UST_1 stellarator and

Status of the 3D printed UST_2 stellarator

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** On leave of absence from NFL, CIEMAT*

UYING Fusion Energy™

Outline

Background
Basic UST_1 and UST_2 data

Design, construction and results in UST_1

- **Conceptual design of UST_1**
- **Engineering design. Development of a construction method**
- **Validation of the construction method and design**
- **Results and conclusions**

Status of the 3D printed UST_2 stellarator

- **Experimental validation of engineering concepts**
- **Conceptual design**
- **UST_2 engineering design. Fabrication tests**
- **Future work**

Background

► I am on a **leave of absence** period from the National Fusion Laboratory, CIEMAT, Spain.

► I worked in CIEMAT for almost 5 years, in Remote Handling, for IFMIF (International Fusion Materials Irradiation Facility), ITER and DEMO.

► Up to now, I have developed the work on stellarators on my own, with personal funds (for three years before CIEMAT work, at nights and weekends during CIEMAT work, and now 1.5 years during the leave of absence), with some help and contribution from CIEMAT.

► **The work is R&D and innovation in engineering,** focused in new **construction methods** for stellarators**. It is not focused on physics and plasma experiments.**

Basic UST_1 data

UST_1 modular stellarator

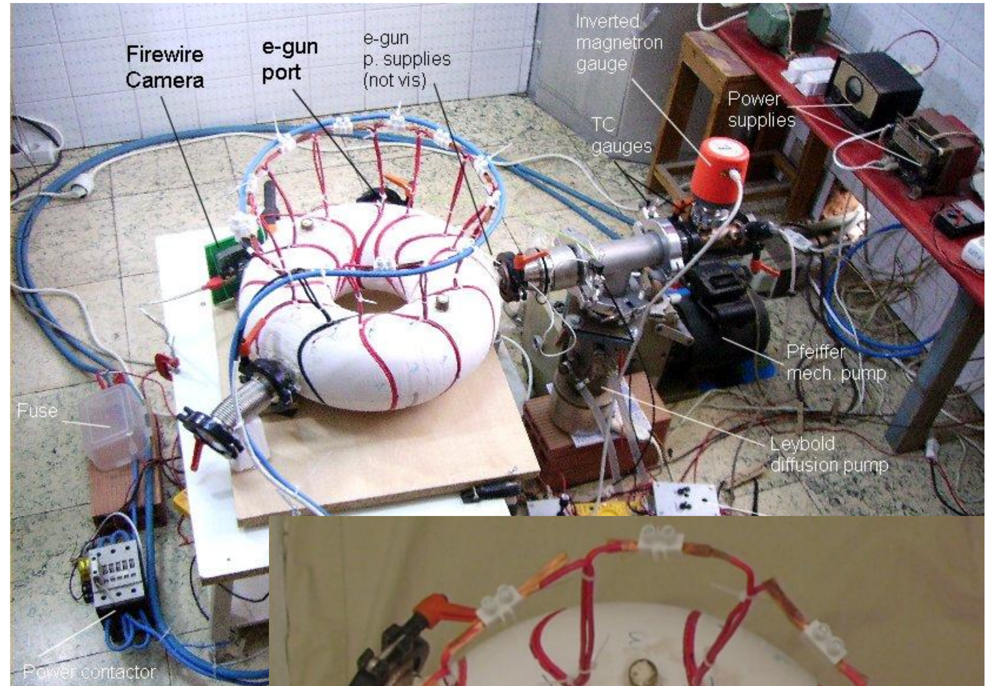
• UST_1 stellarator was designed, built and operated from 2005 to 2007 in my personal laboratory.

• Cost of the whole facility ~ 3000 € (many 2nd hand pieces).

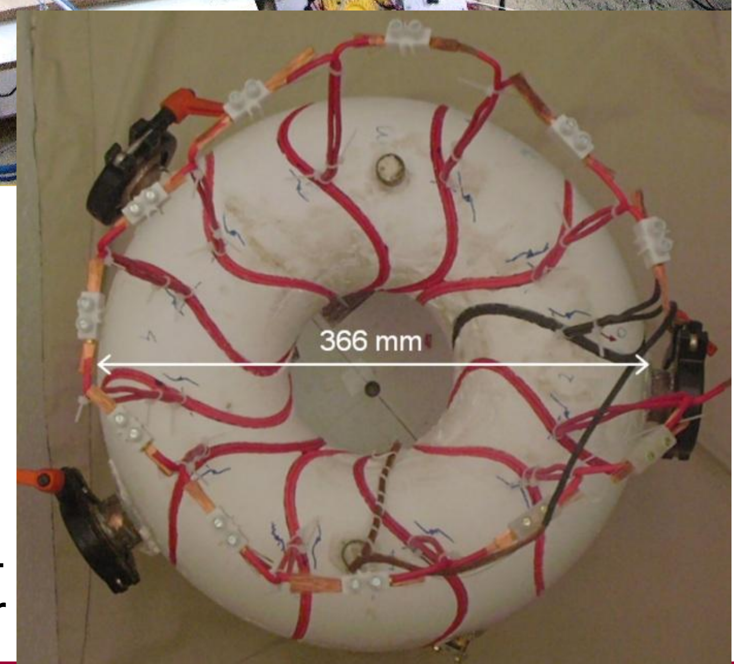
• The coils were built by a new **toroidal milling machine.**

• Correct field line mapping magnetic surfaces were obtained. Also (poor) plasmas obtained.

• **Motivation**: Formation, develop innovative construction methods for stellarators, demonstration effect.



UST_1 facility



UST_1 stellarator

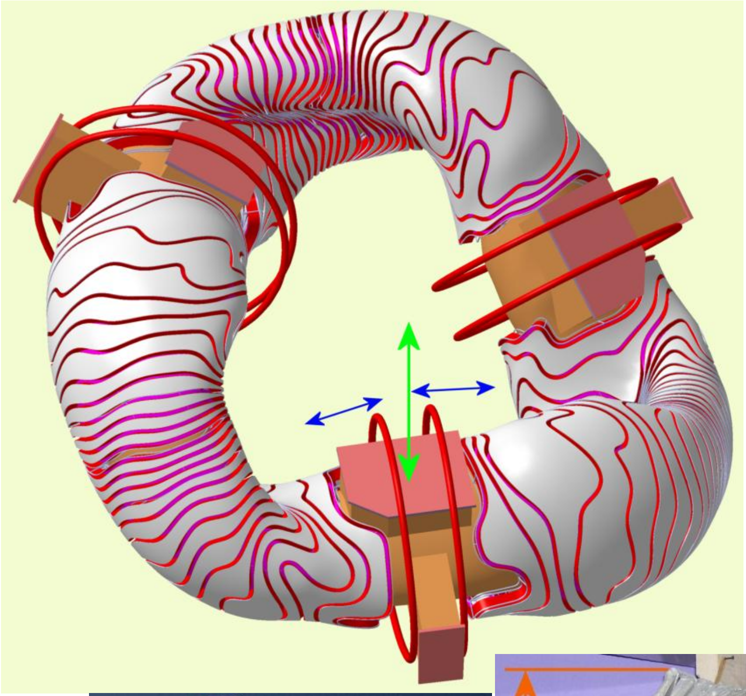
Basic UST_2 data

UST_2 modular stellarator

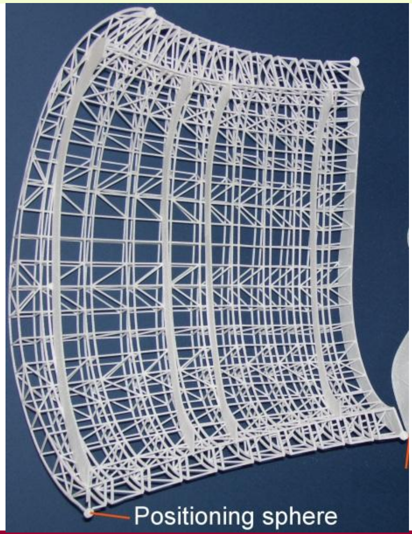
- UST_2 stellarator has been designed during 2nd 1/2 2012 and 2013 (still some elements remain).

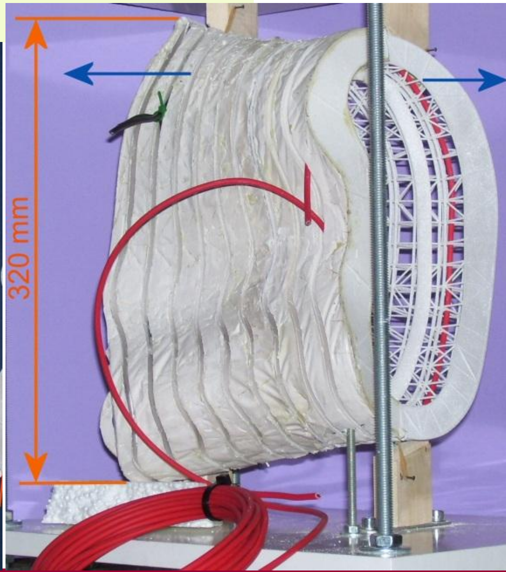
- Early **integration** of the **design** with the **production method** is performed. UST_2 conceived to be produced mostly by **3D printing**.

- Test prototypes of pieces for UST_2 have been produced.



UST_2 concept and design





3D printed prototype and torus sector test

Design, construction and results in UST_1

Conceptual design of UST_1

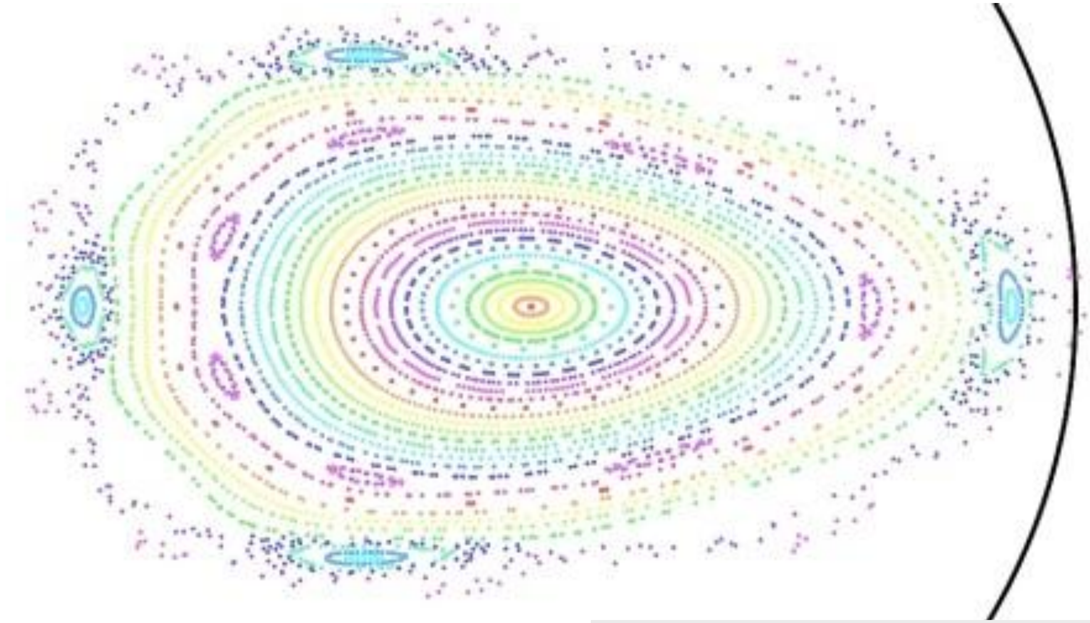
UST_1 objectives and specifications

Technical objectives

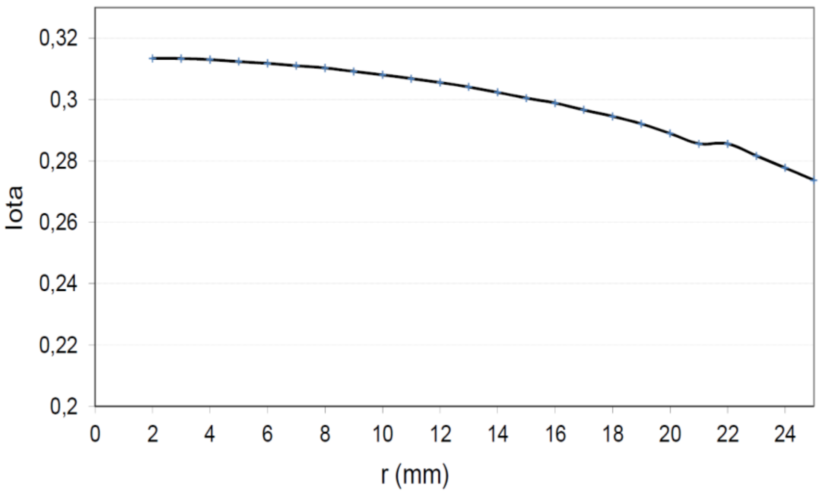
- A relatively compact stellarator was aimed. First a small tokamak was estimated.
- Simple winding surfaces (to finish the construction with the available funds).
- Basic confinement properties (no low order islands, B_{min}, etc).

