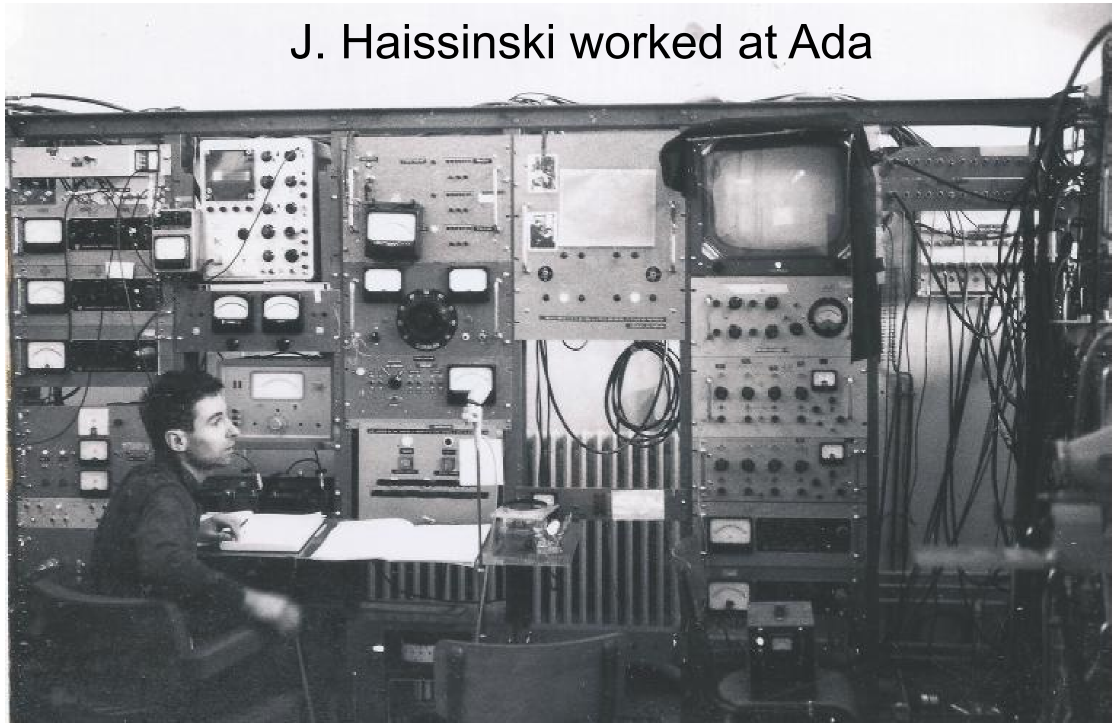


Linac at LAL/Orsay

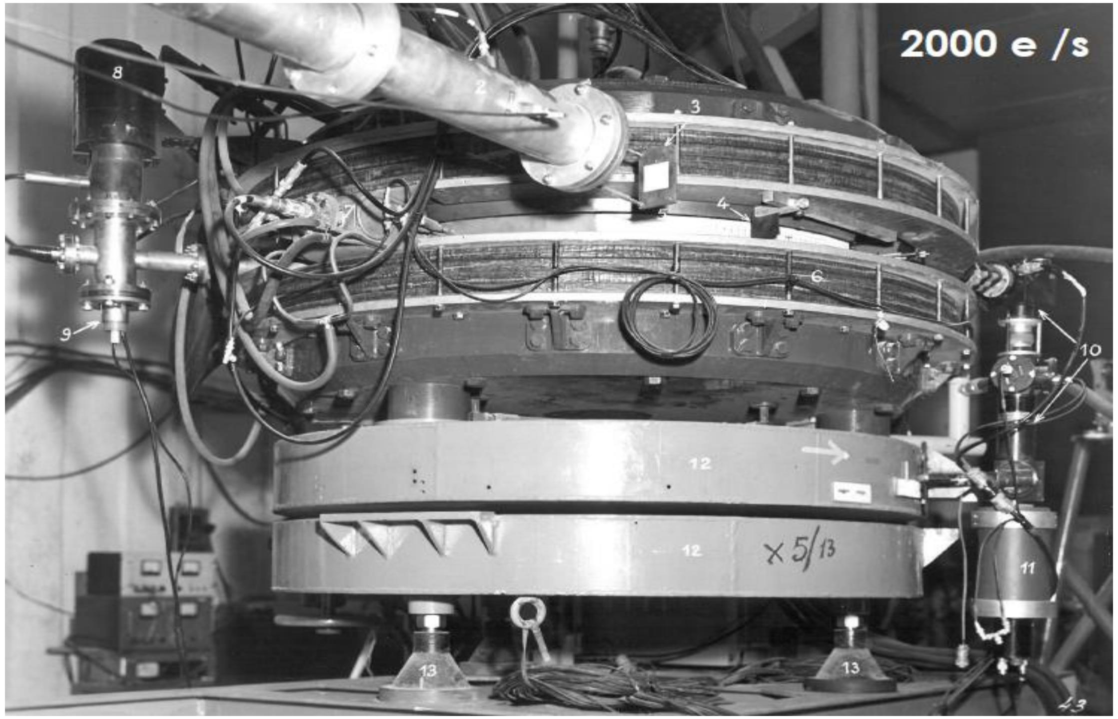


P. Marin and J. Haissinski

Book by P. Marin

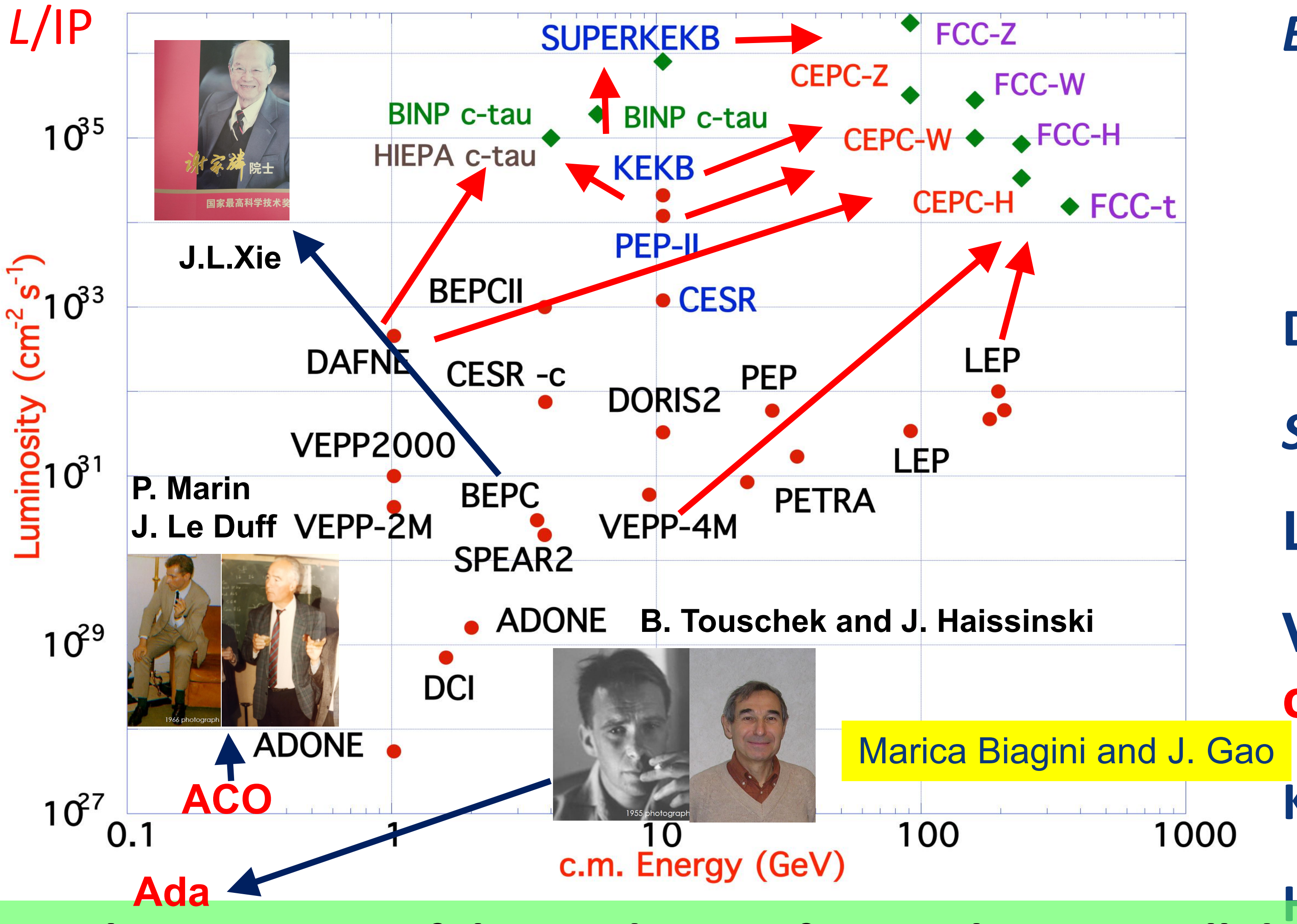


J. Haissinski worked at Ada



Ada at LAL

future circular lepton factories based on proven concepts and techniques from past colliders and light sources



B-factories: **KEKB & PEP-II:**
double-ring lepton colliders,
high beam currents,
top-up injection

DAFNE: crab waist, double ring

Super B-factories, **S-KEKB: low β_y***

LEP: high energy, SR effects

VEPP-4M, LEP: precision E calibration

KEKB: *e^+* source

HERA, LEP, RHIC: spin gymnastics

combining successful ingredients of several recent colliders → highest luminosities & energies

Luminosity from colliding beams

- **For equally intense Gaussian beams**

Collision frequency

Particles in a bunch

$$L = f \frac{N_b^{\ 2}}{4\pi\sigma_x\sigma_y} R$$

Geometrical factor:
- crossing angle
- hourglass effect

Transverse beam size (RMS)

- **Expressing luminosity in terms of our usual beam parameters**

$$L[\mathrm{cm}^{-2}\mathrm{s}^{-1}] = 2.17\times10^{34}(1+r)\xi_y \frac{E[\mathrm{GeV}]I[\mathrm{A}]}{\beta_y[\mathrm{cm}]}$$

where $\xi_y = \frac{r_e N_e \beta_y}{2\pi\sigma_y(\sigma_x+\sigma_y)}$:

$$\xi_y = \frac{r_e N_e \beta_y}{2\pi\sigma_y(\sigma_x + \sigma_y)}$$

Maximum Beam-beam tune shift analytical expressions for lepton and hadron circular colliders

For lepton collider:

$$\xi_{y,\max} = \frac{2845}{2\pi}\sqrt{\frac{T_0}{\tau_y \gamma N_{IP}}} \qquad \xi_{y,\max} = \frac{2845\gamma}{1}\sqrt{\frac{r_e}{6\pi R N_{IP}}}$$

r_e is electron radius
γ is normalized energy
R is the dipole bending radius
N_{IP} is number of interaction points

$$\xi_{x,\max} = \sqrt{2}\,\xi_{y,\max}$$

J. Gao, **Nuclear Instruments and Methods in Physics Research A** 533 (2004) 270–274

J. Gao, Nuclear Instruments and Methods in Physics Research A 463 (2001) 50–61

For hadron collider:

$$\xi_{\max} = \frac{2845\gamma}{f(x)}\sqrt{\frac{r_p}{6\pi R N_{IP}}}$$

where r_p is proton radius

$$f(x) = 1 - \frac{2}{\sqrt{2\pi}}\int_0^x \exp\left(-\frac{t^2}{2}\right)dt$$

$$x^2 = \frac{4f(x)}{\pi \xi_{\max} N_{IP}} = \frac{4f^2(x)}{2845\pi\gamma}\sqrt{\frac{6\pi R}{r_p N_{IP}}}$$

J. Gao, "Review of some important beam physics issues in electron positron collider designs", **Modern Physics Letters A**, Vol. 30, No. 11 (2015) 1530006 (20 pages)

J. Gao, et al, "Analytical estimation of maximum beam-beam tune shifts for electron-positron and hadron circular colliders", Proceedings of ICFA Workshop on High Luminosity Circular e+e- Colliders – Higgs Factory, 2014

Constraints for parameter choice

- Limit of Beam-beam tune shift

$$\xi_y = \frac{2845}{2\pi}\sqrt{\frac{U_0}{2\gamma E_0 N_{IP}}} \times F_l \,*$$

F_l: ξy enhancement by crab waist

J. Gao*

- Beam lifetime due to beamstrahlung

BS life time: 30 min

$$\frac{N_e}{\sigma_x \sigma_z} \le 0.1\eta \frac{\alpha}{3\gamma r_e^2}$$

1) V. Telnov, arXiv:1203.6563v, 29 March 2012
2) V. Telnov, HF2012, November 15, 2012

- Beamstrahlung energy spread

$A=\delta_0/\delta_{BS}$ ($A \ge 3$)

- Beam currect limited by either radiation power or by HOM power per cavity

$$P_{HOM} = k(\sigma_z) e N_e * 2I_b \le 2KW$$

*1) J. Gao, emittance growth and beam lifetime limitations due to beam-beam effects in e+e- storage rings, **Nucl. Instr. and methods A**533（2004）p. 270-274.

* 2) J. Gao, Review of some important beam physics issues in electron positron collider designs, **Modern Physics Letters A**, Vol. 30, No. 11 (2015) 1530006 (20 pages)

3) D. Wang, J. Gao, et al, Optimization parameter design of a circular e+e- Higgs factory, **Chinese Physcis C**, Vol. 40, No. 1 (2016) 017001-017007

4) D. Wang. J. Gao, eta al, Optimization parameter design of a circular e+e- collider with crab-waist, to be submitted to **Chinese Physcis C**

Basic theroy of dynamic aperture in circular accelerator-1

$$H=\frac{p^2}{2}+\frac{K(s)}{2}x^2+\frac{1}{m!B_0\rho}\frac{\partial^{m-1}B_z}{\partial x^{m-1}}x^m L\sum_{k=-\infty}^{\infty}\delta(s-kL)$$

Circular machine

A nonlinear multipole

$$B_z=B_0(1+xb_1+x^2b_2+x^3b_3+\cdots+x^{m-1}b_{m-1}+\cdots)$$

For one multipole $B_z=B_0x^{m-1}b_{m-1}$ m≥3

$$\Psi=\int_0^s\frac{ds'}{\beta_x(s')}+\phi_0$$

$$J=\frac{\varepsilon_x}{2}=\frac{1}{2\beta_x(s)}\left(x^2+\left(\beta_x(s)x'-\frac{\beta_x'x}{2}\right)^2\right)$$

$$H(J,\Psi)=\frac{J}{\beta_x(s)}.$$

$$\Psi_1=\Psi+\frac{2\pi v}{L}-\int_0^s\frac{ds'}{\beta_x(s')}$$

$$J_1=J$$

$$H_1=\frac{2\pi v}{L}J_1.$$

$$I=\frac{x^2B_y|_{x=0,y=0}}{2\rho^2B_0}+\frac{1}{B_0\rho}\sum_{n=1}^{\infty}\frac{1}{n!}\frac{\partial^{n-1}B_y}{\partial x^{n-1}}\bigg|_{x=0,y=0}(x+iy)^n-(1+x/\rho)\left(\left(1+\frac{\Delta P}{P_0}\right)^2-\left(\bar{p}_x-\frac{eA_x}{P_0}\right)^2-\left(\bar{p}_y-\frac{eA_y}{P_0}\right)^2\right)^{1/2}-\frac{e\Phi}{P_0}$$

$$x=\sqrt{2J_1\beta_x(s)}\cos\left(\Psi_1-\frac{2\pi v}{L}s+\int_0^s\frac{ds'}{\beta_x(s')}\right).$$

$$\frac{dJ_1}{ds}=-\frac{\partial H_1}{\partial\Psi_1}$$

$$\frac{d\Psi_1}{ds}=\frac{\partial H_1}{\partial J_1}$$

$$\overline{J_1}=\overline{J_1}(\Psi_1,J_1)$$

$$\overline{\Psi_1}=\overline{\Psi_1}(\Psi_1,J_1)$$

$$\bar{I}=I+K_0\sin\theta$$

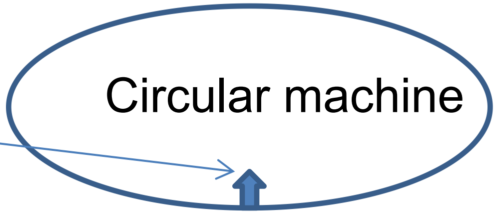
$$\bar{\theta}=\theta+\bar{I}$$

$|K_0|\le 1$ （0.97164) → Analytical DA expressions

J. Gao, “Analytical estimation of the dynamic apertures of circular accelerators”, **Nuclear Instruments and Methods in Physics Research A** 451 (2000) 545-557.

Basic theroy of dynamic aperture in circular accelerator-2

$$H = \frac{p^2}{2} + \frac{K(s)}{2} x^2 + \frac{1}{m! B_0 \rho} \frac{\partial^{m-1} B_z}{\partial x^{m-1}} x^m L \sum_{k=-\infty}^{\infty} \delta(s - kL)$$



$$B_z = B_0(1 + x b_1 + x^2 b_2 + x^3 b_3 + \cdots + x^{m-1} b_{m-1} + \cdots)$$

For one multipole $B_z = B_0 x^{m-1} b_{m-1}$ m≥3

$$A_{\mathrm{dyna},2m} = \sqrt{2\beta_x(s)} \left(\frac{1}{m \beta_x^m (s(2m))} \right)^{\frac{1}{2(m-2)}} \left(\frac{\rho}{|b_{m-1}| L} \right)^{1/(m-2)}$$

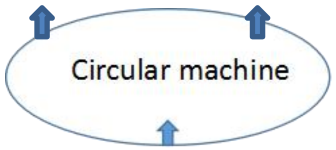
Standard Mapping
Chirikov Criterion

Relation between X and Y $A_{\mathrm{dyna},2m,y} = \sqrt{\frac{\beta_x(s(2m))}{\beta_y(s(2m))} (A^2_{\mathrm{dyna},2m,x} - x^2)}$

Hénon and Heiles problem

For more independent multipoles

$$A_{\mathrm{dyna,total}} = \frac{1}{\sqrt{\sum_i \frac{1}{A^2_{\mathrm{dyna,sext},i}} + \sum_j \frac{1}{A^2_{\mathrm{dyna,oct},j}} + \sum_k \frac{1}{A^2_{\mathrm{dyna,deca},k}} + \cdots}}$$



J. Gao, "Analytical estimation of the dynamic apertures of circular accelerators", **Nuclear Instruments and Methods in Physics Research A** 451 (2000) 545-557.

FCCee

FCC-ee basic design choices

double ring e^+e^- collider ~100 km

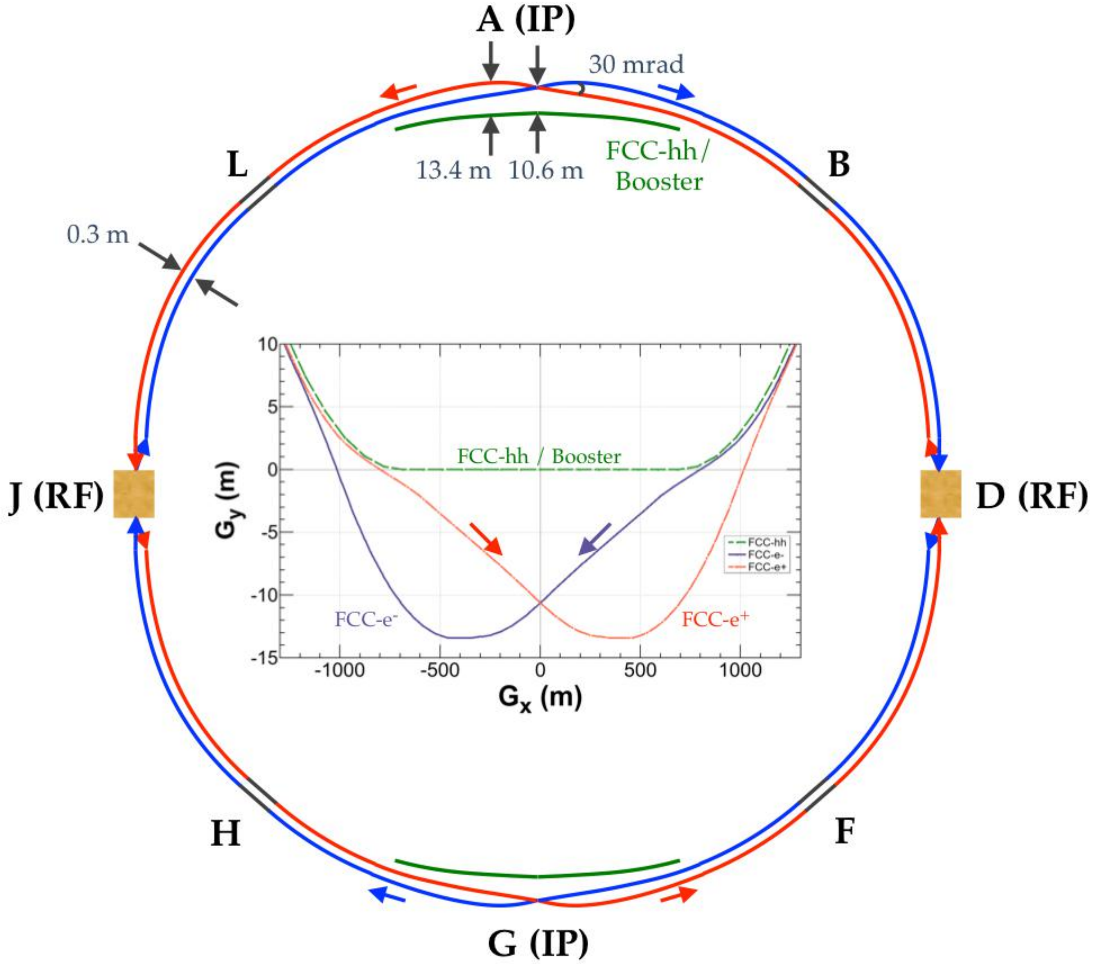
follows footprint of FCC-hh, except around IPs

asymmetric IR layout & optics to limit synchrotron radiation towards the detector

presently 2 IPs (alternative layouts with 3 or 4 IPs under study), **large** horizontal crossing angle **30 mrad, crab-waist optics**

synchrotron radiation power 50 MW/beam at all beam energies; tapering of arc magnet strengths to match local energy

top-up injection scheme; requires **booster synchrotron in collider tunnel**



K. Oide et al.

FCC-ee collider parameters

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5
luminosity per IP [10^{34} cm^{-2}s^{-1}]	230	28	8.5	1.55
beam lifetime rad Bhabha / BS [min]	68 / >200	49 / >1000	38 / 18	40 / 18

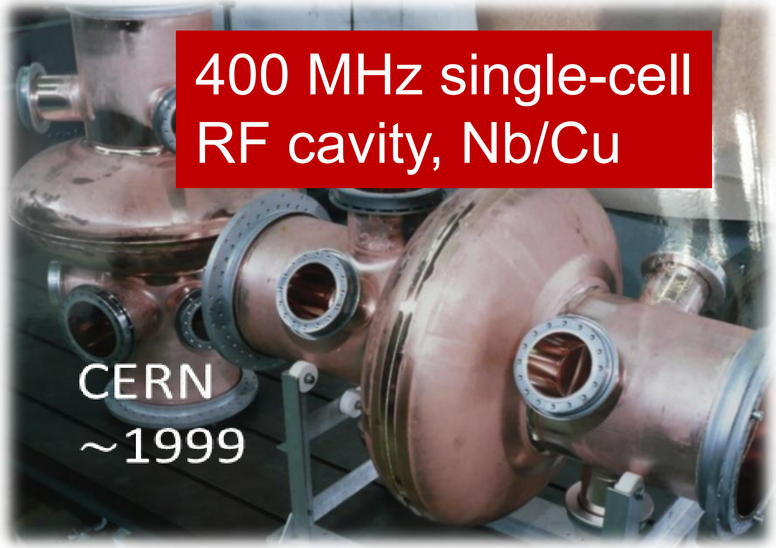
RF systems for circular e^+e^- colliders

	f_{RF} [MHz]	#cavities	#cell/cavity	$V_{RF,tot}$ [MV]	acc. gradient [MV/m]	technology
SuperKEKB	**509**	30 (ARES) 8 (SCC)	1 1	15 12	2 6	warm Cu bulk Nb
charm-tau	**500**	1 / ring	1	2x1	6	bulk Nb
FCC-ee-H	**400**	136 / ring	4	2000	10	Nb/Cu
FCC-ee-t (addt'l)	**800**	372	5	6930	19.8	bulk Nb
CEPC	**650**	240	2	2200	19.7	bulk Nb

