BEAM-BEAM CODE PROGRESS


Special thanks to:
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FCC-week
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Outline

1. Introduction
2. Performance of the Xsuite beam-beam model
3. Scan of x-z instability
4. 3D flip-flop instability
5. Bhabha scattering
6. Summary
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1. Introduction

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### Synergies and New Developments

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<tr>
<th>Tool</th>
<th>MAD-X</th>
<th>Sixtrack</th>
<th>Sixtracklib</th>
<th>PyHEADTAIL</th>
<th>COMBI</th>
<th>Xsuite</th>
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<td>Y. Wu, F. Carrier, T. Pieloni</td>
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<td>EFOL team</td>
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**Introduction**

1.

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**Table:**

- | Tool | MAD-X | Sixtrack | Sixtracklib | PyHEADTAIL | COMBI | Xsuite |
- |      |       |          |             |            |       |        |
- | SAD  |       |          |             |            |       |        |
- | BMAD |       |          |             |            |       |        |
- | PyAT |       |          |             |            |       |        |
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- | Y. Wu, F. Carrier, T. Pieloni |  | EFOL team |  |

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**Diagram:**

- Chart showing tools and their interconnections.
- Key: CHART, CERN, SDSC, FCC.
Simplified tracking simulations with Xsuite

- Exploit superperiodicity of machine (2 IP baseline from CDR)

- In code:
  - 1 IP + tracking over half arc with linear transfer matrix
  - Arc split into 3 segments
  - 2 crab sextupoles between arc segments ($\beta_x=3$ m, $\beta_y=500$ m)

- A «turn» begins in front of the right sextupole:
  - Observation point for coordinates

- Effective radiation (damping+noise) in arc, beamstrahlung in beam-beam element
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Performance of the Xsuite beam-beam models

Time 1 collision on CPU (AMD EPYC 3 GHz, single core)

<table>
<thead>
<tr>
<th>Model</th>
<th>WS</th>
<th>QSS</th>
<th>SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Runtime [s]</td>
<td>~40</td>
<td>~90</td>
<td>~110</td>
</tr>
</tbody>
</table>

Number of calls to the 3 main operations over a single collision

<table>
<thead>
<tr>
<th>Beam-beam with $N_s$ slices</th>
<th>WS</th>
<th>QSS</th>
<th>SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assign slices</td>
<td>0</td>
<td>1</td>
<td>$2N_s - 1$</td>
</tr>
<tr>
<td>Compute stat. moments</td>
<td>0</td>
<td>1</td>
<td>$2N_s - 1$</td>
</tr>
<tr>
<td>Synchrobeam kick</td>
<td>1</td>
<td>$2N_s - 1$</td>
<td>$2N_s - 1$</td>
</tr>
</tbody>
</table>

FCC-ee $Z$

$N_{\text{particles}} = 1 \times 10^6$

$N_{\text{slices}} = 100$

Scaling on GPU

- Before: typical setup with single CPU (~ 1 week)
- GPU significantly reduces computational cost (< 1 day)
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x-z instability

- x-z instability regions reproduced in QSS simulation

**Figure 7:** Growth of $\xi_x$ due to coherent X-Z instability, as a function of $\nu_x$. Red line corresponds to $U_{RF} = 250$ MV, $N_p = 7 \cdot 10^{10}$, green and blue lines – $U_{RF} = 100$ MV, $N_p = 1.1 \cdot 10^{11}$ and $1.7 \cdot 10^{11}$.

FCC-ee Z

Quasi strong-strong ($f=1$)

- $N_{coll} = 1e4$
- $N_{particles} = 1e6$
- $N_{slices} = 300$
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Flip-flop

- Flip-flop instability (1D) observed in other collides (VEPP-2000) \[3\]

- For FCC-ee: 3D flip-flop - direct consequence of beamstrahlung, triggered by an initial asymmetry in bunch intensity \[4\]

  - Inflation of one bunch → beam loss
  - Above a threshold \(\xi_0\) longitudinal blowup drives transverse diffusion → 3D flip-flop
  - Relevant for FCC-ee top-up injection
3D flip-flop

- Scanned asymmetry in bunch intensity: \( N_{w,s} = N_0 \cdot (1 \pm \Delta N) \) (\( \Delta N \in [0,1] \))

- Observed expected blowup of weak bunch

FCC-ee Z
Quasi strong-strong (f=100)

