FCC-ee machine design overview

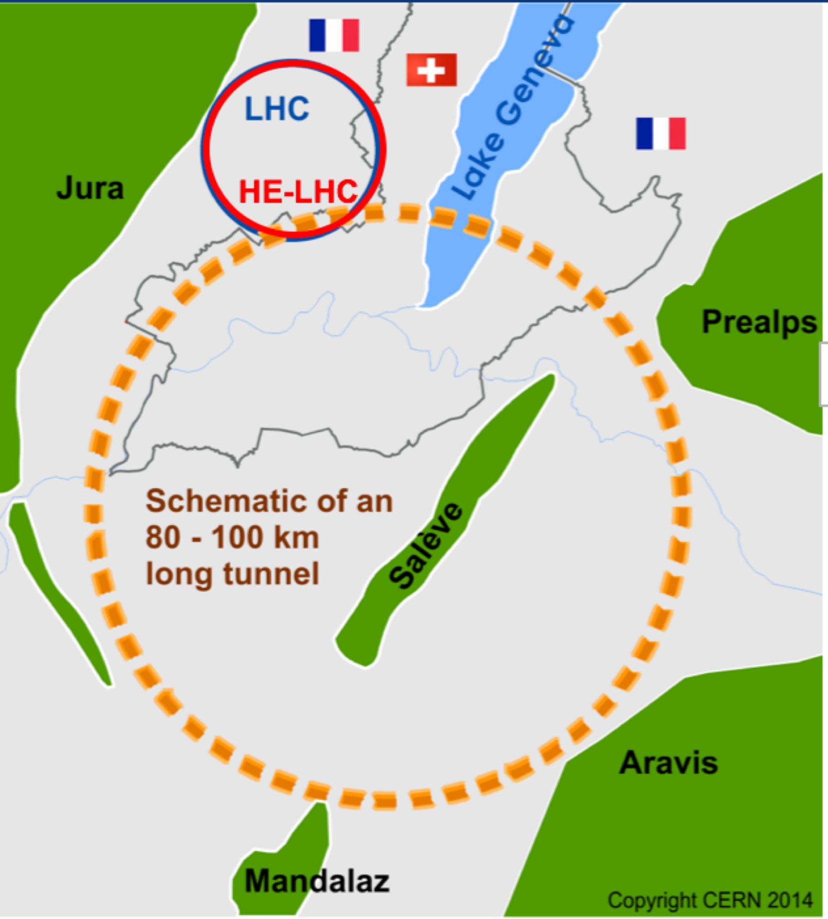
M. Boscolo (INFN-LNF) for the FCC-ee collaboration

Special Thanks to: M. Benedikt, K. Oide, F. Zimmermann

Outline

- Design challenge, key parameters and layout
- Optics design and beam dynamics
- Interaction Region and MDI
- Collective effects
- Energy calibration and polarization
- Injection system
- Vacuum system
- Conclusions

Future Circular Collider (FCC) Study

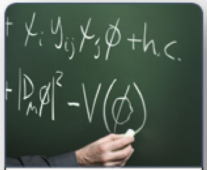


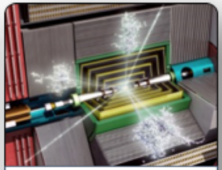
International FCC collaboration (CERN as host lab) to study:

- ***pp*-collider (*FCC-hh*)** → main emphasis, defining infrastructure requirements

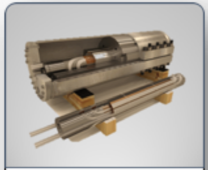
~16 T ⇒ 100 TeV *pp* in 100 km

- **~100 km tunnel infrastructure** in Geneva area, site specific
- ***e⁺e⁻* collider (*FCC-ee*),** as potential first step
- **HE-LHC** with *FCC-hh* technology
- ***p-e* (*FCC-he*) option,** IP integration, e⁻ from ERL


Physics Cases


Experiments

Collider Designs


R&D Programs

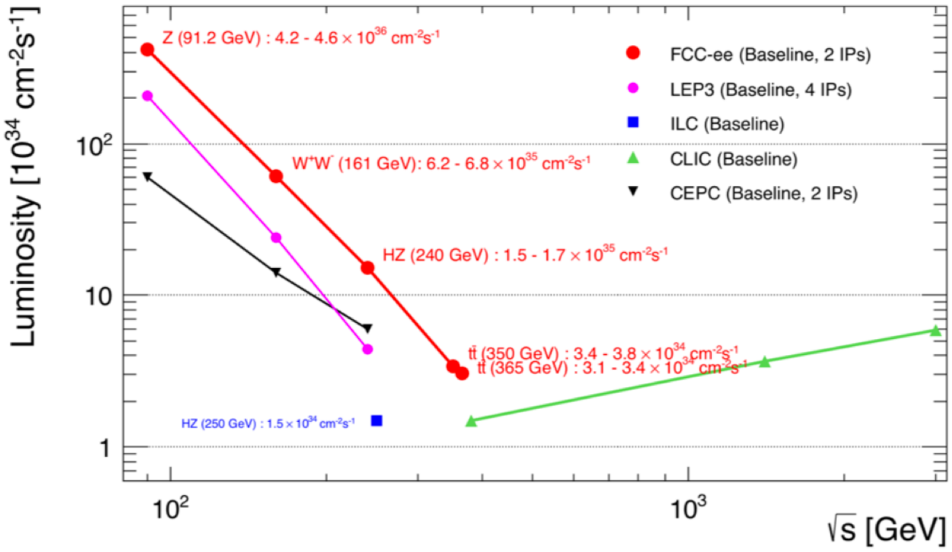
Infrastructures


Cost Estimates

Introduction

- **Great progress has been made in the FCC-ee collider design**
- **FCC-ee CDR summary volume writing and editing is on schedule**

FCC-ee collider is
extremely challenging
but **feasible**
with **great physics potential**



Baseline luminosities

FCC-ee operation model

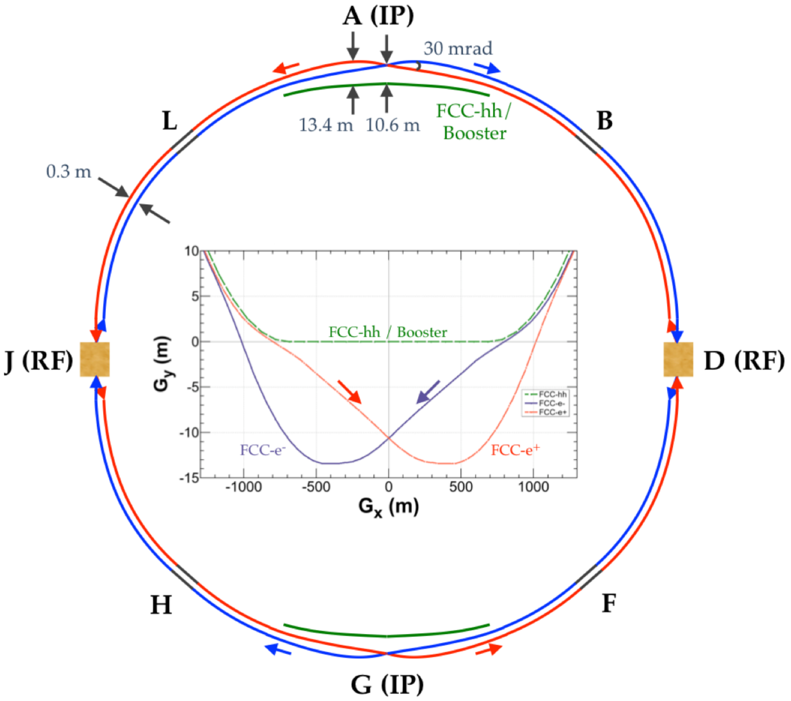
working point	luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	total luminosity (2 IPs)/ yr	physics goal	run time [years]
Z first 2 years	100	26 ab^{-1}/year	**150 ab^{-1}**	**4**
Z later	200	52 ab^{-1}/year		
W	32	8.3 ab^{-1}/year	**10 ab^{-1}**	**1**
H	7.0	1.8 ab^{-1}/year	**5 ab^{-1}**	**3**
machine modification 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)	1.5	0.38 ab^{-1}/year	**1.5 ab^{-1}**	**4**

total program duration: 14 years - ***including machine modifications***

phase 1 (*Z, W, H*): 8 years, **phase 2 (top): 6 years**

Key parameters and baseline optics design

- **Double ring** e+ e- collider ~100 km
- Follow the footprint of FCC-hh, except for around the IPs
- **2 IPs** with **crab-waist scheme**, large horizontal crossing angle of **30 mrad.**
- **Flexible design, for all energies:**
  - **common lattice,** except for a small rearrangement in the RF section
  - **L* = 2.2 m** (length of the free area around the IP), $B_{detector}$ **= 2 T**
  - $E_{critical}$ **< 100 keV** (critical energy of the synchrotron radiation) of incoming beam toward IP from 450 m
- **Top-up injection** scheme to maintain the stored beam current and the luminosity at the highest level during experiment runs. It is necessary to have a booster synchrotron in the same tunnel as the collider.
- **Synchrotron radiation power 50 MW/beam** at all energies.
- **"Tapering"** of magnets along the ring to compensate the sawtooth effect
- Common RF cavities for e+ and e- at ttbar (RF frequency **400 MHz** and **400+800 MHz at ttbar)**



FCC-ee parameters		Z	W^+W^-	ZH	ttbar	
Beam energy	**GeV**	**45.6**	**80**	**120**	**175**	**182.5**
Luminosity / IP	$10^{34}\ cm^{-2}\ s^{-1}$	**230**	**28**	**8.5**	**1.8**	**1.55**
Beam current	mA	1390	147	29	6.4	5.4
Bunches per beam	#	16640	2000	328	59	48
Average bunch spacing	ns	19.6	163	994	2763	3396
Bunch population	10^{11}	1.7	1.5	1.8	2.2	2.3
Horizontal emittance ε_x Vertical emittance ε_y	nm pm	0.27 1.0	0.84 1.7	0.63 1.3	1.34 2.7	1.46 2.9
β_x^* / β_y^*	**m / mm**	**0.15 / 0.8**	**0.2 / 1.0**	**0.3 / 1.0**	**1.0 / 1.6**	
beam size at IP: σ_x^* / σ_y^*	μm / nm	6.4 / 28	13 / 41	13.7 / 36	36.7 / 66	38.2/68
Energy spread: SR / total (w BS)	%	0.038 / 0.132	0.066 / 0.131	0.099 / 0.165	0.144 / 0.196	0.15 / 0.192
Bunch length: SR / total	mm	3.5 / 12.1	3 / 6.0	3.15 / 5.3	2.75 / 3.82	1.97 / 2.54
Energy loss per turn	**GeV**	**0.036**	**0.34**	**1.72**	**7.8**	**9.2**
RF Voltage /station	GV	0.1	0.75	2.0	4/5.4	4/6.9
Longitudinal damping time	turns	1273	236	70.3	23.1	20.4
Acceptance RF / energy (DA)	%	1.9 / ±1.3	2.3 / ±1.3	2.3 / ±1.7	3.5/ (-2.8; +2.4)	3.36 / (-2.8; +2.4)
Rad. Bhabha/ actual Beamstr. Lifetime	min	68 / > 200	59 / >200	38 / 18	37/ 24	40 / 18
Beam-beam parameter ξ_x / ξ_y		0.004 / 0.133	0.01 / 0.141	0.016 / 0.118	0.088 / 0.148	0.099 / 0.126
Interaction region length	mm	0.42	0.85	0.9	1.8	1.8

