Experimental Beam Tests for FCC-ee

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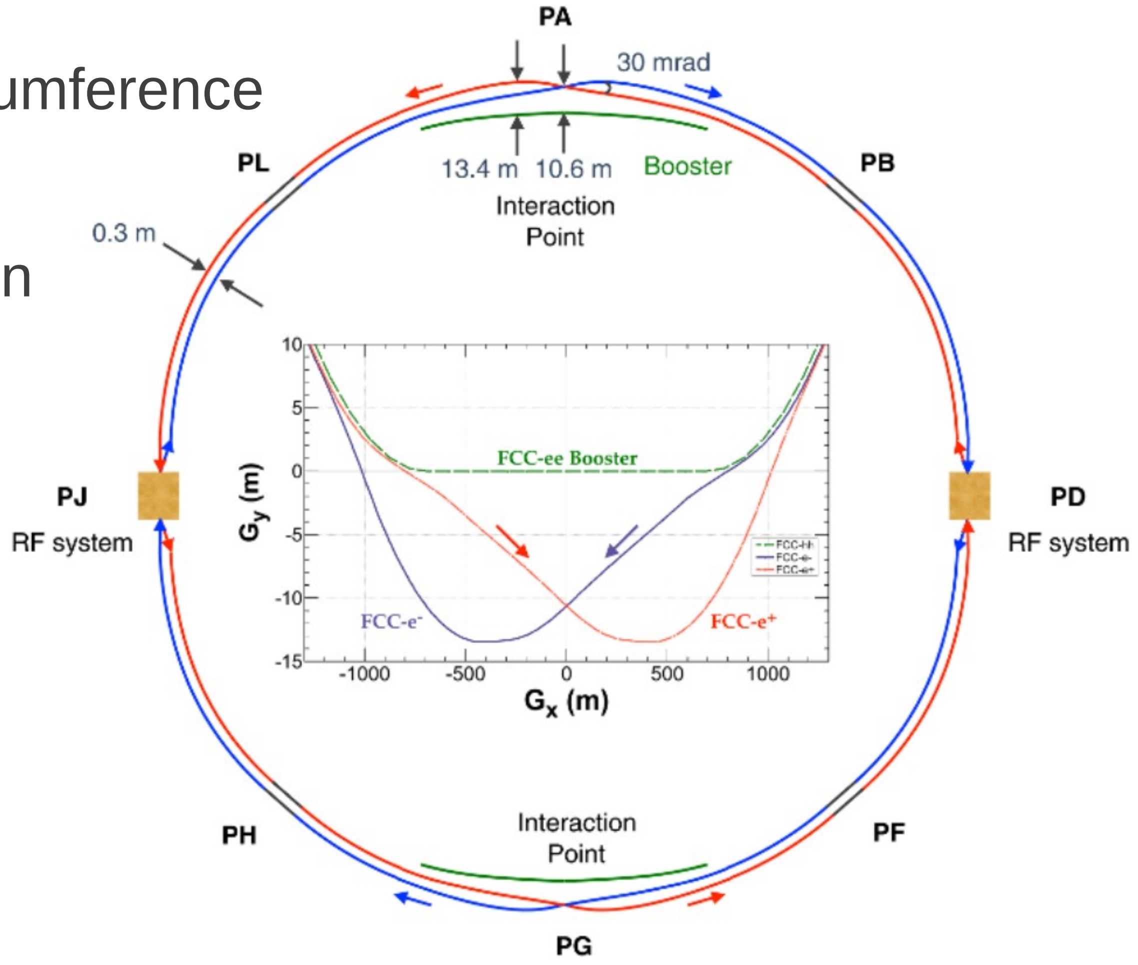
On behalf of
The FCC-ee collaboration

EPS-HEP Conference 2021
European Physical Society conference on high energy physics 2021
28th - 30th July 2021

FCCIS – The Future Circular Collider Innovation Study. This INFRADEV Research and Innovation Action project receives funding from the European Union's H2020 Framework Programme under grant agreement no. 951754.

Introduction FCC-ee

- Electron-positron collider with about 100 km circumference
- Higgs and electro-weak factory
- Rapid cycling booster required for top-up injection
- 4 different c.o.m. energies
- Conceptual Design Report (CDR) in 2019
  - Foresees 2 interaction points (IPs)
  - Alternative designs with 4 IPs
- First stage of the FCC integrated project



M. Benedikt et al. (ed), FCC CDR, Eur. Phys. J. Spec. Top. 228, p. 261-623, 2019.

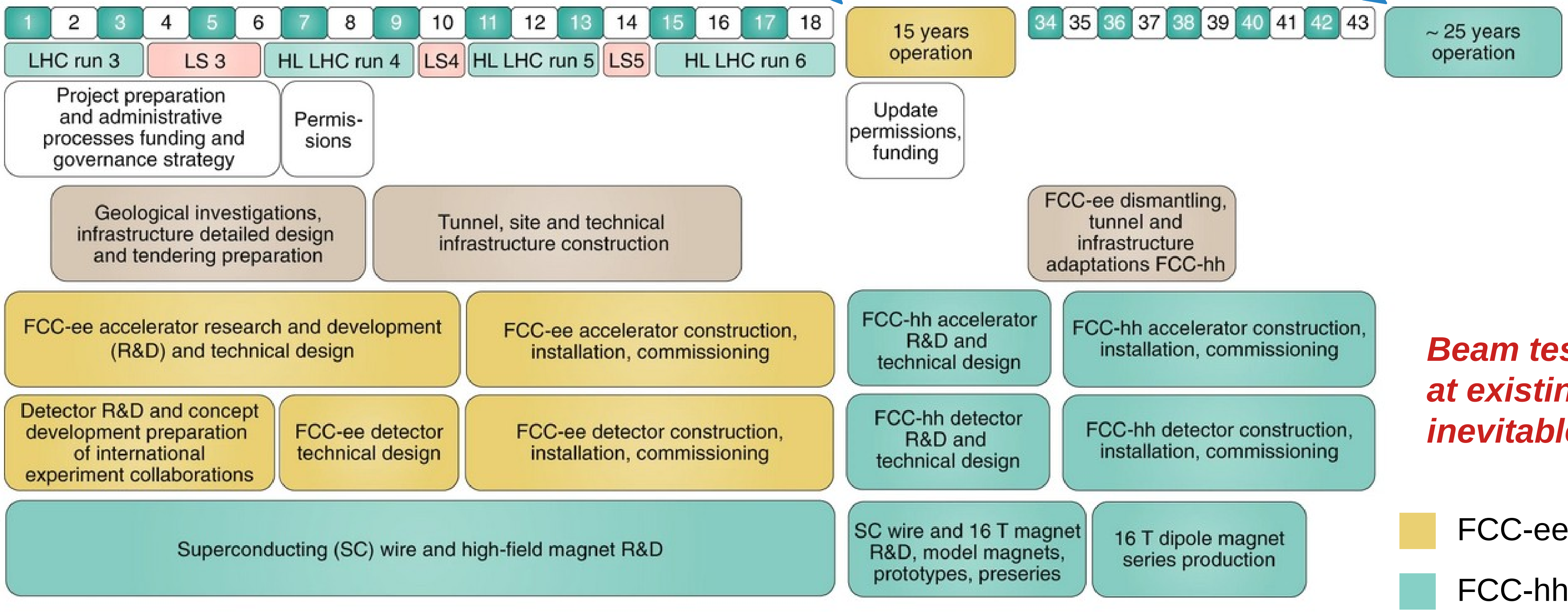
FCC Integrated Project

- Lepton collider (FCC-ee) followed by hadron collider (FCC-hh)

