FCC-ee overview

Frank Zimmermann
MDI working meeting, 10 September 2019

Image: Polar Media/ FCC Study Office

FCC-ee Conceptual Design Report

The European Physical Journal

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Special Topics

FCC-ee: The Lepton Collider
Future Circular Collider Conceptual Design Report Volume 2

Michael Benedikt et al. (Eds.)

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edp sciences ✥ Springer

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[8], A. Arbuzov[17], G. Arduini[64], V. Ari[9], S. Arias[66,31], N. Armesto[46], R. Arnaldi[136,274], S.A. Arsenyev[64], M. Arzeo[64], S. Asai[343], E. Aslanides[31], R.W. Aßmann[49], D. Astapovych[228], M. Atanasov[64], D. Attié[64], D. Attié[64], B. Auchmann[64], A. Audurier[119,258], S. Aull[64], S. Aumon[64], S. Avrillaud[83], G. Aydın[281], A. Azatov[132,137], G. Azuelos[310], P. Azzi[267], O. Azzolini[116], P. Azzurri[268], N. Bacchetta[267], E. Bacchiocchi[266], H. Bachacou[39], Y. Bai[314], S. Baird[64], M.J. Baker[333], M.J. Baldwin[167], H. Ball[64], A. Ball[64], S. Banerjee[54], D.P. Barber[49,316], D. Barducci[214,137], P. Barjhoux[64], D. Barna[172], G.G. Barnaföldi[172], M.J. Barnes[64], A. Barr[190], 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],

- **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.
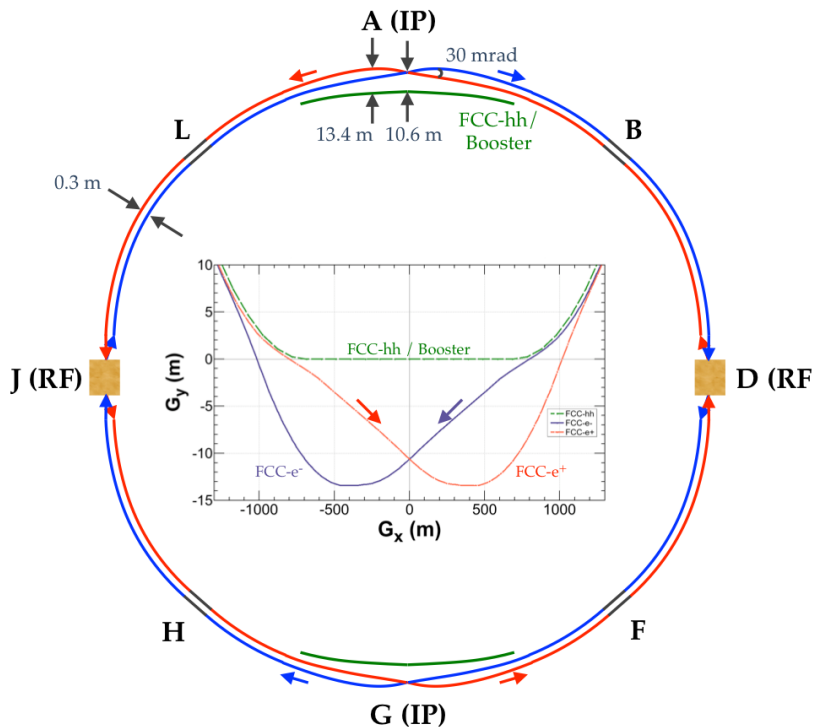
FCC-ee collider parameters

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

FCC-ee luminosity versus energy
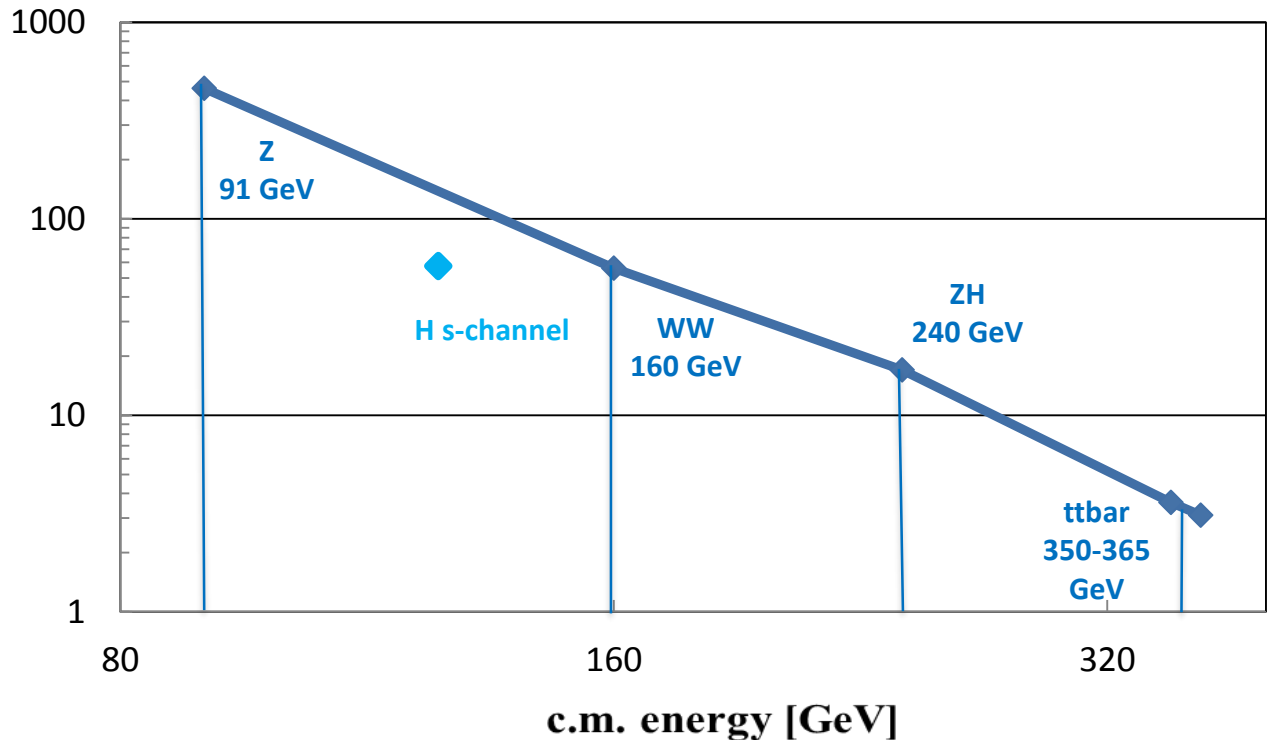
FCC-ee exploits lessons from past & present colliders
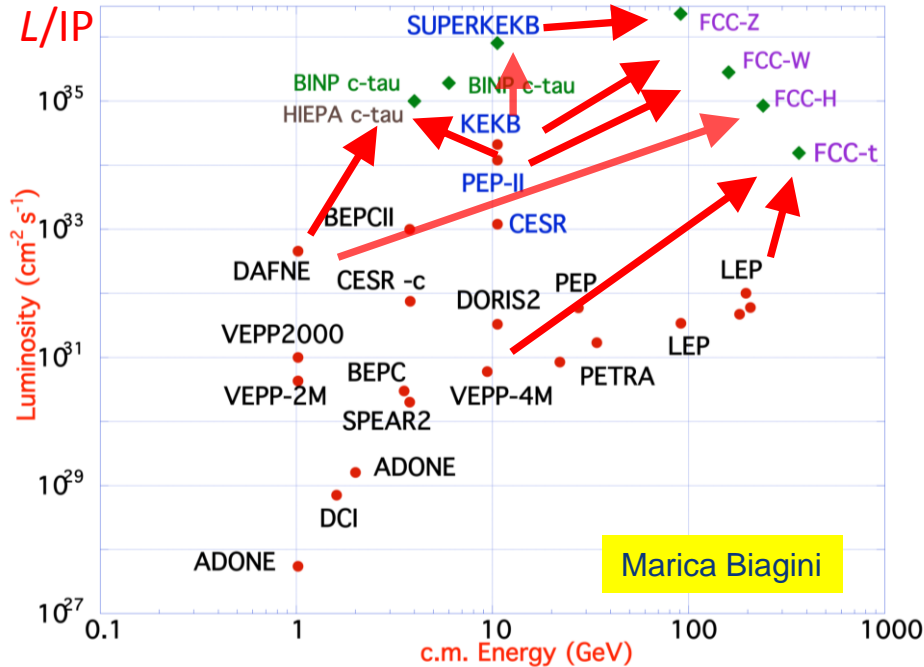
LEP: **high energy, SR effects**

