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

Discusion of possible benefits for experimental and theoretical fusion

Vicente M. Queral (CIEMAT)

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

CEIMAT, 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.

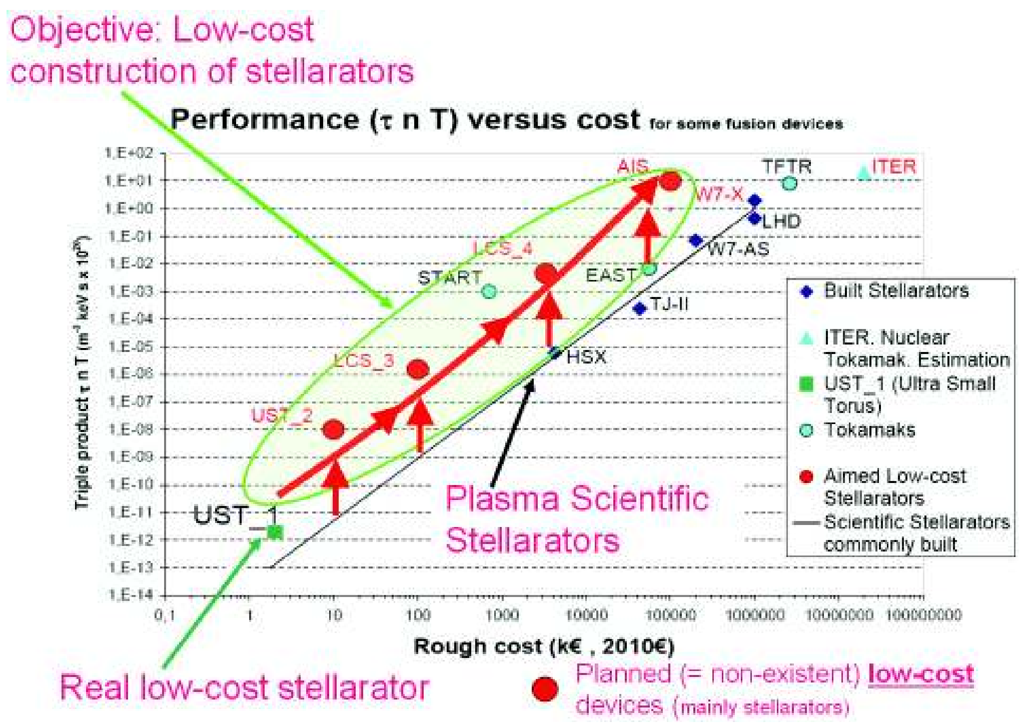
Considerable more technology R&D is needed"

Farrokh Najmabadi, [Naj 06]

We have to find ways to advance such technologies

Summary

Performance ~ cost is the focus of this R&D



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.

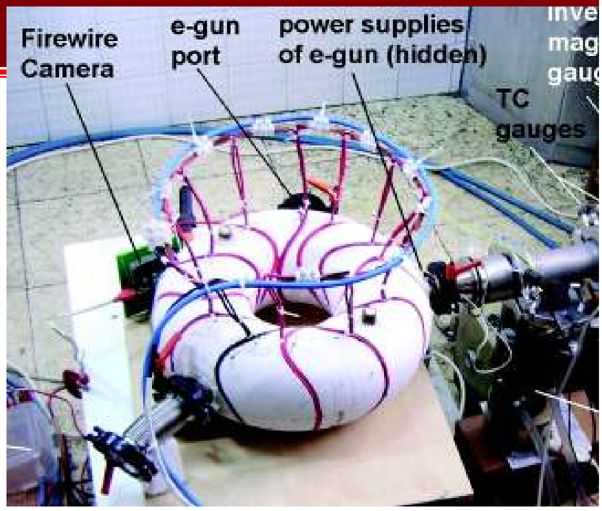
Much lower cost and construction time of stellarators

► **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**.

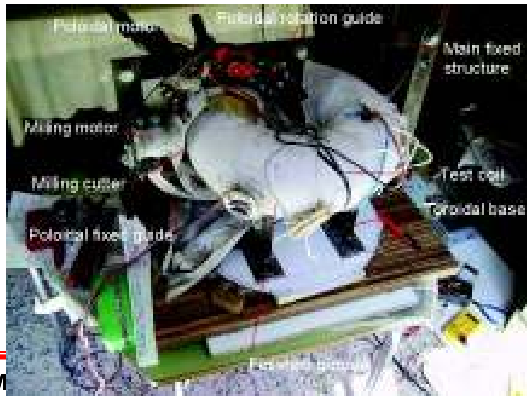
► Also **validation of the calculation/simulation codes** for stellarators has stopped due to **high construction costs of traditional methods.**

► 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, located in Castellón, Spain



Mechanising device

UST_1 = example of feasibility of major cost reduction by innovation (other: FORD T , PCs , ...)