More details in talk by K. Oide

Optics design and beam dynamics

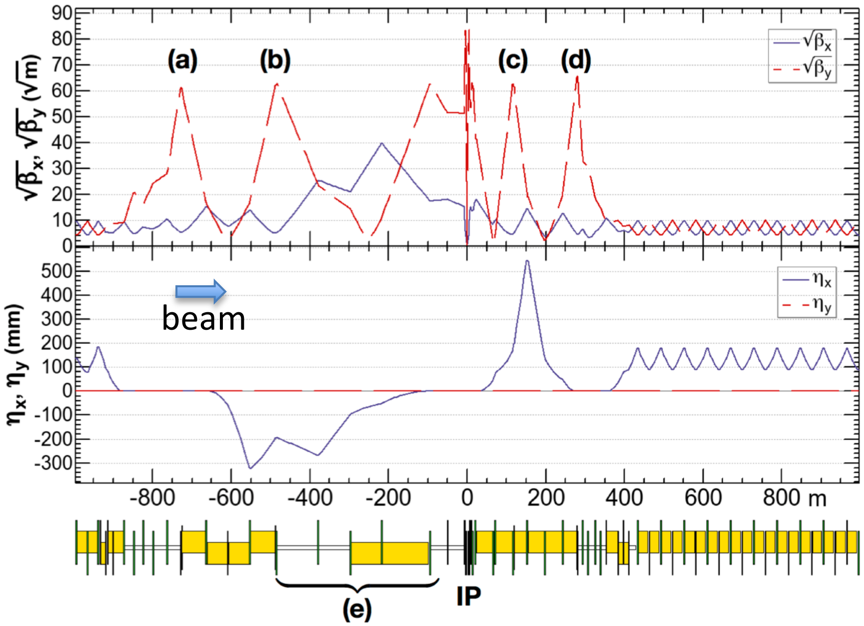
- Baseline optics was established in **2016** [PR-AB 19 (2016) no.11, 111005]
- **FCCWEEK2017:**
  - reduction β_x*
  - 60°/60° arc cell at Z

Motivations for these changes:
- to mitigate the coherent beam-beam instability at Z
- to adopt the twin aperture quadrupole scheme for the arc quads [PR-AB 19 (2016) no.11, 112401]
- to fit the footprint to a new FCC-hh layout

- **FCCWEEK2018:**
  - Further reduction of β* at the IP at Z, $W^\pm$, ZH, ttbar(β_y)
  - Increase of beam energy at ttbar (182.5 GeV)
  - Momentum acceptance at ttbar increased by "asymmetric acceptance"
  - Better packing factor of dipoles in the arcs
  - Special sections for inverse Compton spectrometer
  - Dynamic Aperture improved to maximize luminosity
  - Tolerance study on misalignments very encouraging

Motivations for these changes:
- to mitigate the coherent beam-beam instability also at $W^\pm$, ZH
- to mitigate 3D flip-flop

Asymmetric Interaction Region optics

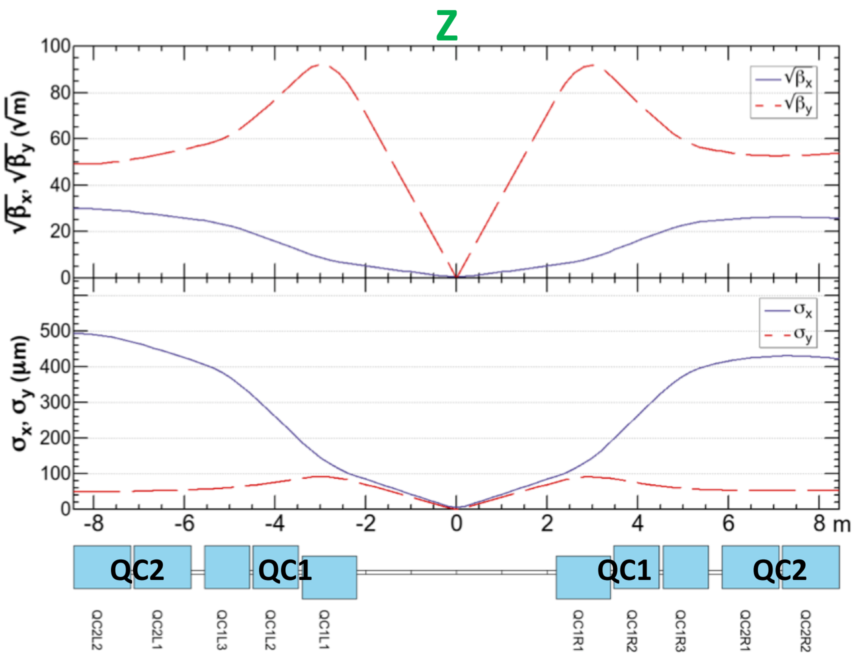


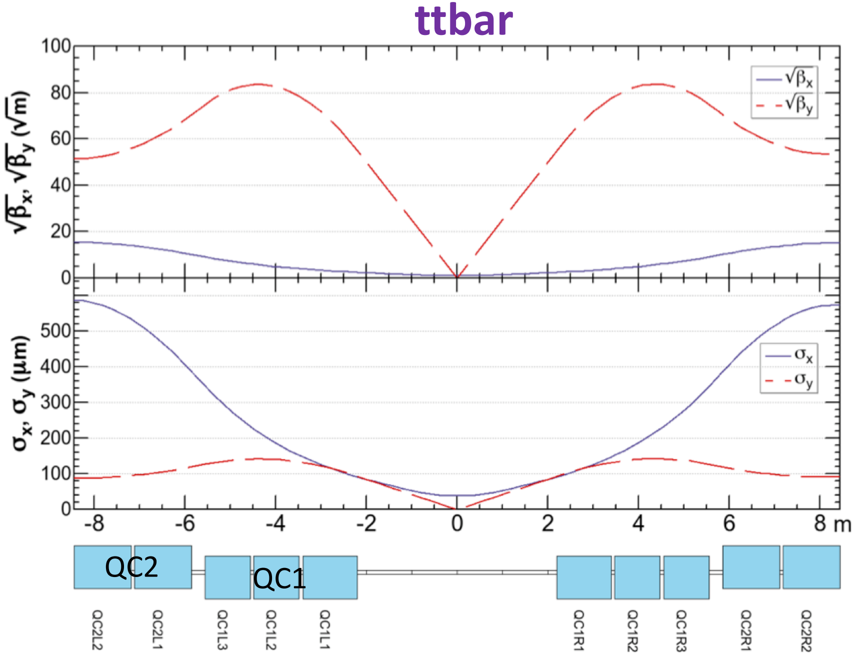
ttbar 182.5 GeV

yellow boxes: dipole magnets

- Asymmetric optics suppresses SR toward the IP, $E_{critical}$ <100 keV from 450 m from the IP
- Local chromaticity correction scheme for y-plane (a-d), incorporated with crab sextupoles (a,d), needed for energy acceptance requirement (up to 2.8%)

Final Focus optics





Only 1st slice of QC1 is defocusing horizontally

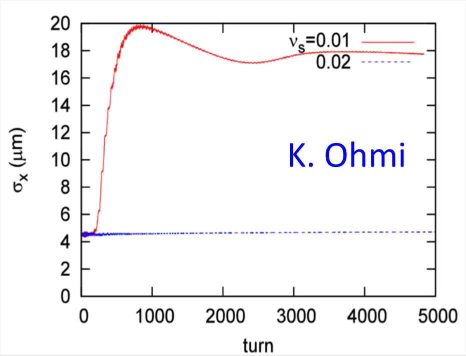
All 3 slices of QC1 are defocusing horizontally

- Flexible optics design: final focus quadrupoles are longitudinally split into three slices
  At the Z chromaticity is reduced for the smaller β^*, smaller beam size

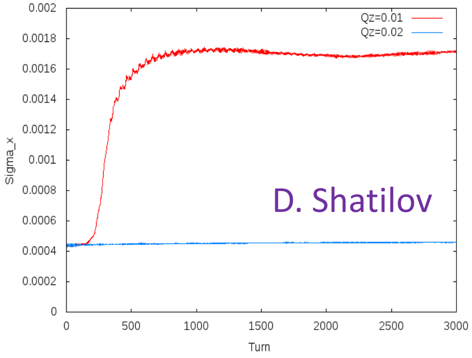
Mitigation of coherent beam-beam instability

A **new coherent instability** in **x-z plane** was first predicted by K. Ohmi with a strong-strong beam-beam simulation (FCCWEEK16)

[PRL 119 (2017) 13, 134801, PR-AB (2018) 21 031002]



D. Shatilov **confirmed the phenomenon** with an independent simulation (turn-by-turn alternating quasi-strong-strong method), very good agreement



