CERN

Modelling of Flux Concentrators for Positron Sources

H. Bajas, Y. Zhao

Outline

- Flux Concentrator in linear accelerators
- Objectives of the study
- Modelling of the geometry and the electrical circuit
- Recall of the model’s outcome from last workshop
- Design proposal for the SuperKEKB e+ source
- Design optimization for the CLIC e+ source
- Conclusion

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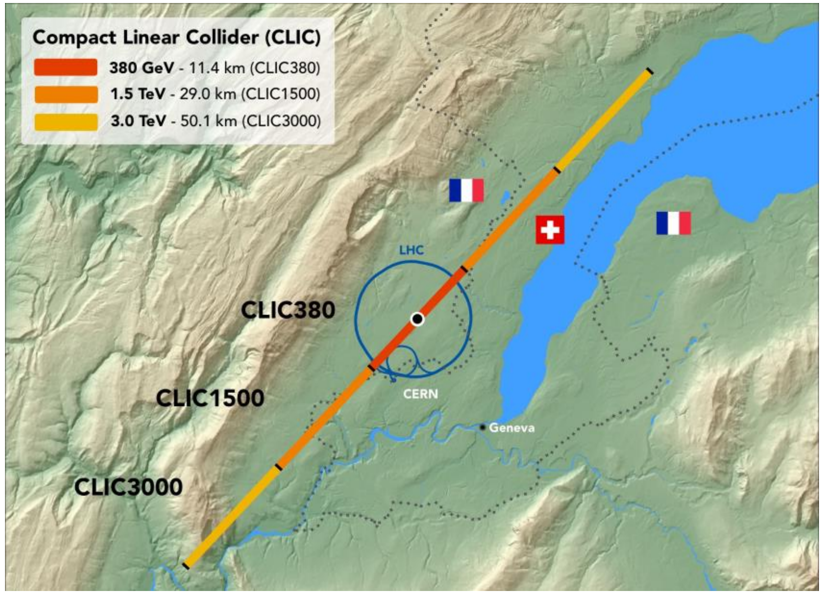
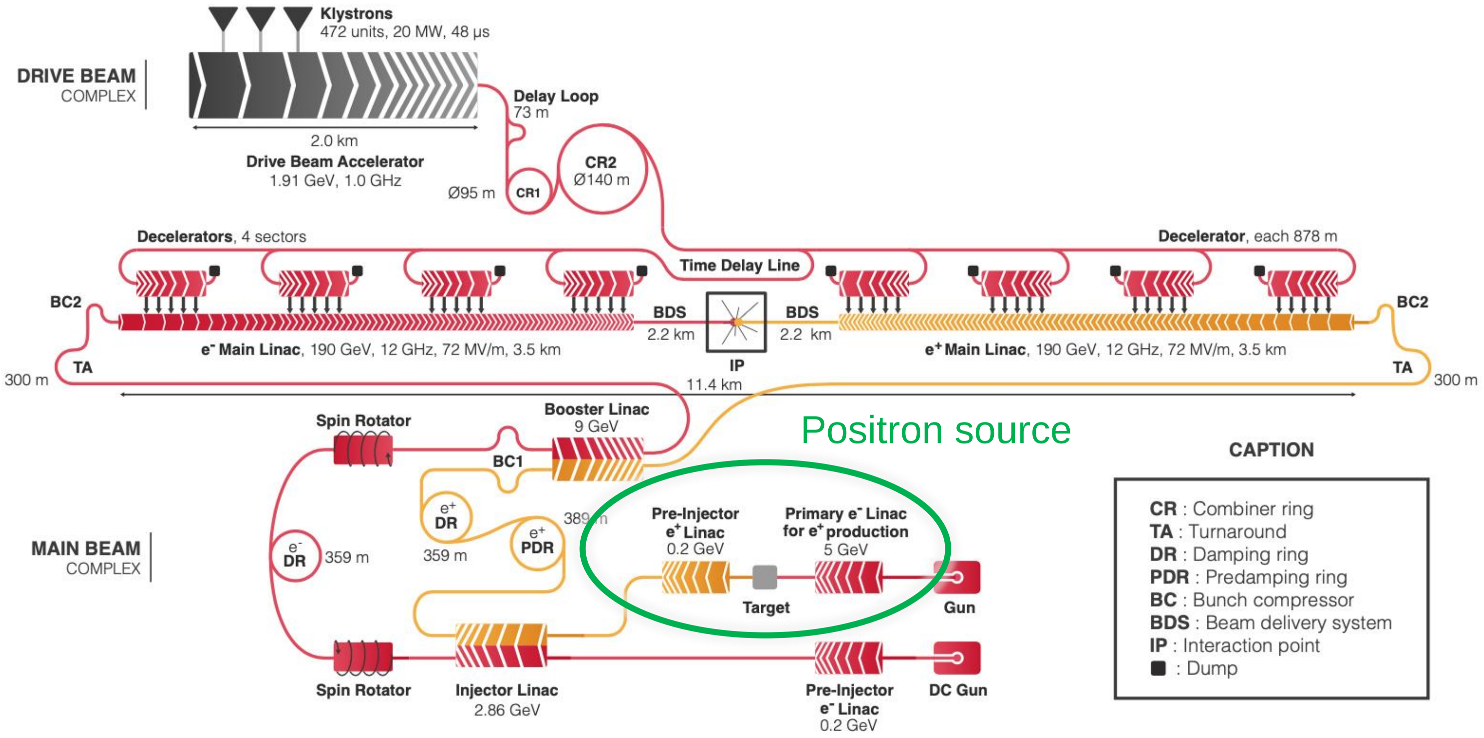
Flux Concentrator in linear accelerators

Future linear colliders, such as CLIC at CERN, would use both electrons and positrons.
The positron source produces positrons from the collision of electrons on fixed target then introduced in the pre-injector.

The quality of the source is of prior importance for the luminosity of the machine.

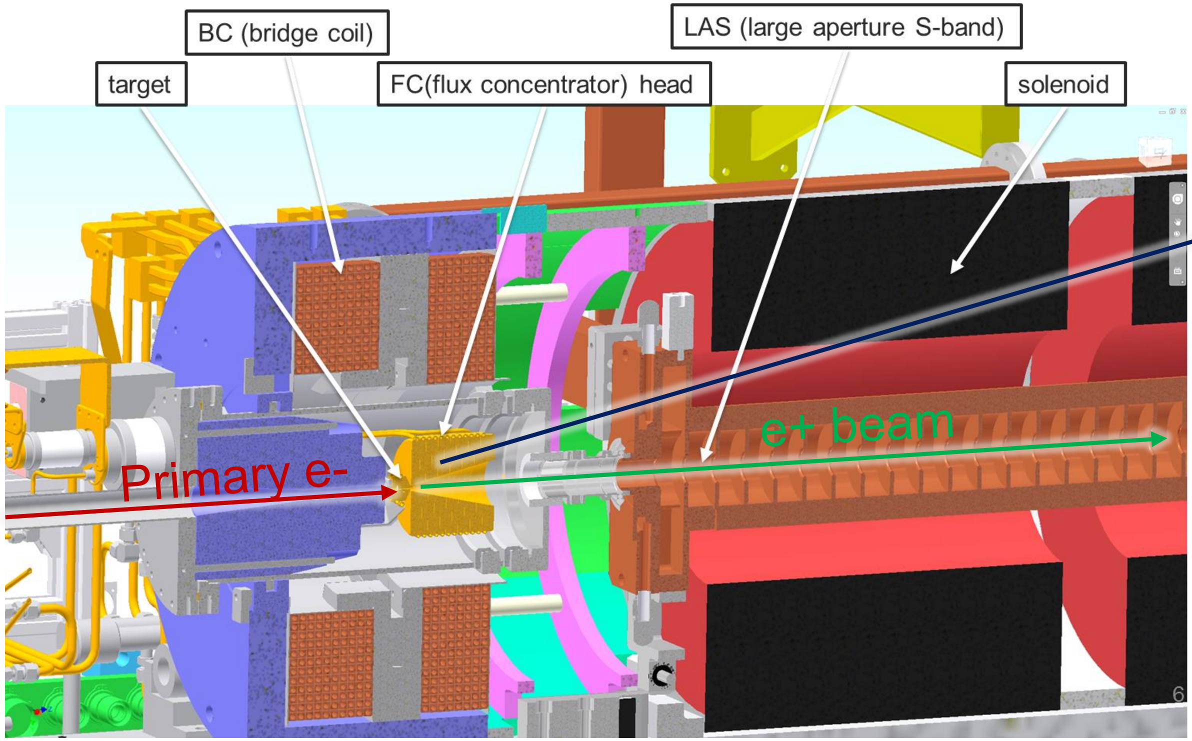


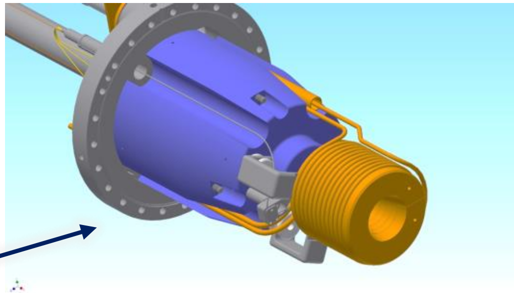


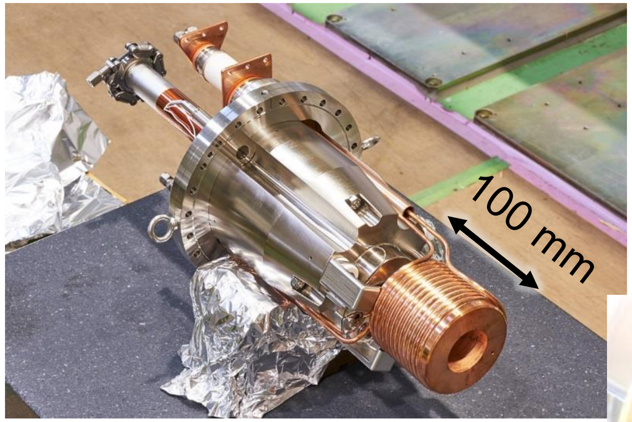
Steinar Stapnes, October 2019, Sendai
International Workshop on Future Linear Colliders

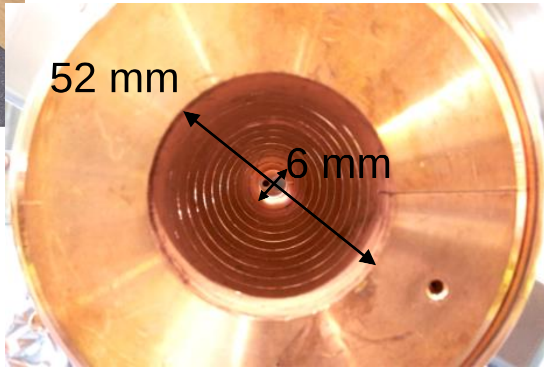
Flux Concentrator in linear accelerators

At the SuperKEKB e+ source









KEK-JAPAN

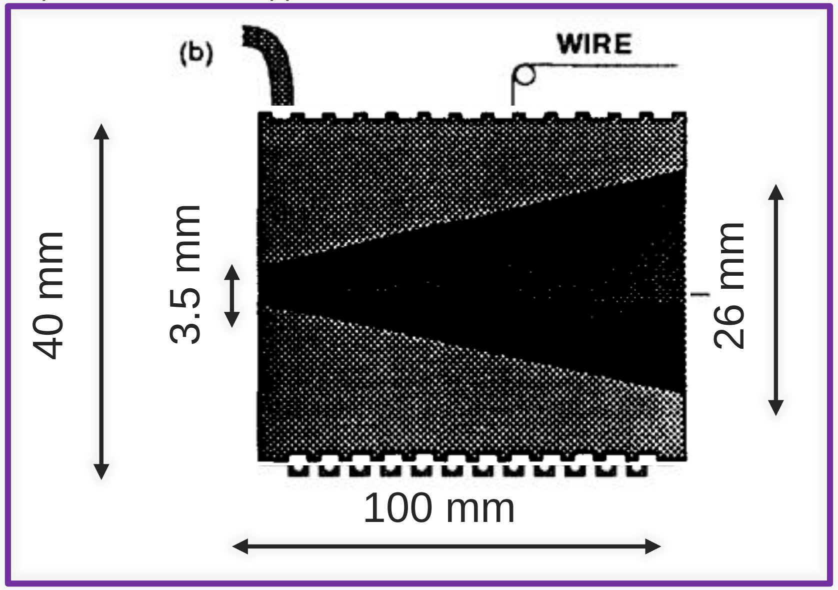
Courtesy Yoshinori Enomoto, October 2019, Sendai International Workshop on Future Linear Colliders

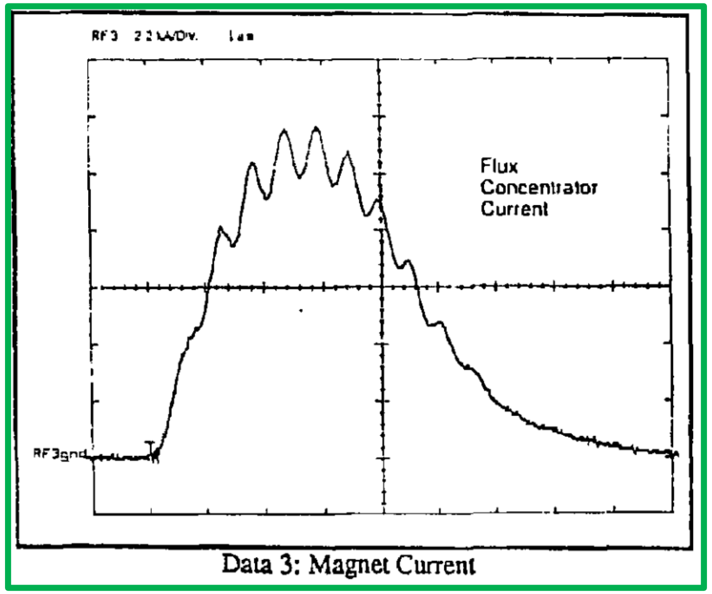
Tapered 12-turns solenoid made of Copper (OFHC)

Working principle of a Flux Concentrator

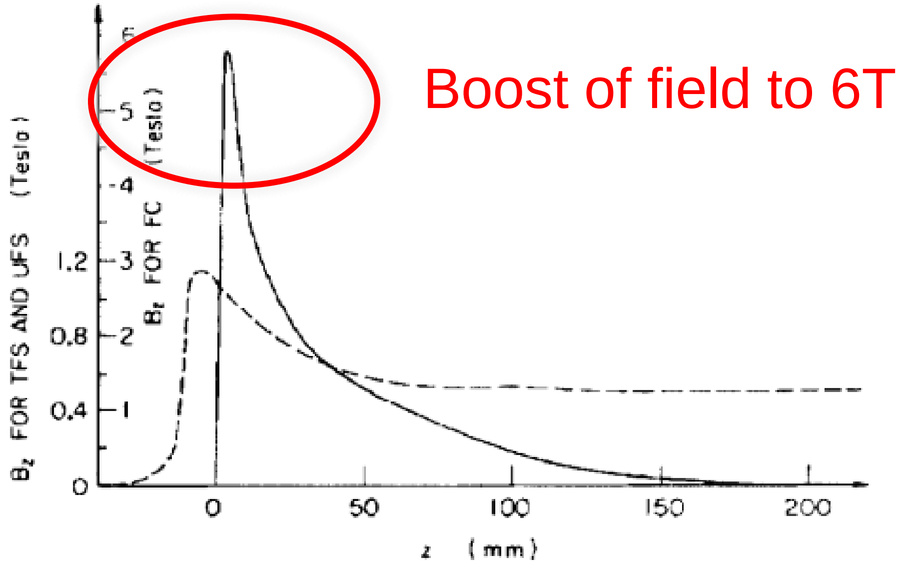
- Based on old concept used for several years at the SLAC positron source.
- High current pulses (13 kA, 5μs) produce pulses of magnet field.
- Axial field sharp rise (~6T) at device entrance followed by a rapid decay to 0 T.

