Level of **confidentiality** : **Free distribution**

Innovative reactor stellarators and construction methods

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Seminar in National Fusion Laboratory, CIEMAT, Madrid, Spain

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Outline

- Background
- Main Proposal. Aim 1
- Decision about 'best' type of device for a reactor
- Aim 2
- Past R&D in innovative construction
- **Results up to now**
- Future work
- Non-technical proposals
- Conclusions

Background

► The **presentation will show** one **improved design of stellarator** (experimental and reactor), the planned **methods to built** it at low cost, and the **concepts and plans for UST_2 stellarator**.
NOTE: In case somebody does not know it, I designed, built an operated UST_1, a very small modular stellarator.

► 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 five months** only ~200 hours (~5 weeks)
- R&D in stellarators during **years 2005, 2006** and first half of **2007**.

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

► ***Acknowledgement : Thanks are given to the researchers which have helped with conversations, contacts, expertise, information, etc.***

Main Proposal

The 'innovative' proposal proposes innovation

NOT pursued : The objective is **NOT** the construction of fusion devices to experiment with plasmas *(whistles…)*

What is proposed (not a typical proposal) :

The objective is to experiment with innovative construction of fusion devices

Plasma experiments will be possible if diagnostics are installed in the devices

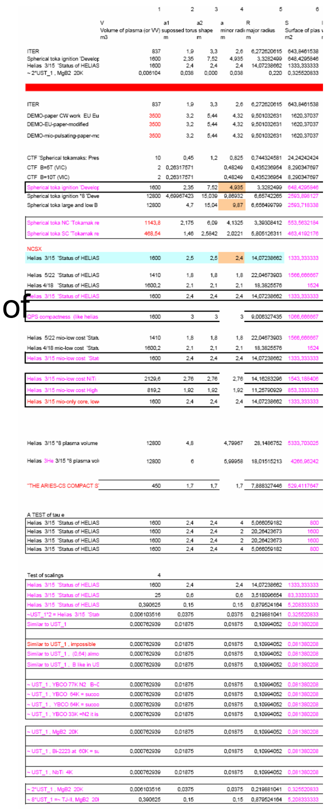
Aim 1

Aim 1

Ideally the same construction concepts should be applicable from small stellarators (tokamaks) up to reactors

However some constructive methods will be more cost-suited for small stellarators than for reactors → Probably small (~UST_2) and medium stellarators (~TJ-II) will be built **using certain different methods** and **materials than large** stellarators (~W7-X) and reactors

Decision about 'best' type of device for a reactor



Estimations from the point of view of economy, not the more usual functional comparison

■ The **spreadsheet table estimates/compares types/sizes of stellarators and tokamaks to decide.**

- **Not** an **accurate** calculation at all. It **estimates the cost** of each experiment or reactor and the **amortization period** for : different sizes, prices of electricity and many others **factors/parameters**. A total of **~170 parameters** are involved in the estimations.
- **Sensitivity studies** have been performed by variation of several parameters ~ some costs ↑ undetermined.

	V	a1	a2	a	R	S	Inc blanket + s	Total eff radius	V B
	Volume of plasma (or VV)	supossed torus sl	minor radi	major radius	Surface of plas	with from plasi	effective radius	Volume having	
	m3	m	m	m	m	m2	m	m	m3
ITER	837	1,9	3,3	2,6	6,272620615	643,8461538	2	4,6	2619,95858
Spherical toka ignition 'Development of the Spherica	1600	2,35	7,52	4,935	3,3282499	648,4295846	2,2	7,135	3344,518662
DEMO-paper CW work EU European Power Plant (	3500	3,2	5,44	4,32	9,501032631	1620,37037	2	6,32	7490,912209
DEMO-EU-paper-modified CW work EU European	3500	3,2	5,44	4,32	9,501032631	1620,37037	2	6,32	7490,912209
DEMO-mio-pulsating-paper-modified EU European	3500	3,2	5,44	4,32	9,501032631	1620,37037	2	6,32	7490,912209
Helias HSR-3/15 'Status of HELIAS reactor studies	1600	2,4	2,4	2,4	14,07238662	1333,333333	2,2	4,6	5877,777778
~ 2*UST_1 , MgB2 20K	0,006104	0,038	0,000	0,038	0,220	0,325520833	0,034375	0,071875	0,022421943

Density of SC	Price of SC or	Weight of con	Cryotemperat	Price of S I		Length of c	Cost of cor	Cost con	C.conductor (SC		Cost/W p	Elect Power (	Elect Pow	Cost of pow	Income per ye	Years for amortization		Total cost
nd cyclotron not considered. Positive indicates OK					current in the coduct		meth. 1	meth 2	meth. 1									
kg/m3	€/kg	kg	K	€/m	A	m	€	€	M€		€/W	MW	MW	M€	M€	year		M€
9000	600	1357743,54	4	10	90	79956009	8E+08	8E+08	799,5601		0,7	600	600	420	-45,382364	-123,16166		5589,36733
9000	8	2151788,45	293	0,1	7	2,39E+08	23908761	2E+07	23,90876		0,7	300	660	462	65,4163863	74,4581784		4870,78496
9000	600	3601556,48	4	10	90	2,12E+08	2,12E+09	2E+09	2120,917	0	0,7	100	536,05	375,235	177,951945	70,2061959	0	12493,3291
9000	600	3601556,48	4	10	90	2,12E+08	2,12E+09	2E+09	2120,917	0	0,7	100	955	668,5	11,537726	1099,21233	0	12682,4107
9000	600	3601556,48	4	10	90	2,12E+08	2,12E+09	2E+09	2120,917	0	0,7	100	100	70	92,276053	141,187875	0	13028,2598
9000	300	2434759,44	4	5	90	1,5E+08	7,51E+08	7E+08	751,469		0,3	30	30	9	153,076494	49,0246979		7504,52885
9000	250	19,5534109	20	5	240	1375,981	6879,904	4888,4	0,00688		0	0	0	0	-17,519764	-0,0009536		0,01670683

