DEVELOPMENT OF THE IP FEEDBACK SYSTEM FOR FCC-ee

J. Salvesen

FCC UK Meeting 12/11/2025

Funding statement

EAJADE

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EAJADE
Europe-America-Japan Accelerator Development Exchange Programme

FCCIS

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FUTURE CIRCULAR COLLIDER

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FCC-ee Modelling

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SuperKEKB Optics Modelling

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SuperKEKB Data Acquisition

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EAJADE coordinators, who enabled my collaboration with KEK

And many more

ABOUT ME

About me

Who Am I

John Salvesen (Jack)

Doctoral Student at CERN: BE-ABP-INC

DPhil Candidate at Oriel College, University of Oxford

CERN Supervisor: *Frank Zimmermann*

University Supervisor: *Phil Burrows*

Project within FCCIS Task 2.3: "Interaction region and machine detector interface design"

Under EAJADE Work package 3: *"Special technologies, devices and systems performance"*

Thesis Goal

Develop a realistic, self-consistent, model of the FCC-ee IP collision feedback system

Including (but not limited to)

- Evaluation of the measurable signals
- Evaluation of machine tolerances
- Feedback hardware considerations

Timeline

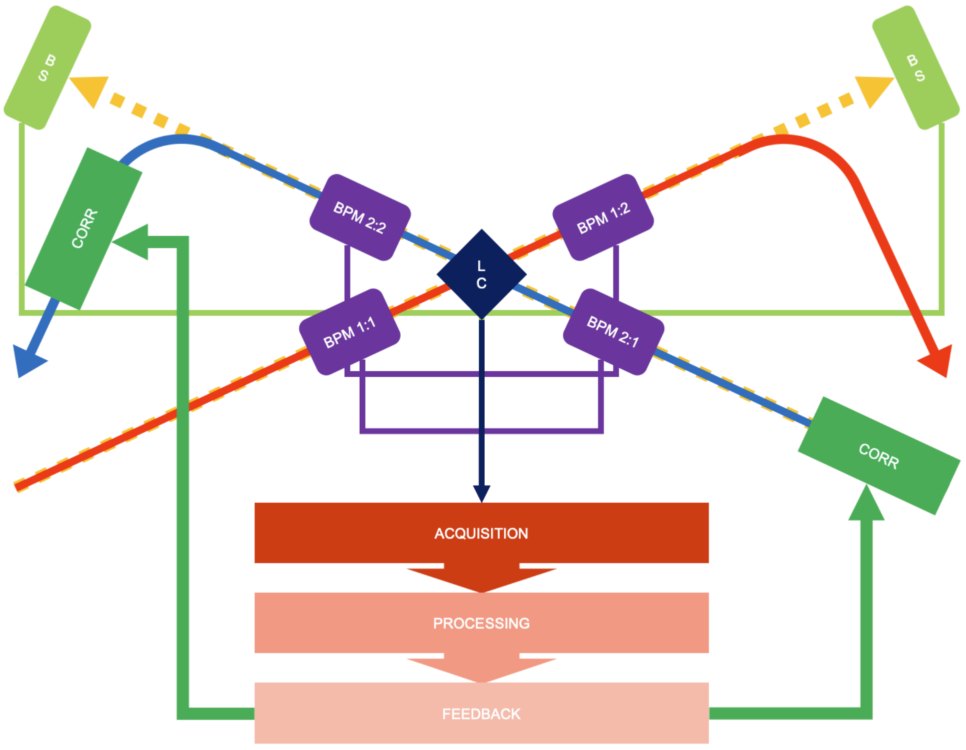
JAI Course Start:	01/10/22
CERN contract start:	01/04/23
CERN contract end:	31/03/26

*Ultimately, to study the **luminosity** performance with feedback in the presence of machine **errors***

Interaction Point Feedback?

Interaction point (IP) feedback locally corrects the beam orbit ***to maintain 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

- Detect an offset using a combination of upstream and downstream BPMs (or by using beamstrahlung light)
- Requires resolution of the monitor better than the downstream offset
- For small offsets (the case required for beam stability) well approximated by the linear model
- Implemented at SLC and SKEKB (vertical)
- *For large beam-beam parameters*

Dithering

- Applies in cases where beam beam parameter is small (all horizontal except tt)
- 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 (horizonal)

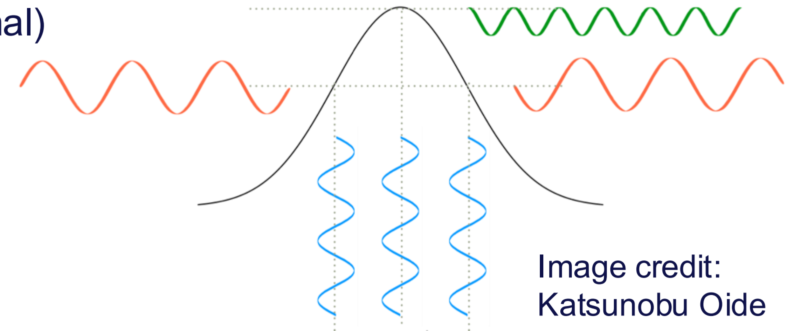


Image credit: Katsunobu Oide

OVERVIEW OF STUDIES

Structure of studies

Not addressed in this talk

Analytic Feedback Modelling
- Estimates of error sources
- PID Optimisation

→

SuperKEKB Data Analysis
- Performance of current systems
- Operational aspects of current systems

→

SuperKEKB Simulation
- Optics modelling of SuperKEKB
- Feedback in simulation

→

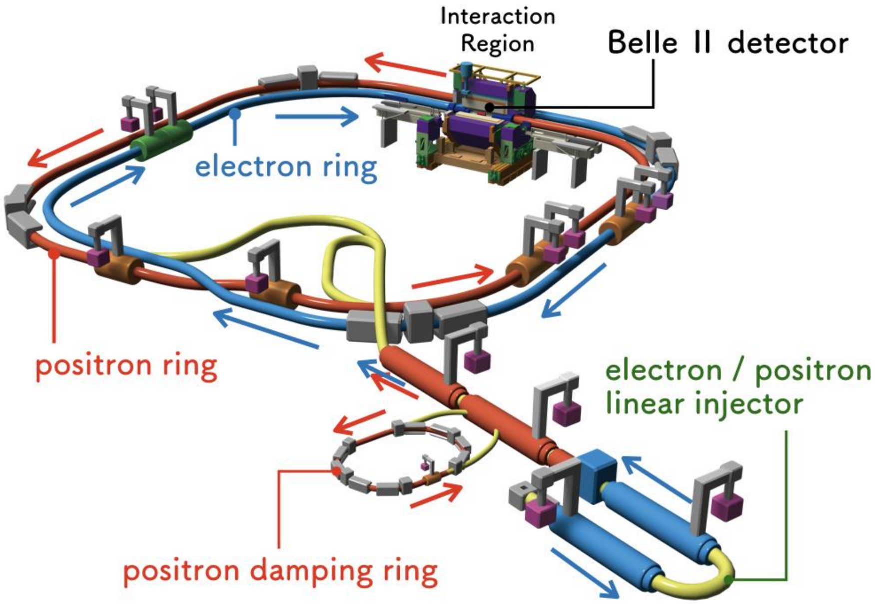
FCC-ee Simulation
- Tolerance identification
- Feedback signal identification
- Feedback in simulation

+some adventures into proton territory with the J-PARC MR

SUPERKEKB FEEDBACK STUDIES

SuperKEKB

- Electron-positron double ring collider, Tsukuba Japan
- B factory, targeted at the Y(4s) resonance (10.58 GeV)
- High Energy Ring (HER): electrons at 7 GeV
- Low Energy Ring (LER): positrons at 4 GeV
- Highly boosted collision
- Experiment: Belle II
- Current world record luminosity of $5.1 \times 10^{34} cm^{-2}s^{-1}$
  - Still far below design luminosity of $6.5 \times 10^{35} cm^{-2}s^{-1}$



SuperKEKB IP Feedback

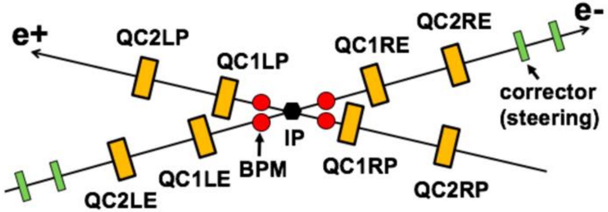
iBump Deflection feedback (KEK)