Tapered 12-turns Copper solenoid





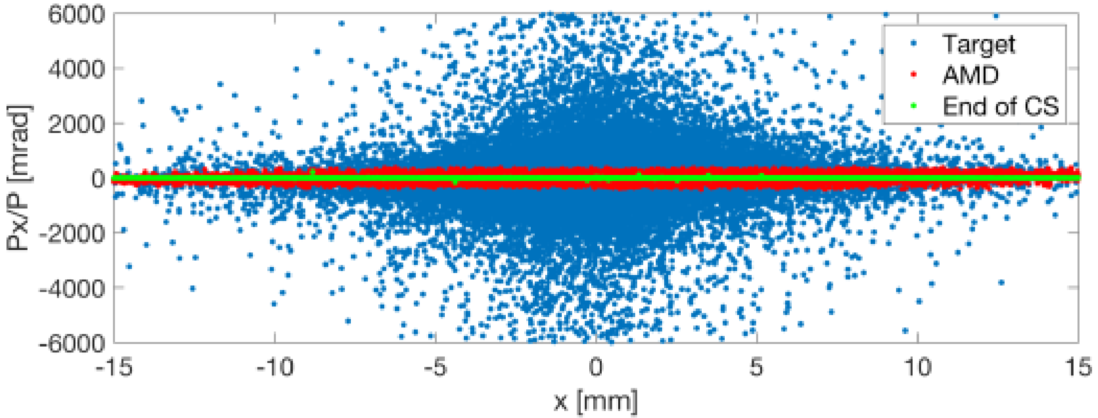
Data 3: Magnet Current



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.

Working principle of a Flux Concentrator

Positron emittance at the exit of
the target, the AMD and the capture section



Purpose of the Adiabatic Matching Device (containing the FC):

- Matching the e+ beam (with very large transverse divergence) to the acceptance of the pre-injector linac.
- Maximise the “so-called” positron yields:

$$\text{yield}_{e+} = \frac{n_{e+}^{\text{produced}}}{n_{e-}^{\text{primary}}}$$

Courtesy I. Chaikovska October 2019, Sendai
International Workshop on Future Linear Colliders

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Objectives of the study

- To study in detail the **working principle** of
  an Adiabatic Matching Device Flux Concentrator (AMD FC)
  by the means of **electromagnetic transient models** using Opera® software.
- To validate the model by direct comparison to experimental data.
- To understand the phenomenology of the axial **field boost** from 2 to 6 T.
- To run **parametric study** in order to **optimize** future AMD FC design.
- To propose solution for KEK design and future FC at CERN.

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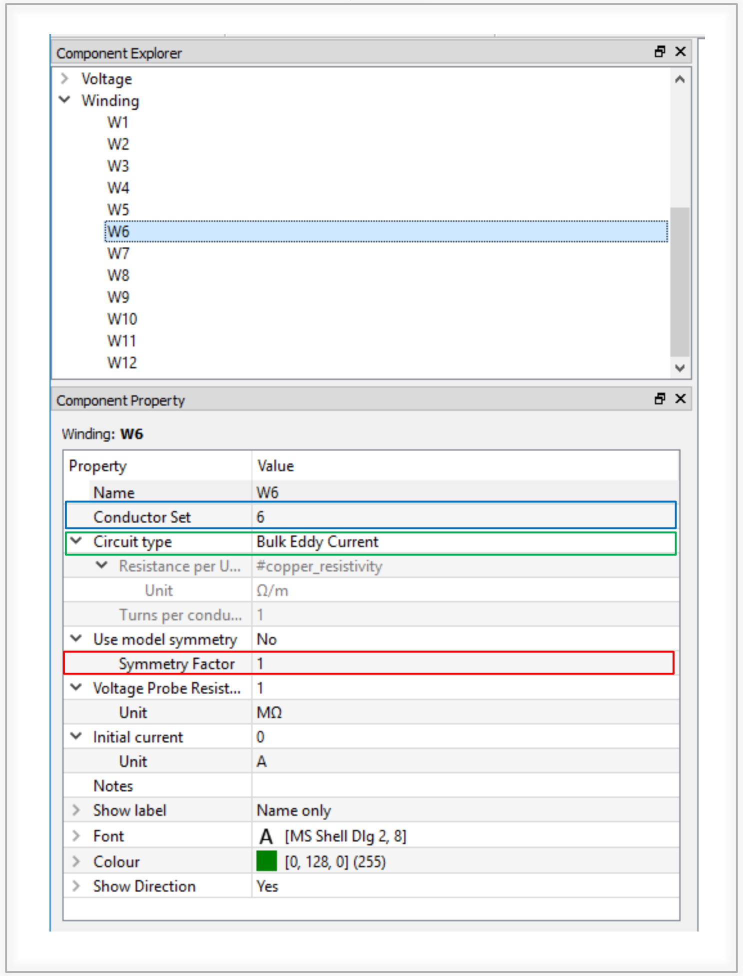
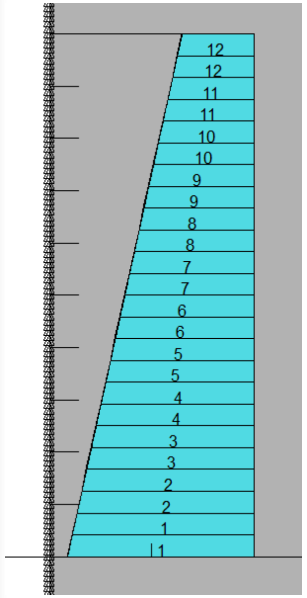
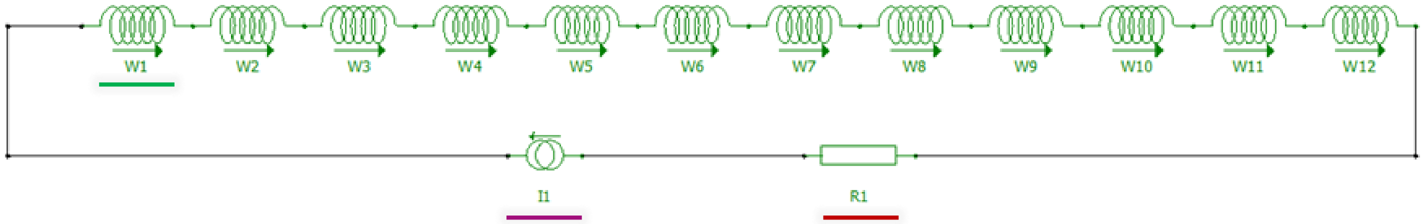
Modelling of the geometry and the electrical circuit

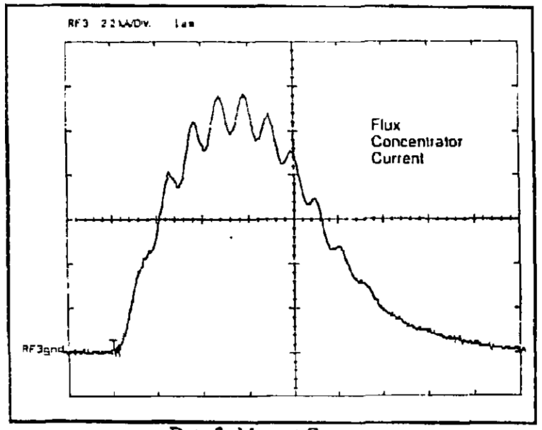
Opera® allows linking the FE model to the circuit elements to impose flow of current (current supply, external resistor and winding elements)







The built-in circuit allows reproducing the experimental pulse of current.



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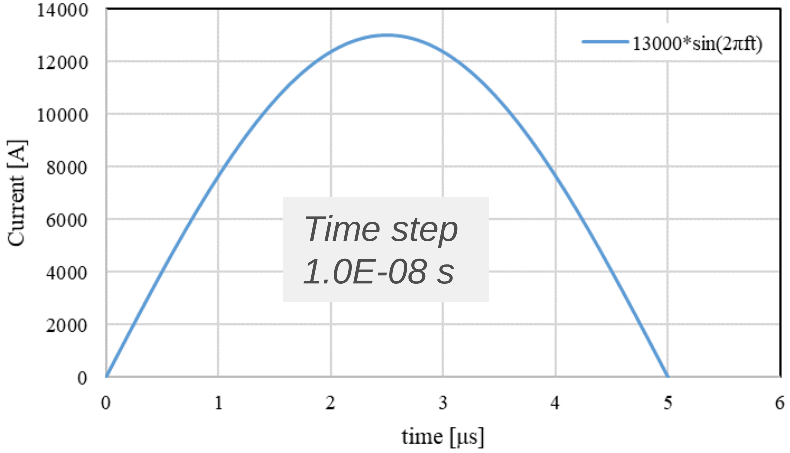

J. De Lamare, et Al. , "SLC Positron Source Flux Concentrator Modulator," SLAC-PUB-5472, May 1991.

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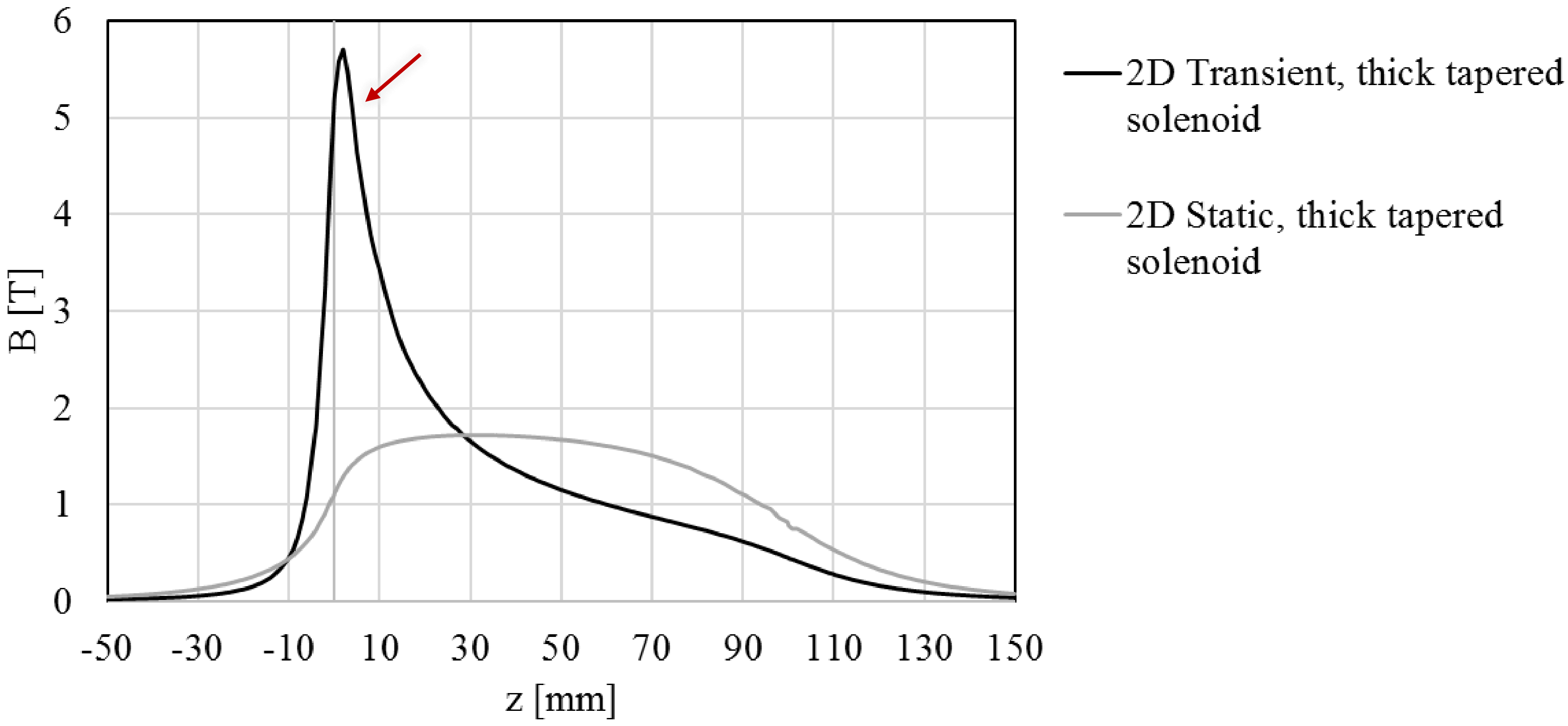
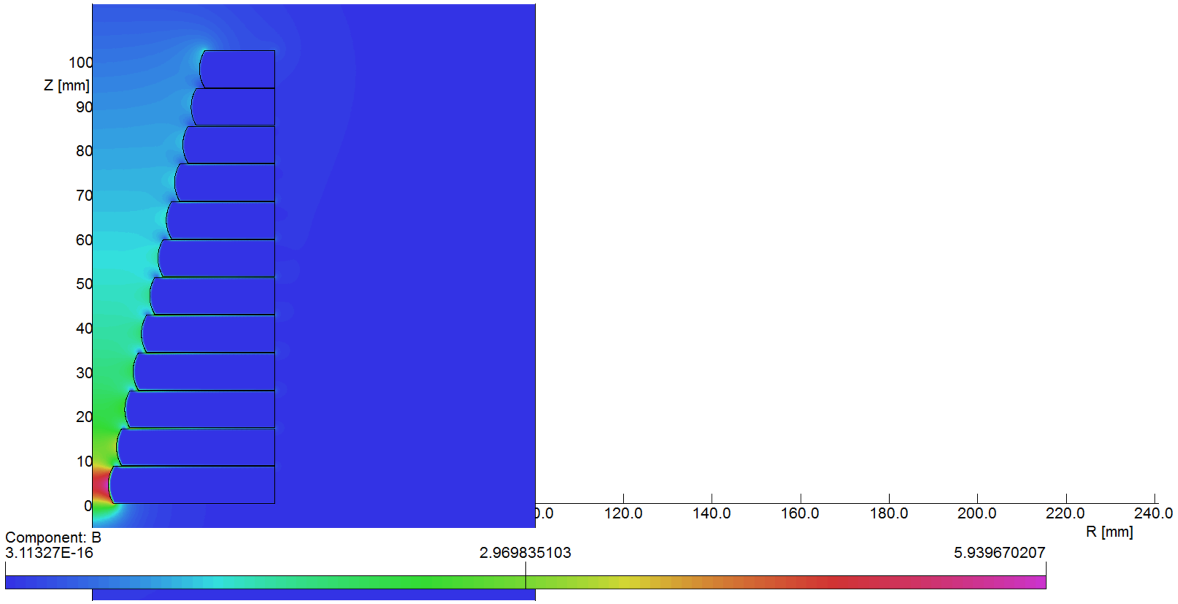
The origin of the field boost



