Status of the manufacturing process of a Nb_3Sn wiggler prototype

Laura García Fajardo. CERN – TE / MSC / MDT

Other authors: F. Antoniou, A. Bernhard, P. Ferracin, J. Mazet, S. Papadopoulou, Y. Papaphilippou, J. C. Pérez, D. Schoerling

CLIC WORKSHOP 2016

CERN, JANUARY 21ST 2016

Outline

1. **Introduction**
    1.1. The need for Nb_3Sn wigglers in CLIC Damping Rings

2. **Nb_3Sn wiggler design overview**
    2.1. General design of Nb_3Sn wigglers for CLIC Damping Rings
    2.2. Design of the five-coil prototype

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

Outline

1. **Introduction**
   1.1. The need for Nb_3Sn wigglers in CLIC Damping Rings
2. **Nb_3Sn wiggler design overview**
   2.1. General design of Nb_3Sn wigglers for CLIC Damping Rings
   2.2. Design of the five-coil prototype
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

Introduction

THE NEED FOR Nb_3Sn WIGGLERS IN CLIC DR

NORMALIZED EMITTANCE TARGETS FOR CLIC DRS:

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
- $\lambda_w = 51$ 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

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

NEXT Nb_3Sn FIVE-COIL PROTOTYPE GOALS:

- Improve the pole-to-coil insulation respect to the five-coil prototype fabricated and tested at CERN in 2012 (***D. Schoerling***)
- Study different design options that enable:
  - ✓ Decreasing the DRs size
  - ✓ Increasing the magnet's working margin

  … while fulfilling the IBS and emittance requirements

λ_w: Wiggler period length
B_w: Magnetic flux density amplitude in the centre of the wiggler gap
IBS: Intra-Beam Scattering

Outline

1. Introduction
    1.1. The need for Nb_3Sn wigglers in CLIC Damping Rings
2. **Nb_3Sn wiggler design overview**
    2.1. **General design of Nb_3Sn wigglers for CLIC Damping Rings**
    2.2. Design of the five-coil prototype
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

Nb_3Sn wiggler design overview

CERN

Some considerations for the design:

- ✓ Vertical racetrack configuration (continuous winding to avoid electrical interconnections)
- ✓ OST RRP 132/169 Nb_3Sn wire, 0.85 mm diameter, insulated with S2-glass braid, 70 µm thick.

Optimization of the main wiggler parameters:

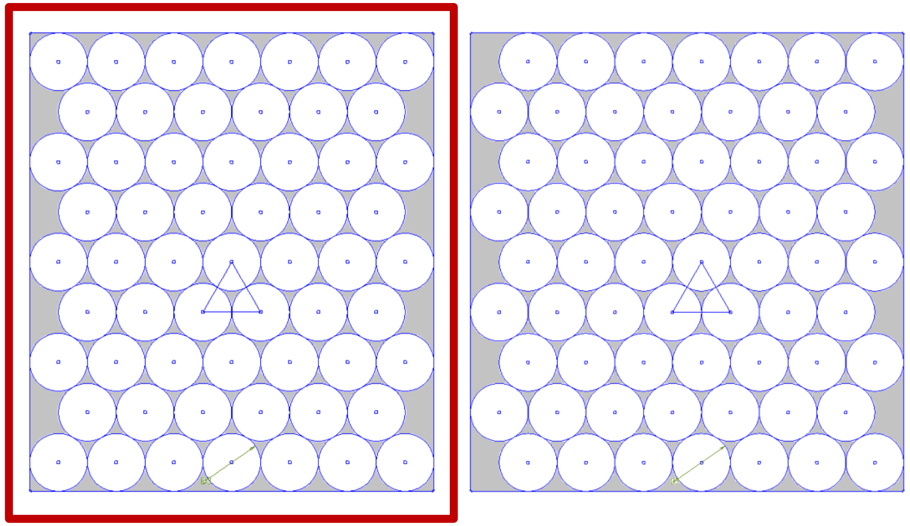
1. Selection of the winding configuration
2. Selection of the ratio between z_c and λ_w
3. Selection of B_w and λ_w

1. 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)*

Selected configuration

Cross section of the coil winding



centred-layers configuration

displaced-layers configuration

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

Nb_3Sn wiggler design overview

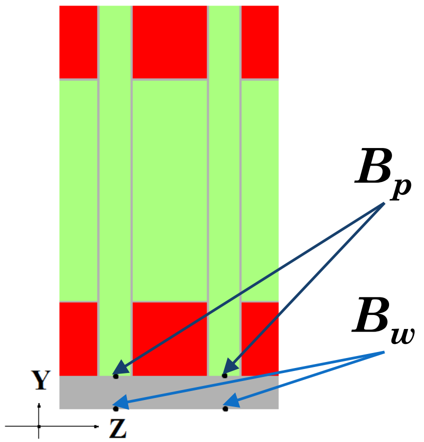
2. SELECTION OF THE RATIO z_c/λ_w THAT ENABLES PRODUCING BETTER FIELD QUALITY IN THE GAP:

FROM THE SOLUTION OF LAPLACE EQUATION IN THE GAP:

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

$n = 1, 3, 5\ldots$

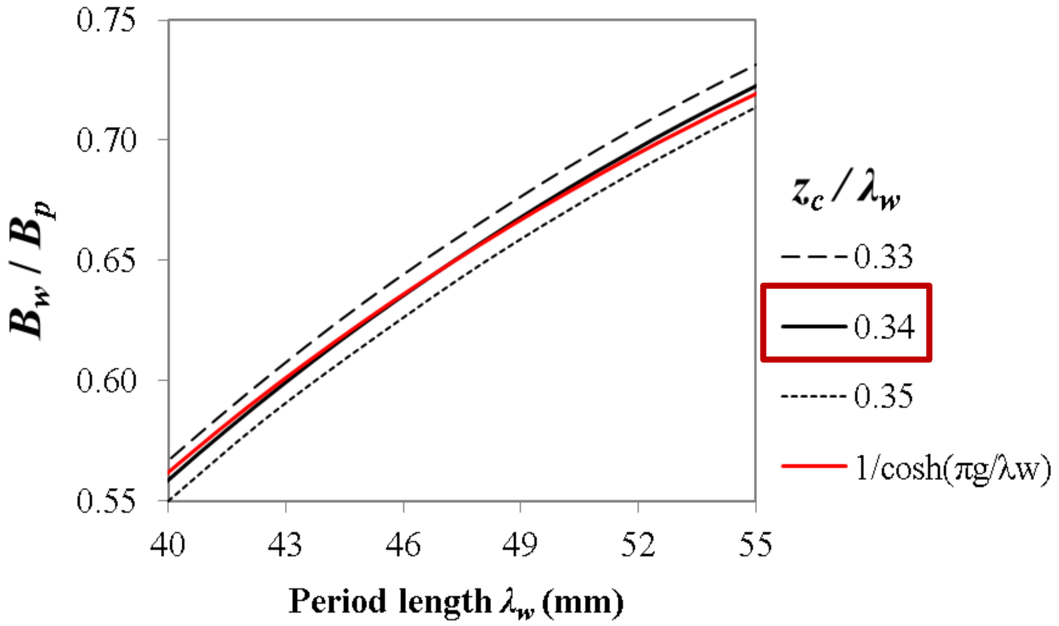
One period 2D model of the wiggler



FROM B_Y EXPRESSION:

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

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



SELECTED RATIO

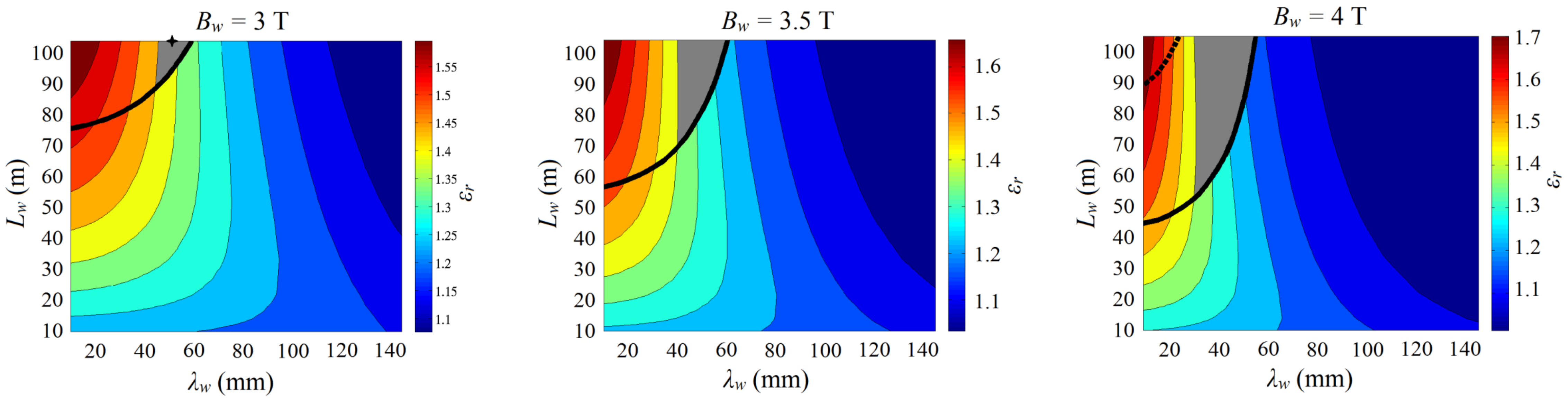
$$B_y = B_w \sin\left(\frac{2\pi}{\lambda_w} z\right)$$

is a good approximation for B_y in the centre of the gap

Nb_3Sn wiggler design overview

3. Selection of B_w and λ_w:

Parametrization of the DR at certain B_w



Black mark on top represents the baseline design

Increasing B_w would provide several λ_w choice options
Gray area: region of interest

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

Horizontal axis: period length of the wiggler (λ_w)
Vertical 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**)

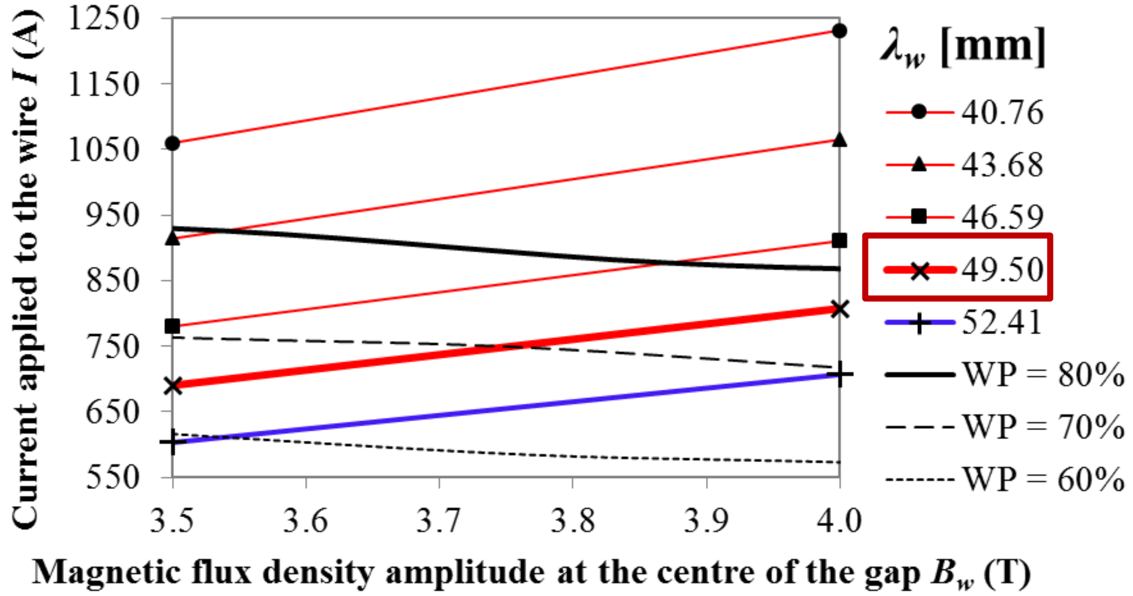
Nb_3Sn wiggler design overview

3. Selection of B_w and λ_w:

Additional restriction:

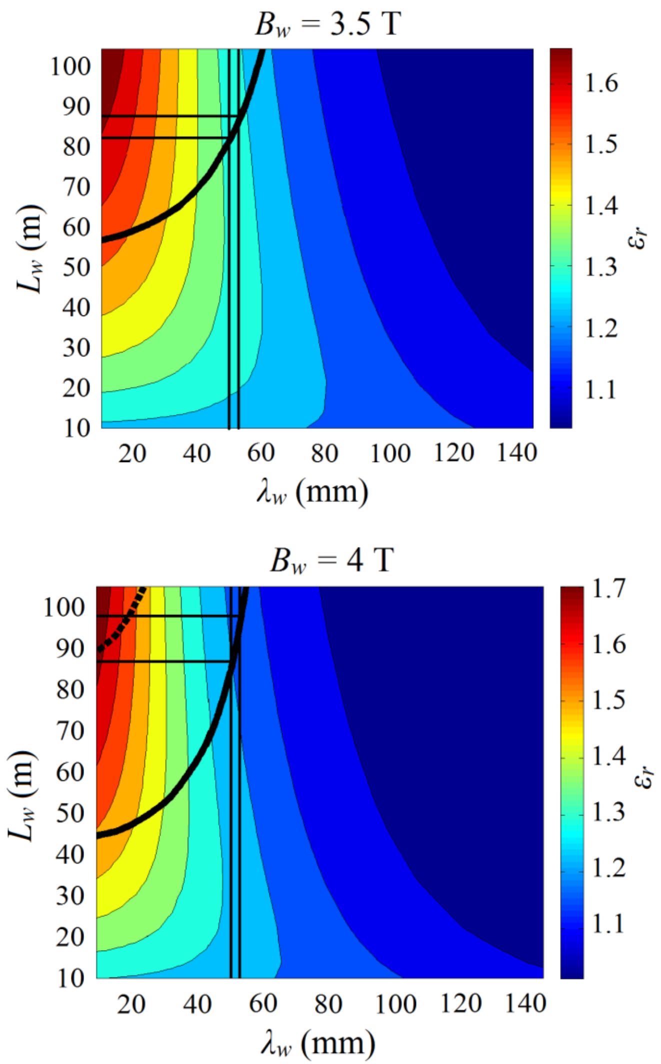
Keeping the working point (*WP*) below 80% of the magnet's current limit for all $3.5\ \text{T} \leq B_w \leq 4\ \text{T}$