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

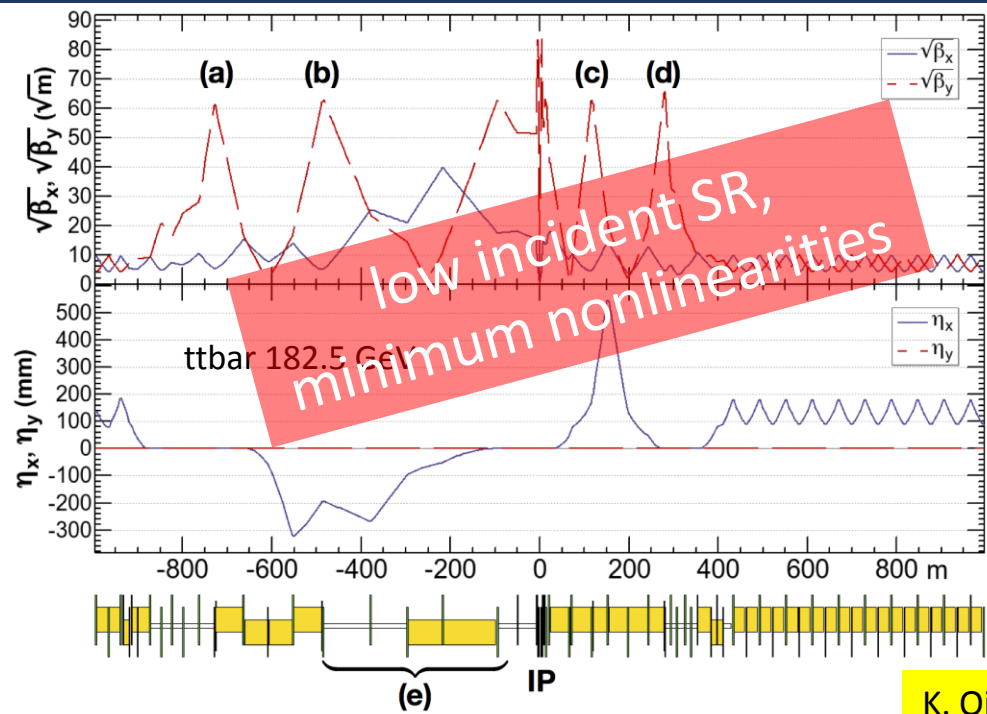DAFNE: **crab waist, double ring**

SuperKEKB: **low β_y^***

VEPP-4M, LEP: **precision energy calibration**

KEKB, SuperKEKB: *e*⁺ source

combining successful ingredients of several recent colliders → extremely high luminosity at high energies

ttbar 182.5 GeV

low incident SR, minimum nonlinearities

Novel asymmetric IR optics to suppress synchrotron radiation toward the IP, $E_{critical}$ **<100 keV from 450 m from IP (e) – lesson from LEP**

H. Burkhardt, K. Oide, et al.

yellow boxes: dipole magnets

4 sextupoles (a – d) for local vertical chromaticity correction combined with crab waist, optimized for each working point – **novel "virtual crab waist", standard crab waist demonstrated at DAFNE**

K. Oide et al., Design of beam optics for the future circular collider e+e- collider rings, **Phys. Rev. Accel. Beams 19**, 111005 (2016).

advanced SC final-focus magnets

final-focus sextupole:
7350 T/m^2; 30 cm long;
canted-cosine-theta
concept; 10-11 T on
surface ; HTS wires

M. Koratzinos

the strongest magnet in FCC-ee
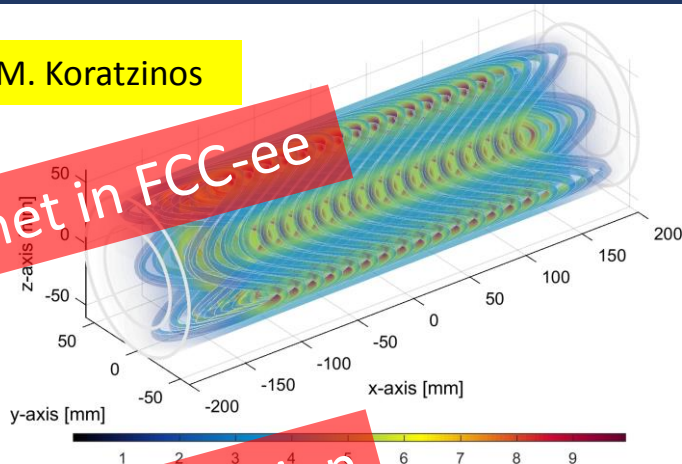
final quadrupole pair
near IP; canted-cosine-
theta concept;
with orbit corrector &
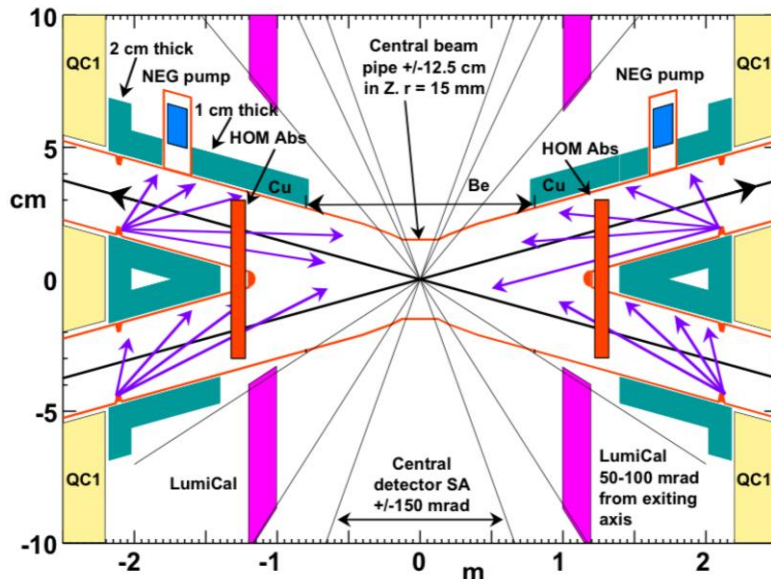skew quadrupole ;
to be built with
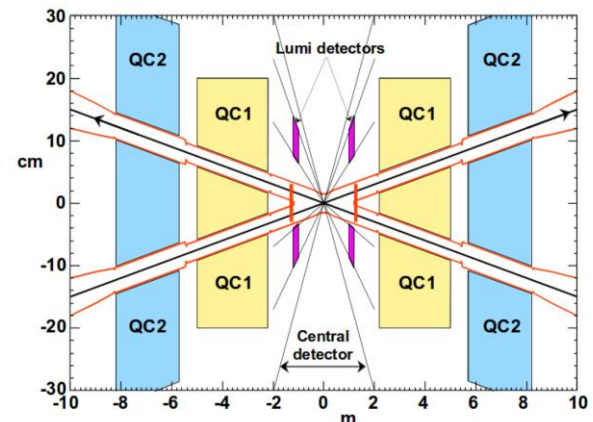Nb-Ti or HTS wires

prototype under construction

A1_corr_L
A2_corr_L
QC1L1
B1_corr
A1_corr_R
A2_corr_R
QC1R1
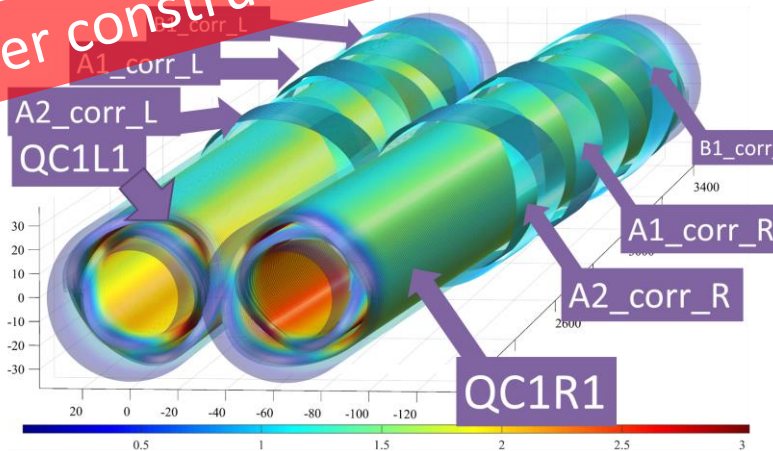
M. Koratzinos

FCC-ee interaction region

3D sketch of key IR systems over first 3 m from IP

Q1 with shielding solenoid

luminometer

IP

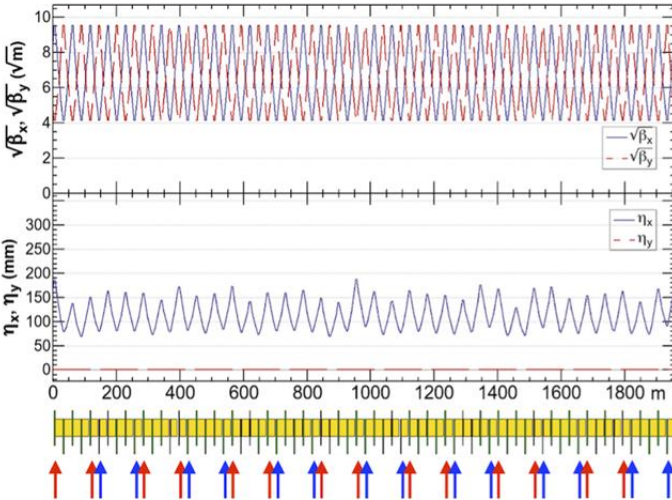compensation solenoid
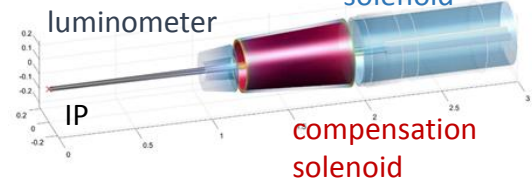
M. Boscolo, N. Bacchetta, A. Bogomyagkov, H. Burkhardt, M. Dam, D. El Khechen, M. Koratzinos, E. Levichev, M. Luckhof, A. Novokhatski, M. Sullivan, et al.
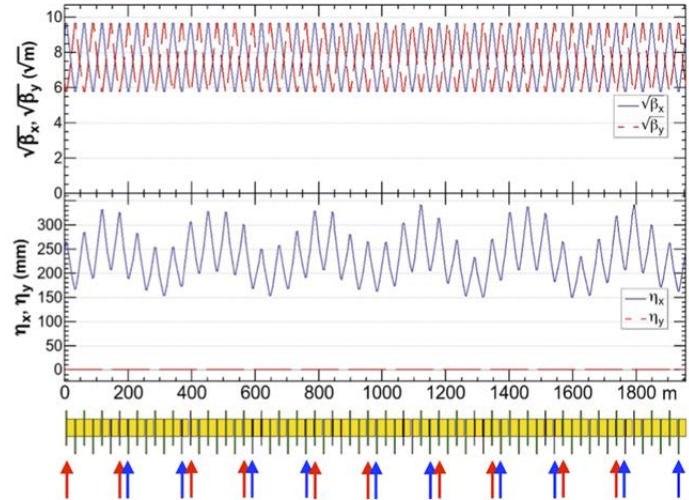
90◦/90◦ (for **ZH** and $t\bar{t}$,) 588 independent sextupole pairs

60◦/60◦ (for **Z** and **WW**), 416 independent sextupole pairs

The beam optics of the arc super cell. The upper and lower rows show $\sqrt{\beta_{x,y}}$ and dispersions, respectively. The locations of the focusing and defocusing sextupoles, SF and SD, are indicated by red and blue arrows, respectively, for each phase advance. Every two sextupoles are paired with a −*I* transformation in between. KEKB had 52 non-interleaved sextupole pairs per ring.