Element	Specifications
Number of periods	2
Plasma volume (litres)	1.1
R, plasma major radius (mm)	125.3
a, ave. plasma minor radius (mm)	21
Aspect ratio	~ 6
B_o Magnetic field at axis (T)	0.089 / 0.045
ι_0 , rotational transform at axis	0.32
ι_a , rotational transform at edge	0.28

Physics characteristics

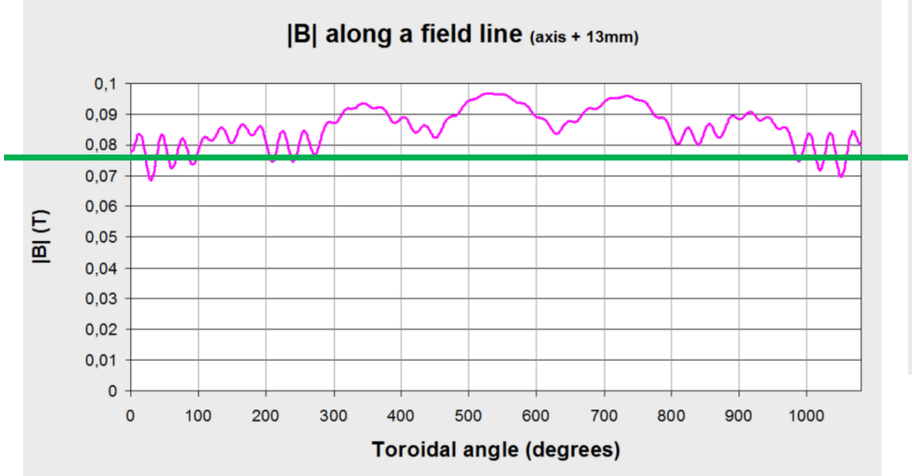


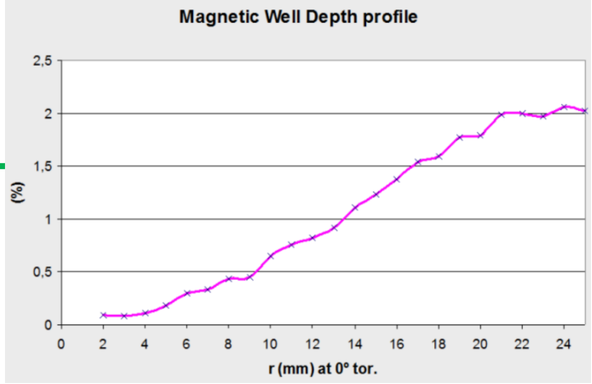
Vacuum Poincaré plot, φ = 0º



Iota profile. Tokamak-like shear !

All obtained by CASTELL code





Magnetic Well profile

Essential features of UST_1

Coil engineering specifications

Element	Specification
Type of coils	Modular coils
Number of coils	12 (3 shapes)
Shaping Parameters of the coils*	1.45, 1.3, 1.55, 0.65
Winding pack size (mm)	7 with x 10.5 depth
Conductor type	Special flexible copper wire
Turns per coil	3 layers x 2 turn/layer = 6
Winding surface shape	Circular, poloidally and toroidally

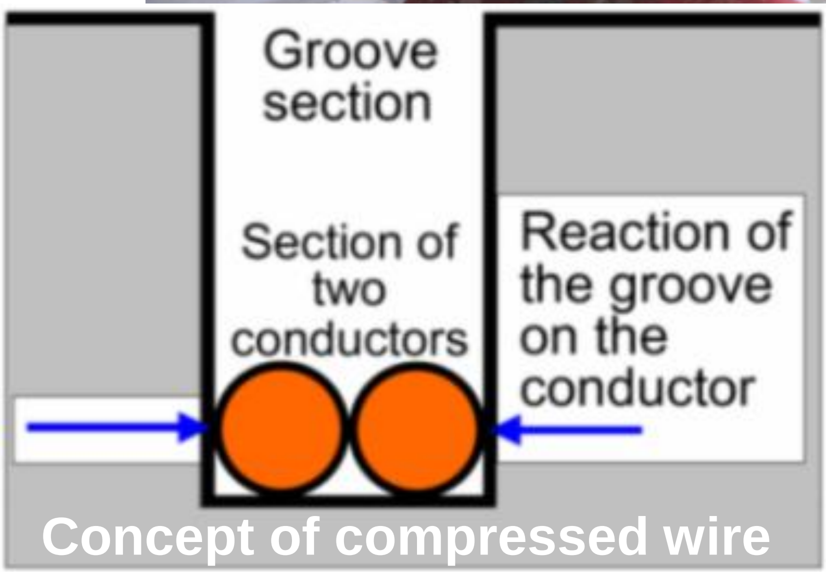
* Four parameters defining the amplitude of a sinusoidal deformation of the coil at four different poloidal angles. Obtained by optimization with CASTELL code

Positioning and winding concept

Two main concepts are developed

- The frame supporting the coils is a single **monolithic frame**. Thus, coil positioning and mechanizing is the same process, very accurate.

- The conductors are **compressed** on the groove walls to avoid the use of numerous fasteners. Then, maximum two turns per layer are convenient.

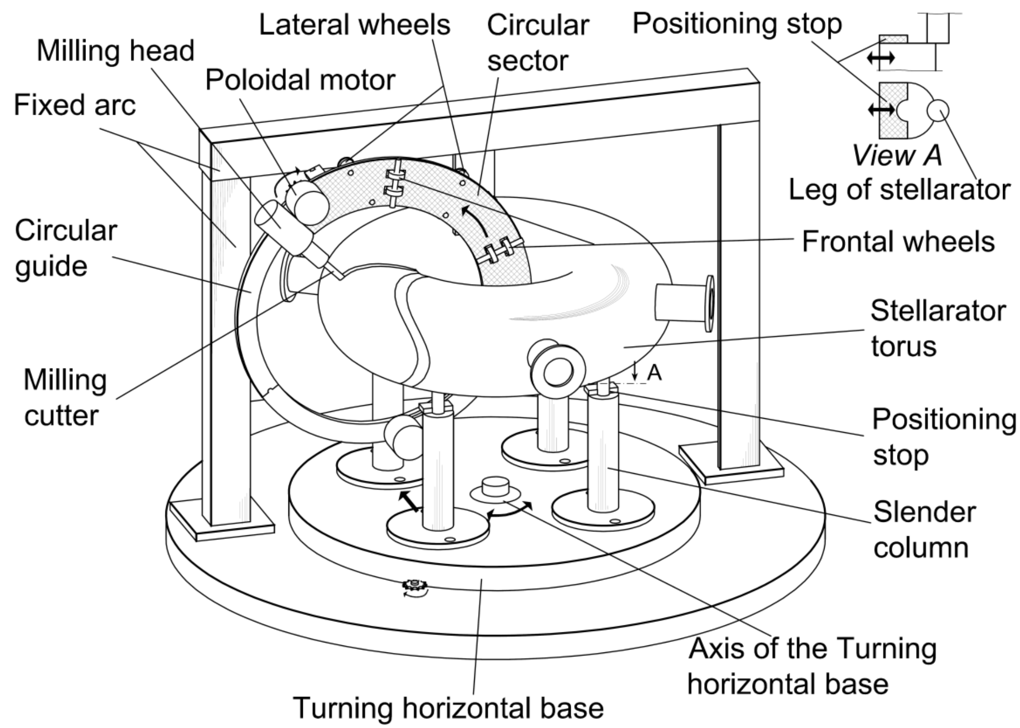


Engineering design. Development of a construction method

Method to build the modular coils

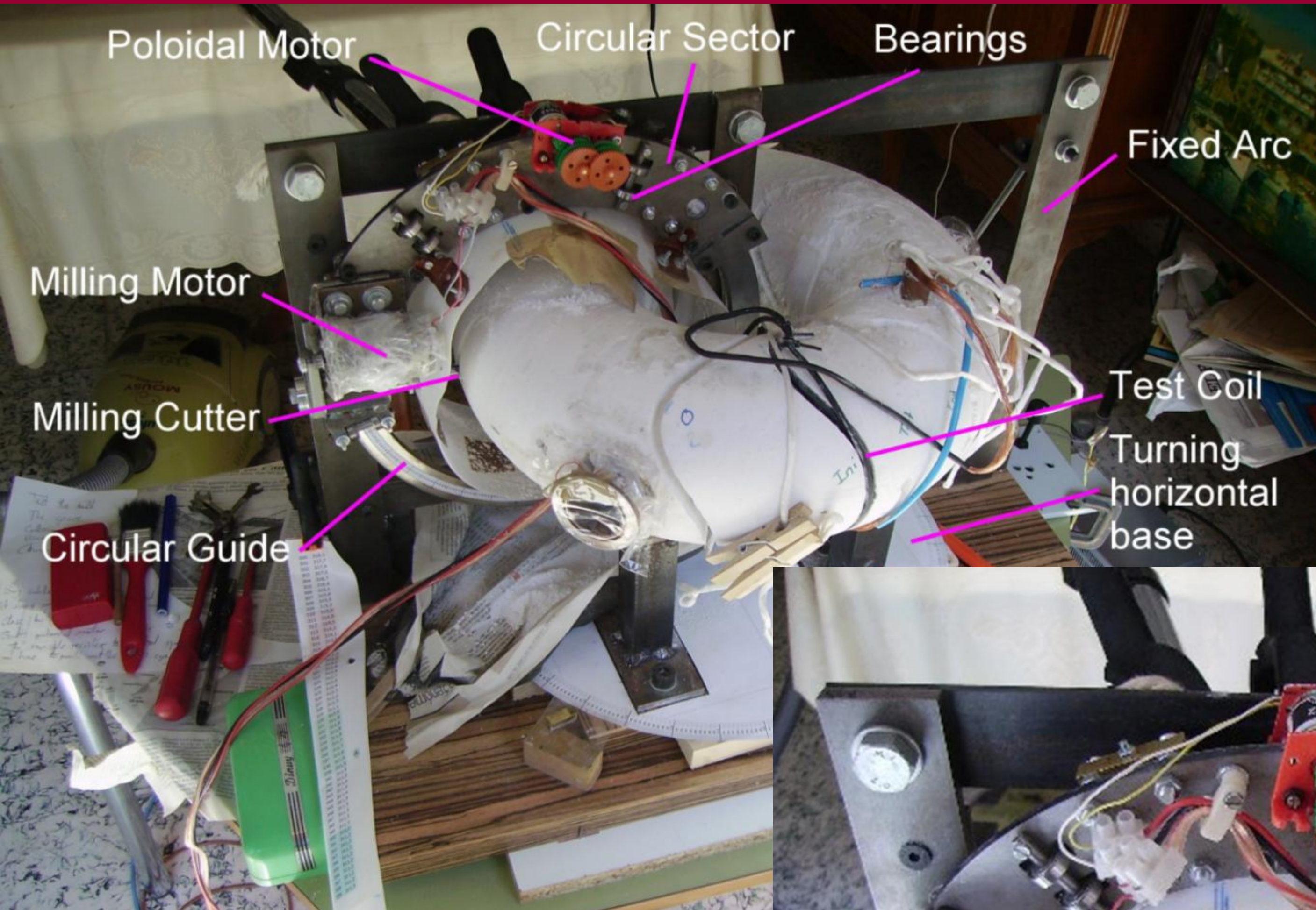
Concept of a toroidal milling machine for stellarators

- The milling head of this special milling machine moves in toroidal and poloidal coordinates.
- The surface being mechanised is not removed from the supports (*Slender columns*) for the whole mechanization → simplicity and reduced field errors.
- Main elements: turning horizontal base, fixed arc supporting a circular guide, and milling head.



