ADVANCING THE SUPERKEKB LATTICE IN XSUITE

CURRENT DEVELOPMENTS AND FUTURE DIRECTIONS

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EAJADE

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FCCIS

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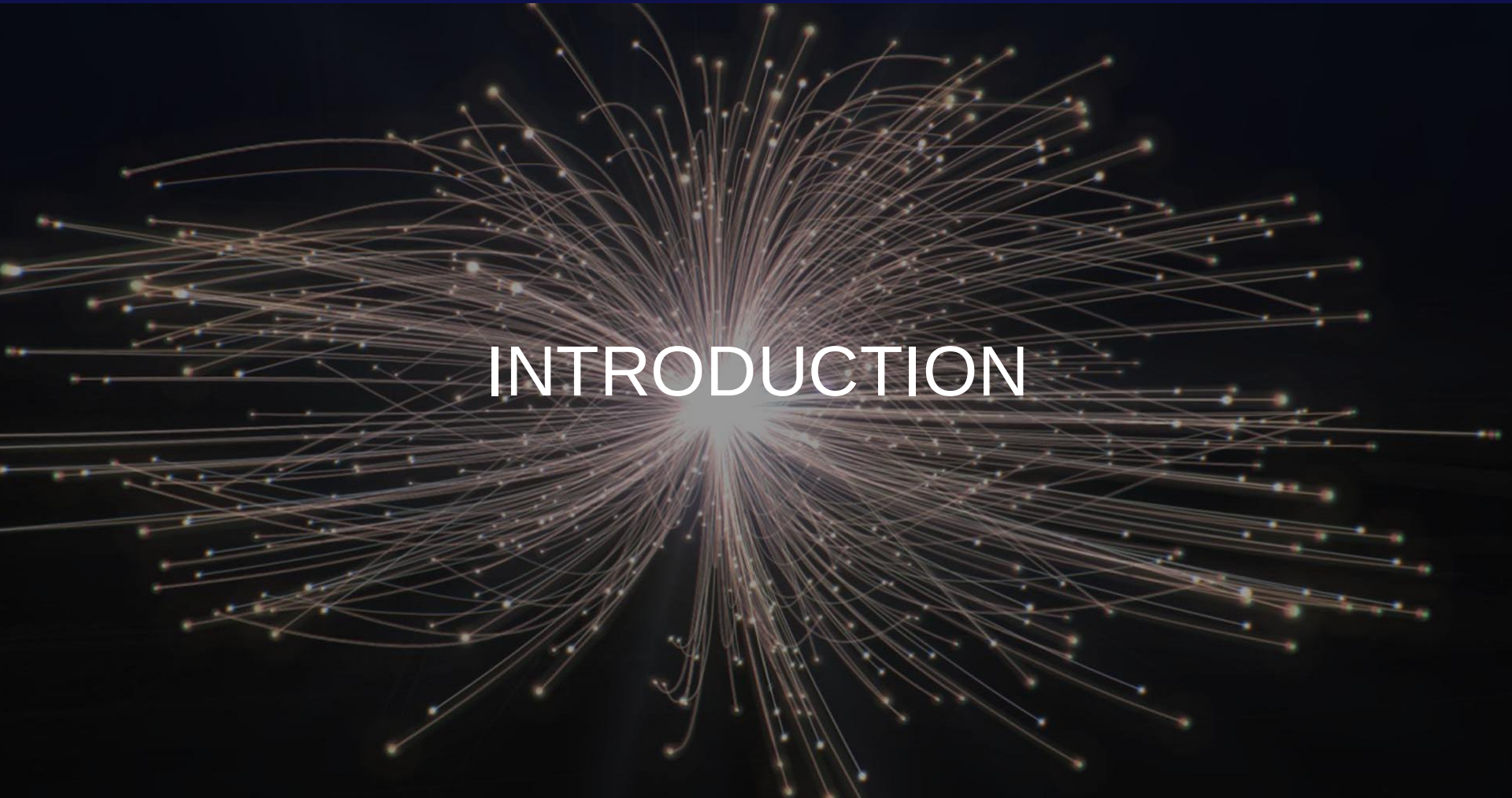
EAJADE coordinators, who enabled this collaboration

And more not mentioned here



INTRODUCTION

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

- Realistic modelling of the measurable signals (BPMs, luminometers and more)
- Realistic feedback hardware considerations (corrector magnets, processing time)
- Self-consistent 6D lattice tracking including modelling of beam-beam interaction

Using this model, study the luminosity performance in the presence of magnet vibrations

But first, can I demonstrate this for SuperKEKB?

FCC-ee SuperKEKB Synergies

FUTURE CIRCULAR COLLIDER

Super KEKB

- Nano-beam scheme

$$\sigma_x \gg \sigma_y$$

- Crab collision optics

$$H_{cw} = a_{cw}\, xy'^2$$

- High crossing angle
  - FCC-ee: 30mrad, SuperKEKB: 83mrad
- Cryogenic final focus
- High Current
  - FCC-ee Z > 1A, SuperKEKB Nominal 3.6A LER, 2.6A HER

Knowledge Transfer

- Effective schemes for knowledge transfer e.g., **EAJADE**
- On site expertise in lattice design (*K. Oide)*