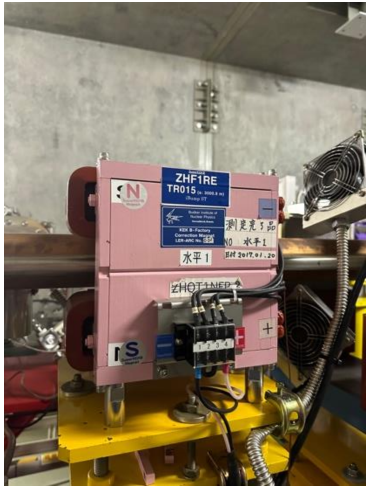
- FPGA based fast feedback (32kHz)
- BPMs ~0.5m from IP
- Matrix approach: offset at IP from BPM readings (linear)
- Dedicated horizontal and vertical correctors in IR straight

Dither Feedback (SLAC)

- Currently unused
- Air cooled, yoke free correctors (left) in IR straight

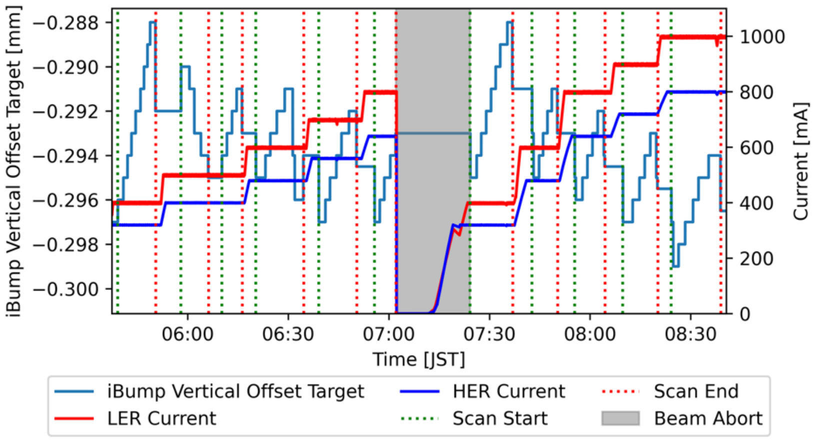
- **LER (e+) beam corrected with global feedback only**
- **HER (e-) beam corrected with IR correctors**

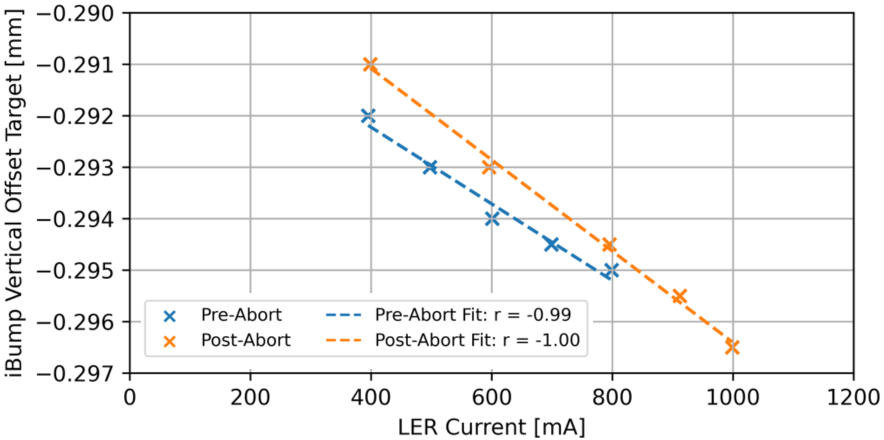


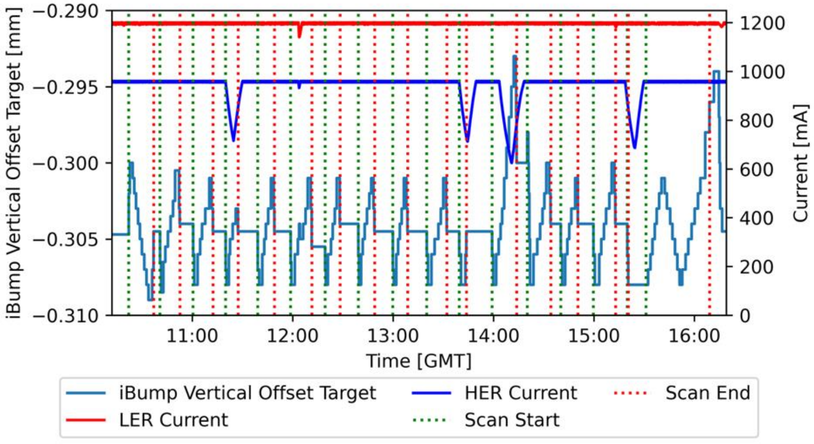


iBump FB: MDs

- **Feedback target: Free parameter to account for errors in IP offset calculation**
  - BPM errors, transfer matrix errors…
- Two MD periods (June 2024, December 2024)
  - iBump FB Target is observed to drift with current
  - Feedback target is constant in stable beam conditions

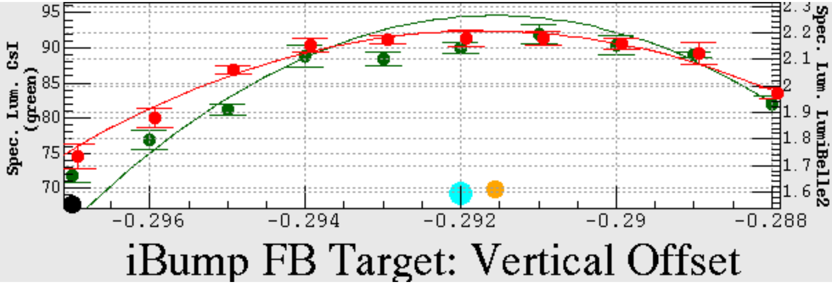


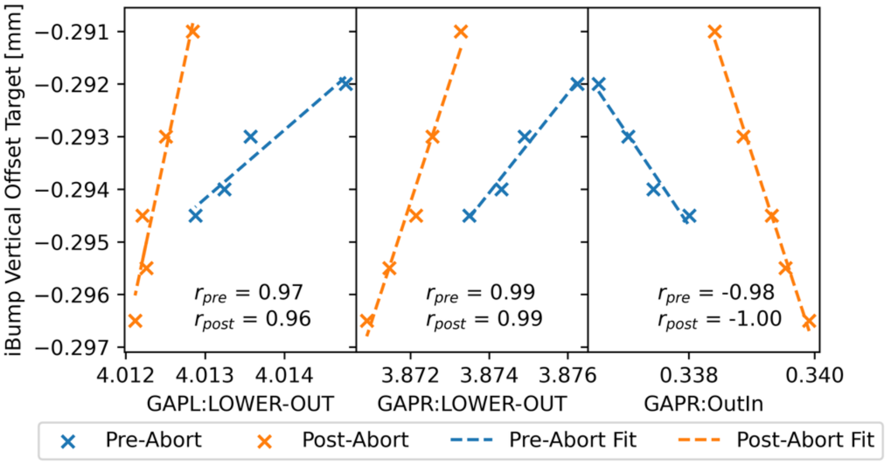




Other key takeaways

- **Luminosity degradation is low for small deviations in feedback target**
  - Luminosity within error bars over a range around optimal
  - Large degradation far from optimal
- **Machine aborts cause hysteretic changes in the machine state**
  - E.g. FFQ motion clearly visible (even without quench)
  - Impact of SR/BS heating on the beampipes and motion?
  - *Require retuning of collisions at every abort*





SUPERKEKB SIMULATION

Motivation

Xsuite

Benchmarking simulations at an existing luminosity frontier lepton collider

- Large number of CERN studies on SuperKEKB:
  - Collimation studies (*G. Broggi, G. Nigrelli*)
  - Optics studies (*J. Keintzel*)
  - Beam Based Alignment studies (*C. Goffing*)
  - Impedance studies (*R. Soos*)
  - Beam-beam studies (*P. Kicsiny*)
  - And more…
- *SuperKEKB Beam-Beam working group*
- Interest from BELLE-II
- And more….