The stellarator UST_1, **3rd 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)

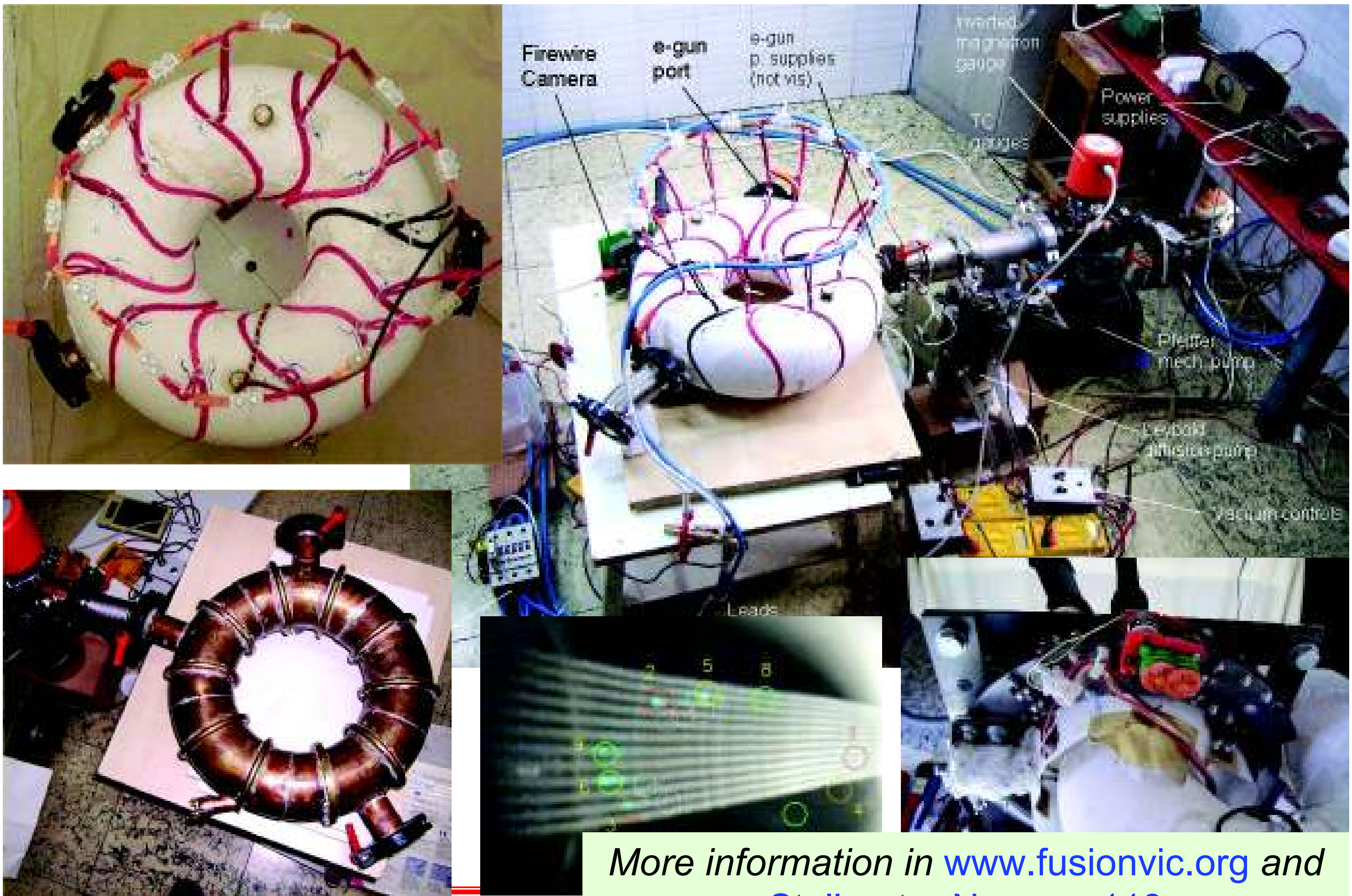
More difficult long term results

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 → $.
- Stellartor CTF (components test facility) ~ neutrons → $.

Please, tell your needs !!!

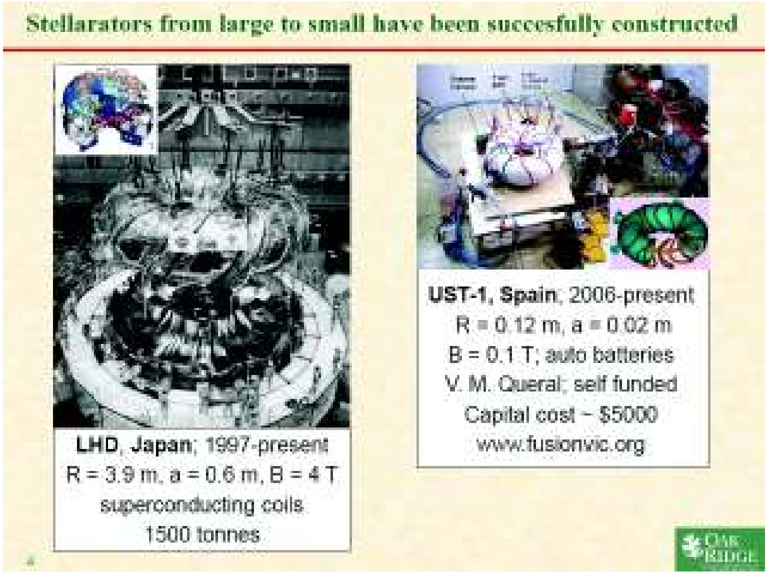
Stellarator UST_1, achievements



More information in www.fusionvic.org *and* Stellarator News n. 118

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*)

