

# Construction of low-cost stellarators by Innovative Rapid Prototyping Methods.

**Discussion** of possible benefits for experimental and theoretical fusion

**Vicente M. Queral (CIEMAT)**

Seminar in National Fusion Laboratory (Given at 'Monday physicist meeting')

CEEMAT, Madrid, Spain

November 2010

## *Outline*

- Background
- Summary
- Stellarator UST\_1, achievements
- Engineering development track. Methods, means and innovations to advance this R&D track. Exploration of interest on it
- Conclusion and summary
- Exploration of possible needs and interests of researchers, LNF, CIEMAT

## Background

▶ The presentation shows a proposal of stellarator engineering development **track** mainly aimed to **facilitate and fasten the experimental and theoretical work in fusion**.

▶ But, the **focus** of the presentation is **engineering**, not physics.

▶ The **ideas** and results in this presentation have been **mainly developed** during **spare time** during the **last years**.

→ Therefore only **very preliminary concepts, low detail** and **estimations** have been produced.

## Background

“Pace of ‘Technology’ research has been considerably slower than progress in plasma physics.

Advanced technologies have a dramatic impact on attractiveness of fusion.

**Considerable more technology R&D is needed”**

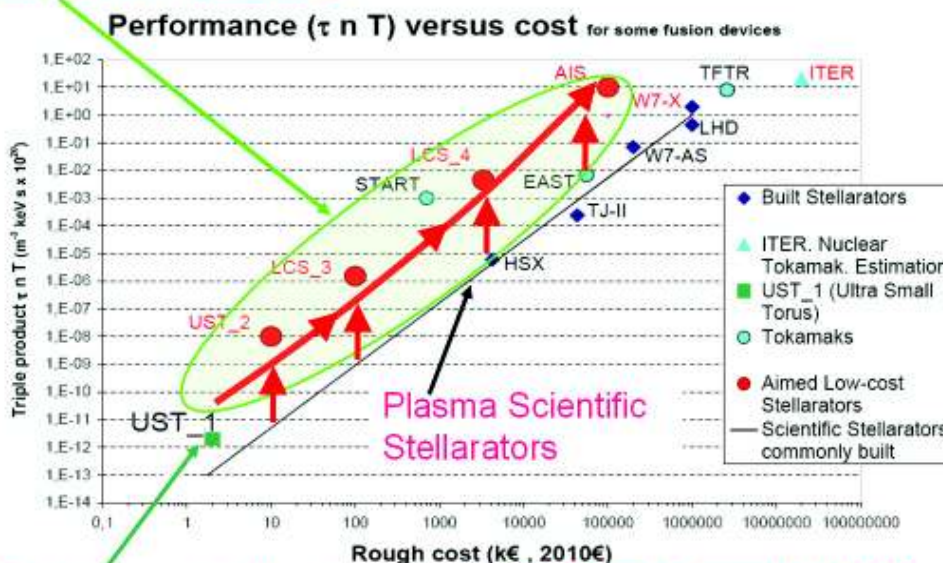
**Farrokh Najmabadi, [Naj 06]**

*We have to find ways to advance such technologies*

# Summary

## Performance ~ cost is the focus of this R&D

Objective: Low-cost construction of stellarators



Real low-cost stellarator

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

The work to develop the devices is only partially included in each device.

For **Innovative RP Methods** then higher development ('D') work is still needed to **innovate in construction.**

**Cost indicated is rough** due to several reasons.

## Objective, results and means

### Objective:

Produce **low cost stellarators and fusion devices** for i.e. :

- Integrate all the engineering issues, including cost, into the stellarator optimization from the very beginning.
- 'Rapid' test, validation and advance codes and theory of stellarator concepts.
- Plasma experiments in several low-cost devices.
- Find an optimal stellarator size for competitive fusion energy.
- Generation of interest in industry and politicians → \$.
- Production of patents for fusion applicable to other fields → \$.

**Note** : 'low cost' means much simpler and lower cost than currently

### Means

- **Low cost 3D printer methods** for stellarator fabrication [Que 08]
- **Sequential feasibility tests** of the **methods** starting from the smaller devices.

## Much lower cost and construction time of stellarators

► **Due to high construction costs of traditional methods** (i.e. NCSX, W7-X): i) Many advanced stellarator concepts are **not being tested** or are **delayed**. ii) Valuable experiments in several configurations (one **advantage of stellarators**) are **not performed**.

► Also **validation of the calculation/simulation codes** for stellarators has stopped due to **high construction costs of traditional methods**.

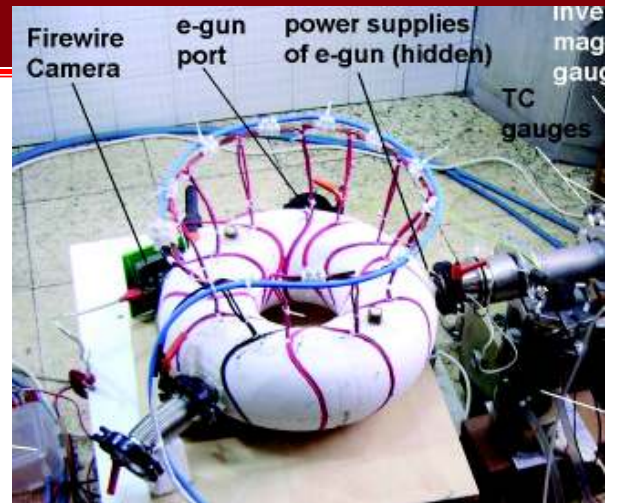
► Confinement of advanced stellarators seems as good as tokamaks (better?) but **we cannot wait 20 years and ~1000M€** cost to test only one concept (i.e. W7-X). **Speed up** the process is one of the keys.

## Innovation is possible. Example

**UST\_1 = example of feasibility of major cost reduction by innovation** (other: FORD T , PCs , ...)

The stellarator UST\_1, **3<sup>rd</sup> modular stellarator in the world**, was built by means of a **special toroidal milling machine for stellarators**.