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

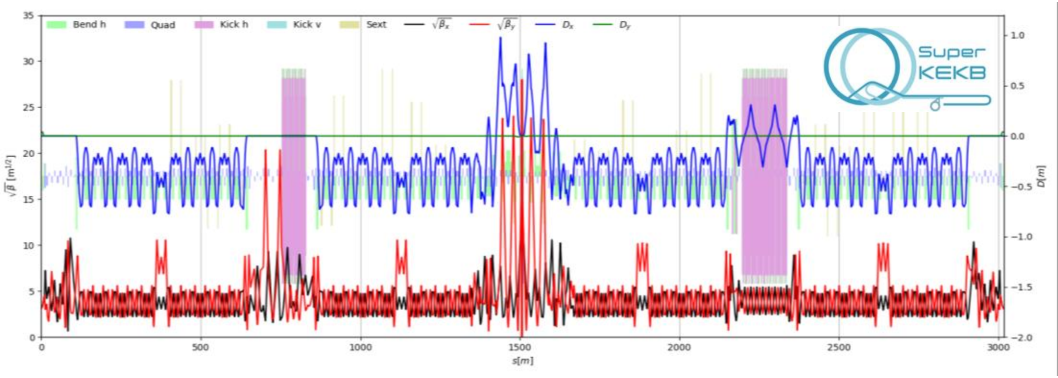
	Weak-strong 6D	Quasi-strong-strong 6D	Strong-strong 6D SG	Strong-strong 6D PIC	Beamstrahlung	Bhabha-scattering	Transverse wakefields	Longitudinal wakefields	Linear tracking	Lattice tracking	Open source	Runs on GPU
GUINEA-PIG [2]	Available	Not available	Not available	Available	Available	Available	Not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

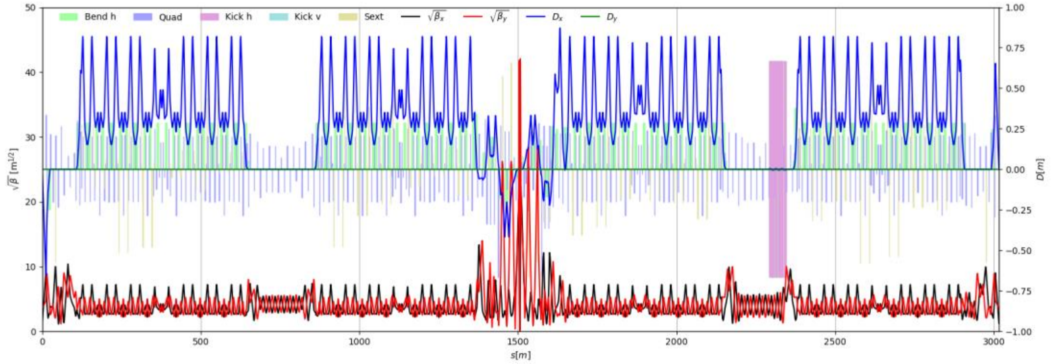
Peter Kicsiny CHART

Available | Not available

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)
  - Work in progress
  - Open source: https://github.com/JPTS2/SAD2XS

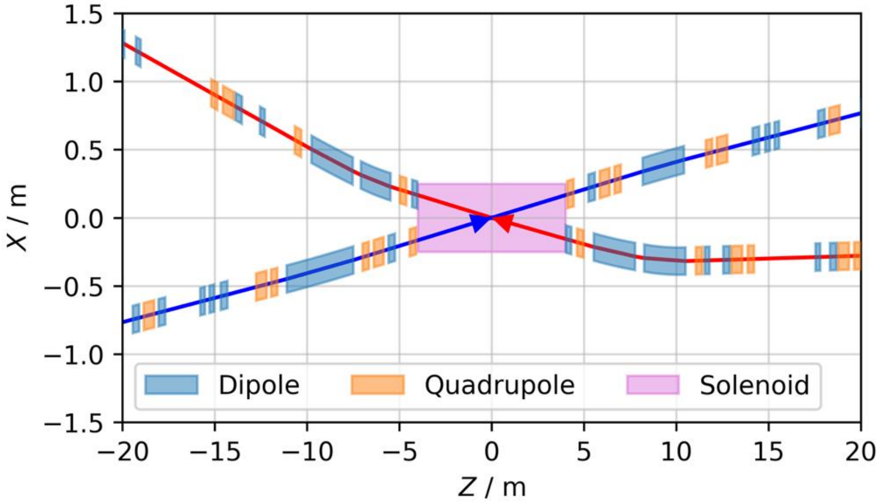




Implementing iBump Feedback in Xsuite

Many features addressed:

- *Monitors at real BPM locations*
- *CO bump knobs generated pre tracking, then used during simulation*
- *Offsets calculated from BPM measurements (not just measured artificially)*



However, some features left out

- *No magnet ramping*
- *No beam-pipe eddy currents*
- *BPM resolution ignored (partly because…)*
- *Only 2 bunches…*

Offset calculated from measurements of y at 4 BPMs
Then calculate y' at the IP in and out
Difference gives beam-beam deflection during collision
This gives the offset

But to get this right, need Strong-Strong!

Does it work?

Initial results are promising:

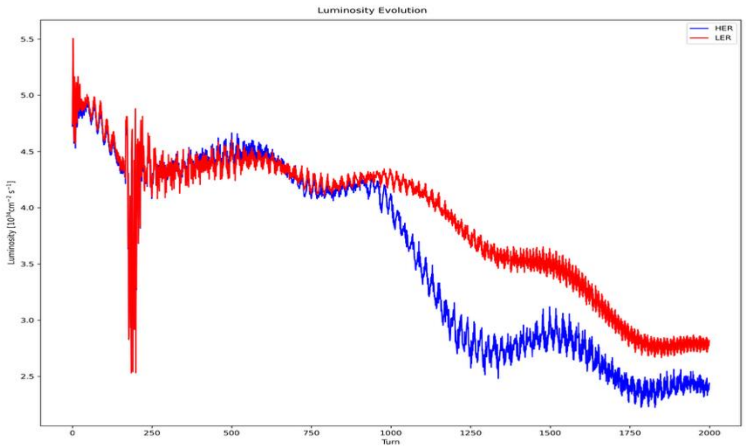
- *Beams track each other well*
- *The offset is well attenuated in response to driven error*

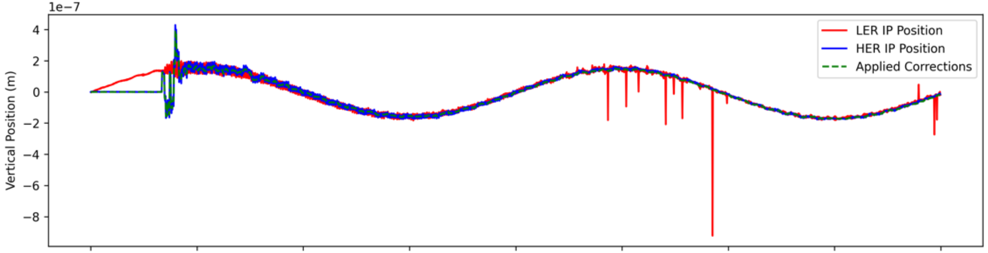
But there are lattice issues:

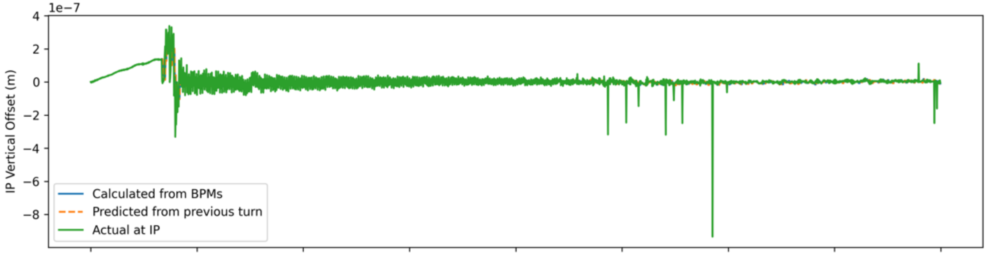
- *Clear emittance blowup seen- noted when running without errors and feedback*
- *Troubleshooting ongoing*