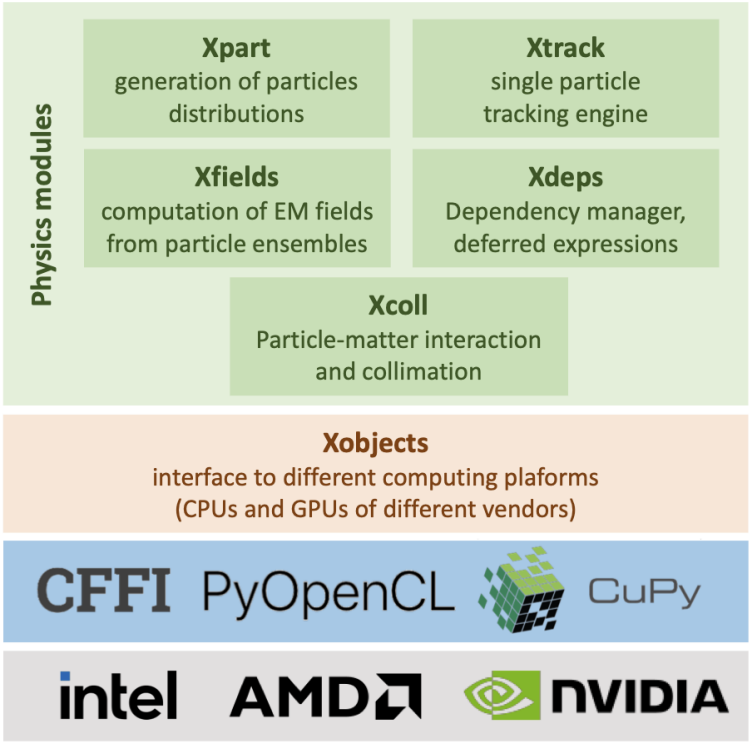
Relevant Presentations

- **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/

Xsuite Overview

- Developed at CERN, since 2021
- Collection of python packages
  - Integrates learning from many previous CERN tools including MAD, Sixtrack, COMBI and PyHEADTAIL
- Supports both CPUs and GPUs
- Demonstrated at: PS, SPS, LHC and more…
- Used for design of: FCC, many medical machines

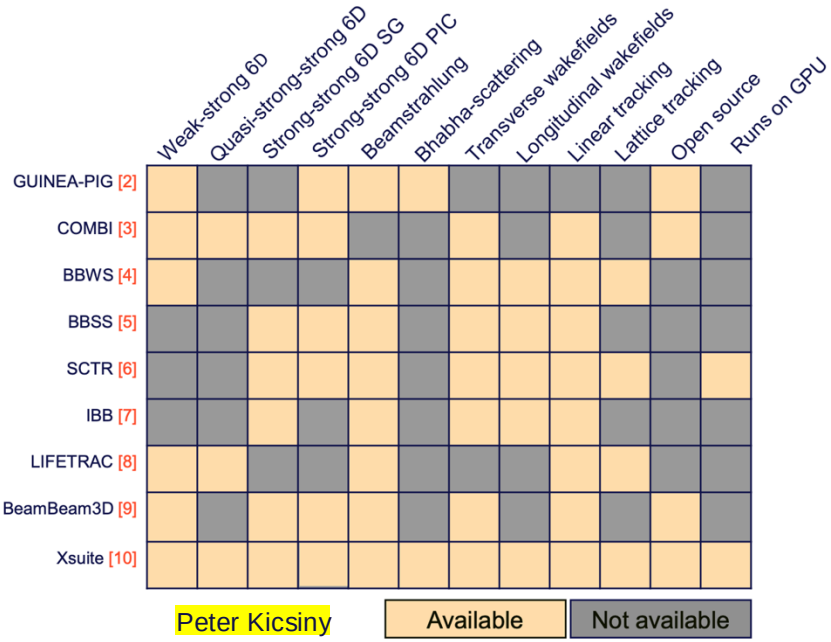
Giovanni Iadarola



Motivation

- 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 more…
- SuperKEKB Beam-Beam working group
- Interest from BELLE-II for IR upgrade model
- And more….

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

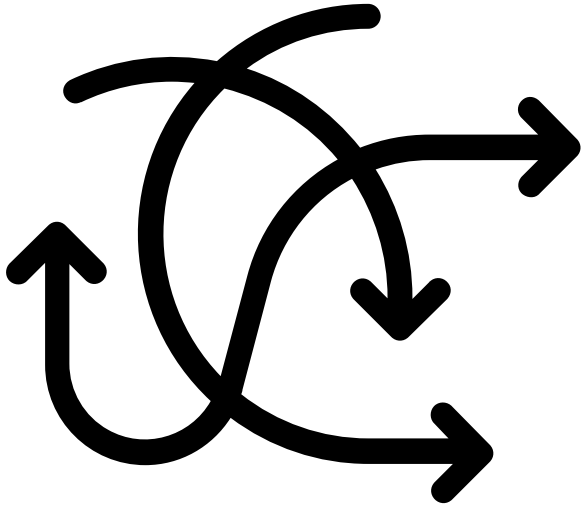


LATTICE CONVERSION

Conversion Challenges

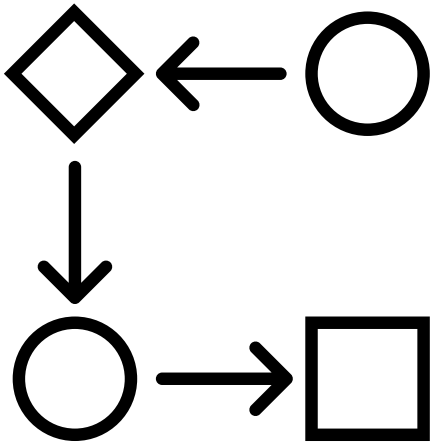
- **Maxwellian fringes**
  - SAD fringes characterised by F1, F2
  - Not supported in Xsuite
- **Complicated IR model**
  - SAD modelling originates from 3D magnetostatic model
  - Xsuite approach: maintain ‘real’ magnets in this sliced region
  - Not only magnetic elements, but reference frame transformations required

