UST_1 stellarator and

Status of the 3D printed UST_2 stellarator

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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.

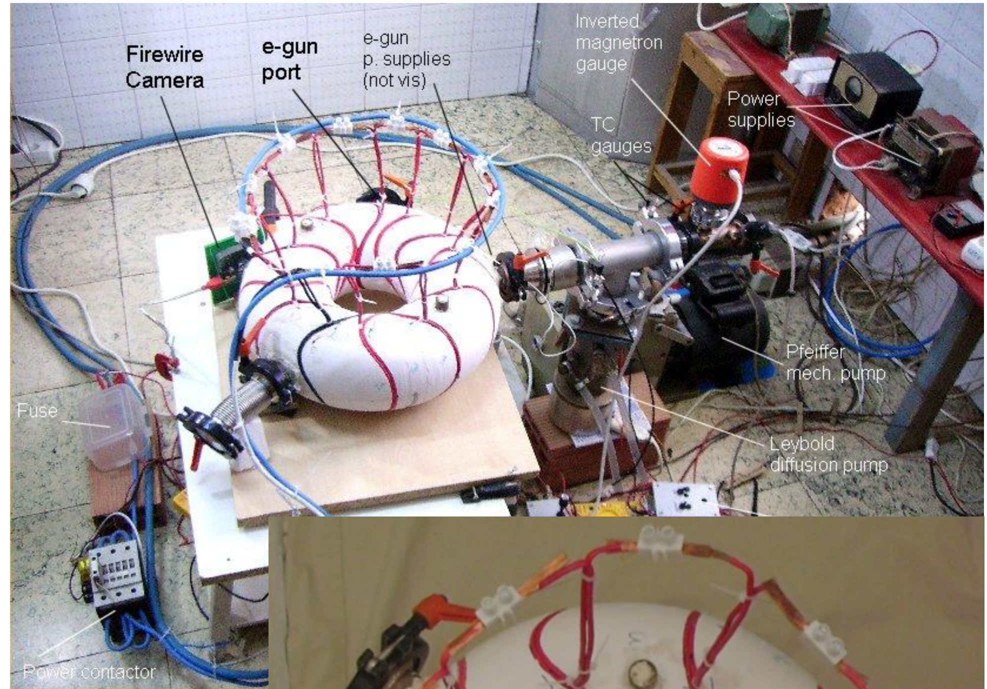
► Up to now, I have developed the work on stellarators on my own, with personal funds (for three years before CIEMAT work, at nights and weekends during CIEMAT work, and now 1.5 years during the leave of absence), with some help and contribution from CIEMAT.

► **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.**

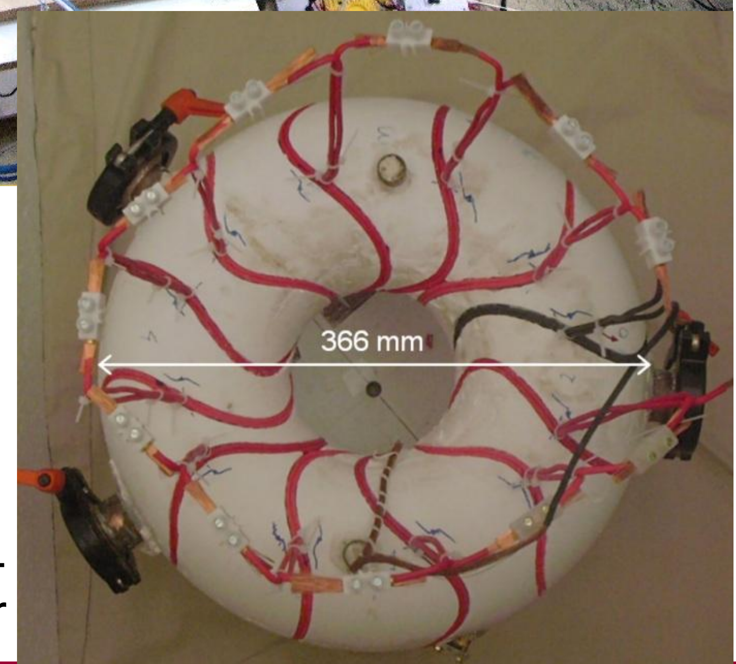
Basic UST_1 data

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



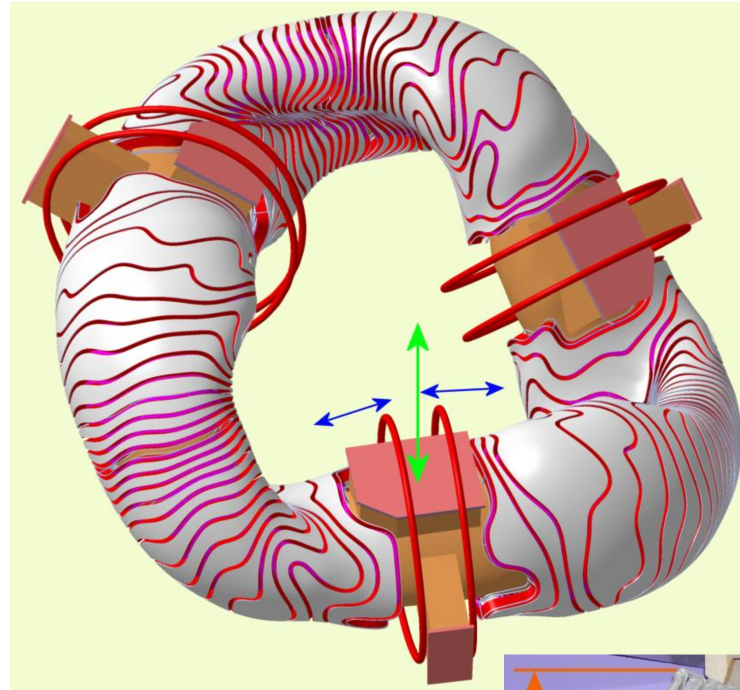
UST_1 stellarator

UST_2 modular stellarator

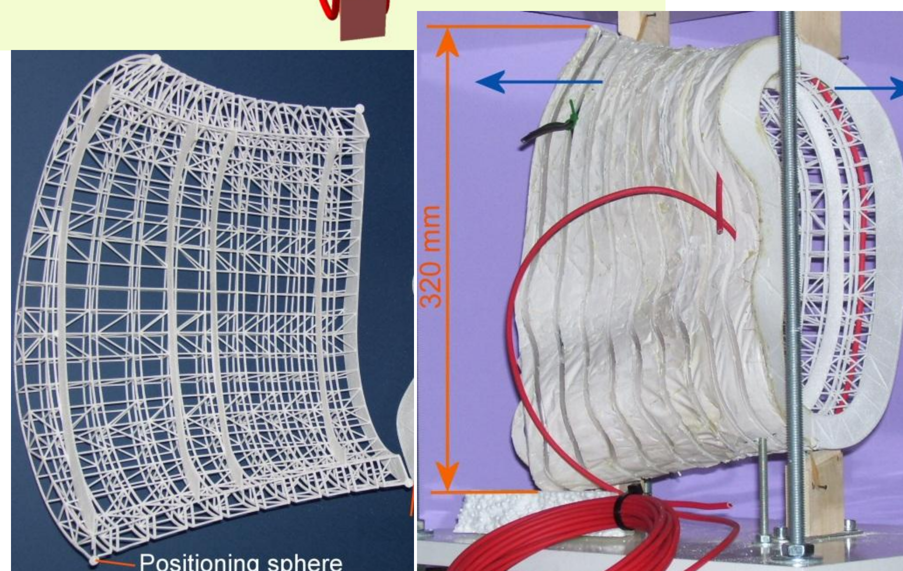
- UST_2 stellarator has been designed during 2nd 1/2 2012 and 2013 (still some elements remain).

- 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

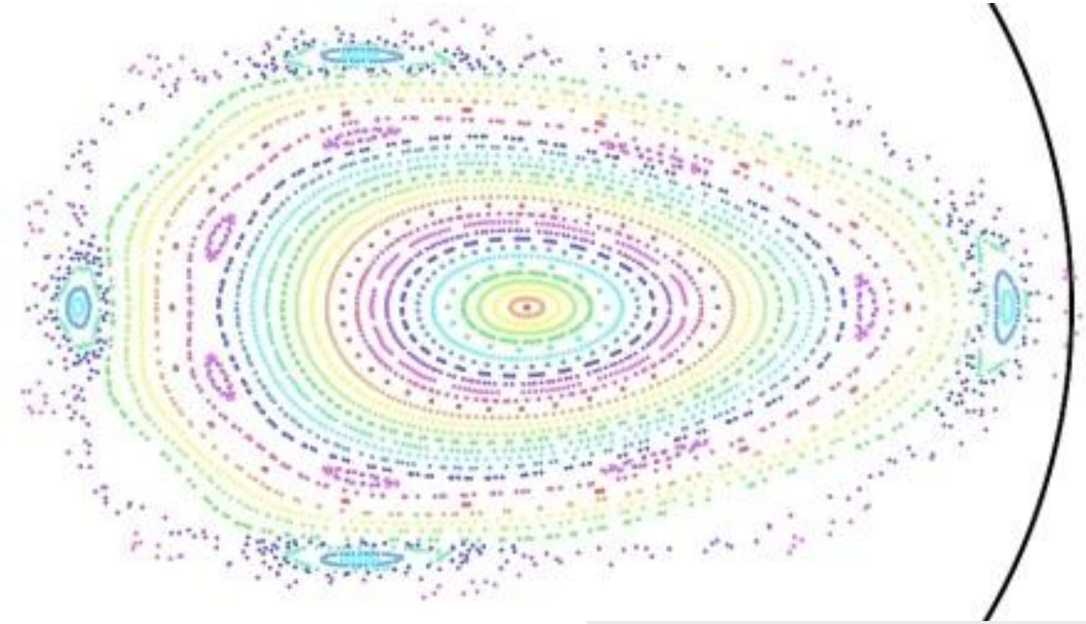
Technical objectives

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

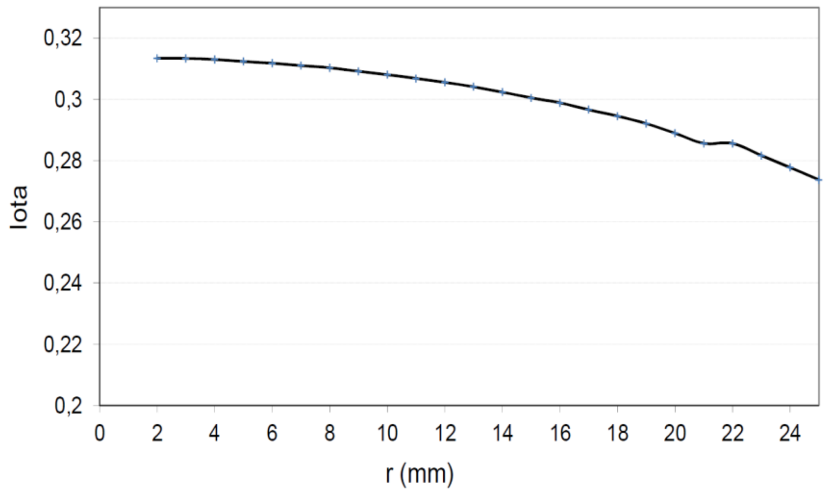
Element	Specifications
Number of periods	2
Plasma volume (litres)	1.1
R, plasma major radius (mm)	125.3
a, ave. plasma minor radius (mm)	21
Aspect ratio	~ 6
B_o Magnetic field at axis (T)	0.089 / 0.045
ι_0 , rotational transform at axis	0.32
ι_a , rotational transform at edge	0.28

Basic features of UST_1

Physics characteristics

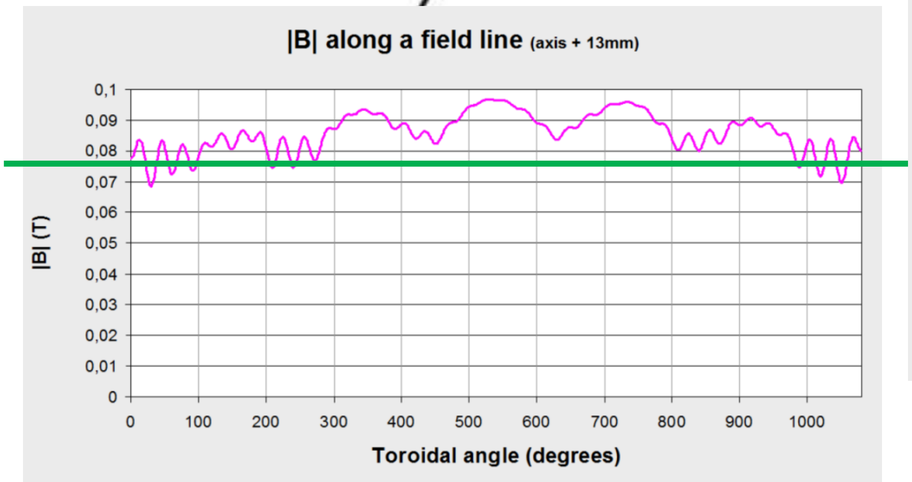


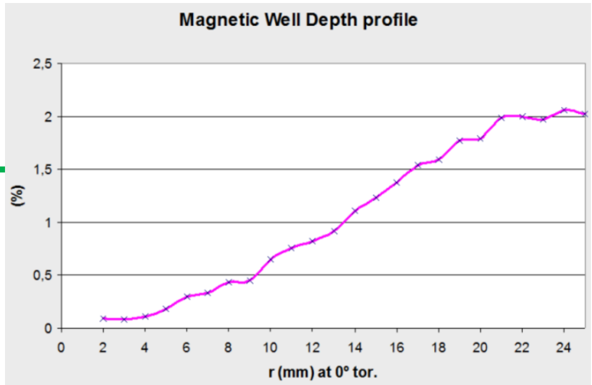
Vacuum Poincaré plot, φ = 0º



Iota profile. Tokamak-like shear !

All obtained by CASTELL code





Magnetic Well profile

General 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

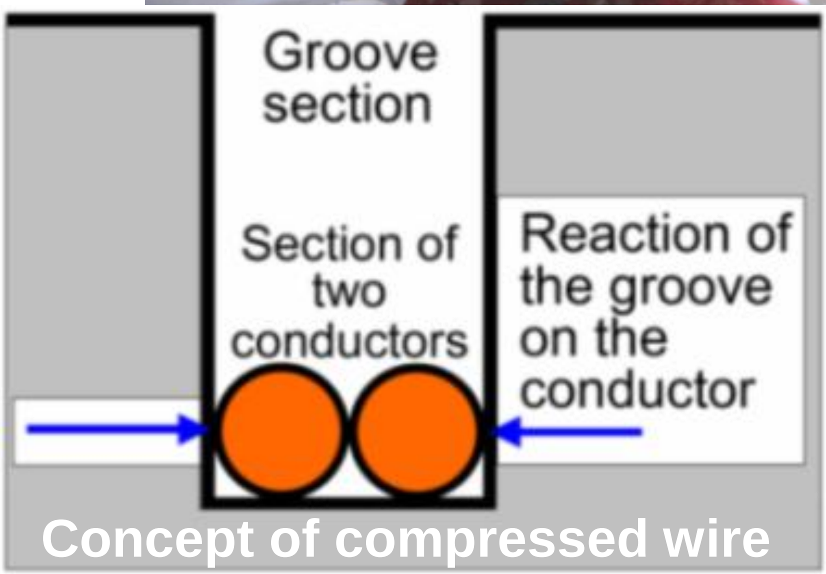
* Four parameters defining the amplitude of a sinusoidal deformation of the coil at four different poloidal angles. Obtained by optimization with CASTELL code

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

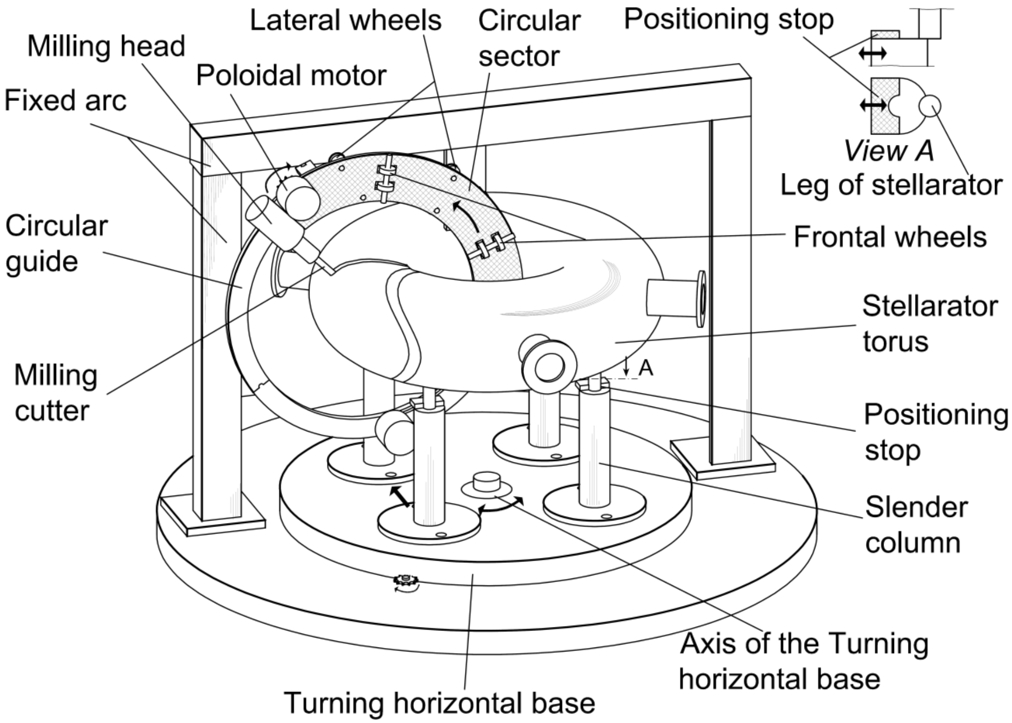
Method to build the modular coils

Concept of a toroidal milling machine for stellarators

• The milling head of this special milling machine moves in toroidal and poloidal coordinates.

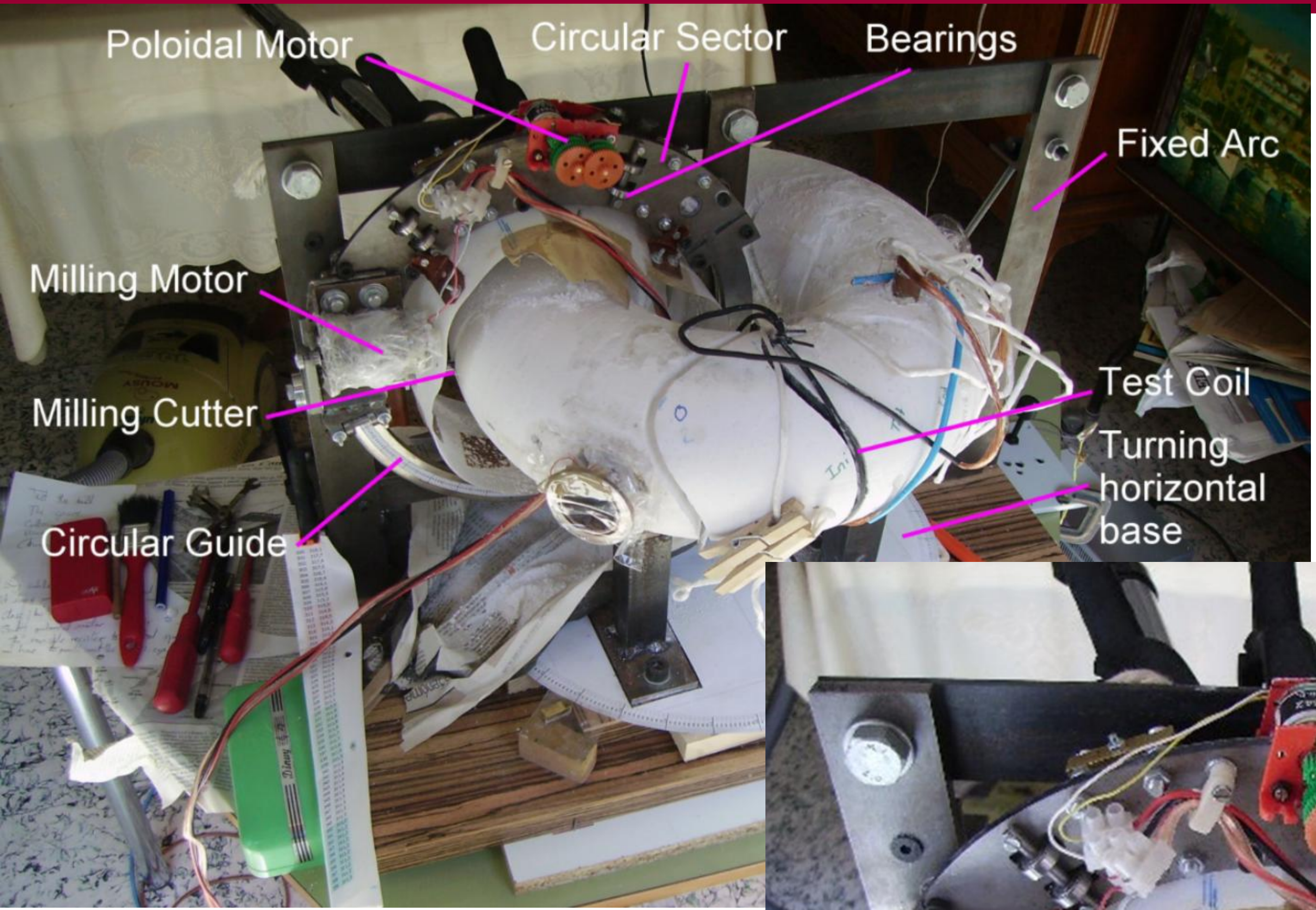
• The surface being mechanised is not removed from the supports (*Slender columns*) for the whole mechanization → simplicity and reduced field errors.

• Main elements: turning horizontal base, fixed arc supporting a circular guide, and milling head.