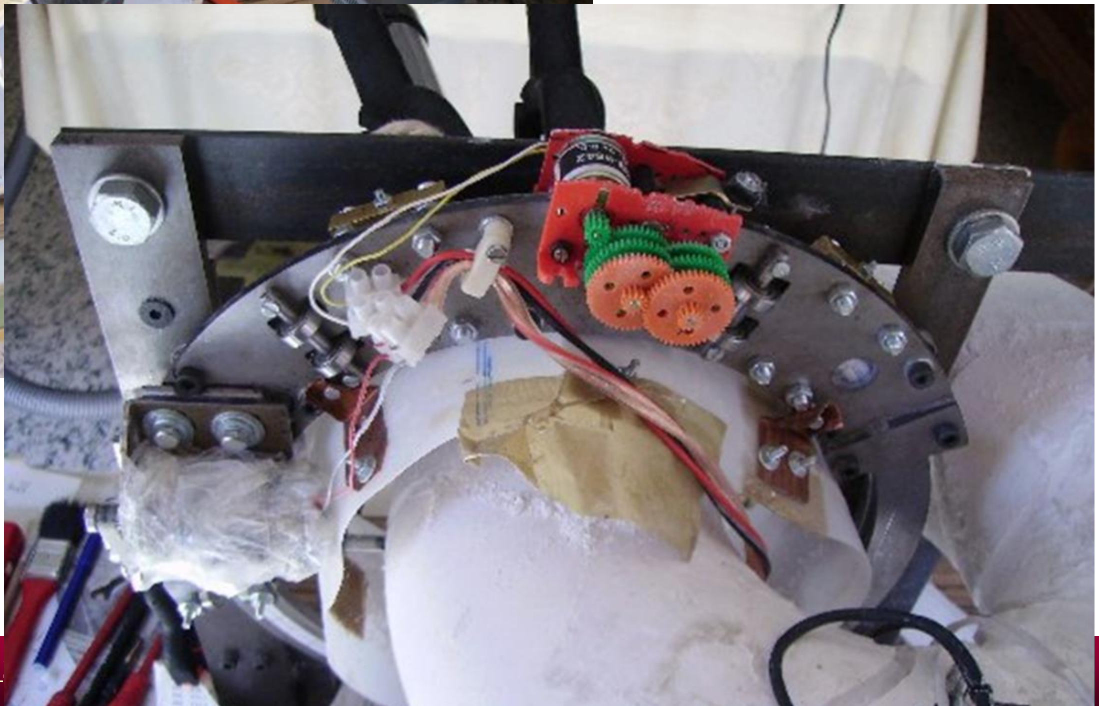
Schematic view of the toroidal milling machine

Method to build the modular coils



12 grooves 7 x 12 mm were mechanised in the plaster frame. Each groove lasted about 2 hours

Implementation of the toroidal milling machine concept



Detail

Method to build the modular coils

Advantages and drawbacks of the toroidal milling machine

► Positioning and adjustment of the coils or frames is not necessary because all the grooves are mechanised on a single toroidal surface.
► Fabrication errors of the grooves are similar to the ones in CNC machines, very small.

► Construction time is reduced and the process simplified.

♦ This milling machine might be unsatisfactory for very convoluted non-circular winding surfaces (i.e. W7-X, NCSX) and compact devices (i.e. QPS), since the inboard part of the coils are very convoluted in a small space, and due to collision of the head at the central torus hole.

Moulding the winding surface

Creating the porexpan mould

Roughing the surface

Vacuum vessel wrapped (thermal expansion layer) inside the mould. Plaster is poured.

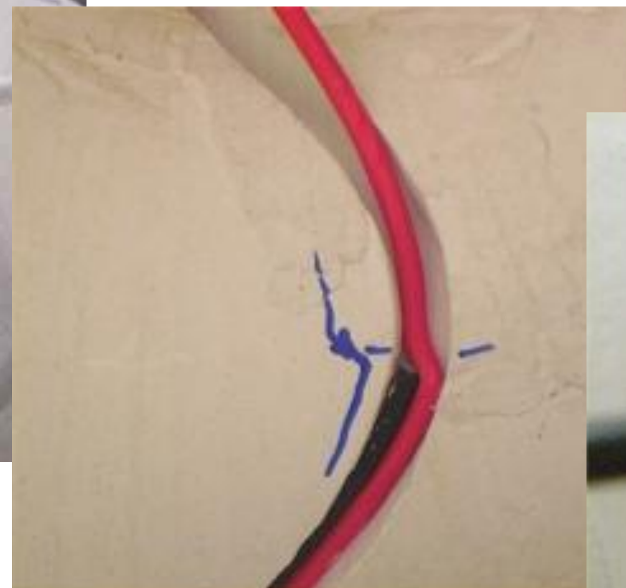
Accurate circular torus

Groove fabrication by method described

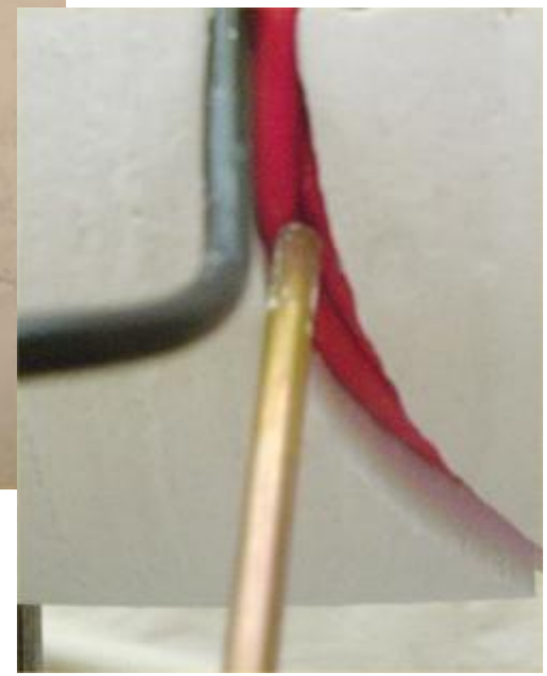
Vacuum vessel

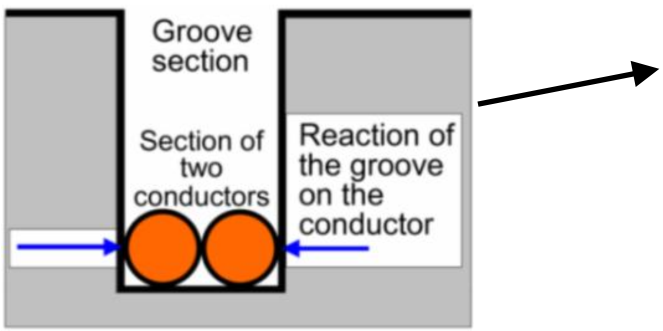
Winding process

Grooves mechanised in the plaster frame



Implementation





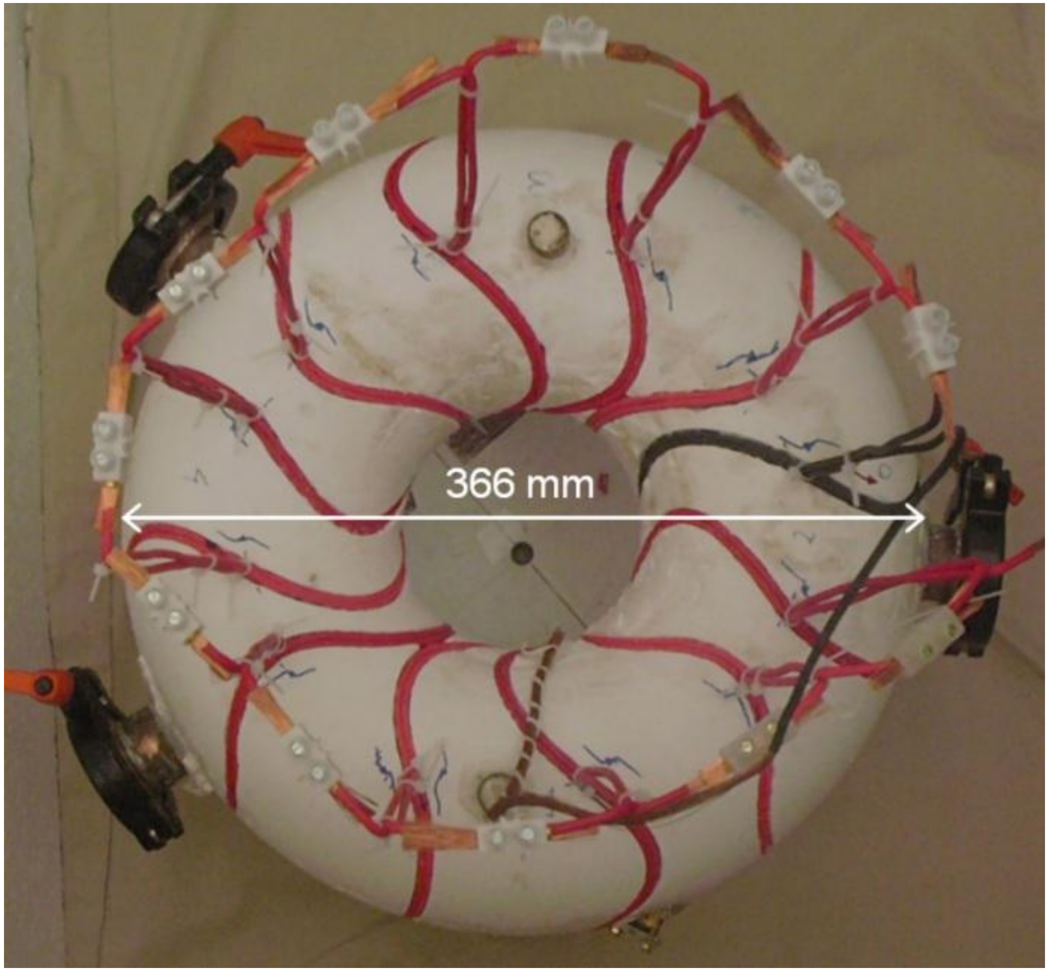
Concept

Internal crossover and auxiliary winding coil (black conductor)

Compressing and placing conductors in the groove

Finished UST_1 stellarator

Almost finished

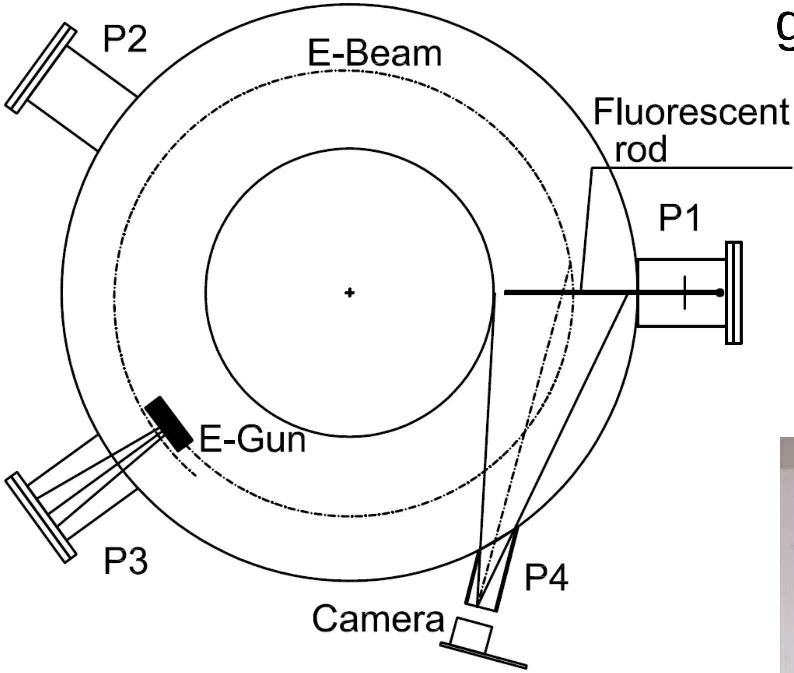


12 coils finished

Validation of the construction method and design

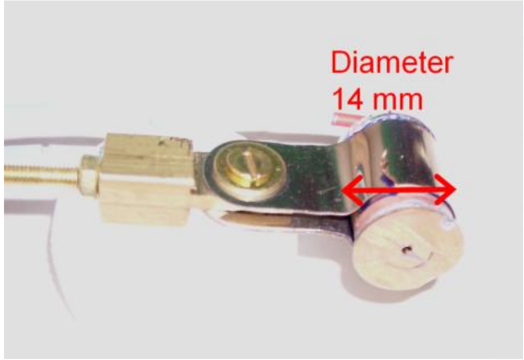
Field line mapping experiments

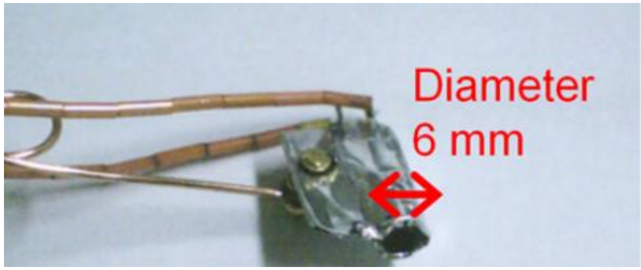
E-guns made in-site

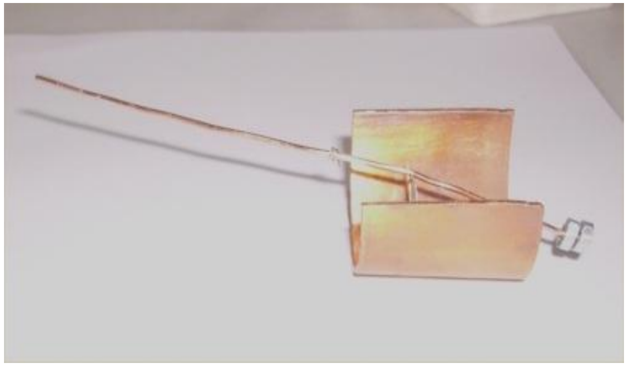


Field line mapping experimental setup

14 mm diameter (top) and 6 mm e-gun (bottom).