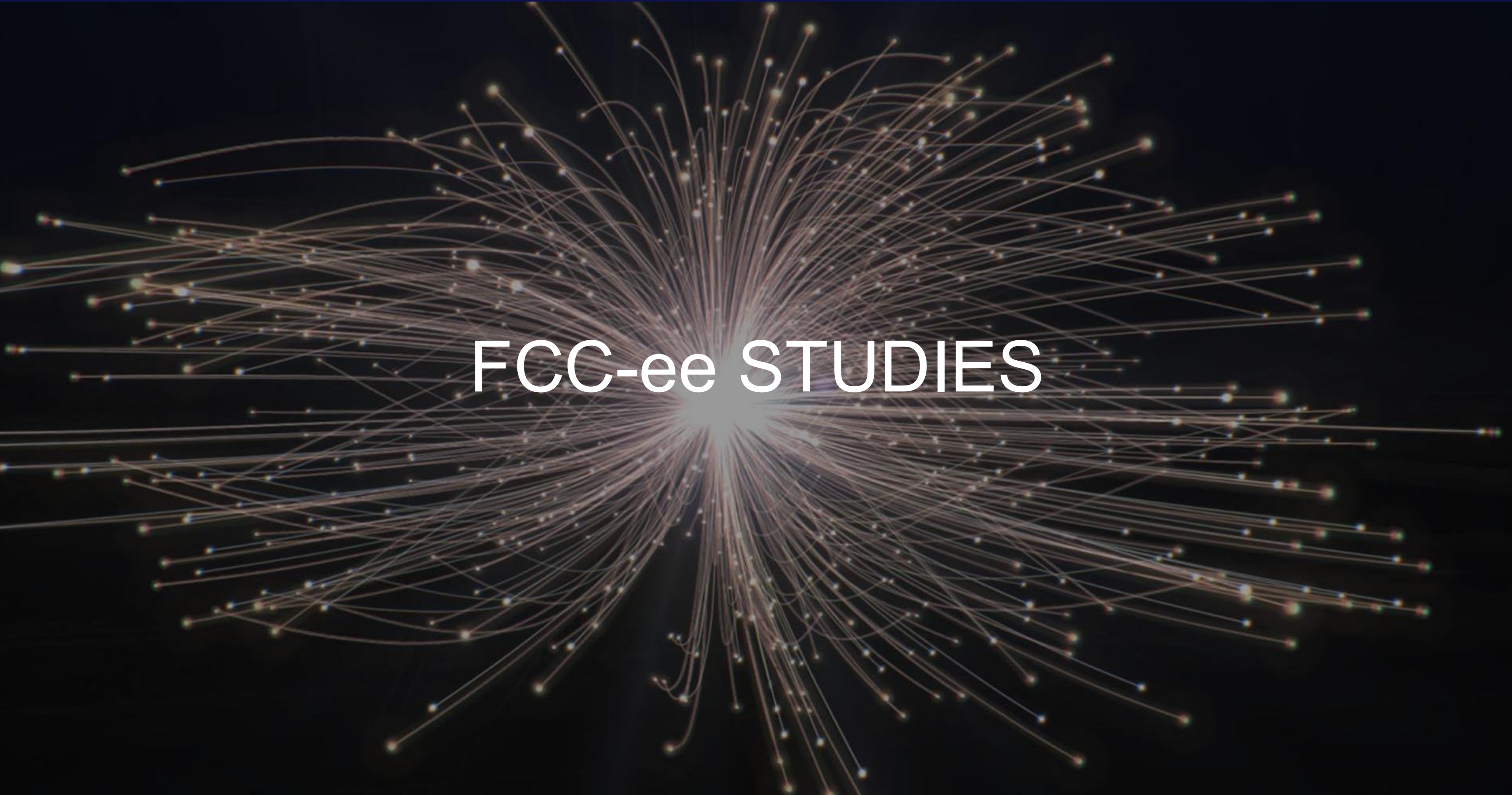
It's a very expensive simulation

- *Need Quantum SR for emittances*
- *Need full lattice for offset orbit*
- *Need strong-strong BB for deflection*









FCC-ee STUDIES

Overview

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

Must also consider impedance, cost…

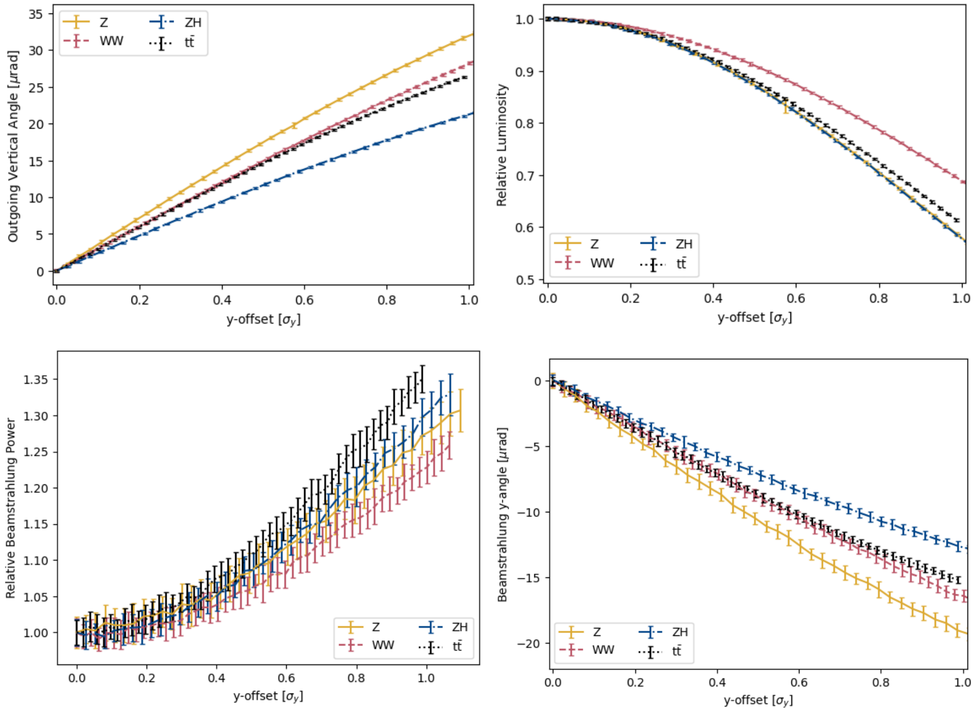
Parameter	Z	WW	ZH	tt
σ_x [μm]	8.84	21.8	13.1	39.9
σ_y^{BS} [nm]	36.5	46.9	37.4	50.6
σ_z^{BS} [mm]	15.5	5.41	4.70	2.17

Proposed strategy

- Beam-Beam deflection for the vertical plane
- Dithering for the horizontal plane
- Similar approach to SuperKEKB Design

Feedback Signals

- Simulations performed using **GUINEA-PIG**
  - Single bunch crossings, PIC code
- Each signal has its challenges
  - Beam-beam deflection
    - L* 2.2m, BPM at 1.1m
    - To detect ~nm offsets at IP, **need sub micron BPM accuracy**
    - Low beam-beam parameter in horizontal
  - Luminosity
    - Scalar signal
  - Beamstrahlung
    - High power load (~300kW at Z)
    - May not be possible to detect with sufficient accuracy at these power loads