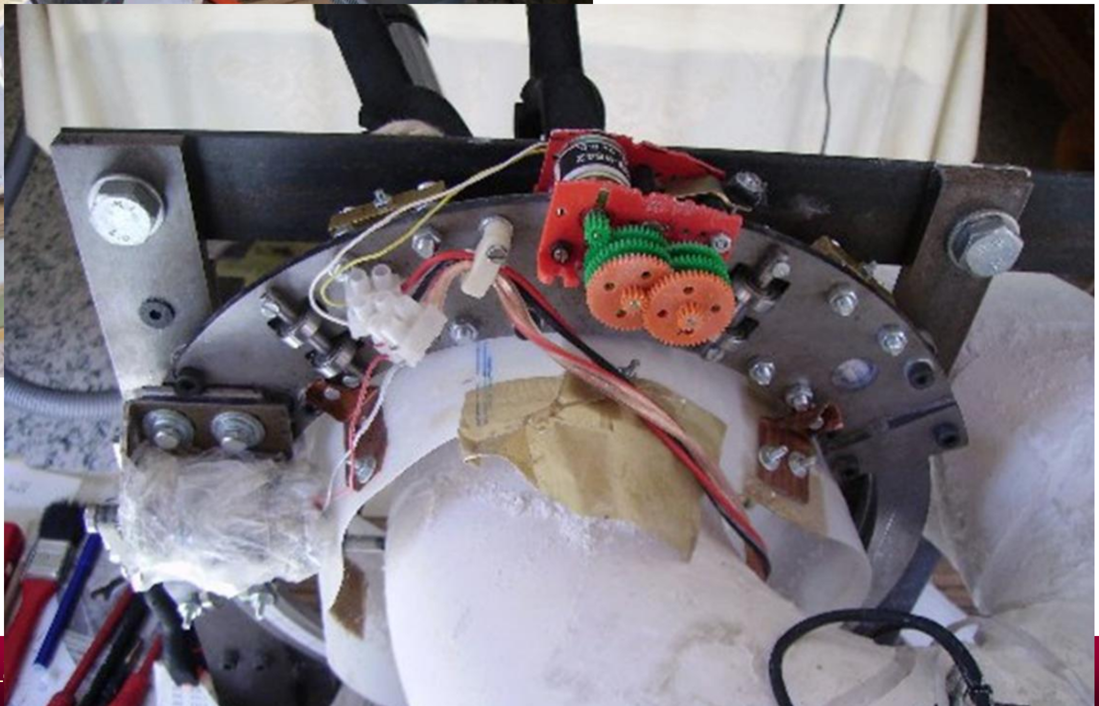
Schematic view of the toroidal milling machine

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

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

Accurate circular torus

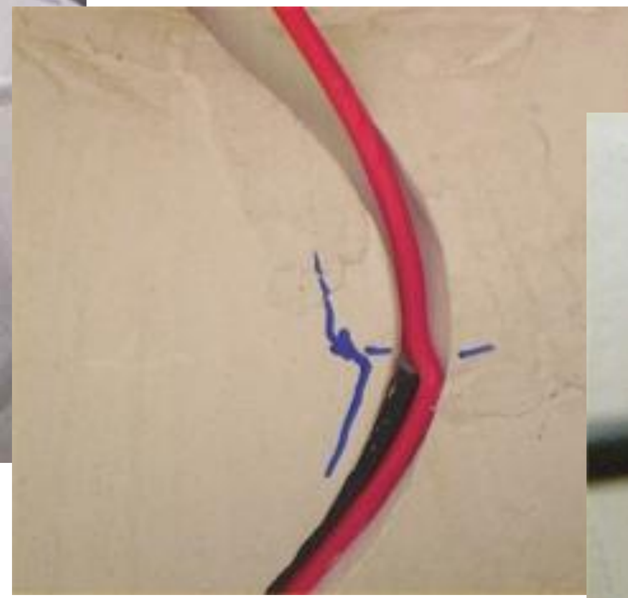
Groove fabrication by method described

Vacuum vessel

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

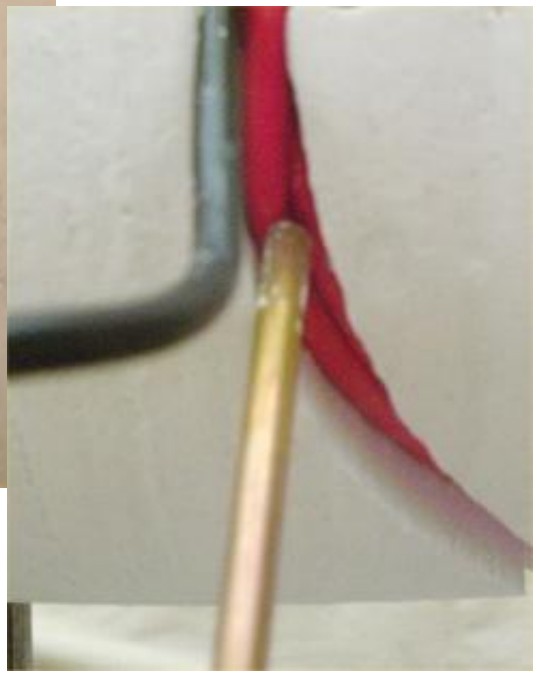
Winding process

Grooves mechanised in the plaster frame

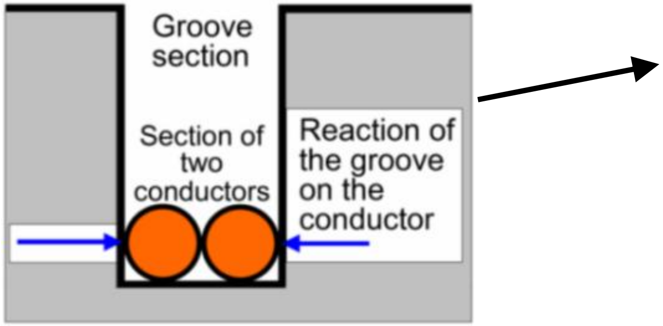


Internal crossover and auxiliary winding coil (black conductor)

Implementation

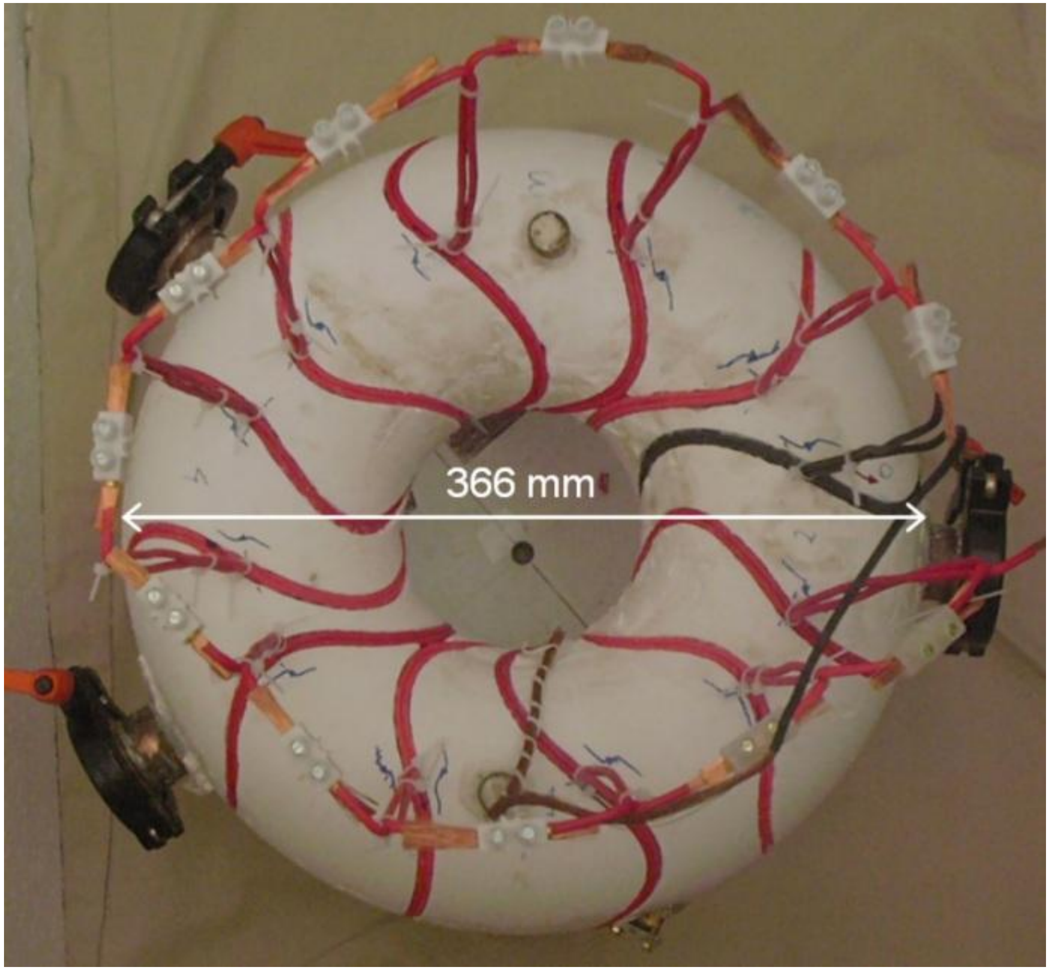


Compressing and placing conductors in the groove



Concept

Almost finished

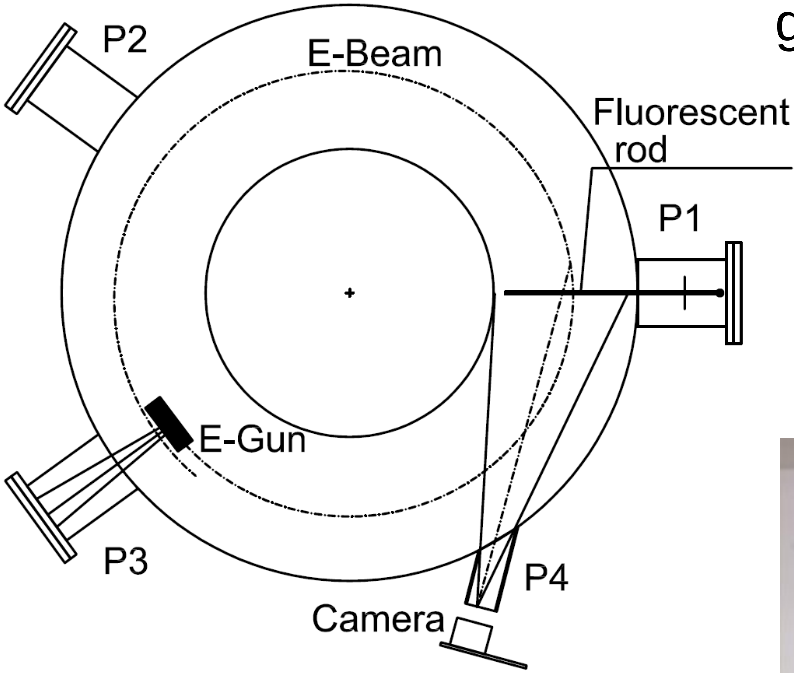


12 coils finished

Validation of the construction method and design

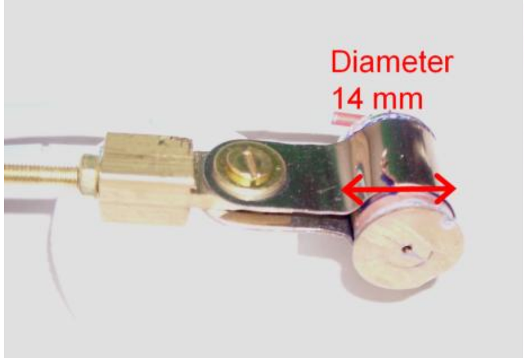
Field line mapping experiments

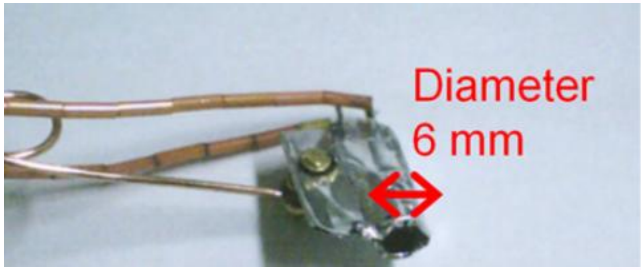
E-guns made in-site

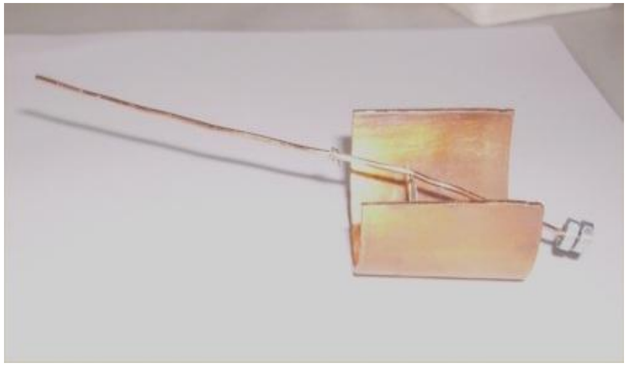


Field line mapping experimental setup

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



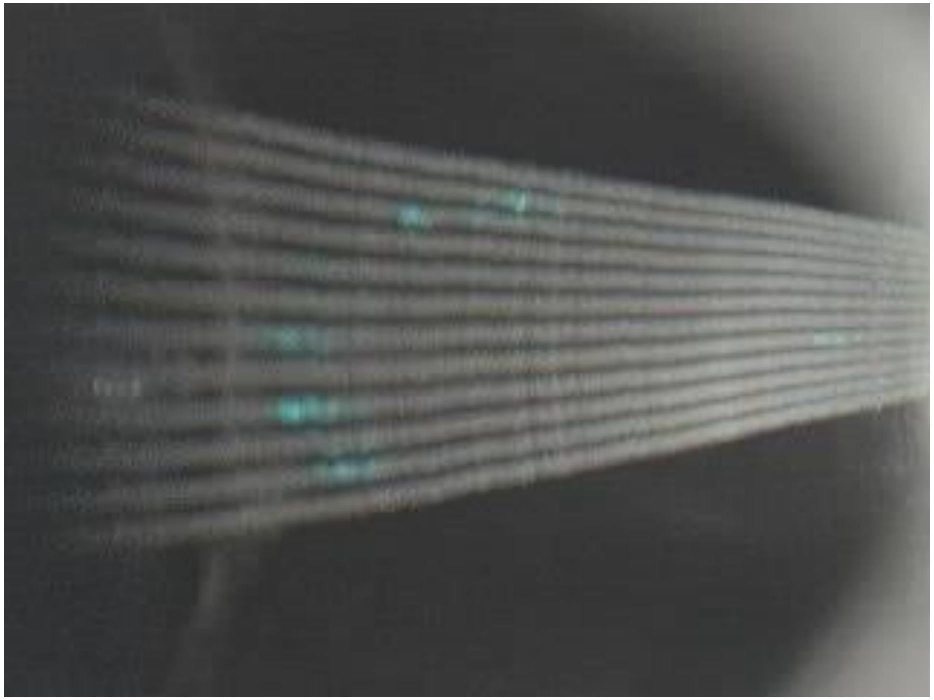




Oscillating fluorescent rod, **simple and economical method**. Port P1

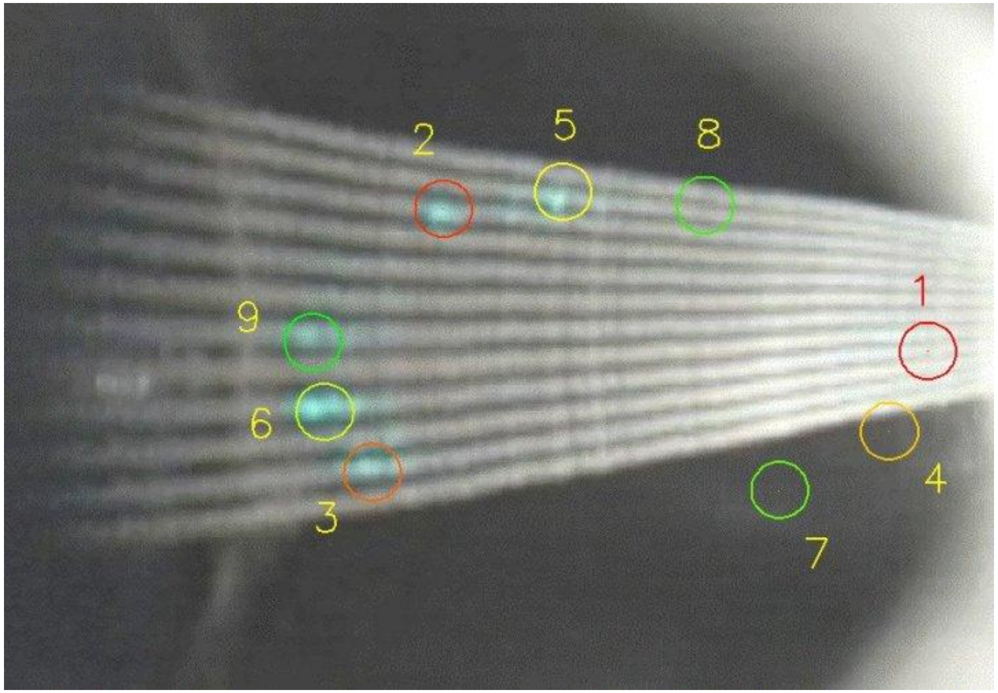
Field mapping experiments

Recorded magnetic surfaces. Comparison calculation-experiment



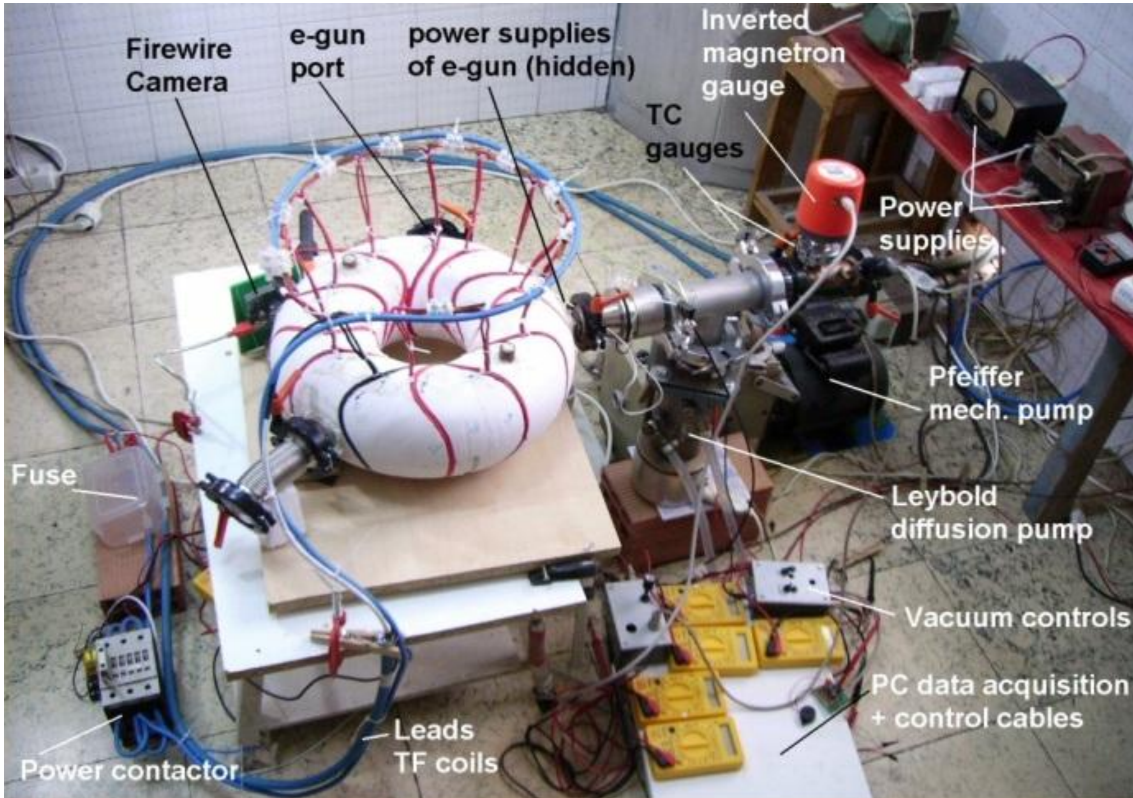
Pulse #202. Experimental fluorescent points on the oscillating rod. 94 eV beam.

N202_F70-135.mpg

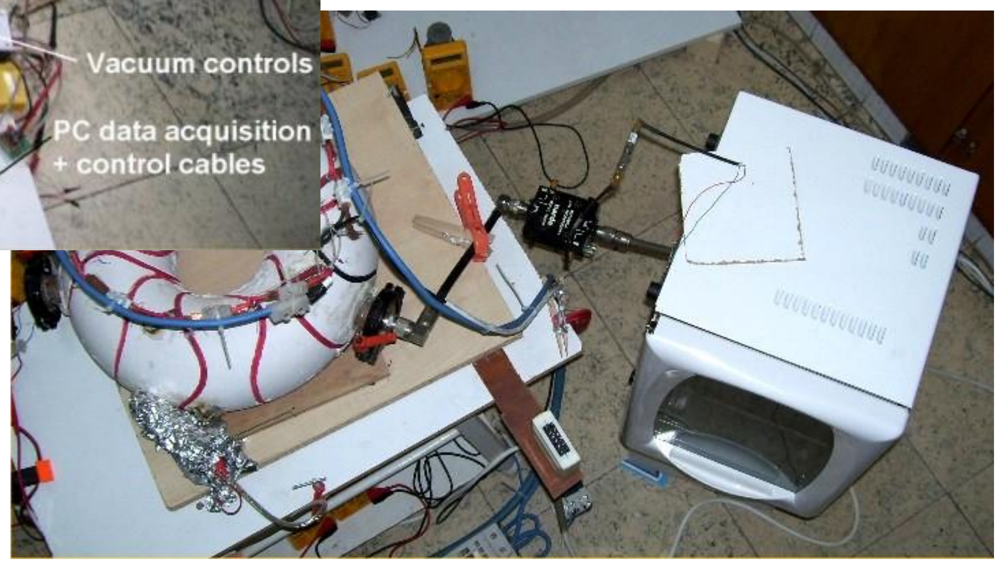


Pulse #202. Overlapping of calculated (numbered circles) and experimental points. Notably agreement is observed.