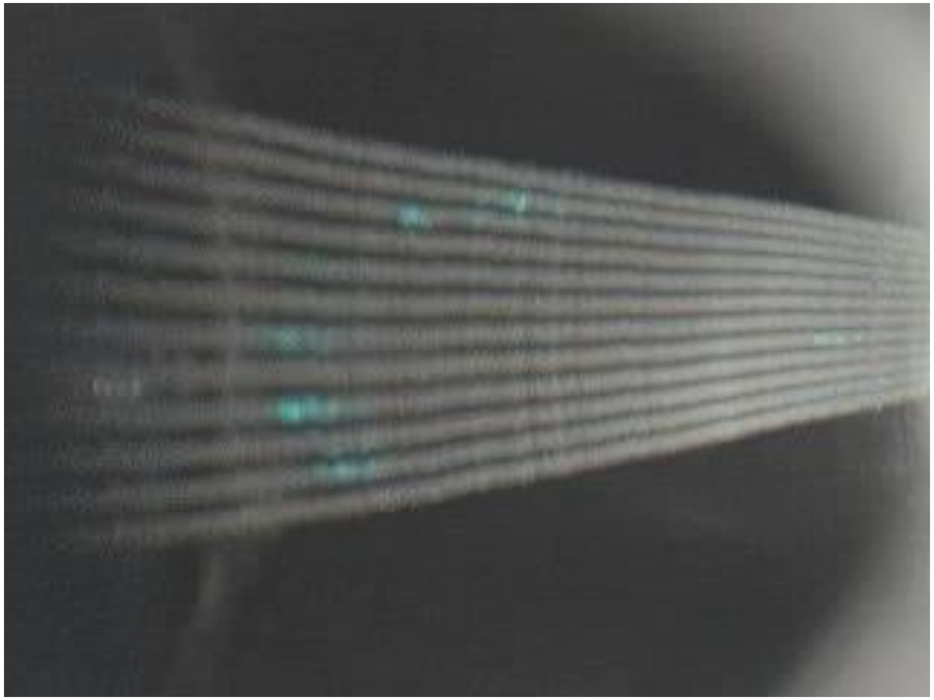




Oscillating fluorescent rod, **simple and economical method**. Port P1

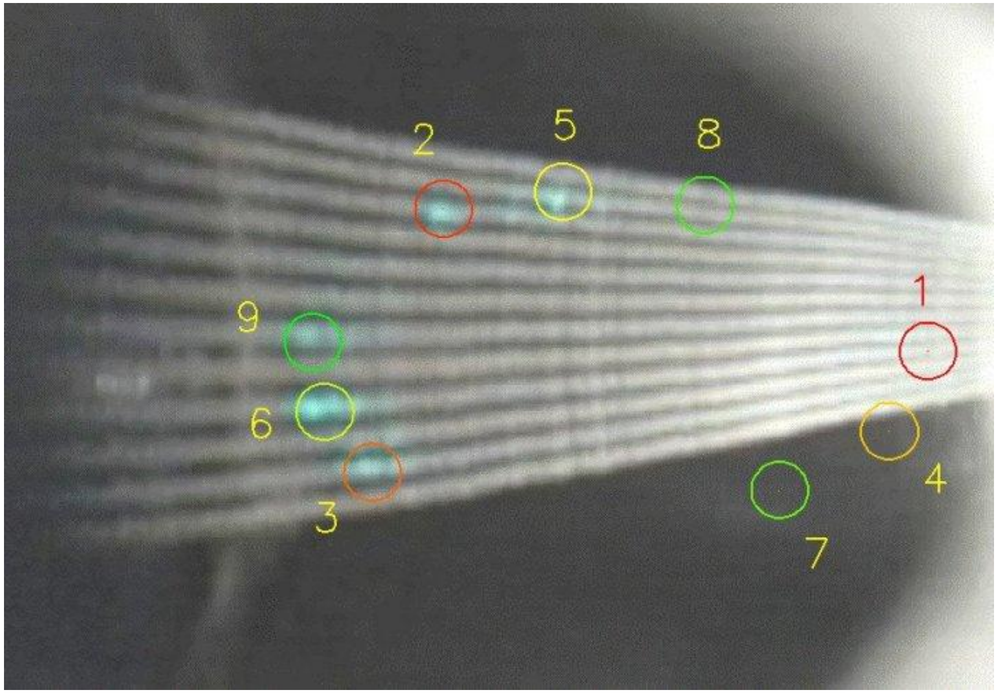
Field mapping experiments

Recorded magnetic surfaces. Comparison calculation-experiment



Pulse #202. Experimental fluorescent points on the oscillating rod. 94 eV beam.

N202_F70-135.mpg



Pulse #202. Overlapping of calculated (numbered circles) and experimental points. Notably agreement is observed.

Results and conclusions

Results and conclusions

► A low cost stellarator has been built and validated.

► The combination of a single monolithic frame with grooves and compression of two turns per layer in the groove resulted in simple and accurate positioning of the coils and fast winding.

► A construction method for stellarator coils based on a new toroidal milling machine has been developed.

► A particularly simple and economical e-beam field mapping system has been devised and utilized.

► Inspiration and encouragement has been generated in other researches and countries. For example, the SCR-1 stellarator being built in Costa Rica is based on the UST_1 design and construction methods.

► UST_1 has contributed to the formation of plasma and fusion engineering students.

Questions?

More information in www.fusionvic.org

Status of the 3D printed UST_2 stellarator

Introduction

- The work with UST_2 is a continuation of the UST_1 one.
- Essentially it tries to test the **feasibility of 3D printing construction methods** for small stellarators. Larger ones in a future!.
- Up to now UST_2 has been funded by me.
- The **budget for materials is very low**, **~5-10 k€. It will depend on contributors (Crowdfunding, other institutions…).**
- Some means (codes,…) from CIEMAT are utilized. Help from fusion expert colleagues has been received.
- UST_2 plasma volume is 10 times larger than UST_1, V_p=10 litres.
- Remember that the **work is R&D and innovation in engineering. It is not focused on physics and plasma experiments.**

Introduction

General objectives of the UST_2 project:

- 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.
- The stellarator should achieve enough quality to be used by a university, for formation and basic plasma experiments.

Technical objectives of UST_2 (and UST_3):

i) Innovative construction methods to lower costs and speed up the production cycle.

ii) As much as possible, turbulence (and neoclassical) optimization.

iii) Potential for innovative divertor implementation.

Decisions to take

Objectives + (cost + schedule) constrains → decisions

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

Initial decisions to take (same as UST_1)
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, and the VV
E) Material for the coil frame

D) The concept of ***Filled-Sparse*** pieces was **concocted**: 3D printed hollow light structures composed of narrow beams and optionally thin external walls, filled with a material able to solidify (resin, plaster, etc, fibre reinforced or not)

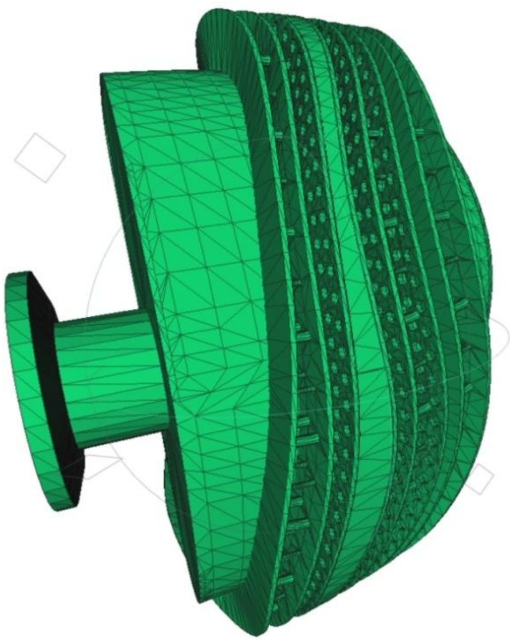
Experimental validation of engineering concepts

Hull Concept

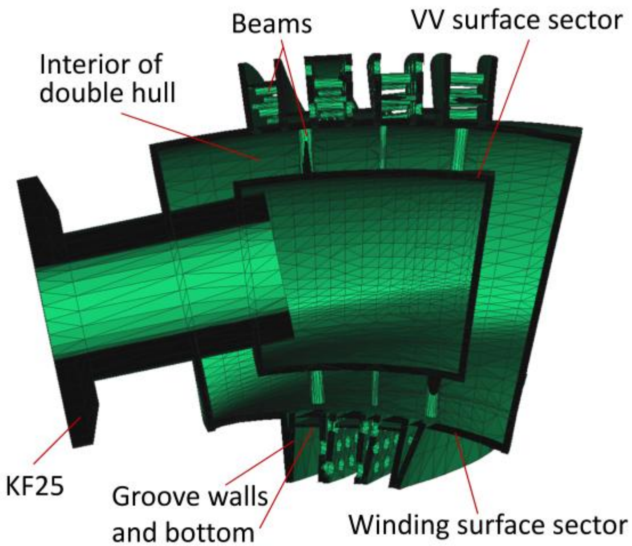
Devised as a double hull structure moulded with a filler

Combination of a sector of the winding surface, a sector of the VV surface, and beams. The internal volume is filled with a material able to solidify.

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



External view of the torus sector test

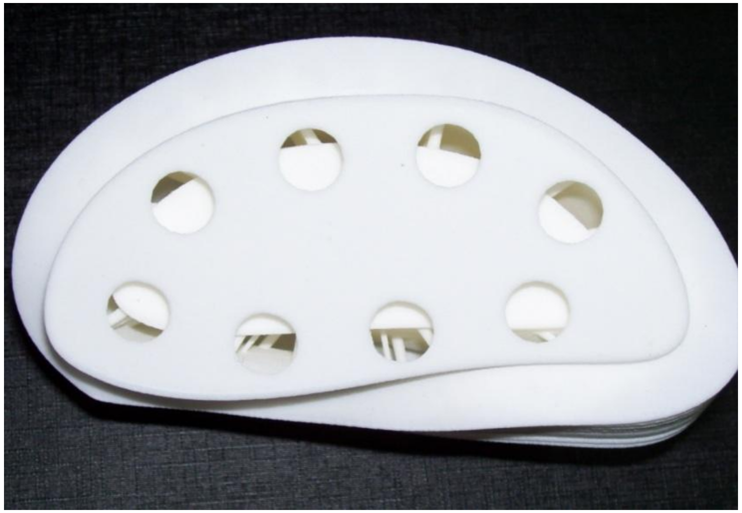


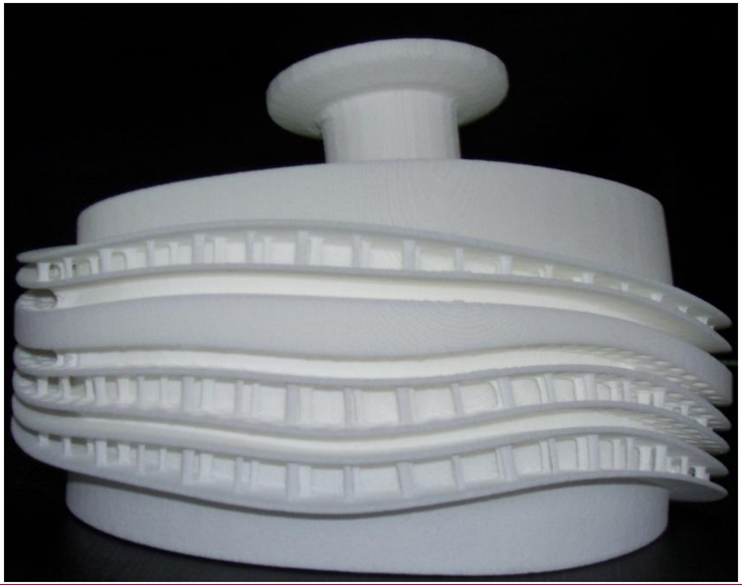
Cut of the sector

3D printed test sector of coil frame

Hull Concept

Results: Robust, dim. errors 0.4% non-isotropic, cost ~∝ R^2





3D printed piece. Nylon. **80 €**

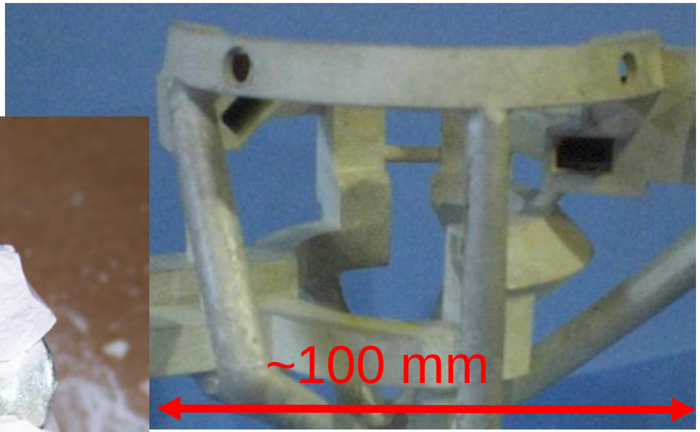
It has been filled with dental plaster and with molten Bi-Sn-Pb alloy

Low-cost coil metal casting tests

Results : Inconclusive. Casting not chosen for UST_2

- The coils, the coil frame, the VV, 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.
- A **permanent** plaster mould has been tested.

