PILOT HYBRID EXPERIMENT WITH REVERSED FIELD PINCH AS NEUTRON SOURCE AND DOUBLE TEST BEDS: AN INNOVATIVE STAGE APPROACH TOWARDS A FULL POWER FUSION-FISSION HYBRID REACTOR

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The research performed by the listed Institutions on this fusion-fission hybrid reactor is at the level of conceptual studies; in this context no experimental activities related to the nuclear fuel cycle are performed or planned in the near future.

Fusion-Fission Hybrid Reactors

Why fusion – fission hybrids?

- **Burning nuclear waste**, mainly minor actinides (and in some Countries also plutonium) produced by fission reactors (main interest on the development of hybrid reactors)
- **Fissile fuel production** for pure fission burner by neutron capture in fertile material (U_{238}, Th_{232})
- **Power generation** induced by fusion neutrons in some fissile fuel with limited actinides production (if a 14.1 MeV neutron induces a single fission reaction of 200 MeV, the fusion energy is amplified by fission by a factor more than 10)

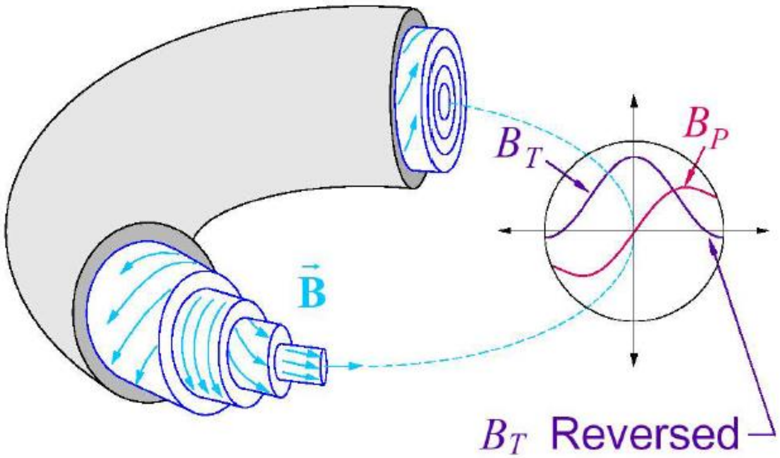
Main advantages

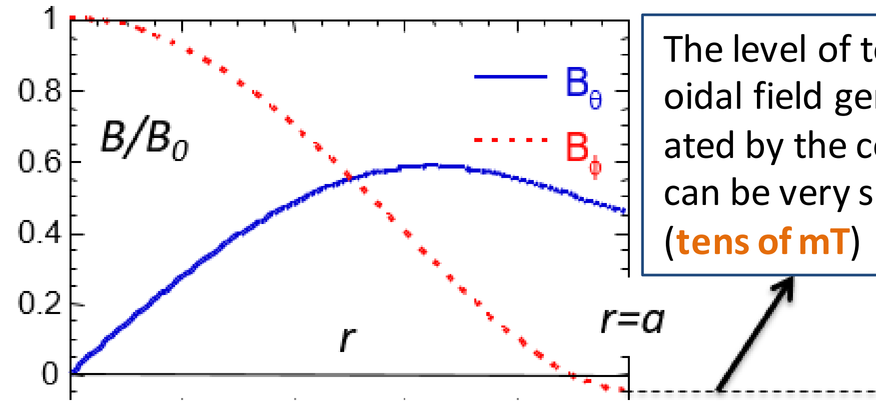
- **Fission: sub-critical** operation (possible operation with high grade of minor actinides)
- **Fusion: limited Q** (power gain), in the order of 1-5 much less than for a pure fusion reactor (less stringent requirements on nuclear materials, power exhaust, …)

Outline

1. Introduction to the Reversed Field Pinch (RFP) configuration
2. Conceptual scheme of a hybrid reactor with a RFP as the fusion core: pro and cons
3. Pilot (reduced power) hybrid reactor with the RFP as neutron source: the proposal of an innovative three staged approach
4. The RFP pilot fusion core: feasibility design, layout and main data
5. The fission test beds: preliminary studies
6. Conclusions

The RFP configuration: distinctive features





The level of tor-oidal field gener-ated by the coils can be very small (**tens of mT**)