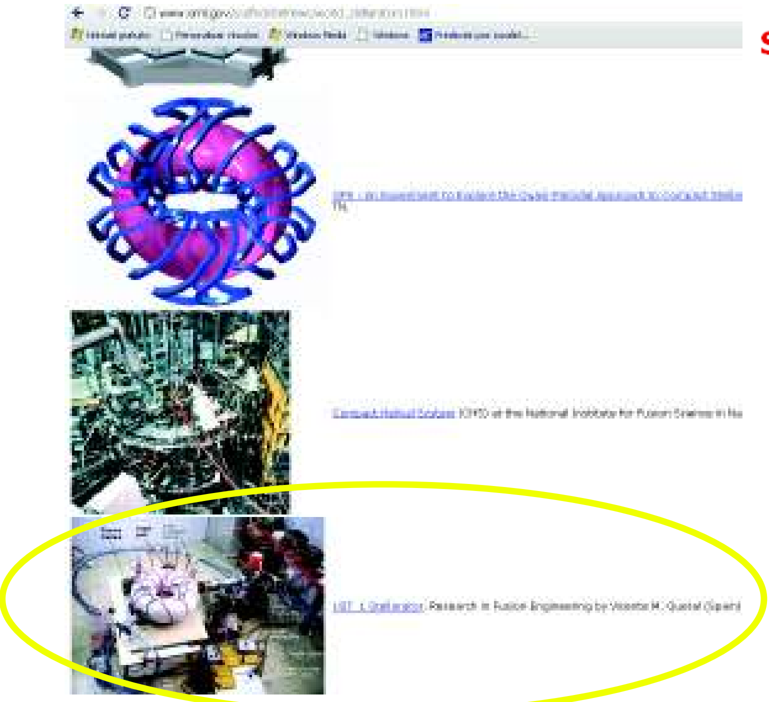


ORNL is one of the larger fusion laboratories in the world

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

UST_1 achievements

stellarator news

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E-Mail: jar@ornl.gov Phone (865) 482-5643
On the Web at http://www.ornl.gov/sci/fed/stelnews

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 toroidal milling 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 . . .

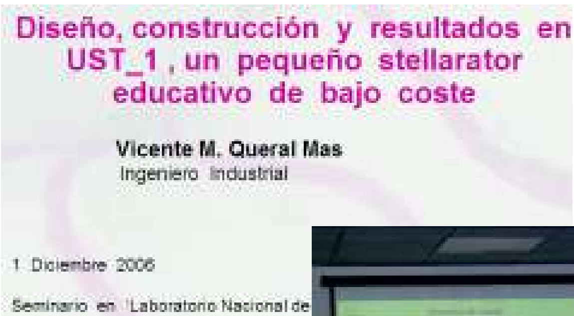
Year 2008

Article about UST_1 published in **'Stellarator News'**, an ORNL publication

Achievements of a 2k€ fusion device, UST_1

Year 2006

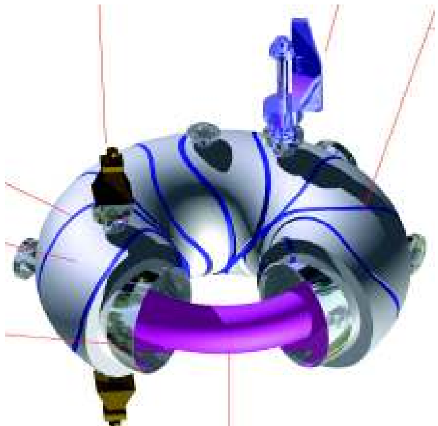
UST_1 was presented in the NFL, CIEMAT, producing great impact and admiration



[Que 06]

Year 2009-2010

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



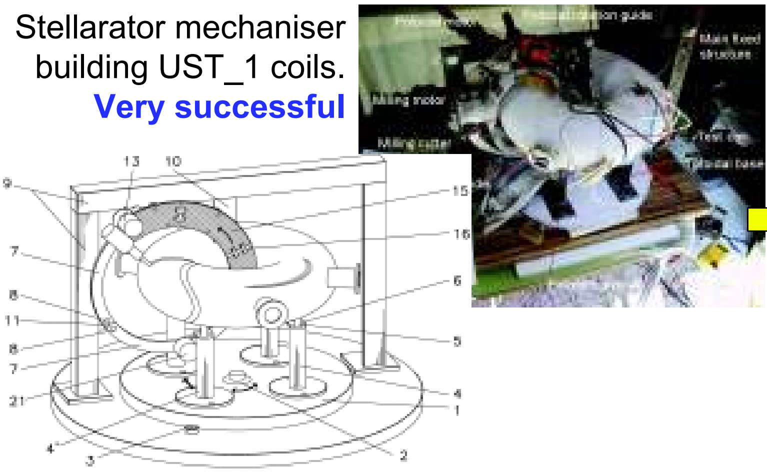
SCR-1 conceptual design presented in the ICPP-LAWPP 2010, Chile

Achievements of a 2k€ fusion device, UST_1

Year 2006 and 2009

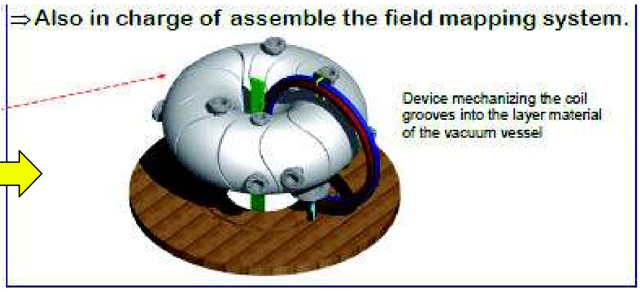
Patent and Utility model applied for. P200600427 and U200901520 (granted).