K. Oide

off-energy dynamic aperture
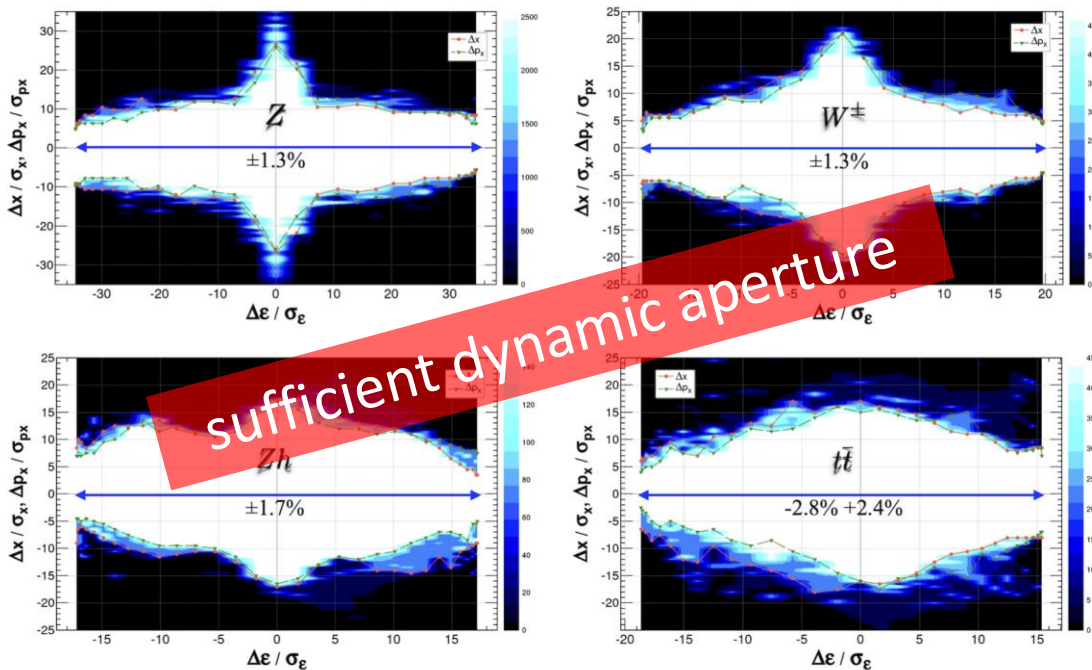
Dynamic apertures in *z-x* plane after sextupole optimisation with particle tracking for each energy.

The initial vertical amplitude for the tracking is always set to $J_y/J_x = \varepsilon_y/\varepsilon_x$. Number of turns ~2 longitudinal damping times.

K. Oide

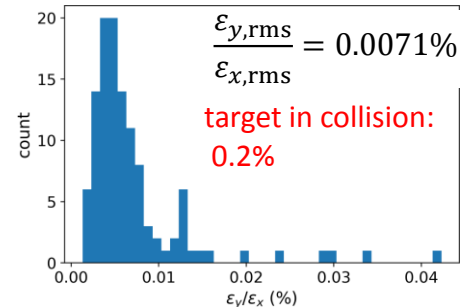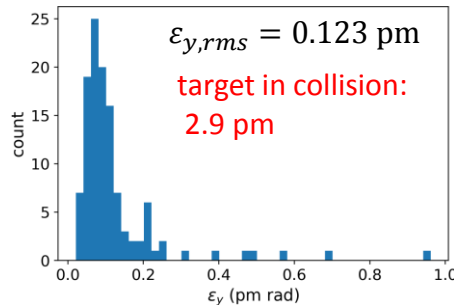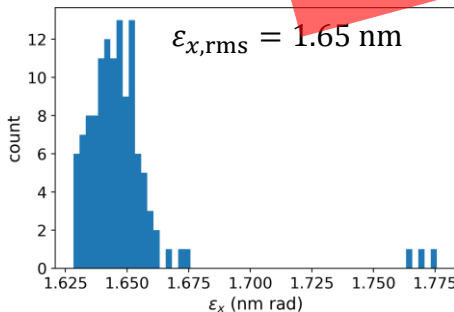important for top-up injection and for beam lifetime with beamstrahlung

vertical emittance with errors

T. Charles, S. Aumon, T. Tydecks,….

realistic misalignments and roll angles

	$\sigma_x(\mu m)$	$\sigma_y(\mu m)$	$\sigma_\theta(\mu rad)$
arc quads	100	100	100
IP quads	100	100	100
sextupoles	100	100	100
dipoles	100	100	100
BPMs	20	20	150

*BPM error relative to quadrupole position

after iterative optics corrections:

well below target emittance with realistic errors

$\varepsilon_{x,\mathrm{rms}} = 1.65$ nm

$\varepsilon_{y,rms} = 0.123$ pm

target in collision: 2.9 pm

$\dfrac{\varepsilon_{y,\mathrm{rms}}}{\varepsilon_{x,\mathrm{rms}}} = 0.0071\%$

target in collision: 0.2%

simulated vertical emittance much smaller than needed

vertical emittance blow up

D. El Khechen

beam beam, after offset correction
no beam beam

invariant emittance w errors & correction & beam-beam from tracking ~0.8 pm

invariant emittance w errors & correction from beam-beam tracking ~0.3 pm

target emittance achieved with realistic errors and beam-beam !

MAD-X invariant emittance w errors & correction ~0.08 pm

also see K. Oide, H. Koiso, Phys. Rev. E 49, 4474 (1994)

EMIT Y (pm)

