Some highlights of experimental ADS programs in Europe

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GUINEVERE collaboration

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SCK•CEN, Belgium **CNRS/IN2P3, France** **CEA/DEN, France**

1st International Workshop on Accelerator-Driven Sub-Critical Systems & Thorium Utilization, Sep 27-29 2010, Virginia Tech

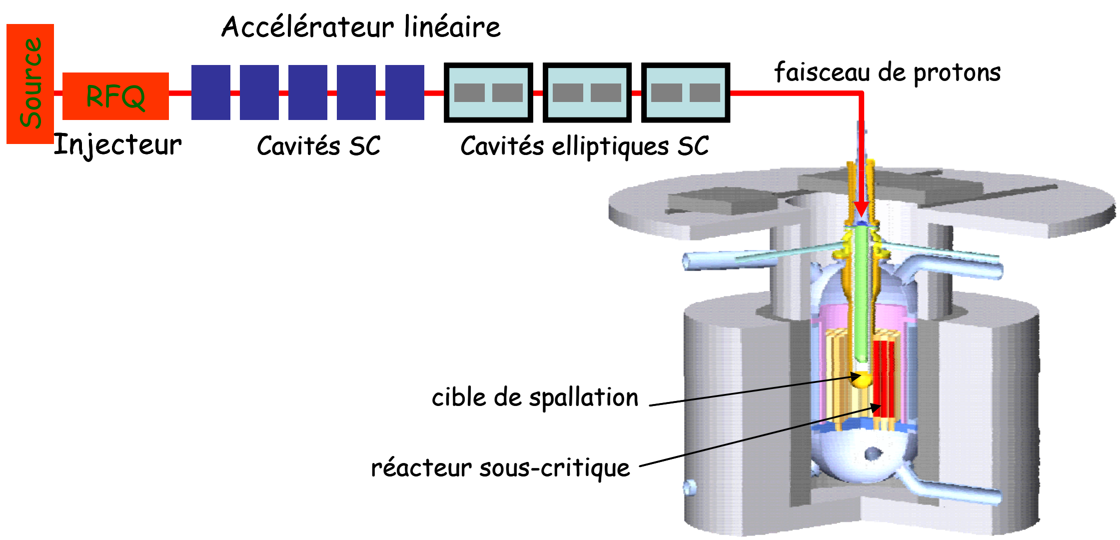
Overview

- Introduction to ADS
- MUSE experimental program
  - MUSE-4
- GUINEVERE project
  - motivations, objectives
  - civil engineering
  - reactor : design & construction
  - accelerator : design & construction
  - accelerator commissioning
  - outlook
- MYRRHA project
  - overview

Not a overview on European programs! Much more than the scope of this talk

ADS concept

- ADS: Accelerator Driven System
- Sub-critical reactor ➔ external neutron source to maintain the chain reaction



- Reactor driven by the source via the accelerator beam
- Allow a fuel with large amounts of minor actinides (impossible in critical reactors because of the small fraction of delayed neutrons)

First experimental ADS programs

- Mid 90's: FEAT and TARC experiments (renewal of ADS concept)
  Fast Energy Amplifier Test, C.Rubbia et al. (CERN, 1995)
  Transmutation by Adiabatic Resonance Crossing, C.Rubbia et al. (CERN, 1996)

  ➔ Validate ADS concepts with spallation targets (high energy p on Pb and U)

  - energy amplification
  - transmutation

  [Andriamonje et al. PLB 398(1995)697, Arnould et al. CERN-SL-99-036 EET (1999)]

- End of 90's : researches structure around key points of ADS aiming at a feasibility demonstration ➔ EURATOM FP5

  ➔ R&D on related technologies

  ➔ Mock-up experiments for physics modeling and simulation validation

  - Neutron source and sub-critical core coupling
  - Spallation target
  - Nuclear Data
  - Fuel
  - Design

Main issues in ADS reactor physics

- Modeling/simulation code validation
  - Models and codes designed mainly for critical thermal reactors
  - No predictive models for fast sub-critical reactors
  - Codes need for validation/performance evaluation
- Monitoring of k_{eff} or reactivity, ρ (safety issue)
  - To guaranty a criticality margin allowing the power control of the reactor through the simple law:

$$P_{th}(t) = C\frac{I(t)}{\rho(t)}$$

safety criterium :

$-5000 \text{ pcm} < \rho < -3000 \text{ pcm}$

➔ Need for absolute reactivity online monitoring during reactor operation (with no reference to a critical state)

➔ Mock-up experiments

Genesis of MUSE experiment

- CEA/DEN (Cadarache) and CNRS collaboration , mid 90's
  - ➔ Study of a coupled system without any power and thermal effects
  - ➔ Separate the neutron source issue from the sub-critical core physics: use of a well known neutron source

➔ Experimental program "MUltiplication d'une Source Externe" aka MUSE with MASURCA reactor