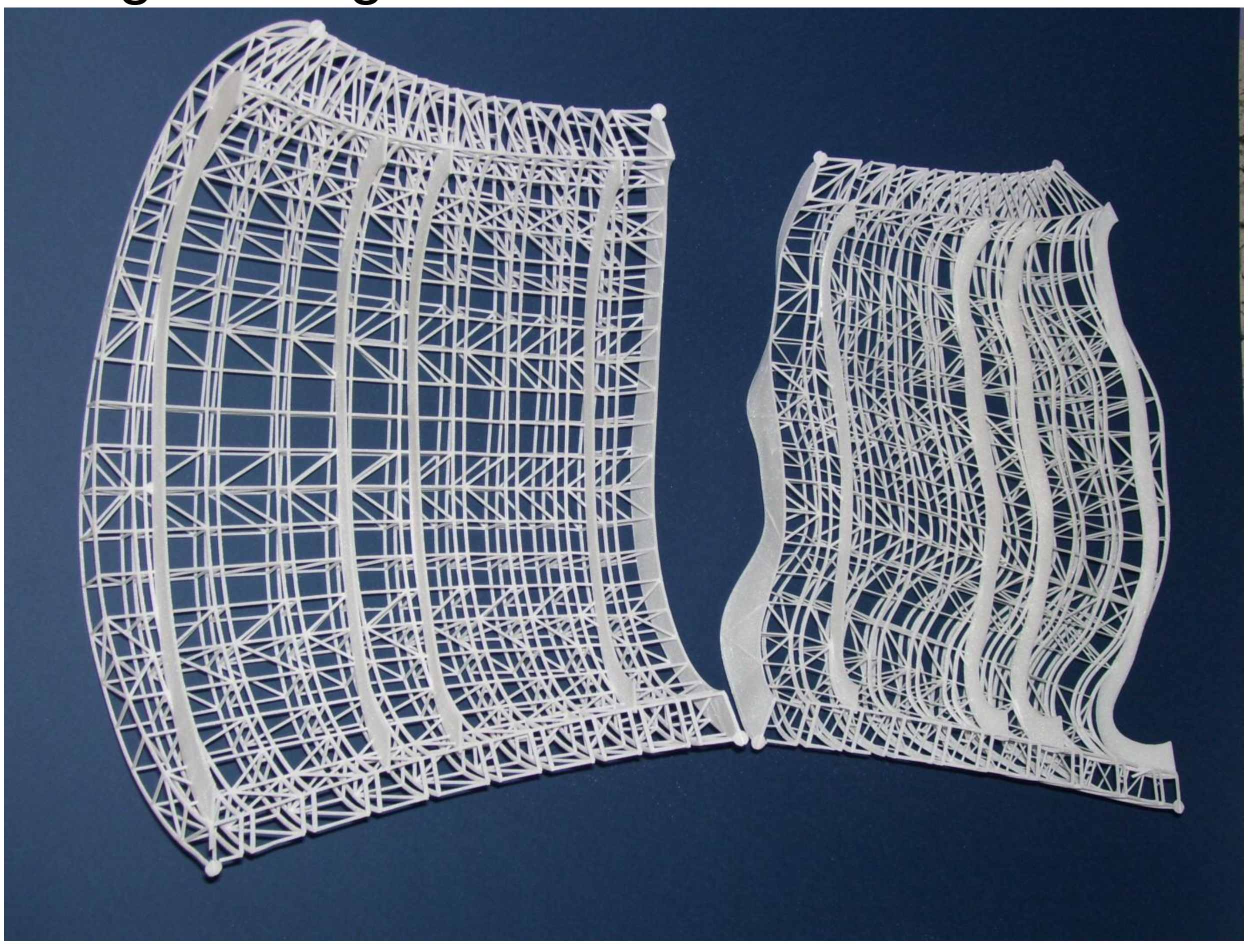
Own test of casting in a "**permanent"** plaster mould. The mould **broke**. However, **some ideas appeared**

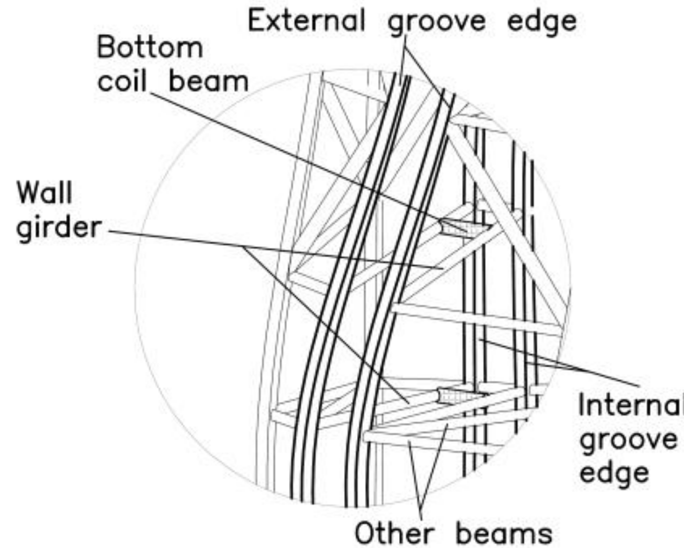


Silver lost wax vacuum casting in plaster mould produced in a specialised company.~ 1000 € in Ag. ~700 € in Cu

Devised as a truss structure without external surfaces

Results : Low cost? (200€, now 500€!), enough strength





Elements of the Truss Concept

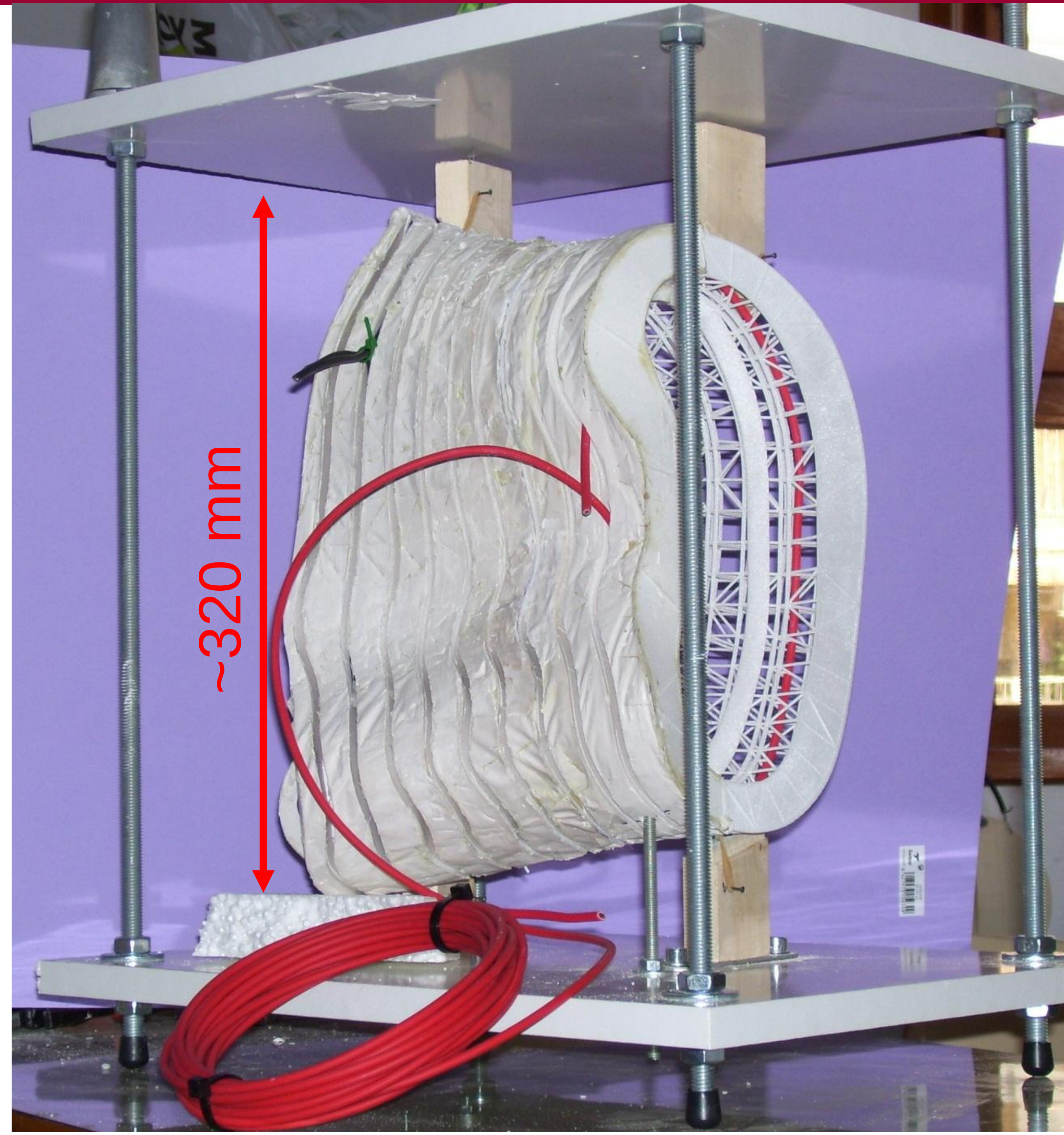
3D printed pieces, Nylon. From company 'Shapeways'. **Filled-sparse** concept before moulding with filler

Truss Concept

Results : Difficult moulding and pair matching, dimensional errors 0.3% isotropic, thermal warping, cost ~$\propto$ R

One half-sector after hard plaster moulding

Truss Concept. Test sector of coil frame



Two views of the test of a coil frame sector

Conceptual design

Introduction

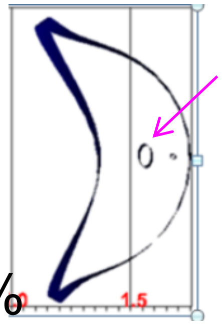
Several magnetic configurations have been assessed

- The aim is to use as much as possible the current physics designs.
- The LCFS of QPS, QIPC2, QIPC3, QIPC6 and NCSX-TU (turbulence improved), have been received from researchers.
- Middle compactness, absence of tips at the poloidal cuts of the plasma, potential for low turbulent transport and reasonable particle confinement time for β ~0% have been considered to select the configuration for UST_2.

- The CASTELL code, 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.

Several devices have been assessed. One case

NCSX-TU
NCSX.Mix



β=4%+Ip
VMEC-Fix

♦ The device is optimised for β=4% +Ip but β_{UST_2} ~0%.

♦ This particular configuration has tips.

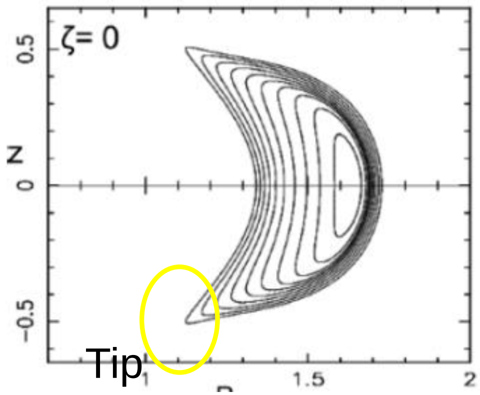
• **New conf. no tips?**

• Complex overlapping

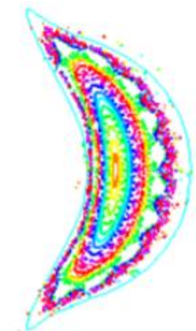
► Potential improved turbulence transport.

Not chosen for UST_2.