And more…



SuperKEKB Optics Conversion Process

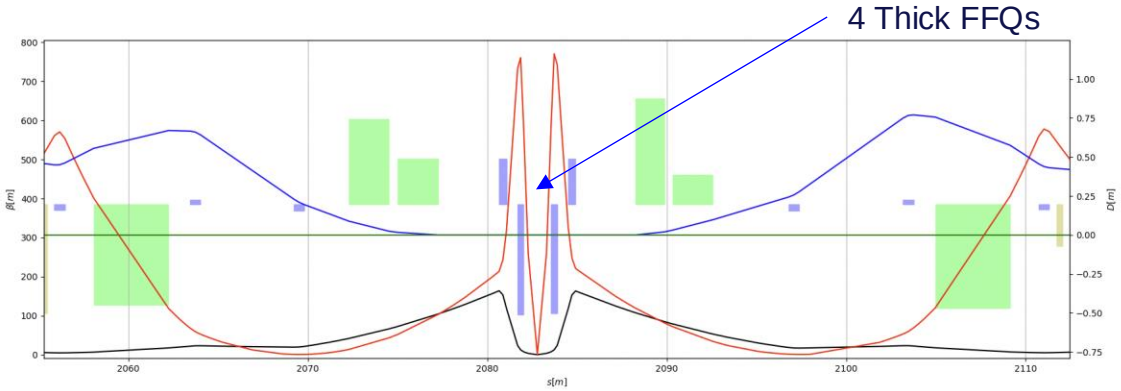
1. Initial Import (SAD2XS)
2. Interaction Region Replacement
3. Initial Lattice Corrections
4. Marker Installation
5. Constraint Extraction
6. Optics Matching (No solenoid)
7. Solenoid Installation
8. Optics Matching (With Solenoid)

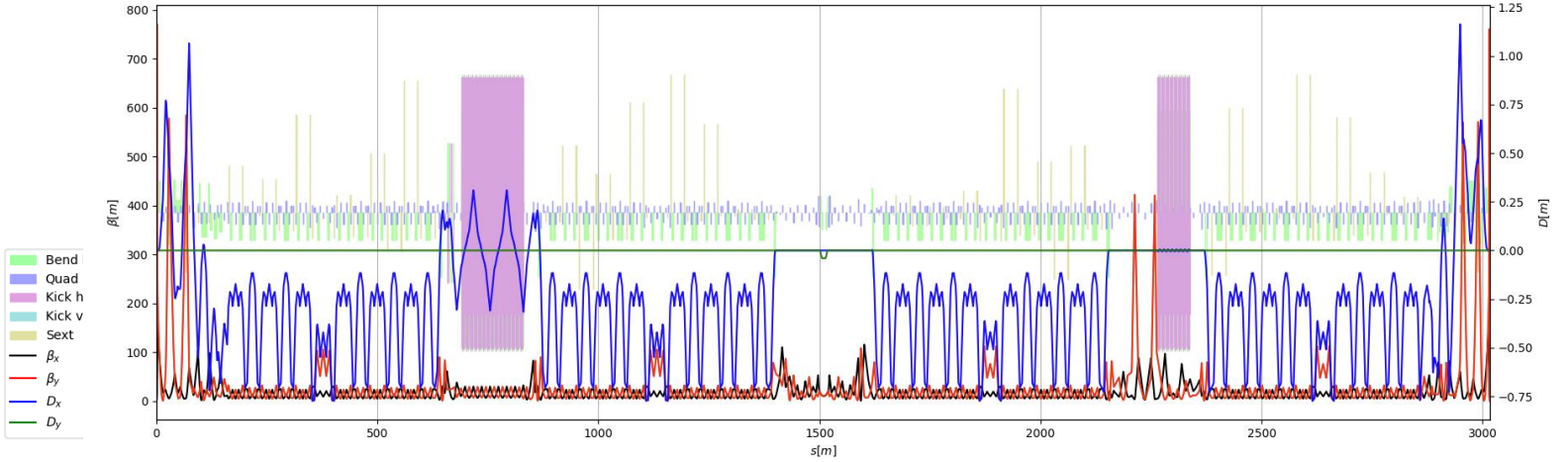


9. *(Troubleshooting and iteration)*

No-Solenoid Lattice

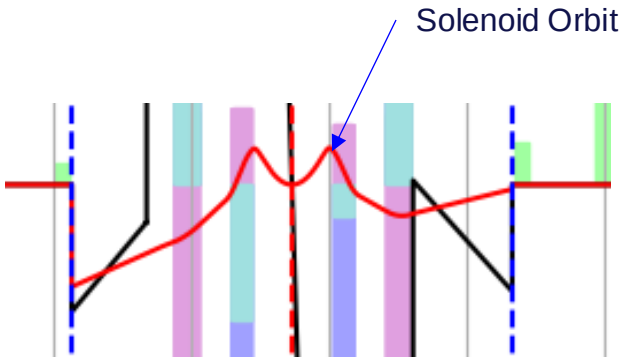
- **Solenoid free lattice developed**
  - Far fewer elements (no slicing of the IR) allows for quicker tracking
  - Required for the optics matching process, and provides an additional tool for studies