- all systems between 400 and 800 MHz, various technologies,
- preference for SC cavities,
- FCC-ee RF system optimized for each working point, CEPC features single system

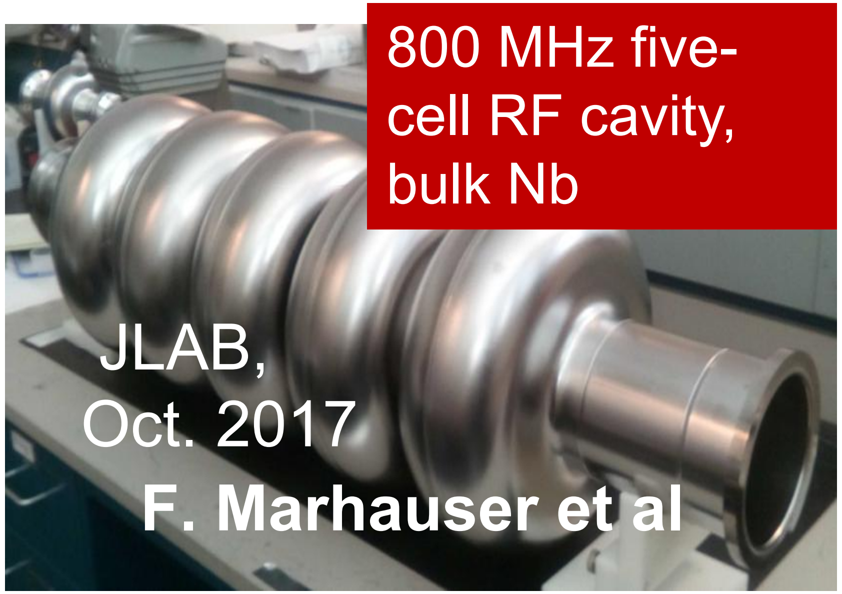
FCC-ee RF cavities – optimized for each running mode

Z running:
single-cell cavities,
400 MHz, Nb/Cu at 4.5 K,
like LHC cavities



Z-pole FCC-ee: 116 single-cell cavities (collider + booster)

$t\bar{t}$ running:
five-cell cavities,
800 MHz bulk Nb at 2 K,
prototyped at JLAB,
added to 400 MHz Nb/Cu four-cell cavities at 4.5 K,
similar to LEP-2 cavities

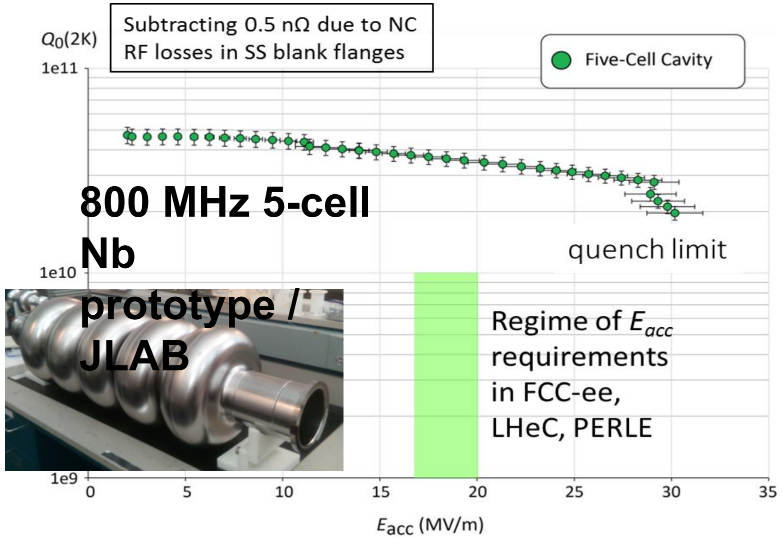


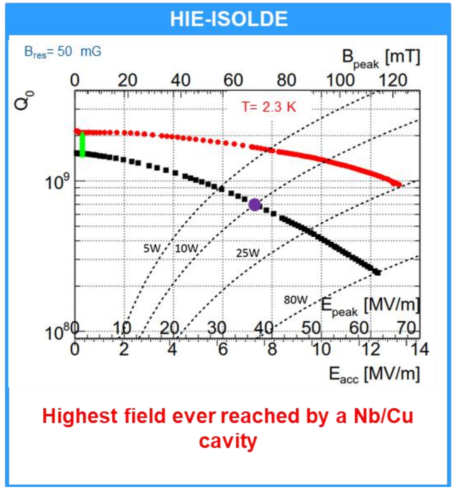
$t\bar{t}$ FCC-ee: 396 four-cell 400 MHz + 852 five-cell 800 MHz cavities (collider + booster)

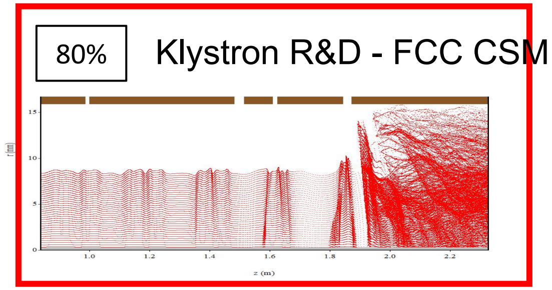
RF R&D activities – towards higher efficiency

Several R&D lines aim at improving performance and efficiency and reducing cost:

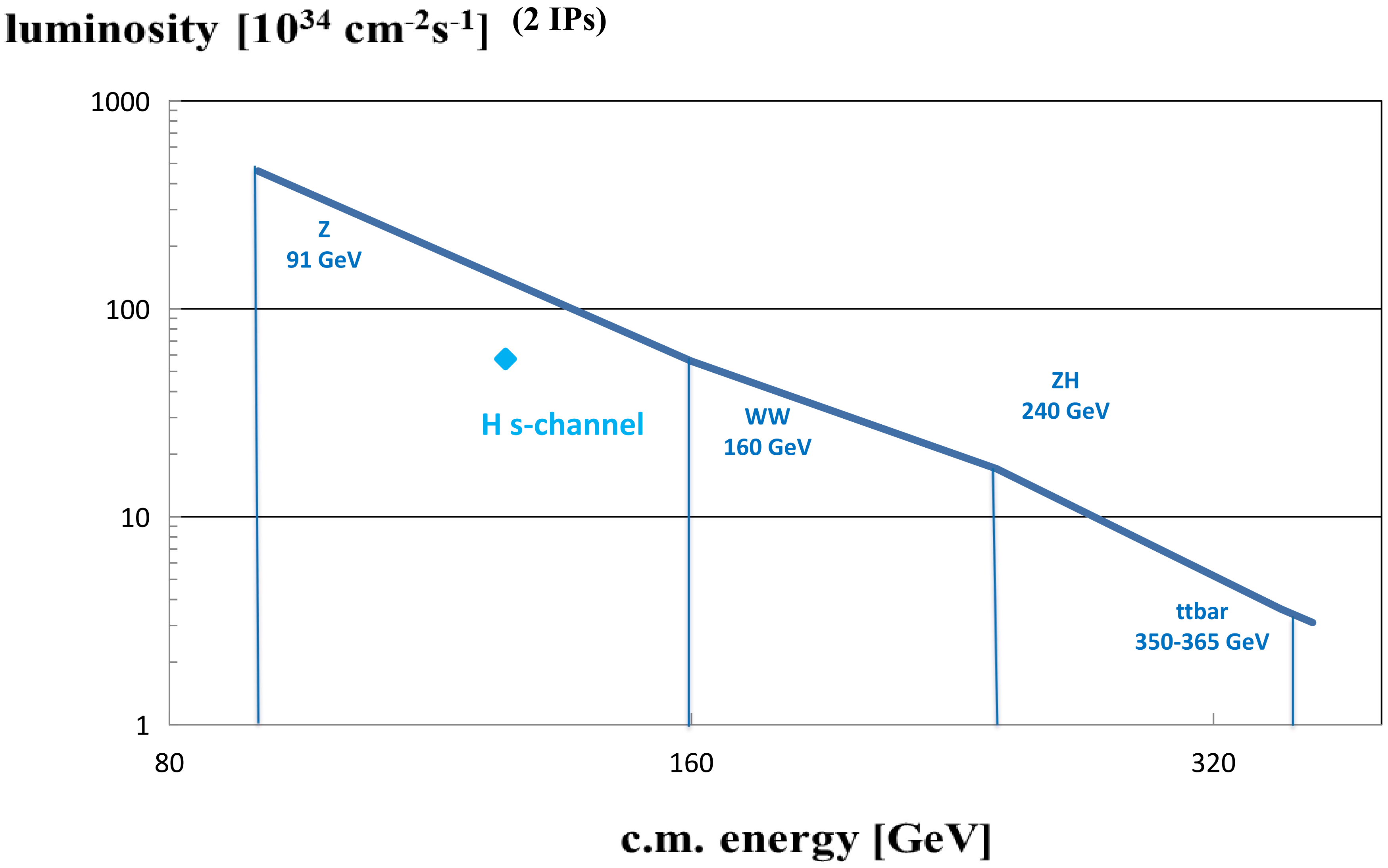
- Improved Nb/Cu coating/sputtering (e.g. ECR fibre growth, HiPIMS)
- New cavity fabrication techniques (e.g. EHF, improved polishing, seamle
- Coating of A15 superconductors (e.g. Nb_3Sn)
- Bulk Nb cavity R&D at FNAL, JLAB, Cornell, also KEK and CEPC/IHEP
- High efficiency klystrons (e.g. COM, BAC, CSM) – synergy with HL-LHC
- MW-class fundamental power couplers for 400 MHz



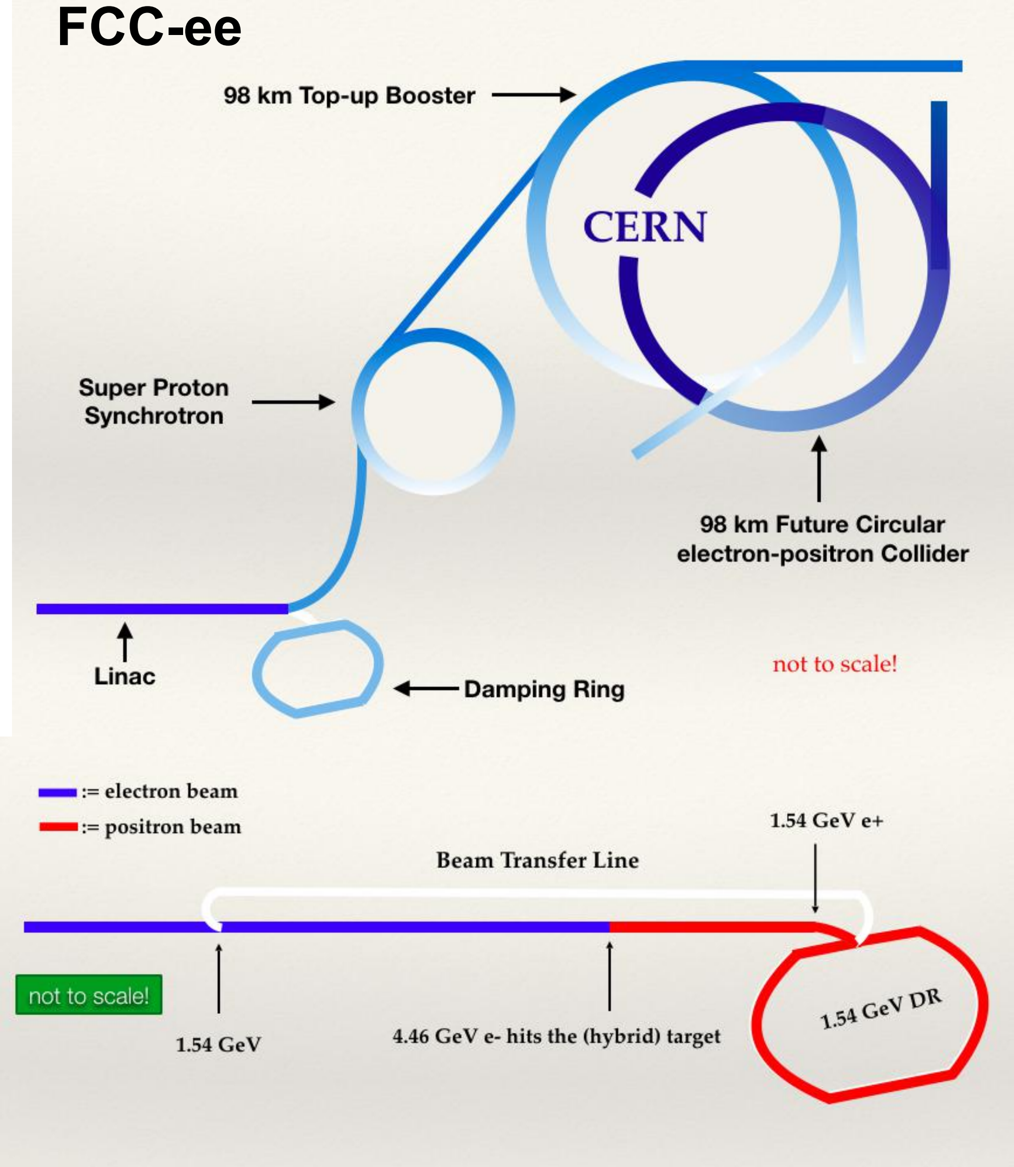




FCC-ee luminosity versus energy



FCCee injector complex



SLC/SuperKEKB-like 6 GeV linac accelerating; **1** or **2** bunches with repetition rate of **100-200 Hz**

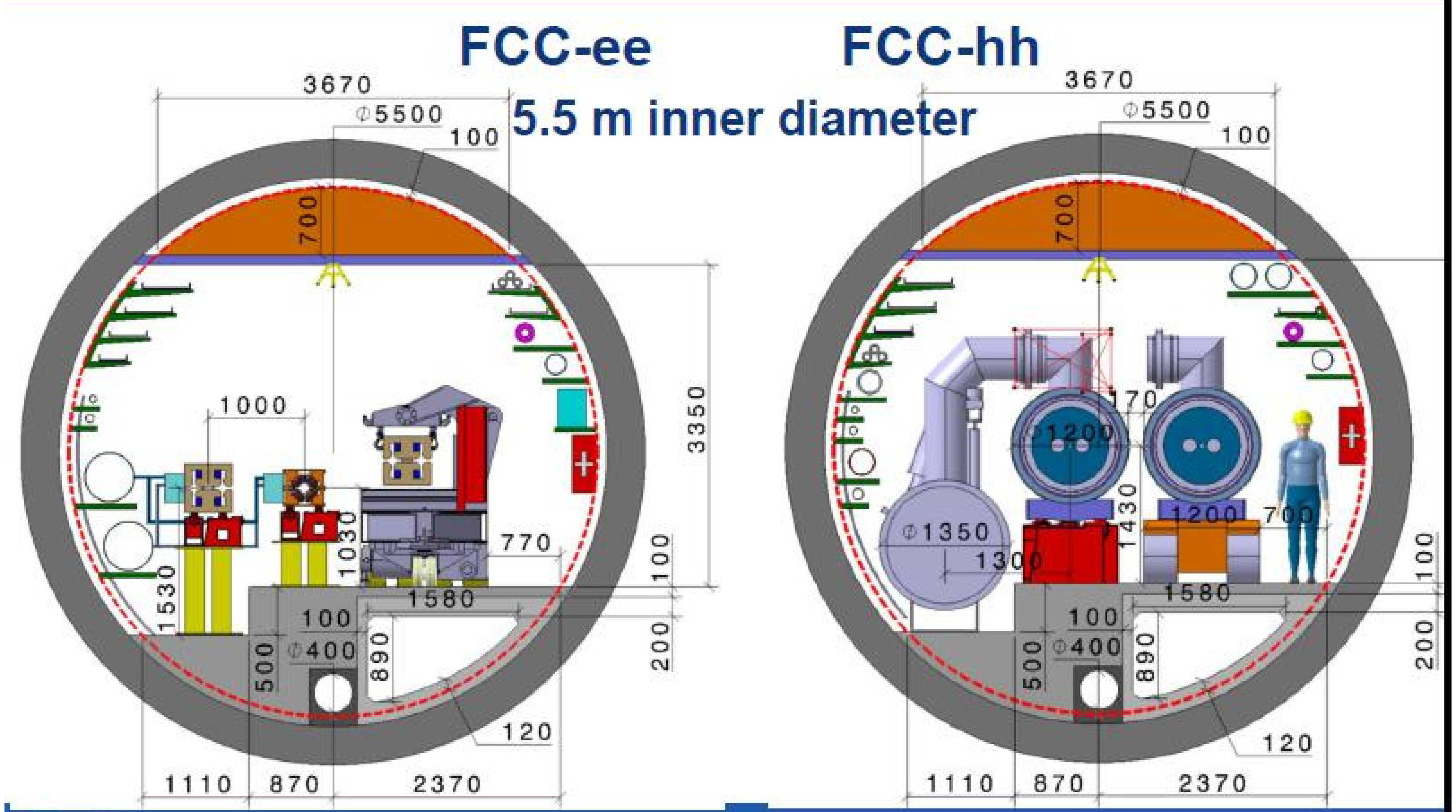
same linac used for e+ production @ **4.46 GeV** e^+ beam emittances reduced in DR @ **1.54 GeV**

injection @ **6 GeV** into Pre-Booster Ring (SPS or new ring) & acceleration to 20 GeV - or alternatively 20 GeV linac

injection to main Booster @ **20 GeV and interleaved** filling of e^+/e^- (**<20 min for full filling**) and continuous top-up

I. Chaikovska, O. Etisken, P. Martyshkin, S. Ogur, K. Oide, Y. Papaphilippou

Tunnel integration in arcs



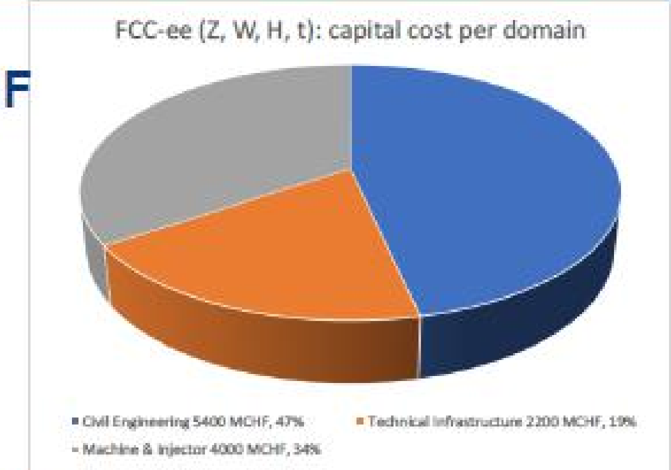
FCC-ee el. power consumption [MW]

Beam energy (GeV)	45.6 Z	80 W	120 ZH	182.5 ttbar
RF (SR = 100)	163	163	145	145
Collider cryo	1	9	14	46
Collider magnets	4	12	26	60
Booster RF & cryo	3	4	6	8
Booster magnets	0	1	2	5
Pre injector	10	10	10	10
Physics detector	8	8	8	8
Data center	4	4	4	4
Cooling & ventilation	30	31	31	37
General services	36	36	36	36
Total	259	278	282	359

FCC integrated project cost estimate

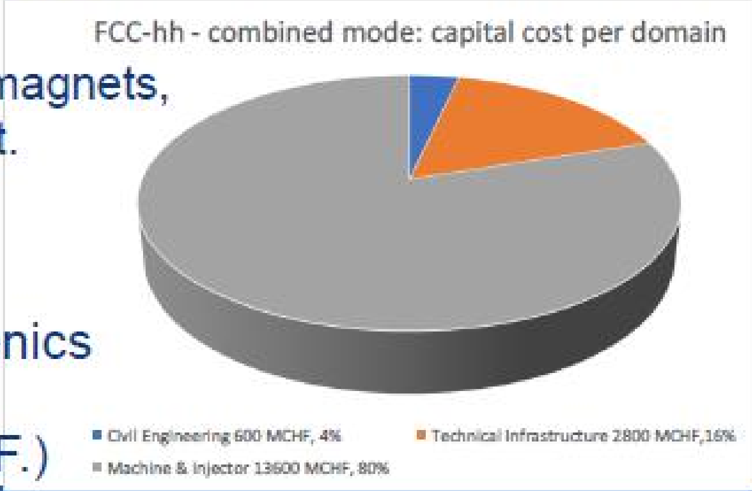
Construction cost phase1 (FCC-ee) is 11,6 BCHF

- 5,4 BCHF for civil engineering (47%)
- 2,2 BCHF for technical infrastructure (19%)
- 4,0 BCHF accelerator and injector (34%)



Construction cost phase 2 (FCC-hh) is 17,0 BCHF.

- 13,6 BCHF accelerator and injector (57%)
  - Major part for4,700 Nb_3Sn 16 T main dipole magnets, totalling 9,4 BCHF, targeting 2 MCHF/magnet.
- CE and TI from FCC-ee re-used, 0,6 BCHF for adaptation
- 2,8 BCHF for additional TI, driven by cryogenics



(Cost FCC-hh stand alone would be 24,0 BCHF.)

FCC-ee RF staging scenario

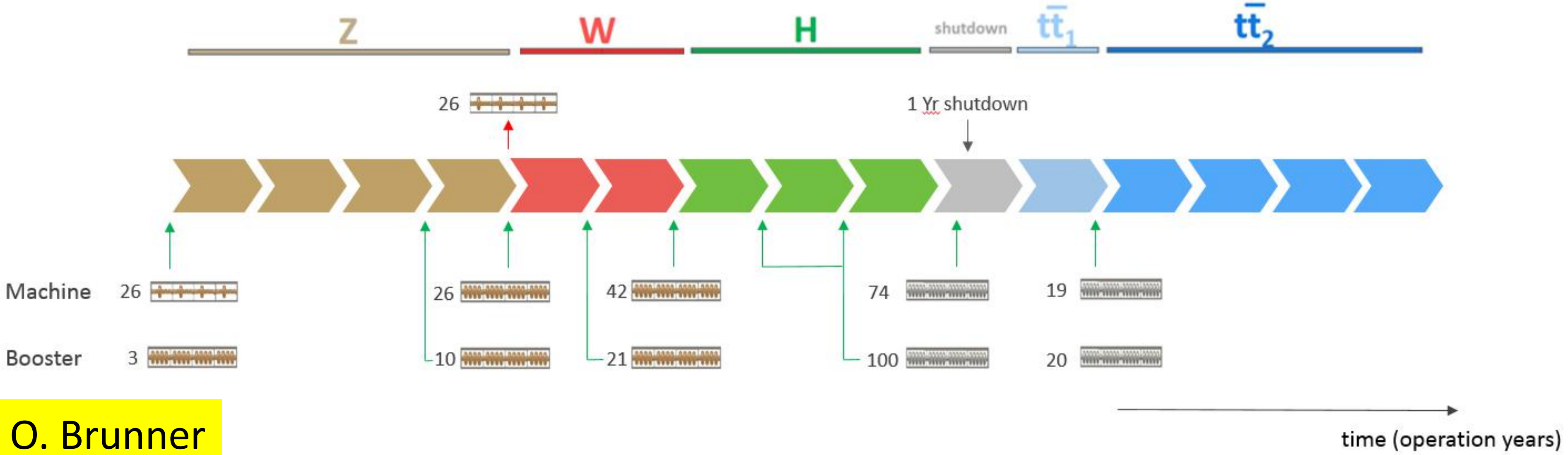
"Ampere-class" machine

WP	V_{rf} [GV]	#bunches	I_{beam} [mA]
Z	0.1	16640	1390
W	0.44	2000	147
H	2.0	393	29
ttbar	10.9	48	5.4