- 1996 : MUSE-2 experiment used a simple Cf source
- 1998 : MUSE-3 experiment used a Genie 26 neutron generator by SODERN (F)
- This pulsed generator revealed several aspects detrimental to kinetics data:

  long pulse, long falling time, bad repeatability, too much H in MASURCA

➔ Need for a cleaner neutron generator

Experimental setup for MUSE-4

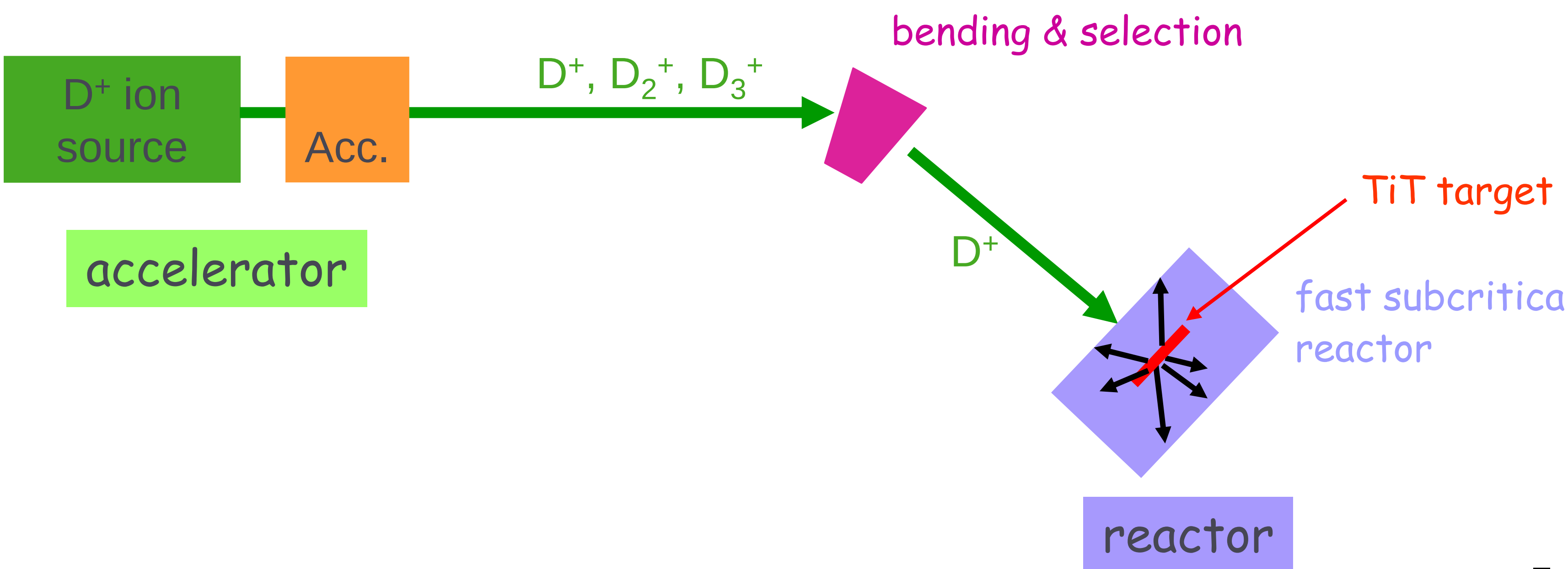
- Neutron production via deuteron irradiation of Tritium or Deuterium targets

  d + T -> n (14 MeV) + α

  d + D -> n (2.6 MeV) + He_3

- Electrostatic deuteron accelerator GENEPI-1

- GENEPI-1 developped by Laboratoire de Physique Subatomique et de Cosmologie (LPSC, former ISN), Grenoble, from CNRS/IN2P3