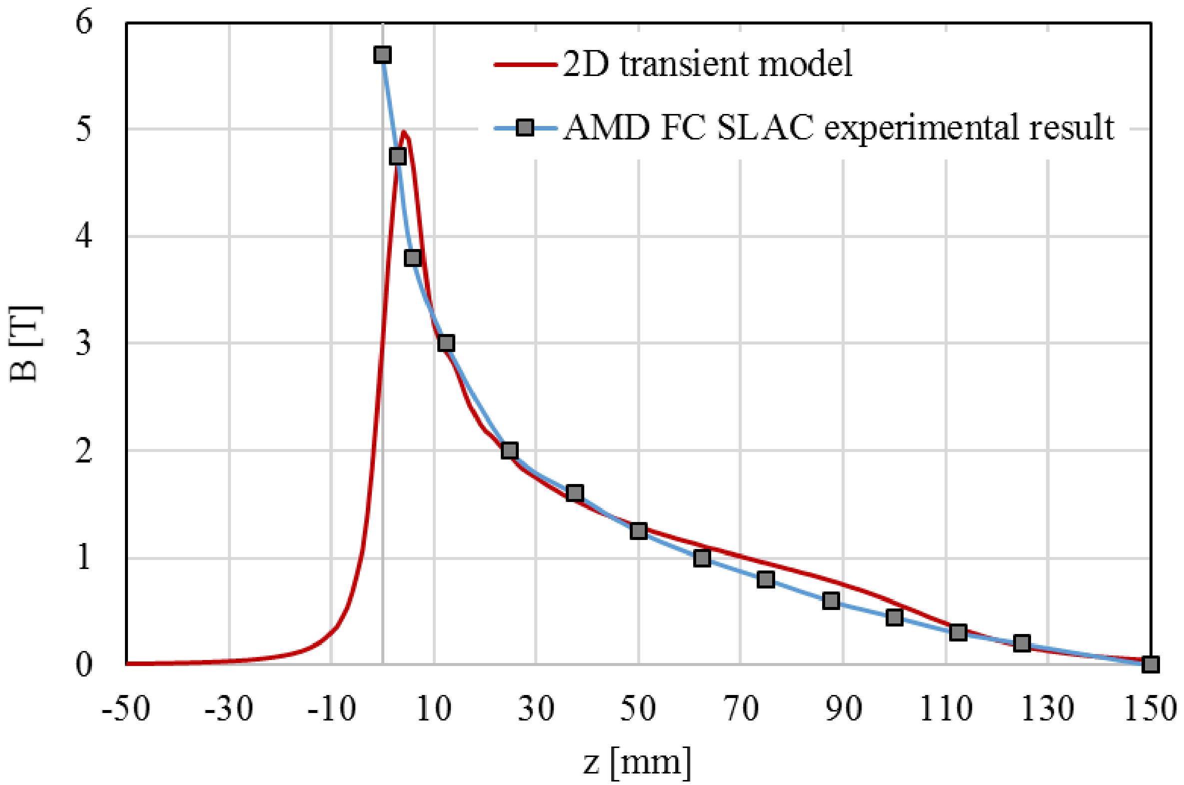
The **boost of field** only occurs for tapered coil in **transient mode** when both **skin effect** and **eddy current** occur.

https://agenda.linearcollider.org/event/8217/

Comparison with experimental result: SLAC



Solenoidal field map



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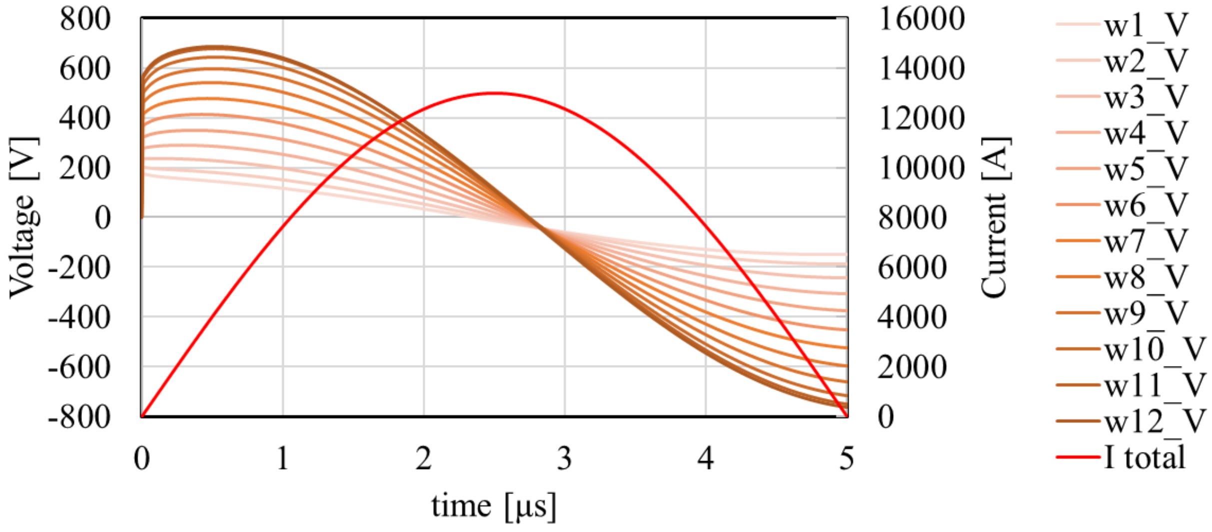
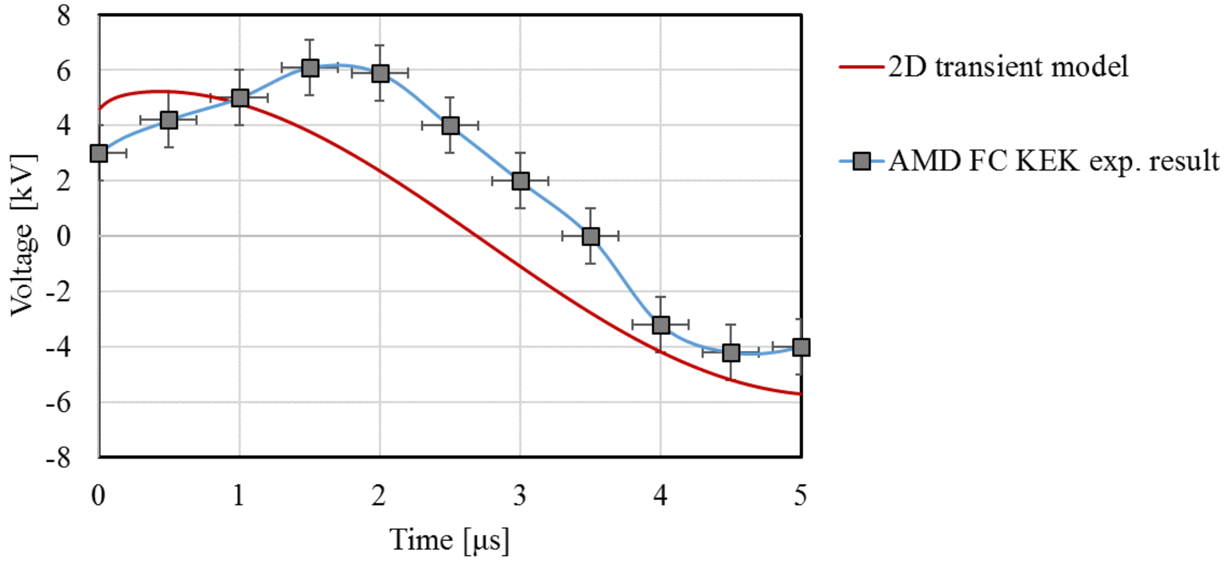
Comparison with experimental result : KEK



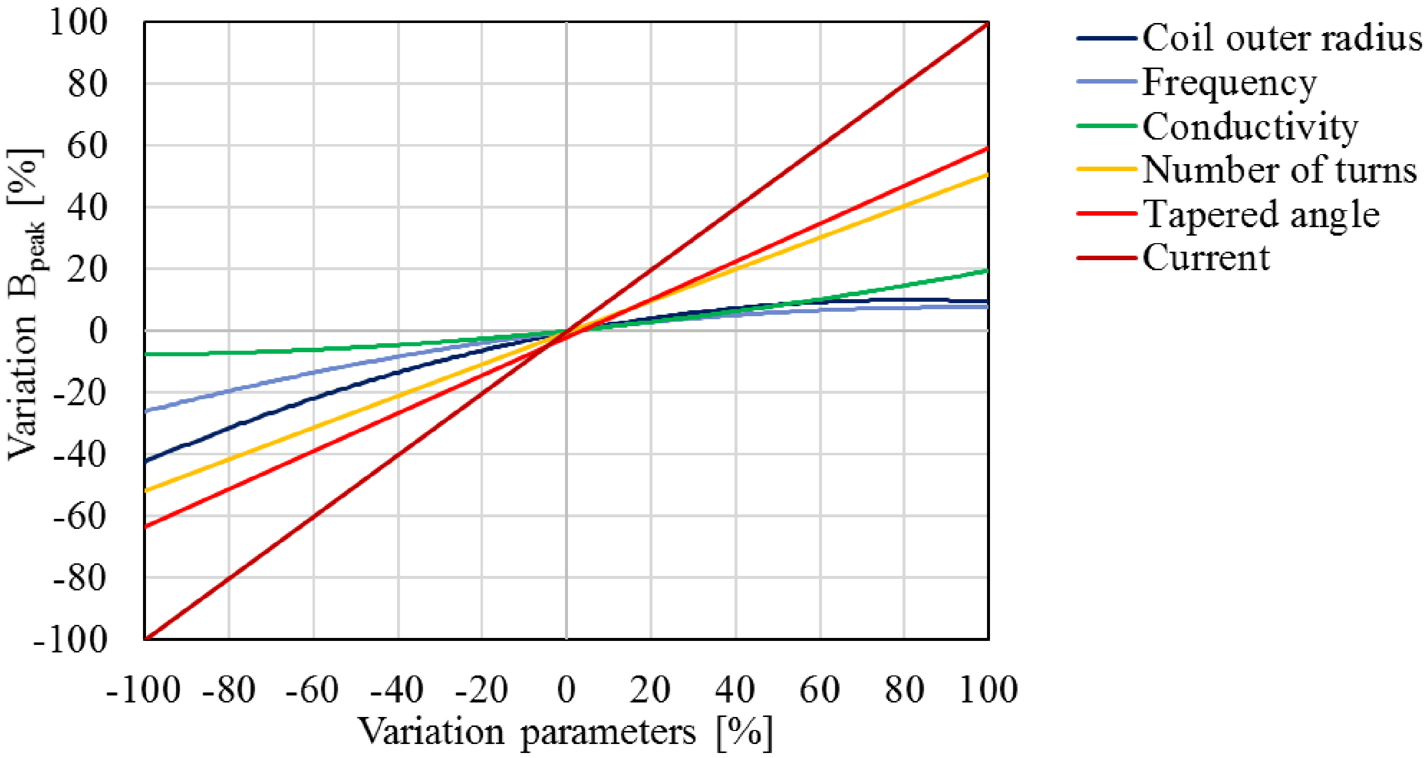
Voltage across each turn

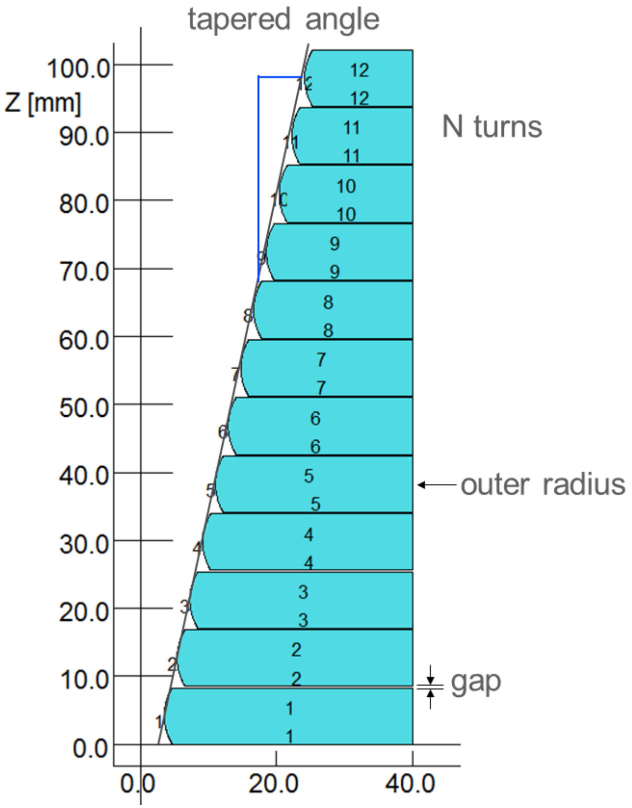


Voltage across the solenoid

https://agenda.linearcollider.org/event/8217/

Parametric study for FC design optimisation





A **tool to optimise** FC's design.

