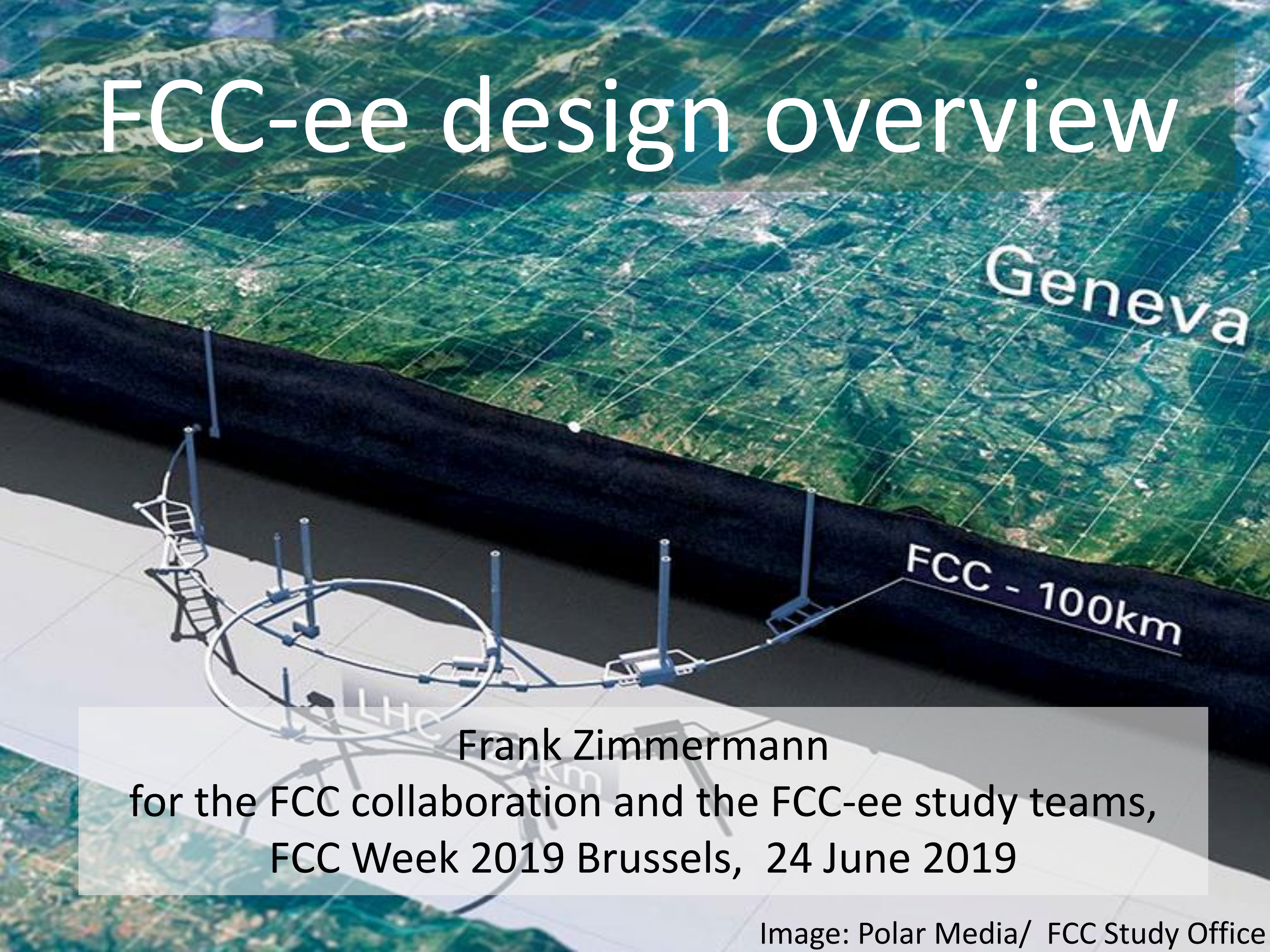
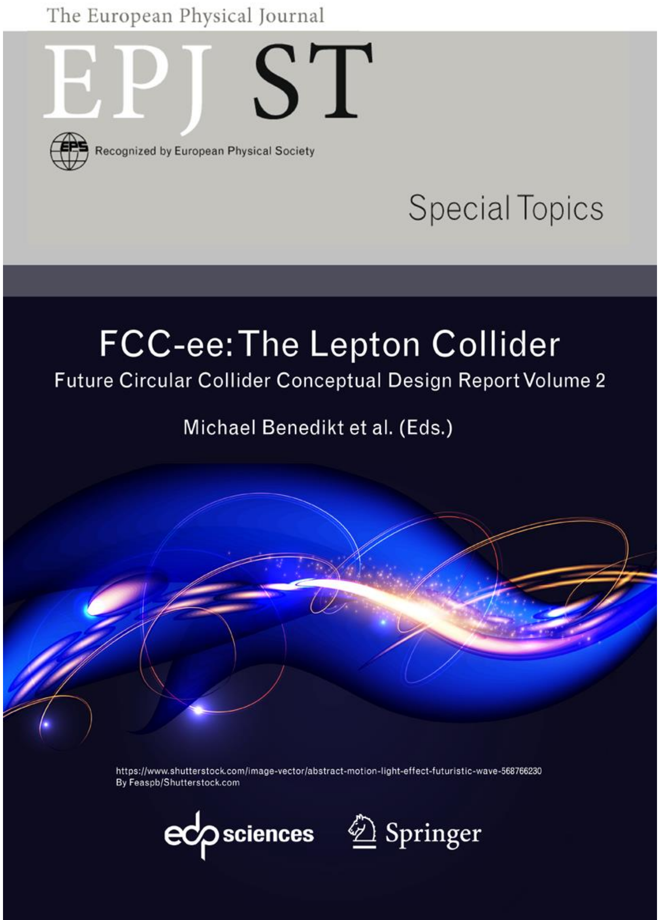
FCC-ee design overview



Frank Zimmermann
for the FCC collaboration and the FCC-ee study teams,
FCC Week 2019 Brussels, 24 June 2019

Image: Polar Media/ FCC Study Office

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

1364 contributors from 351 institutes

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FCC-ee basic design choices

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

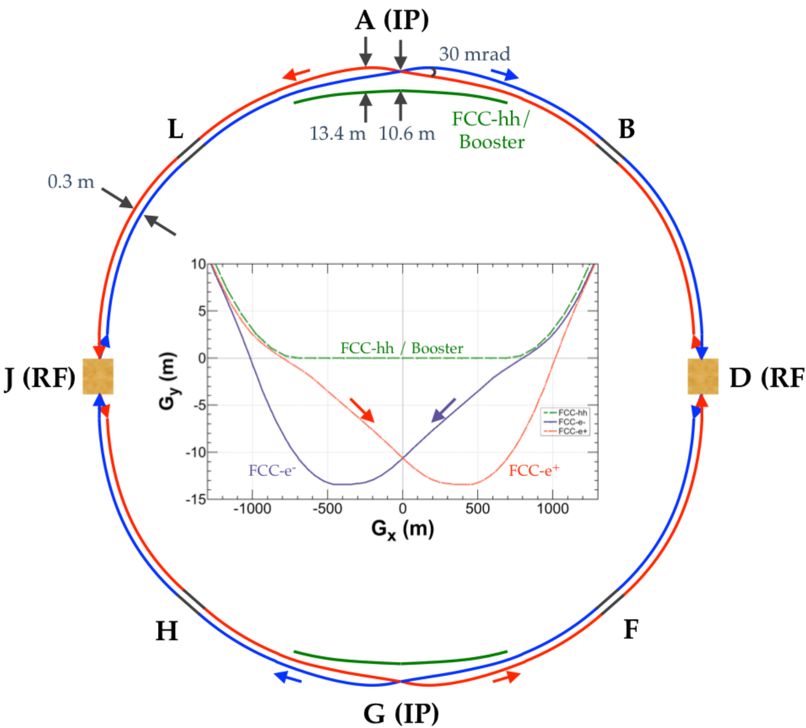
follows footprint of FCC-hh, except around IPs