- **No** intrinsic **limit** on **plasma current**
  - ⇒ **high ohmic heating** due to the slow helical winding of current lines; **burning regime** can be achieved by **ohmic heating** only, without additional heating systems
- **Self generated** internal **toroidal magnetic field** by dynamo mechanism
  - ⇒ **low value** of the reversed field at the edge generated by toroidal coils; in a reactor copper coils at room temperature can be used (**no superconductor**).
- Configuration **not prone to disruptions** because of the magnetic self-organization
- A **divertor** might **not be necessary**

The RFX-mod experiment

SIZE:

a = 0.46 m, R = 2 m

PHYSICAL PARAMETERS:

$I_p \leq 2$ MA

$B_t(0) = 1.9$ T

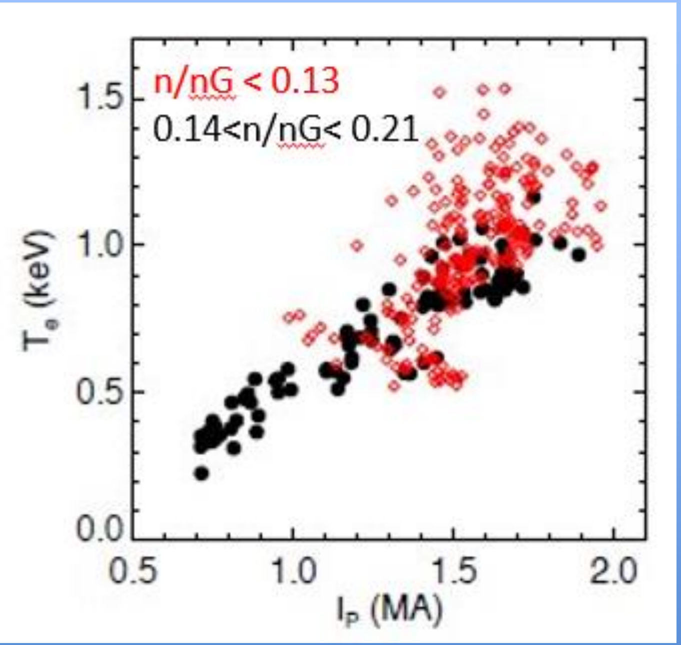
$B_t(a) = -20$ mT

$T_e \leq 1.5$ keV

$n_e \approx 10^{19} - 10^{20}$ m^{-3}

FEATURES:

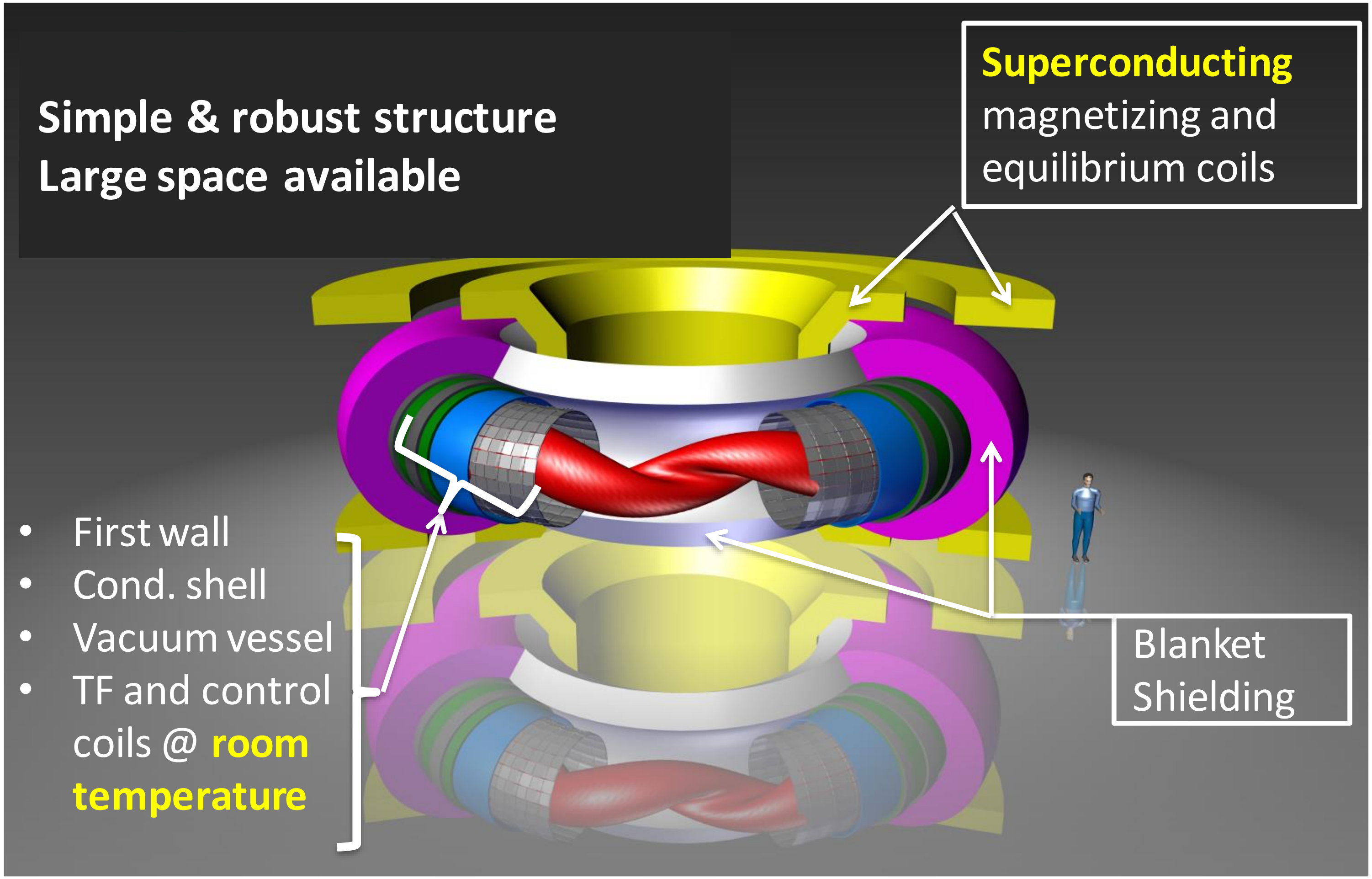
- Copper conducting shell to limit MHD modes
- Saddle coil system for MHD modes control and local PWI reduction
- Pulsed inductive plasma operation