Brief overview of the facility



CODAC systems



ECRH 1kW

Power supplies. 20 kW

More information in www.fusionvic.org

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)

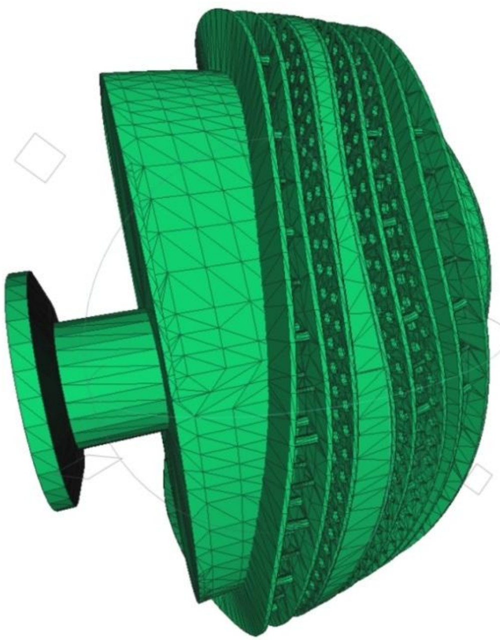
Experimental validation of engineering concepts

Hull Concept

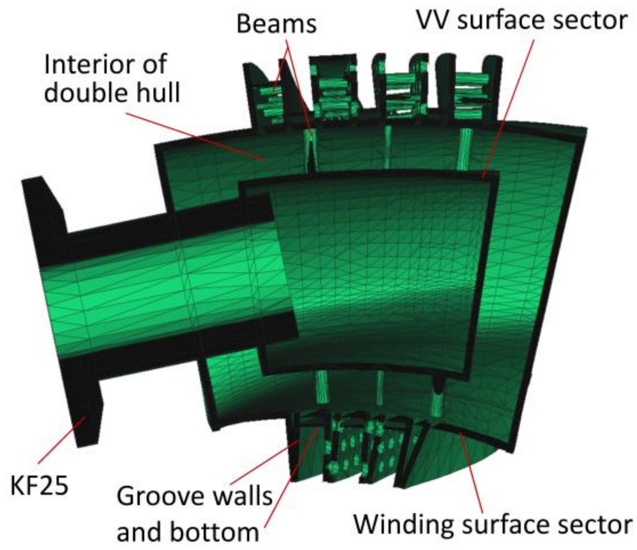
Devised as a double hull structure

Combination of a sector of the winding surface, a sector of the VV surface, internal beams between both surfaces and beams connecting the groove walls.

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



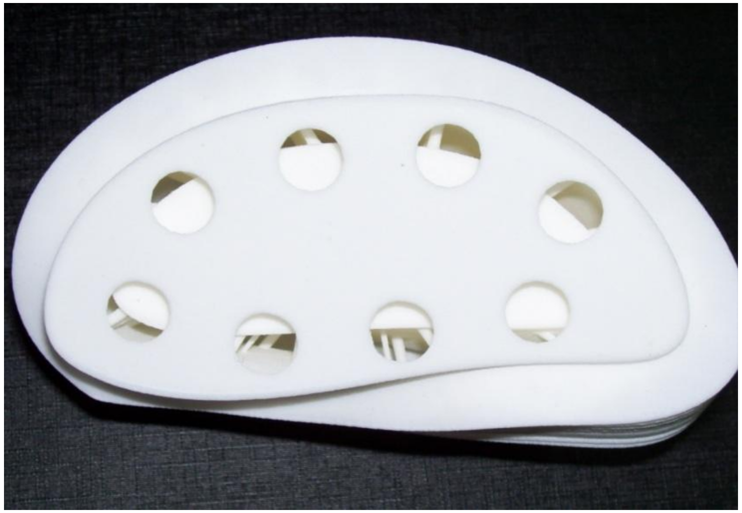
External view of the torus sector test

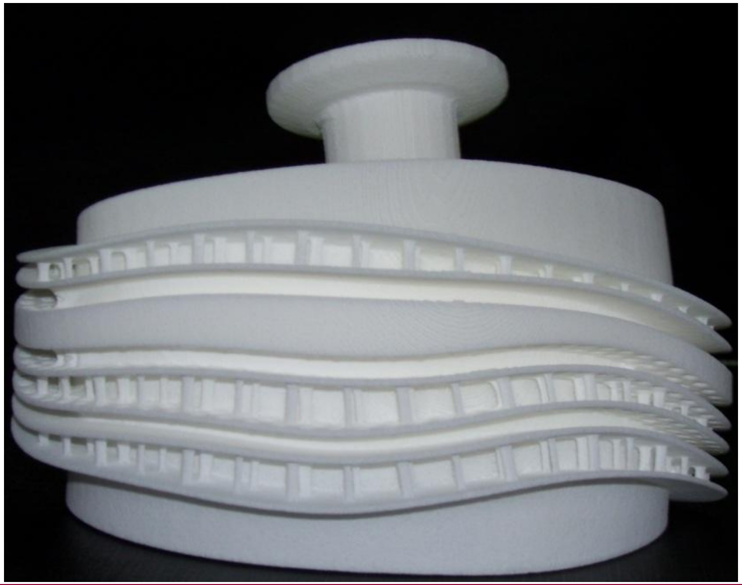


Cut of the sector

3D printed test sector of coil frame

Results: robust, accurate but too expensive





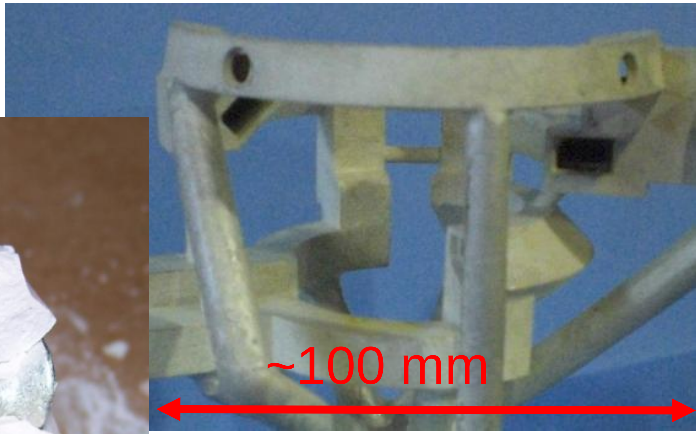
3D printed piece. Nylon. **80 €**

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.

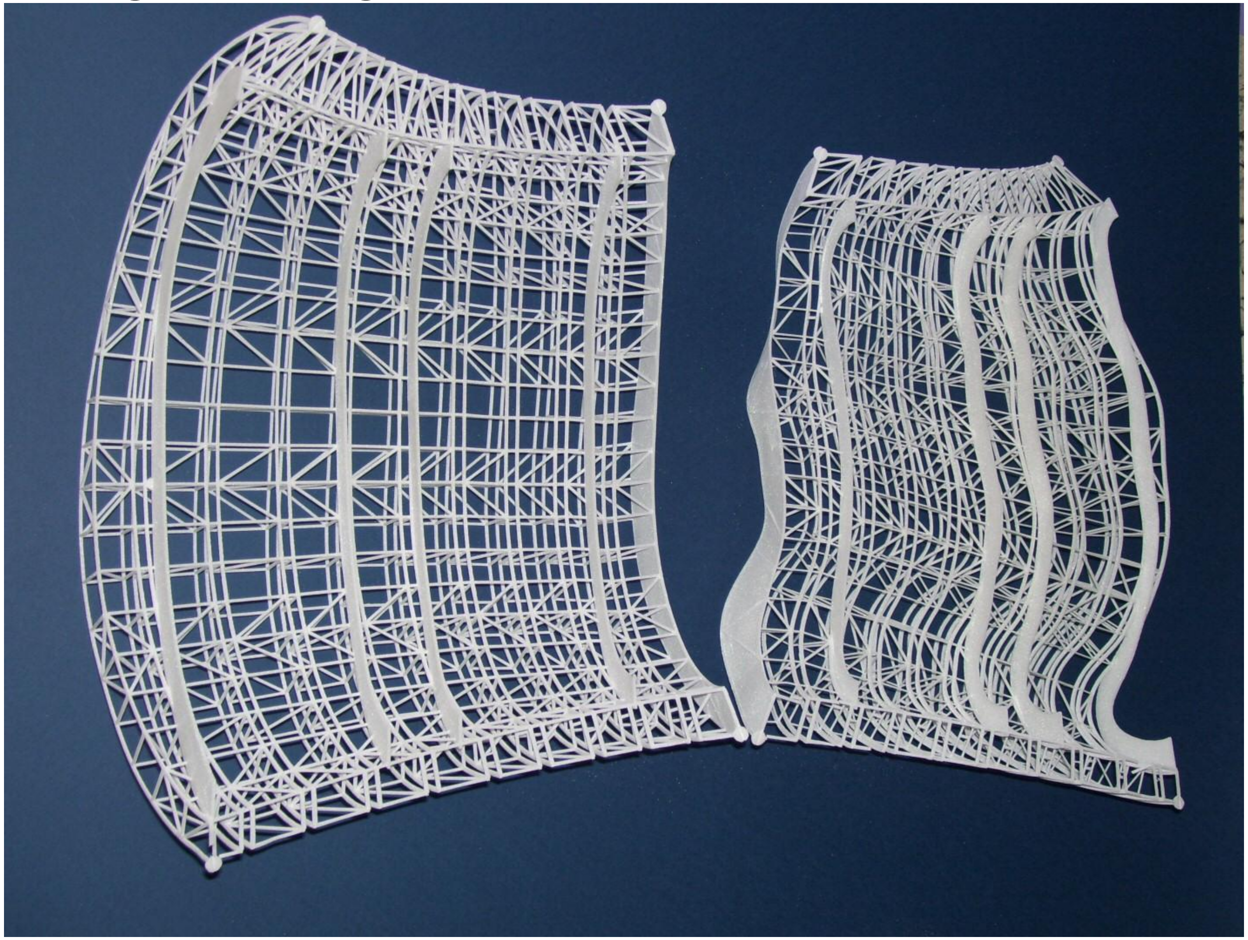


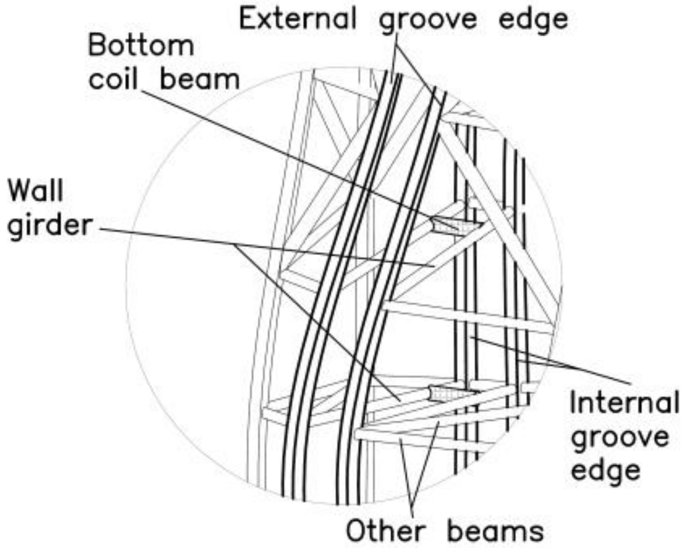
Silver lost wax vacuum casting in plaster mould produced in a specialised company.~ 1000 € in Ag. ~700 € in Cu

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

~UST_2-size 3D printed sector of coil frame test

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





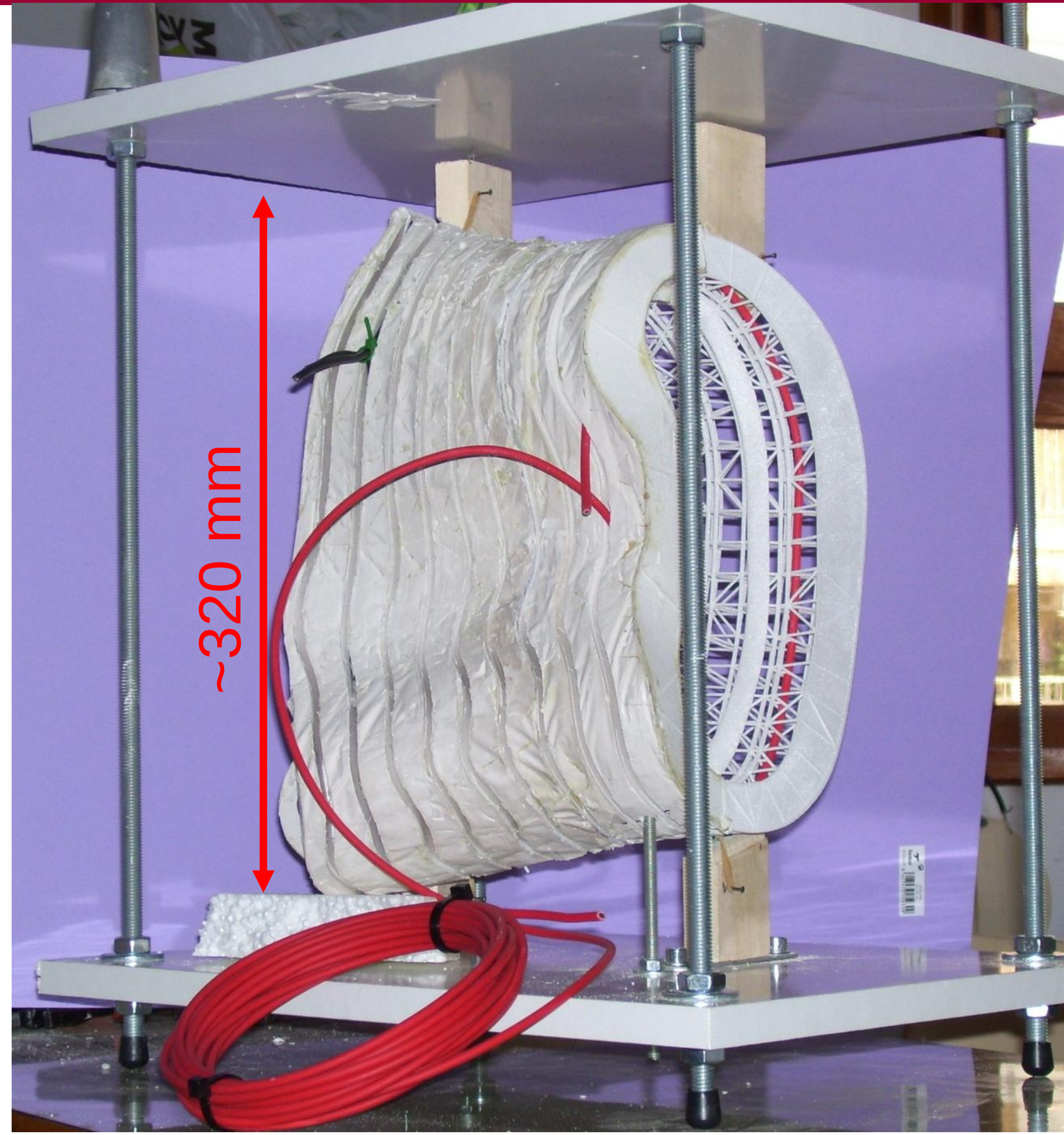
Elements of the Truss Concept

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

Results : Still difficult moulding and pair matching

One half-sector after hard plaster moulding

UST_2-size 3D printed sector of coil frame



Two views of the test of a coil frame sector

Conceptual design

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.

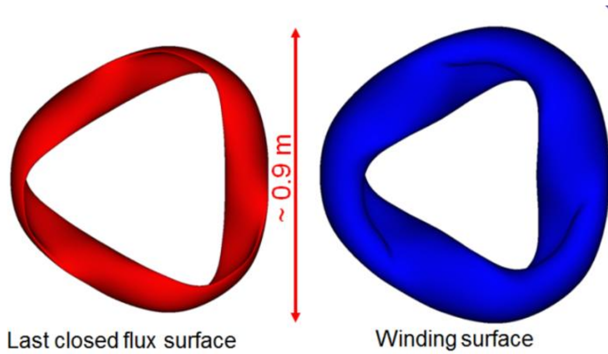
- The CASTELL code, a Java code developed by me during several years, is used for most of the calculations.
- VMEC, DESCUR and NESCOIL are used for the generation of coils and some plasma and winding surfaces.

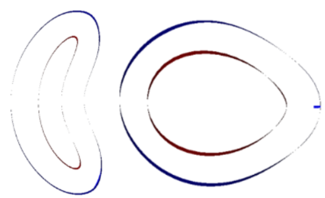
Selected reference magnetic configuration

QIPCC3

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

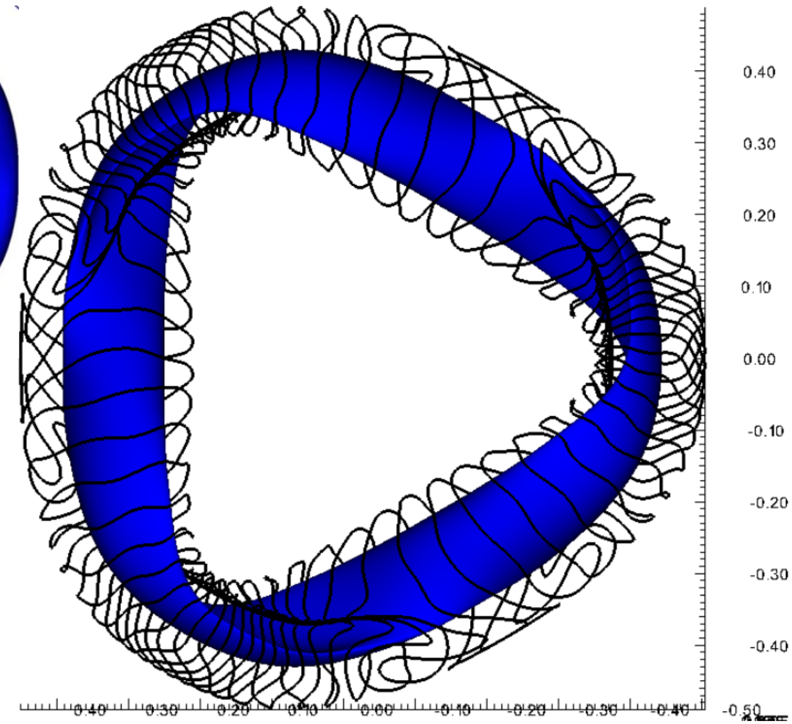
►Decision: Chosen for UST_2

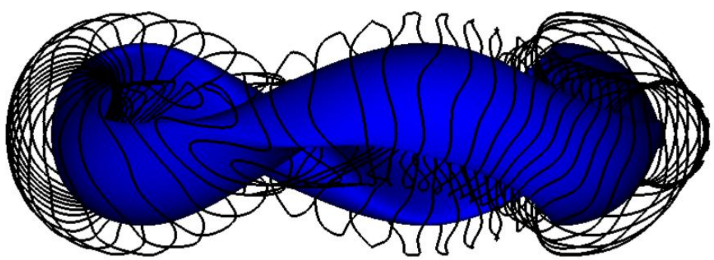




Retrospectively:

♦ 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

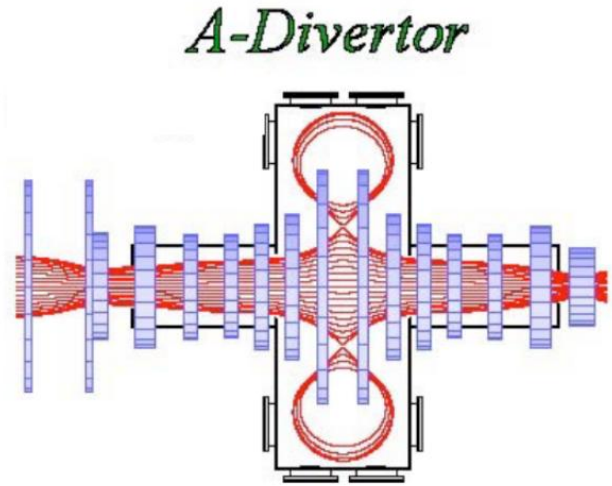
Modification of QIPCC3

Why not to modify QIPCC3 to enhance some engineering features of UST_2?