# of turns
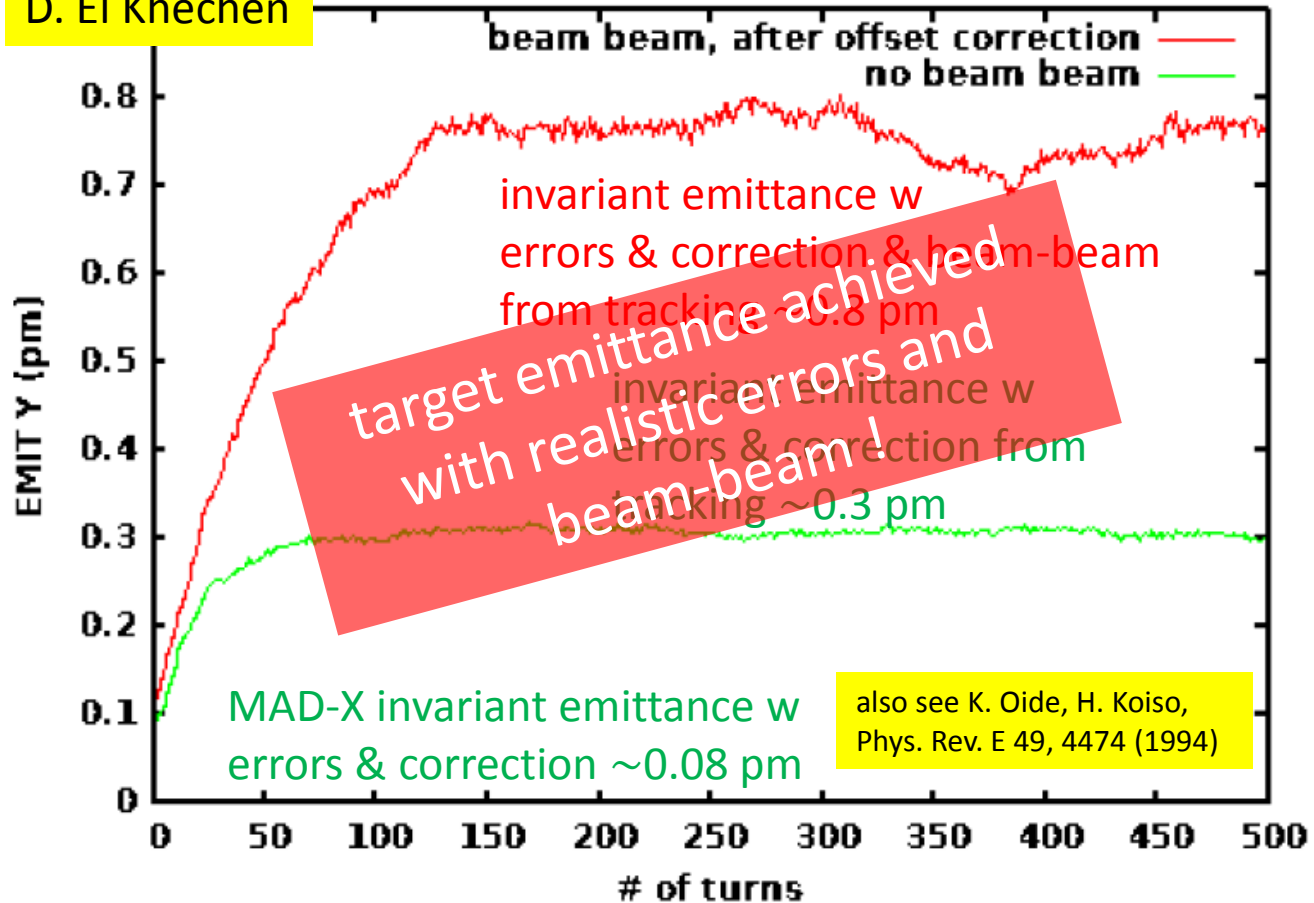
energy calibration at Z & W via resonant depolarisation

Z pole with polarisation wigglers

orbit correction
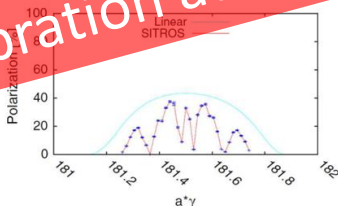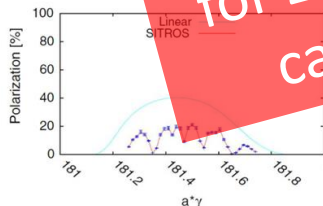

+ harmonic bumps
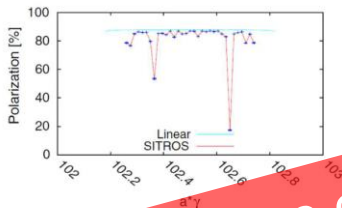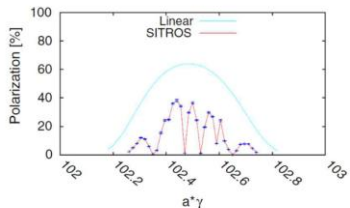
Z pole: 8 asymmetric wigglers per beam lower the polarisation rise time to 12 hours allowing a level of 10% (5%) beam polarisation, sufficient for the energy calibration by RDP, to be obtained in 90 (45) minutes. **W pair threshold**: **spontaneous polarisation** with a rise-time of around 10 hours without wigglers.
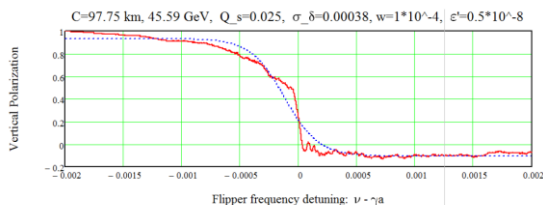
WW threshold

orbit correction

+ harmonic bumps

Achieved in one point !
Largest remaining systematic error: vertical closed-orbit distortions - at the Z, 300 μm error will induce a possible systematic shift of around 45 keV.

~200 **non-colliding 'pilot' bunches** injected at start of fill and polarised using wigglers

depolarisation technique used at LEP

simulated frequency sweep with depolariser

C=97.75 km, 45.59 GeV, Q_s=0.025, σ_δ=0.00038, w=1*10^-4, ε'=0.5*10^-8

Flipper frequency detuning: ν - γa

luminosity-averaged centre-of-mass uncertainty:

~100 keV at Z pole

~300 keV at W pair threshold

for Z and W: precise energy calibration at 10⁻⁶ level
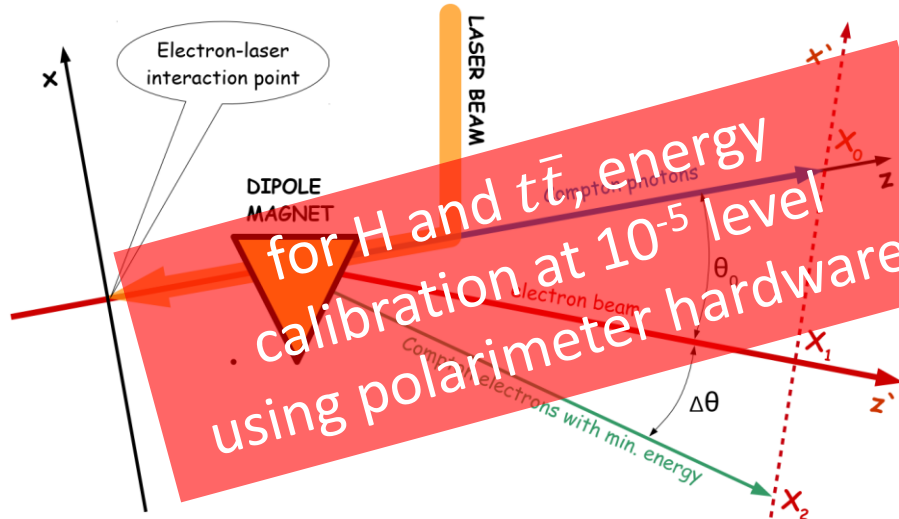
end point of recoil e⁻: independent continuous beam energy monitoring at ~10^{-5} level
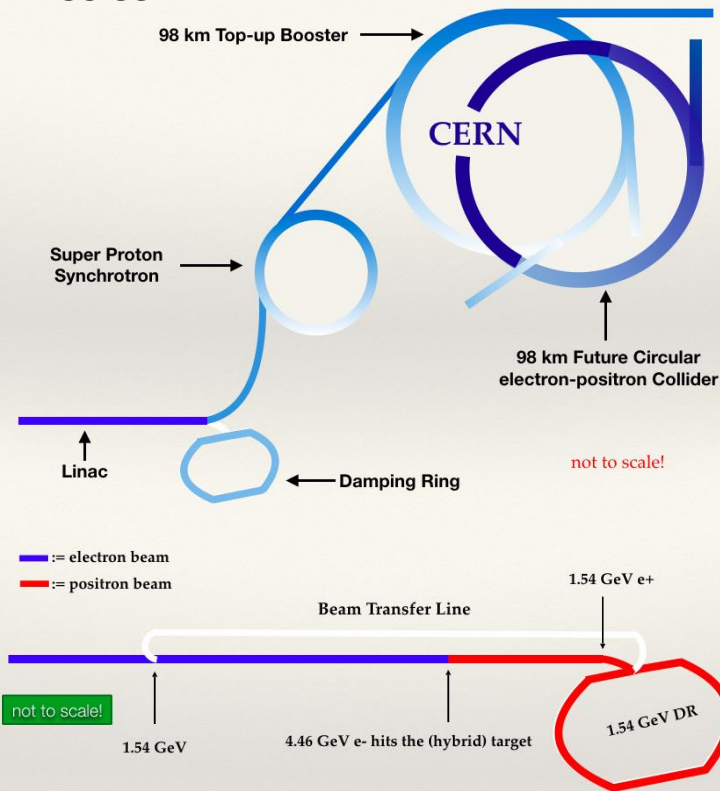
luminosity-averaged centre-of-mass uncertainty for H and $t\bar{t}$ running: a few MeV

N. Muchnoi, arXiv:1803.09595 (2018).

at Z pole **beam energy spread** determined with a relative precision of <0.2%, every 5 minutes by the experiments from acollinearity of the 10^6 muon pairs recorded; this acollinearity also measures the average energy difference between the two beams

injector complex

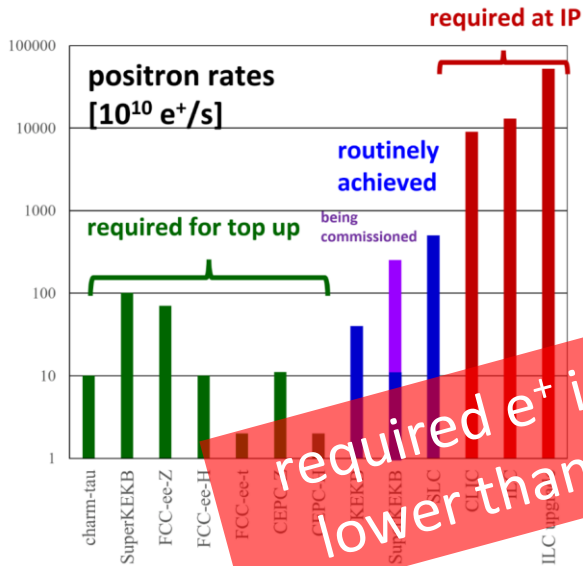
FCC-ee

98 km Top-up Booster

CERN

Super Proton Synchrotron

98 km Future Circular electron-positron Collider

not to scale!

Linac

Damping Ring

■ := electron beam
■ := positron beam

Beam Transfer Line

1.54 GeV e+

not to scale!