Decision about ‘best’ type of device for a reactor

Basic estimations to decide the ‘best’ reactor device

Key parameters are the **comparative cost** of :

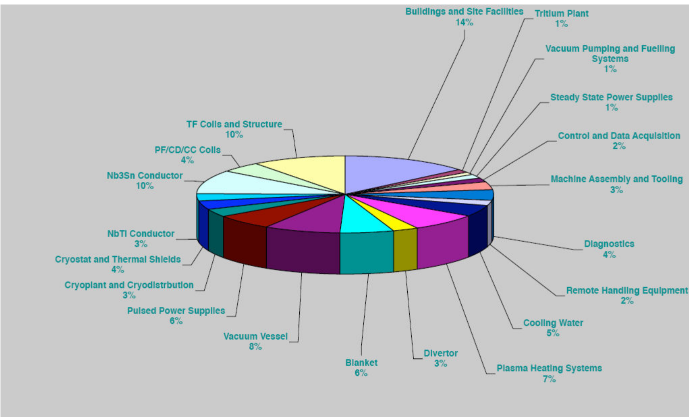
- **Recirculated power.**
- **Availability** = f (**downtime** cost ~ **complexity** ~ maintenance, regime).
- **Cost of construction** of VV, coil frames and coils.
- **Steady** state or **pulsating** work regime.
- Heating and **CD** injectors in continuous work (CW) / Only ignition.
- **Increment of cost** due to **pulses** (**fatigue**) and **disruptions** (**strength**).
- **Surface** of breeding blankets (low activation materials, Li6 →? ↑ cost).
- Type and power of the **power supplies**.
- Superconductor or Cu conductors. SC ~ ‘AC’ or DC coil regime.

NOTES : - In the next only **modular stellarators** are considered.

- One classification of fusion devices for better comparation :
  - ‘Normal’ aspect ratio (A~3-4) tokamaks style ITER and JET
  - Compact/spherical tokamaks (A~1.2-2)
  - Non-compact stellarators (A>~6). W7-X, HSX
  - Relatively compact stellarators (A~3-6). Style NCSX, HRS-3, MHH2, QPS, UST_1….

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 (from 4/1/03) (k)							ECP 53
		Budgeted Cost			VARIANCES				Budget Thru FY07
		BCWS	BCWP	ACWP	Sch Var	SPI	Cst Var	CPI	
	1 - Stellarator Core Systems	**53,018**	**51,692**	**53,649**	**-1,326**	**.97**	**-1,956**	**.96**	**57,483**
	12 Vacuum Vessel Systems	9,567	9,602	9,753	35	1.00	-151	.98	9,650
CLOSED	1201 - Vacuum Vessel Prelim Dsn	424	424	424		1.00	0	1.00	424
CLOSED	1202 - Vacuum Vessel R&D	1,770	1,770	1,771		1.00	-1	1.00	1,770
CLOSED	1203 - Vacuum Vessel Final Dsn	1,218	1,218	1,217		1.00	0	1.00	1,218
CLOSED	1206 - VV Field Weld Joint R&D	16	16	16		1.00	0	.98	16
CLOSED	1250 - Vacuum Vessel Fabrication	5,808	5,808	5,789		1.00	19	1.00	5,808
	1204-VV Sys Procurements (non VVSA)	332	366	536	35	1.10	-169	.68	414
	13 Conventional Coils	3,429	3,232	3,237	-198	.94	-5	1.00	3,967
CLOSED	1301 - TF Design	970	971	970	1	1.00	1	1.00	971
	1302 - PF Design		3	19	3		-16	.17	70
CLOSED	1303 - Central Solenoid Support Design	106	117	155	11	1.10	-38	.76	106
	1350 - TF Coil Fabr Prep	547	547	536		1.00	11	1.02	547
CLOSED	1351 - TF Coil Fabr Supplies	470	470	483	0	1.00	-13	.97	470
	1361 - TF Fabrication	1,336	1,124	1,074	-212	.84	50	1.05	1,803
	1352 - PF Coil Procurement								-
	1353 - CS Structure Procurement								-
	14 Modular Coils	33,541	32,698	34,256	-843	.97	-1,557	.95	36,071
CLOSED	1401 - Mod Coil Prel.Dsn	304	304	304		1.00	0	1.00	304
CLOSED	1402 - Mod.Coil Analyses	239	239	239		1.00	0	1.00	239
CLOSED	1404-MCWF R&D & 1st Prod Casting	2,543	2,543	2,554		1.00	-11	1.00	2,543
CLOSED	1405-Mod Coil Winding R&D Prep	168	168	168		1.00		1.00	168
CLOSED	1406 - Mod. Coil Winding Facility	2,263	2,263	2,263		1.00	0	1.00	2,263
CLOSED	1407 -Mod Coil Winding Facility	2,571	2,571	2,570		1.00	2	1.00	2,571
CLOSED	1410 MC Twisted Racetrack Fabr	1,050	1,050	1,050		1.00	0	1.00	1,050
CLOSED	1412 - Complete Winding Facilities	541	541	541		1.00	0	1.00	541
CLOSED	1413 - Mod Coil Fracture Analysis	28	28	28		1.00	0	1.01	28