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**

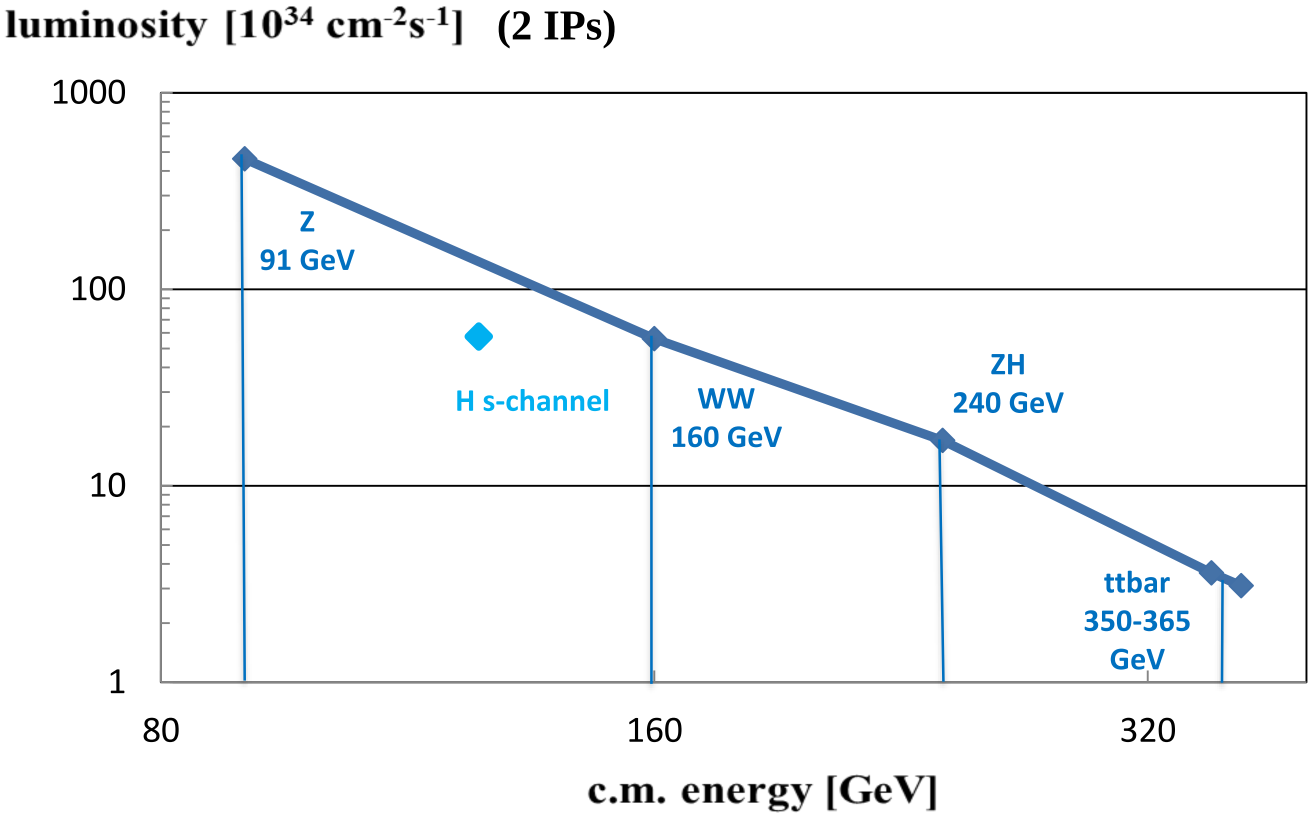


K. Oide et al.

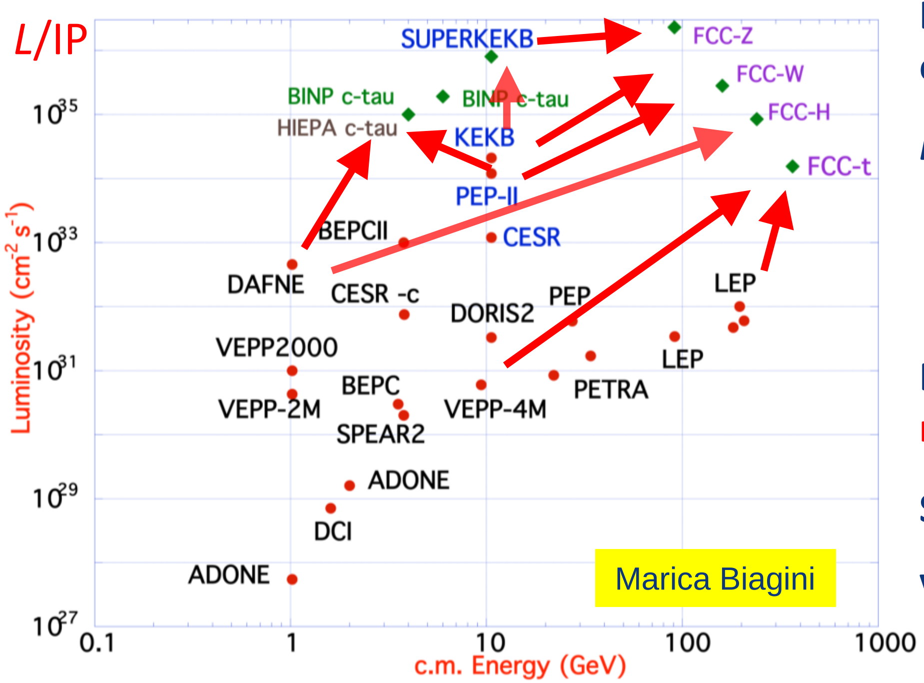
FCC-ee collider parameters

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

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

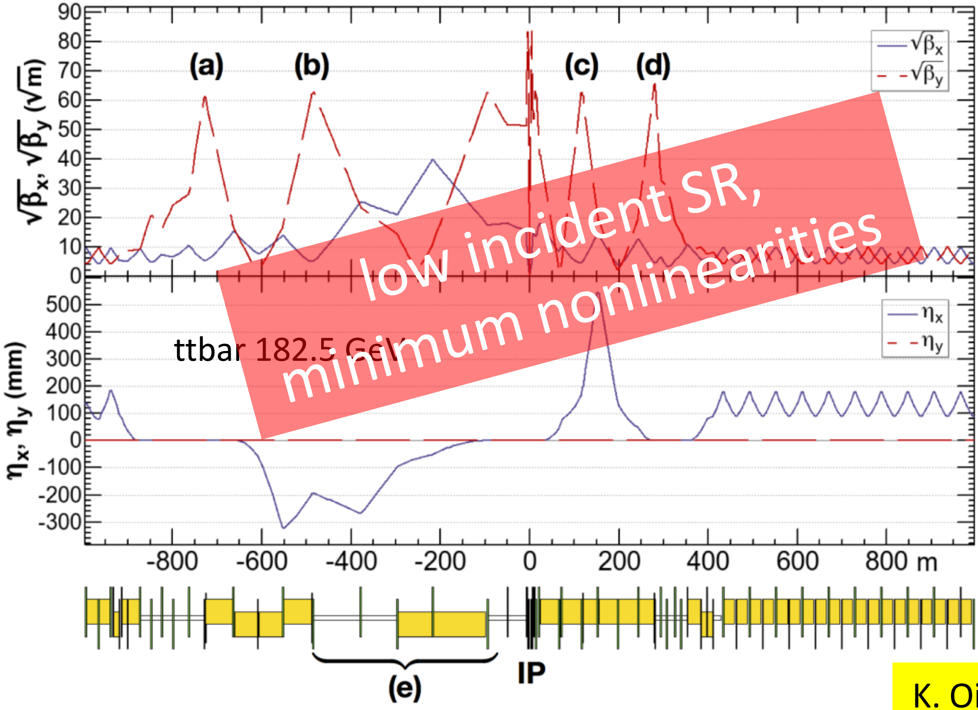
SuperKEKB: low β_y^*

VEPP-4M, LEP: precision energy calibration

KEKB, SuperKEKB: e^+ source

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

FCC-ee asymmetric crab-waist IR optics



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**

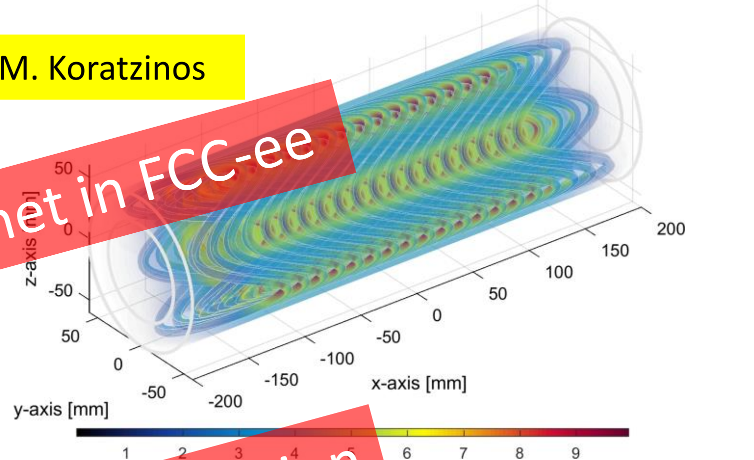
K. Oide et al., Design of beam optics for the future circular collider e^+e^- collider rings, **Phys. Rev. Accel. Beams 19**, 111005 (2016).

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

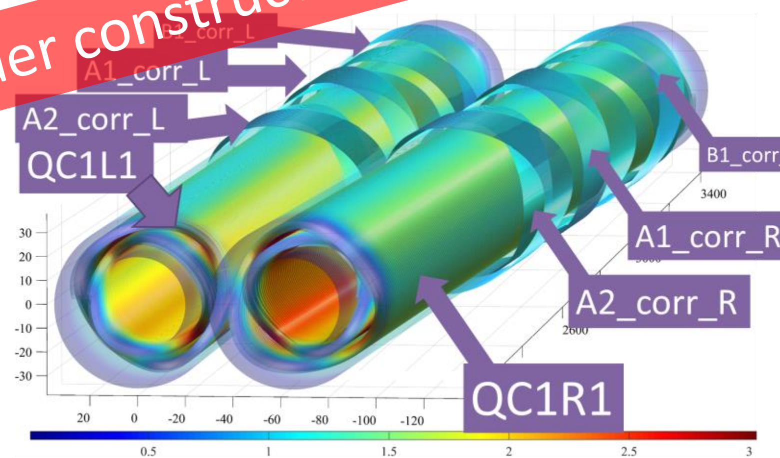
M. Koratzinos

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

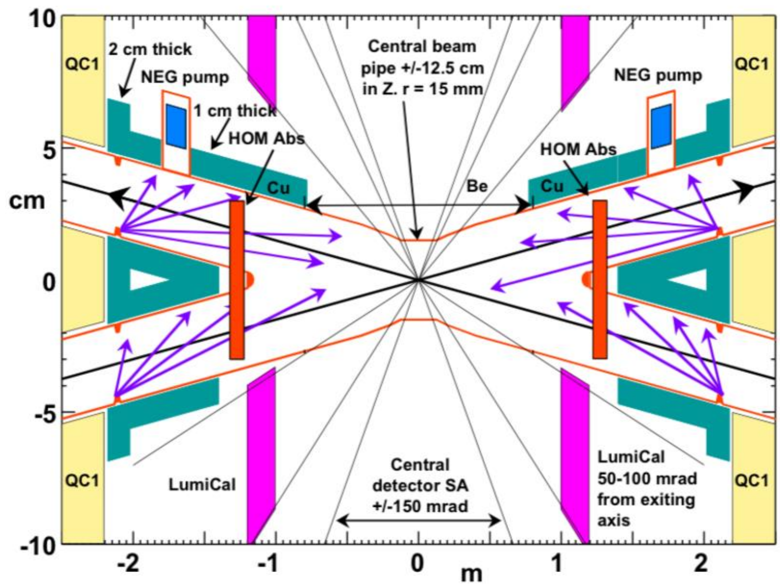


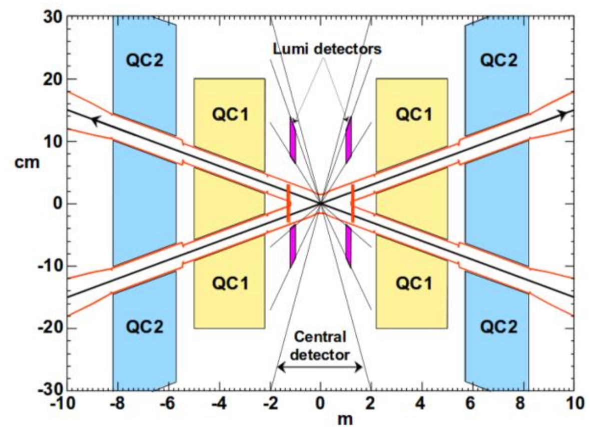
M. Koratzinos

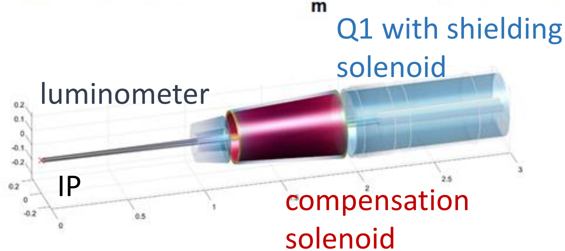
FCC-ee interaction region

A. Novokhatski, M. Sullivan, E. Belli, M. Gil Costa, and R. Kersevan, *Unavoidable trapped mode in the interaction region of colliding beams*, **Phys. Rev. Accel. Beams 20**, 111005 (2017)

M. Boscolo, H. Burkhardt, and M. Sullivan, *Machine detector interface studies: Layout and synchrotron radiation estimate in the future circular collider interaction region*, **Phys. Rev. Accel. Beams 20**, 011008 (2017)





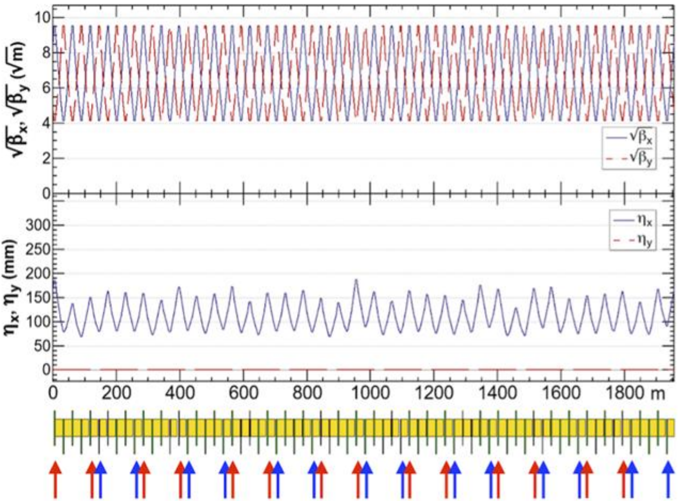


3D sketch of key IR systems over first 3 m from IP

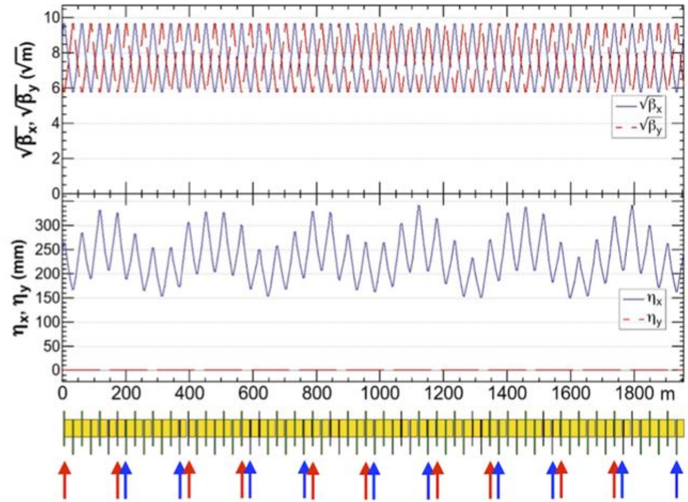
M. Boscolo, N. Bacchetta, A. Bogomyagkov, H. Burkhardt, M. Dam, D. El Khechen, M. Koratzinos, E. Levichev, M. Luckhof, A. Novokhatski, M. Sullivan, et al.