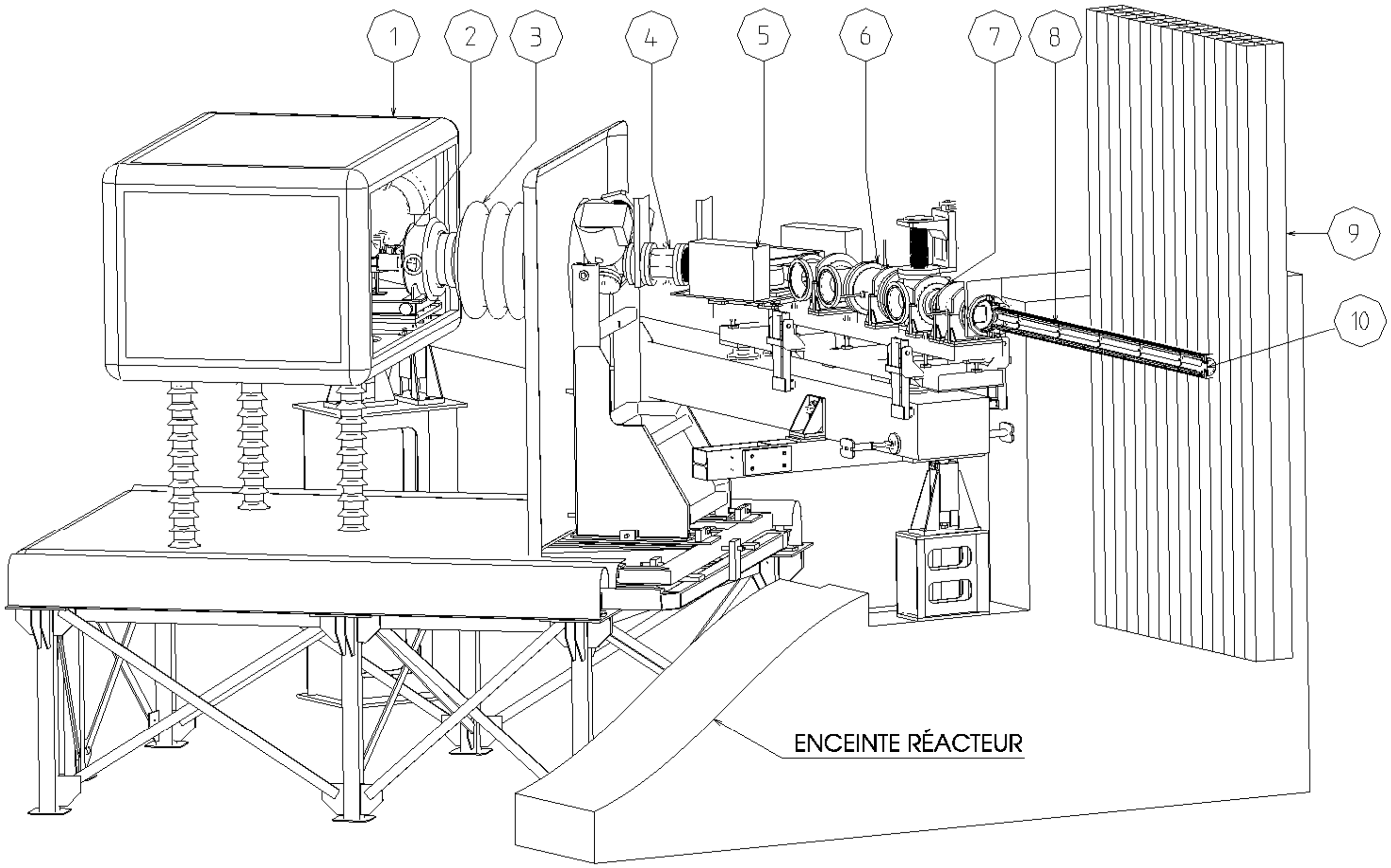


MUSE-4 : GENEPI-1 at MASURCA

- Accelerator requirements for reactor studies
  - short pulse, sharp falling time
  - high current peak intensity, wide source frequency range
  - no hydrogen inside the reactor core
  - geometrical constraints : limited space around MASURCA

- Many safety requirements
  - fire protection, earthquake protection
  - rules for coupled operation accelerator and MASURCA : reactor doubling time against accelerator fast frequency variation
  - neutron irradiation of equipement
  - tritium targets : T detection, glove box, air flowed suits for target handling

