CERN

Flux Concentrator Optimization for Future Positron Sources

H. Bajas, S. Doebert, A. Latina, Y. Zhao

Outline

- Flux Concentrator in linear accelerators
- Modelling of the geometry and the electrical circuit
- Validations of the model
- A tool for FC design optimisation
- Design optimization for the CLIC e+ source
- Update on manufacturing and testing
- Conclusion

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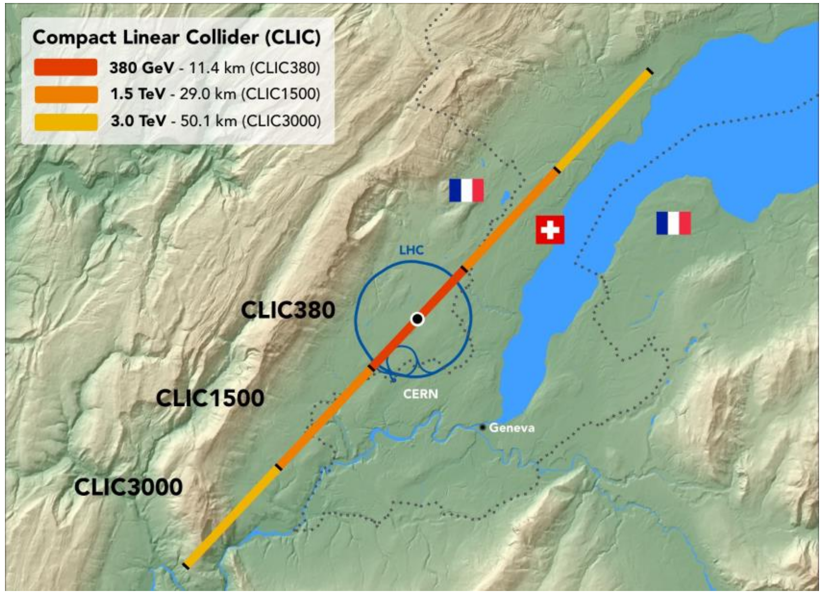
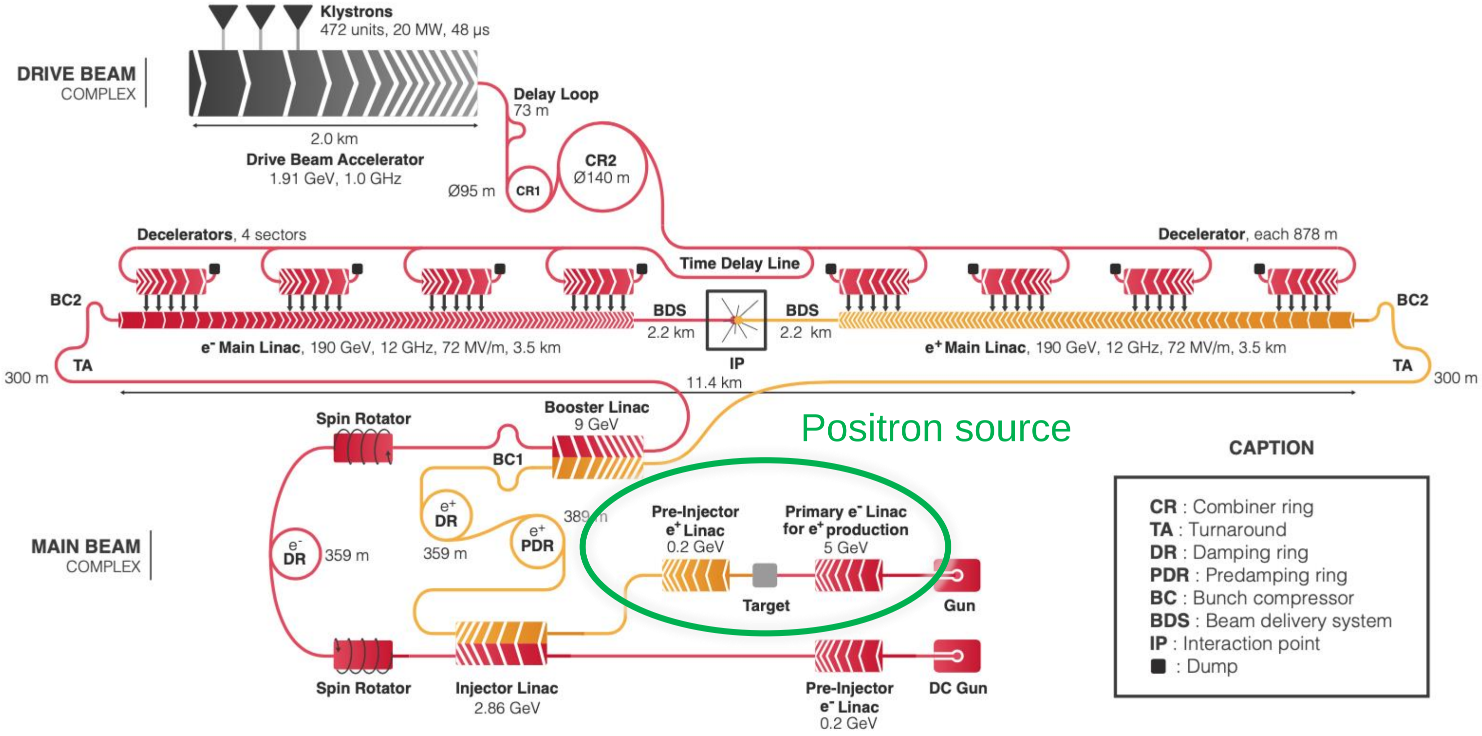
Flux Concentrator in linear accelerators

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.





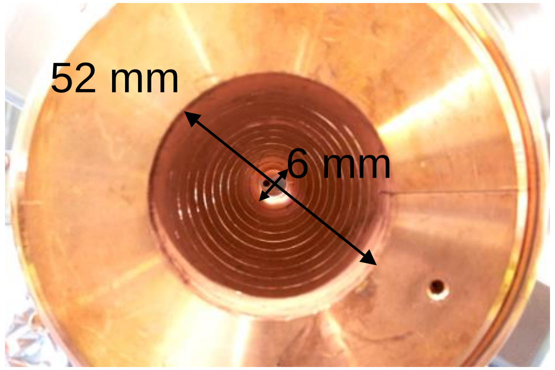
Steinar Stapnes, October 2019, Sendai
International Workshop on Future Linear Colliders

Flux Concentrator at KeK for SuperKeKb experiment

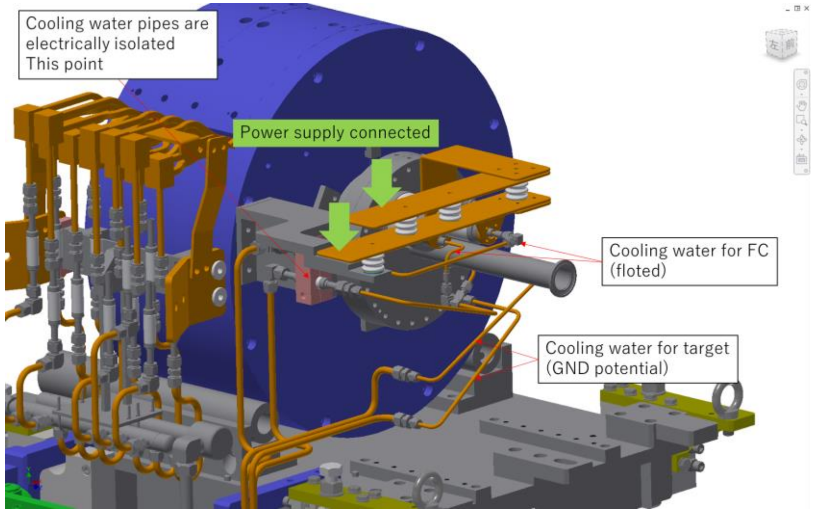
FC mounted on insert

Courtesy of Yoshinori Enomoto

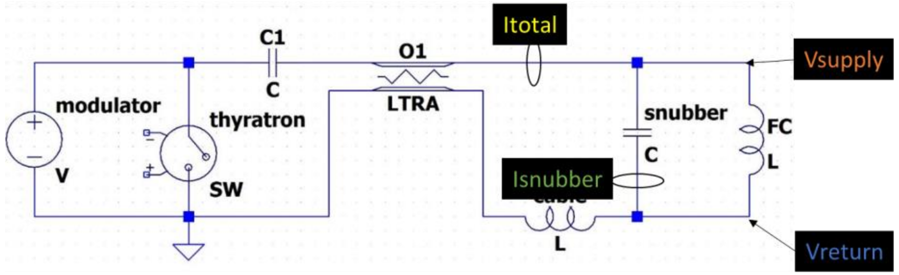
FC tapered bore



FC mounted on test bench



Electrical circuit

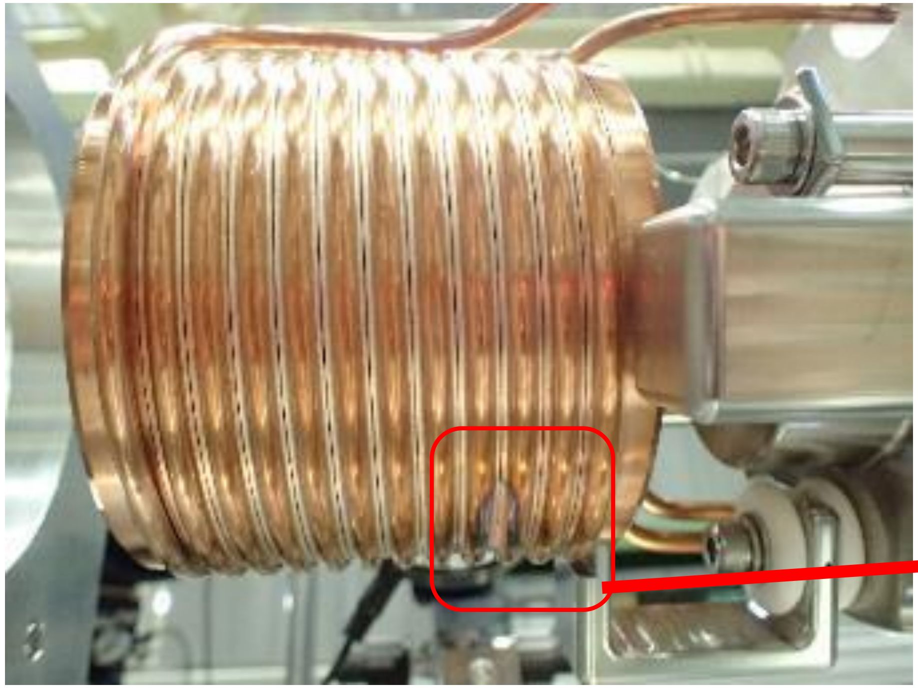


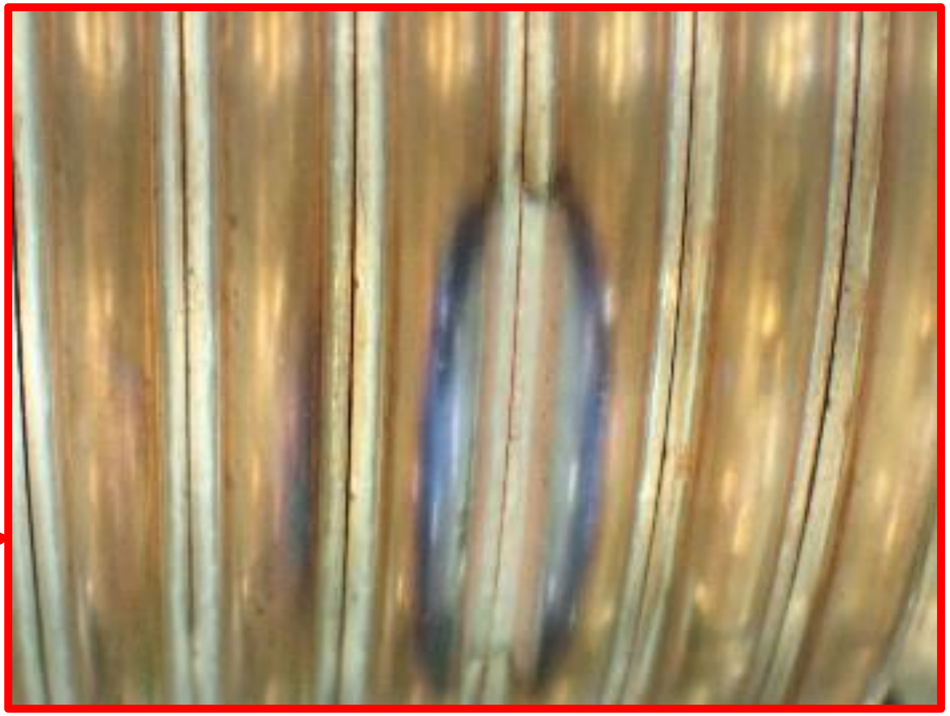
Experimental data (U, I)

Dielectric breakdowns during the test of the KEKB FC

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

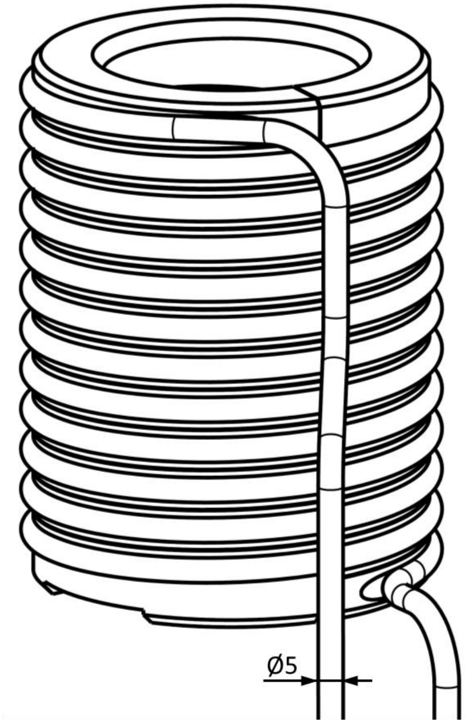
Flux Concentrator design from KEK

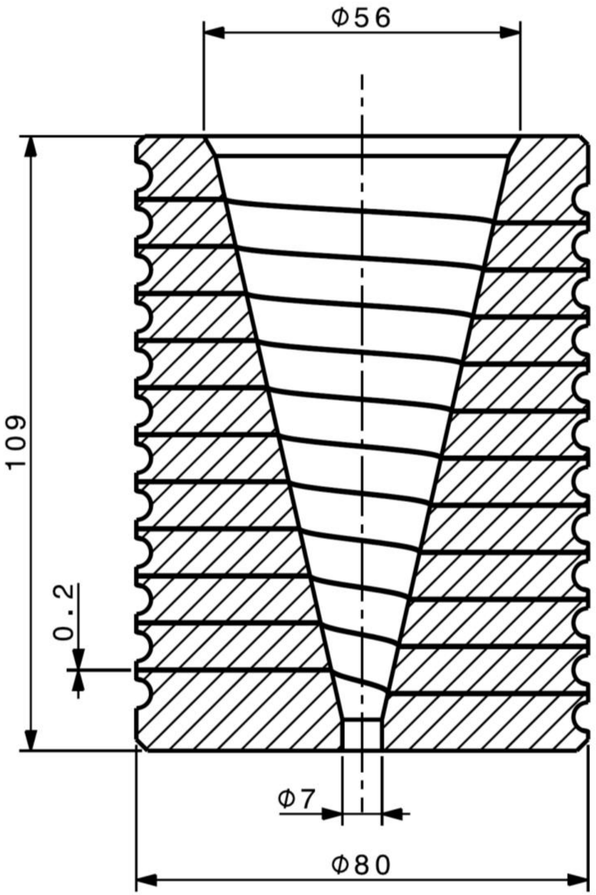


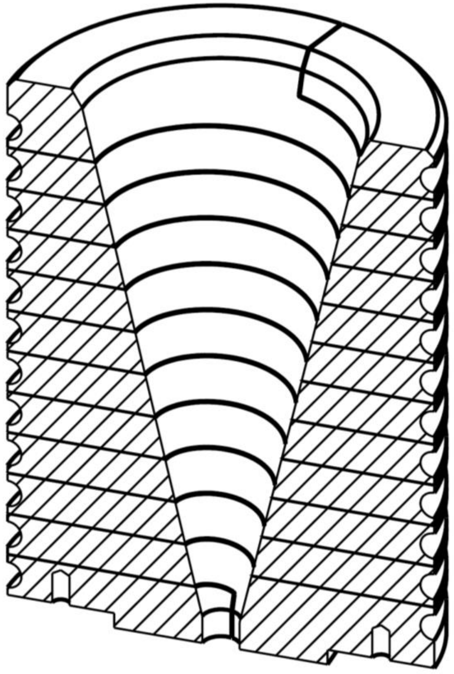


Courtesy Yoshinori Enomoto, October 2019, Sendai International Workshop on Future Linear Colliders

More views of a Flux Concentrator







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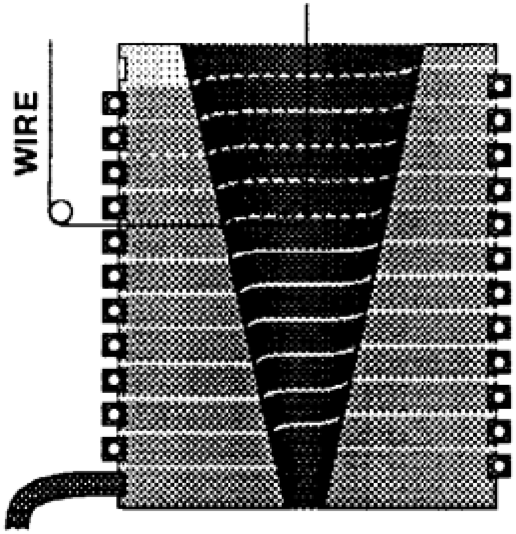
Modelling of the geometry

- 12-turnstapered solenoid (SLAC design)

A.V. Kulikov, SLAC, June 1991



Modelling of the geometry

- 12-turns tapered solenoid (SLAC design)
- Axi-symmetric system
- 2D model

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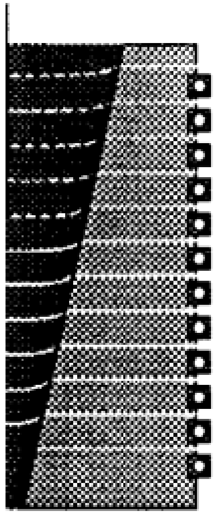

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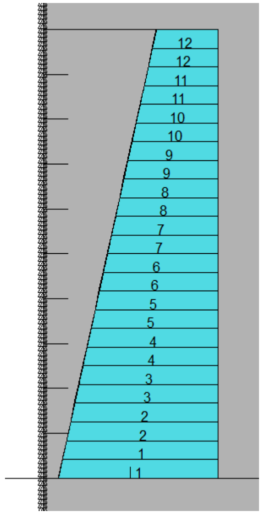