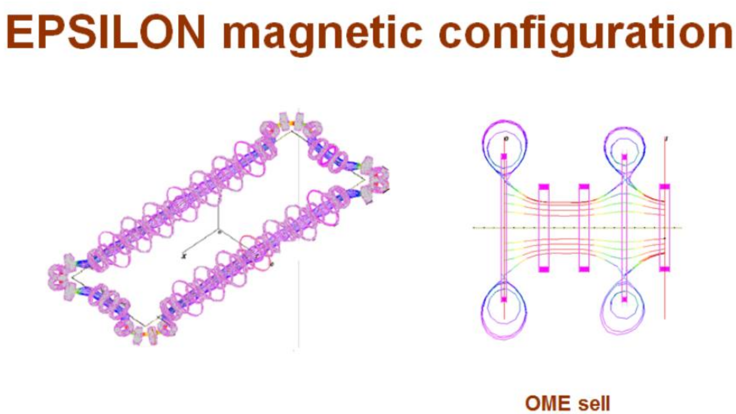
Insight came from,

► Initially:

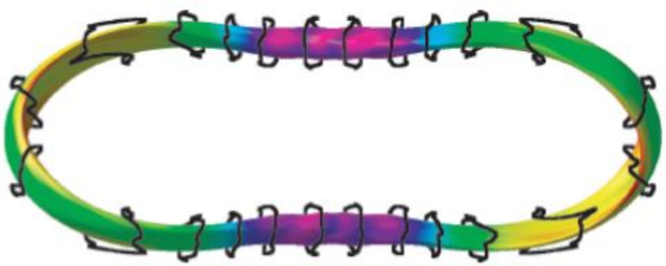
Planned divertor for the GAMMA 10 Tandem mirror. Source of figure [Ima 11]



► Later, after searching, from:



Linked mirrors. Source [Kul 06]

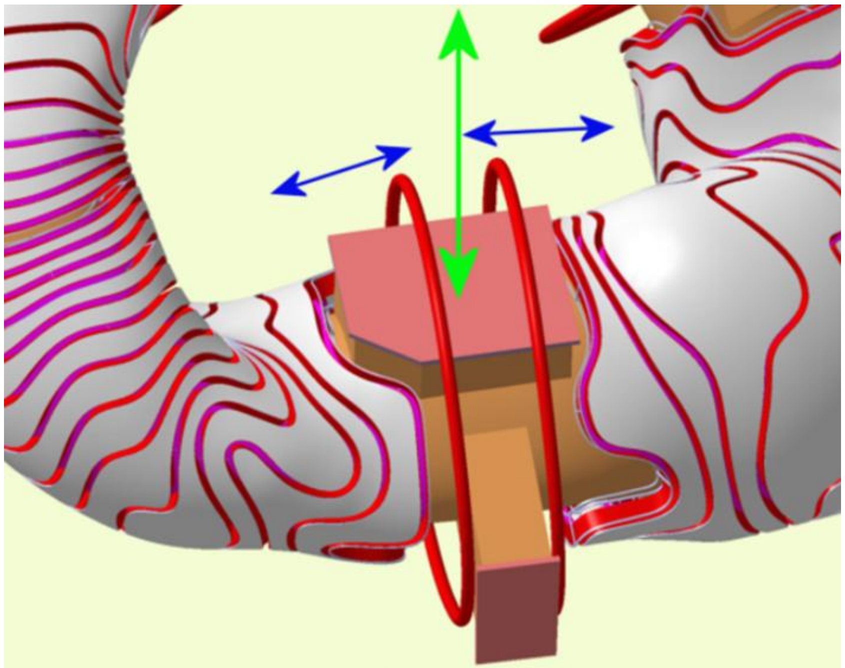


New QI configurations. Source [Spo 10]

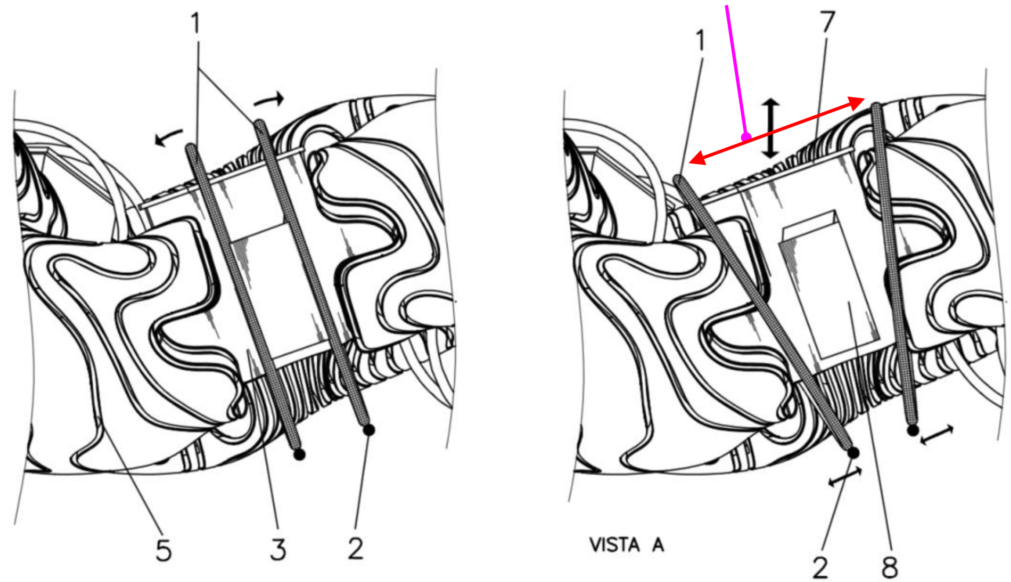
Modification of QIPCC3

One objective: Generate wide ports for fast Remote Handling

Complex CASTELL code optimization processes using also NESCOIL and DESCUR codes



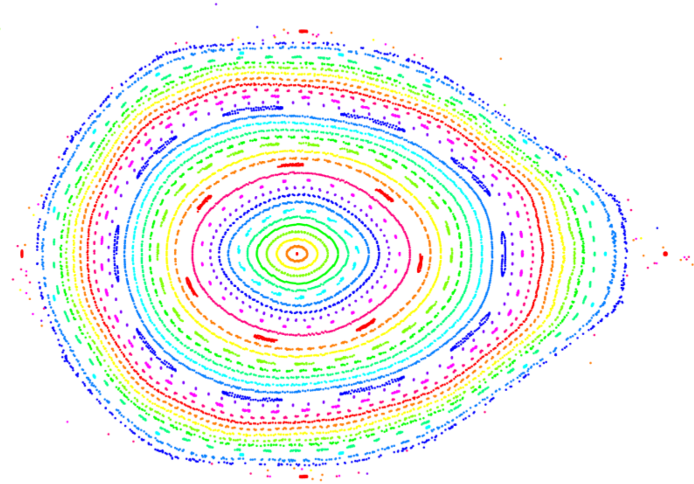
Wide opening for fast Remote Handling

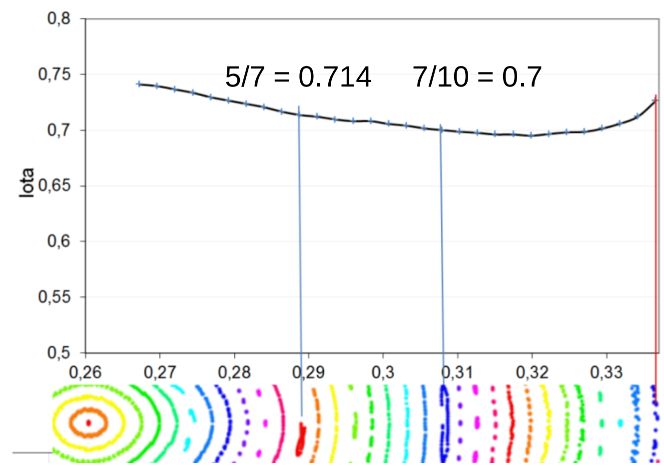


Movable planar non-circular coils for **fast and wide Remote Handling** in-vessel access.
Also space for future **large and powerful divertors**.

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

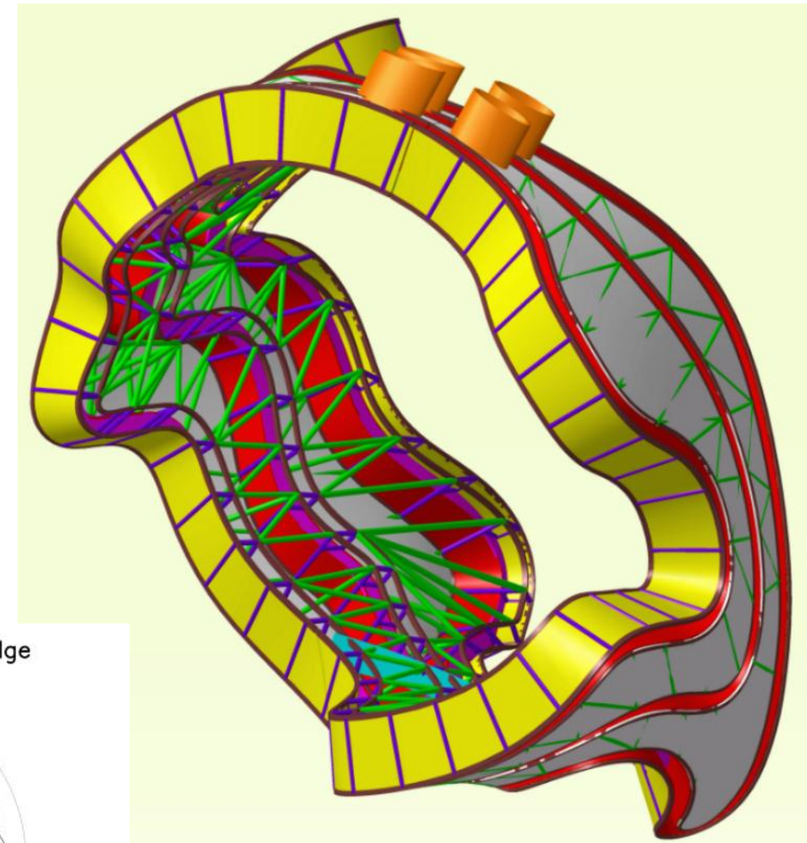
UST_2 specifications

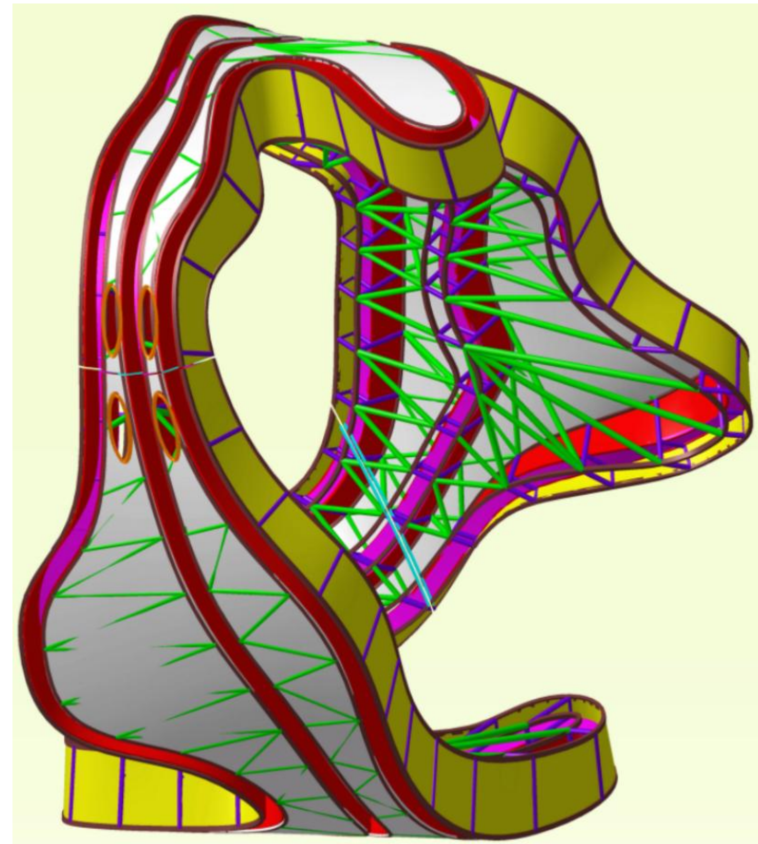
Coil engineering specifications

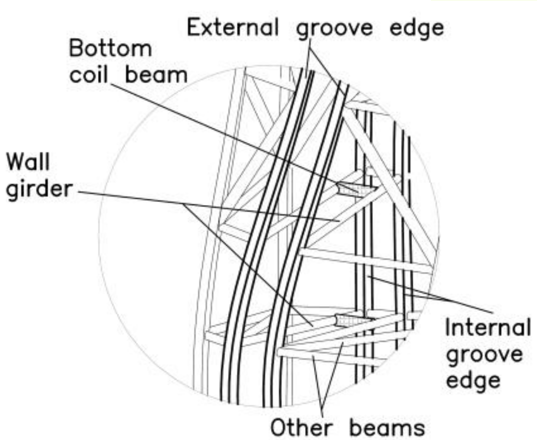
Element	Specification
Type of coils	Modular coils
Number of pancakes = coils	90
Number of non-planar pancakes	84 (14 x 6)
Number of large planar non-circular pancakes	6 (1 x 6)
Winding pack size (mm)	4 with x 12 depth
Conductor type	Flexible copper wire TXL 10 AWG gauge
Turns per pancake	3 layers x 1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

A mix of the Hull Concept and Truss Concept is chosen

3D printed thin cover surfaces and internal truss structure

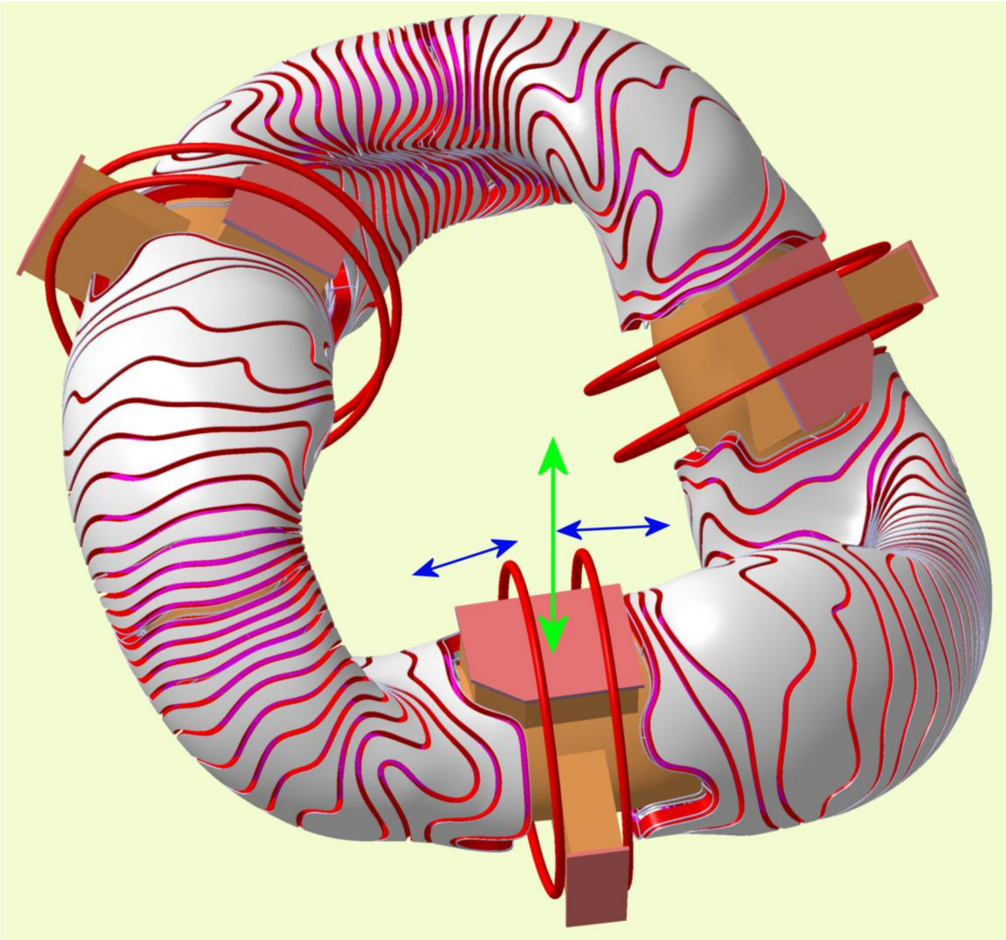




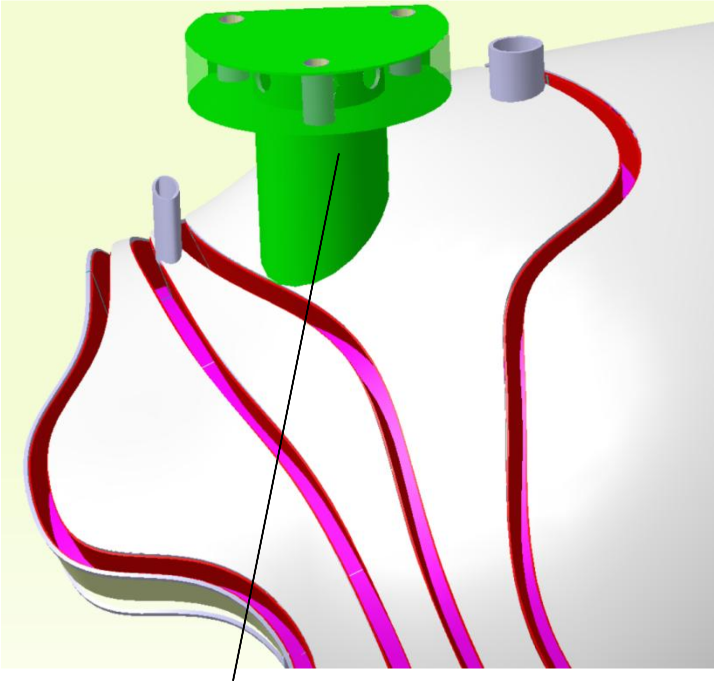


Perspective and top view of the first 3 coils 3D printed. A test. Printed by ‘Shapeways’ company. Cost **108 €** plus taxes and shipping

UST_2 engineering design

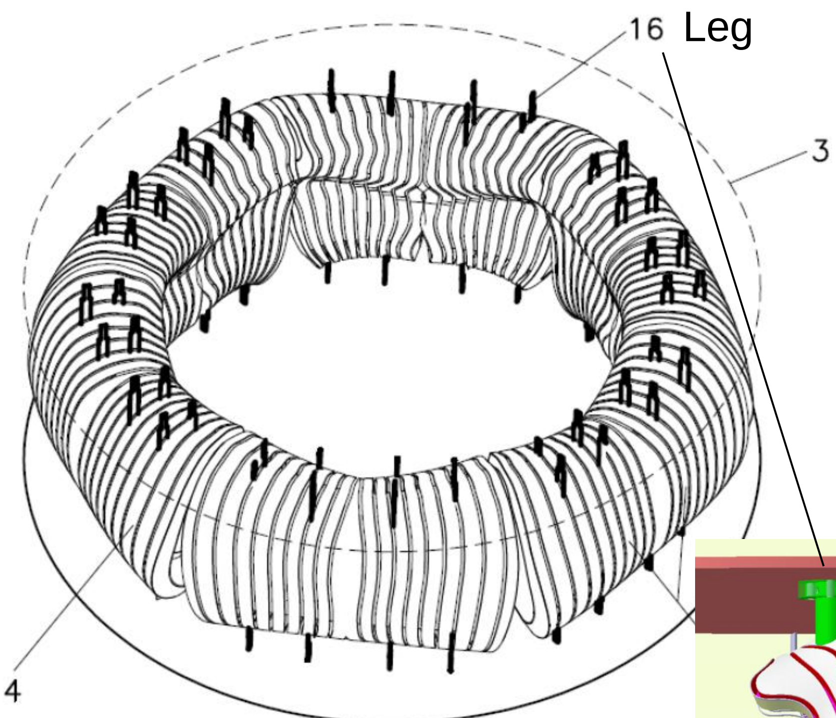


External view of the UST_2 design. Vacuum vessel still unclear

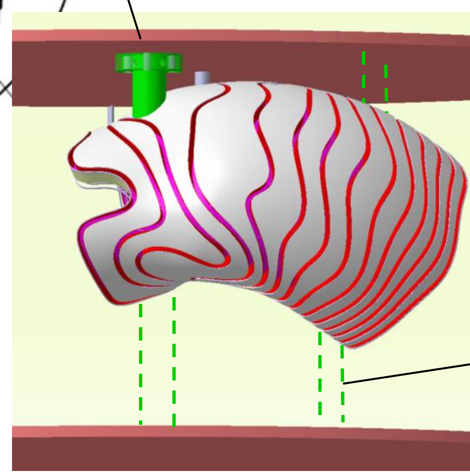


Design of one of the 8 leg per half period. The design of the leg is thought for plaster moulding

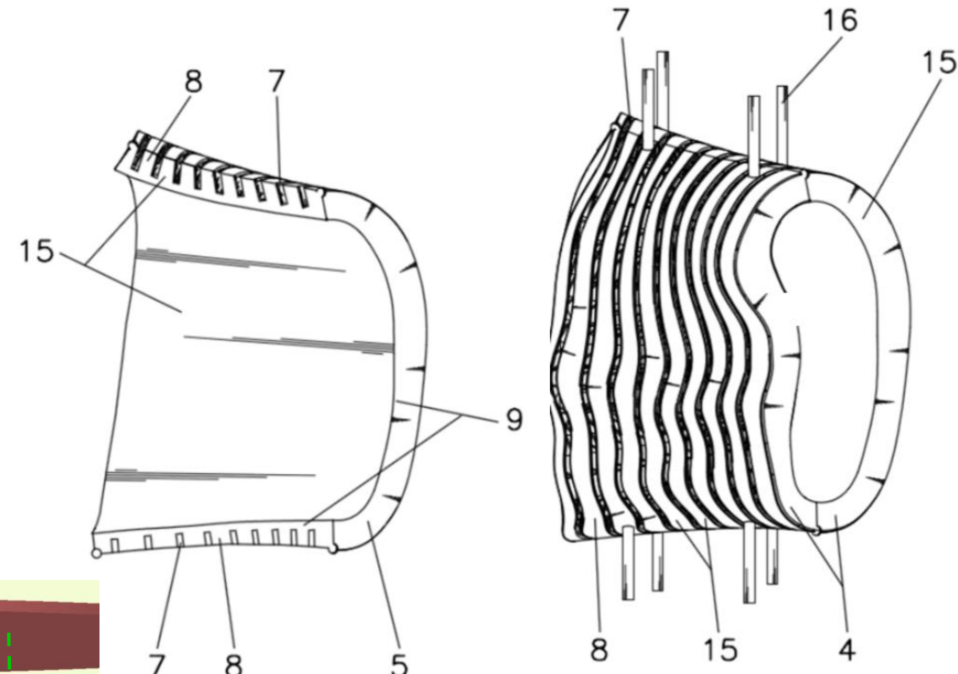
Assembling concepts



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



The other legs not designed yet



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

Vacuum vessel still unclear

A simple low cost VV?

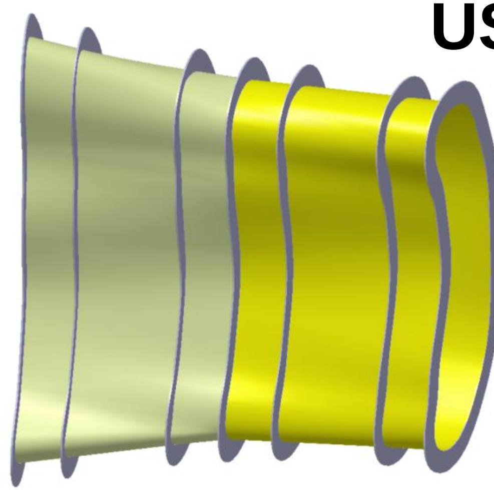
UST_1

Copper elbow

Finished UST_1 vacuum vessel

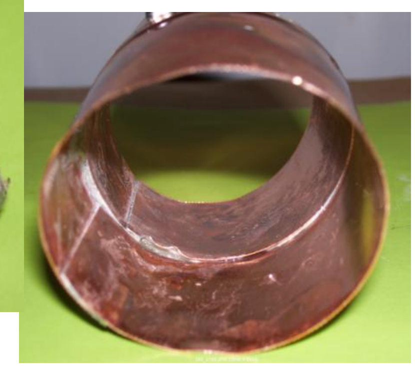
Similarly

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 (prospective) :

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

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)
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 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

UYING Fusion Energy

Excluded slides

Chronology of the development

Initially UST_1 was a white paper full of doubts

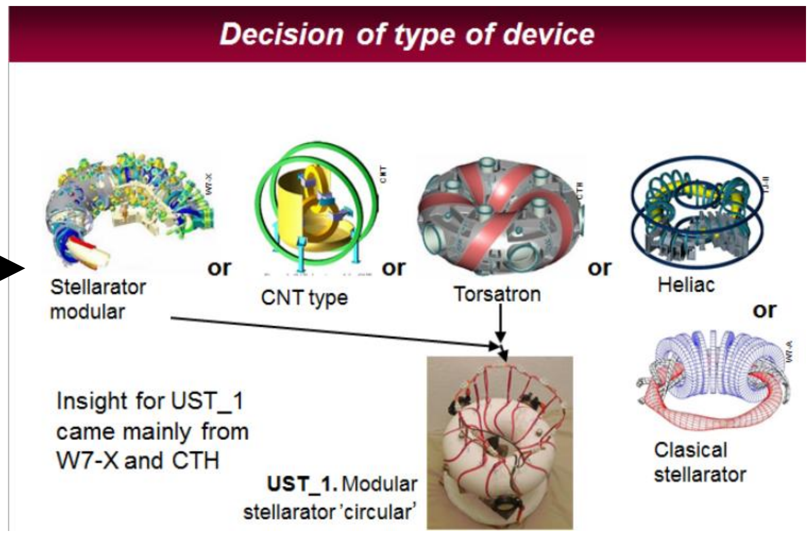
Tokamak? ~ June 2005.
An ETE tokamak scaled 1/6 was estimated → High CS power for I_p + short pulse, capacitors, safety, etc.