arc optics with -*I* sextupole pairs

$90^\circ/90^\circ$ (for **ZH** and $t\bar{t}$,) 588 independent sextupole pairs



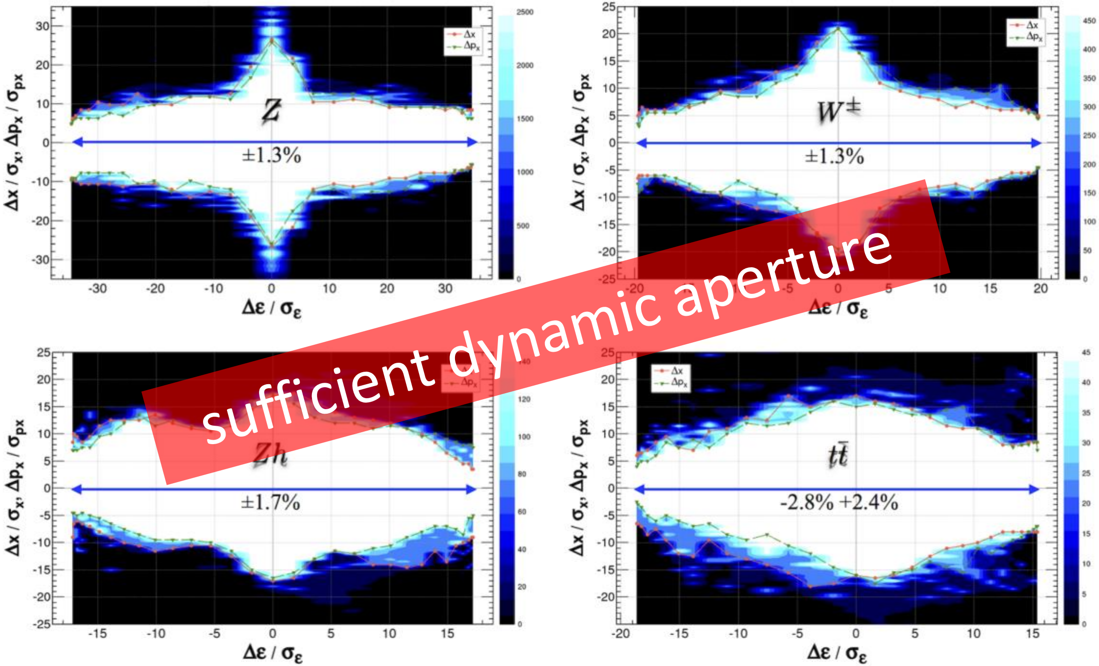
$60^\circ/60^\circ$ (for **Z** and **WW**), 416 independent sextupole pairs



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,….

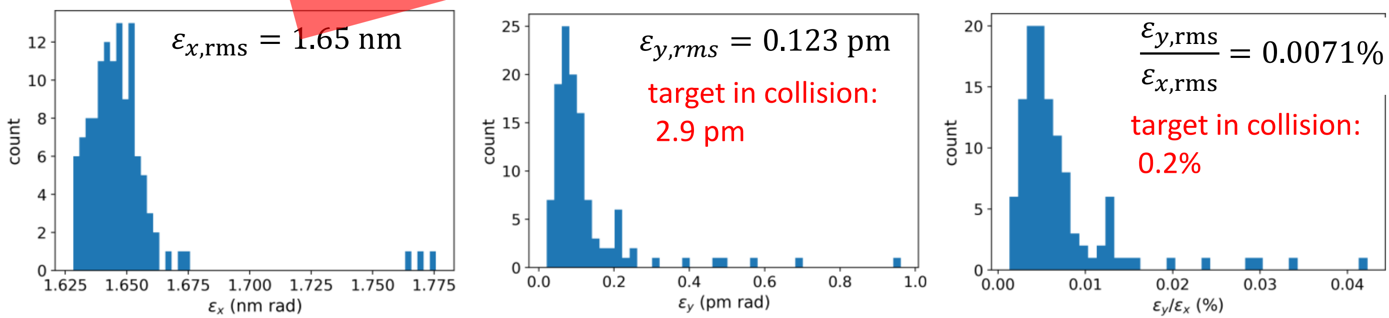
realistic misalignments and roll angles

	$\sigma_x(\mu\text{m})$	$\sigma_y(\mu\text{m})$	$\sigma_\theta(\mu\text{rad})$
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

well below target emittance with realistic errors

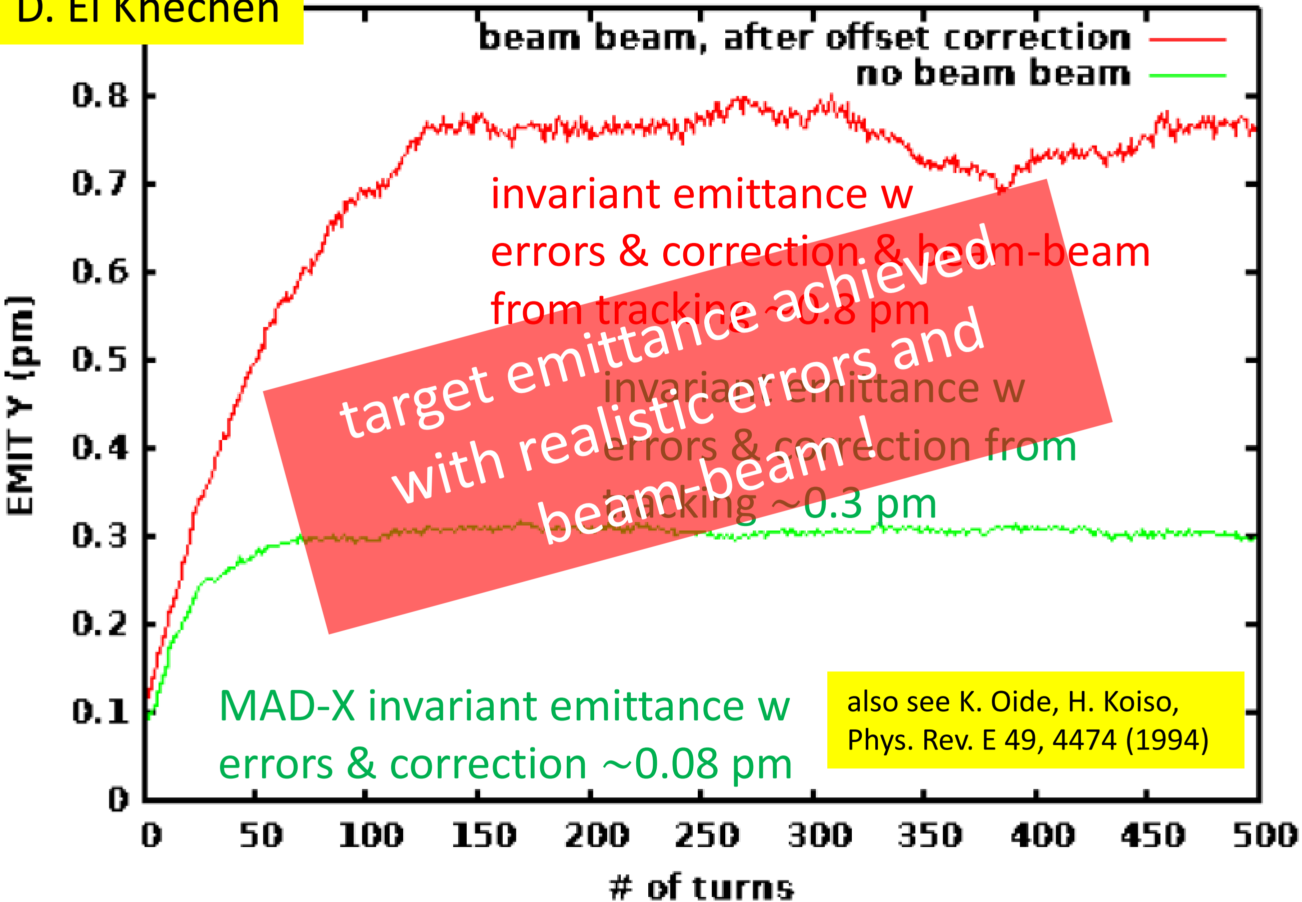
after iterative optics corrections:



simulated vertical emittance much smaller than needed

vertical emittance blow up

D. El Khechen



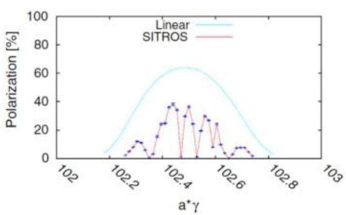
also see K. Oide, H. Koiso, Phys. Rev. E 49, 4474 (1994)

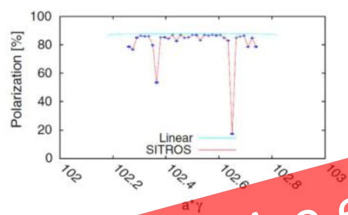
energy calibration at Z & W via resonant depolarisation

E. Gianfelice-Wendt, *Investigation of beam self-polarization in the future e^+e^- circular collider*, **Phys. Rev. Accel. Beams 19**, 101005 (2016).

Z pole with polarisation wigglers

orbit correction + harmonic bumps



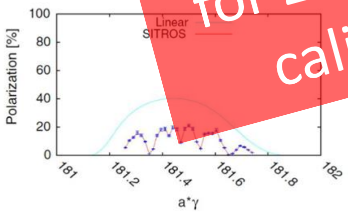


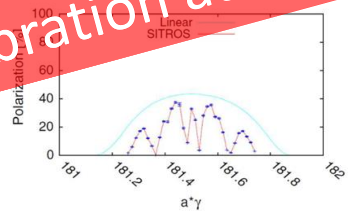
Z pole: 8 asymmetric wigglers per beam lower the polarisation rise time to 12 hours allowing a level of 10% (5%) beam polarisation, sufficient for the energy calibration by RDP, to be obtained in 90 (45) minutes.
W pair threshold: **spontaneous polarisation** with a rise-time of around 10 hours without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

for Z and W: precise energy calibration at 10^{-6} level

WW threshold

orbit correction + harmonic bumps





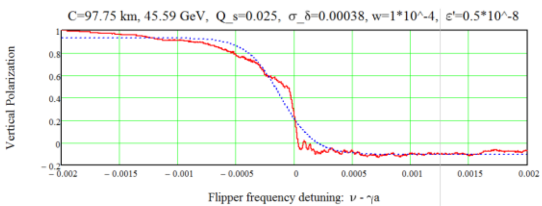
Relocated in one point !
Largest remaining systematic error: vertical closed-orbit distortions - at the Z, 300 µm error will induce a possible systematic shift of around 45 keV.

luminosity-averaged centre-of-mass uncertainty:

~100 keV at Z pole

~300 keV at W pair threshold

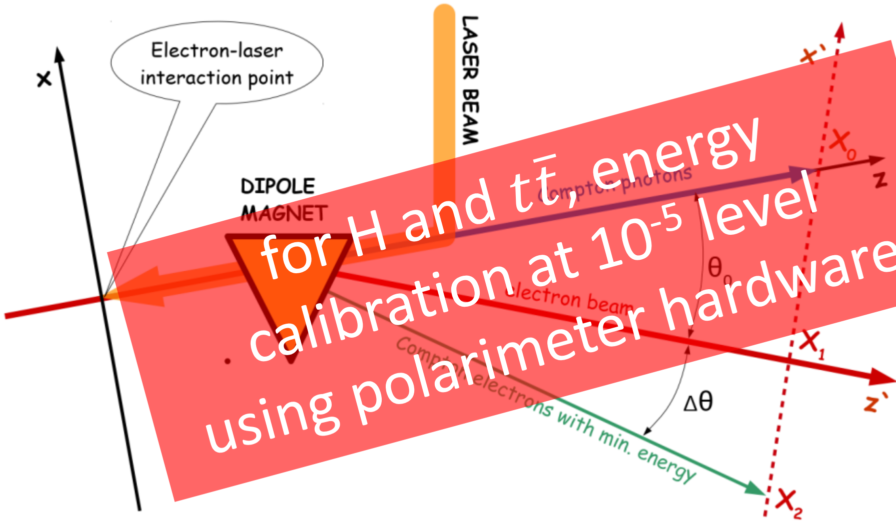
simulated frequency sweep with depolariser