Stellarator mechaniser building UST_1 coils. **Very successful**



Year 2010

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

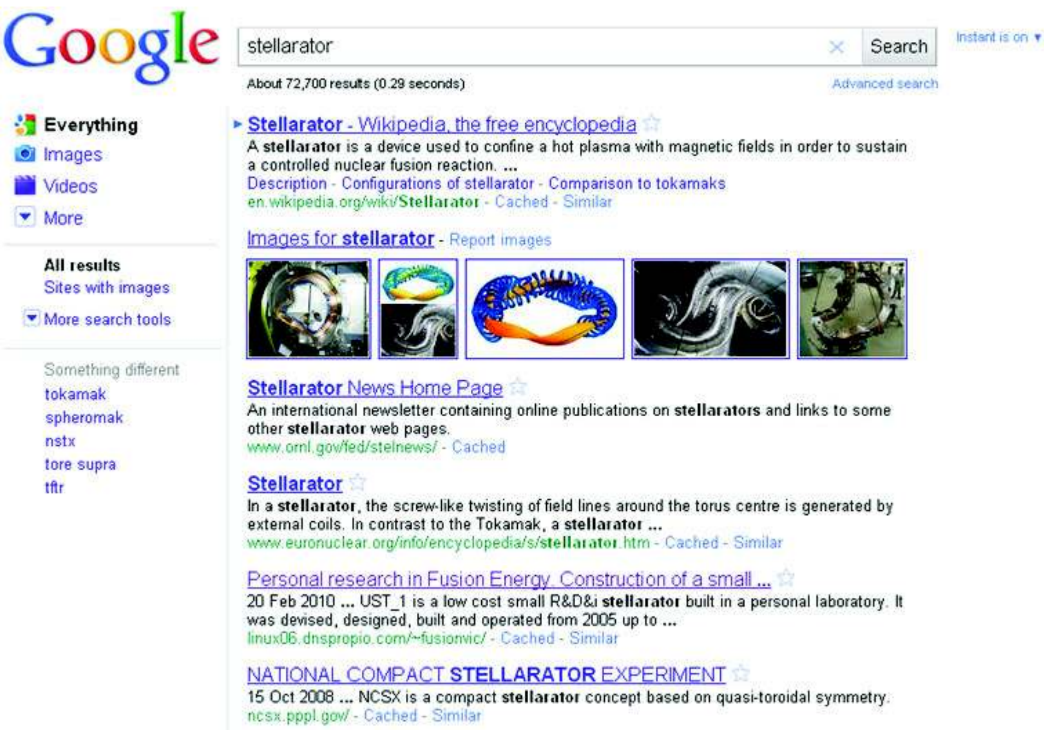


Source of figure : Poster presented in the ICPF LAWPP 2010, Chile

Achievements of a 2k€ fusion device, UST_1

Year 2009 and2010

UST_1 is the **fourth Google.com site** for the search word “Stellarator”

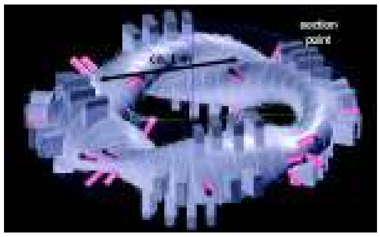


Achievements of a 2k€ fusion device, UST_1

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 :

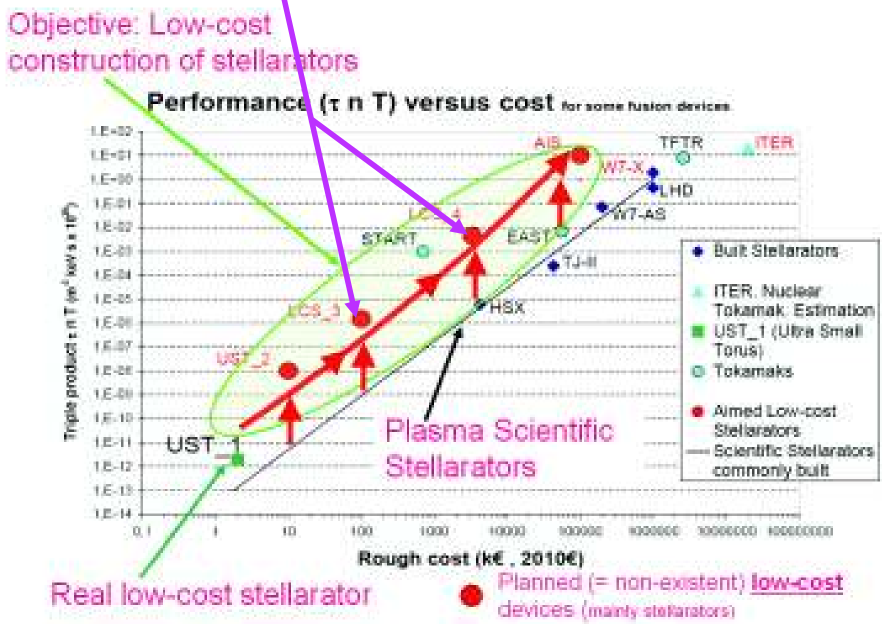
- Integrate all the enginnering issues, including cost, into the stellarator optimization from the very beginning.
- ‘Rapid’ test, validation and advance codes and theory of stellarator concepts.
- Plasma experiments in several low-cost devices.
- Find an optimal stellarator size for competitive fusion 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 '<u>smaller equivalent</u>' devices are not built. Otherwise escalation of costs will occur, like in ITER