FCC-ee commissioning around 2040

FCC-hh commissioning around 2065

Starts at 2021



Beam tests for FCC-ee at existing facilities inevitable

FCC-ee

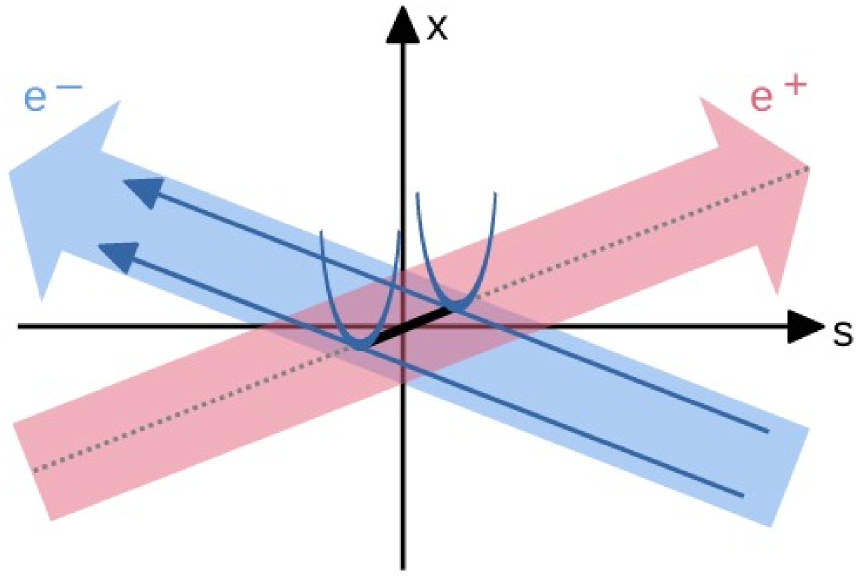
FCC-hh

M. Benedikt et al., Nature Physics 16, 402-407, 2020.

FCC-ee Key Concepts

- 4 different stages
- Innovative positron source
- Top-up injection
- Advanced optics concepts (crab-waist, correction, ...)
- Polarized beams and energy calibration
- State of the art beam-diagnostics

Parameter	Z	WW	ZH	ttbar
Beam energy [GeV]	45	80	120	182.5
Beam current [mA]	1390	147	29	5.4
Bunches per Beam	16640	2000	393	48
Bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss per turn [GeV]	0.036	0.34	1.72	9.21
Long. damping times [turns]	1281	235	70	20
βx*/βy* [cm]	15/0.08	20/0.1	30/0.1	100/0.16
εy* [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
Luminostiy per IP [10^{34} cm^{-2}s^{-1}]	230	28	8.5	1.55

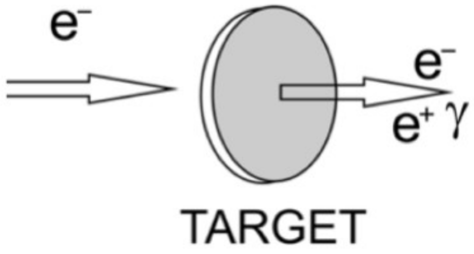


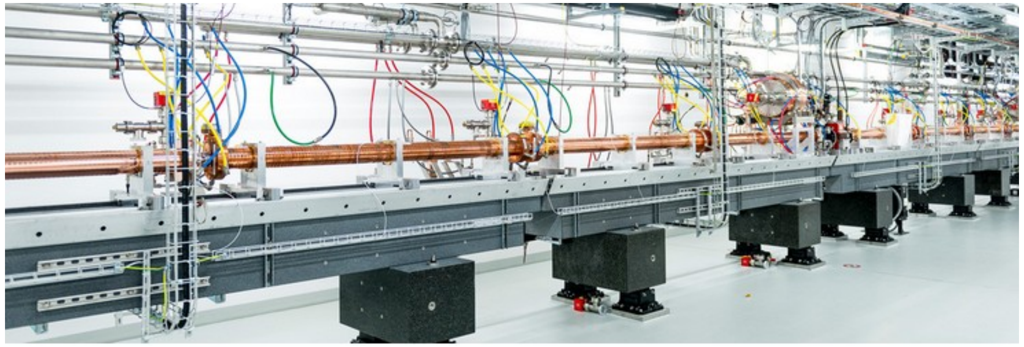
M. Benedikt et al. (ed), FCC CDR, Eur. Phys. J. Spec. Top. 228, p. 261-623, 2019.

Courtesy: I. Chaikovska

Positron Source

Conventional target

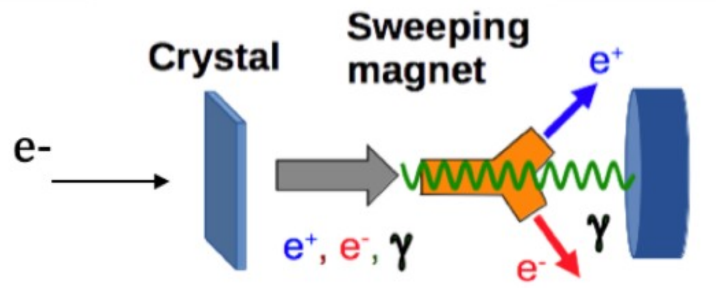




PAUL SCHERRER INSTITUT
PSI

- High atomic number and melting point
- High heat load and peak energy deposition density

Hybrid target



- Can be optimized to reduce peak energy deposition density

SwissFEL at PSI

- X-ray free electron laser
- Study various conventional and hybrid schemes for positron production in FCC-ee
- Study feasibility of using solenoid to capture positrons

I. Chaikovska, FCC-ee positron source, FCC-ee week 2021.

Possibility to study hybrid scheme at MAMI and KEK

Courtesy: E. Gianfelice, N. Muchnoi, S. Nikitin

Spin Polarization

- Spin polarization is built up in lepton beams over time (neglecting depolarization)
- Theoretical maximal polarization limited
- Assuming inhomogeneous magnetic field, e.g. in a synchrotron

Spin polarization build-up time

$$\tau_{st}^{-1} = \frac{5\sqrt{3}}{8}\frac{\hbar r_e \gamma^5}{m_e C}\oint \frac{ds}{|\rho(s)|^3}$$

Maximum theoretical polarization

$$P_{st} = -\frac{8}{5\sqrt{3}}\frac{\oint \frac{ds}{\rho^3(s)}}{\oint \frac{ds}{|\rho(s)|^3}}$$

ρ … bending radius
γ … relativistic gamma factor
C … circumference
$\hbar$ … Planck constant
r_e … classical electron radius
m_e … electron rest mass

- Spin depolarization caused by magnetic misalignments
- Resonant depolarization used for energy calibration

E. Gianfelice, The polarization code challenge, FCC November Week 2020.
N. Muchnoi, FCC-ee polarimeter, arXiv:1803.09595, 2021.
S. Nikitin, Possible beam studies at VEPP-4M, FCC November Week 2020.
FCC-ee polarization workshop, 18-27 October 2017.