1.54 GeV DR

1.54 GeV   4.46 GeV e- hits the (hybrid) target

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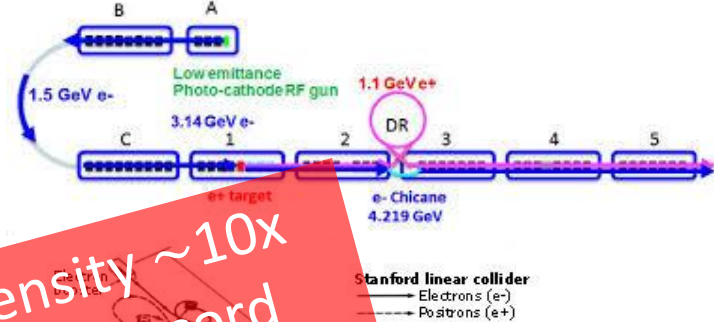
injection @ **6 GeV** into Pre-Booster Ring (SPS or new ring) & acceleration to 20 GeV - or alternatively 20 GeV linac

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

positron source requirements

positron rates [10^{10} e$^+$/s]

required at IP

required for top up

routinely achieved

being commissioned

SuperKEKB injector

Stanford linear collider

SLC complex

required e$^+$ intensity ~10x lower than world record

Routinely achieved positron rates:
SLC, 1 bunch/pulse, 65 nC , 120 Hz, **5x10^{12} e$^+$/s**
KEKB, 2 bunches/pulse 2x0.6 nC, 50 Hz, **4x10^{11} e$^+$/s**

Under commissioning:
SuperKEKB, 2 bunches/pulse 2x4 nC, 50 Hz, **2.5x10^{12} e$^+$/s,**
~1.0x10^{12} e$^+$/s already achieved

	FCC-ee	S-KEKB	SLC	CLIC380	ILC250
e$^+$ / s	**7x10^{11} at Z**	**3 x 10^{12}**	**6 x 10^{12}**	**10^{14}**	**>2x10^{14}**

FCC-ee e$^+$ source flux concentrator

P. Martyshkin, K. Furukawa, I. Chaikovska, K. Oide, et al.
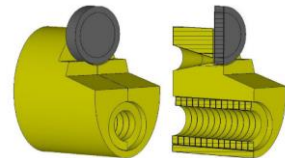
FCC-ee physics operation model

working point	assumed typical luminosity/IP [10^{34} cm^{-2}s^{-1}] = design value minus 15(10)%	total luminosity (2 IPs)/ yr; half of typical luminosity assumed in 1st two years (Z) and 1st year ($t\bar{t}$)	physics goal	run time [yr]
Z first 2 years	100	**26 ab^{-1}/year**	**150 ab^{-1}**	**4**
Z later	200	**48 ab^{-1}/year**		
W	25	**6 ab^{-1}/year**	**10 ab^{-1}**	**1-2**
H	7.0	**1.7 ab^{-1}/year**	**5 ab^{-1}**	**3**
machine modification for RF installation & rearrangement: 1 year				
top 1st year (350 GeV)	0.8	**0.2 ab^{-1}/year**	**0.2 ab^{-1}**	**1**
top later (365 GeV)	1.4	**0.34 ab^{-1}/year**	**1.5 ab^{-1}**	**4**

**total program duration: 15 years – *incl. machine modifications*
phase 1 (*Z, W, H*): 9 years, phase 2 (top): 6 years**

FCC-ee integrated luminosity estimate

$$L_{\text{int}}/\text{year} \approx T\ E\ L_{\text{nominal}}$$

"*E*" value based on operational performance of KEKB, PEP-II, LEP-2, BEPCII, DAFNE, LHC, SPS, LHC injector complex, etc., including top-up injection (see eeFACT2018)

"efficiency"

number of days scheduled for physics per year

nominal = design luminosity minus 10 to 15%

FCC-ee assumptions:
T=185 days, *E*= 75% (w. top-up)

effectively 10^7 s / yr

FCC-ee days scheduled for physics per year
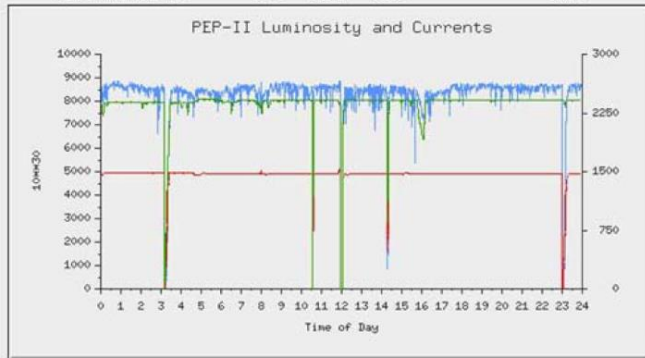
$T =$

365 days
- **17 weeks (119 days) winter shutdown**
    ~2x more than estimated minimum
- 30 days commissioning
- **20 days for MDs**
- 11 days for technical stops

= 185 days

efficiency *E* with top-up injection – example PEP-II

2004

2008

similar results from KEKB

average luminosity ≈ peak luminosity

Example evolutions of PEP-II beam currents and luminosity. Stored beam current of HER (red curve), LER (green), and luminosity (blue) of PEP-II over 24 h.

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
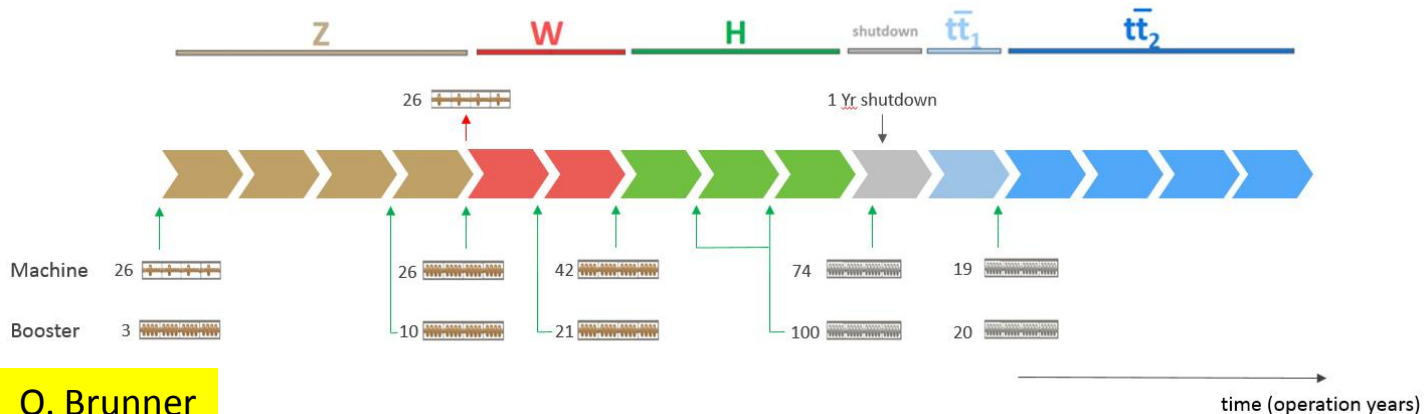
FCC-ee RF cavities – optimized for each running mode

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

400 MHz single-cell
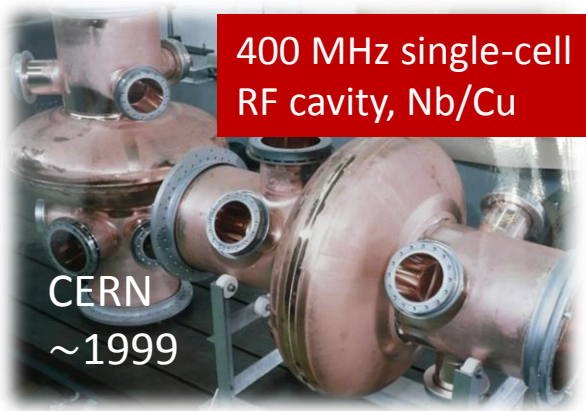RF cavity, Nb/Cu

CERN
~1999

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

800 MHz five-cell
RF cavity, bulk Nb

JLAB,
Oct. 2017
F. Marhauser et al
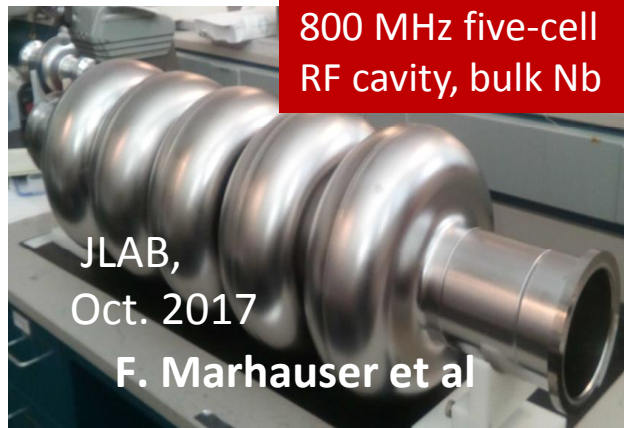
$t\bar{t}$ FCC-ee: 396
four-cell 400
MHz + 852
five-cell 800
MHz cavities
(collider +
booster)

FCC-ee cost-effective, energy-efficient arc magnets

twin-dipole magnet design with 2× power saving 16 MW (at 175 GeV), with Al busbars

300 mm
84 mm
450 mm
136 mm

0   0.5 T   1.0 T
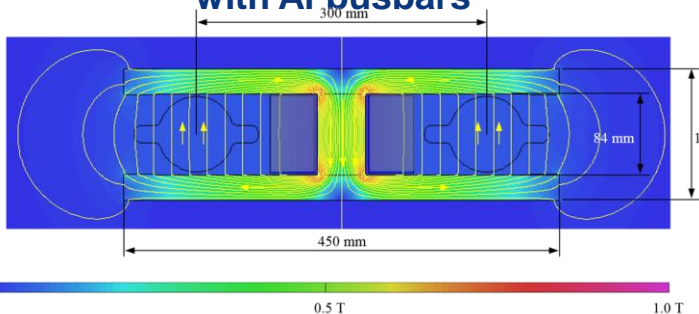
2900 units, 0.057 T, ~22 m

twin F/D arc quadrupole design with 2× power saving; 25 MW (at 175 GeV), with Cu conductor