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% (sorbent, 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

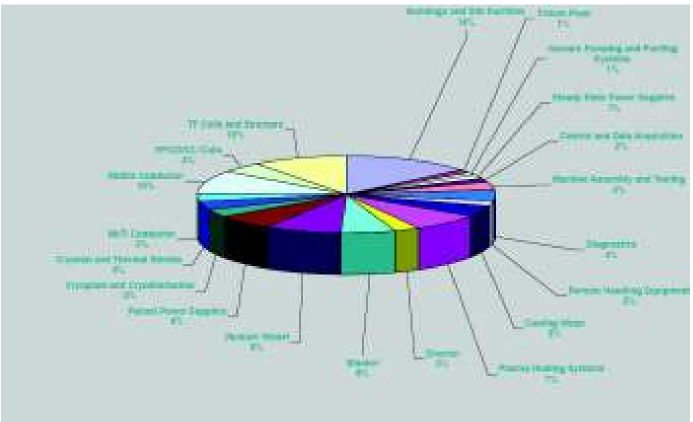
There are other countries and conditions → other values but the same essence

Aim : commercial fusion 'reactor core' 1GW =~ 500-1000 M€ !!!

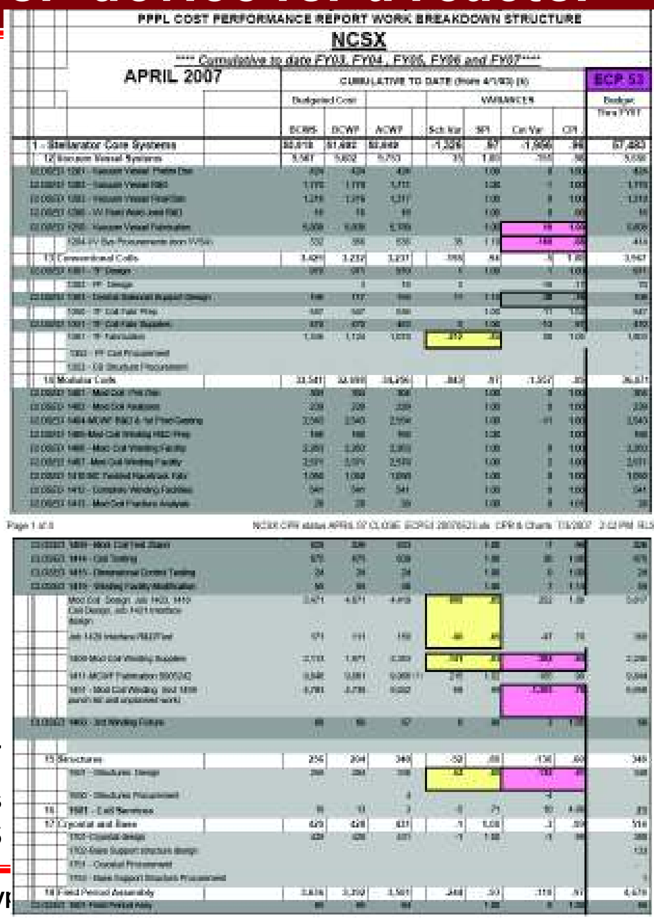
CANDU 670MWe, Konvol 1400MWe and other fission plants have been considered for the % cost average