Courtesy: E. Gianfelice, N. Muchnoi, S. Nikitin

Energy Calibration

- Spin precession frequency Ω given by energy

  ω_0 … revolution frequency
  μ'/μ_0 … magnetic moment anomaly

$$\Omega = \omega_0 \left(1 + \frac{E}{m_e} \frac{\mu'}{\mu_0} \right)$$

- Measuring Ω yields beam energy

- Resonant depolarization by TEM wave with ω_d
- Resonant condition given by $\Omega = n\omega_0 \pm \omega_d$
- Measured energy calibration of 10^{-6} at VEPP-4M
- Corresponds to about 100 keV for FCC-ee

E. Gianfelice, The polarization code challenge, FCC November Week 2020.
N. Muchnoi, FCC-ee polarimeter, arXiv:1803.09595, 2021.
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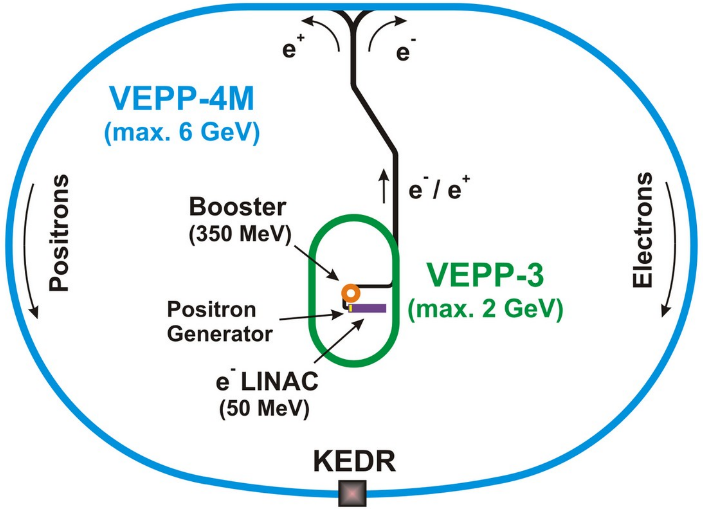


VEPP-4M at BINP

- Electron-positron collider (5+5GeV)
- Understand spin dynamics
- Acquire energy calibration knowledge for FCC-ee

Courtesy: C. Milardi, M. Zobov

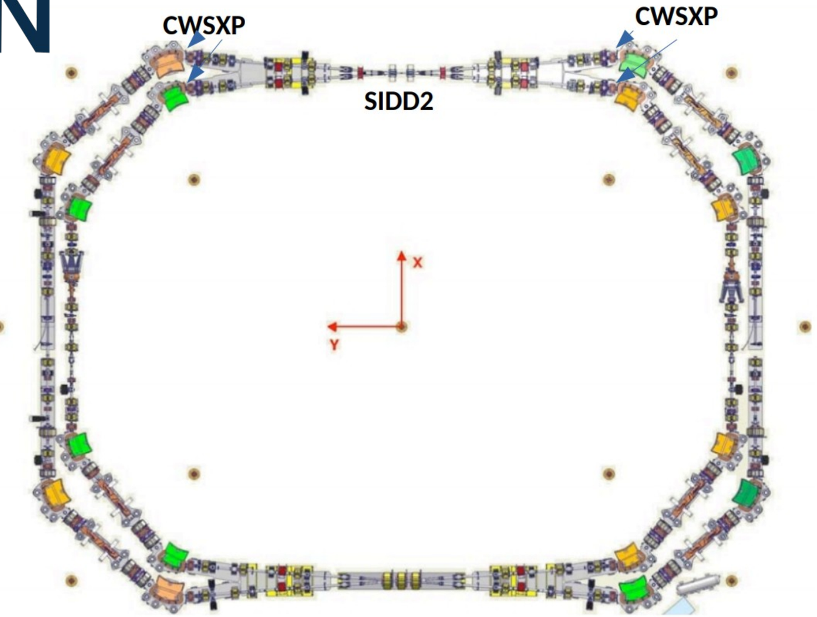
High Currents and Crab-Waist

- Operation with high beam currents 2.45 A (electrons) and 1.4 A (positrons) with 510 MeV
- Very flexible lattice, e.g. operation with negative momentum compaction factor
- First collider using crab-waist collision scheme

DAFNE at INFN

- Electron-positron collider
- Test sensitivity of misalignments on crab-waist
- Operation and hands-on experience with crab-waist optics and optics corrections
- Study effects of high beam currents
- Flexible lattice allows testing various optics

Sextupoles for crab-waist collision scheme



No periodicity, DAFNE is only once cell

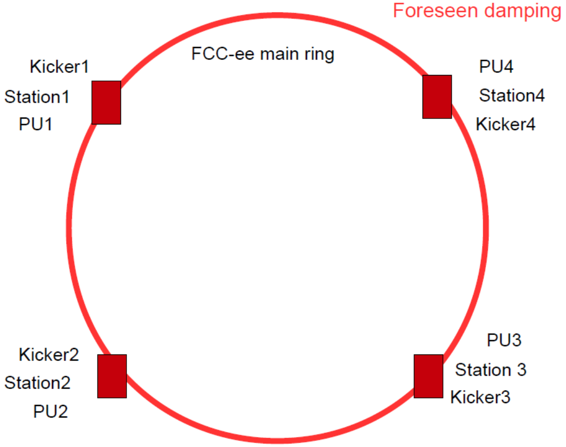
M. Zobov et al., Phys. Rev. Letters 104, p. 174801, 2010.
M. Zobov et al., DAFNE experience with negative momentum compaction, EPAC06, 2006.

