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Design of Nb_3Sn Wiggler Magnets for the Compact Linear Collider and Manufacturing of a Five-Coil Prototype

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Outline

1. **Introduction**
    1.1. The need for Nb_3Sn wigglers in CLIC Damping Rings
    1.2. Main considerations for the Nb_3Sn wiggler design
2. **Nb_3Sn wiggler design**
    2.1. Optimization of the main wiggler parameters
    2.2. 2D magnetic calculations
    2.3. 3D magnetic calculations
3. **Manufacturing process of the five-coil prototype**
    3.1. Winding test with copper wire
    3.2. Coil test with low grade Nb_3Sn wire
    3.3. Production of a five-coil prototype

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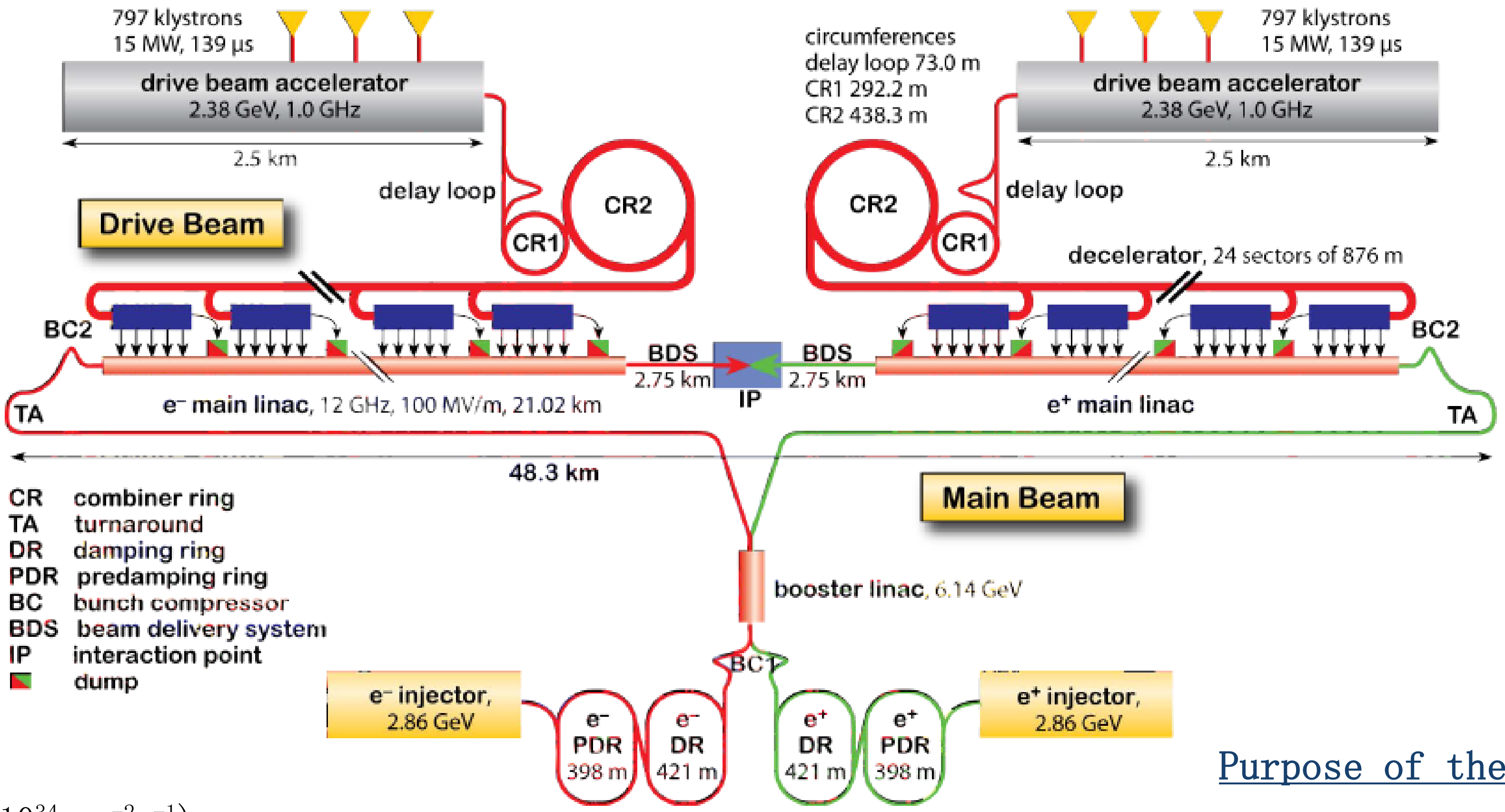
Introduction

The Compact Linear Collider (CLIC) layout



- e+/e− collider
- High luminosity (10^{34} $cm^{-2}s^{-1}$)
- High energy (3 TeV centre of mass energy)
- Two – beam acceleration scheme

Damping Rings (DRs)

Purpose of the DRs

To cool the incoming e+/e− beams to ultralow emittances in all three planes

Picture: CLIC Conceptual Design Report, 2012

Introduction

Normalized emittance targets:

Horizontal	500 nm
Vertical	5 nm
Longitudinal	6 keV·m

Wiggler baseline design for CLIC DRs:

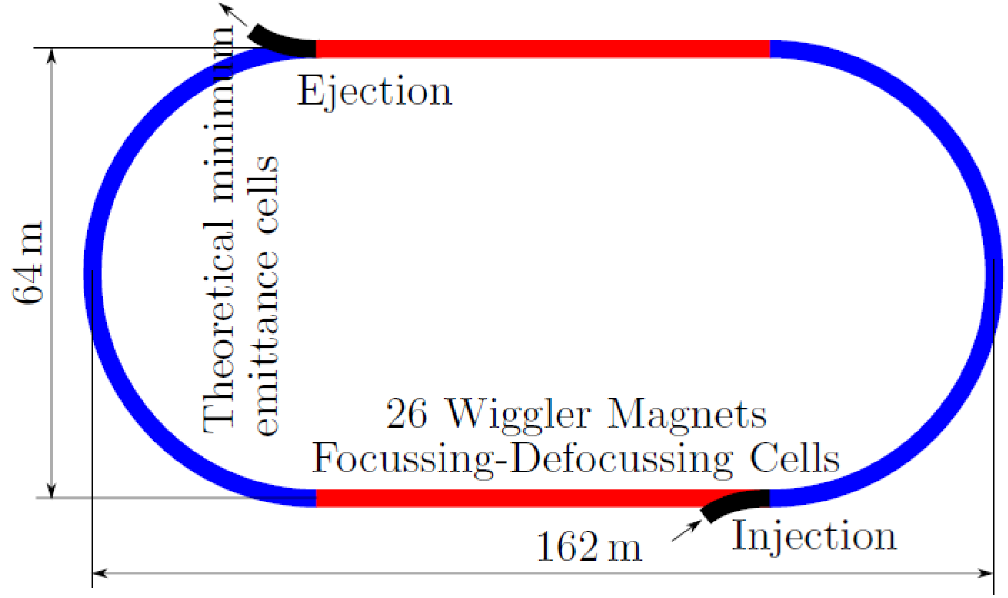
- 26 2-m-long wigglers in each straight section of the DRs
- Nb-Ti superconducting material
- λ_w = 51 mm and B_w = 3 T

A wiggler like this was designed, built and tested at BINP in collaboration with KIT and CERN

- Working point: 85% of magnet's current limit

λ_w: Wiggler period length
B_w: Magnetic flux density amplitude in the centre of the wiggler gap

DR sketch



So why using Nb_3Sn?

