Benchmark on MUC magnetic field calculation
Update

27/04/2023

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Outline

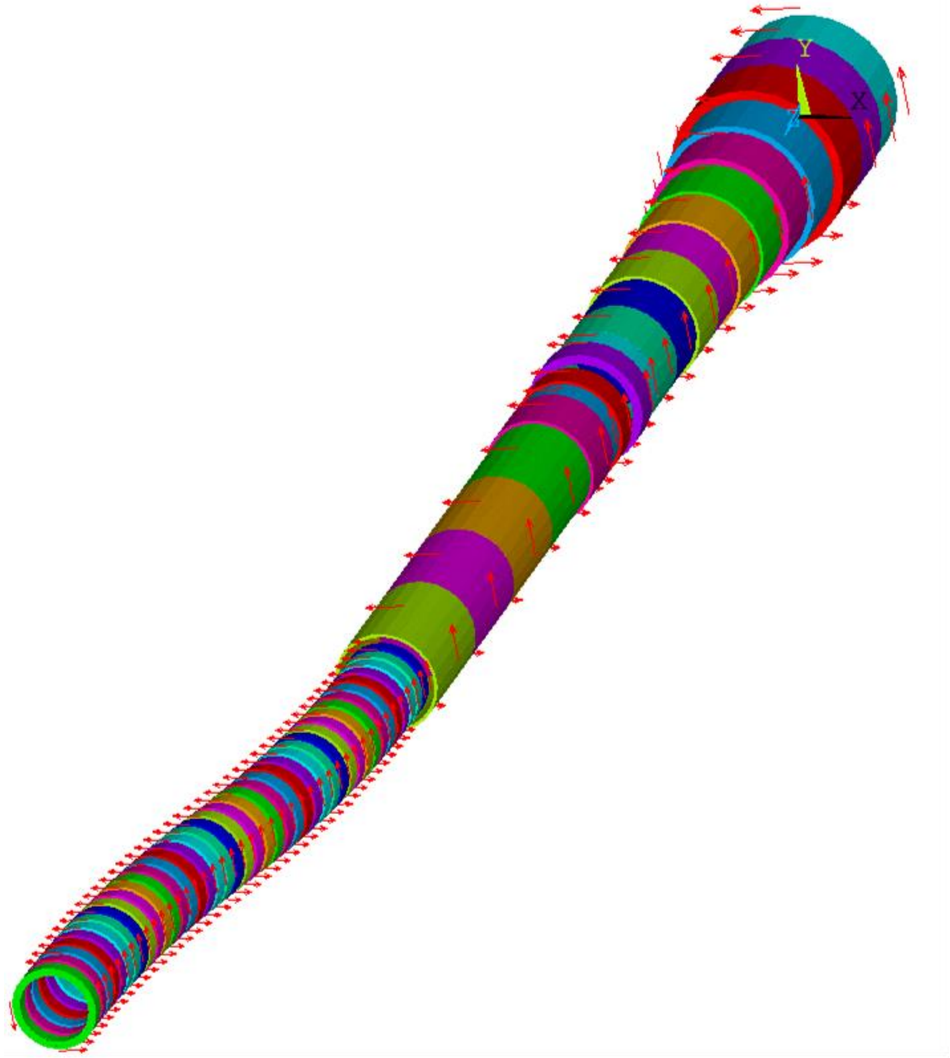
On 16th of March we made a first presentation on:

- Geometry of the tapering and chicane coils implemented
- Spatial components of the magnetic field computed along three paths of points (one path along the coils axis and two oblique off axis paths)
- Three different numerical codes (ANSYS, Current-loop approximation, Daniele C++ code) used to run the simulations
- Four sets of data computed among the three codes and compared

Today we update (from slide 14) the presentation with:

- Comparison of magnetic field computed along the perimeter of coil # 2
- Conclusions

Geometry



Tapering Coil #	Rc(m)	Zc(m)	DR(m)	DZ(m)	NR	NZ	I(A)
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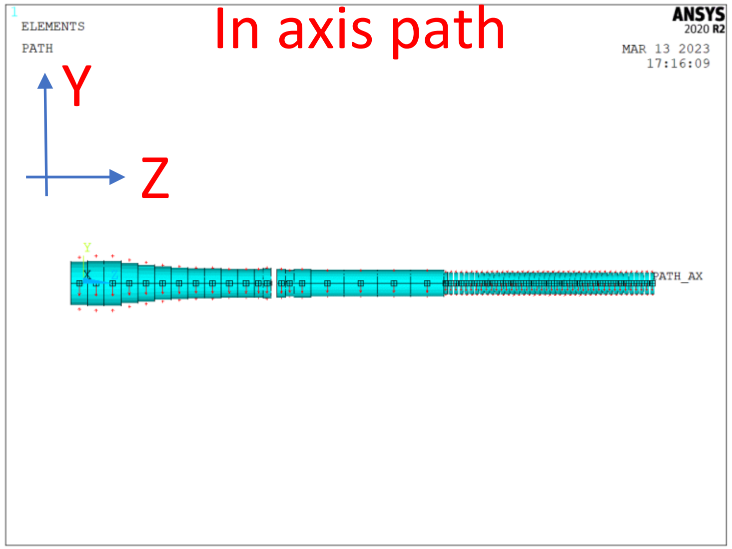
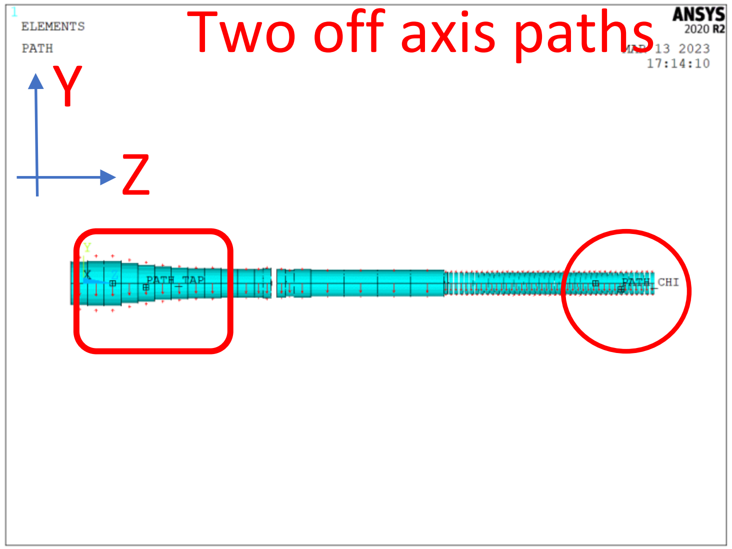
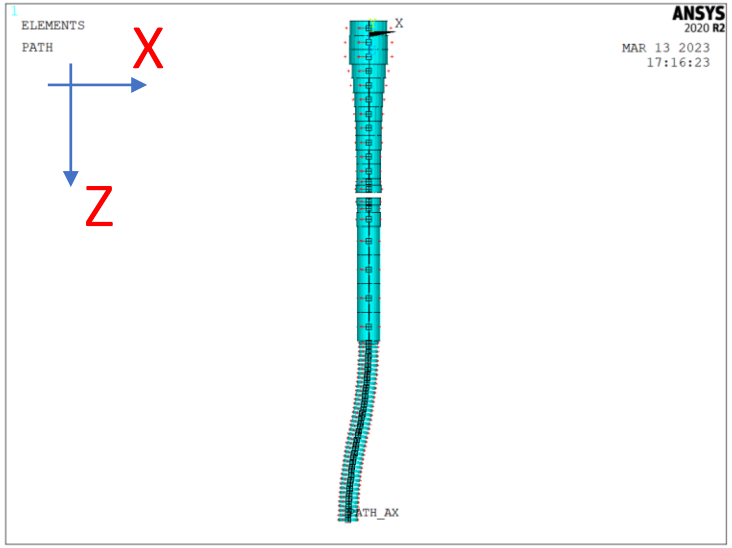
41 Chicane coils:
Inner radius: 430 mm
Outer radius: 530 mm
Length: 180 mm
Current Density: 16.57 A/mm2
Placed at 0.625 deg intervals (250 mm in s)