$$T_e \propto j^{1.1}$$

Purely ohmic heating

Conceptual scheme of a RFP hybrid reactor



Simple, robust and low investment machine

Simple construction:

- **No** additional **heating systems**
- Copper (or copper alloy) toroidal field coils at **room temperature** designed for low magnetic field
- Neutron wall loading handled with the **current technology**
- Superconducting magnetizing/ equilibrium coils with **large space** available
- Blanket **outside** the toroidal field coils

Further advantages:

- Only ohmic heating with near **unitary efficiency** to reach fusion condition
- High machine **accessibility**
- **Large space** for the blanket & shielding

Reduced investment:

- Limited use of **superconductors**
- No additional **heating**
- No **divertor** (to be verified)

Main RFP issues towards the fusion reactor

Main Physics Issues and Open Points

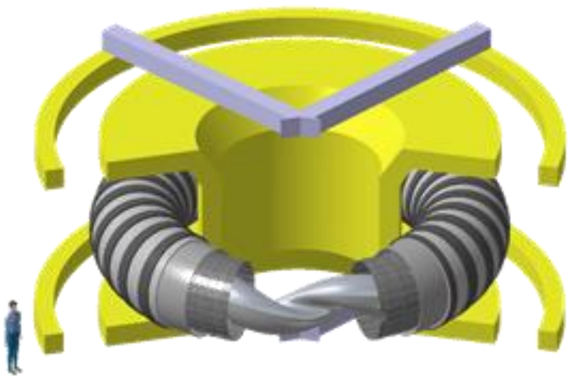
- **Scaling laws** of confinement time, loop voltage, MHD modes dynamics vs. a larger machine and increased plasma current
- **Evolution of the magnetic reconnections and MHD activity** with increased plasma current, temperature, density, Lundquist number, etc. and its impact on power balance
- **Fast ion confinement** and non collisional ion heating
- SOL and **plasma-wall interaction** with increased plasma current, density and reduced modes amplitudes. **Potential of radiative layers**
- **Transport driving mechanisms** and diffusion/dynamics of plasma **impurities** with increased dimension, plasma current, density and temperature

Main Technological issues

- RFP plasma **fueling**
- **Efficient inductive operation** without additional current drive
- Thermal load spread on the first wall and **power exhaust**
- **Impurities and Helium exhaust**

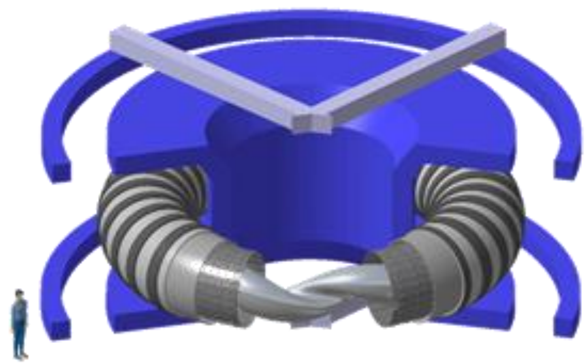
Staged approach of a pilot experiment (R=4, a=0.8)