500 mm
500 mm

0   0.8 T   1.6 T
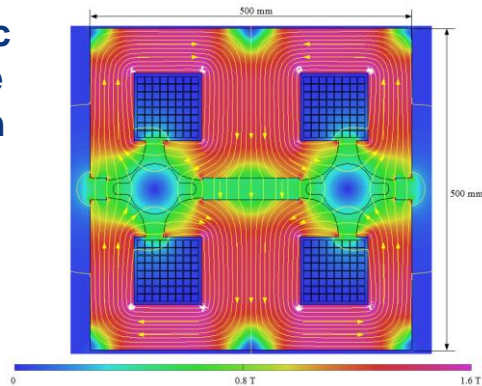
2900 units, 10 T/m, 3.1 m

prototype
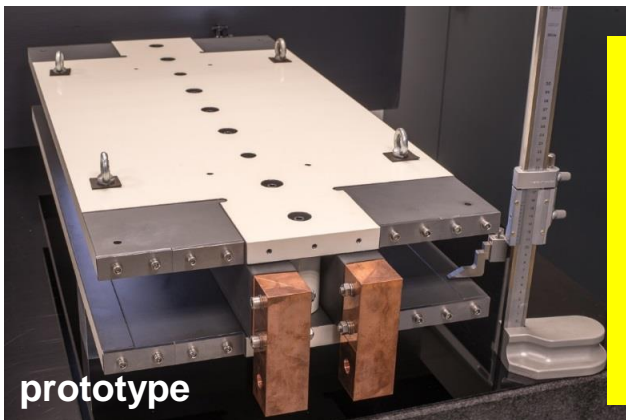
A. Milanese, *Efficient twin aperture magnets for the future circular e+/e- collider,* **Phys. Rev. Accel. Beams 19**, 112401 (2016)

prototype
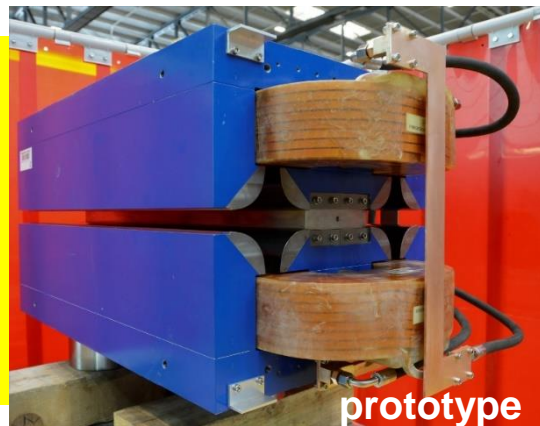
FCC-ee arc vacuum chambers and integration

R. Kersevan, C. Garion

Bellows chamber
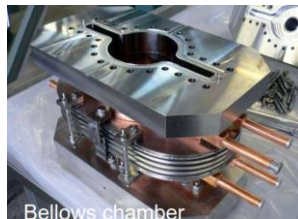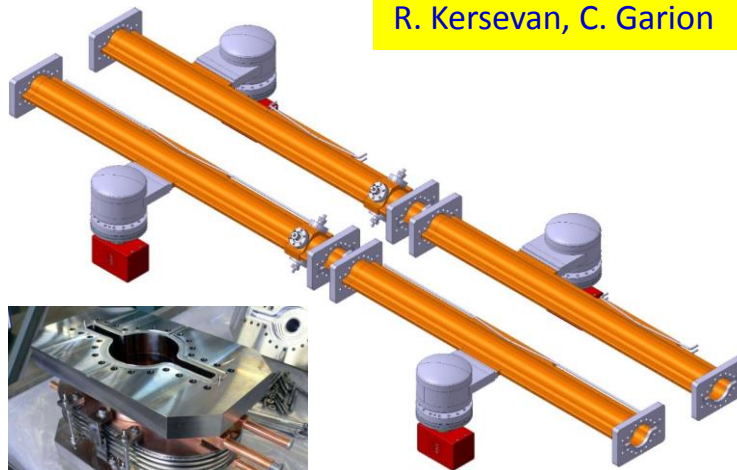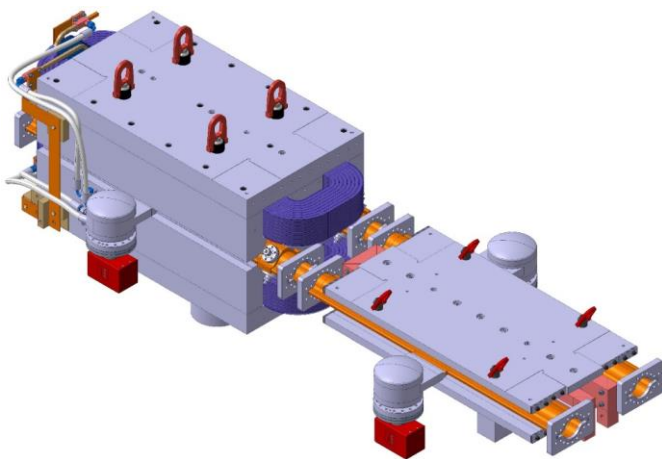
vacuum chamber cross section: 70 mm ID with "winglets" in the plane of the orbit (SuperKEKB-like)

chambers feature **lumped SR absorbers with NEG-pumps** placed next to them, **construction of chamber prototypes and integration with twin magnets**

avoiding μ-wave & e-cloud instability → ultrathin NEG coating

resistive-wall impedance dominant
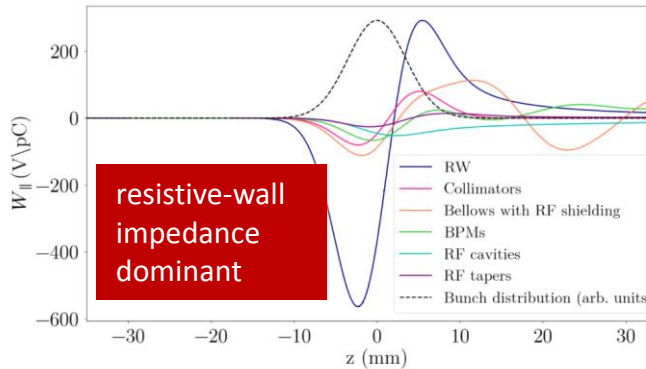
longitudinal wake potentials for a Gaussian bunch with nominal bunch length σ_z = 3.5 mm due to the main FCC-ee components compared with the RW contribution

with 100 nm coating far below μ-wave instability threshold at the Z pole
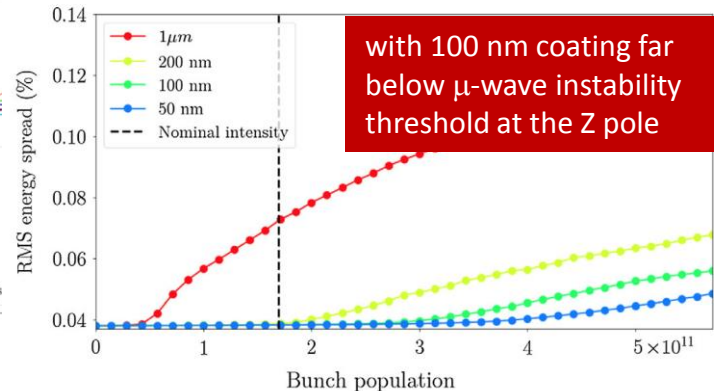
RMS energy spread vs bunch population, at the Z, considering the RW impedance for NEG films with different thicknesses

NEG coatings with thicknesses from 30 nm to 1.1 μm
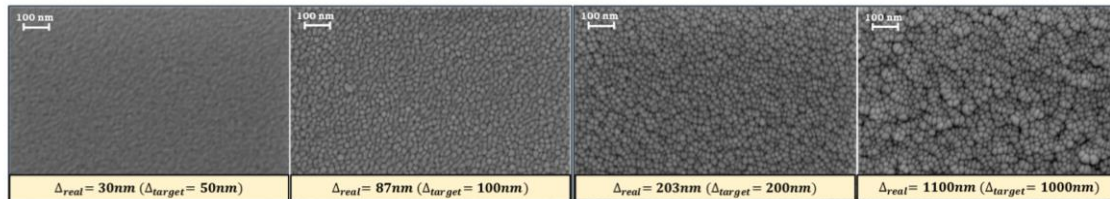
morphology of NEG thin films analyzed by scanning electron microscope

