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Flux Concentrator Opera Model

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Outline

- Background
- Goals of the simulation
- Description of the Opera models
- Axial field profile for different cases of study
- Current density distribution and field boost origin
- Comparison with experimental result
- Parametric study for FC design optimisation

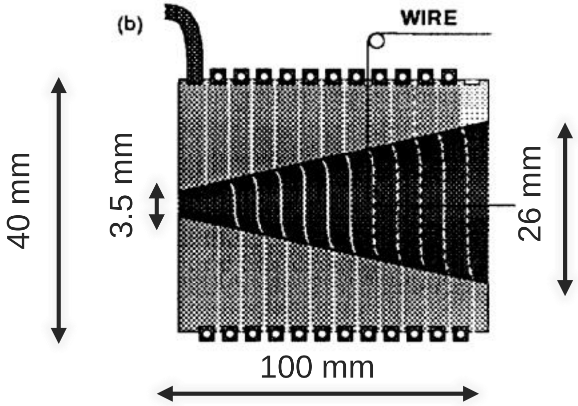
Background

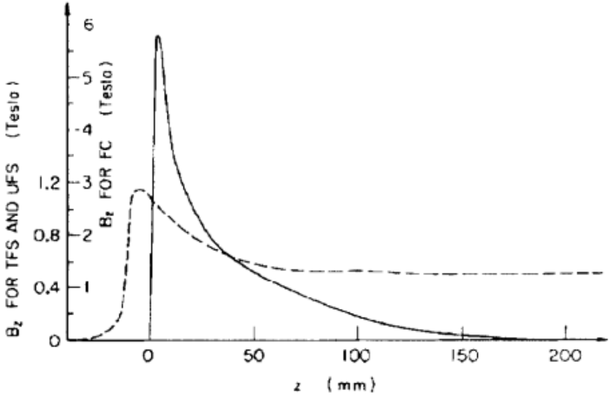
- [1] R. H. Helm, “Adiabatic approximation for dynamics of a particle in the field of a tapered solenoid,” Stanford Linear Accelerator center SLAC, Report No. 4, August 1962.
- [2] M.N. Wilson and K.D. Srivastava, “Design of Efficient Flux Concentrators for Pulsed High Magnetic Fields,” Rutherford High Energy Laboratory, May 1965.
- [3] A.V. Kulikov, S.D. Ecklund, and E.M. Reute, “SLC Positron Source Pulsed Flux Concentrator,” Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309, SLAC-PUB-5473, June 1991.
- [4] J. De Lamare, A.V. Kulikov, R. Cassel, V. Nesterov, “SLC Positron Source Flux Concentrator Modulator,” Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309, SLAC-PUB-5472, May 1991.
- [5] H. Wang, W. Liu, W. Gai, T. Wong, “Modeling and Prototyping of a Flux Concentrator for Positron Capture,” Argonne National Laboratory and Illinois Institute of Technology, IEEE Transaction On Magnetics, Vol. 44, NO.10, Oct. 2008.
- [6] “Design of a Pulsed Flux Concentrator for the ILC Positron Source,” J. Gronberg, R. Abbort, C. Brown et. al., Lawrence Livermore National Lab., Livermore, CA, 1018008, May 2010.
- [7] L. Zang, T. Kamitani, S. Fukuda and Y. Ogawa, “Design Optimization of Flux Concentrator for SuperKEKB,” Proceedings of the IPAC’12, New Orleans, USA, May 2012.
- [8] L. Zang, M. Akemoto, S. Fukuda, et. al., “Prototyping of the Flux Concentrator for SuperKEKB Positron Capture,” The 9th Annual Meeting of Particle Accelerator Society of Japan, 2012.
- [9] J. Zhang on the behalf of CEPC team, “Overall Design of the CEPC Injector Linac,” eeFACT2018, HKUST, Hong Kong, China, 2018.
- [10] CERN, “The Compact Linear Collider (CLIC) 2018 Summary6 Report,” Geneva, 2018.

Background

- Tapered 12-turns solenoid made of Copper
- Axial field sharp rise (~6T) at device entrance followed by a rapid decay to 0 T

Flux Concentrator design from SLAC





A.V. Kulikov, S.D. Ecklund, and E.M. Reute, “SLC Positron Source Pulsed Flux Concentrator,” Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309, SLAC-PUB-5473, June 1991.

