UNIVERSITÉ
DE GENÈVE
FACULTÉ DES SCIENCES
Section de physique

Swiss Accelerator
Research and
Technology

FCCee Lumi

Frank Zimmermann, CERN

CHART Workshop 2023, PSI, 11 October 2023

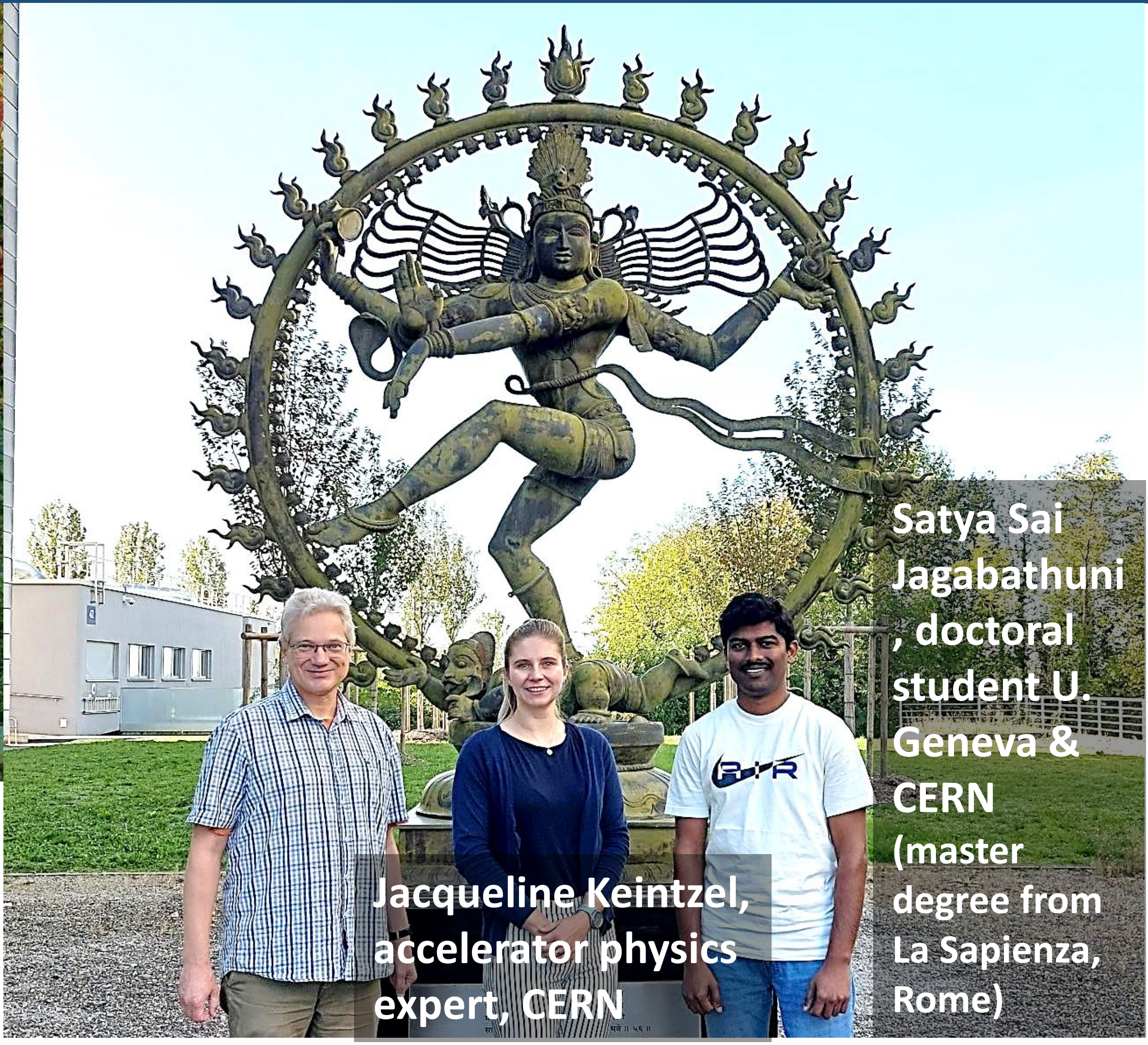
PAUL SCHERRER INSTITUT

the players

Katsunobu Oide,
Visiting Professor at
U. Geneva (former KEK
Accelerator Lab Director)

Frank Zimmermann,
CERN & FCC deputy
study leader, CHART PI

Vaibhavi Gawas,
doctoral student U.
Geneva & CERN
(master degree from
IIT Madras, Chennai)



Jacqueline Keintzel,
accelerator physics
expert, CERN

Satya Sai
Jagabathuni
, doctoral
student U.
Geneva &
CERN
(master
degree from
La Sapienza,
Rome)

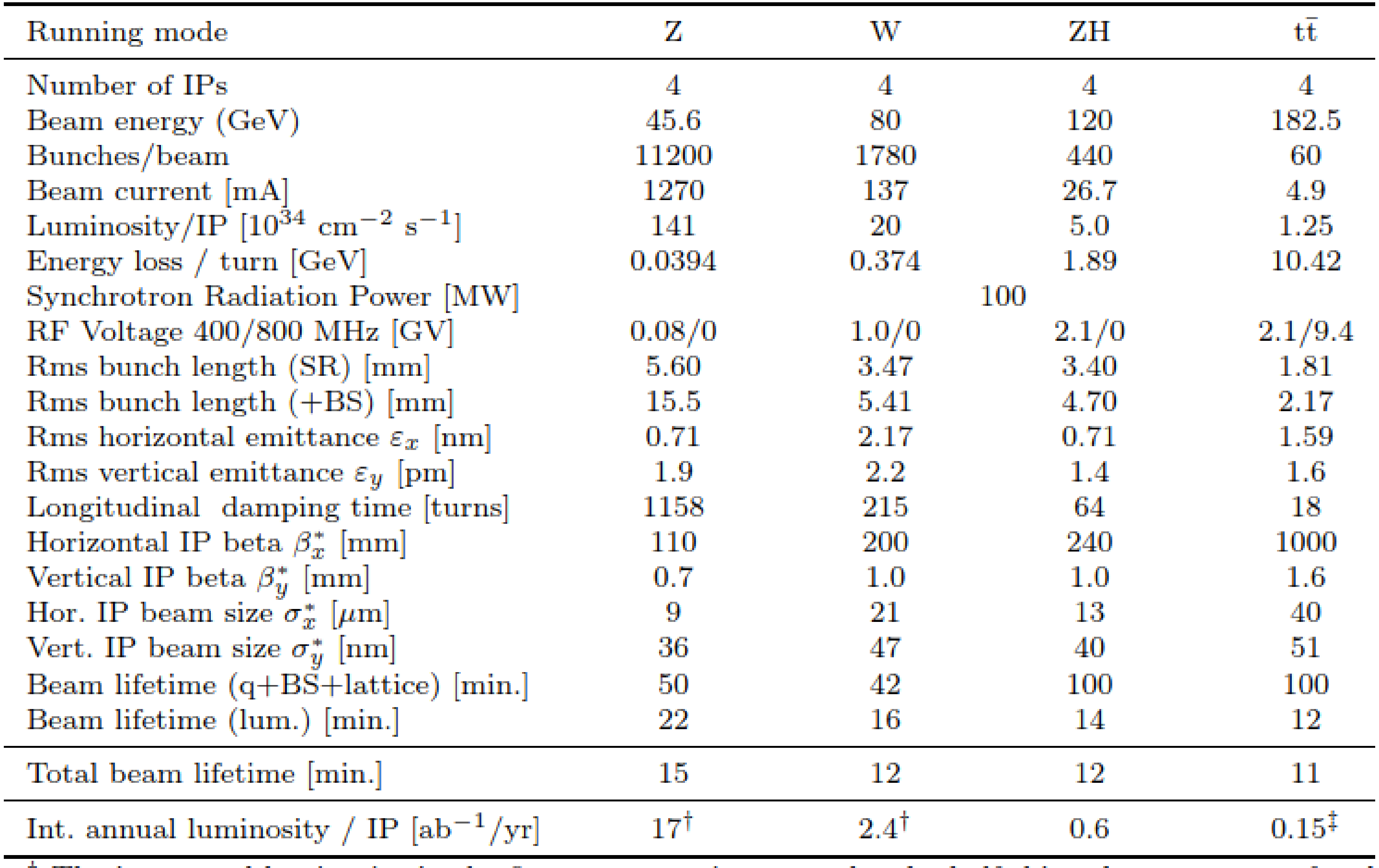
Giuseppe Iacobucci, U. Geneva,
CHART Ex. Board

wonderful unwavering support from Michael Benedikt, Michael Hofer, Rogelio Tomas, …