"high-gradient" machine

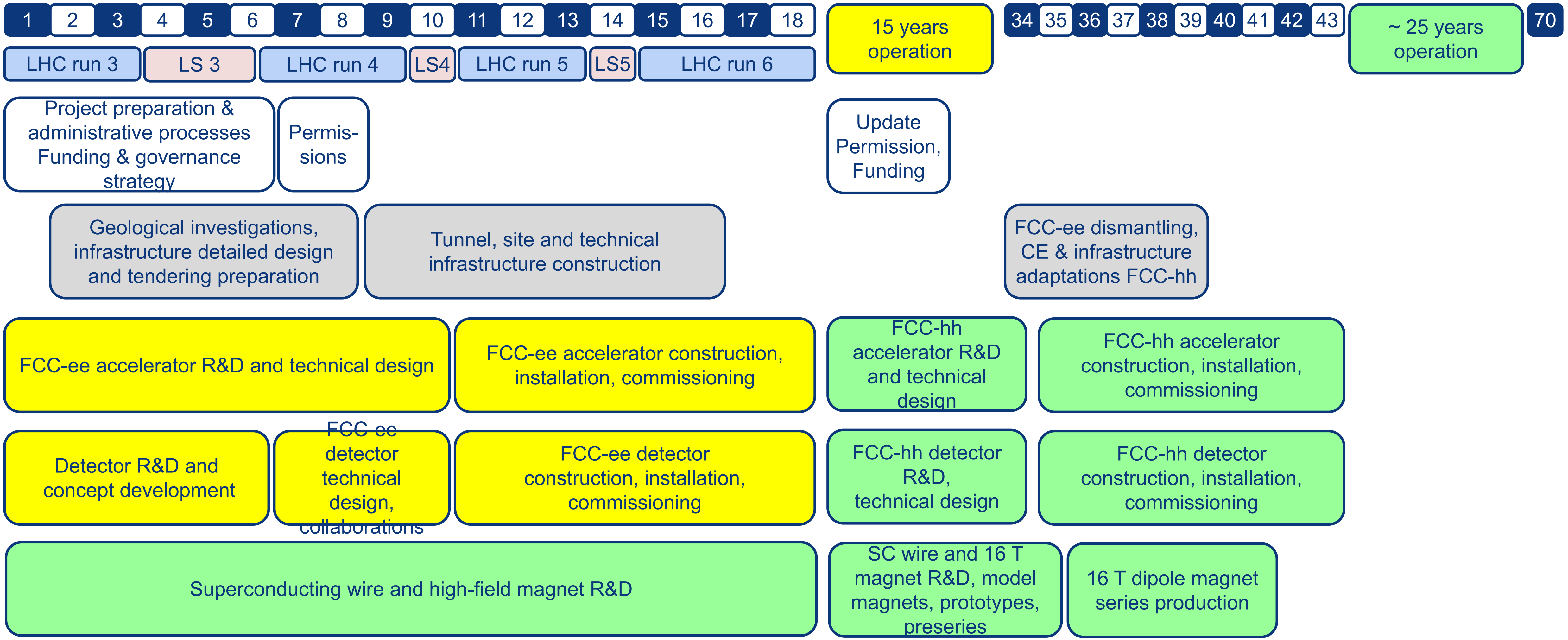
three sets of RF cavities:

- **high intensity (Z, FCC-hh): 400 MHz mono-cell cavities (4/cryom.), Nb/Cu, 4.5 K**
- **higher energy (W, H, t): 400 MHz four-cell cavities (4/cryomodule), Nb/Cu, 4.5 K**
- **$t\bar{t}$ machine complement: 800 MHz five-cell cavities (4/cryom.), bulk Nb, 2 K**
- **installation sequence omparable to LEP (≈ 30 CM/shutdown)**



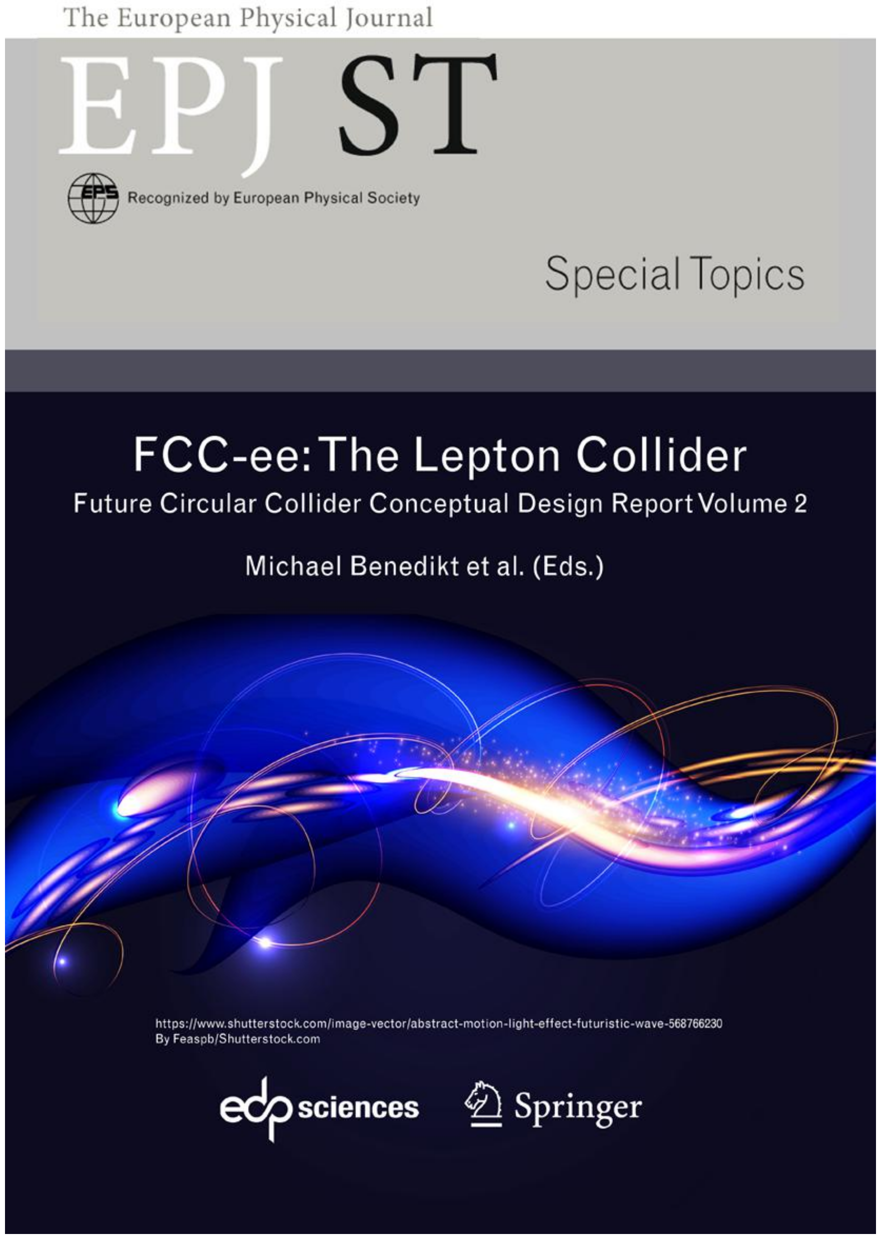
O. Brunner

FCC integrated project technical schedule



FCC integrated project plan is fully integrated with HL-LHC exploitation and provides for seamless further continuation of HEP in Europe.

FCC-ee Conceptual Design Report



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THE EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS

Regular Article

FCC-ee: The Lepton Collider

Future Circular Collider Conceptual Design Report Volume 2

A. Abada[32], M. Abbrescia[117,257], S.S. AbdusSalam[218], I. Abdyukhanov[16], J. Abelleira Fernandez[142], A. Abramov[204], M. Aburaia[284], A.O. Acar[238], P.R. Adzic[287], P. Agrawal[79], J.A. Aguilar-Saavedra[46], J.J. Aguilera-Verdugo[106], M. Aiba[191], I. Aichinger[64], G. Aielli[134,272], A. Akay[238], A. Akhundov[45], H. Aksakal[145], J.L. Albacete[46], S. Albergo[120,260], A. Alekou[311], M. Aleksa[64], R. Aleksan[39], R.M. Alemany Fernandez[64], Y. Alexahin[70], R.G. Alía[64], S. Alioli[126], N. Alipour Tehrani[64], B.C. Allanach[298], P.P. Allport[290], M. Altınlı[112,62], W. Altmannshofer[297], G. Ambrosio[70], D. Amorim[64], O. Amstutz[161], L. Anderlini[123,262], A. Andreazza[127,266], M. Andreini[64], A. Andriatis[167], C. Andris[165], A. Andronic[344], M. Angelucci[115], F. Antinori[129,267], S.A. Antipov[64], M. Antonelli[115], M. Antonello[127,264], P. Antonioli[118], S. Antusch[286], F. Anulli[133,271], L. Apolinário[158], G. Apollinari[70], A. Apollonio[64], D. Appelö[350], R.B. Appleby[311,301], A. Apyan[70], A. Apyan[1], A. Arbey[335], A. Arbuzov[17], G. Arduini[64], V. Arı[9], S. Arias[66,309], N. Armesto[108], R. Arnaldi[136,274], S.A. Arsenyev[64], M. Arzeo[64], S. Asai[236], E. Aslanides[31], R.W. Aßmann[49], D. Astapovych[228], M. Atanasov[64], S. Atieh[64], D. Attié[39], B. Auchmann[64], A. Audurier[119,259], S. Aull[64], S. Aumon[64], S. Aune[39], F. Avino[64], G. Avrillaud[83], G. Aydın[173], A. Azatov[214,137], G. Azuelos[241], P. Azzi[129,267], O. Azzolini[116], P. Azzurri[132,215], N. Bacchetta[129,267], E. Bacchiocchi[266], H. Bachacou[39], Y.W. Baek[74], V. Baglin[64], Y. Bai[331], S. Baird[64], M.J. Baker[333], M.J. Baldwin[167], A.H. Ball[64], A. Ballarino[64], S. Banerjee[54], D.P. Barber[49,316], D. Barducci[214,137], P. Barjhoux[3], D. Barna[172], G.G. Barnaföldi[172], M.J. Barnes[64], A. Barr[190], J. Barranco García[56], J. Barreiro Guimarães da Costa[97], W. Bartmann[64], V. Baryshevsky[95], E. Barzi[70], S.A. Bass[53], A. Bastianin[266], B. Baudouy[39], F. Bauer[39], M. Bauer[54], T. Baumgartner[232], I. Bautista-Guzmán[15], C. Bayındır[82,19], F. Beaudette[32], F. Bedeschi[132,215], M. Béguin[64], I. Bellafont[6], L. Bellagamba[118,258], N. Bellegarde[64], E. Belli[133,271,208], E. Bellingeri[43], F. Bellini[64], G. Bellomo[127,266], S. Belomestnykh[70], G. Bencivenni[115], M. Benedikt[64,a], G. Bernardi[32], J. Bernardi[232], C. Bernet[32,335], J.M. Bernhardt[3], C. Bernini[43], C. Berriaud[39], A. Bertarelli[64], S. Bertolucci[118,258], M.I. Besana[191], M. Besançon[39], O. Beznosov[316], P. Bhat[70], C. Bhat[70], M.E. Biagini[115], J.-L. Biarrotte[32], A. Bibet Chevalier[27], E.R. Bielert[304], M. Biglietti[135,273], G.M. Bilei[131,270], B. Bilki[305], C. Biscari[6], F. Bishara[49,190], O.R. Blanco-García[115], F.R. Blánquez[64], F. Blekman[340], A. Blondel[303], J. Blümlein[49], T. Boccali[132,215], R. Boels[84], S.A. Bogacz[237], A. Bogomyagkov[23], O. Boine-Frankenheim[228], M.J. Boland[321], S. Bologna[291], O. Bolukbasi[112], M. Bomben[32], S. Bondarenko[17], M. Bonvini[133,271], E. Boos[221], B. Bordini[64], F. Bordry[64], G. Borghello[64,275], L. Borgonovi[118,258], S. Borowka[64], D. Bortoletto[190], D. Boscherini[118,258], M. Boscolo[115], S. Boselli[130,269], R.R. Bosley[290], F. Bossu[32], C. Botta[64], L. Bottura[64], R. Boughezal[11], D. Boutin[39], G. Bovone[43], I. Božović Jelisavčić[339], A. Bozbey[238], C. Bozzi[122,261], D. Bozzini[64], V. Braccini[43], S. Braibant-Giacomelli[118,258], J. Bramante[200,193], P. Braun-Munzinger[77], J.A. Briffa[310], D. Britzger[169], S.J. Brodsky[225], J.J. Brooke[291], R. Bruce[64],

Next steps 2019 - 2020

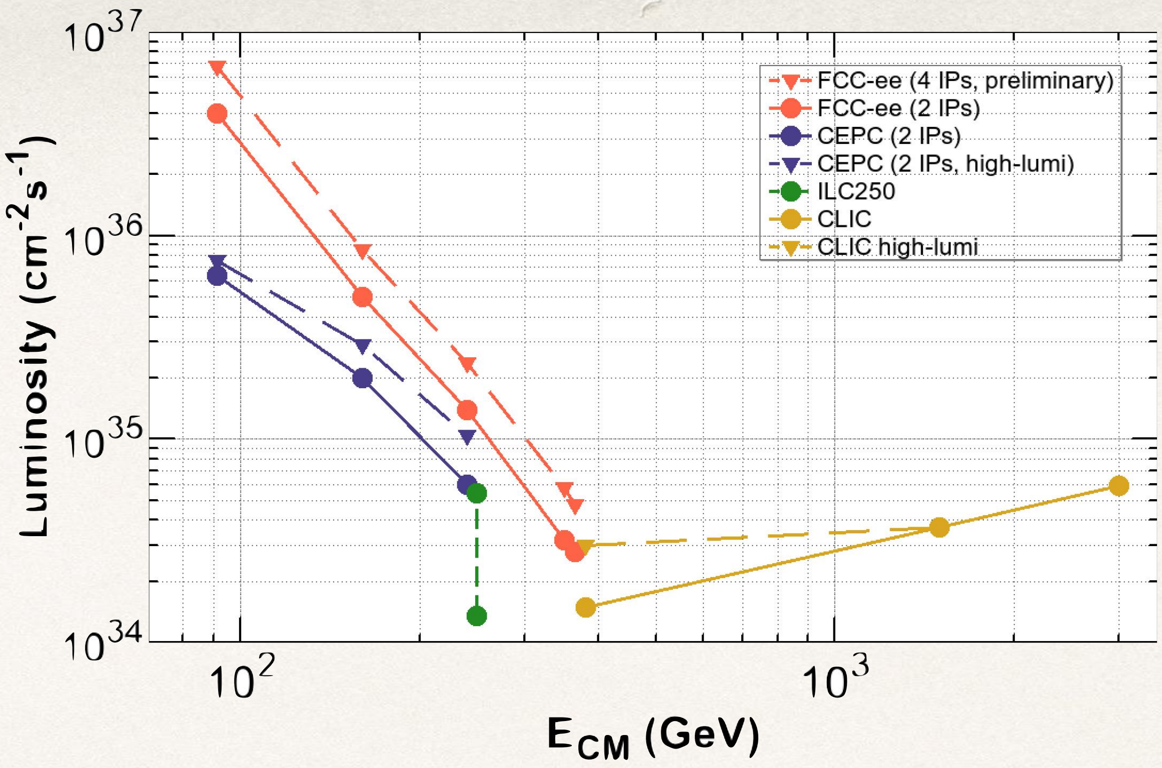
- Iteration of tunnel and surface structures layout and implementation with host states.
- Adaptation of CE, machine designs, etc. according to implementation optimisation.
- Following Integral Project proposal, presently focus on FCC-ee as potential first step (awaiting strategy recommendation).
  - Review and more detailed design for FCC-ee injector concept
  - Detailed design of technical infrastructure for FCC-ee
- Preparation of EU H2020 DS project (INFRADEV call November 2019), focused on preparations for infrastructure implementation.

Next steps 2020 - 2026

2020/21 – 2025/26 project preparation phase (if supported by EPPSU and CERN Council)

- Project preparatory activities with host states (landplot identification and acquisition plan, sector plan, EIA, "debat publique", and study management
- Civil engineering site investigations and construction tender planning
- Technical design towards CDR++/TDR (ATS) (Accelerators, technology, technical infrastructure)
- Development of financing and governance models for project and operation phases including international in-kind contributions (CERN Council and Directorate).

All 4 activities aim at reaching a level by 2025/26 allowing a definitive project decision.



The Next Step for FCC-ee (4 IP, final quads)

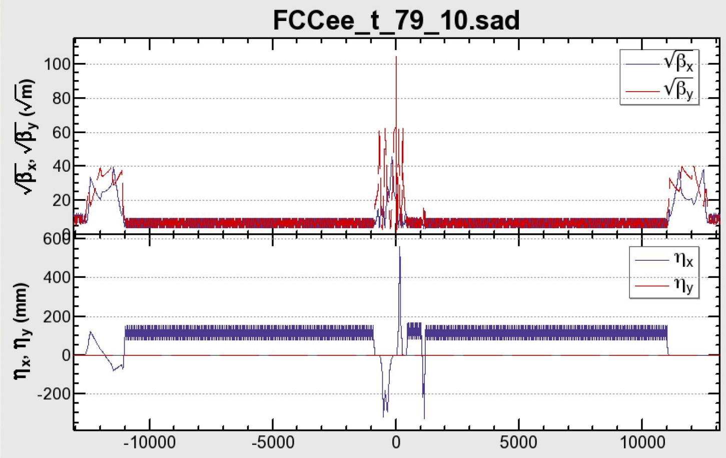
K. Oide (CERN)

Many thanks to M. Benedikt, A. Blondel, P. Janot, K. Ohmi, D. Shatilov, Y. Suetsugu, M. Tobiyama, F. Zimmermann, and all FCC-ee collaborators.

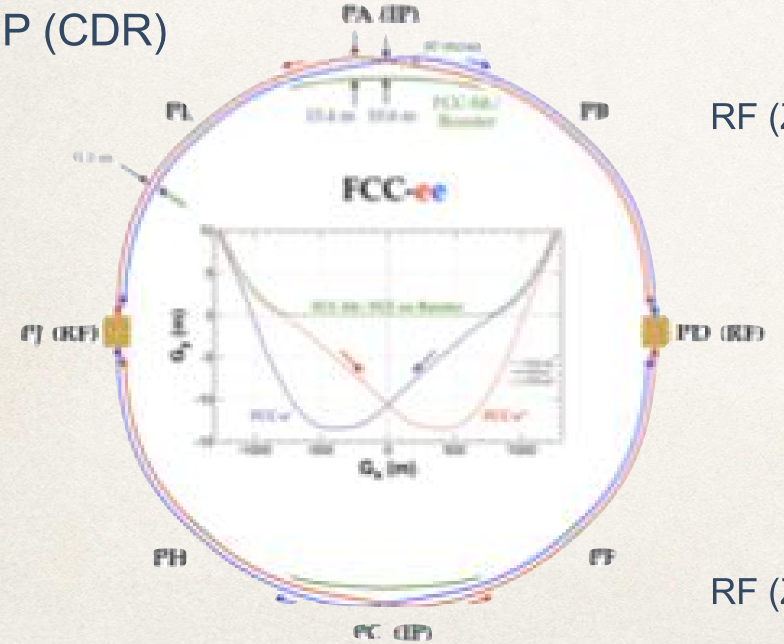
June 26, FCC Week 2019 @ Brussels

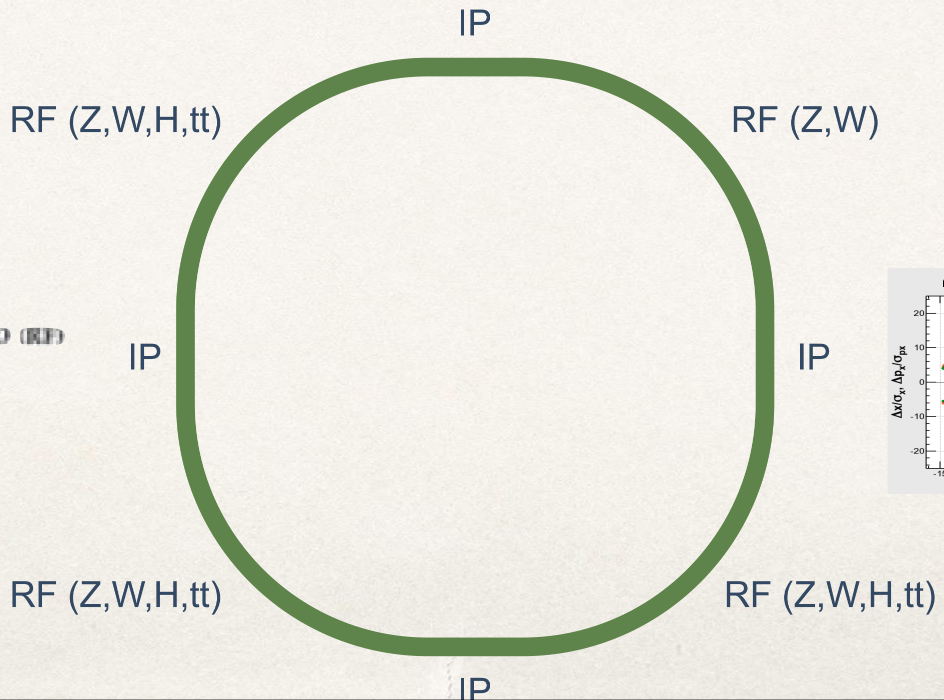
4 IP: layout with perfect period-4

- Equal spacing between IPs:
  - Otherwise more than 4 bunches couple together.
- Complete period 4 periodicity, including the RF (at least at ttbar):
  - For better beam-beam, dynamic aperture, etc.
- RF must be at the midpoint of 2 IPs:
  - For better dynamic aperture and beam cross over at the RF (ttbar).
- Thus the tunnel geometry deviates from the CDR and the current FCC-hh.