More details in:'IP beam parameter otimization' by D. Shatilov

A semi-analytic scaling of the bunch intensity threshold has been derived (K. Ohmi):

$$N_{\mathrm{th}} \propto \frac{\alpha_p \sigma_\delta \sigma_z}{\beta_x^*}$$

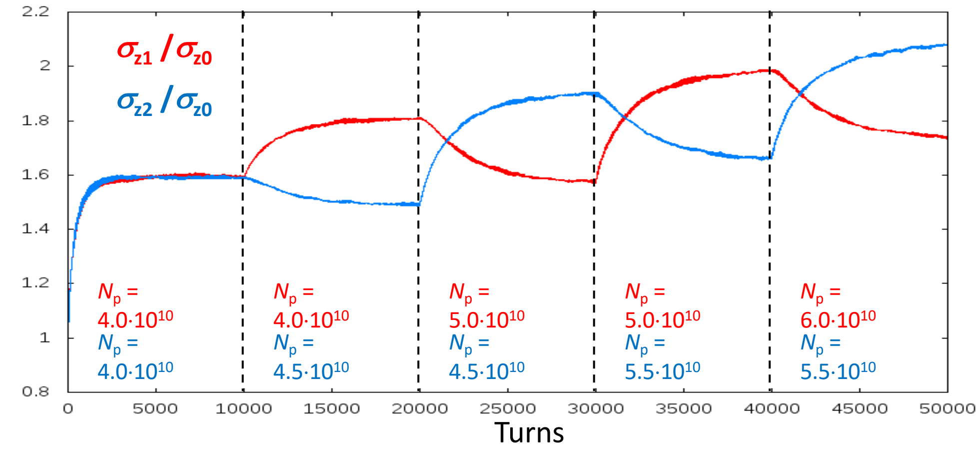
β_x^* has been reduced to ~ 1/3

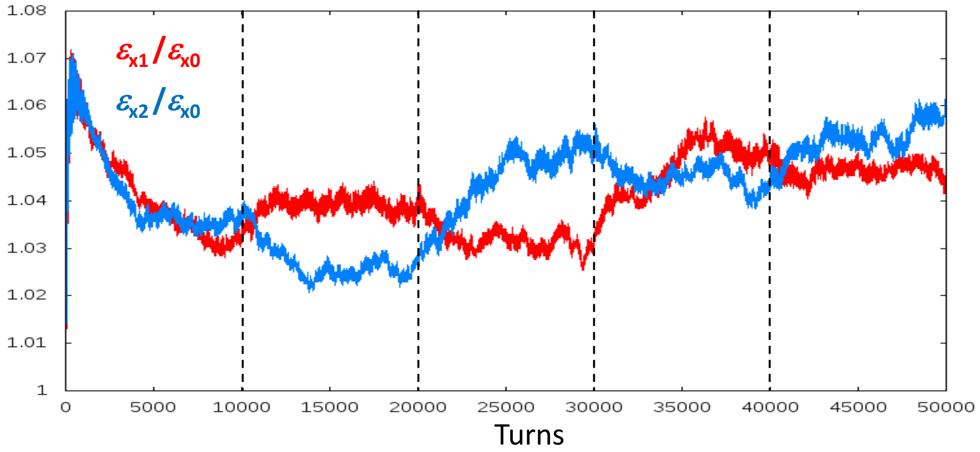
α_p was increased by a factor of 2 (by changing the phase advance of the arc at Z)

compared to the baseline 2016

Bootstrapping

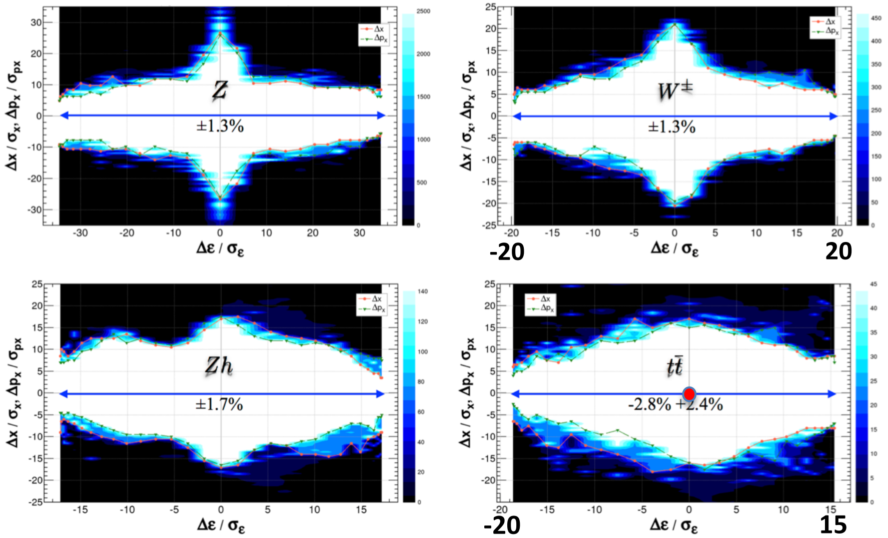
- With the nominal bunch population required for high luminosity, σ_z increases ~3.5 times because of beamstrahlung.
- If we bring into collision so large currents with the “initial” σ_z (energy spread created only by SR), the beam-beam parameters will be far above the limits.
- The beams will be blown up and killed on the transverse aperture, before they are stabilized by the beamstrahlung.
- To avoid this, we must gradually increase the bunch population during collision, so we come to *bootstrapping*.





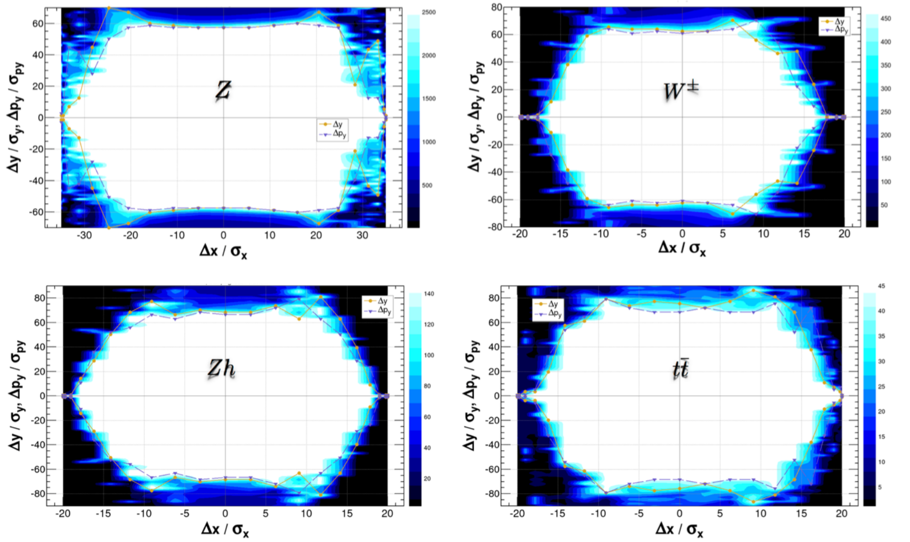
Dynamic Aperture

z-x plane



note the asymmetry to match BS

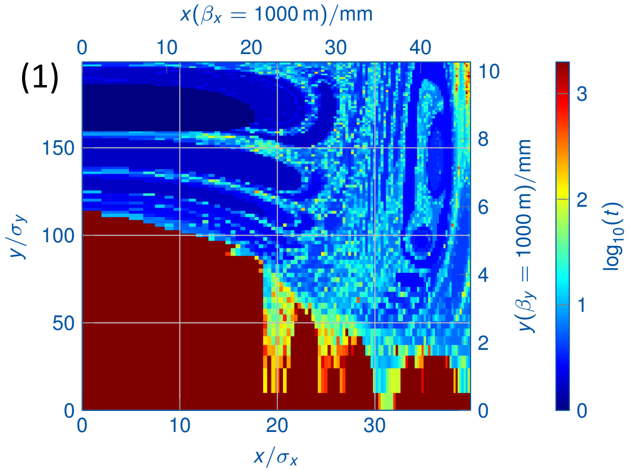
on momentum transverse DA



- DA estimated with SAD, 2 longitudinal damping times
- Effects included in the simulation: SR, tapering, radiation loss in dipoles, quads, sextupoles, crab-waist, Maxwellian fringes, kinematic terms
- DA satisfies requirements without errors and misalignments

Dynamic aperture, ideal and with errors for FCC-ee

More details in talk by T. Tydecks

(1)


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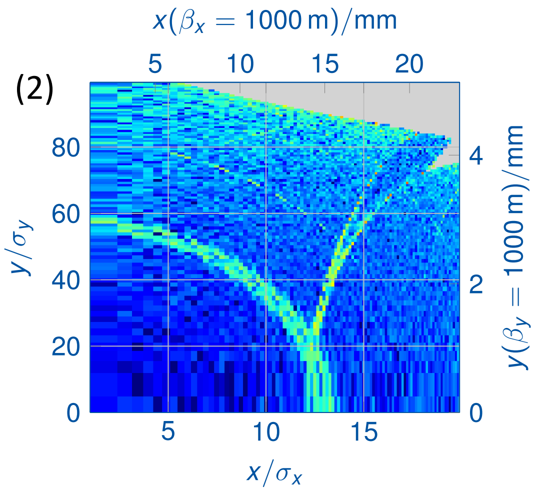

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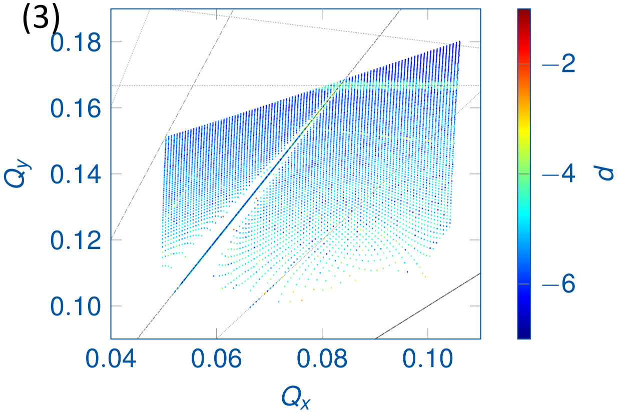
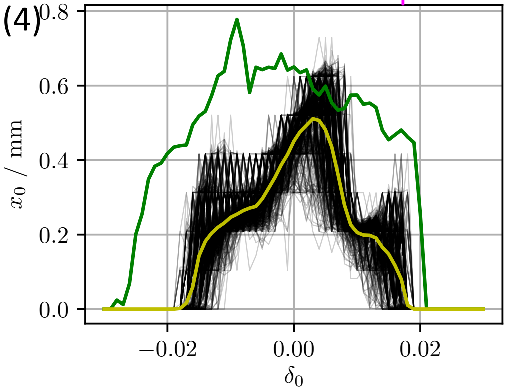


momentum aperture

(4)


- Coarse scan of 4D dynamic aperture (no radiation) (1)
- Frequency map analysis (2, 3)
- Momentum aperture with (black) and without (green) misalignment errors with considerable left over beta beat (80 %)

  Studies are ongoing to correct for beta beat at 175 GeV incl. radiation

  Misalignments used:

	σ_x	σ_y	σ_θ
arc quadrupoles	100 µm	100 µm	100 µrad
IP quadrupoles	50 µm	50 µm	50 µrad
sextupoles	100 µm	100 µm	