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



Selected λ_w for $3.5\ \text{T} \leq B_w \leq 4\ \text{T}$

Larger potential L_w reduction with λ_w = 49.5 mm



Outline

Nb_3Sn wiggler design overview

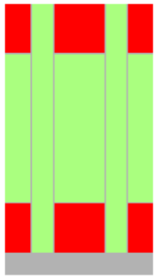
Design of the five-coil prototype

1. Optimization of the end structures to reach the highest B_w value in the main period region:

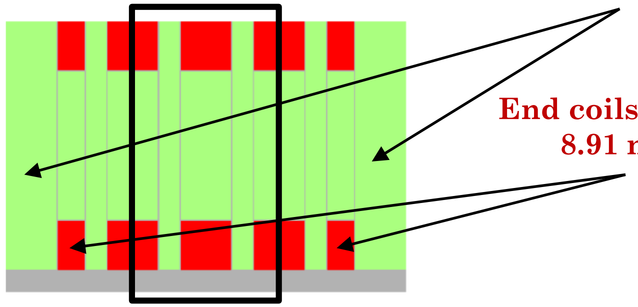
Opera 2D models

After optimization

One-period model



Five-coil model

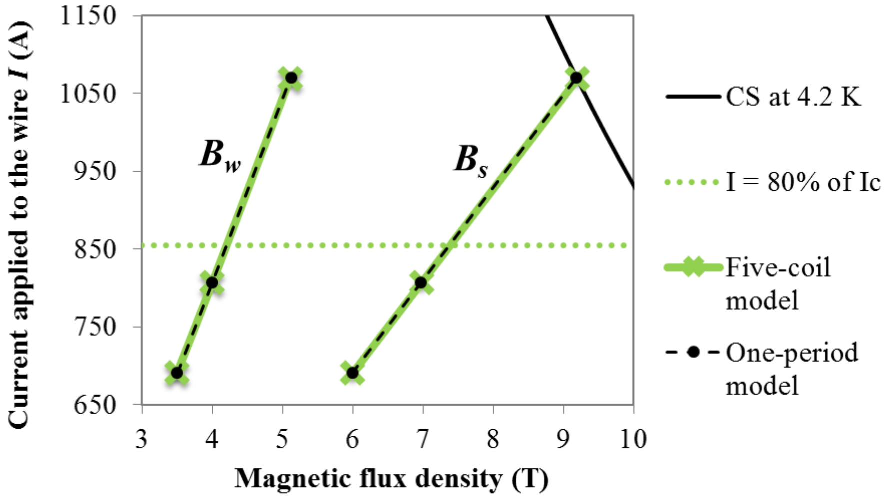


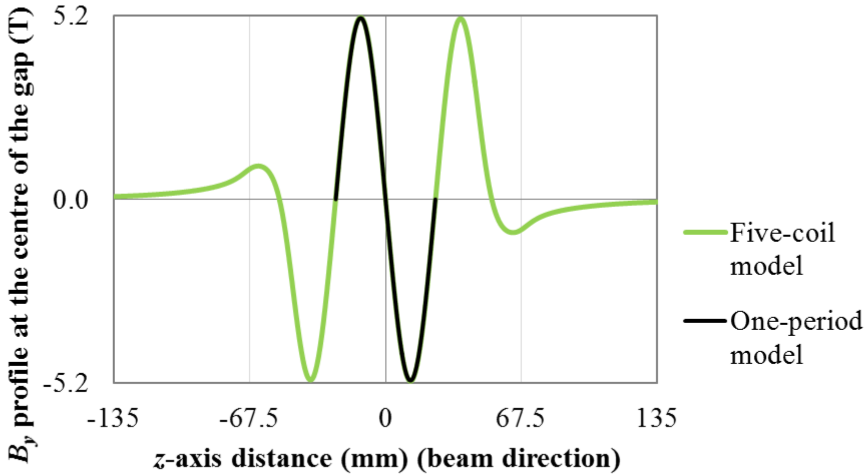
End poles width: 17 mm

End coils width: 8.91 mm

Main period region

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





Nb_3Sn wiggler design overview

DESIGN OF THE FIVE-COIL PROTOTYPE

2. CALCULATION OF THE FIELD HOMOGENEITY IN THE GAP:

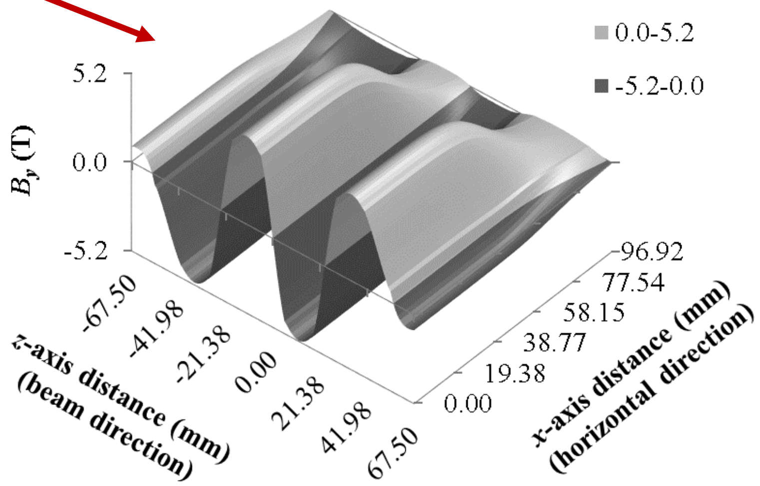
B_y is not constant in the horizontal direction (*x*-axis)

Criterion of good field quality in the wiggler baseline design:

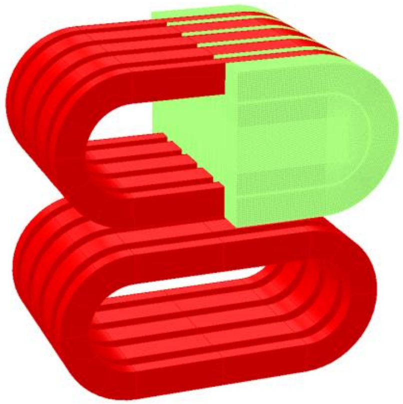
The homogeneity of B_y should remain **within 0.5%**

- at $x = \pm$**10 mm** from the central axis
- at any *z*-position

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



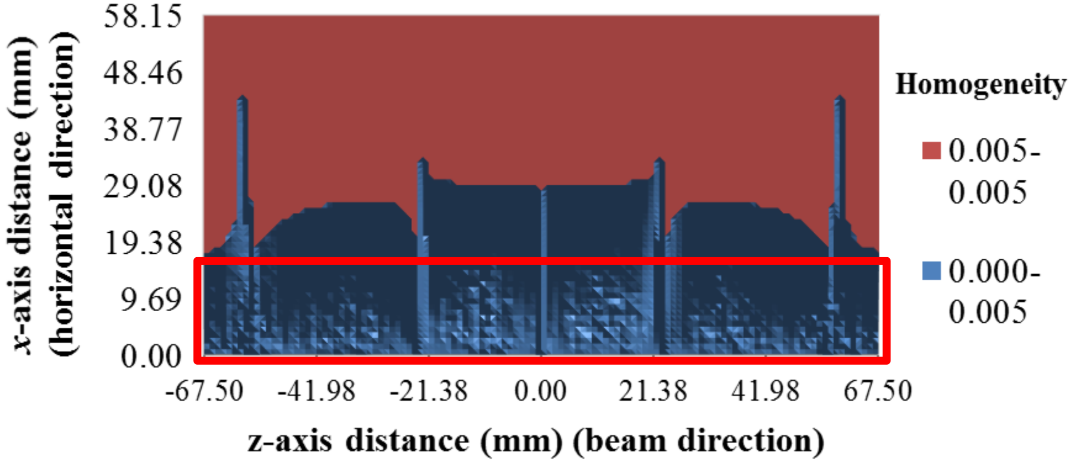
OPERA 3D model:



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

- at $x = \pm$**15 mm** from the central axis
- at any *z*-position

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



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

Outline

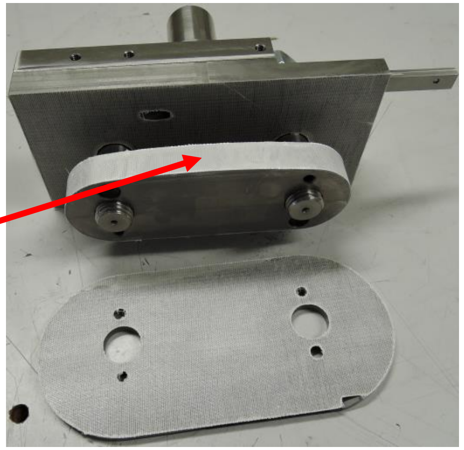
1. **Introduction**
   1.1. The need for Nb_3Sn wigglers in CLIC Damping Rings
2. **Nb_3Sn wiggler design overview**
   2.1. General design of Nb_3Sn wigglers for CLIC Damping Rings
   2.2. Design of the five-coil prototype
3. **Manufacturing process of the five-coil prototype**
   3.1. **Winding test with copper wire**
   3.2. Coil test with low grade Nb_3Sn wire
   3.3. Production of a five-coil prototype