Feedback System

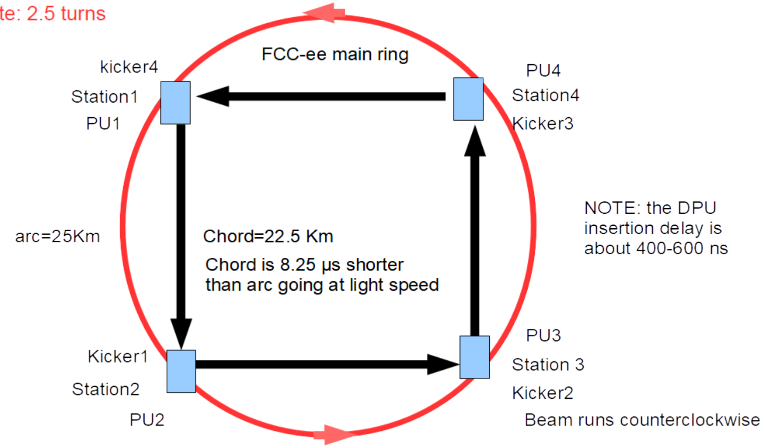
- Dynamic beam simulations show extremely fast coupled bunch instability (few turns) for FCC-ee and booster
- Powerful feedback system required

Since 2008 a new double feedback technique is implemented successfully in DAFNE

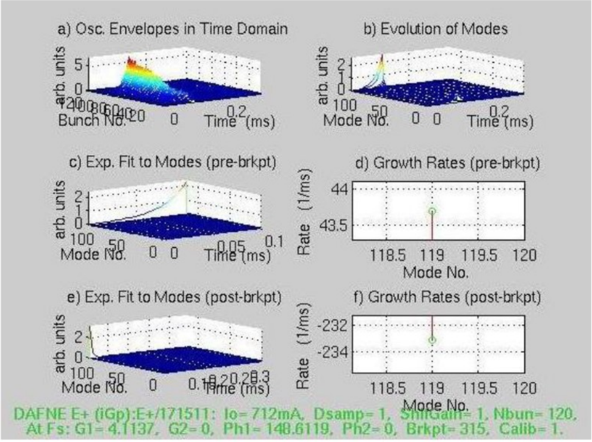
Foreseen damping rate: 2.5 turns



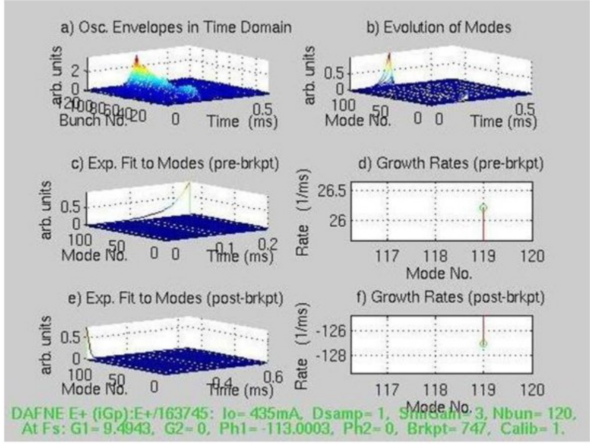
Instabilities with growth rate up to 3 turns → 4 stations



Instabilities with growth rates up to 1-2 turns → 4 stations anticipating correction kicks



Single feedback dumping rate 128 ms^{-1}



Double feedback dumping rate 234 ms^{-1}

DAFNE at INFN

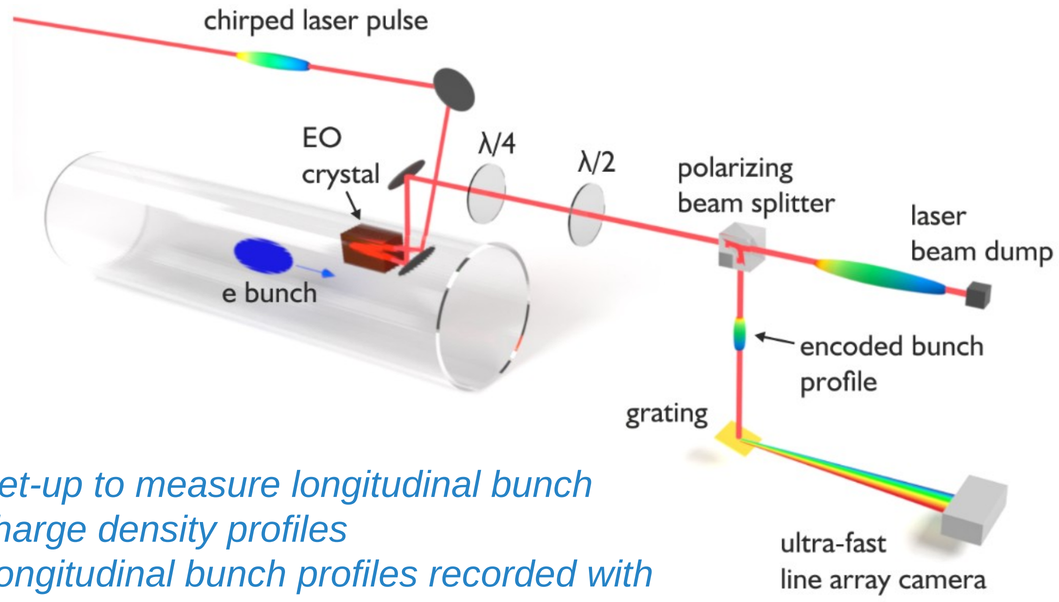
- Test possible feedback system for FCC-ee at DAFNE
- Measure damping performance with different beam and layout conditions

A. Drago, Feedback systems for FCC-ee, eeFACT2016, TUT3AH9, 2016.

Courtesy: A.-S. Müller, G. Niehues

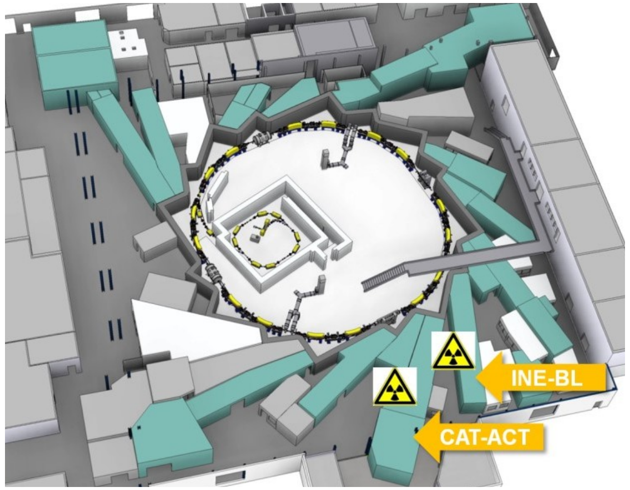
Beam Instrumentation

- Test FCC-ee beam instrumentation at research accelerator
- Flexible energy, bunch length and optics
- Longitudinal bunch length successfully measured



Set-up to measure longitudinal bunch charge density profiles
Longitudinal bunch profiles recorded with electro-optical spectral decoding set-up