Design of the accelerator GENEPI-1

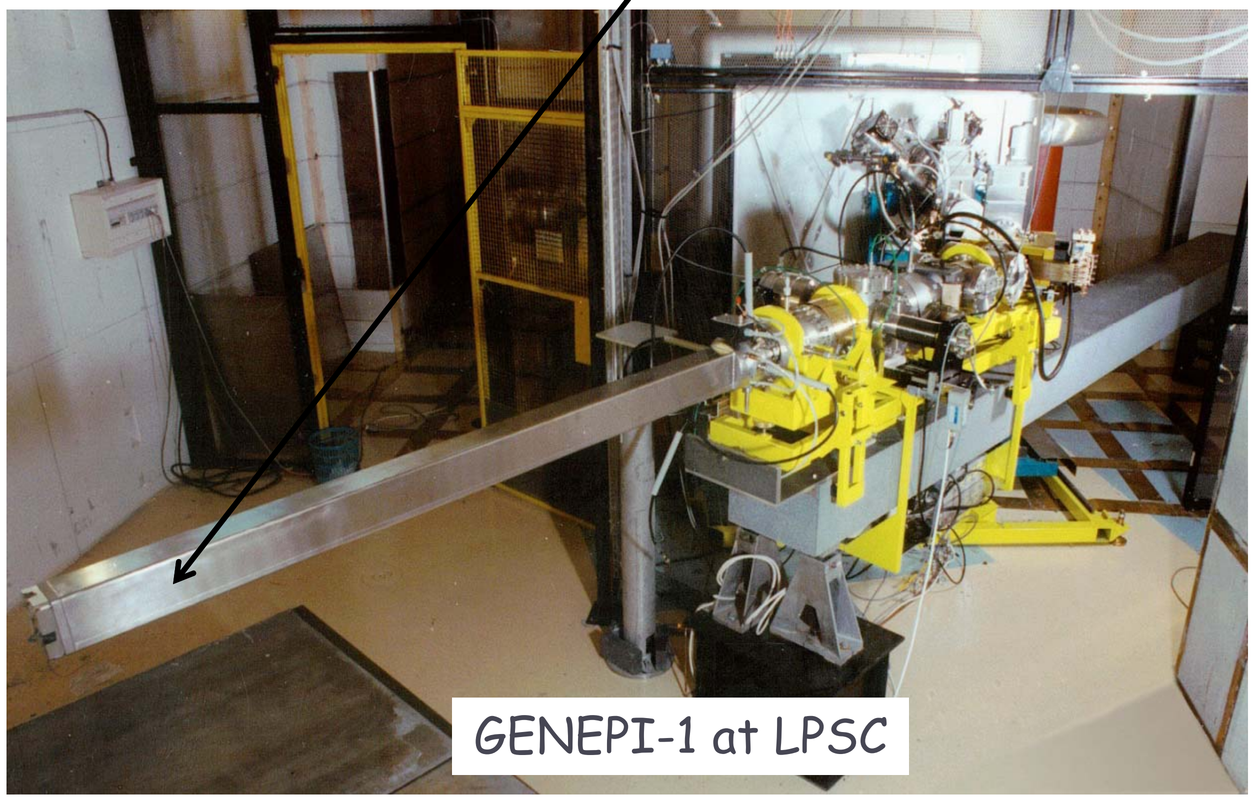


1. High voltage platform
2. Duoplasmatron source
3. Accelerator
4. Quadrupole Q1
5. 45° magnet
6. Quadrupole Q2
7. Quadrupole Q3
8. Thimble with 6 quadrupoles
9. MASURCA assemblies
10. Target

Pictures of GENEPI-1

Special assembly with a channel for GENEPI beam guide

Thimble



GENEPI- 1 at MASURCA: operation & results

- Key dates :
  - 1996-99 : design, construction and commissioning at LPSC
  - 2000 : installation in MASURCA
  - 2001 : first neutrons, safety tests
  - 2002 : first couplings in subcritical configuration on D then T
  - 2003-2004 : operation for experimental program
  - 2007 : end of dismantling

➔ Data on-line reactivity monitoring, limitations of MUSE-4

& recommendations for future experiments

[C.Destouches et al, NIM A 562 (2006), 601-609]

- European Collaboration (2000-2004) within FP5 under the “MUSE” acronym

European contract MUSE FIKW-CT-2000-00063

Motivations for GUINEVERE

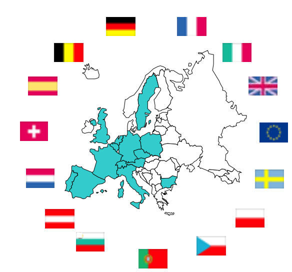
- Extend and complete the MUSE-experiments on sub-critical system reactivity monitoring
- Reactor mock-up with a zero-power core representative of a fast ADS to follow up investigations in support to the design of Fast Transmutation Experimental Facility (MASURCA reactor unavailable until 2013)
- Neutron source that can be operated in various modes:
  pulsed, continuous and interrupted
- Need for an easily available facility in Europe

Objectives of GUINEVERE

- SCK•CEN initiated in collaboration with CNRS and CEA, the project GUINEVERE (Generator of Uninterrupted Intense NEutron at the lead VEnus Reactor)

- Project proposed to EUROTRANS Integrated Project (FP6) partners in 2006 (accepted in December 2006)

- Dedicated to Experimental activities on the Coupling of an Accelerator, a Target and a Subcritical blanket (ECATS)
  - Qualification of sub-criticality level monitoring; Validation of the core power / beam current relationship,
  - Start-up and shut-down procedures, instrumentation validation and specific dedicated experimentation,
  - Interpretation and validation of experimental data, benchmarking and code validation activities etc.,
  - Safety and licensing issues of different component parts as well as that of the integrated system as a whole.