Modelling of the geometry

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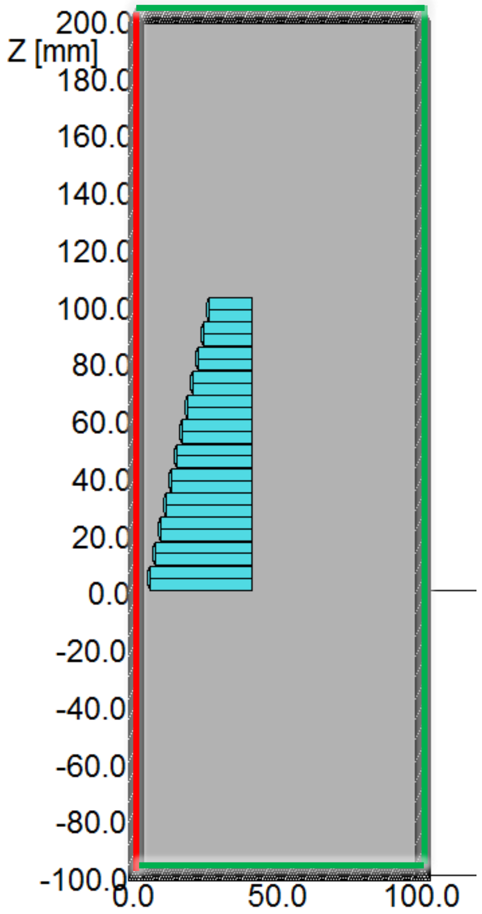
- Boundary conditions:
  - Tangential field for symmetry and far field



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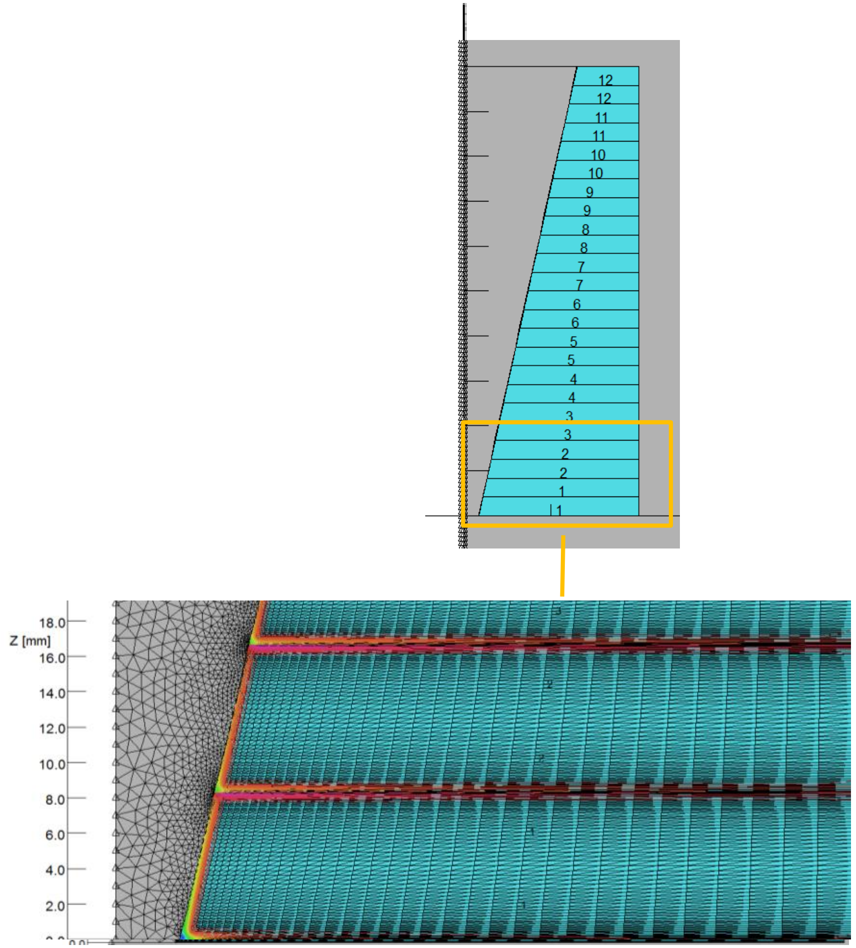
- Material properties
  - Conductivity with linear behavior (OFHC Copper)
- Regular mesh and mesh refinement:
  - quadrilateral Finite Element in conductor and Bias method
- Transient simulation:
  - Eddy Current and Skin effect



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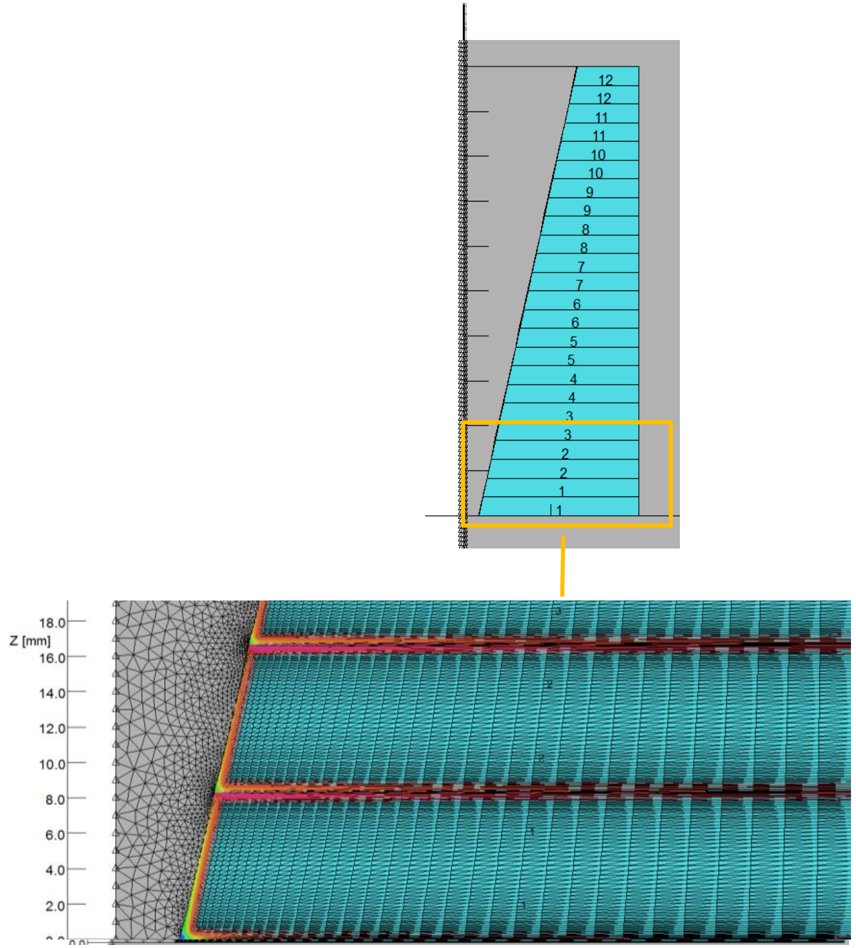
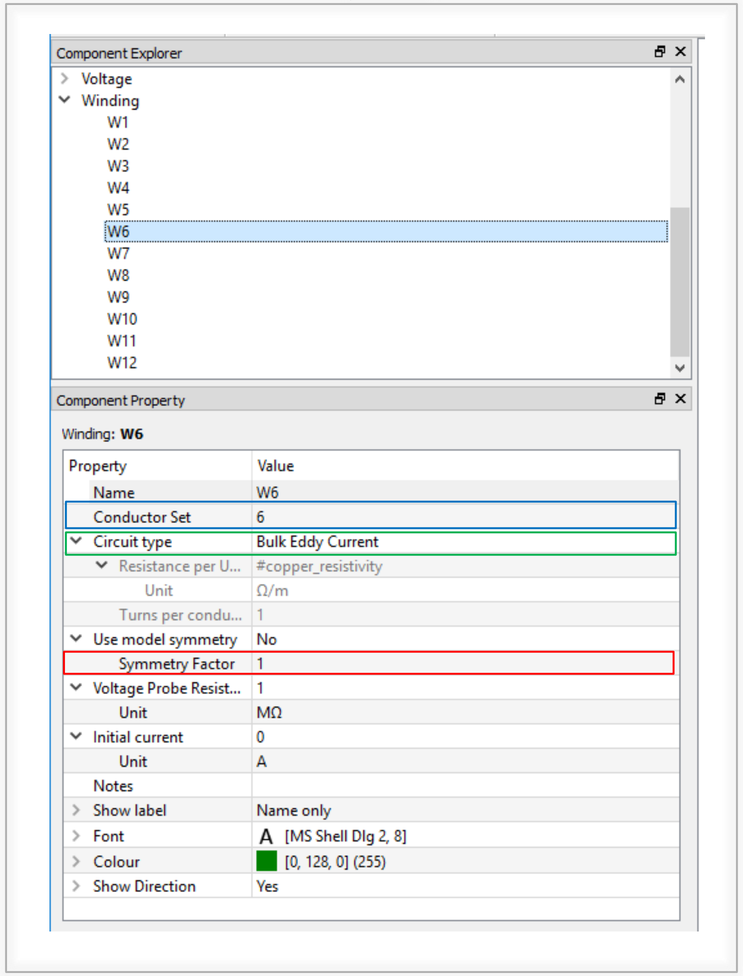
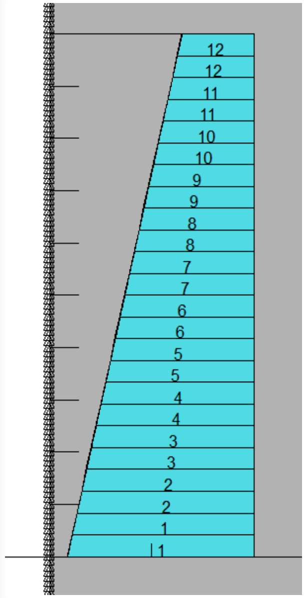


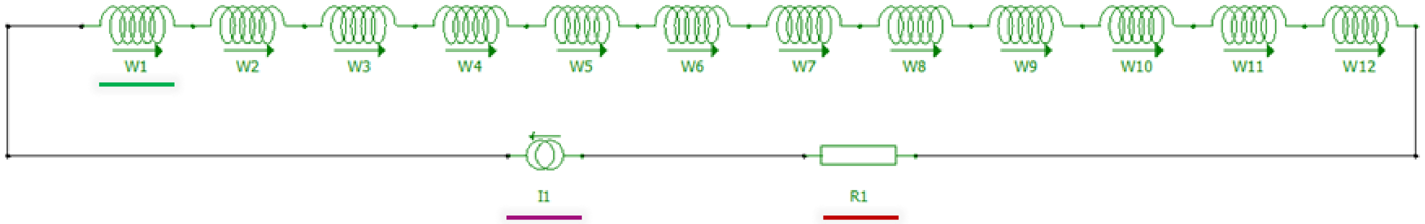
Modelling the electrical circuit

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

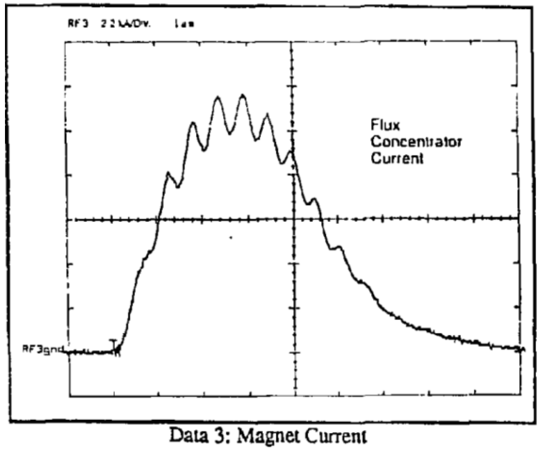


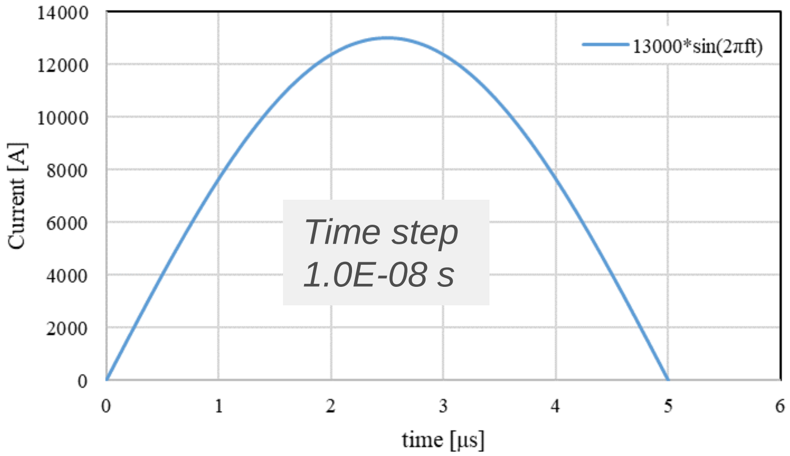


Axi-symmetric model



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





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

Electro-Magnetic transient equations

- The 2-D electromagnetic transient simulation framework of Opera® solves the vector diffusion equation with the magnetic vector potential as the unknown variable:

$$-\frac{1}{\mu}\nabla^2 A_z = J^* - \sigma\frac{\partial A_z}{\partial t}$$

- In order to allow Eddy currents to flow in driving conductor, redistributing the current density so it only flows at the skin of the material conductor, an extra equation is introduced with J^* as unknown:

$$\int_{\Omega_J}\left(-\sigma\frac{\partial A_z}{\partial t} + J^*\right)\partial\Omega = \int_{\Omega_J} J_S \partial\Omega$$

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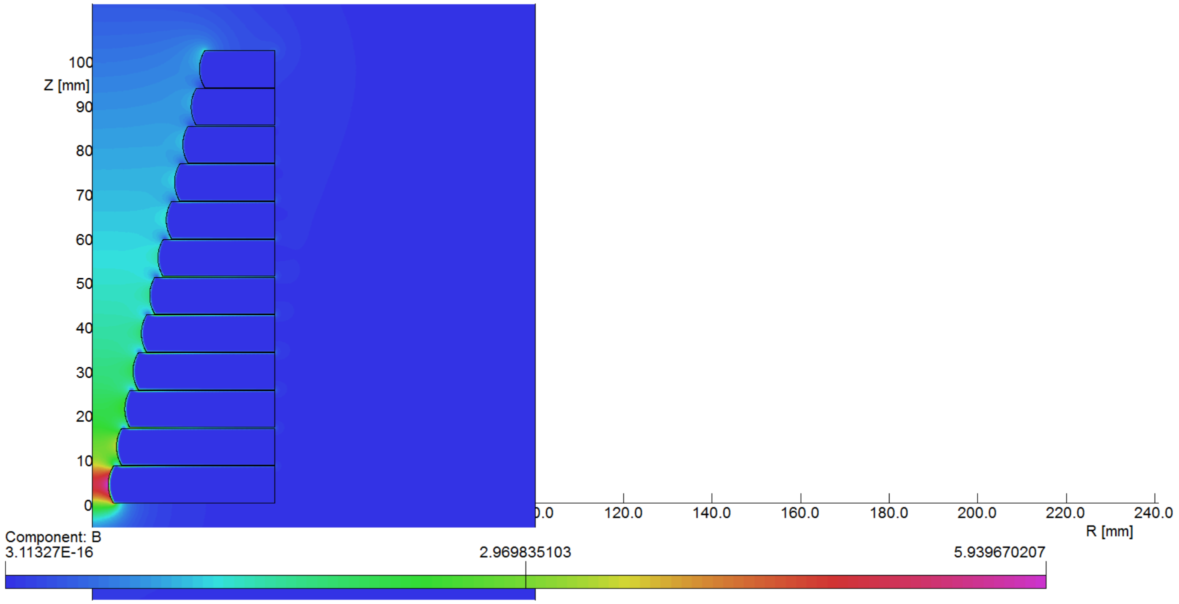
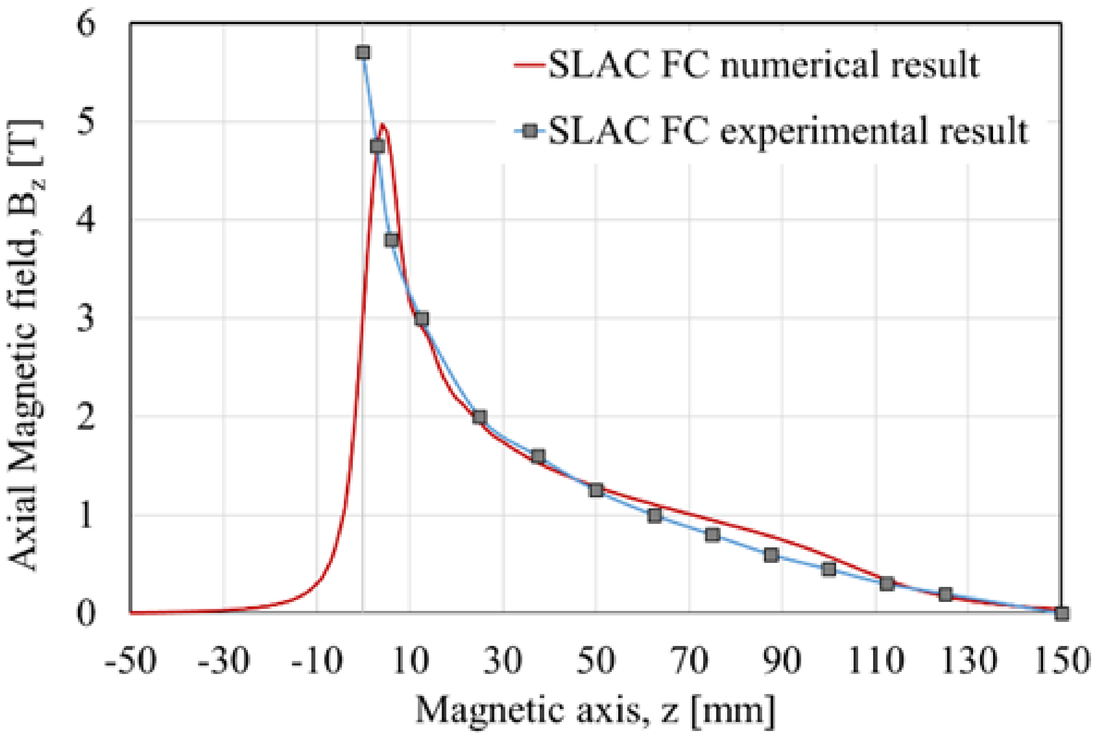
Comparison with experimental result: SLAC

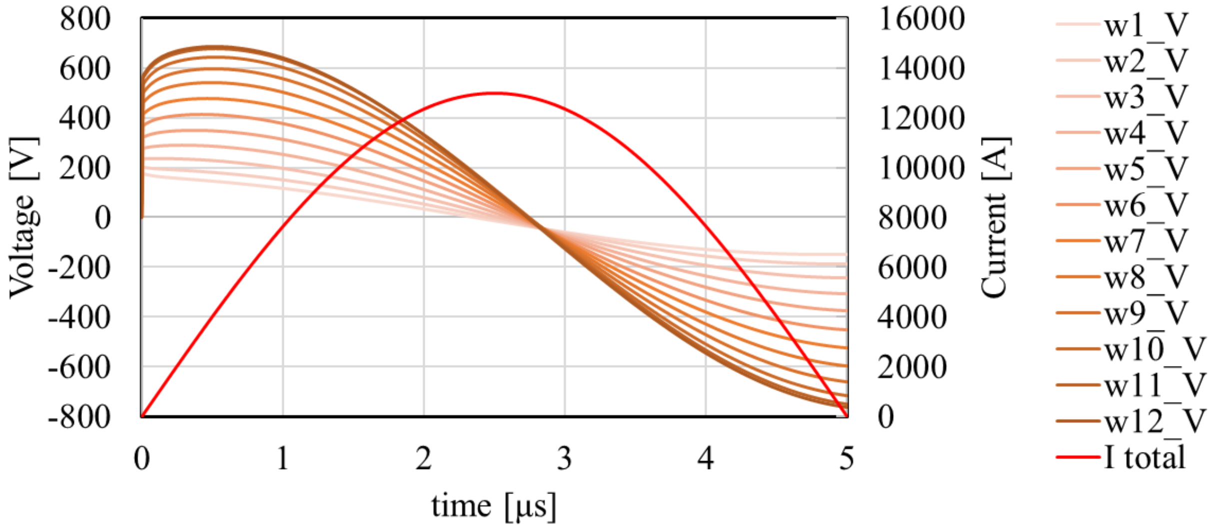


Solenoidal field map

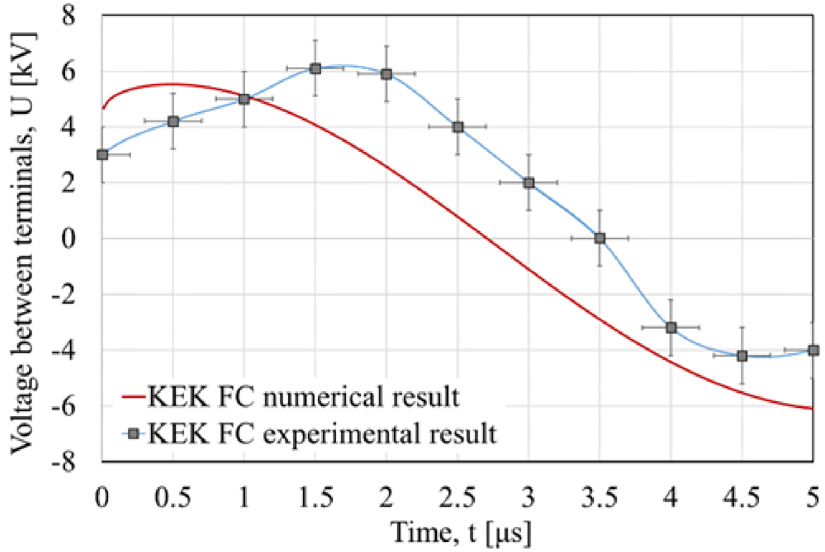


A.V. Kulikov, S.D. Ecklund, and E.M. Reute, “SLC Positron Source Pulsed Flux Concentrator,” Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309, SLAC-PUB-5473, June 1991.

