Space Charge in the High-Intensity Cyclotron Design of IsoDAR

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October 25, 2022

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Acknowledgements

I would like to thank Daniel Winklehner (MIT) and Andreas Adelmann (PSI) for their input, discussions, and material provided for this talk.

I would also like to thank the members of the IsoDAR collaboration for their many efforts towards the IsoDAR project.

Space charge effects

Ferrario et al. (2014)

- Charged particle beams in accelerators $\rightarrow$ guided by external EM fields to follow trajectory (e.g. cyclotrons).

- Inside charged particle beam $\rightarrow$ Coulomb interaction between particles due to self-fields.
  $\implies$ **Space charge effects**.

- **Space charge** $\rightarrow$ collective effect.
  $\implies$ Unwanted collective beam behaviours,
  e.g. *envelope oscillations* and *energy spread growth*.

- Space charge forces $\propto 1/\gamma^2 \implies$ vanish for high-energy beams.

  $\implies$ Very pronounced in the low-energy, **high-intensity** regime.

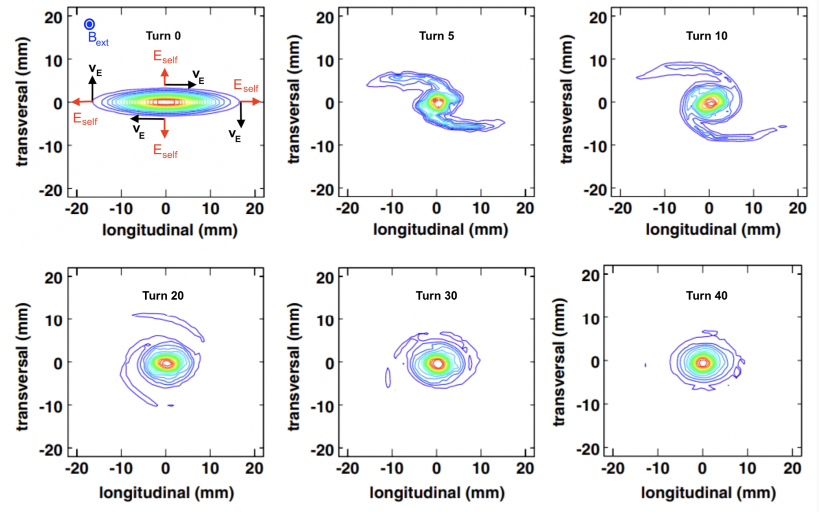
Vortex motion: Fortunate effect

Kolano et al. (2018)

- **Space charge** is usually an undesirable effect.
  $\rightarrow$ **BUT** space charge can induce **vortex motion**.
- **Vortex motion** $\rightarrow$ Interaction between strong radial-longitudinal coupling and space charge effects causes spiral tails in the beam, which wrap around the core, creating an almost stationary beam in the local frame.
- First observed in **PSI Injector 2** $\rightarrow$ 72 MeV high-intensity space-charge dominated machine, reaches 2.2 mA thanks to vortex motion.
- Compact stationary beam is produced after tails are removed by well-placed collimators.

Case study: PSI Injector II

Yang et al. (2010)



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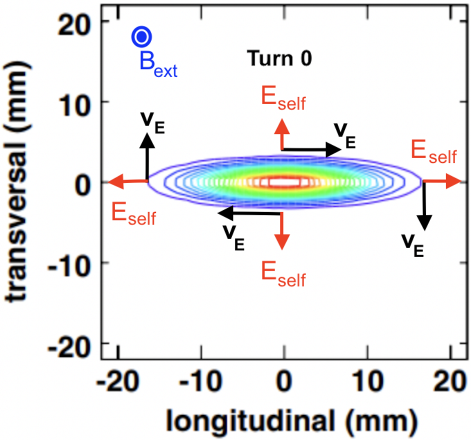
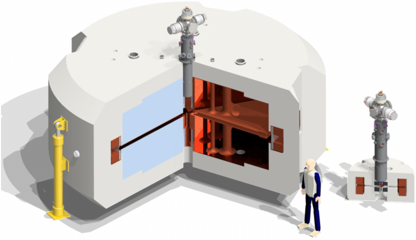


Lorentz force: $\vec{F} = q \cdot (\vec{v} \times \vec{B}_{ext} + \vec{E}_{self})$ Drift: $\vec{v}_E = \frac{\vec{E}_{self} \times \vec{B}_{ext}}{B_{ext}^2}$

The IsoDAR cyclotron
Winklehner et al. (2022)

- Proposed cyclotron for sterile neutrino search experiment.
- Aim: 60 MeV proton beam of 10 mA ($\approx$ 1 order of magnitude above state-of-the-art).



High-intensity beam obtained via:

- H_2^+ ions instead of protons
- Careful collimator placement
- RFQ injection
- Vortex motion

$\Longrightarrow$ First cyclotron designed with vortex motion in mind!

High-fidelity simulations

- To understand complex non-linear space charge effects:
  $\rightarrow$ **High-fidelity self-consistent numerical simulation**.

- Models can reproduce **halo formation** and **predict beam losses**.

- Also help with determining **feasibility of design**, and **uncertainty quantification** & **optimization**.

OPAL: Object-Oriented Parallel Particle Library

Versatile open source tool for charged particle dynamics in large accelerator structures and beamlines, including 3D EM field calculation, collisions, radiation, particle-matter interaction, and multi-objective optimization (Adelmann et al., 2019).

OPAL: a Particle-In-Cell simulation tool

- C++ code, runs on personal laptops as well as large HPC clusters.
- International team of 12 active developers, user base of $\mathcal{O}(100)$.