FCC-ee parameter development: mid-term baseline

Latest parameters for FCC mid-term review

K. Oide

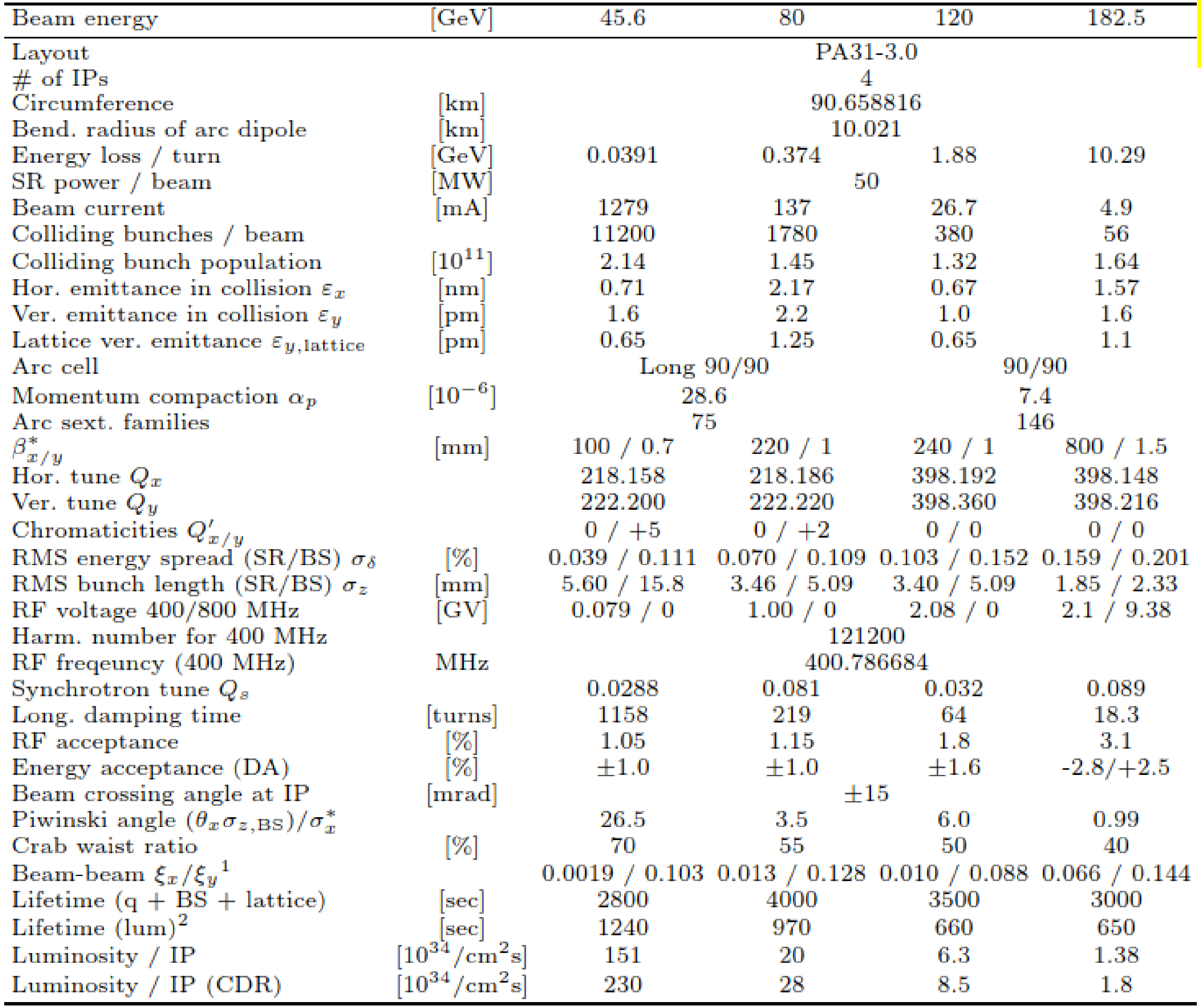


Running mode	Z	W	ZH	$t\bar{t}$
Number of IPs	4	4	4	4
Beam energy (GeV)	45.6	80	120	182.5
Bunches/beam	11200	1780	440	60
Beam current [mA]	1270	137	26.7	4.9
Luminosity/IP [10^{34} cm^{-2} s^{-1}]	141	20	5.0	1.25
Energy loss / turn [GeV]	0.0394	0.374	1.89	10.42
Synchrotron Radiation Power [MW]	100			
RF Voltage 400/800 MHz [GV]	0.08/0	1.0/0	2.1/0	2.1/9.4
Rms bunch length (SR) [mm]	5.60	3.47	3.40	1.81
Rms bunch length (+BS) [mm]	15.5	5.41	4.70	2.17
Rms horizontal emittance ε_x [nm]	0.71	2.17	0.71	1.59
Rms vertical emittance ε_y [pm]	1.9	2.2	1.4	1.6
Longitudinal damping time [turns]	1158	215	64	18
Horizontal IP beta β_x^* [mm]	110	200	240	1000
Vertical IP beta β_y^* [mm]	0.7	1.0	1.0	1.6
Hor. IP beam size σ_x^* [μm]	9	21	13	40
Vert. IP beam size σ_y^* [nm]	36	47	40	51
Beam lifetime (q+BS+lattice) [min.]	50	42	100	100
Beam lifetime (lum.) [min.]	22	16	14	12
Total beam lifetime [min.]	15	12	12	11
Int. annual luminosity / IP [ab^{-1}/yr]	17†	2.4†	0.6	0.15‡

FCC-ee parameter development: “pushed” ZH & $t\bar{t}$

K. Oide

A variant of parameters of FCC-ee collider. SR: synchrotron radiation, BS: beamstrahlung. The parameters for ZH and $t\bar{t}$ are pushed to higher luminosities compared with the mid-term baseline.