- The design of UST\_1 is **innovative**, particularly devised to achieve **low cost**.
- UST\_1 **materials cost** is only **2k€** including the stellarator, heating system, power supplies, 1/10 of milling machine and vacuum system (diagnostics not included)



UST\_1, located in Castellón, Spain



Mechanising device

Construction of low-cost stellarators by Innovative Rapid Prototyping M

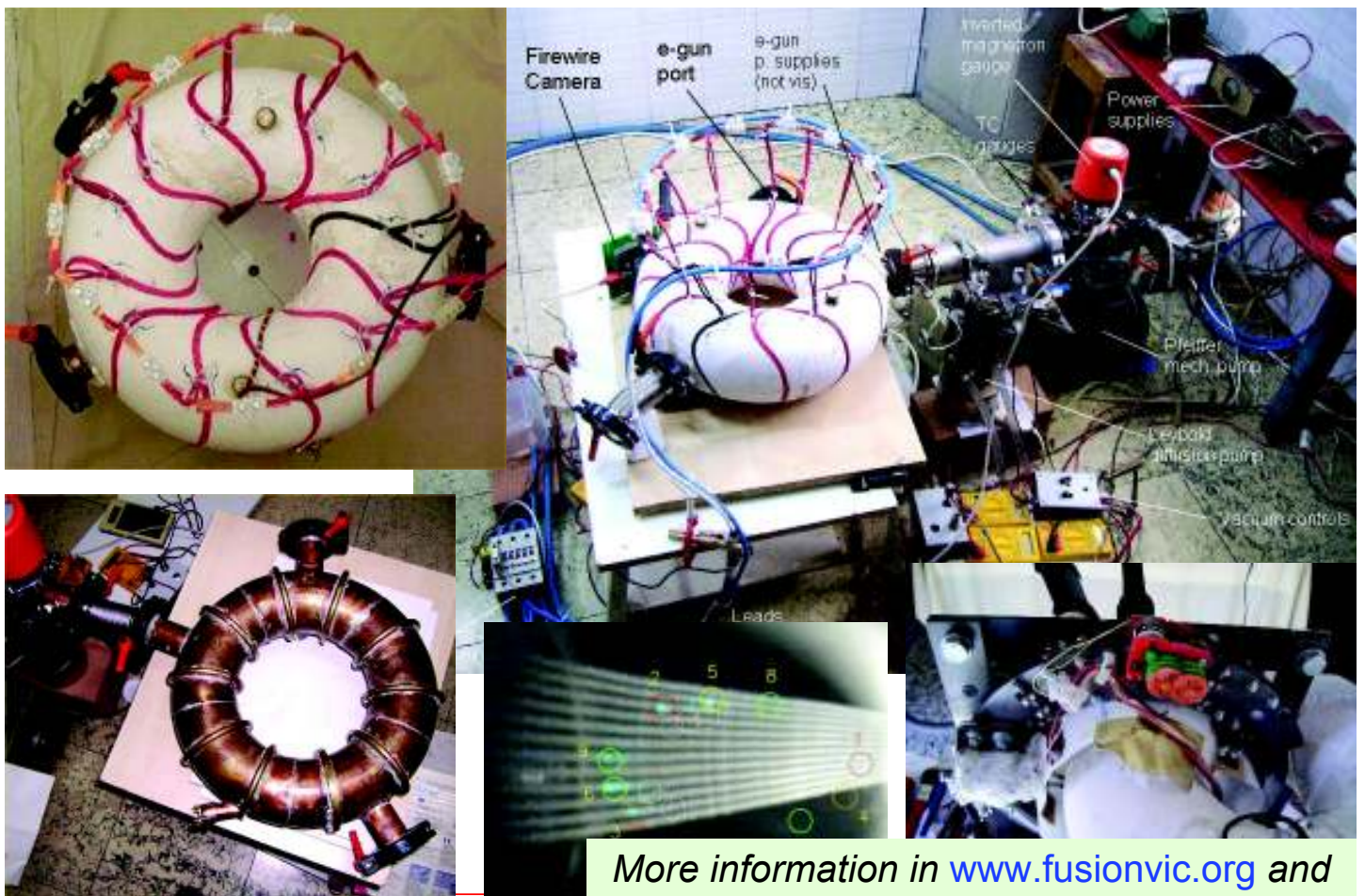
## More difficult long term results

Somebody, by chance, interested in other more **hypothetical/difficult** functionalities of the low-cost stellarators?:

- Mechanical design improvement of stellarators at high fields.
- Material test (FW under intense plasma heating).
- Explosive detection → \$.
- Plasma experiments under high B, n, and P heat density.
- Transmutation → \$.
- Stellarator CTF (components test facility) ~ neutrons → \$.

**Please, tell your needs !!!**

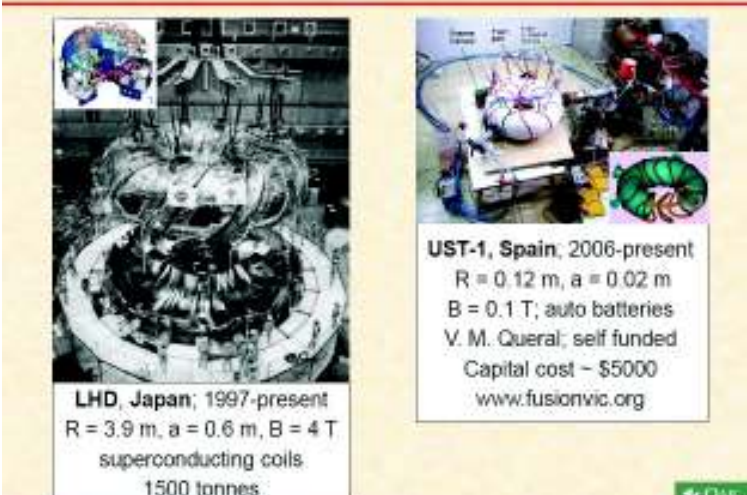
# Stellarator UST\_1, achievements



# Achievements of a 2k€ fusion device, UST\_1

UST\_1 was **considered** one **example of stellarator success in the world** in one presentation of the ORNL fusion lab. director ('Oak Ridge National Laboratory', EEUU )

Stellarators from large to small have been successfully constructed



**LHD, Japan; 1997-present**  
R = 3.9 m, a = 0.6 m, B = 4 T  
superconducting coils.  
1500 tonnes

**UST-1, Spain; 2006-present**  
R = 0.12 m, a = 0.02 m  
B = 0.1 T; auto batteries  
V. M. Queral; self funded  
Capital cost ~ \$5000  
www.fusionvic.org

