

# FCC-ee IP FEEDBACK TOLERANCES & NEW MODELLING OF SUPERKEKB IN XSUITE

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*FCC Week 2025*

# Funding statement

## EAJADE

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## FCCIS

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*FCC-ee Beam-beam simulations*

**G. Iadarola, G. Broggi, H. Sugimoto & K. Oide**

*SuperKEKB Optics Modelling in Xsuite*

**T. Schoerner, N. Fuster Martínez, N. Potylitsina-Kube, K. Ikematsu**

*EAJADE coordinators, who enabled my collaboration with KEK*

**R. Ueki, M. Masuzawa & Y. Funakoshi and all the KEK operators**

*SuperKEKB Measurements*

**And many more**

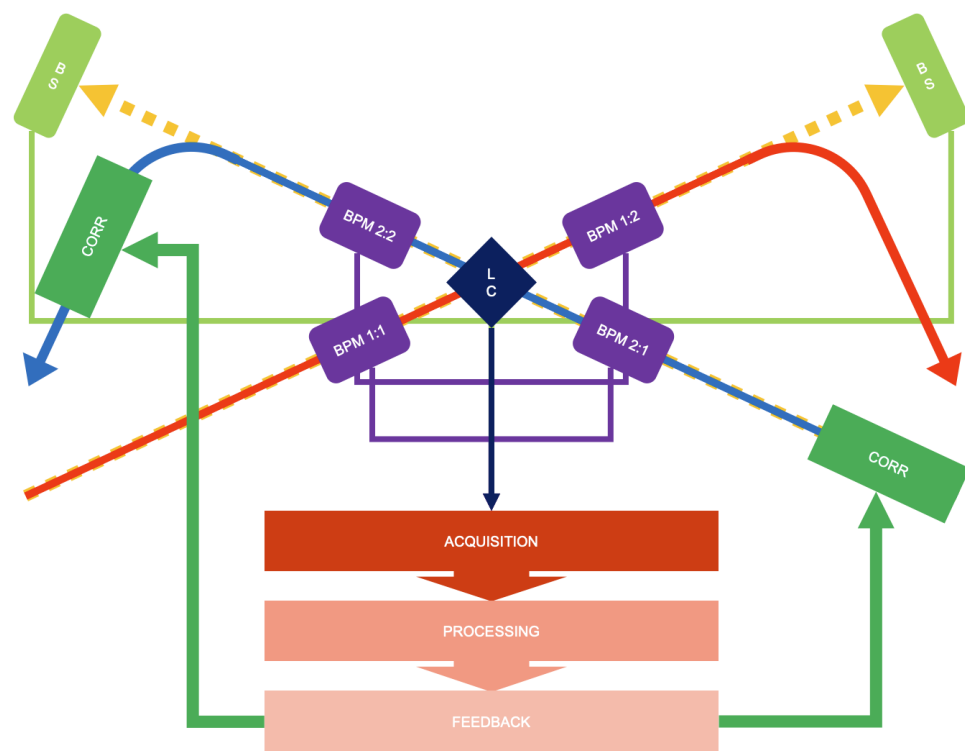


# IP FEEDBACK AT FCC-ee

# Interaction Point Feedback?

*Interaction point (IP) feedback **locally** corrects the beam orbit **maintaining collision and thus luminosity and beam lifetime***

- Beam offsets are calculated from measurements *such as*:
  - Deflection information from BPMs
  - Photon direction and power from Beamstrahlung
  - Luminosity from Luminometers
- Closed orbit corrections are then applied



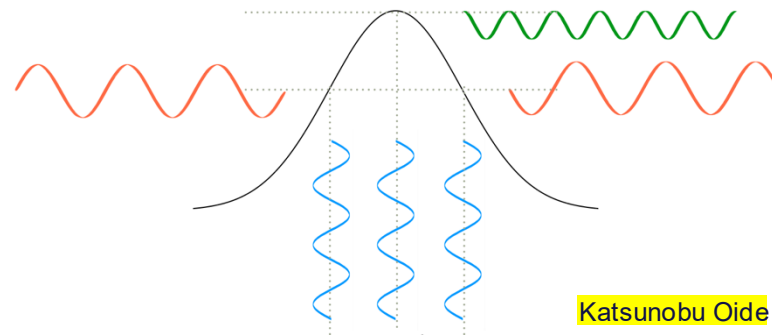
# Feedback Types Under Consideration

## Beam-Beam Deflection

- Offset detected using BPMs upstream and downstream of the IP (or using beamstrahlung light)
- Resolution of the monitor must be better than the downstream offset
- For small offsets (feedback regime) well approximated by the linear model
- Implemented at SLC and SKEKB (vertical)
- *Requires large beam-beam parameters*

## Dithering

- Drive one beam with a known frequency
- Detect the modulation of luminosity
- Nullify this component to optimise luminosity
- Developed at PEP II, implemented at SKEKB (horizontal)
- *Works for small beam-beam parameter*



# The FCC-ee Case

- FCC-ee has highly challenging beam parameters
- ~50nm vertical beam size at the IP
  - Highly sensitive to offset in vertical position and angle
- Long flat bunches “Knife shaped”
  - Low horizontal beam-beam parameter

**Must also consider impedance, cost...**

Parameter	Z	WW	ZH	tt
$\sigma_x$ [ $\mu\text{m}$ ]	8.84	21.8	13.1	39.9
$\sigma_y^{BS}$ [nm]	36.5	46.9	37.4	50.6
$\sigma_z^{BS}$ [mm]	15.5	5.41	4.70	2.17