Page 1 of 4 NCSX CPR status APRIL 07 CLOSE ECP53 20070523.xls CPR & Charts 7/3/2007 2:42 PM RLS

		BCWS	BCWP	ACWP	Sch Var	SPI	Cst Var	CPI	Budget Thru FY07
CLOSED	1409 - Mod. Coil Test Stand	826	826	833		1.00	-7	.99	826
CLOSED	1414 - Coil Testing	675	675	639		1.00	36	1.06	675
CLOSED	1415 - Dimensional Control Testing	24	24	24		1.00	0	1.00	24
CLOSED	1419 - Winding Facility Modification	55	55	48		1.00	7	1.14	55
	Mod Coil Design Job 1403, 1416 Coil Design, Job 1421 Interface design	5,471	4,671	4,419	-800	.85	252	1.06	5,617
	Job 1429 Interface R&D/Test	171	111	158	-60	.65	-47	.70	368
	1408-Mod Coil Winding Supplies	2,113	1,971	2,353	-141	.93	-382	.84	2,245
	1411-MCWF Fabrication S005242	9,646	9,861	9,966 (1)	215	1.02	-105	.99	9,844
	1451 - Mod Coil Winding (incl 1459 punch list and unplanned work)	4,793	4,738	6,042	-56	.99	-1,305	.78	6,650
CLOSED	1460 - 3rd Winding Fixture	60	60	57	0	.99	3	1.05	60
	15 Structures	256	204	340	-52	.80	-136	.60	348
	1501 - Structures Design	256	204	336	-52	.80	-132	.61	348
	1550 - Structures Procurement			4			-4		
	16 1601 - Coil Services	18	13	3	-5	.71	10	4.86	**23**
	17 Cryostat and Base	429	428	431	-1	1.00	-3	.99	514
	1701-Cryostat design	429	428	431	-1	1.00	-3	.99	380
	1702-Base Support structure design								133
	1751 - Cryostat Procurement								-
	1752 - Base Support Structure Procurement								1
	18 Field Period Assembly	3,636	3,392	3,501	-244	.93	-110	.97	4,678
CLOSED	1801-Field Period Assy	65	65	64		1.00	0	1.00	65

Decision of type of device for a reactor → Stellarator (~Compact)

A relatively compact Stellarator (A~5-8) has been selected as the first choice

Some of the many conclusion from the table :

■ A **more compact stellarator** is less expensive due to less SC, blanket, VV and frames. The two last factors depend very much on the construction methods. ~130M€ more expensive the **NbTi SC** of the HSR-5 than for HSR-3. Extra reduction of **blanket cost** is only ~20% when passing from A=6 to A=3 (~QPS), therefore extra difficulties do not compensate.

■ Tokamaks, compact or not, in CW mode, have long/unrealistic amortization period due to high recirculating power, from 800-1400MWe. In CW work only compact Cu-Coil tokamak has cost~=stellas. For tokamaks in pulsating mode, cost is the highest but amortization period is more realistic. **Stellartors achieve the lowest amortization periods and cost similar to the lowest-cost tokamaks**.

■ Construction and maintenance downtime costs due to 3D complex geometry is a key cost factor of **stellarators** with respect tokamaks → focus on R&D&i on **construction and maintenance is essential** and the focuss of this presentation.

Aim 2 : Cost 10 to 100 times less than present

■ **Construction Cost Factor 'c'** :

Cost of device = Cost of materials used **X c**

c ~ 2-4 for automobiles (complex and **dynamic** mechanisms, but large series).
c ~ 20-40 for ITER VV and TF coils structure.
c ~ 50-100 for NCSX VV and modular coils frame.

► Effort must be focussed in **innovative** in-site construction methods having **c ~ 4-10** (reduction 3-10 times) for **stellarators** and **for one unit** produced. **Difficult**.

■ **Materials Cost Factor 'm'** :

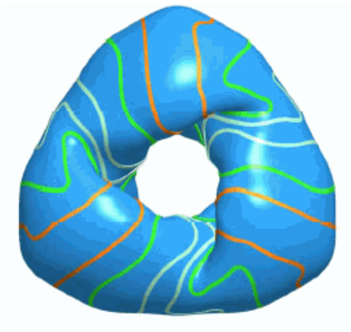
Cost of materials = Cost of present materials commonly used **X m**

► Low cost ('in-site') materials : concrete plaster (fibers), ceramics; sand, expanded polystyrene, *ice* for moulds, etc. **m ~ 0.1 – 0.3** (reduction 3-10 times)

Aim 2 : A reduction from 10 to 100 times the present costs should be pursued

Past ideas and R&D for innovative construction

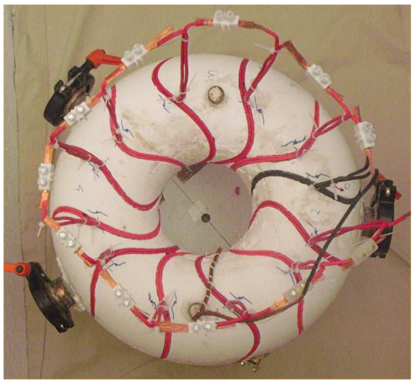
Innovative proposal from ARIES Team



Idea proposed by Farrokh Najmabadi ~ 'out-of-plane force' 'coils wound into groove',"Recent Progress in ARIES Compact Stellarator Study", Farrokh Najmabadi and the ARIES Team ,15th International Toki Conference December, 2005, Toki, Japan.