Goals of the simulation

- To understand the **working principle** of
  an Adiabatic Matching Device Flux Concentrator (AMD FC)
  by the mean of **electromagnetic models** using Opera® software

- To give the phenomenology of the axial **field boost** from 2 to 6 T

- To reproduce the design and result of the SLAC AMD FC

- To run **parametric study** in order to **optimize** future AMD FC design

Description of the Opera models

- 2D model
- Axi-symmetric system
- Geometry of solenoid: → *Straight and tapered, SLAC design*
- Material properties: → *Constant conductivity of Copper*
- Boundary conditions: → *Tangential field for symmetry and far field*
- Powering circuit: → *AC or DC current supply and winding*
- Regular mesh and mesh refinement: → *quadrilateral FE and Bias method*
- Static and dynamic simulation: → *Eddy Current and Skin effect*
- Cases of study: → *decoupling the various effects*

Description of the Opera models

Simple geometries to decouple the effects

Solenoid cases of study

Skin depth

$$\delta = \frac{1}{\sqrt{\pi . f . \mu_o \mu . \sigma}} = 0.15 \text{ mm}$$

Conductor width

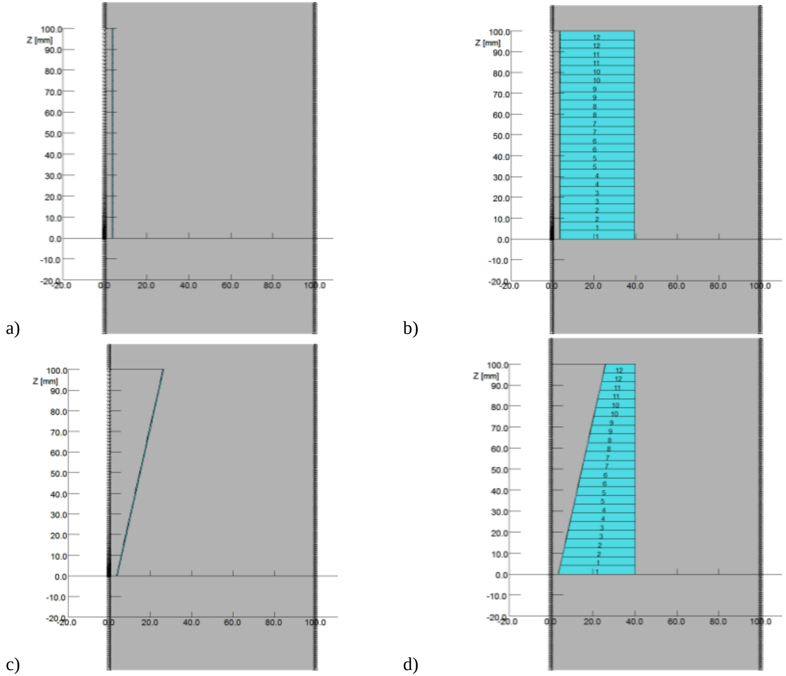
$$w = 3\text{x } \delta = 0.45 \text{ mm}$$