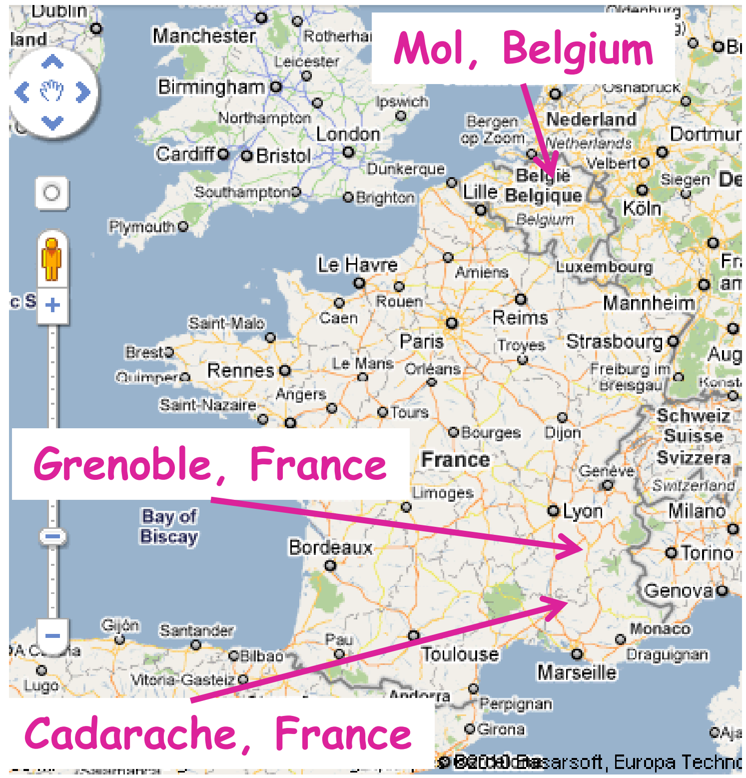
GUINEVERE : a collaborative work

- SCK•CEN is providing the VENUS facility, modifying it to get a Pb-based fast facility able to operate in both critical and sub-critical modes, and is taking the licensing responsibility

- CNRS/IN2P3 is in charge of the design and construction of the GENEPI-3C accelerator and of its installation at SCK Mol

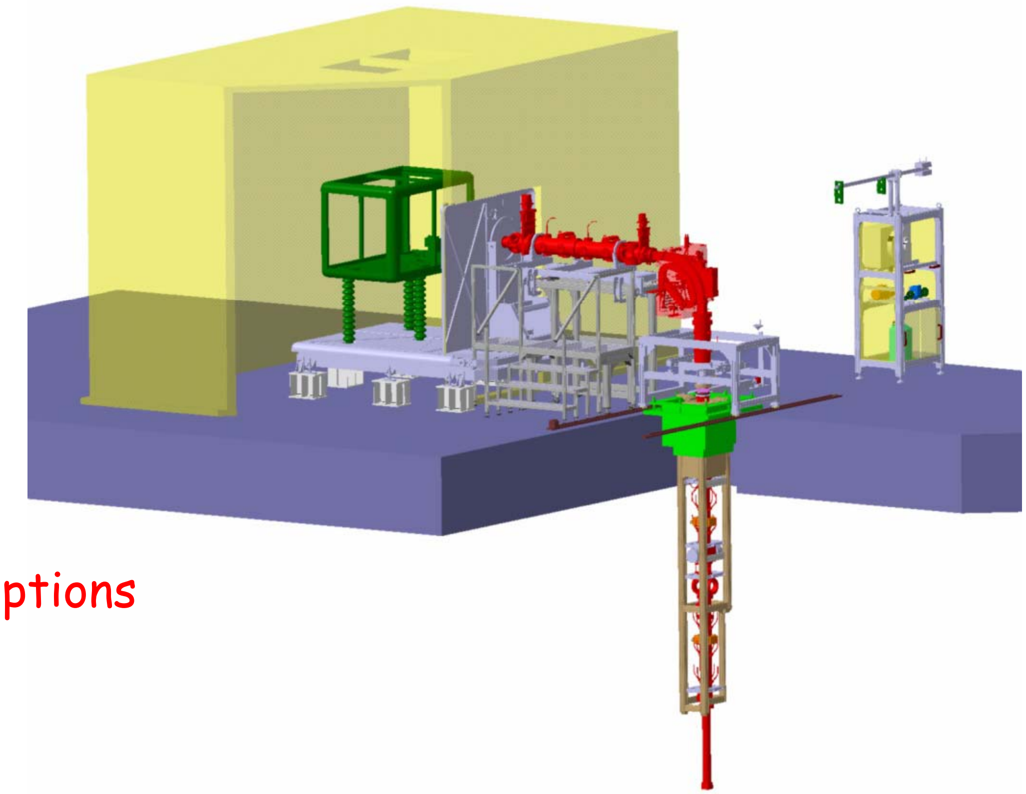
- CEA/DEN provides fuel and lead rodlets

- Partners of EUROTRANS-IP support the design and the licensing of the facility and the experimental program and analysis