OAK RIDGE

ORNL is one of the larger fusion laboratories in the world

One slide of the presentation by Jeffrey H. Harris and Donald A. Spong, ORNL, [Har 09]

# Achievements of a 2k€ fusion device, UST\_1

UST\_1 is **included in the list of world stellarators in ORNL**



Stellarators Around the World

Web site at ORNL  
[http://www.ornl.gov/sci/fed/stelnews/world\\_stellarators.html](http://www.ornl.gov/sci/fed/stelnews/world_stellarators.html)

# UST\_1 achievements



Published by Fusion Energy Division, Oak Ridge National Laboratory  
Building 5700 P.O. Box 2008 Oak Ridge, TN 37831-6169, USA

Editor: James A. Rome Issue 118 December 2008

E-Mail: jar@ornl.gov Phone (865) 482-5643

On the Web at <http://www.ornl.gov/sci/fed/stellnews>

## Year 2008

Article about UST\_1 published in 'Stellarator News', an ORNL publication

### UST\_1, a small, low-cost stellarator

UST\_1, Ultra Small Torus (shown in Fig. 1), is a very small ( $R = 119$  mm) modular stellarator built in a personal laboratory. Two main objectives were pursued: developing innovative low cost construction techniques and allowing the author to learn all aspects of stellarator design, construction, and operation. UST\_1 is located 65 km north of Valencia, Spain, and was designed and built during 2005/06 and operated during 2006/07. Successful experiments to validate the quality of the design and construction have been carried out, particularly field mapping experiments and basic plasma pulses. UST\_1 has proved that low-cost techniques to build accurate stellarators exist. Very probably it is the third modular stellarator in the world, the most economical with acceptable quality, and the first designed and built by only one person.



Fig. 1. The UST\_1 stellarator and some of its auxiliary systems.

Similar small devices with reactor-like geometries probably would be useful to improve the conceptual designs and maintenance procedures for future fusion reactors.

### Summary of features and parameters

UST\_1 is a 2-field period modular stellarator with an aspect ratio = 6 formed by 12 resistive partially optimized modular coils. Each coil is formed by 6 turns of flexible copper conductor wound in a groove machined in a circular torus. The grooves were accurately machined into a single plaster frame by a specially designed toolcutting machine. Electron cyclotron radio-frequency heating (ECRH) at the second harmonic ( $B_0 = 46$  mT and eventually  $B_0 = 90$  mT) heats the plasma using a 0.8-kW, 2.45-GHz commercial magnetron. Typical length of the plasma pulse is 2 s at 46 mT. Toroidal field (TF) current per coil is 2.3 kA-turn.

Additionally, a vacuum system, control and diagnostics systems, and power supplies complement the stellarator.

### In this issue . . .

#### UST\_1, a small, low-cost stellarator

The Ultra Small Torus is the world's smallest and lowest-cost modular stellarator with acceptable quality. It was designed, built, and operated by one person in near Valencia, Spain to learn about fusion. UST\_1 is a two field period modular stellarator with an aspect ratio = 6 formed by 12 resistive partially optimized modular coils. Only 2700 € were spent on materials for the entire facility.

#### Retirement ceremony and Stern-Gerlach medal for Friedrich Wagner

On 27 November, 180 invited guests celebrated the retirement of Friedrich ("Fritz") Wagner from the Max-Planck Institut für Plasmaphysik (IPP). In addition to a scientific colloquium, an exhibition of Wagner's paintings opened in the main IPP hall. It has been announced recently that Prof. Wagner will receive the Stern-Gerlach medal, which is the highest award of the Deutsche Physikalische Gesellschaft, given for extraordinary contributions in experimental physics. 7

All opinions expressed herein are those of the authors and should not be reproduced, quoted in publications, or used as a reference without the author's consent.  
Oak Ridge National Laboratory is managed by UT-Battelle, LLC, for the U.S. Department of Energy.

Construction of low-cost stellarators by Innovative Rapid P

# Achievements of a 2k€ fusion device, UST\_1

## Year 2006

UST\_1 was presented in the NFL, CIEMAT, producing great impact and admiration

Diseño, construcción y resultados en UST\_1, un pequeño stellarator educativo de bajo coste

Vicente M. Queral Mas  
Ingeniero Industrial

1. Diciembre 2006

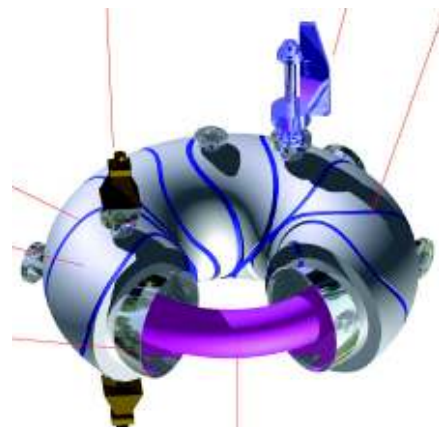
Seminario en Laboratorio Nacional de

[Que 06]



## Year 2009-2010

A larger but very similar stellarator, the SCR-1, is being built in the 'Instituto Tecnológico de Costa Rica'



SCR-1 conceptual design presented in the ICPP-LAWPP 2010, Chile

Construction of low-cost stellarators by Innovative Rapid Prototyping Methods

L 16

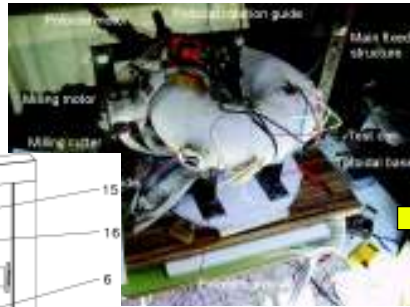
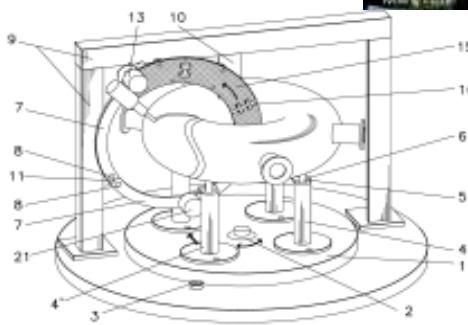