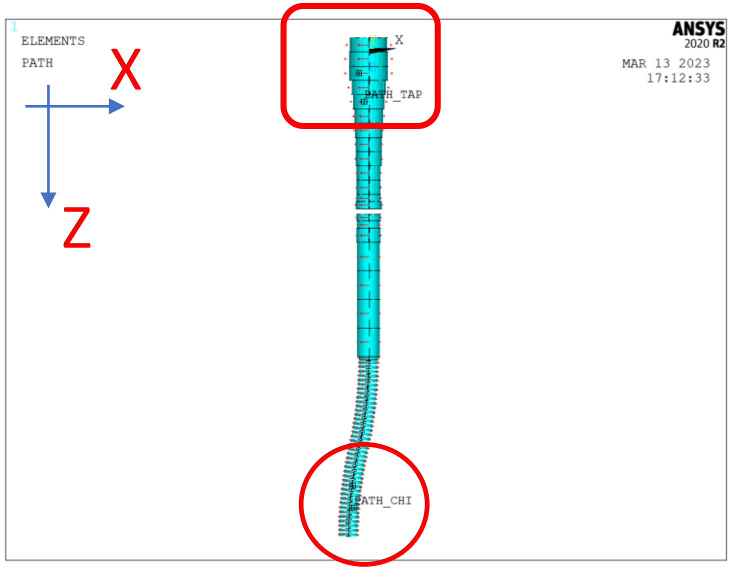
Parameters assumed in C. Rogers past simulations

Paths of points to compute the magnetic field









Numerical codes: ANSYS

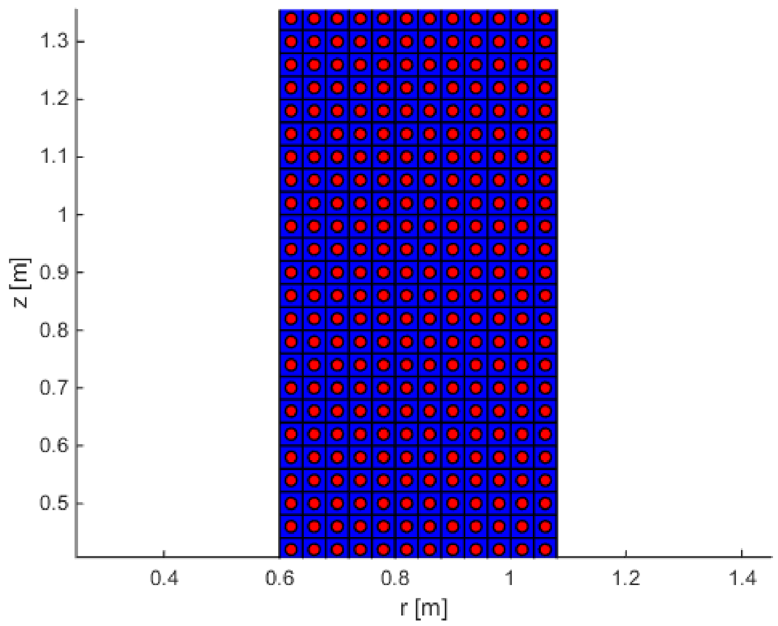
- ANSYS in the case of magnetostatic and linear problems implements a formulation based on the integration of the Biot Savart law *
- It uses a primitive (meshless) current carrying elements (SOURC36)
- Magnetic field can be computed either directly at specific locations or by a finite element mesh made of SOLID96 elements

***Biot-Savart Integration for Bars and Arcs, Miklos Gyimesi et al.** IEEE TRANSACTIONS ON **MAGNETICS,** V OL. 29. NO. 6. NOVEMBER **1993**

Numerical codes: Current-loop approximation

- Based on the well-known analytical solution of the magnetic field produced by a current-carrying ring with infinitely small cross section.
- The solution diverges at the source points (fine as long as we are not interested in the field inside the coil).
- Each coil is sub-divided in several loops in radial and vertical directions.

- Each loop is characterized by its radius, center position, direction cosines of axis, and current.
- Straightforward computation of net vertical forces if concentric non-tilted coils.



Numerical codes: Daniele

- The C++ code provides a numerical integration of the Biot Savart law.
- The code has been written ~1 year ago. It was a quick attempt to have a realistic magnetic field to set up simulation.
- Magnetic field can be computed either directly at specific locations or on a cartesian mesh.

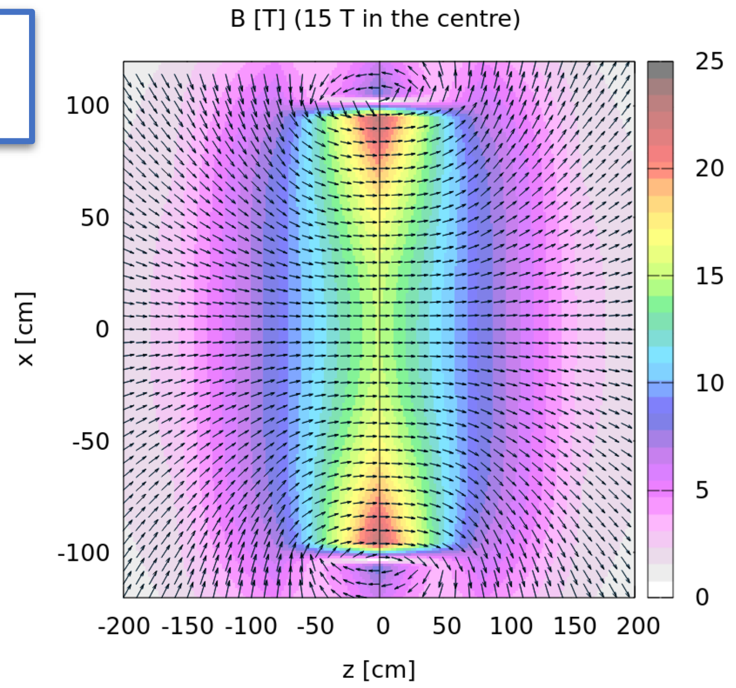
$$\zeta_\pm = z \pm \frac{l}{2},$$
$$h^2 = \frac{4R\rho}{(R+\rho)^2},$$
$$k^2 = \frac{4R\rho}{(R+\rho)^2 + \zeta^2},$$

$$B_\rho = \frac{\mu_0 I}{4\pi}\frac{2}{l}\sqrt{\frac{R}{\rho}}\left[\frac{k^2-2}{k}K(k^2) + \frac{2}{k}E(k^2)\right]_{\zeta_-}^{\zeta_+},$$

$$B_z = \frac{\mu_0 I}{4\pi}\frac{1}{l}\frac{1}{\sqrt{R\rho}}\left[\zeta k\left(K(k^2) + \frac{R-\rho}{R+\rho}\Pi(h^2,k^2)\right)\right]_{\zeta_-}^{\zeta_+}.$$