NOTE: UST_1 was designed and built without notice of it.

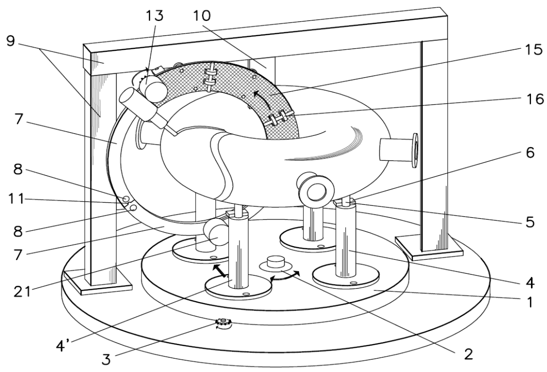
Fusion device, built



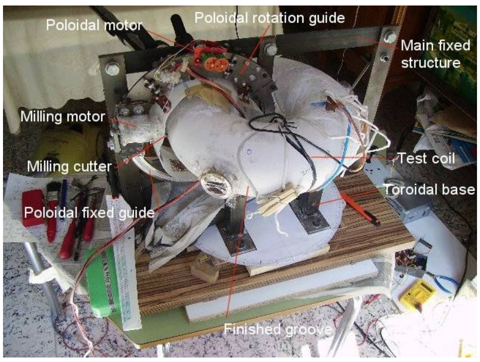
UST_1 stellarator. Photo July 2006

Past ideas and R&D for innovative construction

One method and machine to build low cost accurate stellarators



'Mechaniser' for stellarators. February 2006. Figure of the patent applied for



Mechanising the plaster frame and groves for UST_1 stellarator. Photo ~April 2006

Notable success

►The stellarator works properly and **high accuracy** at very **low cost** of the stellarator core, only ~150€ including VV, plaster frame and conductor/coils

Past ideas and R&D for innovative construction

Innovative proposal from ARIES Team.

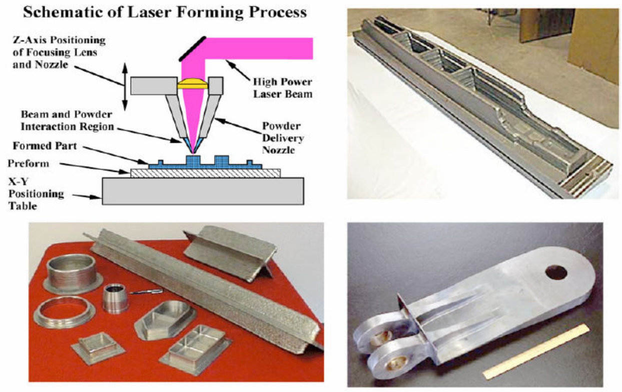


Fig. 4. Schematic of arc deposition process, layered buildup, and finished components.

'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

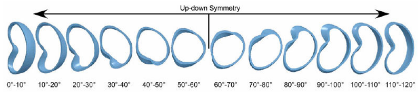


Fig. 3. Progression of coil structure shapes over a field period.

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

Results up to now

(only ~one month of work up to now – little time)

In-site Construction proposed

Some of the many problems found :

■ The first three to ~ten reactors will be doubtful and different designs (the same happened in fission reactors and experimental fusion devices) → **no industrial serial process savings.**

+

■ Industry **increases costs** to cover **indeterminacies** of one of a kind new devices.

+

■ **Large** and massive **components** are costly or impossible to **transport**. Later **accurate assembling**.

+

■ Maintenance/repair of **SC coils** is practically impossible in **present methods** (~**high cost** of achieving extreme confidence and extensive tests).

→

As much as possible
'In-site Construction' is proposed

*(mainly for large **stellarators** and for the **'first' reactors**)*

NOTE : **In-site construction is also suggested by the ARIES Team** : "The size and mass ~1000 tonnes! of one field period structure suggests that the field period coil structure should be fabricated at the construction site", extract from "ARIES-CS coil structure advanced fabrication approach", L. M. Waganer et al. and ARIES Team

In-site Construction proposed. Self-construction

Proper design of the stellarator core and auxiliary systems for In-site Self-construction by the same systems

Self-construction ↔

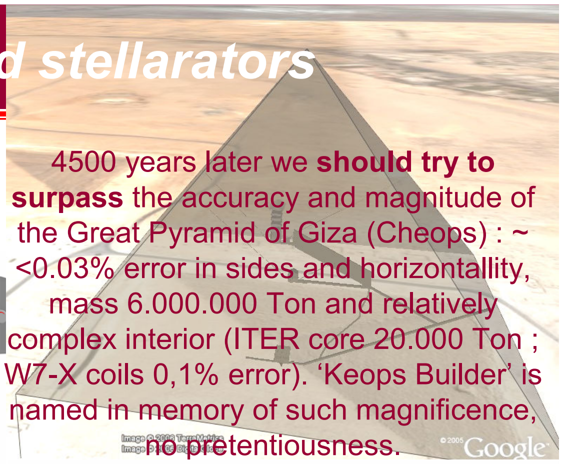
►The design of the exp. device/reactor must be properly designed to be mostly built by the components/systems needed in the fusion facility.