- From CLIC point of view: Possibility of decreasing the DR size
- From magnet point of view: Possibility of increasing the working margin

Picture: CLIC Conceptual Design Report, 2012

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Introduction

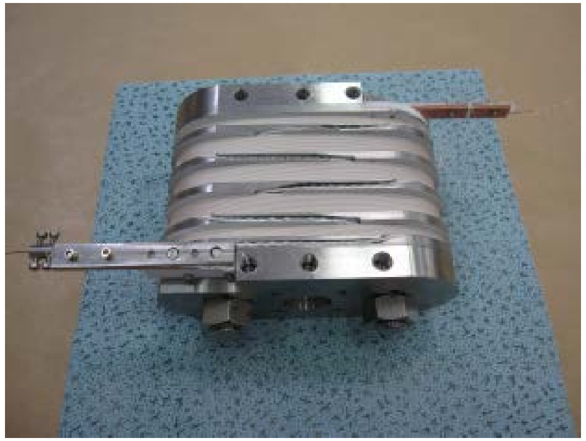
Five-coil prototype tested at CERN in 2012 *(D. Schoerling)*

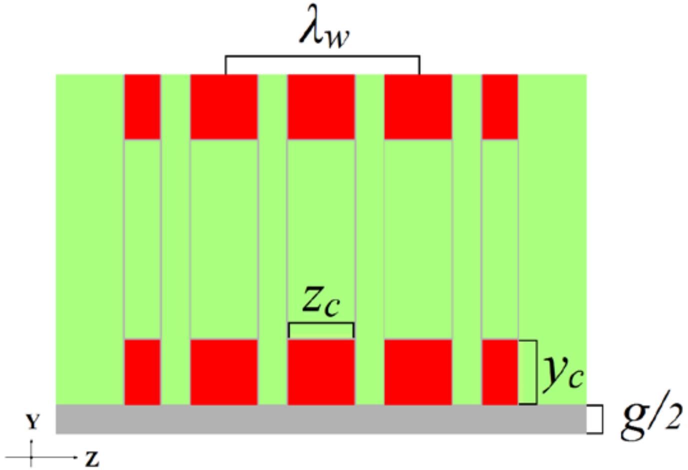
- λ_W = 41.8 mm and B_W = 3 T

Test interrupted after reaching 75% of the magnet's current limit

Poor insulation between coils and poles caused shorts to ground

Vertical racetracks to avoid electrical interconnections





Cross section of the prototype

Next Nb_3Sn five-coil prototype goals:

- Improve the pole-to-coil insulation
- Study different design options that enable:
  - ✓ Decreasing the DRs size
  - ✓ Increasing the magnet's working margin

  … while fulfilling the emittance requirements

OST RRP 132/169 Nb_3Sn wire specifications:

Diameter [mm]	0.85
Sub-element size [μm]	< 50
J_c SC [A/mm^2] at B = 12 T and T = 4.3 K	2450
J_c SC [A/mm^2] at B = 15 T and T = 4.3 K	1280
SC fraction (%)	45.45
Wire insulation (S2-glass braid) thickness (μm)	70

λ_W: Period length; g: Magnetic gap
y_c *and* z_c: vertical and horizontal coil dimensions
B_W: Magnetic flux density amplitude in the centre of the wiggler gap

J_c: Critical current density

Photo: D. Schoerling, PhD. Dissertation, 2012

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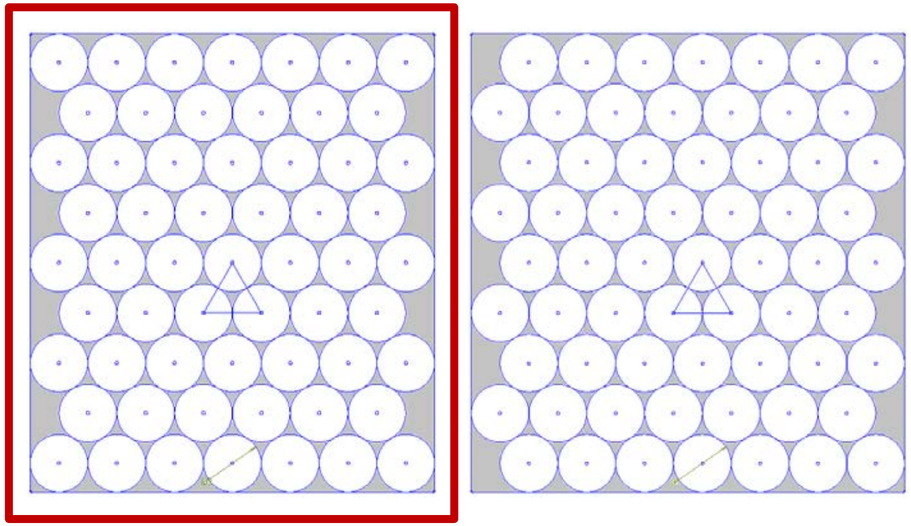
Nb_3Sn wiggler design

Selection of the winding configuration with the largest packing factor:

(packing factor: ratio between the area occupied by wires and the area of the coil's cross section)

Cross section of the coil winding



centred-layers configuration

displaced-layers configuration

Selected configuration

Comparing the packing factor of both configurations for the same *n* and *m*:

$$f_c > f_d \quad \text{if} \quad n < 2m$$

which means

$$y_c < z_c\sqrt{3}$$

f_c and f_d: packing factor of the centred and displaced-layers configurations

n and *m*: number of wire layers and number of wire turns in the first (lowest) layer

y_c and z_c: vertical and horizontal coil dimensions

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Nb_3Sn wiggler design

Selection of the ratio between coil width and period length (z_c/λ_w):

B components in the gap of the wiggler:

$$B_x = 0$$

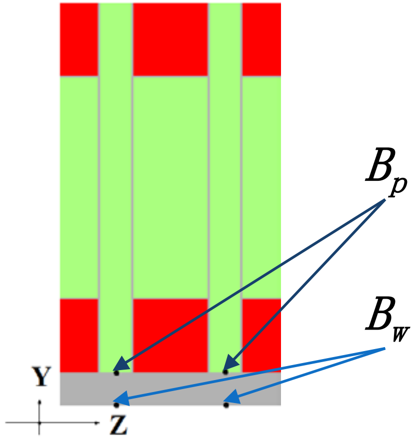
n = 1, 3, 5…

$$B_y = \sum_{n=1}^{\infty} B_n \sin\left(n \tfrac{2\pi}{\lambda_w} z\right)\cosh\left(n \tfrac{2\pi}{\lambda_w} y\right)$$

$$B_z = \sum_{n=1}^{\infty} B_n \cos\left(n \tfrac{2\pi}{\lambda_w} z\right)\sinh\left(n \tfrac{2\pi}{\lambda_w} y\right)$$

