Status of UST_2 stellarator construction

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UYING Fusion Energy

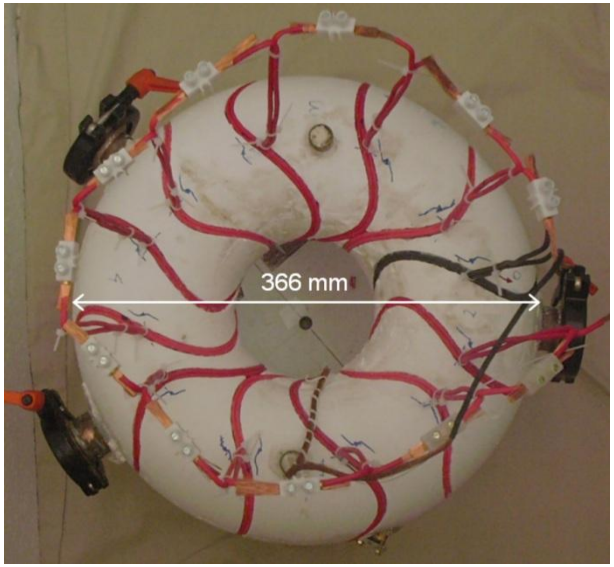
Outline

- Background. Introduction
- Experimental validation of engineering concepts
- Assessment of different alternatives
- Current reference design and future work

Background

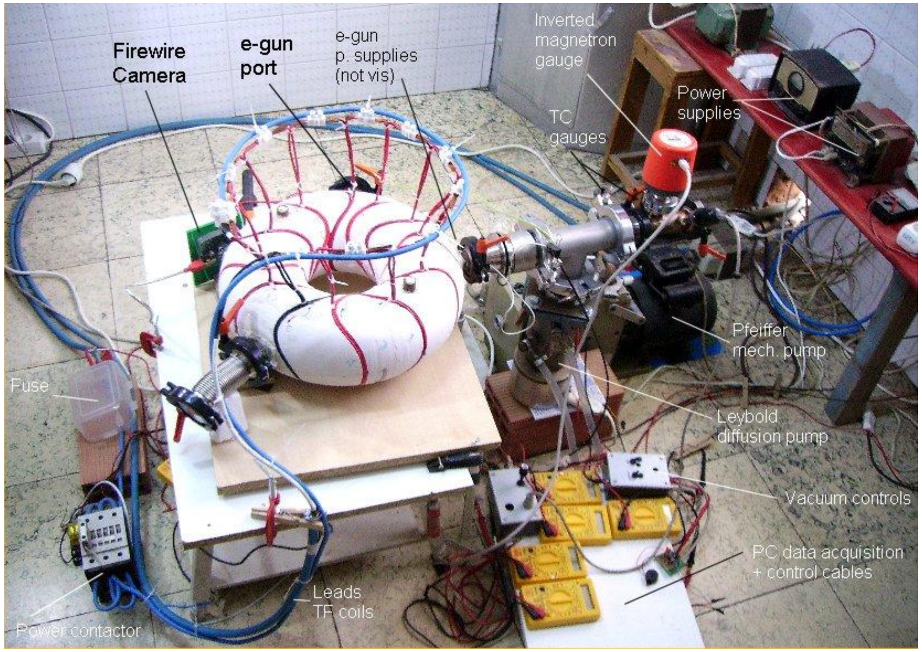
The present work is the continuation of the UST_1 one.

UST_1 (Ultra Small Torus 1), is a small R=125mm modular stellarator, funded, designed, built and operated by me during 2005/07 in my own laboratory.



UST_1 stellarator

UST_1 facility



The current **UST_2** project/PhD-thesis is also funded by me and built in my lab., though some means from CIEMAT are utilized. Therefore, the **budget for materials is very low**, **~3-5 k€.**

Introduction

● I will report briefly the current **status** of the UST_2 stellarator.

● The work is R&D and **innovation** in engineering. Not focused on physics and plasma experiments.

● **General objectives of the work with UST_2**:

- Contribute to my PhD on “Rapid manufacturing methods for geometrically complex nuclear fusion devices”.
- Build a small stellarator to prove the results of the R&D.
- Formation.

Decisions to take

Objetives + (cost + schedule) constrains → decisions

● **Technical objectives of UST_2 (and UST_3)**:

i) Innovative construction methods to lower costs and speed up production cycle. As much as possible **ii)** turbulence (and neoclassical) optimization and **iii)** innovative divertor implementation

- Important decisions have to be taken at the very beginning of the design. Thus, **test and validation** of the dubious (low-cost) concepts is carried out.

Decisions to take
A) What magnetic configuration to use?
B) Size of the device
C) Coils inside/outside the VV?
D) Method to build: the coils, the coil frame, the VV
E) Material for the coil frame

R&D carried out to support the decisions

Experimental validation and assessment of the concepts have been produced

▪ **Experimental tests** of pieces have been produced to early detect **insurmountable problems** of the concepts and to roughly estimate the **cost** of the device.

▪ **Theoretical assessment** of several different **magnetic configurations** has been produced by preliminary engineering designs and observation of advantages/drawbacks of each design for UST_2.

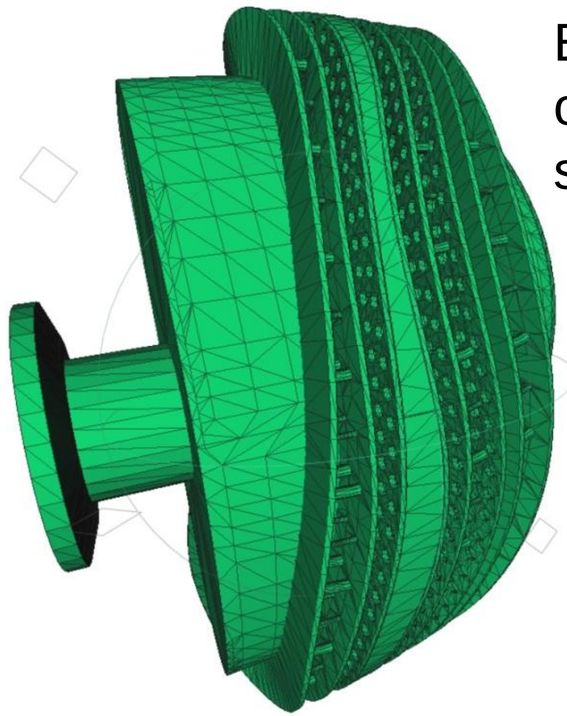
Experimental validation of engineering concepts

1^{st} test, a scaled-down 3D printed sector of coil frame

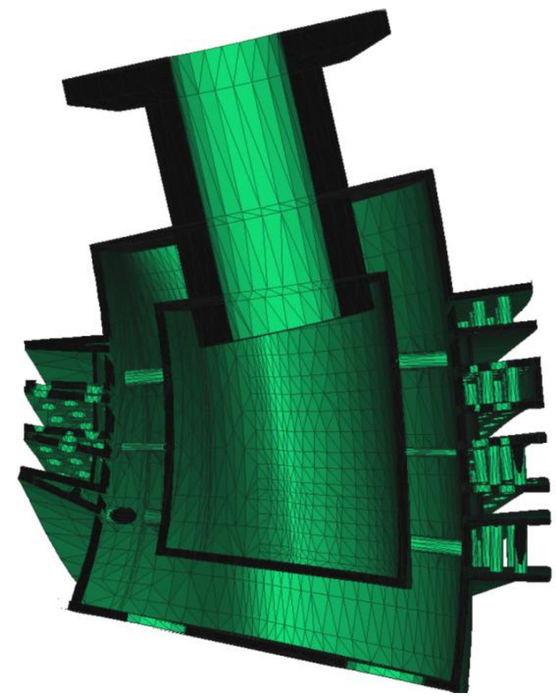
The concept of *Hollow-Sparse* pieces is developed

- The concept of ***Hollow-Sparse*** pieces was concocted: 3D printed pieces, very hollow and light, finally filled with a material able to solidify (resin, plaster, etc, fibre reinforced or not).

- The 3D printed pieces cost about 1-2 € /cm^3, very expensive. Cost has to be reduced to allow affordable or low-cost devices.