Tapered parameter

$$\alpha = \frac{R_f - R_i}{L} = \frac{26-3.5}{100} = 0.225$$

Thin and straight

Thick and straight



Thin and tapered

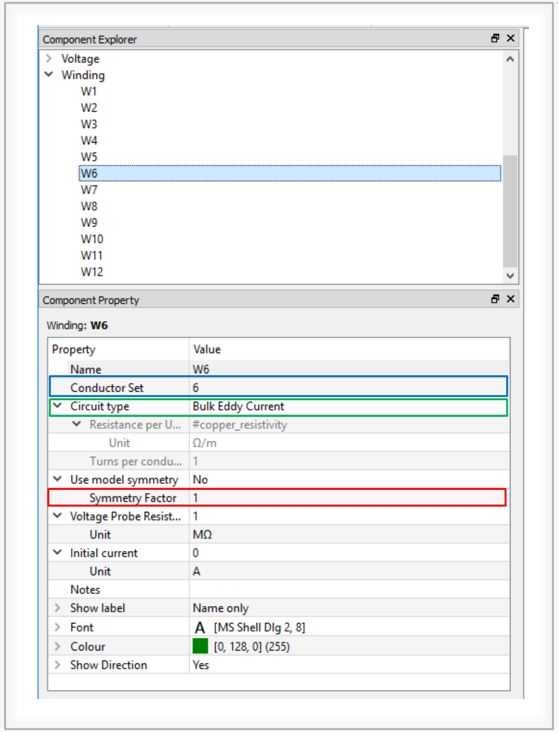
Thick and tapered

$$w = R_o - R_i = 36.5 \, mm$$

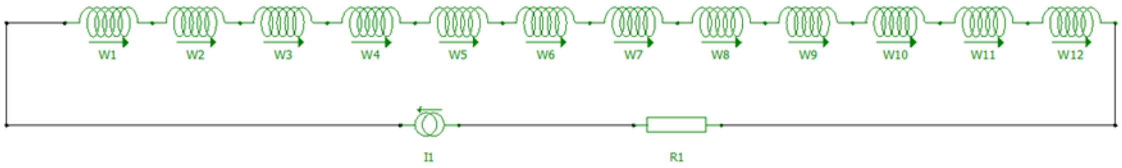
$$w(z) = R_o - (R_i + \alpha z)$$

Description of the Opera models

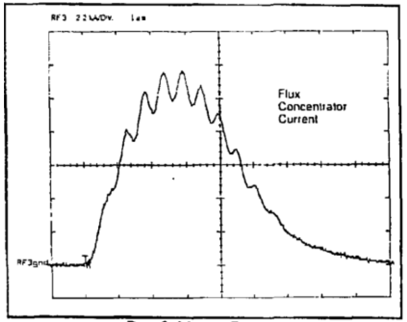
Powering circuit



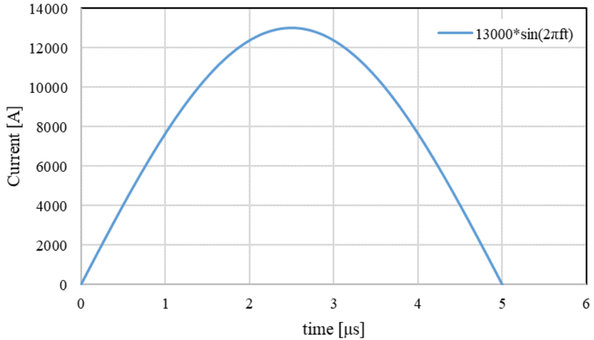
Opera links the FE model to circuit elements
(current supply external resistor and winding elements)



The built-in circuit allows to reproduce experimental powering ramp.