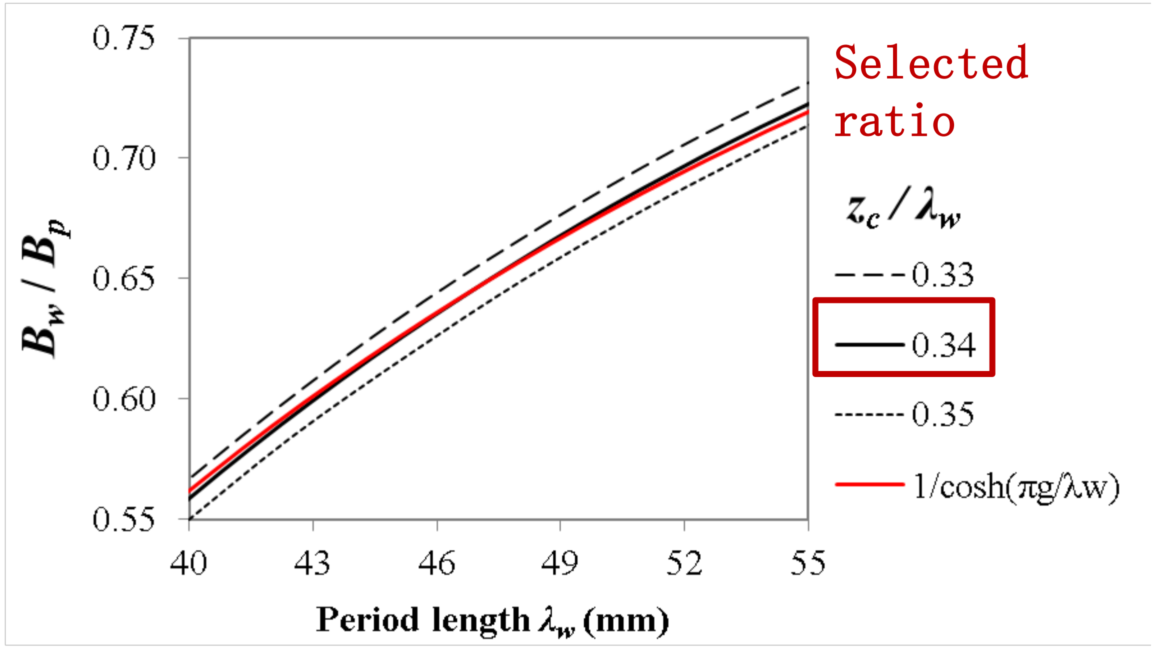
From B_y expression:

$$\frac{B_{w,n}}{B_{p,n}} = \frac{1}{\cosh\left(n \frac{\pi}{\lambda_w} g\right)}$$



One period of the wiggler

Numerical calculations with OPERA 2D for different z_c/λ_w values



Taking z_c/λ_w = 0.34, n = 1 is a good approximation for B_y in the centre of the gap

$$B_y = B_w \sin\left(\tfrac{2\pi}{\lambda_w} z\right)$$

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Nb_3Sn wiggler design

Selection of B_w and λ_w:

Output emittances of CLIC DRs are dominated by the Intra-Beam Scattering (IBS) effect

***x*-axis**: period length of the wiggler (λ_w)

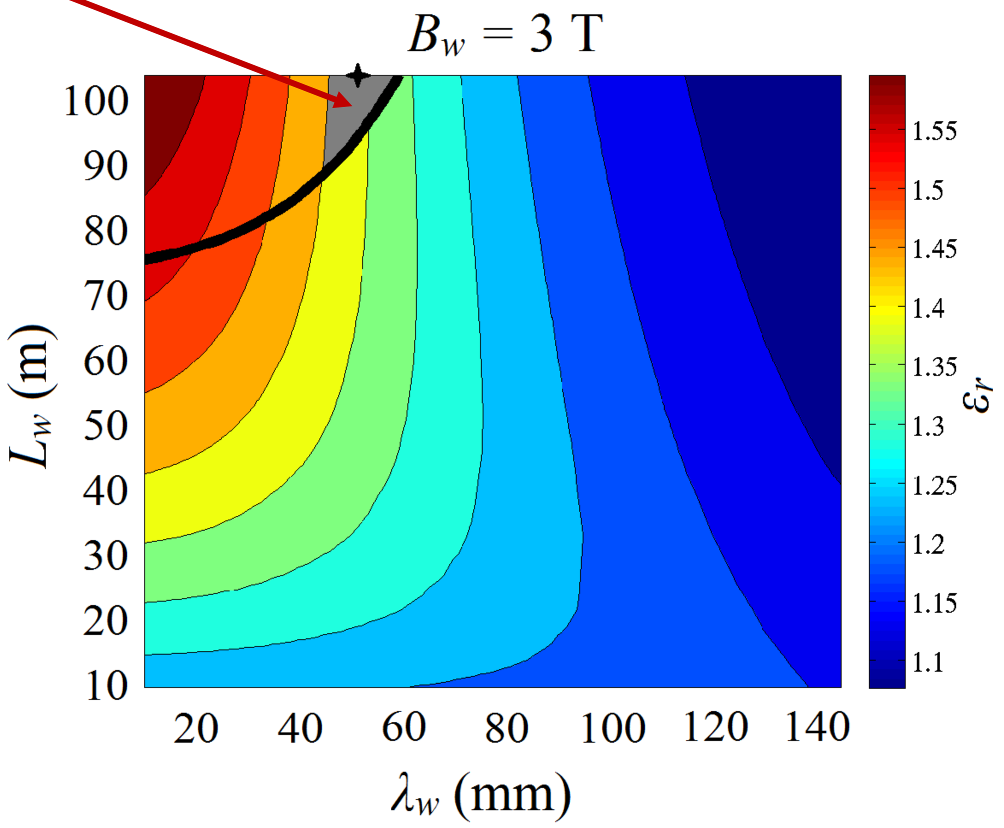
***y*-axis**: total length of the DR occupied by wigglers (L_w)

Black line: normalized horizontal emittance limit (500 nm)

Coloured bands: IBS impact (ε_r) (keep ≤ 1.4)

Parametrization of the DR at certain B_w:

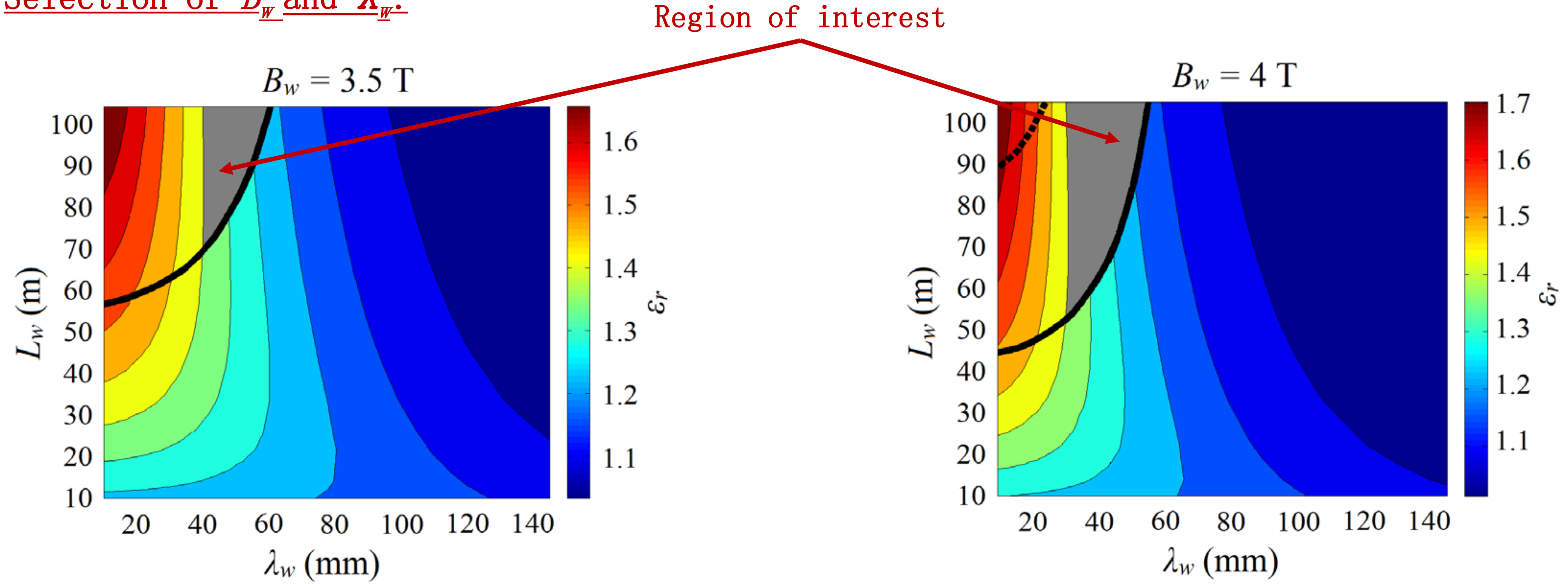
Region of interest



Black mark on top represents the baseline design

Nb_3Sn wiggler design

Selection of B_w and λ_w:



Increasing B_w would provide several λ_w choice options

Choosing certain period length within the range **40 mm ≤ λ_w ≤ 55 mm** it's possible to work within the range **3.5 T ≤ B_w ≤ 4 T** with a fixed wiggler geometry *(keeping the IBS impact lower than 1.4)*

Nb_3Sn wiggler design

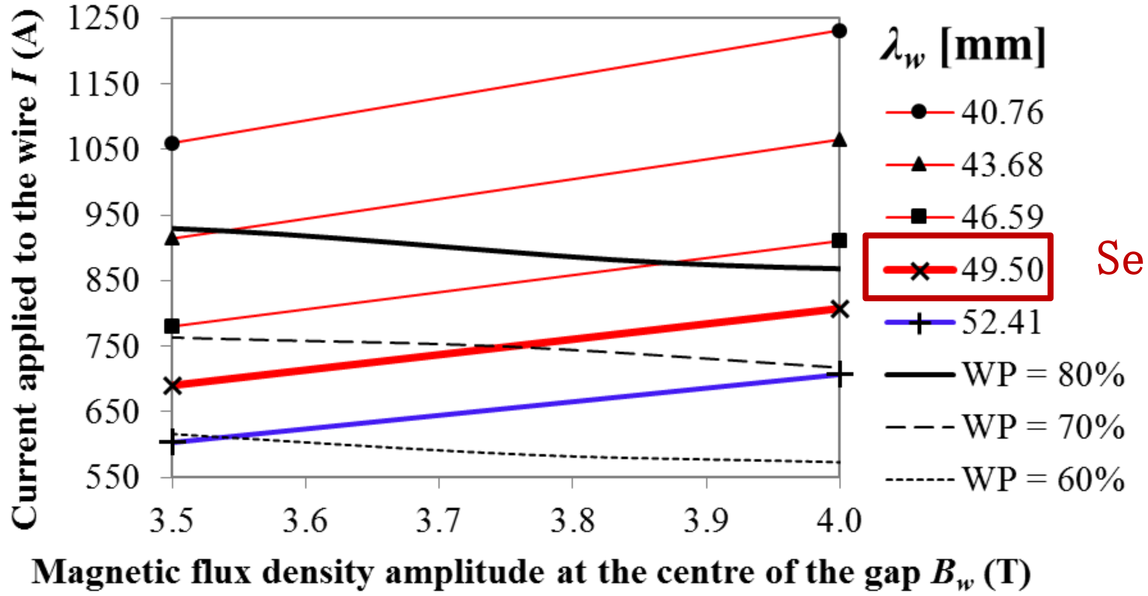
Optimization of the main wiggler parameters

Selection of B_w and λ_w:

Additional restriction:

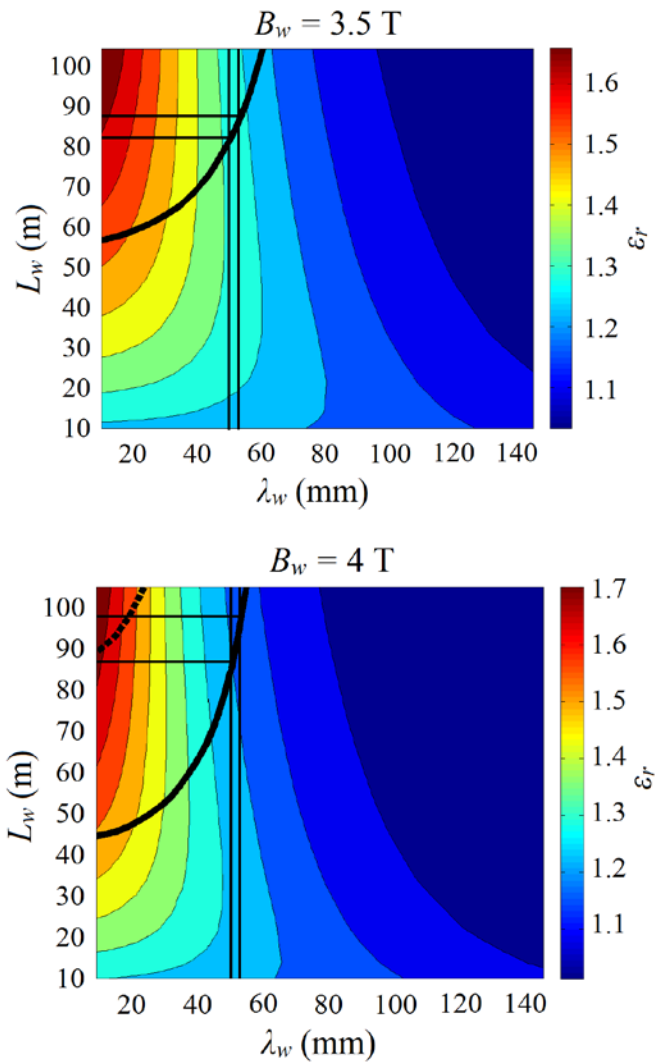
Keeping the working point (*WP*) below 80% of the magnet's current limit for all $3.5\ \mathrm{T} \leq B_w \leq 4\ \mathrm{T}$