Requires the evaluation of elliptic integrals

Evaluation of the magnetic field of a single coil

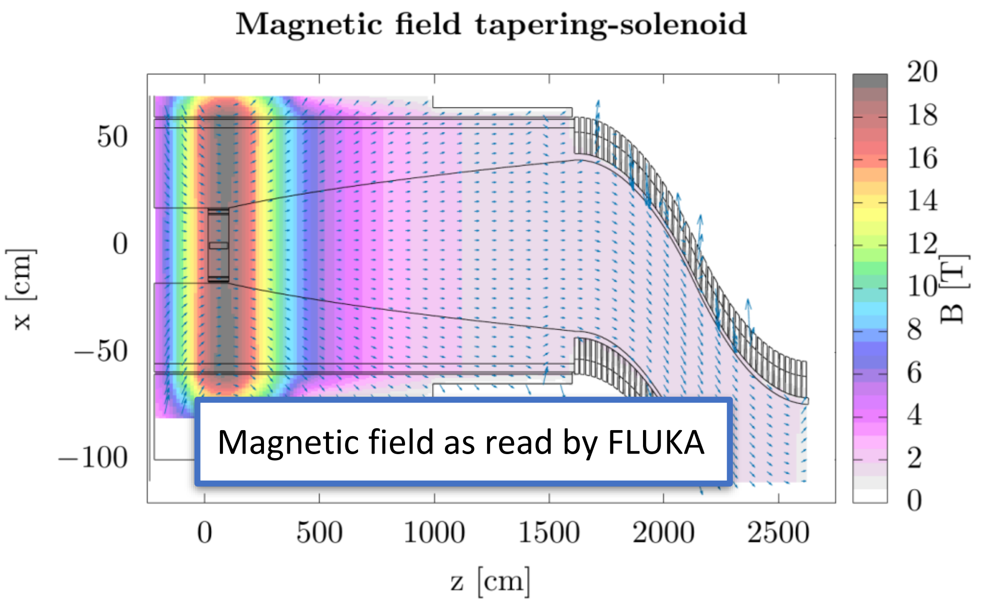


Results to FLUKA

- Magnetic fields can be implemented in FLUKA via dedicated user routines or magnetic cards.
- Using the magnetic cards is less error prone and (in general) the preferred approach.
- It is possible to have 3D cartesian meshes or 2D when dealing with cylindrical symmetry.

```
MGNCREAT         100                                                   TAP
MGNCREAT                                             20        40        &
MGNCREAT         0.0       -200                      80      1700       &&
*
MGNDATA    4.276E-06 4.262E+00  -0.09739 4.261E+00   -0.1948 4.260E+00TAP
MGNDATA      -0.2924 4.258E+00   -0.3901 4.256E+00   -0.4879 4.253E+00 &
MGNDATA       -0.586 4.251E+00   -0.6844 4.24
MGNDATA      -0.8817 4.251E+00   -0.9803 4.25
...
MGNDATA    1.164E-01 1.260E-01 7.313E-02 6.4                            &&
MGNDATA    3.247E-02 5.155E-02 2.907E-02 5.418E-02 2.842E-02 5.380E-02 &&
MGNDATA    2.863E-02 5.232E-02 2.902E-02 5.045E-02                     &&
* STOP DATA SOLENOID TAPERING
MGNFIELD           1                            VACINS     VACIN       TAP
MGNFIELD           1                             COIL1    COIL18       TAP
MGNFIELD           1                              Shld                 TAP
```

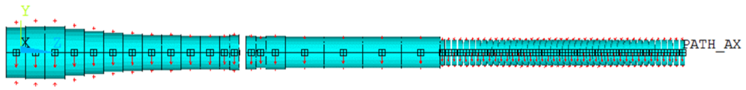
Actual snapshot from the FLUKA inputfile.

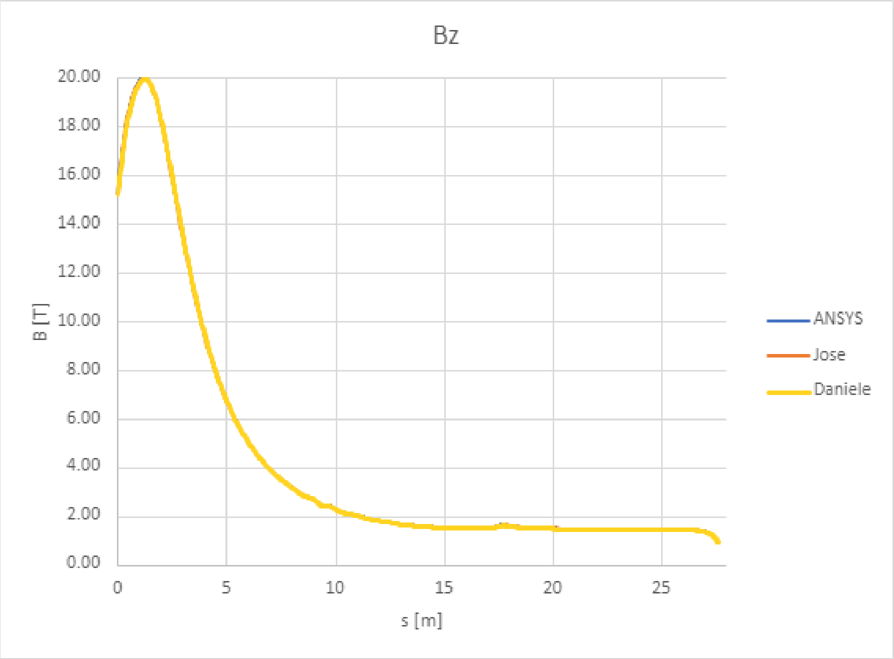


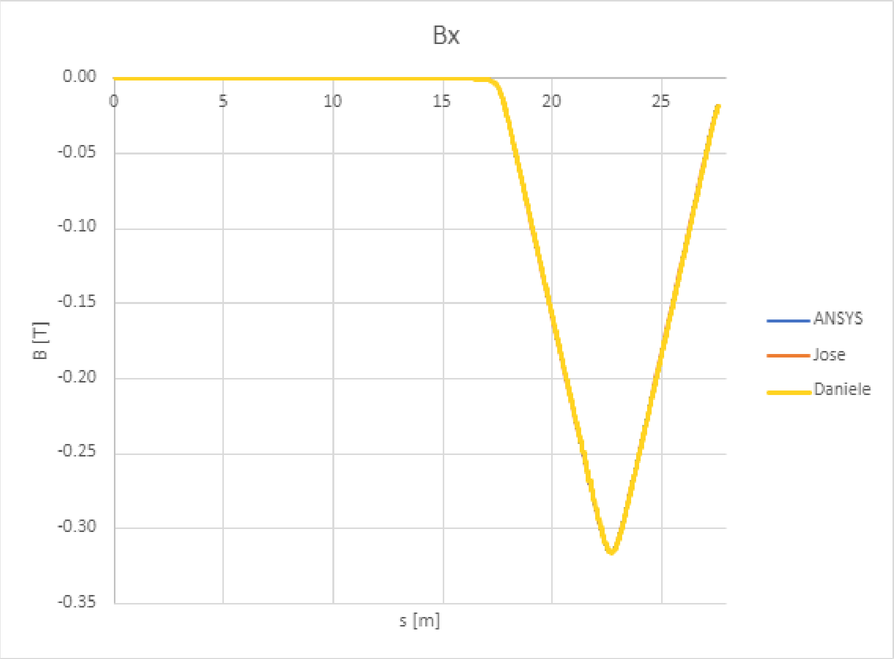
Sets of data

1. in axis points with tapering and chicane coils ON
2. in axis points with only chicane coils ON
3. off axis points in the tapering region with tapering and chicane coils ON
4. off axis points in the chicane region with tapering and chicane coils ON

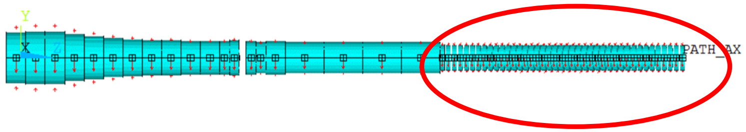
Results: in axis point with tapering and chicane coils ON