Manufacturing process of the five-coil prototype

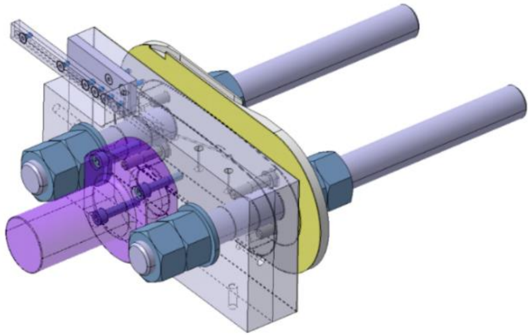
Winding test with copper wire

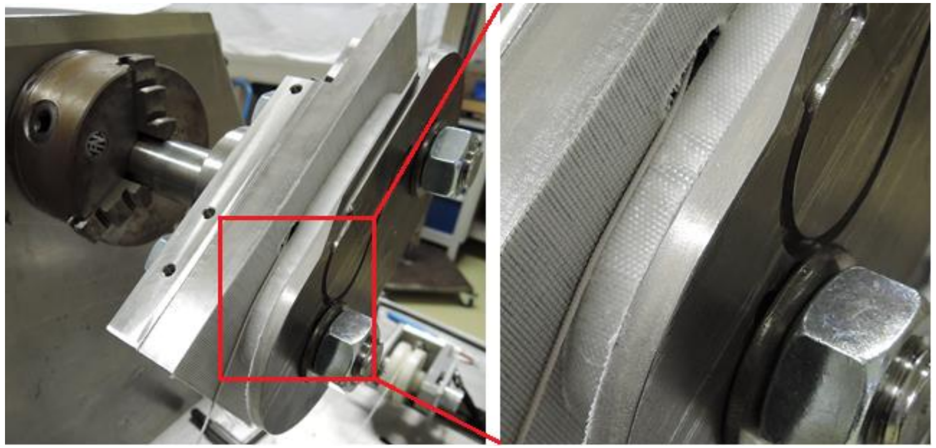
1. Define the real coil thickness to consequently produce the winding poles

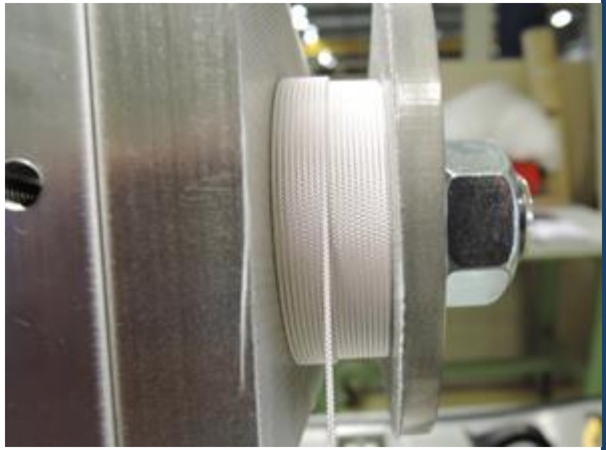
The upper part of the winding pole is slightly curved to ease the winding



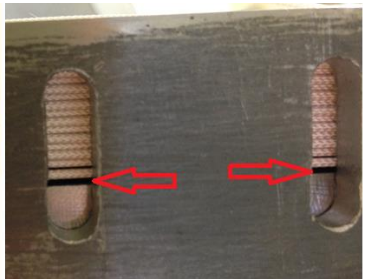
Assembly for the winding test with copper wire







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



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

Drawing by Javier Parrilla Leal, CERN

Outline

1. **Introduction**
   1.1. The need for Nb_3Sn wigglers in CLIC Damping Rings
2. **Nb_3Sn wiggler design overview**
   2.1. General design of Nb_3Sn wigglers for CLIC Damping Rings
   2.2. Design of the five-coil prototype
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

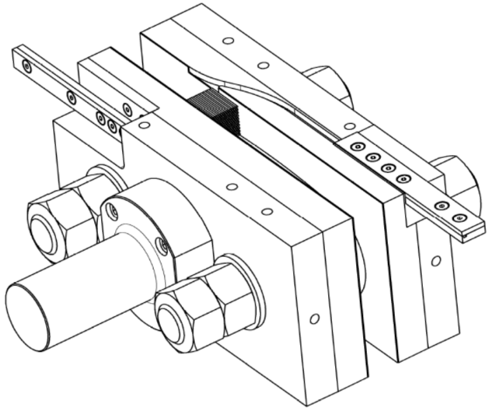
Manufacturing process of the five-coil prototype

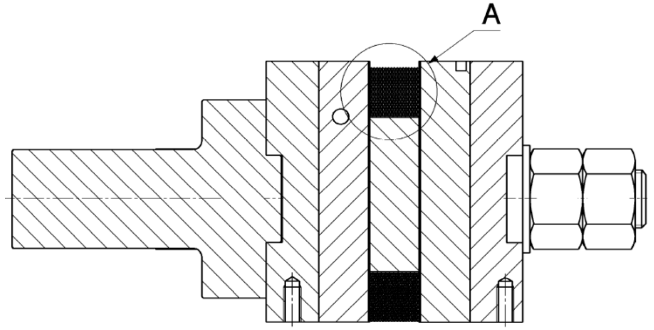
Coil test with low grade Nb_3Sn wire

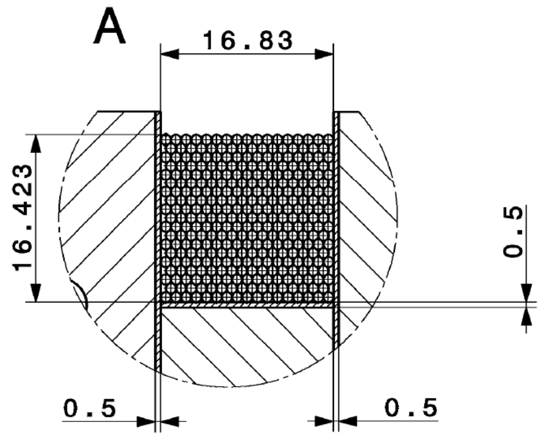
2. Perform electrical tests to check the insulation effectiveness and inspect the coil size increase after heat treatment

- Coil is currently under heat treatment (HT)
- Vacuum impregnation and 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