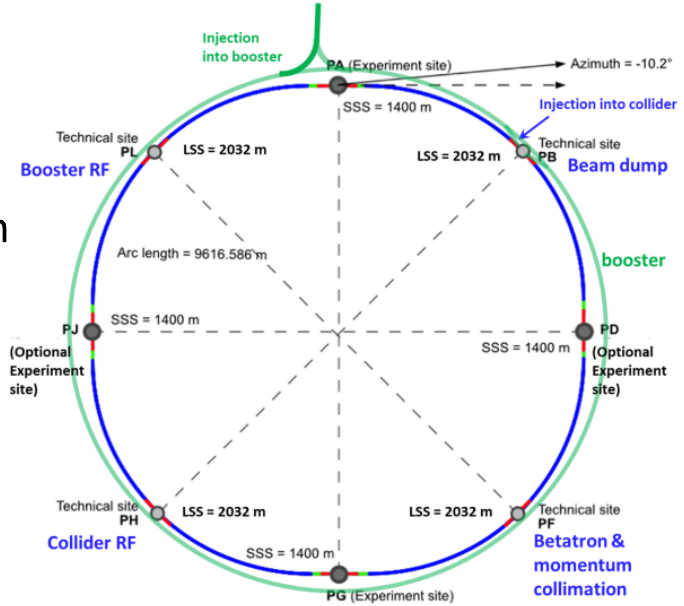


Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-3.0			
# of IPs		4			
Circumference	[km]	90.658816			
Bend. radius of arc dipole	[km]	10.021			
Energy loss / turn	[GeV]	0.0391	0.374	1.88	10.29
SR power / beam	[MW]	50			
Beam current	[mA]	1279	137	26.7	4.9
Colliding bunches / beam		11200	1780	380	56
Colliding bunch population	[10^{11}]	2.14	1.45	1.32	1.64
Hor. emittance in collision ε_x	[nm]	0.71	2.17	0.67	1.57
Ver. emittance in collision ε_y	[pm]	1.6	2.2	1.0	1.6
Lattice ver. emittance $\varepsilon_{y,\mathrm{lattice}}$	[pm]	0.65	1.25	0.65	1.1
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10^{-6}]	28.6		7.4	
Arc sext. families		75		146	
$\beta^*_{x/y}$	[mm]	100 / 0.7	220 / 1	240 / 1	800 / 1.5
Hor. tune Q_x		218.158	218.186	398.192	398.148
Ver. tune Q_y		222.200	222.220	398.360	398.216
Chromaticities $Q'_{x/y}$		0 / +5	0 / +2	0 / 0	0 / 0
RMS energy spread (SR/BS) σ_δ	[%]	0.039 / 0.111	0.070 / 0.109	0.103 / 0.152	0.159 / 0.201
RMS bunch length (SR/BS) σ_z	[mm]	5.60 / 15.8	3.46 / 5.09	3.40 / 5.09	1.85 / 2.33
RF voltage 400/800 MHz	[GV]	0.079 / 0	1.00 / 0	2.08 / 0	2.1 / 9.38
Harm. number for 400 MHz		121200			
RF freqeuncy (400 MHz)	MHz	400.786684			
Synchrotron tune Q_s		0.0288	0.081	0.032	0.089
Long. damping time	[turns]	1158	219	64	18.3
RF acceptance	[%]	1.05	1.15	1.8	3.1
Energy acceptance (DA)	[%]	±1.0	±1.0	±1.6	-2.8/+2.5
Beam crossing angle at IP	[mrad]	±15			
Piwinski angle $(\theta_x \sigma_{z,\mathrm{BS}})/\sigma^*_x$		26.5	3.5	6.0	0.99
Crab waist ratio	[%]	70	55	50	40
Beam-beam ξ_x/ξ_y[1]		0.0019 / 0.103	0.013 / 0.128	0.010 / 0.088	0.066 / 0.144
Lifetime (q + BS + lattice)	[sec]	2800	4000	3500	3000
Lifetime (lum)[2]	[sec]	1240	970	660	650
Luminosity / IP	[10^{34}/cm^{2}s]	151	20	6.3	1.38
Luminosity / IP (CDR)	[10^{34}/cm^{2}s]	230	28	8.5	1.8

FCC-ee optics design – changes & updates from CDR

K. Oide

- Arc FODO cell structure. **Phase advance at lower energies (Z, W$^{\pm}$) is now 90°/90° with twice the cell length** (long 90/90), instead of equal length with a phase advance of 60°/60°.
- Twin aperture dipoles & quad's. **Separation between two beams was increased to 35 c**m from the CDR's 30 cm.
- **The superperiodicity is now 4**, corresponding to the 4 IP scheme.
- Multi-family −I-paired sextupoles in the arc. The number of families is about ½ of the CDR's as a result of the doubled superperiodicity. The multi-family scheme provides great flexibility for controlling additional parameters such as the chromatic behavior at the IP or RF.
- **The RF section for the collider is concentrated in one LSS (PH) for all energies**. This seems to induce an additional non-structure synchrobetatron resonance, limiting the choice of the transverse tune space at some energies.
- The number of sextupoles in the IR is 2/side/IP × 2 sides × 4 IP × 2 beam = 32 for both beams. It employs the **'virtual' crab sextupoles** incorporated in vertical local chromaticity correction sextupoles (FCC-ee scheme demonstrated at SuperKEKB!).
- **Critical photon energies of incoming SR from dipoles <100 keV** up to 400 m upstream of IP.
- **Perfect solenoid compensation with counter-solenoids** between the face of the last quadrupole (QC1L/R1) and IP. This scheme guarantees a perfect achromatic coupling correction with no leak of vertical orbit and dispersion to the outside. This scheme also guarantees a perfect removal of harmful beam-beam effects coupled to the chromatic coupling, from which SuperKEKB has been suffering so far. This compensation scheme, due to dispersion and synchrotron radiation in the solenoid fields with crossing angle, generates a vertical emittance of 0.5 pm at the Z.
- IR now incorporates **polarisation wigglers and space for Compton polarimeter**. The latter can detect spin precession angle at each IP to provide more constraints for beam energy calibration.
- Vertical chromaticities are set to **+5 and +2 at Z and W$^{\pm}$, respectively, and to 0 at other energies**, to suppress TMCI. **Dynamic aperture (DA) & beam lifetime optimised for these chromaticities**.



FCC-ee tune scans: beam-beam + lattice

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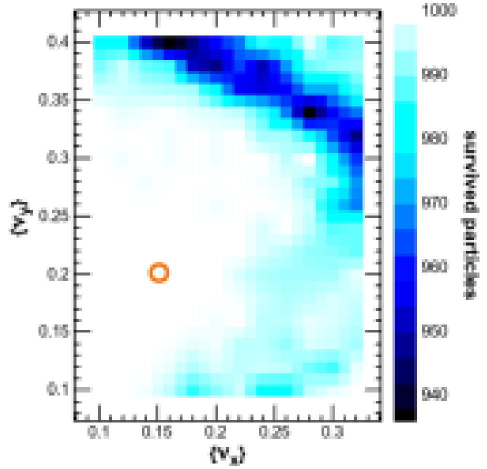
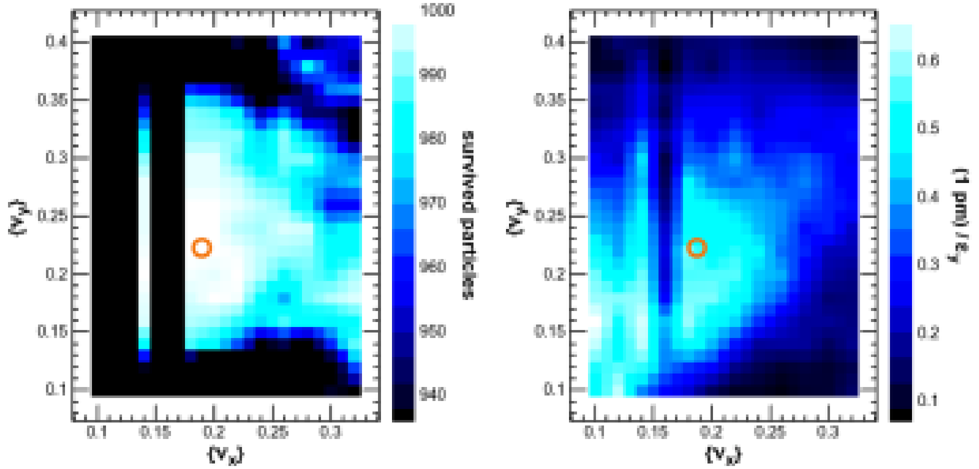
Z

FCCee_z_566_nosol_4_ts
$N = 1.51\text{x}10^{11}$, Crab waist = 70%,
$\beta^*_{x,y} = \{.11\text{ m}, .7\text{ mm}\}$, $\nu_z = -.02867$, $\varepsilon_{y,\text{lattice}} = .99936$ pm



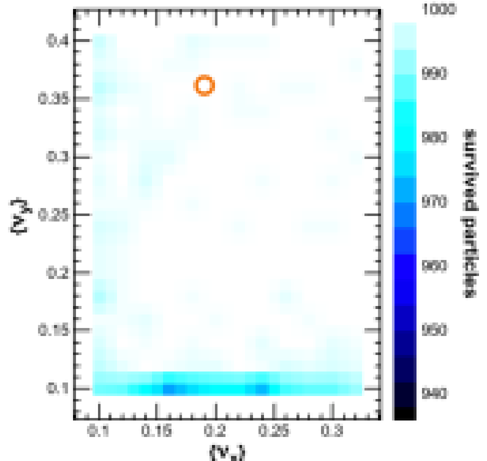
WW

FCCee_w_566_nosol_ts
$N = 1.45\text{x}10^{11}$, Crab waist = 55%,
$^*_{x,y} = \{.22\text{ m}, 1\text{ mm}\}$, $\nu_z = -.08101$, $\varepsilon_{y,\text{lattice}} = 1.00046$ pm