Such components/systems i.e could be :
- Remote Handling System cranes/manipulators used initially as 3D printers/building robots.
- External VV used as isolation or mould box for the device/reactor.
- Vacuum System used for pure atmosphere~vacuum deposition~SC
- 'Winding Device' used for first winding and also for re-winding and for maintenance tasks (~ LHD winding device).
- Heating Systems used for ceramics and metal processing.
- Other. As much as possible.

● Integration and a construction order has to be defined.

Results up to now

Selected a method to build stellarators

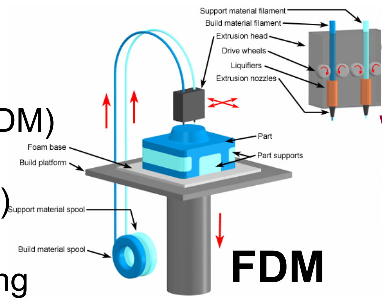


4500 years later we **should try to surpass** the accuracy and magnitude of the Great Pyramid of Giza (Cheops) : ~ <0.03% error in sides and horizontallity, mass 6.000.000 Ton and relatively complex interior (ITER core 20.000 Ton ; W7-X coils 0,1% error). 'Keops Builder' is named in memory of such magnificence,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

'Keops Builder'

Main **rapid prototyping methods** are :

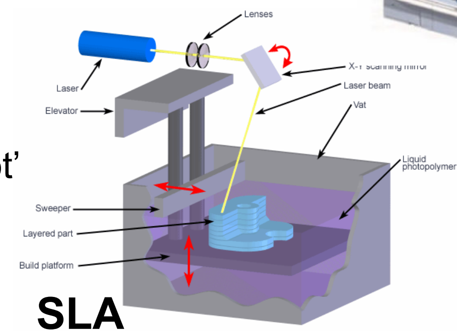
- Fused Deposition Modeling (FDM)
- Stereolithography (SLA)
- Selective Laser Sintering (SLS)
- 'Ink'-Jet 3D Printing
- Laminated Object Manufacturing (LOM)



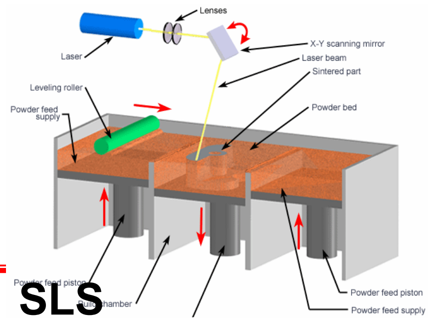
FDM

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

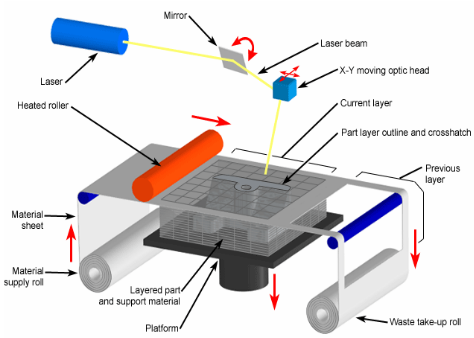


SLS

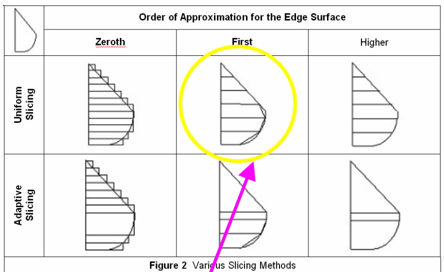
Results up to now

Selected a method to build stellarators

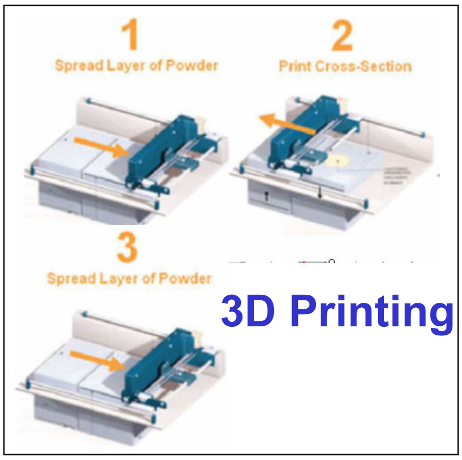
'Keops Builder' will likely be a modified LOM (Laminated Object Manufacturing) method to make moulds