Comparison with experimental result : KEK



Voltage across each turn

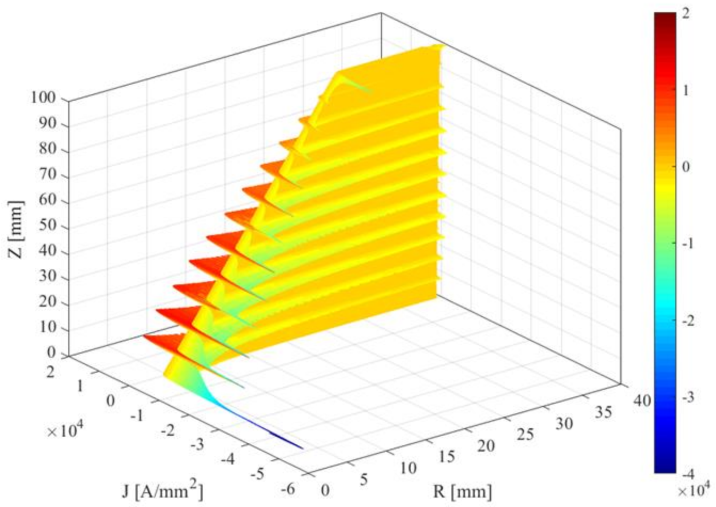


Voltage across the solenoid

Courtesy of Yoshinori Enomoto

Current density distribution at maximum current

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**.

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

Current density distribution at maximum current

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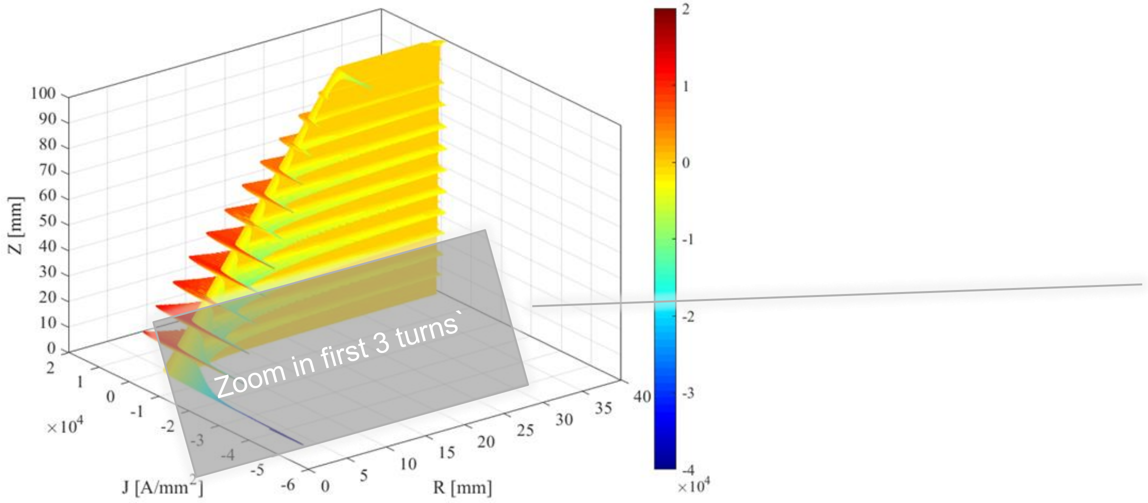

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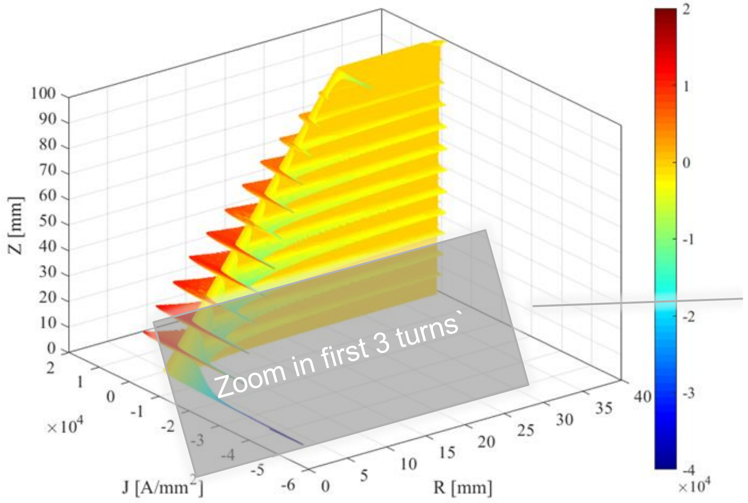

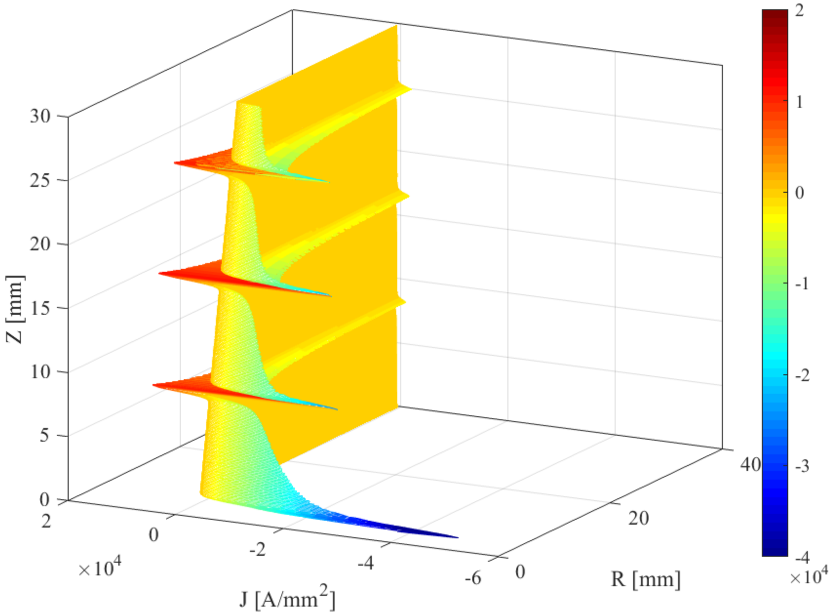

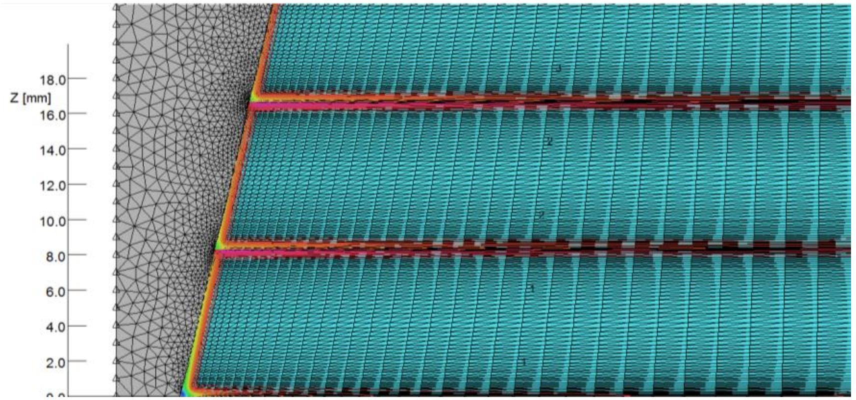

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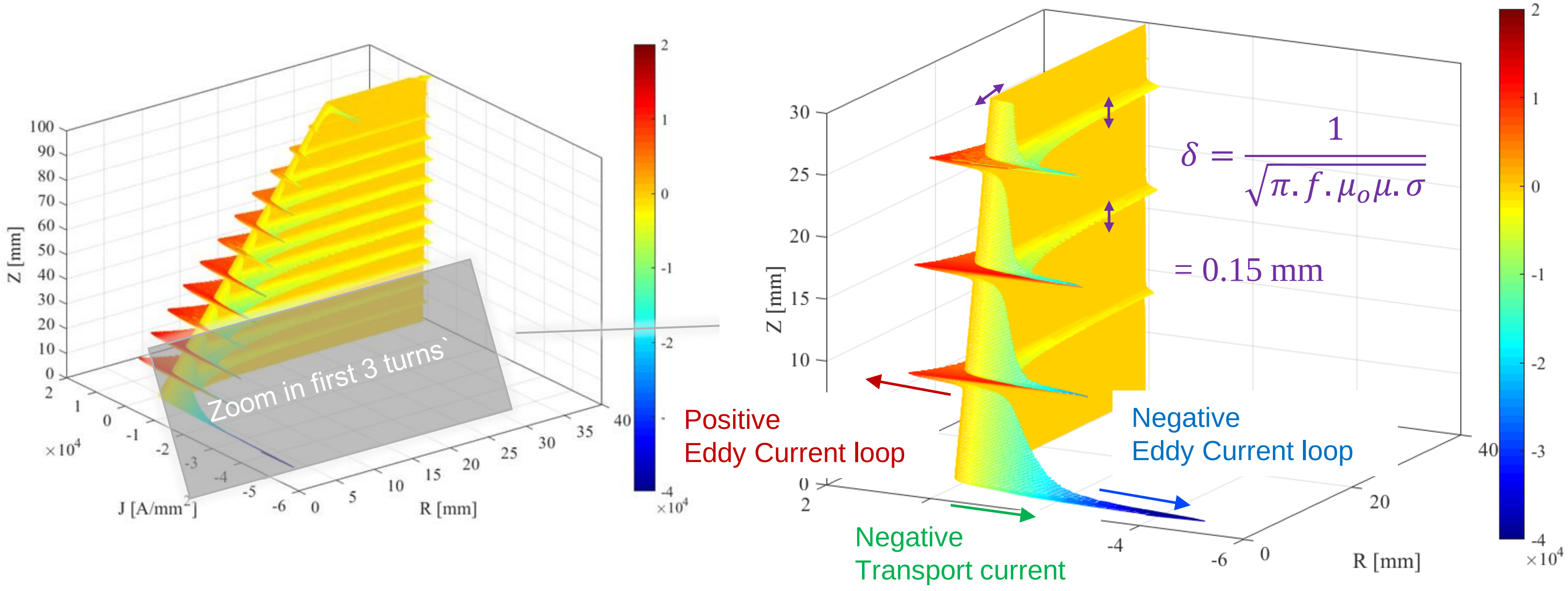

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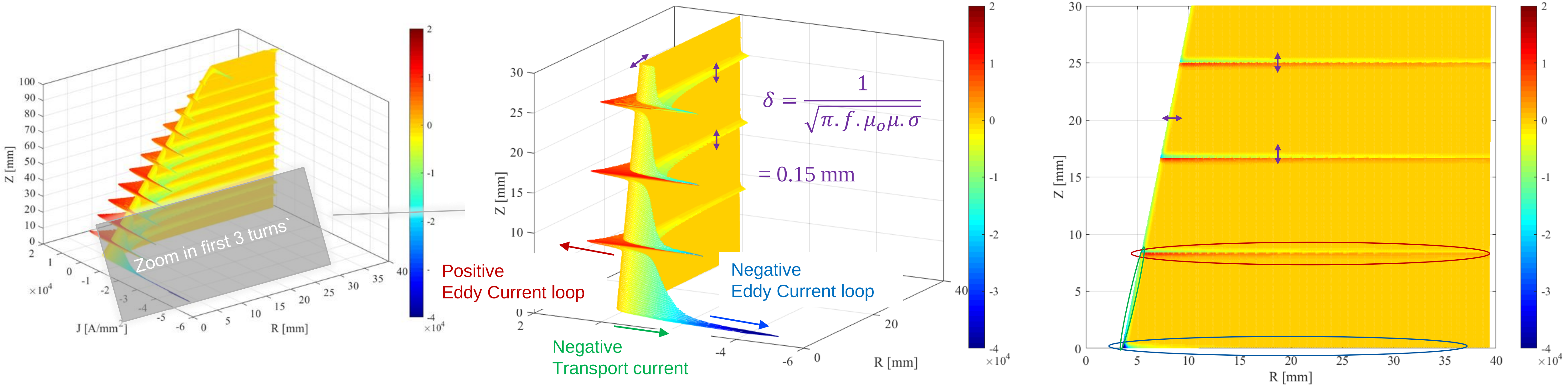

The pulse of current produces strong **eddy current loops** that circulate in opposite directions within each turn.

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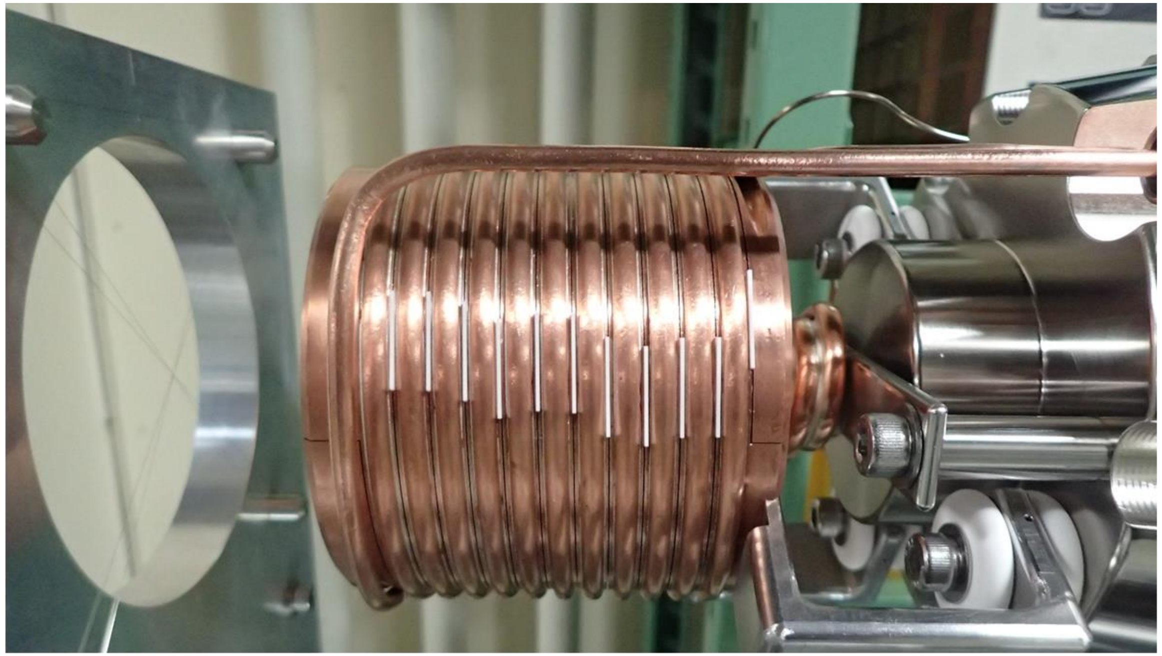
Insulating material between the turns

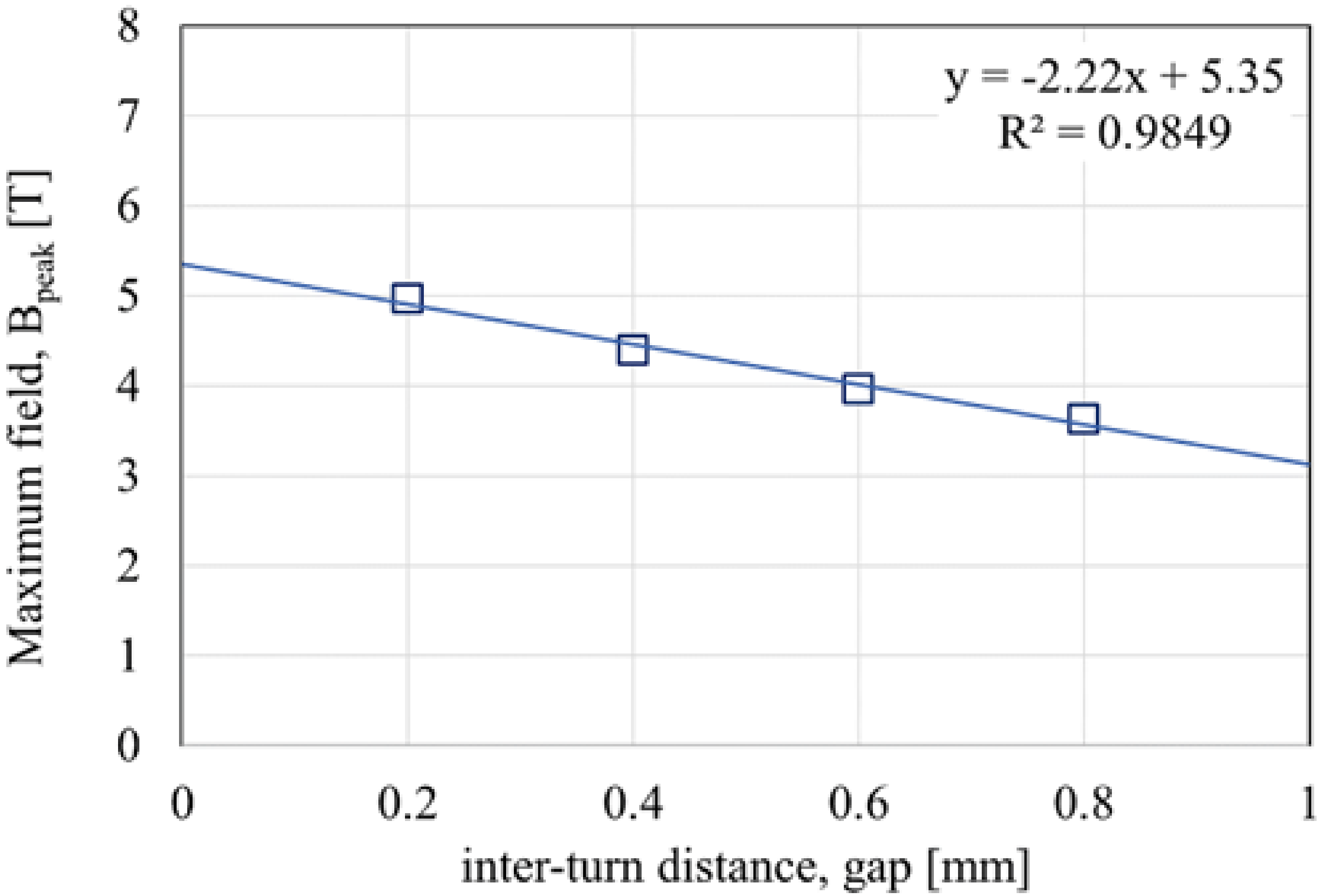


20mm x 25mm x 0.2mm or 0.3 mm Zirconia (ZrO_2) plates are inserted from 3 direction