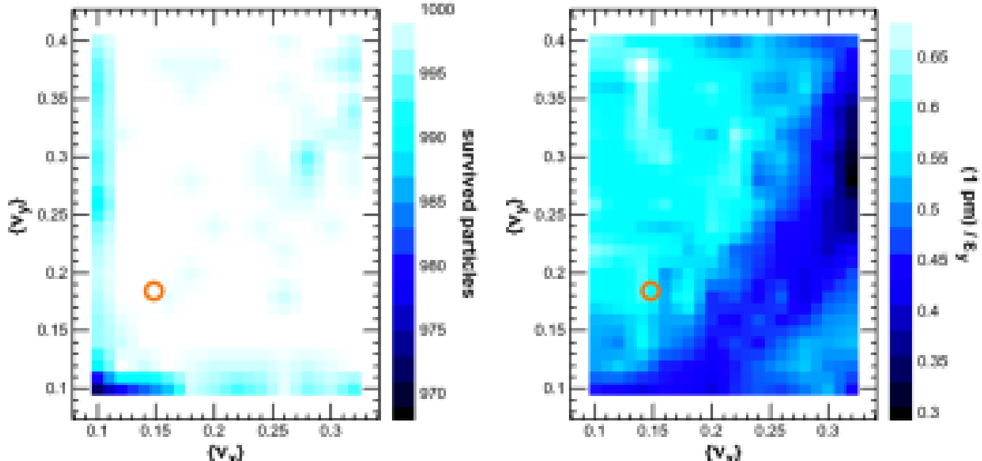
ZH

FCCee_h_565_nosol_7_ts
$N = 1.15\text{x}10^{11}$, Crab waist = 50%,
$\beta^*_{x,y} = \{.24\text{ m}, 1\text{ mm}\}$, $\nu_z = -.03123$, $\varepsilon_{y,\text{lattice}} = 1.00490$ pm



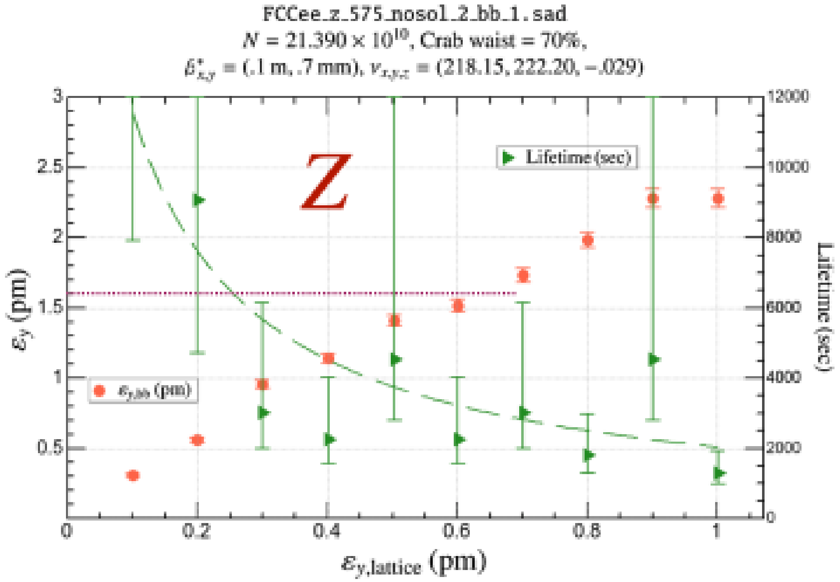
$t\bar{t}$

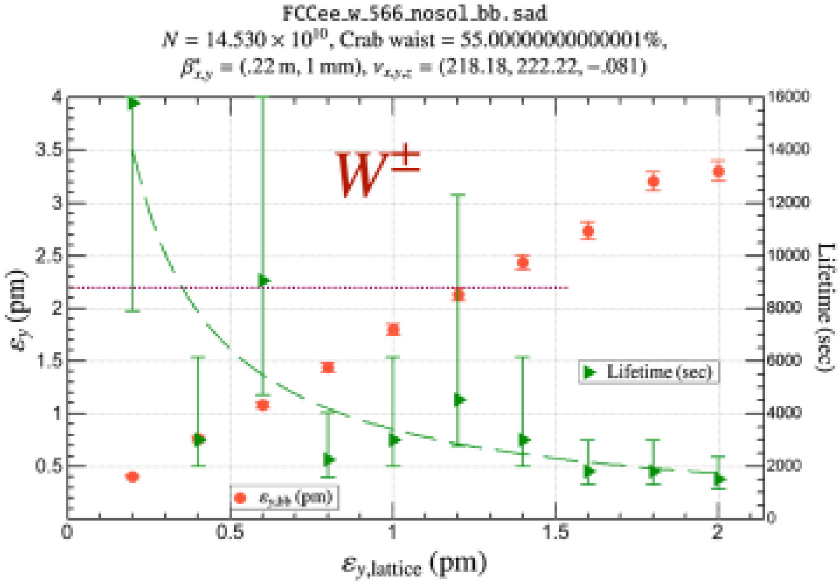
FCCee_t_565_nosol_2_ts
$N = 1.55\text{x}10^{11}$, Crab waist = 40%,
$\beta^*_{x,y} = \{1.01\text{ m}, 1.56\text{ mm}\}$, $\nu_z = -.08966$, $\varepsilon_{y,\text{lattice}} = 1.08717$ pm

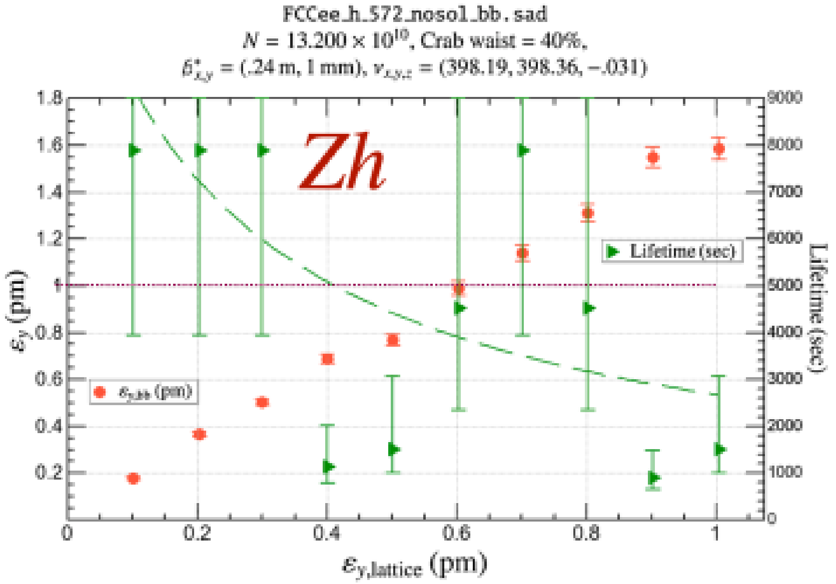


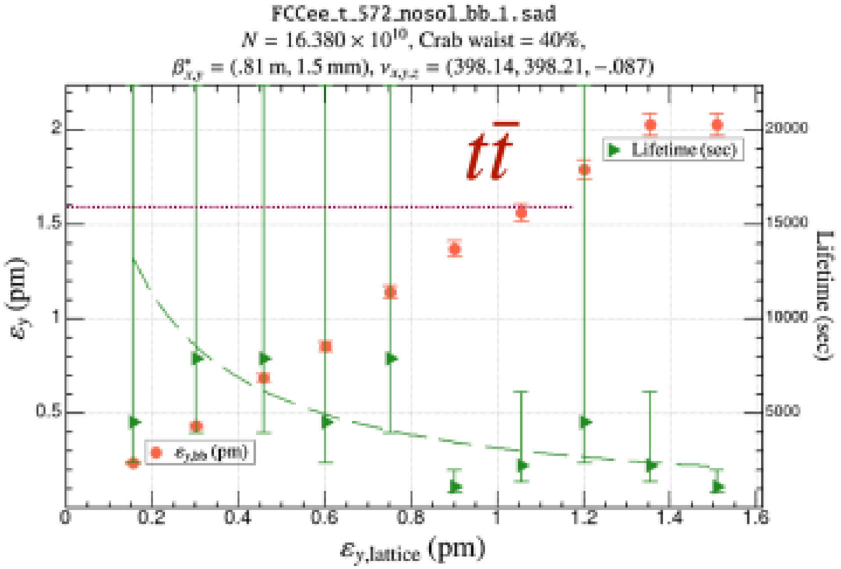
emittance blow up & beam lifetime versus lattice vertical emittance

K. Oide


FCCee_z_575_nosol_2_bb_1.sad
$N = 21.390 \times 10^{10}$, Crab waist = 70%,
$\beta^*_{x,y} = (.1\text{ m}, .7\text{ mm})$, $\nu_{x,y,z} = (218.15, 222.20, -.029)$


FCCee_w_566_nosol_bb.sad
$N = 14.530 \times 10^{10}$, Crab waist = 55.00000000000001%,
$\beta^*_{x,y} = (.22\text{ m}, 1\text{ mm})$, $\nu_{x,y,z} = (218.18, 222.22, -.081)$