1st phase: RFP plasma physics investigation



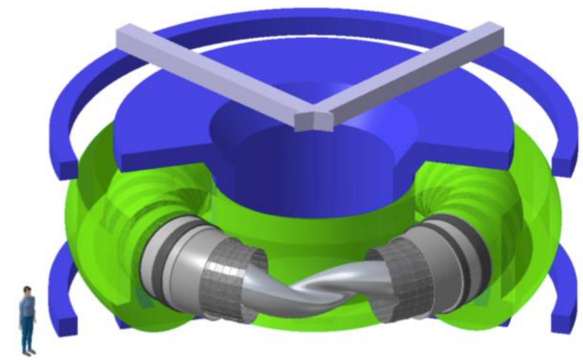
- Magnetization and equilibrium by copper coils @ room temp.
- Reduced volt-second and plasma current
- Double swing - Single pulse

2nd phase: Technological issues investigation



- Superconducting magnetizing/equilibri-um coils
- Plasma current up to full performances
- Double swing - Pulsed continuous operation

3rd phase: Operation of the pilot experiment with D-T



- The nuclear shield is added.
- Reduced size test beds for irradiation of fissile material and for possible tritium generation

Staged approach of a pilot experiment

Same basic machine, diagnostics and auxiliaries systems in all phases with successive modifications and improvements

→ (cost & time saving and machine optimization)

Phase 1 – Assessment of **physics issues** in a room temperature machine (basic plant systems)

Phase 2 – Assessment of **technological issues** with superconducting magnetizing and equilibrium coils (adding: superconducting coils, cryogenic system, quench protection, power supplies)

Phase 3 – Operation of a pilot **experiment with D-T** (adding: shielding, Tritium systems, test beds with fissile fuel)

The Pilot RFP machine performances*

The case study for the pilot: R = 4 m, a = 0.8 m

Plasma current [MA]	6	8	10	12	
Loop voltage [V]	8.0	6.6	5.7	5.1	⬇
Input (heating) power [MW]	48	53	57	61	≈
T_e [keV]	4.4	6	7.7	9.5	⬆
Fusion power with D-T [MW]	1.25	6.6	22.4	55	⬆⬆
$Q = P_{fus}/P_{inp}$	0.03	0.12	0.39	0.9	
14.1 MeV Neutrons [10^{18} s^{-1}]	0.4	2.4	7.8	19	
Neutron flux [10^{12} $cm^{-2}s^{-1}$]	0.4	1.9	6.2	15	

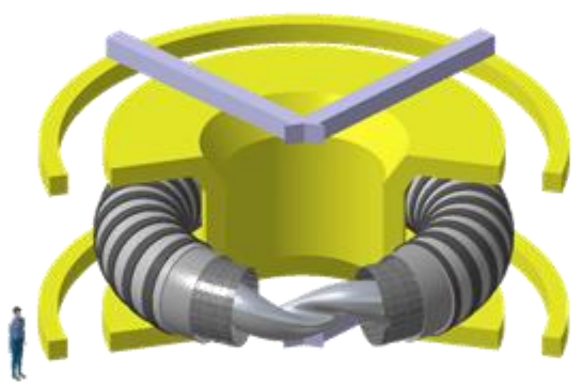
- Scaling from RFX-mod data and doubling of τ_E (expected in the new improved experiment);
- Plasma density $n/n_G = 0.3$;
- First wall thermal loading < 0.6 MW/m^2 with 12 MA plasma current for a wetted wall;
- Performances derived according to the scaling laws of RFX-mod:

$$T_e \propto j^{1.1} \quad \text{and} \quad V_{loop} \propto R\, a^{-0.35}\, I_p^{-0.65}$$