Karlsruher Institut für Technologie



KARA at KIT

- Electron storage ring with flexible lattice
- Test various technological and beam instrumentation challenges
- R&D for FCC-ee

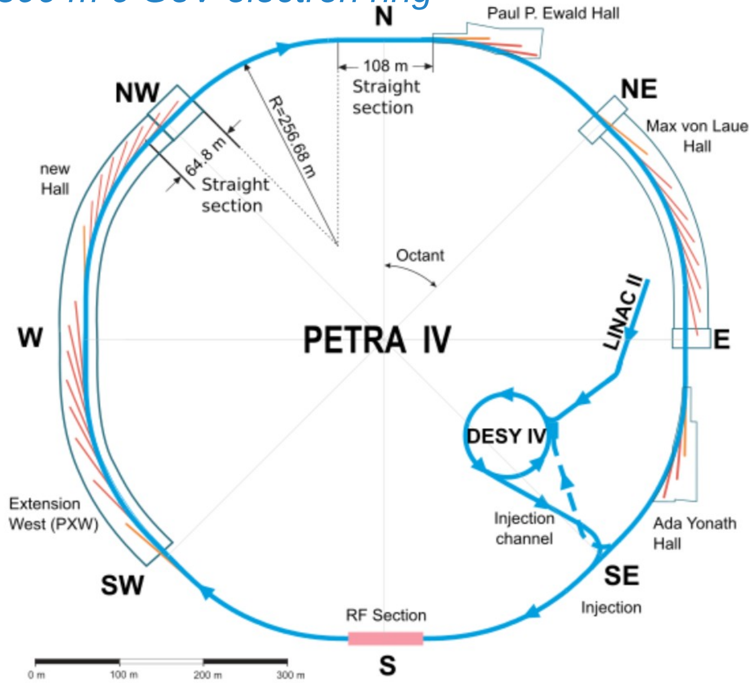
A.-S. Müller and G. Niehues, Developing and testing beam diagnostics, beam tests and girders, FCC Week 2021.

Courtesy: *I. Agapov, T. Charles*

Optics Tuning

- FCC-ee and PETRA III (IV) have comparable vertical emittance of < 10 (3) pm
- Tight alignment tolerances for FCC-ee and light sources like PETRA III / PETRA IV

2300 m 6 GeV electron ring



PETRA IV tolerances

- **Magnet errors**
  - Dipole offset = 50 µm
  - Other magnets offset = 30 µm
  - Girder offset = 50 µm
  - Girder roll = 200 µrad
  - Magnet roll = 200 µrad
  - Magnet calibration = 1E-3

Current FCC-ee tolerances

Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔTHETA (μrad)	ΔPHI (μrad)
Arc quadrupole*	50	50	200	100	100
Arc sextupoles*	50	50	200	100	100
Dipoles	1000	1000	300	-	-
Girders	150	150	-	-	-
IR quadrupole	100	100	250	100	100
IR sextupoles	100	100	250	100	100
BPM**	40	40	100	-	-

* misalignments relative to girder placement
** misalignments relative to quadruple placement

PETRA at DESY

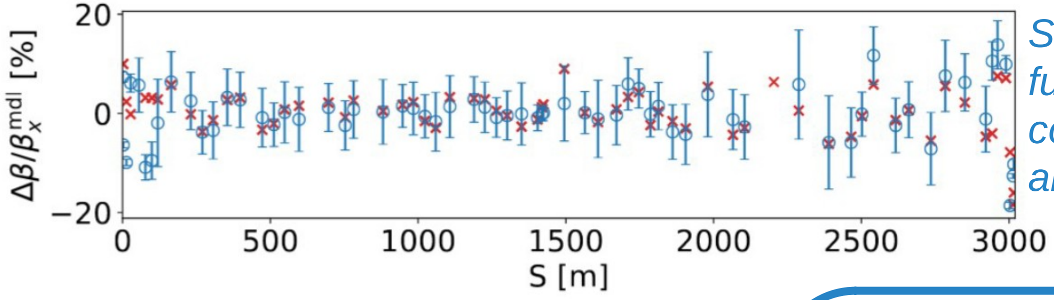
- Help defining alignment tolerances for FCC-ee
- Understand emittance growth from misalignments

I. Agapov, Possible beam studies at PETRA III, FCC November Week 2020.
T. Charles, Status and plans for optics corrections and emittance performance, FCC Week 2021.

Courtesy: A. Wegscheider

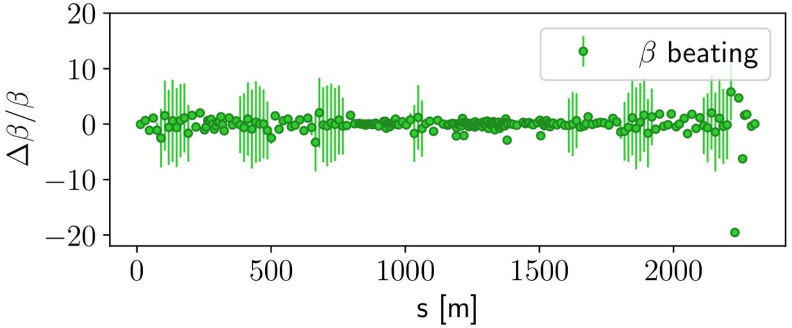
Turn-by-Turn Measurements

- Turn-by-Turn measurements performed at PETRA III and SuperKEKB
- Performed with Optics Measurements and Corrections code used routinely for LHC



SuperKEKB horizontal β-function for electron ring and comparision of Turn-by-Turn and Closed Orbit Distortion

PETRA III β-function



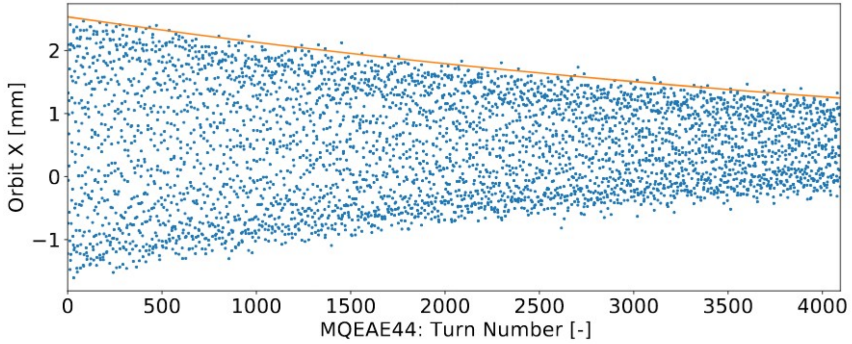
J. Keintzel, IPAC 2021, TUPAB009, 2021.