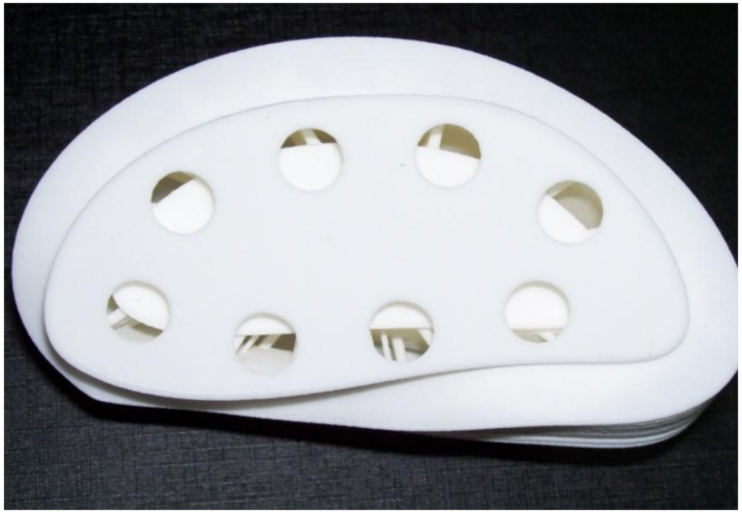
External view of the torus sector **test**

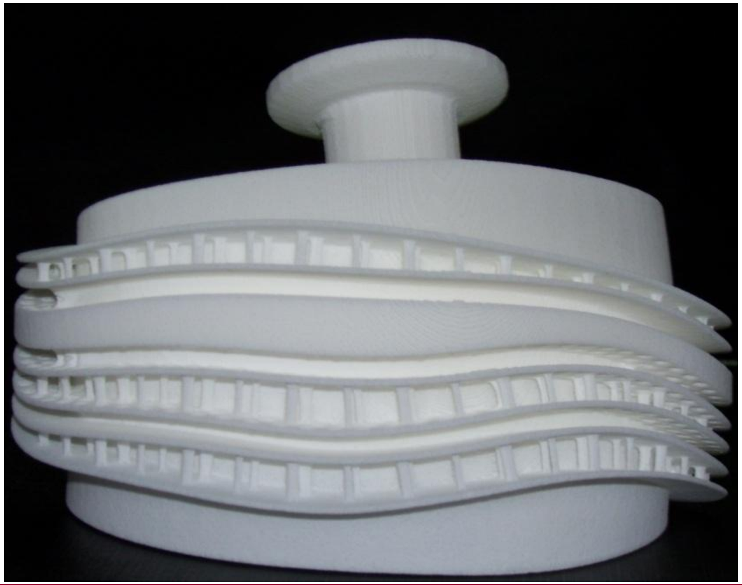


Cut of the sector

1st test, a scaled-down 3D printed sector of coil frame

Results: robust, accurate but too expensive





3D printed piece. Nylon.
80 €

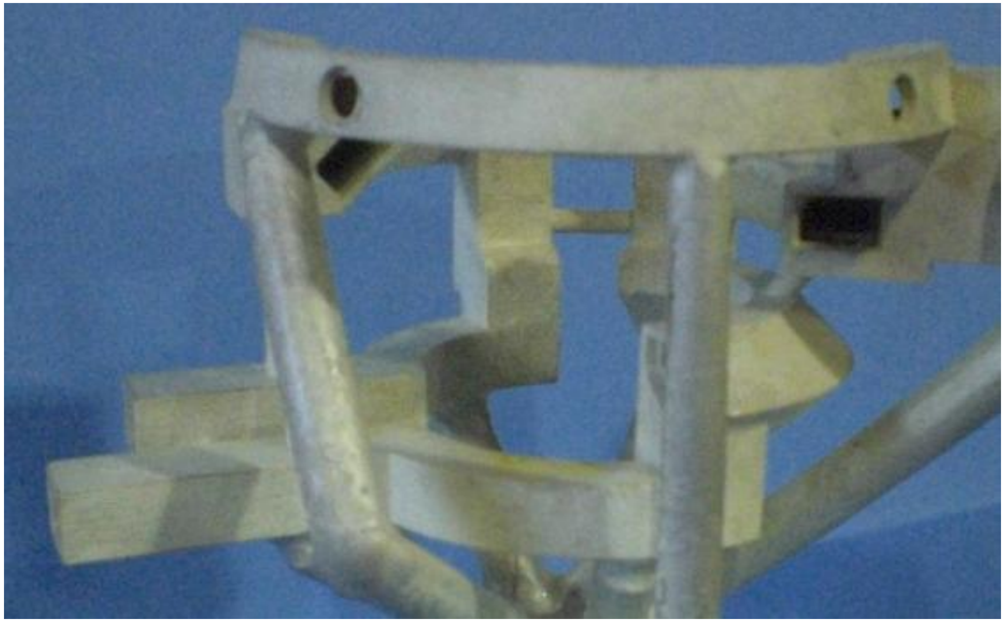
It has been filled with dental plaster and with molten Bi-Sn alloy

2^{nd} tests, low-cost coil metal casting

Results : Inconclusive. Casting not chosen as reference

- The coils, the coil frame, the VV or all, might be casted.
- Metal casting tend to be expensive for few units.
- For small series (<10 units) sand casting (**non-permanent mould**) is the most common and cheaper.
- About 20-40 k€ may be estimated for 20 coils of the size of UST_2 (~3-fold the photo).

~100 mm

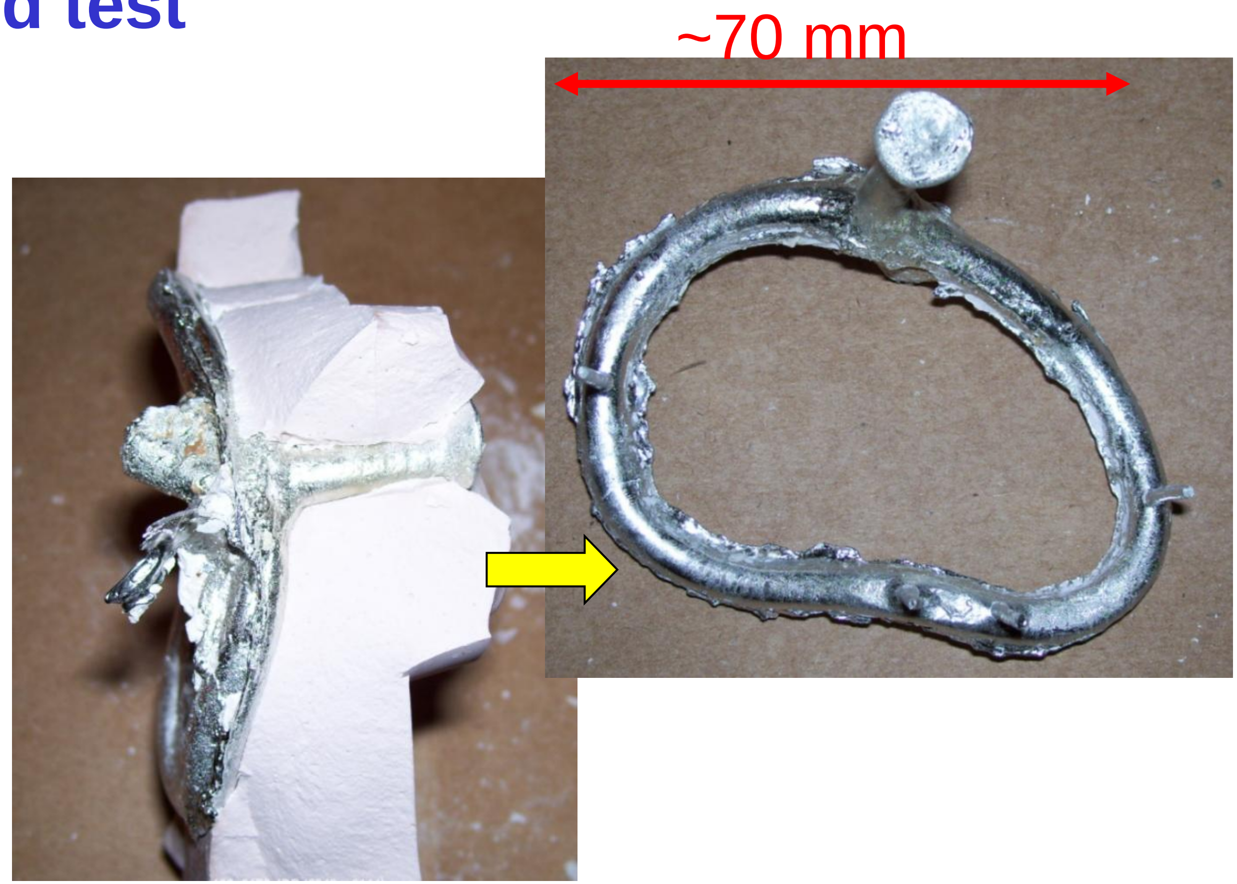


Lost wax vacuum casting in plaster mould produced in a specialised company. Silver.
~ 1000 € in Ag. ~ 700 € in Cu

Permanent plaster mould test

- The aim would be to create **permanent plaster moulds** for 5-10 pieces of Al or Cu coils (usually imposible).