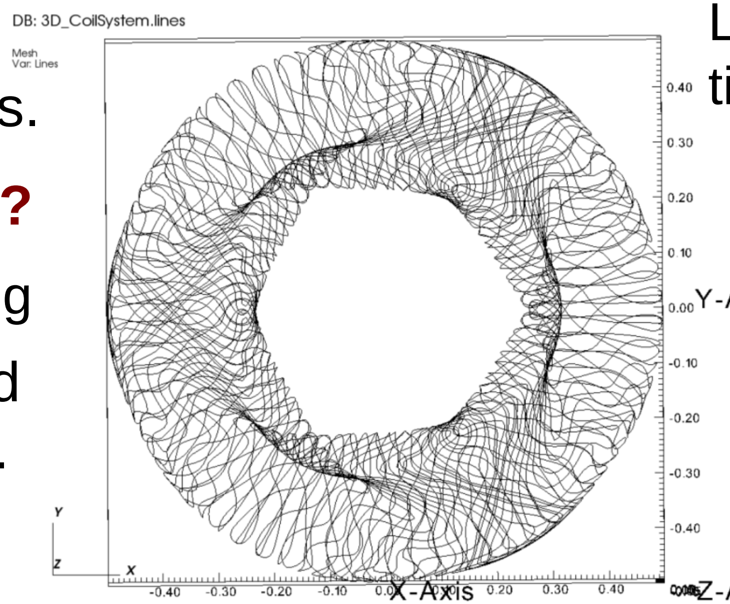
OK for UST_3



LCFS with tips [Myn 10]



Poor surfaces. Require many coils, very near the LCFS for good result



Two overlapped winding surfaces and coils

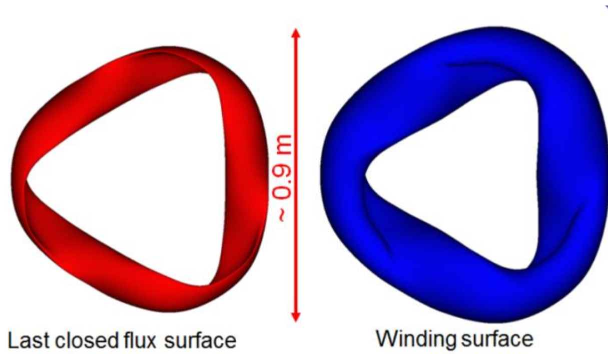
LCFS in vacuum for NCSX and NCSX-TU, Mixed

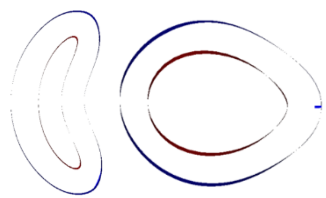
LCFS supplied by H. Mynick

QIPCC3

- ▸ LCFS and plasma varies little with β.
- ▸ High confinement obtained for β=0% (to be confirmed by better codes).
- ▸ Middle compactness.
- ▸ High iota.

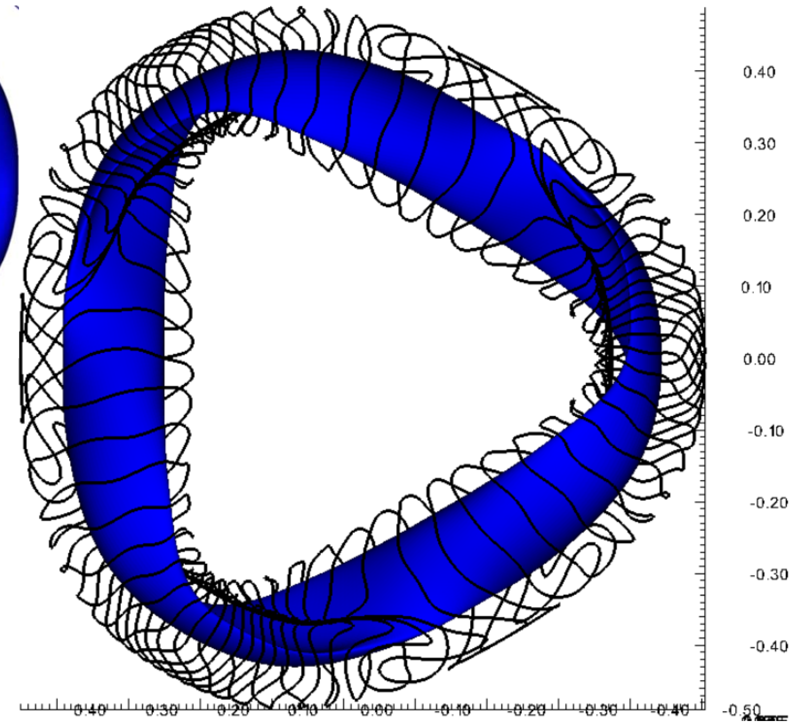
►Decision: Chosen for UST_2

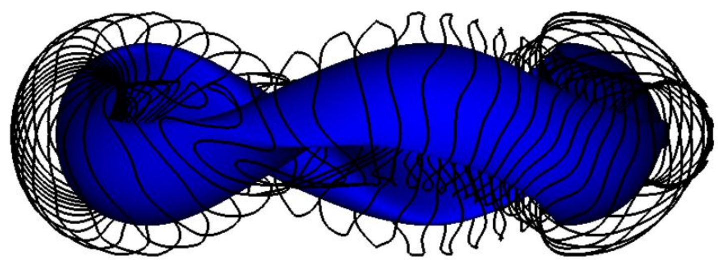




Retrospectively:

♦ The distance coil-LCFS must be low, otherwise coil shape is unfeasible or confinement worsen





Iota [0.67 , 0.71] A~6.8

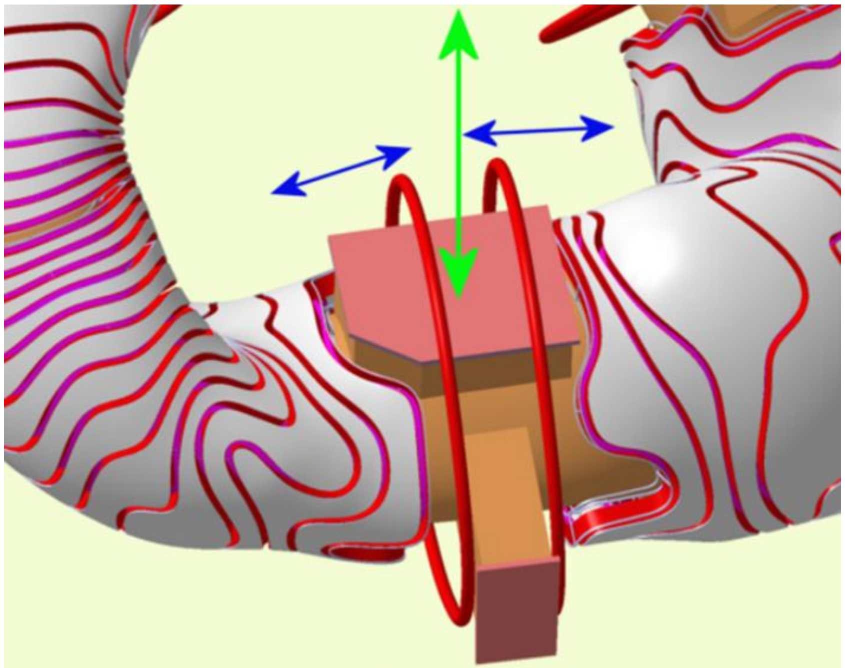
From CASTELL ,[Mik 04],VMEC

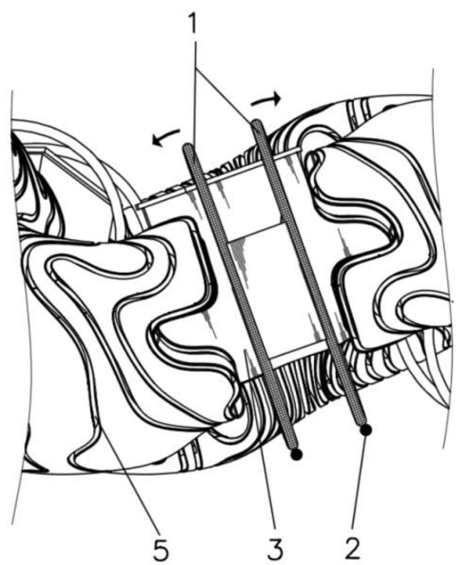
LCFS supplied by J. Nührenberg and team

Modification of QIPCC3

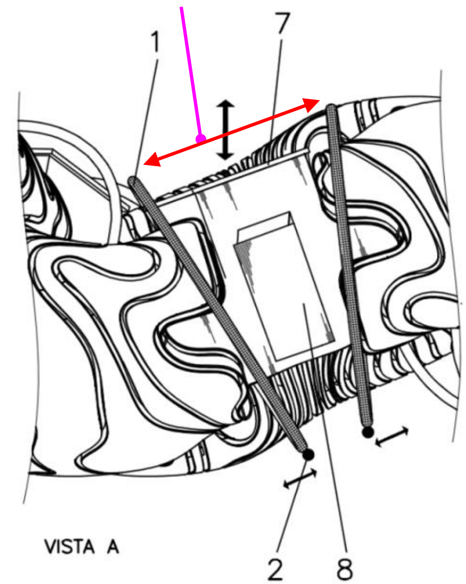
One objective: Generate wide ports for fast Remote Handling

Complex CASTELL code optimization processes
using also NESCOIL and DESCUR codes





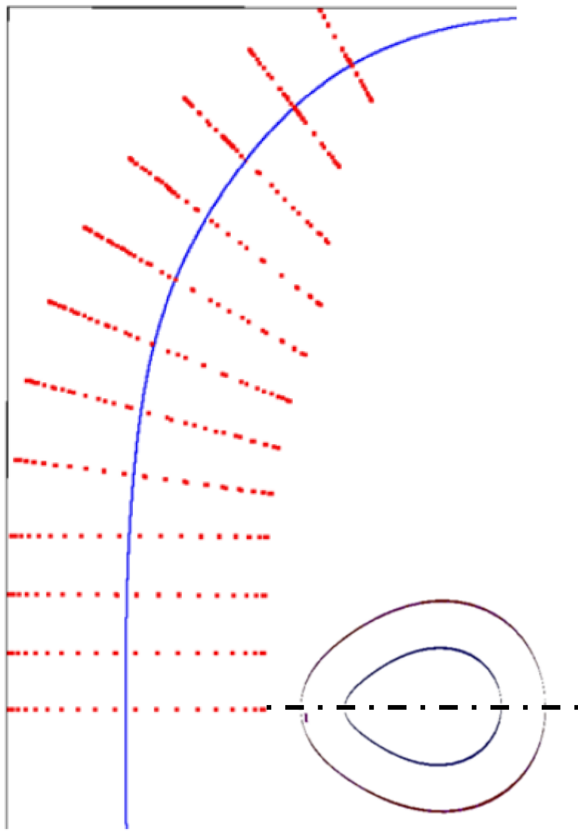
Wide opening for fast
Remote Handling



Movable planar non-circular coils for **fast and wide Remote Handling** in-vessel access.
Also space for future **large and powerful divertors**.

The straight section is stretched by CASTELL code, plus re-optimization

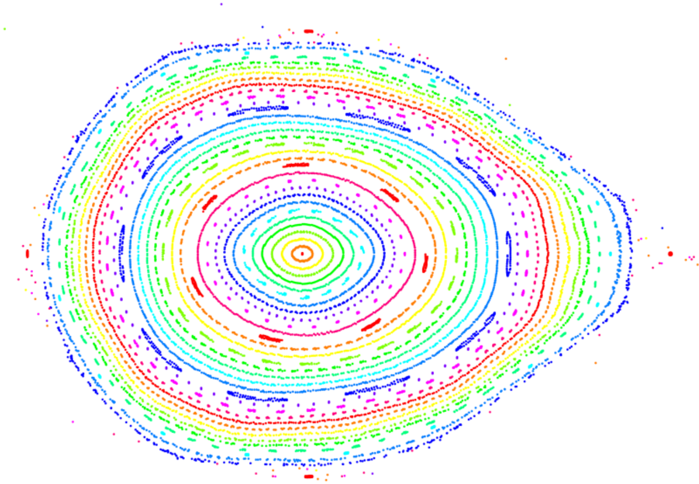
- **Automatic CASTELL code processes:** The QIPCC3 straight section is stretched (addition of poloidal cuts and compression of QIPCC3 sections), CASTELL DESCUR-like code application, two NESCOIL runs, confinement, iota and magnetic well profiles calculated by Monte Carlo method.
- Only about 500 configurations have been compared. Long lasting computations.
- Increasing elongation of the straight section gave decreasing confinement for the best configuration.
- The re-optimization is poor (about 3 times less confinement than the original QIPCC3). However, the main objective is engineering.