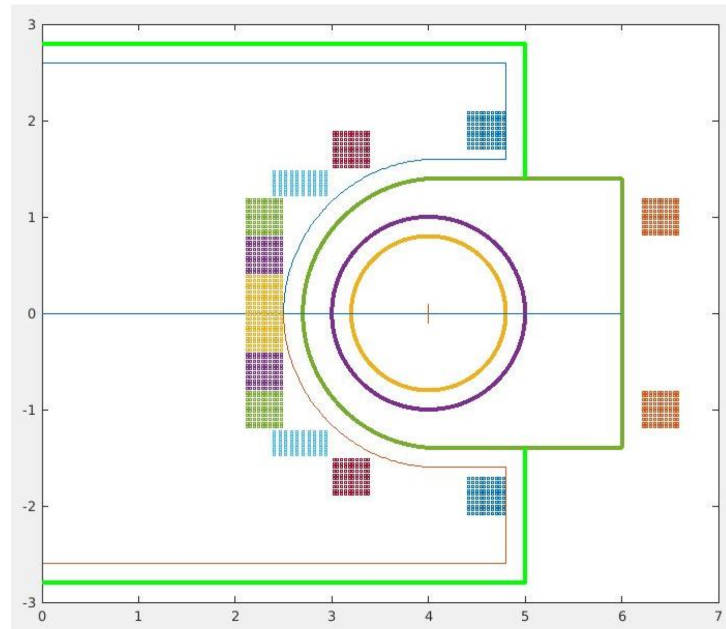
(see: R. Piovan et al. "A continuous pulsed Reversed Field Pinch core for an ohmically heated hybrid reactor", Fusion Engineering and Design 136 (2018) 1489-1493)

Phase 1 – Copper machine at room temp.

- Copper @ room temperature magnetizing/equilibrium coils
- First wall, conducting shell, vessel, TF and control coils (at room temperature) in the final configuration
  → no changes during the Phases 1, 2 and 3



R = 4 m, a = 0.8 m

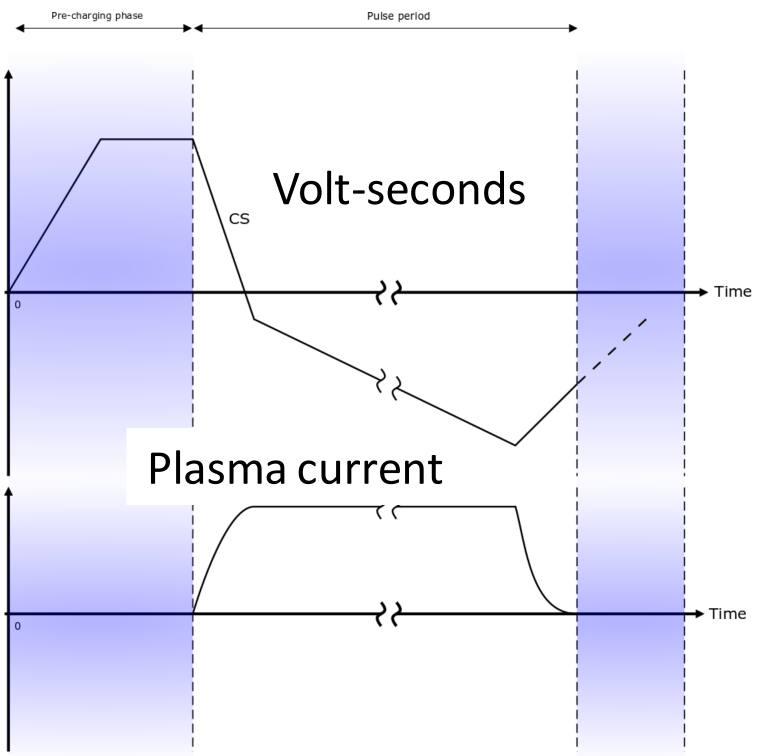


Total Amp-turns = 22 MAt
Magnetizing flux Φ_m = 77 Vs

(RFX-mod R=2m, a=0.46m: 10 MAt, Φ_m=15 Vs)

Phase 1 – Investigation of the physics issues

- Single pulse
- Double swing
- Total available volt-seconds: **155 Vs**



Plasma current [MA]	6	8
Loop voltage [V]	8	6.6
Flat-top [s]	7.5	3.9
T_e [keV]	4.4	6