PETRA at DESY

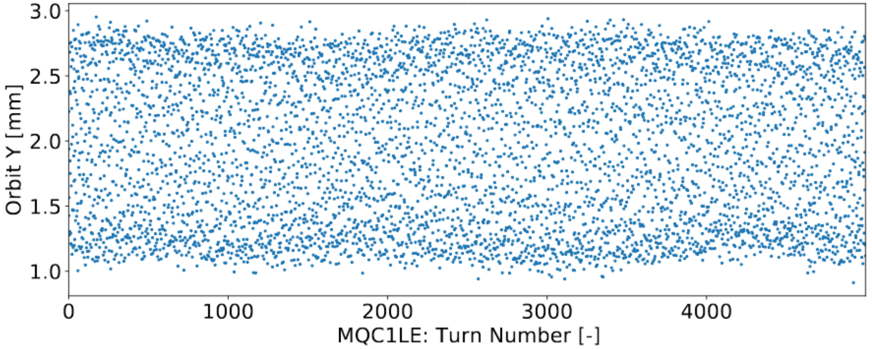
SuperKEKB at KEK

- Optics measurements
- Test codes
- Test correction strategies

SuperKEKB electron ring single kick



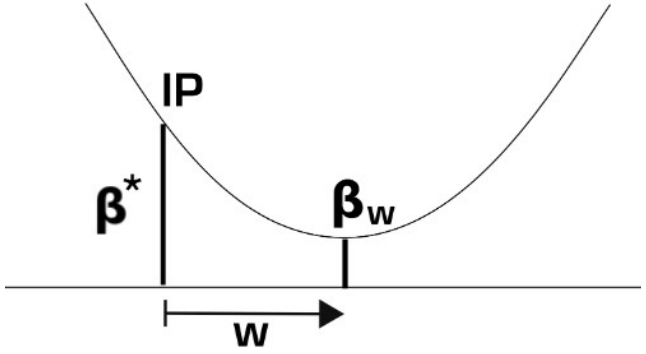
SuperKEKB electron ring driven motion



Courtesy: P. Thrane

K-Modulation

Minimum β-function not always at IP but shifted by waist w



- Successfully performed in SuperKEKB including fringe fields
- Used to determine β* by varying quadrupole strength
- β-function at quadrupoles estimated by tune change

ΔKL … relative change of integrated quadrupole strength
ΔQ … relative change of tune

$$\bar{\beta} \approx \pm \frac{4\pi \Delta Q}{\Delta KL}$$

- β_w propagated from β_0 at the final focus quadrupoles and β* given by

$$\beta^* = \beta_w + \frac{w^2}{\beta_w}$$

L … distance from IP to first quadrupole*

$$\beta_0 = \beta_w + \frac{(L^* \pm w)^2}{\beta_w}$$

- Proposed βy* = 0.09 mm, 3 times smaller than design
- Can help to increase luminosity

SuperKEKB at KEK

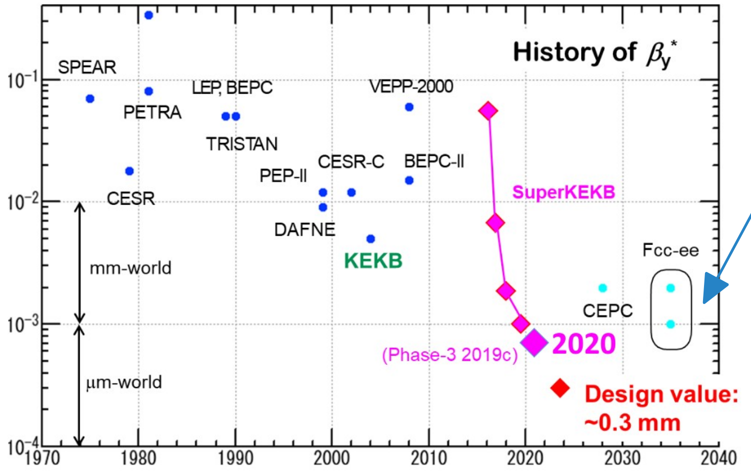
- Perform K-modulation
- Understand dynamics around the IP

P. Thrane et al., Phys. Rev. Accel. Beams 23, p. 012803, 2020.
P. Thrane et al., CLIC-Note-1077, 2017.

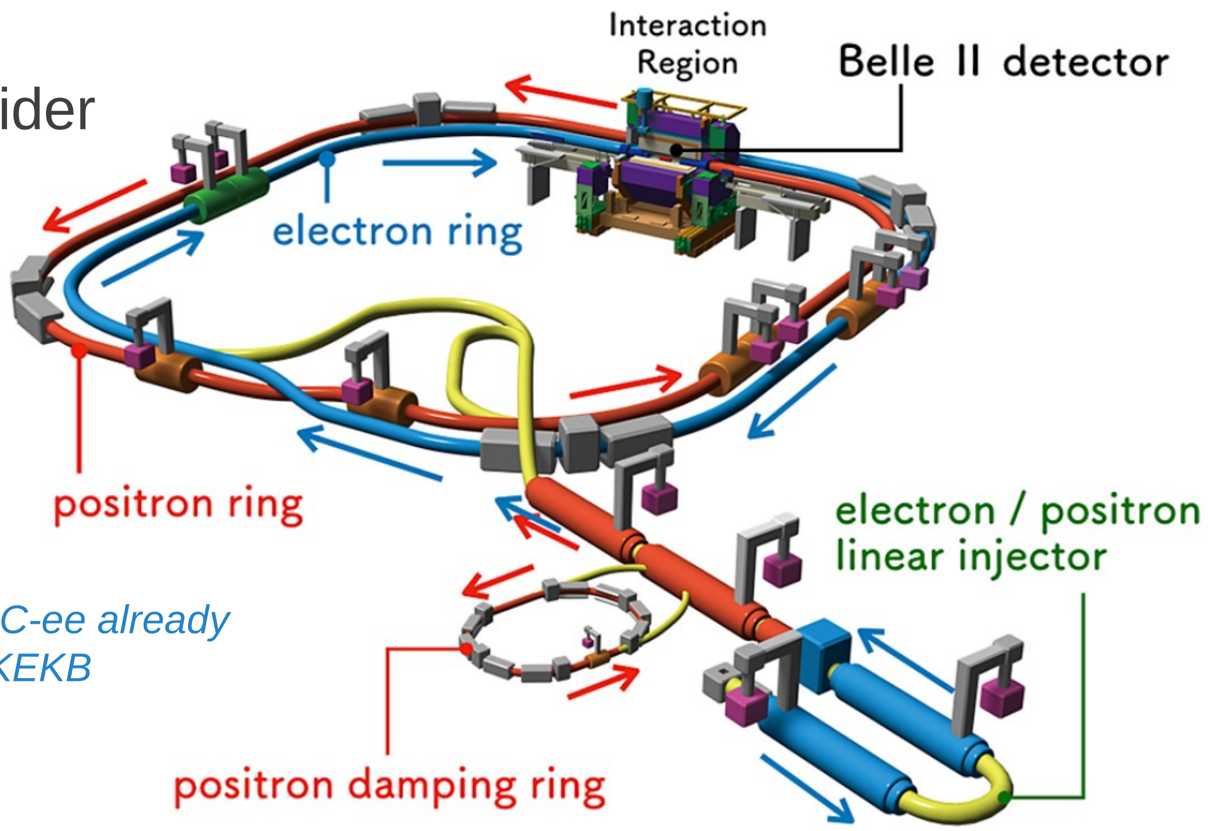
Courtesy: Y. Ohnishi

SuperKEKB - A Small FCC-ee?