→ Rejected

Type of stellarator? June-October 2005.
Modular seemed best but no means to design it

Stellarator? ~ June 2005.
Seemed possible (long pulse, possible low plasma T, etc)

→



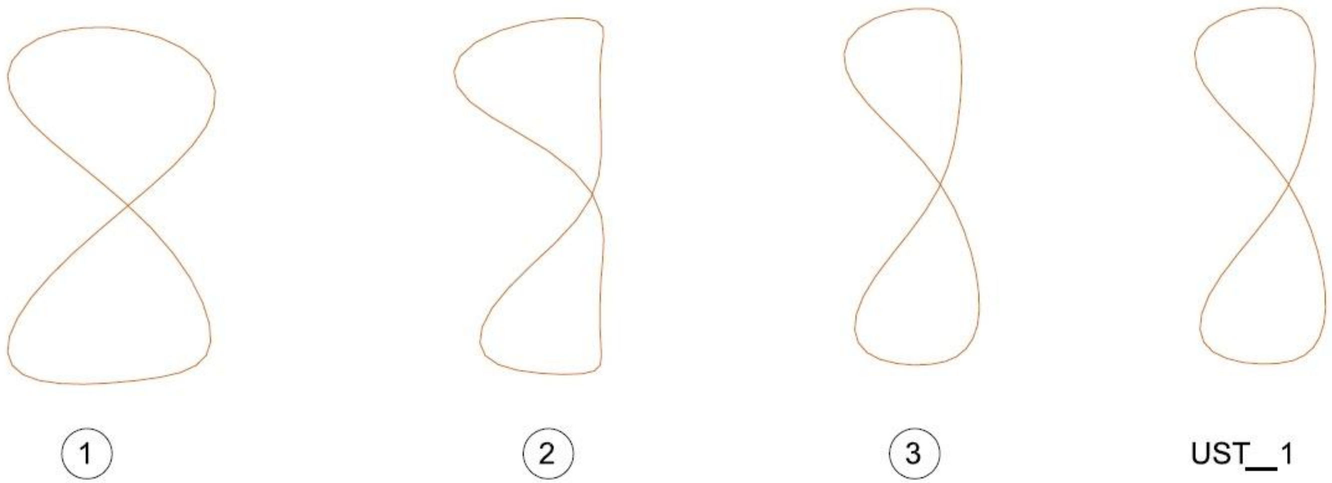
A classical st. Designed with CASTELL code. **January 2006**

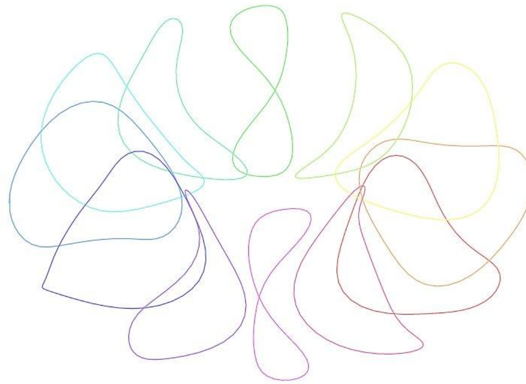
→ Rejected

Modular st.
More improved CASTELL
January 2006

UST_1 = Ultra Small Torus 1

Selection from ~10000 configurations





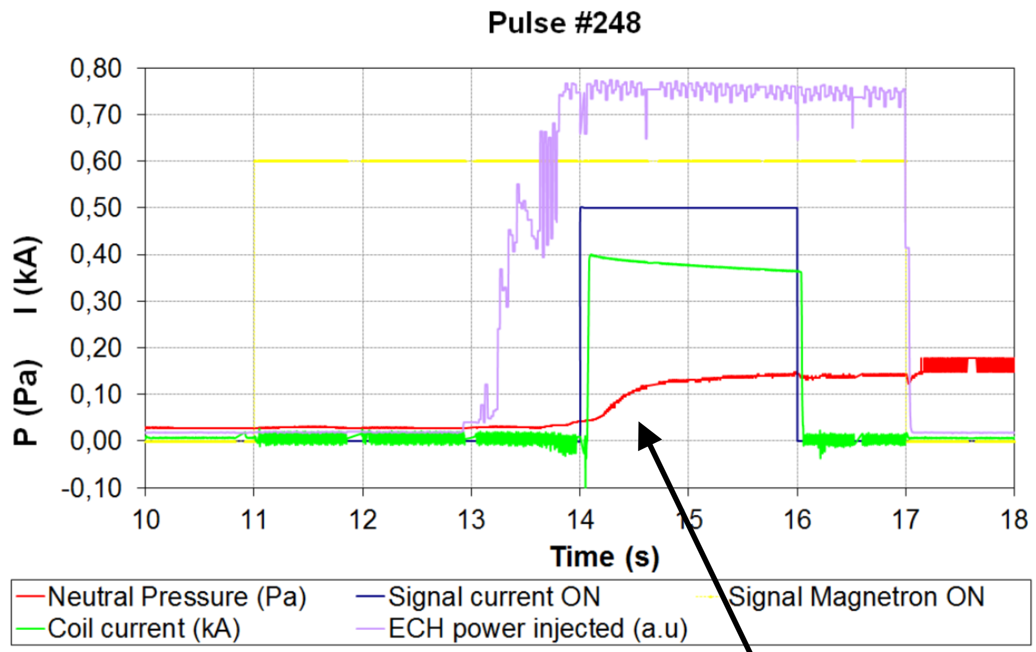
Summary of the optimization process
In a 4-dimensional space, CASTELL code calculates several properties of the configuration. A spreadsheet is created and the results are ordered mainly according to iota, plasma volume and σ of $|B|_{min}$. The best set of shaping parameters are heuristically selected. More refining loops. UST_1 parameters were selected.

Few tens of plasma pulses produced

- After e-beam field mapping the ECRH system was installed and pulses from #211 to #254 generated plasmas.

- Plasmas did not achieve any satisfactory degree of purity.

- The cause is likely desorption from the walls.



Chronogram of pulse #248

Increase of neutral pressure in the VV

251_Part_Cut.avi

Experiences learned

(focussed on the potential construction of another small stellarator)

• Winding **one turn per layer** compressed in the groove may be simpler and faster than winding two (need of an auxiliary conductor).

• The manufacture of the special sleeved conductor lasted long. Thin wall **commercial copper wire** should be used, i.e.TXL 10.

• An improved but still low cost **vacuum vessel construction** method should be devised and tested. It is challenging.

• The toroidal milling machine is unsuited for very convoluted winding surfaces. **Additive rapid prototyping** methods might be superior to the subtractive construction.

• The **toroidal milling machine is expensive** (design and construction time) if at least several stellarators are not fabricated.

• UST_1 is unable for valuable plasma experiments. A **stellarator scaled at least 3-fold UST_1** might be worthy for plasma experiments

Several devices have been assessed

QPS

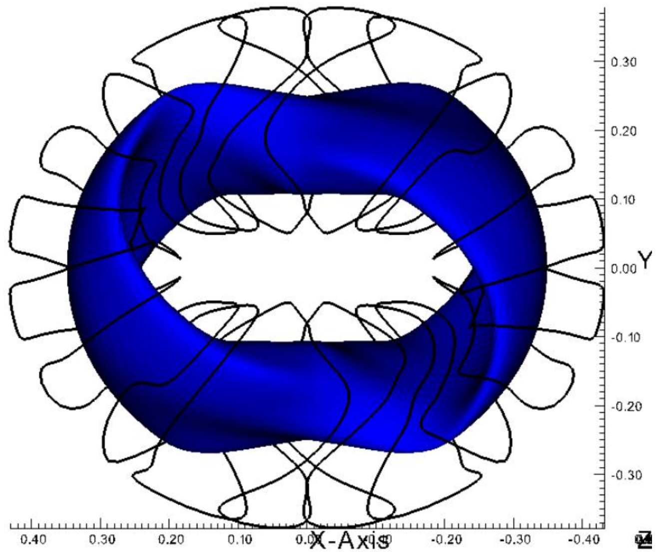
- The device is optimised for β~2% but β_{UST_2} ~0%.

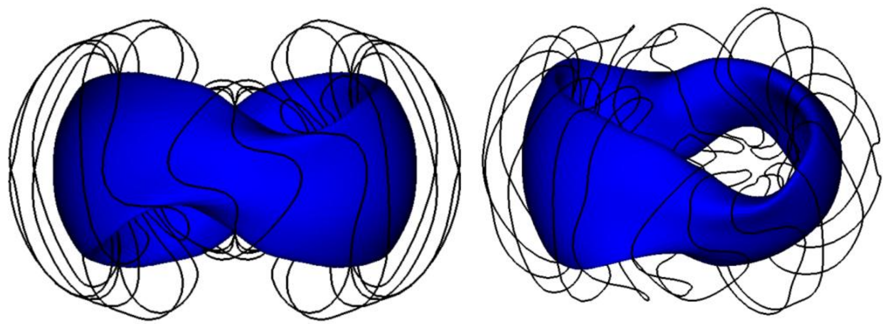
♦ Relatively poor confinement obtained for β=0% (to be confirmed by better codes).

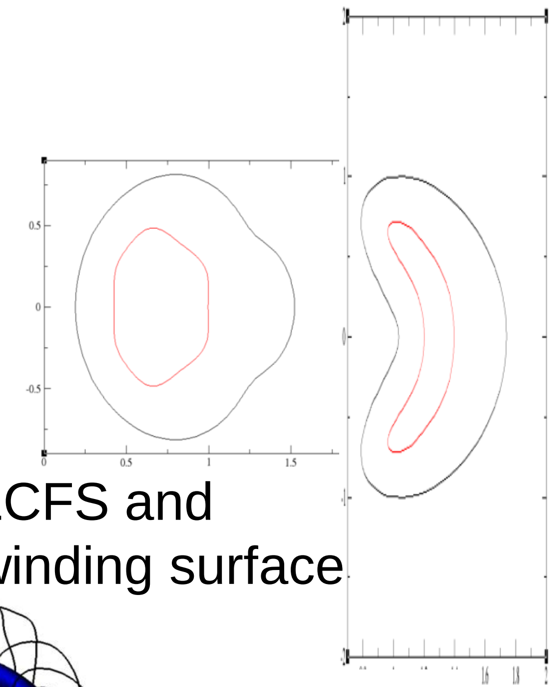
♦ Too compact to allocate inboard blankets, if reactor.

► Potential improved turbulence transport.

►Decision: Not chosen for UST_2

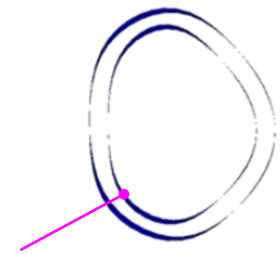






LCFS and winding surface

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



β=2% VMEC Free boundary run

LCFS, winding surface and coils supplied by J. Harris and D. Spong

QIPCC2

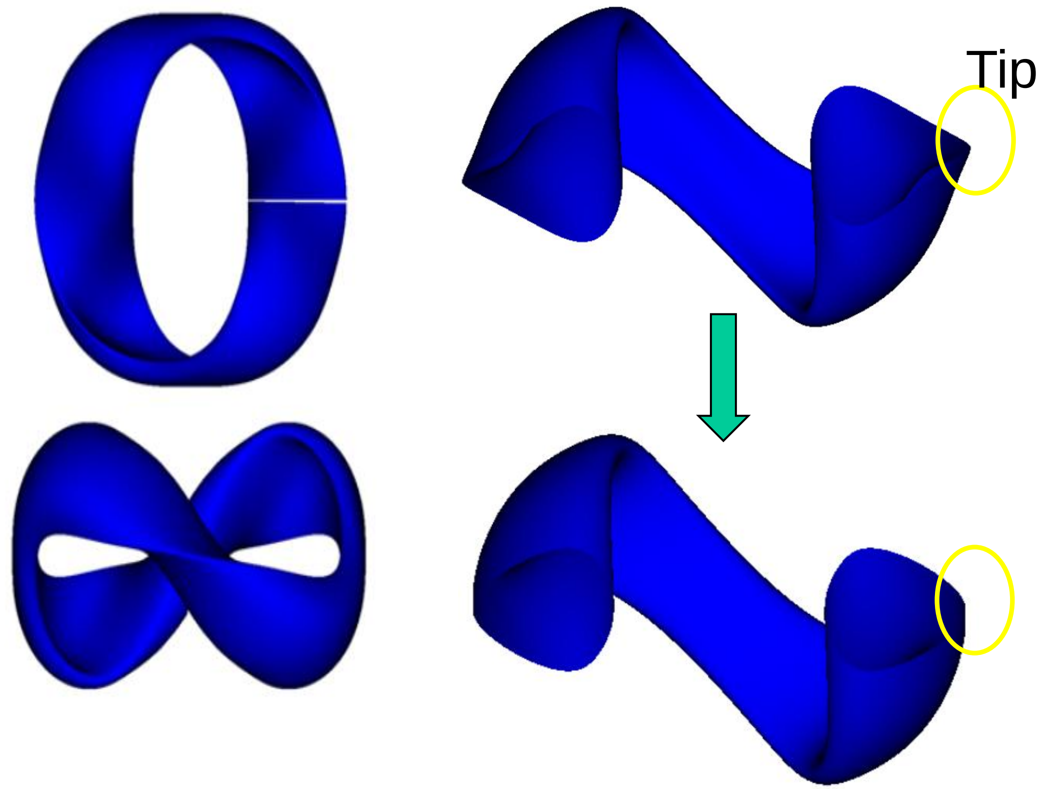
♦ Considered too large helical excursion.

♦ Configuration with LCFS tips. Unfeasible coils.

► Acceptable confinement.

► Potential improved turbulence transport.

► Decision: Not chosen for UST_2



Using DESCUR code the LCFS was rounded

QIPC6 Large aspect ratio. **Not chosen**

LCFSs supplied by J. Nührenberg and team

Several devices have been assessed

NCSX-TU
NCSX
Mix

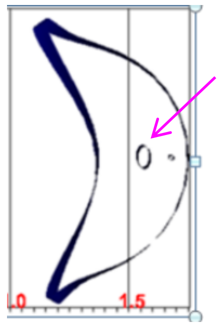
♦ The device is optimised for β=4% +Ip but β_{UST_2} ~0%.

♦ This particular configuration has tips.

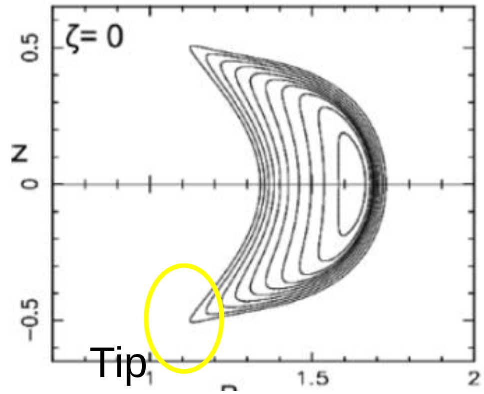
• Complex overlapping

► Potential improved turbulence transport.

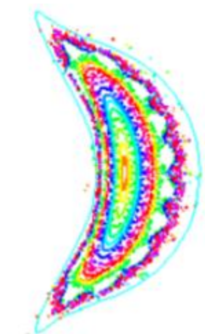
►Decision: Not chosen for UST_2



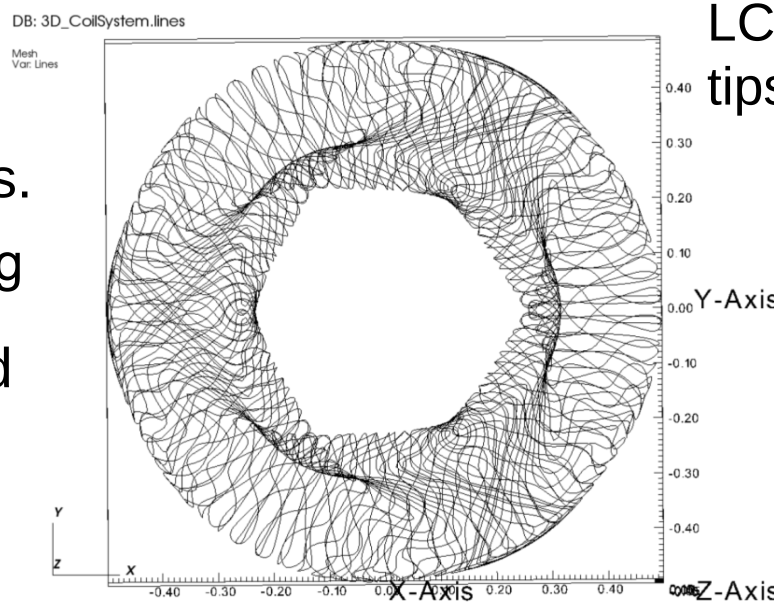
β=4%+Ip
VMEC-Fix



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

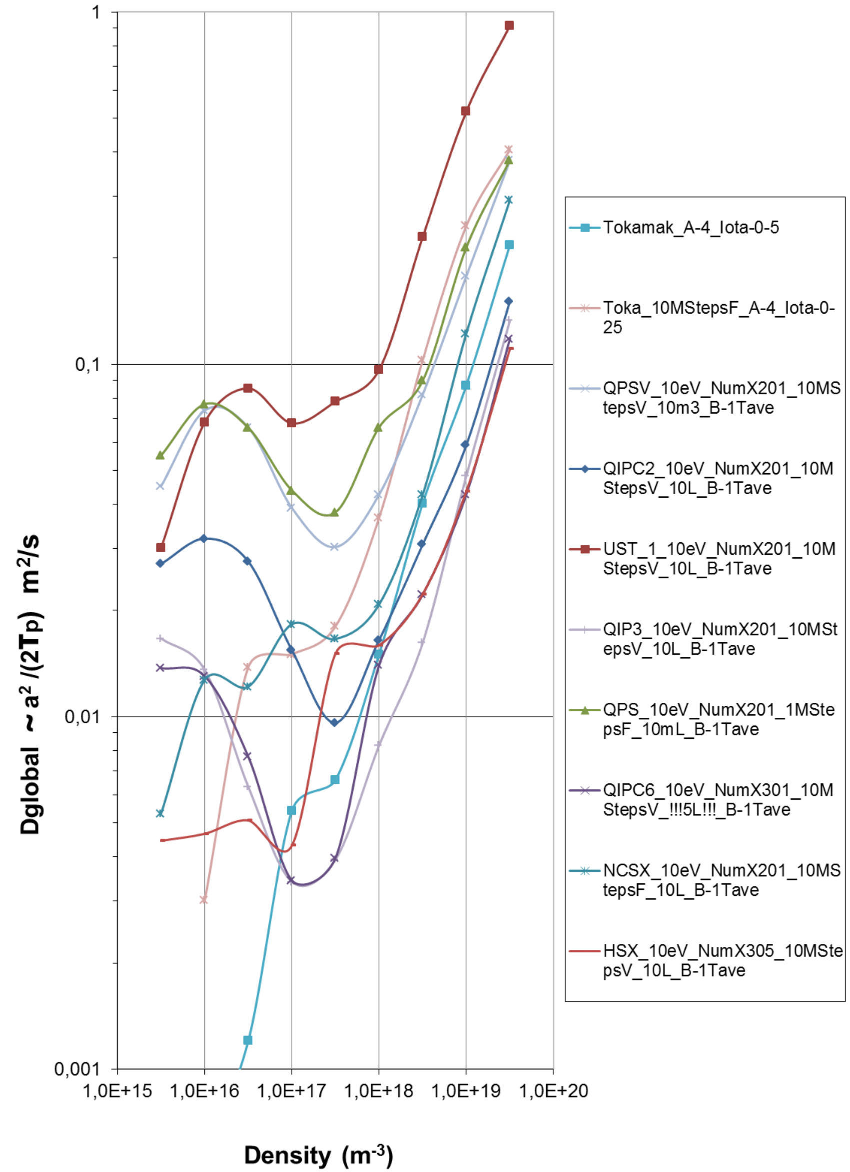
Several devices assessed

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

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

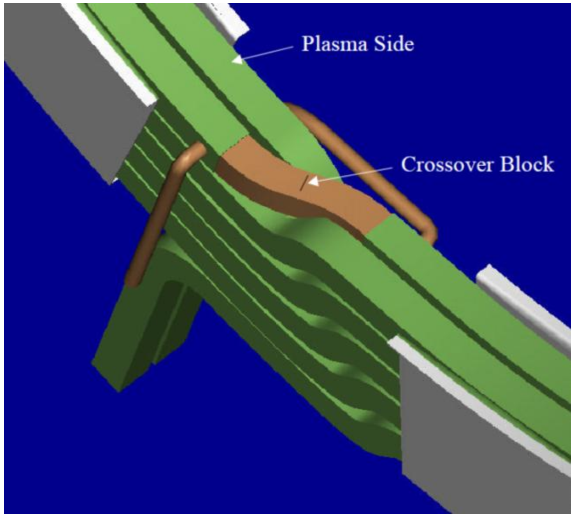
Neoclassical transport **estimation/comparison** of possible devices for UST_2. Particle confinement time, from CASTELL code. E_r=0. (to be confirmed by well-validated codes)

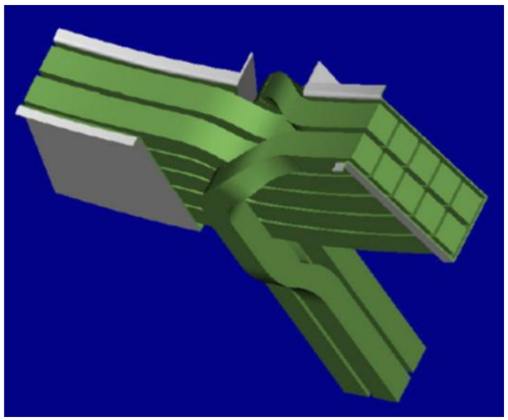
Comparison of QPS QPSV QIPC2 QIPC3 QIPC6 HSX NCSX UST_1 Toka. Bave=1T . Protons 10 eV. V=10L