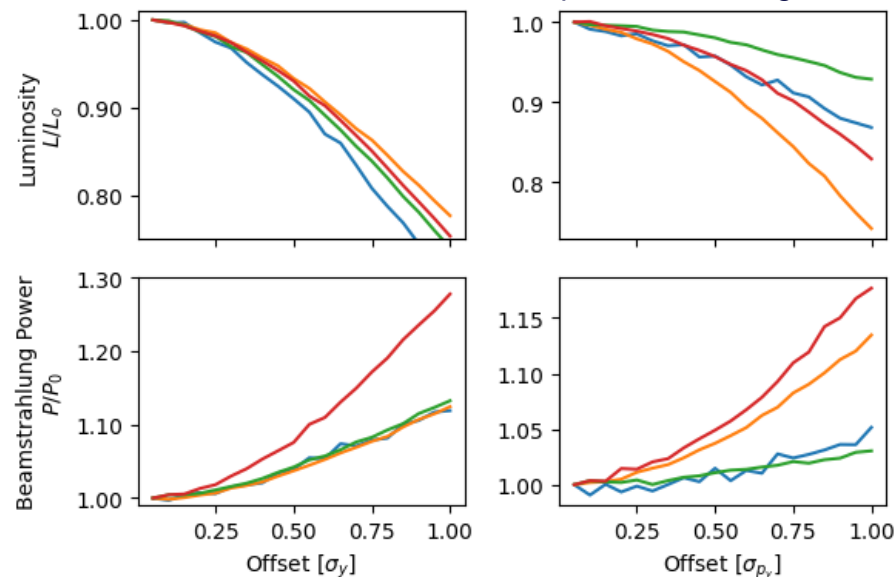
## Proposed strategy

- Beam-Beam deflection for the vertical plane
- Dithering for the horizontal plane
- Similar approach to SuperKEKB Design
  - Excellent opportunity to test the approach
  - More complicated at FCC-ee with 4IPs vs 1IP at SuperKEKB

# Design Considerations: Performance Requirements

- Many considerations in the design of such a system:
  - Required performance
  - Possible signals
  - And more...
- Performance requirements have implications for hardware design
  - Beam instrumentation requirements
  - Corrector magnet requirements
- Expected performance also directly impacts physics performance

Equilibrium luminosity and beamsstrahlung with beam-beam offset in vertical position and angle



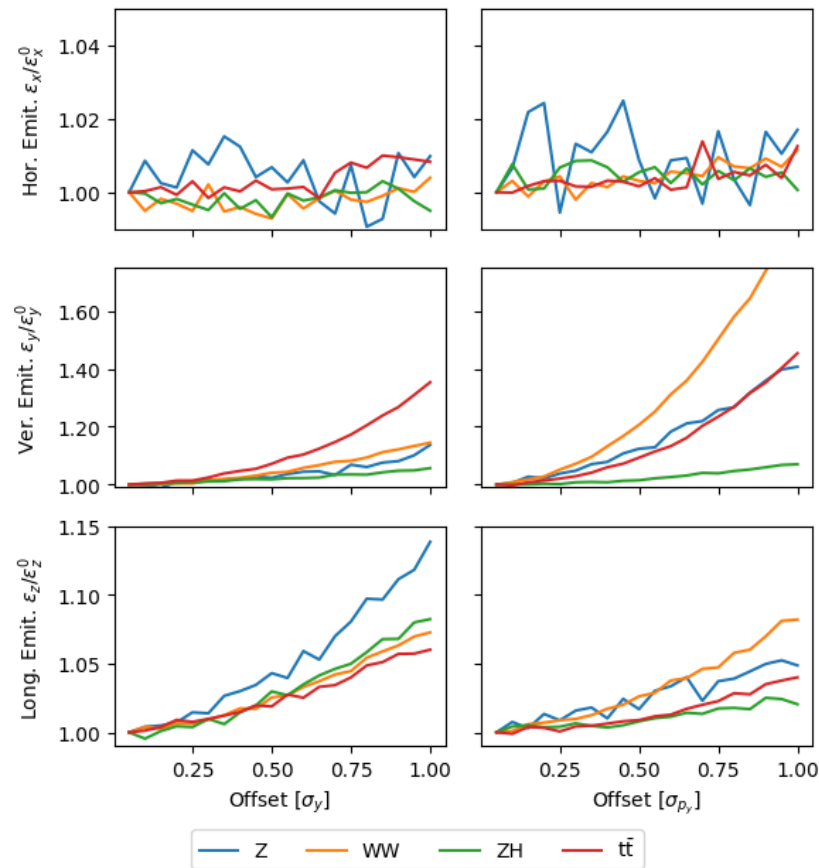
Naïve view: only consider equilibrium luminosity:

Only ~5% luminosity loss with a  $0.5\sigma$  offset 😊

# Performance Requirements: Machine Stability

- A step towards greater detail: Machine stability
  - Ensure particles are not lost and beam distribution is not irreparably damaged
- Tracking simulations performed with Xsuite
  - Weak-strong beam beam + linearised lattice
  - **Track to equilibrium with offset strong beam**
- Many aspects studied:
  - Emittance evolution
  - Luminosity degradation
  - Beamsstrahlung power
  - Beam distribution changes

Equilibrium emittance with beam-beam offset in vertical position and angle



# Performance Requirements: Machine Stability

Previous studies (CDR, 4IP version):