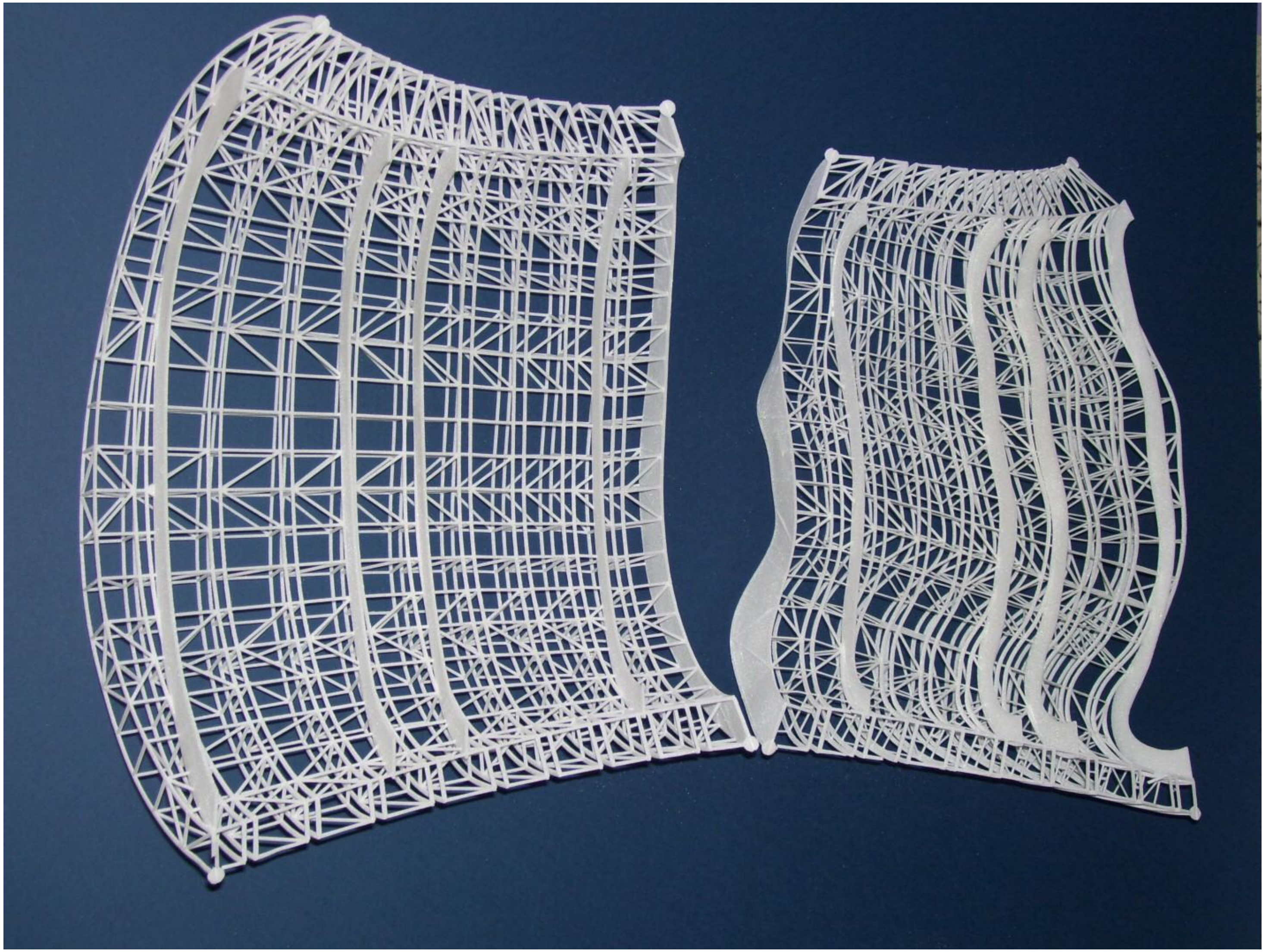
- The cost would be reduced 5-10 fold since several coils are identical.



Own test of casting in a "**permanent**" plaster mould. The mould **broke**. However, **some ideas appeared** to allow permanent plaster moulds for Al

3^{rd}, a UST_2-size 3D printed sector of coil frame

Results : Low cost (200 €), enough strength



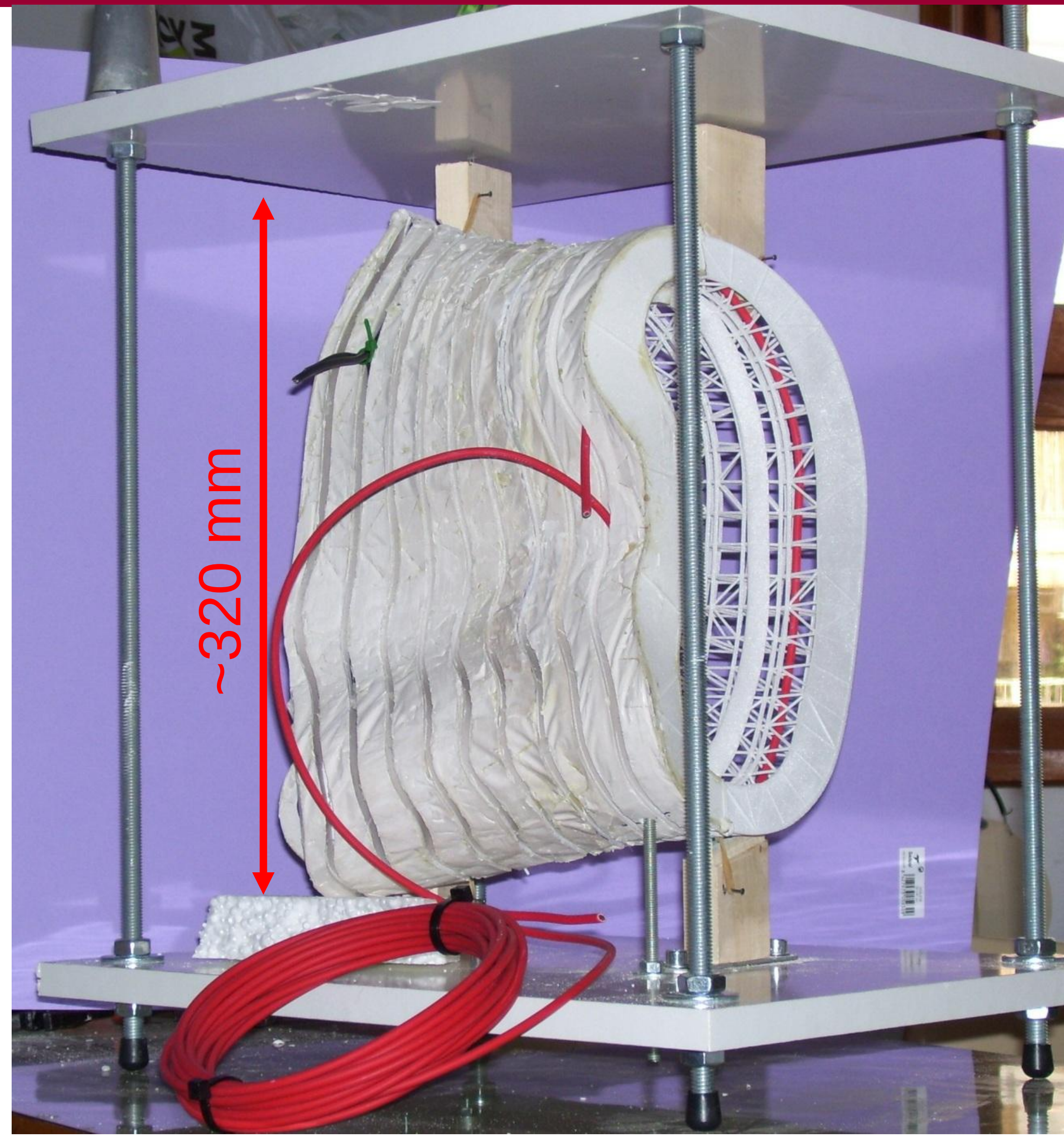
3D printed pieces, Nylon. From company 'Shapeways'. **Hollow-Sparse** concept before moulding with filler

3rd, a UST_2-size 3D printed sector of coil frame

Results : Still difficult moulding and pair matching

One half-sector after hard plaster moulding

3rd, a UST_2-size 3D printed sector of coil frame



Two views of the test of a coil frame sector

Assessment of different alternatives

Introduction

- The aim is to use as much as possible the current physics designs,

however:

  - It has to be decided what device to build.
  - Coil designed for other devices (i.e. QPS) hardly match the needs.
  - Many times only the LCFS is available.