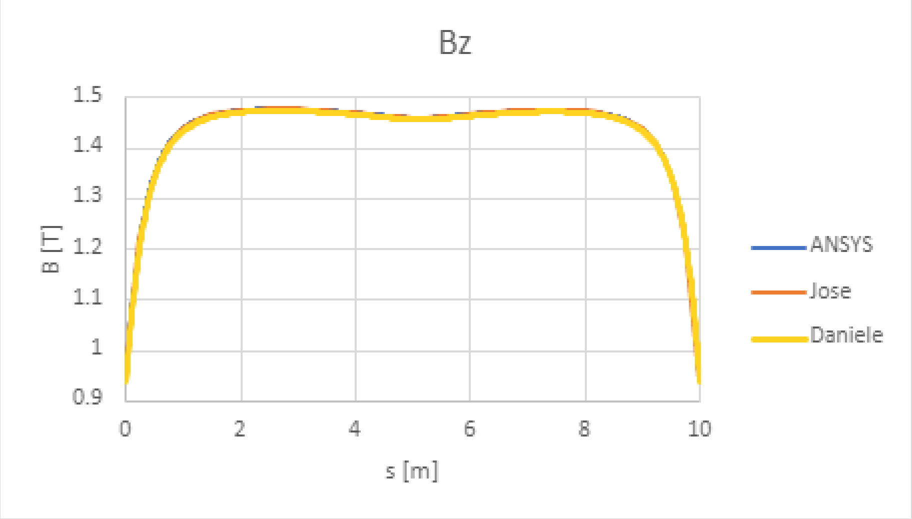


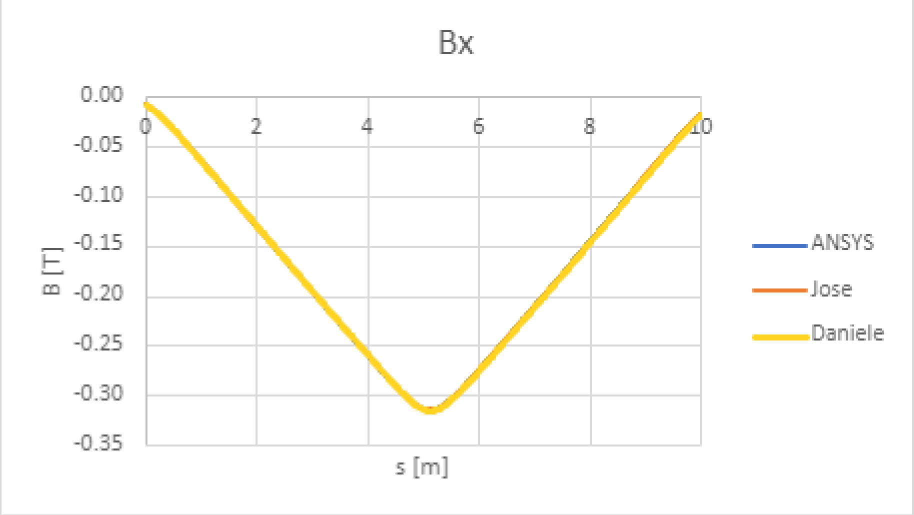




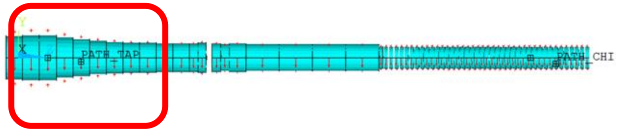
Results: in axis point with only chicane coils ON