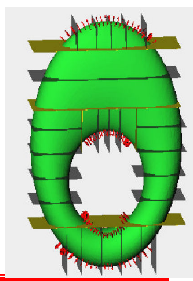
Traditional LOM method



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



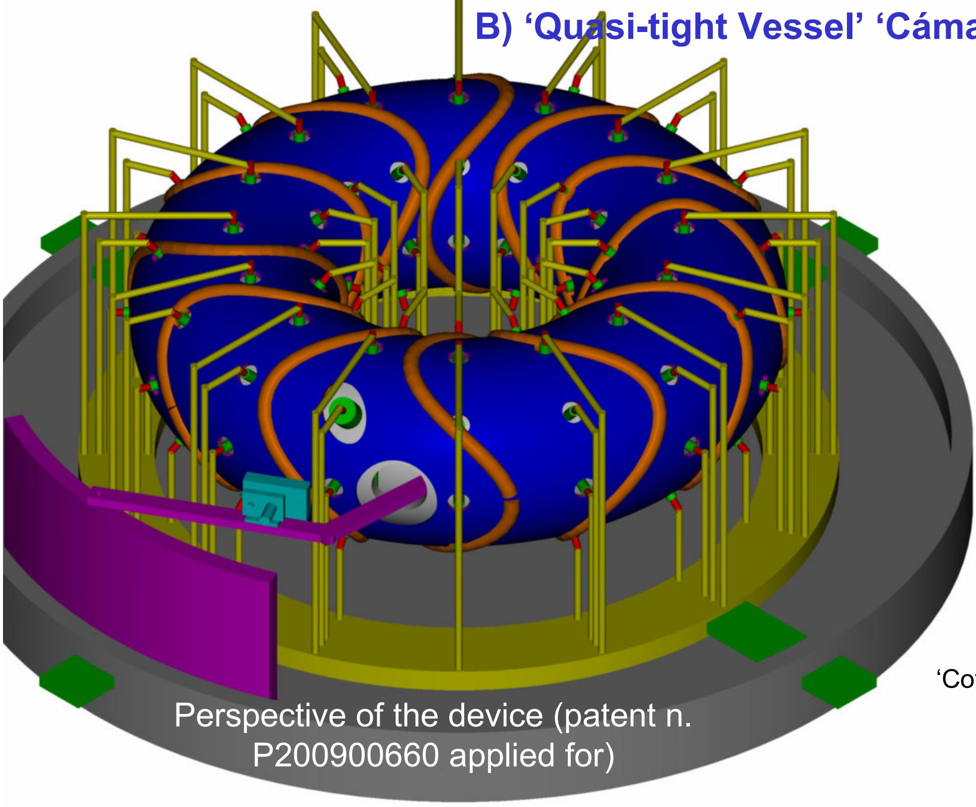
▼**Thick LOM** method, Delft University of Technology, The Netherlands



- 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**… fiber reinforced or, metal (Sn-Pb, Aluminium, Brass…) if vacuum cover fails.

Concept of a stellarator core

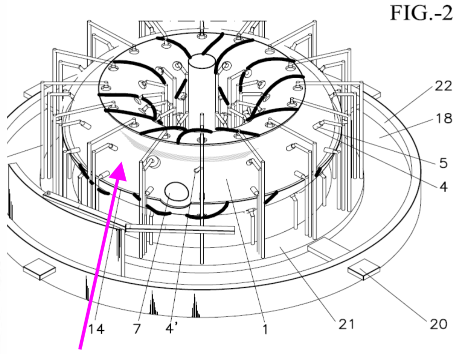
A) 'Covered Vessel' 'Cámara Recubierta' outside the Coil Frame
B) 'Quasi-tight Vessel' 'Cámara Casi Hermética'

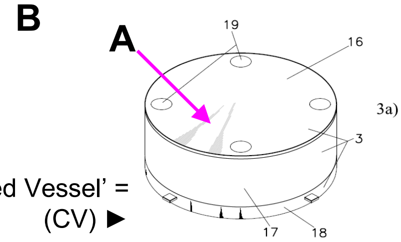


Perspective of the device (patent n. P200900660 applied for)

▼ Cut of the Coil Frame and the 'Quasi-tight Vessel'

FIG.-2

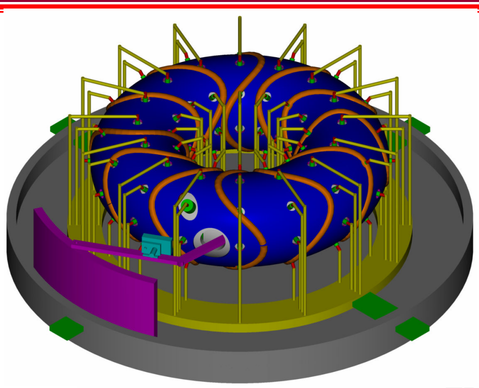


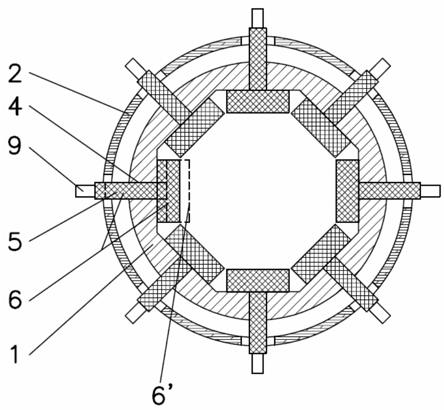


'Covered Vessel' = (CV) ▶

Concept of a stellarator core

(First, preliminary)
DEMO proposal in the path of low cost and high availability **stellerators**