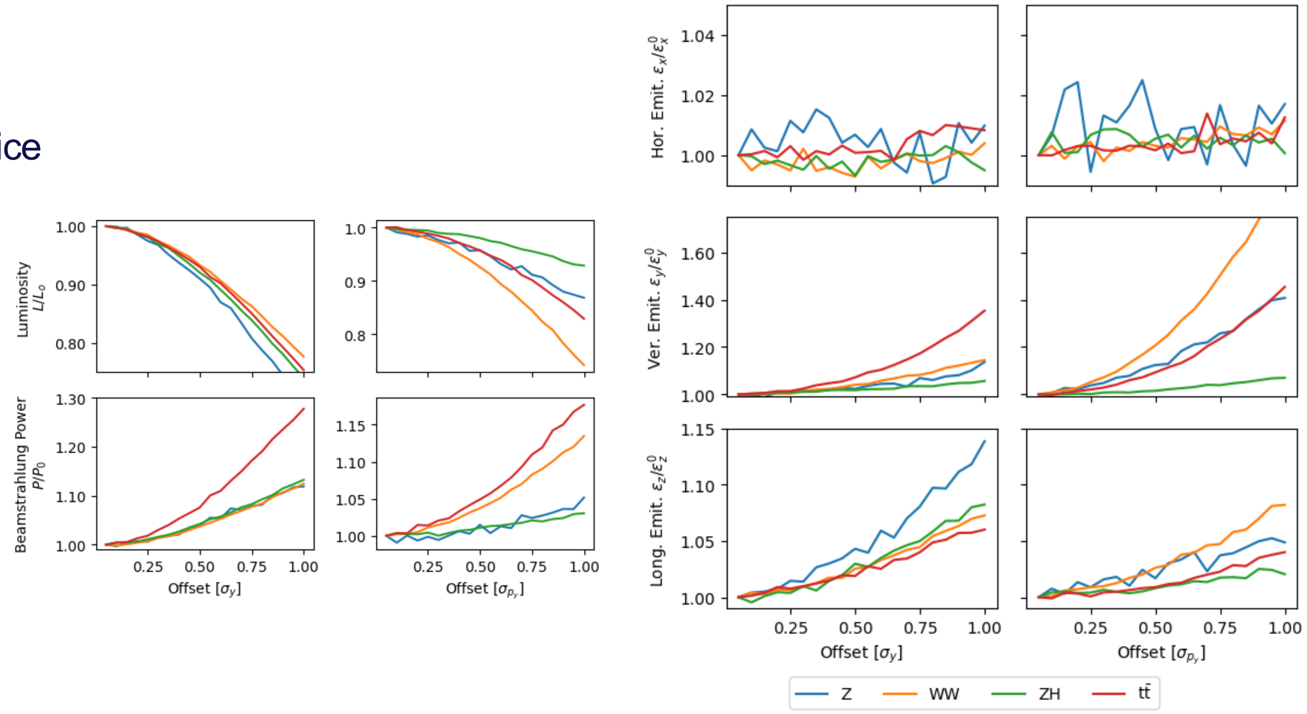


BS Power [kW]	Z	WW	ZH	tt
Nominal	229	95.5	63.6	40.2
GP 1 σ_x offset	239	94.0	63.4	29.0
GP 1 σ_y offset	299	120	84.5	54.3

Performance Requirements: Machine Stability w.r.t. Offsets

- Tracking simulations performed with Xsuite
  - Weak-strong beam beam
  - Linearised lattice
  - Planned to move to fully lattice

- Many aspects studied:
  - Emittance evolution
  - Luminosity degradation
  - Beamsstrahlung power
  - Beam distribution changes



Performance Requirements: Machine Stability

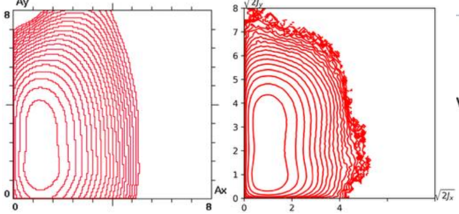
Previous studies (CDR):

- Studies performed using LIFETRAK
- CDR lattice (4 IP) required vertical orbit at IP **within** $\sim\mathbf{0.05}\boldsymbol{\sigma_y}$
- New Xsuite simulations benchmarked against this

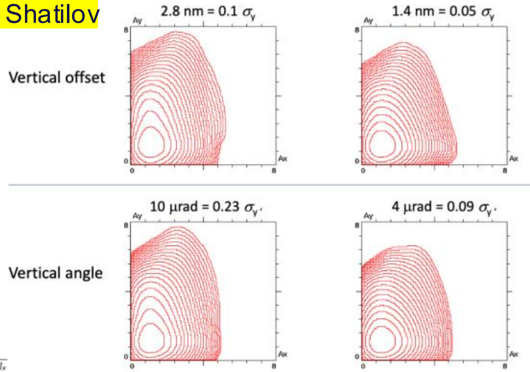
New lattices are better optimised, and requirements are relaxed

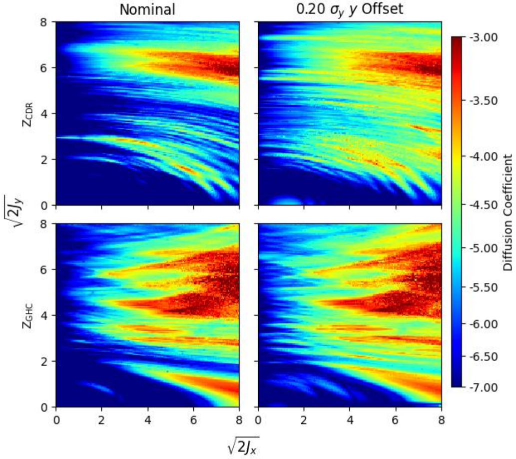
- Reduced beam core blowup
- Different resonance due to change in working point, but less aggravated by offsets

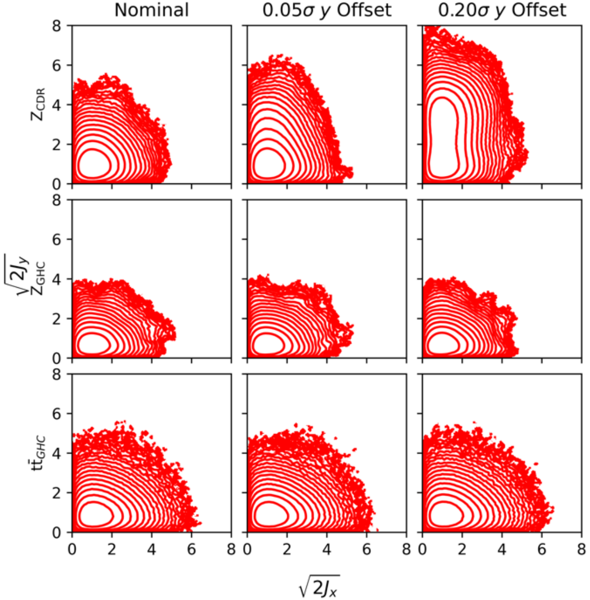
LIFETRAK Xsuite



Dmitry Shatilov







Performance Requirements: Other Groups

Energy Calibration and Polarisation

Beam energy measurements is influenced by IP offsets

Target 100keV CoM measurement:

Shift of 100keV for 1nm offset with 1um dispersion

Luminosity Detection

IP centred within the detector within ~500um

Required by the luminosity calorimeter

Dictates the scale of the closed orbit bumps

Misc.

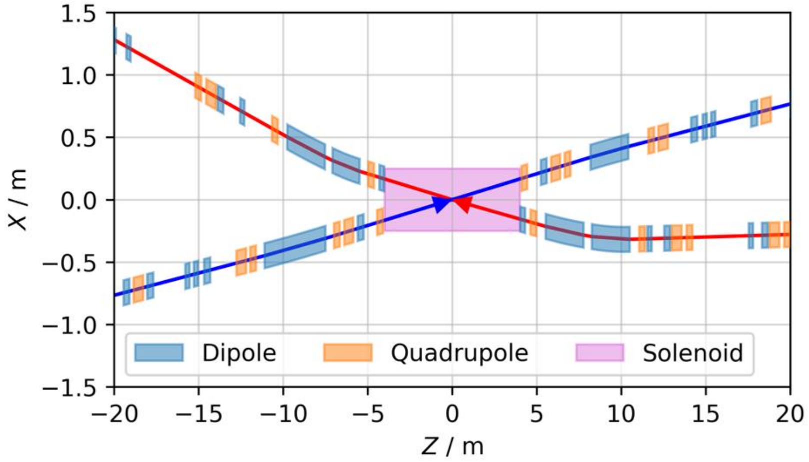
System must behave under interplay with global orbit feedback

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

OUTLOOK

Outlook

- Varied studies across a range of tools and machines
  - *FCC-ee Beam-Beam with GUINEA-PIG and Xsuite*
  - *SuperKEKB Optics modelling with SAD and Xsuite*
  - *SuperKEKB Beam-Beam with GUINEA-PIG and Xsuite*
  - *Xsuite optics work has led to efforts on other lattices, including J-PARC MR*
- Further work ahead of thesis
  - *Finalise a test feedback system in the FCC-ee lattice*
- Where possible, continue to engage with international collaborative efforts!