Decision about 'best' type of device for a reactor

Costs for two devices as an example

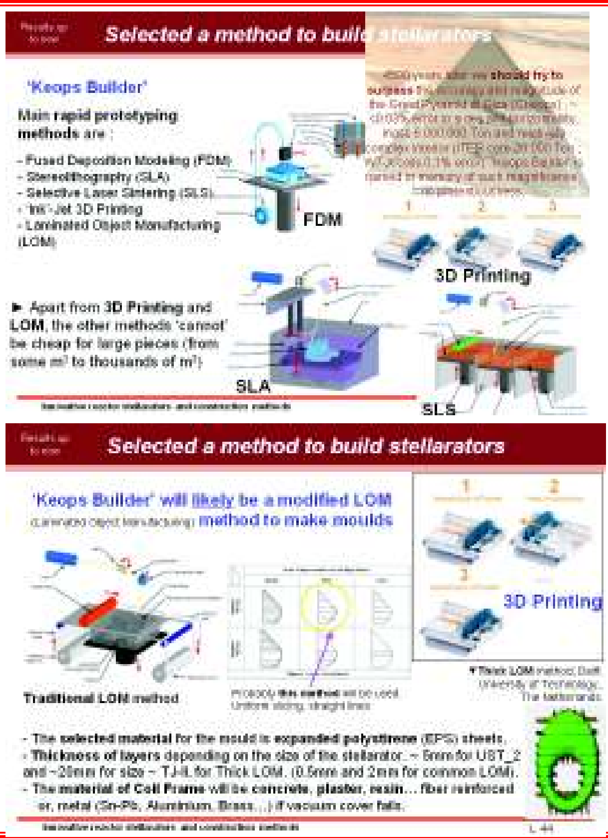


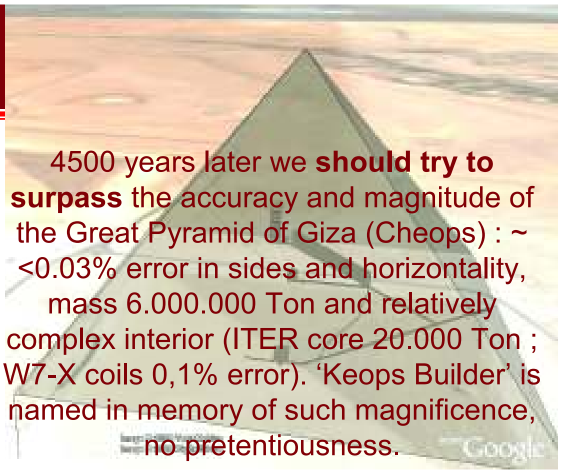
Distribution of the **ITER** costs (still **theoretical** costs). Total cost could be considered 6000M€ - cost varies with time!



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

Method : Low cost 3D printer





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). 'Keops Builder' is named in memory of such magnificence, no pretentiousness.

Something similar was proposed in 2007 [Wag 07]

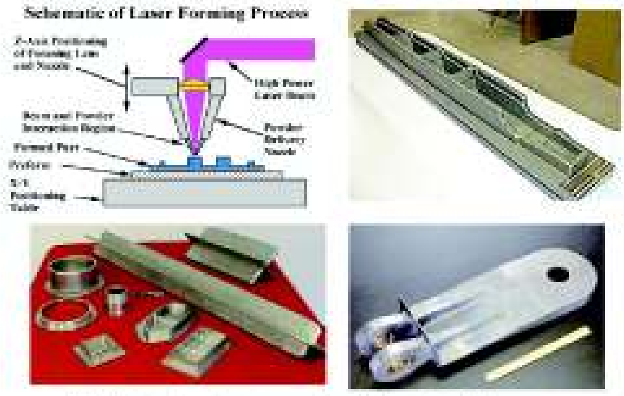
Proposed in 2009 in CIEMAT by Queral

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.



'Additive manufacturing' is proposed in 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, …) → 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**

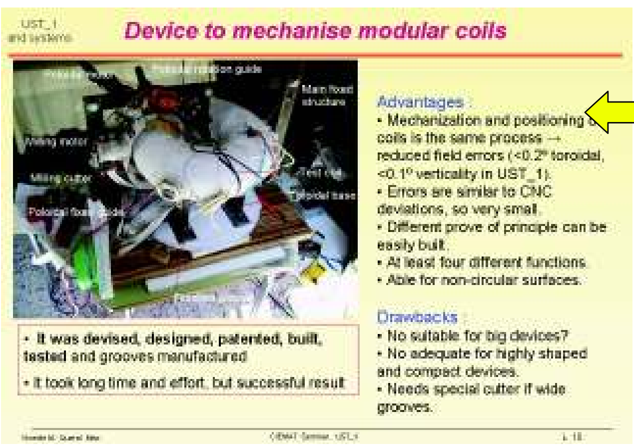
"Additive manufacturing, a relatively new manufacturing process, appears to be a better fabrication method for this component". **I partially agree** →

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

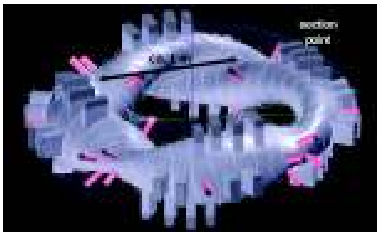
(also proposed by H. P. Laqua and J. Kisslinger in 2010)

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]

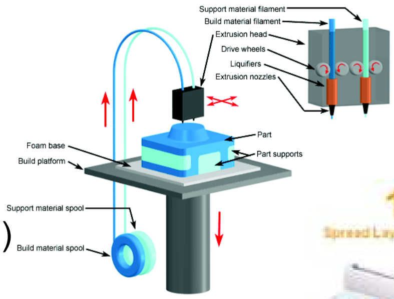
As Farrokh Najmabadi says, technology innovation is essential and necessary for the whole fusion world

Selected method to build stellarators (presented in 2009)

'Keops Builder'

Main **rapid prototyping methods** are :