It works well but not perfect
→discharge decreased but happened
→further investigation is needed

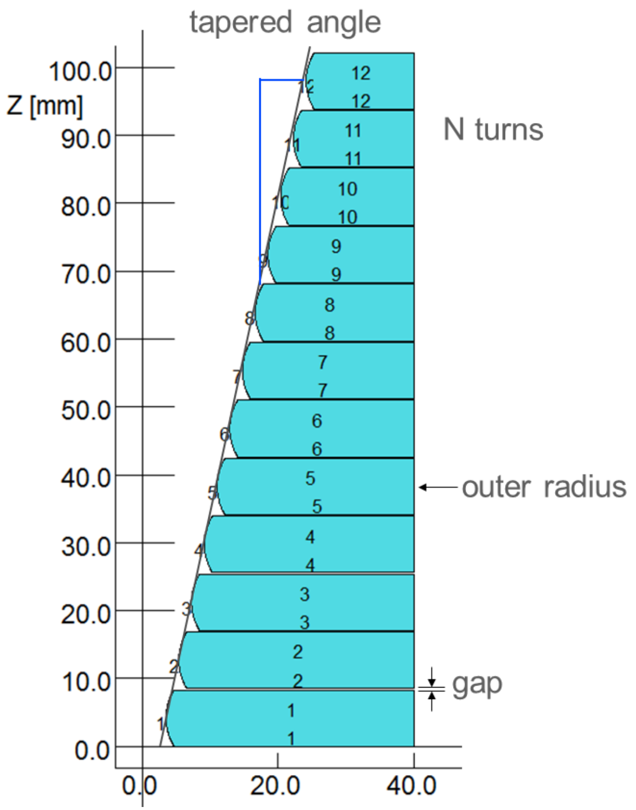
Courtesy of Y. Enomoto

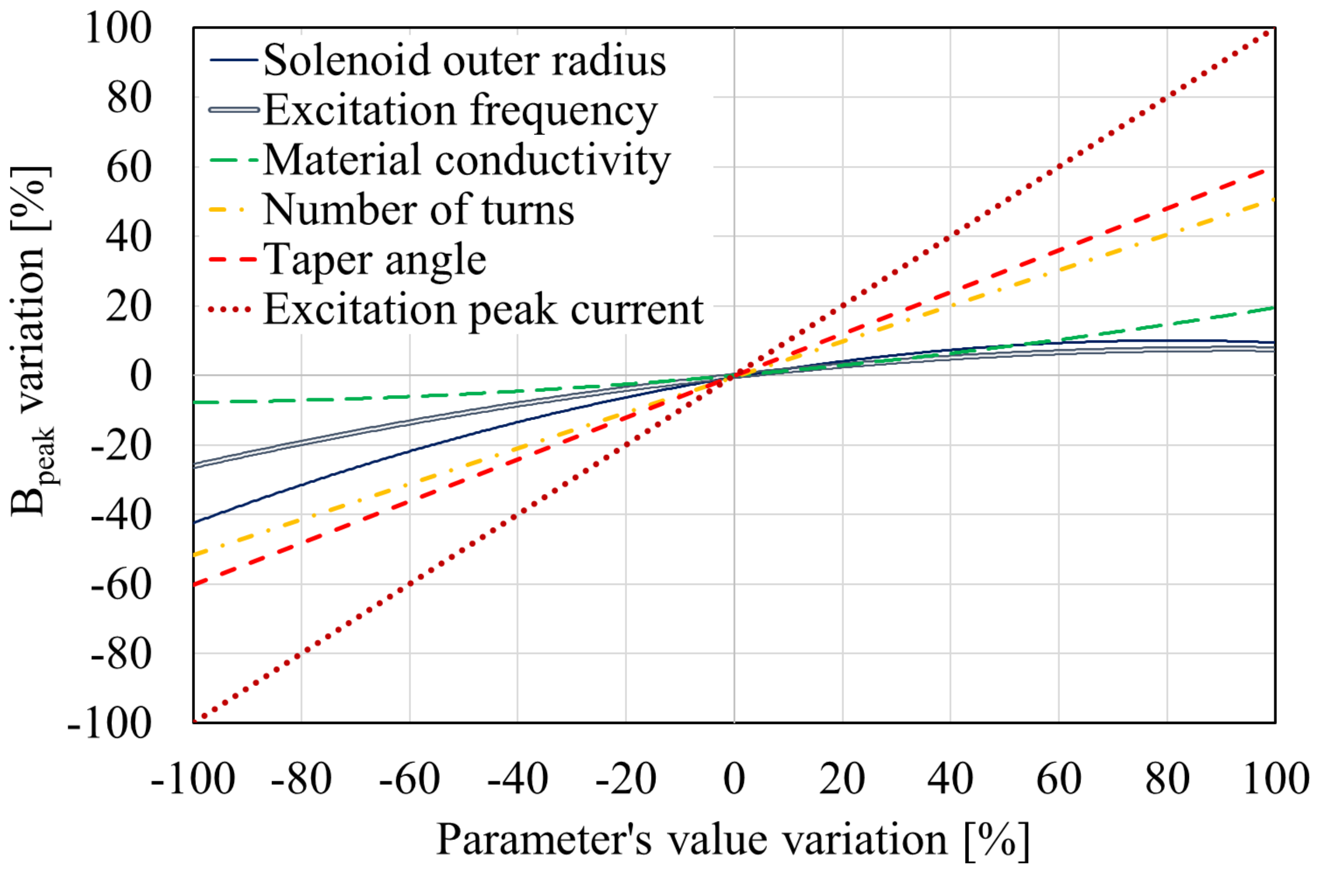
Increasing the size of the gap between turns



The peak field decreases with increasing gap.
And … the voltages increase as well.

A tool for FC design optimisation



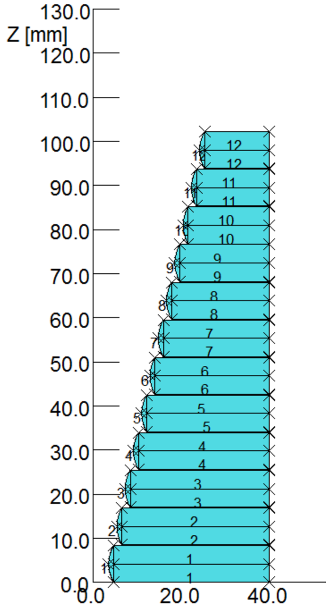


A **tool to optimise** FC's design.

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

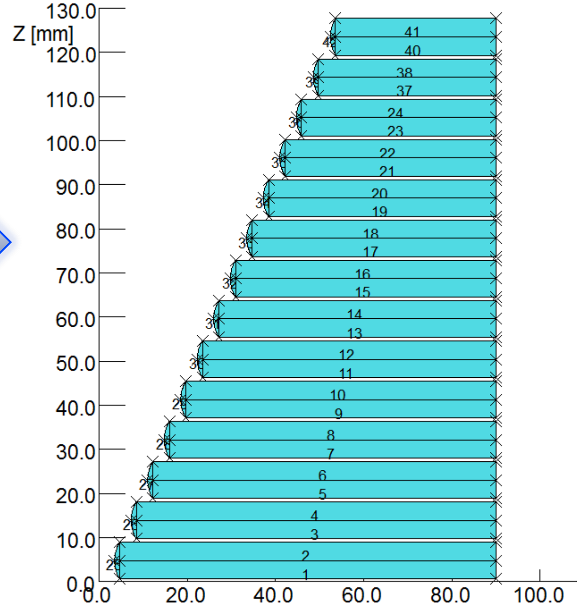
https://indico.cern.ch/event/879495/

Modified design to cope with breakdown issue



SLAC design

gap=0.2 mm
σ=5.67 10^7 S/m
R_o=40 mm
N=12 turns
γ=0.255
f=100 kHz



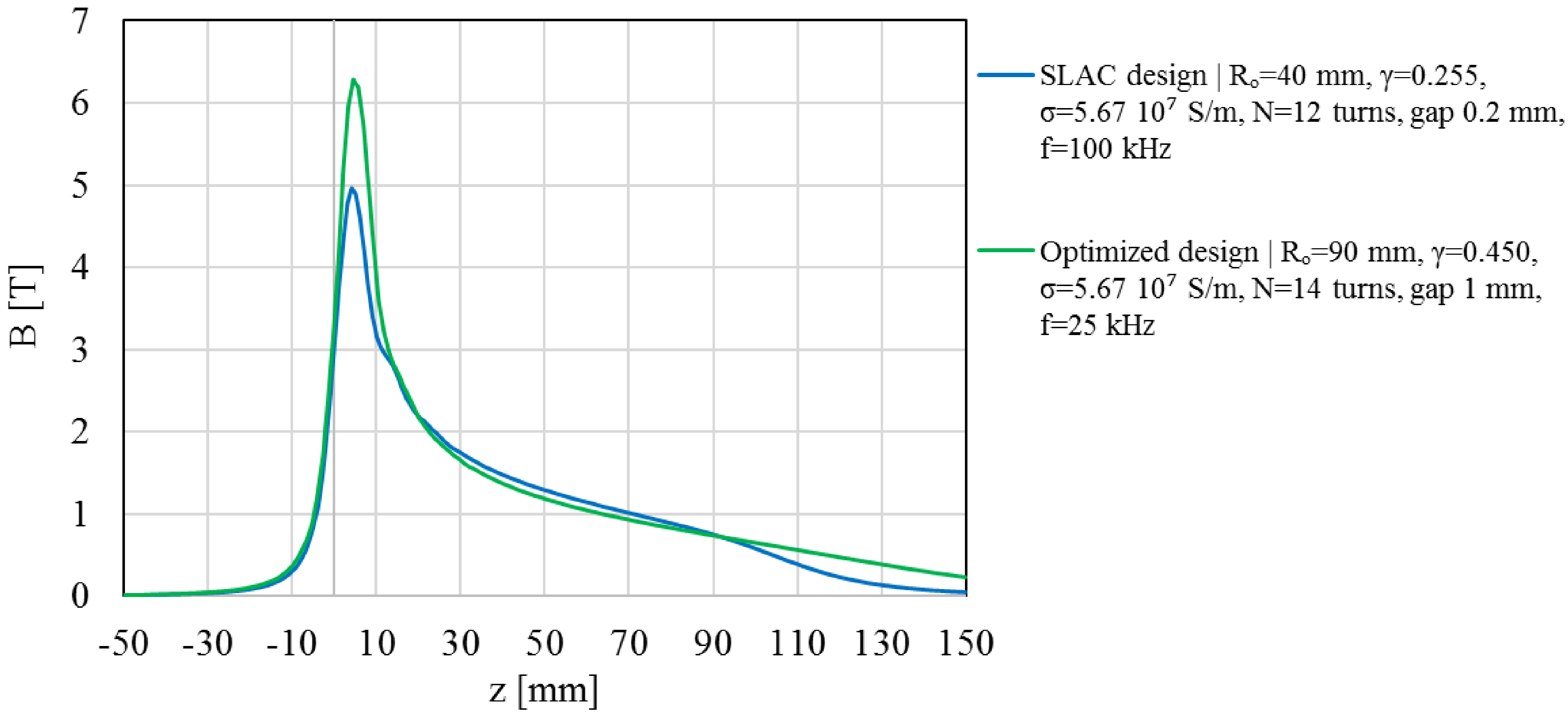
Modified design

gap=0.8 mm
σ=5.67 10^7 S/m
R_o=90 mm
N=14 turns
γ=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.

Expected results for the modified design



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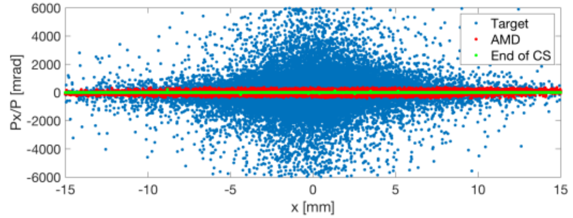
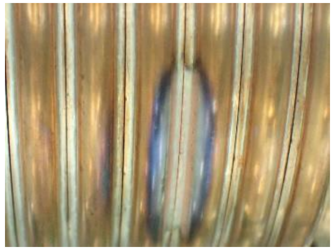
Design optimization for the CLIC e+ source

- 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!).

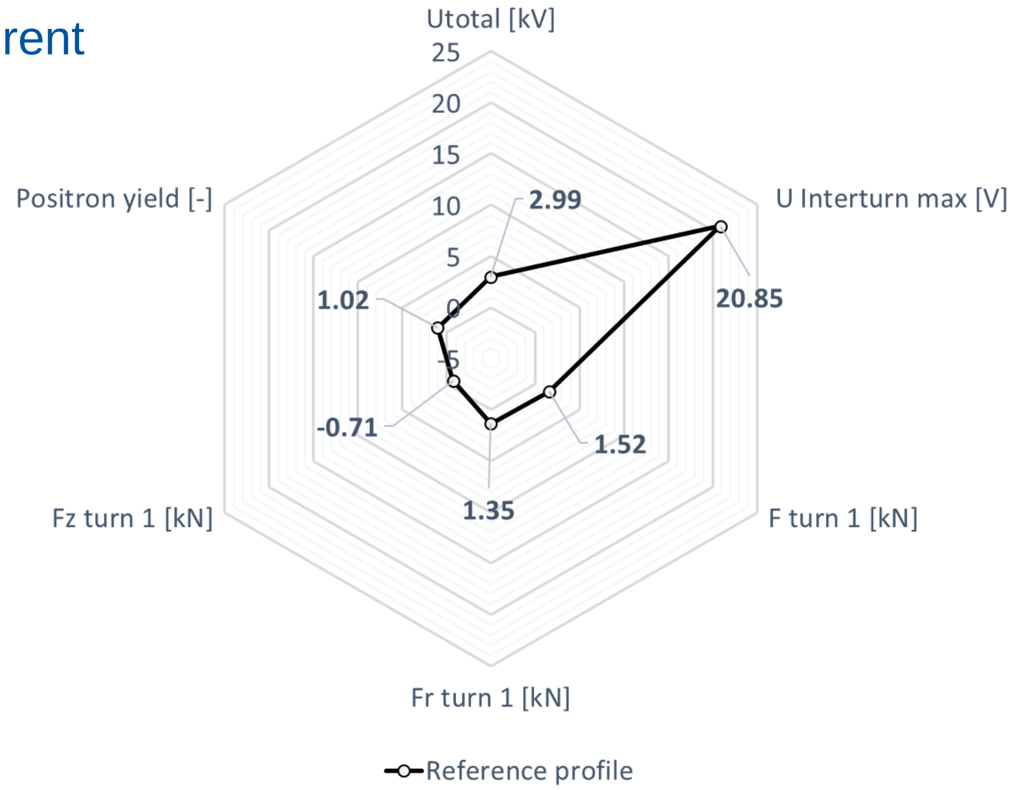
Y. Zhao, "Optimisation of the CLIC positron source", 2021, https://jacow.org/ipac2021/papers/wepab014.pdf

A. Latina, "RF-Track: Beam Tracking in Field Maps Including Space-Charge Effects, Features and Benchmarks", 2017.
https://geant4.web.cern.ch/

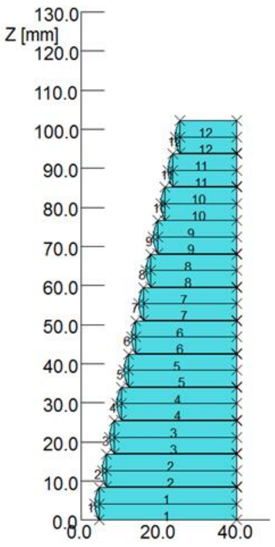
Design optimization for the CLIC e+ source

Graphics containing the parameters to optimize.