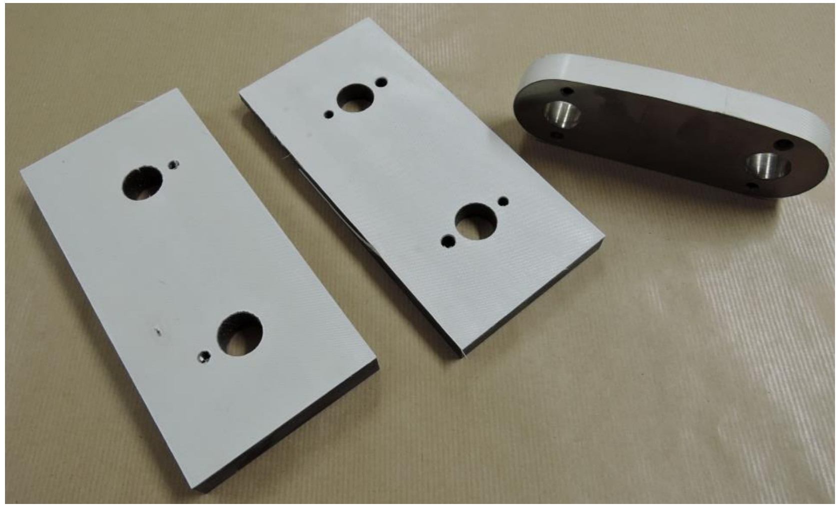


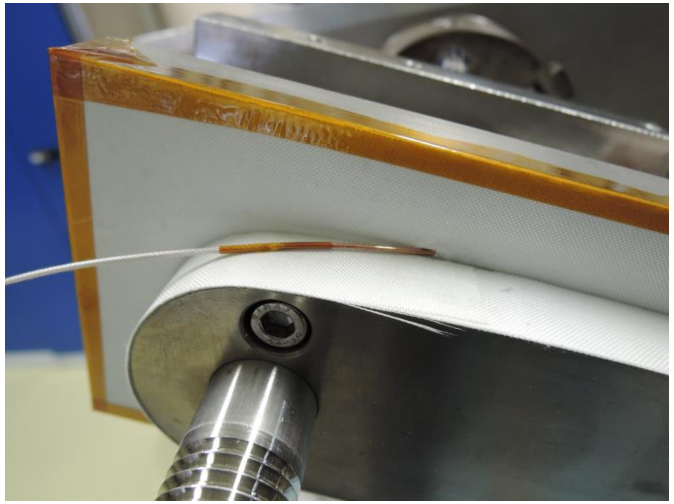


Drawings by Thomas Sahner, CERN

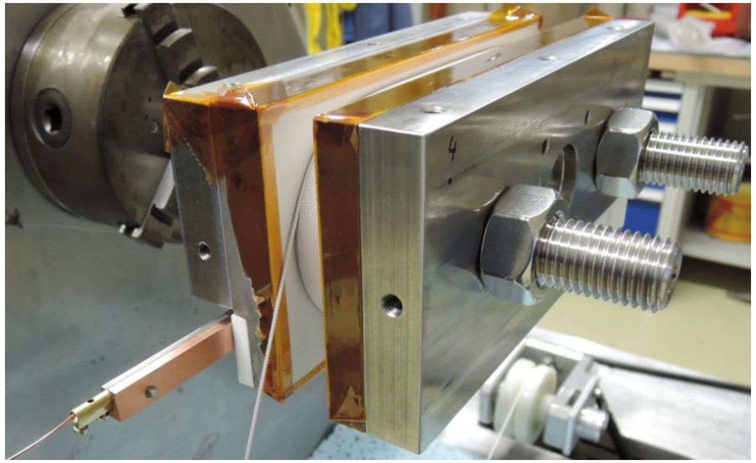
Manufacturing process of the five-coil prototype