- Therefore some calculations are performed.

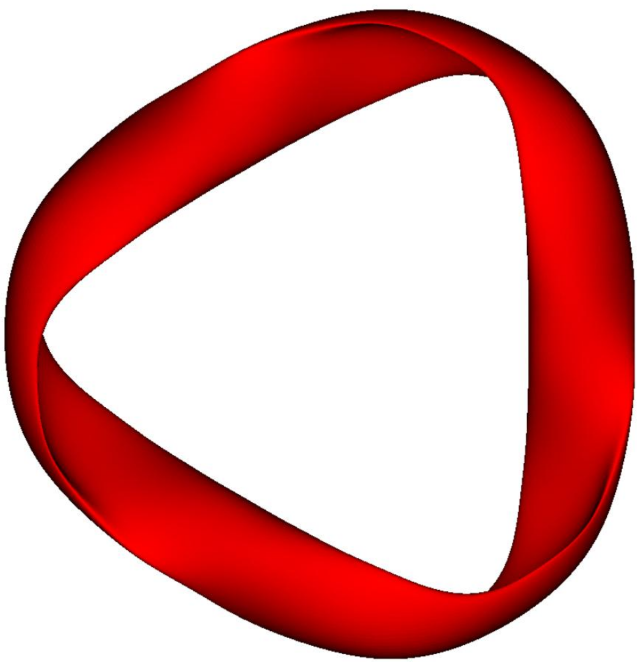
- The CASTELL code (formerly named SimPIMF), a Java code developed by me during several years, is used for most of the calculations.

- VMEC, DESCUR and NESCOIL are used for the generation of coils and some plasma and winding surfaces, and other.

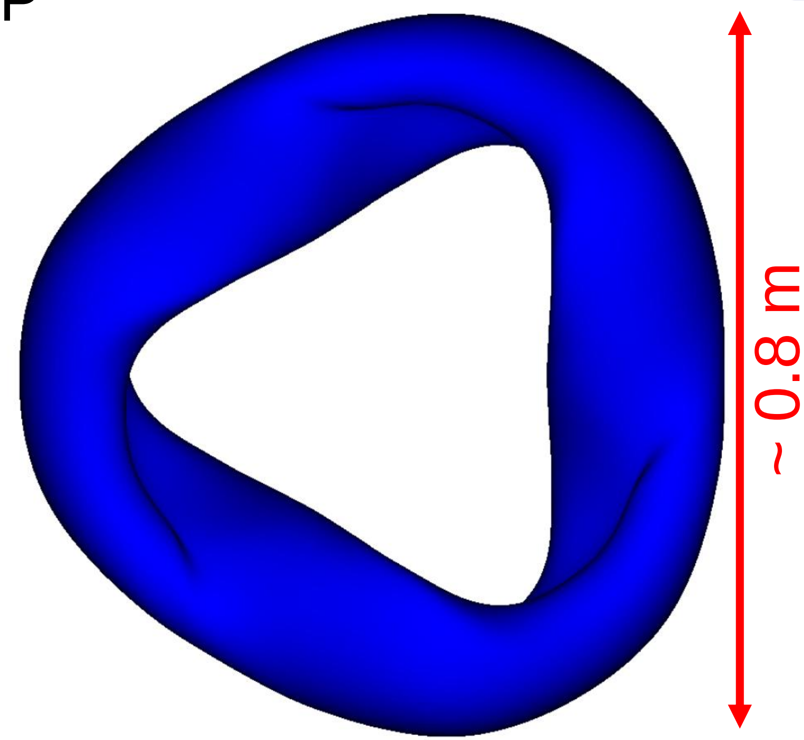
Reference magnetic configuration

The current reference configuration is a QIPCC of 3 periods

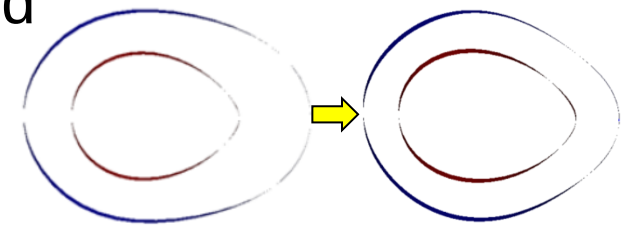
Only the magnetic configurations already developed by physicists and received from the authors are considered: Aries-CS, HSR-3, HSR-4, NCSX-TU, QPS, QIPCC 2P 3P and 6P

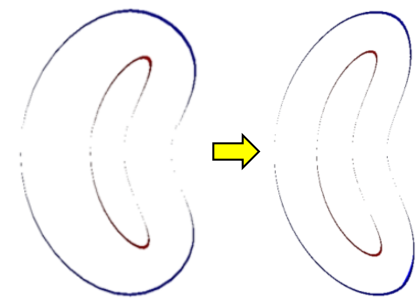


Last closed flux surface



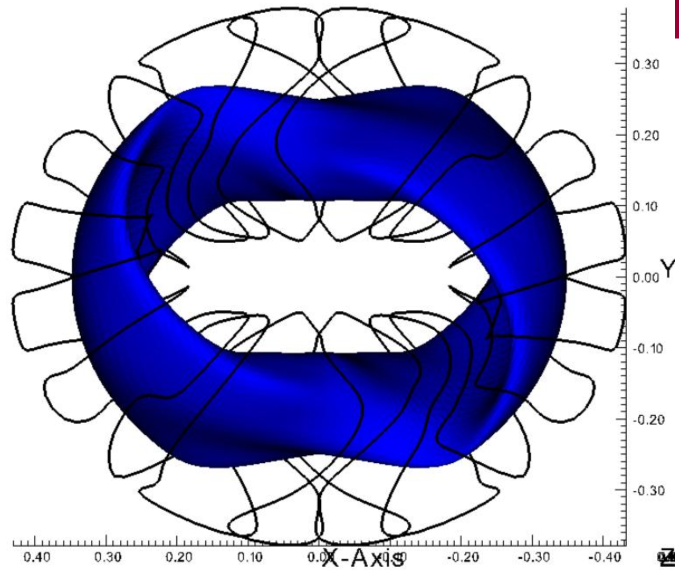
Winding surface



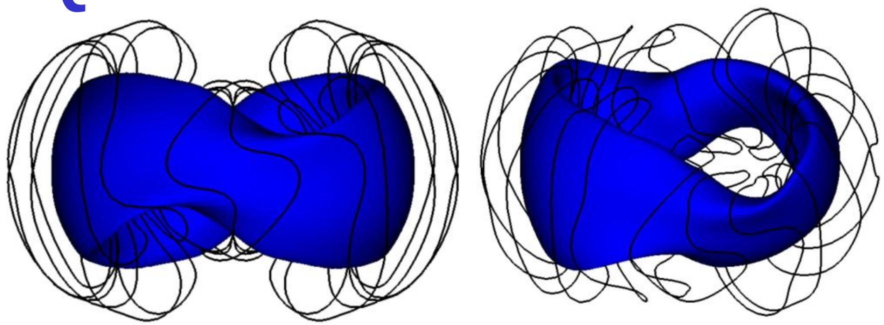


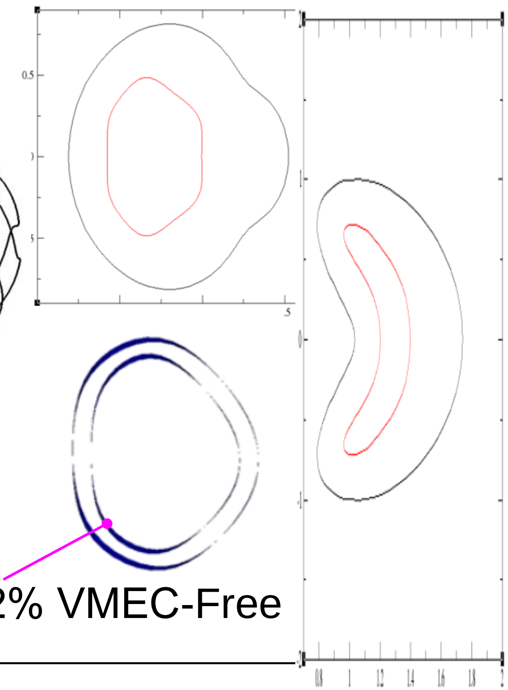
Cross sections of the plasma and winding surface