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



SLAC design
@ 25 kHz & 13 kA

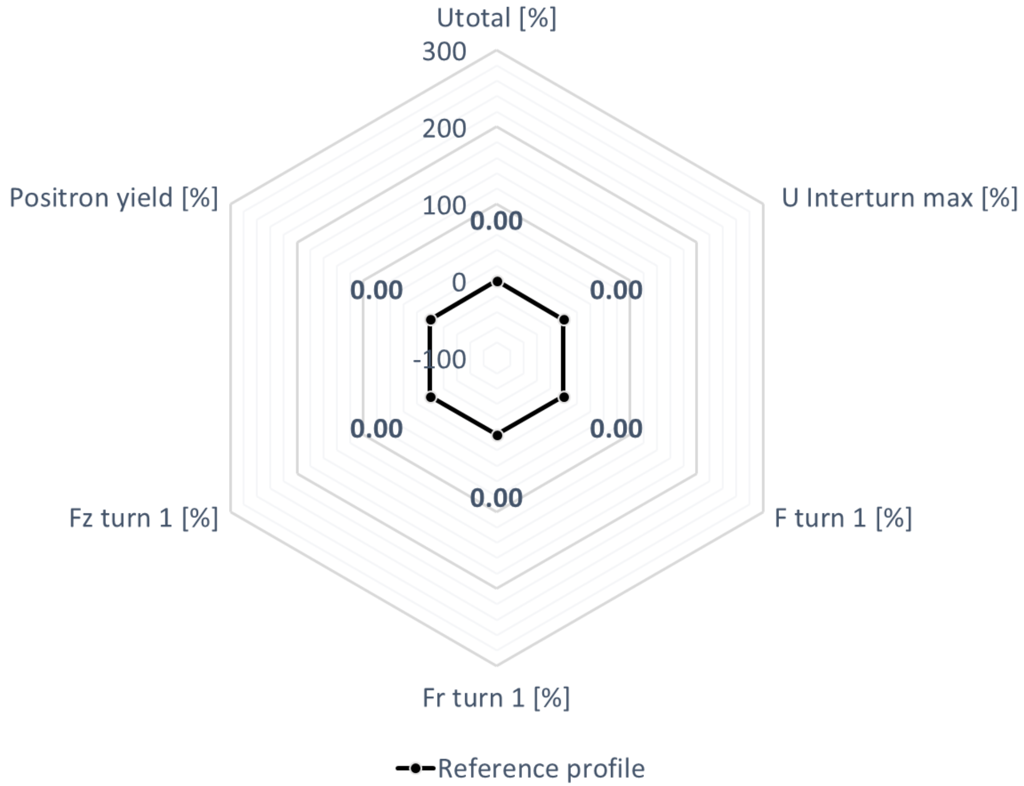


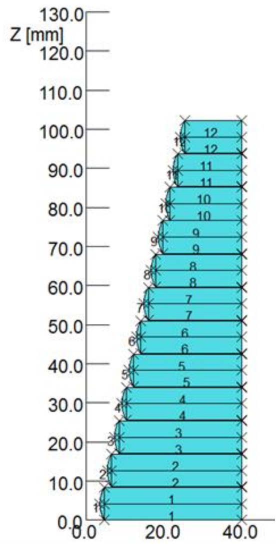
Design optimization for the CLIC e+ source

Normalization of each parameter to its reference value:

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

SLAC design (reference)
@ 25 kHz & 13 kA

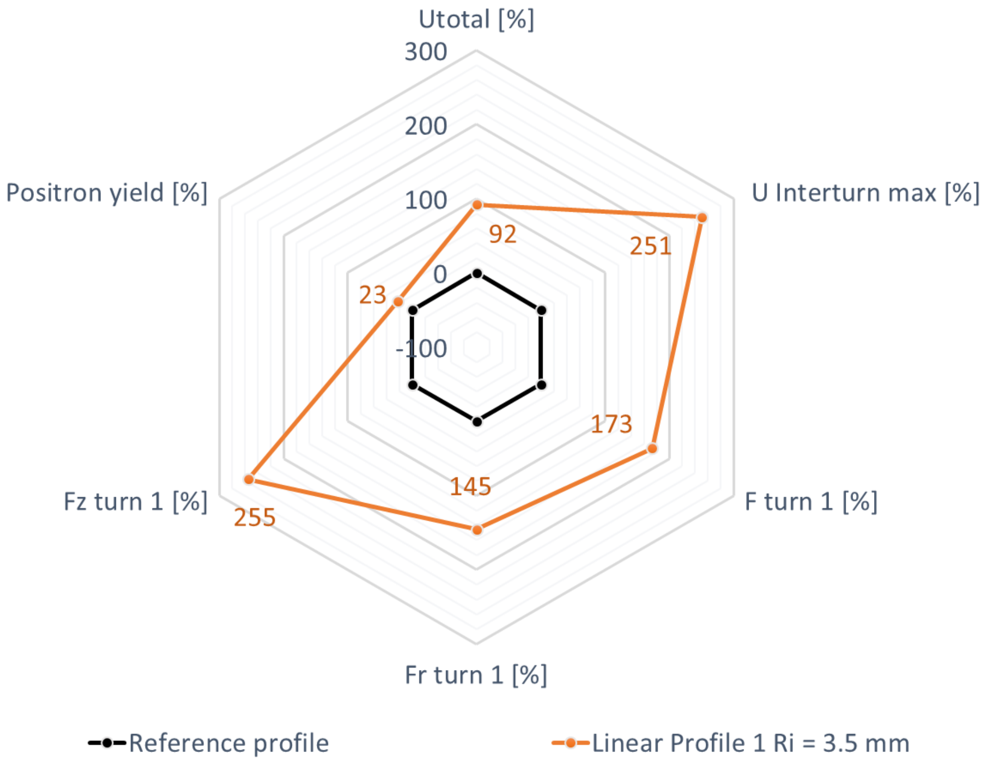




Design optimization for the CLIC e+ source

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

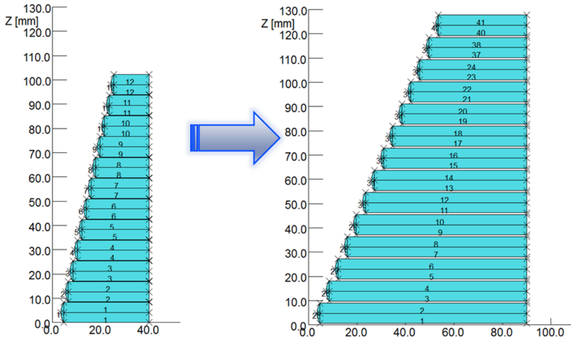
- The yield increases by 23%
- The voltage increases by 92% (due to the gap increase and current increase)
- The forces get ~3 times higher



SLAC design (reference) @ 25 kHz & 13 kA

Vs.

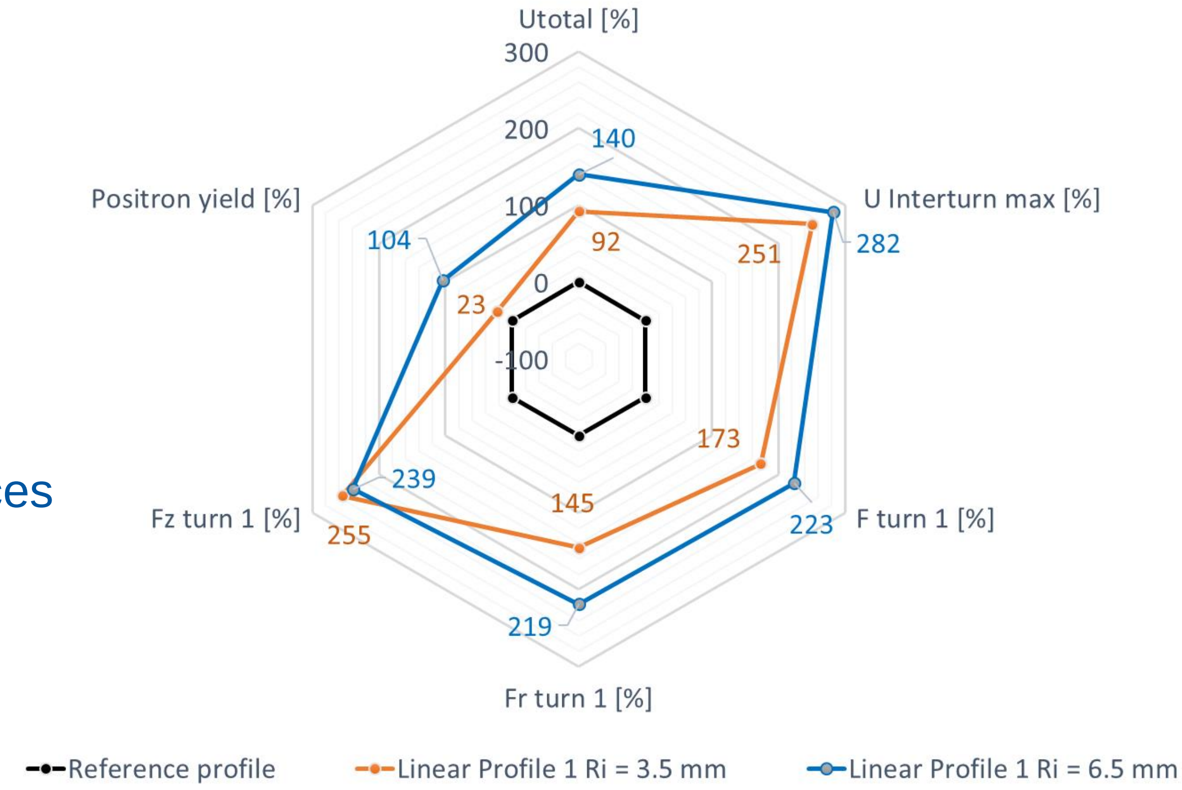
linear modified design @ 25 kHz & 13.8 kA



Design optimization for the CLIC e+ source

- Increasing the aperture (from **3.5** to **6.5** mm) **increases the yield by 104%** (from 1.25 to 2.08).

- But… both voltages and Lorentz forces grow very fast!



SLAC design @ 25 kHz & 13 kA

Vs.

linear modified design

Vs.

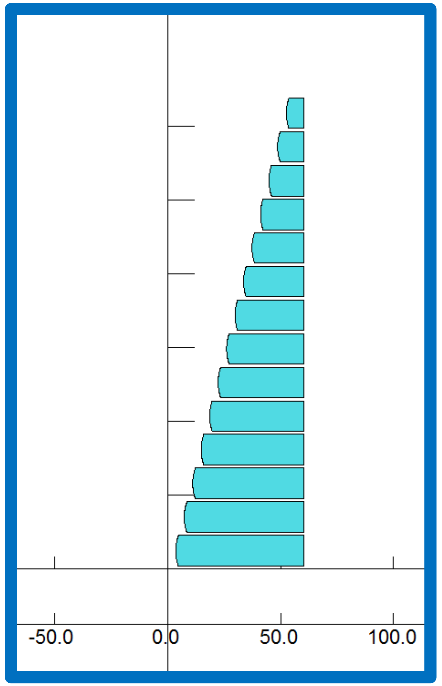
linear modified design with large aperture

How can one lower down the other parameters keeping high yield?

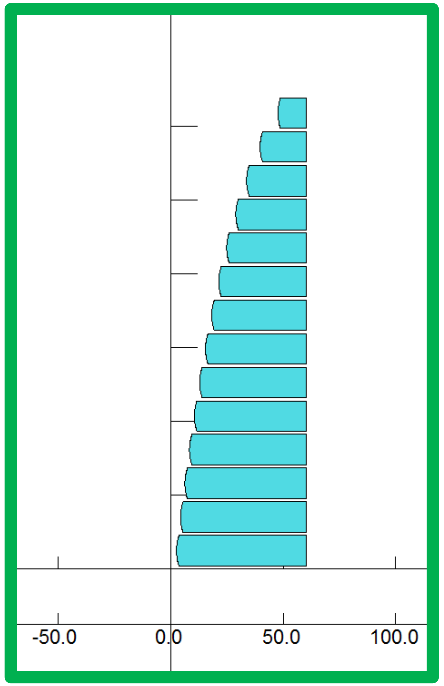
Design optimization for the CLIC e+ source

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

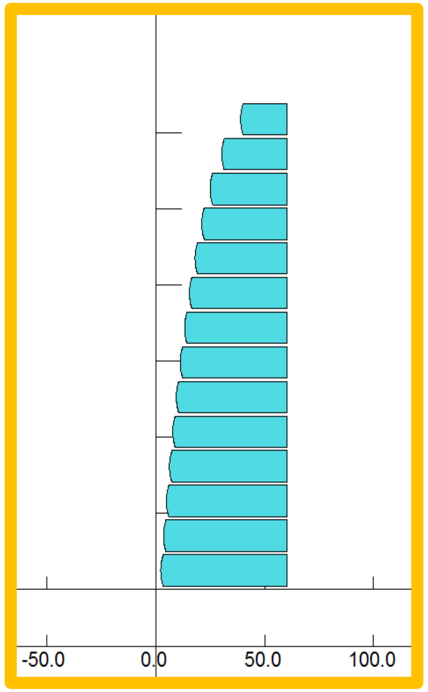
Linear



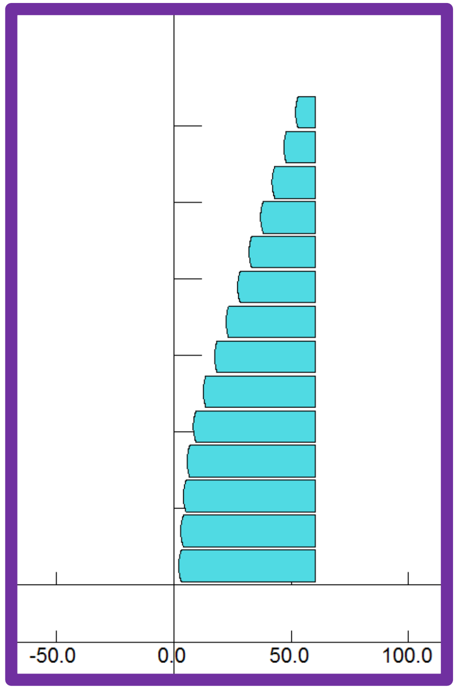
Concave downward (1)



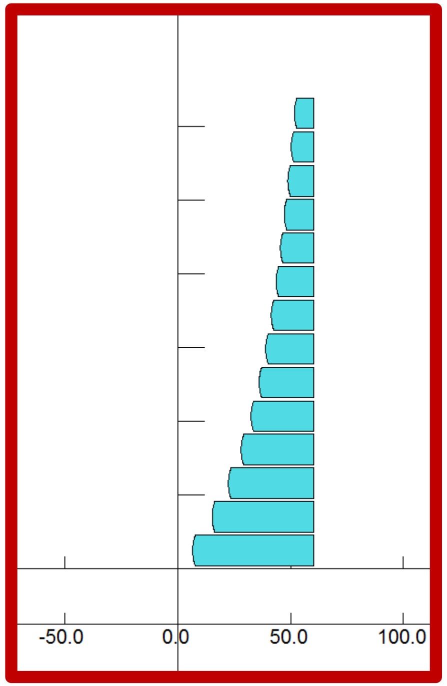
Concave downward (2)



Concave downward + linear (3)

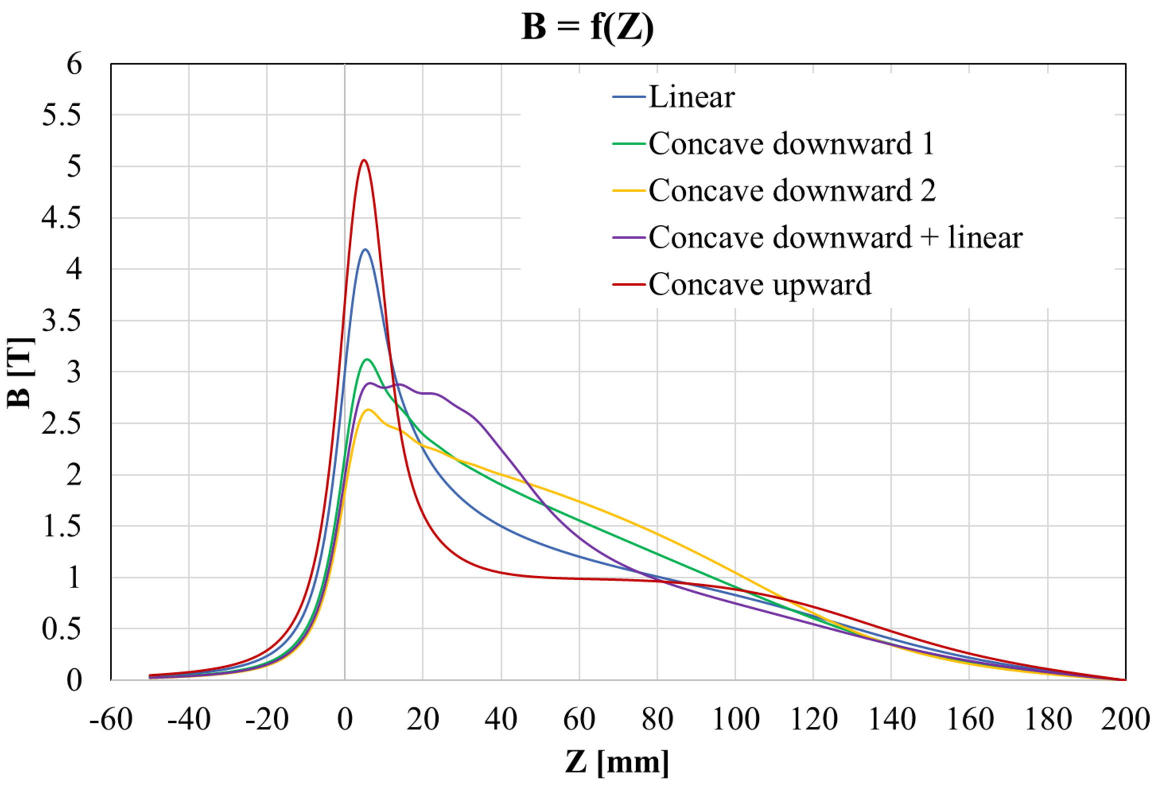


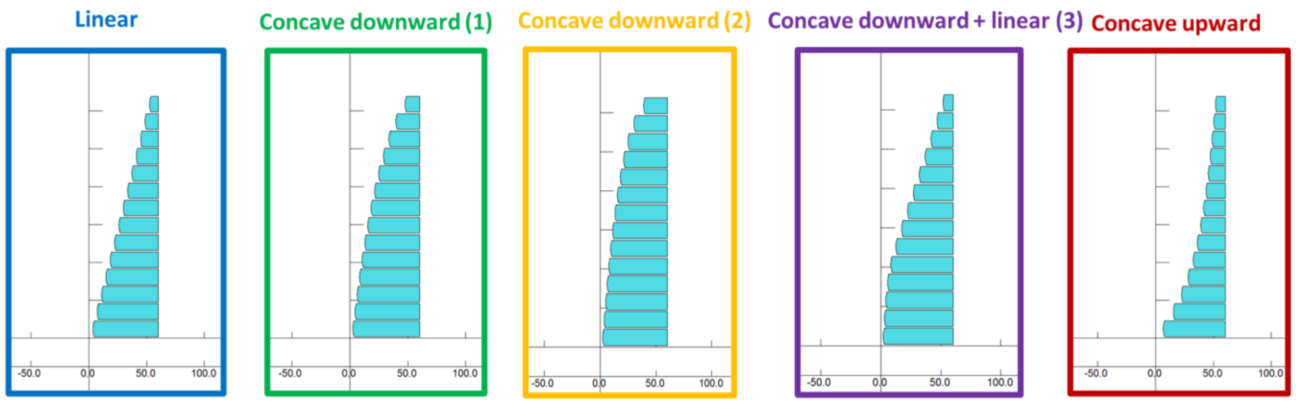
Concave upward



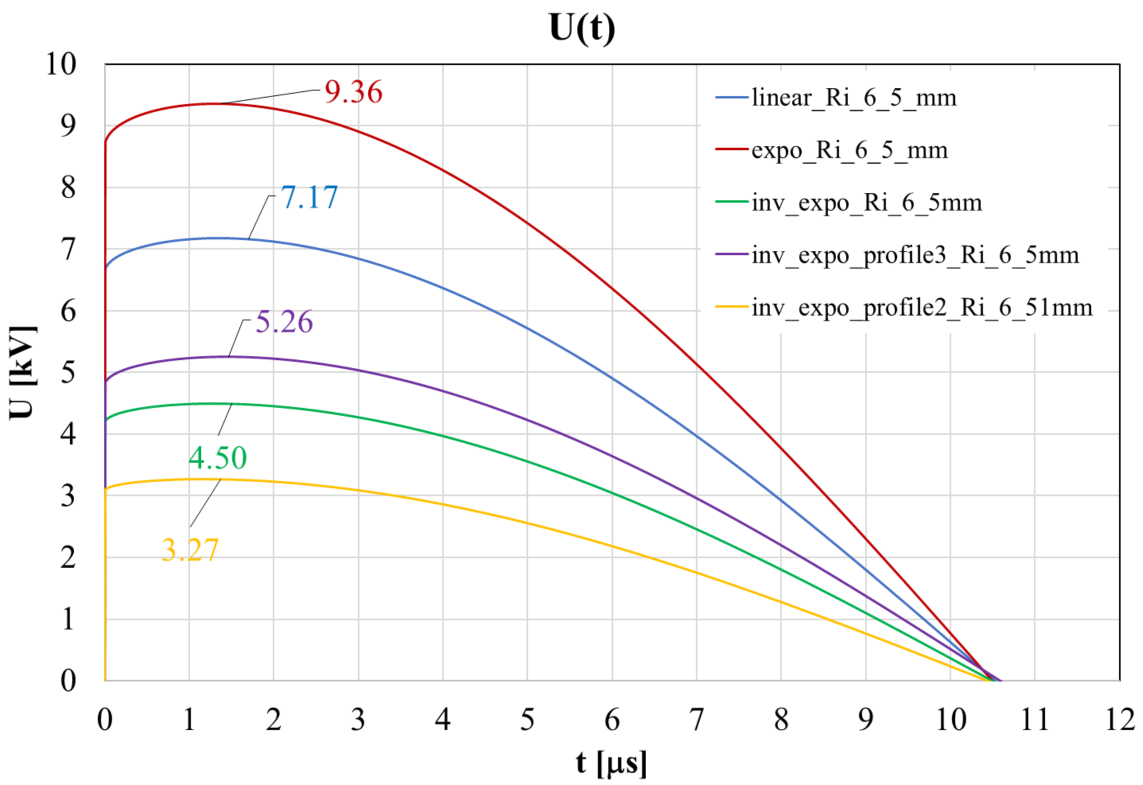
How does the shape impact the parameters to optimize?