- SuperKEKB electron-positron double ring collider
- Crab-waist collision scheme as in FCC-ee
- -I transformation between sextupoles
- Top-up injection like in FCC-ee
- Record low βy* of 0.8 mm



Lowest βy for FCC-ee already reached in SuperKEKB*



SuperKEKB is a small version of FCC-ee!
Understanding SuperKEKB essential for FCC-ee!

K. Akai et al., SuperKEKB Collider, arXiv:1809.01958v2, 2018.

Courtesy: Y. Funakoshi, K. Furukawa

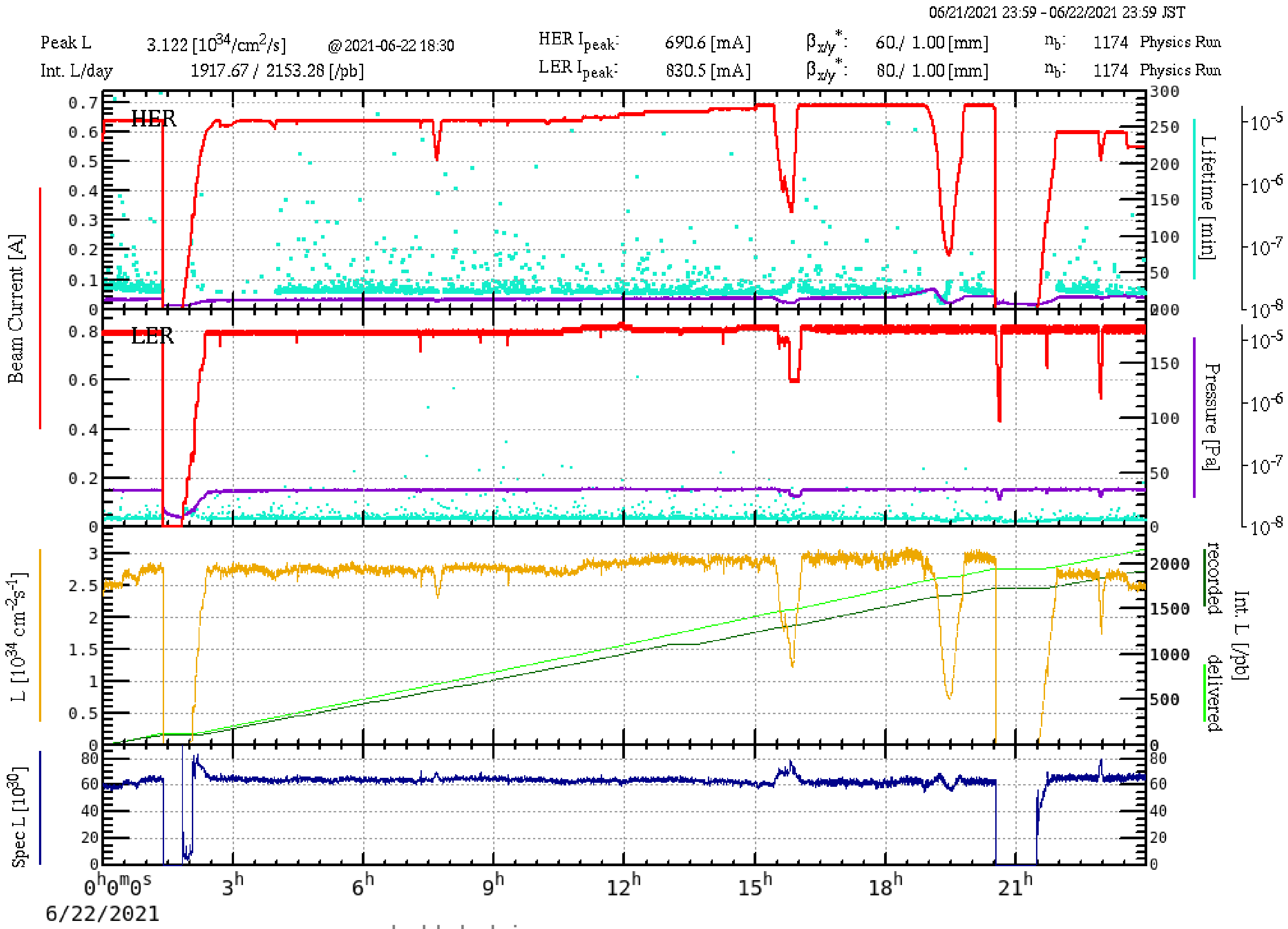
Record Luminosity

- Positron ring with 4 GeV and $\beta x^*/\beta y^* = 80/1$ mm with 80% CW
- Electron ring with 7 GeV and $\beta x^*/\beta y^* = 60/1$ mm with 40% CW

- Record luminosity in June 2021
- About **3.1 x 10^{34} cm^{-2}s^{-1}**

- Specific luminosity defined as

$$L_{SP} = \frac{L}{n_b I_+ I_-}$$

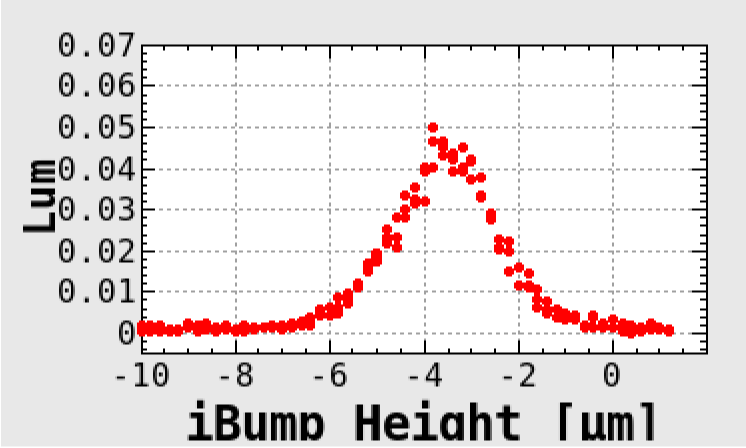


www-superkekb.kek.jp

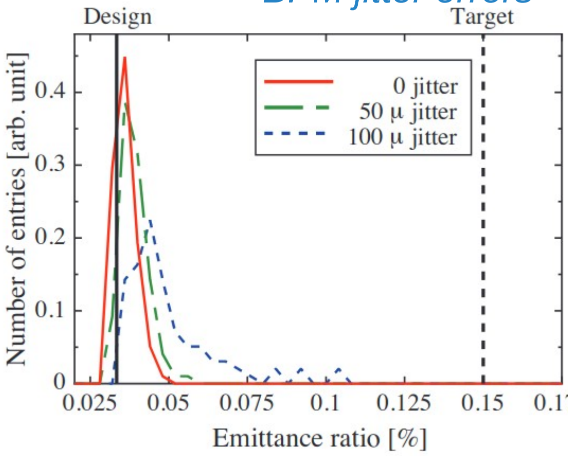
Performance Optimisation

- iBump: vertical orbit bump at the IP to increase luminosity
  - Feedback system based on beam-beam deflection
  - Correct strengths improve luminosity
- Optics correction in simulations
  - Increased dynamic aperture
  - Acceptable emittance ratio