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

depolarisation technique used at LEP

energy calibration using Compton polarimeter & E spread



for H and $t\bar{t}$ energy calibration at 10^{-5} level using polarimeter hardware

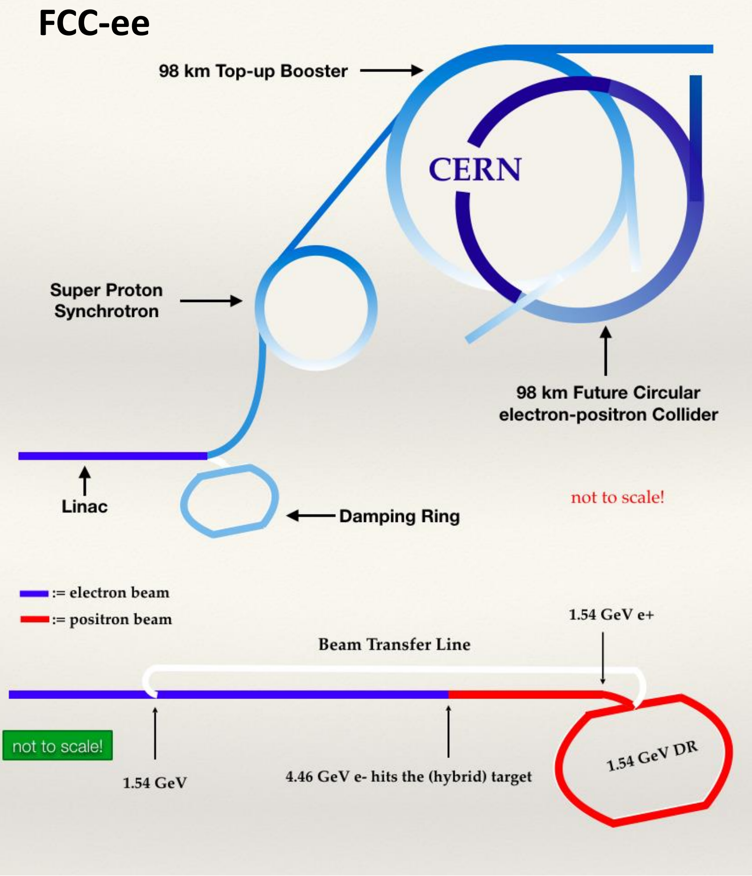
end point of recoil e^-: independent continuous beam energy monitoring at $\sim 10^{-5}$ level

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



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

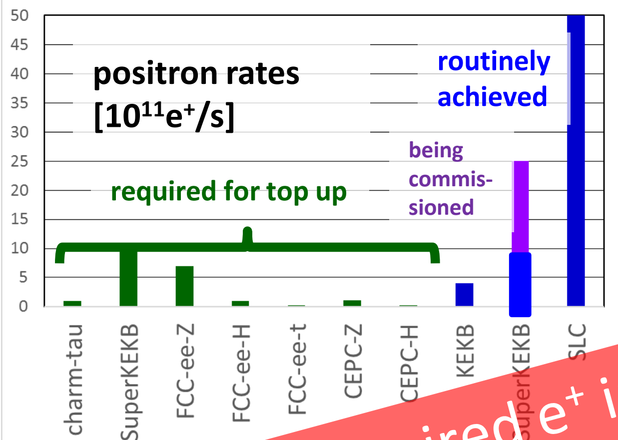
same linac used for e+ production @ **4.46 GeV** e^+ beam emittances reduced in DR @ **1.54 GeV**

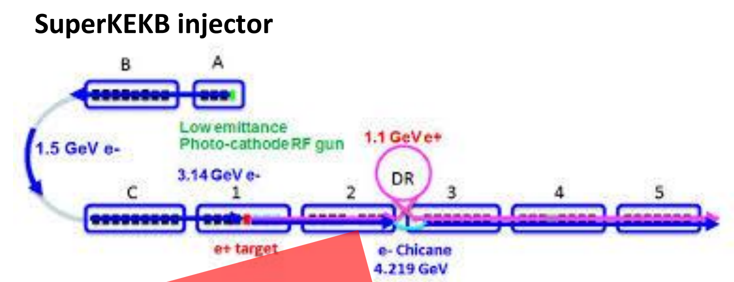
injection @ **6 GeV** into Pre-Booster Ring (SPS or new ring) & acceleration to 20 GeV - or alternatively 20 GeV linac

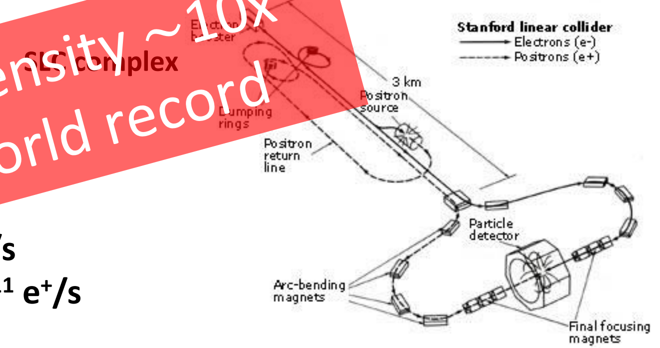
injection to main Booster @ **20 GeV and interleaved** filling of e^+/e^- (**<20 min for full filling**) and continuous top-up

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

positron source requirements







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

Routinely achieved positron rates:

SLC, 1 bunch/pulse, 65 nC, 120 Hz, **5×10^{12} e+/s**

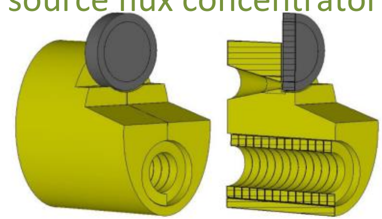
KEKB, 2 bunches/pulse 2x0.6 nC, 50 Hz, **4×10^{11} e+/s**

Under commissioning:

SuperKEKB, 2 bunches/pulse 2x4 nC, 50 Hz, **2.5×10^{12} e+/s,** ~1.0×10^{12} e+/s already achieved

	FCC-ee	S-KEKB	SLC	CLIC380	ILC250
e^+ / s	7×10^{11} on Z pole	3×10^{12}	6×10^{12}	10^{14}	$>2\times10^{14}$

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

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

number of days scheduled for physics per year

"efficiency"

nominal = design luminosity minus 10 to 15%

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

effectively 10^7 s / yr

"*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)

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

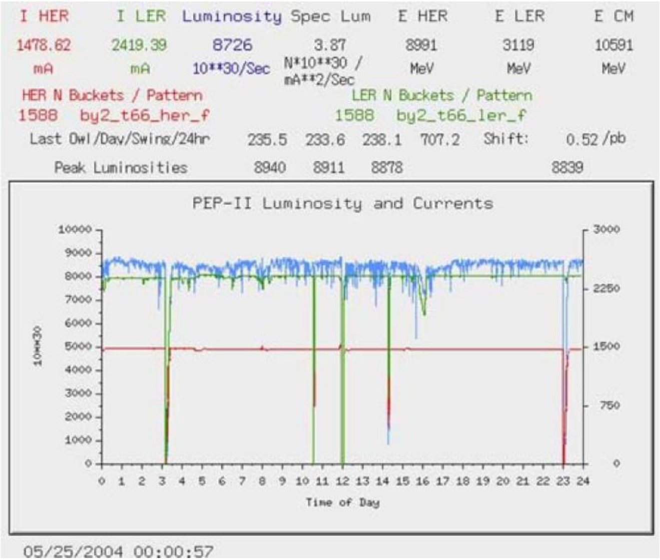
– **20 days for MDs**

– 11 days for technical stops

= 185 days

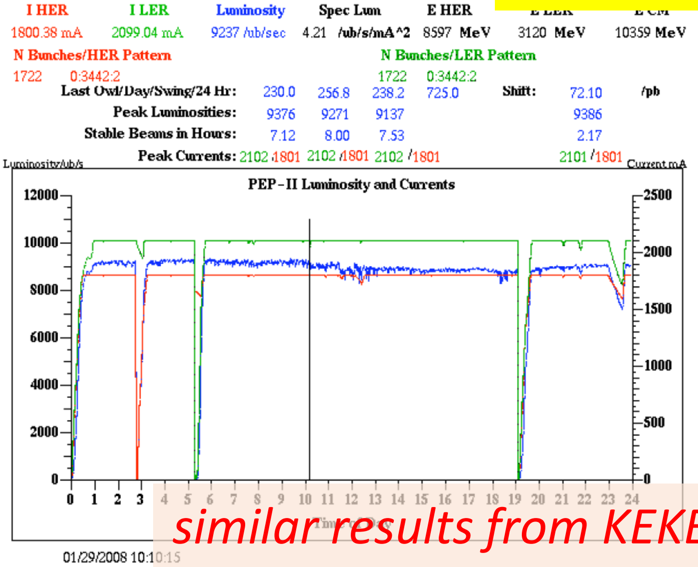
efficiency *E* with top-up injection – example PEP-II

2004



2008

J. Seeman



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

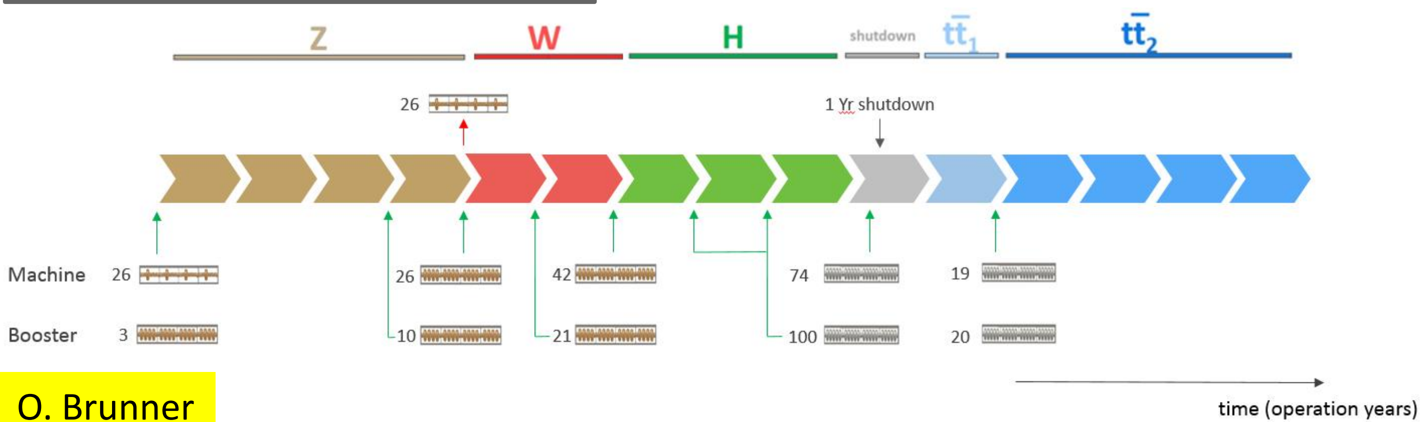
"Ampere-class" machine

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

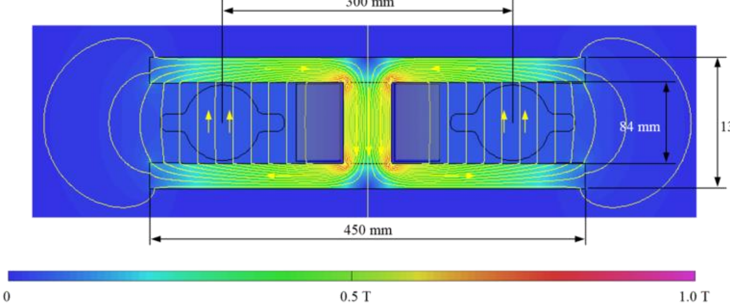
Z-pole FCC-ee: 116 single-cell cavities (collider + booster)

$t\bar{t}$ 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)