Calculation of magnetic errors

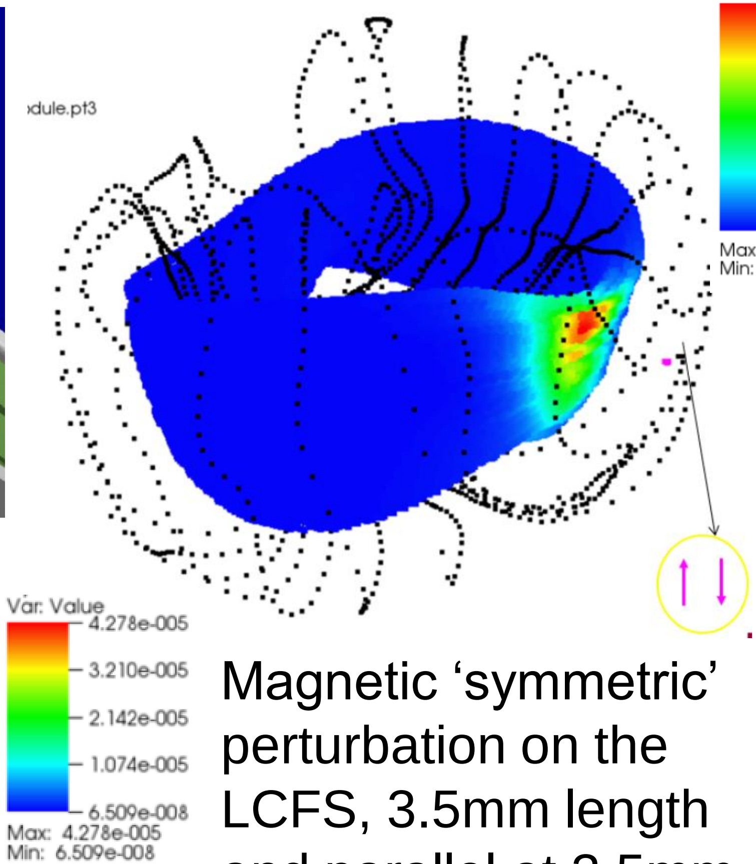
Due to crossovers





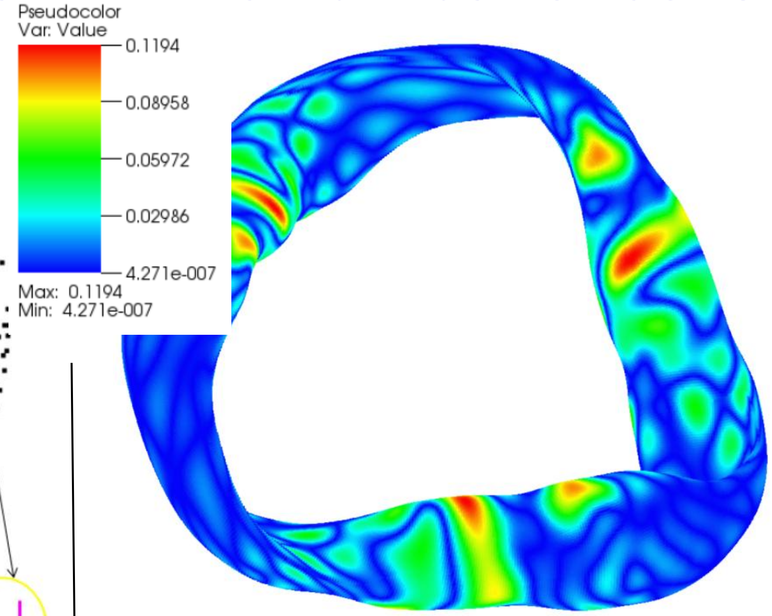
Two Types of crossovers.

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)

Due to finite number of coils



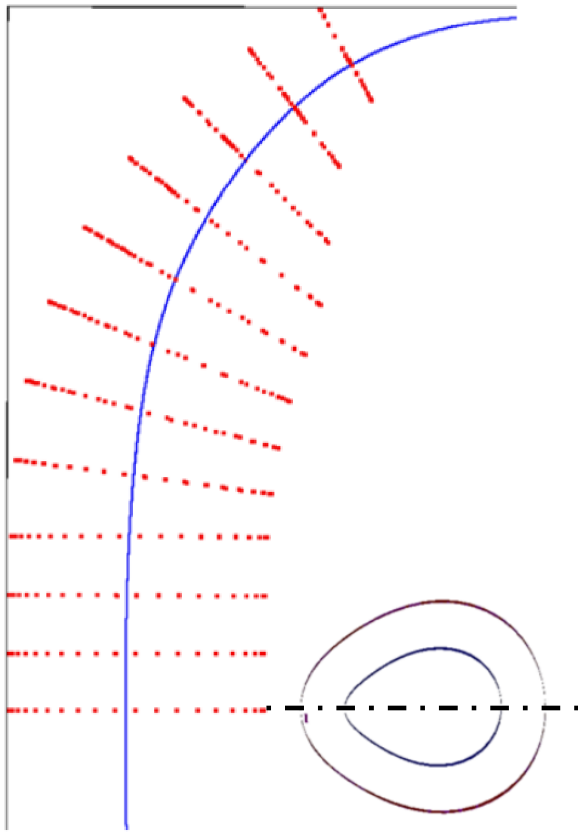
90 coils, UST_2.
'Modular error'

UST_2 is optimized for good confinement, not for low errors (Ave. error: 2%, Maximum error: 12 %)

Process of modification of QIPCC3

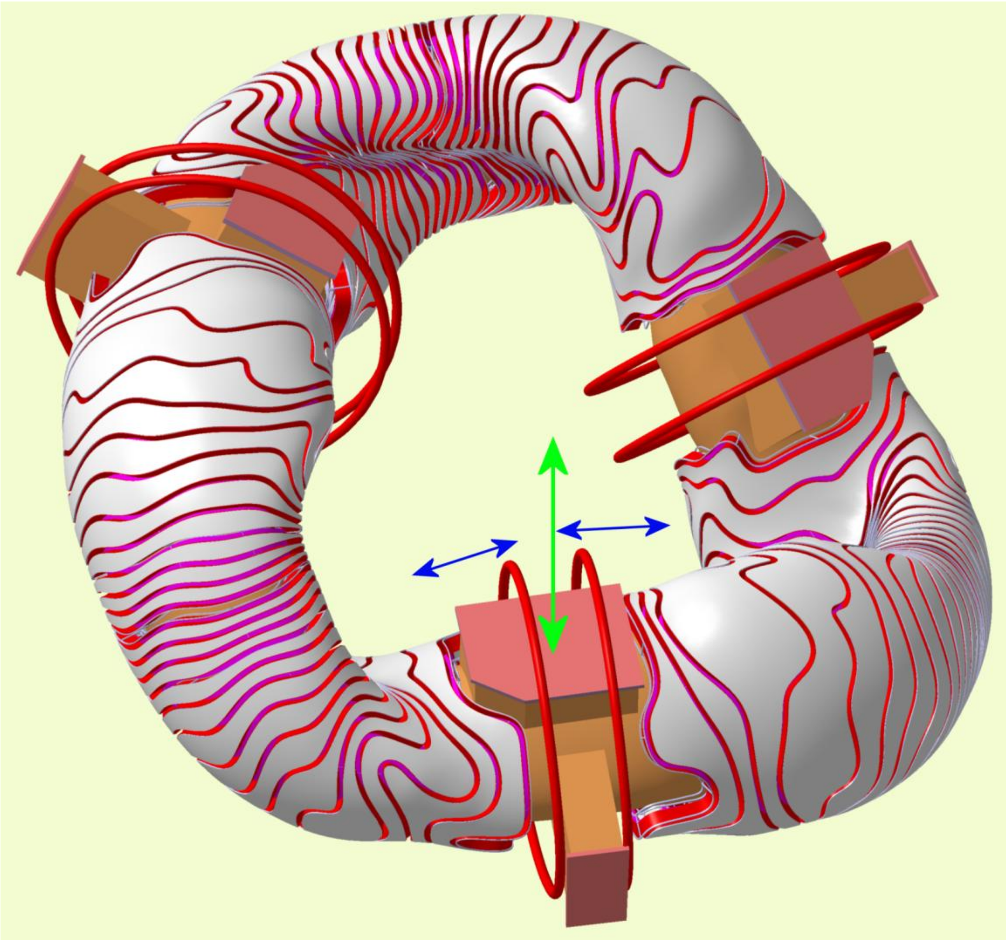
The straight section is stretched by CASTELL code, plus re-optimization

- **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 engineering design



External view of the UST_2 design

This design can be considered definitive. It will be hardly modified.

- The **vacuum vessel** will have only three main ports. The wide ports for vertical access in figure are a possibility for the future.

- The fabrication method of the **VV** will depend on funds: **i)** Manually, similarly to UST_1 or **ii)** Direct metal 3D printing if abundant funds are obtained (unlikely).

Possible long term activities

Built the ‘Keops Builder’ 3D printer?

Similarly to the construction of the *toroidal milling machine* for UST_2, the construction of a special 3D printer for stellarators may be necessary for large devices.

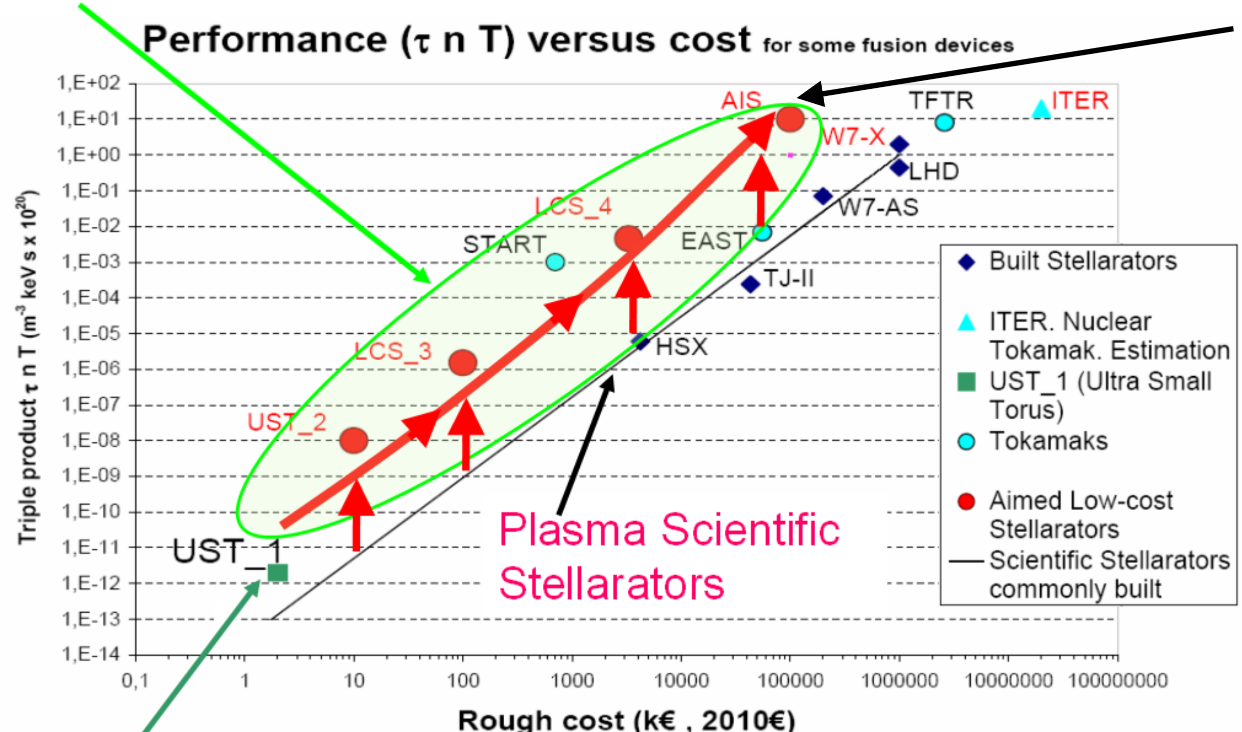
Modified standard cranes and systems might simplify the construction of ‘Keops Builder’

D-Shape large 3D printer. Likely the largest in the world. Source of photo Enrico Dini.

Possible long term activities

Sequential low-cost rapid manufacturing of larger devices

Objective: Low-cost construction of stellarators



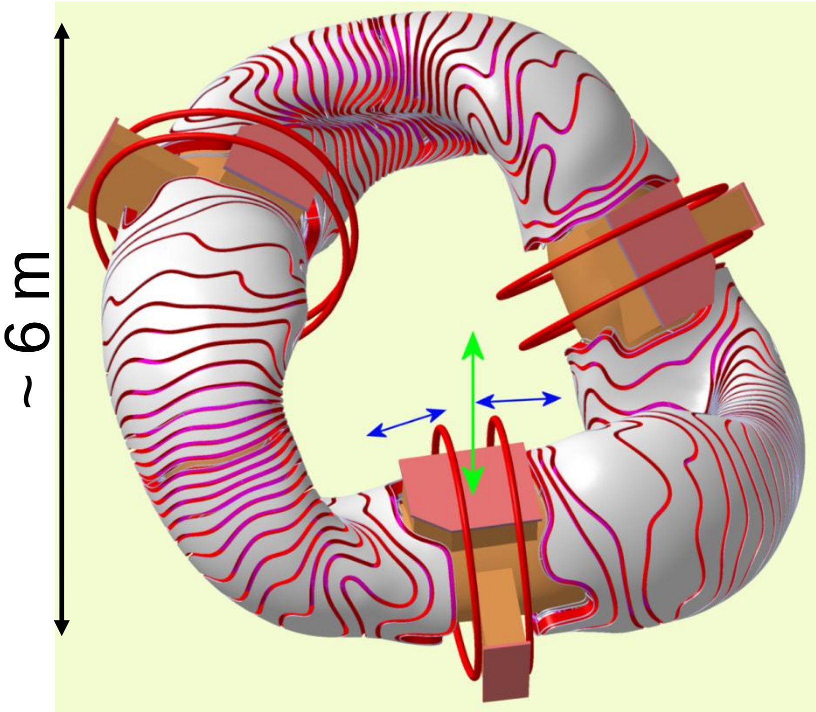
Real low-cost stellarator

Planned (= non-existent) **low-cost** devices (mainly stellarators)

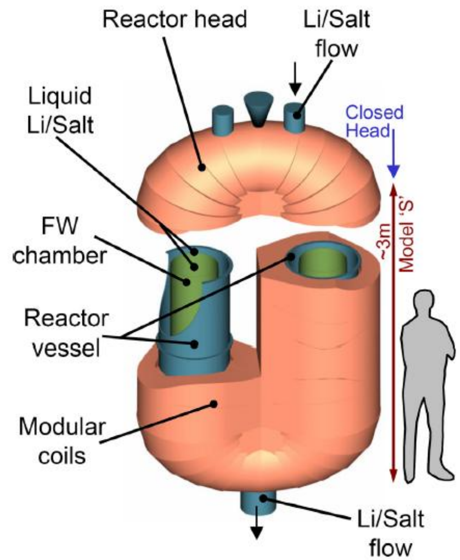
Concept : High-field pulsed Allure Ignition Stellarator (AIS) (2010). [Que 10] High-field, few ignition pulses. Somewhat similar to the IGNITOR, FIRE and FAST concepts, but for a stellarator.

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

Possible Allure Ignition Stellarator (AIS) concepts



UST_2-like but formed 100% by copper coils (Alcator C-Mod like), following the AIS concept. Also vertical position?



Original 2010 AIS concept: two periods, low twist, vertical RH (shape similar to QPS)

Other concepts?

Extra slides

Table of results from UST_1 optimization

Order	Iota_1	Ripple_1	%T	Bmin_Desvia	Average_Rip	PlasmaSiz	Iota_2	Speci	Speci	MinDistanc	Fr	Pitch_On	Pitch2	Pitch3	Pitch4	H	Positi	up/dwon	well	
5	0,32121037	0,21300687	0	0,00374385	0,11439581	0,05125	0,33552672	9,98	10	0,009852	0	1,4	1,25	1,6	0,65	1	0,13	1,045	0,005	
73	0,32177544	0,19787124	0	0,00318734	0,11406053	0,05	0,33412121	9,75	9,82	0,007882	0	1,5	1,35	1,55	0,6	1	0,13	1,038	0,007	
65	0,32024554	0,20227083	0	0,00373036	0,10963253	0,05125	0,33327691	9,59	9,7	0,008333	0	1,5	1,3	1,55	0,65	1	0,13	1,041	0,011	
66	0,31997029	0,21509815	0	0,00312266	0,11926719	0,05125	0,33323999	9,88	9,96	0,008333	0	1,5	1,3	1,6	0,55	1	0,13	1,041	0,008	
58	0,31962951	0,21167492	0	0,00411215	0,11538991	0,05125	0,33303551	9,76	9,81	0,008784	0	1,5	1,25	1,6	0,6	1	0,13	1,042	0,006	
100	0,32221723	0,20706325	0	0,00441405	0,11215376	0,055	0,33275596	9,55	9,68	0,007348	0	1,55	1,35	1,55	0,6	1	0,13	1,033	0,013	
21	0,31750303	0,22302173	0	0,00378824	0,12245854	0,05	0,33218611	10,2	10,3	0,00895	0	1,4	1,35	1,6	0,55	1	0,13	1,046	0,002	
38	0,31735654	0,21121886	0	0,00379767	0,11032161	0,0525	0,33182238	9,74	9,83	0,008867	0	1,45	1,3	1,55	0,65	1	0,13	1,046	0,009	THIS
46	0,31811712	0,20618378	0	0,00347575	0,11421107	0,0525	0,33172369	9,91	9,94	0,008416	0	1,45	1,35	1,55	0,6	1	0,13	1,043	0,004	
31	0,31552703	0,22044592	0	0,0037769	0,1160773	0,05125	0,33076228	9,89	9,98	0,009318	0	1,45	1,25	1,6	0,6	1	0,13	1,048	0,009	
39	0,31629678	0,22423351	0	0,00345106	0,12014642	0,0525	0,33013713	10	10,1	0,008867	0	1,45	1,3	1,6	0,55	1	0,13	1,044	0,006	
84	0,31663715	0,2027263	0	0,00370281	0,11769417	0,055	0,32961367	9,7	9,78	0,008056	0	1,55	1,25	1,6	0,55	1	0,13	1,041	0,009	
91	0,31780244	0,19299761	0	0,00414231	0,11246796	0,05375	0,32909387	9,54	9,63	0,00778	0	1,55	1,3	1,55	0,6	1	0,13	1,036	0,009	
99	0,31631804	0,20671245	0	0,00468787	0,11574988	0,055	0,32851403	9,66	9,76	0,007348	0	1,55	1,35	1,55	0,55	1	0,13	1,039	0,011	
83	0,3154783	0,19315352	0	0,00436111	0,10875171	0,0525	0,32830247	9,39	9,51	0,008056	0	1,55	1,25	1,55	0,65	1	0,13	1,041	0,013	
11	0,31369671	0,21665571	0	0,00410095	0,11192947	0,05125	0,32827982	9,9	9,98	0,009401	0	1,4	1,3	1,55	0,65	1	0,13	1,046	0,007	
4	0,31422598	0,2092244	0	0,0035935	0,11873827	0,05125	0,32806725	10	10,1	0,009852	0	1,4	1,25	1,6	0,6	1	0,13	1,044	0,006	
19	0,31346058	0,21258333	0	0,00432119	0,11584367	0,05	0,32744505	10,1	10,1	0,00895	0	1,4	1,35	1,55	0,6	1	0,13	1,045	0,003	
	Cut																			
90	0,30859755	0,21014439	0	0,00433755	0,11578788	0,055	0,32115361	9,61	9,69	0,00778	0	1,55	1,3	1,55	0,55	1	0,13	1,041	0,009	
63	0,31314478	0,20095219	0	0,00297516	0,1167087	0,05625	0,32018027	9,75	9,83	0,008333	0	1,5	1,3	1,55	0,55	1	0,13	1,022	0,008	
18	0,30694923	0,2152499	0	0,00340183	0,12000274	0,0525	0,32006331	10,1	10,2	0,00895	0	1,4	1,35	1,55	0,55	1	0,13	1,043	0,007	
55	0,30714644	0,20132164	0	0,00371561	0,1123814	0,05375	0,31927263	9,61	9,72	0,008784	0	1,5	1,25	1,55	0,6	1	0,13	1,039	0,012	