Interaction Region Layout

Unique and flexible design at all energies

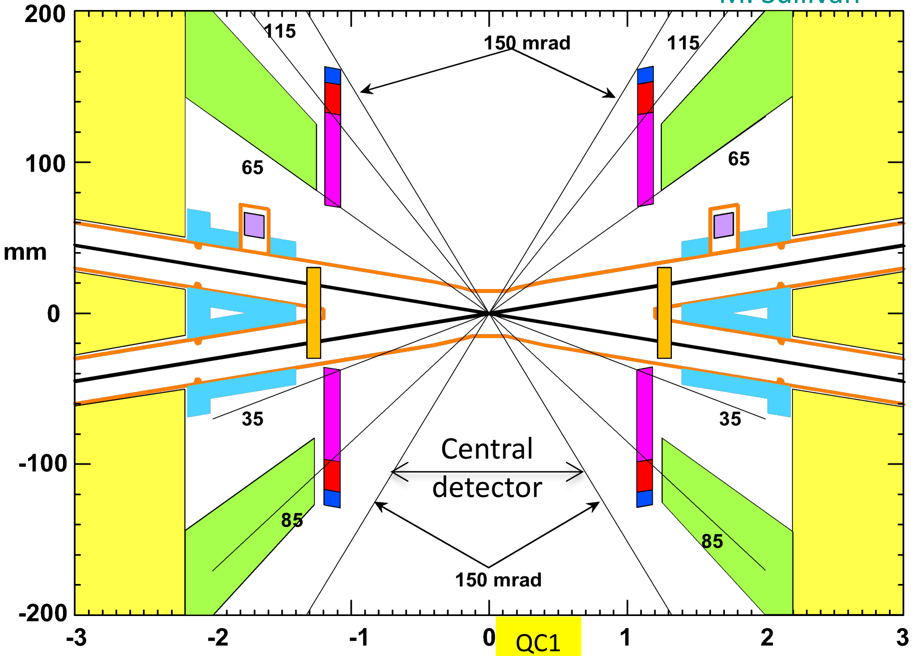
Last year in 1st MDI workshop baseline design layout was reviewed and discussed:

L*, opening angle acceptance, solenoid compensation scheme, LumiCal space, IR HOM and trapped modes analysis, vacuum chamber

This year we added important elements to the MDI design discussion and new topics addressed:

Mechanical design and assembly concept, HOM absorber design, cryostat, water cooling system, remote vacuum connection, flanges, bellows, vacuum pump, vibration studies, orbit correction, fast luminosity monitor for machine tuning, BPMs

M. Sullivan



2018 updates on:
Lumical and shielding (W)

BEAM PIPE:

- **Be** in central region for LumiCal window, then **Cu**
- **15 mm** in the central region and up through QC1, 20 mm through QC2, 35 mm in the arcs
- **SR masks** at FF quads before/after QC2 and after QC1
- **warm** beam pipe, liquid cooled (similarly to SuperKEKB) to cope with SR and HOM heating

SR photon rates

	Energy (GeV)	Critical energy (keV)	number of bunches	Current (mA)	Incident γ/xing (500μm from tip)	Incoming on central pipe/xing	γ rate on central pipe (Hz)
tt+	**182.5**	113.4	33	5.41	3.32E+09	1195	1.18E+08
tt	**175**	100	40	6.4	3.06E+09	1040	1.25E+08
h	**125**	36.4	328	29	1.05E+09	10.3	1.01E+07
W	**80**	9.56	1300	147	6.11E+08	0.18	7.02E+05
Z	**45.6**	1.77	16640	1390	9.62E+07	1.92E-04	9.58E+03

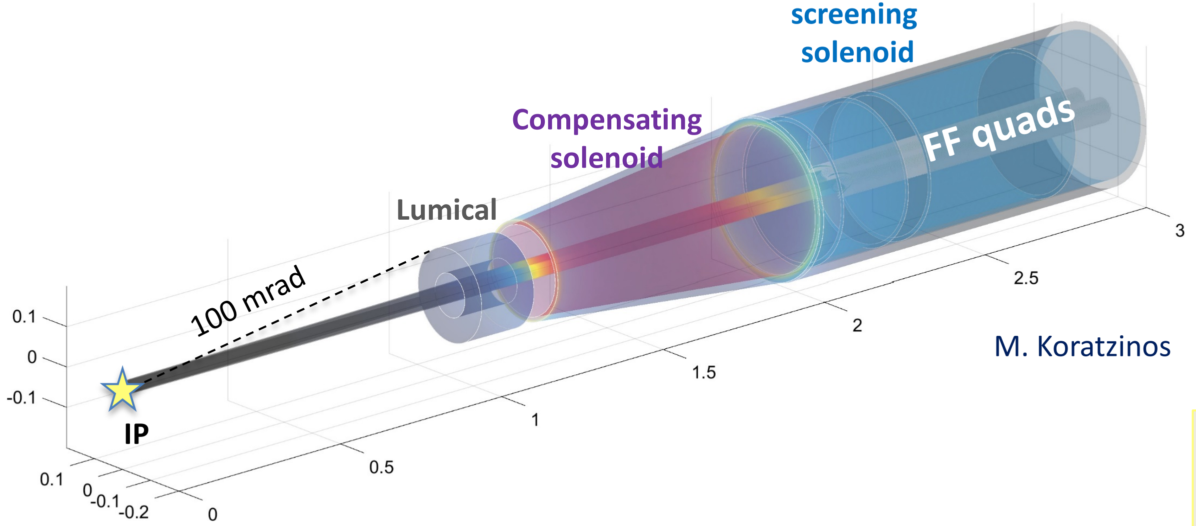
rate of photons that strike the central pipe that come from the mask tip

M. Sullivan

- No SR from dipoles or from quads hits directly the central beam pipe (cylinder +/- 12.5 cm in Z with a 1.5 cm radius)
- Non-Gaussian beam tails, considered out to +/-20 σ_x and +/-60σ_y
- On-axis beam
- Quadrupole radiation that may strike mask surfaces included
- G4 full simulation of interaction region (M. Lückhof, poster) and CLD detector shows low occupancy (with W shielding) (A. Kolano talk, for details)

Baseline for Solenoid Compensation Scheme

- **screening solenoid** that shields the detector field inside the quads (in the FF quad net solenoidal field=0)
- **compensating solenoid** in front of the first quad, as close as possible, to reduce the ε_y blow-up (integral BL~0)

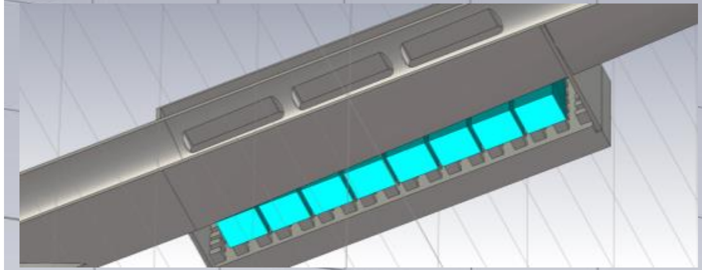


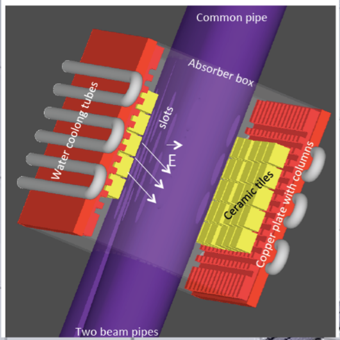
M. Koratzinos

0.34 pm is the overall ε_y blow-up for 2IPs @Z

detector solenoid dimensions 3.76m (inner radius) (outer radius 3.818m) × **4m** (half-length) (CLD)
drift chamber at z=2m with 150 mrad opening angle (IDEA design)

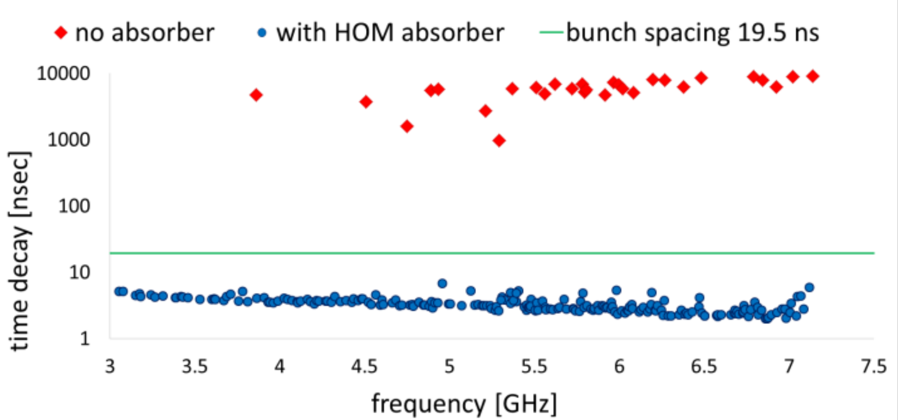
FCC ee IR beam pipe with water-cooled HOM absorbers