- Previous requirement: vertical orbit at IP **within**  $\sim 0.05\sigma_y$
- New Xsuite simulations benchmarked against these LIFETRAK studies

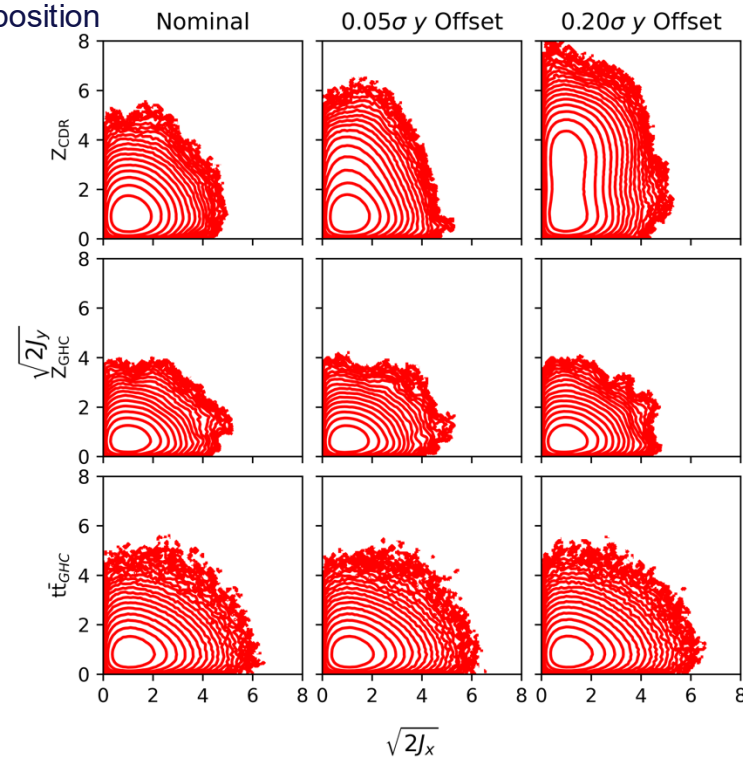
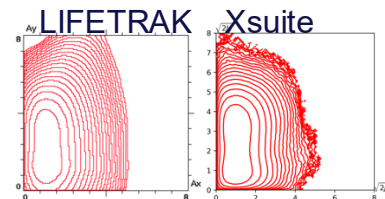
***New lattices are better optimised, and requirements are relaxed***

- Reduced beam core blowup
- Different resonance due to change in working point, but less aggravated by offsets

*So is the naïve luminosity only tolerance fine?*

Dmitry Shatilov

Equilibrium normalised action space distribution with beam-beam offset in vertical position



# Performance Requirements: Other Inputs

## Energy Calibration and Polarisation

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Beam energy measurements is influenced by IP offsets

Target 100keV CoM measurement:

**EPOL: Shift of 100keV for 1nm offset with 1um dispersion**

<https://doi.org/10.17181/zb0qc-acj59>

## Luminosity Detection

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IP centred within the detector within ~500um

Required by the luminosity calorimeter

Dictates the scale of the closed orbit bumps

## Misc.

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System must behave under interplay with global orbit feedback

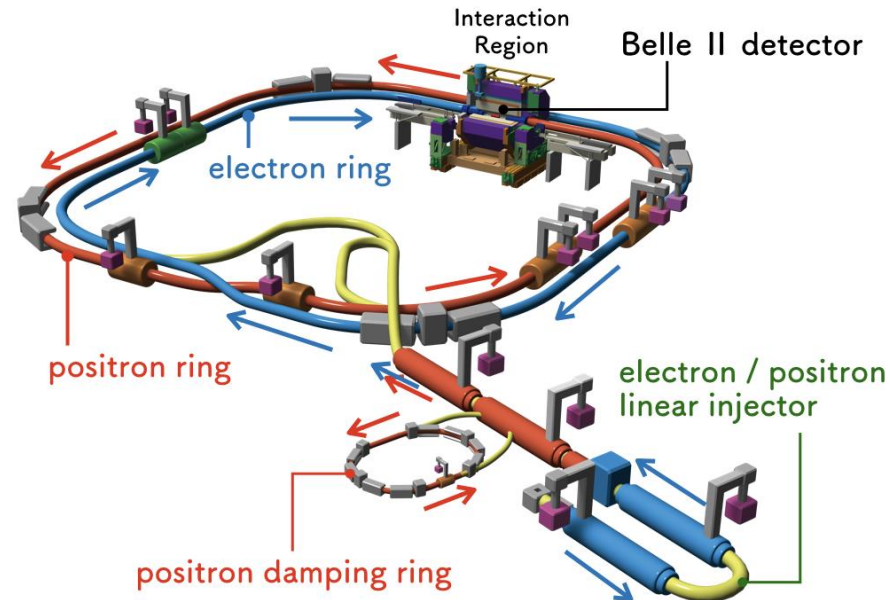
Frequency of correction depends on the vibrational modes of the final focus quadrupoles (under design)



# MODELLING SUPERKEKB IN XSUITE

# SuperKEKB

- Electron positron collider at KEK, Tsukuba Japan
- B factory, targeting the  $Y(4s)$  resonance (10.58 GeV)
- Asymmetric Double ring collider:
  - High Energy Ring (HER): electrons at 7 GeV
  - Low Energy Ring (LER): Positrons at 4 GeV
  - Highly boosted collision at the BELLE-II detector
- Current world record luminosity of  $5.1 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$ 
  - But still far below design luminosity of  $6.5 \times 10^{35} \text{cm}^{-2} \text{s}^{-1}$