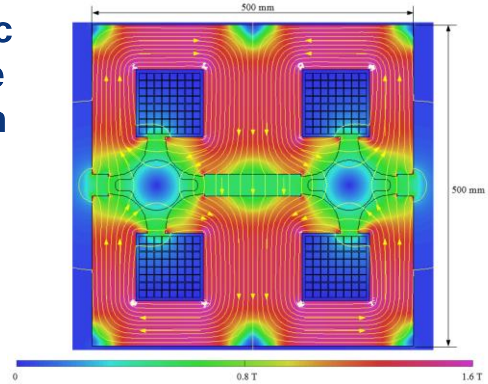
FCC-ee cost-effective, energy-efficient arc magnets

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

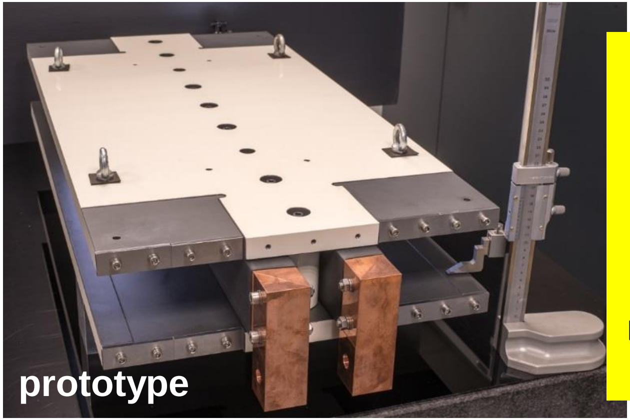


2900 units, 0.057 T, ~22 m

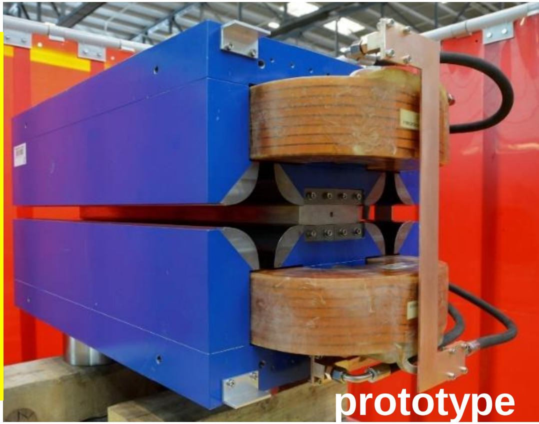
twin F/D arc quadrupole design with 2× power saving; 25 MW (at 175 GeV), with Cu conductor



2900 units, 10 T/m, 3.1 m

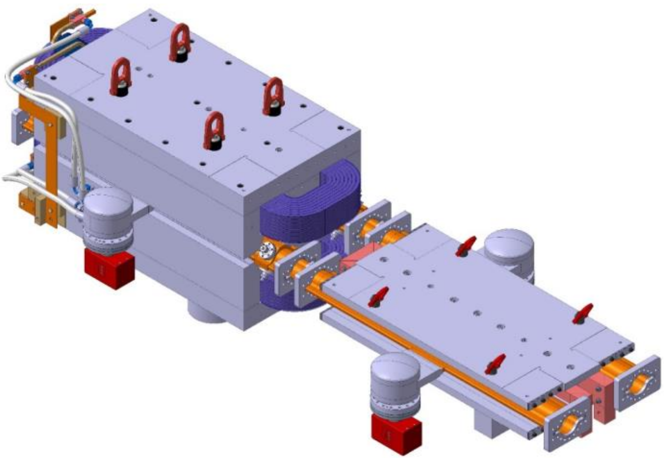


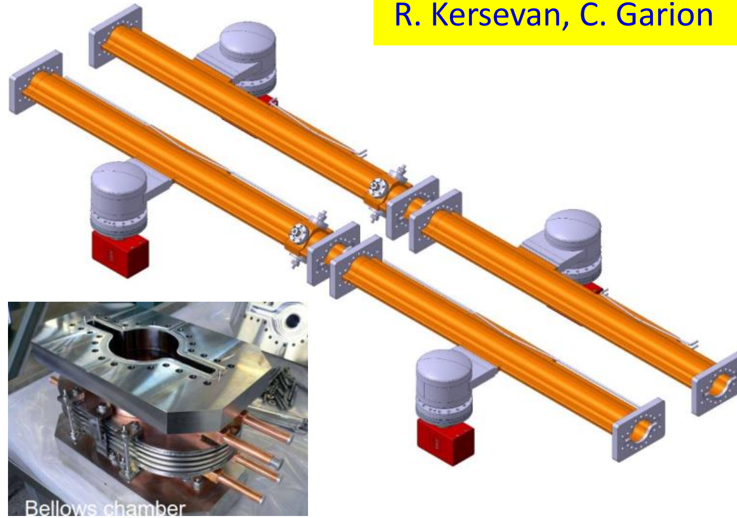
A. Milanese, *Efficient twin aperture magnets for the future circular e+/e- collider*, **Phys. Rev. Accel. Beams 19**, 112401 (2016)



FCC-ee arc vacuum chambers and integration

R. Kersevan, C. Garion

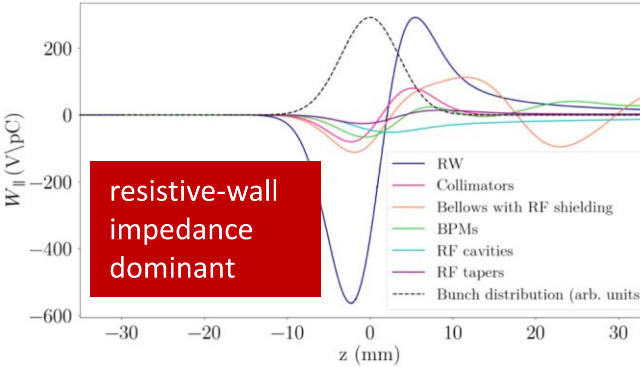




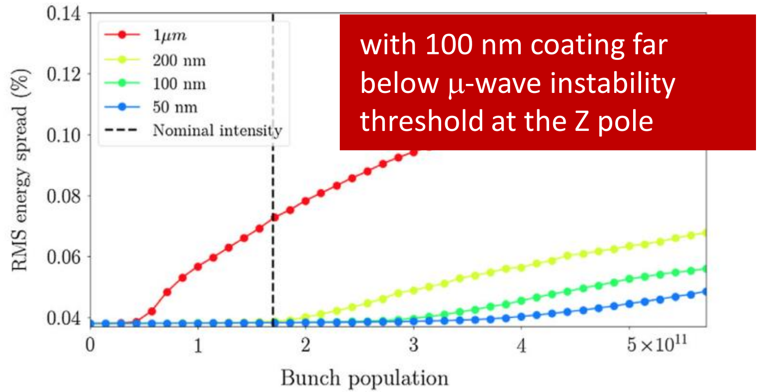
vacuum chamber cross section: 70 mm ID with ”winglets” in the plane of the orbit (SuperKEKB-like)

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

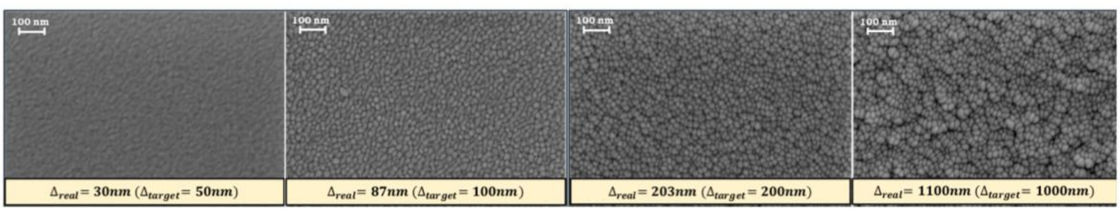


longitudinal wake potentials for a Gaussian bunch with nominal bunch length σ_z = 3.5 mm due to the main FCC-ee components compared with the RW contribution



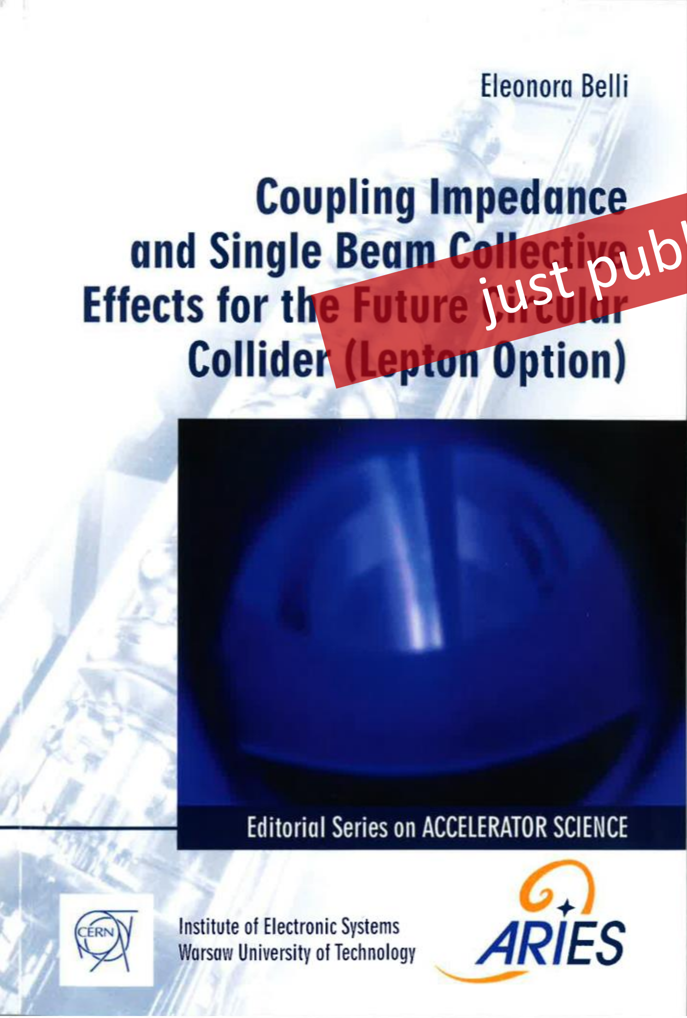
RMS energy spread vs bunch population, at the Z, considering the RW impedance for NEG films with different thicknesses

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) just published



COLLECTIVE EFFECTS FOR THE FUTURE CIRCULAR COLLIDER (LEPTON OPTION)

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Dipartimento di Fisica
Ph.D. School on Accelerator Physics, Cicle XXXI
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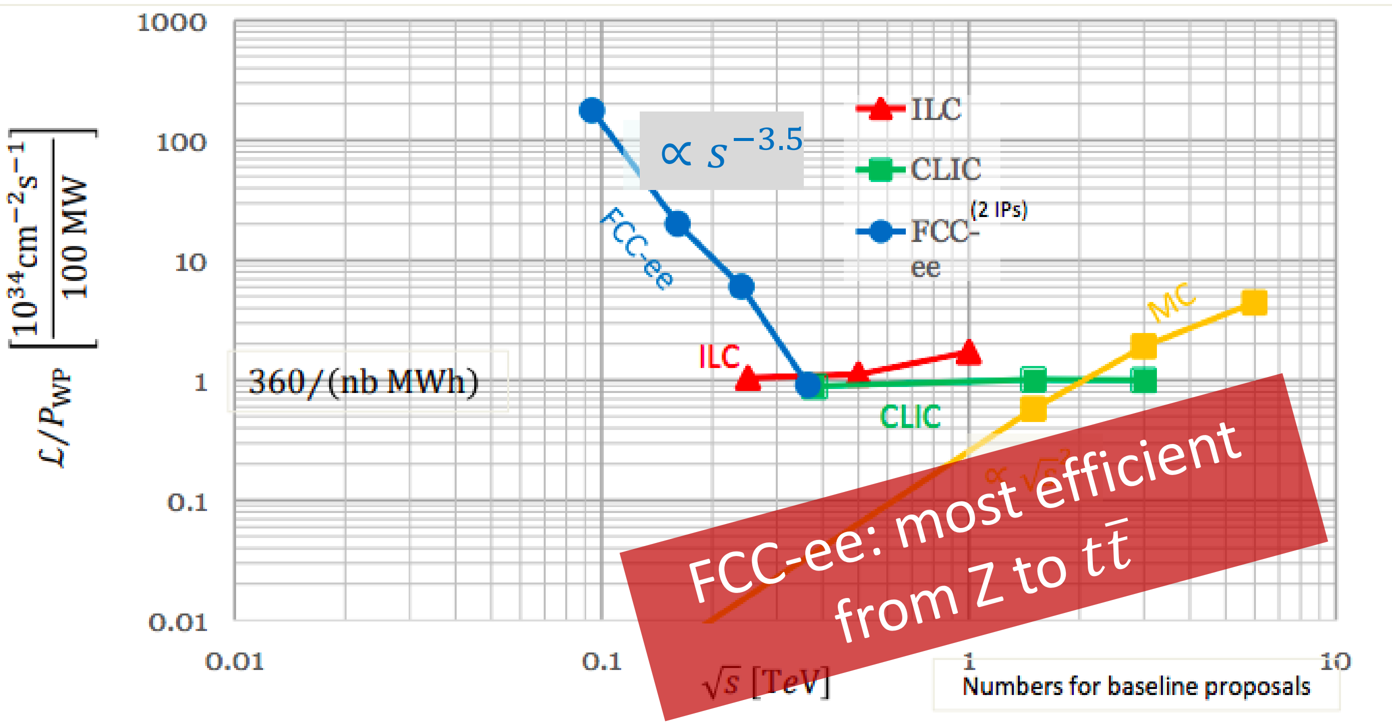
Beams Department, Accelerators and Beam Physics Group
Supervisor: Dr. Giovanni Rumolo

This project was supported in part by the European Commission Horizon 2020 Research and Innovation programme under Grant Agreement No. 730871.