# Achievements of a 2k€ fusion device, UST\_1

## Year 2006 and 2009

**Patent and Utility model applied for.** P200600427 and U200901520 (granted).

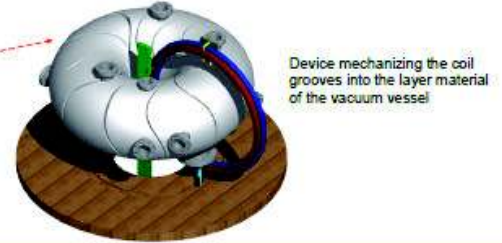
Stellarator mechaniser building UST\_1 coils.  
**Very successful**



## Year 2010

The same method of producing low cost stellarators is planned for **SCR-1**

⇒ Also in charge of assemble the field mapping system.



Source of figure : Poster presented in the ICPF LAWPP 2010, Chile

# Achievements of a 2k€ fusion device, UST\_1

## Year 2009 and 2010

UST\_1 is the **fourth Google.com site** for the search word "Stellarator"



stellarator

About 72,700 results (0.29 seconds)

Advanced search

Everything

Images

Videos

More

All results

Sites with images

More search tools

Something different

tokamak

spheromak

nstx

tore supra

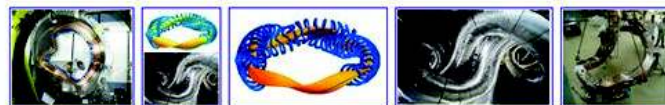
tfr

► [Stellarator - Wikipedia, the free encyclopedia](#) ☆

A **stellarator** is a device used to confine a hot plasma with magnetic fields in order to sustain a controlled nuclear fusion reaction. ...

Description - Configurations of stellarator - Comparison to tokamaks  
[en.wikipedia.org/wiki/Stellarator](http://en.wikipedia.org/wiki/Stellarator) - Cached - Similar

[Images for stellarator](#) - Report images



► [Stellarator News Home Page](#) ☆

An international newsletter containing online publications on **stellarators** and links to some other **stellarator** web pages.

[www.ornl.gov/fed/stelnews/](http://www.ornl.gov/fed/stelnews/) - Cached

► [Stellarator](#) ☆

In a **stellarator**, the screw-like twisting of field lines around the torus centre is generated by external coils. In contrast to the Tokamak, a **stellarator** ...

[www.euronuclear.org/info/encyclopedia/s/stellarator.htm](http://www.euronuclear.org/info/encyclopedia/s/stellarator.htm) - Cached - Similar

► [Personal research in Fusion Energy Construction of a small...](#) ☆

20 Feb 2010 ... UST\_1 is a low cost small R&D&i **stellarator** built in a personal laboratory. It was devised, designed, built and operated from 2005 up to ...

[linux06.dnspropio.com/~fusionmic/](http://linux06.dnspropio.com/~fusionmic/) - Cached - Similar

► [NATIONAL COMPACT STELLARATOR EXPERIMENT](#) ☆

15 Oct 2008 ... NCSX is a compact **stellarator** concept based on quasi-toroidal symmetry.

[ncsx.pppl.gov/](http://ncsx.pppl.gov/) - Cached - Similar

# Achievements of a 2k€ fusion device, UST\_1



Slide from the 2009 presentation in CIEMAT [Que 09]



Slide from the 2006 presentation in CIEMAT [Que 06]

Year 2010

UST\_1 constructive method is proposed for the German “Small scale stellarator experiments” concept, Stellarator News 124, 2010



“The three-dimensional (3D) vacuum vessel could be manufactured by casting, where the lost form is made by rapid prototyping....

This vacuum vessel could already incorporate the support structure of the coil winding and the port tubes similar to the report in [Que 08]. ...

.... This method would guarantee a sufficiently high positional accuracy of the coils without time-consuming and expensive measurement and adjustment procedures” [Laq 10]

## Conclusion

- High **creativity** and **innovation** achieved a **2k€** (0.002M€) fusion device with notable features.
- What could be achieved with 0.1M€, 10M€ or 1000M€ if **creativity** and **innovation** is added?

# Engineering development track

## Methods, means and innovations to advance this R&D track

### Exploration of interest on it

## *Objective, results and means*

### **Objective :**

Produce **low cost stellarators** and **fusion devices** for :

- Integrate all the engineering issues, including cost, into the stellarator optimization from the very beginning.
- 'Rapid' test, validation and advance codes and theory of stellarator concepts.
- Plasma experiments in several low-cost devices.
- Find an optimal stellarator size for competitive fusion energy.
- Generation of interest in industry and politicians → \$.
- Production of patents for fusion applicable to other fields → \$.

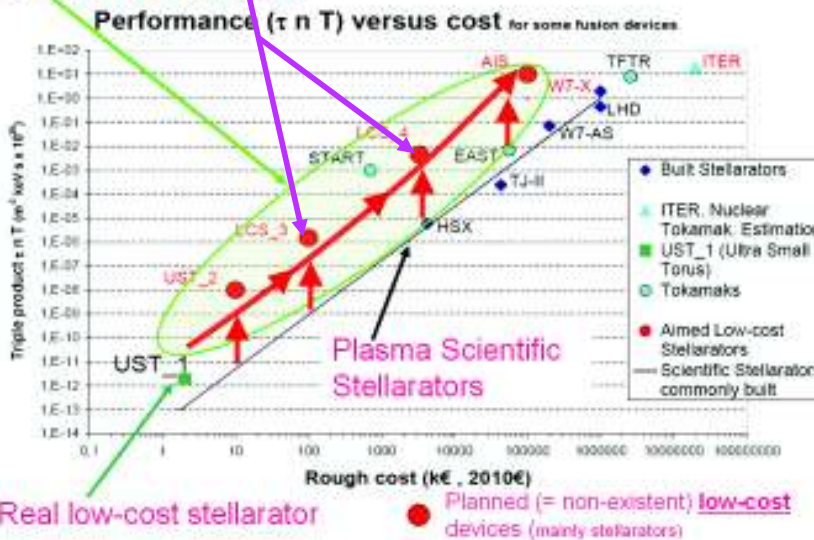
### **Remember**

- ▶ The **focus** of the presentation is **engineering**, not physics.