UST_1

Some of the ~10000 configurations computed

Table of results from UST_2 re-optimization

	Iota 1/5	Iota 1/2	Iota 4/5	Free	MagWell 1/5	MagWell 1/2	MagWell 4/5	Free	Ave. error B on surf	Max. error B on surf	Distance from coil 1 to planar coil 0
Final series of calculations											
0	0,745098039	0,7109375	0,69649805	0	7,74E-04	0,003160142	0,002569013	1	0,015608524	0,079302344	0,001780502
1	0,749019608	0,7109375	0,692607	0	4,10E-04	0,003340406	0,002887658	1	0,015586085	0,078180614	0,002002498
2	0,749034749	0,711538462	0,72222222	0	0,001282883	0,002317614	NaN	0	0,023149772	0,238392526	0,001119903
3	0,728346457	0,701960784	0,6953125	1	5,18E-04	0,002287208	0,002688822	1	0,016512383	0,088458531	0,015974181
4	0,732283465	0,701960784	0,69140625	0	4,67E-04	0,002491243	0,002950144	1	0,016453344	0,089583131	0,015153067
5	0,732283465	0,705882353	0,69140625	0	4,49E-04	0,002677444	0,003185485	1	0,016395171	0,089378631	0,014949422
6	0,732283465	0,705882353	0,6953125	0	4,82E-04	0,001891048	0,001917556	1	0,016868778	0,088723387	0,017293521
7	0,732283465	0,705882353	0,6953125	0	4,69E-04	0,002076414	0,002224254	1	0,016761668	0,087871936	0,017575223
8	0,732283465	0,705882353	0,69140625	0	4,50E-04	0,002173133	0,002394445	1	0,016707483	0,087871279	0,017411366
9	0,707509881	0,692913386	0,69140625	1	4,36E-04	0,002817011	0,002216768	1	0,017134387	0,090800405	0,018807202
10	0,711462451	0,692913386	0,69140625	1	4,90E-04	0,002892194	0,00241243	1	0,017074867	0,089384018	0,01861812
11	0,711462451	0,692913386	0,69140625	1	5,19E-04	0,003048567	0,002788585	1	0,016987469	0,088066347	0,018830686
Other in relation to the previous. With always the same magnetic axis (no so accurate +-2mm are observed in the variation on the postion of the axis											
0	0,7421875	0,708171206	0,69379845	0	7,61E-04	0,003435092	0,00298142	1	0,015973196	0,089203179	5,47E-04
1	0,728346457	0,701960784	0,6953125	1	4,82E-04	0,002277566	0,002696534	1	0,016527978	0,089346011	0,015419556
2	0,706349206	0,691699605	0,69803922	1	7,79E-04	0,003460427	0,003222168	1	0,016242147	0,081806343	0,016526842
3	0,73828125	0,708171206	0,69379845	0	7,32E-04	0,002902603	0,002501524	1	0,015948247	0,089636454	7,91E-04
4	0,732283465	0,701960784	0,6953125	0	5,26E-04	0,00209408	0,002313693	1	0,01667941	0,088805501	0,016676794
5	0,706349206	0,691699605	0,69411765	1	6,83E-04	0,003269062	0,002848301	1	0,016432456	0,083011205	0,017627209
6	0,724409449	0,701960784	0,69140625	1	3,58E-04	0,00216376	0,00244486	1	0,017150839	0,09597157	0,017332466
7	0,732283465	0,705882353	0,6953125	0	4,95E-04	0,001901906	0,001927163	1	0,016834987	0,087757825	0,017739872
8	0,706349206	0,691699605	0,69411765	1	6,23E-04	0,003120768	0,002497093	1	0,01663612	0,084483263	0,018328311
Folder : SEVERAL-Cases_Better_magAxisPositionThe next are executed with the correct calculated magnetic axis											
0	0,744094488	0,71372549	0,6953125	0	7,27E-04	0,003358598	0,003396739	1	0,015976518	0,089208913	7,54E-05
1	0,728346457	0,701960784	0,692607	1	5,57E-04	0,002148526	0,002202617	1	0,016512913	0,090043617	0,017033059
2	0,707509881	0,688976378	0,69921875	1	8,16E-04	0,003430414	0,002974087	1	0,016227592	0,081541729	0,016932734
3	0,725490196	0,703125	0,692607	1	4,80E-04	0,002392155	0,00301173	1	0,016832315	0,089224974	0,018175136
4	0,732283465	0,701960784	0,6953125	0	5,43E-04	0,002103731	0,002319237	1	0,016664918	0,088435544	0,016880568
5	0,703557312	0,688976378	0,69921875	1	7,19E-04	0,003228275	0,002794039	1	0,016439626	0,083004399	0,017625789
6	0,725490196	0,69921875	0,692607	1	5,74E-04	0,002308624	0,00251154	1	0,017148716	0,095540852	0,017416588
7	0,732283465	0,708661417	0,69140625	0	3,33E-04	0,001861587	0,001751506	1	0,016940326	0,092100463	0,015885857
8	0,703557312	0,688976378	0,69921875	1	6,67E-04	0,003082556	0,002449124	1	0,01664138	0,084478567	0,018336404
Folder 26_24_84SC_6LC1-142Curr_6-7Mod-70Equ											
0	0,732283465	0,705882353	0,6953125	0	4,68E-04	0,001886235	0,001907138	1	0,01687094	0,089014226	0,01723645
1	0,732283465	0,705882353	0,6953125	0	4,73E-04	0,001887801	0,001914173	1	0,01685161	0,088574705	0,017481795
2	0,732283465	0,705882353	0,6953125	0	4,96E-04	0,001923131	0,001945206	1	0,01684549	0,087918545	0,017581512

		Min Distance among coils	ConfTimeInverse	ConfTimeDirect	ConfTimeParticles/PartLost_PerU-Time	Death_Particles	coef_Mag_grid	B_Axis_Y-0	StepsBetweenCollisions	inct
Final series of calculations										
0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0
3	0	0,004520563	26458,31137	73238,8394	82426,12045	161	350	0,624918	33201	4,15E-09
4	0	0,004518056	29043,77391	67867,3786	74137,46029	179	350	0,62610317	33201	4,15E-09
5	0	0,004523312	30081,16318	68274,2567	78991,69876	168	350	0,62725499	33201	4,15E-09
6	0	0,004558873	32270,97787	72764,7298	83991,17337	158	350	0,61424017	33201	4,15E-09
7	0	0,004526612	29653,35526	67005,3439	72915,41424	182	350	0,61576621	33201	4,15E-09
8	0	0,004562697	24569,10288	63712,368	70965,80424	187	350	0,61683575	33201	4,15E-09
9	0	0,004555496	28471,31631	67491,4366	74975,17171	177	350	0,60303786	33201	4,15E-09
10	0	0,004575287	19946,04162	60467,6557	65372,44036	203	350	0,60411484	33201	4,15E-09
11	0	0,004563294	25744,25509	64966,7232	70214,84335	189	350	0,60546665	33201	4,15E-09
Other in relation to the previous. With always the same magnetic axis (no so accurate +-2mm are observed in the variation on the postion of the axis										
0	0	0	0	0	0	0	0	0	0	0
1	0	0,004519205	24339,37116	60914,2427	74975,17171	177	350	0,6248642	33201	4,15E-09
2	0	0,004485625	20316,83445	50849,2393	55994,11558	237	350	0,62265947	33201	4,15E-09
3	0	0	0	0	0	0	0	0	0	0
4	0	0,004535302	28917,1575	70283,2187	78991,69876	168	350	0,61964274	33201	4,15E-09
5	0	0,004473804	21894,63072	60230,7213	68759,61343	193	350	0,61682928	33201	4,15E-09
6	0	0,004607359	30316,72164	71919,0491	81414,75701	163	350	0,61592183	33201	4,15E-09
7	0	0,004560255	32603,97588	71499,4759	81917,31724	162	350	0,61446775	33201	4,15E-09
8	0	0,004427245	23339,5686	55839,0892	65696,0663	202	350	0,61146941	33201	4,15E-09
Folder : SEVERAL-Cases_Better_magAxisPositionThe next are executed with the correct calculated magnetic axis										
0	0	0	0	0	0	0	0	0	0	0
1	0	0,004525544	24888,83402	65320,9968	74399,57502	179	350	0,62543494	33084	4,16E-09
2	0	0,004484538	23079,71567	60940,9514	72378,10486	184	350	0,62282916	33084	4,16E-09
3	0	0,004611703	30228,23586	72150,7715	82207,03197	162	350	0,62160684	33084	4,16E-09
4	0	0,004535761	25567,95955	67002,2647	72915,60511	182	350	0,61974006	33201	4,15E-09
5	0	0,004473684	18554,94807	57541,6466	67946,58191	196	350	0,61681461	33084	4,16E-09
6	0	0,004607341	33266,26263	68978,7523	78801,97062	169	350	0,61584724	33084	4,16E-09
7	0	0,004555465	27784,98893	78606,4649	87306,63287	152	350	0,61410521	33201	4,15E-09
8	0	0,004427098	23923,03398	64982,6151	71599,73865	186	350	0,61143664	33084	4,16E-09
Folder 26_24_84SC_6LC1-142Curr_6-7Mod-70Equ										
0	0	0,004558581	31906,70104	74072,1684	83463,07942	159	350	0,61425949	33201	4,15E-09
1	0	0,004559392	32334,73977	69376,0154	77154,83264	172	350	0,61440623	33201	4,15E-09
2	0	0,004559392	29115,11895	68544,7169	78062,3855	170	350	0,61440328	33201	4,15E-09

	Temperature	Density	Num Particles	Steps	Current large coils*	Radius of large coils	Expansion of poloidal cuts	Indentation. Coef 2 , 0	Modif on axis Coef 0 , 2	Modif on axis Coef 0 , 1
Final series of calculations										
0	0	0	0	0	1,1428	0,07	0,1	0,0025	0,0015	0,005
1	0	0	0	0	1,1428	0,07	0,1	0,002625	0,0015	0,005
2	0	0	0	0	1,1428	0,07	0,1	0,00275	0,0015	0,005
3	116050	1,00E+17	20	1,60E+08	1,1428	0,07	0,15	0,0025	0,0015	0,005
4	116050	1,00E+17	20	1,60E+08	1,1428	0,07	0,15	0,002625	0,0015	0,005
5	116050	1,00E+17	20	1,60E+08	1,1428	0,07	0,15	0,00275	0,0015	0,005
6	116050	1,00E+17	20	1,60E+08	1,1428	0,07	0,2	0,0025	0,0015	0,005
7	116050	1,00E+17	20	1,60E+08	1,1428	0,07	0,2	0,002625	0,0015	0,005
8	116050	1,00E+17	20	1,60E+08	1,1428	0,07	0,2	0,00275	0,0015	0,005
9	116050	1,00E+17	20	1,60E+08	1,1428	0,07	0,25	0,0025	0,0015	0,005
10	116050	1,00E+17	20	1,60E+08	1,1428	0,07	0,25	0,002625	0,0015	0,005
11	116050	1,00E+17	20	1,60E+08	1,1428	0,07	0,25	0,00275	0,0015	0,005
Other in relation to the previous. With always the same magnetic axis (no so accurate +-2mm are observed in the variation on the postion of the axis										
0	0	0	0	0	1,1428	0,07	0,15	0,0025	0,0015	0,003
1	116050	1,00E+17	20	1,60E+08	1,1428	0,07	0,15	0,0025	0,0015	0,005
2	116050	1,00E+17	20	1,60E+08	1,1428	0,07	0,15	0,0025	0,0015	0,007
3	0	0	0	0	1,1428	0,07	0,175	0,0025	0,0015	0,003
4	116050	1,00E+17	20	1,60E+08	1,1428	0,07	0,175	0,0025	0,0015	0,005
5	116050	1,00E+17	20	1,60E+08	1,1428	0,07	0,175	0,0025	0,0015	0,007
6	116050	1,00E+17	20	1,60E+08	1,1428	0,07	0,2	0,0025	0,0015	0,003
7	116050	1,00E+17	20	1,60E+08	1,1428	0,07	0,2	0,0025	0,0015	0,005
8	116050	1,00E+17	20	1,60E+08	1,1428	0,07	0,2	0,0025	0,0015	0,007
Folder : SEVERAL-Cases_Better_magAxisPositionThe next are executed with the correct calculated magnetic axis										
0	0	0	0	0	1,1428	0,07	0,15	0,0025	0,0015	0,003
1	116050	1,00E+17	20	1,60E+08	1,1428	0,07	0,15	0,0025	0,0015	0,005
2	116050	1,00E+17	20	1,60E+08	1,1428	0,07	0,15	0,0025	0,0015	0,007
3	116050	1,00E+17	20	1,60E+08	1,1428	0,07	0,175	0,0025	0,0015	0,003
4	116050	1,00E+17	20	1,60E+08	1,1428	0,07	0,175	0,0025	0,0015	0,005
5	116050	1,00E+17	20	1,60E+08	1,1428	0,07	0,175	0,0025	0,0015	0,007
6	116050	1,00E+17	20	1,60E+08	1,1428	0,07	0,2	0,0025	0,0015	0,003
7	116050	1,00E+17	20	1,60E+08	1,1428	0,07	0,2	0,0025	0,0015	0,005
8	116050	1,00E+17	20	1,60E+08	1,1428	0,07	0,2	0,0025	0,0015	0,007
Folder 26_24_84SC_6LC1-142Curr_6-7Mod-70Equ										
0	116050	1,00E+17	20	1,60E+08	1,1428	0,07	0,2	0,0025	0,0015	0,005
1	116050	1,00E+17	20	1,60E+08	1,1428	0,07	0,2	0,0025	0,0015	0,005
2	116050	1,00E+17	20	1,60E+08	1,1428	0,07	0,2	0,0025	0,0015	0,005

Some of the ~ 500 configurations computed.
UST_2 marked in blue

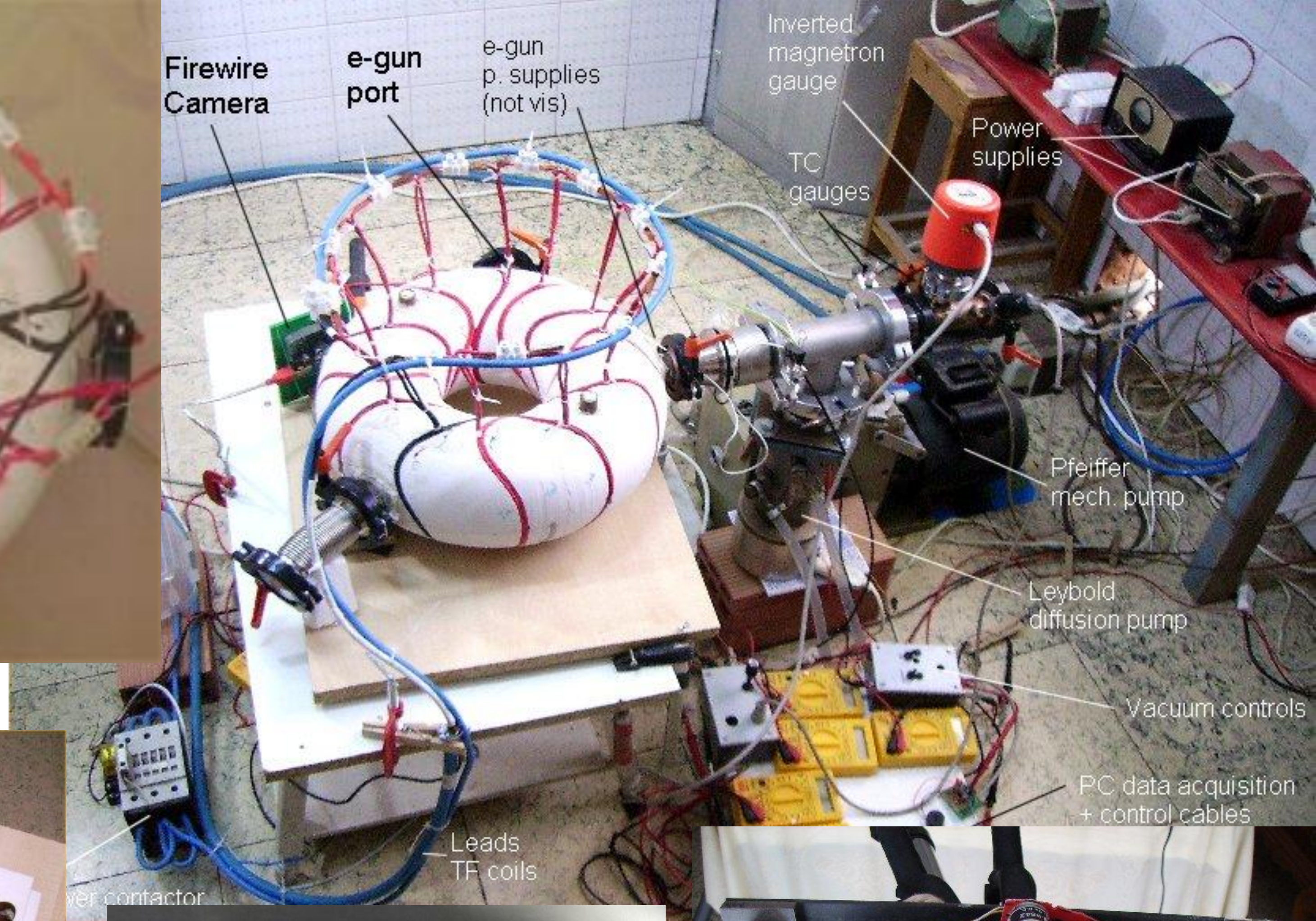
Internal view of one piece

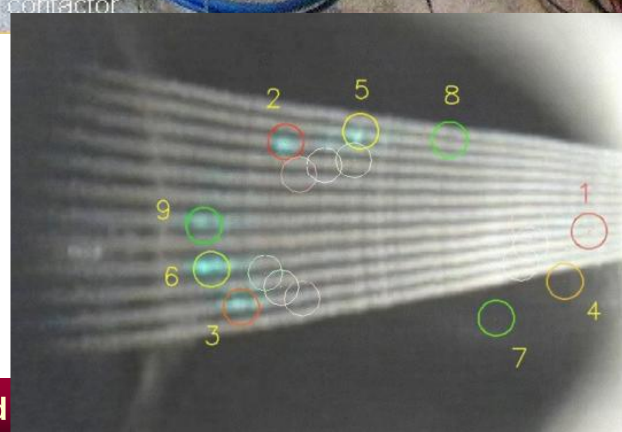
Matters for discussion and future

We could have talked about many other matters, i.e.:

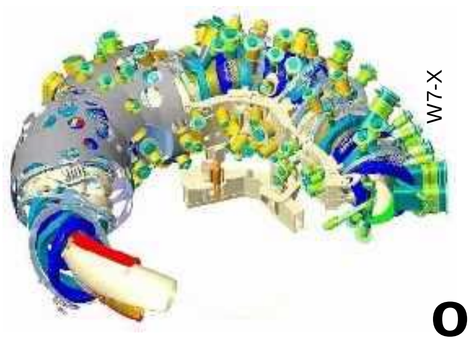
- Why QIPCC3 and not QIPPC6 or QIPPC2 or NCSX-TU or …?.
- VV construction method (still not clear for low cost).
- Why such winding surface and not others?.
- Bo, Te, n, neoclassical transport and other physics parameters.
- Stress on coil frame and limit of Bo for certain materials.
- Why 3D printing+moulding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

but perhaps not enough time for them.


Firewire Camera
e-gun port
e-gun p. supplies (not vis)
Inverted magnetron gauge
Power supplies
TC gauges
Pfeiffer mech. pump
Leybold diffusion pump
Vacuum controls
PC data acquisition + control cables
Leads TF coils


2
5
8
9
1
6
4
3
7

Gradually the doubts faint…

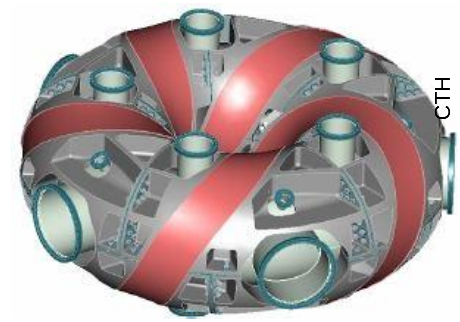


or

Stellarator modular

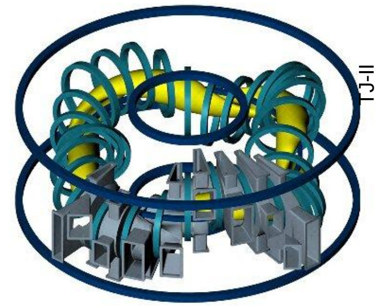
or

CNT type



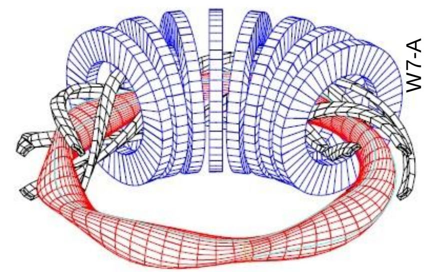
or

Torsatron



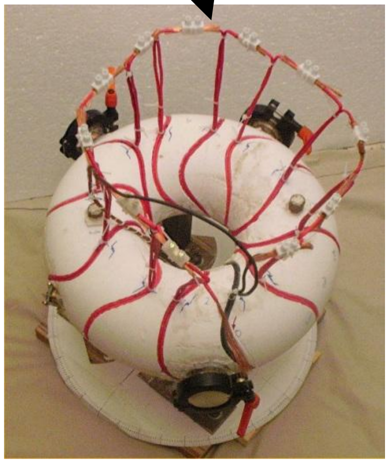
Heliac

or



Clasical stellarator

Insight for UST_1 came mainly from W7-X and CTH



UST_1. Modular stellarator 'circular'

A simple low cost VV

Standard copper elbow

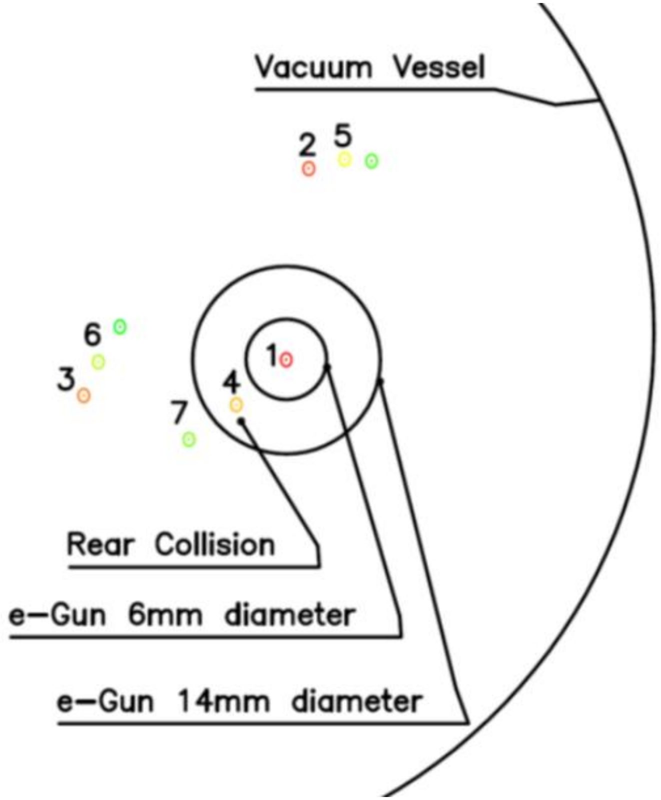
Five elbows.
R=119mm.