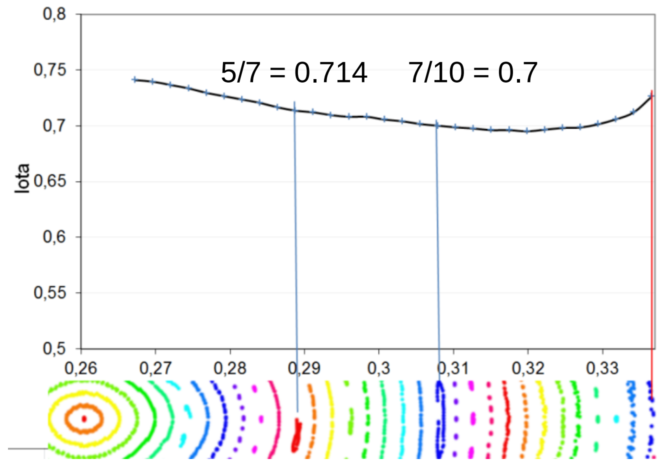


Stretched and compressed poloidal cuts

UST_2 specifications

Element	Specification
Number of periods	3
Plasma volume (litres)	10
R, plasma major radius (mm)	260
a, ave. plasma minor radius (mm)	~ 37
Aspect ratio	~ 7
B_o Magnetic field at axis (T)	0.045 / 0.089 / Higher
ι_0 , rotational transform at axis	0.74
ι_a , rotational transform at edge	0.69
Vacuum max. magnetic well	0.2%





Vacuum magnetic surfaces at φ = 0 and Iota profile, from CASTELL

UST_2 engineering design.
Fabrication tests

UST_2 specifications

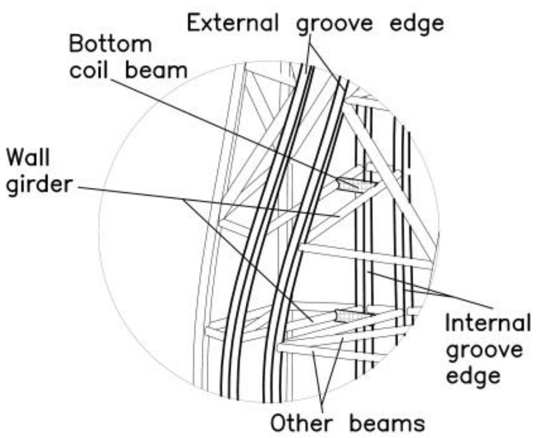
Coil engineering specifications

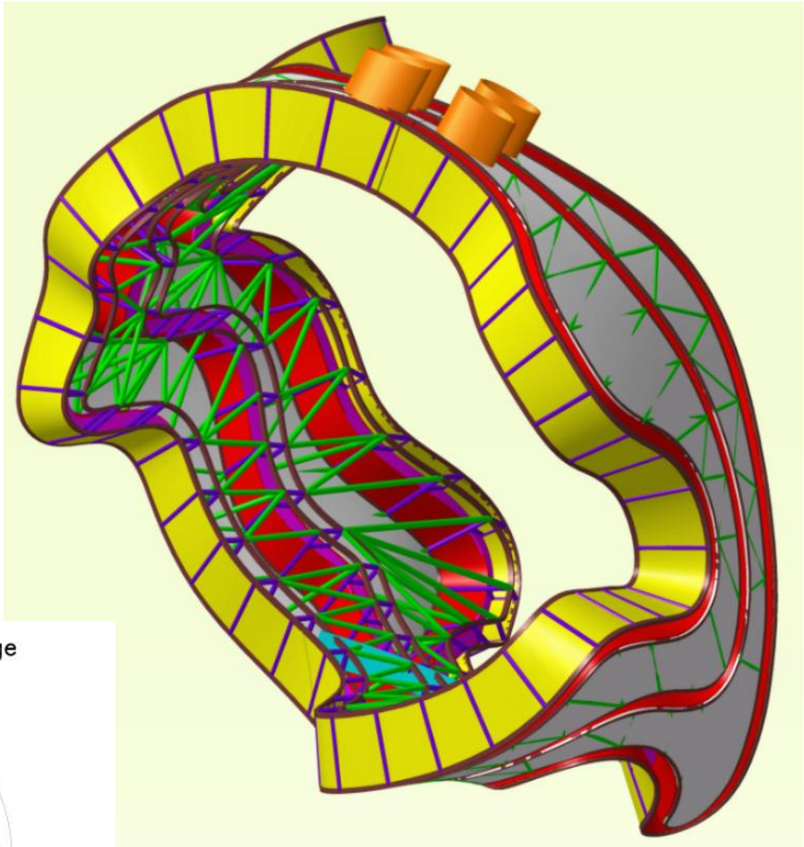
Element	Specification
Type of coils	Modular coils
Number of pancakes = coils	90
Number of non-planar pancakes	84 (14 x 6)
Number of large planar non-circular pancakes	6 (1 x 6)
Winding pack size (mm)	4 with x 12 depth
Conductor type	Flexible copper wire TXL 10 AWG gauge
Turns per pancake	3 layers x 1 turn/lay. = 3

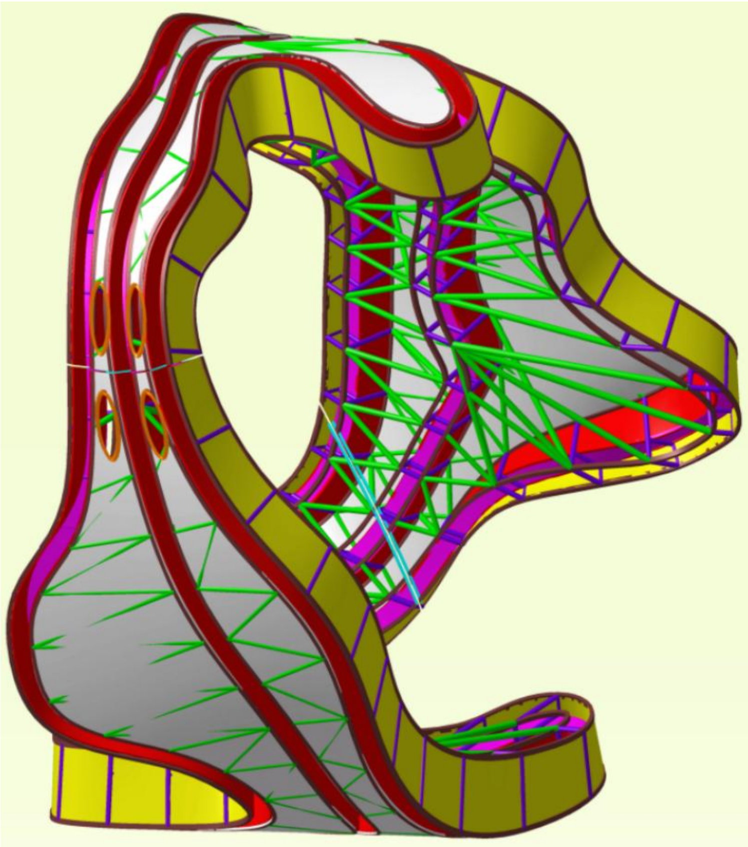
UST_2 engineering design

A mix of the Hull Concept and Truss Concept is chosen

3D printed thin cover surfaces and internal truss structure

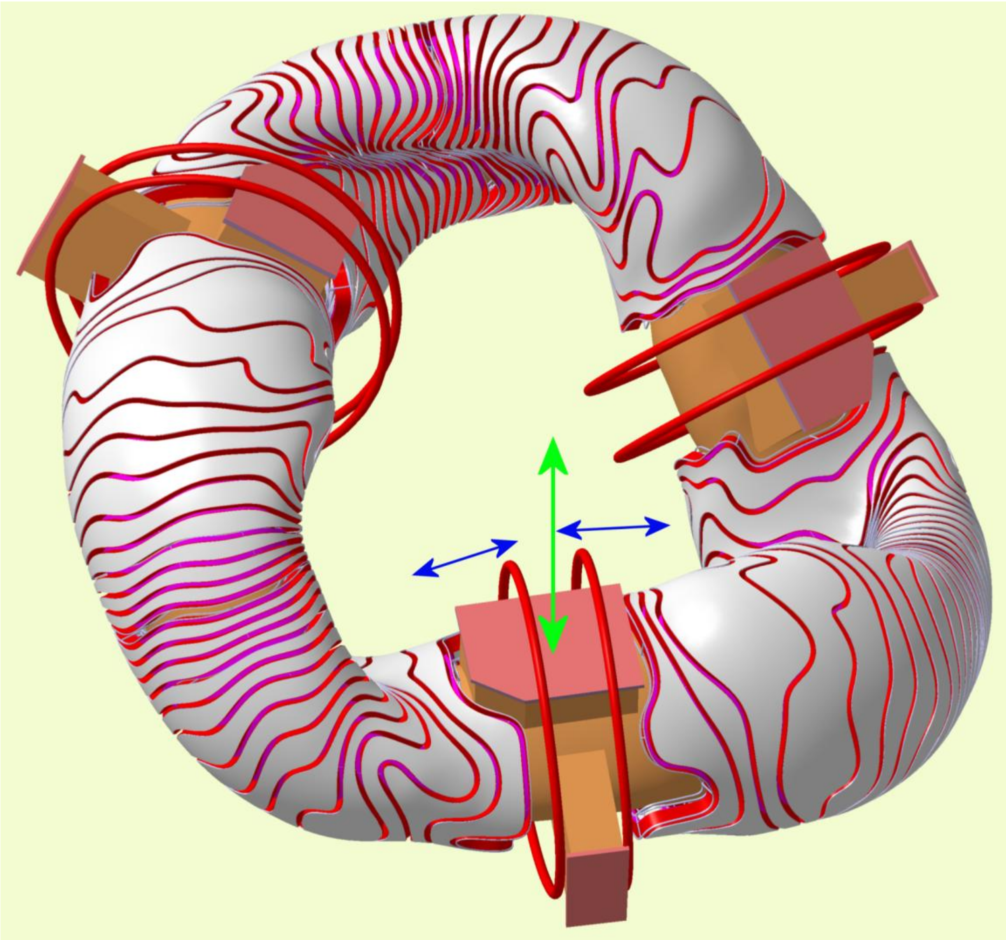




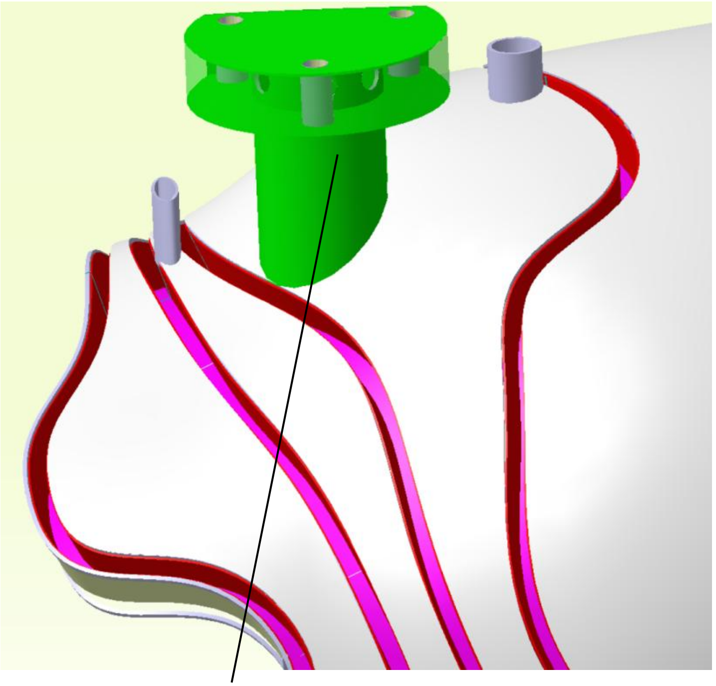


Perspective and top view of the first 3 coils 3D printed. A test. Printed by ‘Shapeways’ company. Cost **108 €** plus taxes and shipping