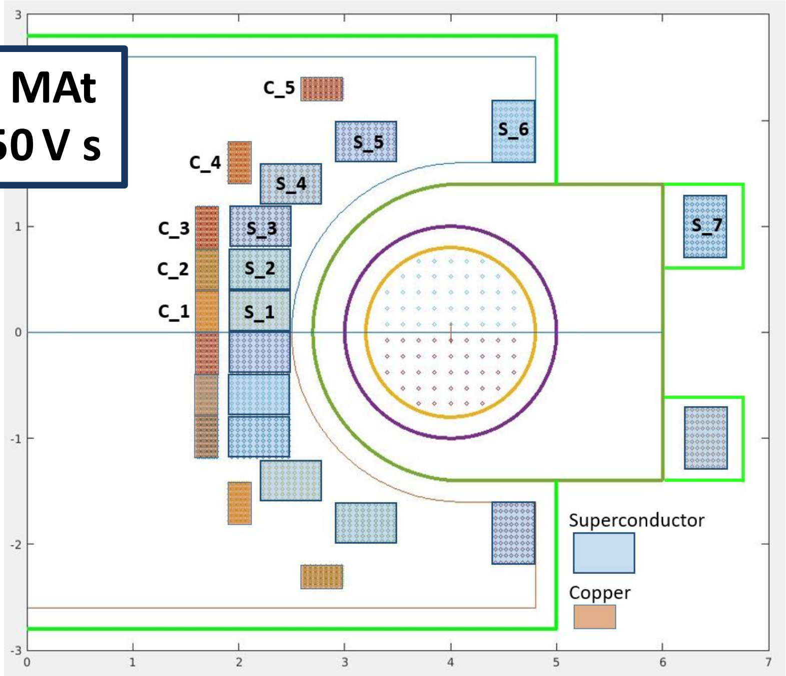
RFP physics issues

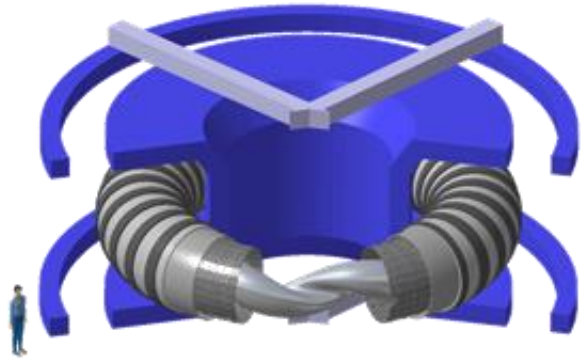
- **RFP scaling laws up to 8 MA**
- **Control of the MHD modes**
- **Impurity behaviour**
- **Reconnection dynamics**
- **Plasma physics nearly fusion condition**
- **Alpha particle confinement**
- **Plasma-wall interaction at high current**
- **...**

Phase 2 – Superconducting coils

- Superconducting magnetizing/equilibrium coils (**max 8.5 T**)
- Double system (copper/ superconducting) to limit dB/dt in superconductors
- Plasma current up to max performances
- Unchanged first wall, conducting shell, vessel, TF and control coils

I_M = 51 MAt
Φ_M = 150 V s





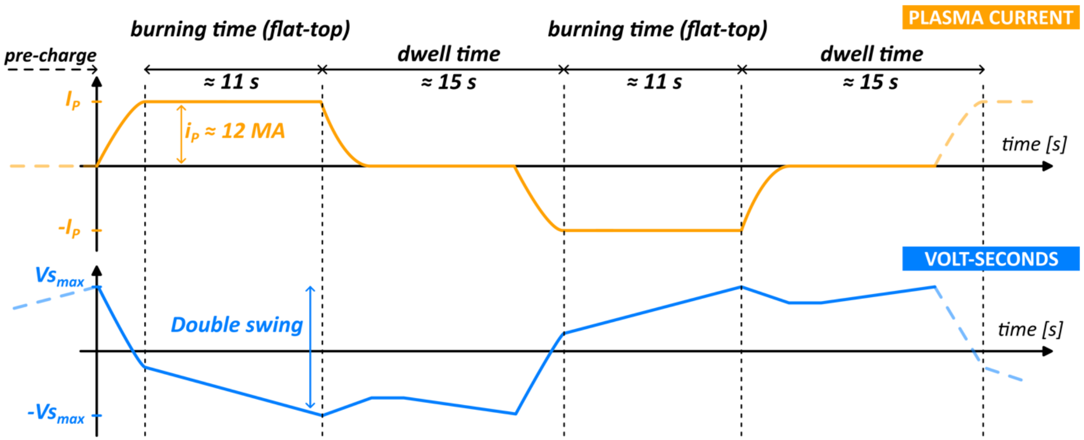
Full plasma performance with D operation

Plasma current [MA]	12
Loop voltage [V]	5.1
Flat-top [s]	11
T_e [keV]	9.5

Phase 2 – Investigation of the tech issues

Efficient operation at max plasma current without current drive

- Fast initial RFP plasma current rise (> than 10 MA/s)
- Reduced dwell time (< 15 s)
- Plasma current reverses alternatively