# Motivation

## Benchmark simulation tools at an existing luminosity frontier lepton collider



- Large number of CERN studies on SuperKEKB:
  - IP Feedback studies (J. Salvesen)
  - Collimation studies (*G. Broggi*)
  - Optics studies (*J. Keintzel*)
  - Beam Based Alignment studies (*C. Goffing*)
  - Impedance studies (*R. Soos*)
  - Beam-beam studies (*P. Kicsiny*)
  - And many more...
- *SuperKEKB Beam-Beam working group*
- Interest from BELLE-II for IR upgrade model

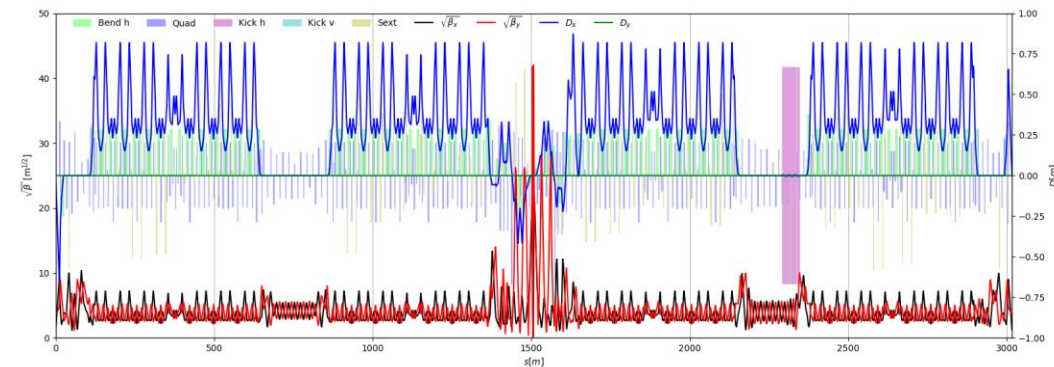
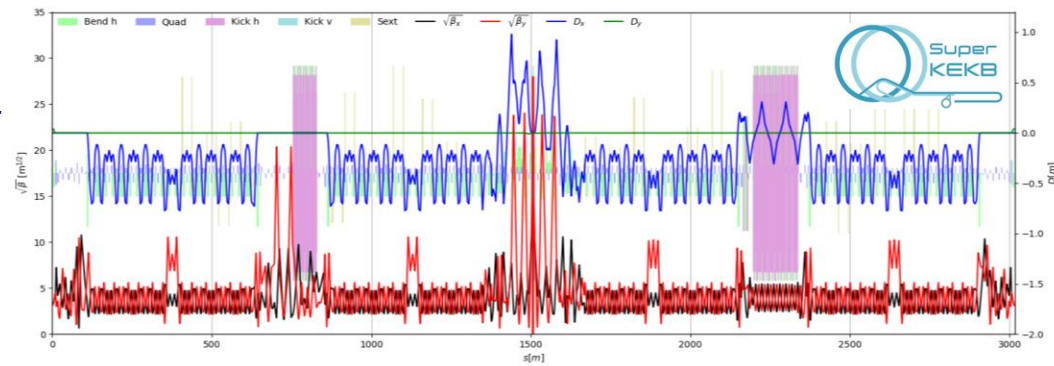
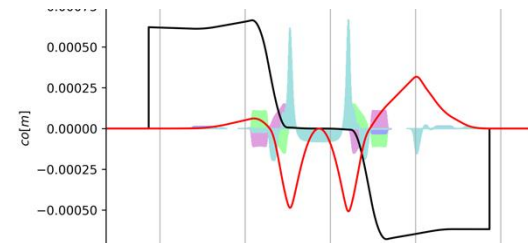
	Weak-strong 6D	Quasi-strong-strong 6D	Strong-strong 6D SG	Strong-strong 6D PIC	Beamstrahlung	Bhabha-scattering	Transverse wakefields	Longitudinal wakefields	Linear tracking	Lattice tracking	Open source	Runs on GPU
GUINEA-PIG [2]	Available	Not available	Available	Available	Available	Available	Available	Available	Available	Available	Available	Available
COMBI [3]	Available	Available	Available	Available	Available	Available	Available	Available	Available	Available	Available	Available
BBWS [4]	Available	Available	Available	Available	Available	Available	Available	Available	Available	Available	Available	Available
BBSS [5]	Available	Available	Available	Available	Available	Available	Available	Available	Available	Available	Available	Available
SCTR [6]	Available	Available	Available	Available	Available	Available	Available	Available	Available	Available	Available	Available
IBB [7]	Available	Available	Available	Available	Available	Available	Available	Available	Available	Available	Available	Available
LIFETRAC [8]	Available	Available	Available	Available	Available	Available	Available	Available	Available	Available	Available	Available
BeamBeam3D [9]	Available	Available	Available	Available	Available	Available	Available	Available	Available	Available	Available	Available
Xsuite [10]	Available	Available	Available	Available	Available	Available	Available	Available	Available	Available	Available	Available

Peter Kicsiny
Available
Not available

Whilst computationally expensive, with Xsuite functionality, full **self-consistent** simulations including many effects are possible *Lattice, Beam-beam, Space-Charge, Wakefields, Collimation, ...*