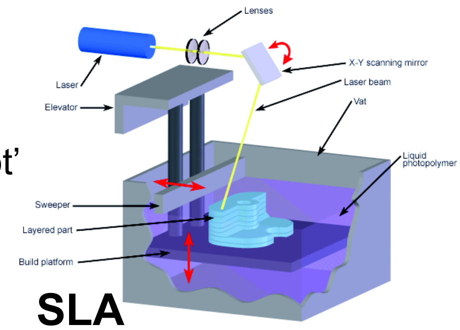
- Fused Deposition Modeling (FDM)
- Stereolithography (SLA)
- Selective Laser Sintering (SLS)
- 'Ink'-Jet 3D Printing
- Laminated Object Manufacturing (LOM)



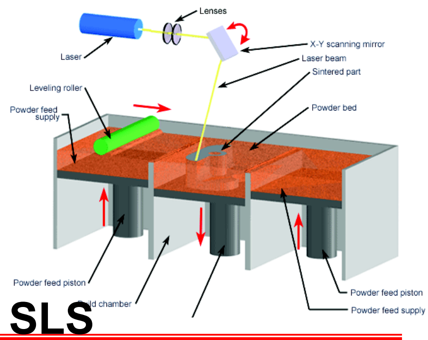
FDM

3D Printing

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



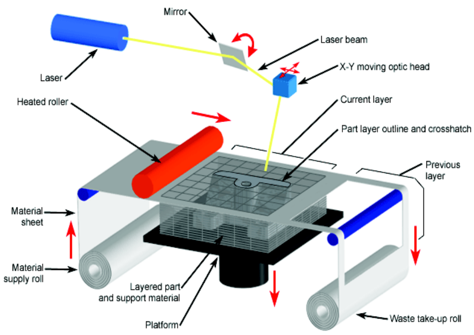
SLA



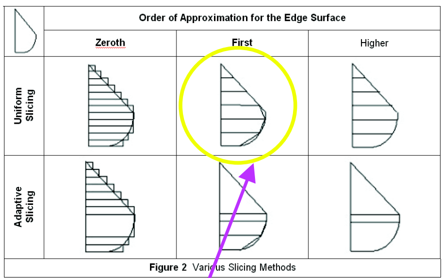
SLS

Selected method to build stellarators (presented in 2009)

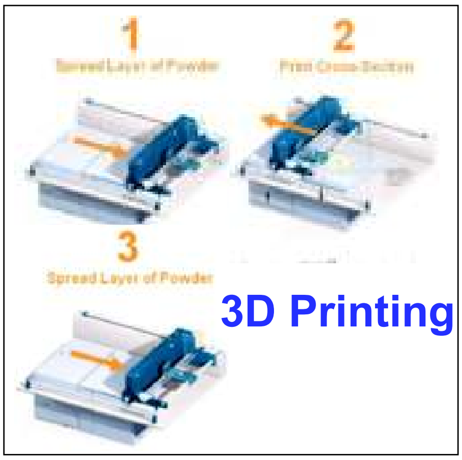
'Keops Builder' will likely be a modified LOM (Laminated Object Manufacturing) method to make moulds



Traditional LOM method



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



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

- The **selected material** for the mould is **expanded polystirene** (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.

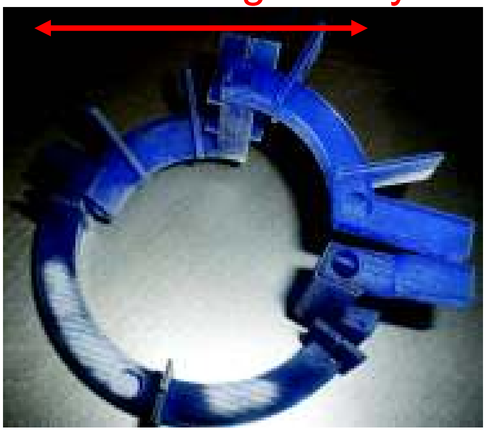
Where the first 3D printed stellarator will be built ?

In USA?
In Germany?

In Spain?

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

~10 cm. Larger easy

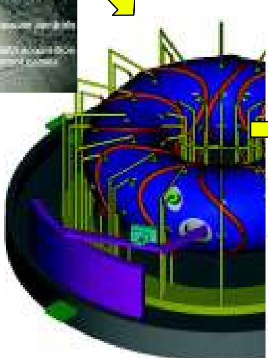


Plastic-wax piece for rapid prototyping

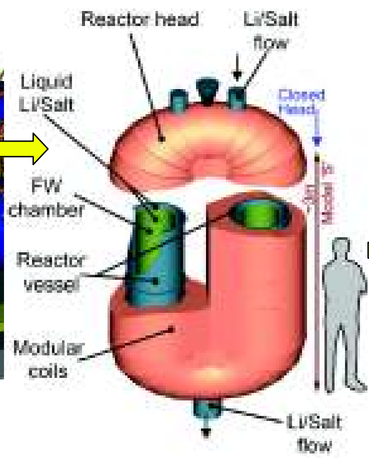
Silver 3D coil to temper crankshafts and others

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)