Several devices have been assessed

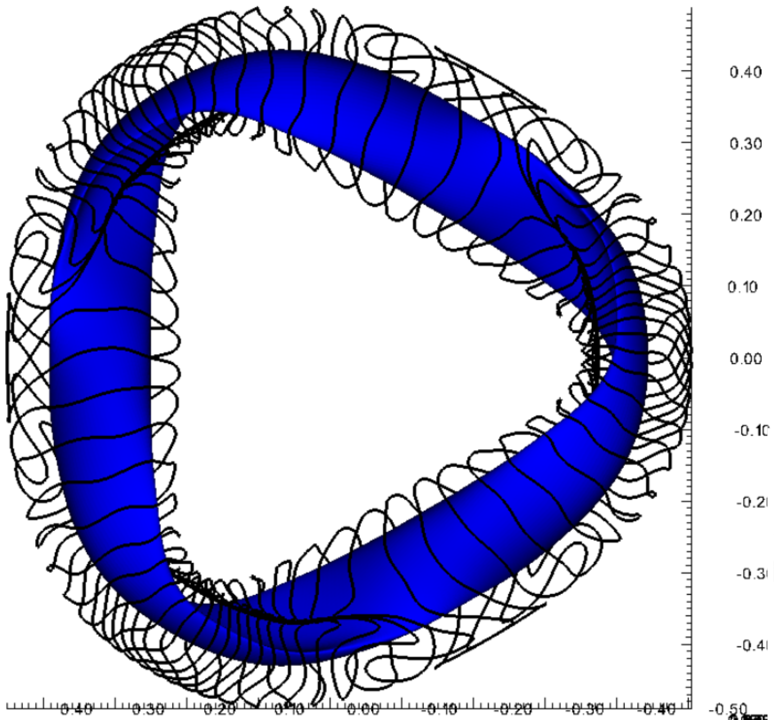


QPS

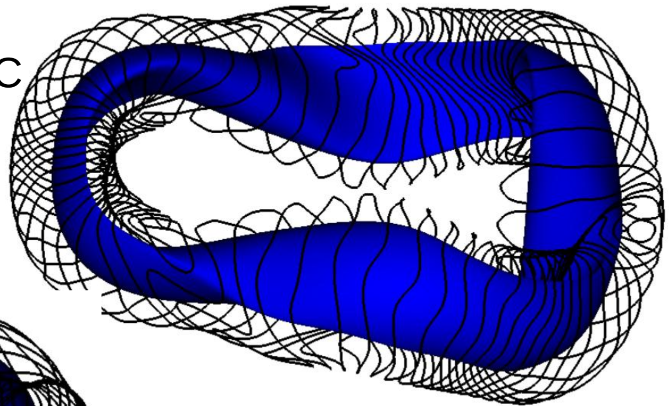




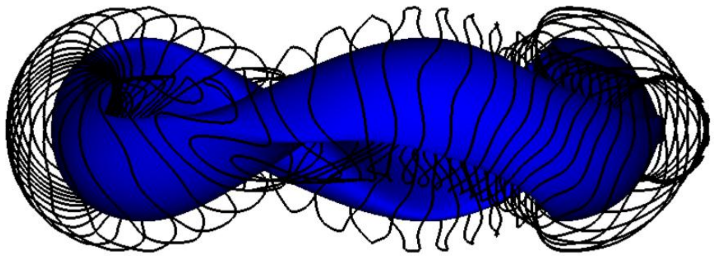
Iota ~[0.16 , 0.26] without Ip.
A ~ 2.7
From CASTELL and VMEC