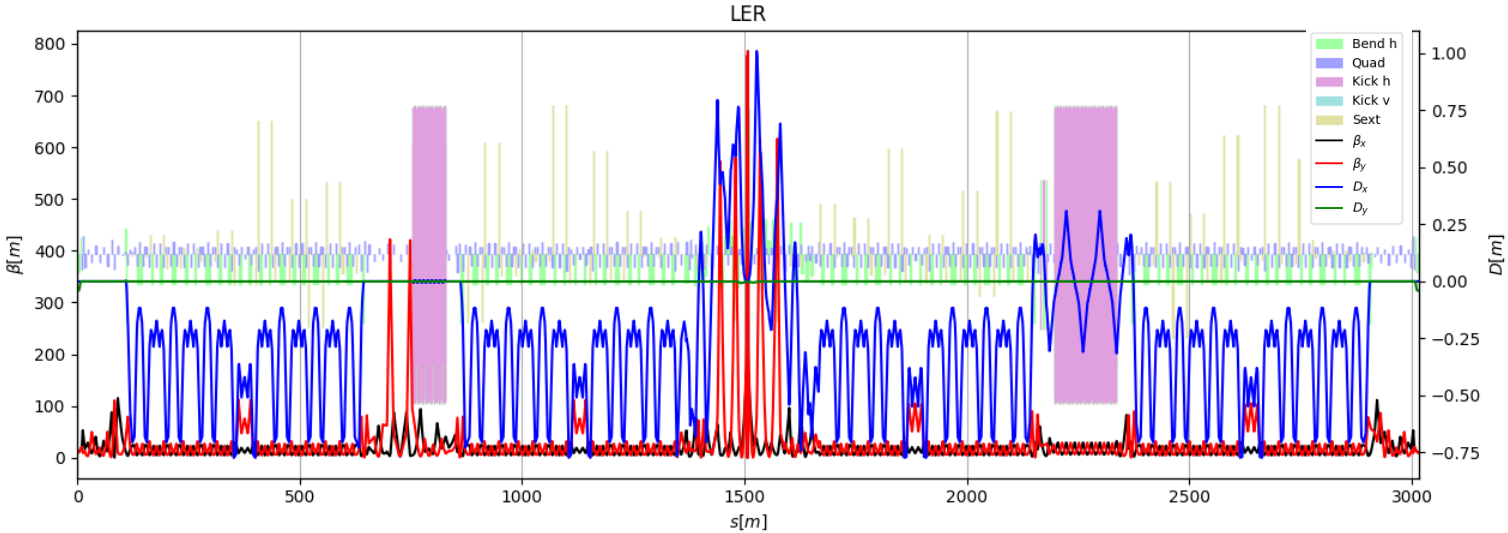




Solenoid Lattice

- **Solenoid installed successfully**
  - Optics tests ongoing, orbit checks ongoing
- **Coupling matching**
  - SAD approach of R1, R2, R3, R4 not currently available in Xsuite (natively uses Mais-Ripken)





The lattice version being converted has residual coupling (R3) at the IP in SAD. Coupling matched to 0 in Xsuite -> optics differences

Radiation Testing

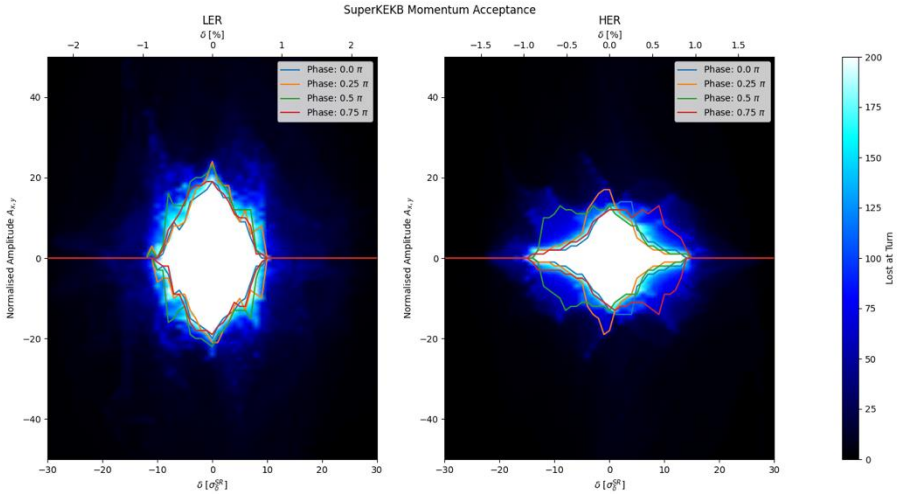
- **Emittance**
  - HER shows good agreement
  - LER shows much more significant deviation
  - Order of magnitude looks good on everything, but the details are being further investigated
- **Damping partitions**
  - LER and HER in both SAD and Xsuite agree on partition numbers of 1:1:2 to 3 significant figures

LER	Xsuite	SAD	Δ/SAD [%]	Unit
Emittance x	4.673	4.032	15.9	[nm]
Emittance y	0.797	0.552	44.4	[pm]
Emittance z	3.809	3.351	13.7	[um]
Energy loss	1.785	1.519	17.5	[MeV / turn]
Mom. compac.	296.1	297.8	-0.57	[1E-6]

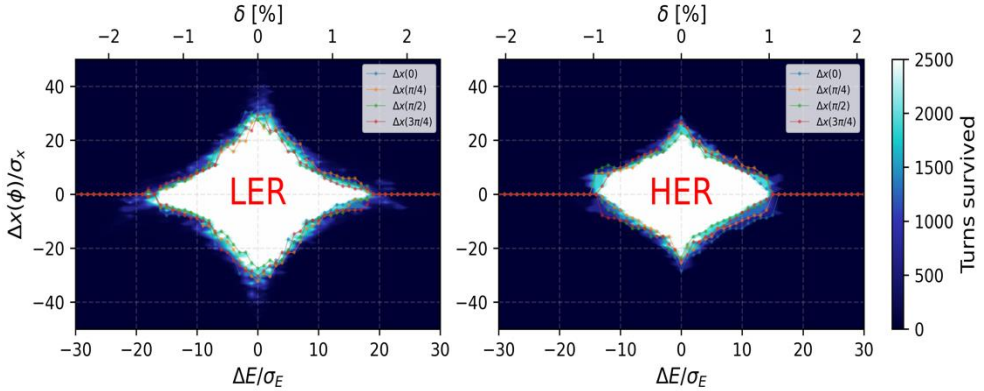
HER	Xsuite	SAD	Δ/SAD [%]	Unit
Emittance x	4.452	4.465	-0.29	[nm]
Emittance y	0.497	0.567	-12.3	[pm]
Emittance z	3.302	3.180	3.84	[um]
Energy loss	2.503	2.434	2.83	[MeV / turn]
Mom. compac.	459.1	454.3	1.06	[1E-6]