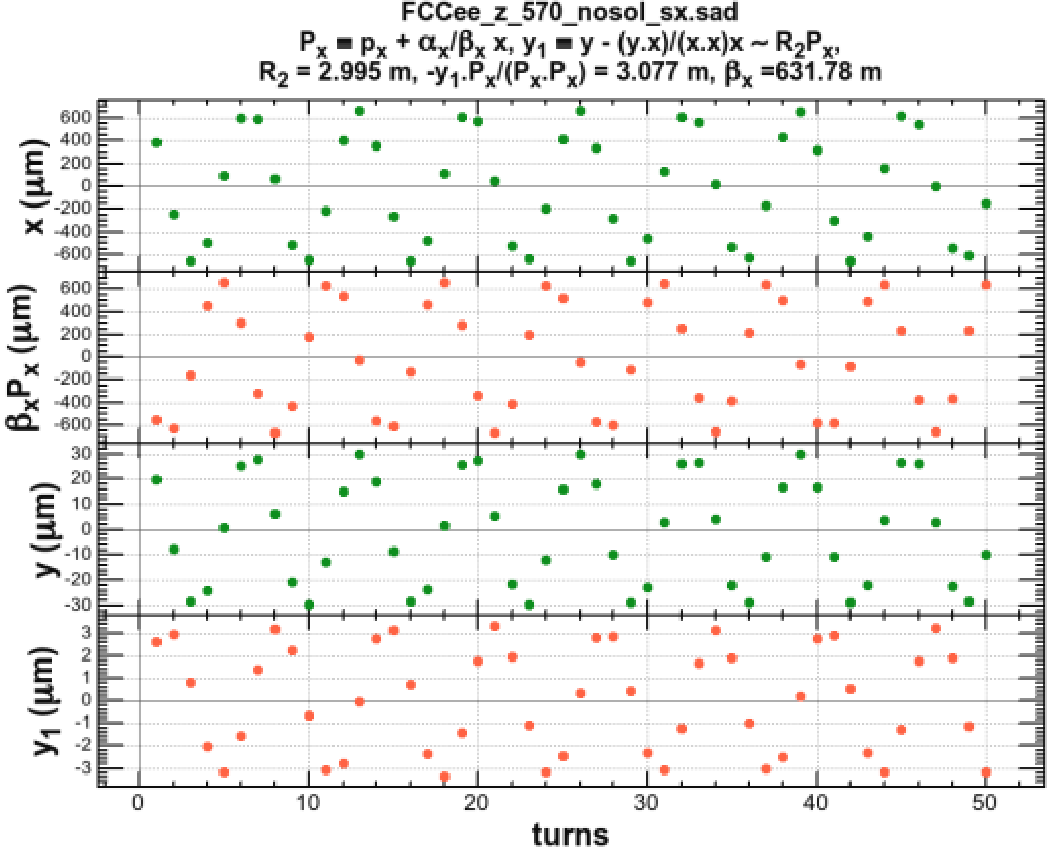

FCCee_h_572_nosol_bb.sad
$N = 13.200 \times 10^{10}$, Crab waist = 40%,
$\beta^*_{x,y} = (.24\text{ m}, 1\text{ mm})$, $\nu_{x,y,z} = (398.19, 398.36, -.031)$


FCCee_t_572_nosol_bb_1.sad
$N = 16.380 \times 10^{10}$, Crab waist = 40%,
$\beta^*_{x,y} = (.81\text{ m}, 1.5\text{ mm})$, $\nu_{x,y,z} = (398.14, 398.21, -.087)$

measurement of coupling & dispersion at BPMs

- There are many ways to measure the coupling at each BPM. One of them is to use turn-by-turn BPM to excite the horizontal betatron oscillation over many turns. It may be difficult for higher energies esp. at $t\bar{t}$ due to the very strong damping, but should be possible at Z, which requires the most stringent correction.

- Once such a horizontal oscillation is excited, the vertical signal at the same BPM will be observed due to the coupling. There are two components in the vertical signal, due to R_1 ($X \to y$) and R_2 ($P_X \to y$). Although both are detectable, *the signal by R_1 can be contaminated by a rotation error of the BPM*. As we do not know a way to eliminate such a rotation error, let us consider only R_2 here.



$y_1 \perp x \approx R_2 P_X$

An example of turn-by-turn oscillation at a BPM. There is a coupling $R_2 \sim 3$ m at this BPM. A horizontal vibration by $1\sigma_x$ induce the vertical oscillation by $\sim 30\,\mu$m. The component y_1 which is orthogonal to x gives the measurement of R_2 ($y_1 \sim R_2 P_X$).

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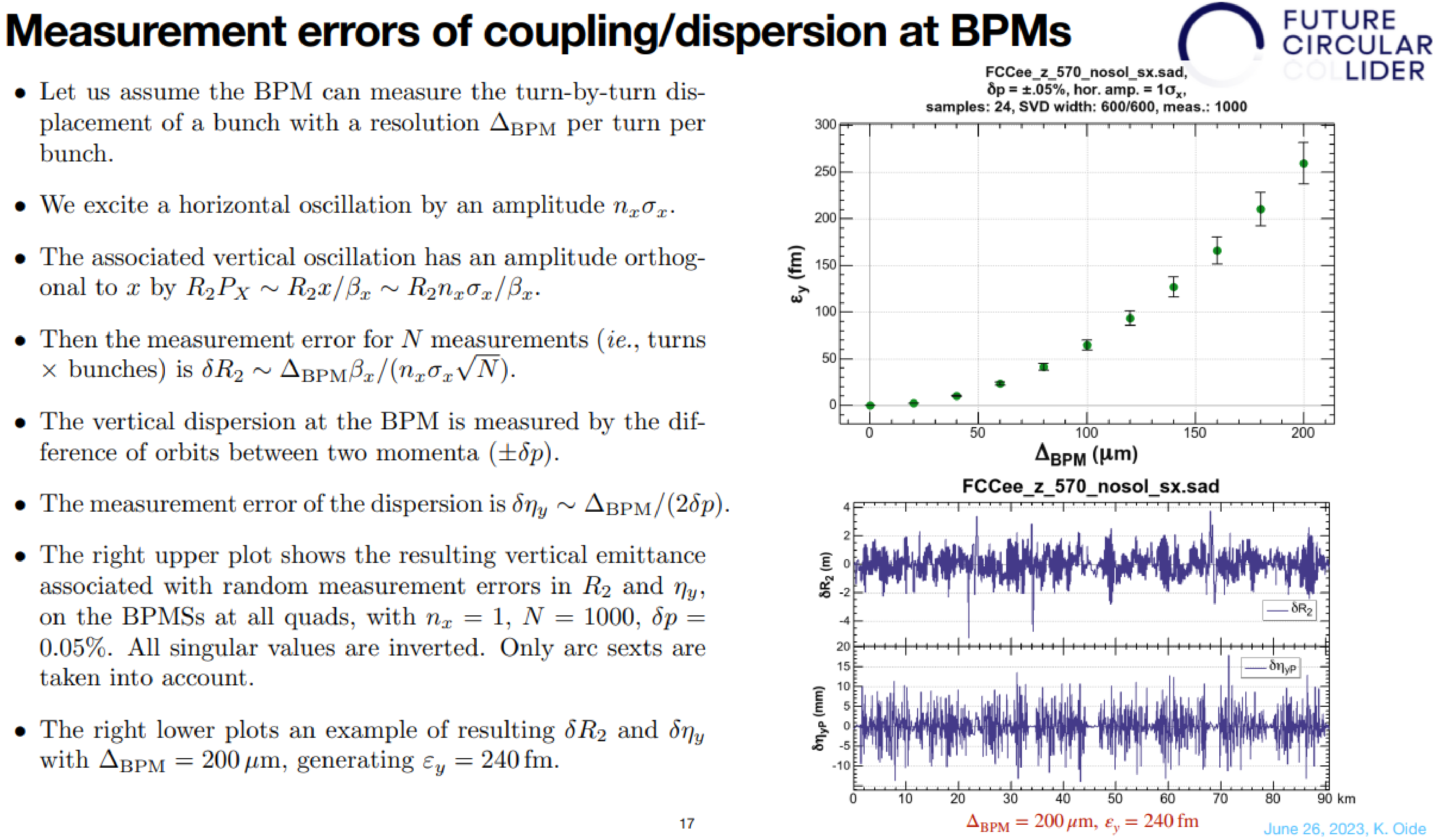
FCC-ee emittance vs BPM resolution

K. Oide



Measurement errors of coupling/dispersion at BPMs

- Let us assume the BPM can measure the turn-by-turn displacement of a bunch with a resolution $\Delta_{\rm BPM}$ per turn per bunch.
- We excite a horizontal oscillation by an amplitude $n_x\sigma_x$.
- The associated vertical oscillation has an amplitude orthogonal to x by $R_2 P_X \sim R_2 x/\beta_x \sim R_2 n_x \sigma_x/\beta_x$.
- Then the measurement error for N measurements (*ie.*, turns × bunches) is $\delta R_2 \sim \Delta_{\rm BPM}\beta_x/(n_x\sigma_x\sqrt{N})$.
- The vertical dispersion at the BPM is measured by the difference of orbits between two momenta ($\pm\delta p$).
- The measurement error of the dispersion is $\delta\eta_y \sim \Delta_{\rm BPM}/(2\delta p)$.
- The right upper plot shows the resulting vertical emittance associated with random measurement errors in R_2 and η_y, on the BPMSs at all quads, with $n_x = 1$, $N = 1000$, $\delta p = 0.05\%$. All singular values are inverted. Only arc sexts are taken into account.
- The right lower plots an example of resulting δR_2 and $\delta\eta_y$ with $\Delta_{\rm BPM} = 200\,\mu$m, generating $\varepsilon_y = 240$ fm.