Iota [0.67 , 0.71] A~6.8
From CASTELL ,[Mik 04],VMEC

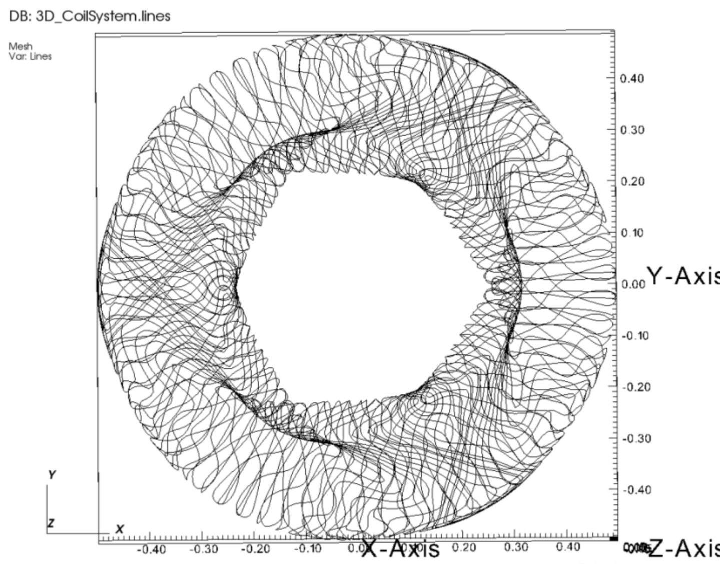


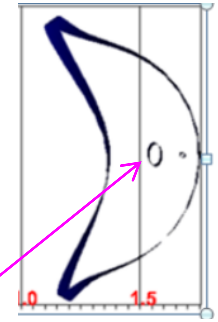
QIPCC3

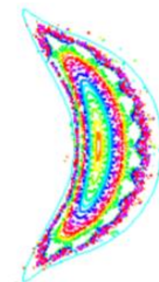


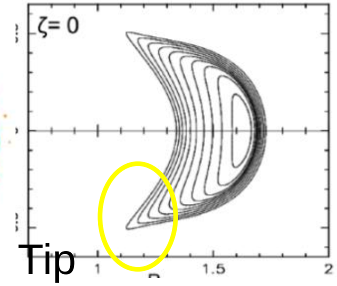
Several devices have been assessed

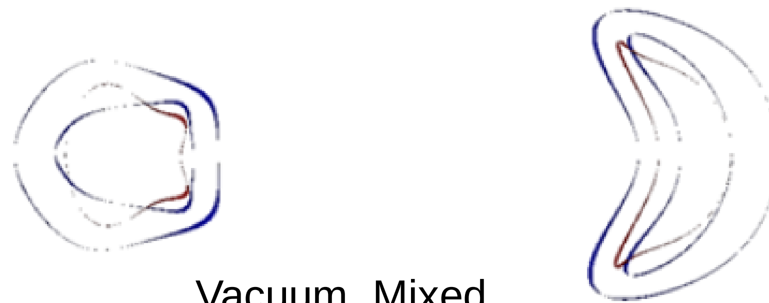
NCSX-TU
NCSX
Mix

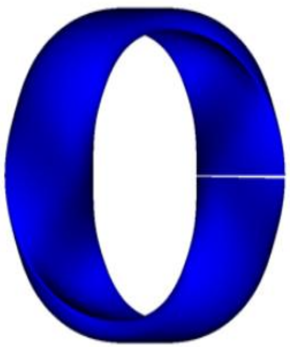


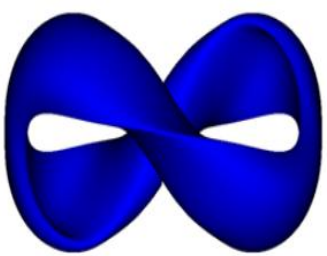




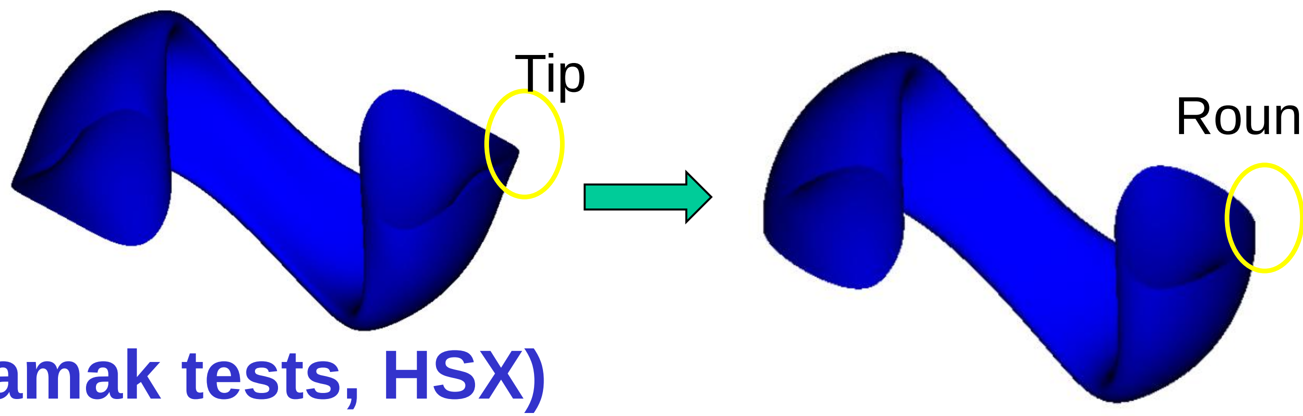








QIPCC2



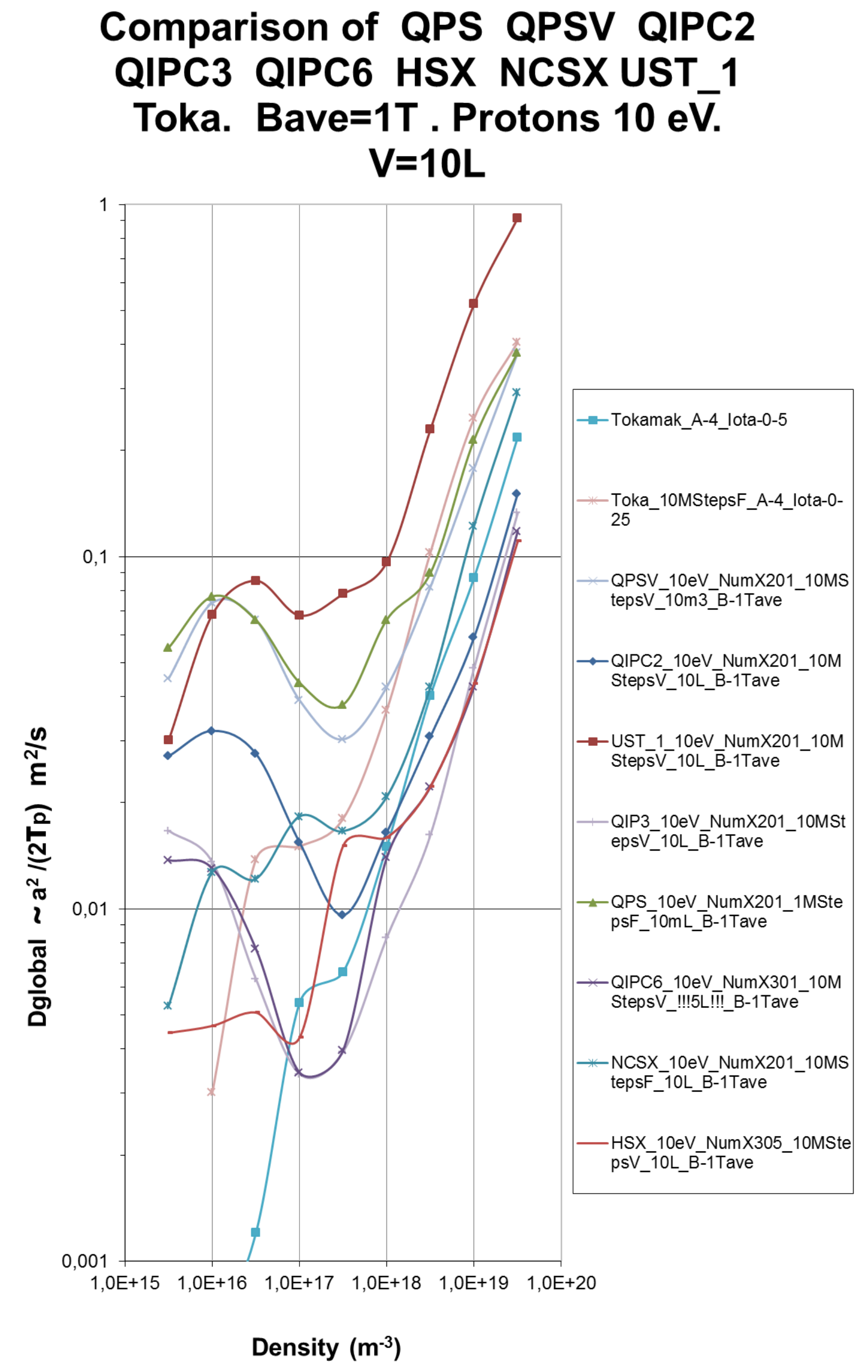
QIPC6, (three tokamak tests, HSX)

Thinking both in UST_2 size and reactor. Difficult balance of:

- Neoclassical confinement (~iota…).
- Expected turbulent confinement.
- Alpha particle confinement.
- Middle compactness (~inboard blanket).
- Simple control (~↓currents,↓shift, …).
- Reasonable coil shape and space.
- LCFS tips ~ cost ~ performance.
- Cost.

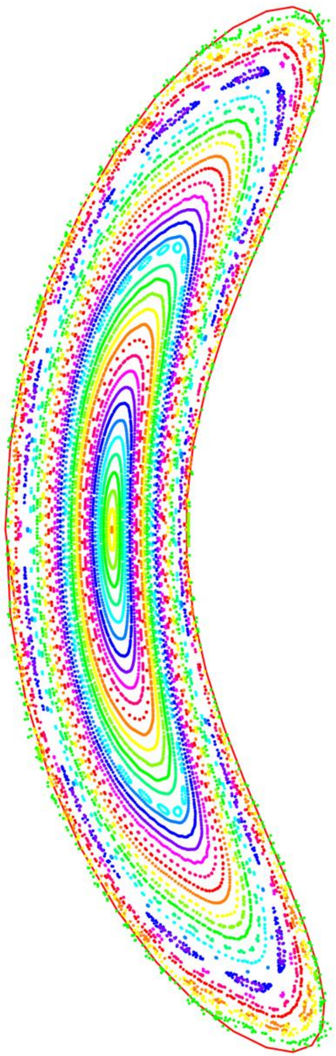
Neoclassical transport **estimation/comparison** of possible devices for UST_2.

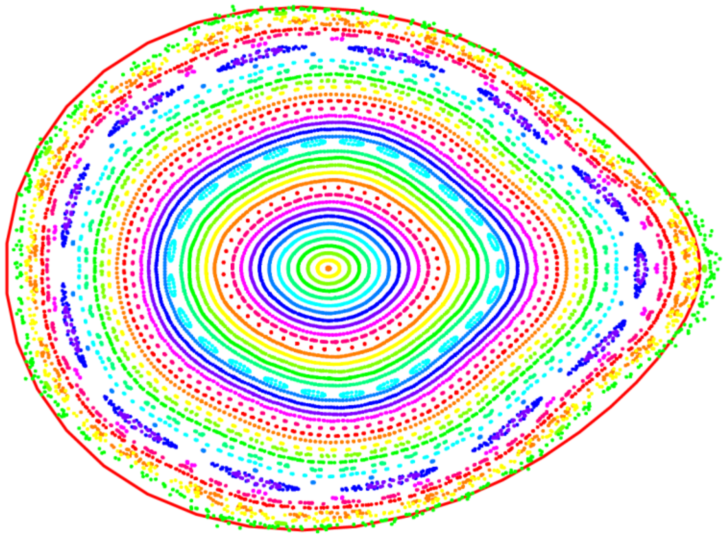
From CASTELL. **T**p = particle conf. time. E_r=0



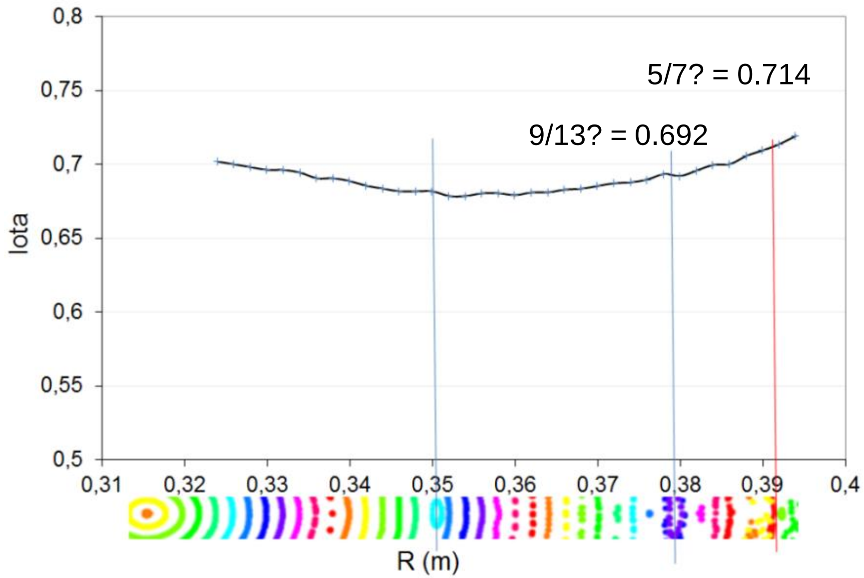
1st test. Generation of the original magnetic surf.