Radiation Testing

- **Momentum Acceptance and Dynamic aperture**
  - MA and DA reduced vs SAD values
    - Not observed with FCC-ee comparisons
    - *Implies an issue with the lattice*
    - Longitudinal acceptance closer
    - Transverse planes greatly reduced
  - Several reasons posed:
    - Coupling match discrepancy
    - FFQ corrector discrepancy
    - Sextupoles improperly configured
    - Solenoid reference shift discrepancy

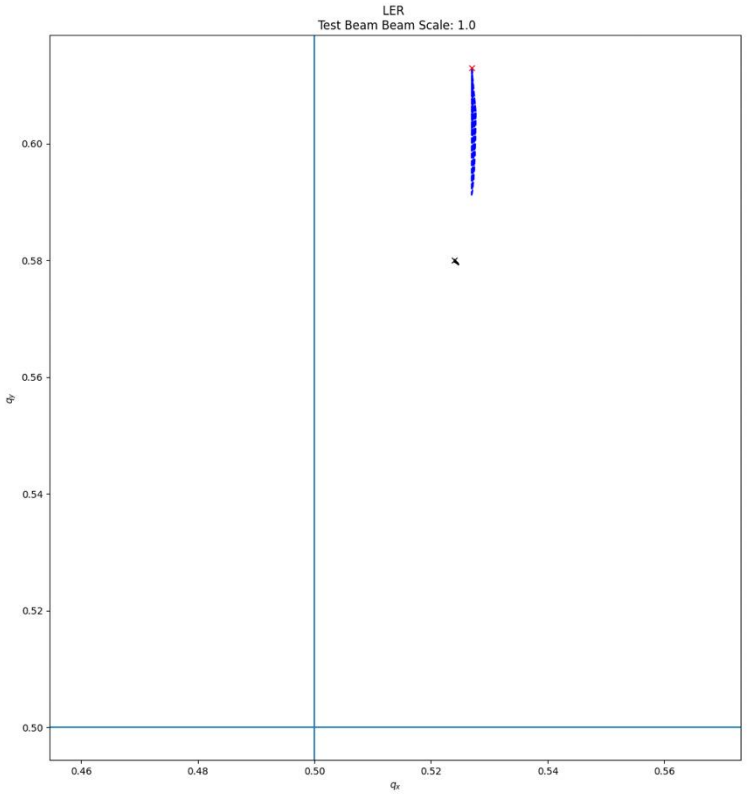


Xsuite (top) vs SAD (bottom)

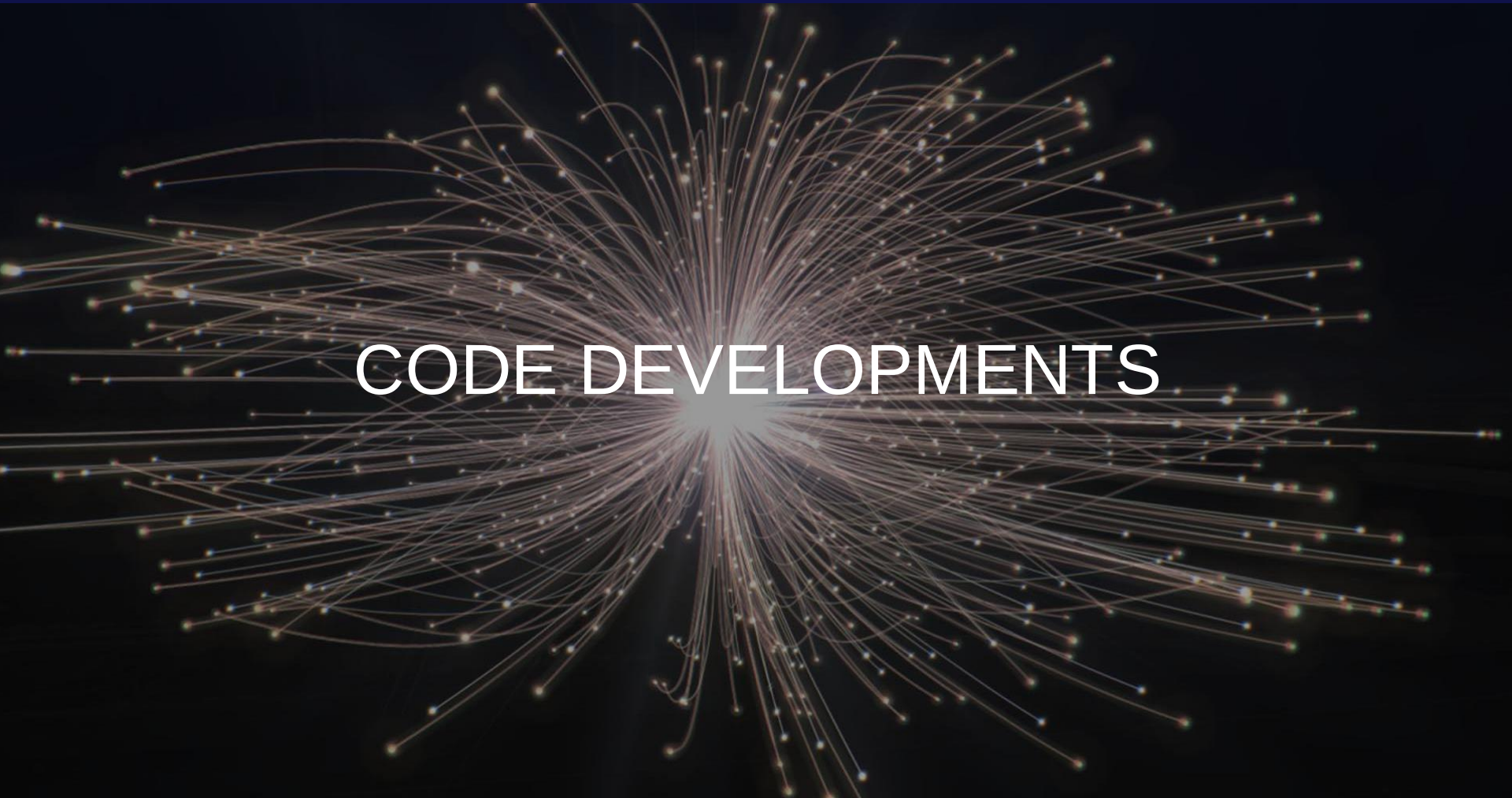


Beam-Beam installation

- **Beam beam installation possible**
  - Possible to run in weak-strong and strong-strong configurations
- **Tune footprints**
  - Initial tests performed
  - Order of magnitude looks correct, but no extensive checks