$\Delta_{\rm BPM} = 200\,\mu{\rm m},\ \varepsilon_y = 240$ fm

June 26, 2023, K. Oide

The correction of sext misalignment using coupling/dispersion measurements at BPMs seems OK, giving smaller vertical emittance than required (~300fm), even with a poor BPM resolution.

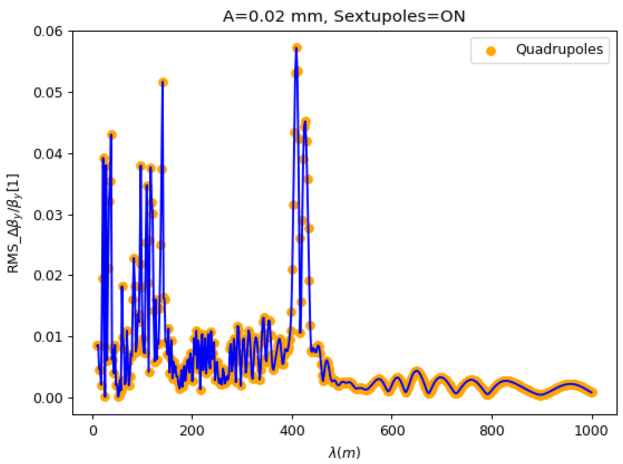
Sensitivity to Coherent Misalignments

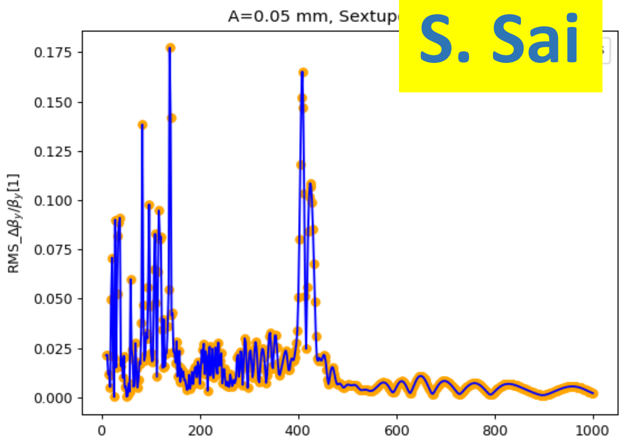
S. Sai

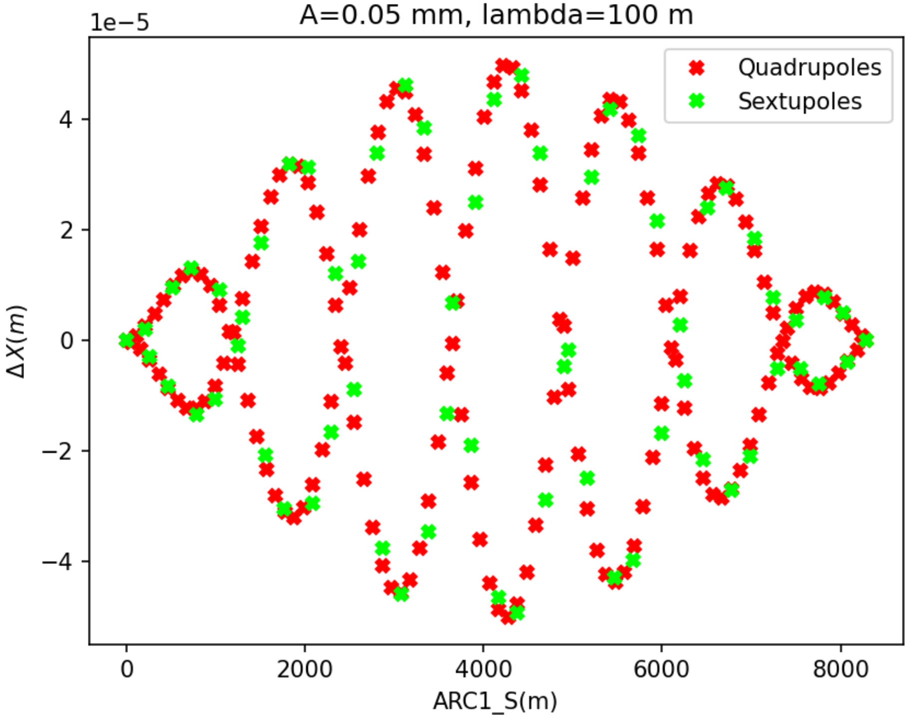
Goal: identify wavelengths over which magnets need to be well aligned

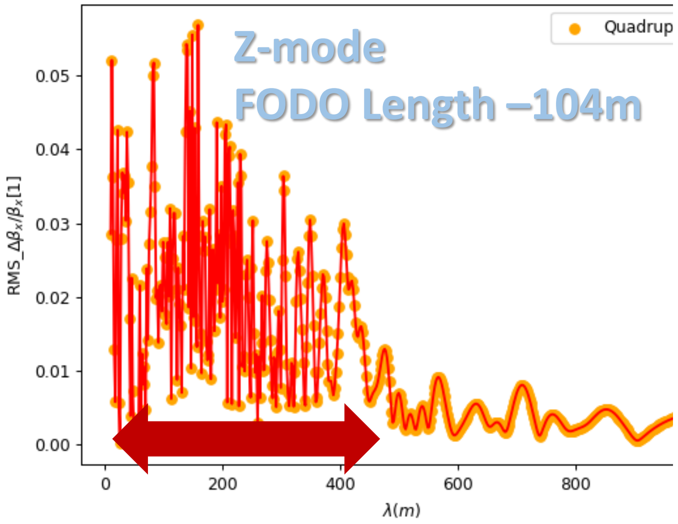
Model: $$\Delta X = A * \sin\left(S * \frac{2\pi}{\lambda} \right) \sin\left(\pi * \frac{S - S\_start}{S\_end}\right)$$

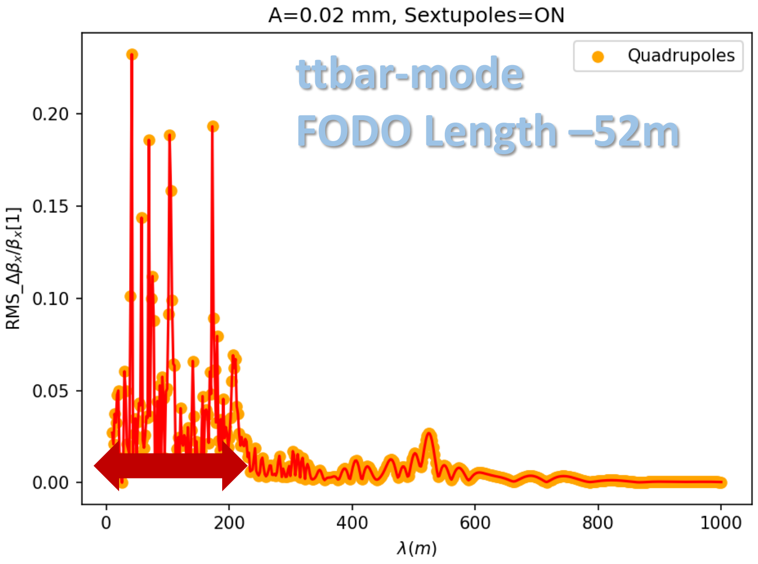
where S_start and S_end are the Arc start and end positions respectively