# SuperKEKB Lattice Conversion

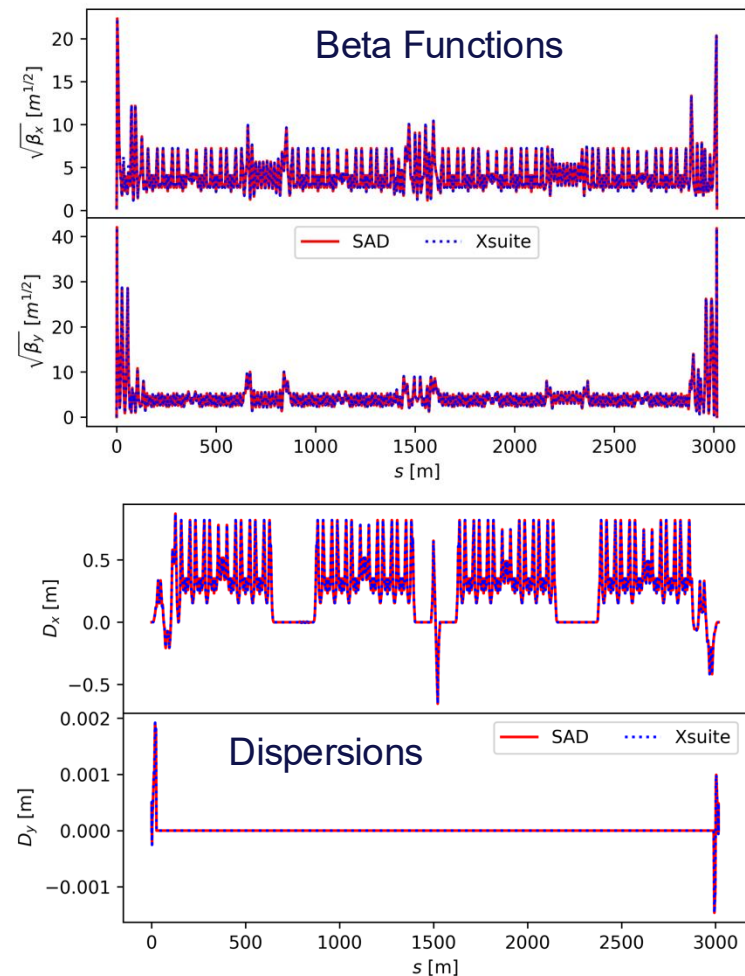
- Lattice conversion is non-trivial
  - Differences in fringe modelling, complex sliced IR region
  - See Recent eeFACT presentation: “*Consistent representation of lattices between optics code for FCC-ee, SuperKEKB, and more*”
  - <https://indico.jacow.org/event/75/contributions/6782/>
- Led to development of a SAD to Xsuite converter (SAD2XS, J. Salvesen, G. Iadarola)
  - Work in progress, not fully general*
  - Open source: <https://github.com/JPTS2/SAD2XS>
  - Tested on FCC-ee, J-PARC MR



# Optics Tests

- **Multiple lattices in development**
  - **SAD IR**, NOSOL, “Thick” FFQ + SOL
  - *Here showing SAD IR Model*
- Linear optics show excellent agreement
  - Rematching required due to modelling differences
  - Expect some optics deviation due to fringe modelling differences + rematching

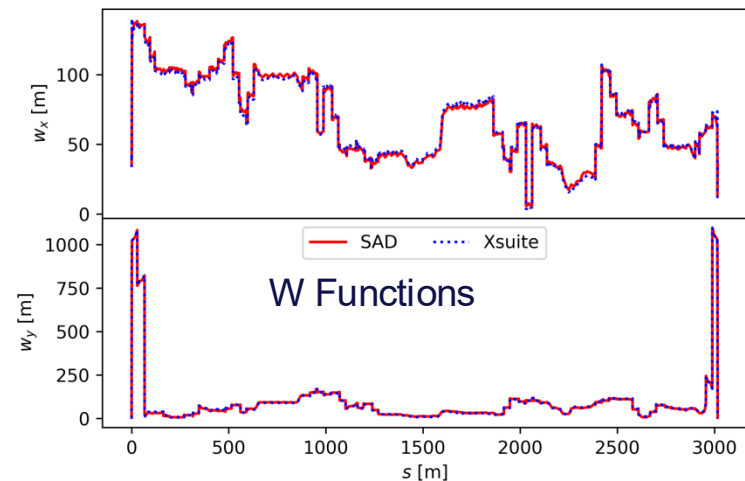
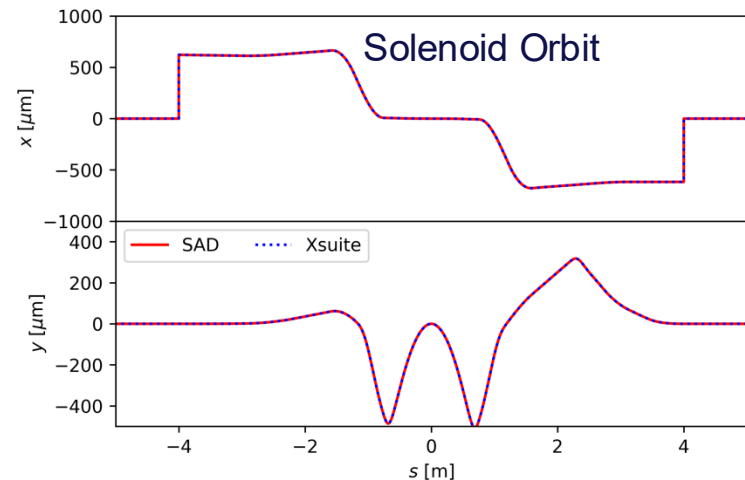
## HER