FCC-ee el. power consumption [MW]

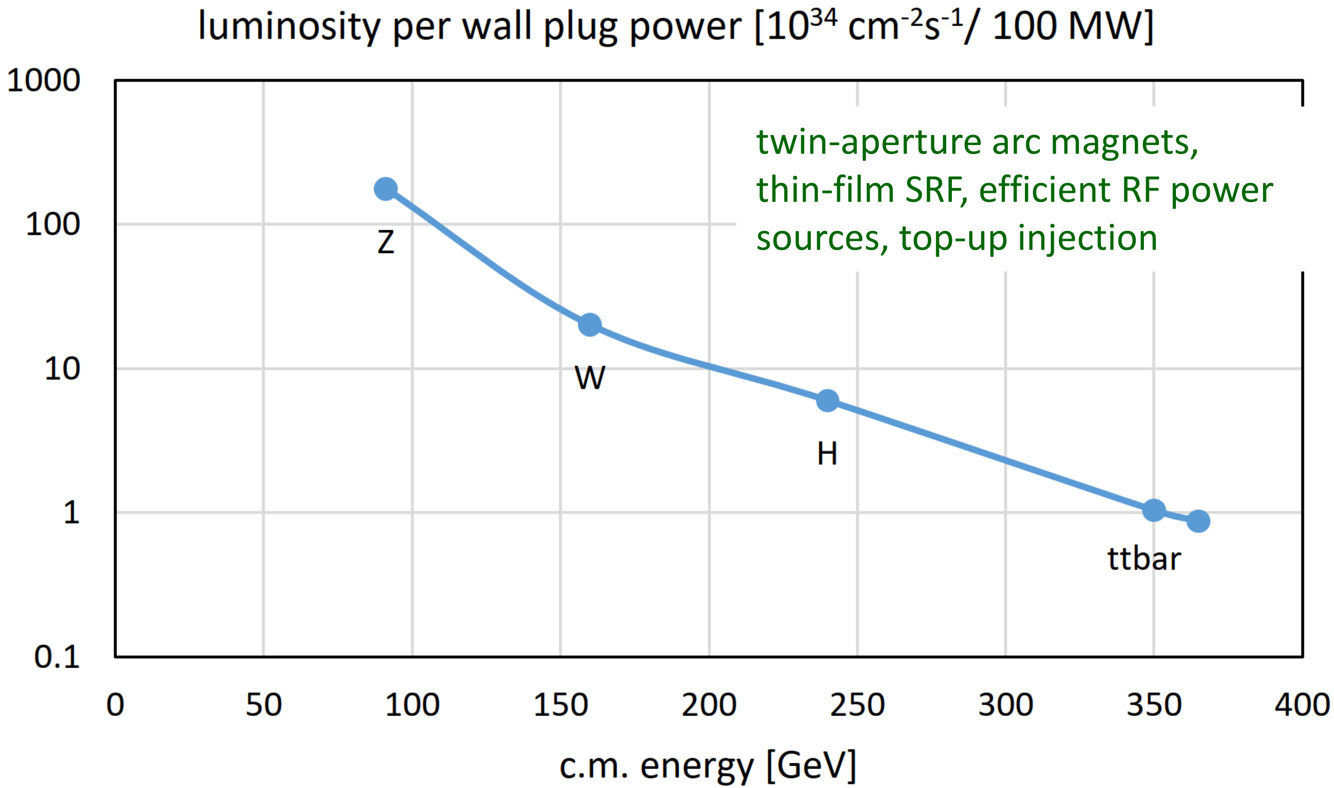
Beam energy (GeV)	45.6 Z	80 W	120 ZH	182.5 ttbar
RF (SR = 100)	163	163	145	145
Collider cryo	1	9	14	46
Collider magnets	4	12	26	60
Booster RF & cryo	3	4	6	8
Booster magnets	0	1	2	5
Pre injector	10	10	10	10
Physics detector	8	8	8	8
Data center	4	4	4	4
Cooling & ventilation	30	31	31	37
General services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



electricity cost ~200 euro per Higgs boson

integrated luminosity per construction cost

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 !

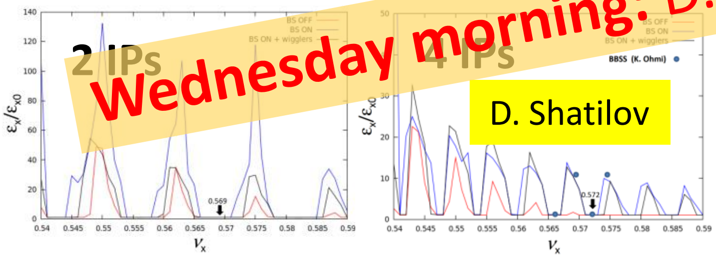
options to further boost FCC-ee performance

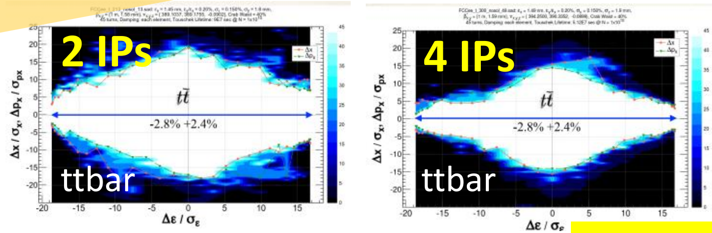
shorter beam lifetime → higher luminosity

Wednesday morning: D. Shatilov, K. Oide, K. Ohmi

4 interactions points

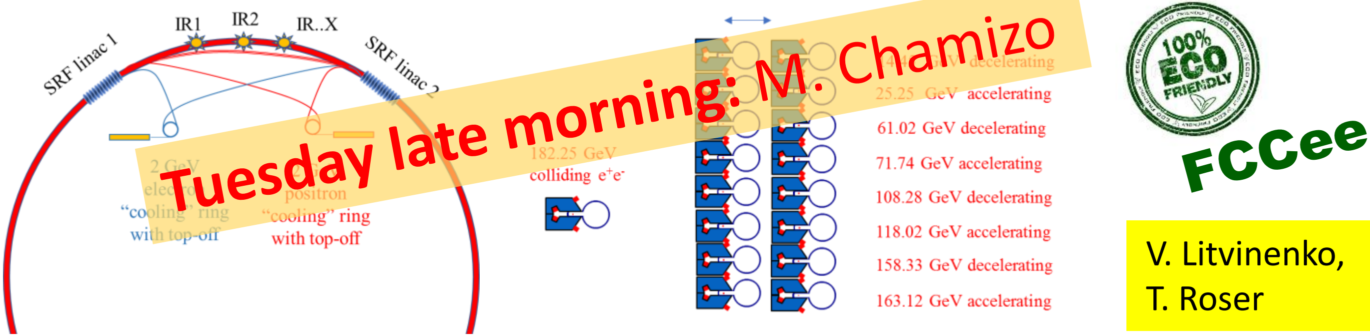
ε_x blow up due to coherent instability vs Q_x | off-mom. dynamic aperture



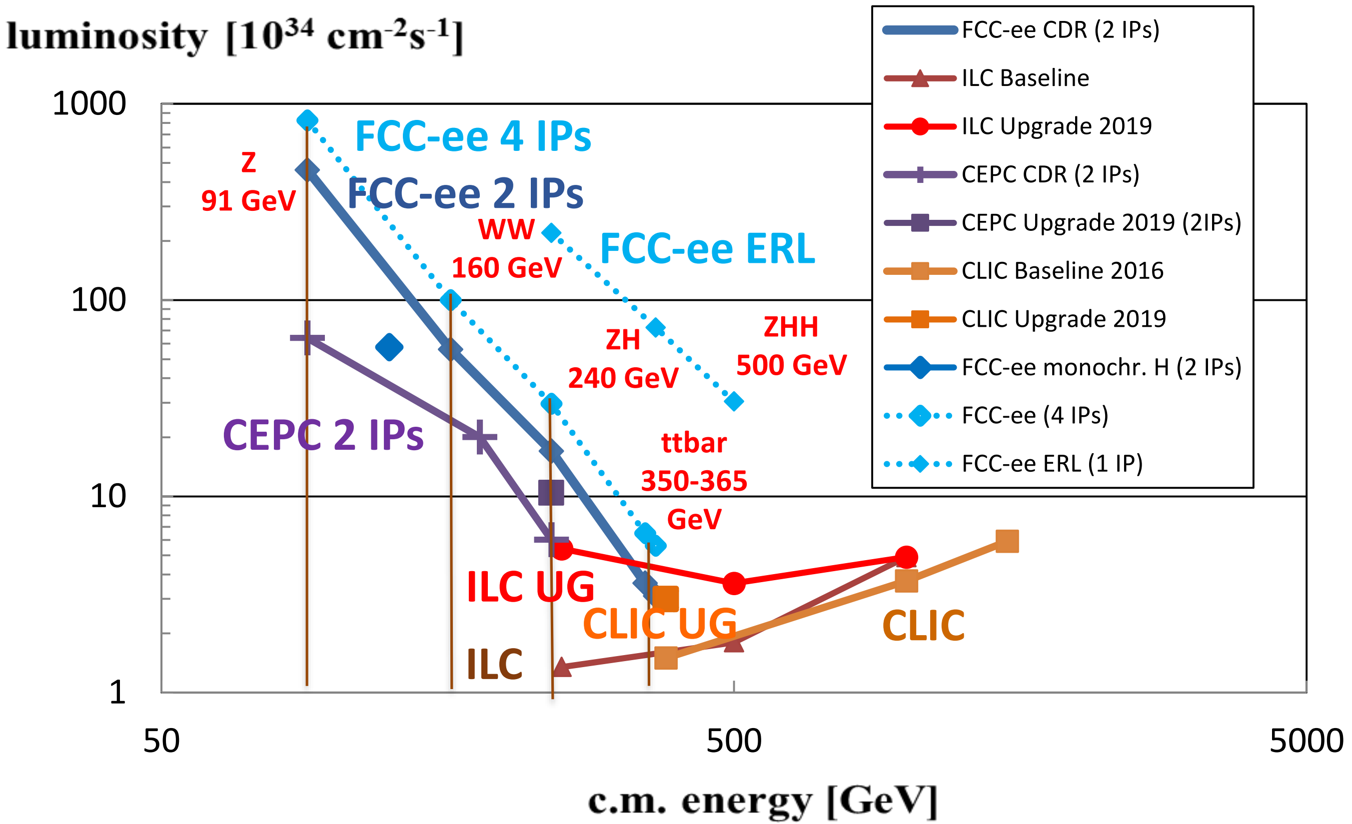


ERL based FCC-ee upgrade for higher luminosity & energy

Tuesday late morning: M. Chamizo



FCC-ee luminosity in perspective



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

conclusions

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, …)**

FCC-ee accelerator session Tuesday afternoon

16:30-18:00	**FCC-ee Injector Linacs, chair Lenny Rivkin, PSI**	
16:30-16:48	**John Seeman, SLAC**	**SLAC/SLC 2-mile S-band Linac**
16:48-17:06	**Kazuro Furukawa, KEK**	**SuperKEKB S-band/C-band Linac**
17:06-17:24	**Heung-Sik Kang, PAL**	**IR PAL-XFEL S-band Linac**
17:24-17:42	**Takahiro Inagaki, SPring-8**	**The SACLA C-band Linac**
17:42-18:00	**Hans Braun, PSI**	**SwissFEL C-band Linac & S-band Linac for FERMI**

hot topics!