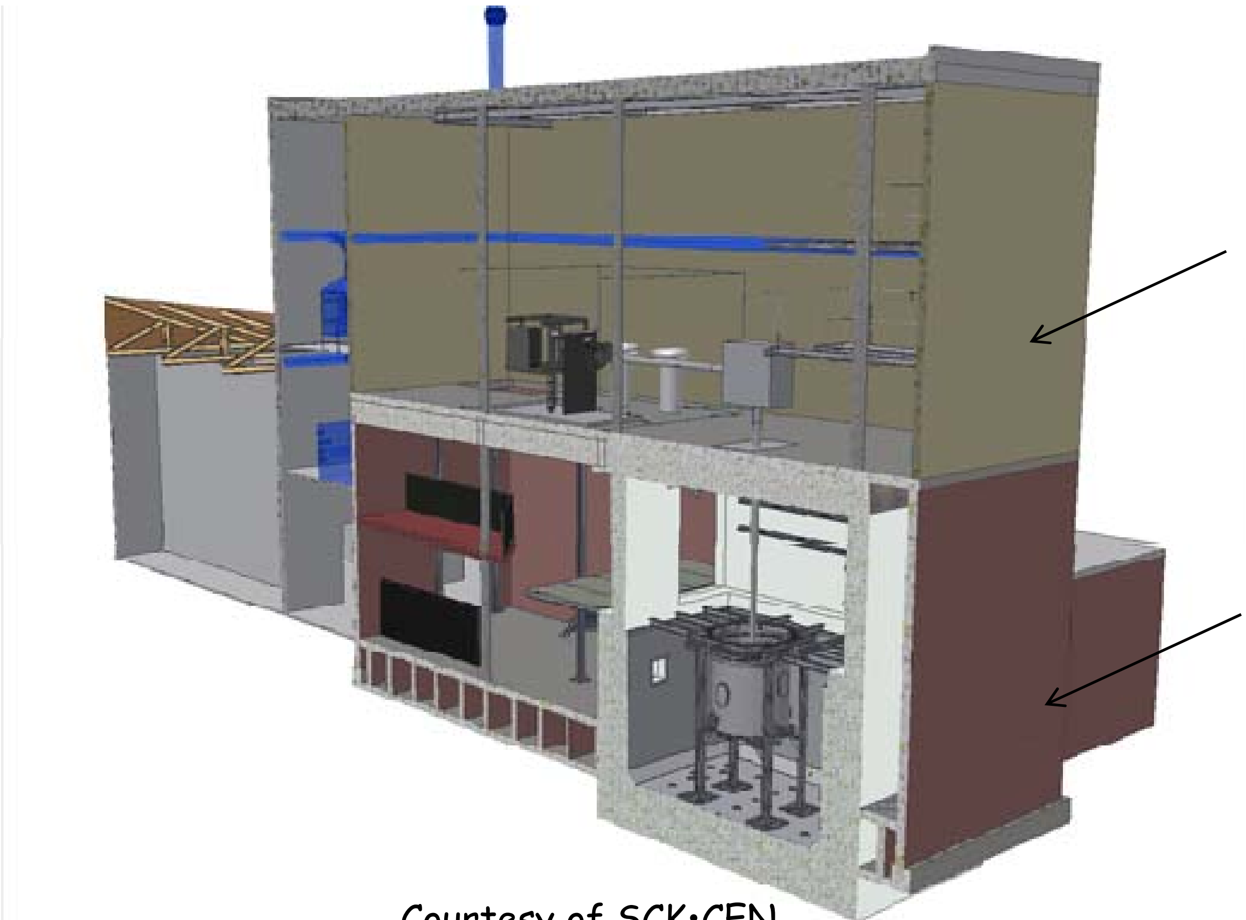
Accelerator requirements for GUINEVERE

- Similar requirements as GENEPI-1/2
- Additionally, new specifications
  - Beam specifications
    - Pulsed intense beam
    - Continuous beam (DC)
    - DC w/ programmable interruptions
  - Accelerator design
    - Vertical coupling to the reactor
    - Accommodate reactor topology for operation & core loading/unloading



Civil engineering at SCK•CEN

- Construction of an additional floor above the VENUS bunker to host the GENEPI-3C accelerator for a vertical coupling



Courtesy of SCK•CEN

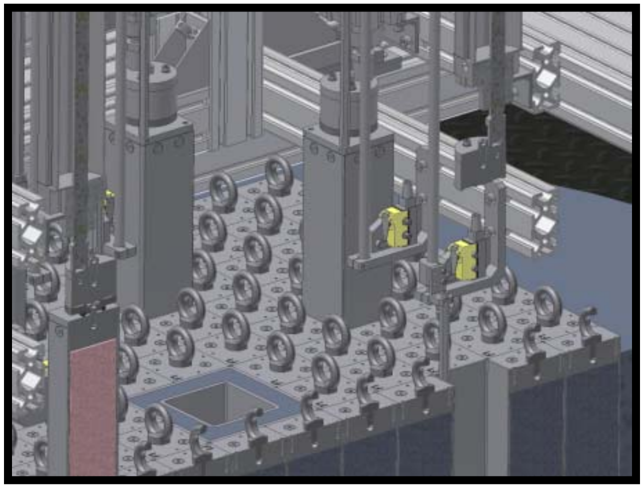
Construction phase (2007-2009)