# Optics Tests

- **Multiple lattices in development**
  - **SAD IR, NOSOL, “Thick” FFQ + SOL**
  - *Here showing SAD IR Model*
- Solenoid region strictly benchmarked as the defining feature of the lattice
- Non-linear optics under initial investigation
  - Overall agreement good
  - Deviation expected due to linear optics rematching: sextupoles see different beta
  - No non-linear rematching

## HER



# Beam Beam Studies

- **Beam beam installation working**
  - Tested in Weak-Strong and Strong-Strong configurations
- **Benchmarking**
  - Installation of beam-beam element benchmarked vs expected beam beam tune shifts
  - Tune shifts agree within 1%

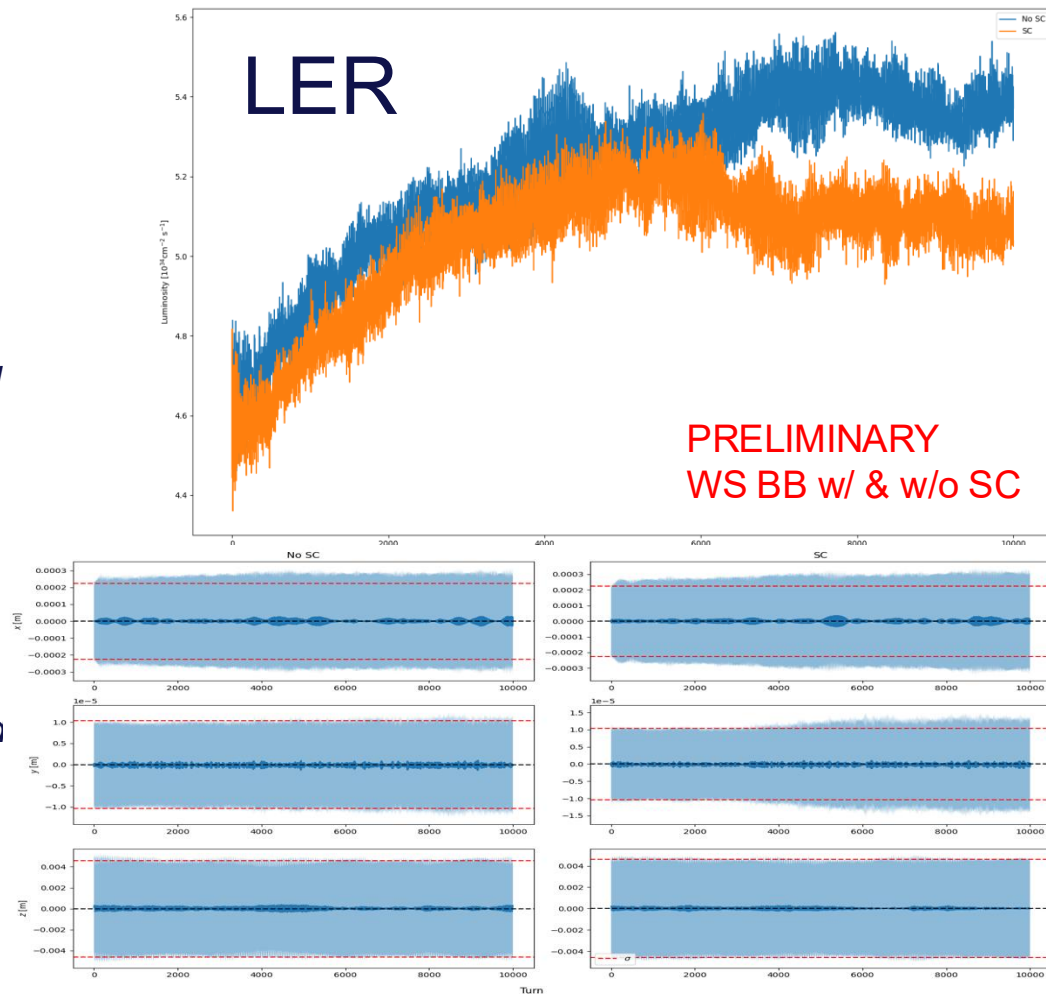
$$\Delta\nu_{y,bb} = \xi_{bb}^{(\pm)} = \frac{N^{(\mp)} r_e}{2\pi\gamma^{\pm}} \frac{\beta_y^*}{\sigma_y^* \sigma_x^* \sqrt{1 + \theta_P^2}}$$

Parameter (08/06/22)	Unit	LER	HER
Norm. Hor. Emitt.	mm.mrad	31.4	62.9
Norm. Vert. Emitt.	mm.mrad	0.362	0.633
RMS Bunch Length	mm	4.6	5.1
Bunch Intensity	1E9	36.86	30.71
N. Bunches	1	2300	

```
#####
LER Tune Shift
#####
D. Zhou Formula [1E-3]:      (3.120, 38.470)
Xsuite Calculated [1E-3]:    (3.112, 38.354)
Relative Difference [%]:      (-0.267, -0.302)
#####
HER Tune Shift
#####
D. Zhou Formula [1E-3]:      (1.970, 29.260)
Xsuite Calculated [1E-3]:    (1.964, 29.362)
Relative Difference [%]:      (-0.310, 0.349)
#####
```

# Combined studies

- Initial combined effects studies have been performed
  - Studies are in the early testing phase
  - Currently at proof of concept stage- detailed simulations to come as the lattices are further benchmarked**
  - Some effect with space charge is observed- driving some blowup in the vertical plane
- In this simulation, space charge is excluded from the IR*
  - Major orbit impact when space charge elements occur within the sliced IR region