Thank you
for your attention.

APPENDIX A: ANALYTIC MODELLING

How to quickly test feedback approaches?

To test the response to a range of frequencies need to take a ***systems analysis approach***

Look at the response function of the system to a range of different frequencies

To scan over such a range of frequencies need a model that is:

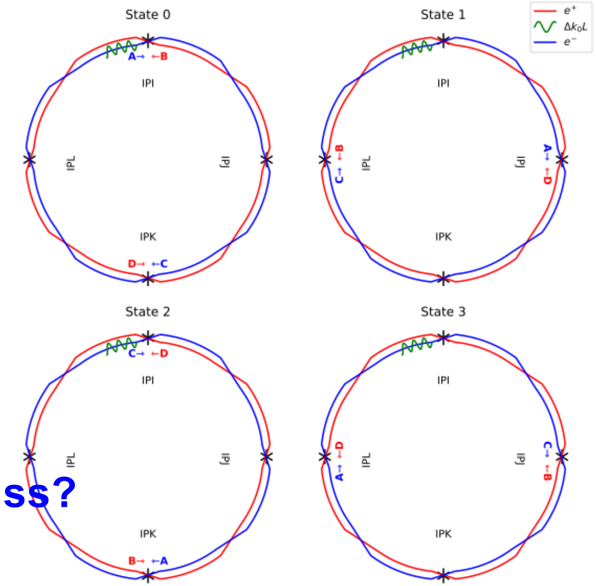
- Fast!
- Well understood
- Expandable

→ **Analytic modelling**

Model Description

Vertical only (y, y')

- Transfer IP to IP with transfer matrix
  - *Linear Optics only*
- Drift back from IP to FFQ with error
  - Sinusoidal error at a single frequency per test
- Apply correction bump
  - *Based on feedback prediction*
- Linear Beam-Beam force at the IP
- Close correction bump
  - Perfect CO bump
- Continue to next IP….
- At end of turn, perform feedback calculation



What does this miss?

- Radiation damping
- Coupling
- Horizontal plane
- Emittance growth (single particle per bunch for centroid motion)

Sacrifices made for ensure computational efficiency-

10,000 turns for 1000 frequencies per test

How to analyse?

The system has a natural response to driven errors:

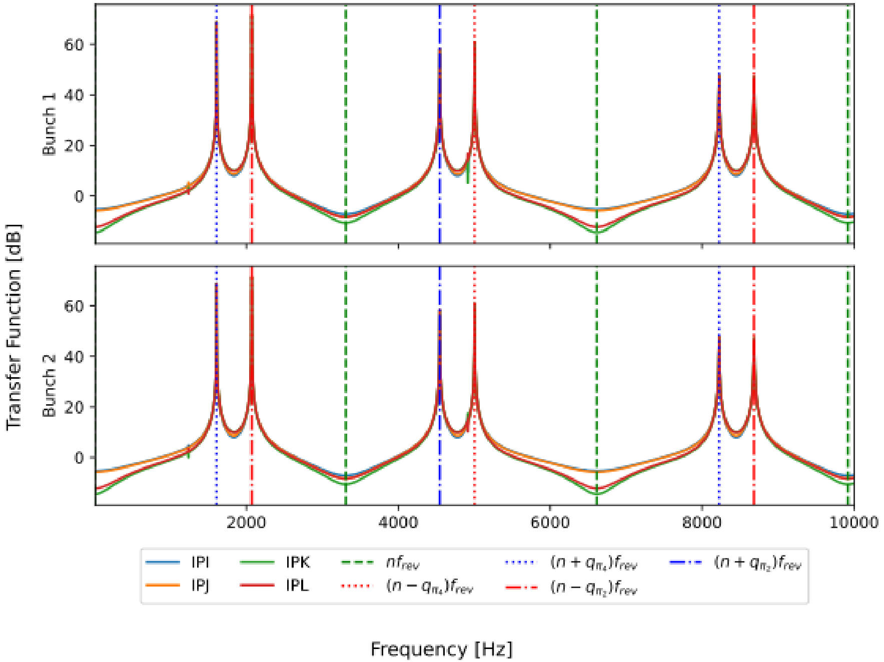
Peaks in the IP offset are observed around the π-mode tunes

This transfer function shows the response in the case of white noise

We must consider what errors the machine will be subject to, to calculate the residual offsets at the IP:

We need a noise spectrum

4IP IP offset (no FB)



Generating noise spectra

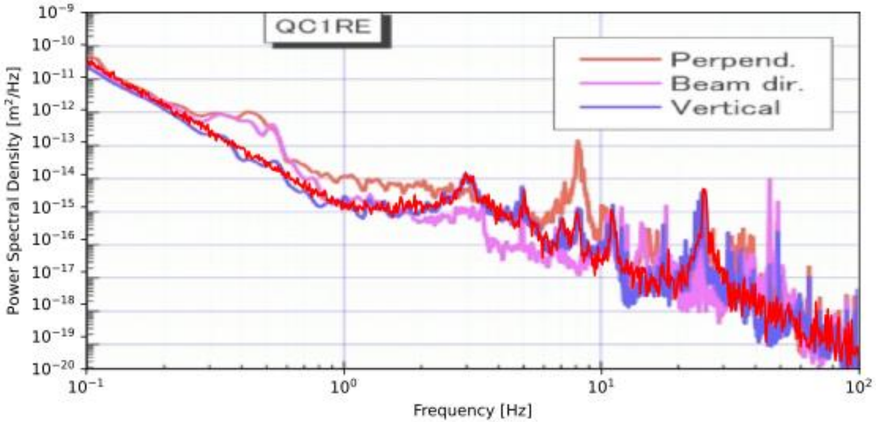
Need some reference to base the noise spectrum on

For FCC-ee: take the pessimistic approach that the tunnel is as noisy as the LHC tunnel

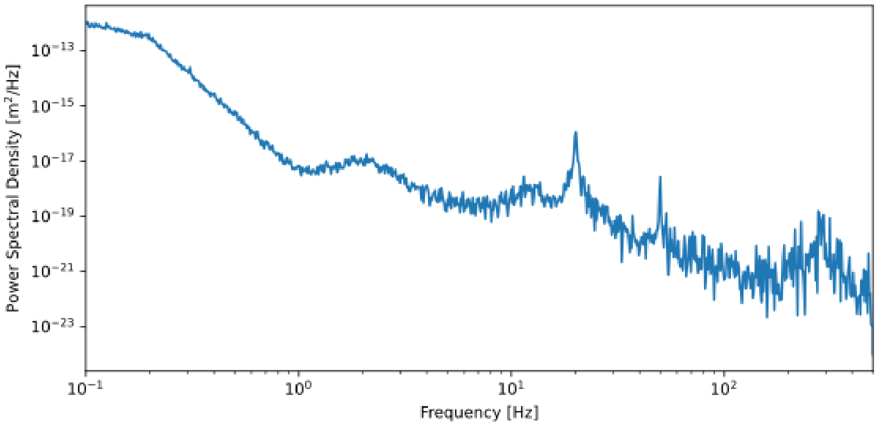
From measurements at SKEKB, the tunnel floor spectrum and the FFQ spectrum are very similar, but the **FFQ spectrum has additional resonance peaks**: natural modes of the FFQ