In particular it is possible to **increase the gap between turns** compensating the loss of field.

https://indico.cern.ch/event/879495/

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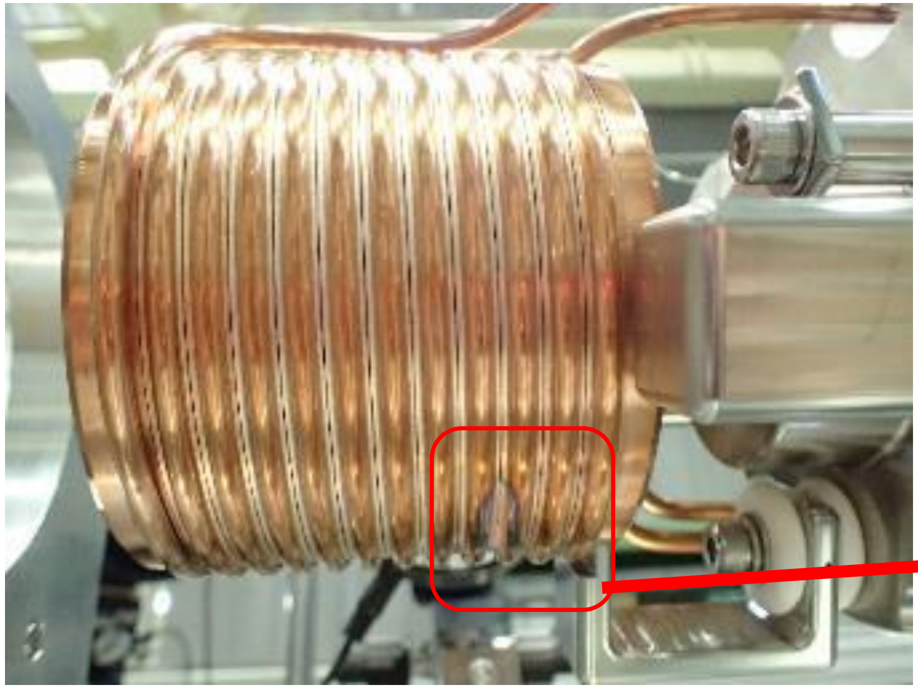
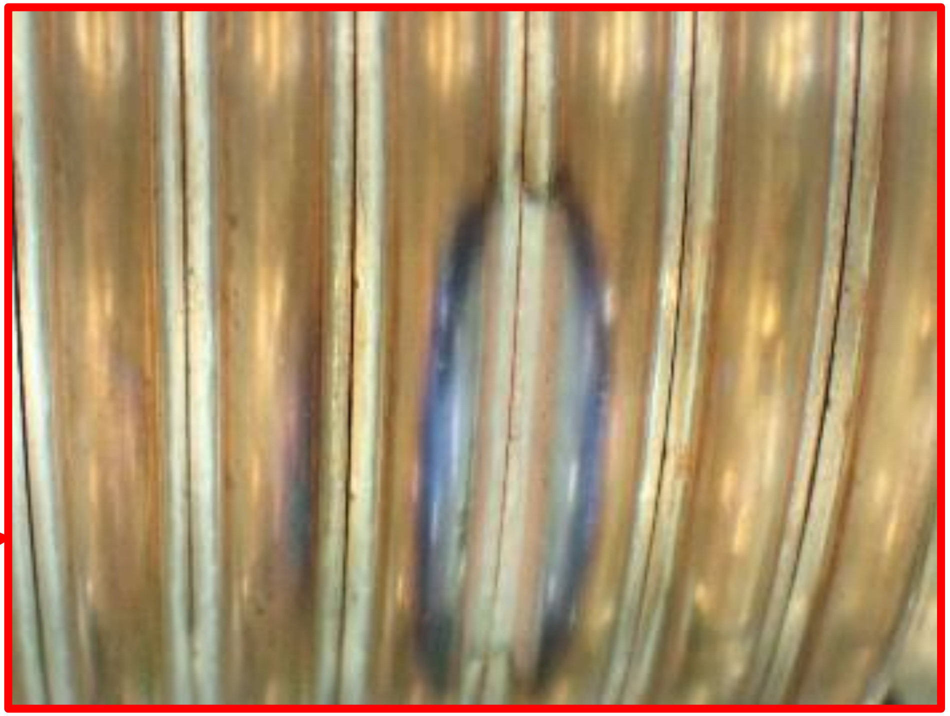
Dielectric breakdowns during the test of the KEKB FC

- Issue of **electrical arcing** between turns at full current discharge during FC test.

Flux Concentrator design from KEK





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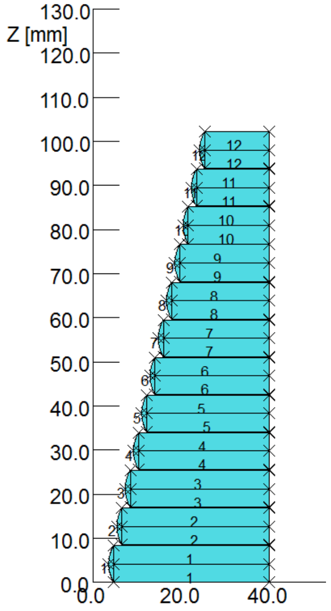
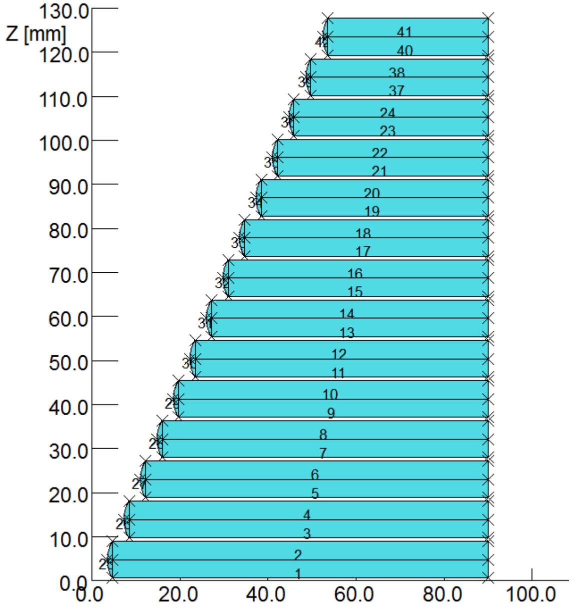
Modified design to cope with breakdown issue



SLAC design

gap=0.2 mm
$\sigma=5.67\ 10^{7}$ S/m
$R_o=40$ mm
N=12 turns
$\gamma=0.255$
f=100 kHz



Modified design

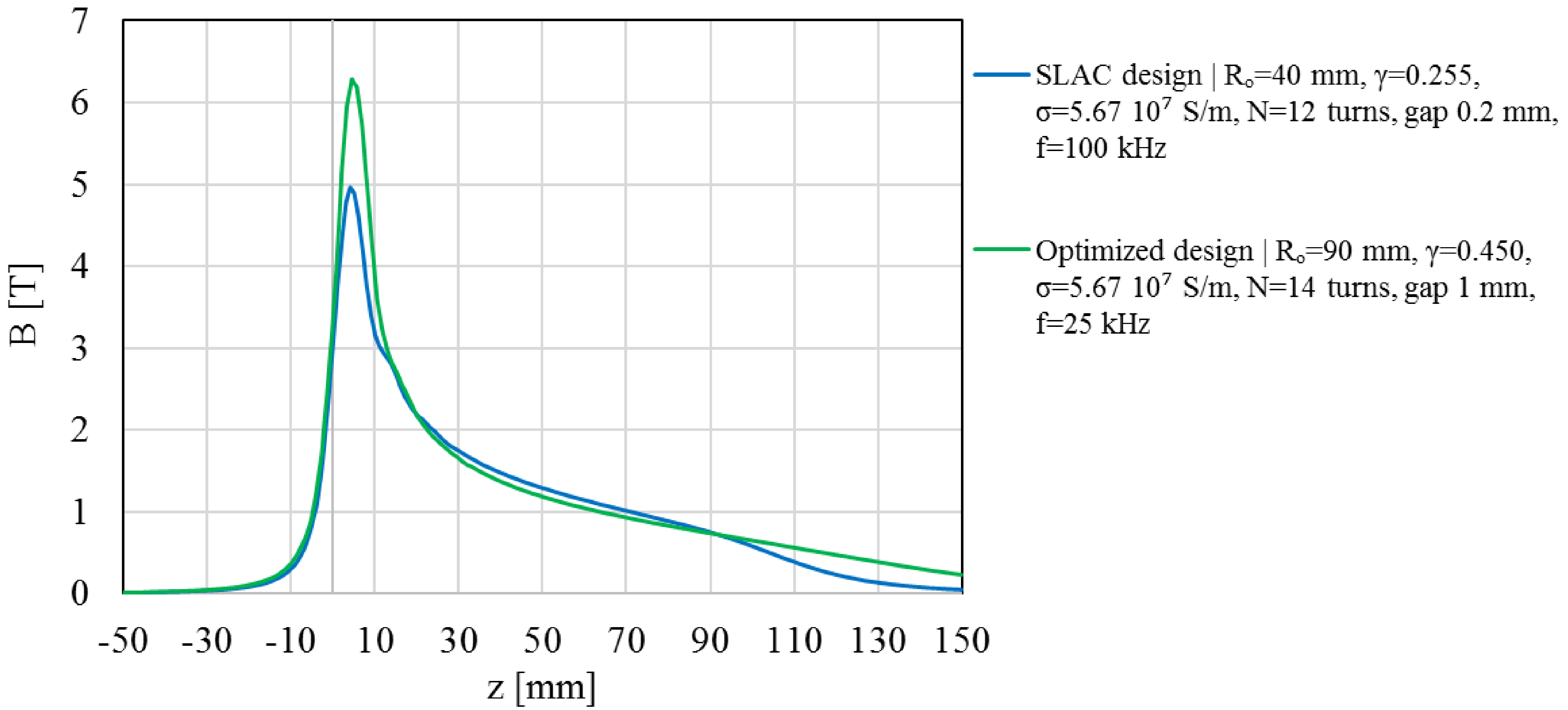
gap=0.8 mm
$\sigma=5.67\ 10^{7}$ S/m
$R_o=90$ mm
N=14 turns
$\gamma=0.450$
f=25 kHz

The **gap** between turns is increased and the loss of field compensated with 2 extra turns and larger tapered angle.

The voltage between turns is minimized using lower frequency and larger outer radius.

https://indico.cern.ch/event/879495/

Expected results for the modified design



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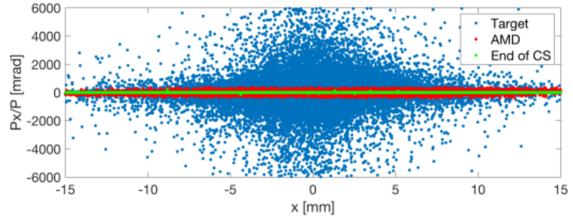
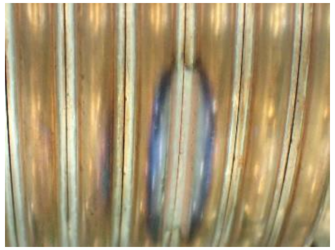
Design optimization for the CLIC e+ source

- Parameters to optimize:
  - To maximize:
    - the *positron yield* (purpose of the device)



  - To minimize:
    - the *total voltage* & the *inter-turn voltage* (power supply limitation & electrical breakdown)



    - the Lorentz forces (mechanical displacement, vibration)

Design optimization for the CLIC e+ source

- OPERA computes: the field, the voltages and the Lorentz forces.

- The positron yield is computed using RF-track and GEANT4 by Yongke Zhao (many thanks!).

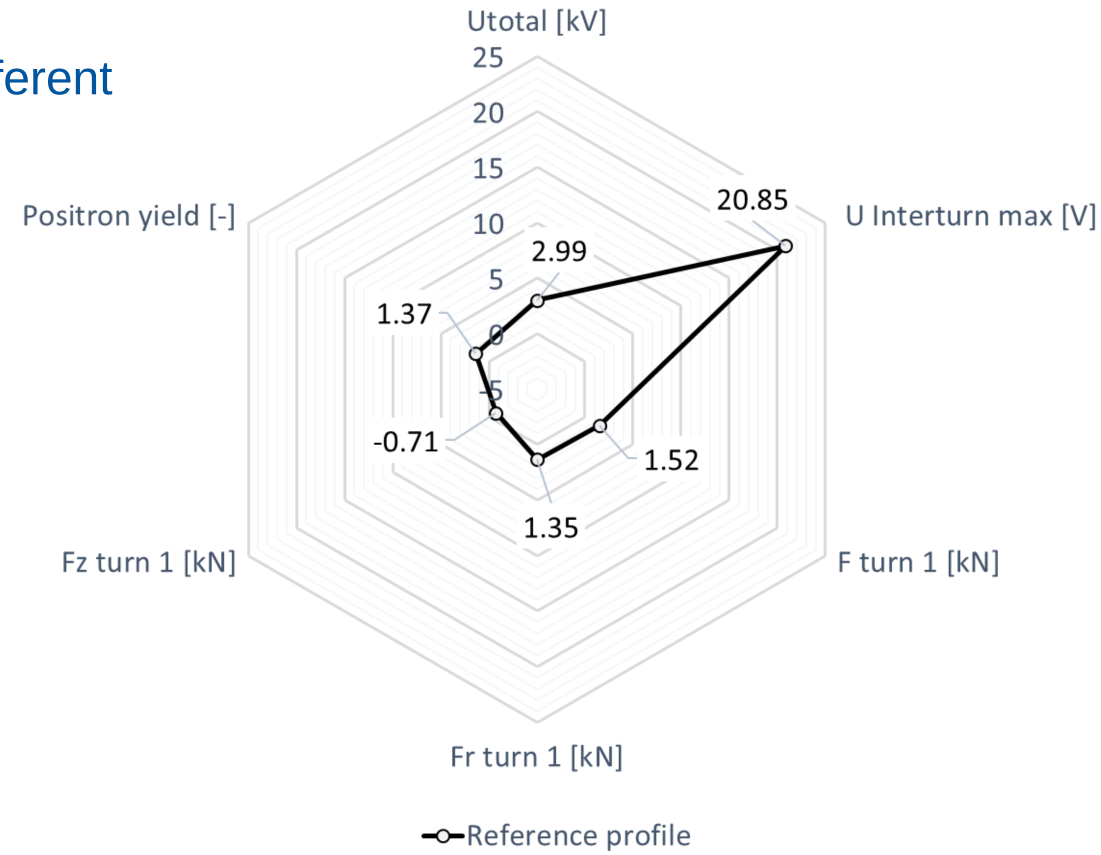
  https://indico.cern.ch/event/862915/

Design optimization for the CLIC e+ source

Graphics containing the parameters to optimize.

Use of the radar plot to compare different design of FC.