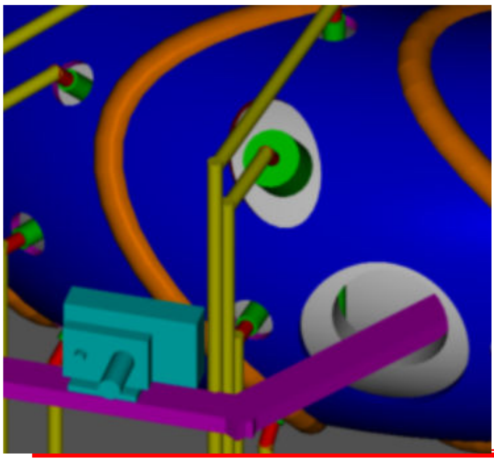
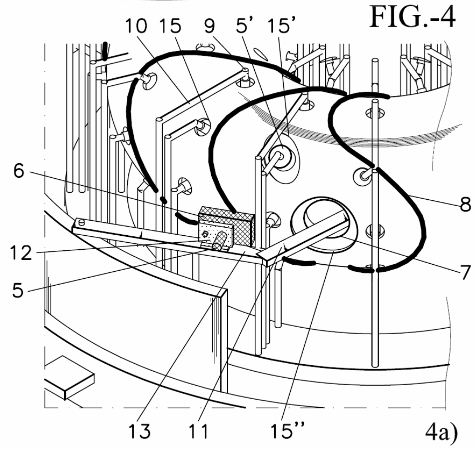
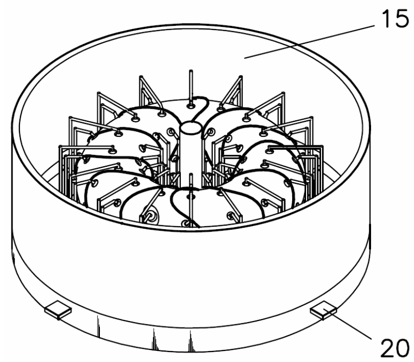


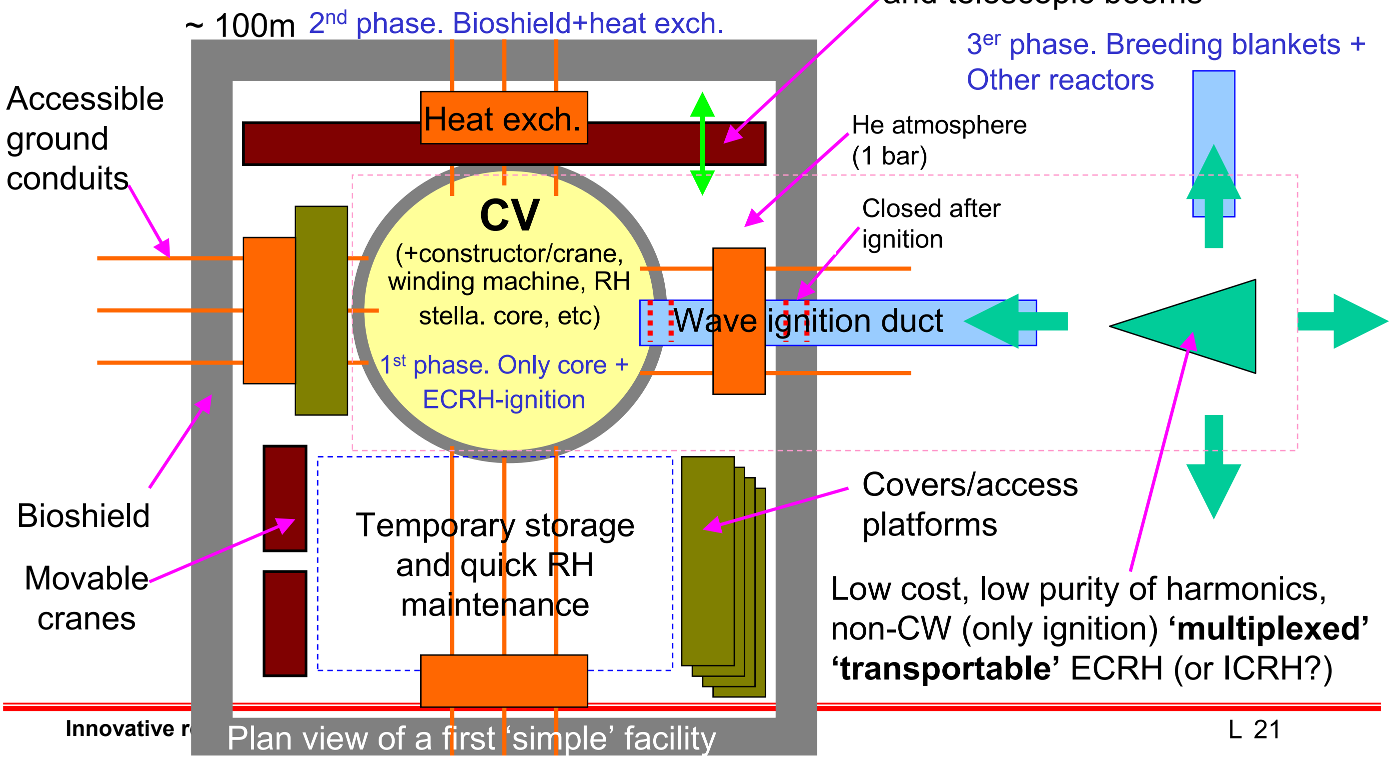
FIG.-4





Concept of a 'low cost' power plant

Concepts and strategy (phases) for a <u>first</u> low cost plant → validation by scaling



Superconductor option studied for UST_2

Cost of SC wire and cryosystem has been estimated/calculated

Estimated SC and cryo system costs for modular stellarators of size ~UST_1 at **different cryogenic temperatures** and **SC material**.