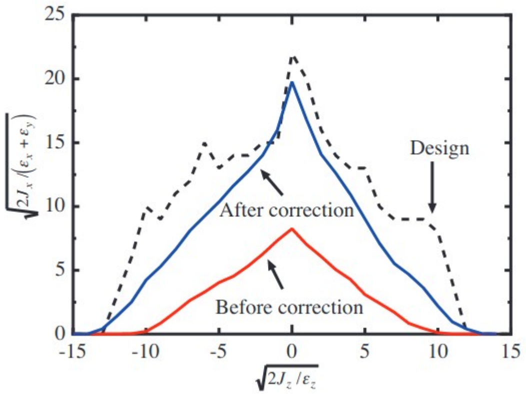
Measurements 26th February 2021
From Belle measurement



BPM jitter errors



Dynamic aperture increases after correction



H. Sugimoto et al., IPAC 2012, TUPPC020, 2012.

Design: includes fringe field of solenoid, beam-beam interaction, intra-beam scattering and some machine errorr
Target: tentative target including other machine errors (misalignments, rotation,...)

SuperKEKB at KEK

- Experience of luminostiy improvement techniques
- Optics corrections in simulations and validation in experiments

Courtesy: T. Ishibashi, K. Ohmi, R. Yang

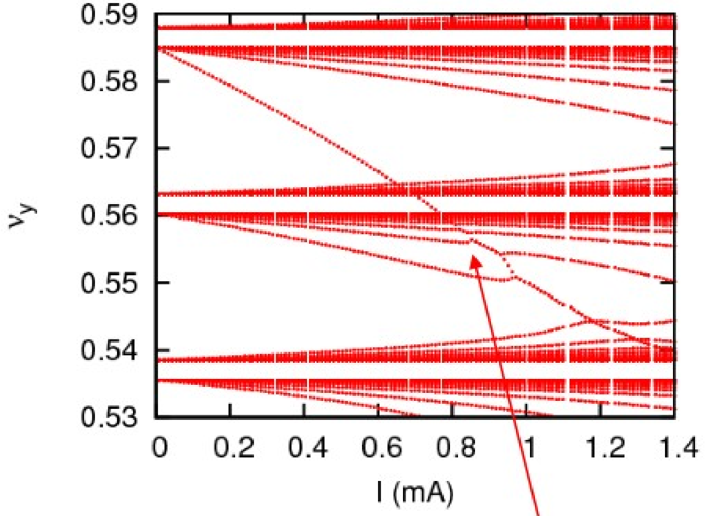
Impedance and Collimation

- Design bunch current not yet reached
  - Tunes decrease with higher bunch current
  - Impedance from collimators

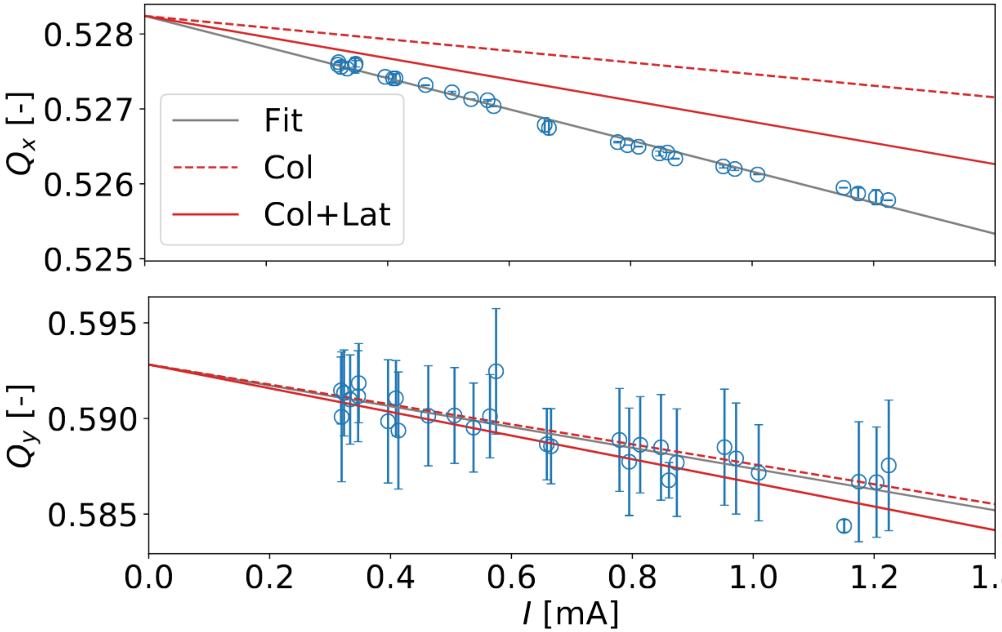
Example for TMCI threshold simulations for vertical tunes from 0.53 - 0.59
→ unstable around 0.9 mA bunch current
→ different working point used in SuperKEKB

SuperKEKB at KEK

- Understand impact of various impedance sources for FCC-ee
- Aim to improve impedance model



Positron ring with 80/2 mm, working point at 0 mA of (0.528, 0.593)
Col: Tune shift due to collimator impedance
Col+Lat: Tune shift due to collimators and known lattice impedance
Known impedance sources can explain only about 80% of tune horizontal tune shift → probably unkown impedance sources



J. Keintzel, IPAC 2021, TUPAB010, 2021.
K. Ohmi, Private communication, 2021.

Summary

- FCC-ee commissioning foreseen around 2040
- Beam tests at exisiting facilities essential for finalizing design of FCC-ee
- Examples of possible beam tests
  - SwissFEL at PSI: Positron source
  - VEPP-4M at BINP: Spin dynamics and energy calibration
  - DAFNE at INFN: Optics, high bunch current studies, feedback system
  - KARA at KIT: Beam instrumentation
  - PETRA III at DESY: Optics tuning, optics measurements and corrections
  - SuperKEKB at KEK: Optics measurements and corrections, impedance studies, luminosity improvement studies

Thank you!

Experimental Beam Tests for FCC-ee

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