Scenarios for achieving $3.5\ \mathrm{T} \leq B_w \leq 4\ \mathrm{T}$ with $40\ \mathrm{mm} \leq \lambda_w \leq 55\ \mathrm{mm}$ values:



Selected λ_w

Larger potential L_w reduction with λ_w = 49.5 mm



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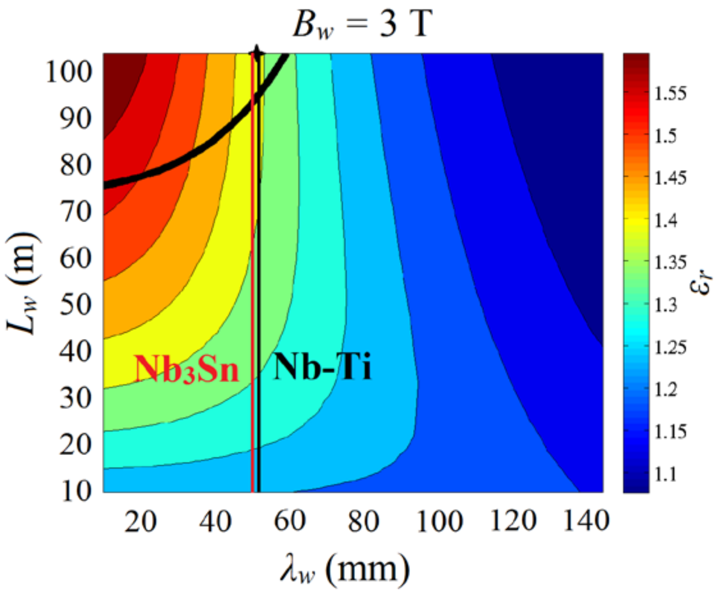
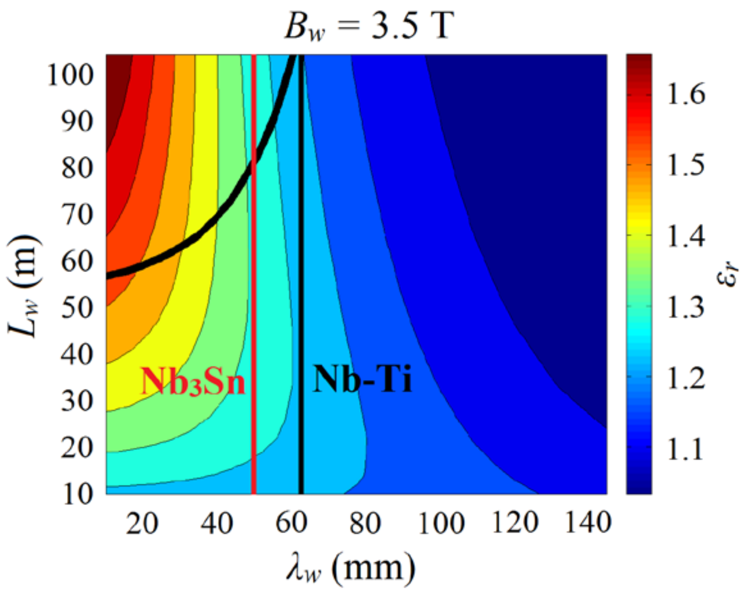
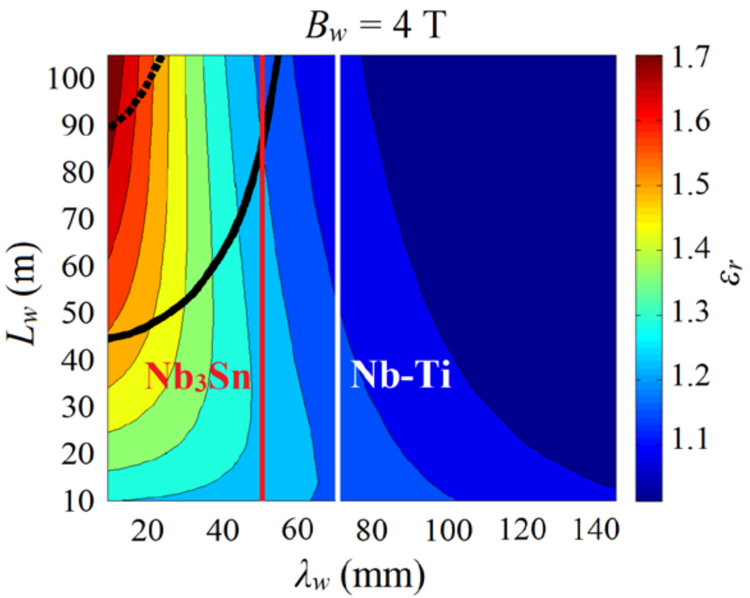
Nb_3Sn wiggler design

Comparison between Nb_3Sn and Nb-Ti scenarios:







B_w = 3 T

Nb_3Sn:
λ_w = 49.5 mm; *WP* = 54%

Nb-Ti:
λ_w = 51 mm; *WP* = 85%

Baseline

B_w = 3.5 T

Nb_3Sn:
λ_w = 49.5 mm; *WP* = 65%

Nb-Ti:
λ_w = 63 mm; *WP* = 80%

B_w = 4 T

Nb_3Sn:
λ_w = 49.5 mm; *WP* = 76%

Nb-Ti:
λ_w = 71 mm; *WP* = 80%

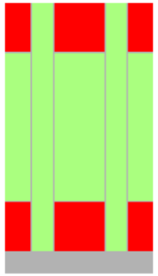
Nb_3Sn wiggler design

2D magnetic calculations

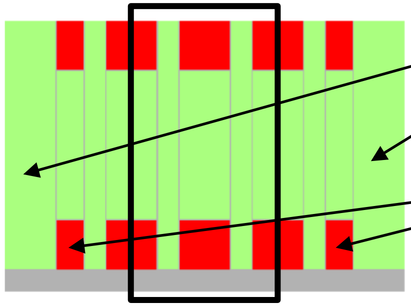
Optimization of the end structures' width to reach the highest B_w value in the main period region:

Opera 2D models

One-period model



Five-coil model



After optimization

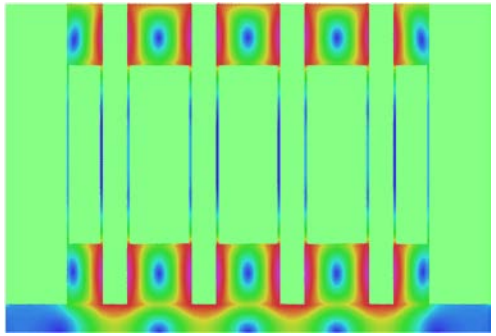
End poles width: 17 mm

End coils width: 8.91 mm

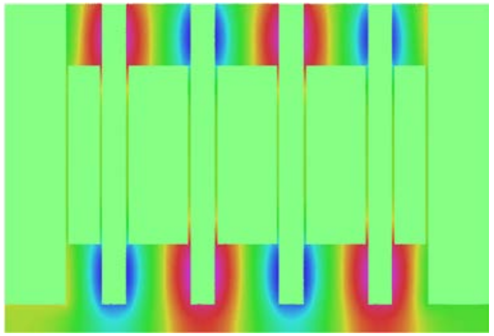
Main period region

Contours from OPERA 2D:

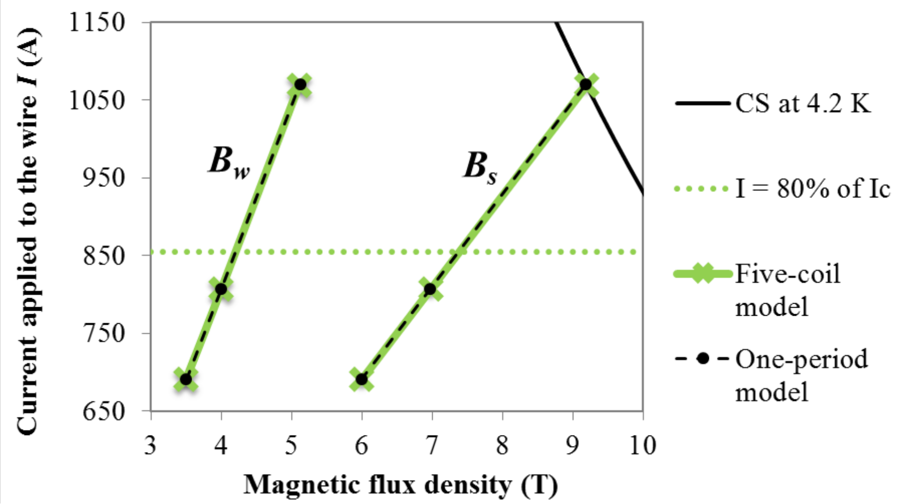
B

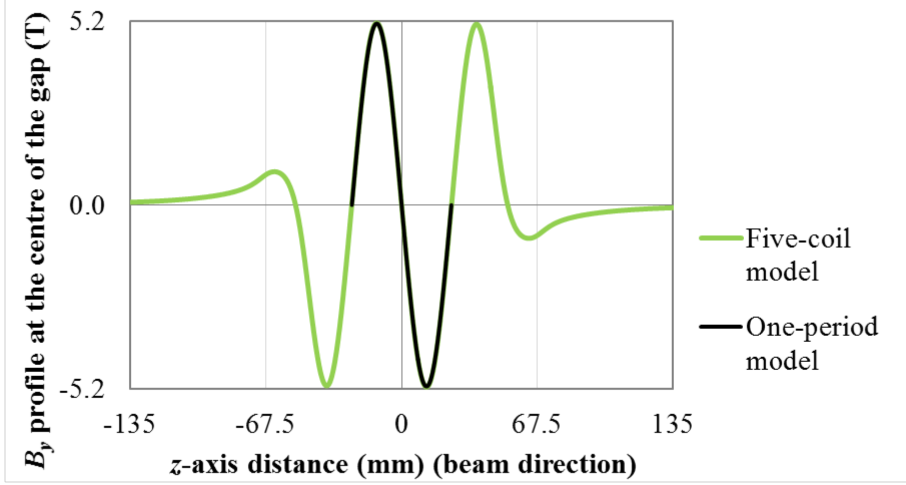


B_y



Load-line (B_s: peak magnetic flux density at the coils surface)





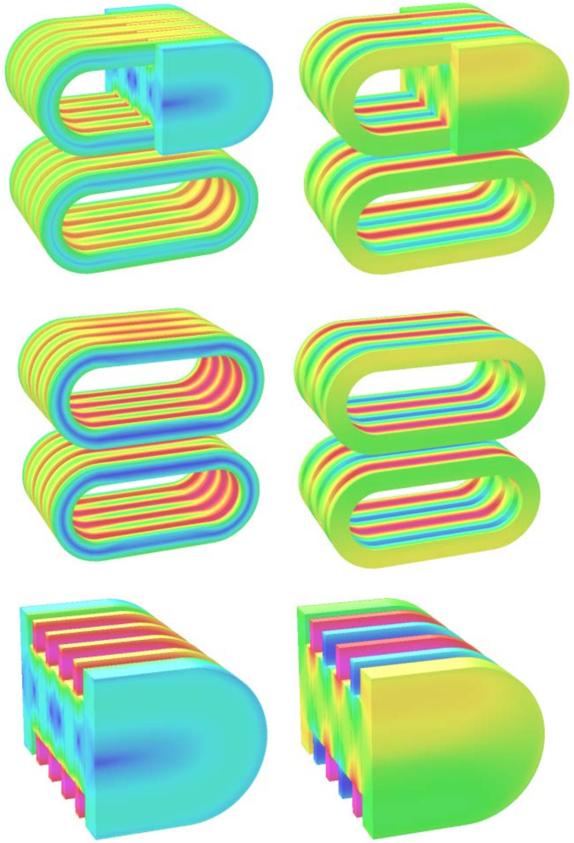
Nb_3Sn wiggler design

3D magnetic calculations

Good field region:

OPERA 3D model:

B $\quad$ B_y



B_y is not constant in the horizontal direction (x-axis)

Criterion of good field quality in the wiggler baseline design:

The homogeneity of B_y should remain **within 0.5%**

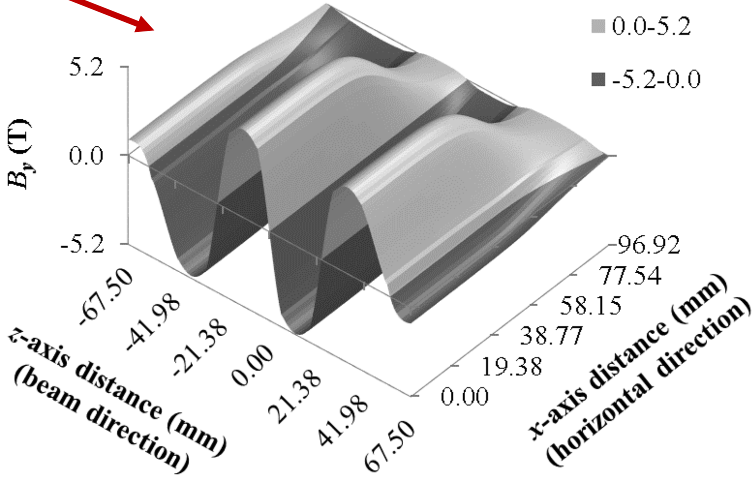
- at x = **±10 mm** from the central axis
- at any z-position