Technological issues

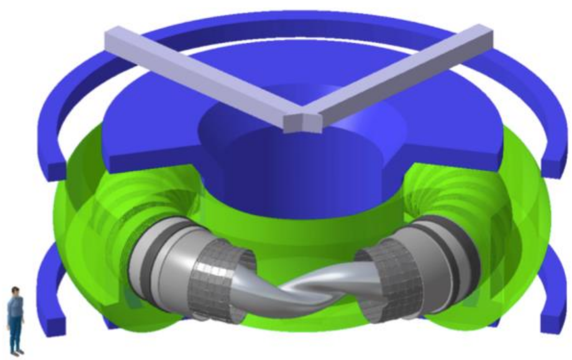
- Pumping and re-fueling during operation and dwell time
- Impurities exhaust
- Superconductor ac losses
- Fatigue check

… and study of plasma physics at maximum plasma current

IAEA

Phase 3 – Operation with D-T

3rd phase:
Operation of the pilot experiment with D-T



- Nuclear plants and building
- Neutron shield
- Test beds for fissile materials and Lithium fertilization

14.1 MeV neutron production

Q ≈ 0.9

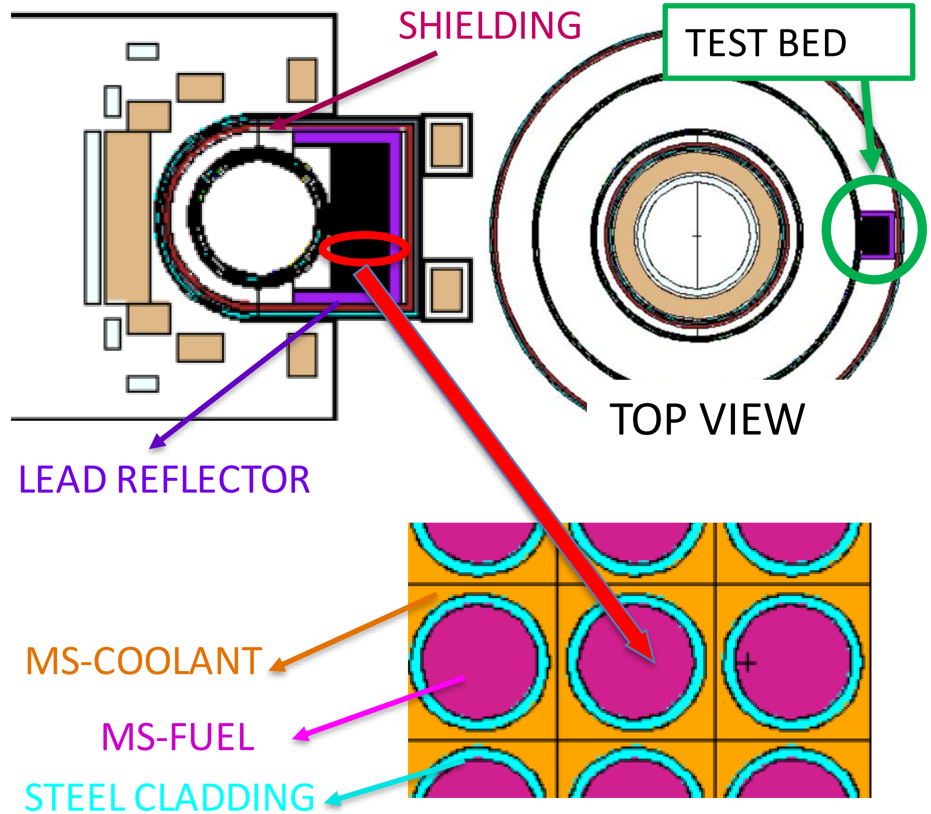
	9 MA	12 MA
FUSION POWER	12 MW	55 MW
Neutron production rate [10^{18} s^{-1}]	4.4	19
Neutron flux [10^{12} $cm^{-2}s^{-1}$]	3.6	15
Neutron wall loading [MW/m^2]	0.08	0.35
Thermal wall loading [MW/m^2] ($P_{ohm}+P_{\alpha}$)	0.46	0.57

Phase 3 – SSR as FFHR fission system

Stable Salt Reactor (SSR)

- Molten salt fuel, non-circulating, to replace solid pellets in conventional fuel assemblies.
- Closed pool type reactor (coolant fills the tank)
- Fast spectrum to burn actinides