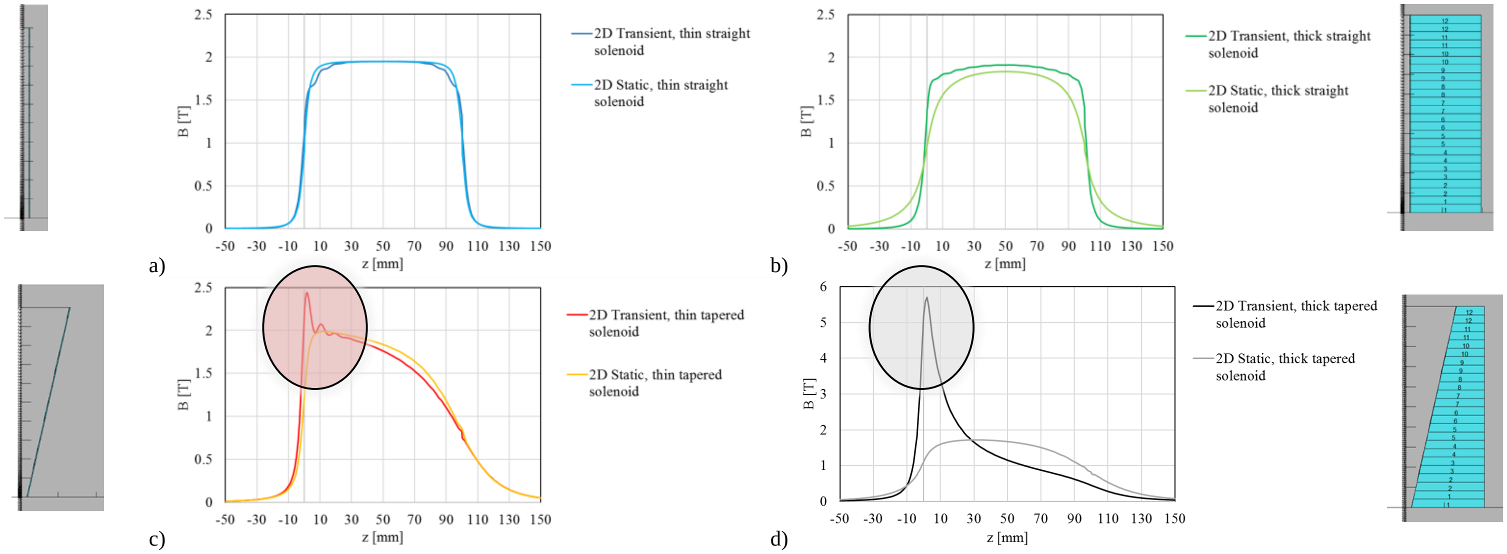


Data 3: Magnet Current



Axial field profile for different cases of study

Comparison between Static and transient simulations



Field boost occurs only in tapered solenoid

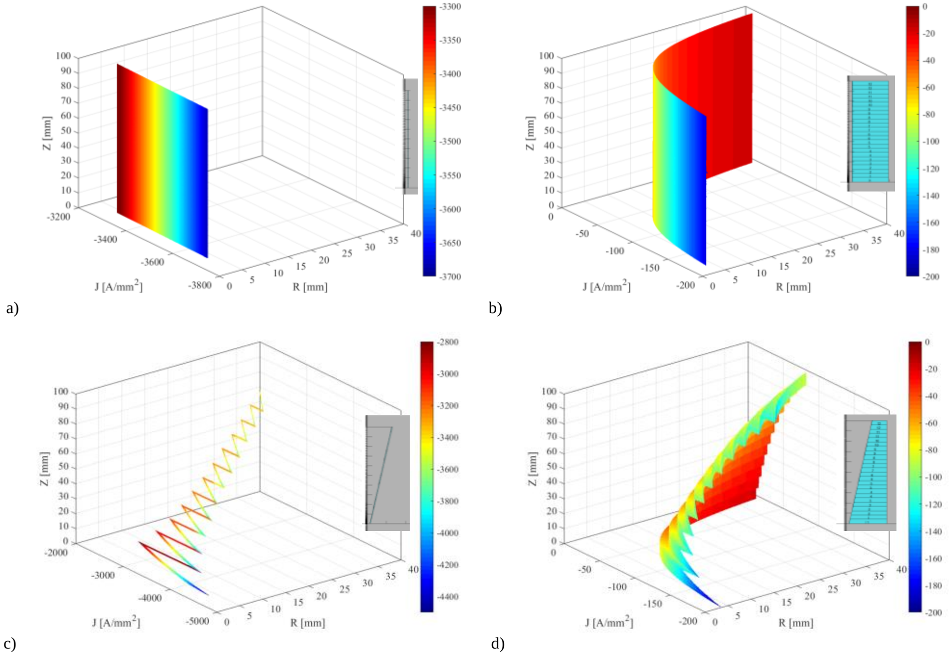
Field above **5 T** obtained for **tapered thick solenoid** (2D model is enough)

Current density distribution and field boost origin

Comparison between Static and transient simulations

Constant *J*

J inversely proportional to *R*



J decreases with *Z*

J decreases both with *Z* and *R*

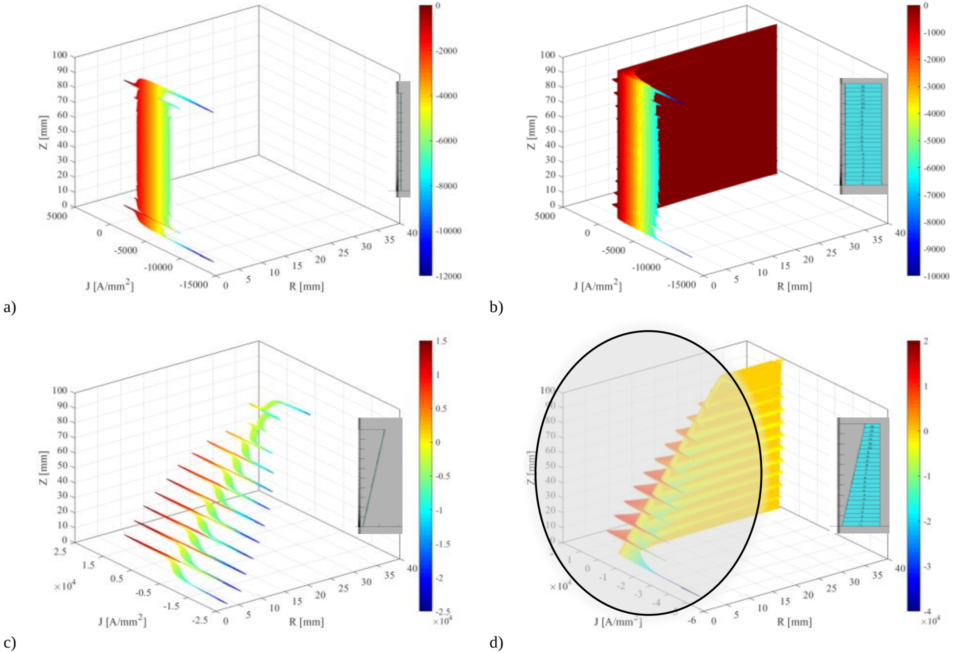
In **static** simulation, the **current** preferably **flows** from the **inner side** to the periphery of the turns