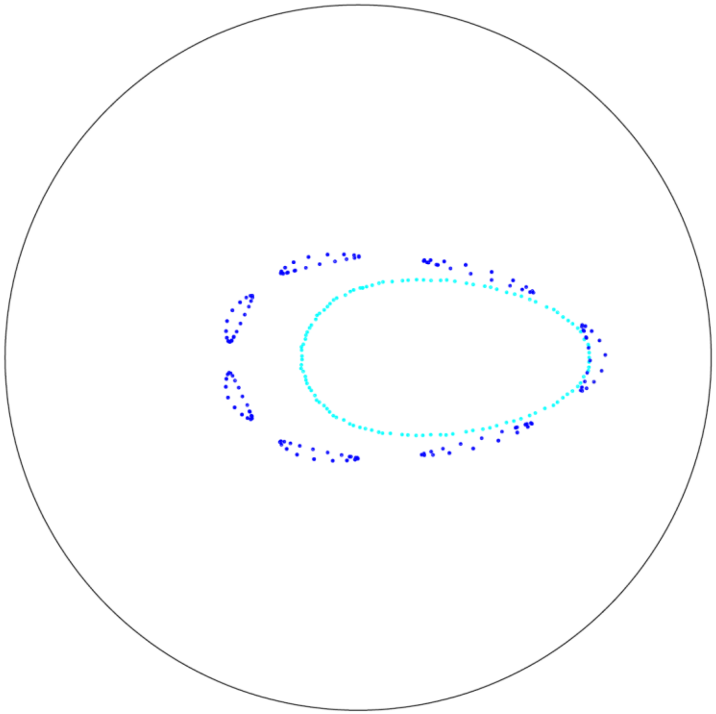
Reinforcements and opening for port

Finished vacuum vessel.
3 large ports and one small

Field line mapping experiments

Many issues solved to record the magnetic surfaces





Rear collision. Collision of e-beam with the large e-gun after 3 turns. The very small 6mm Ø was used to solve the issue

Large drifts. Beam energy for enough fluorescence produces high drifts in UST_1

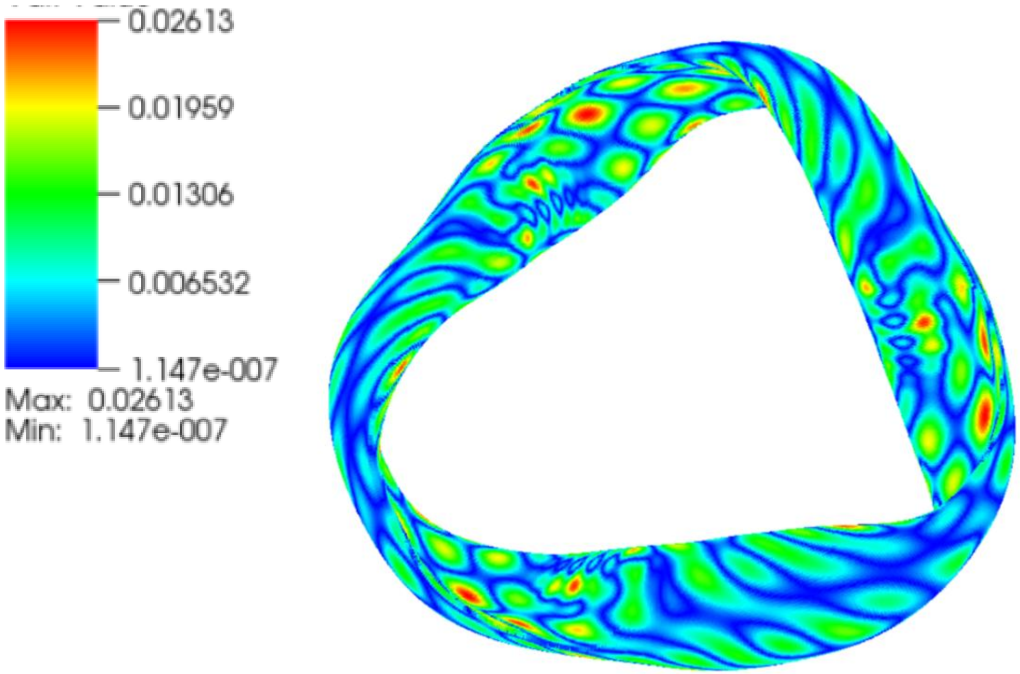
Summary of decisions taken

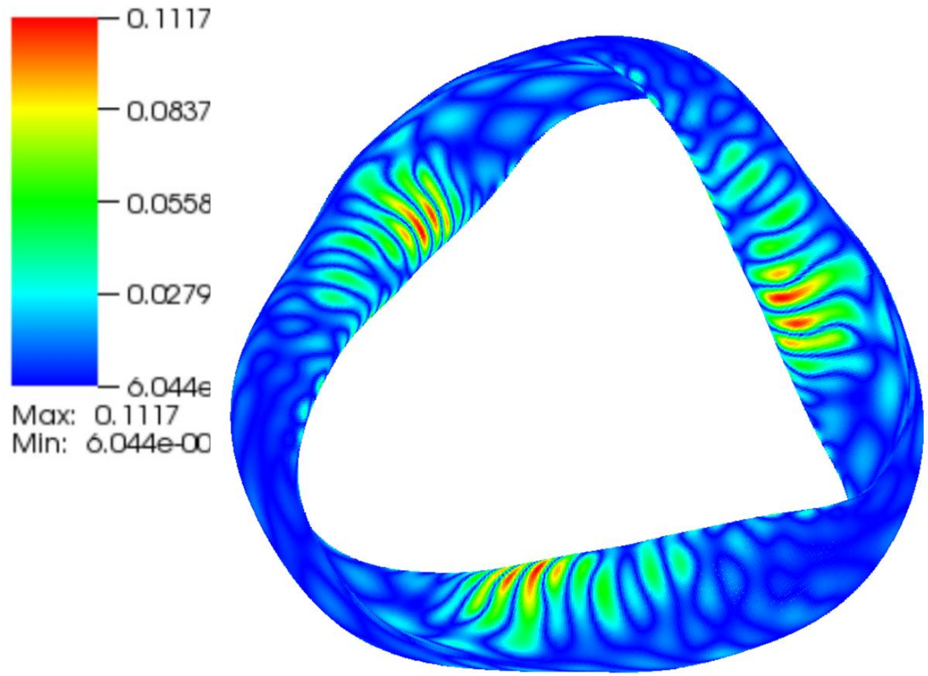
Objectives + cost+schedule constrains → decisions

	Comments	Decision taken
A) Magnetic configuration to chose?	Middle compactness, LCFS unchanged for any size, low turbulence potential, design available now, …	A modified QIPCC 3P
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	Coils outside
D) Method to build the coil frame, VV, …	3D printing, metal casting, moulding, milling, mix?	3D printing + moulding

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

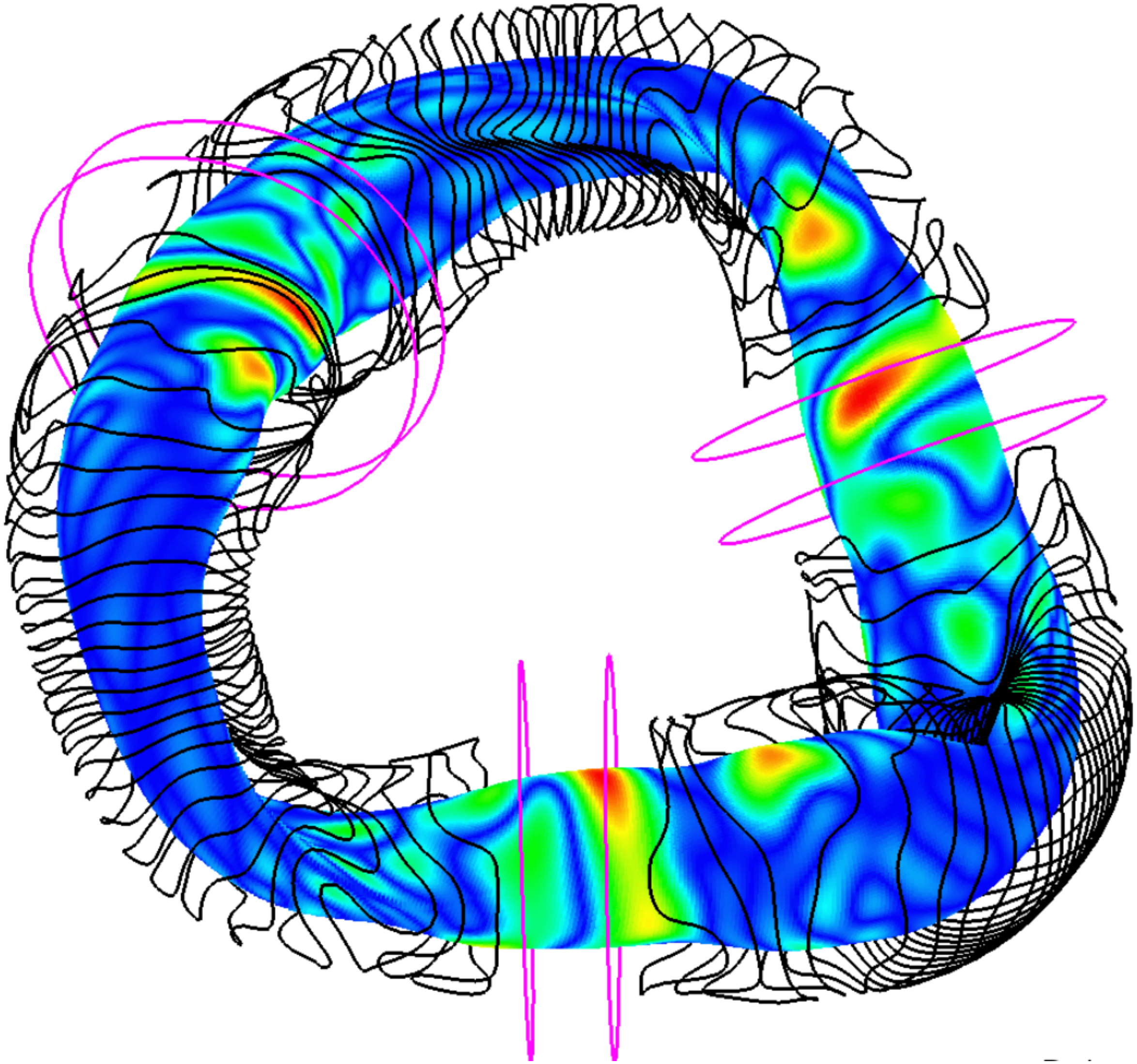
Ave. error: 0.70%
Maximum error: 2.6 %

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

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

Magnetic errors due to finite num. coils

UST_2



R&D carried out to support the decisions

Experimental validation and assessment of the concepts have been produced

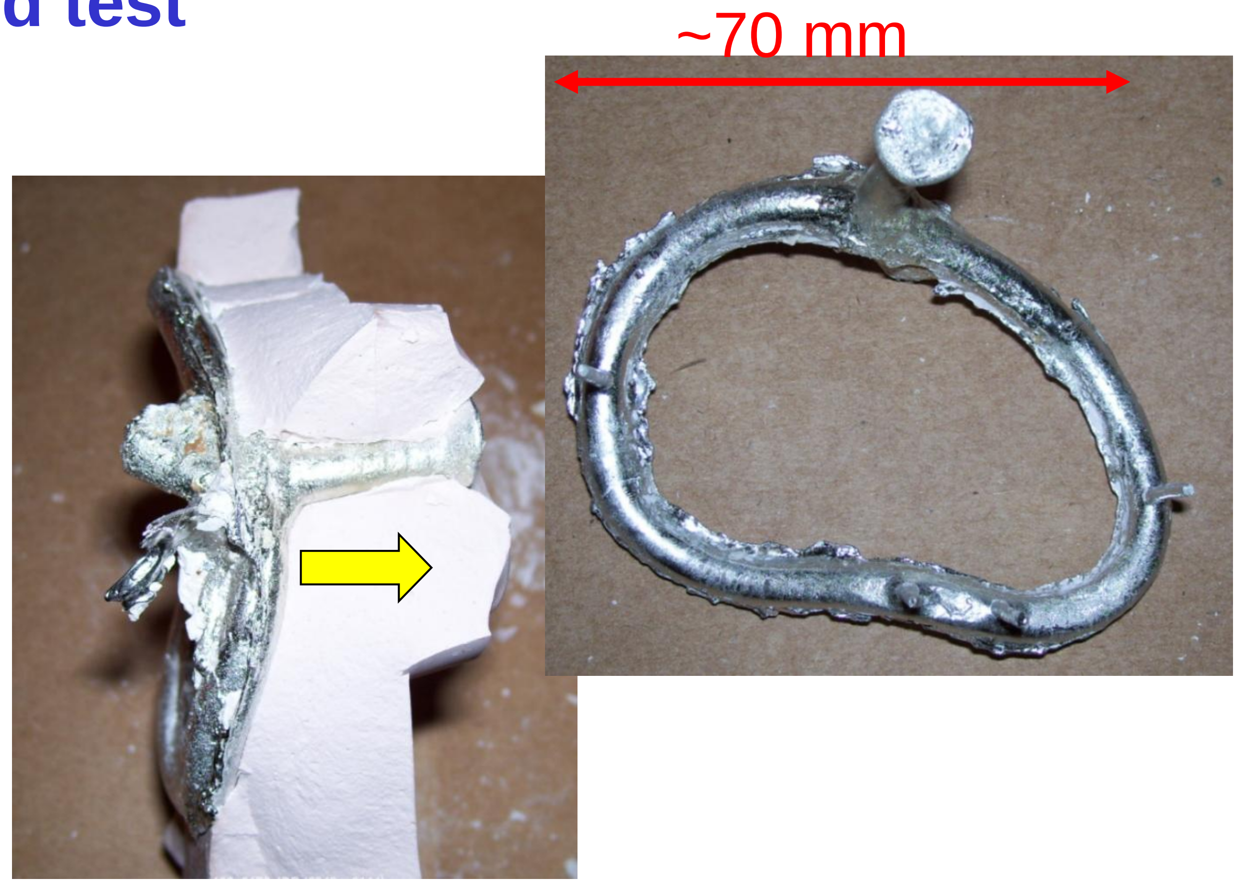
- **Experimental tests** of pieces have been produced to early detect **insurmountable problems** of the concepts and to roughly estimate the **cost** of the device.

- **Theoretical assessment** of several different **magnetic configurations** has been produced.

Permanent plaster mould test

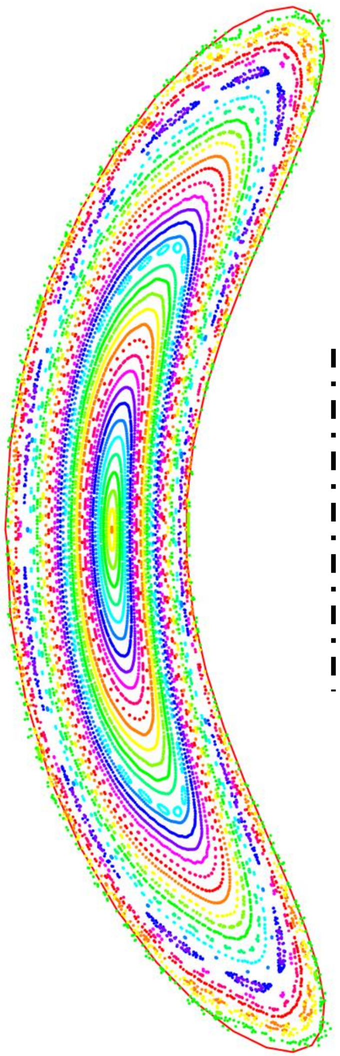
- The aim would be to create **permanent plaster moulds** for 5-10 pieces of Al or Cu coils (usually impossible).

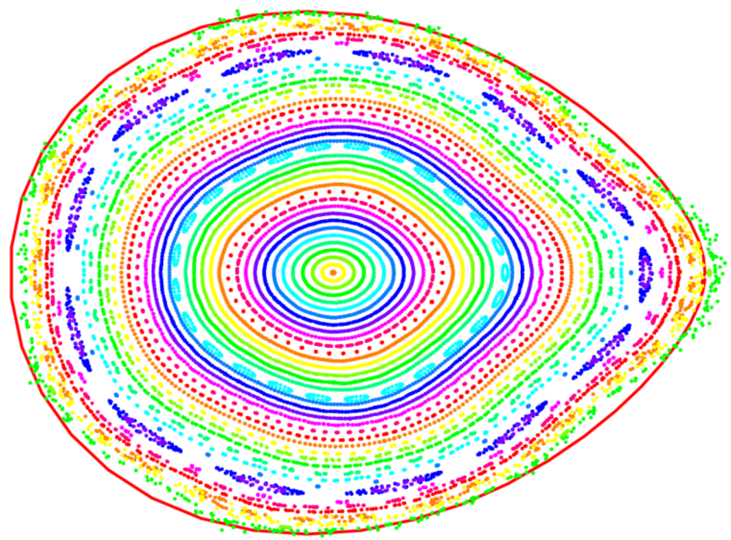
- The cost would be reduced 5-10 fold since several coils are identical.



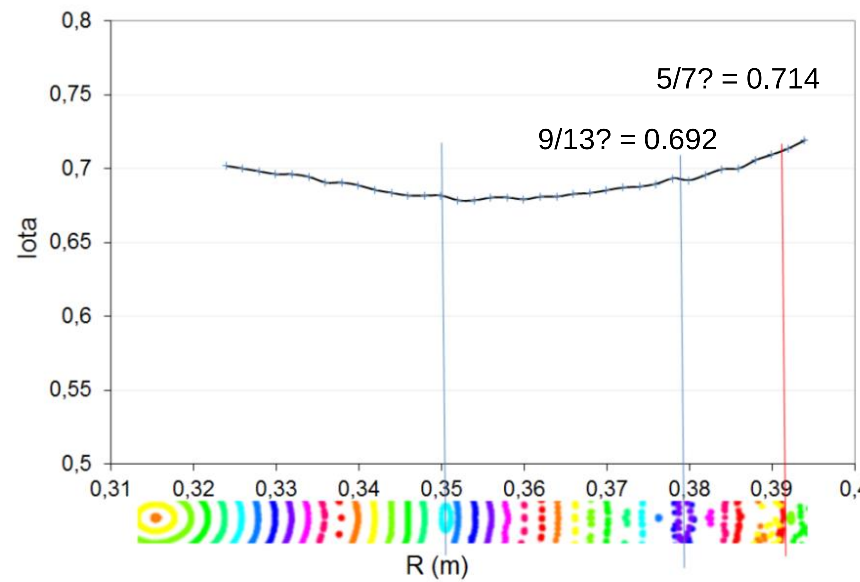
Own test of casting in a "**permanent"** plaster mould. The mould **broke**. However, **some ideas appeared** to allow permanent plaster moulds for Al

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

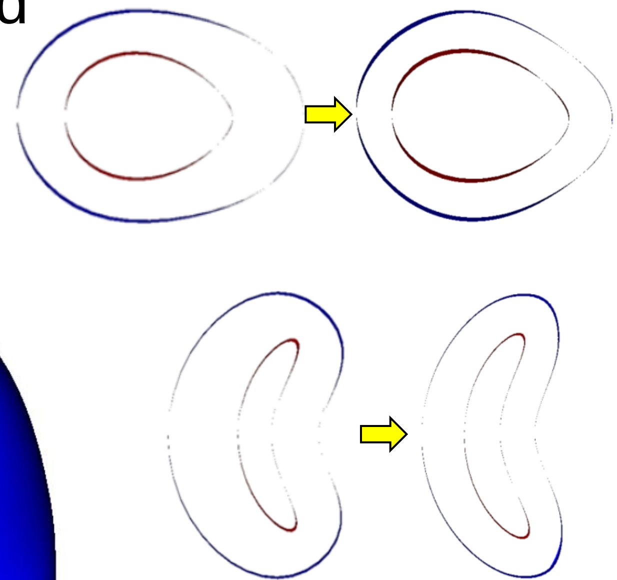
Iota = [0.67 , 0.71] from [Mik 04]

Magnetic surfaces at φ = π/3

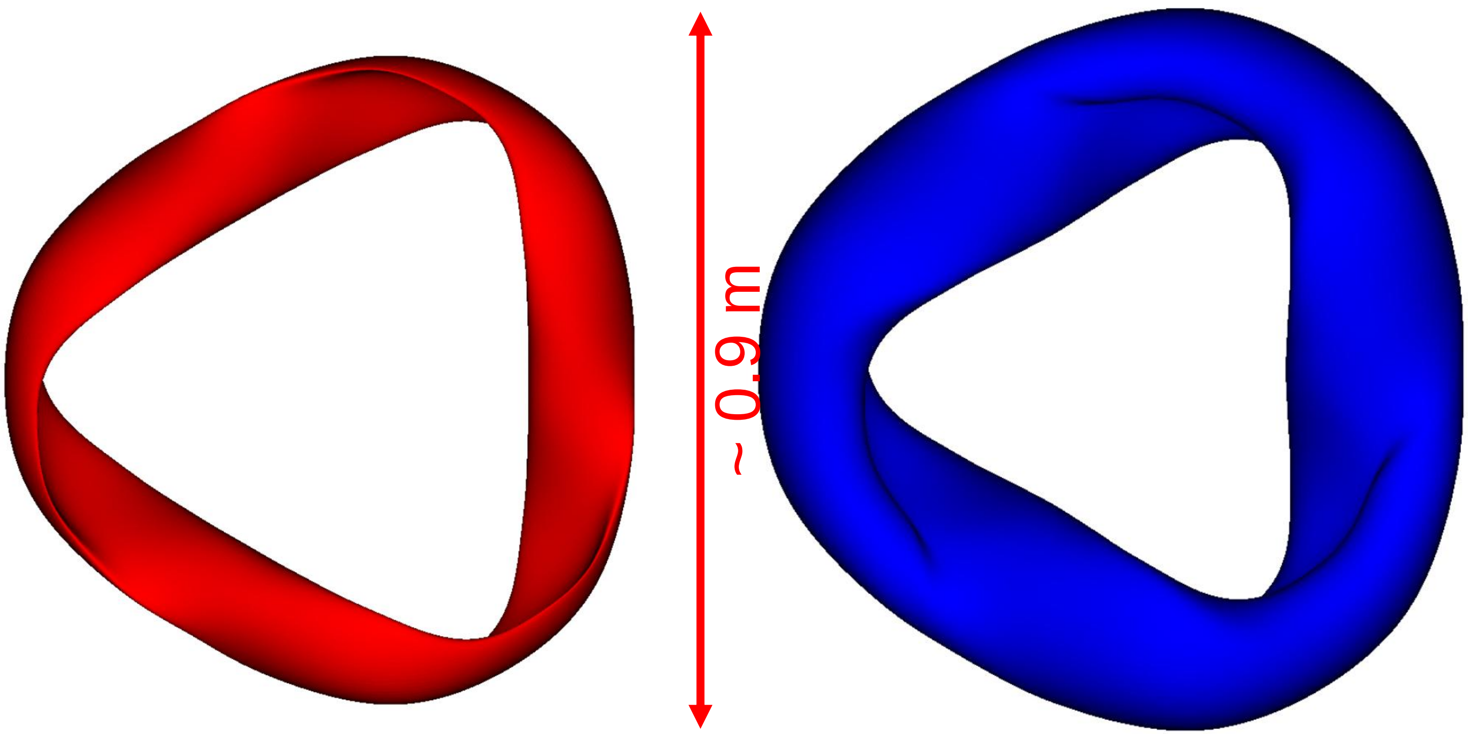
Reference magnetic configuration

The base reference configuration is a QIPCC of 3 periods

Only the magnetic configurations already developed by physicists and received from the authors are considered.



Cross sections of the plasma and winding surface



Last closed flux surface

Winding surface