SLAC design
@ 25 kHz & 13 kA

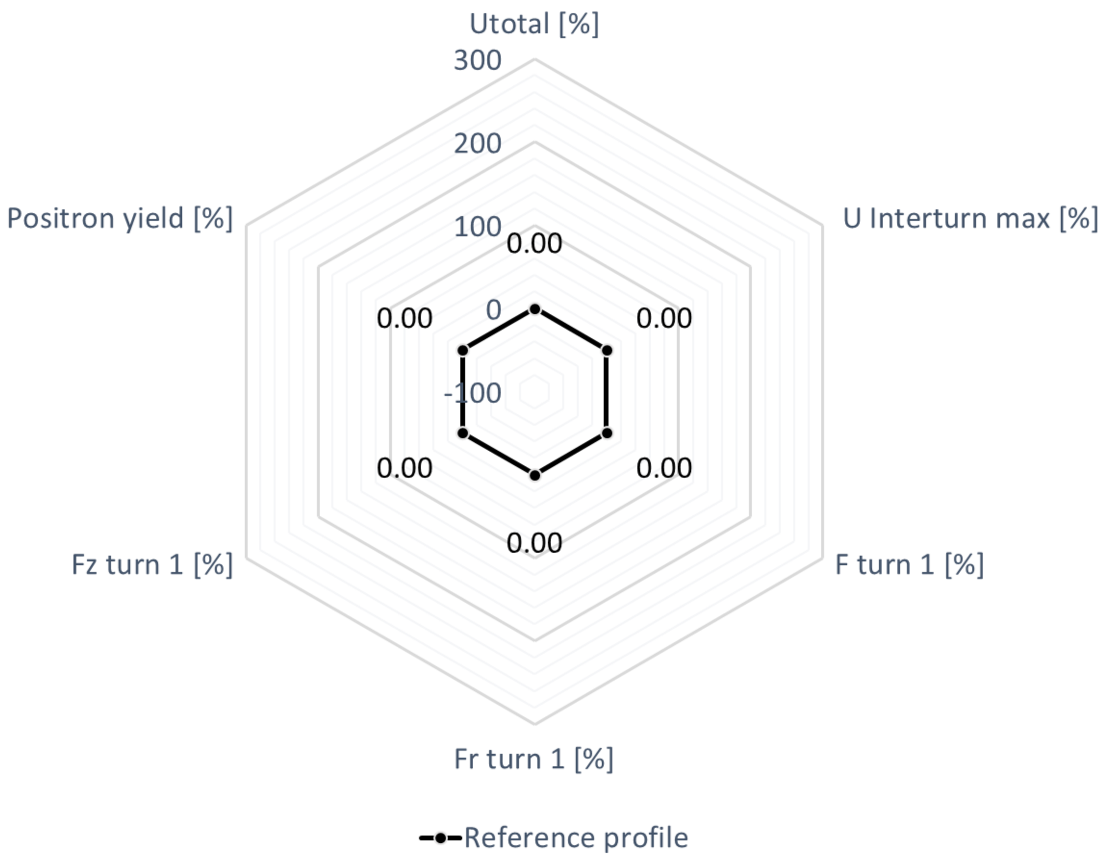


Design optimization for the CLIC e+ source

Normalization of each parameter to its reference value:

$$Var\,[\%] = 100 * \frac{(V - V_{ref})}{V_{ref}}$$

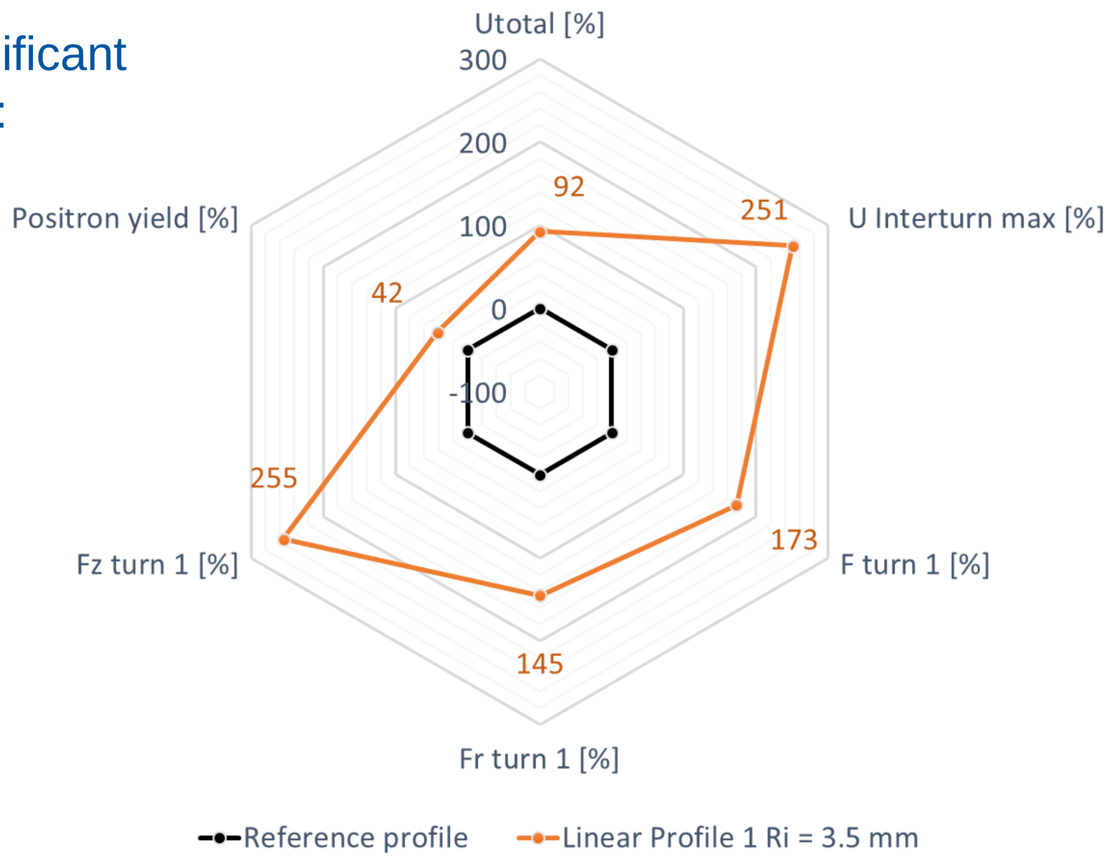
SLAC design
@ 25 kHz & 13 kA



Design optimization for the CLIC e+ source

The modified design induces a significant increase of each parameters' value:

- The yield increases by 42%
- The voltage increases by 92% (due to the gap increase and current increase)
- The forces get ~3 times higher



SLAC design (reference) @ 25 kHz & 13 kA

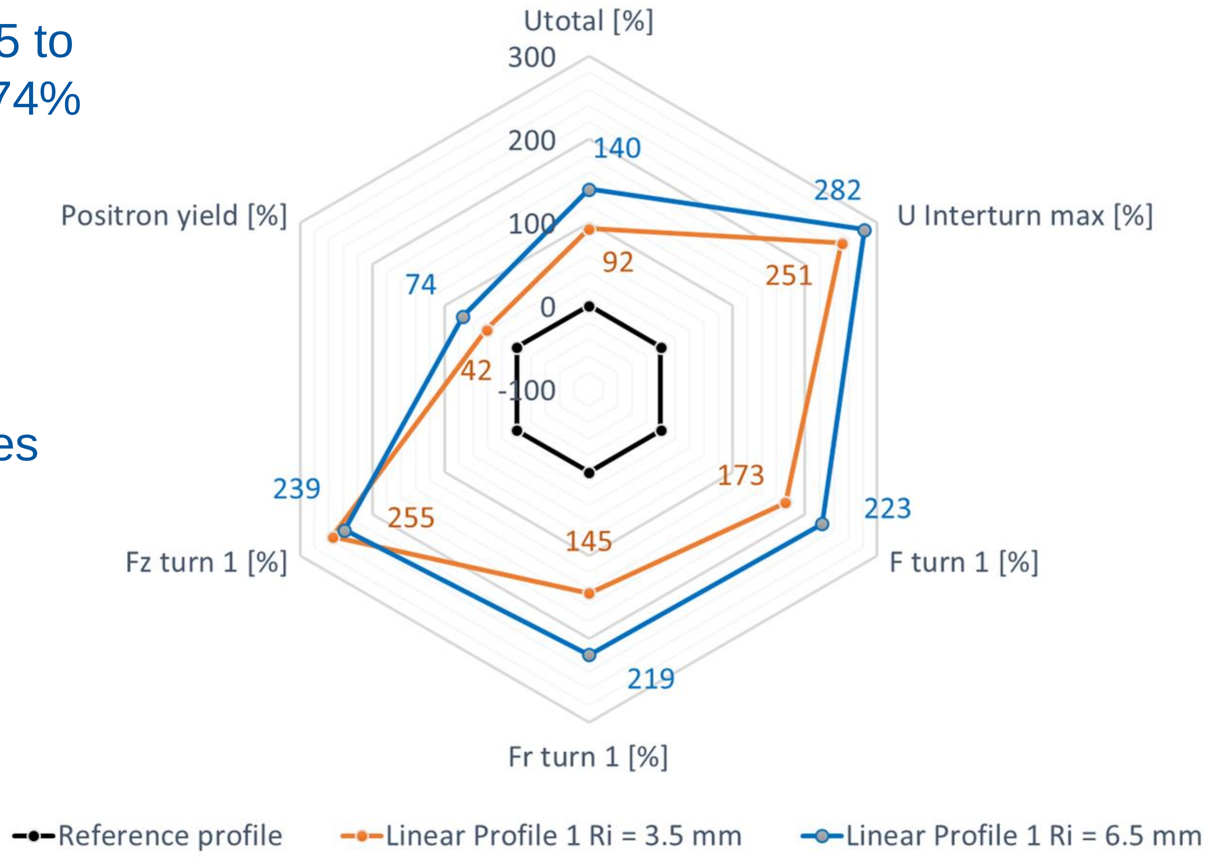
Vs.

linear modified design @ 25 kHz & 13.8 kA

Design optimization for the CLIC e+ source

- Increasing the aperture from 3.5 to 6.5 mm increases the yield by 74% (from 1.37 to 2.39).

- Both voltages and Lorentz forces grow very fast!



SLAC design
@ 25 kHz & 13 kA

Vs.

linear modified design

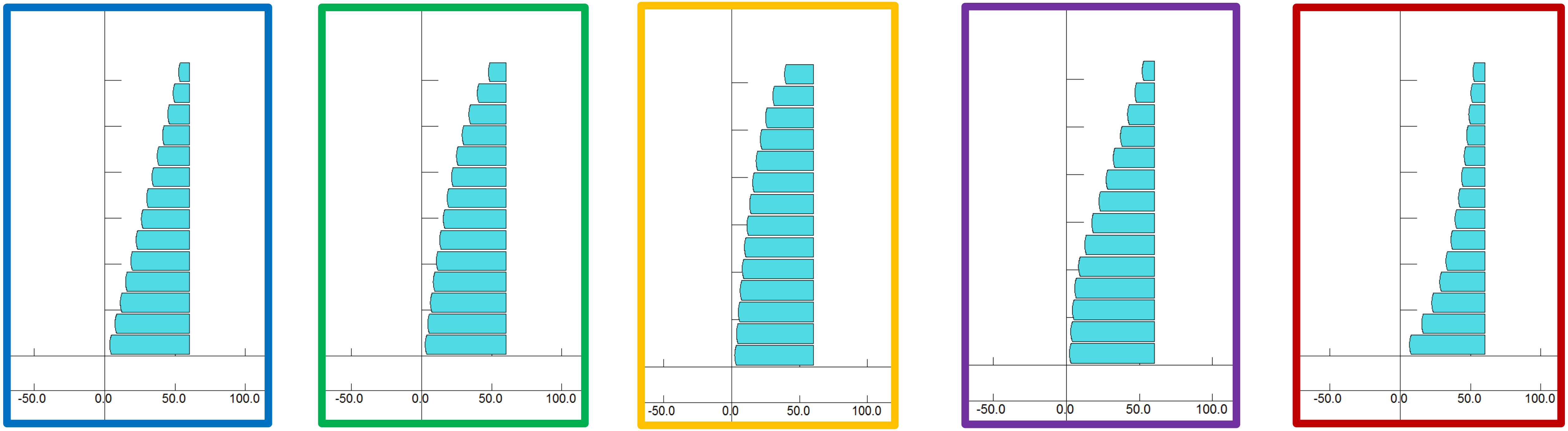
Vs.

linear modified design with large aperture

Design optimization for the CLIC e+ source

- From linear to non-linear profile for the FC aperture:

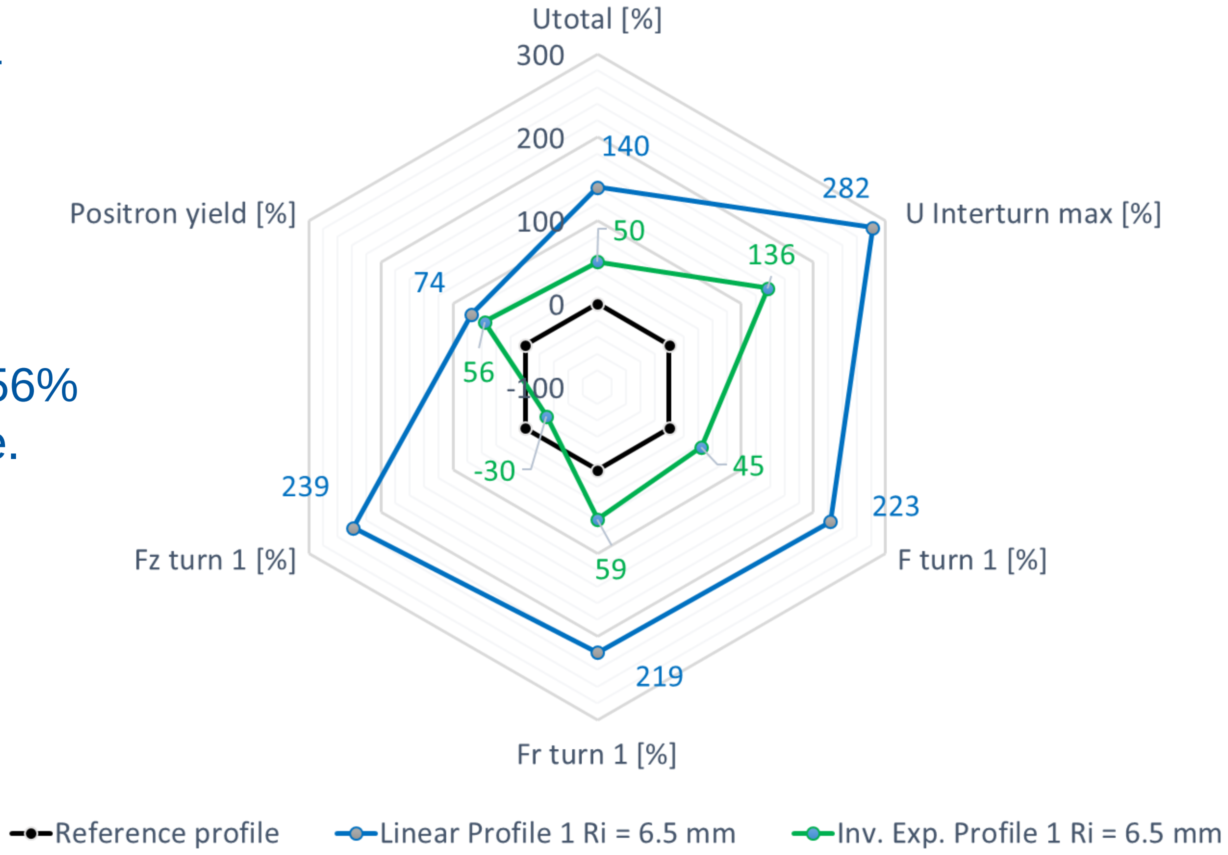
Linear | Concave downward (1) | Concave downward (2) | Concave downward + linear (3) | Concave upward

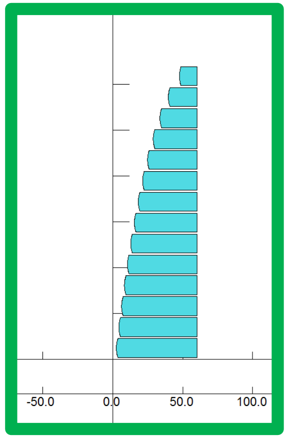


How does the shape impact the parameters to optimize?