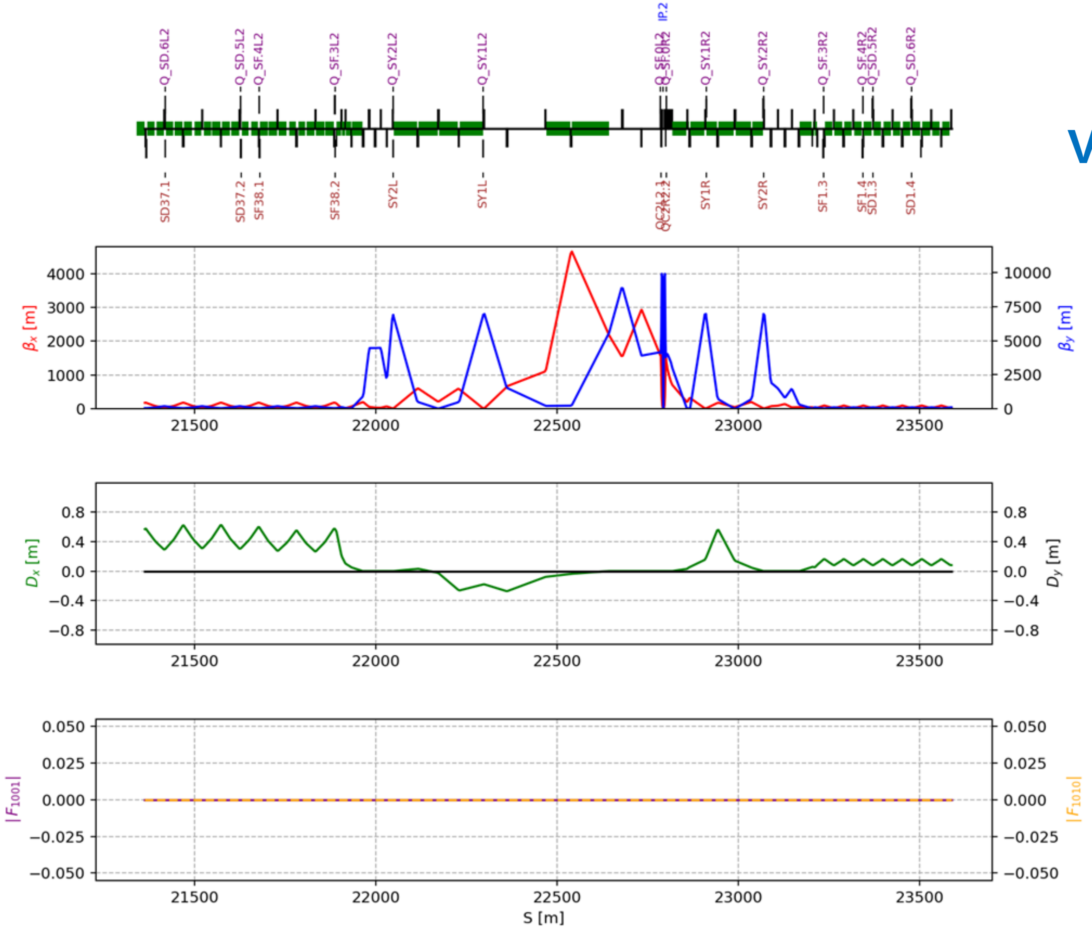


Coherent misalignments at wavelengths above 500 m do not have a significant impact on the machine performance

FCC-ee Interaction Point Tuning Knobs

Extra skew windings at the Final Focus doublet and at least the nearest 6 sextupoles on each side of IP, to help control vertical dispersion & coupling at the IP

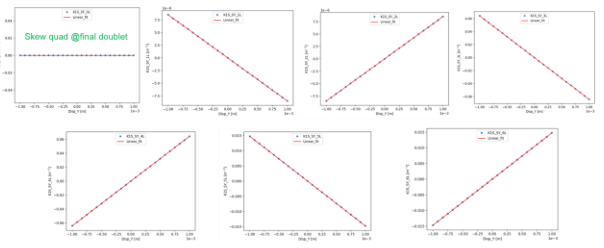
Skew quads Final doublet Sextupoles



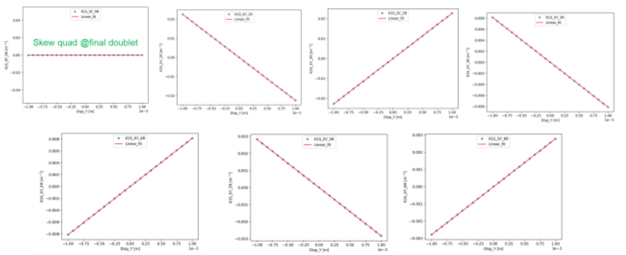
example: vertical IP dispersion knob

S. Sai

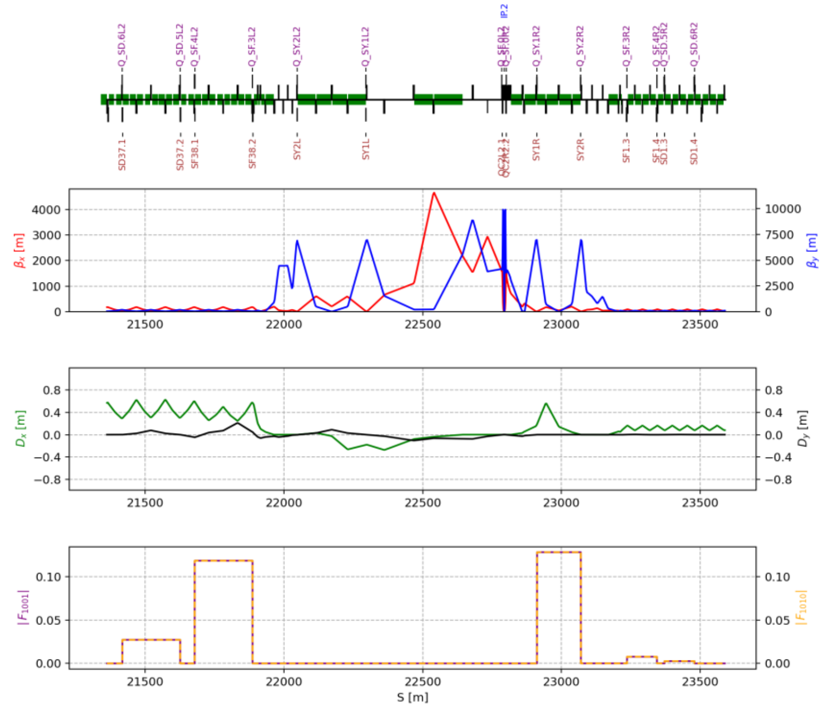
Skew quad strengths (left of IP) as a function of knob-D_y^*



Skew quad strengths (right of IP) as a function of knob-D_y^*



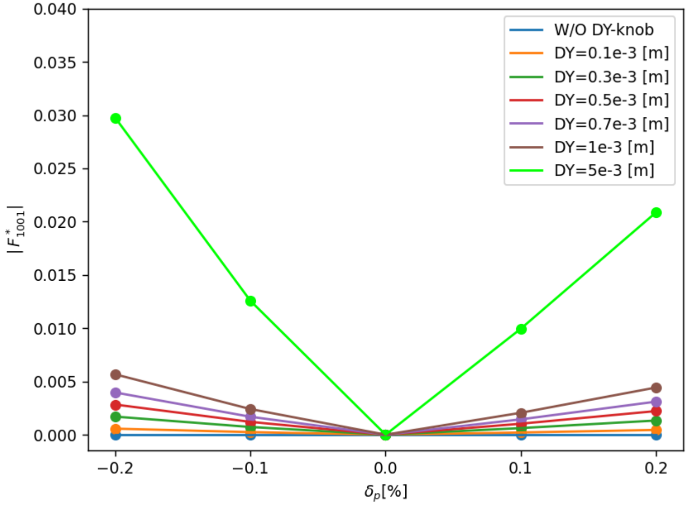
Vertical Dispersion Knob for $D_y^* = 1$mm