Result: Satisfactory reconstruction of surfaces using 180 and 72 coils='pancakes' for QIP3





Magnetic surfaces for QIP3 at φ = 0 . LCFS in solid red



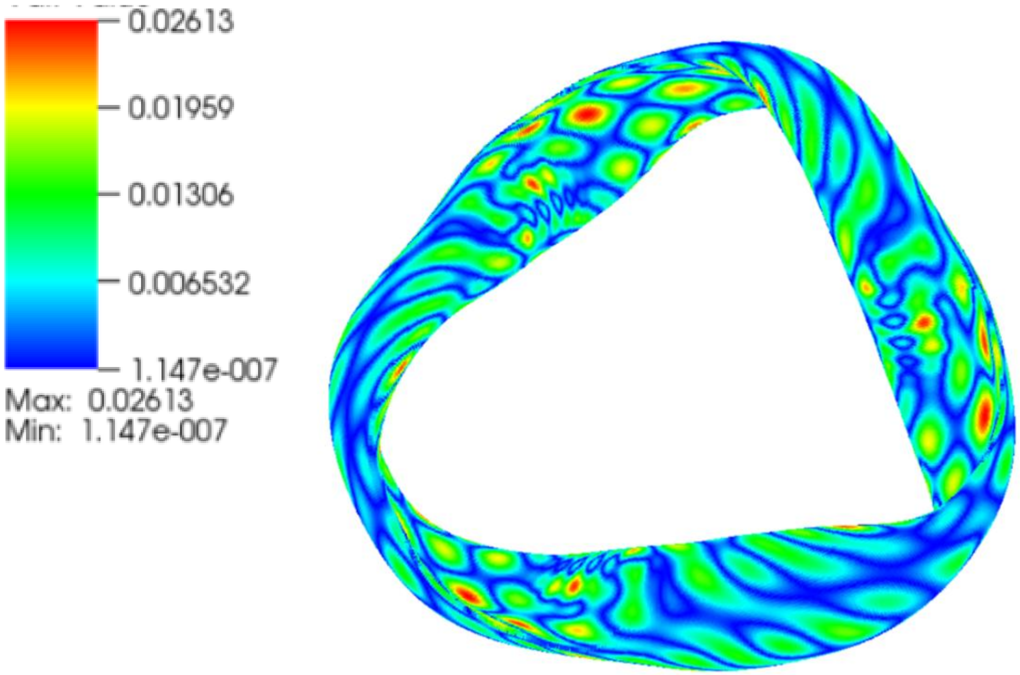
Iota profile from CASTELL

Iota = [0.67 , 0.71] from [Mik 04]

Magnetic surfaces at φ = π/3

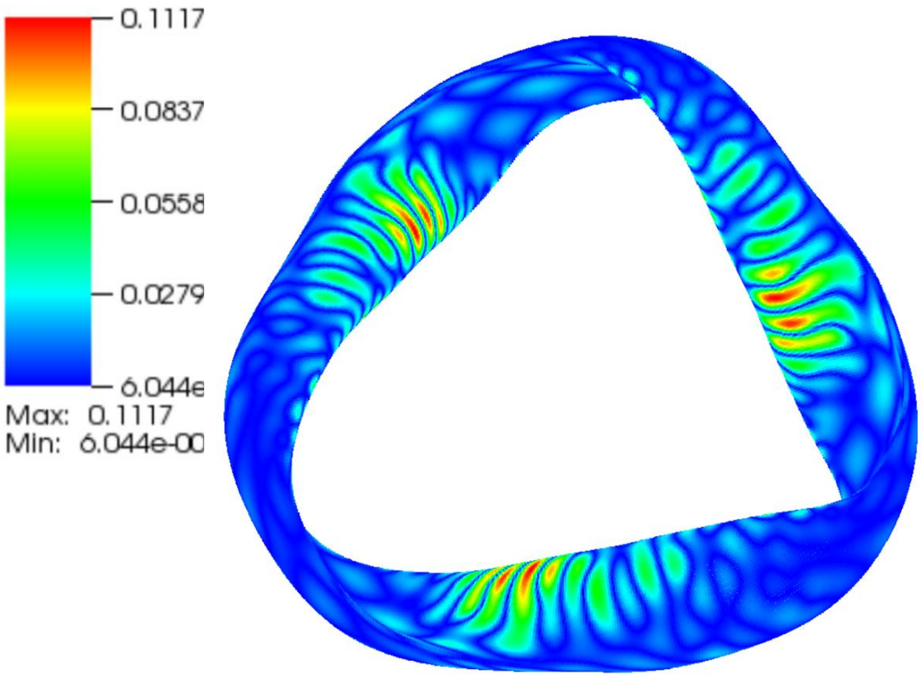
2^{nd} test. Balance number of coils ~ modular ripple

Result: ~72 ‘coils’=pancakes selected as starting point



Error of ***B·n*** (per unit) on the magnetic surface for **180 coils** (almost perfect). QIPCC configuration N_p=3

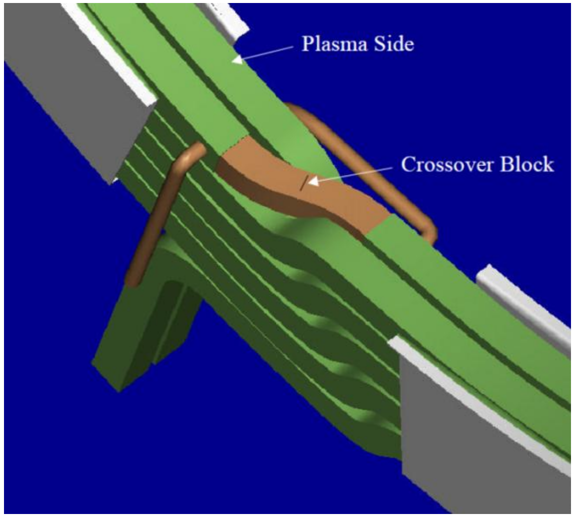
Ave. error: 0.70%
Maximum error: 2.6 %

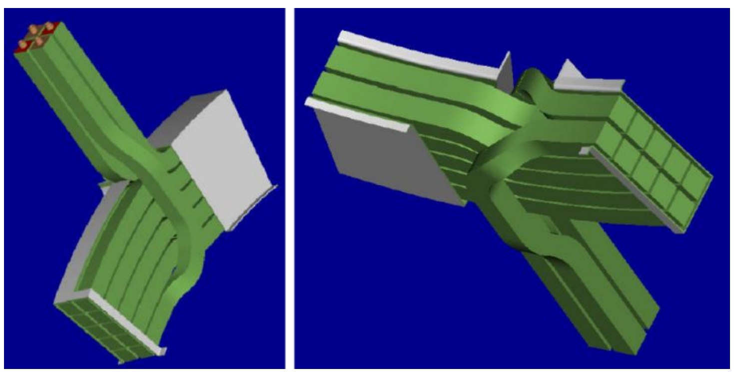


72 coils (real alternative). QIPCC3. ***‘Modular error’*** is observed.

Ave. error: 1.36% **>~ 1%** [Min 00]
Maximum error: 11 %

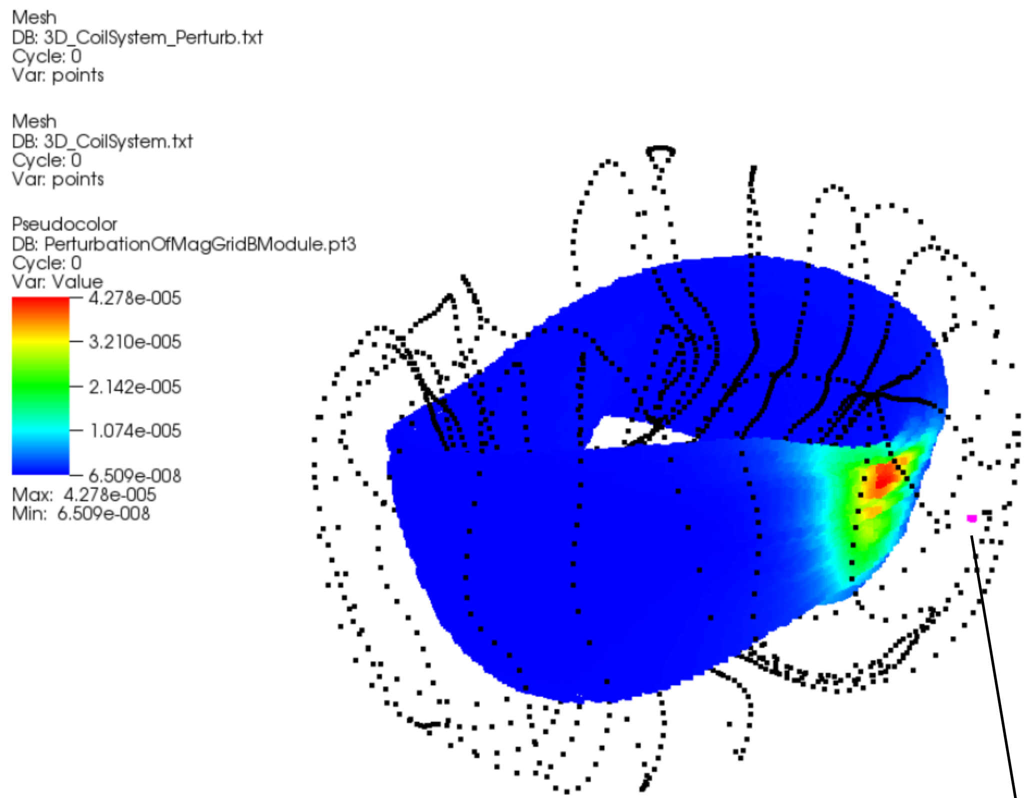
Result : ‘Symmetrised’ crossovers produce acceptable errors