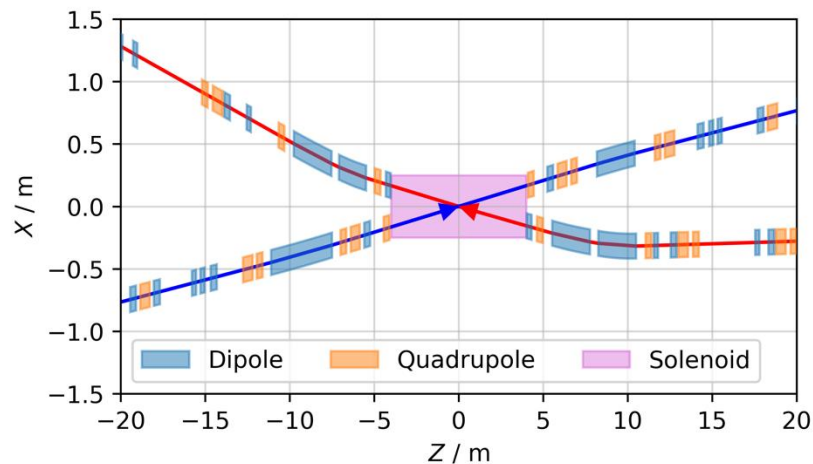




# OUTLOOK

# Outlook

- IP Feedback
  - *New lattice working points show greater tolerance to offsets*
  - *100keV energy measurement is a challenging target, both for IP tuning knobs (v. disp.) and for IP Feedback (v. offset)*
  - *Further studies using full non-linear lattice and future full feedback simulations planned*
- SuperKEKB Modelling
  - *Excellent agreement observed so far*
  - *Many technical improvements to Xsuite from this effort*
  - *Many interested users*
  - *We look forward to benefiting from collaboration and testing- please get in touch!*





Thank you  
for your attention.



# APPENDIX A: FCC-EE MODELLING

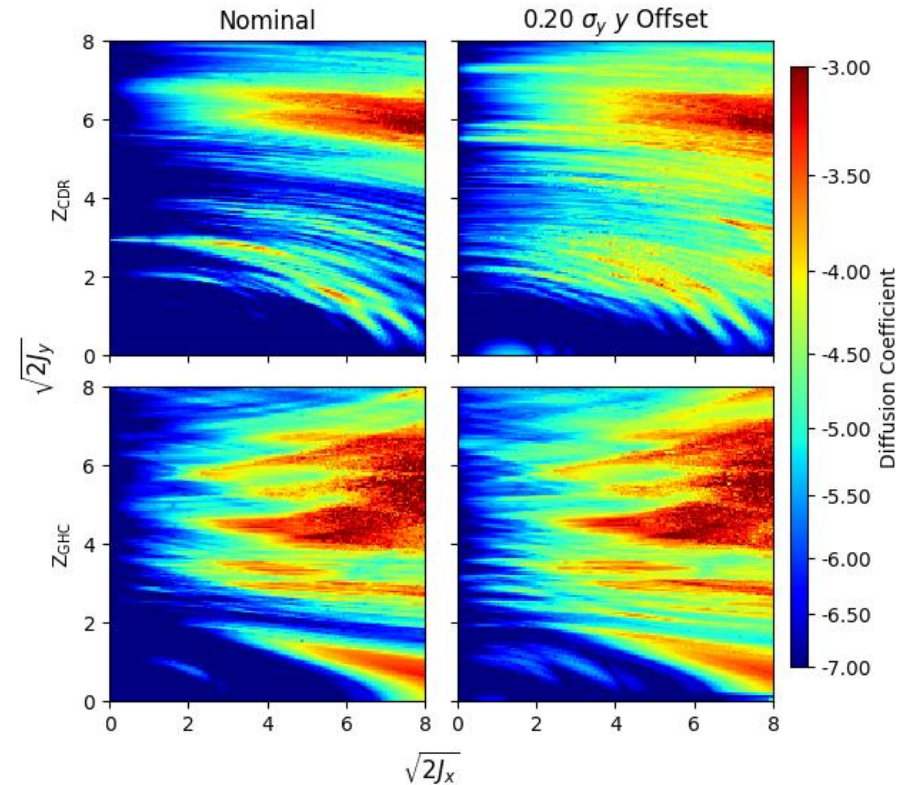
# Simulation Description

- Linear lattice:
    1. Crab Sextupole (thin)
    2. CS to IP Transfer Map
    3. Beam-beam element
    4. IP to CS Transfer Map
    5. Crab Sextupole (thin)
    6. Arc Transfer Map (SR damping + noise)
  - Tracked for eight longitudinal damping times
  - At Z 1000 particles tracked (due to long damping time) leading to greater noise
  - At WW, ZH, tt, 10,000 particles tracked
- Beam-beam
    - Installed in weak strong mode
    - Strong beam held offset
    - Weak beam distribution analysed
    - Linear lattice  $\frac{1}{4}$  turn so models identical offset at all IPs

# Performance Requirements: Machine Stability

***New lattices are better optimised, and requirements are relaxed***

- By comparison to CDR very different tune working point
- Seen in different resonances in tune space
- Change in diffusion with offset seems reduced with the GHC lattice