# Proposal of line of engineering development

Achieve know-how sequentially from the smaller devices about **low-cost construction**. There is no construction know-how if 'smaller equivalent' devices are not built. Otherwise escalation of costs will occur, like in ITER

Objective: Low-cost construction of stellarators



Concept of cyclical development approach

## Fission and fusion costs

Average rough costs, only as a reference

	Approx. %	Approx. %
	Fission plant	Coal plant
Buildings	20%	10%
Reactor (with steam gen. & other)	30% (~1000M€)	15 % boiler
Turbines + alternator	20%	15%
Other	10%	10 %
		30% (sorbet, ash issues, clean coal)
Engineering + supervision + contingency and others	20%	20%
Total overnight cost	2000-4000M€/GW	1000-3000M€/GW

Example of New Nuclear "All-In" Cost to Build "Low Cost" Case

- "Overnight" Cost: \$ 3,596/kW
- Escalations in Costs: \$ 2,637/KW
- Cost of Capital: \$ 2,625/kW
- "All-In" Costs \$ 8,858/kW

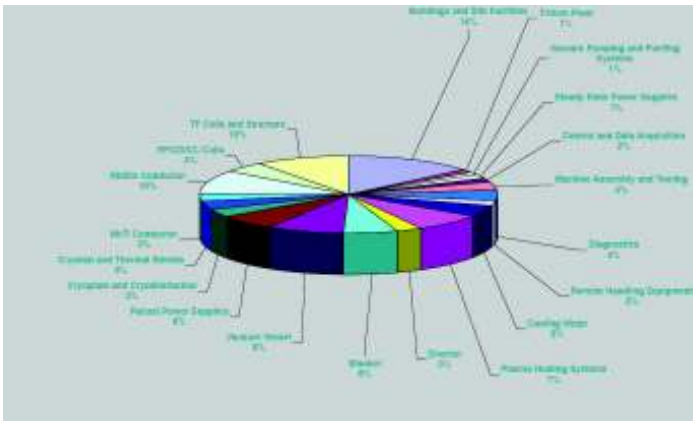
There are other countries and conditions → other values but the same essence

**Aim : commercial fusion 'reactor core' 1GW ≈ 500-1000 M€ !!!**

CANDU 670MWe, Konvol 1400MWe and other fission plants have been considered for the % cost average

# Decision about 'best' type of device for a reactor

## Costs for two devices as an example



Distribution of the ITER costs (still theoretical costs). Total cost could be considered 6000M€ - cost varies with time!

Real costs of NCSX. Total cost in April 2007 ~55M\$. (rounded values) Frames 12M\$, Windings 20 M\$, VV 10M\$, Other 5M\$, Project 10M\$

### PPPL COST PERFORMANCE REPORT WORK BREAKDOWN STRUCTURE

#### NCSX

\*\*\* Cumulative to date FY03, FY04, FY05, FY06 and FY07 \*\*\*

APRIL 2007 CUMULATIVE TO DATE (thru 4/30/07)

Task	Budgeted Cost			VARIANCES					Fiscal FY07
	BCWS	BCWP	ACWP	Sch Var	SP	Cost Var	CP		
1 - Stellarator Core Systems	32,878	\$1,602	\$2,849	-1,226	\$7	-1,506	\$4	\$7,223	
12 - Blanketing Systems	8,561	5,682	6,763	35	1,80	-307	\$6	5,098	
12.00021 12E1 - Vacuum Vessel Plate Dev	874	424	424	0	1.00	0	1.00	424	
12.00021 12E2 - Vacuum Vessel Plate	1,176	1,176	1,176	0	1.00	0	1.00	1,176	
12.00021 12E3 - Vacuum Vessel Installation	1,276	1,276	1,276	0	1.00	0	1.00	1,276	
12.00021 12E4 - VV (Heat Shield, Lead Field)	16	16	16	0	1.00	0	1.00	16	
12.00021 22E6 - Stellarator Vacuum Penetration	6,509	6,509	6,509	0	1.00	0	1.00	6,509	
13 - Coil Assembly and Support Systems	552	552	552	0	1.11	-18	0.11	414	
13.1 - Central Solenoid	1,420	1,215	1,231	205	0.84	-215	1.02	3,842	
13.00021 13E1 - T. Support	973	973	973	0	1.00	0	1.00	973	
13.00021 13E2 - T. Support	0	0	0	0	0	0	0	0	
13.00021 13E3 - Central Solenoid Support Structure	166	117	166	49	1.16	-49	1.00	166	
13.00021 13E4 - Coil Plate Prep	367	367	367	0	1.00	0	1.00	367	
13.00021 13E5 - Coil Support	476	476	476	0	1.00	0	1.00	476	
13.00021 13E6 - Fabrication	1,126	1,126	1,126	0	1.00	0	1.00	1,126	
14 - Coil Manufacturing									
14.00021 14E1 - Coil Structure Procurement	31,541	6,899	31,541	843	0.11	-1,354	0.30	8,617	
14.00021 14E2 - Coil Support Procurement	369	369	369	0	1.00	0	1.00	369	
14.00021 14E3 - Coil Support	256	256	256	0	1.00	0	1.00	256	
14.00021 14E4 - Coil Support	2,569	2,569	2,569	0	1.00	0	1.00	2,569	
14.00021 14E5 - Coil Support	1,060	1,060	1,060	0	1.00	0	1.00	1,060	
14.00021 14E6 - Coil Support	540	540	540	0	1.00	0	1.00	540	
14.00021 14E7 - Coil Support	26	26	26	0	1.00	0	1.00	26	

Page 1 of 3 NCSX CPIR status APR04.07 CLOSING CPM2 20070214.xls CPM & Charts 1/3/2007 3:42 PM MSN