The homogeneity of B_y in the five-coil prototype remains **within 0.5%**

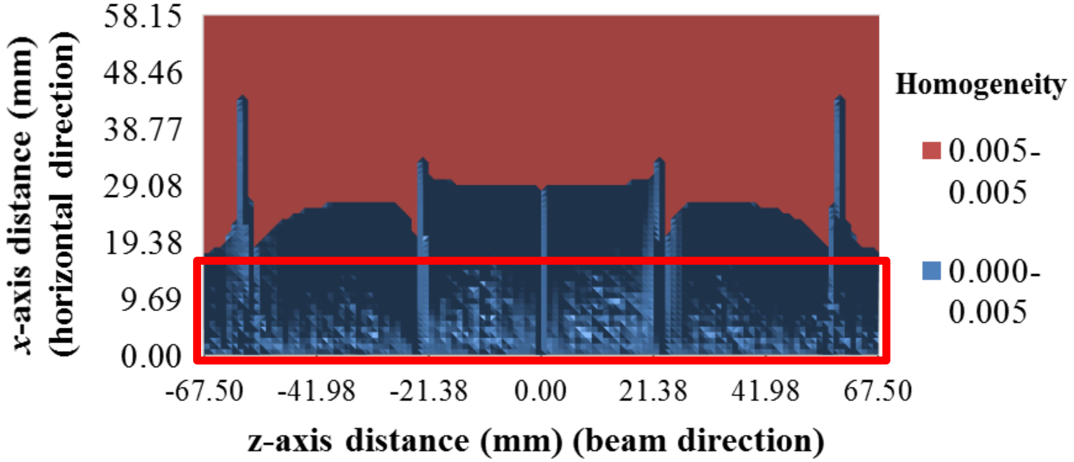
- at x = **±15 mm** from the central axis
- at any z-position

B_y homogeneity: relative error of B_y in the horizontal plane respect to B_y at $x = 0$

Field map: Vertical component of the magnetic flux density B_y at the centre of the gap



Field homogeneity map: $|(B_y(0) - B_y(x))/B_y(0)|$



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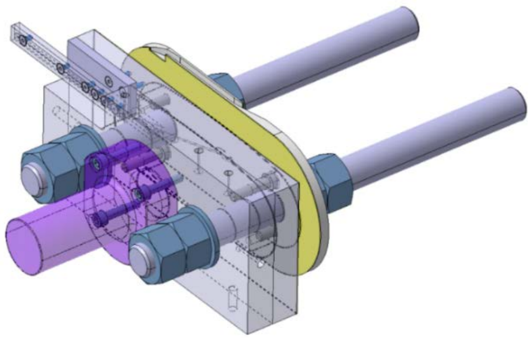
Manufacturing process

Fiberglass squeezes during winding

Goal of the test:

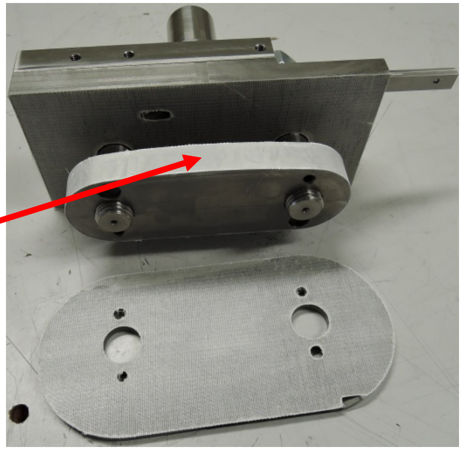
Define the real coil thickness to consequently produce the winding poles

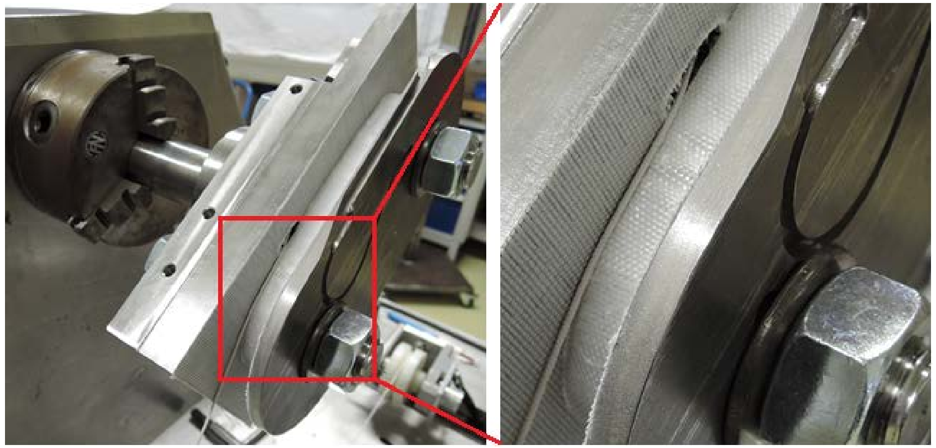
Assembly for the winding test with copper wire

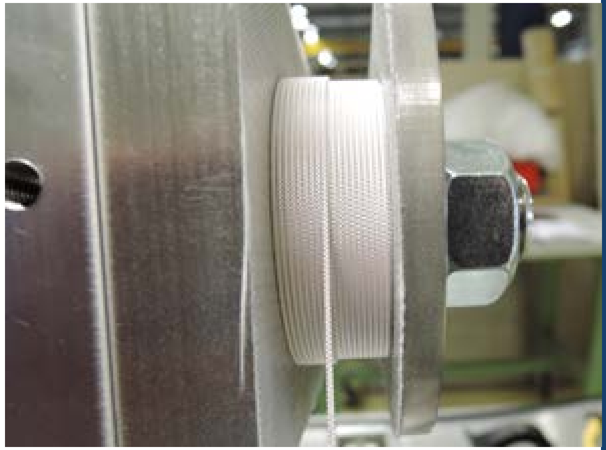


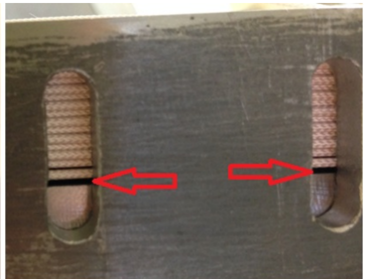
- Poles insulates with 150 µm of fiberglass cured with ceramic binder
- Copper wire with the same diameter and insulation of the Nb_3Sn wire

The upper part of the winding pole is slightly curved to ease the winding









Gaps were observed in the straight part of the winding pole due to spring-back of the wire

Drawing by Javier Parrilla Leal, CERN

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Manufacturing process

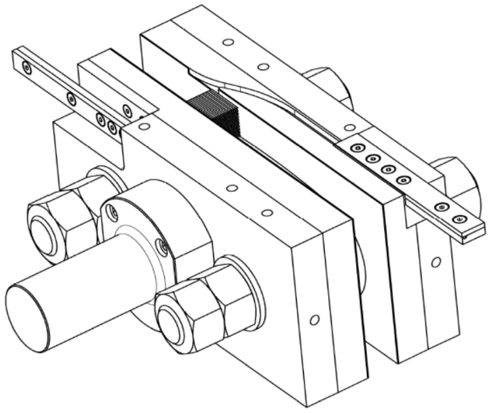
During heat treatment, the diameter of the OST-RRP Nb_3Sn wire increases ~ 2%