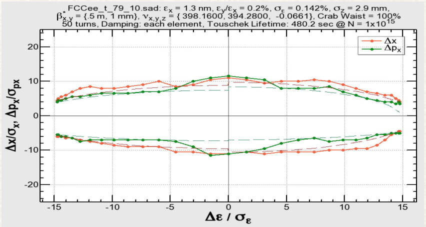


2 IP (CDR)

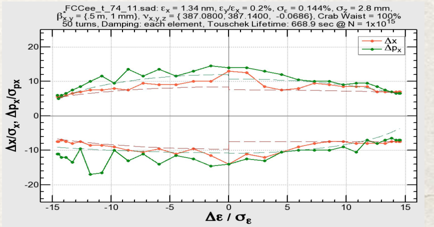




4 IP



2 IP

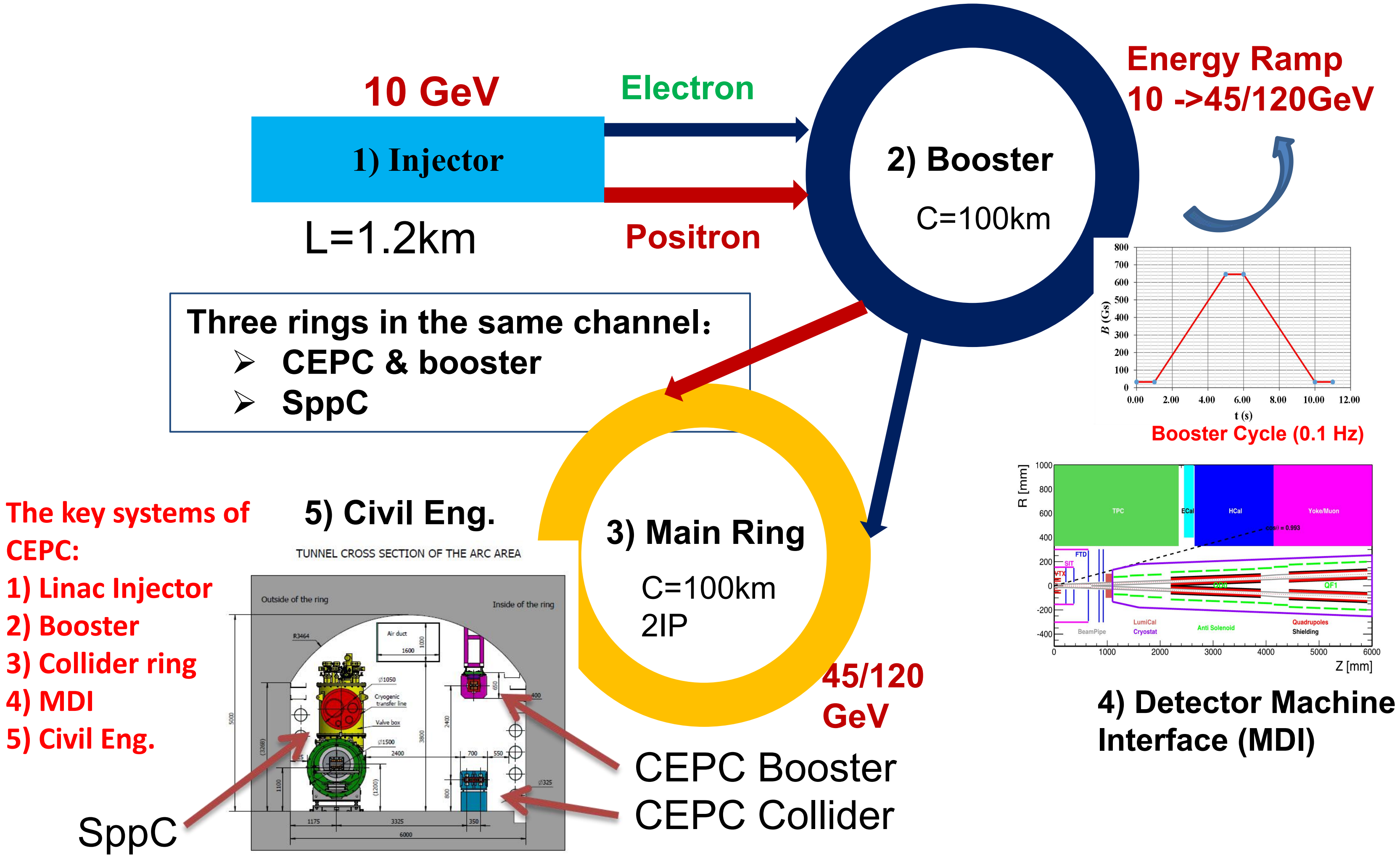


Tentative Summary

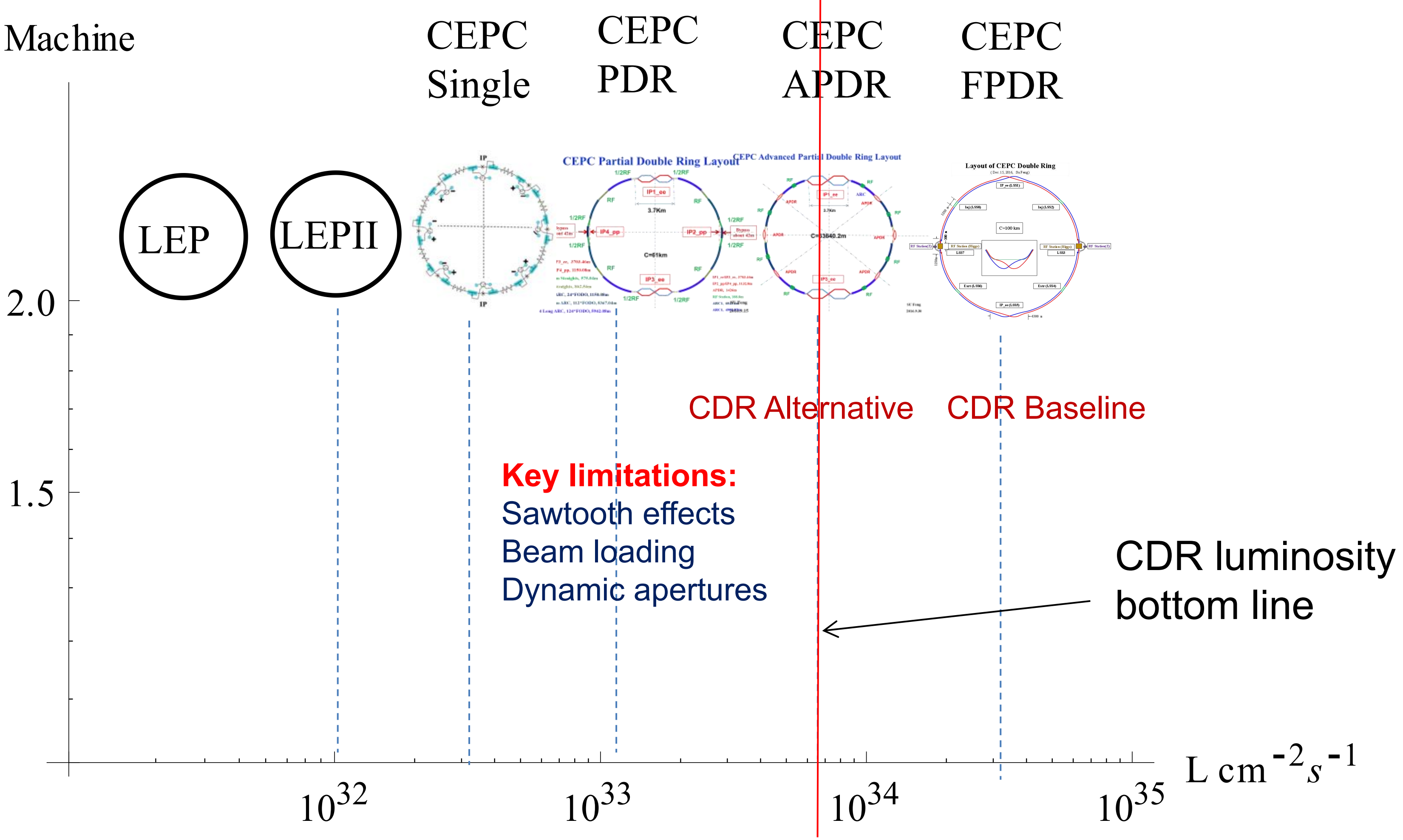
- At least two issues (4 IP and final quads) have been addressed to go to the next step of FCC-ee beyond the CDR.
- 4 IP scheme looks acceptable so far: See D. Shatilov's presentation on the expected beam-beam performance and the luminosity.
- 4 IP will have a huge impact on the layout, FCC-hh design, many components such as RF, injection, beam abort, polarimeter, etc.
- Attention is necessary on the robustness of the final quads and solenoids against beam losses.
- Detailed design studies on various components must be done, after the above issues are fixed. Some items which are not much affected by the number of IP's can be started now.

CEPC

CEPC Accelerator Chain and Systems



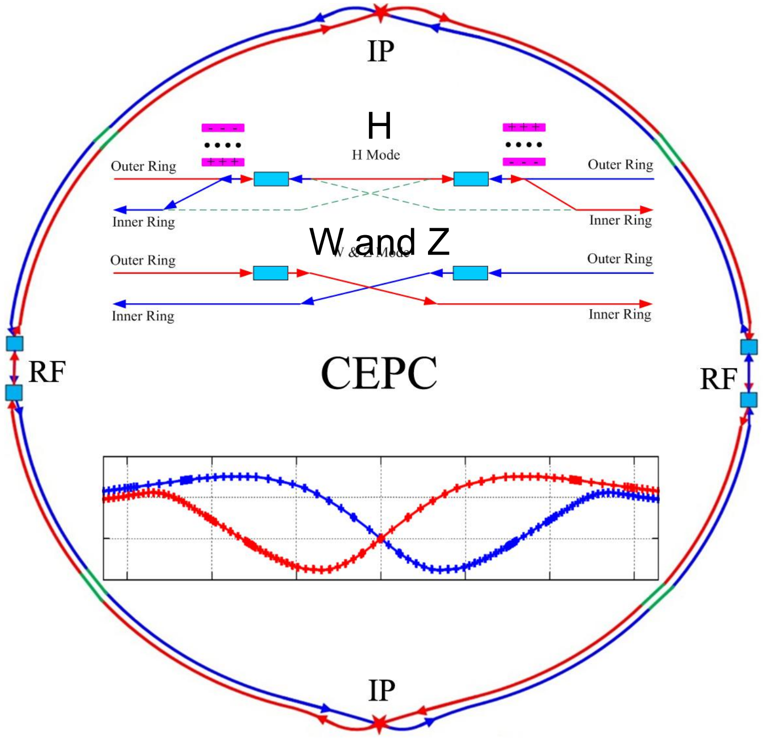
Collider Schemes vs Luminosity Potentials



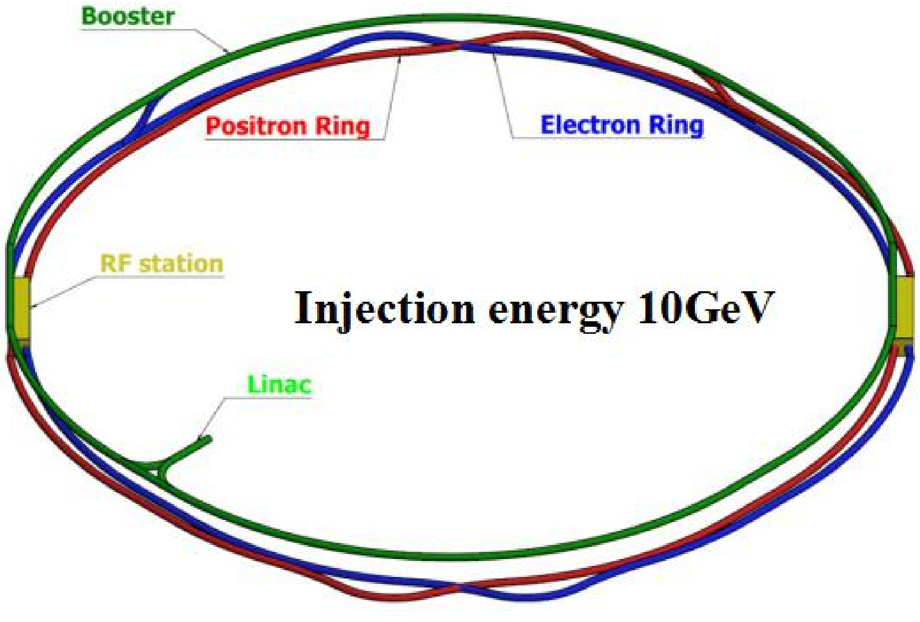
Luminosity H 10^32 (102GeV) <~2*10^34 >2~5*10^34 (cm^-2s^-1)

Luminosity Z 10^32 <~1*10^34 >100*10^34 (cm^-2s^-1)

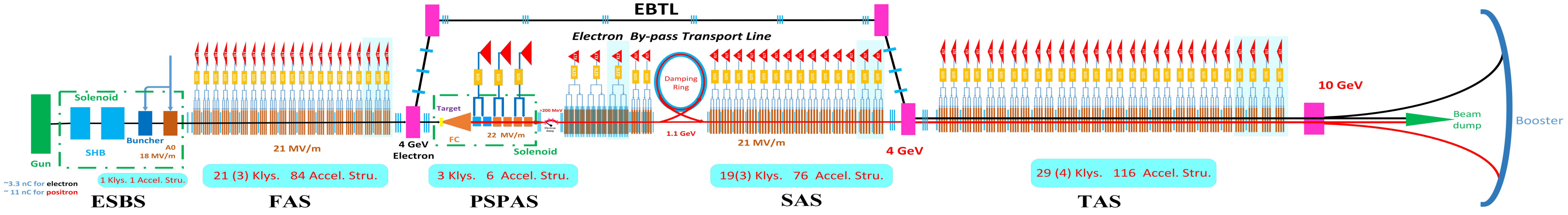
CEPC CDR Baseline Layout



CEPC collider ring (100km)



CEPC booster ring (100km)



CEPC Linac injector (1.2km, 10GeV)

CEPC CDR Parameters

	Higgs	*W*	*Z*（*3T*）	*Z*（*2T*）
Number of IPs	2			
Beam energy (GeV)	**120**	**80**	**45.5**	
Circumference (km)	100			
Synchrotron radiation loss/turn (GeV)	1.73	0.34	0.036	
Crossing angle at IP (mrad)	16.5×2			
Piwinski angle	2.58	7.0	23.8	
Number of particles/bunch N_e (10^{10})	15.0	12.0	8.0	
Bunch number (bunch spacing)	**242 (0.68μs)**	**1524 (0.21μs)**	**12000 (25ns+10%gap)**	
Beam current (mA)	17.4	87.9	461.0	
Synchrotron radiation power /beam (MW)	**30**	**30**	**16.5**	
Bending radius (km)	10.7			
Momentum compact (10^{-5})	1.11			
β function at IP β_x^* / β_y^* (m)	**0.36/0.0015**	**0.36/0.0015**	**0.2/0.0015**	**0.2/0.001**
Emittance $\varepsilon_x/\varepsilon_y$ (nm)	1.21/0.0031	0.54/0.0016	0.18/0.004	0.18/0.0016
Beam size at IP σ_x/σ_y (μm)	20.9/0.068	13.9/0.049	6.0/0.078	6.0/0.04
Beam-beam parameters ξ_x/ξ_y	0.031/0.109	0.013/0.106	0.0041/0.056	0.0041/0.072
RF voltage V_{RF} (GV)	2.17	0.47	0.10	
RF frequency f_{RF} (MHz) (harmonic)	650 (216816)			
Natural bunch length σ_z (mm)	2.72	2.98	2.42	
Bunch length σ_z (mm)	3.26	5.9	8.5	
HOM power/cavity (2 cell) (kw)	0.54	0.75	**1.94**	
Natural energy spread (%)	0.1	0.066	0.038	
Energy acceptance requirement (%)	**1.35**	**0.4**	**0.23**	
Energy acceptance by RF (%)	2.06	1.47	1.7	
Photon number due to beamstrahlung	0.1	0.05	0.023	
Lifetime _simulation (min)	100			
Lifetime (hour)	**0.67**	**1.4**	**4.0**	**2.1**
F (hour glass)	0.89	0.94	0.99	
Luminosity/IP *L* ($10^{34}cm^{-2}s^{-1}$)	**2.93**	**10.1**	**16.6**	**32.1**

CEPC New Parameters for Higgs

	tt	*Higgs*	*W*	*Z* (3*T*)	*Z* (2*T*)
Number of IPs	2				
Beam energy (GeV)	**175**	**120**	**80**	**45.5**	
Circumference (km)	100				
Synchrotron radiation loss/turn (GeV)	7.61	1.68	0.33	0.035	
Crossing angle at IP (mrad)	16.5×2				
Piwinski angle	0.91	3.78	8.5	27.7	
Number of particles/bunch N_e (10^{10})	24.15	17.0	12.0	8.0	
Bunch number (bunch spacing)	**34 (4.9μs)**	**218 (0.76μs)**	**1568 (0.20μs)**	**12000 (25ns+10%gap)**	
Beam current (mA)	3.95	17.8	90.4	461.0	
Synchrotron radiation power /beam (MW)	**30**	**30**	**30**	**16.5**	
Bending radius (km)	10.7				
Momentum compact (10^{-5})	0.91				
β function at IP β_x^* / β_y^* (m)	1.2/0.0037	**0.33/0.001**	**0.33/0.001**	**0.2/0.001**	
Emittance $\varepsilon_x/\varepsilon_y$ (nm)	2.24/0.0068	0.89/0.0018	0.395/0.0012	0.13/0.003	0.13/0.00115
Beam size at IP σ_x/σ_y (μm)	51.8/0.16	17.1/0.042	11.4/0.035	5.1/0.054	5.1/0.034
Beam-beam parameters ξ_x/ξ_y	0.077/0.105	0.024/0.113	0.012/0.1	0.004/0.053	0.004/0.085
RF voltage V_{RF} (GV)	8.93	2.4	0.43	0.082	
RF frequency f_{RF} (MHz) (harmonic)	650 (216816)				
Natural bunch length σ_z (mm)	2.54	2.2	2.98	2.42	
Bunch length σ_z (mm)	2.87	3.93	5.9	8.5	
HOM power/cavity (kw)	0.53 (5cell)	0.58 (2 cell)	0.77 (2 cell)	**1.94** (2 cell)	
Energy spread (%)	0.14	0.19	0.098	0.080	
Energy acceptance requirement (%)	**1.57**	**1.7**	**0.90**	**0.49**	
Energy acceptance by RF (%)	2.67	3.0	1.27	1.55	
Photon number due to beamstrahlung	0.19	0.104	0.050	0.023	
Beamstruhlung lifetime /quantum lifetime* (min)	~ 60	30/50	>400		
Lifetime (hour)	**0.7**	**0.22**	**1.2**	**3.2**	**2.0**
F (hour glass)	0.89	0.85	0.92	0.98	
Luminosity/IP *L* (10^{34}cm^{-2}s^{-1})	**0.38**	**5.2**	**14.5**	**23.6**	**37.7**

*include beam-beam simulation and real lattice

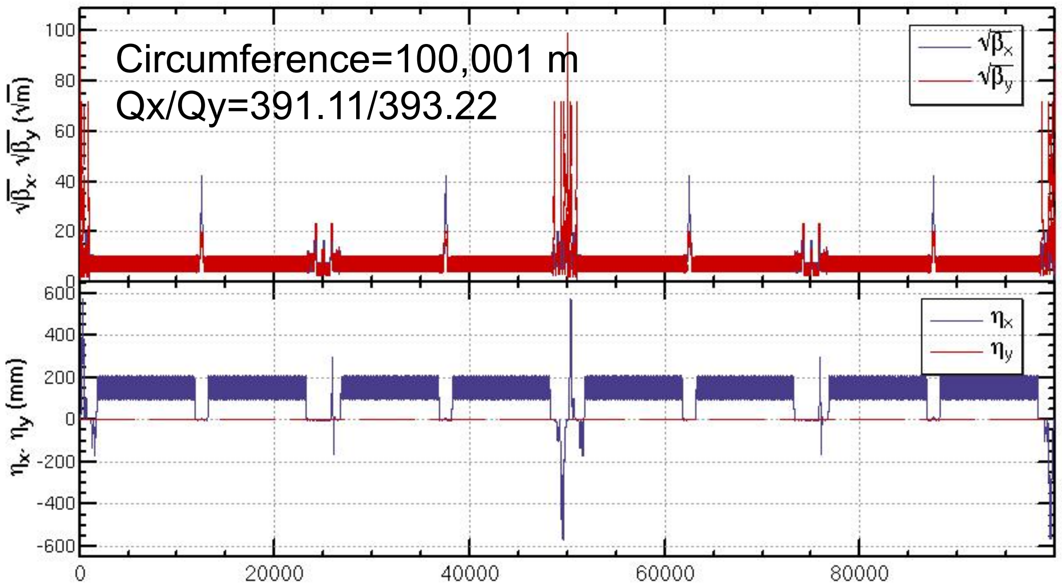
Lattice design with luminosity of $5 \times 10^{34}/cm^2/s$

Higgs

- Fit parameter list with luminosity of $5 \times 10^{34}/\mathrm{cm}^2/\mathrm{s}$
  - Smaller emittance and βy at IP lead to larger chromaticity
  - 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
  - ARC region: longer quadrupoles
- Reduction of dynamic aperture requirement from injection
  - Straight section region: larger βx at injection point
- Maximization of bend filling factor to increase single bunch charge
  - 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

Lattice design with luminosity of $5 \times 10^{34}/cm^2/s$ Higgs

- An preliminary optics fulfilling requirements of the new parameters list, geometry, photon background and key hardware was got.
- For the tt mode
  - Space in the RF region left for extra cavities
  - Magnet strength are in the limit except the SC magnets
  - Lower the FD strength and increase beta functions at IP to make pole-tip field and beam-stay-clear region of the FD not larger than the ones of Higgs mode



Magnets parameters for Higgs mode

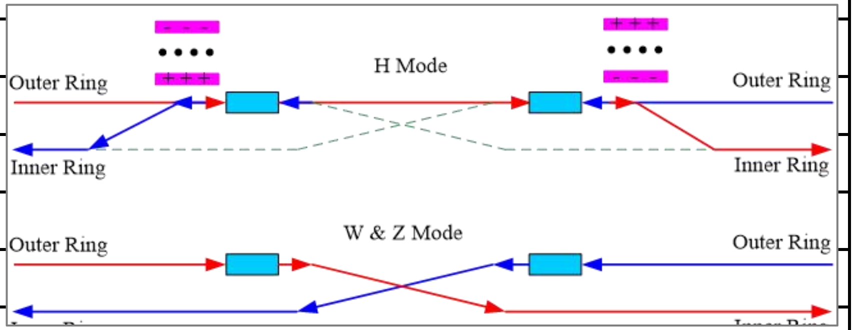
Magnets	Strength	Length
QD0	77 T/m	2×1.5m
QF1	63 T/m	2.0m
B0S	362 Gauss	5×5.179m
B0L	362 Gauss	5×5.499m

CEPC vs FCC-ee: Z (2T)

	CEPC-CDR	*CEPC-30MW*	*CEPC-38MW*	*FCC-ee*
Number of IPs	2	2	2	2
Energy (GeV)	45.5	**45.5**	**45.5**	45.6
Circumference (km)	100	100	100	100
SR loss/turn (GeV)	0.036	0.036	0.036	0.036
Half crossing angle (mrad)	16.5	16.5	16.5	15
Piwinski angle	23.8	27.9	33.0	28.5
N_e/bunch (10^{10})	8.0	12.0	15.0	17
Bunch number	12000	**14564 (20.6ns+10%gap)**	**15000**	16640
Beam current (mA)	461	839.9	1081.4	1390
SR power /beam (MW)	**16.5**	**30**	**38.6**	**50**
Bending radius (km)	10.7	10.7	10.7	10.76
Momentum compaction (10^{-5})	1.11	1.11	1.11	1.48
β_{IP} x/y (m)	0.2/0.001	**0.2/0.001**	**0.2/0.001**	0.15/0.0008
Emittance x/y (nm)	0.18/0.0016	0.18/0.0016	0.18/0.0016	0.27/0.001
Transverse σ_{IP} (um)	6.0/0.04	6.0/0.04	6.0/0.04	6.4/0.028
ξ_x/ξ_y/IP	0.004/0.079	0.004/0.093	0.004/0.098	0.004/0.133
V_{RF} (GV)	0.1	0.10	0.10	0.1
f_{RF} (MHz) (harmonic)	650	650	650	400
Nature bunch length σ_z (mm)	2.42	2.42	2.42	3.5
Bunch length σ_z (mm)	8.5	10.0	11.8	12.1
HOM power/cavity (kw)	1.94 (2cell)	**2.29 (1cell)**	**3.15 (1cell)**	?
Energy spread (%)	0.08	0.1	0.115	0.132
Energy acceptance (DA) (%)	1.5	**0.6**	**0.7**	1.3
Energy acceptance by RF (%)	1.7	1.7	1.7	1.9
Lifetime by rad. Bhabha scattering (hour)	2.9			1.13
Lifetime (hour)	2.5	**2.0**	1.8	1.0
L_{max}/IP ($10^{34}cm^{-2}s^{-1}$)	**32.1**	**74.5**	**101.6**	**230**

CEPC Collider Ring SRF Parameters

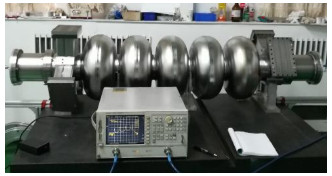
New machine parameters 20190226 SRF parameters 20190301	CDR (2-cell)			HL-Z (new2) (1-cell)				HL-Z (2-cell)	Performance Limits & Risks
	H	W	Z	H	W	Z (a)	Z (b)	Z	
Luminosity / IP [10^{34} cm^{-2}s^{-1}]	2.93	10.1	**32.1**	2.93	10.1	**74.5**	**74.5**	**74.5**	
SR power / beam [MW]	30	30	16.5	30	30	30	30	30	
RF voltage [GV]	2.17	0.47	0.1	2.17	0.47	0.1	0.1	0.1	
Beam current / beam [mA]	17.4	87.7	460	17.4	87.7	838	838	838	
Bunch charge [nC]	24	19.2	12.8	24	19.2	19.2	19.2	19.2	
Bunch number / beam	242	1524	12000	242	1524	14564	14564	14564	
Bunch length [mm]	3.26	5.9	8.5	3.26	5.9	10	10	10	
Cavity number (650 MHz)	**240**	2 x 108	**2 x 60**	**240**	2 x 120	**2 x 120**	**2 x 60**	**2 x 120**	Smart by-pass could be a better approach than 1-cell.
Cell number / cavity	**2**	2	**2**	**1**	1	**1**	1	**2**	Common 1-cell for Z & H/W necessary or different cavity?
Idle cavities on line / ring	0	12	60	0	0	0	**60**	0	Z 2x60 symmetry detune parked half cavities for FM CBI
Cavity gradient [MV/m]	**20**	9.5	3.6	**40**	17	3.6	7.2	1.8	Current status: ~ 10 MV/m in storage ring. Field emission
Q_0 for long term operation	**1.5E10**	1.5E10	1.5E10	**3E10**	3E10	3E10	3E10	1.5E10	~ 1E9 in storage ring. Field emission. Magnetic shield
Input power / cavity [kW]	250	278	**275**	250	250	**250**	**500**	250	~ 300 kW in storage ring. Window events and damages
Klystron max power [kW]	800	800	800	800	800	800	**1400**	800	Klystron max power limit: 1200 kW? KLY # & $
Number of cavities / klystron	2	2	2	2	2	2	**2**	2	Avoid RF power source reconfiguration
HOM power / cavity [kW]	0.57	0.75	**1.94**	0.29	0.37	**2.28**	2.28	**4.57**	HOM coupler capacity (not HOM power per cavity) : 1 kW
Optimal Q_L	1.5E6	3.2E5	4.7E4	3.1E6	5.8E5	2.6E4	5.2E4	1.3E4	Coupler variation range, coupler kick to beam
Optimal detuning [kHz]	0.2	1.0	**17.8**	0.1	0.5	**32.3**	**16.1**	**64.6**	Fundamental mode coupled bunch instability
Wall loss / cavity @ 2 K [W]	25.6	5.9	0.9	25.6	4.8	0.2	0.9	0.2	Field emission will drastically increase the cryogenic load.
Total cavity wall loss [kW]	6.1	1.3	0.1	6.1	1.2	0.05	0.05	0.05	(cryogenic wall loss in two rings)