Coil test with low grade Nb_3Sn wire

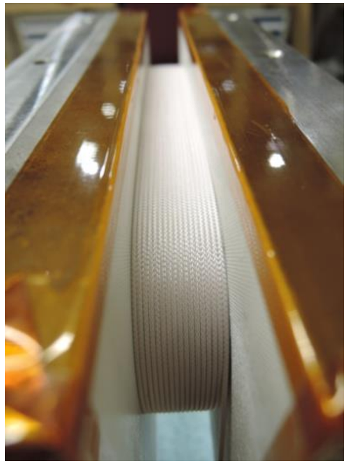




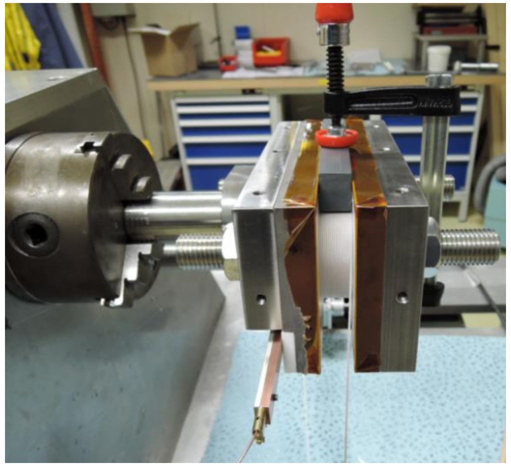
Winding process

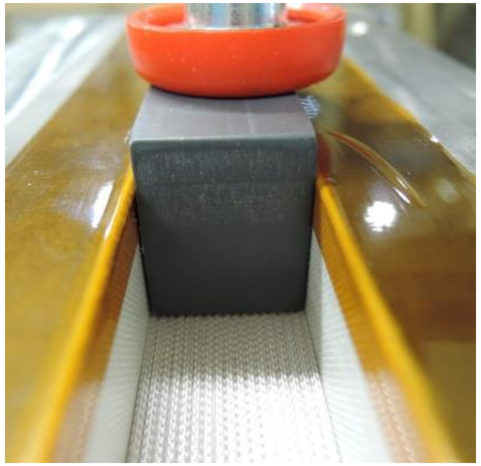


First layer wound



Clamping the wound layers to minimize the spring effect

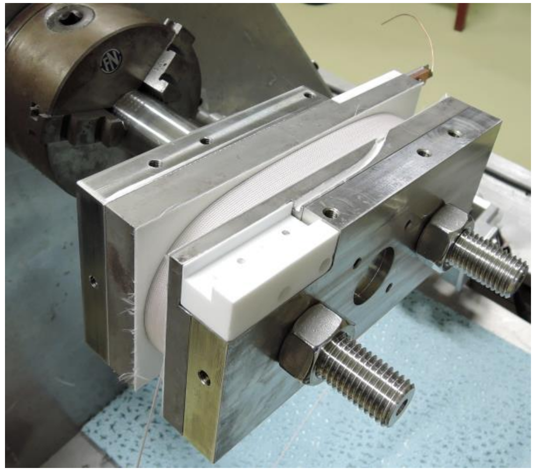


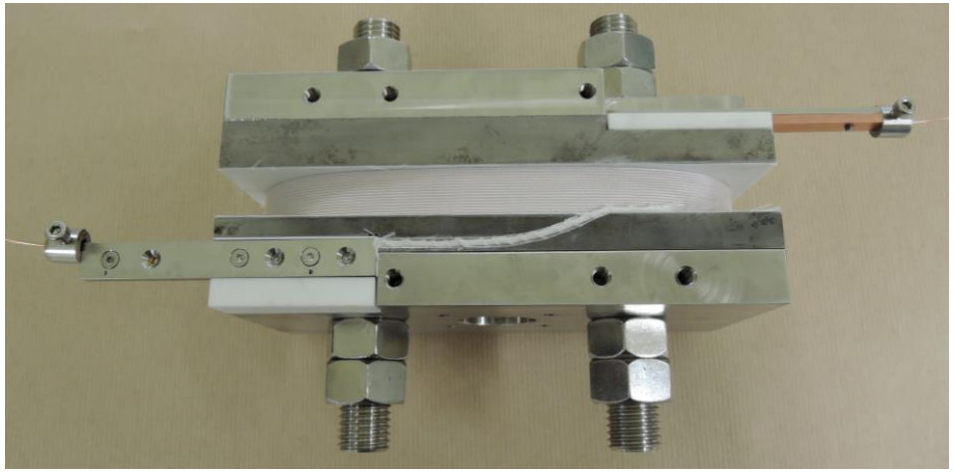


Coil winding performed by Jacky Mazet, CERN

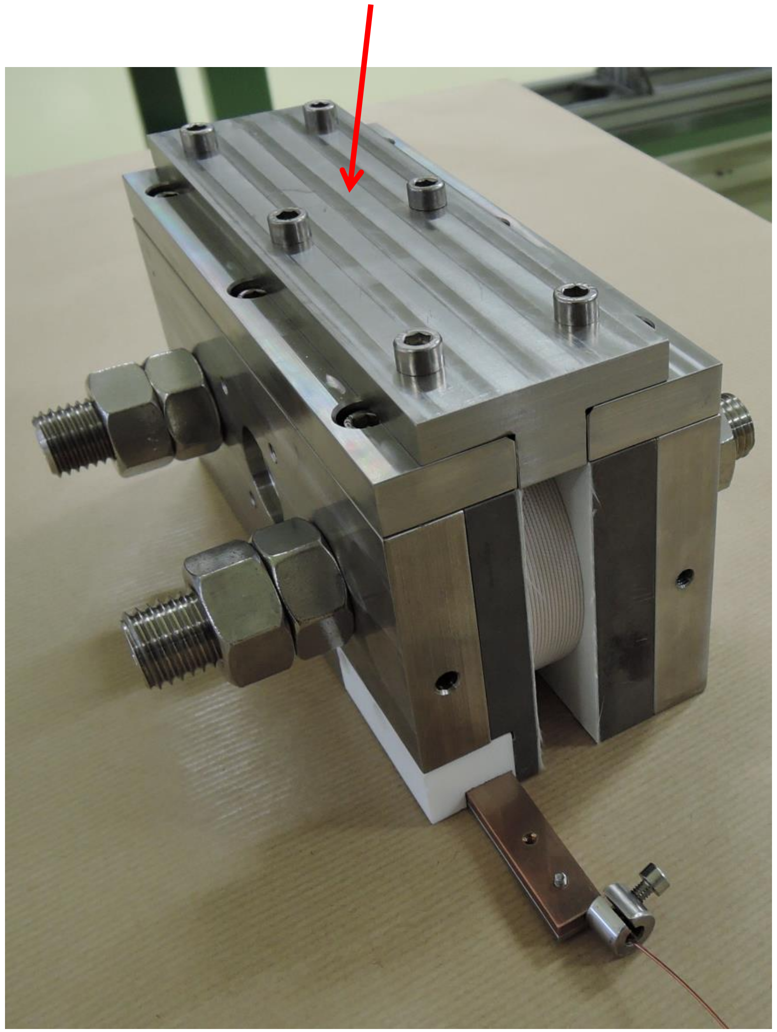
Manufacturing process of the five-coil prototype