FCC-ee accelerator session Wednesday morning

08:30-10:00	**FCC-ee Machine Design (1), chair Ralph Assmann, DESY**	
08:30-08:48	**Katsunobu Oide, KEK**	**Issues for the next step**
08:48-09:06	**Dmitry Shatilov, BINP**	**Beam-beam effects for 4 IPs**
09:06-09:24	**Tessa Charles, U. Melbourne**	**Low emittance tuning of FCC-ee**
09:24-09:42	**Eliana Gianfelice, FNAL**	**Beam polarization for energy calibration in FCCee**
09:42-10:00	**Klaus Heinemann, U. NMex.**	**Bloch equation for Spin-Orbit Dynamics**
10:30-12:00	**FCC-ee Machine Design (2), chair Jie Gao, IHEP**	
10:30-10:48	**Mauro Migliorati, Sapienza**	**Collective effects with ttbar configuration**
10:48-11:06	**Dmitry Teytelman, Dimtel**	**Feedback scenarios**
11:06-11:24	**Toshiyuki Mitsuhashi, KEK**	**X-ray interferometer & SuperKEKB test**
11:24-11:42	**Arto Niemi, CERN**	**FCC-ee machine availability**
11:42-12:00	**Kazuhito Ohmi, KEK**	**SuperKEKB status and LPA collisions**

FCC-ee accelerator session Wednesday afternoon

13:30-15:00	**FCC-ee Injector Design, chair John Seeman, SLAC**	
13:30-13:48	**Katsunobu Oide, KEK**	**Baseline scheme**
13:48-14:06	**Daniel Schulte, CERN**	**Alternatives**
14:06-14:24	**Mauro Migliorati, Sapienza**	**Collective effects in the booster synchrotron**
14:24-14:42	**Iryna Chaikovska, LAL**	**Positron source for FCC-ee**
14:42-15:00	**Frank Zimmermann, CERN**	**Injection damping & transverse stability in PBR**

more hot topics!

FCC-ee accelerator session Thursday morning

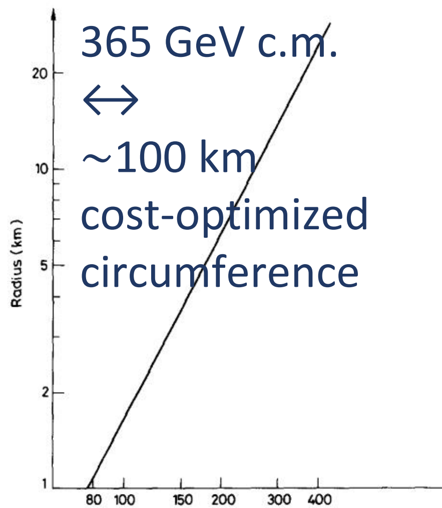
08:30-10:00	**FCC-ee Machine Detector Interface (1), chair Maria Chamizo, BNL**	
08:30-08:48	**Manuela Boscolo, INFN**	**Overview of MDI issues toward the TDR**
08:48-09:06	**Eugene Levichev, BINP**	**Mechanical design of the interaction region**
09:06-09:24	**Mike Koratzinos, MIT**	**Final-focus quadrupoles and solenoids**
09:24-09:42	**Dima El Khechen, CERN**	**Beam-beam blow-up issues**
09:42-10:00	**Emmanuel Perez, CERN**	**Beam-beam effects on luminosity measurement**
10:30-12:00	**FCC-ee Machine Detector Interface (2), chair Eugene Levichev, BINP**	
10:30-10:48	**Marian Luckhof, Hamburg U.**	**Synchrotron radiation background studies**
10:48-11:06	**Helmut Burkhardt, CERN**	**Beam losses at IR**
11:06-11:24	**Emilia Leogrande, CERN**	**Detector performance with smaller IP beam pipe**
11:24-11:42	**Alexander Novokhatski, SLAC**	**HOM and heating with smaller IP beam pipe**
11:42-12:00	**Manuela Boscolo, INFN & Mike Sullivan, SLAC**	**Synchrotron radiation with smaller IP beam**

"An e^+-e^- storage ring … of a few hundred GeV in the centre of mass <u>can be built with present technology</u>. …would seem to be … most useful project on the horizon." **Burt Richter 1976**

"Of course, it should not be the size of an accelerator, but its costs which must be minimized."

Gus Voss, builder of PETRA
IEEE PAC, Dallas, 1995

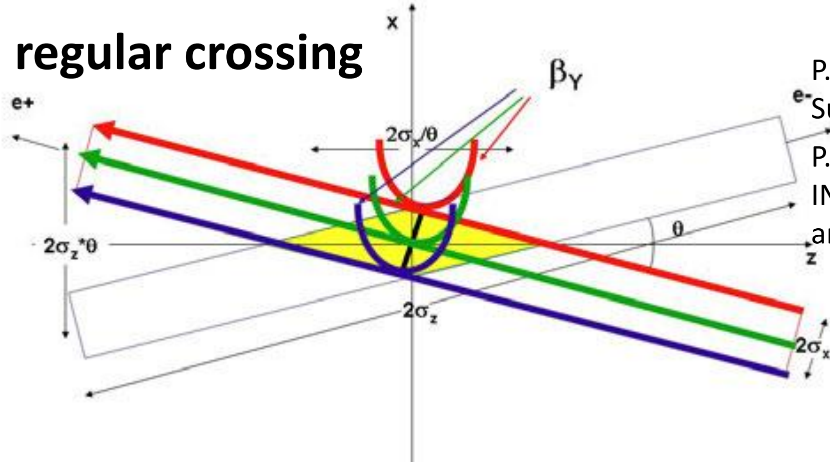
B. Richter, *Very High Energy Electron-Positron Colliding Beams for the Study o Weak Interactions*, NIM 136 (**1976**) 47



spare slides

crab-waist crossing for flat beams

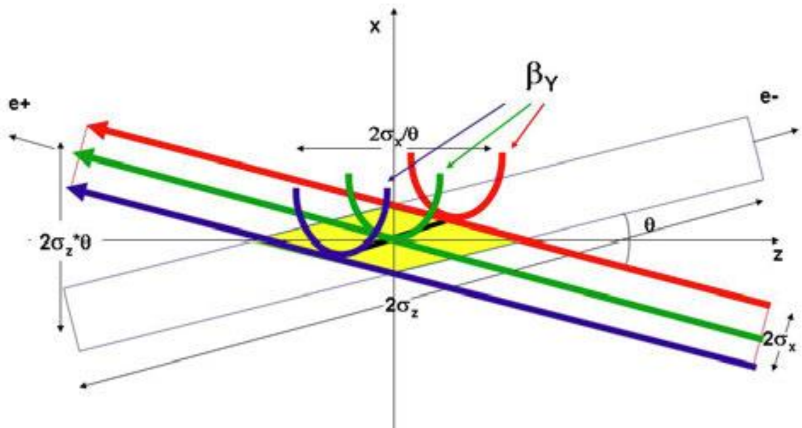
regular crossing



P. Raimondi, Proceedings of the 2nd SuperB Workshop, Frascati, March 2006.

P. Raimondi, D. Shatilov, and M. Zobov, INFN Report No. LNF07/003; arXiv:physics/0702033

crab waist crossing

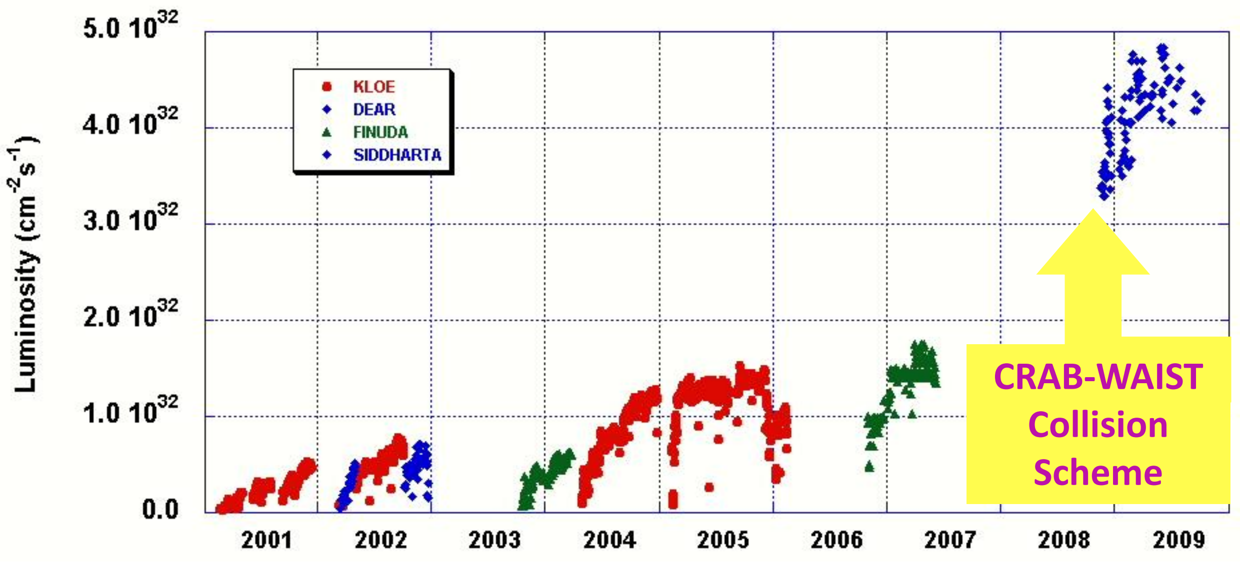


vertical waist position in *s* varies with horizontal position *x*

- **allows for small β_y*** and for small $\varepsilon_{x,y}$
- avoids betatron resonances (→**higher beam-beam tune shift**)

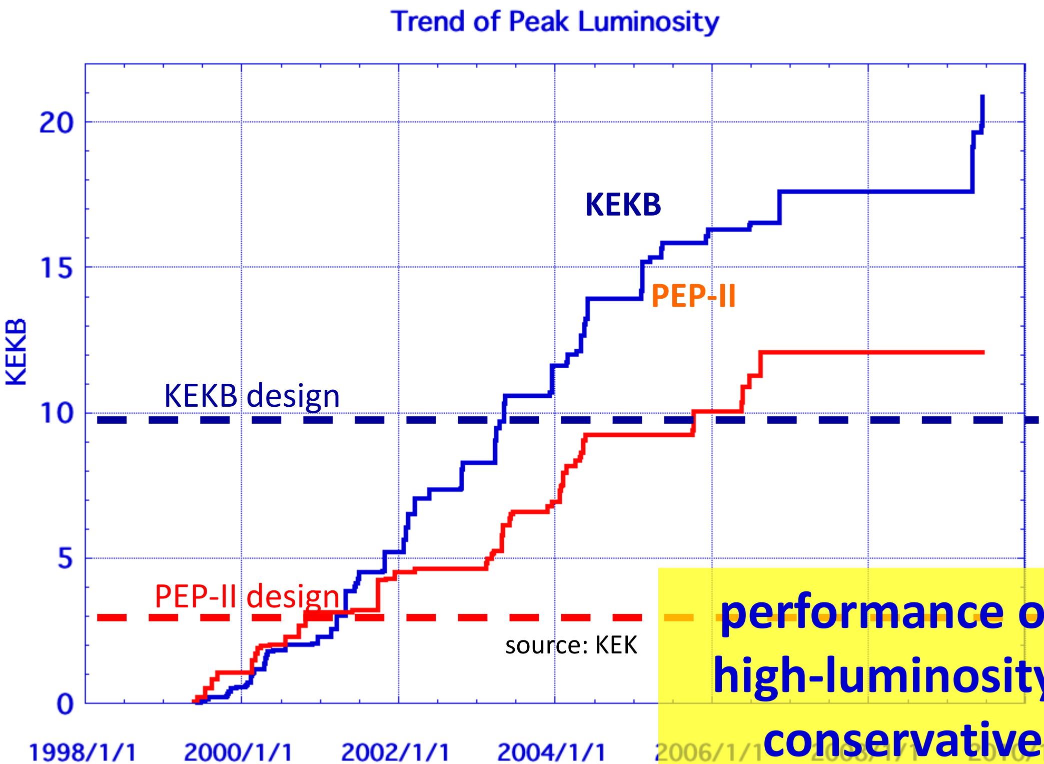
DAΦNE: “crab waist” collisions, est. 2008/09