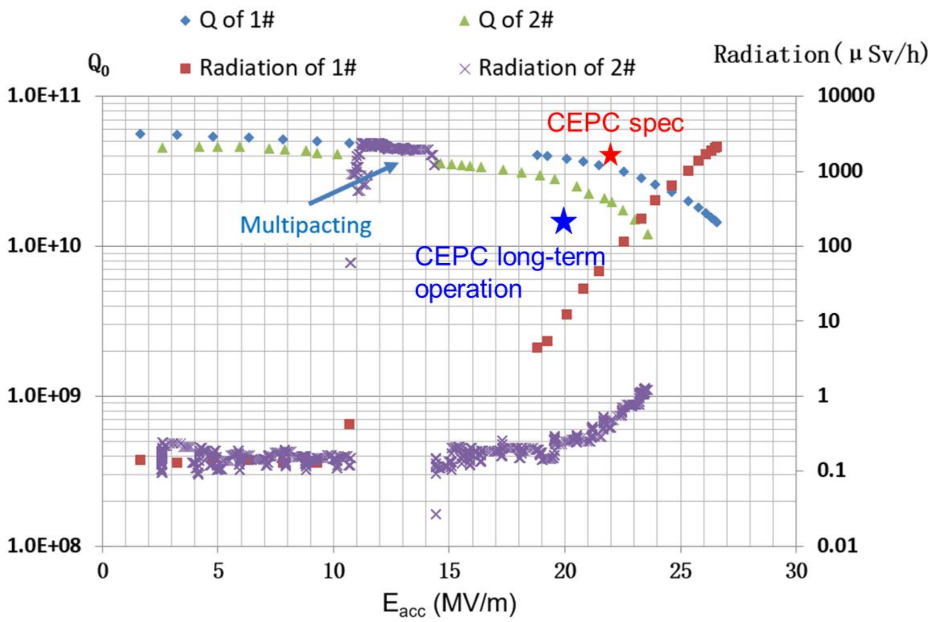
CEPC SRF Technology R&D Status

CEPC 650 MHz 2-cell cavity by OTIC

CEPC 650 MHz 2-cell cavity by HERT



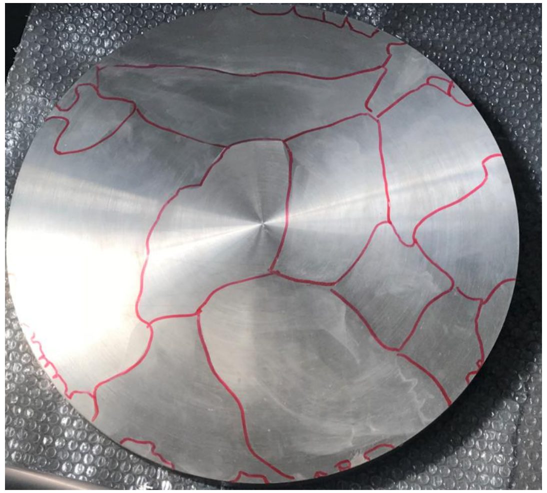
CEPC 650 MHz 5-cell cavity with waveguide HOM coupler by HERT

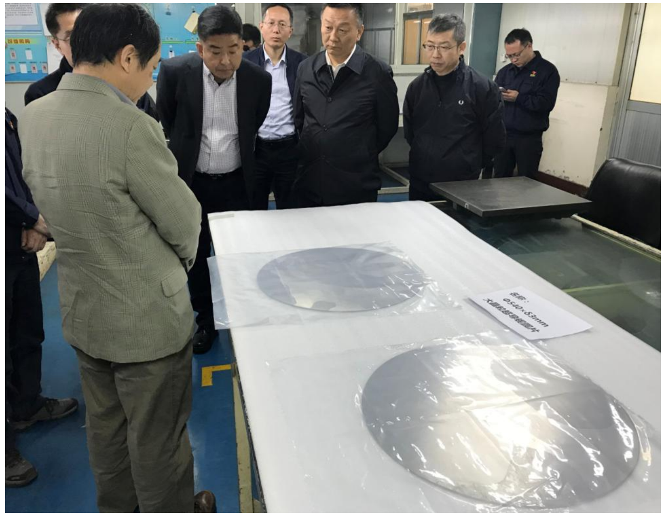


- 650 MHz 2-cell cavity (BCP without Nitrogen-doping) reached 3.2E10 @ 22 MV/m (**nearly reached CEPC collider cavity vertical test spec 4E10 @ 22 MV/m**)
- Nitrogen-doping and EP on 650 MHz cavity under investigation.
- **EP facility under commissioning.**

650 MHz 1-Cell Cavity (Large Grain)

- 650 MHz 1-cell cavity (large grain) is favorable for HL-Z, which have higher Q and gradient than fine grain.
- Target of Vertical test: **5E10 @ 42MV/m at 2.0 K**.
- Four cavities are under fabrication now, which will be tested in the middle 2019.



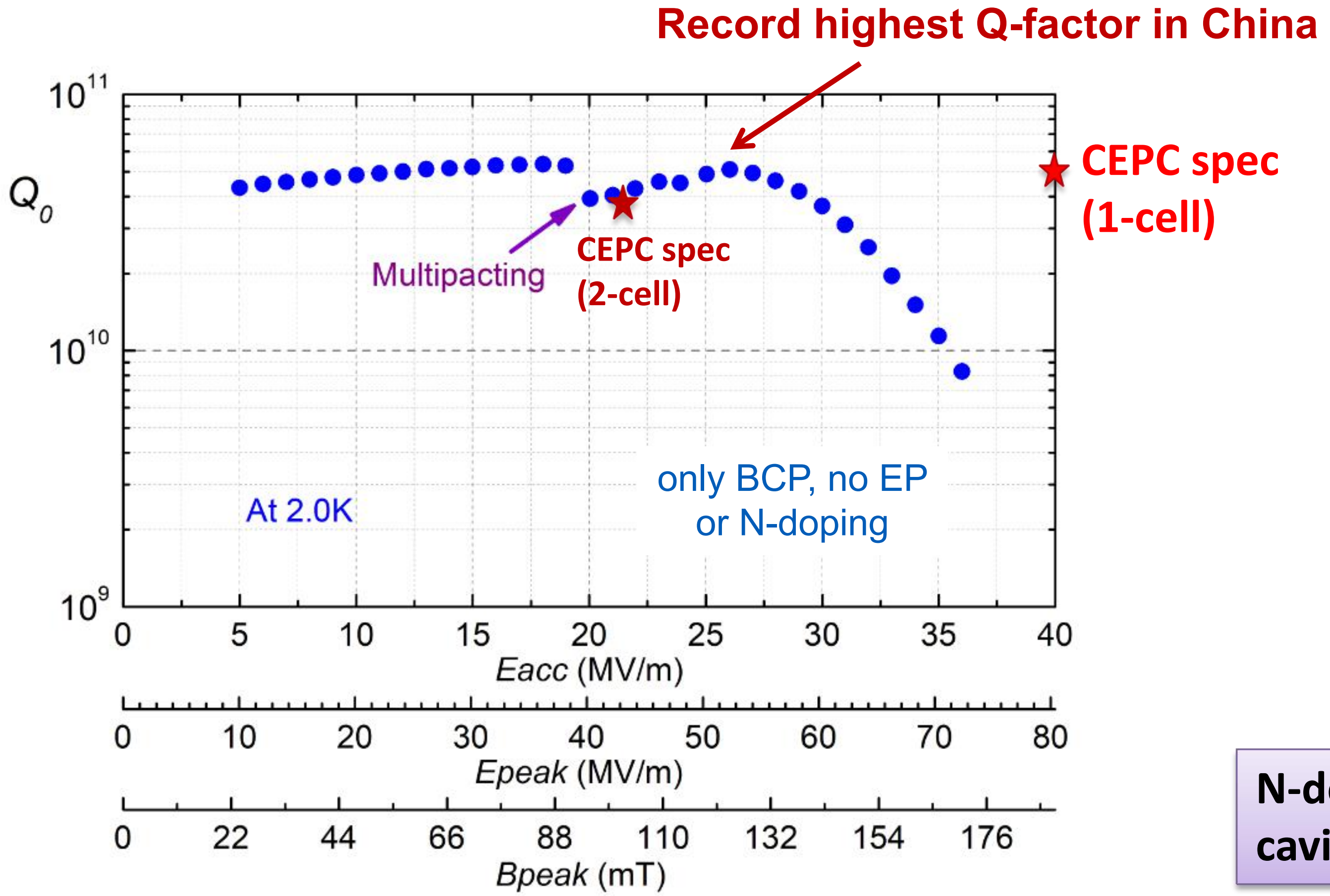


Large grain Nb sheets made by OTIC

High Q and High Gradient R&D (650 MHz FG)

Accelerating gradient (Eacc) reach 36.0 MV/m，**Q = 5.1E10 @ Eacc = 26 MV/m。**

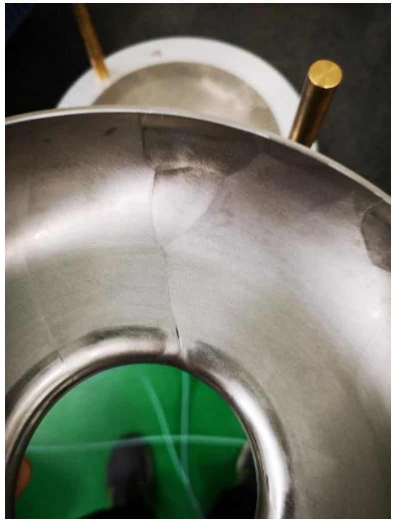
Next, increase the Q and Eacc through N-doping, EP, etc. Target: **5E10@42MV/m** for vertical test.

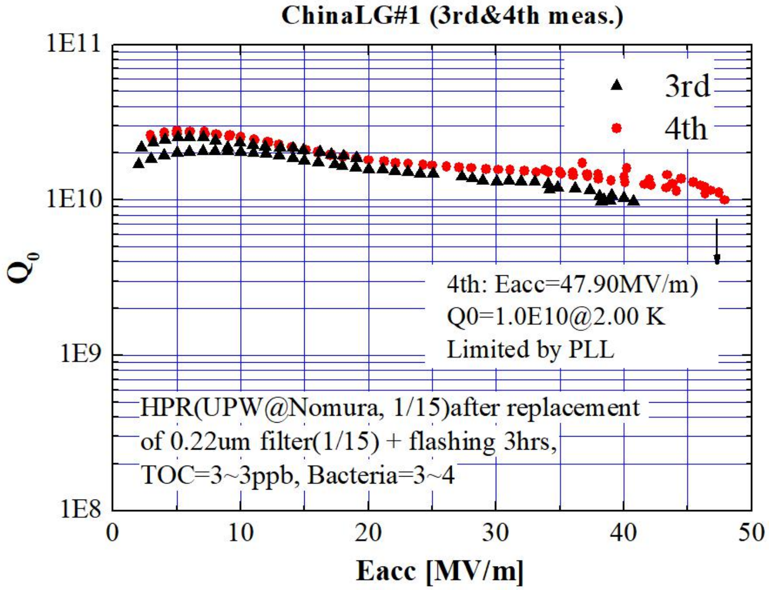


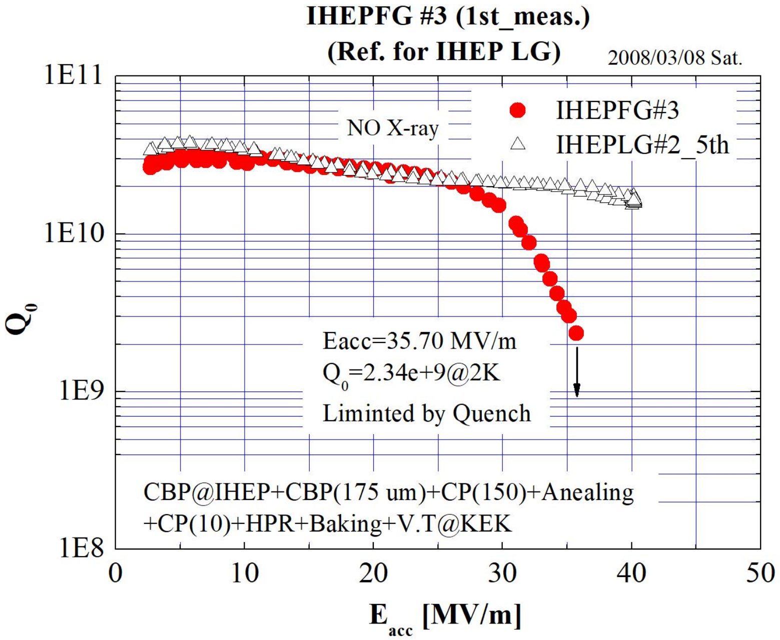
650 MHz 1-cell cavity

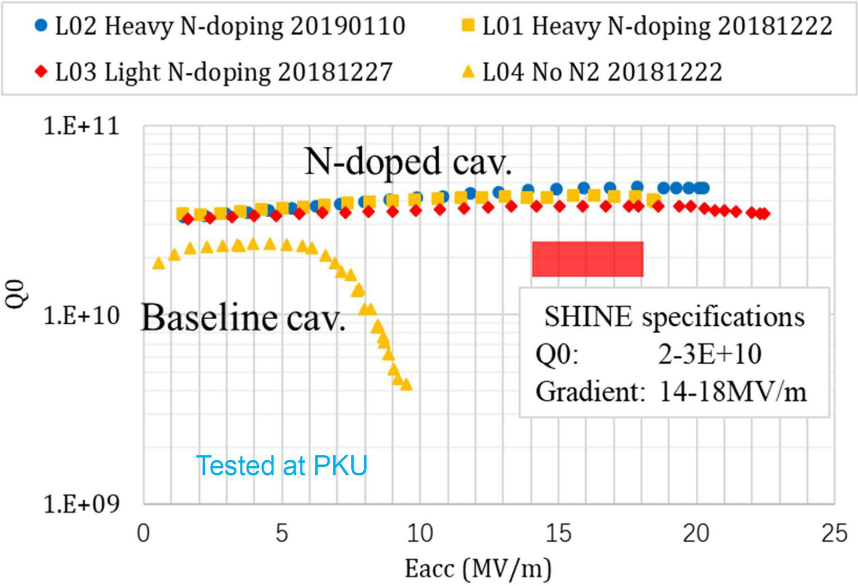
N-doping + EP will increase the 650 MHz cavity performance in near future

IHEP High Q and High Gradient R&D (1.3 GHz LG)



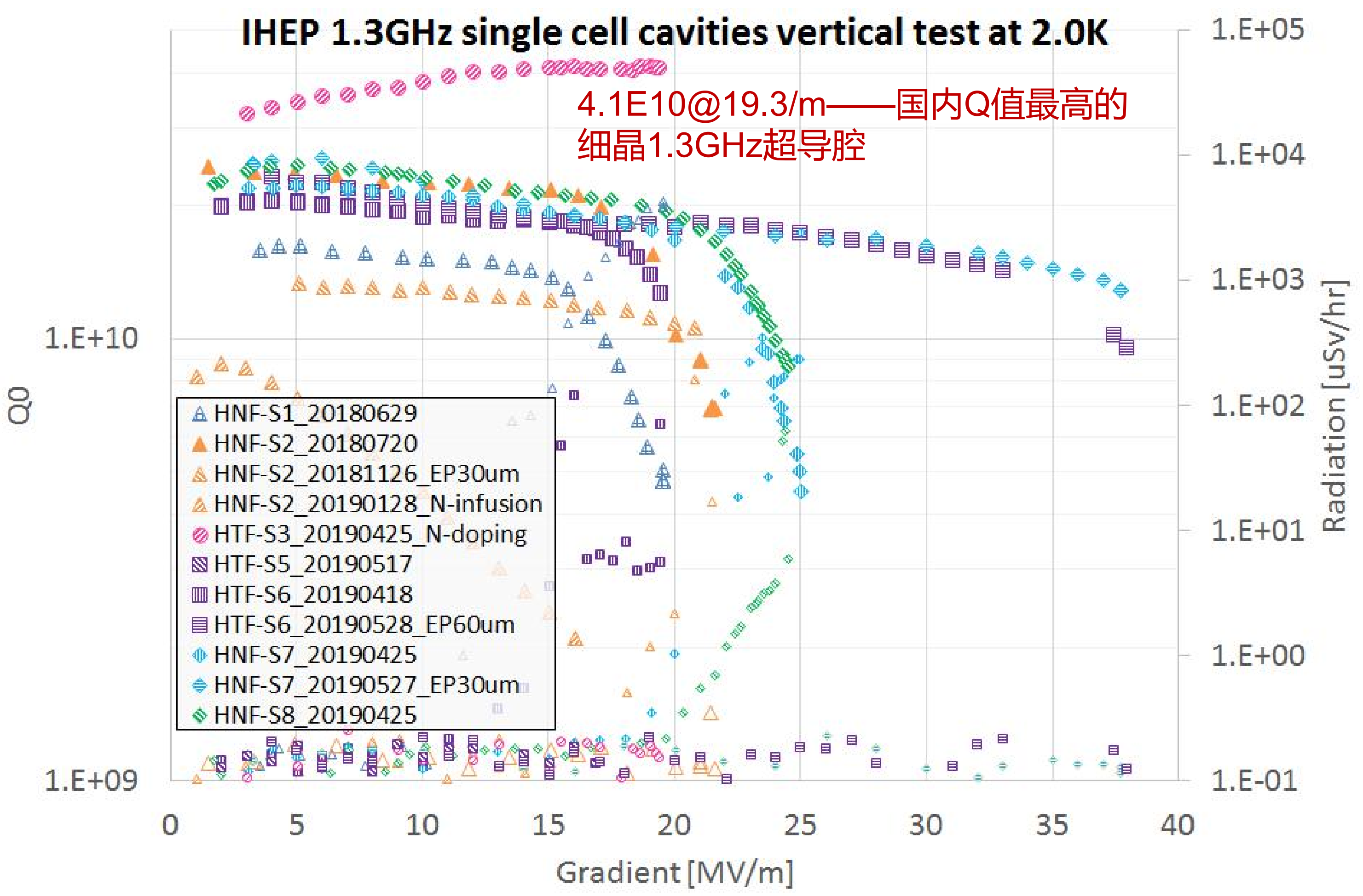






- Alternative cavity material for SHINE project. N-doping on LG shows promising results. Three LG single cell cavities in fabrication.
- All previous IHEP 1.3 GHz single cell cavities were CBP treated and got very high gradient. We have many experience. 9-cell large grain Pi mode ~ 20 MV/m with several cells exceeds 35 MV/m.
- Try high gradient without CBP first. And recover CBP machine and recipe in the same time.

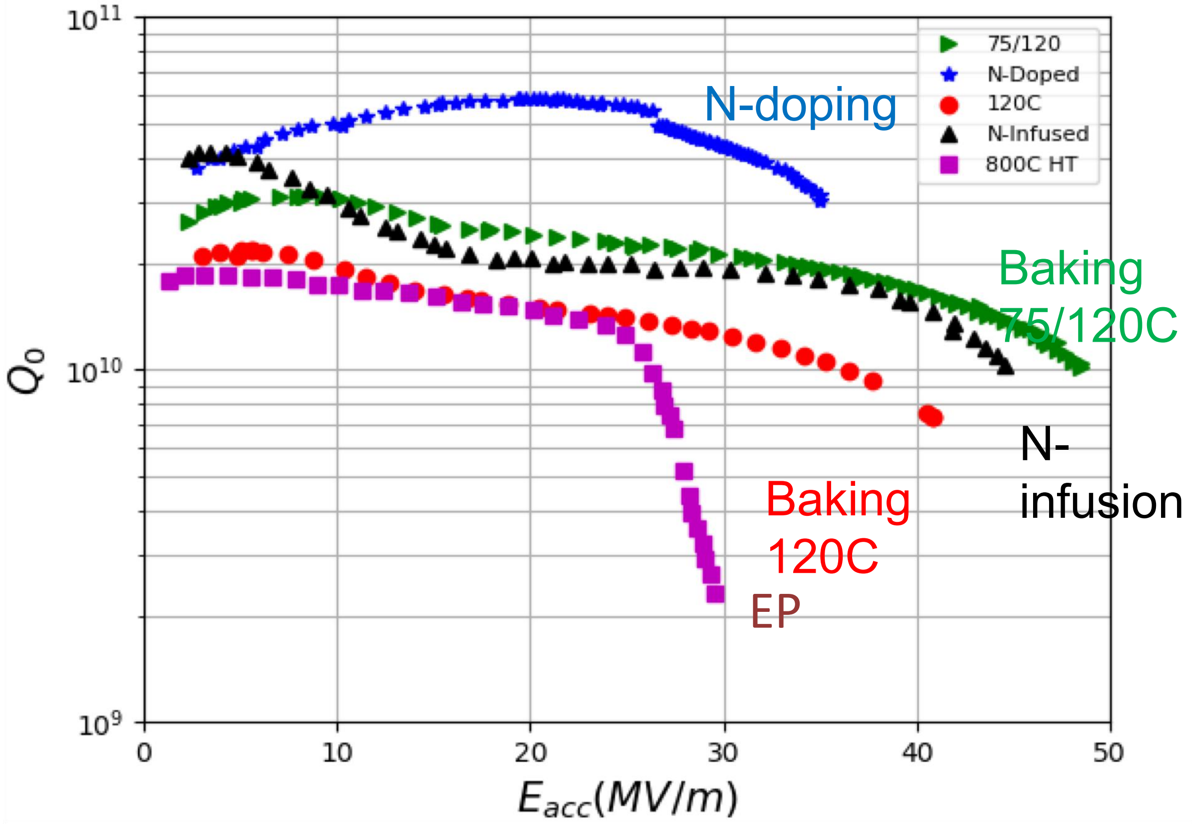
IHEP High Q and High Gradient R&D (1.3 GHz FG)



- All IHEP-made 1.3 GHz 1-cell cavities.
- All vertical tests at IHEP.
- **Highest Q** (4E10 at 16 MV/m) achieved by EP and N-doping at KEK.
- **Highest gradient** (38 MV/m) achieved by *improving (but not optimized)* OTIC's *simple EP and post-EP cleaning* and *improving clean assembly* at IHEP.
- Aiming for **gradient frontier** (1-cell > 45 MV/m and 9-cell > 40 MV/m) by optimizing cavity EBW and IHEP's new EP tool, and using Kyoto camera and TMAP.
- Aiming for **Q frontier (with high gradient)** by N-doping with IHEP's new furnaces and new recipe, and fundamental mechanism research.