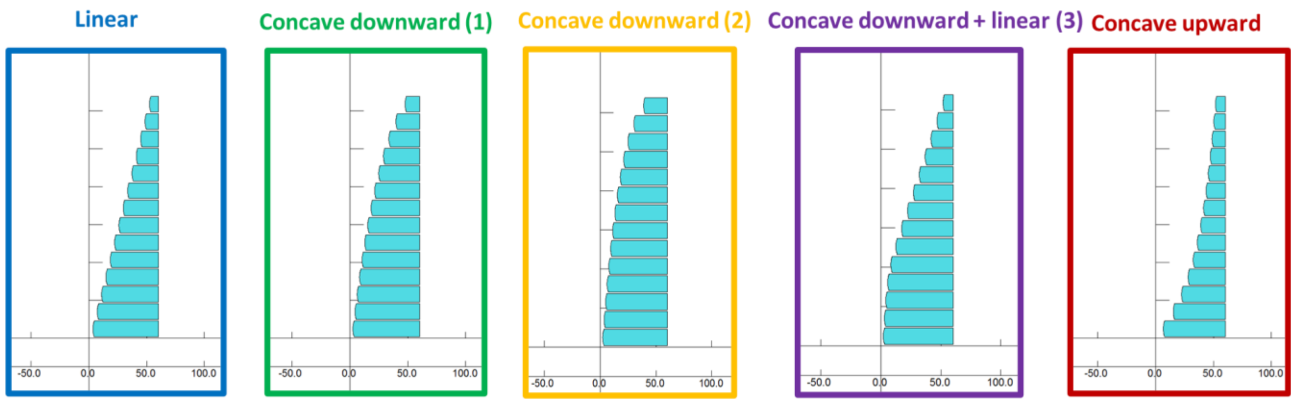
Design optimization for the CLIC e+ source





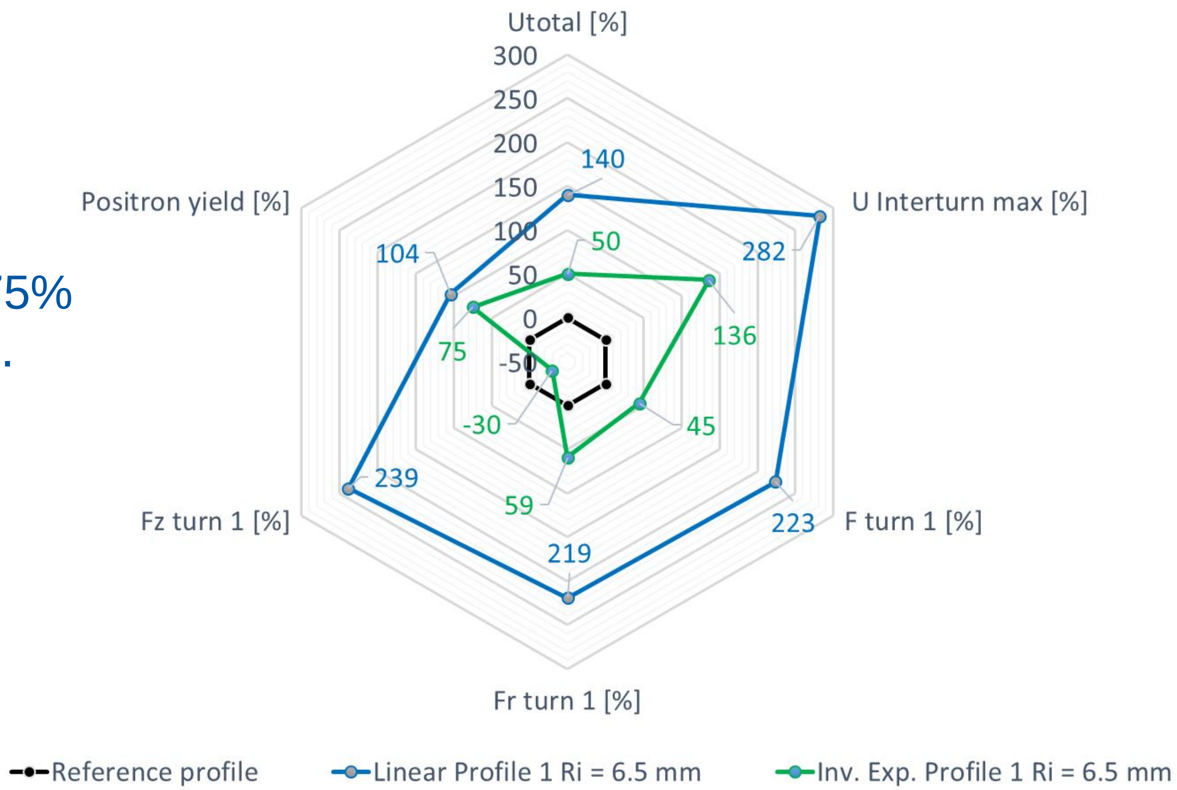
Design optimization for the CLIC e+ source





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 75% higher than the reference case.



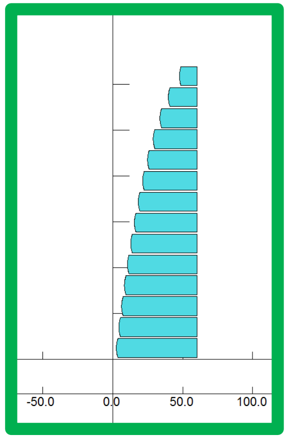
SLAC design
@ 25 kHz & 13 kA

Vs.

linear modified design with large aperture

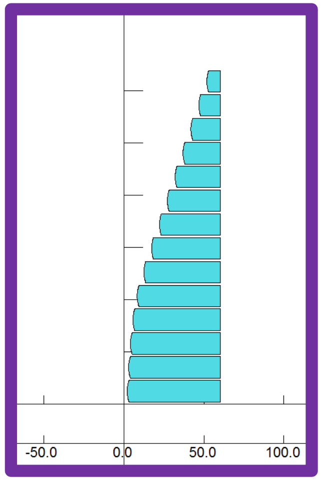
Vs.

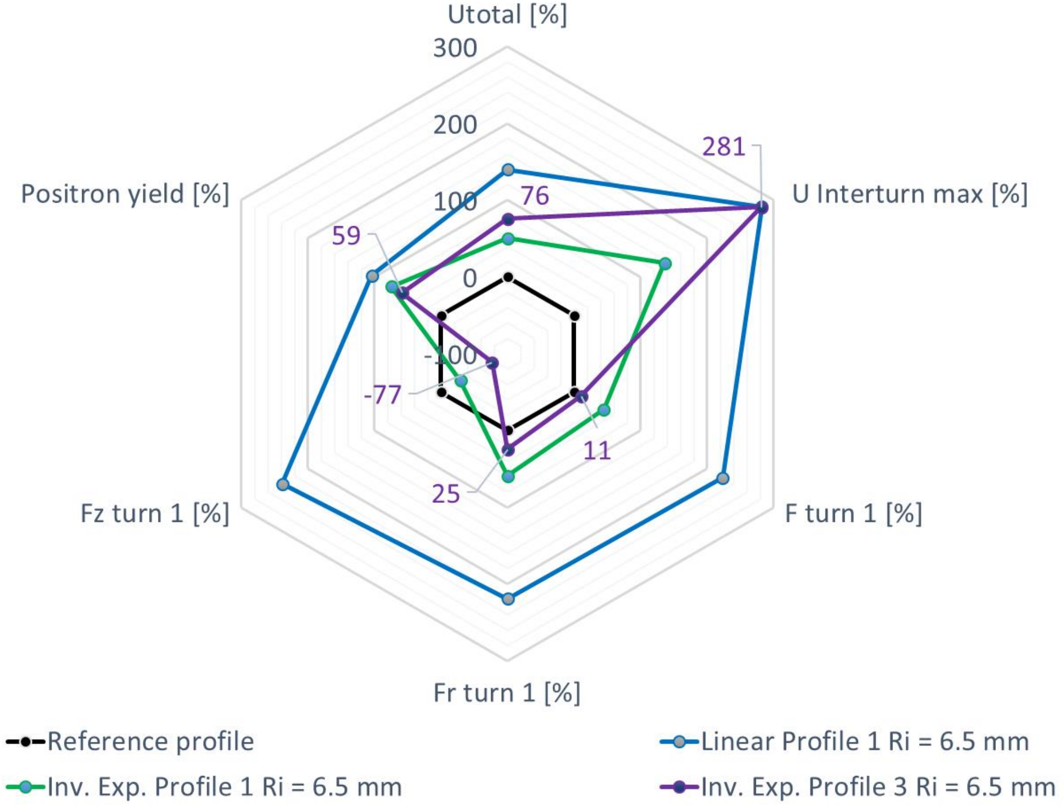
Non-linear design (1) Concave downward



Design optimization for the CLIC e+ source

- Using more exotic shape <u>allows to decrease the Lorentz forces</u>.
- The yield gets slightly lower though.
- The voltage gets higher.





SLAC design
@ 25 kHz & 13 kA

Vs.

linear modified design with large aperture

Vs.

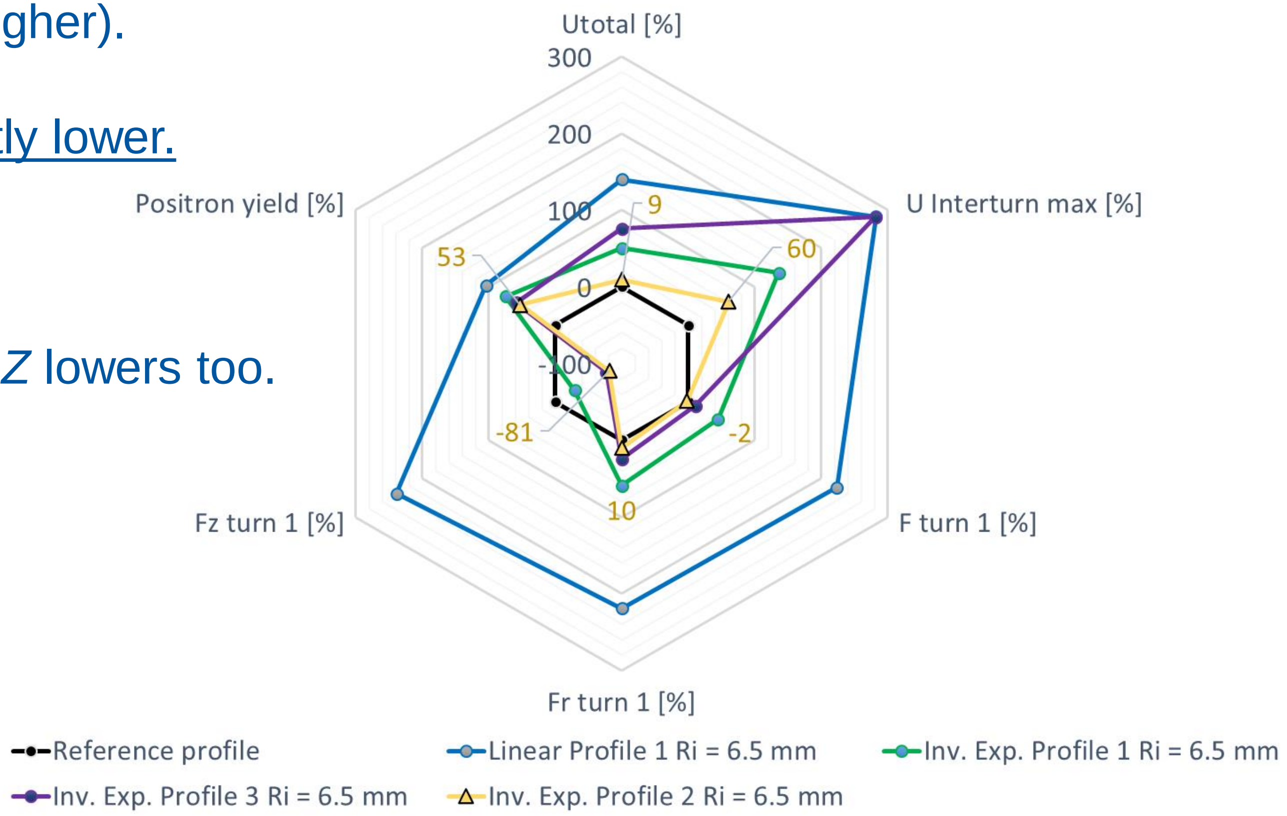
Non-linear design (1) Concave downward

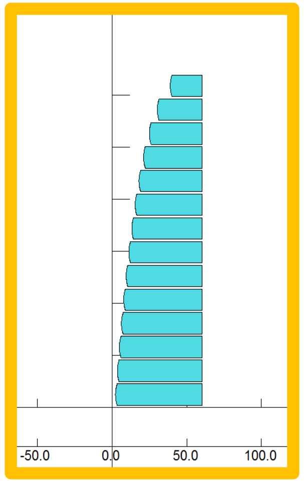
Vs.

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 (53% 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.

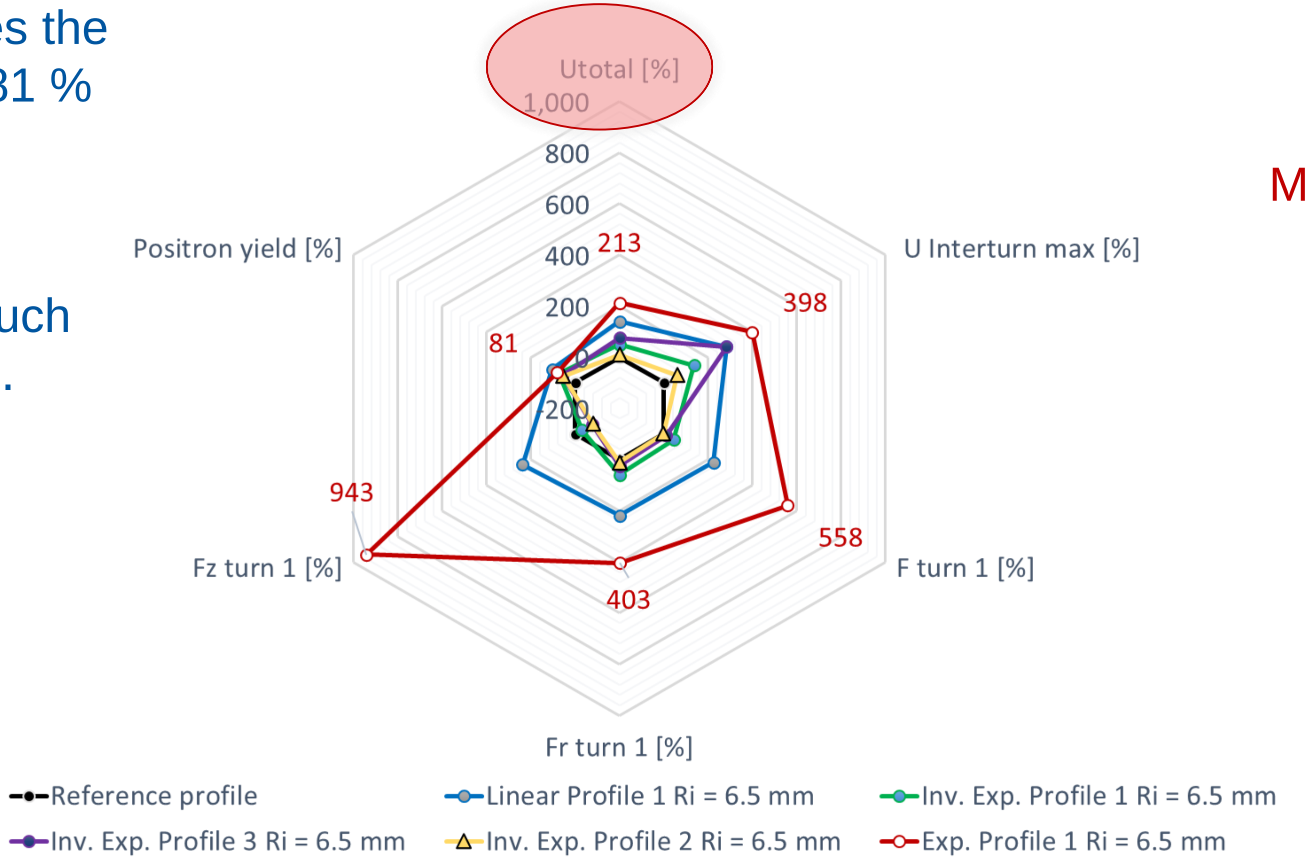
Non-linear design (3) Concave downward + linear

Vs.

Non-linear design (2) Concave downward

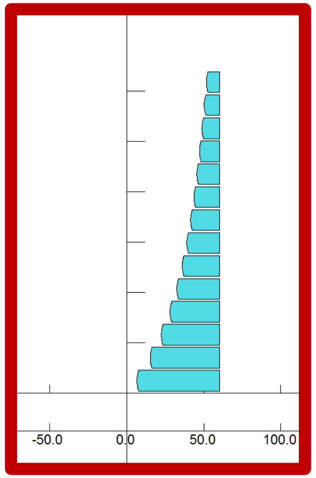
Design optimization for the CLIC e+ source

- The upward concavity gives the second highest yield with 81 % increase.
- Voltages and forces are much higher than the linear case.



Adding the upward concavity case

Mind the change of scale !!