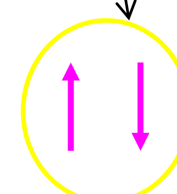




Two Types of crossovers.

Source of figures [NCS 98]





Magnetic ‘symmetric’ perturbation on the LCFS, 3.5mm length and parallel at 3.5mm distance, opposite currents. Scale in T, Bo =1T. QPS-(UST_2 Size)

Current reference design and future work

Decisions taken

Objetives + cost+schedule constrains → decisions

Decisions to take	Comments	Present reference
A) What magnetic configuration to chose?	Middle compactness, LCFS unchanged for any size, low turbulence potential, design available now, …	QIPCC 3P is the reference candidate
B) Size	A cost-reasonable size	Vp = ~ 10 Litres
C) Coils inside/outside the VV?	If inside: Coil frame material limitations or perfect coil closure required	Outside (likely)
D) Method to build: the coils, the coil frame …	3D printing, metal casting, moulding, milling, mix?	3D printing + moulding

Present status

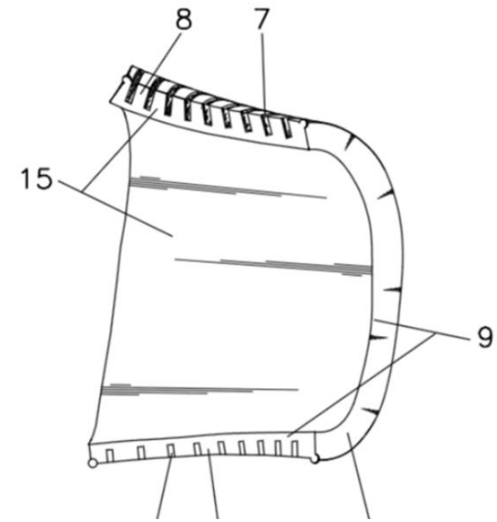
Initial tests performed ✓

Decision of device to build ✓

Conceptual design ✓

Detailed design ✗

Construction ✗



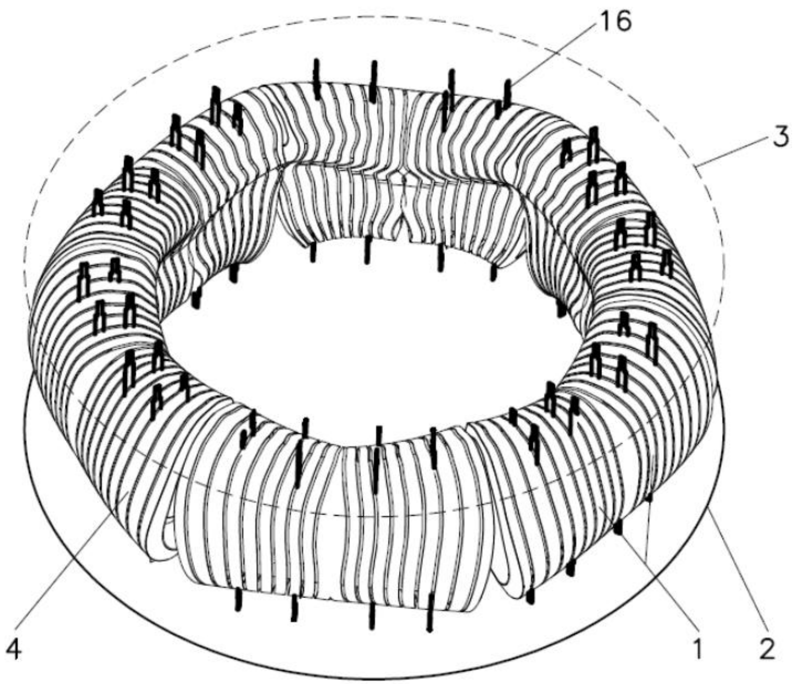
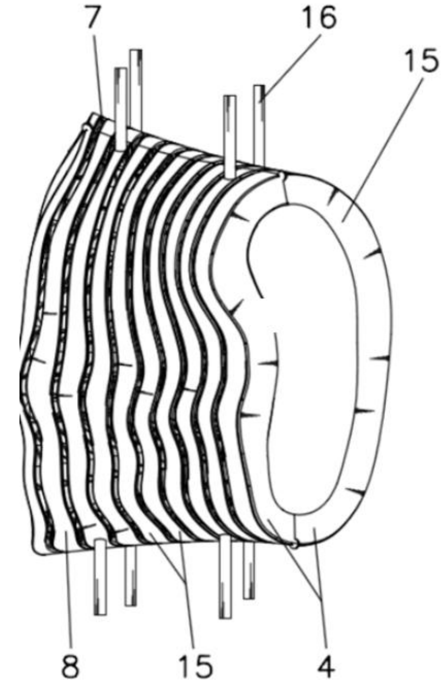


Figure depicting the assembling concepts (non-stellarator symmetry in this figure)



Concept of Hollow-Sparse pairs of pieces outside the VV

Future work

Short term : ~ 3-4 months

- Finish the engineering design.
- Try to rise funds in Kickstarter (**contributions are welcomed!**).
- Build UST_2 (independently if funds are raised or not).

Middle term: ~ 1 year (UST_3)

Design and raise interest and funds in CIEMAT, in any institution in Spain or in anyplace, in a **low-cost** device, likely a stellarator, of :
- **0.1 m^3** plasma volume.
- B_o =~ **0.5 T** (1 T).
- **Turbulence improved** (**you are invited to contribute!**) device with innovative **power extraction** (divertor or other?).

Questions?

Any contribution to UST_2-3?

Any synergy between groups or departments?

Any interest on me for something similar to this in LNF?

Acknowledgement

I would like to give thanks to **all** the people and researchers helping in the development, in particular:

Jefrey Harris and team (ORNL, QPS LCFS and coils)
Juergen Nueremberg and team (IPP Max-Planck, QIPCCs LCFS)
H. E. Mynick (PPPL, NCSX-TU LCFS)
Jesús Romero (NESCOIL teaching, other)
Antonio Lopez-Fraguas (DESCUR code)
Gerardo Veredas (CAD)
Juan A. Jiménez (VMEC teaching)
Víctor Tribaldos (stellarators)
Jose A. Ferreira (vacuum)
Cristobal Bellés (I. T. help)
Other

References

[Mik 04] “Comparison of the properties of Quasi-isodynamic configurations for Different Number of Periods”, M. J. Mikhailov et al., 31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.28G, P-4.166 (2004)

[Min 00] “Use of a Genetic Algorithm for Compact Stellarator Coil Design” William H. Miner et al., Dec 2000

[Myn 10] “Reducing turbulent transport in toroidal configurations via shaping” H. E. Mynick et al., PHYSICS OF PLASMAS 18, 056101 (2011), December 2010

[NCS 98] "Status of Non-Axisymmetric Coils Study". Presentation for NCSX Project Workshop, 23-25 September 1998

End

Thanks

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Extra slides

Matters for discussion and future

We could talk about many other matters, i.e.:

- Why QIPCC3 and not QIPPC6 or QIPPC2 or NCSX-TU or …?.
- VV construction method (still not clear for low cost).
- Why such winding surface and not others?.
- Bo, Te, n, neoclassical transport and other physics parameters.
- Stress on coil frame and limit of Bo for certain materials.
- Why 3D printing+moulding and not casting or milling or …?.
- Material for the frame: Metal, plastic, resin, plaster, concrete, ceramics?.
- Many others.

but, better **when the development will be more advanced**