NB: extensive testing not yet performed due to optics and radiation troubleshooting ongoing

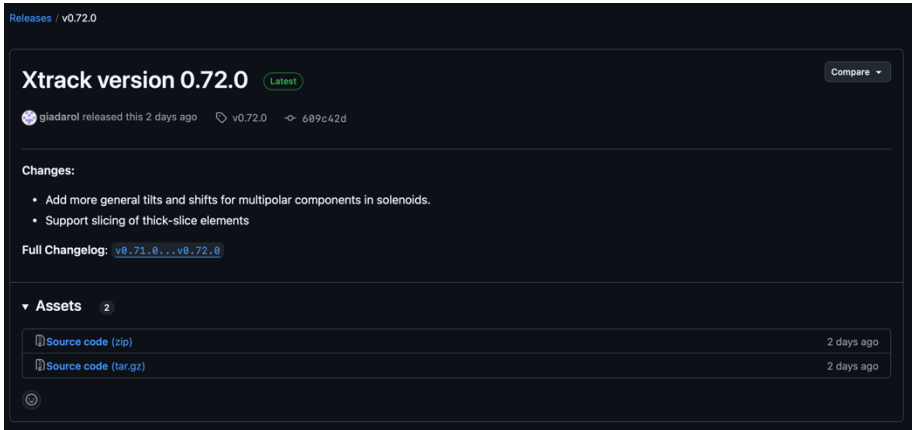


CODE DEVELOPMENTS

Xsuite Developments

- **Multipole offsets and rotations inside a solenoid**
  - Required for modelling SuperKEKB IR
- **Update to radiation handling with slicing**
  - Update to thin slicing of previously thick sliced elements
  - Better modelling of synchrotron radiation

Giovanni Iadarola



Xtrack 0.72.0 or higher required to use the SuperKEKB model

SAD2XS

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

OUTLOOK

Outlook: SuperKEKB Xsuite Model

- Lattice already being used for studies
  - See next presentation from G. Broggi
- Correction coupling match to use SAD R1, R2, R3, R4 natively
- Chromatic matching
- Radiation and beam-beam benchmarking

Any input and help greatly appreciated!

Upcoming publication(s):

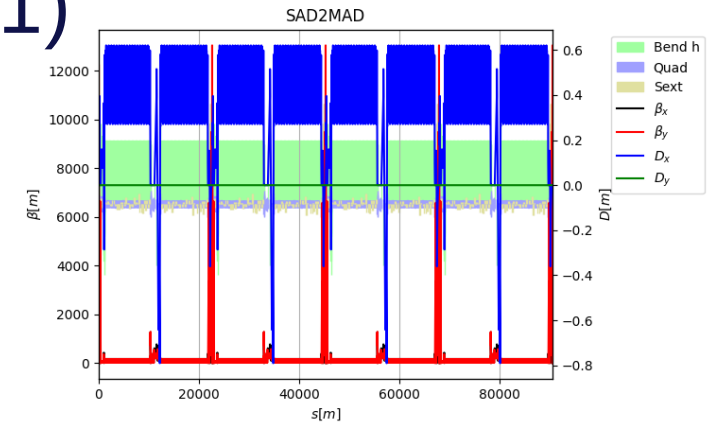
- *Consistent representation of lattices between optics code for FCC-ee, SuperKEKB, and more [eeFACT25]*
- *Modelling Optics and Beam-Beam Effects of SuperKEKB with Xsuite [IPAC25]*

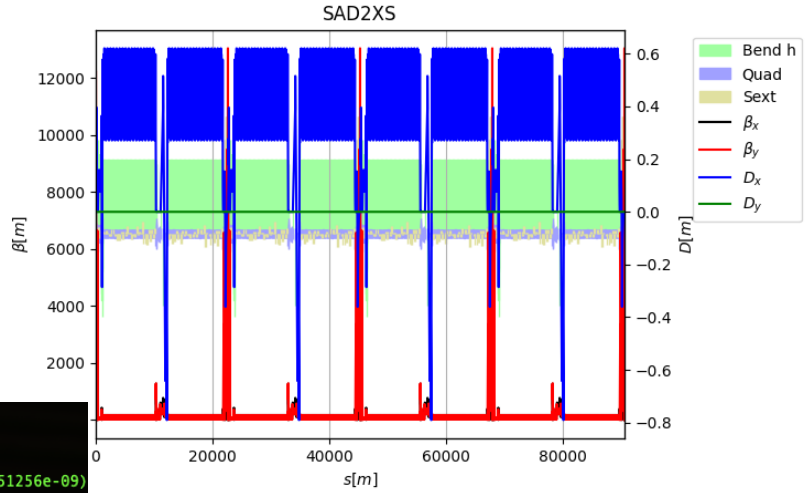
Thank you for your attention.