Current density distribution and field boost origin

Comparison between Static and transient simulations

J within δ

J within δ
Current only flows around the coil's aperture

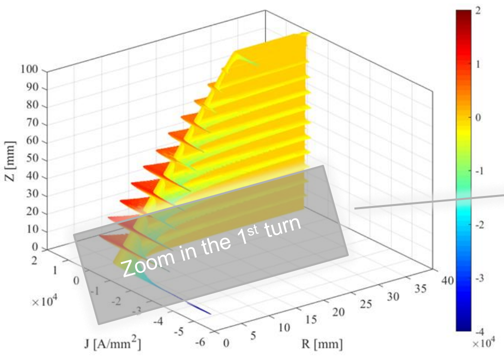


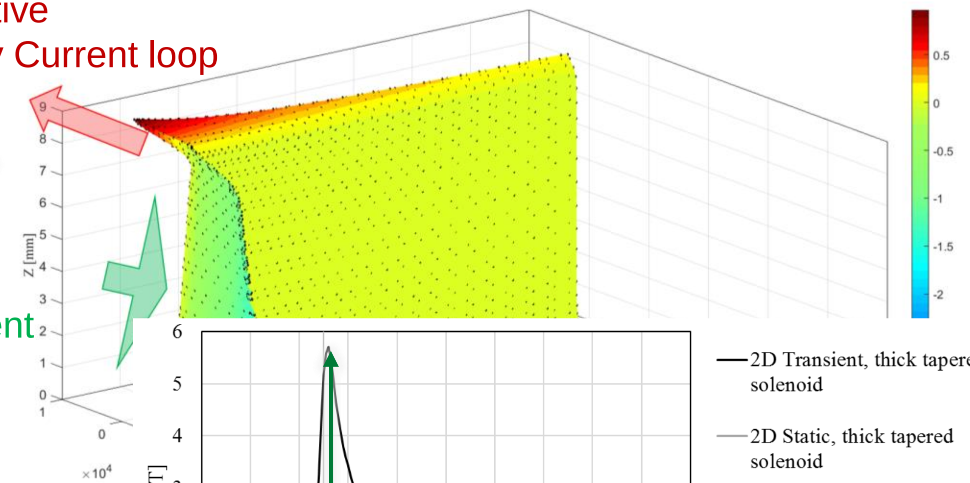
J within δ
Negative and positive currents

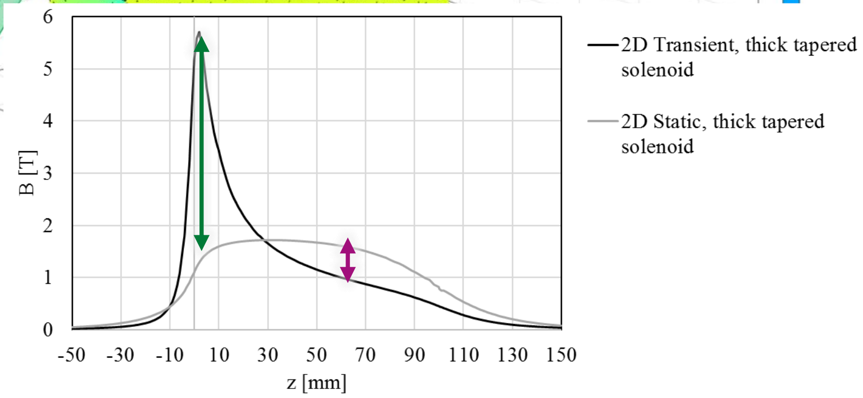
J within δ
Opposite currents
Current also flows at the coil's periphery

In **transient** simulation, the **current flows** at the **skin** of the turns
For the tapered case, **opposite flows of current** circulate within each turn

Current density distribution and field boost origin



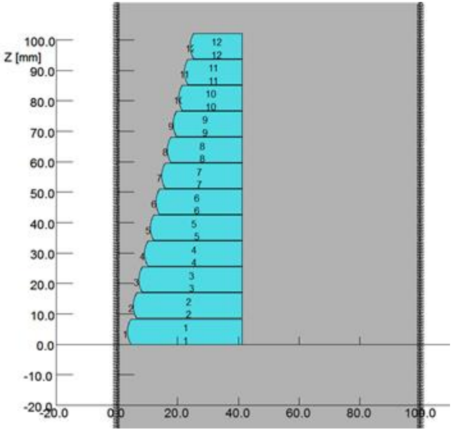


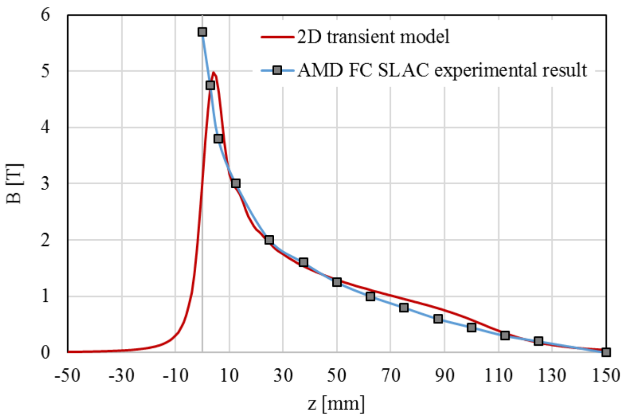


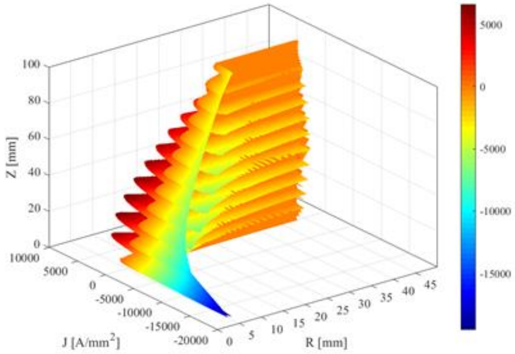
The AC excitation produced strong **Eddy currents**
that circulate in opposite directions
adding or subtracting to the transport current
hence producing the field boost at the device entrance
thus reducing the field at the device exit

Comparison with experimental result

- SLAC design is modelled. It includes:
  - 200 microns gap between the turns
  - Round conductor tip (for numerical singularity removal)
  - Excellent agreement between numerical and experimental curves