FCC-ee Approximated PSD: LHC tunnel floor plus 20Hz resonant peak

SKEKB QC1RE: measured & approximated

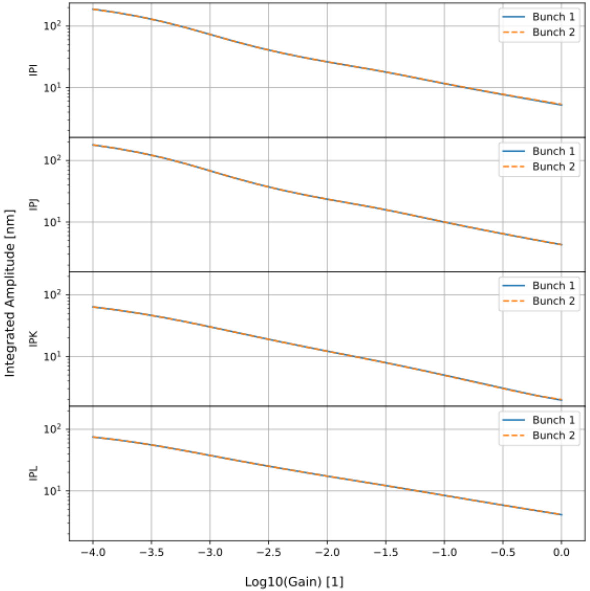


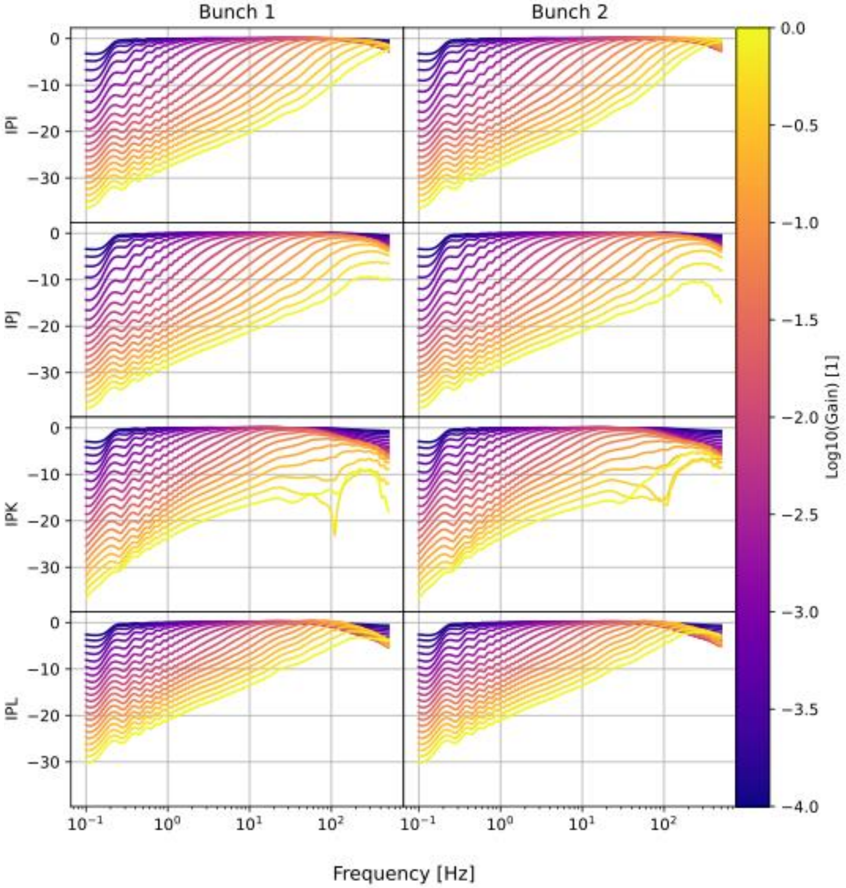
FCC-ee FFQ Approximated Noise Spectrum



Parameter scans

Then scan the impact of varying different parameters on the relative transfer function (vs natural oscillation) and then on the integrated RMS amplitude at the IP

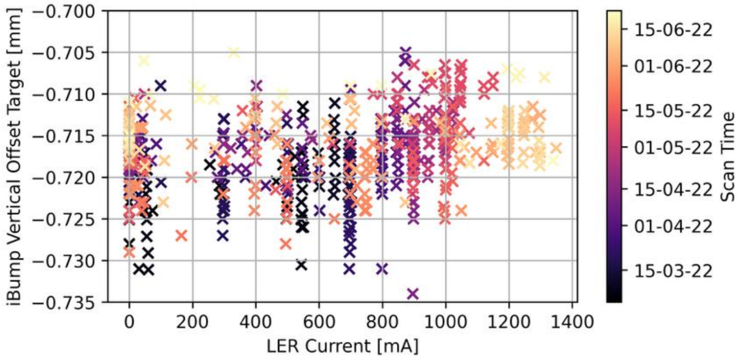


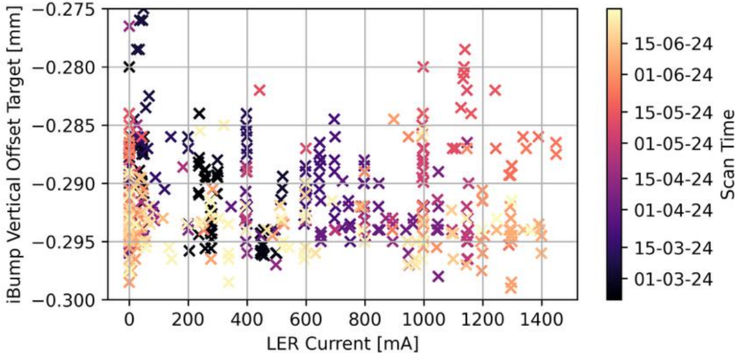


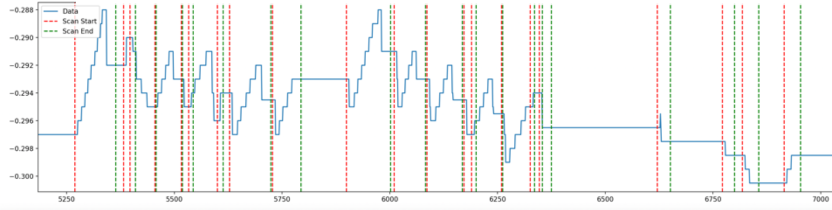
APPENDIX B: IBUMP MDS

iBump FB: Historical Data

- Following dedicated MDs, historical data also analysed
- **No clear trends observed**
- Many different machine configurations:
  - Not possible to use parameters such as beam current as predicative in the long term
  - Changes to machine configuration clearly have an impact
  - **Impacts may also be due to aborts** (as observed during the MD)







APPENDIX C: SUPERKEKB MODELLING

Relevant Presentations

- **Report on IP Feedback studies at SuperKEKB**
  - 188th FCC-ee Accelerator design meeting & 59th 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**
  - 200th FCC-ee Accelerator design meeting & 71st 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

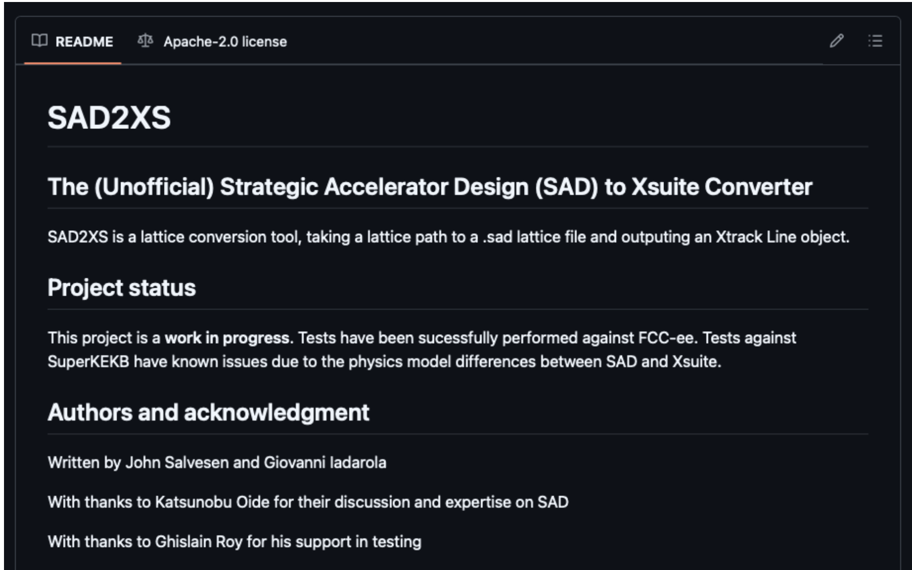
- Authors: *John Salvesen, Giovanni Iadarola*
- Status: Active development
- Tested on: SuperKEKB, FCC-ee, JPARC MR
- Open source: https://github.com/JPTS2/SAD2XS

- 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


README Apache-2.0 license

SAD2XS

The (Unofficial) Strategic Accelerator Design (SAD) to Xsuite Converter

SAD2XS is a lattice conversion tool, taking a lattice path to a .sad lattice file and outputing an Xtrack Line object.