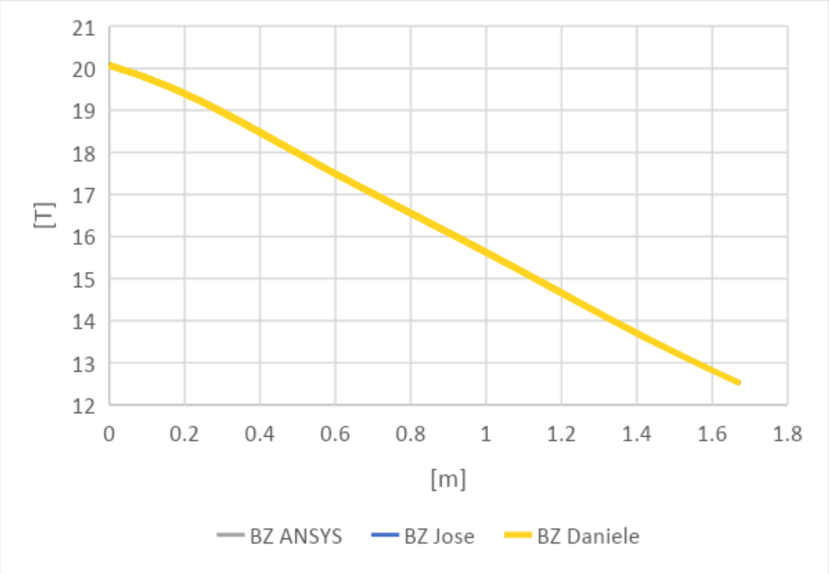


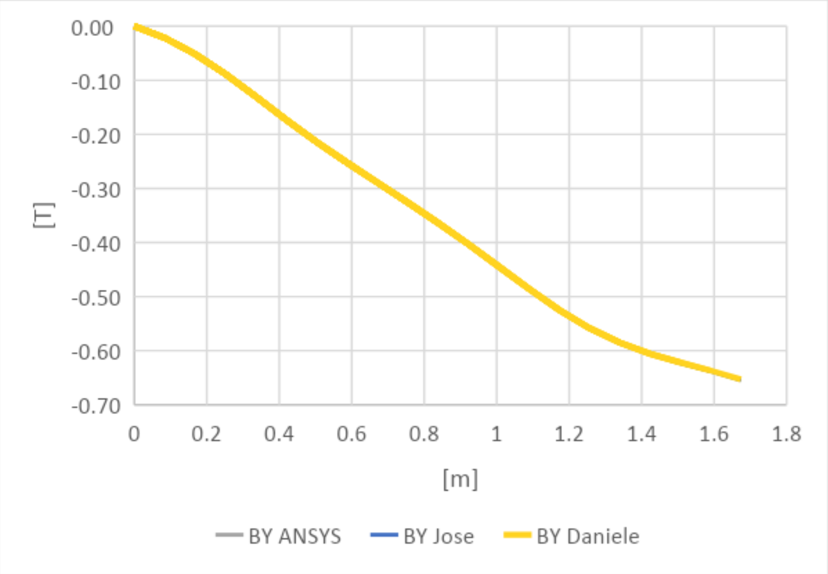


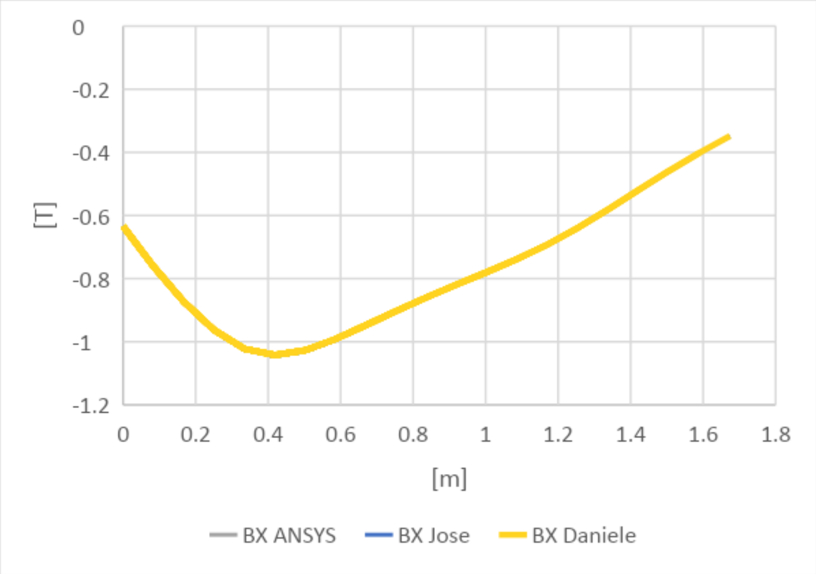


Results: off axis point in the tapering region

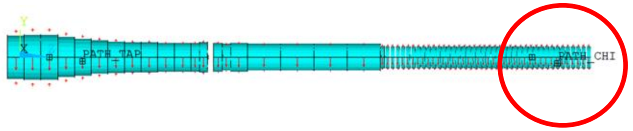


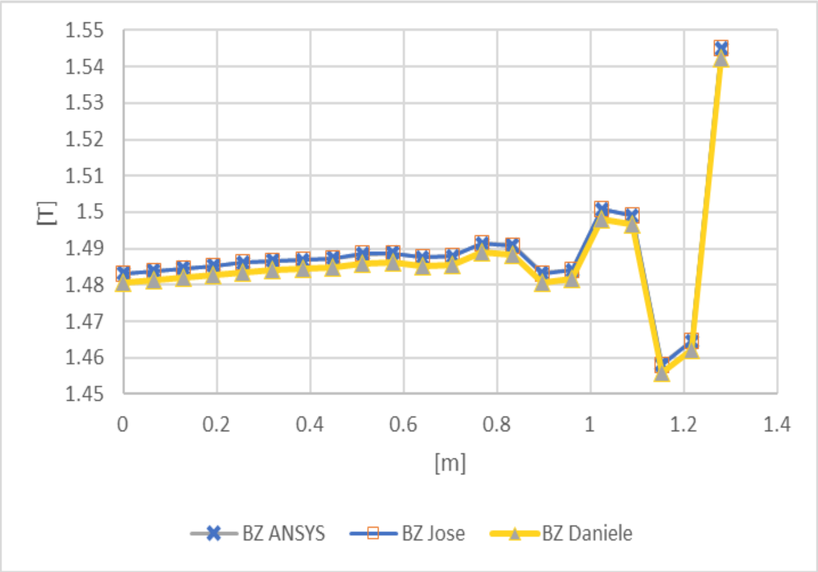


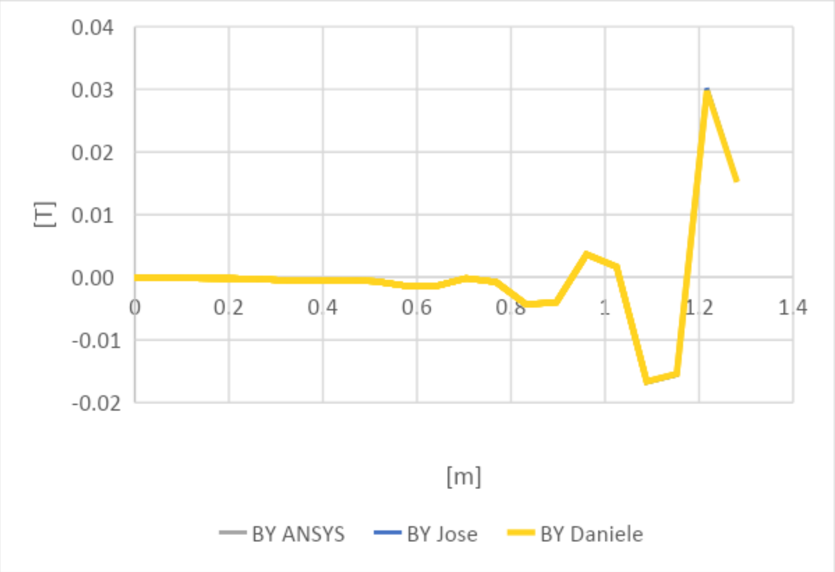


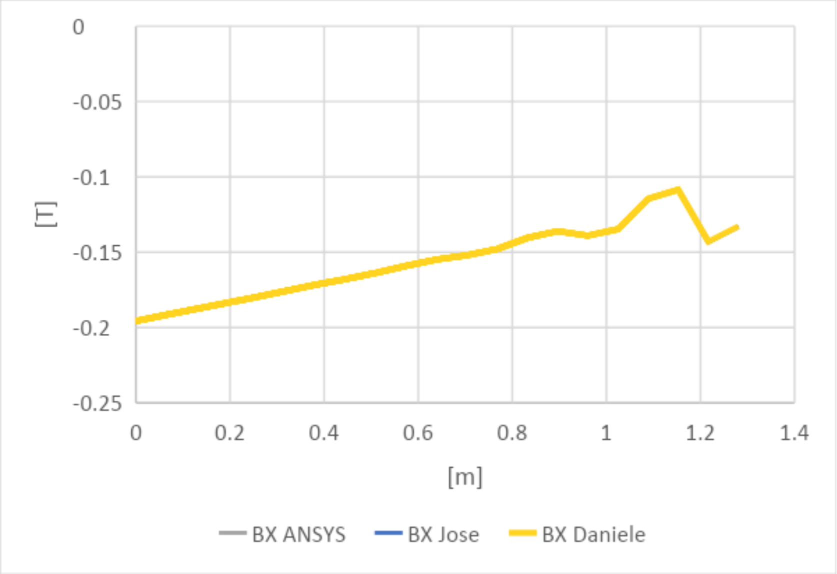


Results: off axis point in the chicane region

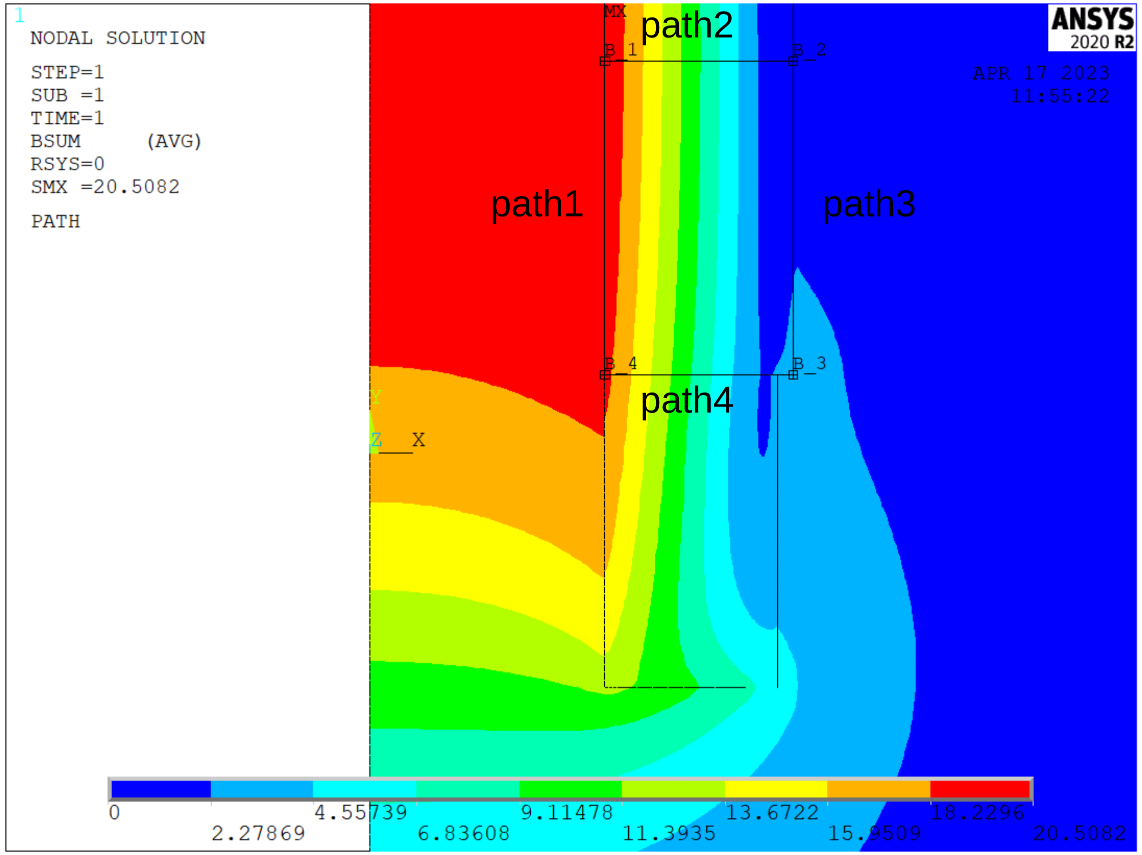








Geometry



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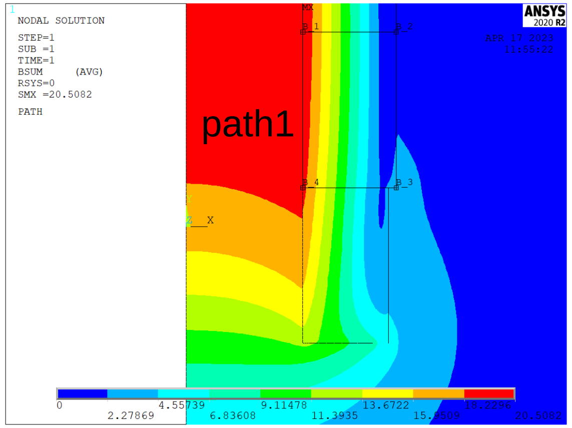
We have computed the two components of the magnetic field along the perimeter of coil #2 which is divided in four paths. In these simulations the chicane coils are not considered.