Summary table of the test results

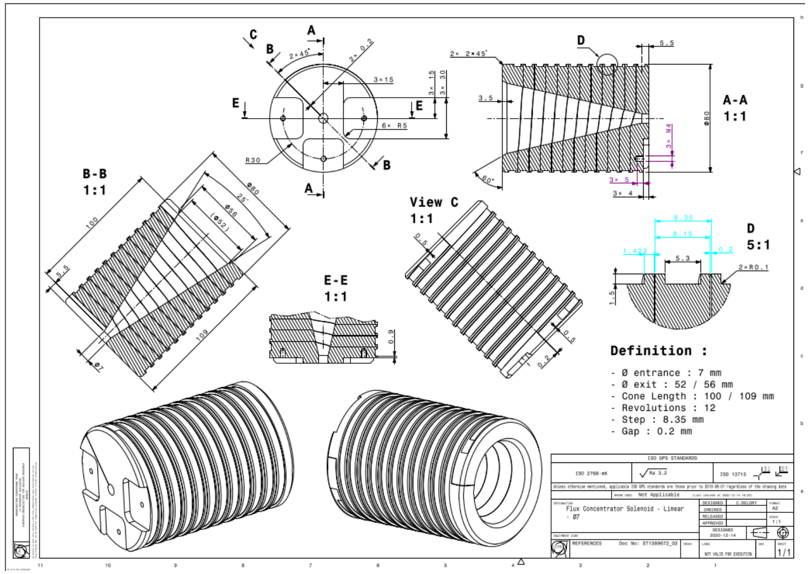
Parameters	Units	Reference profile	Linear Profile 1 Ri = 3.5 mm	Linear Profile 1 Ri = 6.45 mm	Inv. Exp. Profile 1 Ri = 6.45 mm	Inv. Exp. Profile 2 Ri = 6.5 mm	Inv. Exp. Profile 3 Ri = 6.45 mm	Exp. Profile 1 Ri = 6.5 mm
Ri	[mm]	3.5	3.5	6.45	6.45	6.52	6.45	6.5
Ro	[mm]	40	60	60	60	60	60	60
w_{turn}	[mm]	8.33	8.33	8.33	8.33	8.33	8.33	8.33
gap	[mm]	0.2	0.8	0.8	0.8	0.8	0.8	0.8
f	[kHz]	25	25	25	25	25	25	25
I_{peak}	[kA]	13.00	13.80	13.80	13.80	13.80	13.80	13.80
B_{peak}	[T]	3.98	5.99	4.19	3.12	2.63	2.89	5.06
U_{total} [kV]	[kV]	2.99	5.75	7.18	4.50	3.28	5.26	9.36
U Interturn max [V]	[V]	20.85	73.07	79.60	49.26	33.4	79.51	103.76
F turn 1 [kN]	[kN]	1.52	4.15	4.92	2.20	1.49	1.69	10.00
Fr turn 1 [kN]	[kN]	1.35	3.30	4.30	2.14	1.49	1.68	6.78
Fz turn 1 [kN]	[kN]	-0.71	-2.51	-2.39	-0.50	-0.13	-0.16	-7.35
Positron yield [-]	**[-]**	**1.02**	**1.25**	**2.08**	**1.78**	**1.56**	**1.62**	**1.85**

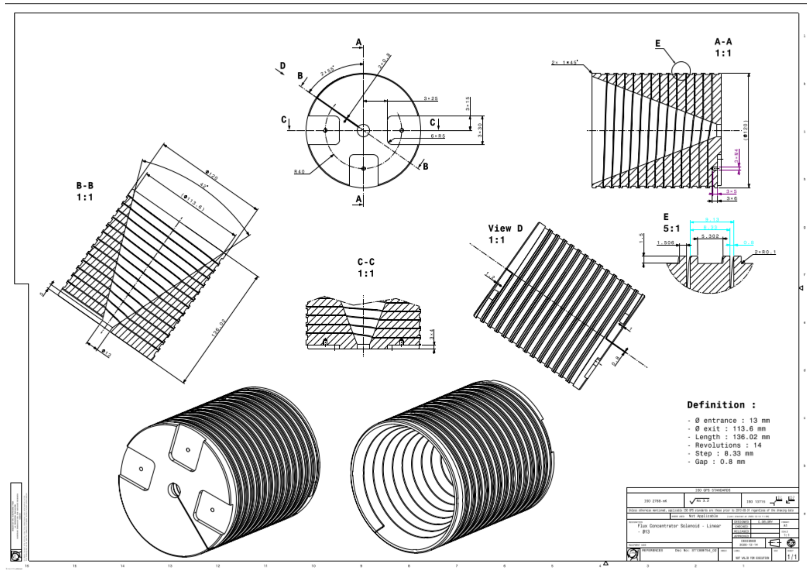
Outline

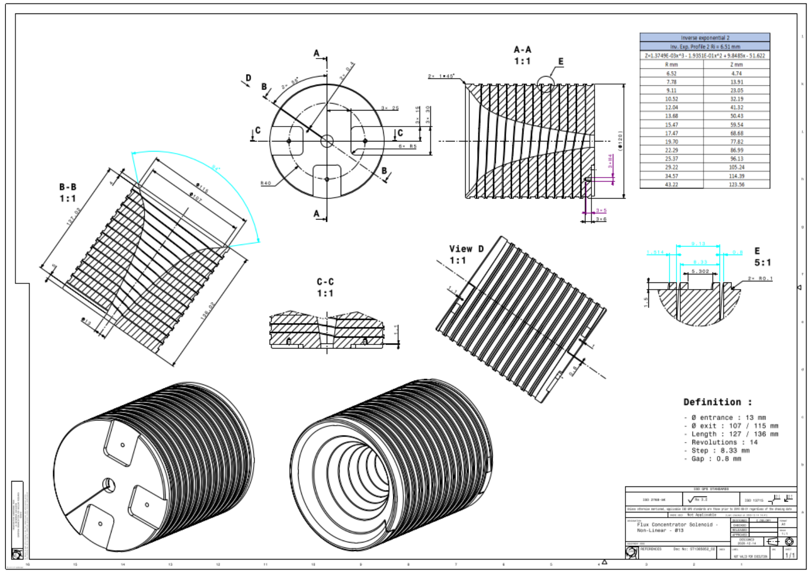
- Flux Concentrator in linear accelerators
- Modelling of the geometry and the electrical circuit
- Validations of the model
- A tool for FC design optimisation
- Design optimization for the CLIC e+ source
- Update on manufacturing and testing
- Conclusion

Update on manufacturing and testing

Production of technical drawing with the CERN design office (EN-MME)







Goal: test and validate the various features studied by the model, we are planning to manufacture several samples:

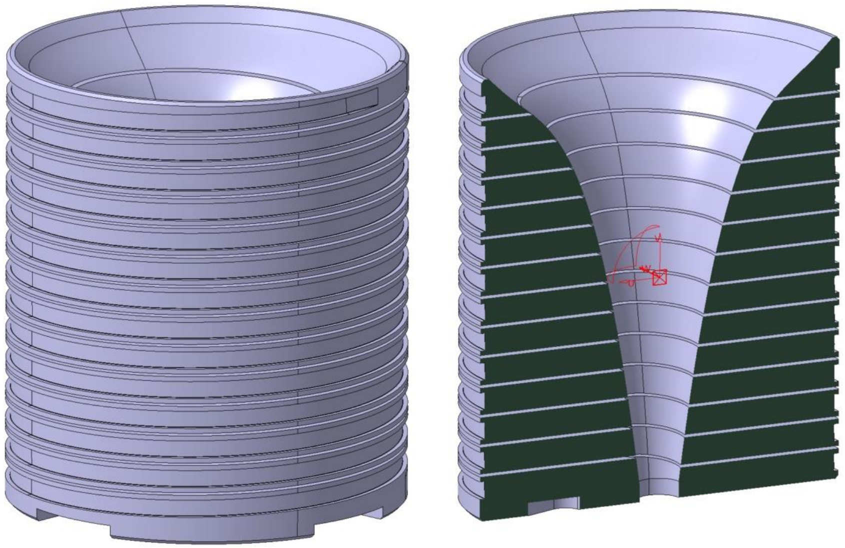
- Reference from SLAC design
- CLIC optimized with larger aperture
- Non-linear profile

Two materials are considered: Copper and Titanium

Update on manufacturing and testing

Manufacturing techniques consideration

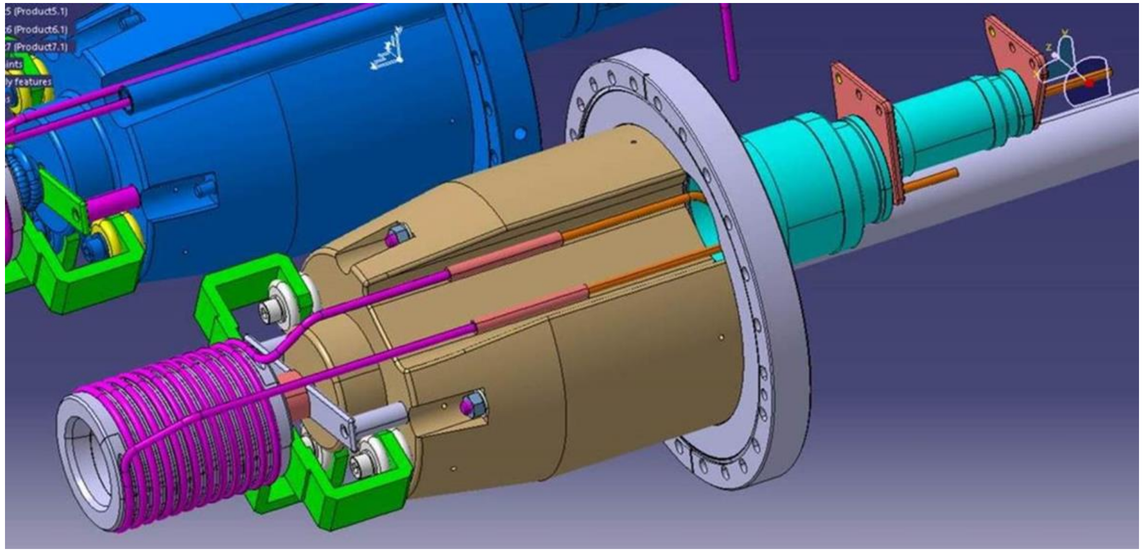
"Classic" Machining with
Electric Discharge Machining (EDM)

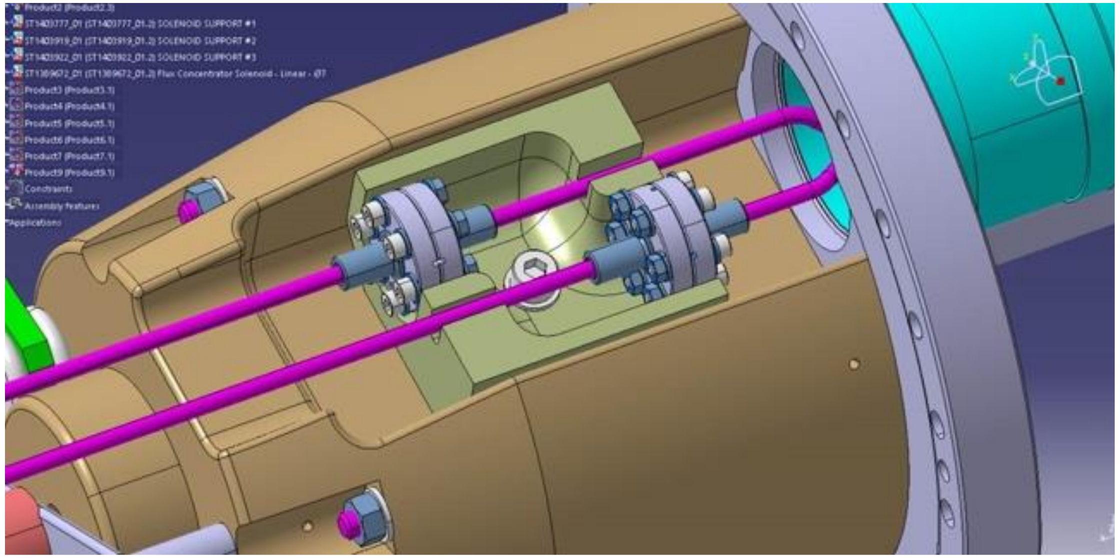


"Innovative" Machining with
3D printed (available at CERN with Titanium)

Update on manufacturing and testing

Produce prototype that can be integrated at the KEK test bench (see Enomoto's presentation)





Conclusion

- Construction and validation of a transient electromagnetic model of Flux Concentrator using Opera® software.
- 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 led to the doubling of the positron yield.
- Adapting the coil's profile (non-linear) limits the detrimental voltages and the Lorentz forces.
- Prototypes are planned to be manufacture at CERN and tested at KEK.

CERN

Backup

Design optimization for the CLIC e+ source

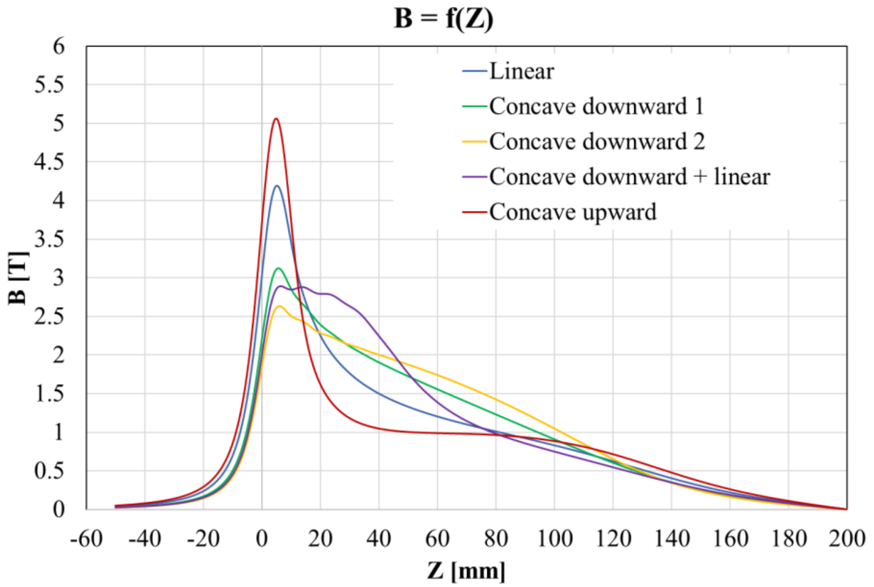
The shape of the FC profile significantly impacts the shape of the field distribution.

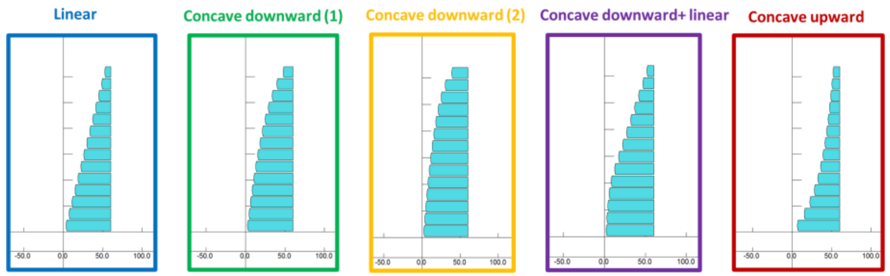
The downward concavity leads to:

- 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

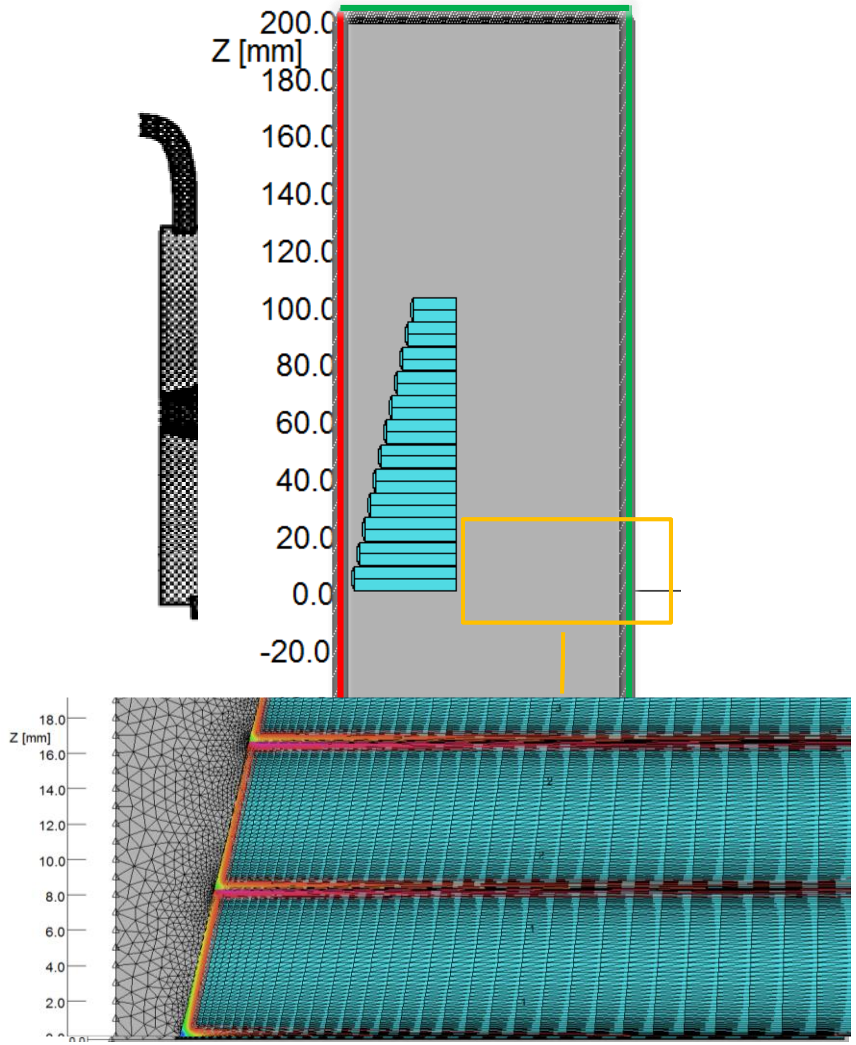




What is a «GOOD FIELD DISTRIBUTION» in terms of positron yield?

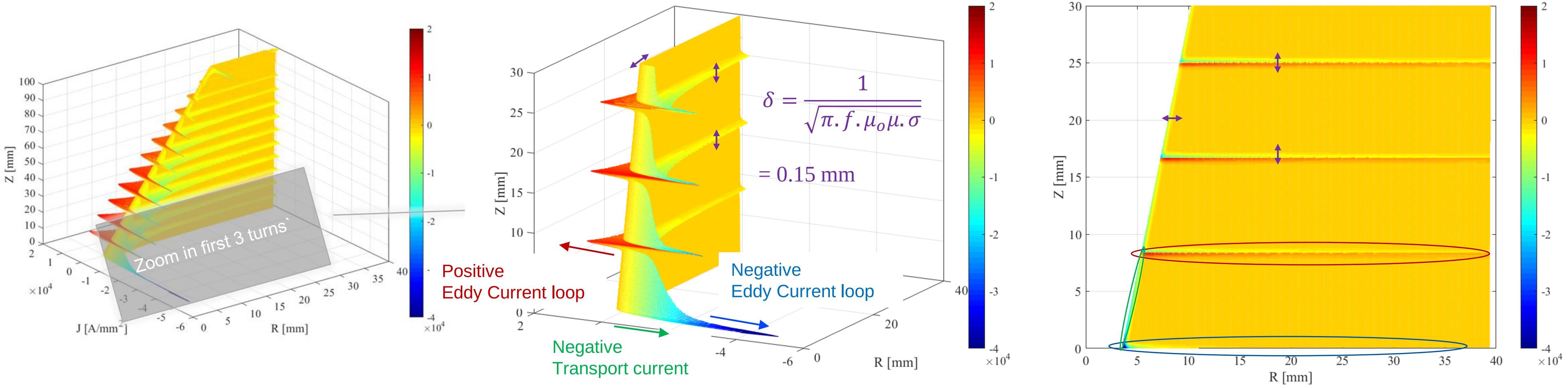
Modelling of the geometry

- 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



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.