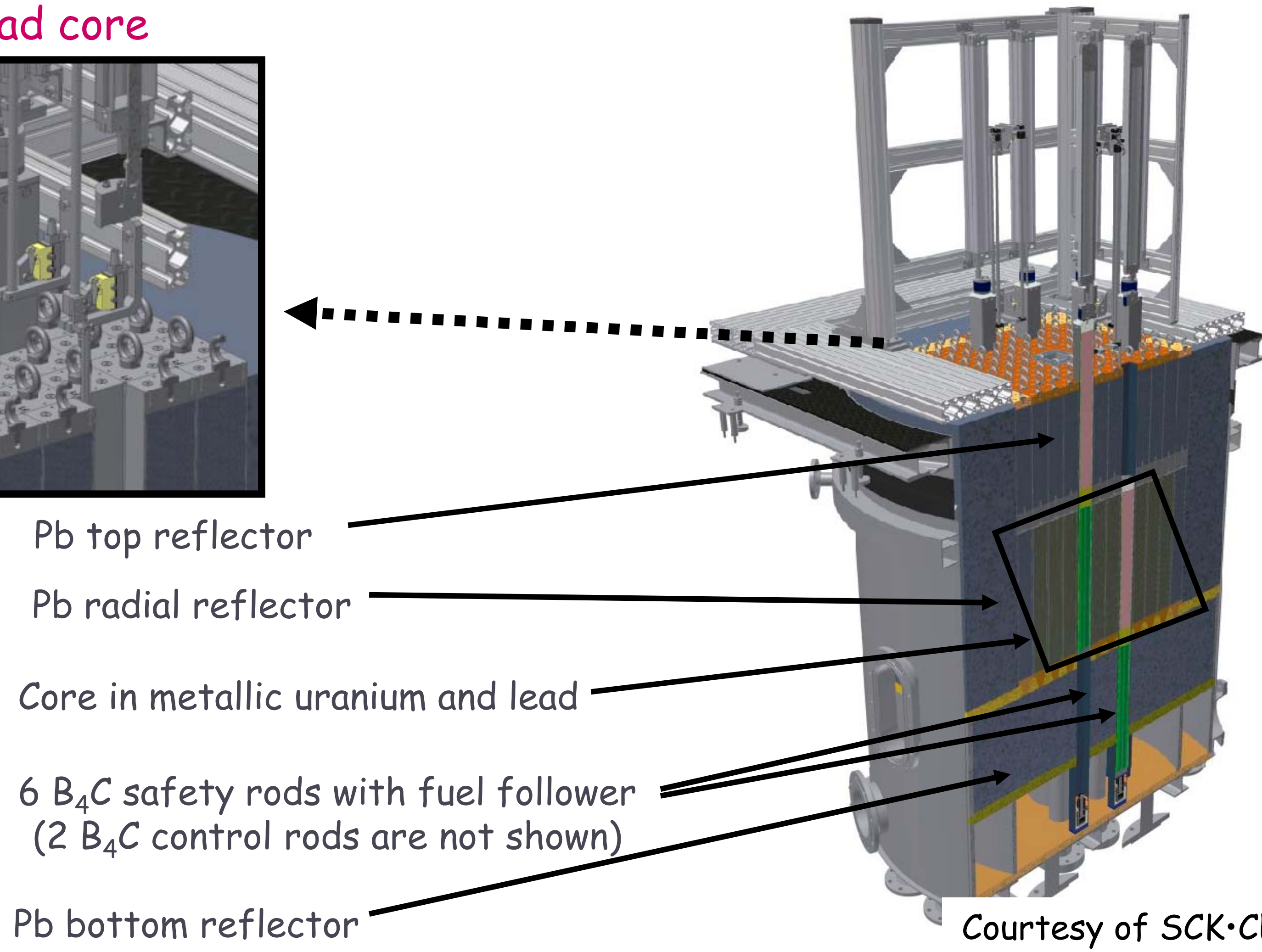
Courtesy of SCK•CEN

Avril 2009

VENUS for GUINEVERE: set-up of a modular reactor design

- Modifying of the water moderated VENUS core
  ➔ fast lead core

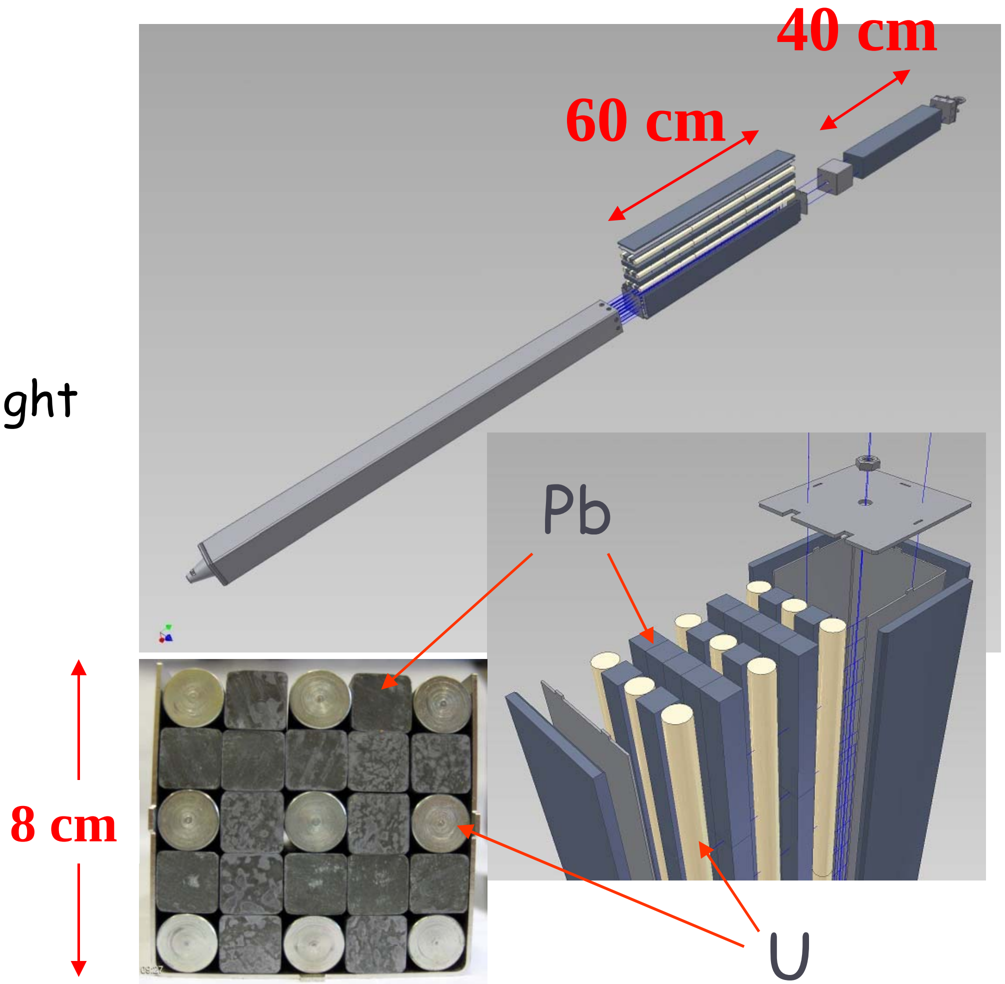




Courtesy of SCK•CEN

Modular fuel assemblies

- CEA fuel rodlets
  - U-metal
  - Enrichment 30 %
  - Diameter= 1.27 cm
  - Length= 20 cm