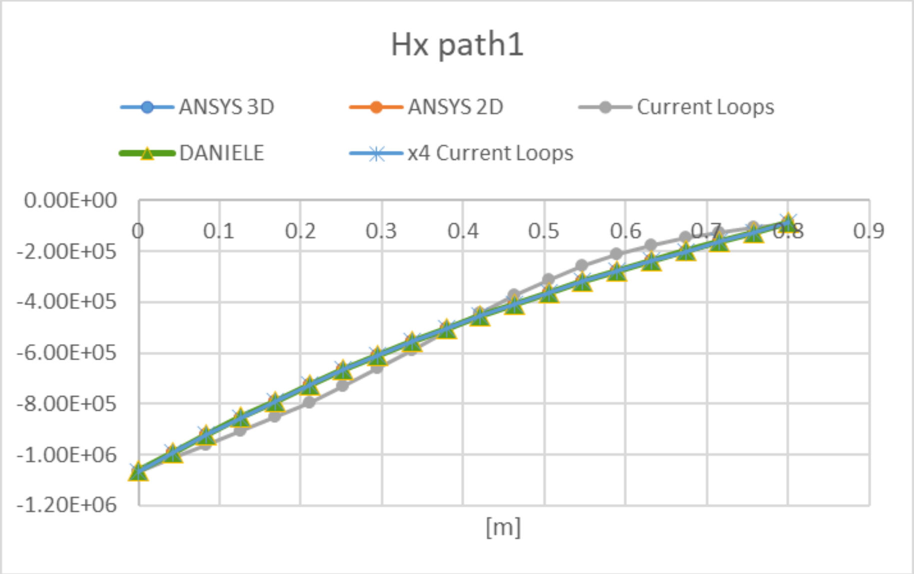
Each path has 20 subdivisions, therefore the field is computed in 80 points in total

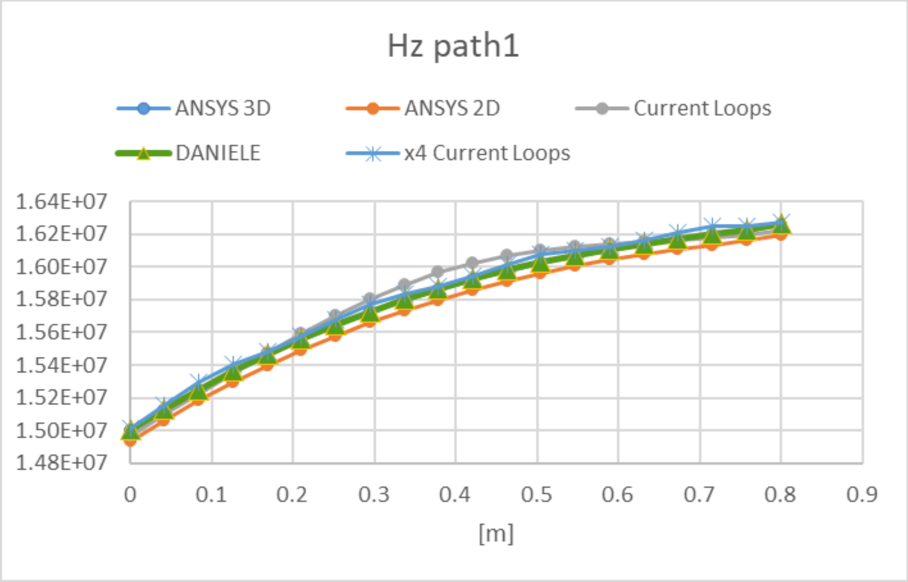
Numerical codes

- Three different numerical codes (ANSYS, Current-loop approximation, Daniele C++ code) used to run the simulations
- On top of that also the 2D ANSYS magnetic vector potential formulation implemented by the PLANE 13 element has been used
- The current loop approximation has been run with two different settings:
    1. NR*NZ turns in each coil.
    2. (4*NR)*(4*NZ) turns in each coil.
    3. Singularity at source point is overcome by skipping the contribution of that source point
- Daniele C++ code has been run with
    1. 600 layers per magnet
    2. Singularity is overcome by zero contribution from the radial element located in the point (i.e. the magnetic field inside the infinitesimal element is given by all the others).