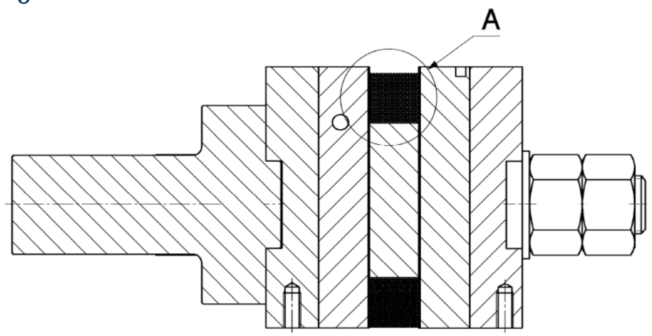
Goals of the test:

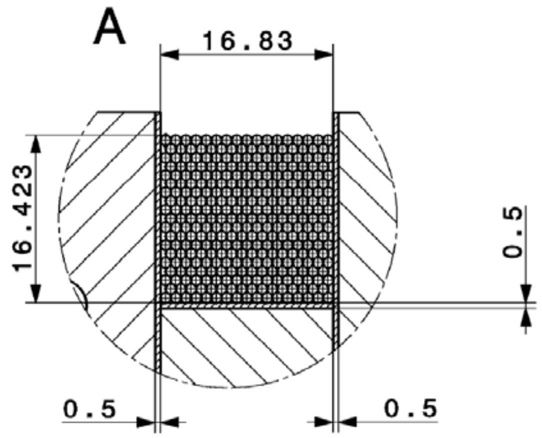
- Correctly establish the vertical dimension of the side plates
- Do electrical tests to check the insulation effectiveness

- Coil will undergo heat treatment (HT) and vacuum impregnation
- Electrical tests will be carried out
- Coil will be cut transversally to check the position of the wires and the dimensions change after HT
- Coil will be cut longitudinally to check the existence of gaps due to expansion and contraction of the winding pole during and after HT

Assembly for the coil test with low grade Nb_3Sn wire







Drawings by Thomas Sahner, CERN

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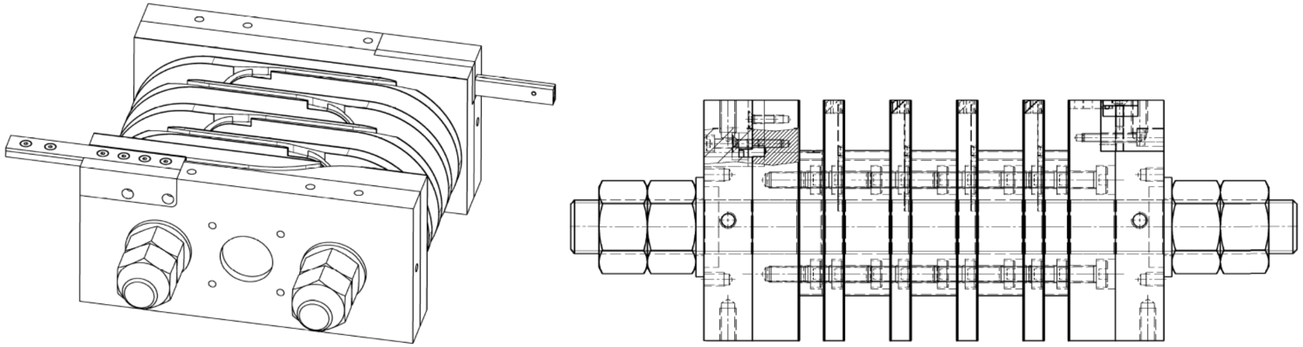
Manufacturing process

Activities:

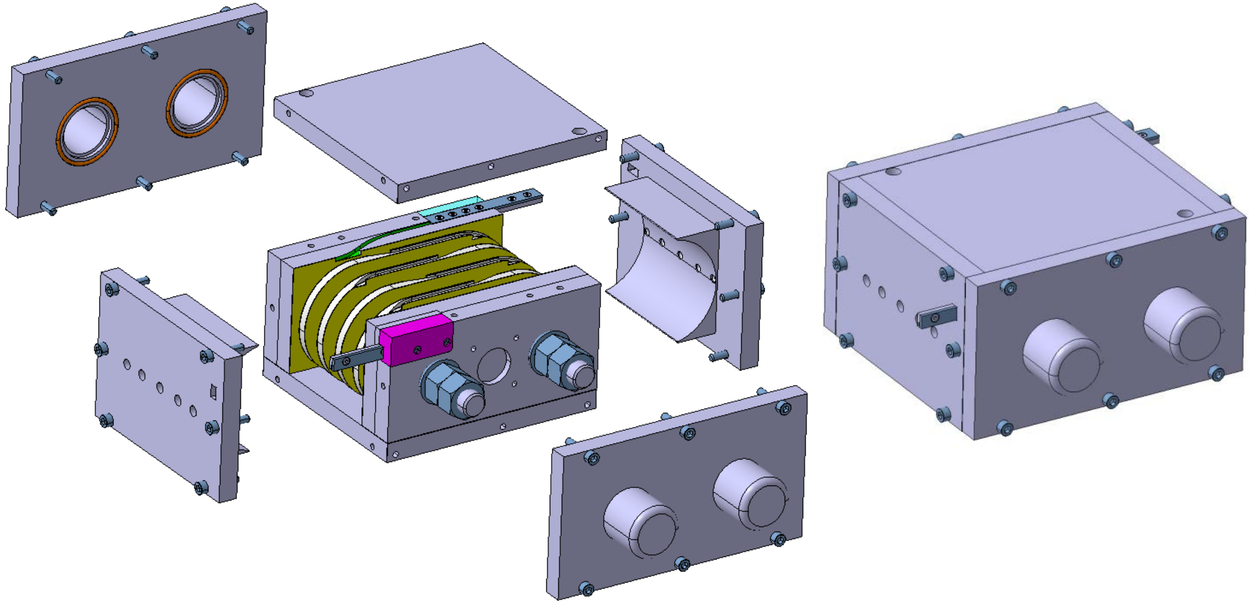
- The five-coil prototype will be wound with the Nb_3Sn wire and will undergo HT
- After HT, the coils will be impregnated with radiation-resistant epoxy with low viscosity
- The mould will be made of aluminium and treated with a releasing agent for removing the parts after the impregnation process
- The magnet will be trained in liquid helium at 4.2 K
- A mirror configuration will be used and Hall probes will be glued on the magnetic mirror for field measurement

These activities are foreseen to be completed by February 2016

Assembly for the five-coil prototype



Parts of the aluminium impregnation mould



Drawings by Thomas Sahner and Rafael Martin-Caro Cristobal, CERN

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Conclusions

- The main design parameters of a superconducting wiggler magnet that will be wound with OST RRP Nb_3Sn strand 0.85 mm diameter insulated with S2-glass braid, have been established

- For 15 mm magnetic gap and 49.5 mm period length, several scenarios that meet CLIC DR emittance and IBS impact constraints while keeping the working point below the 80% of the magnet's current limit, are possible by changing the peak magnetic flux density at the centre of the gap from 3.5 T to 4 T

- With such design, in principle it would be possible to decrease the size of CLIC DRs by 20% respect to the baseline design. It is also possible to keep the baseline design and work at 54% of the magnet's current limit

- The five-coil prototype is foreseen to be built and tested by February 2016

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Thank you