Courtesy: Anna Grassellino
- TTC Meeting, TRIUMF, Feb., 2019

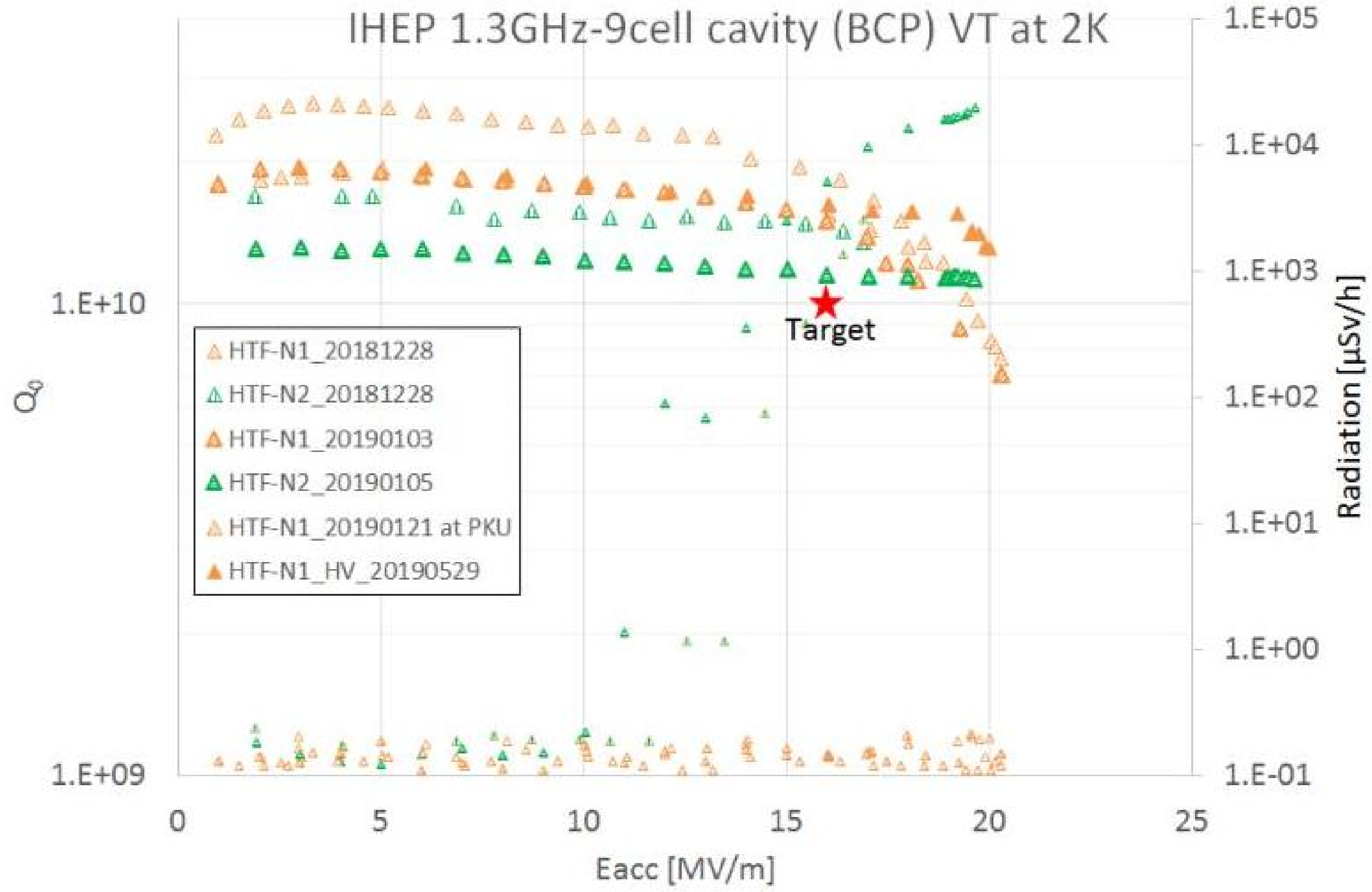
State of the Art in High-Q and High-G (1.3 GHz, 2K)

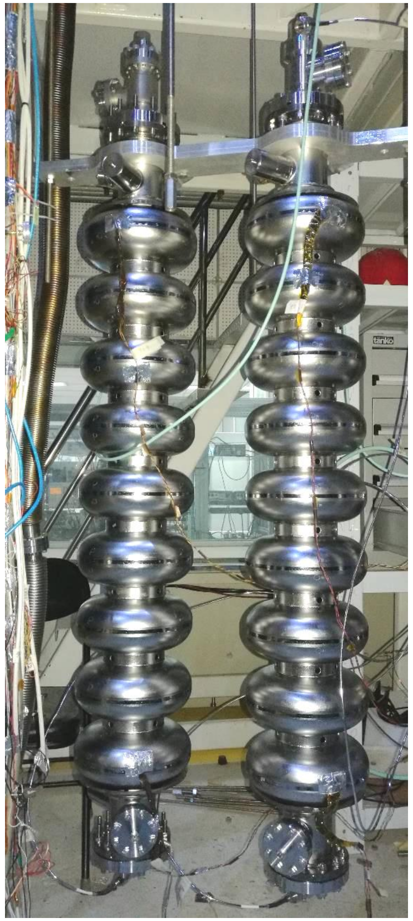


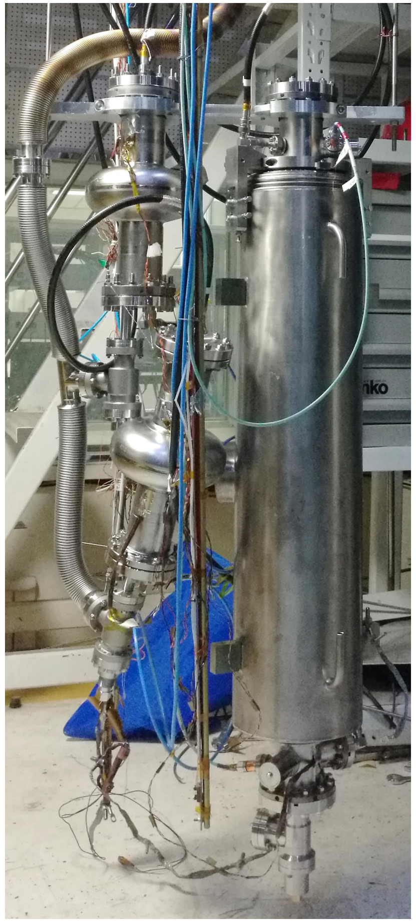
- **N-doping** (@ 800C for ~a few min.)
  - Q >3E10, G = 35 MV/m
- **Baking w/o N** (@ 75/120C)
  - Q >1E10, G =49 MV/m (Bpk-210 mT)
- **N-infusion** (@ 120C for 48h)
  - Q >1E10, G = 45 MV/m
- **Baking w/o N** (@ 120C for xx h)
  - Q >7E9, G = 42 MV/m
- **EP** (only)
  - Q >1.3E10, G = 25 MV/m

- **High-Q** by **N-Doping** well established, and
- **High-G** by N-infusion and **Low-T baking** still to be understood and reproduced, worldwide.

IHEP SHINE 1.3 GHz 9-cell cavities (BCP)

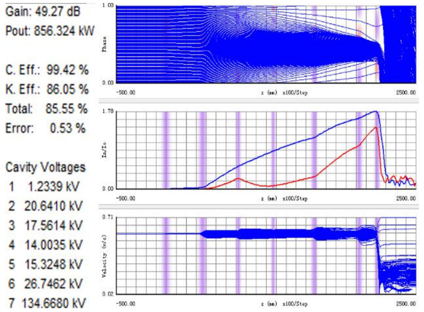




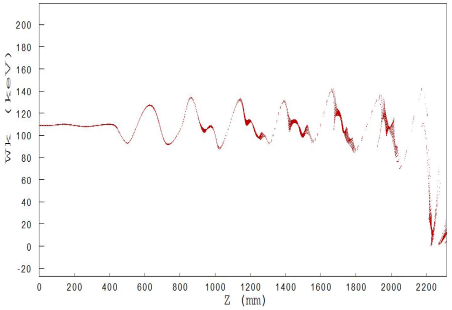


High Efficiency 650Mhz Klystron Development

Single beam klystron@110kV/9.1A

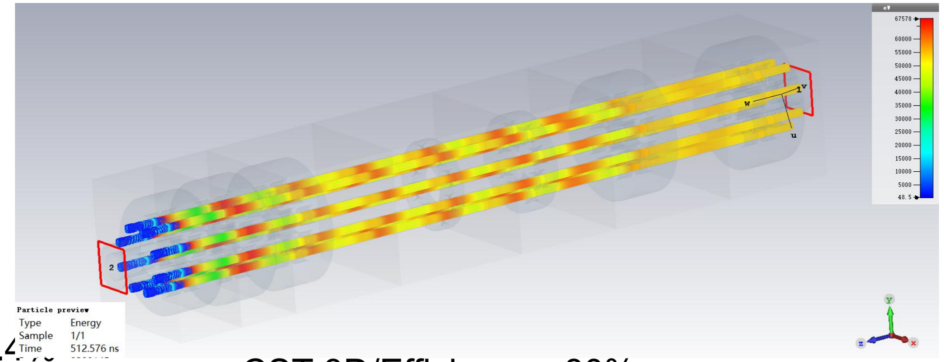


AJDISK code/Efficiency 85.6%

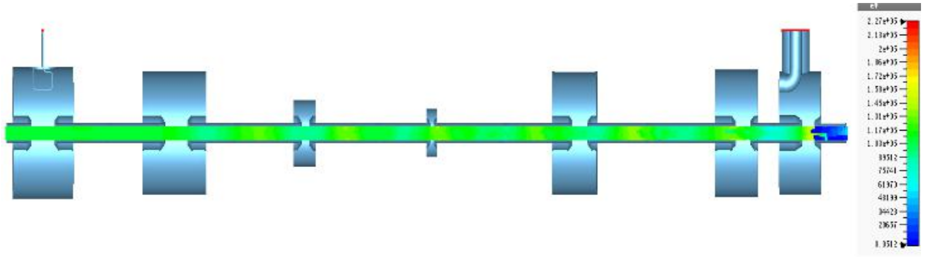


EMSYS-2.5D/Efficiency 81.4%

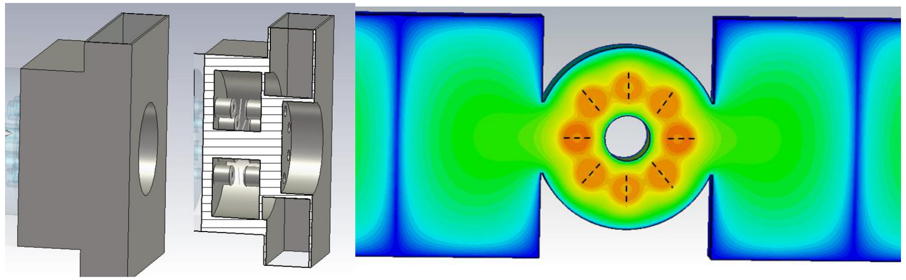
Multi-beam klystron@8 beams



CST-3D/Efficiency ~80%



CST-3D/Efficiency>78%



Cavity detailed design

1st Klystron Prototype Manufacture

① Components

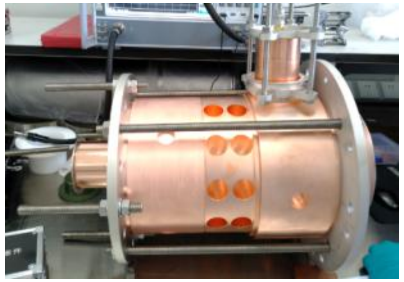
Modulator anode

Focusing electrode

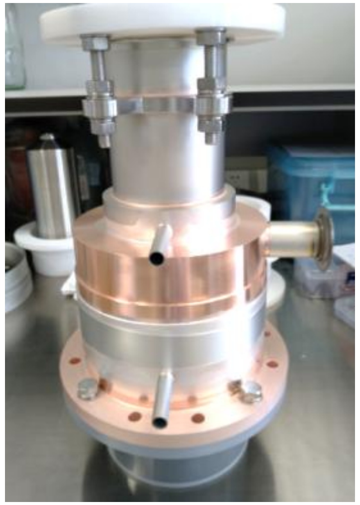
Cathode

Pumping out pipe

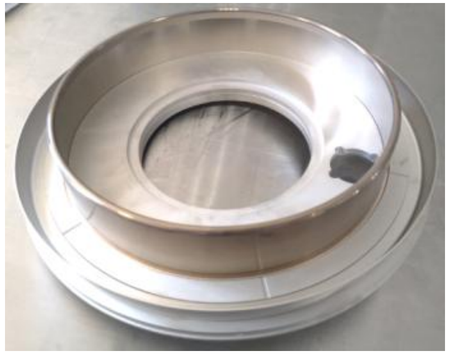
Input coupler



Cavity



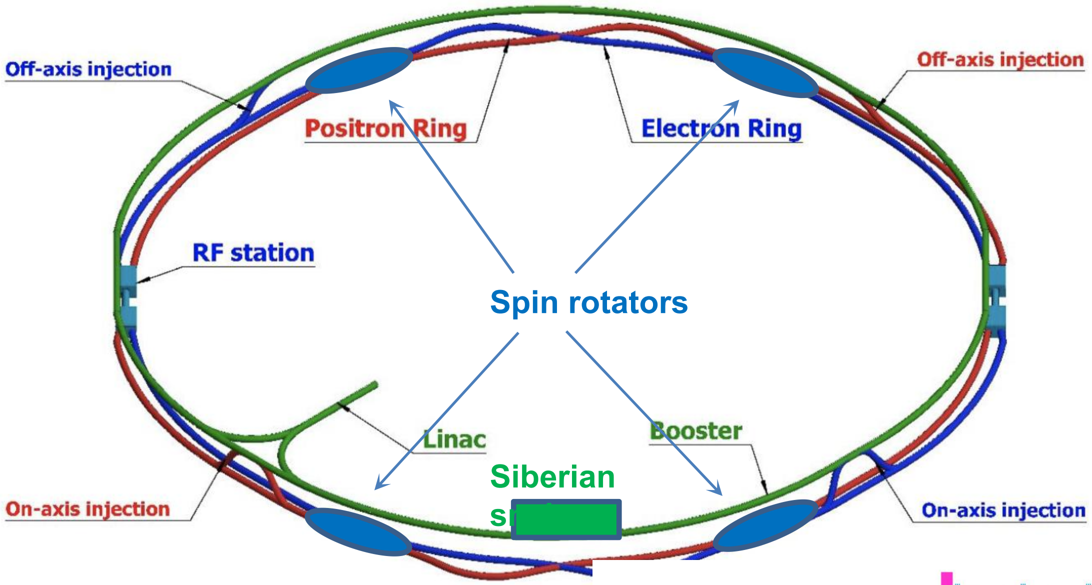
Output window

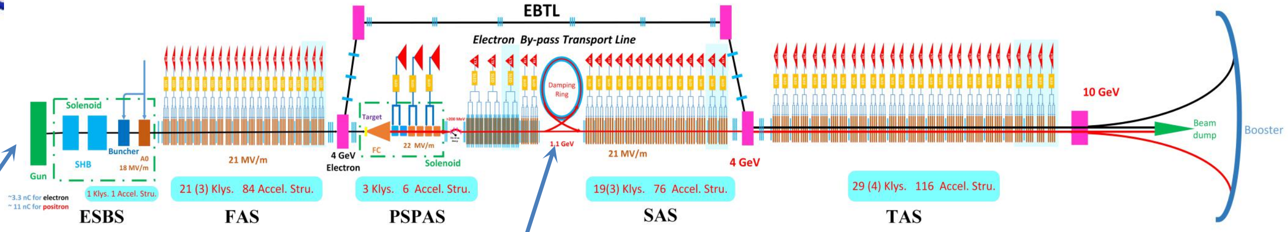


Gun support

51

Beam Polarization Considerations at CEPC-Z





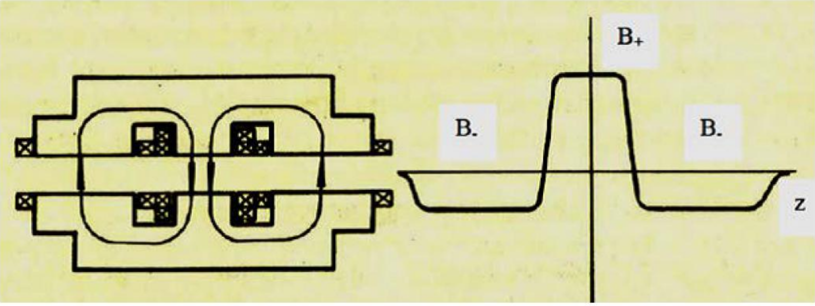
- **Minimal** inclusion of beam polarization @ Z-pole
  - Resonant Depolarization for energy calibration only
  - Dedicated polarization wigglers, rf depolarizer, polarimeter in the storage ring
- **Comprehensive** inclusion of beam polarization @ Z-pole
  - Resonant Depolarization for energy calibration **+ polarized e+e- colliding beams**
  - Dedicated polarization wigglers (not necessary), rf depolarizer, polarimeter in the storage ring
  - Polarized e- gun, low energy e+ damping/polarizing ring (optional)
  - Siberian snake in the booster
  - Spin rotators in the storage ring and the injector chain

CEPC Self Polarization at Z-pole with Asymmetric Wigglers

- **Special wigglers to speed up self-polarization:**

N_w	B_+	L_+	B_-	L_-	$\frac{\tau_p}{\tau_p^w}$	u	$\frac{\Delta E_w}{\Delta E}$	$\frac{P_0^w}{P_0}$
10	0.6T	1m	0.15T	2m	13.4	0.34	3.2	0.99

u: Fraction of radiation energy loss enhancement. **:Factor of beam energy spread enhancement.**

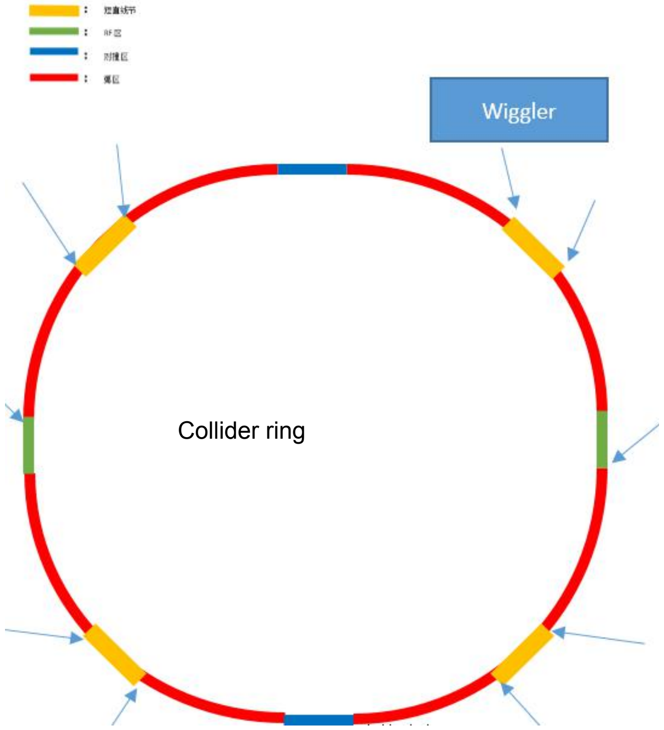


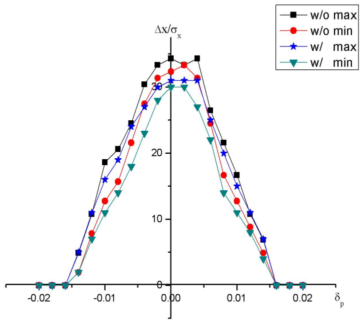
$$P(t) = P_0^w\left(1 - e^{\frac{-t}{\tau_p^w}}\right)$$

$\tau_p^w = 19.6h,\ P(t) = 5\%,\ P_0^w = 0.913,$

$t = 1.10h$

5% is enough for energy calibration.

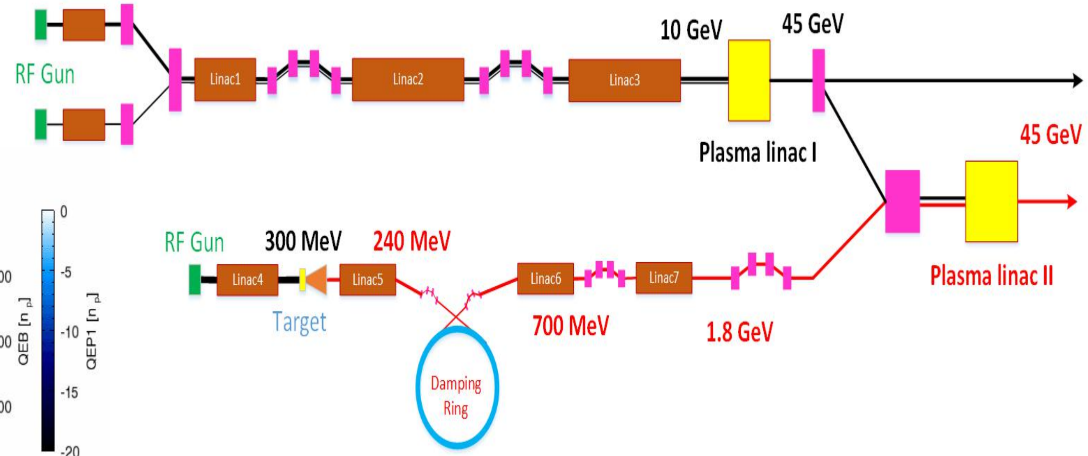


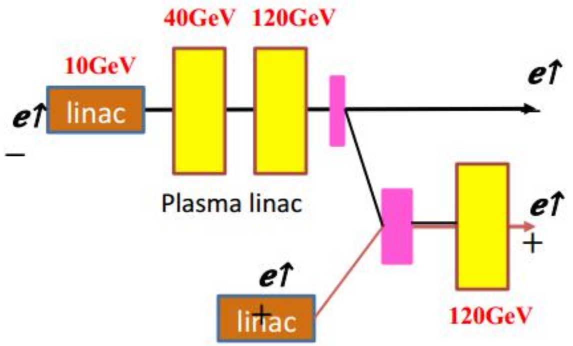


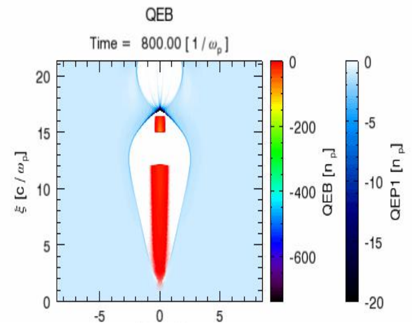
DA

Experimental Verification Planfor CEPC Plasma Injector Scheme

A dedicated budget of 8Million has been alocated by IHEP

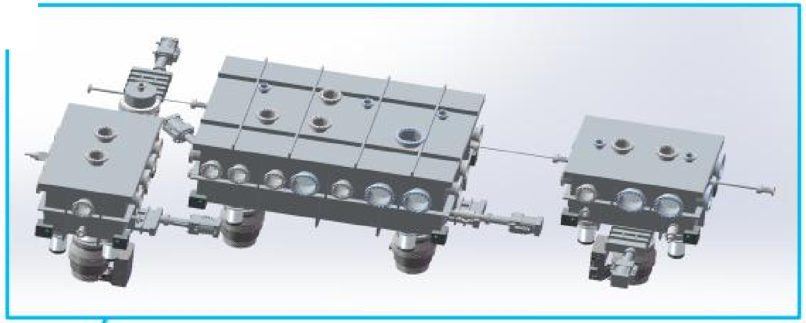


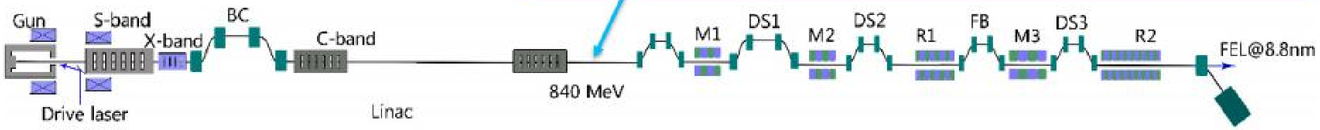




Plasma density $n_0(cm^{-3})$	5.15×10^{16}
Driver charge $Q_d(nC)$	6.47
Driver energy $E_d(GeV)$	10
Driver length $L_d(\mu m)$	285
Driver RMS size $\sigma_d(\mu m)$	10
Driver normalized emittance $\epsilon_{nd}(mm\ mrad)$	10
Trailor charge $Q_t(nC)$	1.25
Trailor energy $E_t(GeV)$	10
Trailor length $L_t(\mu m)$	35
Trailor RMS size $\sigma_t(\mu m)$	5
Trailor normalized emittance $\epsilon_{nt}(mm\ mrad)$	100

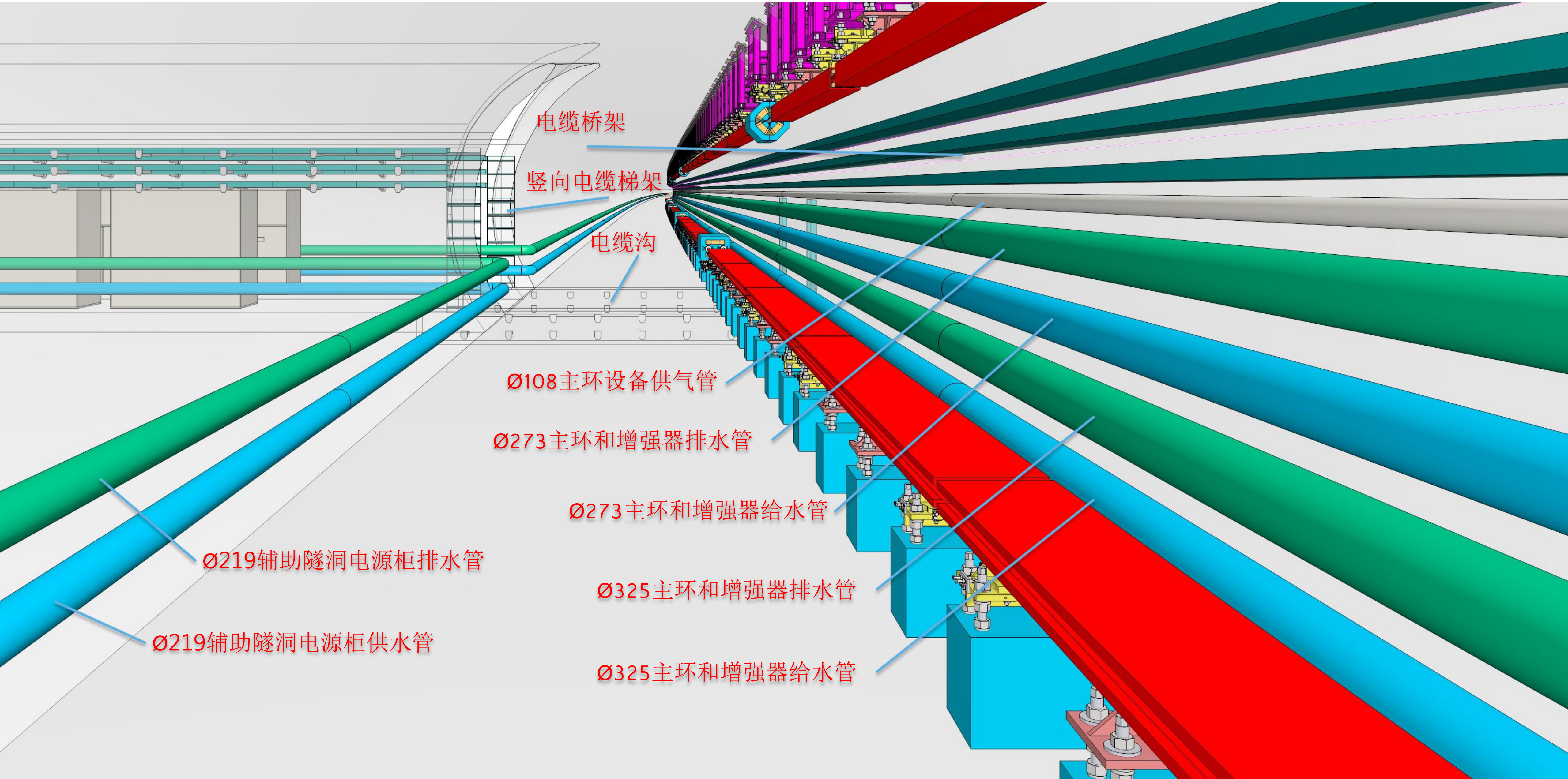
Trailor energy $E_t(GeV)$	45.5
Trailor normalized emittance $\epsilon_{nt}(mm\ mrad)$	98.9
TR	3.55
Energy spread $\delta_E(\%)$	0.7
Efficiency (driver -> trailor)	68.6%