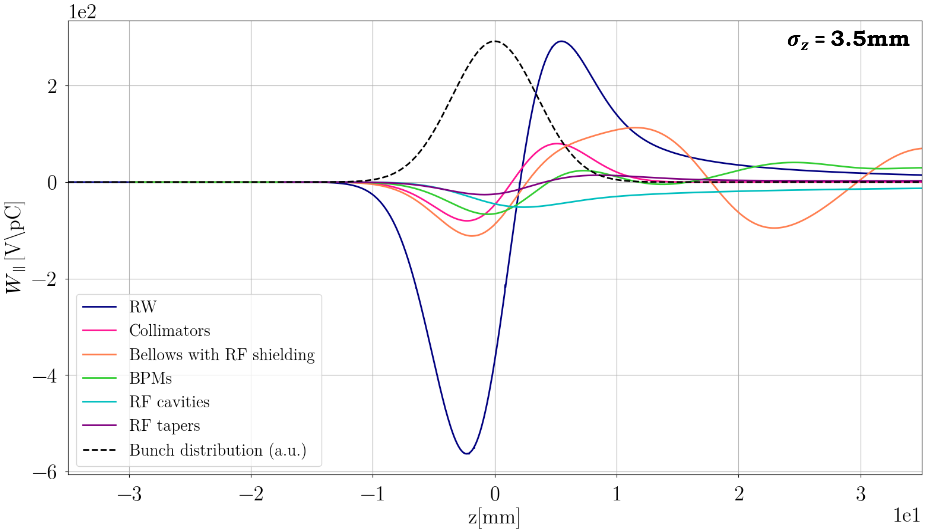
HOM absorber design for 10 kW power

Efficiency of Damping Trapped and Propagating Modes



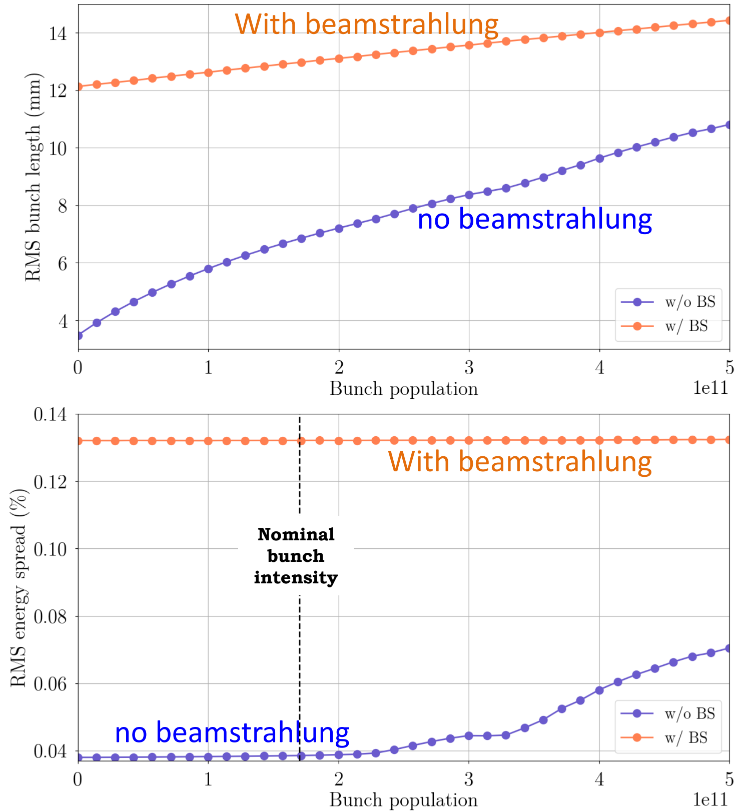
Longitudinal impedance model

More details in talk by E. Belli



Component	Number	k_{loss}[V/pC]	P_{loss}[MW]
Resistive Wall (100nm)	97.75 km	210	7.95
Collimators	20	18.69	0.7
RF cavities	52	17.14	0.65
RF double tapers	13	24.71	0.93
BPMs	4000	40.11	1.5
Bellows	8000	49.01	1.85
Total		**359.6**	**13.6** 3.7x smaller than 50 MW (SR)

Microwave instability

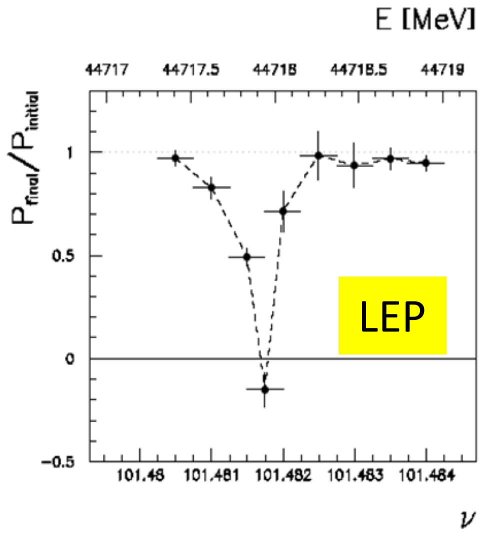


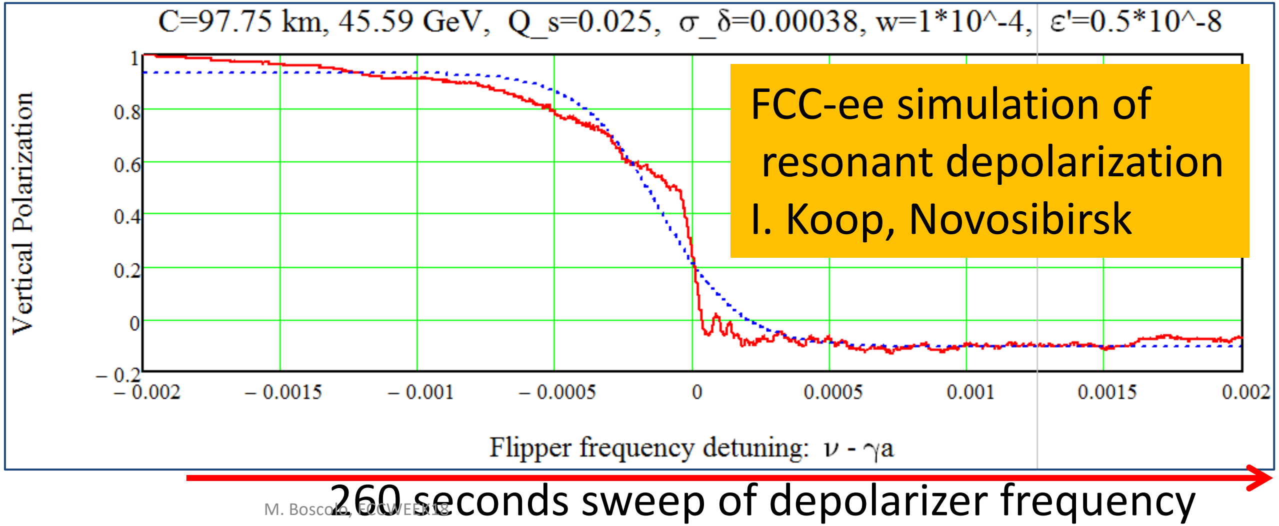
- MI threshold ≈ 1.5x larger than nominal bunch population
- Beamstrahlung allows to increase the threshold

FCC-ee Beam Polarization and Energy Calibration (I)

A. Blondel

1. **Priority from Physics** : ΔE/E ~O(10^{-6}) around Z pole and WW threshold **→Z,W mass&width**
2. Exploit natural transverse beam polarization present at Z and W (E.Gianfelice, S.Aumon)
   2.1 This is a unique capability of e+e- circular colliders
   2.2 Sufficient level is obtained if machine alignment is good enough for luminosity
   2.2 Resonant depolarization has intrinsic stat. precision of ~10^{-6} on spin tune (I.Koop)
   2.3 Required hardware (polarimeter, wigglers depolarizer) is defined & integrated (K.Oide)
   2.4 Running mode with 1% non-colliding bunches and wigglers defined (Koratzinos)





FCC-ee Beam Polarization and Energy Calibration (II)

3. **From spin tune measurement to center-of-mass determination** $\nu_s = \frac{g-2}{2}\frac{E_b}{m_e} = \frac{E_b}{0.4406486(1)}$

   3.1 Synchrotron Radiation energy loss (9 MeV @Z in 4 'arcs') calculable to < permil accuracy

   3.3. Beamstrahlung energy loss (0.62 MeV per beam at Z pole), compensated by RF (Shatilov)

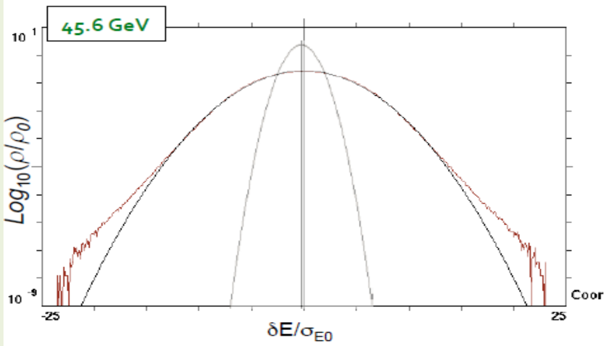
   3.4 layout of accelerator with IPs between two arcs well separated from RF

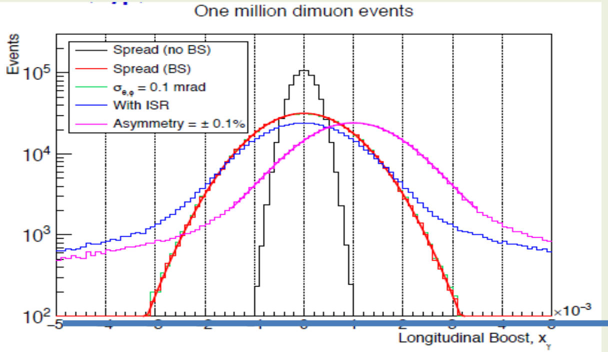
   ➔ $0.5\,(E_{CM}^A + E_{CM}^G) = (E_b^+ + E_b^-)\cos(\alpha_{crossing}/2)$

   3.5 E_b^+ vs E_b^- asymmetries and energy spread can be measured/monitored in expt:

   $e+e- \rightarrow \mu+ \mu-$ longitudinal momentum shift and spread (Janot)

D. Shatilov: beam energy spectrum without/with beamstrahlung





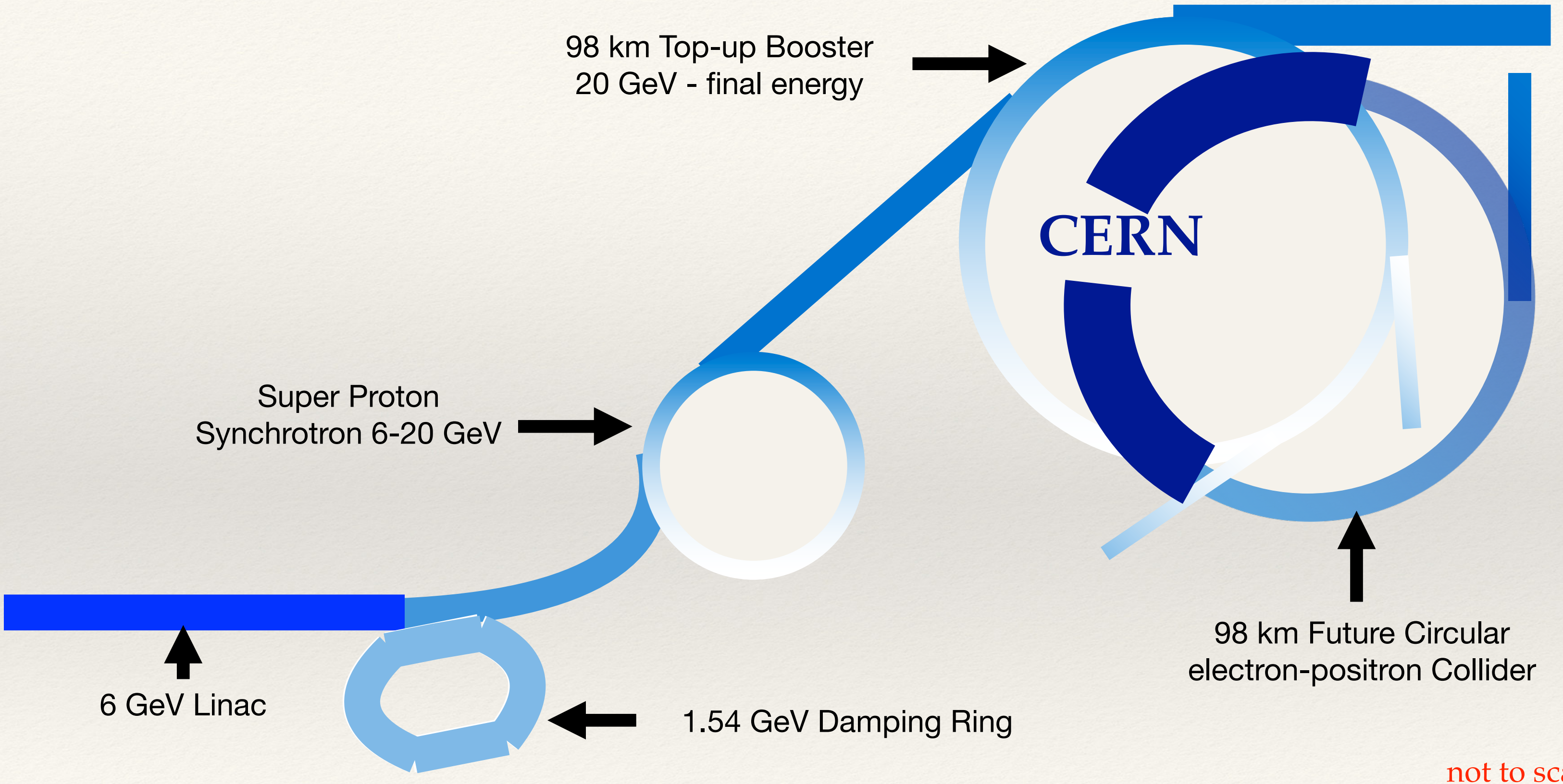
P. Janot: 2 min @Z = 10^6 μ+ μ- /expt.
→ 50 keV meast!