APPENDIX A: SAD2XS

SAD2XS Tests: FCC-ee GHC (1)

- Test import using the FCC-ee GHC (v24.3)
- Test lead to the discovery of the *DZ* geometric correction
- Test optics versus standard FCC-ee Xsuite import process:
  - Convert SAD to MADX lattice using SAD2MADX (K. Oide)
  - Import to an Xsuite Line using Xtrack.Line.from_madx_sequence()
- **Optics fully recovered**
- **Closure is better than standard process**

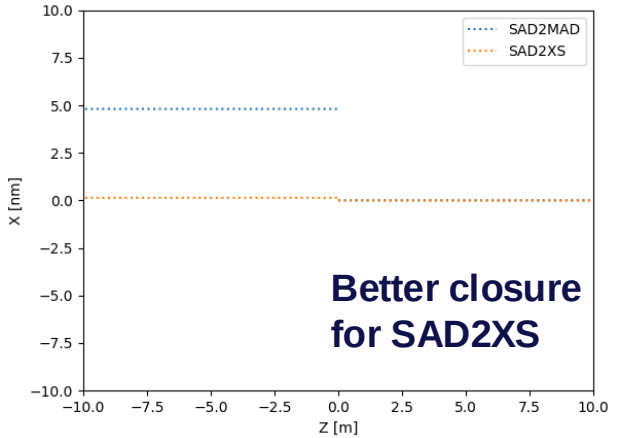


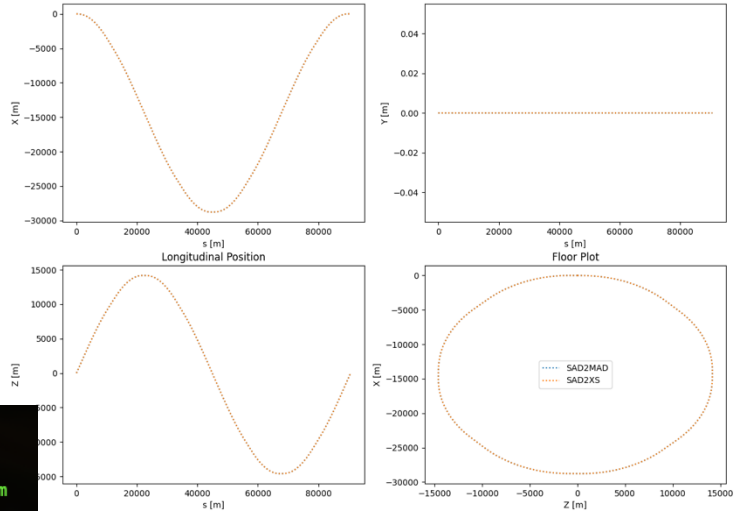



```
IP Beta Comparison
SAD2MAD IP Beta: (0.10999999930501582, 0.0006999998541653924)m
SAD2XS IP Beta: (0.10999999899294556, 0.0006999998597821936)m
IP Beta Difference: (3.1207025852353354e-10,-5.616801186485165e-12)m
Tune Comparison
SAD2MAD Tune: (218.15840000135154, 222.19999998769137)
SAD2XS Tune: (218.15840000156143, 222.19999998990428)
Tune Difference: (-2.098943241435336e-10,-2.212914296251256e-09)
```

SAD2XS Tests: FCC-ee GHC (2)

- Test import using the FCC-ee GHC (v24.3)
- Test lead to the discovery of the *DZ* geometric correction
- Test optics versus standard FCC-ee Xsuite import process:
  - Convert SAD to MADX lattice using SAD2MADX (K. Oide)
  - Import to an Xsuite Line using Xtrack.Line.from_madx_sequence()
- **Optics fully recovered**
- **Closure is better than standard process**



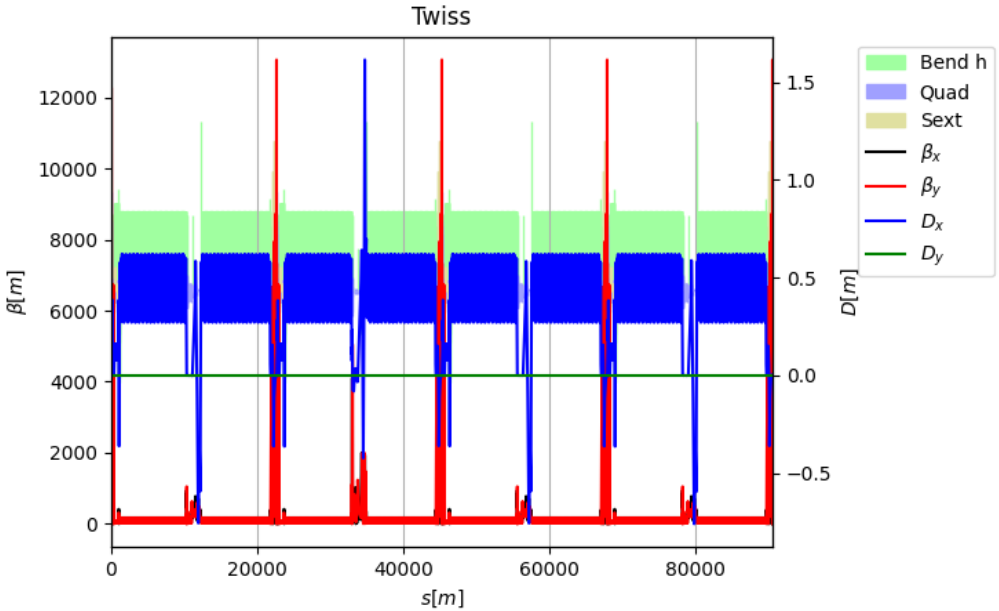



```
Survey Path Comparison
SAD2MAD Survey Path Length: 90658.71376410239 m
SAD2XS Survey Path Length: 90658.71376409227 m
Survey Path Length Difference: 1.0113581083714962e-08 m
```

```
Twiss Path Comparison
SAD2MAD Twiss Path Length: 90658.71376410754m
SAD2XS Twiss Path Length: 90658.71376409747m
Twiss Path Length Difference: 1.0069925338029861e-08m
```

SAD2XS Tests: FCC-ee GHC Collimation

- Test import using the FCC-ee GHC collimation lattice
- Lead to implementation of subline importing
  - Subline at IRF used for the collimation insertion
- **Optics fully recovered**
- **Closure is missing, but this is true in SAD also**