UST_2 engineering design

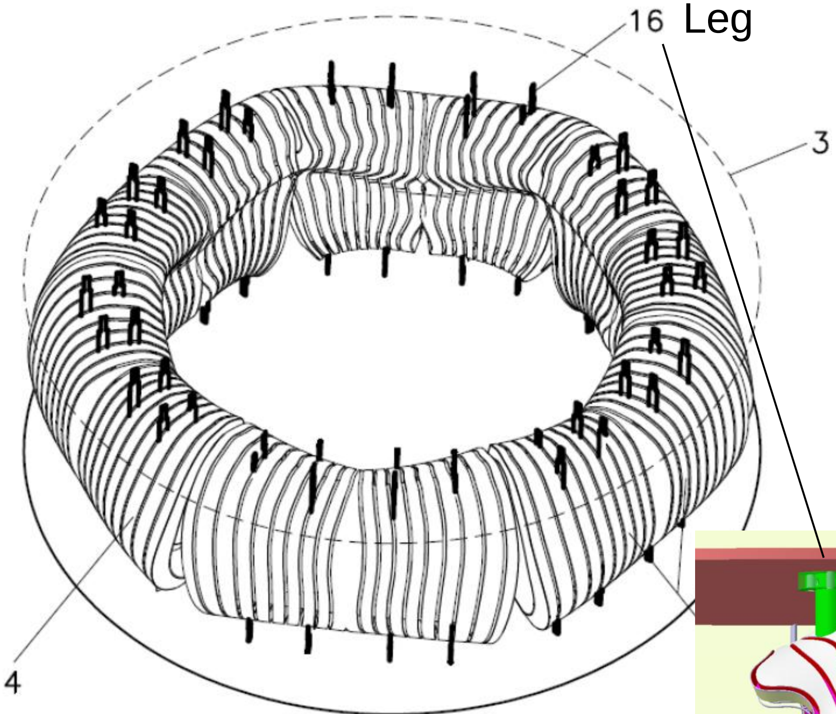


External view of the UST_2 design. Vacuum vessel still unclear

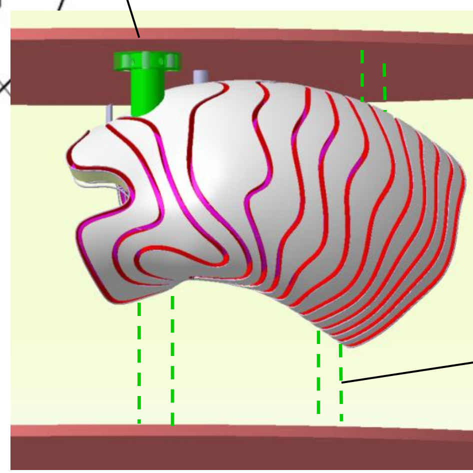


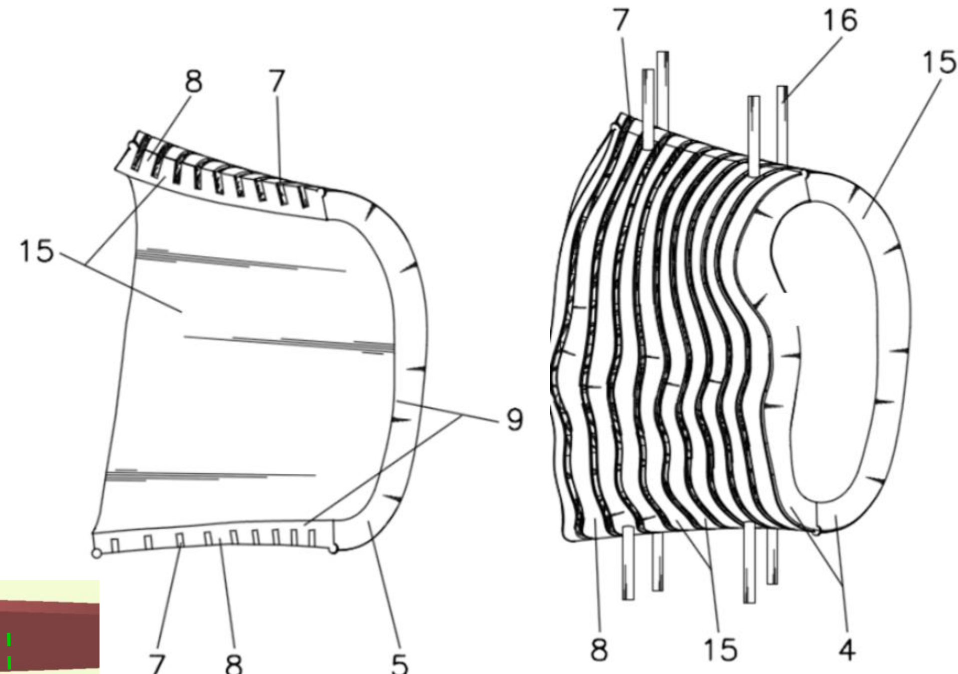
Design of one of the 8 leg per half period. The design of the leg is thought for plaster moulding

Assembling concepts



Leg





Concept of *Filled-sparse* pairs of pieces outside the VV

Sketches depicting the assembling concept
(non-stellarator symmetry in the top figure)

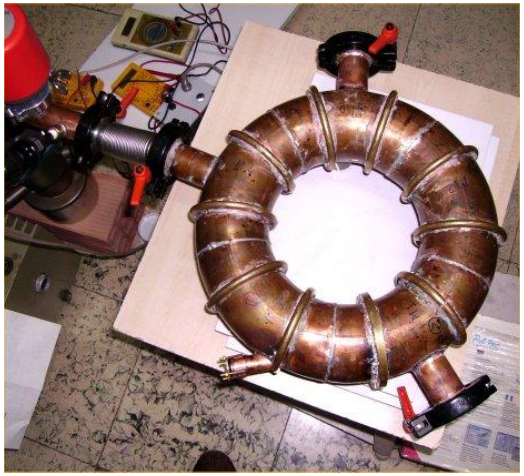
The other legs not designed yet

Vacuum vessel still unclear

A simple low cost VV?

UST_1

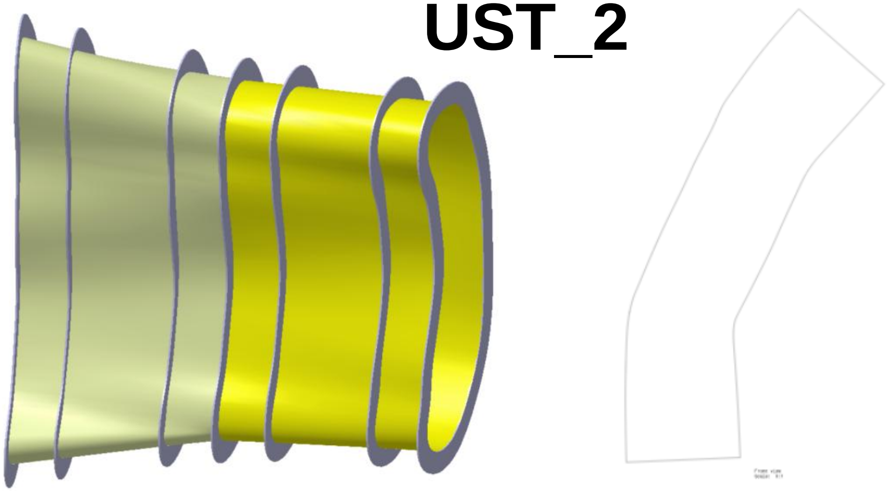
Copper elbow



Finished UST_1 vacuum vessel

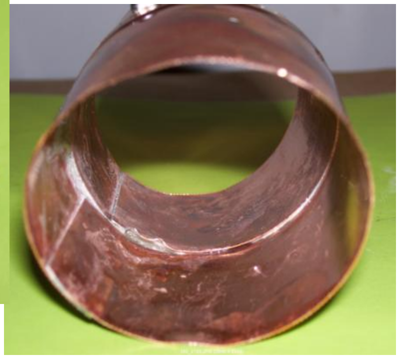
Similarly

UST_2



One of the ideas. VV converted into unfolding surfaces, with reinforcements

Test of soldering segments on a mandrel



Future work

Present status and next future work

Present status

Initial tests performed	✓
Decision of device to build	✓
Conceptual design	✓
Detailed design	70%
Construction	✘

Short term : ~ 3 - 4 months

- Finish the engineering detailed design.
- Try to rise funds by **Crowdfunding** (**contributions are welcomed!. See** in brief my campaign in **www. fusionvic.org** (top link) or search **www.indiegogo.com**)
- Build UST_2 (independently if funds are raised or not).

Future work

Middle term: ~ 1 year (UST_3)

Design and raise interest and funds in CIEMAT, in any institution in Spain or in the world, for a **low-cost** device:

- Likely a **stellarator**.
- **0.1 m^3** plasma volume.
- B_o =~ **0.5 T** (1 T), **high field** for its size.
- **Turbulence improved** (**you are invited to contribute!**) device with innovative **power extraction** (divertor or other?).

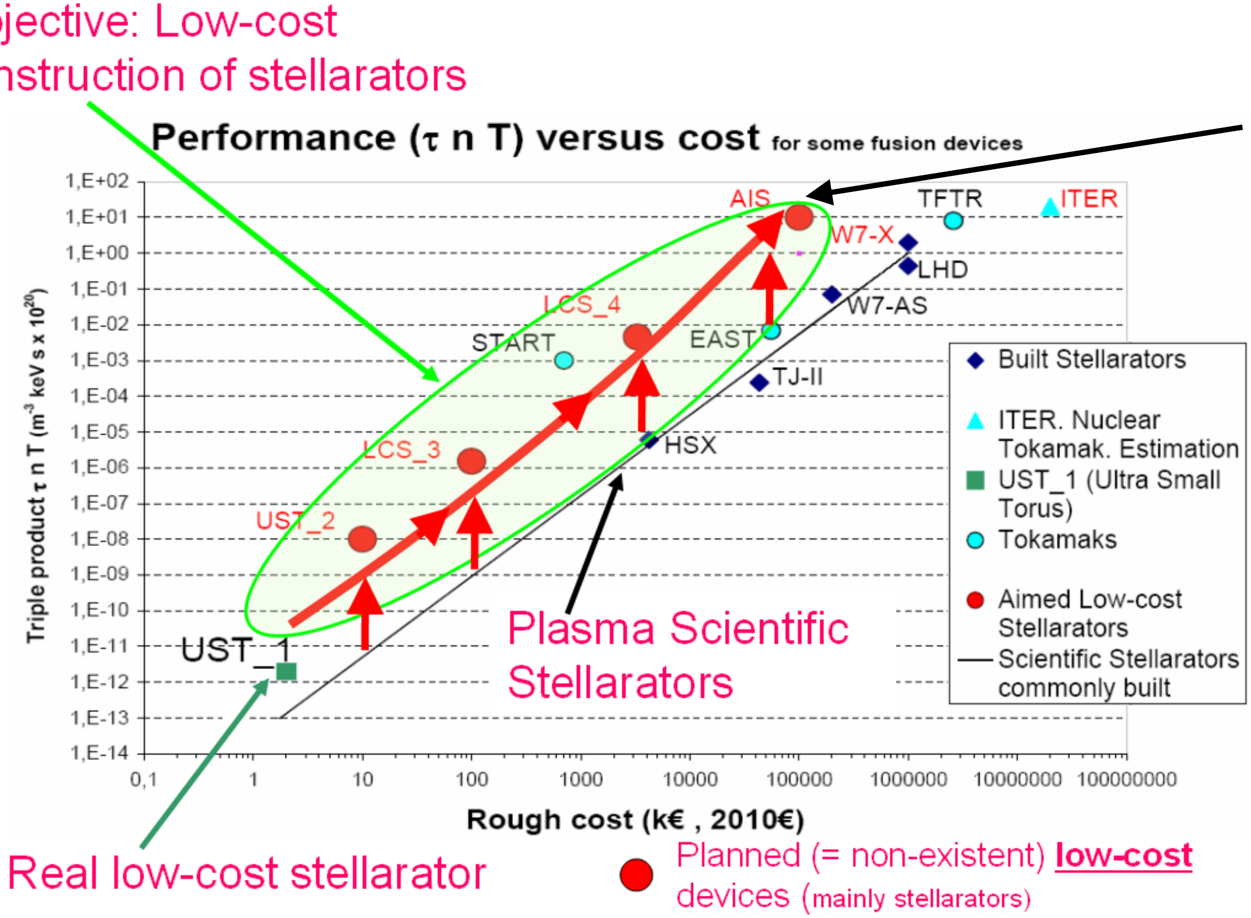
Long term potential work

- Build a large 3D printer for stellarators, the ‘*Keops Builder*’ ?
- Build a high-field pulsed Allure Ignition Stellarator (AIS) [Que 10]?

Possible long term activities

Sequential low-cost rapid manufacturing of larger devices

Objective: Low-cost construction of stellarators



Concept : High-field pulsed Allure Ignition Stellarator (AIS) (2010). [Que 10] High-field, few ignition pulses. Somewhat similar to the IGNITOR, FIRE and FAST concepts, but for a stellarator.

Cost and performance is only a coarse value for rough comparison among devices

Questions?

Any contribution to UST_2-3?

Any interest on me for something similar?

Acknowledgement

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

Jefrey Harris, Donald Spong and team (ORNL, QPS LCFS and coils)
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Antonio Lopez-Fraguas (DESCUR code update and teaching)
Gerardo Veredas (CAD teaching)
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., December 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.

[Kul 06] "Project EPSILON – a way to steady state high b fusion reactor", V.M. Kulygin, V.V. Arsenin, V.A. Zhil'tsov, et al., IAEA XXI Fusion Energy Conference, 16 -21 October 2006, Chengdu, China.

[Ima 11] "Status and plan of gamma 10 tandem mirror program", T. Imai, et al., TRANSACTIONS OF FUSION SCIENCE AND TECHNOLOGY VOL. 59 Jan. 2011

[Que 10] "High-field pulsed Allure Ignition Stellarator", Stellarator News, n. 125, 2010

[Spo 10] "New QP/QI Symmetric Stellarator Configurations", Donald A. Spong and Jeffrey H. Harris, Plasma and Fusion Research: Regular Articles, Volume 5, S2039 (2010)

End

Thanks

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