z boost

4. work in progress: errors from betatron motion in non-planar orbits, transverse impedance, RF asymmetries, optimum depolarizer set-up vs Q_s at W, opp. sign vertical dispersion.

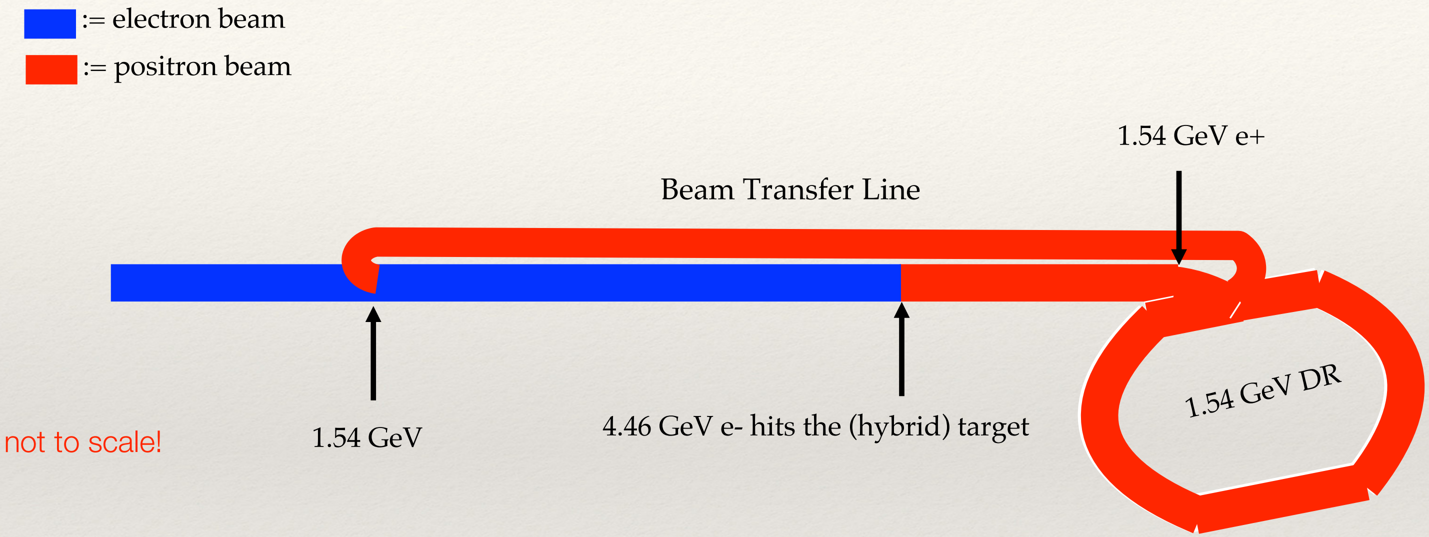
➔ On track to match goal of 100 (300) keV errors on E_{CM} at Z (WW) energies.

FCC-ee Layout



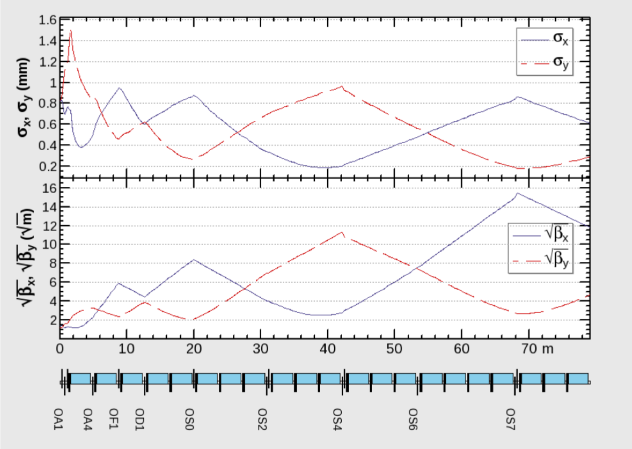
not to scale!

Positron Flow Scheme

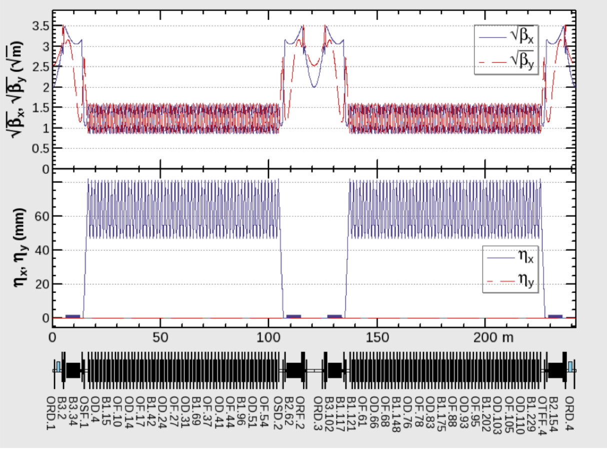


❖ The **1.54 GeV damping ring** will be **at the end of the Linac** and **electrons** will be transferred from a branching point in the linac at 1.54 GeV (its drawing is omitted in the layout scheme). We may tilt the DR just by a small angle in order not to bend e+ beam noticeably. In this way, the BTL can share the same tunnel as the main linac.

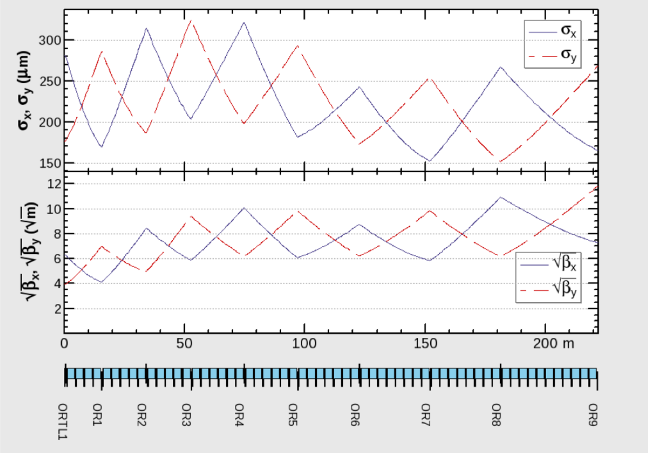
Linac up to 1.54 GeV



Damping Ring at 1.54 GeV



Linac 1.54-6 GeV



- ❖ The **S- band linac** has a branching point at **1.54 GeV** for emittance cooling of electron beam in the Damping Ring. After emittance cooling they will be transferred back to the linac to reach **6 GeV**.

- ❖The **positrons** will be **created** in the linac by impinging on a hybrid target **at 4.46 GeV**, and the created e+ **will be accelerated up to 1.54 GeV** in the remaining part of the linac. **then** they will be **injected into the DR**. After emittance cooling in the DR, they will be **transferred back to the linac to reach 6 GeV**.

- ❖ Linac will have **200 Hz** repetition with **2 Bunches per RF pulse**. The bunch charge is **2E10** particles, but throughout e+ creation, 200 Hz with 4 Bunches per RF pulse, or simply another linac for e+ creation is needed. **Linac** is in total **301 meters** with **25 MV/m** gradient in the **2856 MHz** cavities. The **DR** is **241 m** and can host 5 trains, each train with 2 bunches. The DR has **2 superconducting 400 MHz** cavities (1.5 meter each) with **4 MV**.

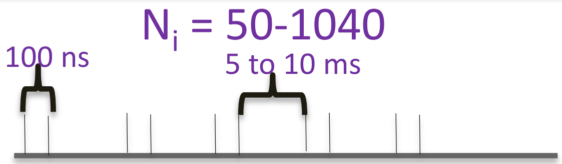
SLC/SUPERKEKB-like linac (higher gradient)

FCC-ee injector **baseline** scheme

more details in talk by Y. Papaphilippou

LINAC

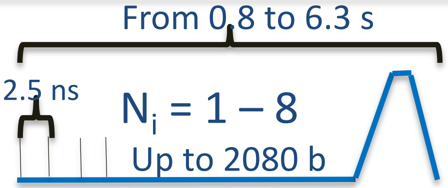
- Longer pulses with **1 or 2** bunches with rep. rate **100-200 Hz**, **2.8 GHz** RF
- Maximum linac bunch intensity ~ **2.1 x 10^{10} particles** (both species).
- Twice as much needed for e+ production, i.e. **4 x 10^{10} particles/bunch**



2.8 GHz LINAC @ 100-200 Hz, 6 GeV

PREBOOSTER

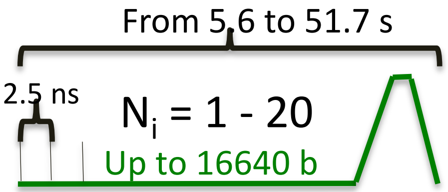
- Injected several times (from **50 to 1040**), @ **6 GeV** into of PBR (SPS or new ring) with 1 Linac bunch to 1 ring bucket (**400 MHz** RF system), up to **2080** bunches
- PBR ramp to **20 GeV** with **0.2 s** ramp rate and cycle length **below 6.3 s**



