A Virtual Reactor Model for Inertial Fusion Energy

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OUTLINE

• Introduction
  – Fusion vs Fission
  – Inertial Confinement Fusion Principle
  – Reactor Concept

• Why a Virtual Reactor Model ?

• VXM: definition & theory

• HIPER VRM: Context Elements
Thermonuclear Energy

**Fission**

\[ ^{235}\text{U} \rightarrow ^{236}\text{U} \rightarrow ^{92}\text{Kr} \quad 90 \text{ GJ / g} \]

Long life radioactive waste !!

**Fusion**

\[ ^{1}\text{H} + ^{2}\text{H} \rightarrow ^{3}\text{H} + ^{4}\text{He} + 3.5 \text{ MeV} \]

\[ n + 14.1 \text{ MeV} \]

340 GJ / g
Thermonuclear Fusion

• Thermonuclear fusion of light elements
  – Easier reaction: \( D + T \rightarrow ^{4}\text{He} \ (3.5\text{MeV}) + \text{n} \ (14.1\text{MeV}) \)

• Lawson Criterion for a positive energy balance:

\[
\text{n (particle density) x } \tau \text{ (reaction duration) } \geq k
\]

\[
k = 10^{14} \text{ cm}^{-3} \text{ at } 200 \text{ MK}
\]

\( \rightarrow \) two options:
Thermonuclear Fusion

• **Magnetic Confinement Fusion**
  – Low density: \( n \approx 10^{14} \text{ cm}^{-3} \)
  – Nearly continuous process

  \[ \textit{Tokamaks} \Rightarrow \textit{ITER} \]

• **Inertial Confinement Fusion**
  – High density: \( n \approx 10^{26} \text{ cm}^{-3} \)
  – Short life time: \( \tau \approx q \cdot 10^{-11} \text{ s} \)
  – Repetition rate \( \approx 10 \text{ Hz} \)

  \[ \textit{High power pulsed laser} \Rightarrow \textit{HIPER} \]
What is **Inertial Confinement Fusion**?

**ICF principle**

- **DT Cryogenic shell**
  - \( \approx 1 \text{ mg} \)
- **Target irradiation by primary Energy source**
- **Plasma expansion drives the shell implosion (rocket effect)**
- **Central Hot spot Ignition**
- **Combustion**
Primary energy source for ICF

Ablation Pressure law (Mbar)

Primary Energy source

Intensity: $2.10^{13} - 2.10^{15}$ W/cm$^2$

Energy: 1 - 10 MJ.

Duration: ~ 10 ns
Energy source for ICF

• Only high power pulsed lasers can provide (today) the required performance.
  – Laser-matter interaction and implosion experiments have been widely studied since the sixteen’s

• Two large laser facilities are expected to demonstrate ICF (with a small thermonuclear gain) in the current decade: LMJ in France and NIF in USA.
ICF demonstration

Laser Megajoule (LMJ - PETAL)
Bordeaux - CESTA

National Ignition Facility (NIF)
Livermore - LLNL
Next step: HIPER
a reactor for Inertial Fusion Energy

• HIPER will be the European High Power Laser Energy Research facility

• Objectives:
  • “single build” demonstration power plant
  • Minimum infrastructure required to achieve fusion at a level capable of a significant energy surplus
  • Time required to plan, fund, design, construct and commission a pilot plant of this scale estimated at 20 – 30 years
Elements of an IFE Reactor
Energy loop of an IFE reactor

- Fusion: $G = 30 - 200$
- Blanket: $g = 1 - 1.2$
- Electric Conversion: $\varepsilon = 0.3 - 0.4$
- Driver: $\eta_D = 0.05 - 0.35$
- Auxiliary devices
- Recirculating Fraction: $f$

Electricity grid

Repetition rate ~ 10 Hz for 1 GW yield
IFE Reactor structure

- Target Fab. & Storage
- Materials handling & treatment
- Target Injection
- Reaction chamber
- Driver Energy bench
- Steam-turbine generator
- Building
Tritium loop in an IFE reactor

\[ ^6\text{Li} + n \rightarrow T + ^4\text{He} + 4.8 \text{ MeV} \]
\[ ^7\text{Li} + n + 2.5 \text{ MeV} \rightarrow T + ^4\text{He} + n' \]

T breeding ratio $\sim 1.15$
Why a Virtual Reactor Model?

Two loops are obvious

However...
Why a Virtual Reactor Model?

Materials supply

- Target fab & storage
- Tritium reprocessing
- Materials Handling & Treatment

Reactors

- Target injection
- Building
- Chamber
- Heat exchanger & steam turbine generator

- Laser
- Energy Banc & Auxiliary devices

Grid

Color codes:
- Green: Materials
- Blue: Synchronism
- Orange: Alignment
- Red: Energy
Developing a VRM: Why?

• In order to validate VIRTUALLY the concept and to develop the design (R&D)
• To go « one shot » towards the demonstration powerplant (Engineering Development)
Definition

The Virtual-X is a mean to simulate X assembly (physical design) and X operations (functional design) of the “to-be” X before its actual integration in order deliver at TRLX a “competitive”, “OK for operations & services”, “OK for certification” and “OK for production” definition file.
VXM : the theory

Operational & Functional Analysis

- Identification, organization and characterization of operations and functions
- Production of supporting models (trees, scenarios...)
- Derive “system” requirements

Model Based System Engineering

- Formal modeling of the operations and functions (scenarios, flow...)
- Formal modeling of the functional and physical architecture
- Derive “technical” requirements
- Modeling of specifications

Initial specification from acquirer

Trace to

Acquirer requirements

Drive

Other requirements from internal & external sources

Trace to

Other stakeholder requirements

Assigned to

System technical requirements

Derived technical requirements

Logical solution representations

Drive

Physical solution representations

Design solution

Specified requirements

Figure 1 – Mapping of bundle activities on EIA 632 building block design process
Virtual-X: major concepts (theory)

- **Induced Tasks – Identify/Establish:**
  - Functionnall Architecture
  - X End-to-End Numerical Process (workflow analysis with input/output data)
  - Virtual Testing Generic process
  - Virtual Labs Developments (for each sub-system)
  - CCL: CAD-CAE links (tools + management)
  - Back-bone unified middleware for managing simulation data, hierarchical models (from analytics to numerical multiscale and multiphysics models) and results (SLM tool)
HIPER VRM: Some Context Elements (Practice)

- A « very complex » system
  - Major Sub-systems decomposition – Coupling loops identification
  - European – Multi-teams Collaborative Project

- Code Packages :
  - Under development for each sub-system with different maturity levels

- Process :
  - Simulation-Based Design Decisions
  - Numerical Design associated to experimental programs

- Constraints/Difficulties :
  - Multi-purpose:
    - Simulation-Based Global Performance Demonstration
    - Used for virtual tests (scientific tool)
    - Flexibility towards scientific codes developments and improvements
    - V&V and robustness

...
HIPER VRM in practice

• Exhaustive Functional Analysis
• Set of nominal processes and critical events to be simulated
• Examples of processes to be simulated:
  – Ignition/Combustion Process
  – Target Engagement
  – Neutron energy deposition and Heat Exchange