Design optimization for the CLIC e+ source

- The use of non-linear shape induces a dramatic drop of the voltages.
- The Lorentz forces decrease significantly.
- The yield get lower but is still 56% higher than the reference case.





SLAC design
@ 25 kHz & 13 kA

Vs.

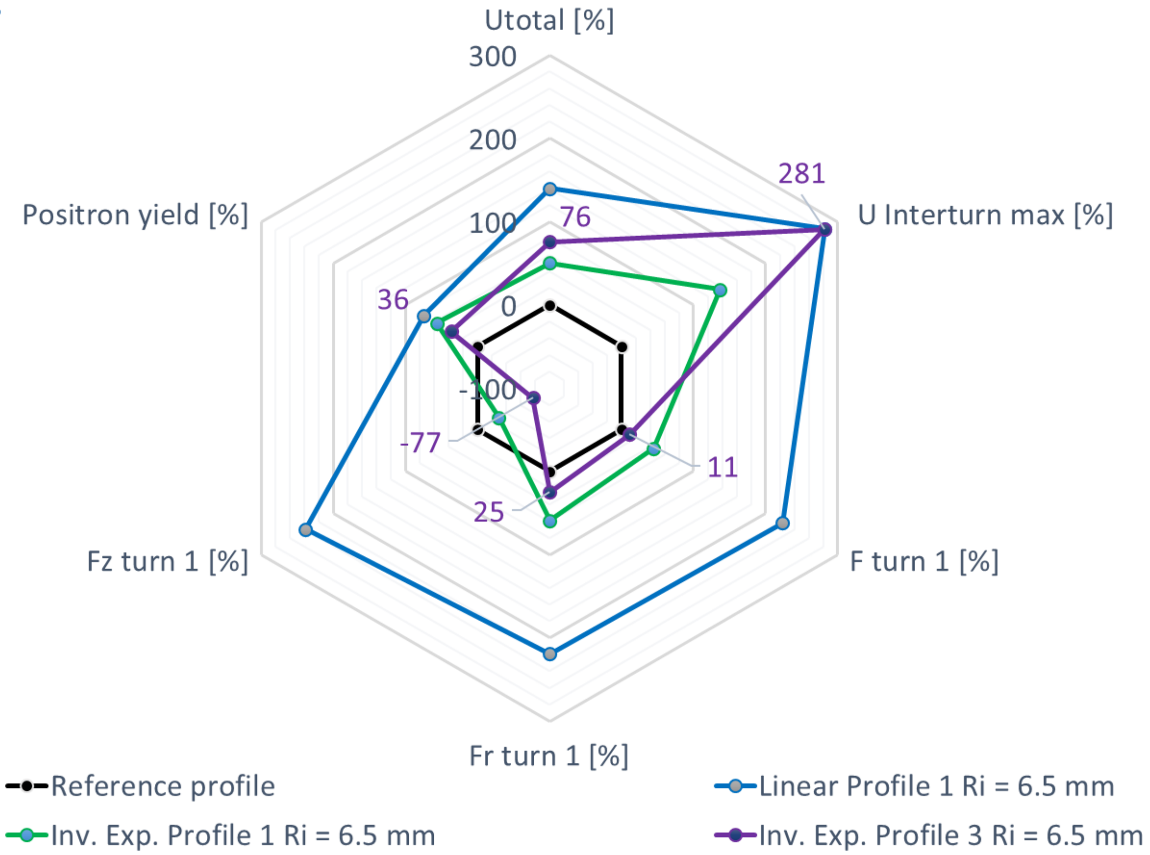
linear modified design with large aperture

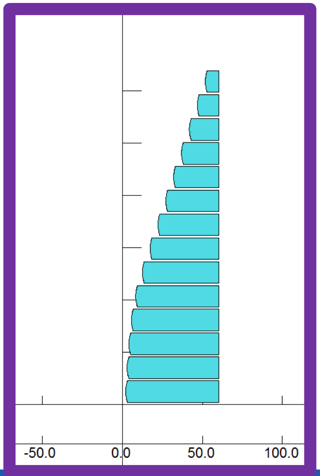
Vs.

Non-linear design (1) Concave downward

Design optimization for the CLIC e+ source

- Using more exotic shape allows to decrease the Lorentz forces.
- The yield gets lower though.
- The voltage gets higher.





SLAC design
@ 25 kHz & 13 kA

Vs.

linear modified design with large aperture

Vs.

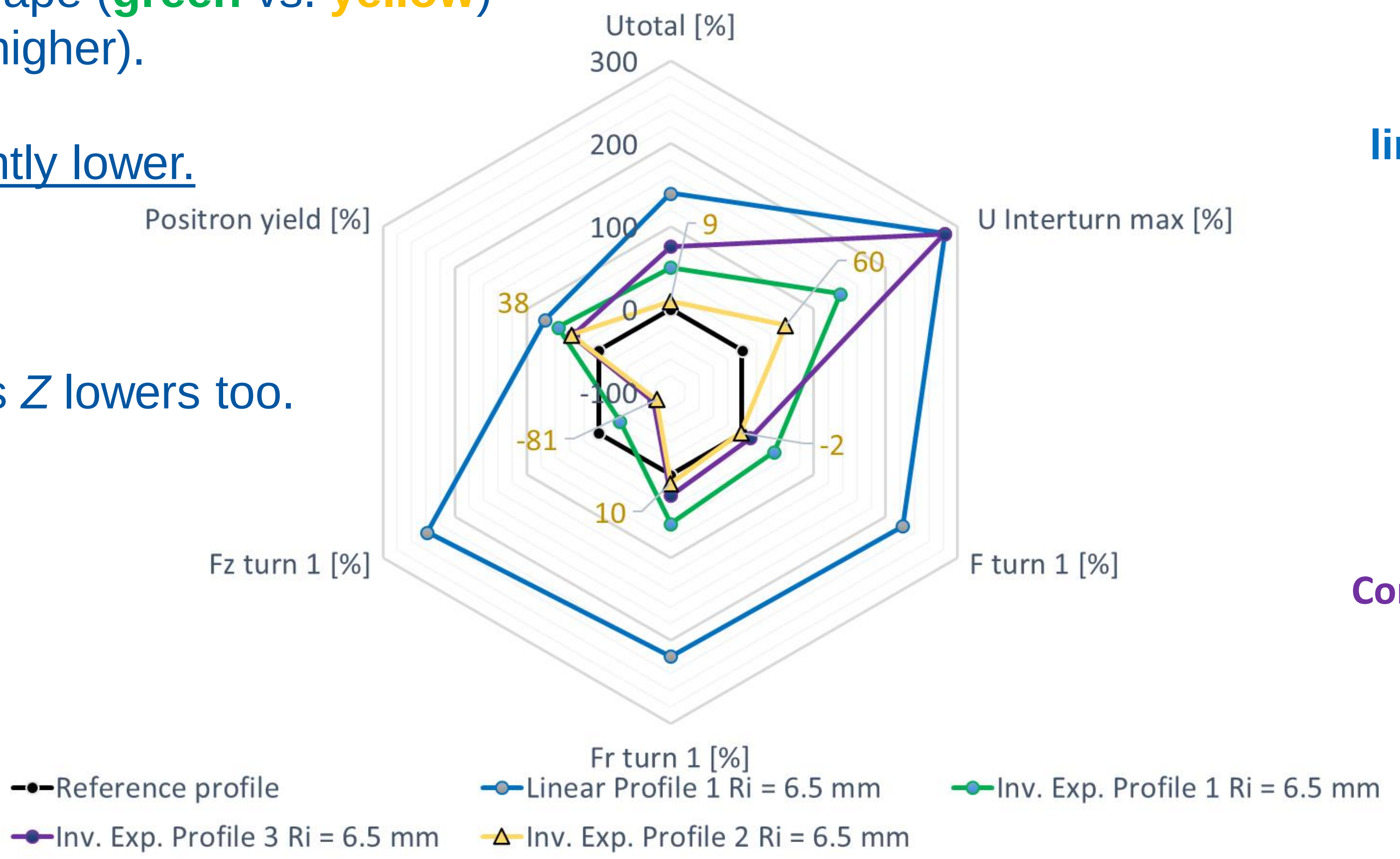
Non-linear design (1) Concave downward

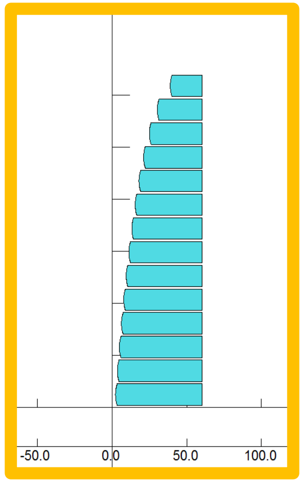
Vs.

Non-linear design (3) Concave downward + linear

Design optimization for the CLIC e+ source

- Adapting the non-linear shape (**green** vs. **yellow**) preserves the yield (38% higher).
- The voltages get significantly lower.
- The detrimental forces directed along the coil axis *Z* lowers too.





SLAC design
@ 25 kHz & 13 kA

Vs.

linear modified design with large aperture

Vs.

Non-linear design (1) Concave downward

Vs.

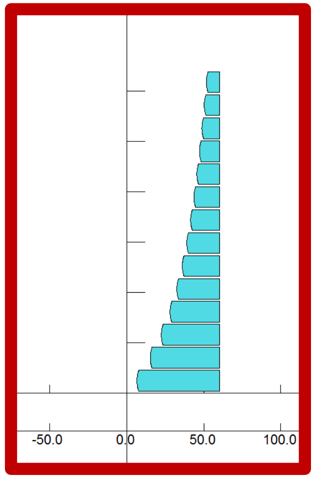
Non-linear design (3) Concave downward + linear

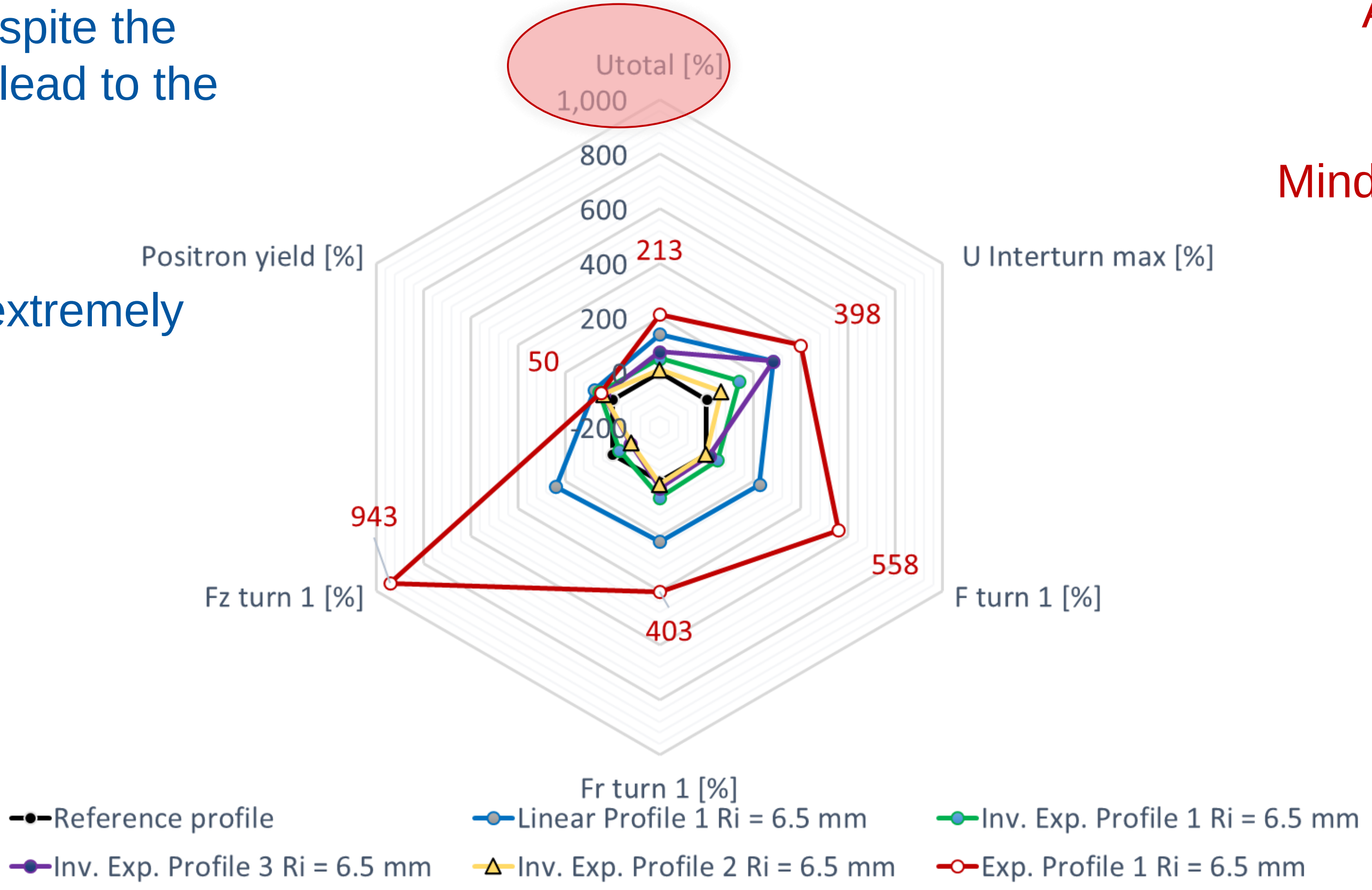
Vs.