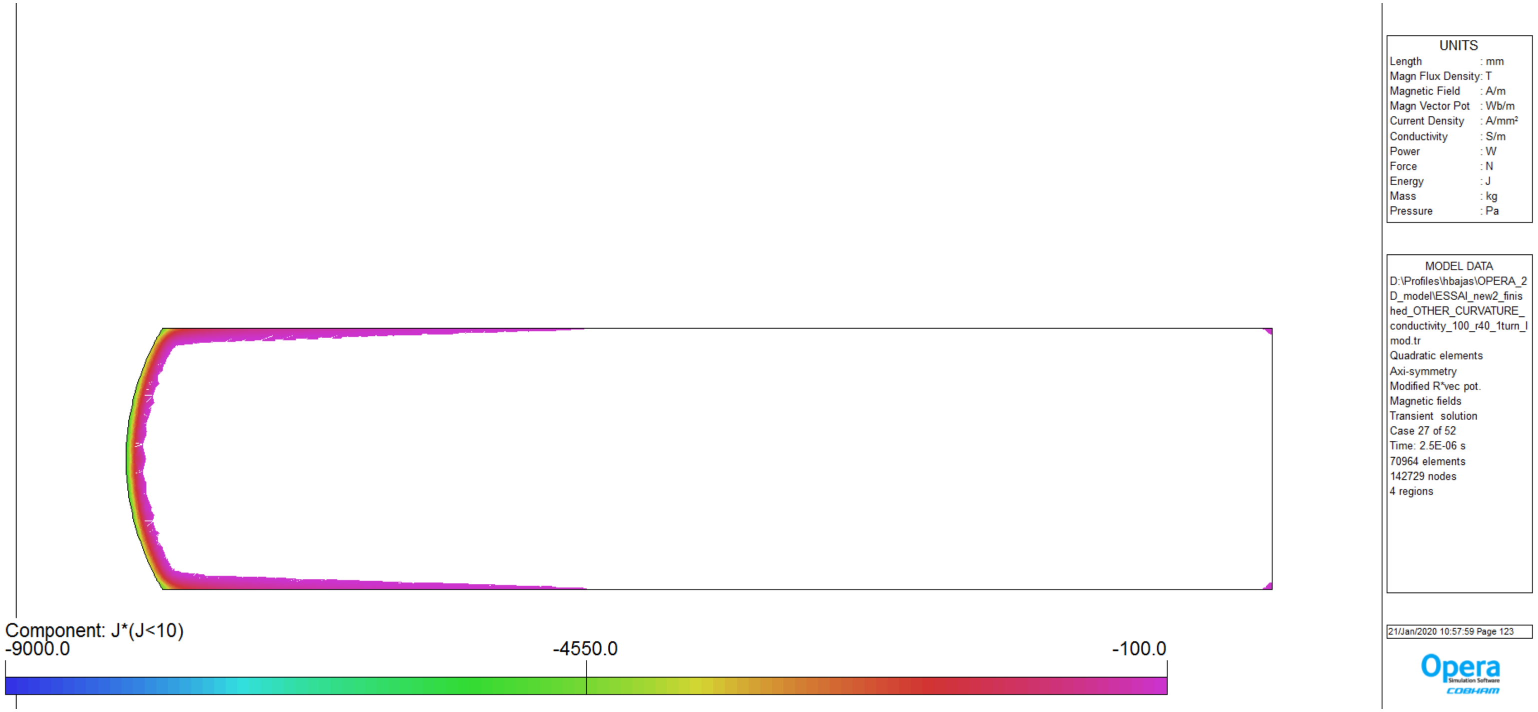
The current density concentrates at **the skin of the conductor**.

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

The eddy currents depend on the adjacent turns

Let’s model
One-turn coil

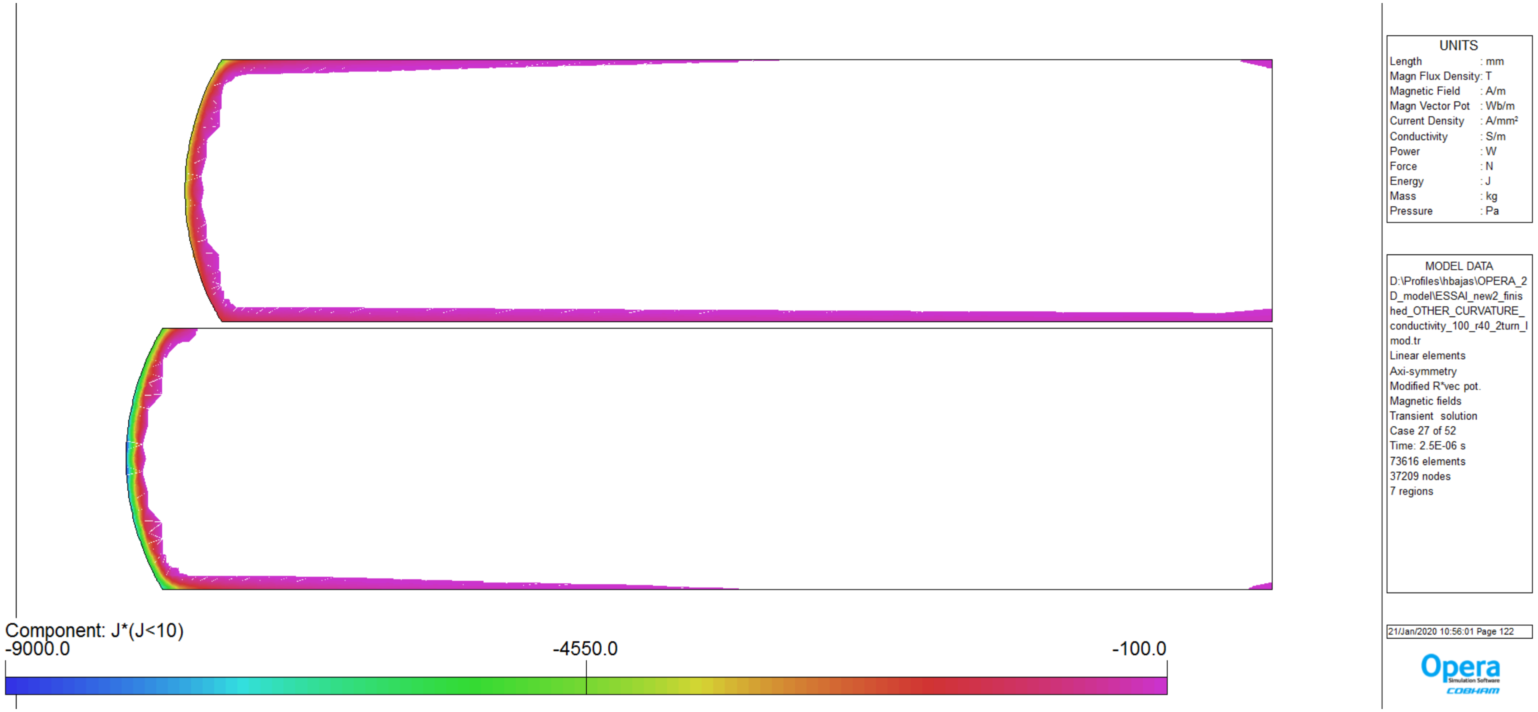
The current density is only negative



The eddy currents depend on the adjacent turns

Let’s model
Two-turn coil

The current density is both positive & negative

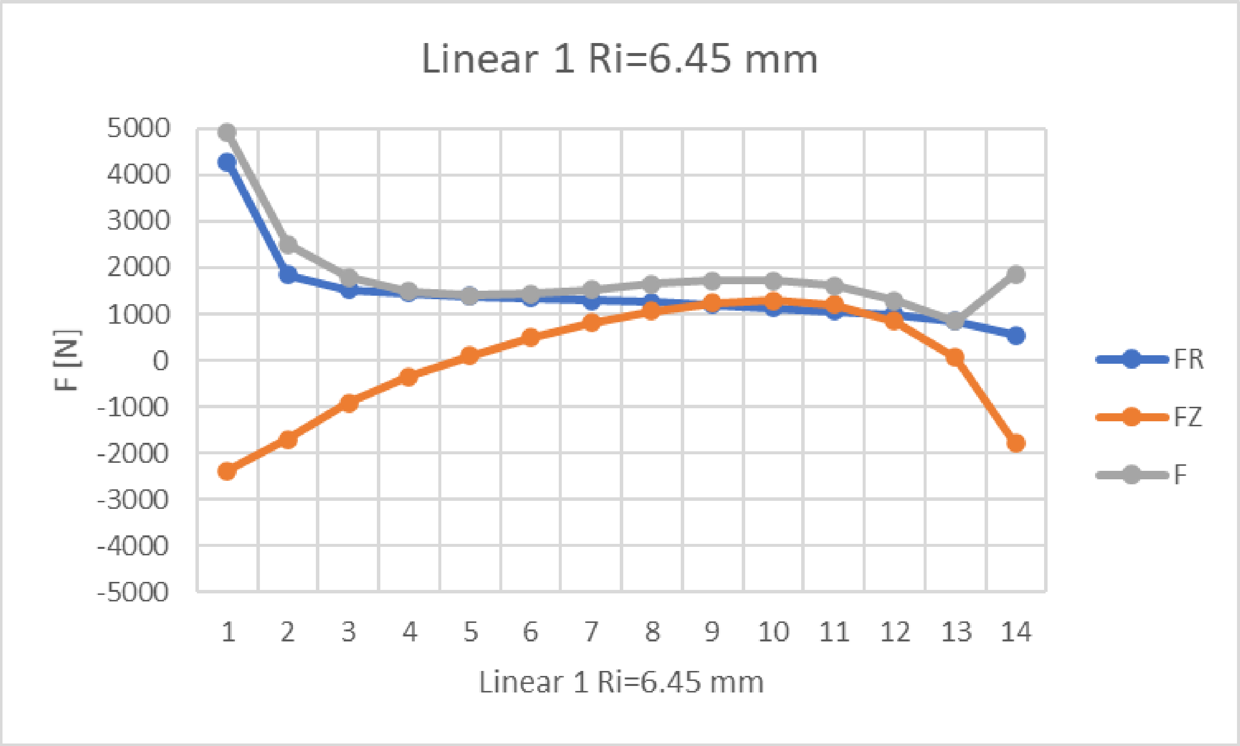


Third run of optimisation

The Lorentz force are now available as output data.

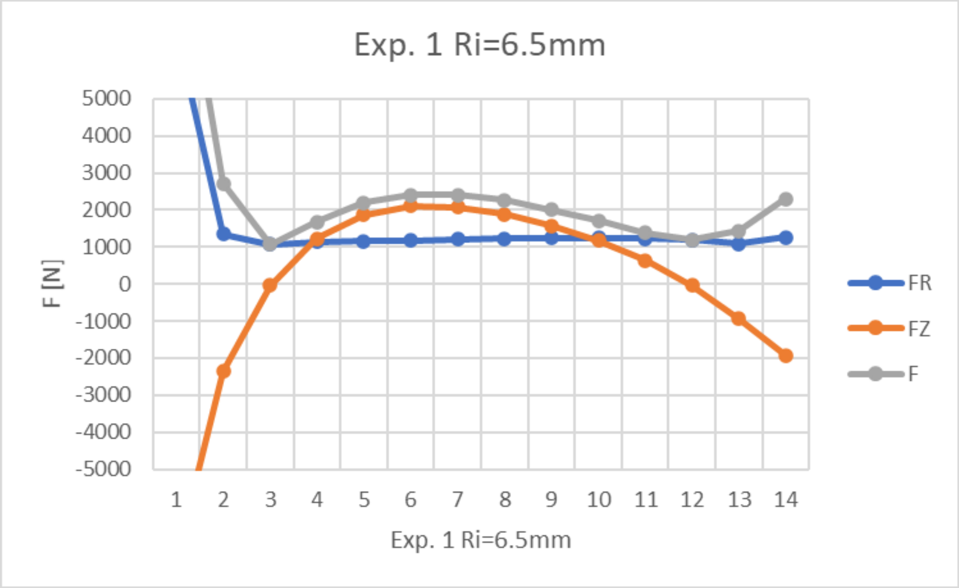
The forces are not only directed along the radius in the outward direction.

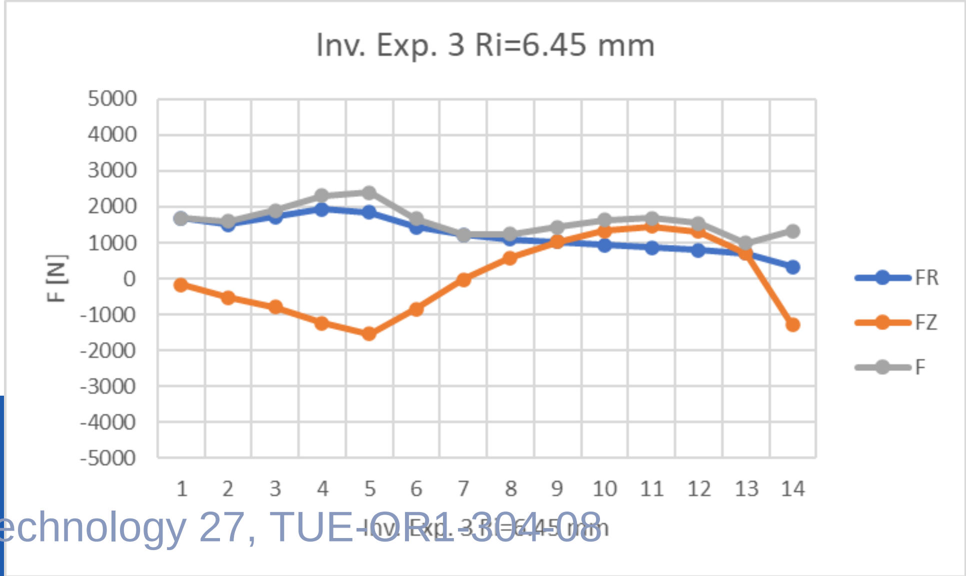
A significant compressive force applies to the FC along the solenoid axis.



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

It changes a lot with the geometry.

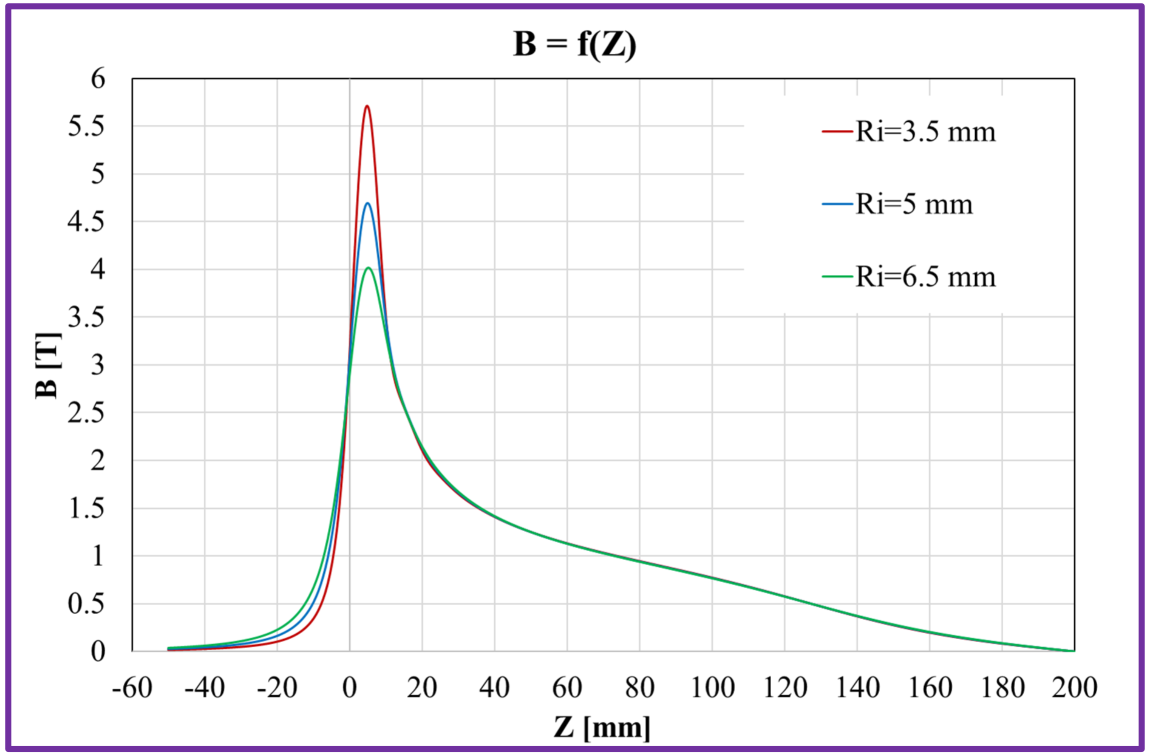


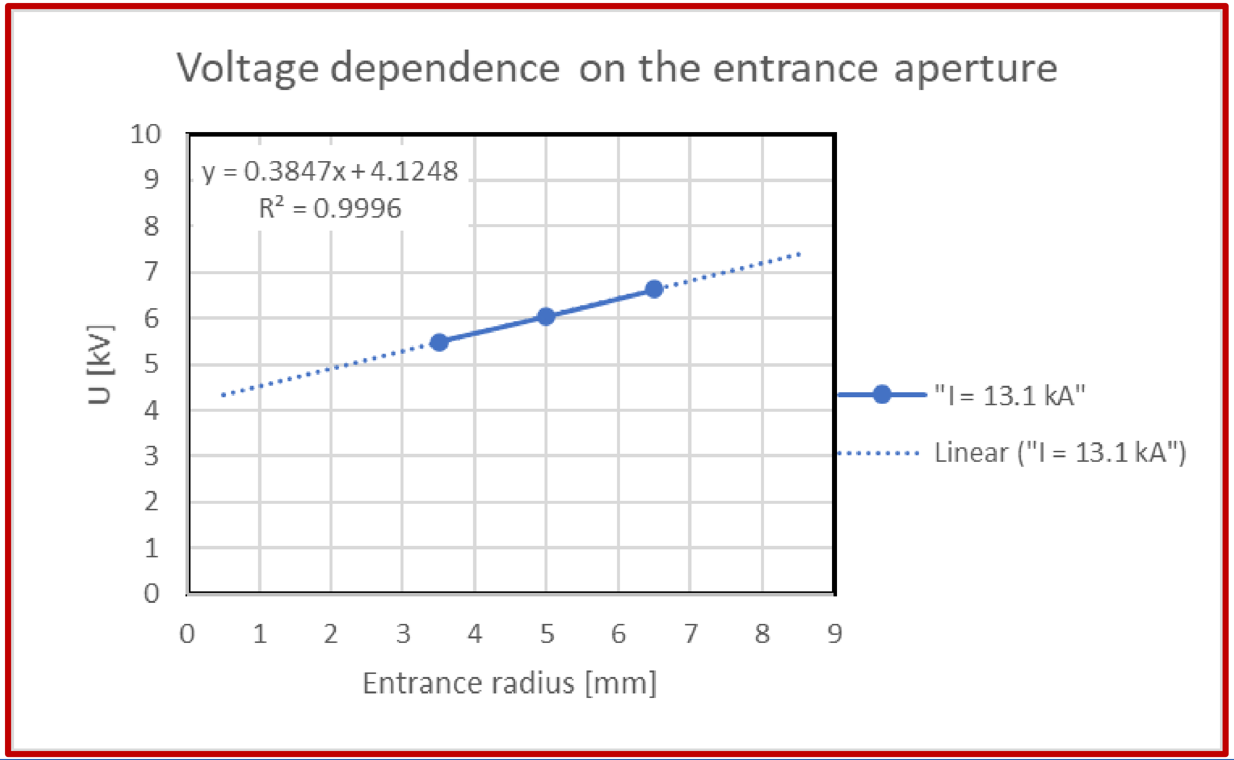


Design optimization for the CLIC e+ source

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

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