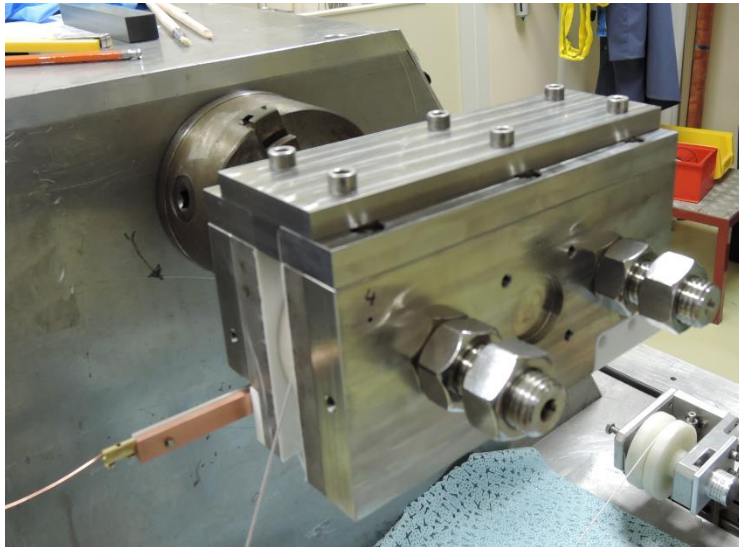
COIL TEST WITH LOW GRADE Nb_3Sn WIRE

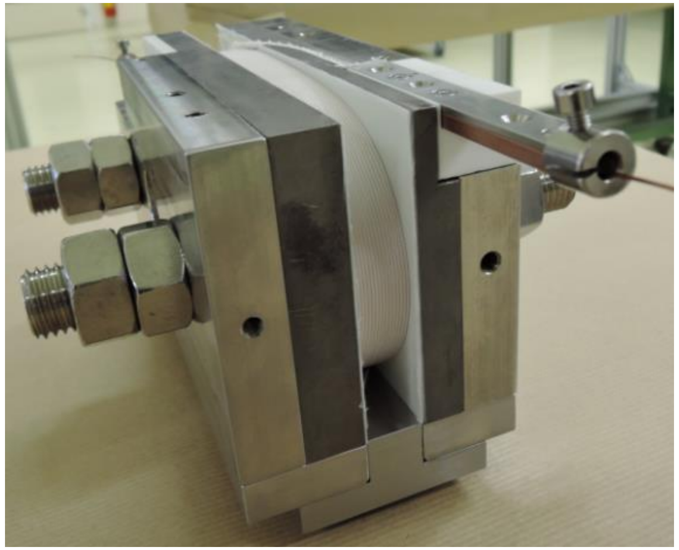




Additional piece to clamp the straight part of the coil







Coil winding performed by Jacky Mazet, CERN

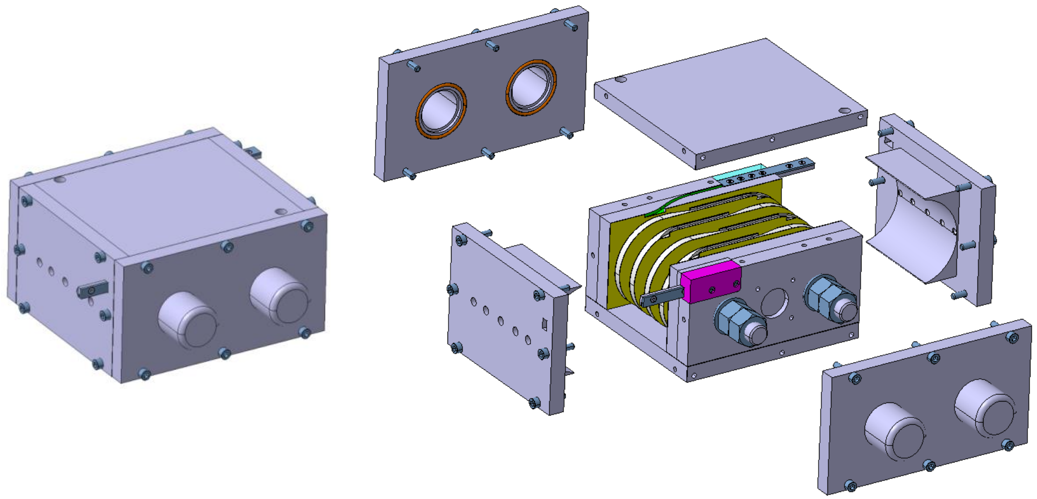
Outline

Manufacturing process of the five-coil prototype

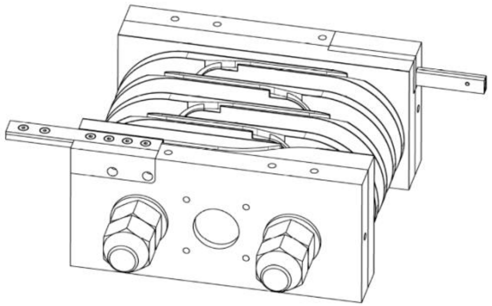
3. Activities

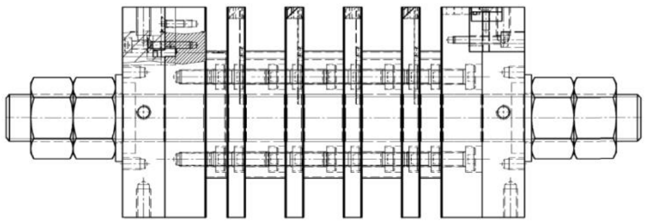
- The five-coil prototype will be wound with the Nb_3Sn wire and will undergo HT
- After HT, the coils will be impregnated with radiation-resistant epoxy with low viscosity
- The magnet will be trained in liquid helium at 4.2 K
- A mirror configuration will be used and Hall probes will be glued on the magnetic mirror for field measurement

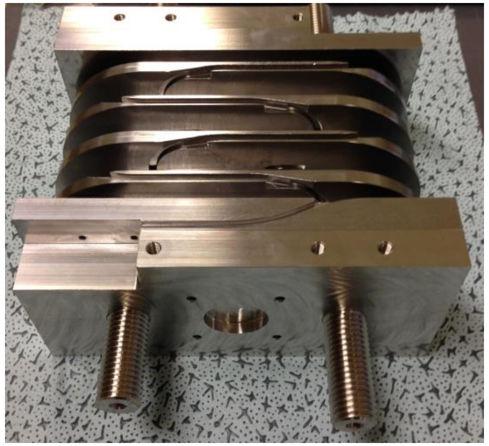
Parts of the aluminium impregnation mould

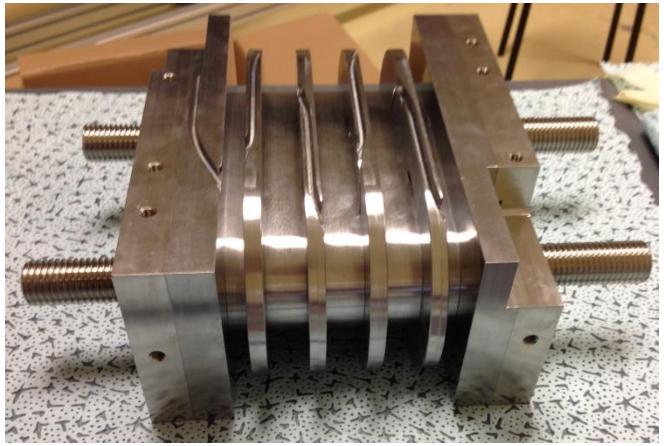


Assembly for the five-coil prototype









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

Conclusions

- Main design parameters of a Nb_3Sn wiggler were established to meet CLIC DR emittance and IBS impact constraints while keeping the *WP* below the 80% of the magnet's current limit. Several scenarios are possible by changing B_w 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

- The first winding test with copper wire enabled defining the correct thickness of the winding pole and evidenced the need for clamping the straight section of the coil

- One coil was wound with low grade Nb_3Sn wire and is currently under heat treatment to check the coil growth and test the insulation effectiveness

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

Thank you