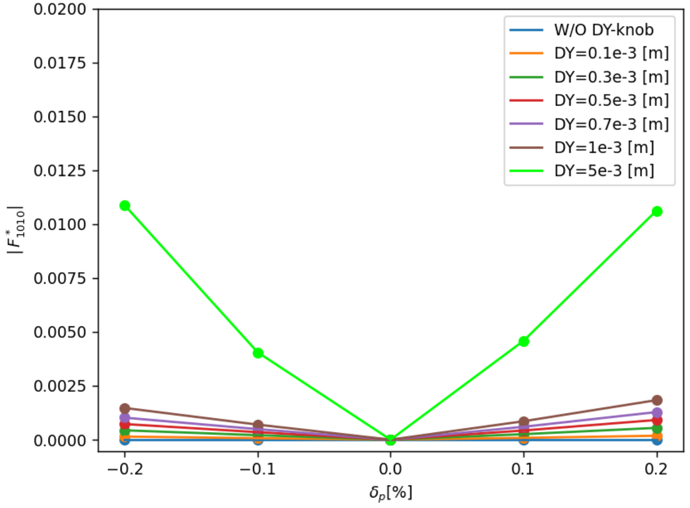


created so far:
- **vertical dispersion knob,**
- **coupling knobs $|\mathbf{F}^*_{1010}|$ and $|\mathbf{F}^*_{1001}|$**

FCC-ee IP Tuning Knobs – Cross Talk Study examples

cross talk of ΔD_y^*: chromatic coupling



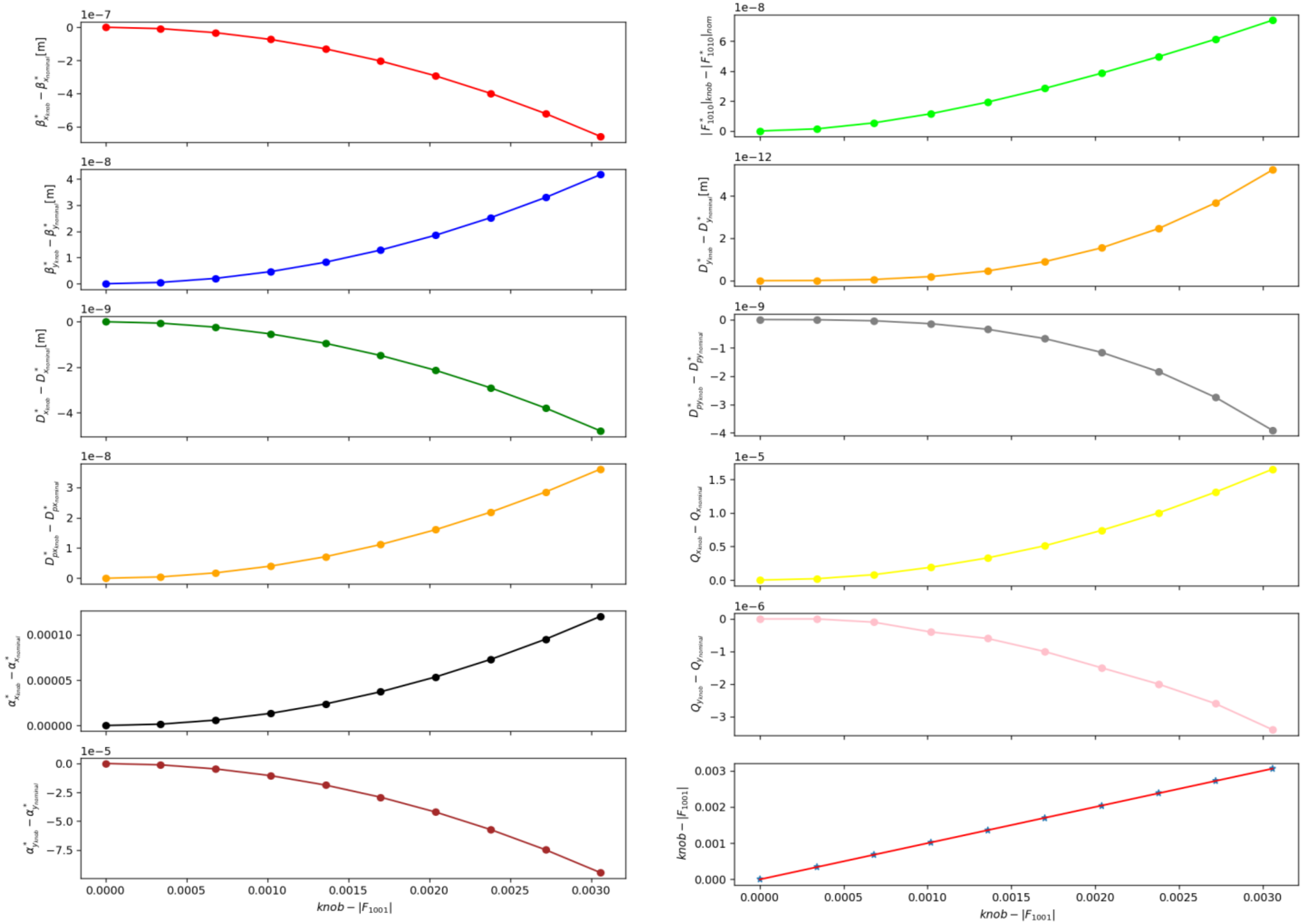


Knobs created do not have a significant effect on other IP parameters, over a reasonable range of values.

Dispersion knob setting of ≥5 mm: impact on chromatic behaviour.

cross talk of $\Delta|F^*_{1001}|$: impact on other linear optics parameters

S. Sai



Monitoring FCC-ee Interaction-Point Collision Parameters

V. Gawas

PhD thesis scope (start 1 October 2023):

- examine the FCC-ee **luminometer concept** and the implied **alignment or beam-stability tolerances**
- develop, or get familiar with, a **concept for the beamstrahlung monitor** including shielding to handle the significant power and to screen the signal against lower-energy photons from **radiative Bhabha scattering**. This may require Guinea-Pig, plus GEANT or FLUKA simulations, and a collaboration with experts in the CERN STI and BI groups
- further study **additional information on the collision and IP beam distributions** that could be gained from a small-radius **silicon vertex detector**, possibly in collaboration with experts from the University of Geneva
- with the simulated beamstrahlung monitor and/or SVD signals, explore **if and how this information combined with the luminosity monitor and the tuning knobs developed in a parallel PhD thesis project can be used to infer, control and optimize the IP beam and optics parameters**

Outlook – Possible Future Topics

K. Oide

- reconcile actual simulations of optics correction with the estimation presented above
- weak-strong beam-beam simulations with crab-waisted strong beam
- further evaluation of the detector background from beam-gas, beam pipe hitting, etc.

…

- additional IP tuning knobs: waist (x,y), beta* (x,y), horizontal dispersion, chromatic coupling,…
- simultaneous applications of two (or more) knobs: impact on useful knob range ?
- further wavelength sensitivity studies

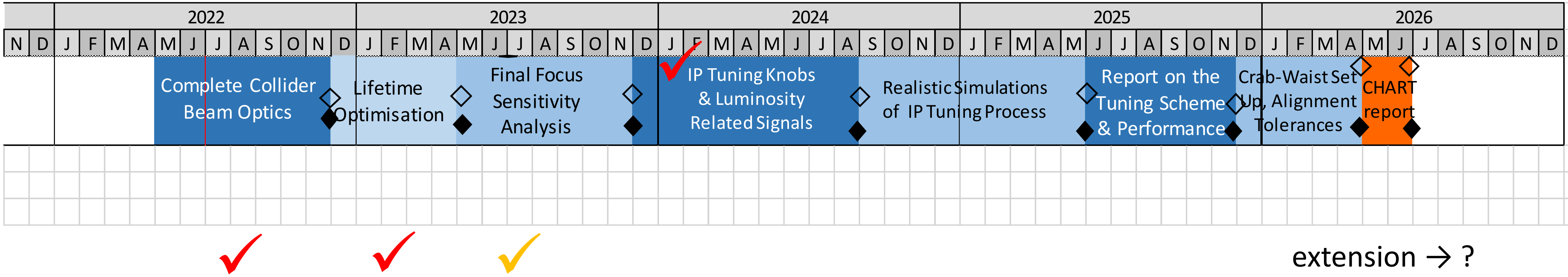
S. Sai

…

- lumical & beamstrahlung monitor concepts & expected signals
- luminosity tuning: identification of useful realistic signals (Bhabha/lumical, beamstrahlung, rad. Bhabha (?), vertex information ??)
- usage & development of suitable simulations tools
- applications of IP tuning knobs to study effect for perfect machine
- application of IP tuning knobs to optimise luminosity in a machine with errors

V. Gawas

original “FCCee Lumi” timeline



extension → ?