A. Adelmann (PSI), A. Albà (PSI), P. Calvo (CIEMAT), M. Frey (U. St Andrews), A. Gsell (PSI), Ch. Kraus, S. Muralikrishnan (JSC), N. Neveu (SLAC), P. Piot (NIU), Ch. Rogers (RAL), J. Snuverink (PSI), D. Winklehner (MIT)

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https://gitlab.psi.ch/OPAL/src/-/wikis/home

OPAL simulations of IsoDAR: Vortex motion

Winklehner et al. (2022).

Sensitivity Analysis of the design

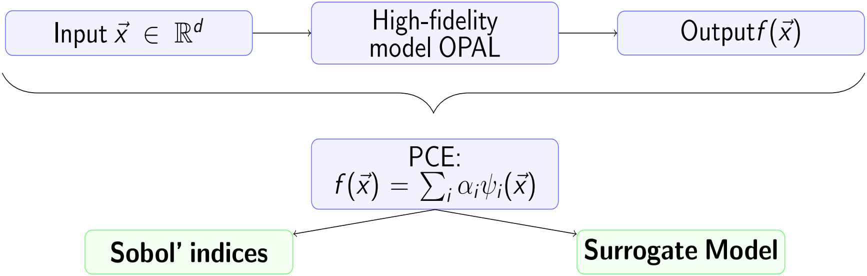
- Uncertainty Quantification (UQ) of the IsoDAR design
  $\rightarrow$ **Global Sensitivity Analysis**: How do Quantities of Interest (*QoI*) depend on design variables?

- Sobol' indices (Sobol, 2001) using PCE: **Polynomial Chaos Expansion** (Sudret, 2008; Adelmann, 2019).

- Apart from allowing to determine the robustness of the design, the PCE method also allows us to obtain a **Surrogate Model**.

Surrogate Modelling

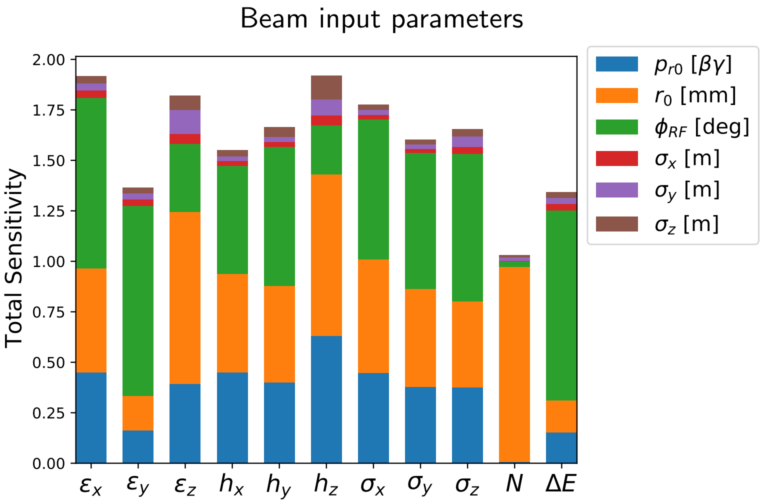
Surrogate Model: black-box that mimics the behaviour of the high-fidelity simulations when given a set of input parameters.



Allows for **fast multi-objective optimization**.

Sensitivity Analysis of the design: Results

Winklehner, Mayani, et al. (2022)



Sensitivity Analysis of the design: Results

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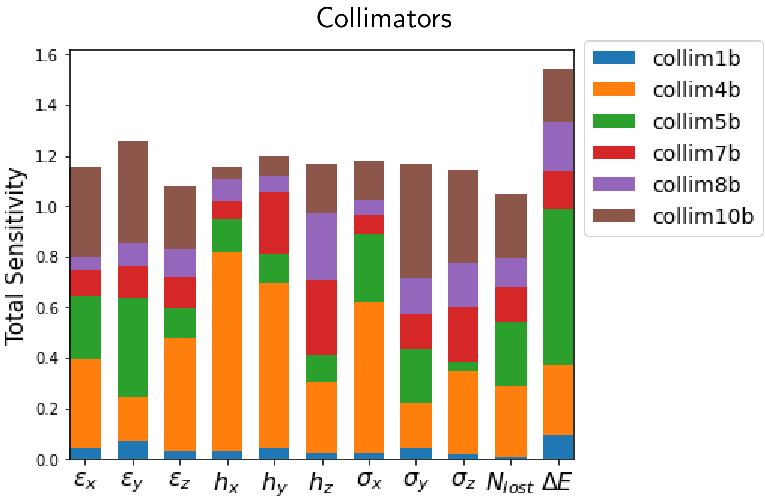

Results of optimization via surrogate models

Winklehner, Mayani, et al. (2022)

- **First trial at optimisation:** design variables fall back to the original design values.

- **Collimator placement optimisation:** High-fidelity simulations of IsoDAR with optimal placements show no significant improvement in beam quality at the end of the cyclotron.

  $\implies$ Current collimator placements are **robust**!

- **Future studies:**
  $\rightarrow$ Create a more general surrogate model by training on a wider range of design values.
  $\rightarrow$ Repeat the multi-objective optimisation and perform a more complete study of the optimality of the design.

Summary

- **Summarize the content of this presentation:**
  - We can take advantage of space charge effects in the design of high-intensity cyclotrons e.g. IsoDAR.
  - Precise simulations together with uncertainty quantification allow to study robustness and feasibility.

- **Where is the gap regarding space charge effects?**
  - Computational demand for precise simulations, which take into account statistical meaningful halo prediction for example, takes considerable amount of time.
  - No good theoretical/approximation models to aid in the design.

- **What is needed to bridge this gap?**
  1. More research on surrogate models.
  2. Efficiently use the upcoming computing resources i.e. **Exascale**.

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