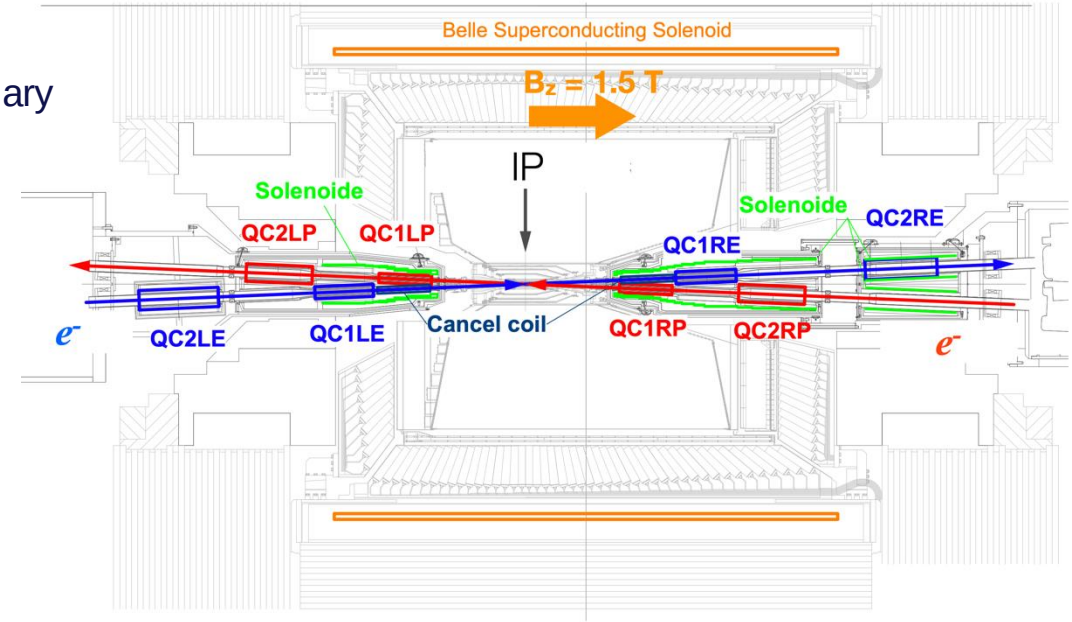


APPENDIX B: SOLENOID MODELLING

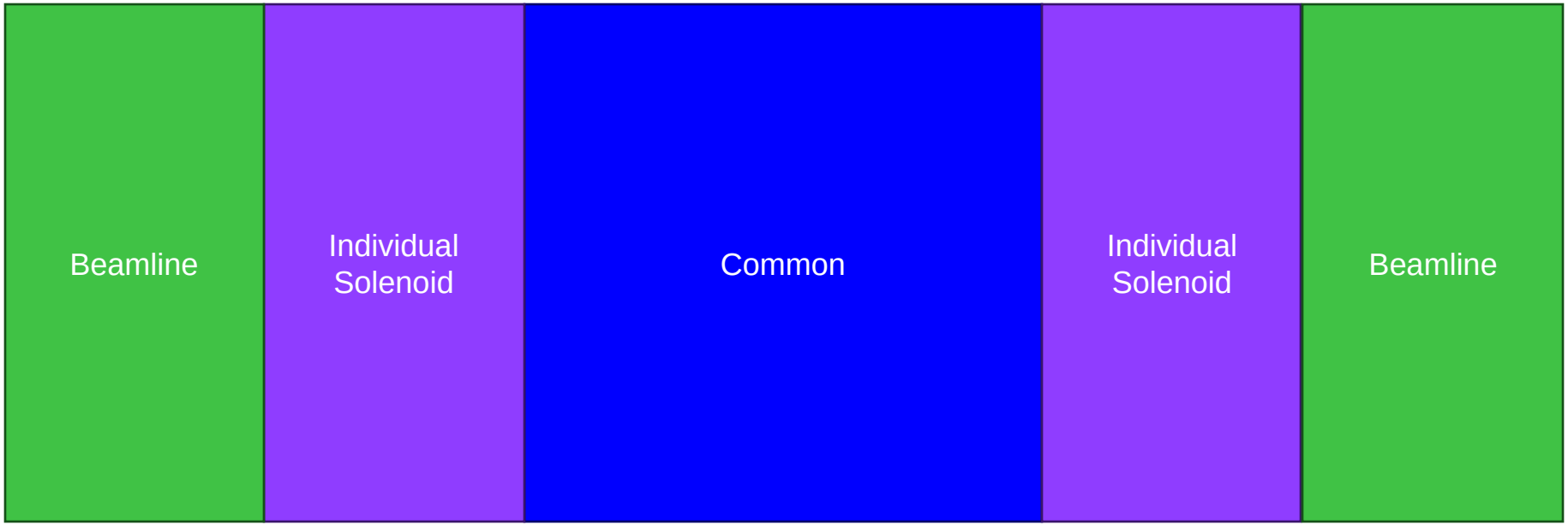
SuperKEKB Solenoid Modelling Overview

- Sliced solenoid region is split into multiple sections
  - “Individual solenoid”
  - “Common solenoid”
- Reference frame transforms at each boundary
- Solenoid data from BELLE-II field maps
  - Measurements along beampipes
  - Separate data for LER and HER

Belle II and QCS



SuperKEKB Solenoid Model Geometry



$p_x \approx 0$ $p_x \approx 0$ $p_x \approx \sin(\theta_c/2)$ $p_x \approx 0$ $p_x \approx 0$

Solenoid Reference Frame Transforms

- Around whole solenoid:
  - Redefinition of orbit: X Rotation, Y Rotation, X, Y shift
  - Alignment of arcs: S Rotation
  - RF Correction: Zeta shift
- Around common solenoid:
  - Reference frame shift: X rotation, X shift
  - RF Correction: Zeta shift

Corrector Coils in IR