Project status

This project is a **work in progress**. Tests have been sucessfully performed against FCC-ee. Tests against SuperKEKB have known issues due to the physics model differences between SAD and Xsuite.

Authors and acknowledgment

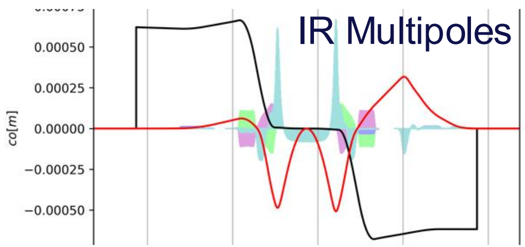
Written by John Salvesen and Giovanni Iadarola

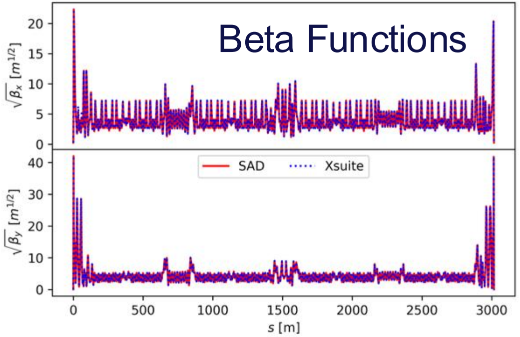
With thanks to Katsunobu Oide for their discussion and expertise on SAD

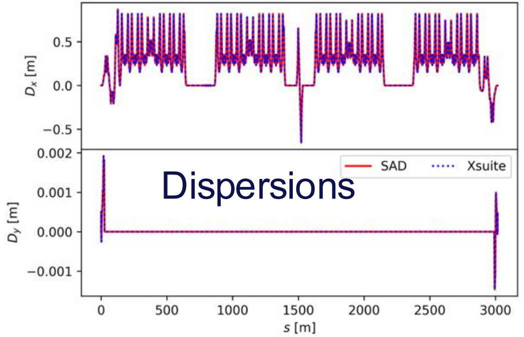
With thanks to Ghislain Roy for his support in testing

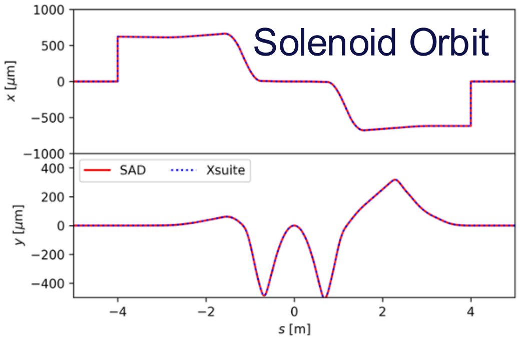
Optics Tests

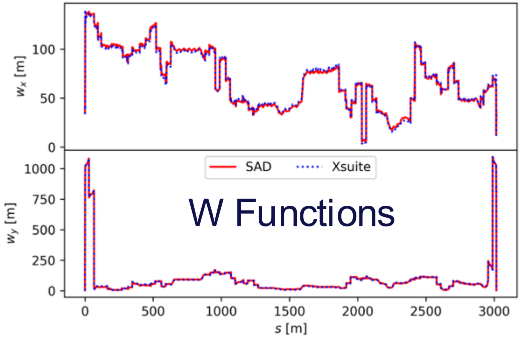
- **Multiple lattices in development**
  - **Featuring full SAD IR multipoles**
- Linear optics show excellent agreement
  - Rematching process required due to modelling differences
  - Expect some optics deviation
- Non-linear optics show excellent agreement











Beam-Beam installation

Beam-beam tune shift

- **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%

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

```
##############################################
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)
##############################################
```

Parameters taken from June 8, 2022, Parameter table

Parameter	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	

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

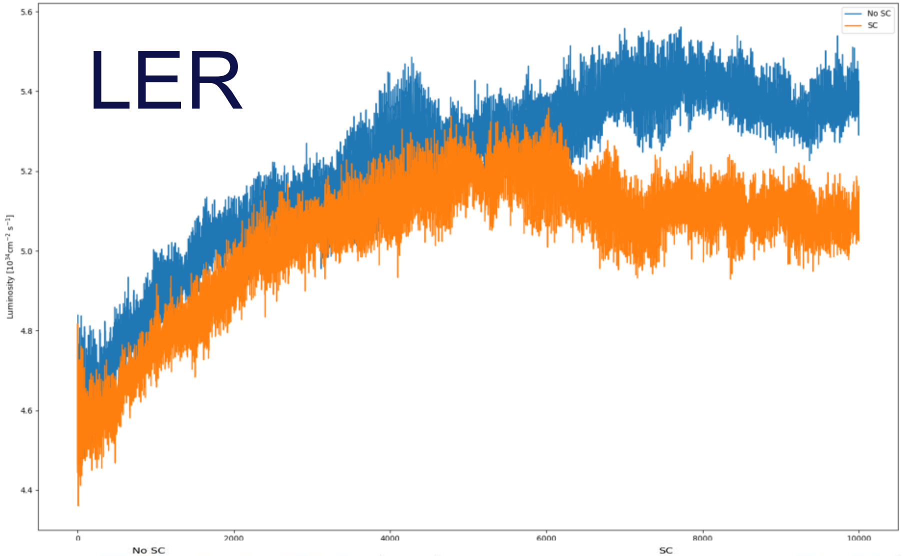
$$-\Delta\nu_{y,sc} = \xi_{sc} = \frac{N r_e}{(2\pi)^{3/2}\sigma_z \beta^2 \gamma^3} \oint ds \frac{\beta_y}{(\sigma_x + \sigma_y)\sigma_y}$$

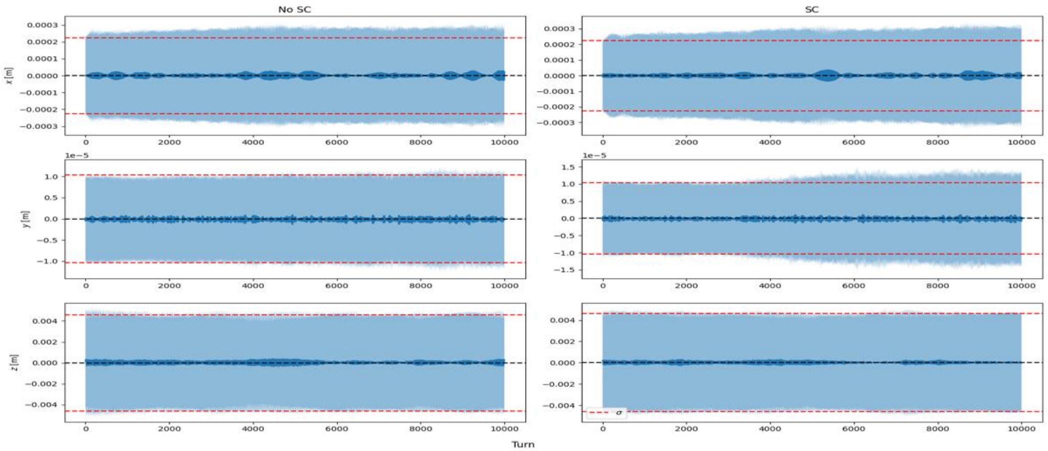
```
##############################################
LER Tune Shift
##############################################
K. Ohmi Formula [1E-3]:      (-1.163, -17.792)
Xsuite Calculated [1E-3]:    (-1.174, -17.455)
Relative Difference [%]:     (1.001, -1.892)
##############################################


##############################################
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)
##############################################
```

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
- ***Space charge is excluded from the IR***
  - Major orbit impact when space charge elements occur within the sliced IR region





APPENDIX Z: J-PARC MR STUDIES

J-PARC MR Studies

Collaborative effort : J. Salvesen, A. Oeftiger and G. Iadarola

- Excellent test of the SAD2XS code created for SuperKEKB
- Multiple implementations:
  - Direct SAD2XS conversion
  - Manual conversion (by hand, more elegant lattice file)
- **Optics well recovered**
  - Beta beating w.r.t SAD on 1E-8 level
  - Survey recovered and closed
  - Fast and easy to use