DAΦNE Peak Luminosity



M. Zobov et al., *Test of “Crab-Waist” Collisions at the DAΦNE Φ Factory,* **Phys. Rev. Lett. 104**, 174801 (2010)

KEKB & PEP-II: high current, high *L*



I_{e+}=1.6 A, I_{e-}=1.2 A

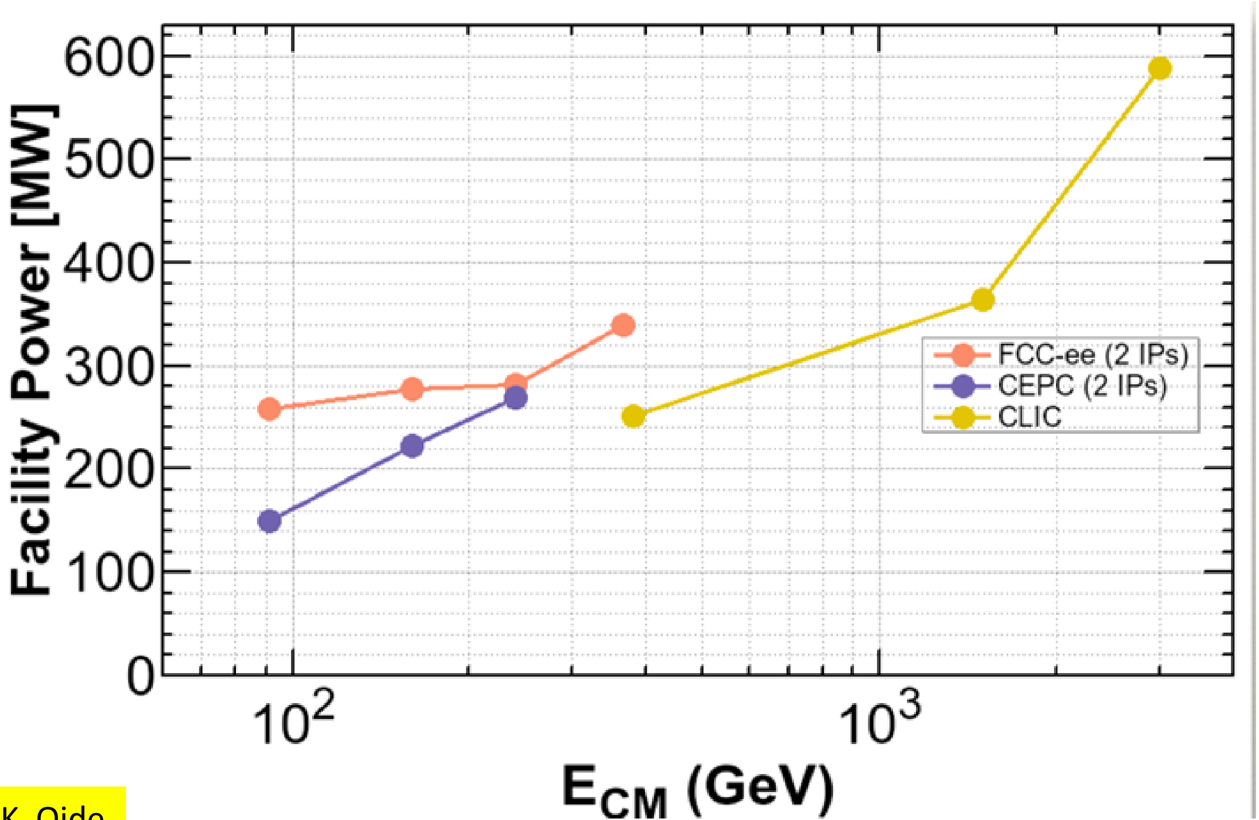
P_{SR} ~ 5 MW
C = 3 km

I_{e+}=3.2 A, I_{e-}=2.1 A

P_{SR} ~ 8 MW
C = 2.2 km

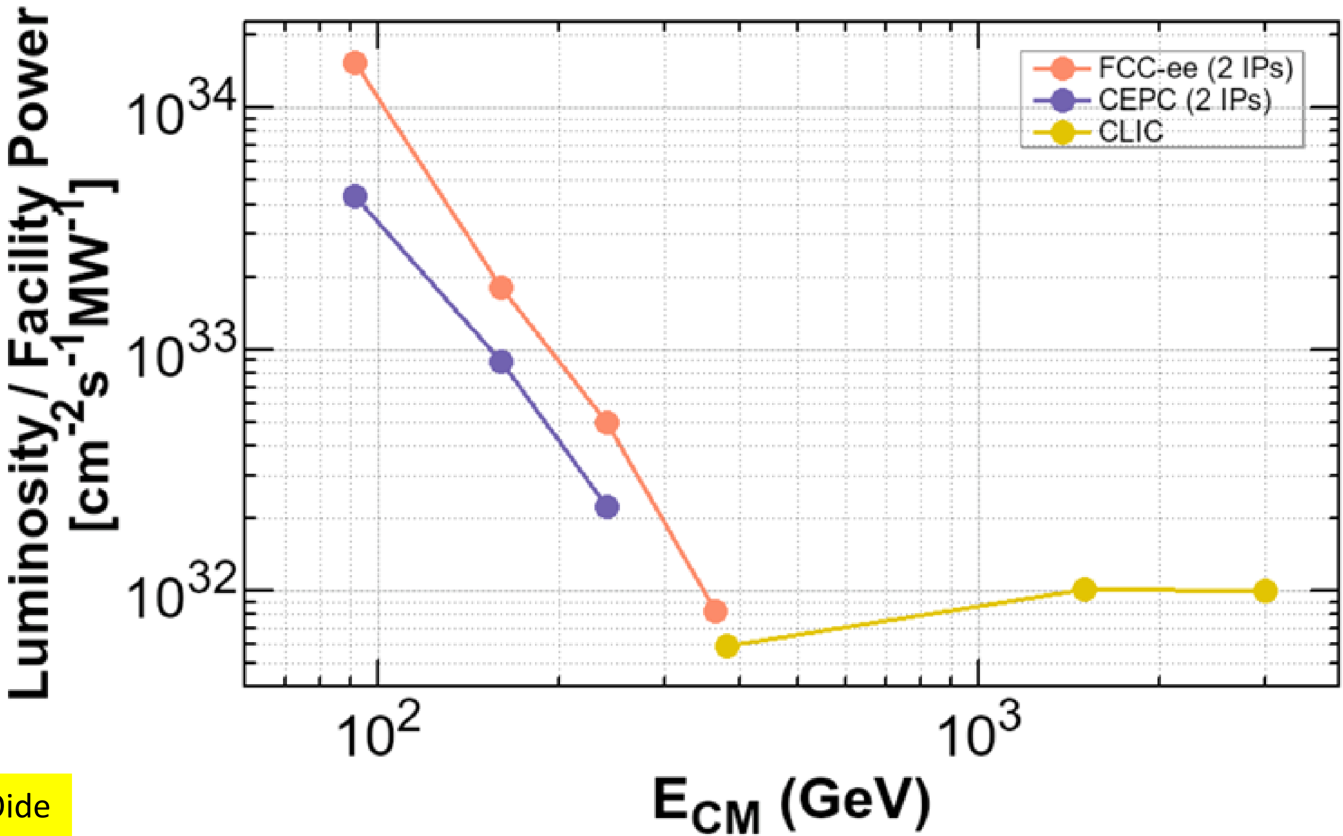
performance of high-current high-luminosity e^+e^- factories conservatively predicted

facility power versus c.m. energy



K. Oide

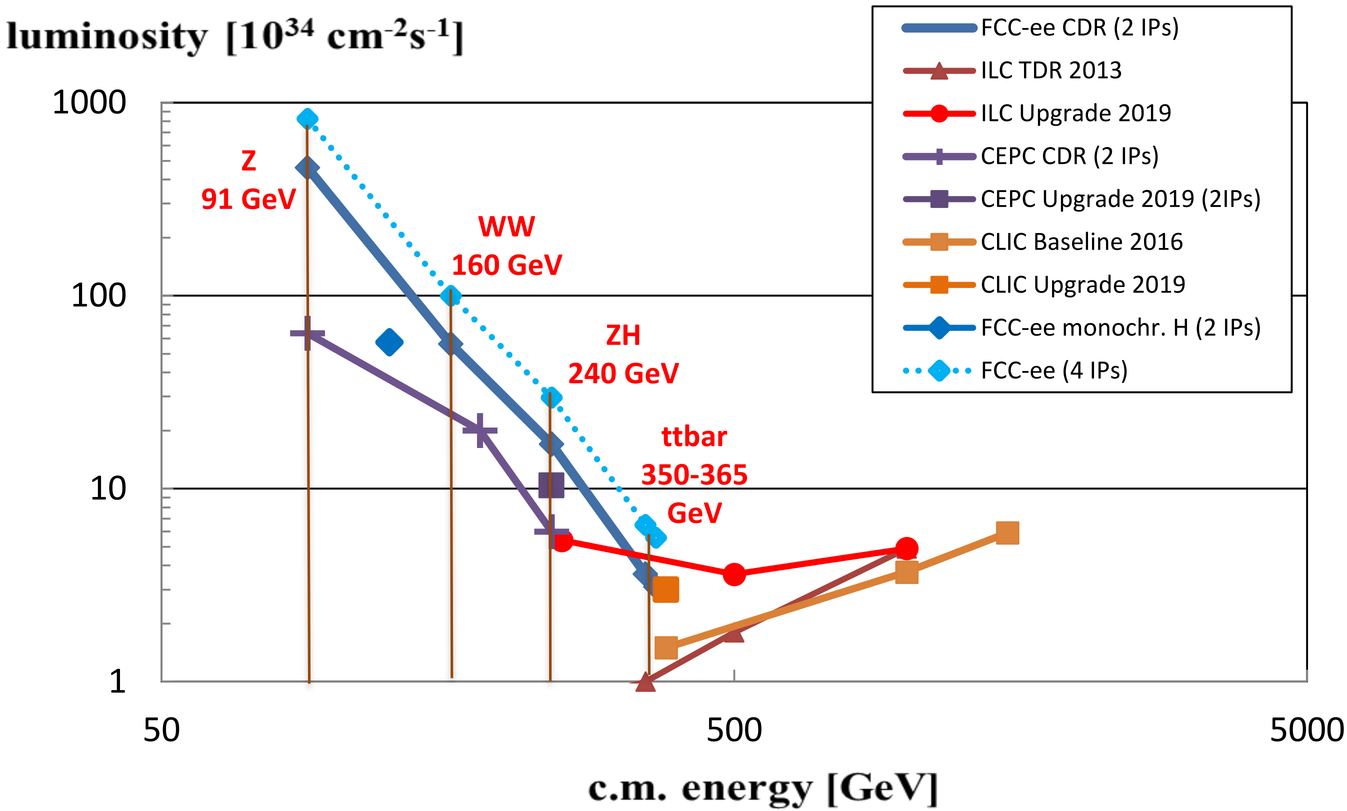
luminosity per facility power



K. Oide

winding the final quadrupole, jig in action

FCC-ee luminosity in perspective



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"The 100 km tunnel is essential"
Thomas Roser, BNL, June 2019