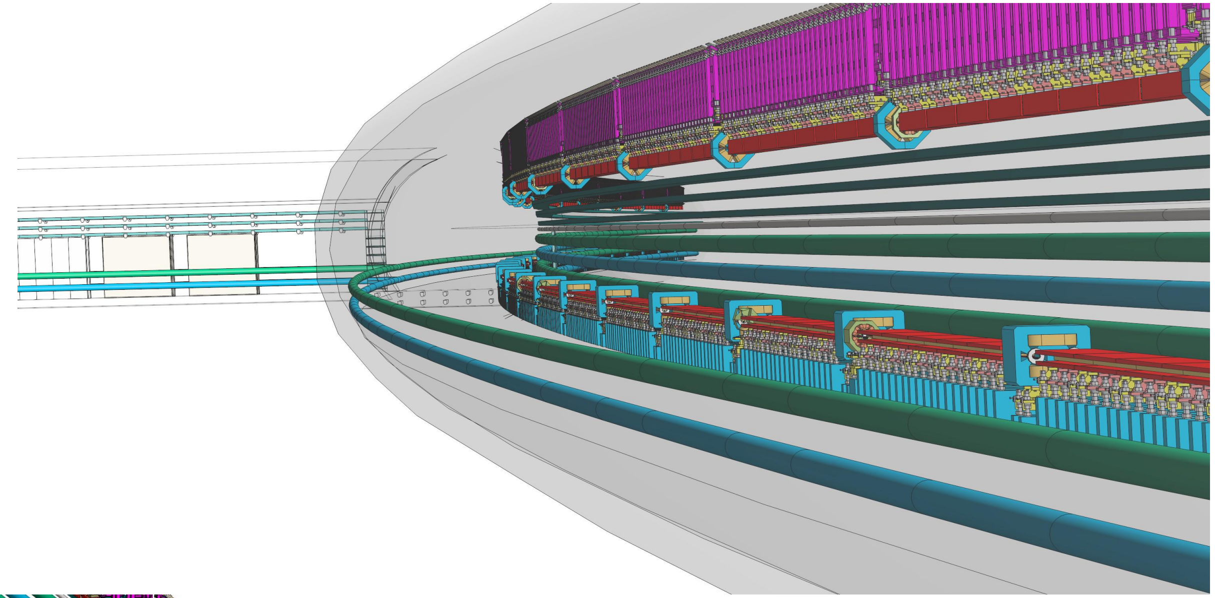


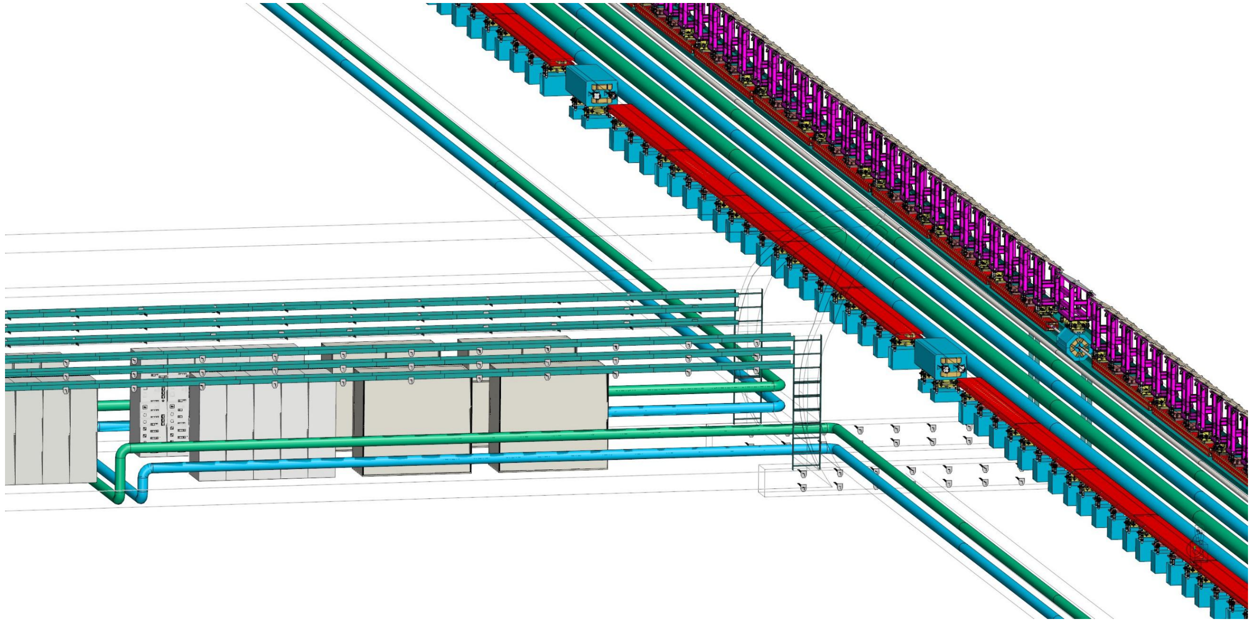
- **Electron plasma acceleration will be tested in Shanghai's Soft XFEL Facility**
- **Positron plasma acceleration scheme will be tested at FACET-II at SLAC**

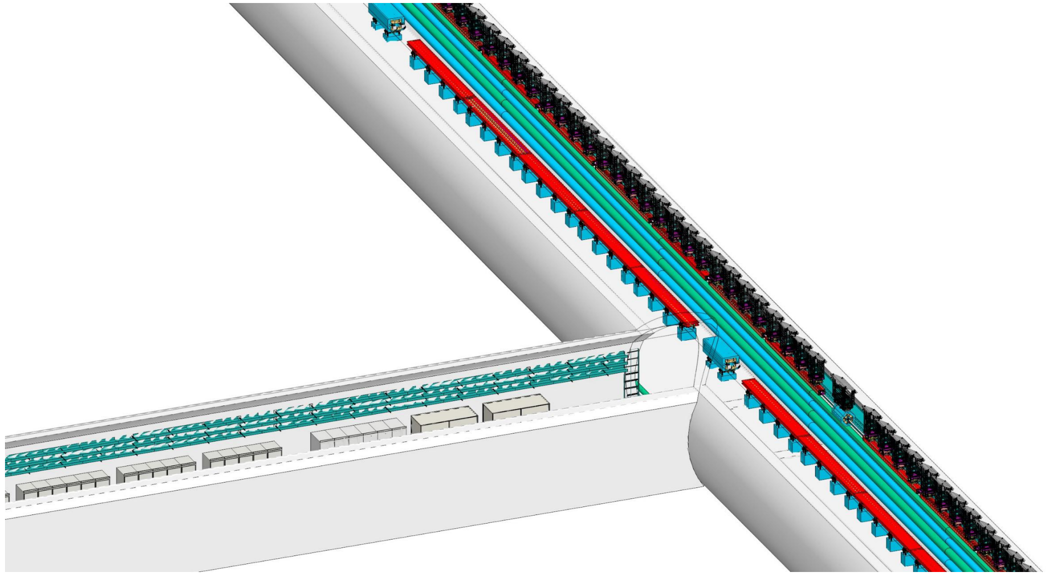
CEPC Main Tunnel and Auxiliary Tunnel-1



CEPC Main Tunnel and Auxiliary Tunnel-2







CEPC Power for Higgs and Z

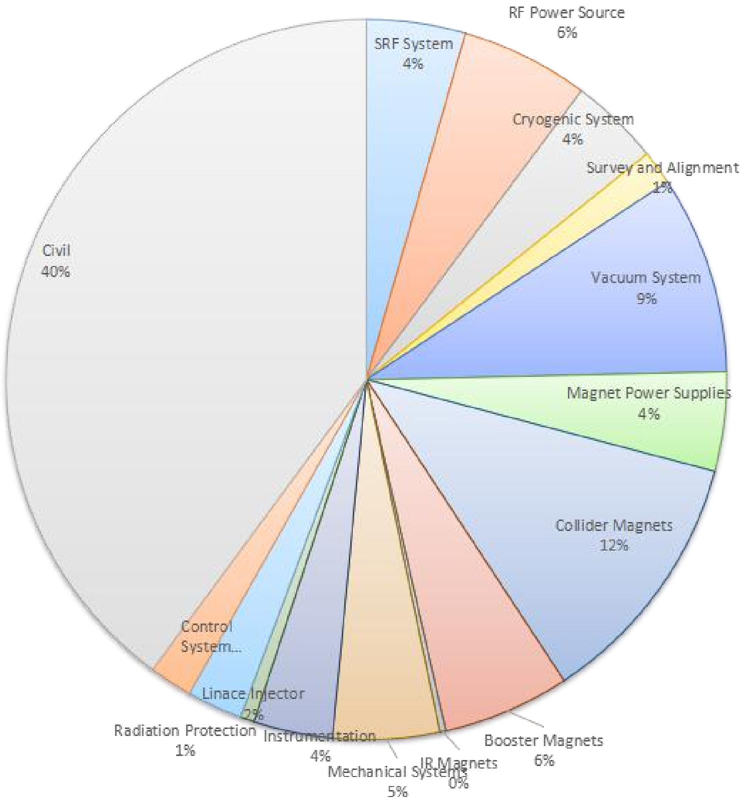
	System for Higgs (30MW)	Location and electrical demand(MW)						Total (MW)
		Ring	Booster	LINAC	BTL	IR	Surface building	
1	RF Power Source	103.8	0.15	5.8				109.75
2	Cryogenic System	11.62	0.68			1.72		14.02
3	Vacuum System	9.784	3.792	0.646				14.222
4	Magnet Power Supplies	47.21	11.62	1.75	1.06	0.26		61.9
5	Instrumentation	0.9	0.6	0.2				1.7
6	Radiation Protection	0.25		0.1				0.35
7	Control System	1	0.6	0.2	0.005	0.005		1.81
8	Experimental devices					4		4
9	Utilities	31.79	3.53	1.38	0.63	1.2		38.53
10	General services	7.2		0.2	0.15	0.2	12	19.75
	Total	213.554	20.972	10.276	1.845	7.385	12	266.032

266MW

	System for Z	Location and electrical demand(MW)						Total (MW)
		Ring	Booster	LINAC	BTL	IR	Surface building	
1	RF Power Source	57.1	0.15	5.8				63.05
2	Cryogenic System	2.91	0.31			1.72		4.94
3	Vacuum System	9.784	3.792	0.646				14.222
4	Magnet Power Supplies	9.52	2.14	1.75	0.19	0.05		13.65
5	Instrumentation	0.9	0.6	0.2				1.7
6	Radiation Protection	0.25		0.1				0.35
7	Control System	1	0.6	0.2	0.005	0.005		1.81
8	Experimental devices					4		4
9	Utilities	19.95	2.22	1.38	0.55	1.2		25.3
10	General services	7.2		0.2	0.15	0.2	12	19.75
	Total	108.614	9.812	10.276	0.895	7.175	12	148.772

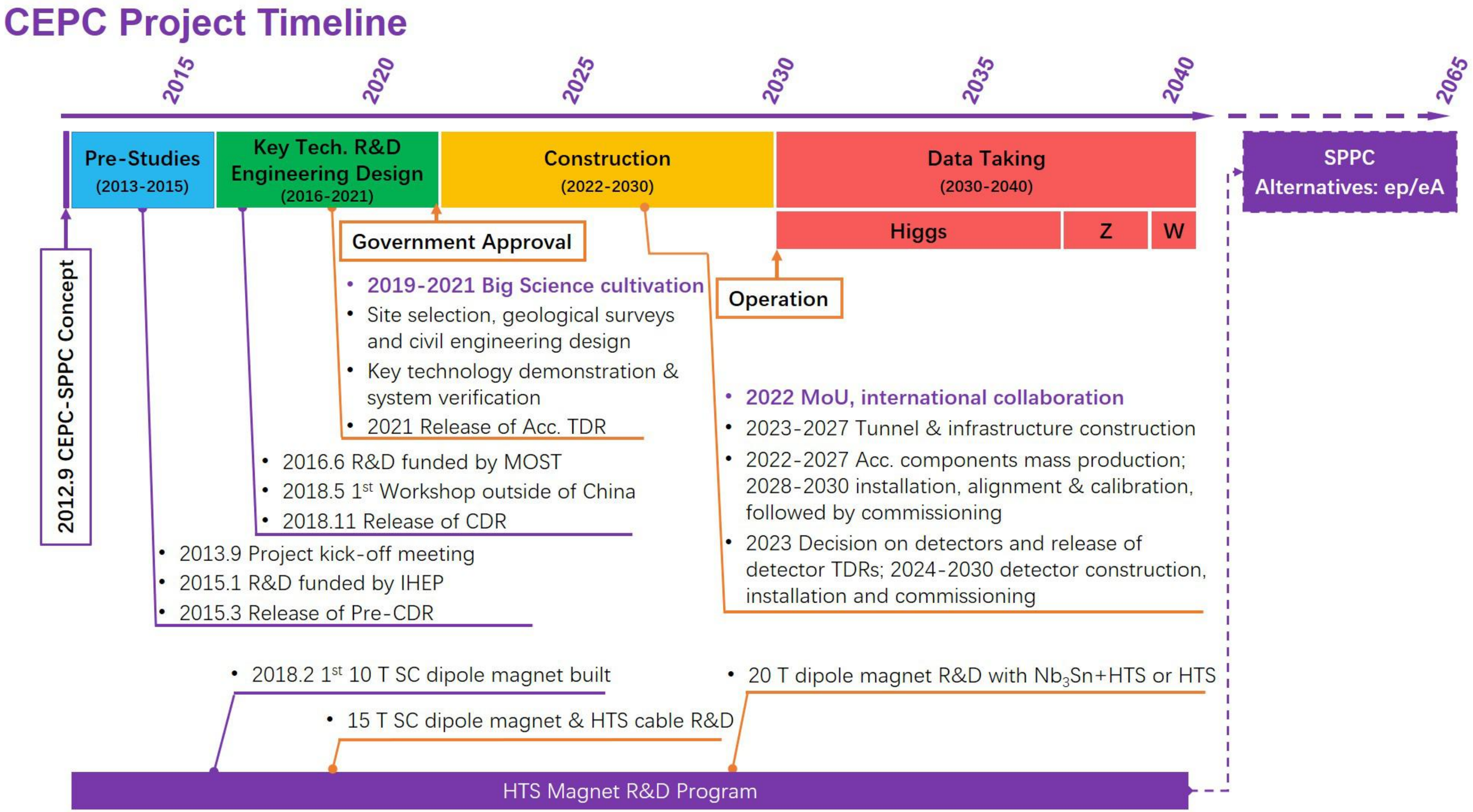
149MW

CEPC Cost Breakdwon (no detector)



Total cost of CEPC: 5Billion USD

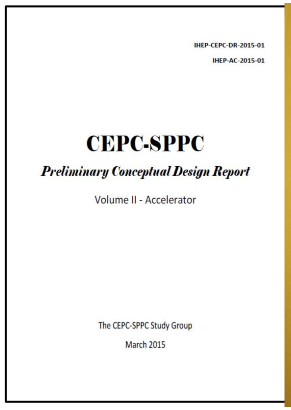
CEPC Timeline



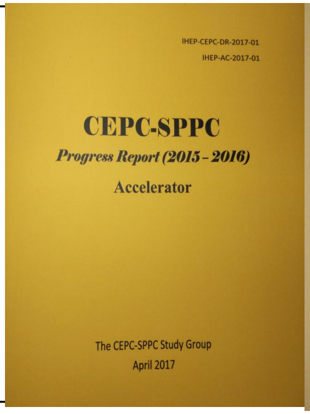
CEPC Accelerator from Pre-CDR to CDR

CEPC accelerator CDR completed in June 2018 (to be printed in July 2018)

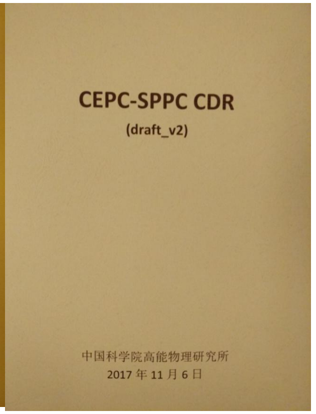
- – Executive Summary
1. Introduction
2. Machine Layout and Performance
3. Operation Scenarios
4. CEPC Collider
5. CEPC Booster
6. CEPC Linac
7. Systems Common to the CEPC Linac, Booster and Collider
8. Super Proton Proton Collider
9. Conventional Facilities
10. Environment, Health and Safety
11. R&D Program
12. Project Plan, Cost and Schedule
- – Appendix 1: CEPC Parameter List
- – Appendix 2: CEPC Technical Component List
- – Appendix 3: CEPC Electric Power Requirement
- – Appendix 4: Advanced Partial Double Ring
- – Appendix 5: CEPC Injector Based on Plasma Wakefield Accelerator
- – Appendix 6: Operation as a High Intensity γ-ray Source
- – Appendix 7: Operation for e-p, e-A and Heavy Ion Collision
- – Appendix 8: Opportunities for Polarization in the CEPC
- – Appendix 9: International Review Report



March 2015



April 2017



Draft CDR for Mini International Review in Nov. 2017

CDR Version for International Review June 2018

Formally relased on Sept. 2, 2018:arXiv：1809.00285

http://cepc.ihep.ac.cn/CDR_v6_201808.pdf

FCCee vs CEPC

EPPSU 2019, Granada Spain

Higgs Factories

- e+e- linear
  - –*ILC* Input #77
  - –*CLIC* Input #146
- e+e- circular
  - –*FCC-ee* Input #132
  - –*CepC* Input #51
- μ+μ- circular
  - –*μ-HF* Input #120

Requirement: high luminosity $O(10^{34})$ at the Higgs energy scale

Usually, compared to the LHC – which is, as a machine :

- 27 km long
- SC magnets (8T)
- 150 MW power total
- ~ 10 years to build
- Cost "1 LHC Unit" *

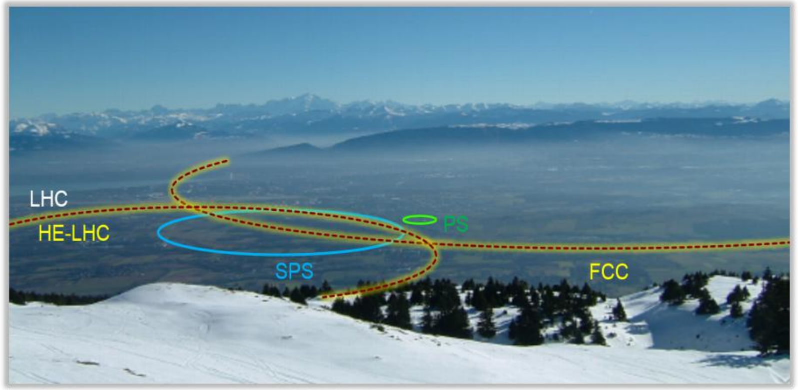
Fermilab

* *as a project, i.e. w/o existing tunnel and injectors*

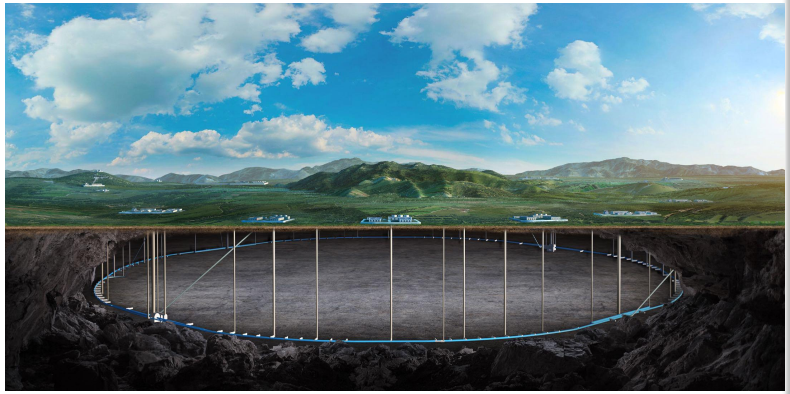
Circular e+e- Higgs Factories

Input #132

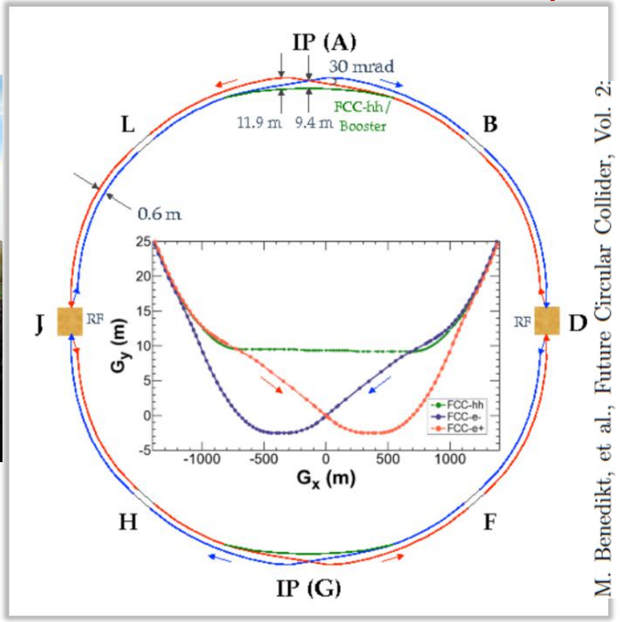
FCC-ee CDR (2019)



FCC



CEPC



Key facts:

100 km tunnel, three rings (*e-*, *e+*, booster)

SRF power to beams: FCCee100 MW;

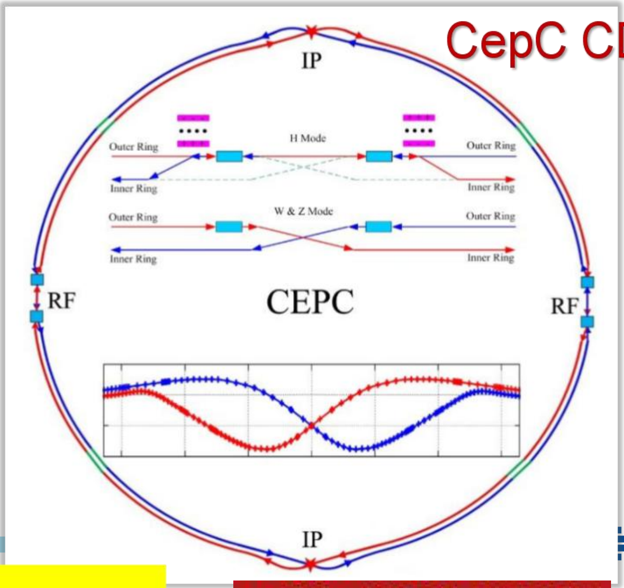
CEPC 60 MW

Total site power ~300MW

Cost est. *FCCee* 10.5 BCHF (+1.1BCHF for tt)

CEPC 5Billion USD

CepC CDR (2018)