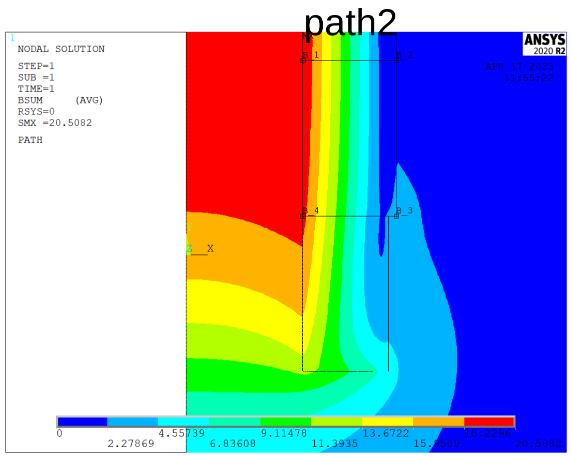
Results comparison along path 1

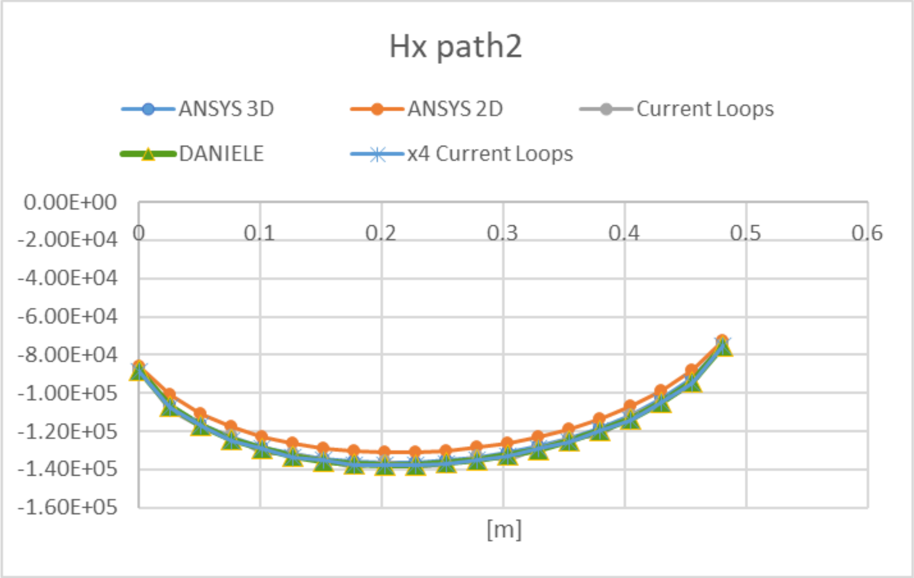


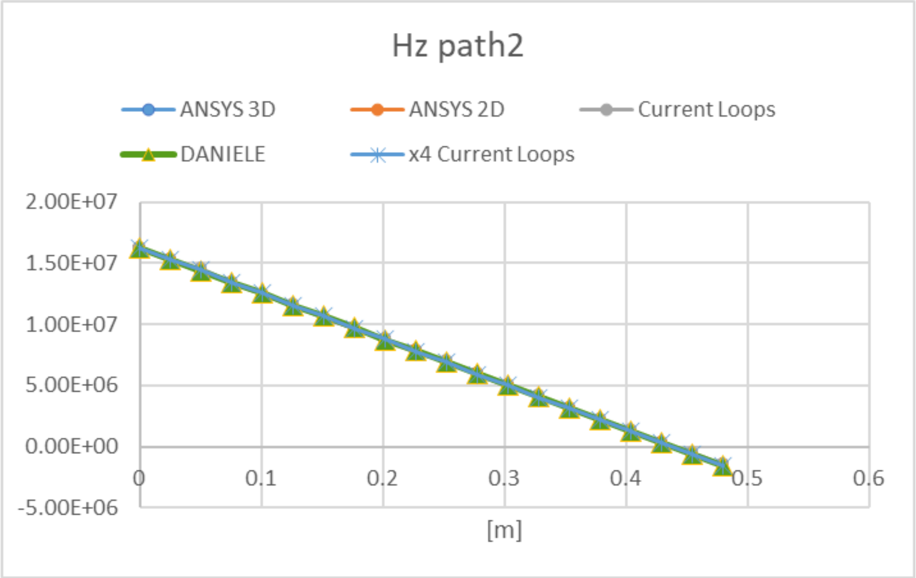




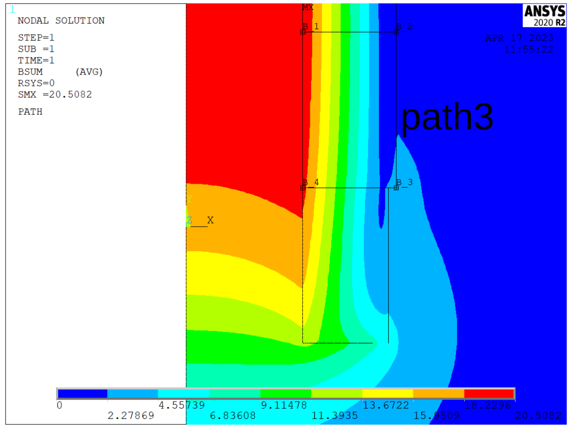
Results comparison along path 2

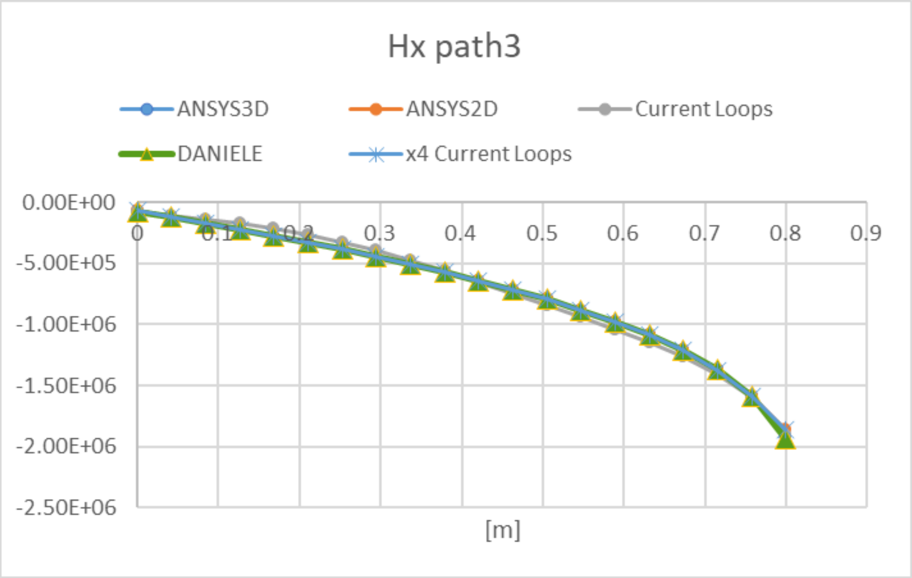


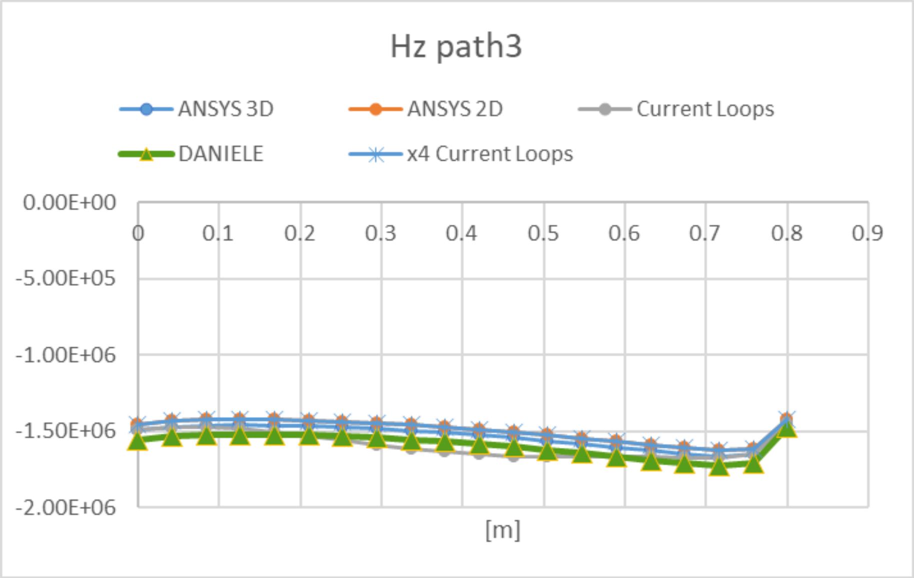




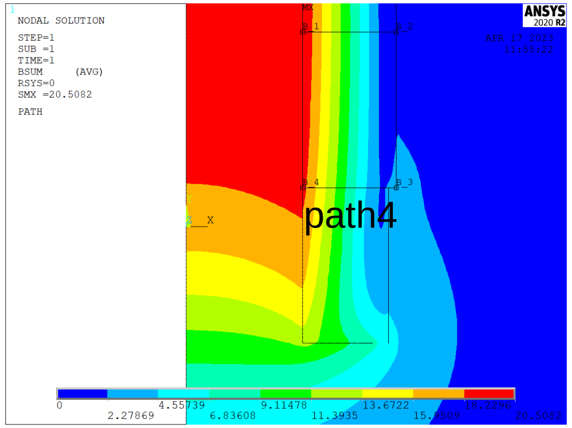
Results comparison along path 3

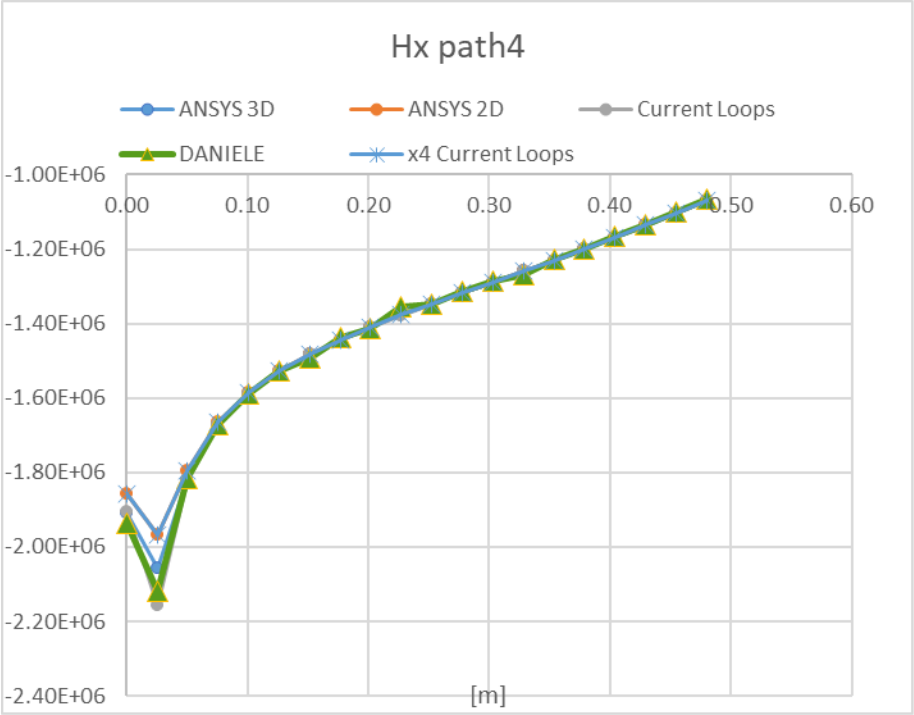


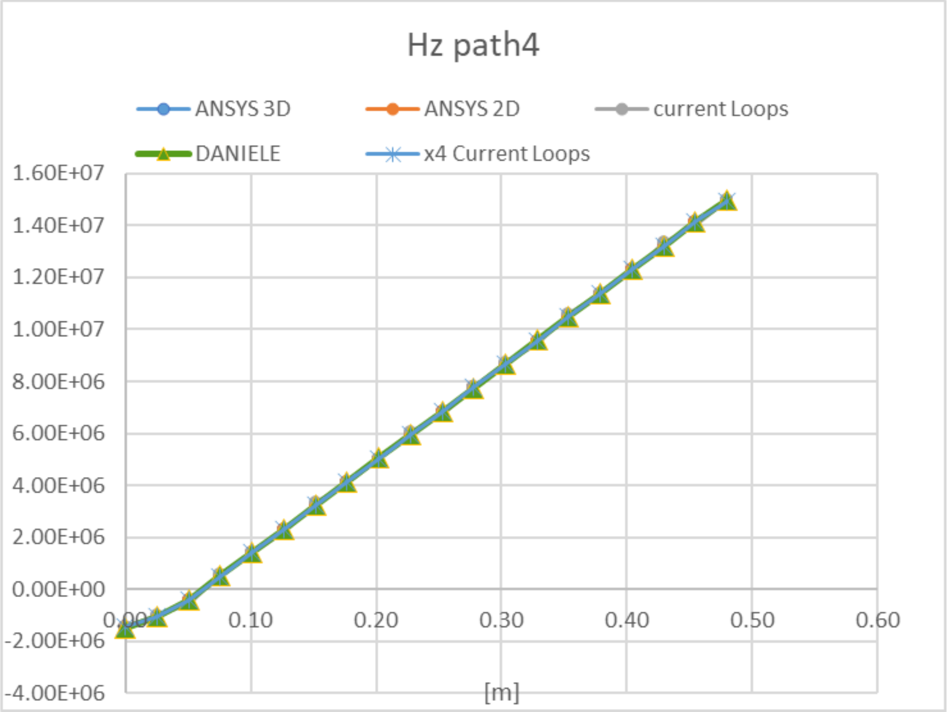




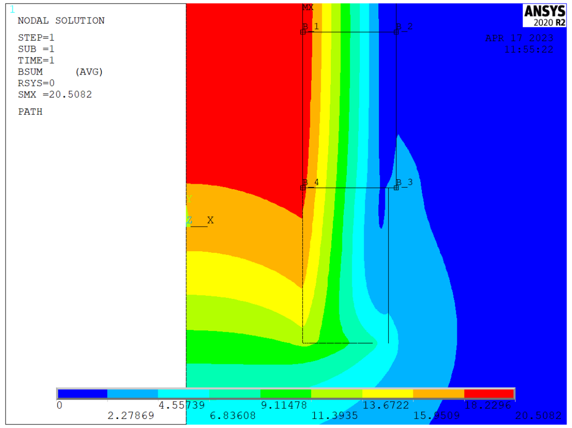
Results comparison along path 4

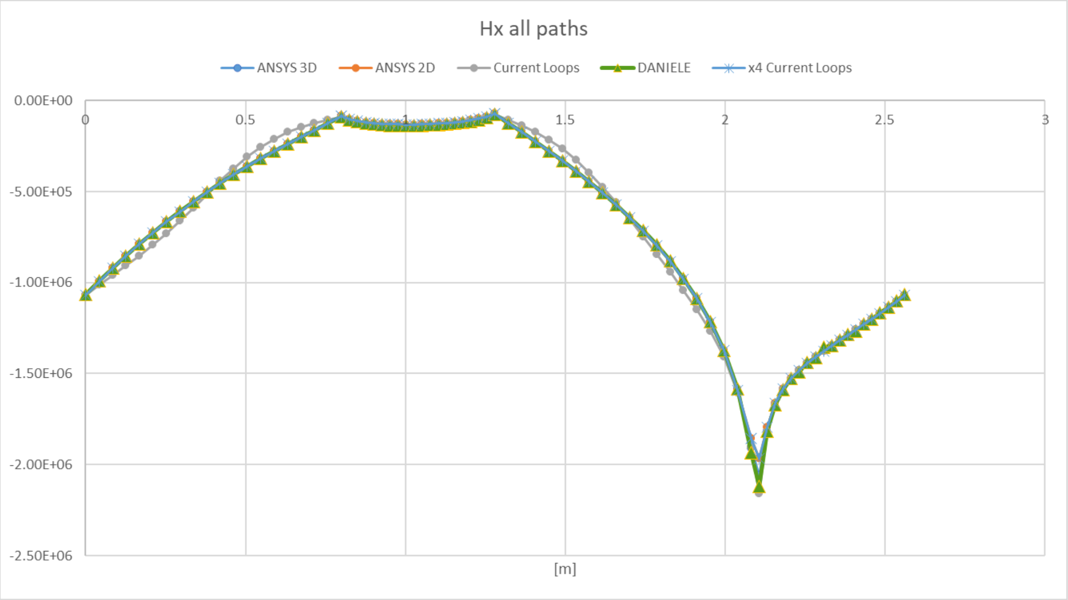


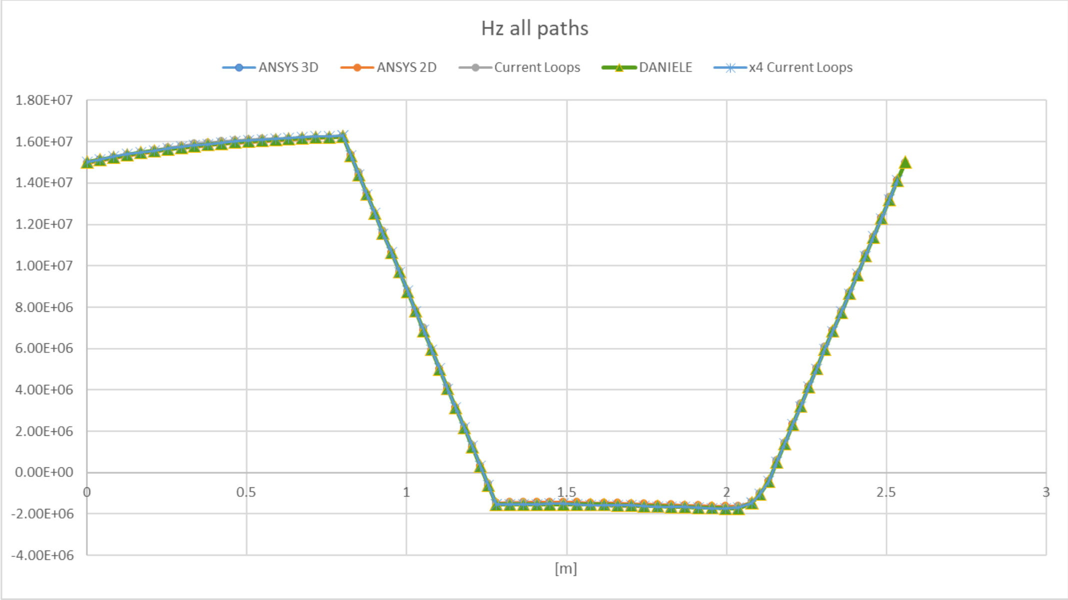




Results comparison along all paths







	Circulation [A]	Error %
ANSYS 3D	14504271.29	0.45
ANSYS 2D	14424577.95	0.99
Current loop	14582060.81	-0.09
Current loop 4X	14580457.98	-0.08
Daniele C++	14582060.81	-0.09
Total current	**14569440.00**	

Conclusions

- A benchmark exercise has been implemented to validate three different numerical codes used for the design of the MUC
- The three components of the magnetic field have been compared along four different paths
- The benchmark outcome shows that the three codes provide results in a good agreement
- Final remark: the current assumption of the tapering field follows the inverse cubic field from past MAP studies. Deviation from this function are fine as long as the magnetic field decrease is adiabatic.
- A further benchmark exercise has been studied, comparing the magnetic field along the perimeter of coil #2. Also in this case we can state that the codes used show a good agreement with the computed results