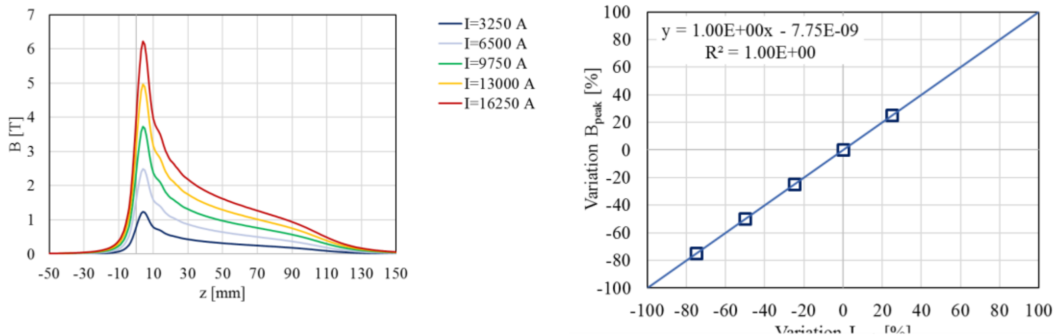
Parametric study for FC design optimisation

- Sensitivity analysis of the model to the design parameters is carried out on:
  - Current’s Amplitude and Frequency
  - Material conductivity
  - Coil geometry:
    - gap size, solenoid outer radius, number of turns

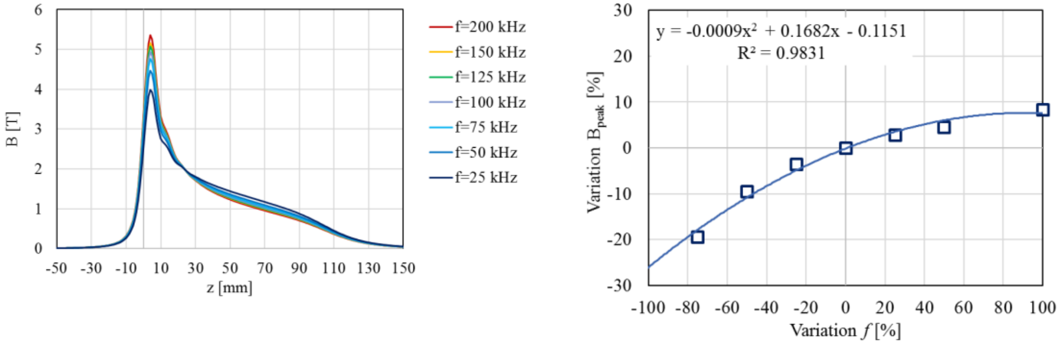
Parametric study for FC design optimisation

Current & Frequency variations

- The peak field linearly scale with the current (slope =1)



- Lowering *f* from 100 kHz to 25 kHz results in 20% lower peak field



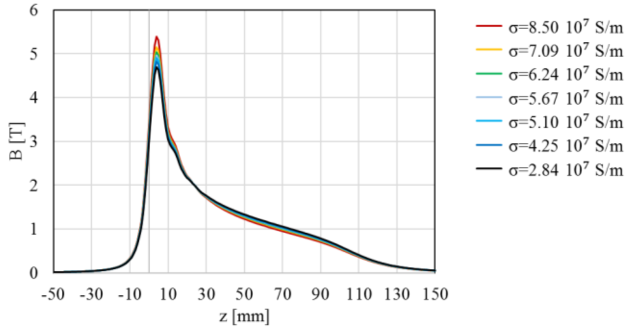
Parametric study for FC design optimisation

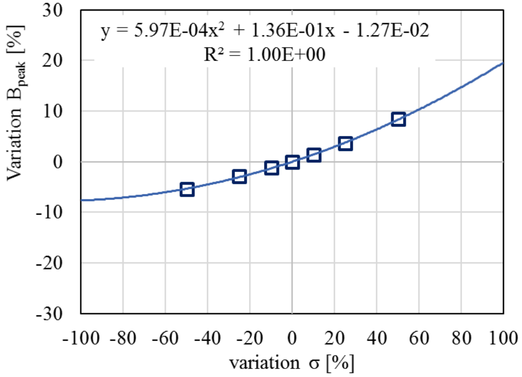
Material conductivity

- The field is rather slightly impacted by the value of the conductivity. It scales with a quadratic function of σ.

- In that sense, the coil material could be change from copper (σ= 5.67 10^7 S/m) to Aluminum (σ = 3.77 10^7 S/m)
  with only 3% variation on the peak field.

- An FC made Titanium ($\sigma = 2.38\times10^6$) would also perform with a field variation of 6 %.