13.00021 13E1 - T. Support	973	973	973	0	1.00	0	1.00	973
13.00021 13E2 - T. Support	0	0	0	0	0	0	0	0
13.00021 13E3 - Central Solenoid Support Structure	166	117	166	49	1.16	-49	1.00	166
13.00021 13E4 - Coil Plate Prep	367	367	367	0	1.00	0	1.00	367
13.00021 13E5 - Coil Support	476	476	476	0	1.00	0	1.00	476
13.00021 13E6 - Fabrication	1,126	1,126	1,126	0	1.00	0	1.00	1,126
14 - Coil Manufacturing								
14.00021 14E1 - Coil Structure Procurement	31,541	6,899	31,541	843	0.11	-1,354	0.30	8,617
14.00021 14E2 - Coil Support Procurement	369	369	369	0	1.00	0	1.00	369
14.00021 14E3 - Coil Support	256	256	256	0	1.00	0	1.00	256
14.00021 14E4 - Coil Support	2,569	2,569	2,569	0	1.00	0	1.00	2,569
14.00021 14E5 - Coil Support	1,060	1,060	1,060	0	1.00	0	1.00	1,060
14.00021 14E6 - Coil Support	540	540	540	0	1.00	0	1.00	540
14.00021 14E7 - Coil Support	26	26	26	0	1.00	0	1.00	26
15 Structures	256	204	348	-52	0.80	-136	0.28	348
15.00021 15E1 - Structural Design	256	204	256	0	1.00	0	1.00	256
15.00021 15E2 - Structural Procurement	0	0	92	0	0	-92	0	92
16 - Support	0	0	0	0	0	0	0	0
17 - Support and Base	626	626	626	0	1.00	0	1.00	626
17.00021 17E1 - Support structure Design	626	626	626	0	1.00	0	1.00	626
17.00021 17E2 - Support structure Design	0	0	0	0	0	0	0	0
17.00021 17E3 - Support structure Design	0	0	0	0	0	0	0	0
18 - Field Period Detachable	2,816	3,210	3,501	484	0.93	-285	0.31	4,819
18.00021 18E1 - Field Period Assembly	88	88	88	0	1.00	0	1.00	88

## Method : Low cost 3D printer

**Selected a method to build a stellarator**

**'Keeps Builder'**  
Main rapid prototyping methods are:

- Fused Deposition Modeling (FDM)
- Stereolithography (SLA)
- Selective Laser Sintering (SLS)
- Ink-Jet 3D Printing
- Laminated Object Manufacturing (LOM)

▶ Apart from 3D Printing and LOM, the other methods 'cannot' be cheap for large pieces (from some m<sup>3</sup> to thousands of m<sup>3</sup>)

**Selected a method to build stellarators**

**'Keeps Builder' will likely be a modified LOM** (Laminated Object Manufacturing) method to make moulds

▶ The selected material for the mould is expanded polystyrene (EPS) sheets.

- Thickness of layers depending on the size of the stellarator. - 5mm for UST\_2 and -25mm for size - T-J-I, for Thick LOM. (0.5mm and 2mm for common LOM).
- The material of Coil Frame will be concrete, plaster, resin... fiber reinforced or, metal (Co-Pb, Aluminium, Brass...) if vacuum cover fails.

4500 years later we should try to surpass the accuracy and magnitude of the Great Pyramid of Giza (Cheops) : ~ <0.03% error in sides and horizontality, mass 6.000.000 Ton and relatively complex interior (ITER core 20.000 Ton ; W7-X coils 0,1% error). 'Keeps Builder' is named in memory of such magnificence, no pretentiousness.

Something similar was proposed in 2007 [Wag 07]

Proposed in 2009 in CIEMAT by Queral

The same proposed by H. P. Laqua in 2010 [Laq 10]

Method for building and maintenance proposed in [Que09]

# Past ideas and R&D for innovative construction

## Innovative proposal from ARIES Team.

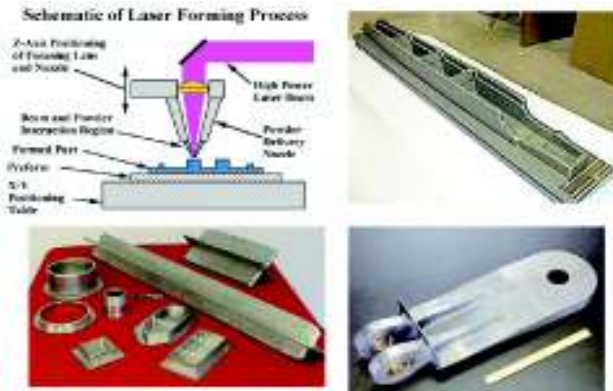


Fig. 4. Schematic of an deposition process, layered buildup, and finished component.

'Additive manufacturing' is proposed in **September 2007**. "ARIES-CS COIL STRUCTURE ADVANCED FABRICATION APPROACH" LESTER M. WAGNER,... and **ARIES Team** (i.e. J. Lyon, F. Najmabadi, P. R. Garabedian, L. Ku, D. Spong, ...) → **the critical importance of stellarator construction is in mind of well-known researchers**



Fig. 3

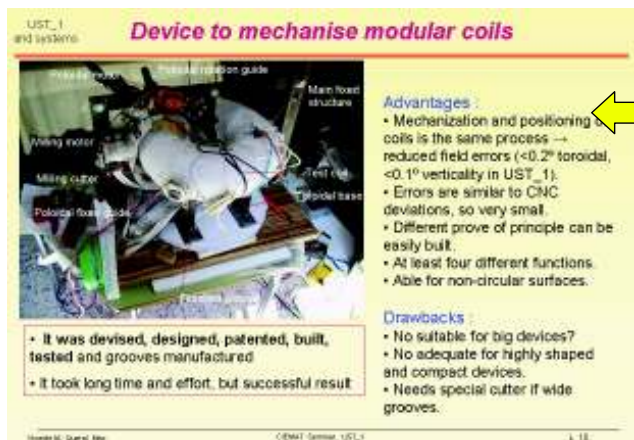
"In summary, the complexities of the chosen structural shape, as shown in Fig. 3, do not lead to a reasonably priced, conventional fabrication approach". **I agree**

"Additive manufacturing, a relatively new manufacturing process, appears to be a better fabrication method for this component". **I partially agree**

OK, perhaps it is a good method for long term, 5-20 years. But for the next future, 1-10 years → **specific methods to build stellarators must be developed**

## Method : Low cost 3D printer (also proposed by H. P. Laqua and J. Kisslinger in 2010)

**Built in 2006 in UST\_1 (v. Queral stellarator)**



Slide from the presentation in CIEMAT in 2006 [Que09]

**New small scale stellarator Experiments.**

Stellarator News 124, 2010



"The three-dimensional (3D) vacuum vessel could be manufactured by casting, where **the lost form is made by rapid prototyping**....