# APPENDIX B: SUPERKEKB XSUITE LATTICE

# Relevant Presentations

- **Report on IP Feedback studies at SuperKEKB**
  - 188<sup>th</sup> FCC-ee Accelerator design meeting & 59<sup>th</sup> FCCIS WP2.2 Meeting [10/07/24]
  - <https://indico.cern.ch/event/1433104/>
- **Introduction to Xsuite: An integrated beam physics simulation framework**
  - SuperKEKB MDI Taskforce meeting [19/12/24]
  - <https://kds.kek.jp/event/52865/>
- **Update on SuperKEKB Xsuite Modelling**
  - コミッショニング・ミーティング (56) [13/12/24] {*Commissioning Meeting (56)*}
  - <https://kds.kek.jp/event/53089/>
- **SuperKEKB Xsuite Model Development**
  - Modelling SuperKEKB with Xsuite [30/10/24]
  - <https://indico.cern.ch/event/1471245/>
- **Update from December 2024 EAJADE Secondment**
  - 200<sup>th</sup> FCC-ee Accelerator design meeting & 71<sup>st</sup> FCCIS WP2.2 Meeting [16/01/25]
  - <https://indico.cern.ch/event/1497833/>
- **Advancing the SuperKEKB Lattice in Xsuite**
  - Belle-II Beam Background Group Meeting [29/01/25]
  - <https://indico.belle2.org/event/14239/>

# Ex. SAD2XS development

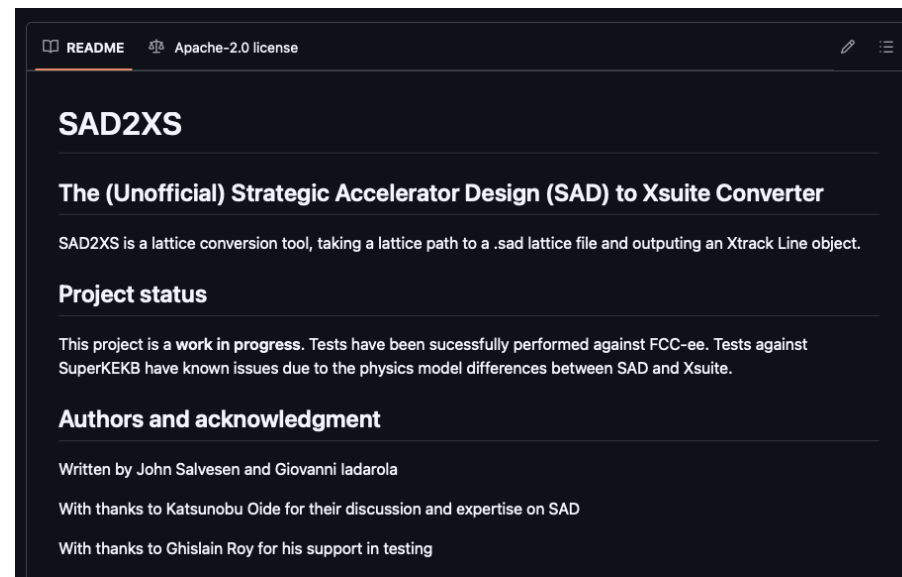
## Converts a SAD lattice file to a Xsuite Line

- Authors: *John Salvesen, Giovanni Iadarola*
- Status: Active development
- Tested on: SuperKEKB, FCC-ee, JPARC MR
- Open source: <https://github.com/JPTS2/SAD2XS>
  
- Tests and improvements ongoing! If you are interested in new features, please contact me!

**N.B. SAD2XS is not a part of the Xsuite software package.**

## Example use-case

In deployment in personal FCC-ee workflow to convert native SAD FCC-ee lattice to Xsuite for tracking and beam-beam studies



The screenshot shows the GitHub README for the SAD2XS project. At the top, it indicates the license is Apache-2.0. The main heading is "SAD2XS". Below that, it describes the project as "The (Unofficial) Strategic Accelerator Design (SAD) to Xsuite Converter". A brief description states: "SAD2XS is a lattice conversion tool, taking a lattice path to a .sad lattice file and outputting an Xtrack Line object." The "Project status" section notes that the project is a work in progress, with successful tests against FCC-ee and known issues against SuperKEKB. The "Authors and acknowledgment" section lists John Salvesen and Giovanni Iadarola as authors, and thanks Katsunobu Oide and Ghislain Roy for their contributions.

# Space Charge installation

- **Space Charge installation working**
  - Tested in frozen mode, but PIC and quasi-frozen modes also possible
- **Benchmarking**
  - Installation of space-charge elements benchmarked vs expected tune shifts
  - Close agreement vs formula + integration
- **Highly sensitive to element location**
  - *For tune shift benchmarking, the IR region is excluded*

Parameters also taken from June 8, 2022, Parameter table

## Space charge tune shift

- Tune shift

$$-\Delta\nu_{y,sc} = \xi_{sc} = \frac{Nr_e}{(2\pi)^{3/2}\sigma_z\beta^2\gamma^3} \oint ds \frac{\beta_y}{(\sigma_x + \sigma_y)\sigma_y}$$

```
#####
LER Tune Shift
#####
K. Ohmi Formula [1E-3]:      (-1.163, -17.792)
Xsuite Calculated [1E-3]:   (-1.174, -17.455)
Relative Difference [%]:    (1.001, -1.892)
#####

#####
HER Tune Shift
#####
K. Ohmi Formula [1E-3]:      (-0.166, -2.499)
Xsuite Calculated [1E-3]:   (-0.168, -2.456)
Relative Difference [%]:    (1.297, -1.714)
#####
```