- For Bo =~ 0.2T cost is :

Type	**Cryo T (K)**	**Cost SC (€)**	**Cost of surplus cryo (€)**	**Comment**	**Pre-selected**
MgB2	20	700	~ 2000	Balanced, ↓cost	MgB2
Bi-2223	60	17000↑	~ 700	Expensive	
YBCO	64	7000↑	~ 300	Difficult~tape	
NbTi	4	~100	~ 17000	Unbalanced	

- If size UST_2 = 2 x UST_1 & B~0.4T & MgB2 → 7000€ SC + 7000€ cryo
- **MgB2** is adequate for low B (~1-2T at wire) and medium cryo T. **Balance is achieved**

Results up to now

Superconductor option studied for UST_2

Rough estimations about the cryosystem have been obtained

Decision about superconductor type **not taken yet** because :

- Cryo-tests not yet performed : Cryocooler<>dewar, He~Ne~N2, isolation cost & methods, 2nd hand availability, safety, etc. ↑ range of costs ~100€ (LN dewar) to ~100.000€ (new cryocooler for 4K and some W).
- **Samples** of MgB2 asked for. Expected short term reception.
- Small compact stellarators have **space constrains** for the SC windings → Bo low (~ 0.2T / 1T ~ Cryo temperature).
- Small modular coils 'cannot' be **wound** using YBCO/Bi2223 'commercial' **tapes.**
- Small stellarator → cryosystem cost is more relevant.
- All **factors are very interelated** : Aim 1, density of current~space~compactness, tape wire~torsatron/modular, objetive~cryo-focus…

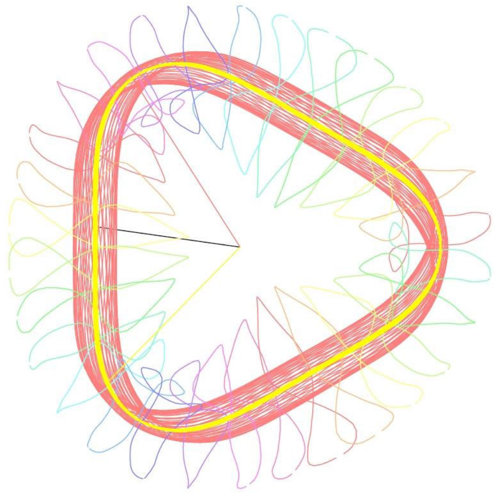
Results up to now

Modular coils obtained. Simulations

Definiton of 3 modular coil sets received

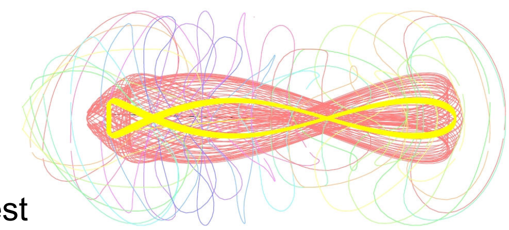
► Andreas **Werner** (IPP Max-Planck, Germany) supplied the definition of the coils of the **HSR Helias reactors** (HSR-3 and HSR-4).

- The definition of coils have been **imported** into the SimPIMF code and a **test** has been carried out for the HSR-3 model ~**scaling 1/64**



► F. **Najmabadi** and L. **Ku,** (ARIES Team, USA) supplied the **NCSX coils**.

- Not yet imported into SimPIMF



Basic simulation to test the HSR-3 model

Results up to now

Other concepts preliminarily devised

Apart from the concepts shown previously (VV outside coils, Keops Builder, in-site construction, etc) :

- Desing of **Coil Frames** for easy winding, unwinding, re-winding of SC coils

- **Methods for winding/removal** such coils in-site (~ LHD and new ones)

- **Remote Handling** systems

Future work

Steps :

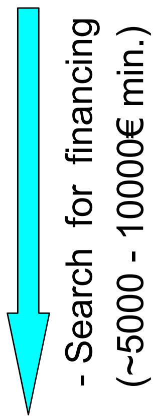
1st

- Carry out **initial tests of feasibility** of the innovative concepts *(mainly Keops Builder).*
- Carry out initial tests of **cryogenic systems.**
- **Integrate** and then improve the conceptual designs.
- Detailed design.
- **Construction and enhancement of the *Keops Builder* (*KeB*)**.

2nd

- **Build** one or several stellarators by means of the ***KeB.***
- **Enhancement** of all the systems.

In parallel :



Non-technical proposals

► **Bonus for the first electricity produced by fusion.** Propose to **governments and companies** :

- A payment of about **10 times the market price** of electricity for the electricity produced from a first reactor.
- A payment of about **3 times the market price** times for the 2nd and 3rd fusion power plants (or more plants, ~ country size)

► Right of **property of the patents** in the **fusion** field lasting more than 20 years (30, 40? years), **shared** between participants in the developments.

► **Plan of construction of a series of low cost stellarators** to produce a kind of **natural selection and competition** between different **constructive methods**, following a simultaneous **Serial & Parallel** study/test/construction at different sizes : ~UST_2 (x 4) → ~TJ-II (x 4) → ~W7-X (x 4) → ~reactor

Conclusions

- The presentation has tried to briefly shown the **present status** of the **UST_2 development** and the **related reactor studies.**

- The UST_2 'construction' and reactor studies are **advancing at slow but firm pace.**

- Concepts are presented to **CIEMAT, companies, other institutions, etc,** in case any **concept** might seem **fundable** or **interesting** to such institutions**.**

- The current work is presented also to show that my **personal interest** in this line of R&D&i still **continues**.

End

Thanks