E. Belli et al., **Phys. Rev. Accel. Beams 21**, 111002 (2018)

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

figure of merit for lepton colliders

E. Jensen, EPPSU symposium, Granada
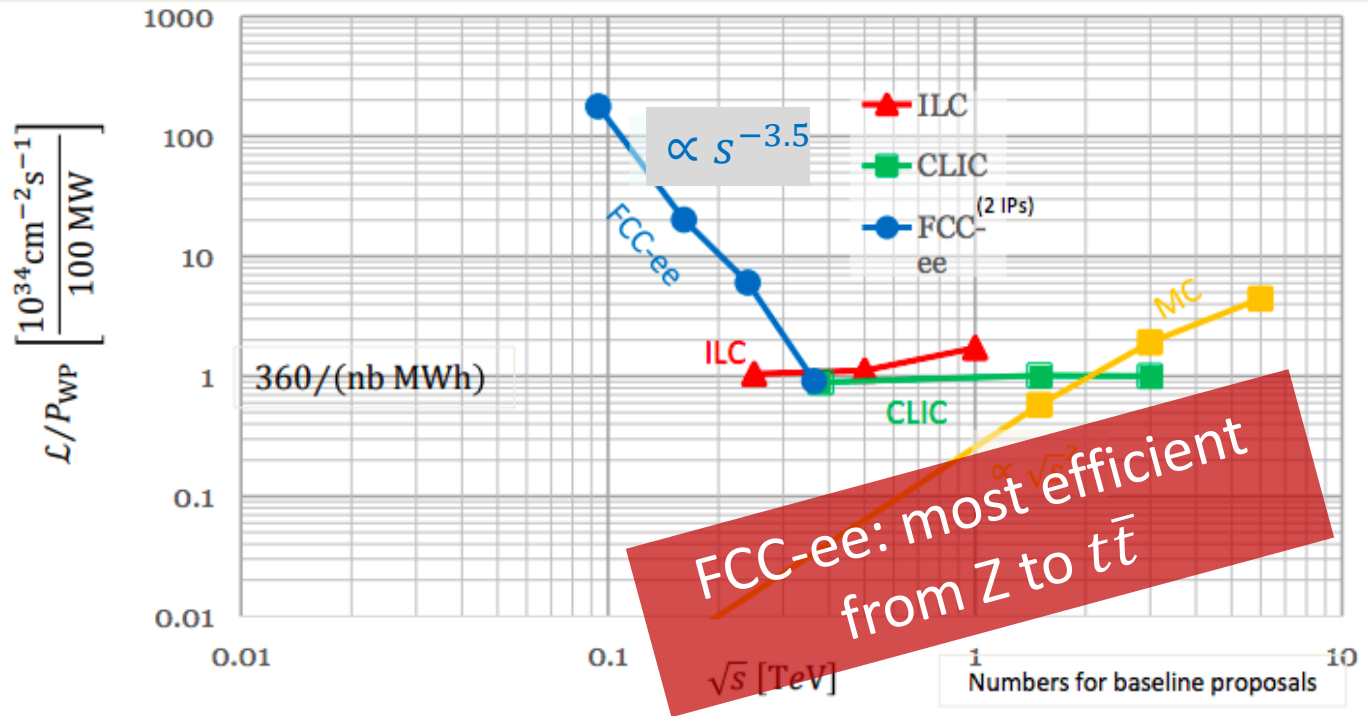
FCC-ee: a sustainable accelerator

luminosity per wall plug power [10^{34} cm^{-2}s^{-1}/ 100 MW]

twin-aperture arc magnets, thin-film SRF, efficient RF power sources, top-up injection

Z

W

H

ttbar

c.m. energy [GeV]
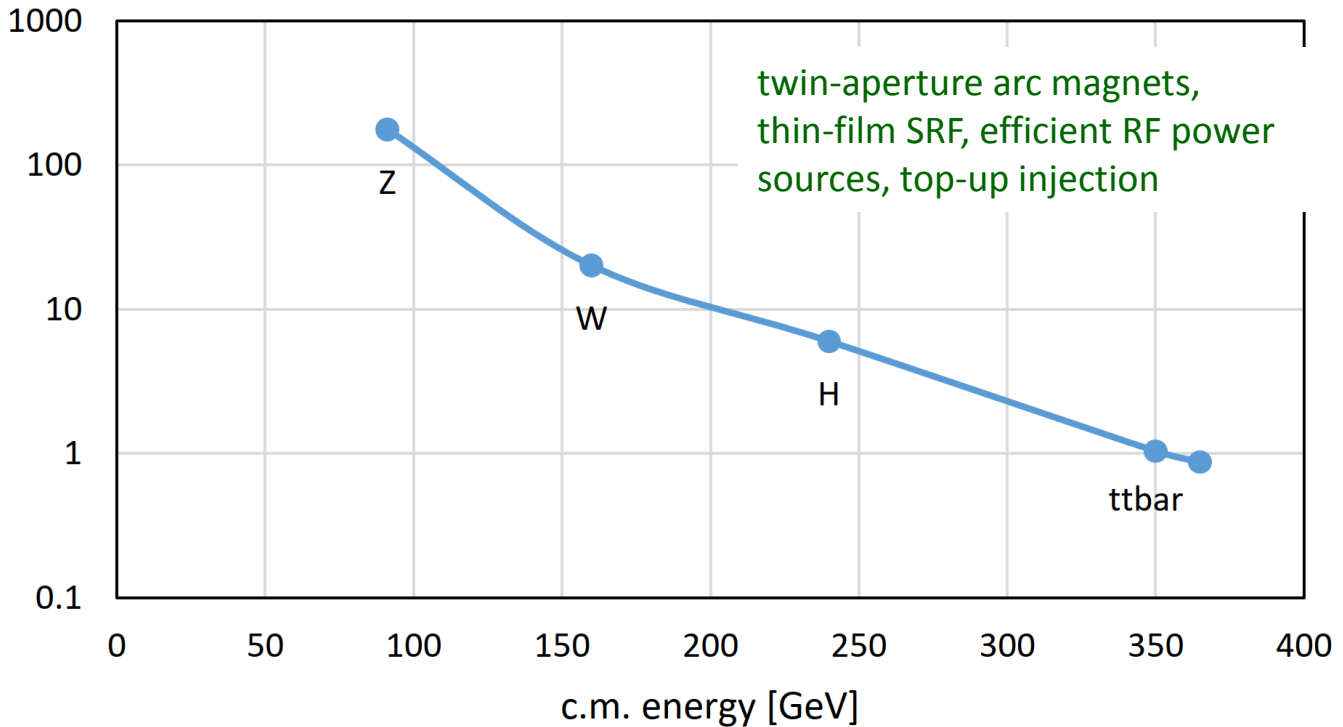
electricity cost ~200 euro per Higgs boson

for the H running, **with 5 ab^{-1} accumulated over 3 years**, total investment cost corresponds to
10 kCHF per produced Higgs boson

for the Z running with **150 ab^{-1} accumulated over 4 years** total capital investment cost corresponds to
10 kCHF per 5×10^6 Z bosons
= the number of Z bosons collected by each experiment during the entire LEP programme !

construction cost per luminosity dramatically decreased compared with LEP !

options to further boost FCC-ee performance

shorter beam lifetime → higher luminosity

4 interactions points

ε_x blow up due to coherent instability vs Q_x off-mom. dynamic aperture

2 IPs

4 IPs

D. Shatilov

2 IPs

$t\bar{t}$

-2.8% $+2.4\%$

ttbar

4 IPs

$t\bar{t}$

-2.8% $+2.4\%$

ttbar
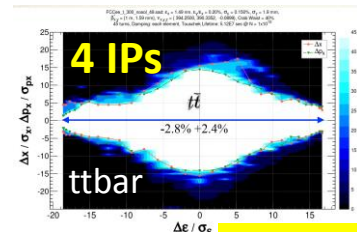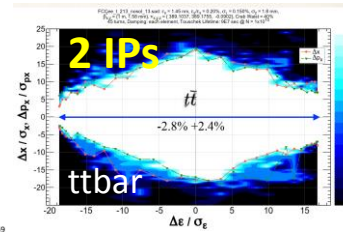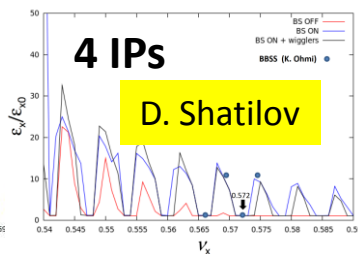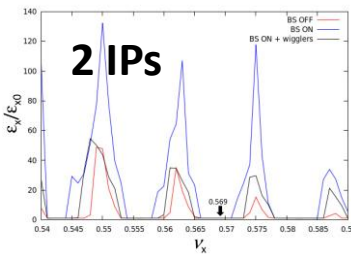
K. Oide

ERL based FCC-ee upgrade for higher luminosity & energy

IR1   IR2   IR..X

SRF linac 1

SRF linac 2

2 GeV
electron
"cooling" ring
with top-off

2 GeV
positron
"cooling" ring
with top-off
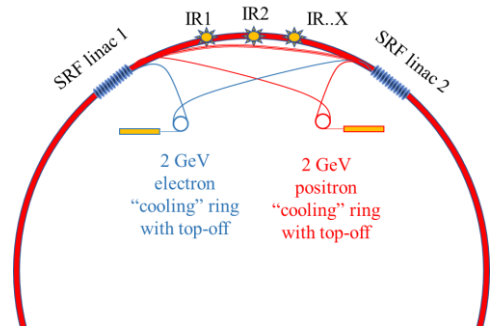
182.25 GeV
colliding e⁺e⁻
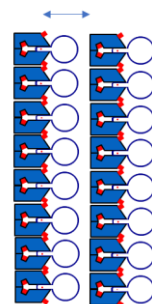
14.45 GeV decelerating
25.25 GeV accelerating
61.02 GeV decelerating
71.74 GeV accelerating
108.28 GeV decelerating
118.02 GeV accelerating
158.33 GeV decelerating
163.12 GeV accelerating

100%
ECO
FRIENDLY

FCCee

V. Litvinenko,
T. Roser

FCC-ee luminosity in perspective

luminosity [10^{34} cm^{-2}s^{-1}]

Legend:
- FCC-ee CDR (2 IPs)
- ILC Baseline
- ILC Upgrade 2019
- CEPC CDR (2 IPs)
- CEPC Upgrade 2019 (2IPs)
- CLIC Baseline 2016
- CLIC Upgrade 2019
- FCC-ee monochr. H (2 IPs)
- FCC-ee (4 IPs)
- FCC-ee ERL (1 IP)