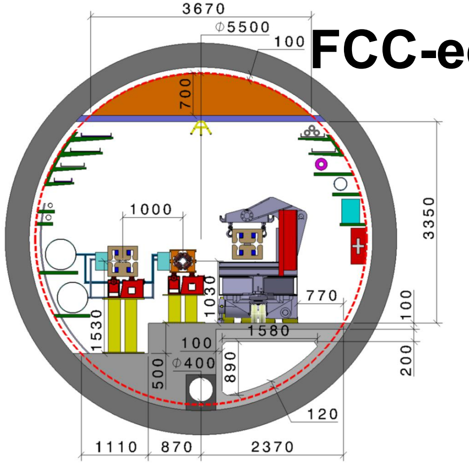
Input #51

arXiv:1809.00285

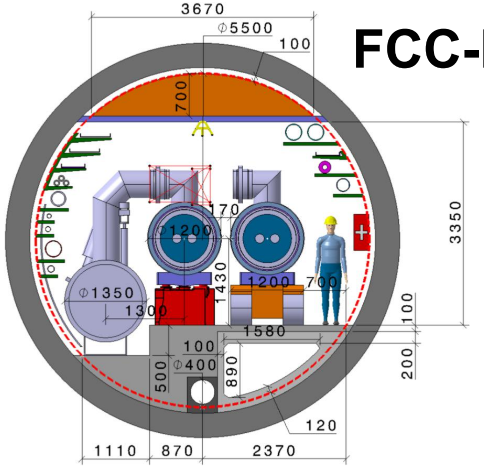
FCC-ee and CEPC – lepton energy frontier

double ring e^+e^- colliders as Z, W, H and t factory at $E_{c.o.m.}$ of 90 - 365 GeV; As Higgs factory: **design luminosities 17 (6) x 10^{34} $cm^{-2}s^{-1}$** (2 IPs) ; **β_y^*= 1.0 (1.5) mm; crab waist** collision scheme; **beam lifetime >12 minutes**; **top-up** injection, **e^+ rate ~ $1x10^{11}$ /s** ; **CDRs complete**

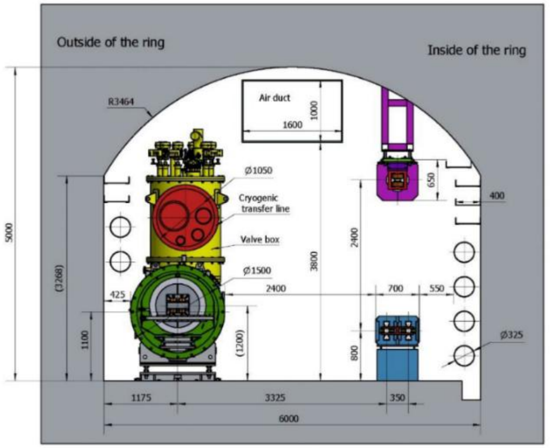
- **FCC-ee and CEPC are part of integrated proposals and each followed by a hadron collider with common footprint.**
- **Circumference** ~100 km
- **Presently 2 IPs,** alternatives with 3 / 4 IPs under study
- **Synchrotron radiation power 50 (30) MW/beam** at all beam energies, cf. LEP2 with 11 MW/beam; SR power/length ~factor 10 below light sources
- **Top-up injection** scheme requires **booster synchrotron in collider tunnel**



FCC-ee



FCC-hh



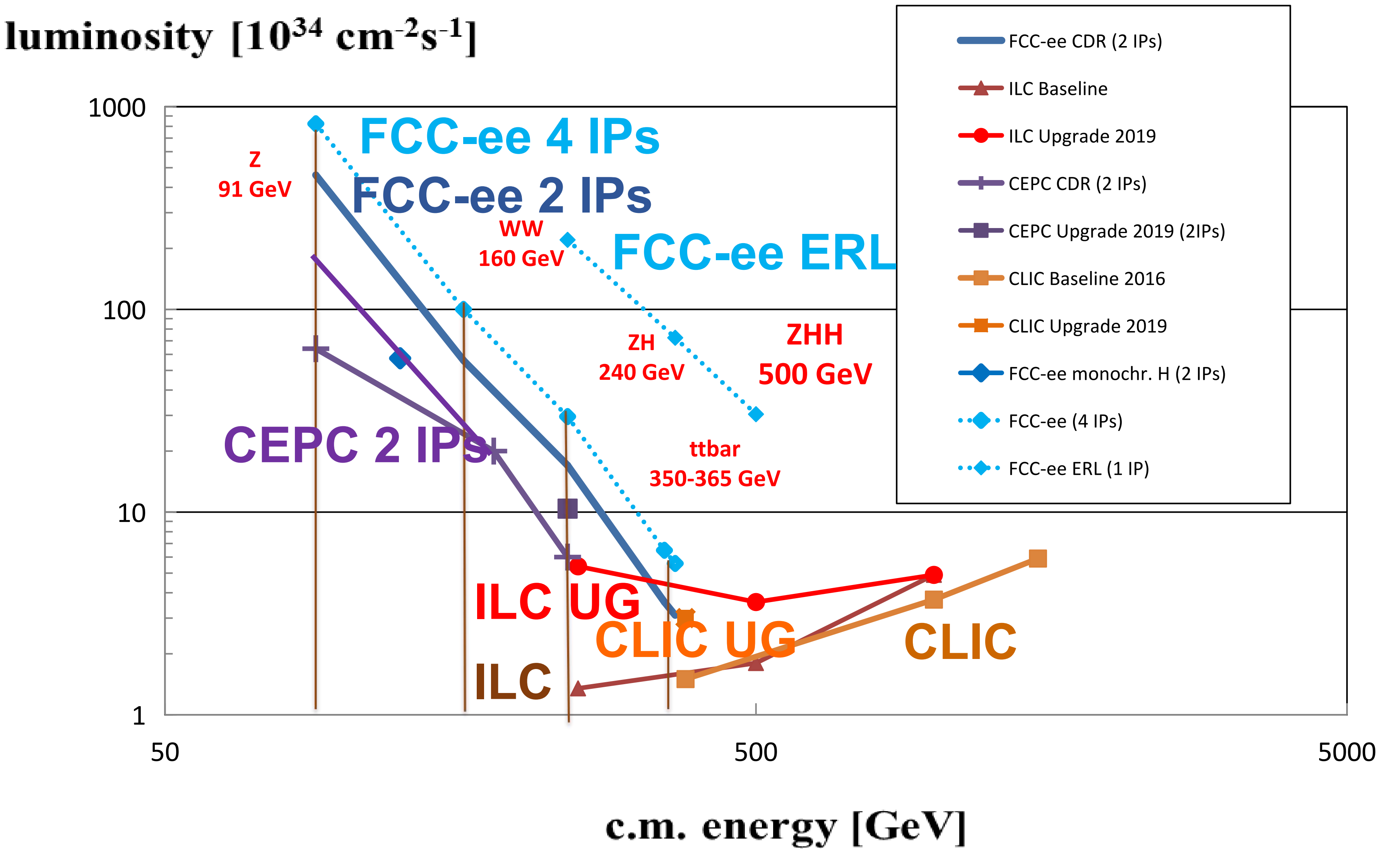
CEPC
SppC

values in brackets refer to CEPC

Key parameters of future circular e^+e^- colliders

Collider (all double rings)	Beam energy [GeV]	Peak luminosity (per IP) [10^{34} cm^{-2}s^{-1}]	β_y* [mm]	beam current [mA]	Collision scheme	Beam lifetime [min]	e^+ top-up rate [10^{11}/s]
SuperKEKB	4 (e^+), 7 (e^-)	**80**	**0.3**	**3600 (e^+), 2600 (e^-)**	**Nano-beam**	**<5**	**10**
BINP c-t	1-3	**5-20**	**0.5**	**2200**	**Crab waist**	**<10**	**1**
HIEPA c-t	1.5-3.5	**~10**	**0.6**	**2000**	**Crab waist**	**<10**	**1**
FCC-ee (Z)	45.6	**230**	**0.8**	**1500**	**Crab waist**	**68**	**7**
FCC-ee (H)	120	**8.5**	**1.0**	29	**Crab waist**	**12**	**1**
FCC-ee (t)	182.5	1.6	**1.6**	5	**Crab waist**	**12**	**0.2**
CEPC (Z)	45.5	**32**	**1.0**	**460**	**Crab waist**	150	**1.1**
CEPC (H)	120	3	**1.5**	17	**Crab waist**	**26**	**0.2**

Many similar parameters and strong synergies for design



Benno List, Daniel Schulte, Dmitry Shatilov, Cheng Hui Yu, Vladimir Litvinenko, Thomas Roser

RF systems for circular e^+e^- colliders

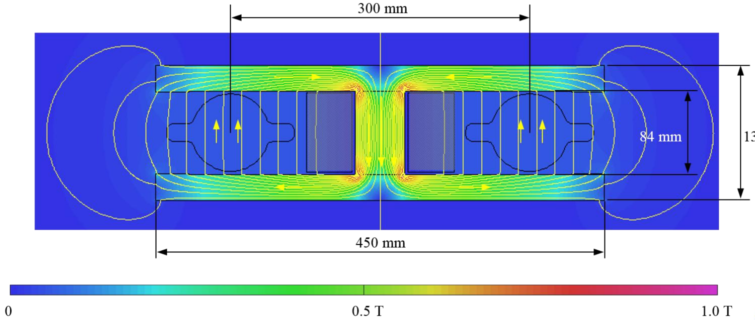
	f_{RF} [MHz]	#cavities	#cell/cavity	$V_{RF,tot}$ [MV]	acc. gradient [MV/m]	technology
SuperKEKB	**509**	30 (ARES) 8 (SCC)	1 1	15 12	2 6	warm Cu bulk Nb
charm-tau	**500**	1 / ring	1	2x1	6	bulk Nb
FCC-ee-H	**400**	136 / ring	4	2000	10	Nb/Cu
FCC-ee-t (addt'l)	**800**	372	5	6930	19.8	bulk Nb
CEPC	**650**	120 or 240	1 or 2	2200	40 or19.7	bulk Nb

- all systems between 400 and 800 MHz, various technologies,
- preference for SC cavities,
- FCC-ee RF system optimized for each working point, CEPC features single system

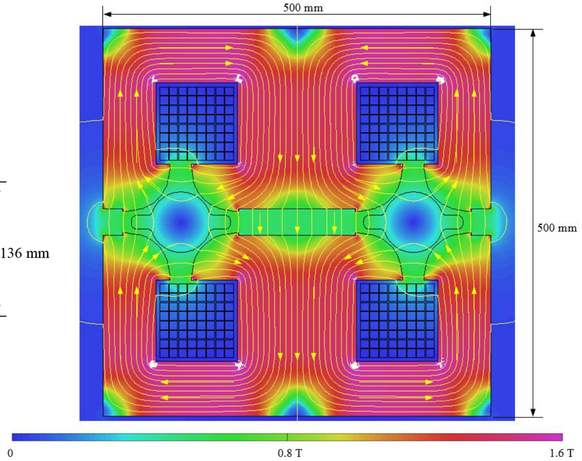
Design of low-power magnets for FCC-ee and CEPC

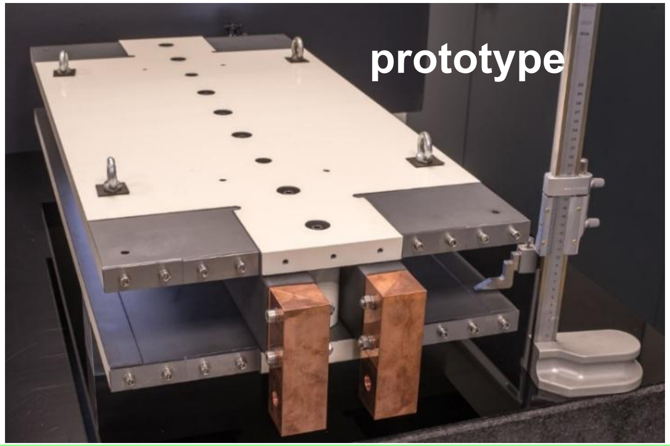
FCC-ee

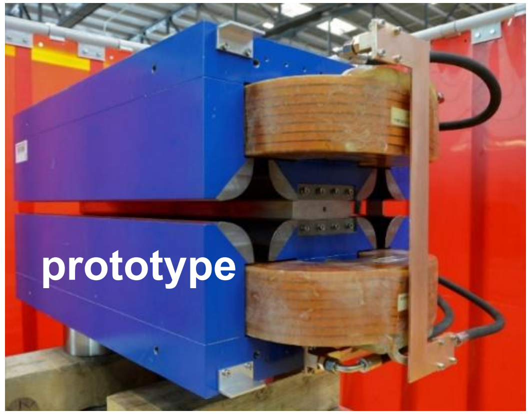
Twin-dipole design with 2× power saving 16 MW at 175 GeV



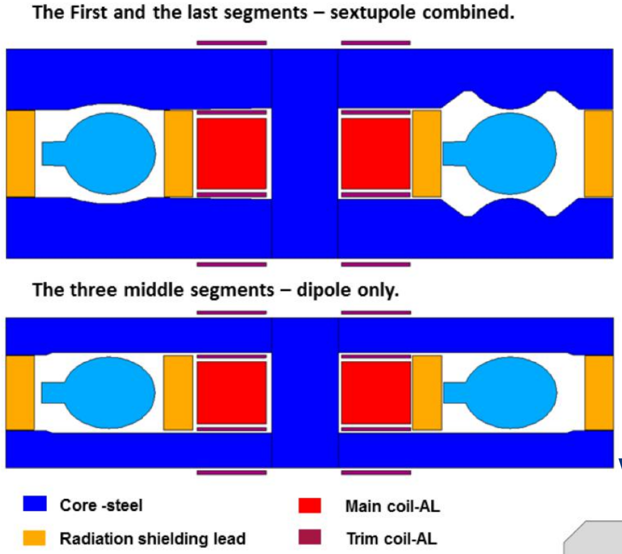
Twin F/D arc quad with 2× power saving 25 MW at 175 GeV





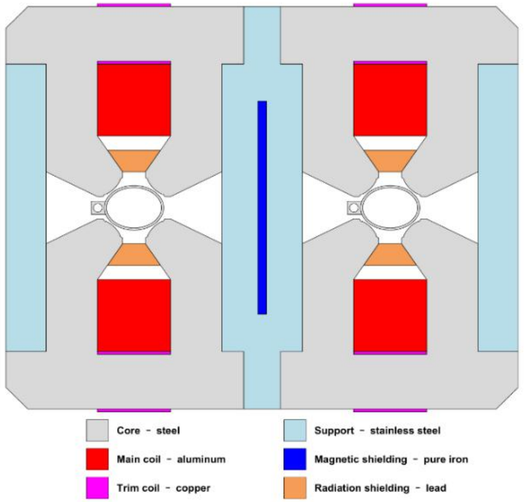


CEPC



Twin arc magnet combined function dipole with sextupole component

Twin F/D arc quad with 2× power saving



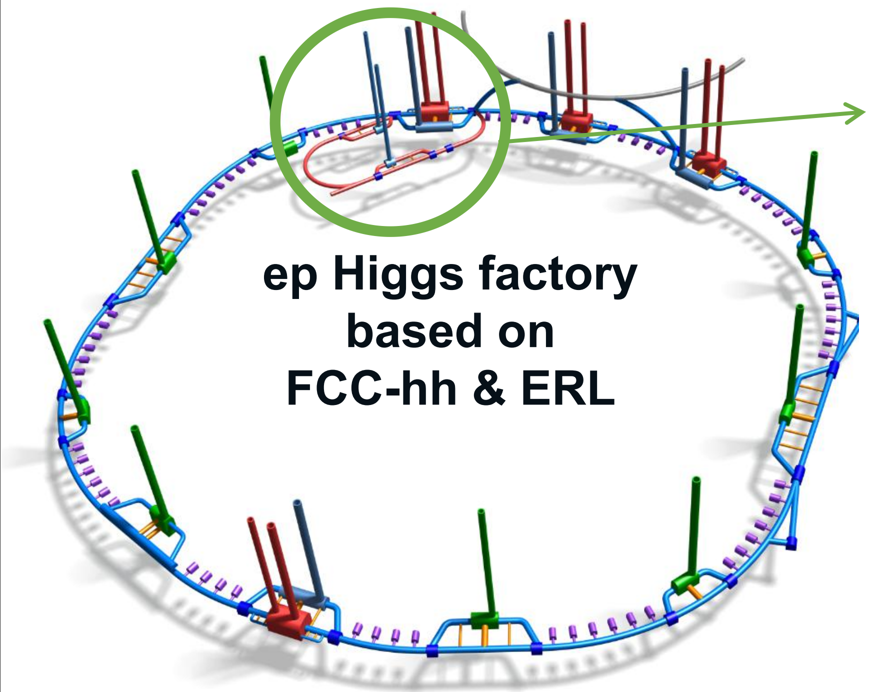
power reduction by factor 2 w.r.t. single-aperture magnets

FCC-eh & CEPC-SppC

Future hadron colliders will provide possibility for lepton-hadron collisions.

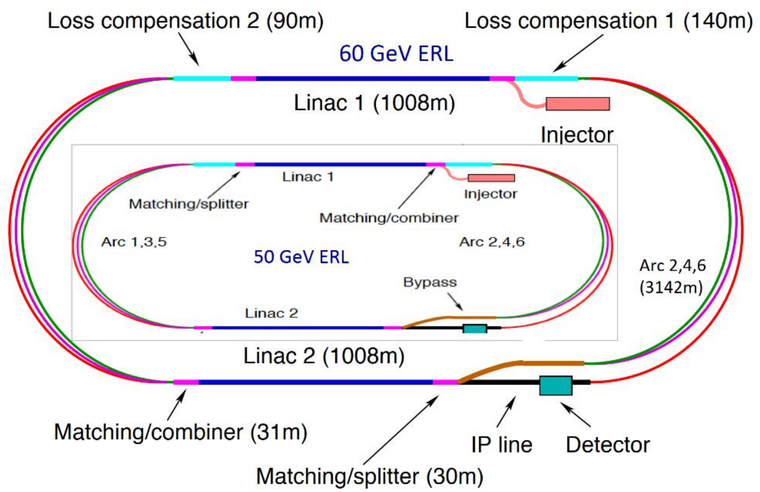
FCC-eh: ~60 GeV e^- from Energy Recovery Linac (PERLE test facility proposal Orsay)

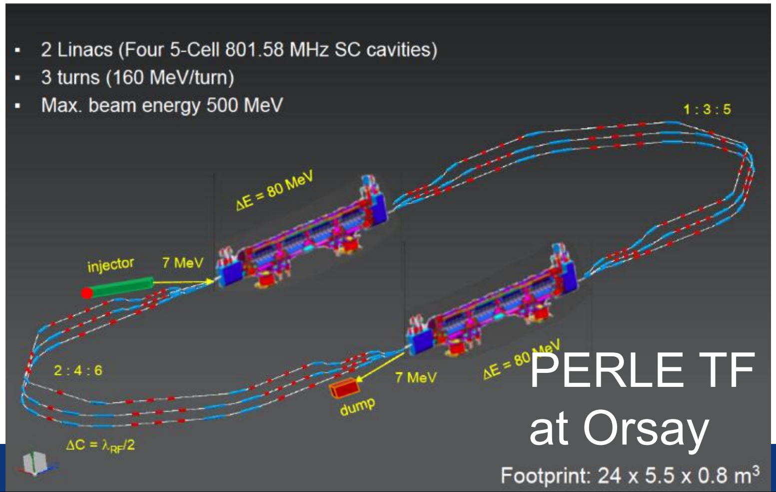
SppC: e-beam from co-existing CEPC in same tunnel



ep Higgs factory based on FCC-hh & ERL

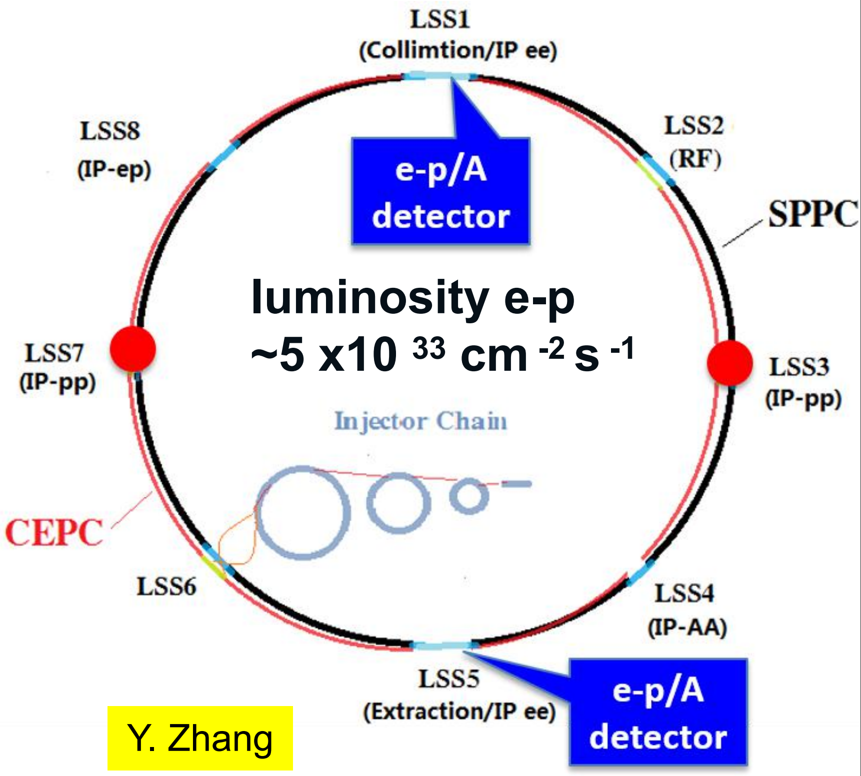
luminosity ~10^{34} cm^{-2} s^{-1}





CEPC-SppC

- machines coexisting
- proton experiment bypasses



luminosity e-p ~5 x10^{33} cm^{-2} s^{-1}

Y. Zhang

Technical Challenges in Energy-Frontier Colliders proposed

		Ref.	E (CM) [TeV]	Lumino sity [1E34]	AC-Power [MW]	Value [Billion]	B [T]	E: [MV/m] (GHz)	Major Challenges in Technology
CC hh	FCC-hh	CDR	~ 100	< 30	580	24 or +17 (aft. ee) [BCHF]	~ 16		High-field SC magnet (SCM) - Nb3Sn: Jc and Mechanical stress Energy management
	SPPC	(to be filled)	75 – 120	TBD	TBD	TBD	12 - 24		High-field SCM - IBS: Jcc and mech. stress Energy management
CC ee	FCC-ee	CDR	0.18 - 0.37	460 – 31	260 – 350	10.5 +1.1 [BCHF]		10~20 (0.4 / 0.8)	High-Q SRF cavity at < GHz, Nb Thin-film Coating Synchrotron Radiation constraint Energy efficiency (RF efficiency)
	CEPC	CDR	0.046 - 0.24 (0.37)	32~ 5	150 – 270	5 [B$]		20 (~ 40) (0.65)	High-Q SRF cavity at < GHz, LG Nb-bulk/Thin-film Synchrotron Radiation constraint High-precision Low-field magnet
LC ee	ILC	TDR update	0.25 (-1)	1.35 (– 4.9)	129 (– 300)	< 5.3 > (for 0.25 TeV) [BILCU]		31.5 – (45) (1.3)	High-G and high-Q SRF cavity at GHz, Nb-bulk Higher-G for future upgrade Nano-beam stability, e+ source, beam dump
	CLIC	CDR	0.38 (- 3)	1.5 (- 6)	160 (- 580)	5.9 (for 0.38 TeV) [BCHF]		72 – 100 (12)	Large-scale production of Acc. Structure Two-beam acceleration in a prototype scale Precise alignment and stabilization. timing

A. Yamamoto, 190513a

7-10 YEARS FROM NOW

WITH PROPOSED ACTIONS / R&D DONE / TECHNICALLY LIMITED

- ***ILC:***
  - Some change in cost (~6-10%)
  - All agreements by 2024, then
  - **Construction** (2024-2033)
- ***CLIC:***
  - TDR & preconstr. ~2020-26
  - **Construction** (2026-2032)
  - 2 yrs of commissioning
- ***CepC:***
  - Some change in cost & power
  - TDR and R&D (2018-2022)
  - **Construction** (2022-2030)
- ***FCC-ee:***
  - Some change in cost & power
  - **Preparations** 2020-2029
  - Construction 2029-2039
- ***HE-LHC:***
  - **R&D and prepar'ns** 2020-2035
  - Construction 2036-2042
- ***FCC-hh*** (w/o FCC-ee stage)***:***
  - **16T magnet prototype** 2027
  - Construction 2029-2043
- ***μ^+-μ^- Collider :***
  - **CDR completed** 2027, cost known
  - Test facility constructed 2024-27
  - Tests and TDR 2028-2035

Fermilab

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V. Shiltsev, A. Yamomoto