- \( N_{\text{coll}} = 5e4 \)
- \( N_{\text{particles}} = 1e7 \)
- \( N_{\text{slices}} = 300 \)
3D flip-flop – comparison to a 1D model

- Analytical model (Khoi’s model) to estimate blowup
- Khoi’s 1D model [5] does not take into account nonlinear diffusion at high asymmetries
- Khoi’s 3D [5] model includes diffusion in a phenomenological way

FCC-ee Z
Quasi strong-strong (f=100)
$N_{\text{coll}} = 5e4$
$N_{\text{particles}} = 1e7$
$N_{\text{slices}} = 300$

$$N_{w,s} = N_0 \cdot (1 \pm \Delta N)$$
3D flip-flop – comparison to a 3D model

Parameters to be found from simulations

- Model validates tracking
- Good predictions at small $\Delta N$
- Allows fast parameter scan for first estimates of blowup
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Bhabha scattering

- Coulomb scattering of relativistic charges of opposite sign

 ocasional bremsstrahlung (radiative Bhabha) photons
Small angle Bhabha scattering [6]

- Dominated by t-channel (scattering) process

$E'_{\gamma} \sim E_{\text{beam}}$

luminosity in lepton colliders

primary particles lost within a turn

- Main limitation of FCC-ee beam lifetime (alongside beamstrahlung)
Bhabha scattering event generator in Xsuite

- Modeled with the method of equivalent photons [7]
- Successful benchmark of event generator against GUINEA-PIG [8]
- Ready to simulate beam lifetime
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Summary

Progress so far
➢ Development progress in the Xsuite beam-beam model (https://github.com/xsuite)
  ➢ Beamstrahlung, Bhabha scattering, luminosity (soft-Gaussian)
➢ Successful benchmark of all approximations (WS, QSS, SS)
  ➢ FMA, x-z instability, 3D flip-flop (including validation of Khoi’s model)

Ongoing work
➢ Combination of beam-beam + full lattice
➢ Beam lifetime studies

Next steps
➢ Simulations with updated FCC-ee parameters (4 IPs)
➢ Impact of lattice imperfections (misalignment, orbit and optics corrections)
➢ Top-up injection
➢ Benchmark at SuperKEKB

Thank you!
References

[1] G. Iadarola, Xsuite update
https://indico.cern.ch/event/1263239/contributions/5314669/attachments/2612972/4515112/000_Xsuite_fcc.pdf

https://cds.cern.ch/record/2816655

[3] D. Shwartz et al., Recent Beam-Beam Effects at VEPP-2000 and VEPP-4M
arXiv:1409.5590

https://doi.org/10.18429/JACoW-eeFACT2018-TUYBA02

https://indico.cern.ch/event/1193165/contributions/5015797

doi:10.1016/S0920-5632(96)90021-3

[7] C. Weizsäcker, E. Williams

[8] D. Schulte, GUINEA-PIG
https://gitlab.cern.ch/clic-software/guinea-pig
3D flip-flop

Driven by asymmetry in bunch intensity: $N_{w,s} = N_0 \cdot (1 \pm \Delta N)$

- **Strong bunch** shrinks
- 1D variant previously observed in VEPP-2000 [3]
- FCCee: 3D flipflop [4] – interplay of longitudinal and transversal beam sizes

FCC-ee Z
Quasi strong-strong ($f=100$)
- $N_{\text{coll}} = 5e4$
- $N_{\text{particles}} = 1e7$
- $N_{\text{slices}} = 300$
FMA – FCC-ee Z footprint

\[ D = \log_{10} \left[ \sqrt{\sigma_{Q_x,i}^2 + \sigma_{Q_y,i}^2} \right] \]

- Validation of Xsuite weak-strong model

\[ Q_x \max \approx 0.573806 \]

\[ Q_x \min \approx 0.57335 \]

xsuite

LIFETRAC [8]
FMA – Footprint of other FCCee energies

- **WW**: 80 GeV
- **ZH**: 120 GeV
- **TTbar**: 175 GeV
- **TTbar**: 182.5 GeV
x-z instability

Stable $Q_x = 0.57$

Unstable $Q_x = 0.575$
x-z instability

**Stable** $Q_x = 0.57$

- Flip-flop driven by numerical noise
  - Irrelevant as it happens only in unstable configurations

**Unstable** $Q_x = 0.575$

- Successful benchmark of (quasi-)strong-strong model