FCC-ee 4 IPs
FCC-ee 2 IPs
FCC-ee ERL

Z
91 GeV

WW
160 GeV

ZH
240 GeV

ZHH
500 GeV

ttbar
350-365
GeV

CEPC 2 IPs

ILC UG

ILC

CLIC UG

CLIC

c.m. energy [GeV]

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

integrated project technical schedule

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |

15 years operation

| 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 |

~ 25 years operation | 70 |

| LHC run 3 | LS 3 | LHC run 4 | LS4 | LHC run 5 | LS5 | LHC run 6 |

Project preparation & administrative processes Funding & governance strategy

Permis-sions

Update Permission, Funding

Geological investigations, infrastructure detailed design and tendering preparation

Tunnel, site and technical infrastructure construction

FCC-ee dismantling, CE & infrastructure adaptations FCC-hh

FCC-ee accelerator R&D and technical design

FCC-ee accelerator construction, installation, commissioning

FCC-hh accelerator R&D and technical design

FCC-hh accelerator construction, installation, commissioning

Detector R&D and concept development

FCC-ee detector technical design, collaborations

FCC-ee detector construction, installation, commissioning

FCC-hh detector R&D, technical design

FCC-hh detector construction, installation, commissioning

Superconducting wire and high-field magnet R&D

SC wire and HFM magnet R&D, model magnets, prototypes, preseries

HFM dipole magnet series production

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

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%)

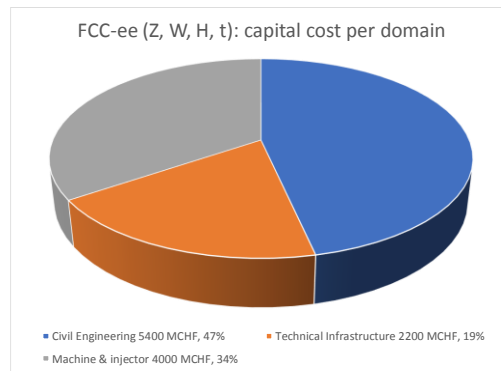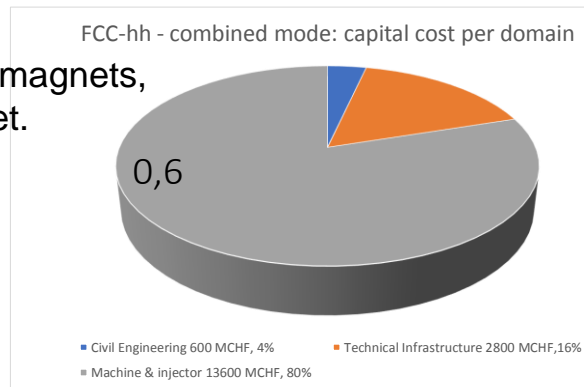FCC-ee (Z, W, H, t): capital cost per domain

- Civil Engineering 5400 MCHF, 47%   - Technical Infrastructure 2200 MCHF, 19%
- Machine & injector 4000 MCHF, 34%

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

- 13,6 BCHF accelerator and injector (57%)
    - Major part for 4,700 Nb_3Sn 16 T main dipole magnets, totalling 9,4 BCHF, targeting 2 MCHF/magnet.

- CE and TI from FCC-ee re-used,
  BCHF for adaptation

- 2,8 BCHF for additional TI, driven by cryogenics

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

FCC-hh - combined mode: capital cost per domain

0,6

- Civil Engineering 600 MCHF, 4%   - Technical Infrastructure 2800 MCHF,16%
- Machine & injector 13600 MCHF, 80%

FCC - next steps

2019-2020:

- Layout **optimisation** and work on **implementation with host states**

- Near-term focus on **FCC-ee as potential first step** (awaiting strategy recommendation)

- Preparation of **EU H2020 DS project** (INFRADEV call November 2019), focused on infrastructure implementation

2020/21 – 2025/26:

project preparation phase (if supported by EPPSU and CERN Council)

FCC-ee injector considerations – proposed WPs
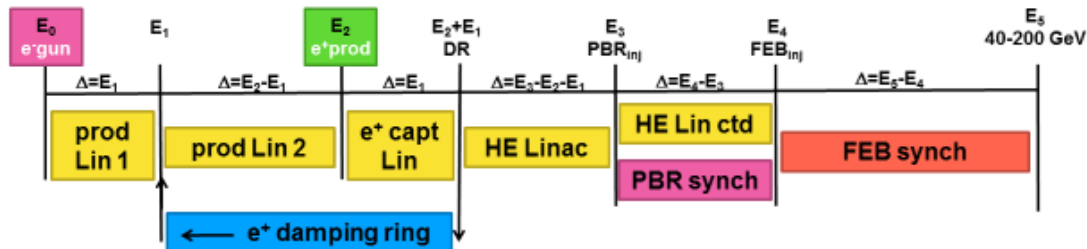
WP0: Electron Gun and injector *(PSI)*

WP1: Production Linac (PL 1 to E1, PL2 to E2) *(PSI)*
- PL1: 2 electron bunches or 2 production bunches acceleration to E1
- PL2: 2 electron bunches or 2 production bunches & 2 positron bunches (energy gain E2-E1)

WP2: Positron production (E2) *(LAL)*
- Target design, - capture optimisation
- Energy choice (E2), production bunch intensity versus production energy, etc.

WP3: Positron Capture Linac (E1) *(PSI)*
- Pre acceleration of 2 positron bunches (before DR) and acceleration (after DR) of 2 e+ bunches (energy gain E1 per passage)
- Acceleration of 2 electron bunches (energy gain E1)

WP4: Damping Ring (E1) *(INFN)*
- Choice of E1
- Impedance, space charge, e+ emittances, etc.

WP5: High Energy Linac (acceleration from (E1+E2) to E3 or E4) *(PSI)*
- Choice of end energy kept flexible at the moment,
- Optimisation with Full Energy Booster (FEB) or Pre-Booster Ring (PBR) design at later stage

WP6: Pre-Booster Ring (PBR), *(CERN)*
- Either SPS or new ring
- Impact of injection energy E3
- Full ring design

WP7: Full-Energy Booster (FEB) *(CEA)*
- Impact of injection energy E4
- Full ring design

WP8: Beam transfer system design, *(CERN)*
- Transfer line design (from High Energy Linac onwards)
- Injection and extraction concepts, linked to ring designs
- HW concepts

Goal (WPs 0,1,3,5): demonstrator experiment in 2023

H2020 DS project preparation

Goal: Carry out technical design study for a 100 km long frontier circular collider infrastructure at CERN that will extend Europe's leadership in the domain of fundamental physics research until the end of the 21st century. Focus on priority topics, to prepare construction project by 2026, in line with call scope:
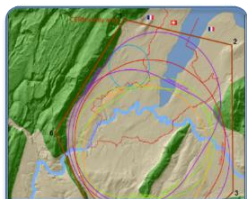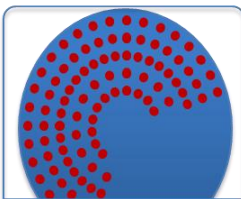

Site Selection

Optimization of collider designs, site selection, placement and implementation, work with host states

Resources & Environment

Plans for construction and operation including resource efficiency & environmental impacts.

Governance Organisation Construction Operation

Development of governance structure, construction & operation budget and funding strategy

Scientific User Collaboration

Ensure that a scientific user community is built up to exploit the facility from the start on

Coherently Integrate Europe

Coherently integrate the infra-structure in the European research landscape

1) Optimise the FCC-ee collider parameters and layout; possible beam-beam code benchmarking at DAFNE-TF (**BINP**, CERN, INFN-LNF)

2) Develop and openly document the collider beam optics, including 4 IP option (**CERN**, BINP, DESY?)

3) Establish procedures for optics corrections and emittance tuning plus document the expected performance and the required beam instrumentation and feedback systems, participation in the commissioning of the ESRF-EBS low emittance ring and tool bernchmarking. (**DESY**, KIT, UOX, CERN, ESRF)

4) Establish complete impedance budget for collider and booster and evaluate single-beam collective effects for different modes of operation (**Sapienza/INFN**, DESY, SLAC)

5) Collimation system, aperture model, and machine protection (DESY, INFN-Sapienza, CERN)

6) Design and document the top-up injection concept (**PSI**, CERN)

7) Develop and document the machine detector interface, final focus magnet system, background control, and luminosity measurements (**INFN**, BINP, BNL?, CNRS/LAL??, CNRS/LAPP, SLAC?)

8) Refine methods for energy calibration through resonant depolarisation including optics tuning, possible use of pilot bunches and polarisation wigglers, and error assessment; develop and document the overall energy calibration strategy (FNAL?, BINP, CERN)

9) Design and document the full-energy booster (**CEA**, BINP?, CERN)

FCC-ee design incorporates **many lessons from recent & present e⁺e⁻ colliders,** and goes further! - **excellent off-momentum dynamic aperture** required & achieved ; small vertical emittance expected

technology for high-energy/luminosity circular collider exists today, warm & SC magnets & RF systems, vacuum system with SR/e-cloud/impedance mitigation, linac, e⁺/e⁻ prod./inj./damping devices

FCC-ee design includes: **power-saving twin-aperture arc magnets, high-efficiency RF power sources (klystrons, IOTs or SSAs), energy staging with optimized RF system at each energy, top-up injection, and maximum integrated luminosity**

FCC-ee = **efficient and sustainable collider at the e⁺e⁻ energy frontier**: **highest luminosity per input power, highest luminosity per construction cost, most precise energy calibration, and ultimate upgrade potentials (ERL-based FCC-ee, 100 TeV FCC-hh, …)**

*enjoy
this
workshop !*