This vacuum vessel could already incorporate **the support structure of the coil winding and the port tubes similar to the report in [Que 08]** ...

.... This method would **guarantee a sufficiently high positional accuracy of the coils without time-consuming and expensive measurement and adjustment procedures**" [Laq 10]

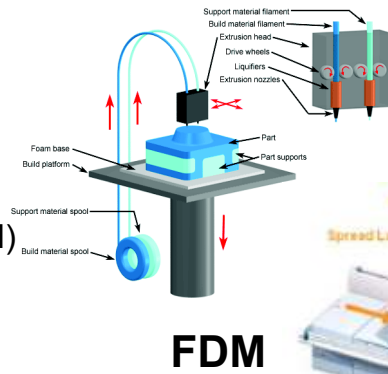
**As Farrokh Najmabadi says, technology innovation is essential and necessary for the whole fusion world**

# Selected method to build stellarators (presented in 2009)

## 'Keops Builder'

Main rapid prototyping methods are :

- Fused Deposition Modeling (FDM)
- Stereolithography (SLA)
- Selective Laser Sintering (SLS)
- 'Ink'-Jet 3D Printing
- Laminated Object Manufacturing (LOM)

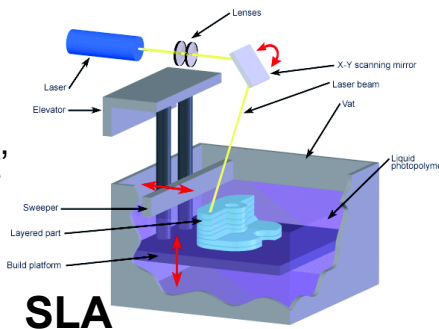


FDM

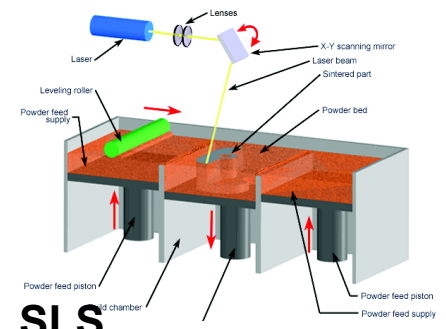


3D Printing

► Apart from **3D Printing** and **LOM**, the other methods 'cannot' be cheap for large pieces (from some m<sup>3</sup> to thousands of m<sup>3</sup>)



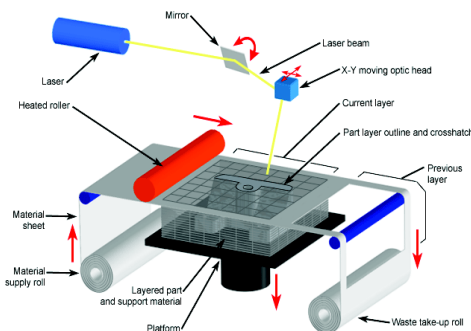
SLA



SLS

# Selected method to build stellarators (presented in 2009)

'Keops Builder' will likely be a modified LOM (Laminated Object Manufacturing) method to make moulds

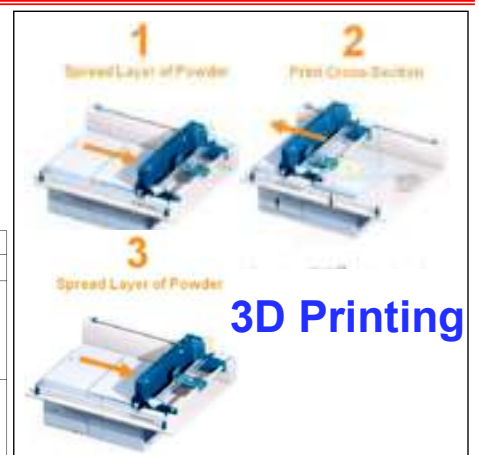


Traditional LOM method

	Order of Approximation for the Edge Surface		
	Zeroth	First	Higher
Uniform Slicing			
Adaptive Slicing			

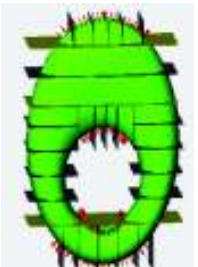
Figure 2 Various Slicing Methods

Probably this method will be used. Uniform slicing, straight lines



3D Printing

▼ Thick LOM method, Delft University of Technology, The Netherlands



- The **selected material** for the mould is **expanded polystyrene (EPS)** sheets.
- **Thickness of layers** depending on the size of the stellarator. ~ 5mm for UST\_2 and ~20mm for size ~ TJ-II, for Thick LOM. (0.5mm and 2mm for common LOM).
- The **material of Coil Frame** will be **concrete, plaster, resin...** fibre reinforced or, metal (Sn-Pb, Aluminium, Brass...) if vacuum cover fails.

# Where the first 3D printed stellarator will be built ?

In USA?  
In Germany?