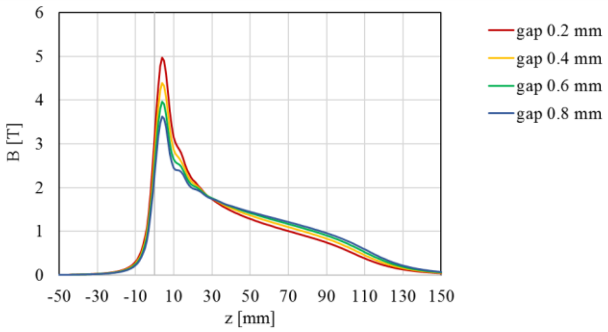


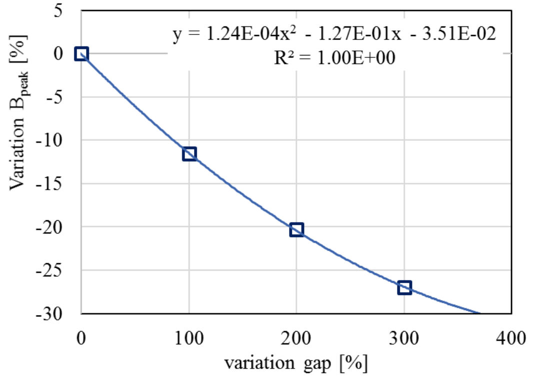


Parametric study for FC design optimisation

Gap size between the turns

- Half a Tesla lost every 200 microns gap.
- The gap could be optimize so that to improve the electrical insulation between the turns.
- Insulating material could be inserted between the turn.
- Doubling the gap of SLAC design reduced the field by 12%

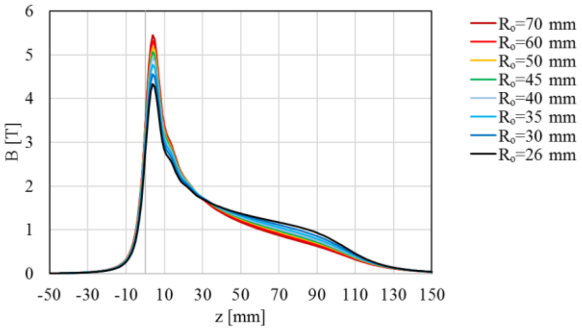


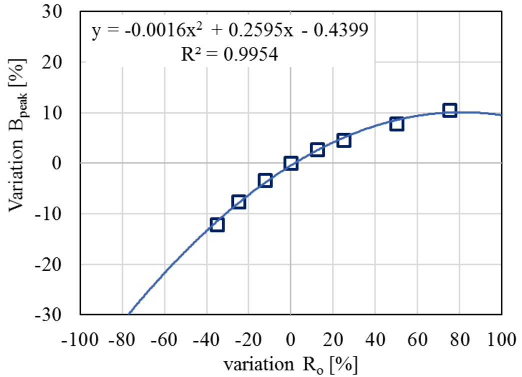


Parametric study for FC design optimisation

Solenoid's outer radius

- Increasing the outer radius enhances the field.
- A solenoid of 60 mm radius (instead of 40 mm) would increase the field by 7 %.
- Thicker magnet could be more robust or thermally easier to cool down

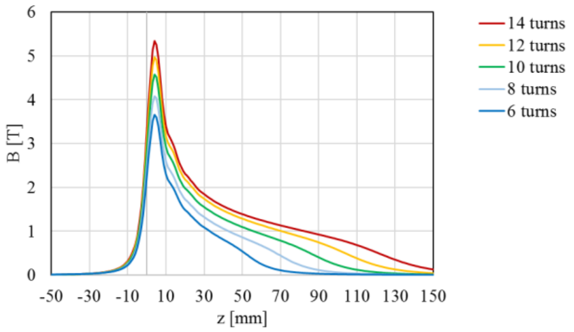


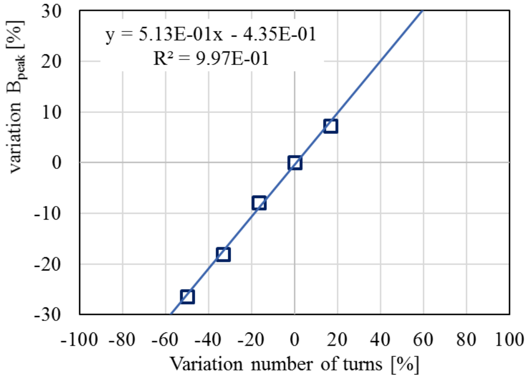


Parametric study for FC design optimisation

Solenoid's number of turns

- The peak field linearly scale with the number of turns.
- Two extra turns lead to 8% enhancement of the field.