Thermal Power Pick	≈ 40 MWth
Core Dimensions	81 cm x 109.8 cm
Reflector Thickness	30 cm
Fuel Rod Radius	1 cm
Cladding Thickness	0.2 cm
Rods mutual distance	2.7 cm
Active Height	197 cm

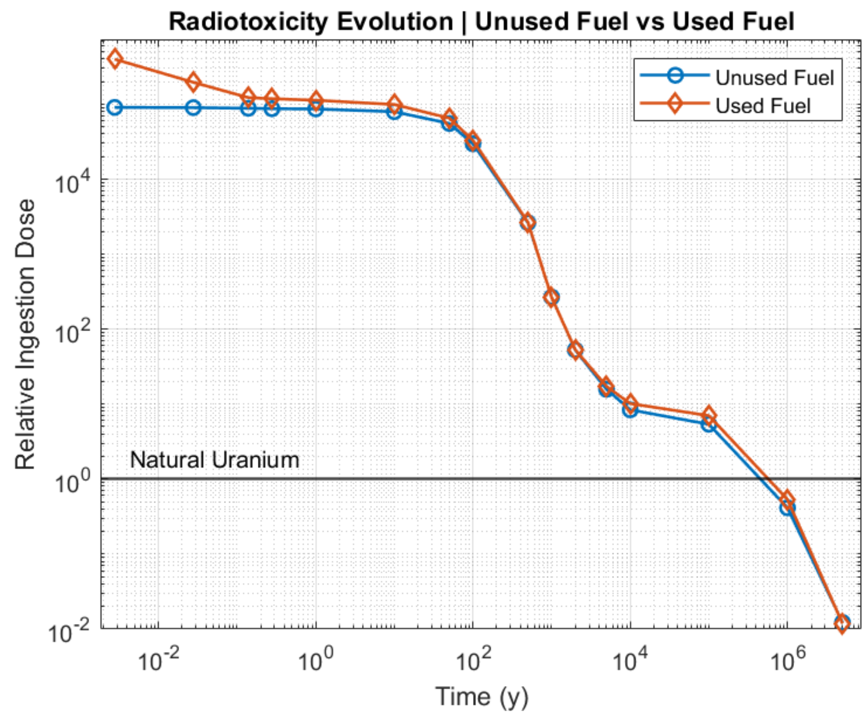


Fuel	UCl3 - PuCl3 - AnCl3 LnCl3 - KCl
Primary Coolant	ZrF4 - ZrF2 - NaF

Phase 3 – Dose Evolution Results

- The benchmark is the Radiotoxicity of Natural Uranium (here defined as Ingestion Dose)
- Little differences in Dose Evolution between the two cases of unused (new) fuel and used (final) fuel
- Good result since we could produce energy without a significant increase of disposal time

Neutron Flux (ϕ)	$\propto 10^{14} \frac{n}{cm^2 s}$
Nuc. Lib. MCNP6	ENDF/B VII.0
Nuc. Lib. FISPACT-II	TENDL 2017



Phase 3 – Future Studies

- Test beds design and layout optimization
- Which is the required flux condition (intensity and spectrum) for disposal time decrease?
- Investigation on heterogeneous configuration (actinide targets in the middle of the core)
- Design of Superconductors shielding
- Study on Tritium production

Conclusions (1)

- The conceptual study of a FFH reactor based on a RFP plasma configuration shows the **relative simplicity** and possible **good accessibility** of this solution.

- From **RFX-mod scaling**, preliminary studies show the possibility of reaching, with the **available basic technologies,** about **50 MW fusion power** and **15 10^{12} n/s/cm^2** of **14.1 MeV neutron**.

- **Continuous inductive pulsed operation** has been identified with the possibility of a high duty cycle in the FFHR.

- A **staged approach** for a pilot experiment is proposed in order to tackle the **physics (Stage 1) and technological (Stage 2) issues**. **D-T operation (Stage 3) at Q $\approx$ 1** allows the implementation of reduced test beds for irradiation of fissile materials and for Tritium production

Conclusions (2)

- In a full size FFHR a **fission blanket** based on a non-circulating molten salt fuel can produce energy without increasing the radiotoxicity in the long term; by modifying the fuel and blanket set up, it may also be possible to decrease the long term radiotoxicity, thereby returning to the natural uranium level in a shorter time scale

- **Results from RFX-mod2** (machine improvements in progress) **are crucial** in order to assess the viability of a RFP as fusion core in a hybrid reactor, contributing to assess the scaling laws and the MHD modes dynamics and their control.

Thank you

for

your attention