PBR from 6 to 20 GeV

BOOSTER

- Transferred to main Booster (**1 - 8** PBR cycles), with **400 MHz** RF frequency, to a bunch structure required by the collider (from **50** to **16640** bunches)
- Accelerated to corresponding energy with ramp time of **0.32 - 2 s**, and total cycle length up to **51.7 s**



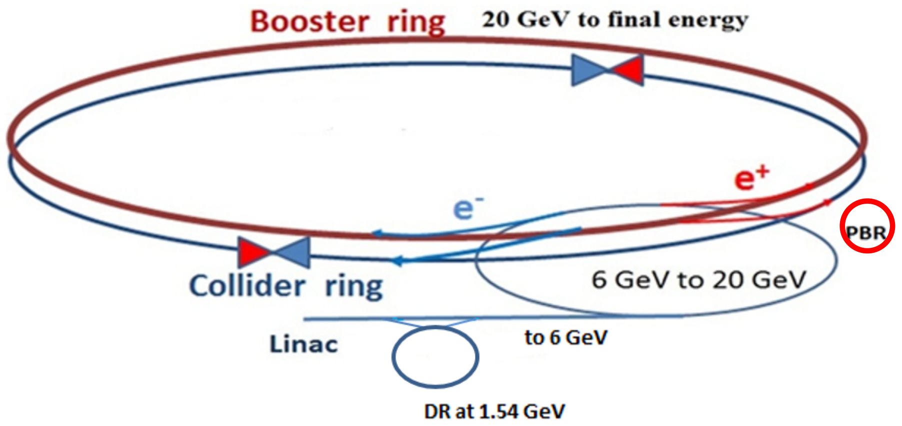
BR from 20 to 45.6-182.5 GeV

MAIN RINGS

- Transferred to the collider by accumulating current for the full filling or single injection for top-up
- **Interleaved** filling of e+/e- and continuous top-up (able to accommodate **bootstrapping**)
- Full filling below **20 min** for both species, but also able to accommodate bootstrapping
- Top-up target time, based on **5 %** of current drop due to corresponding lifetime, always achieved
- **80 %** transfer efficiency

FCC e^+e^- Pre-Booster Ring(s) Design

Two different options are under consideration as pre-accelerator before the bunches are transferred to the high-energy booster: using the existing SPS and a completely new ring.



SPS

$C = \sim 6.9\ km$

μ_x is moved to $3\pi/4$.

Wiggler magnets are proposed to reduce ε_x and τ.

O. Etisken
Y. Papaphilippou
F. Antoniou
A.K.Ciftci

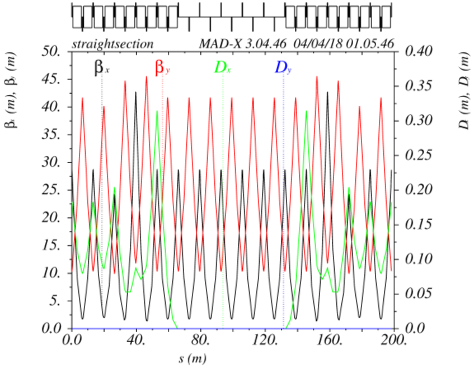
Alternative design

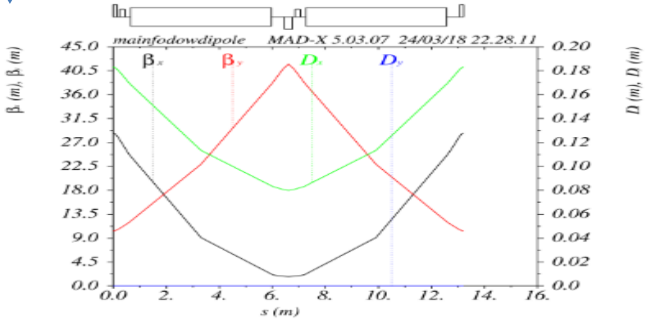
$C = \sim 2.3\ km$

$\varepsilon_x = 5\ nm.rad$ at 20 GeV

$\frac{\Delta E}{E} = \sim \pm 1.5\%\ at\ 6\ GeV$

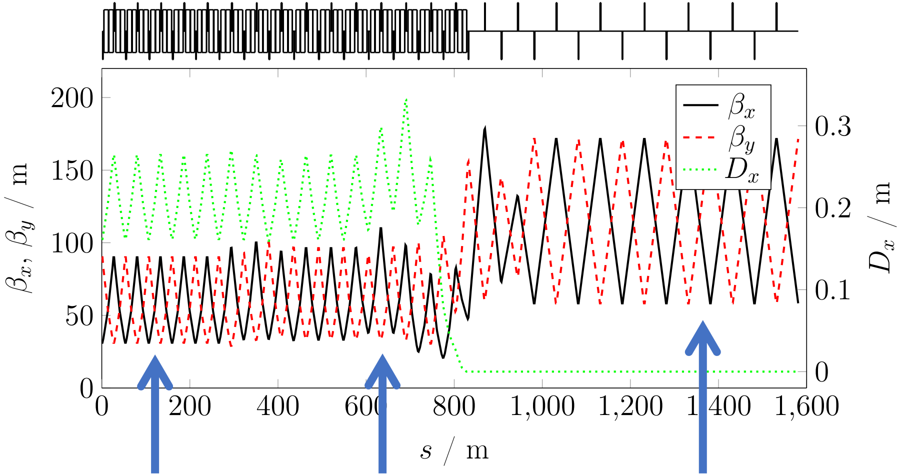
$\tau = 0.1\ s\ at\ 6\ GeV$





more details in talk by B. Harer

Booster synchrotron



Long arcs
L_{cell} = 54 m

Dispersion suppressor of hadron collider
L_{cell} = 56.6 m

Straight section with RF installation
L_{cell} = 100 m

Both 60°/60° and 90°/90° optics provided

Booster parameters:

E **/ GeV**	**45.5**	**80**	**120**	**182.5**
n_b	16640	2000	393	50
n_p /10^{10}	2.13	1.44	1.13	2.0
n_{cycles}	10	10	10	20
t_{cycle} / s	51.74	13.3	7.53	5.6
t_{fill} / s	1034.8	288	150.6	244

Maximum filling time of the collider (both species):
$t_{fill} \simeq$ 17 min

Not compatible with damping time @ 20 GeV: τ_x = 10.05 s

Strong intra-beam-scattering because equilibrium emittance ε_x = 12 pm rad

→ **Installation of 16 9-m long wiggler magnets**

- **Decrease damping time to τ_x = 0.1 s**
- **Increase emittance ε_x = 180 pm rad**

Top-up injection

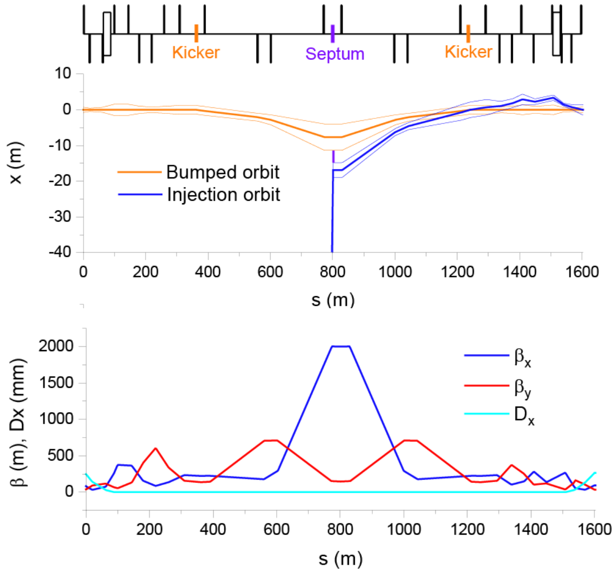
more details in talk by M. Aiba

- Top-up injection, which keeps the beam current constant, is essential for FCC-ee collider rings
  - To maximise luminosity production efficiency despite the short beam lifetime, about 20 minutes when beamstrahlung is taken into account during collision
  - To stabilize the machine under the heat load of 100 MW synchrotron radiation
- Conceptual study has shown positive result:

  top-up injection is feasible with no strong technical challenge*

* "Top-up injection schemes for future circular lepton collider", M. Aiba et al., NIM-A, 880, pp.98-106 (2018)

Layout, orbits and optics for Conventional injection scheme



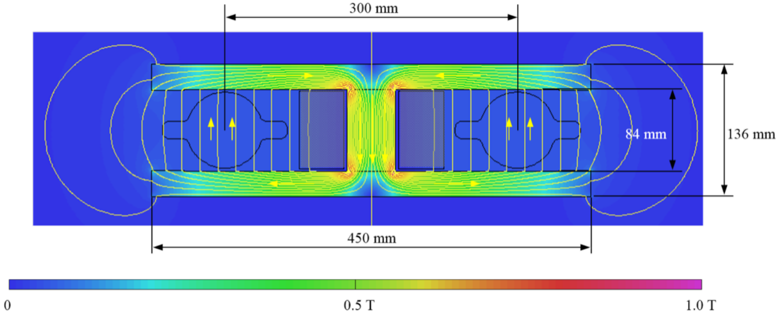
FCC-ee dual aperture main magnets

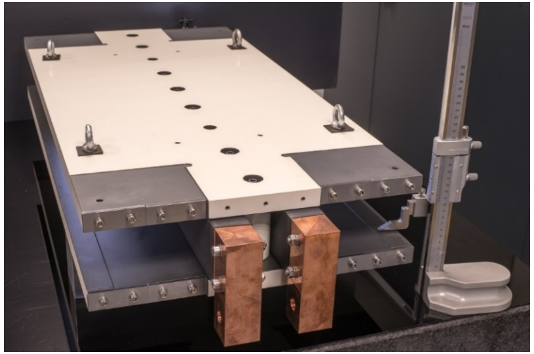
low power low cost design factor 2 power saving by dual aperture, combined yokes