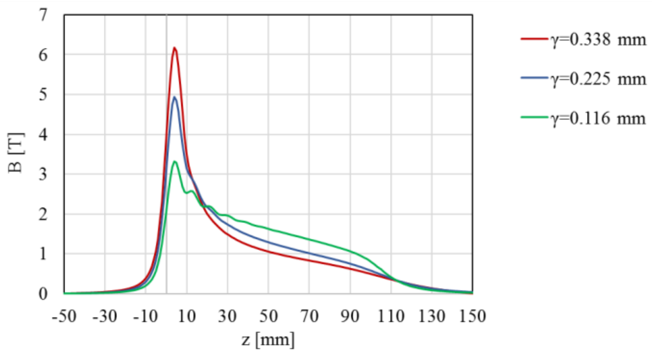


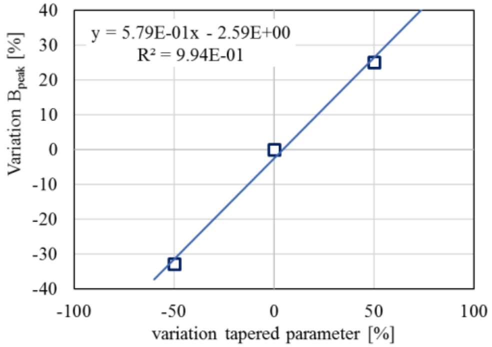


Parametric study for FC design optimisation

Solenoid's tapered parameters

- The peak field linearly scale with the tapered angle.
- 50% larger angle implies 25% increase of the field.



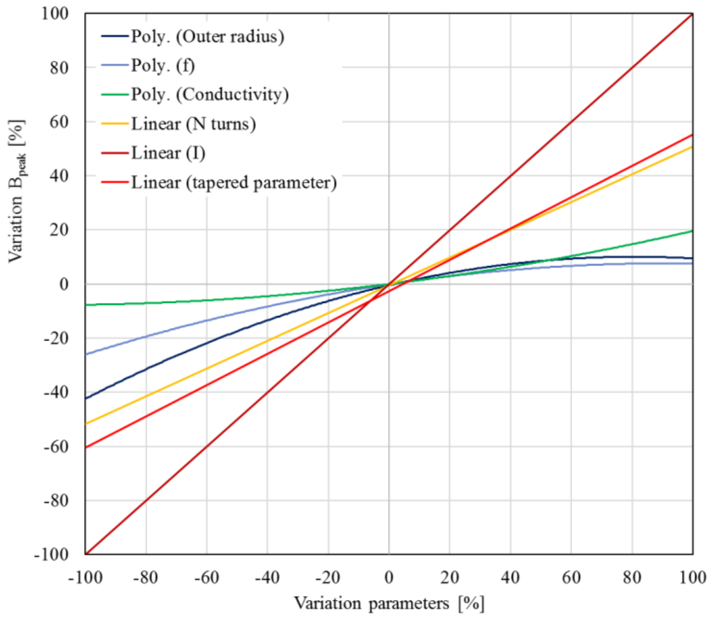


Parametric study for FC design optimisation

Summary of the sensitivity analysis

- Most impacting: *current level*
- Middle impact: *number of turns & tapered angle*
- Less impacting: *frequency & conductivity*

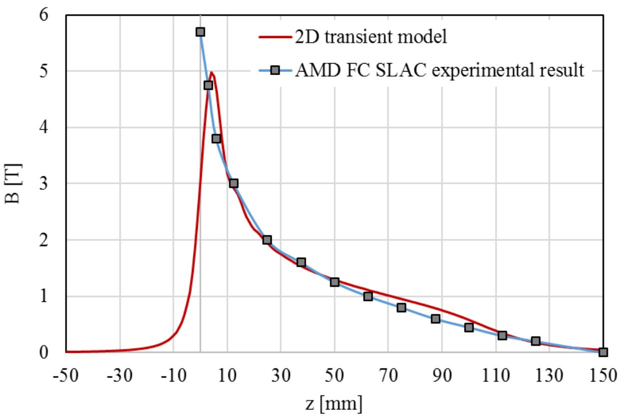
The model offers a **tool to optimise** the design of flux concentrator in terms of magnetic behaviour.

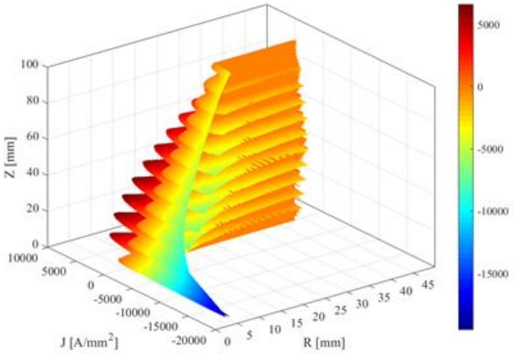


Conclusion

- Development of a **parametric numerical model** of Flux Concentrator using Opera software.
- Understanding of the field boost as the creation of **Eddy current loops circulating in opposite directions** in each turn. Phenomenon that only occurs in the case of tapered solenoid in transient mode. The **current flows only within the skin depth** of the conductor.
- **Validation of the model** and measurement by direct comparison of the field profile.
- Possible optimisation of the design thanks to **sensitivity analysis** for future FC.

Thank you for your attention!





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