Non-linear design (2) Concave downward

Design optimization for the CLIC e+ source

- The upward concavity despite the highest peak field do not lead to the highest yield.
- Voltages and forces get extremely high.





Adding the upward concavity case

Mind the change of scale !!

Conclusion

- Construction of a transient electromagnetic model of Flux Concentrator using Opera® software.
- Validation of the model by direct comparison with available experimental data (current, voltage and magnetic field).
- Parametric study for optimization of the electromagnetic behavior (voltage and field) to cope with breakdown voltage issue.
- Export of 2D field maps as input for particles tracking software packages (GEANT4, RF-track) and positron yield computations.
- New design of the coil's geometry using non-linear profiles for coupled optimization: electromagnetic, mechanical (Lorentz forces) and optical behavior (positron yield).
- The optimization process lead to an interesting design that produces a better positron yield of 1.89 (38% gain) keeping low voltages (3kV, 10% extra) and lower forces (-81% F_z, -2% F_{total}).

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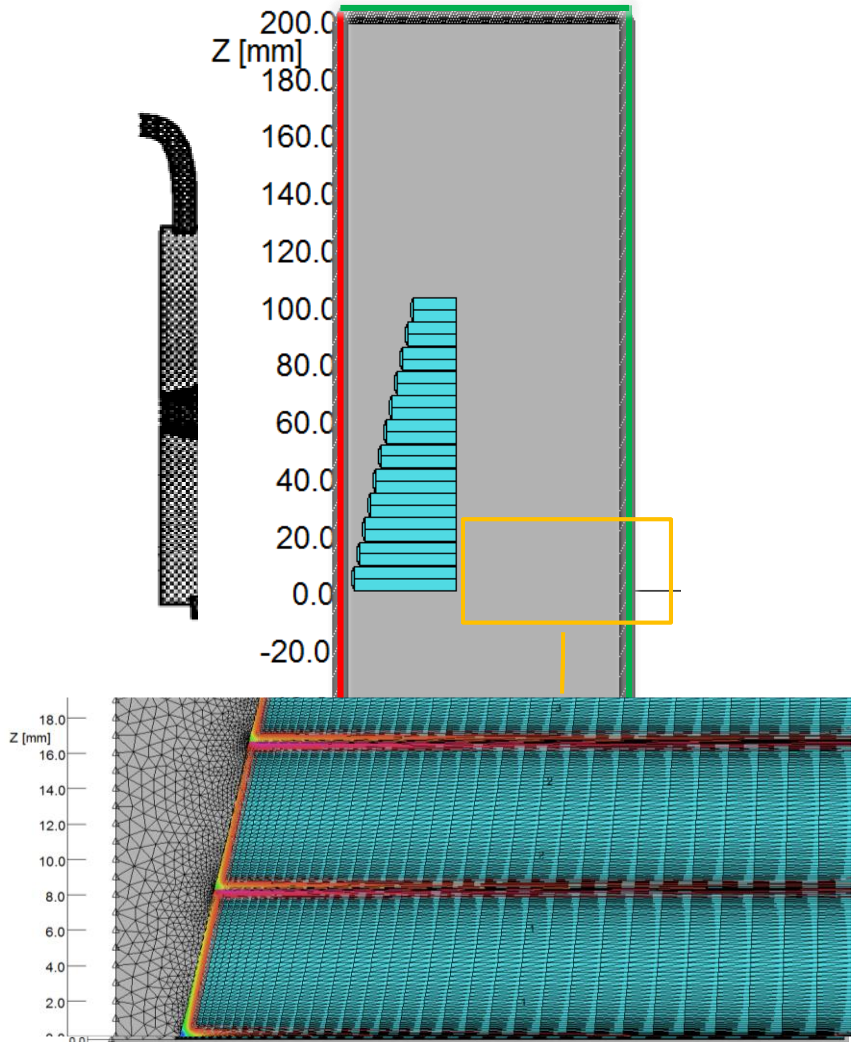
Modelling of the geometry

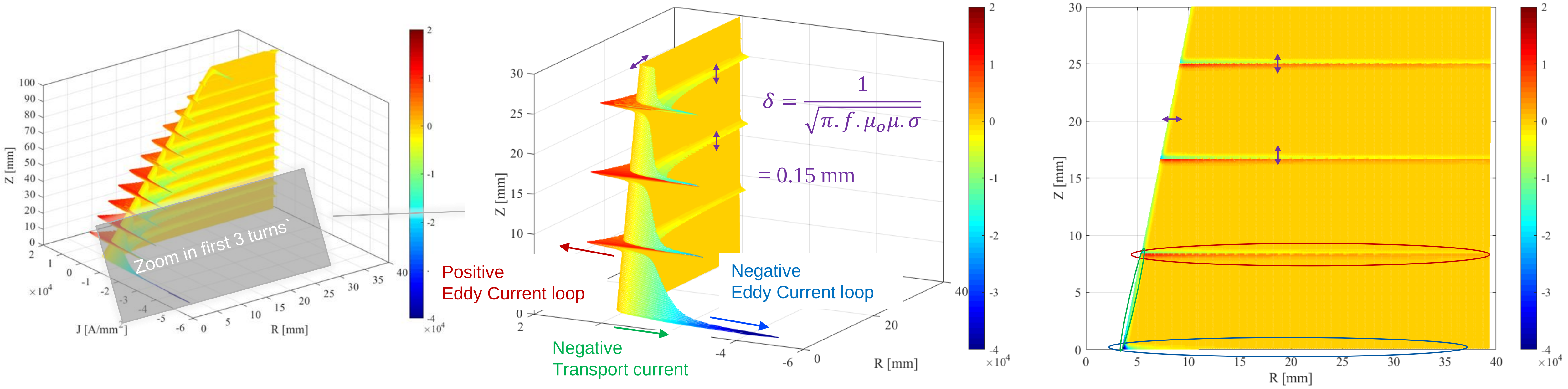
- 12-turnstapered solenoid (SLAC design)
- 2D model
- Axi-symmetric system
- Boundary conditions:
  - Tangential field for symmetry and far field
- Material properties
  - Conductivity with linear behavior (OFHC Copper)
- Regular mesh and mesh refinement:
  - quadrilateral Finite Element in conductor and Bias method
- Transient simulation:
  - Eddy Current and Skin effect



Backup

The origin of the field boost

Tapered solenoid in transient



The pulse of current produces strong **eddy current loops** that circulate in opposite directions within each turn.

The current density concentrates at **the skin of the conductor**.

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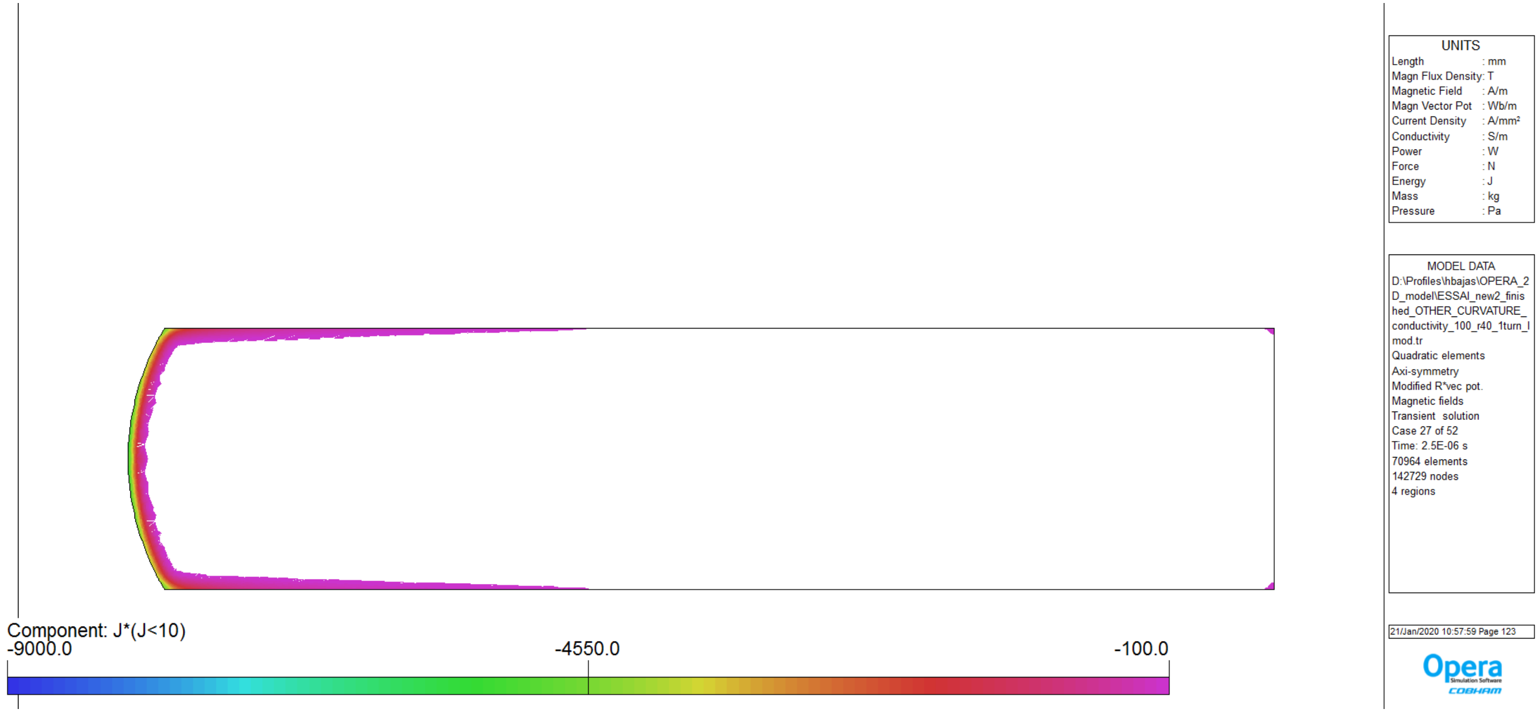
The eddy currents depend on the adjacent turns

Let's model
One-turn coil

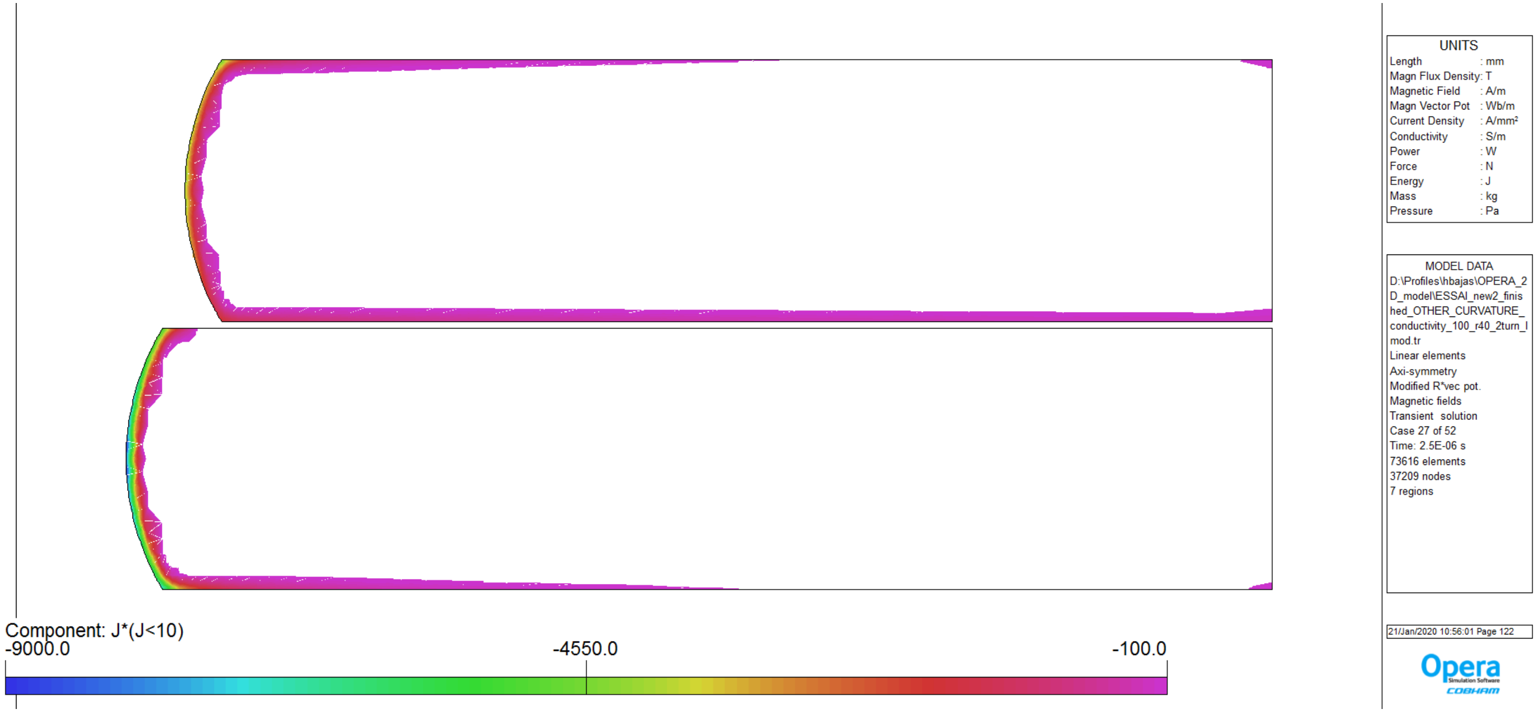
The current density is only negative



The eddy currents depend on the adjacent turns

Let’s model
Two-turn coil

The current density is both positive & negative

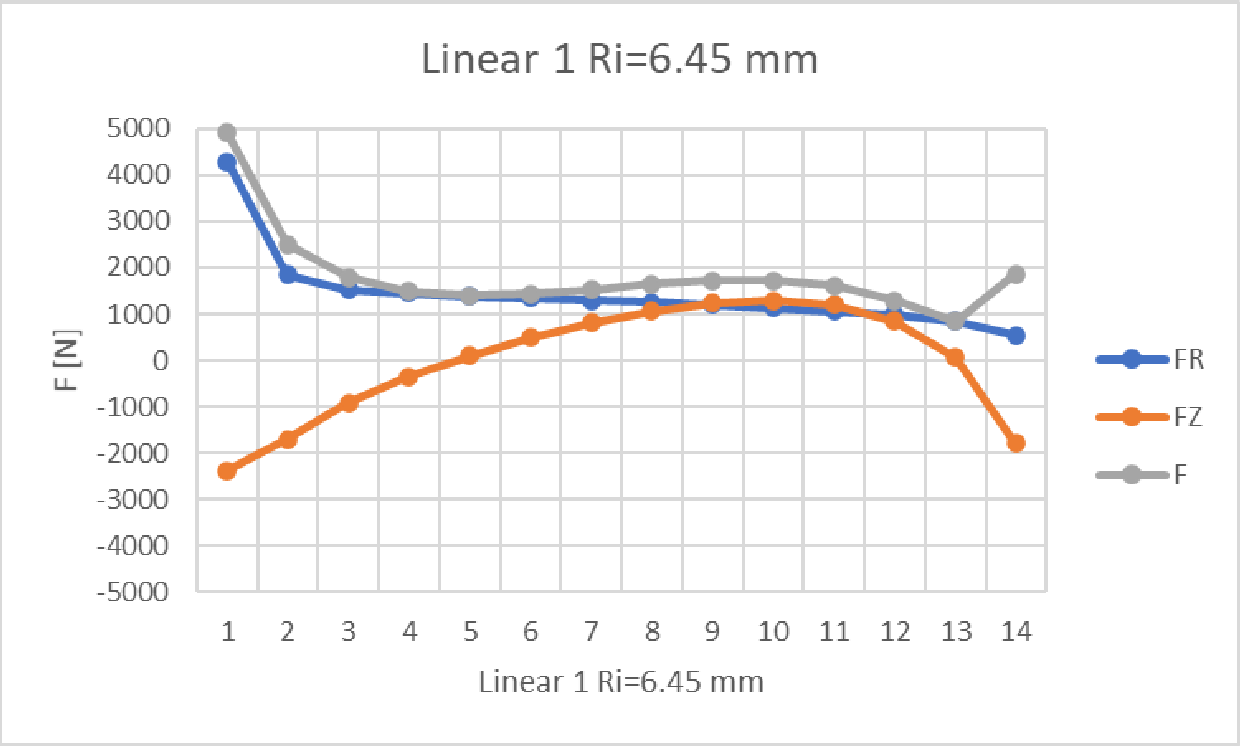


Third run of optimisation

The Lorentz force are now available as output data.