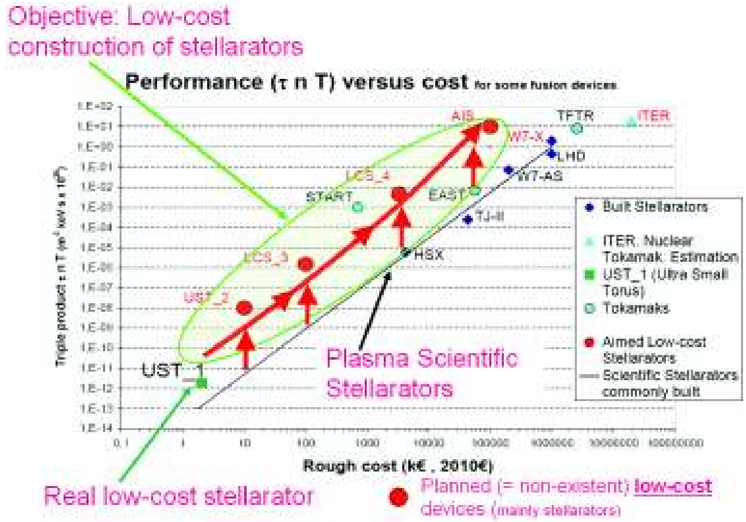
Assembly of the W7-X bus bars using helium balloons to suspended them.
[Source of photo, Stellarator News n. 128]

Conclusion and summary

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 €



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- 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 <u>methods</u>** for stellarator fabrication [Que 08]
- **<u>Sequential</u> feasibility tests** of the **<u>methods</u>** starting from the smaller devices.

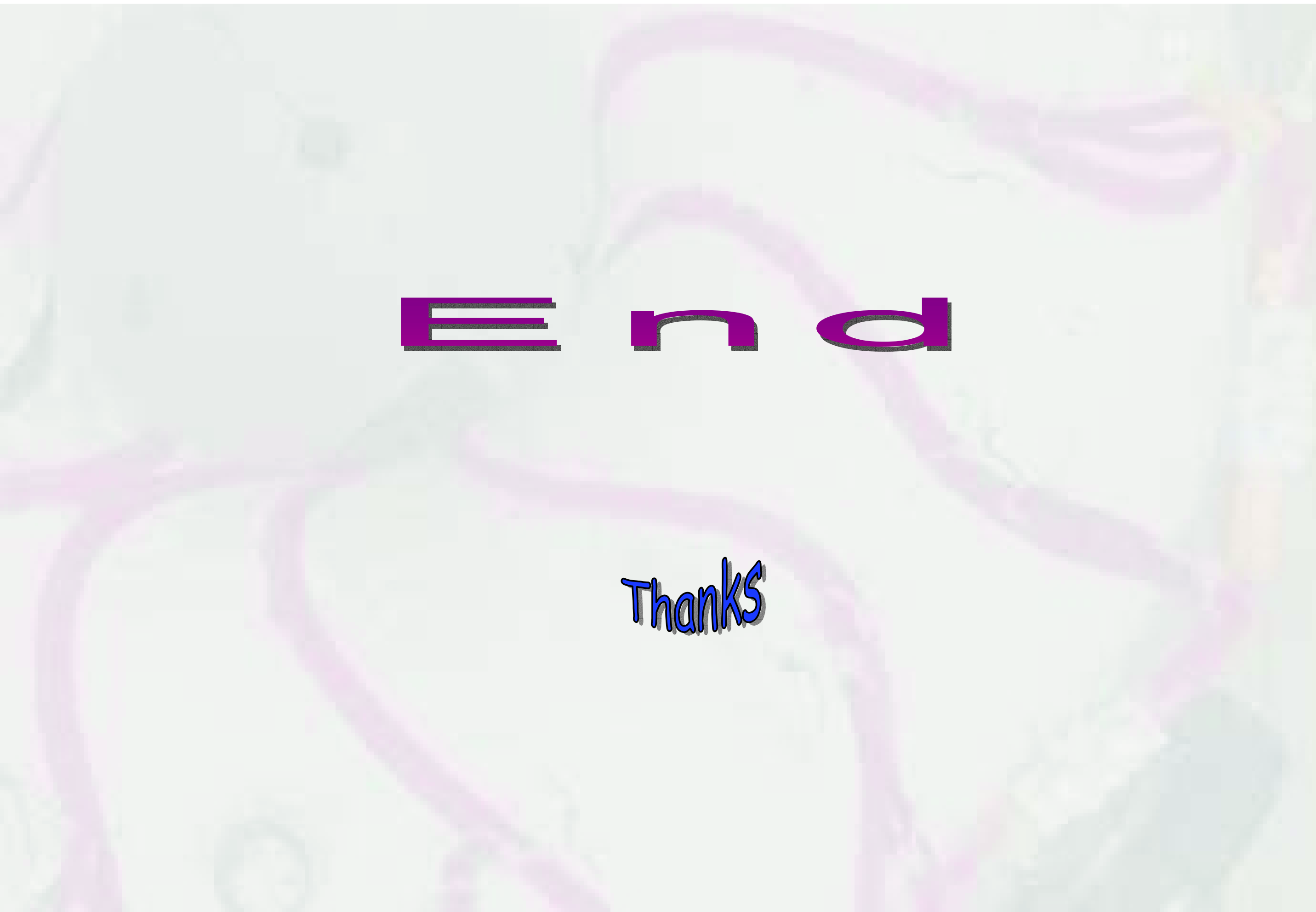
Conclusion

- 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



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[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, Daejon, Korea April 20, 2006

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