One friend company already produce (high field) shaped coils for temper

**In Spain?**

~10 cm. Larger easy

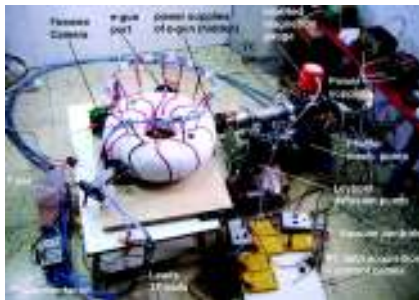


Plastic-wax piece for rapid prototyping

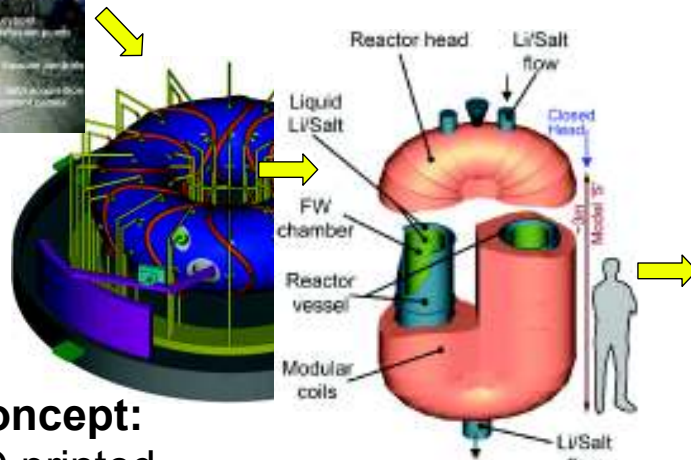


Silver 3D coil to temper crankshafts and others

## Method : Produce real things cheap and fast



Real, 2006,  
2k€ !!, UST\_1,  
~ 2000h of work



**Concept:**  
3D printed reactor  
proposed in  
2009

**Concept :** High-field pulsed Allure Ignition Stellarator. 2010

Produce any real stellarator at a reasonable cost and in time (better than NCSX, QPS, W7-X and ITER)

**Any real stellarator, fast !!!**

**New methods are needed!!**



## Method : Produce real things cheap and fast



Stellarators are geometrically complex.

**Innovative construction methods are required** (size of the device does not matter much to develop such methods)

Assembly of the W7-X bus bars using helium balloons to suspended them.

[Source of photo, Stellarator News n. 128]

Construction of low-cost stellarators by Innovative Rapid Prototyping Methods

L 33

## Conclusion and summary

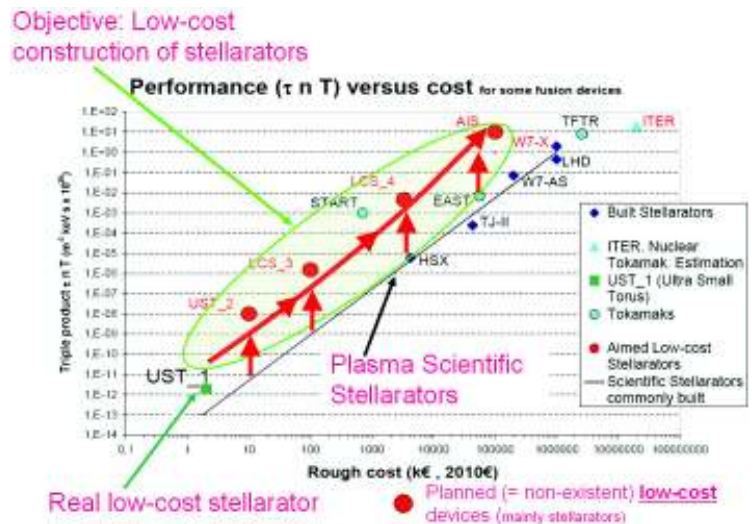
Construction of low-cost stellarators by Innovative Rapid Prototyping Methods

L 34

# Phases of the project. Unknown

Phases and time schedule are unknown because they depend on knowledge from previous phases, € available and time per year dedicated to the development

The key is to produce devices at low €, innovate, test the innovations, advance and obtain €



## Objective, results and means

### Objective :

Produce **low cost stellarators** (high field?) fusion devices for :

- 'Rapid' test, validation and advance codes and theory of stellarator concepts.
- Integrate all the engineering issues, including cost, into the stellarator optimization from the very beginning.
- Plasma experiments in several low-cost devices.
- Find an optimal stellarator size for competitive fusion energy.
- Generation of interest in industry and politicians → \$.
- Production of patents for fusion applicable to other fields → \$.

**Note :** 'low cost' means much simpler and lower cost than currently

### Means

- **Low cost 3D printer methods** for stellarator fabrication [Que 08]
- **Sequential feasibility tests** of the **methods** starting from the smaller devices.

## Conclusion

- High **creativity** and **innovation** achieved a **2k€** (0.002M€) **fusion device** with notable features.
- What could be achieved with 0.1M€, 10M€ or 1000M€ if **creativity** and **innovation** is added?

**Exploration of possible needs  
and interests of researchers,  
LNF, CIEMAT**

# *Discussion*

**E n d**

Thanks

## References

### References :

[Flu 08] “Implementing Agreement on High Temperature Superconductivity (HTS)” ; Presentation in FASI FASI-IEA NEET WORKSHOP ; René Flükiger ; Moscow, 30-09-2008

[Har 09] “Stellarators as fusion-fission reactor candidates” ; Jeffrey H. Harris, Donald A. Spong, Fusion Energy Division ‘Oak Ridge National Laboratory’ ; Third Fusion-Fission Hybrids Workshop College Park, Maryland 9-11 March 2009

[Laq 10] “New small scale stellarator experiments” ; H. P. Laqua, J. Kisslinger ; Stellarator News 124, February 2010

[Naj 06] “Towards Attractive Fusion Power Plants” ; Farrokh Najmabadi, University of California San Diego ; Presentation in the Korean National Fusion Research Center, Daejeon, Korea April 20, 2006

[Que 09] “Innovative reactor stellarators and construction methods” ; Vicente M. Queral ; Presentation in 'National Fusion Laboratory', CIEMAT ; 3 April 2009

## References

### References :

[Que 08] “UST\_1, a small, low-cost stellarator” ; Vicente Queral ; Stellarator News 118 ; December 2008

[Que 10] “High-field pulsed Allure Ignition Stellarator” ; Vicente Queral ; Stellarator News 125 ; April 2010

[Sar 09] “Commercial superconductors, Cryogenics and Transformers” ; Dr. Philip Sargent, Diboride Conductors Ltd. ; 2009

[Wel 09] A. Weller, et al., “International Stellarator/Heliotron Database progress on high-beta confinement and operational boundaries,” Nucl. Fusion 49 (2009) 065016.

[Wob 06] “The Helias Reactor” ; Presentation in unknown place and date ; 2006?

[Wag 07] September 2007. “ARIES-CS COIL STRUCTURE ADVANCED FABRICATION APPROACH” LESTER M. WAGANER,... and ARIES Team (i.e. J. Lyon, F. Najmabadi, P. R. Garabedian, L. Ku, D. Spong, ...) ‘Additive manufacturing’