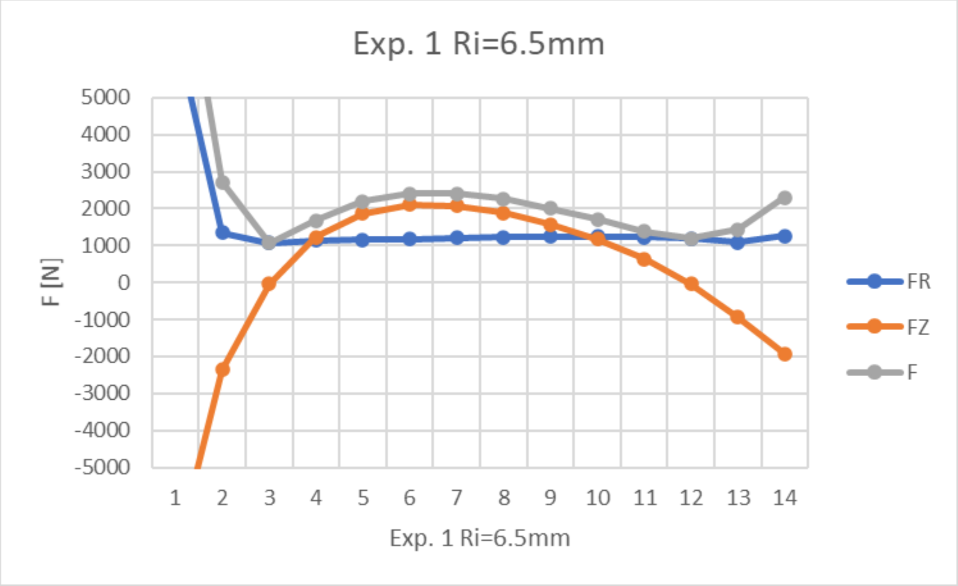
The forces are not only directed along the radius in the outward direction.

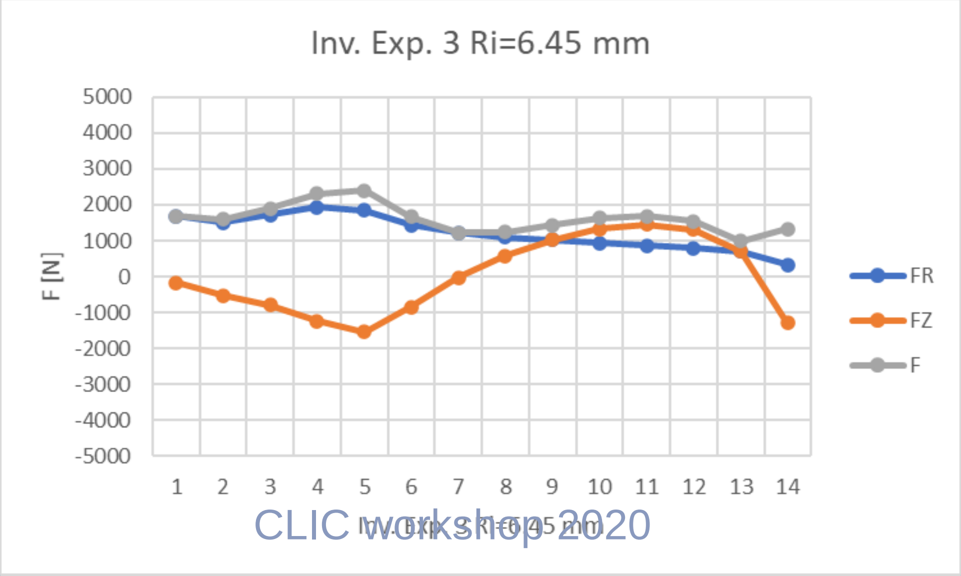
A significant compressive force applies to the FC along the solenoid axis.



The distribution of the force along and accross the coil is complexe and need further investigation.

It changes a lot with the geometry.

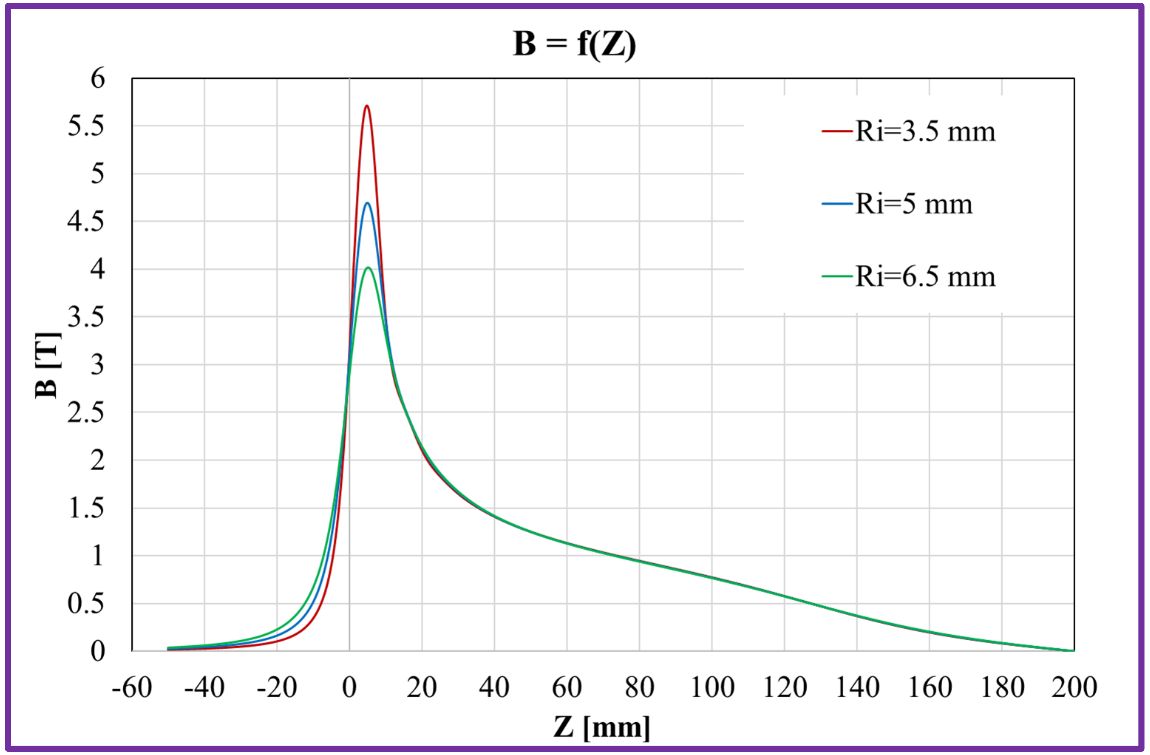


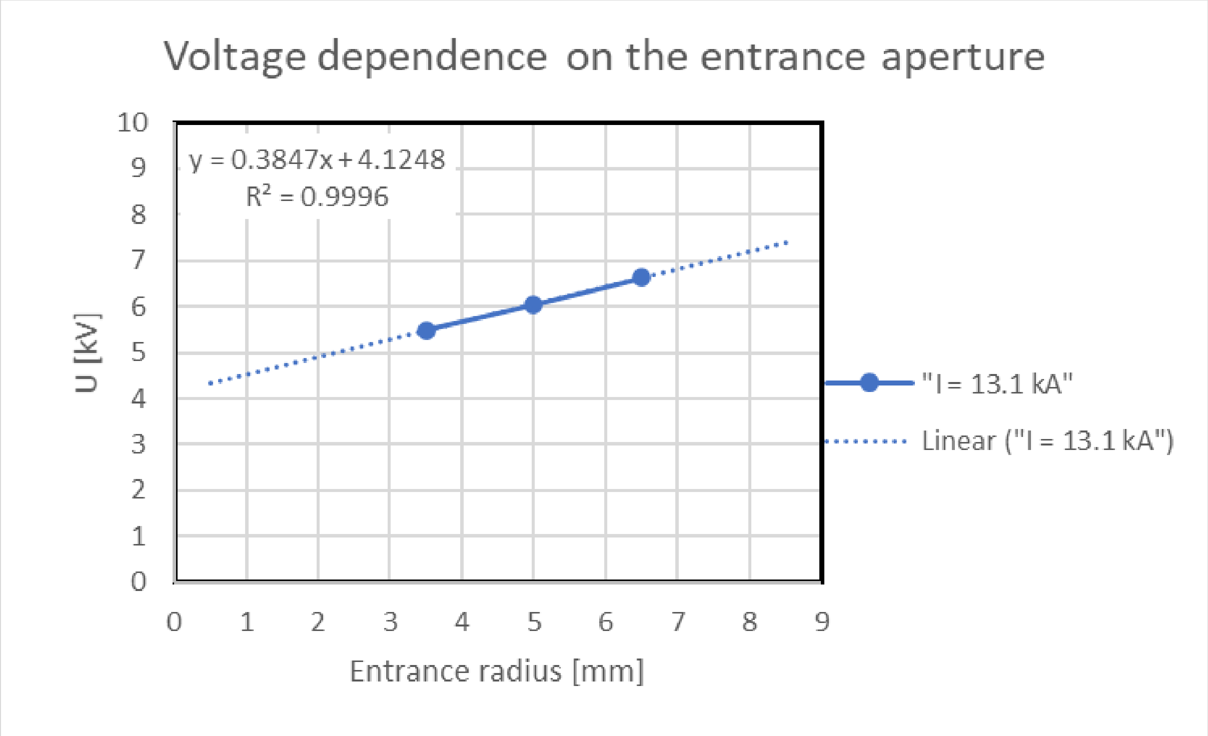


Design optimization for the CLIC e+ source

- Increasing the entrance aperture yields to higher positron but:
  - The field decreases with the aperture
  - The voltage increases with the aperture

R. H. Helm, SLAC, Report No. 4, August 1962.





Design optimization for the CLIC e+ source

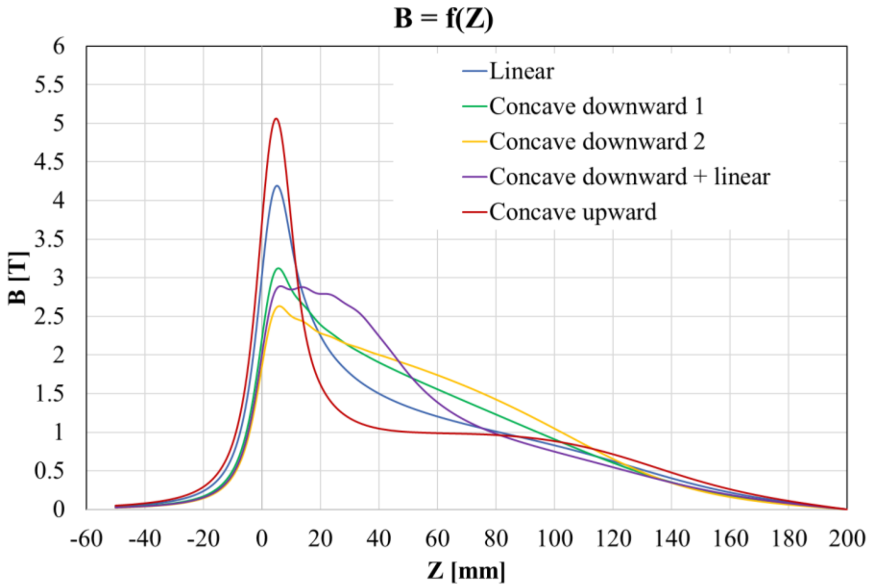
The shape of the FC profile significantly impacts the shape of the field distribution.

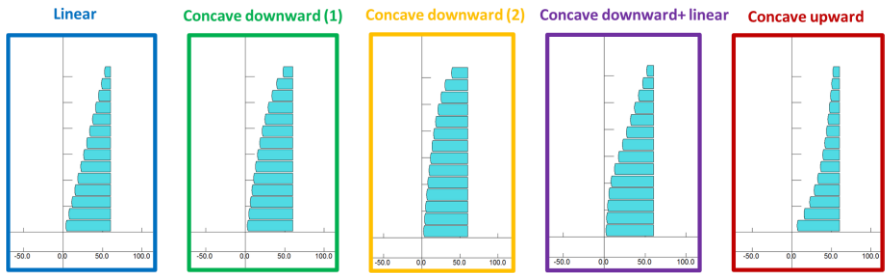
The downward concavity leads to:

- a broad distribution in the low field domain (< 3T) that extend to Z=50 mm
- Small fringe field Z < 0 mm

- The upward concavity leads to:
  - a “peaky” distribution in the high field domain (>4T)
  - Larger fringe field

- More complex shape:
  - The field distribution can be more or less broad according to the design





What is a «GOOD FIELD DISTRIBUTION» in terms of positron yield?

Design optimization for the CLIC e+ source

The voltage accross the magnet is largely impacted by the coil design.

Still the tradeoff between Good Field Distribution and Voltage level should be done.