magnetic models

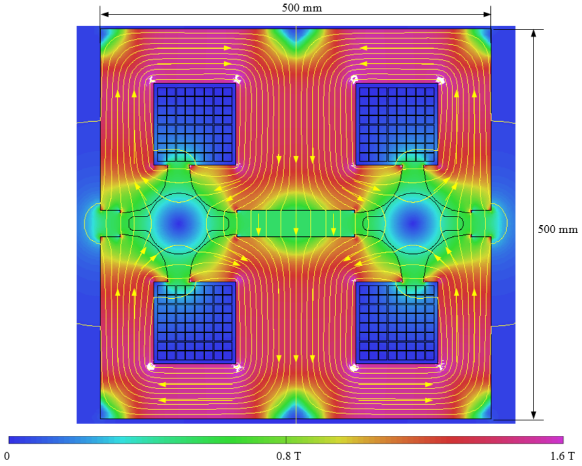
prototypes

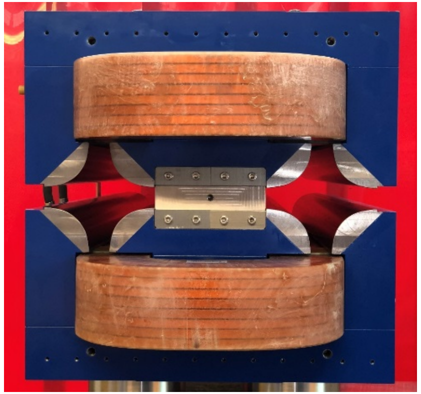
dipole





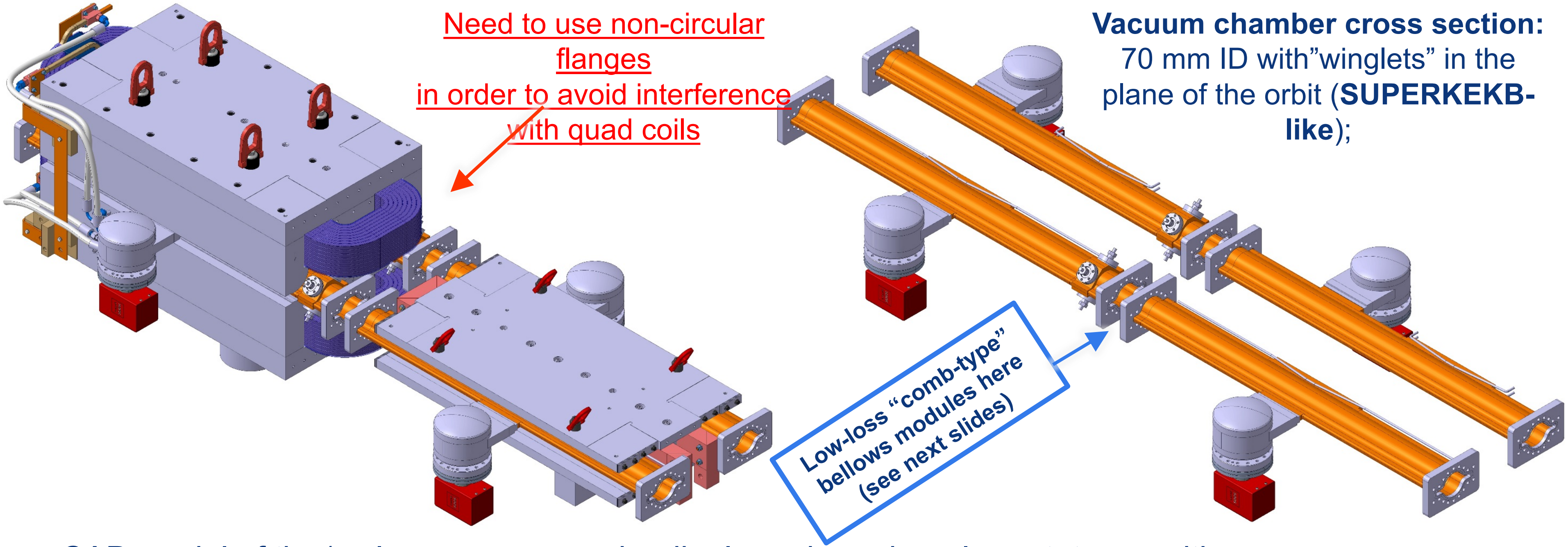
quadrupole





A. Milanese, FCC Week 2017

Vacuum chamber geometry

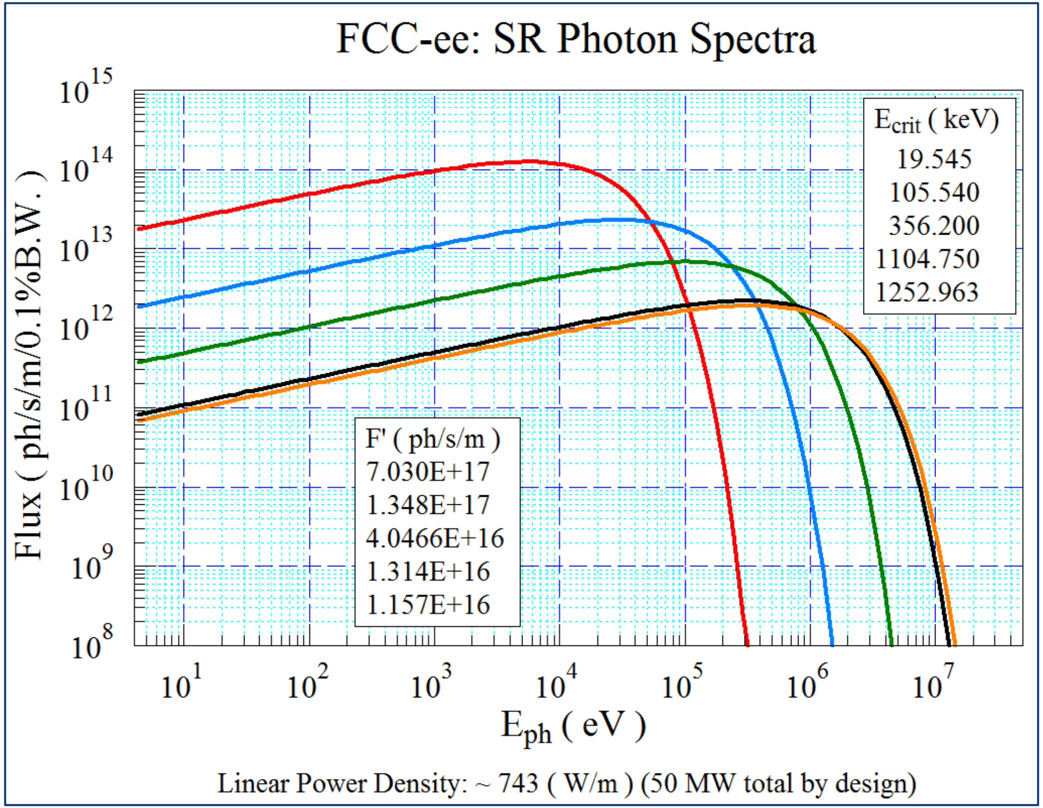


Vacuum chamber cross section: 70 mm ID with"winglets" in the plane of the orbit (**SUPERKEKB-like**);

- CAD model of the1m-long common-yoke dipole and quadrupole prototypes with arc vacuum chambers (courtesy of **M. Gil Costa, CERN/CIEMAT**) ;
- The chambers feature **lumped SR absorbers** with **NEG-pumps** placed next to them;

SR spectra and outgassing loads

- **Z-Pole: very high photon flux (→ large outgassing load);**
- **Z-pole: compliance with scheduled operation (integrated luminosity first 2 years), requires quick commissioning to I_{NOM}=1.390 A;**
- **t-pole (182.5): extremely large and penetrating radiation, critical energy 1.25 MeV;**
- **t-pole (and also W and H): needs design which minimizes activation of tunnel and machine components;**
- **W, H-pole: intermediate between Z and T; still E_{crit} > Compton edge (~100 keV)**



FCC-ee RF staging scenario

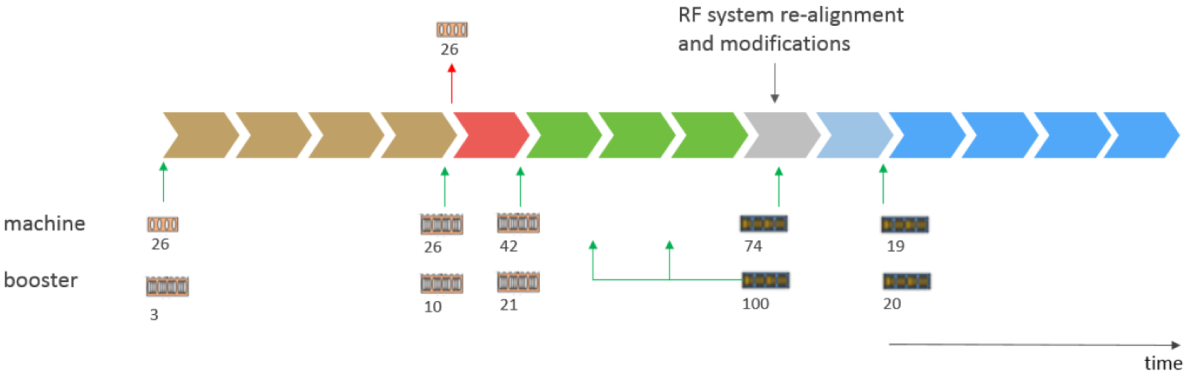
E_{beam} (GeV)	V_{tot} (GV)	n_{bunch}	I_{beam} (mA)
45.6	0.1	16640	1390
80	0.75	2000	147
120	2.0	328	328
182.5	4.0	48	48

three sets of RF cavities to cover all options for FCC-ee & booster:

- **installation sequence comparable to LEP (≈ 30 CM/shutdown)**
- **high intensity (Z, FCC-hh): 400 MHz mono-cell cav, ~1 MW source**
- **higher energy (W, H, t): 400 MHz four-cell cavities (4/cryomodule)**
- **ttbar machine complement: 800 MHz five-cell cavities (4/cryom.)**

RF system needs to compensate for 100 MW SR losses → 200 MW with 50% klystrons efficiency (Klystron efficiency was ~55% at LEP2)

Recent (2015) breakthroughs in klystron design promise 90% efficiency
Assume 85% will be achieved and take 10 – 20% margins



Conclusions

- FCC-ee collider is an extremely challenging but feasible with unprecedented physics potential
- **Great progress has been made in the FCC-ee collider design**
- **CDR summary volume progressing as scheduled**
- The wide energy range is challenging
  - Large SR energy loss
  - New instabilities from beam-beam interaction and Beamstrahlung
  - Asymmetric IR optics to control SR in the IR (at all energies)
  - Strong sawtooth effect (mostly at ttbar), tapering of magnet strength
  - Asymmetric energy acceptance at tt (BS effect)
  - Bootstrapping injection
  - Proper parameters choice for stable beams at collisions (β_x*, α_c, cell phase advance, tunes,..)
  - 10% polarization (E_b measurement) in 2-3 h

Converting DAΦNE to Test Facility ?

DAΦNE will **shut down** as a **collider** at the **end** of **2019**

proposal:

exploiting DAΦNE as an

European/International high-current beam facility

some ideas:

- impedance, HOM effects for accelerator components
- SR effects on vacuum, SEY measurements
- positron source studies
- multi-cell SC cavities for high current CW operation, provided compatibility rf frequency