- Fuel assembly
  - 60 cm active length in height + 40 cm lead reflector
  - 8 cm in lateral dimension



➔ FA structure manufacturing completed

Courtesy of SCK•CEN

GUINEVERE cores

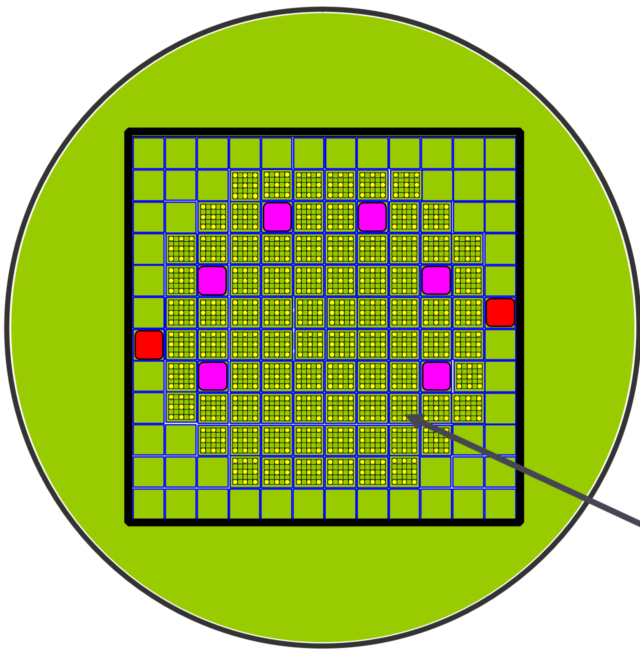
- Critical configuration (CR):

88 Fuel Assemblies
6 safety rods (~14 $)
2 control rods (~1.1 $)
Λ= 0.39 μs
βeff= 748 pcm
Peripheral assemblies ~230 pcm

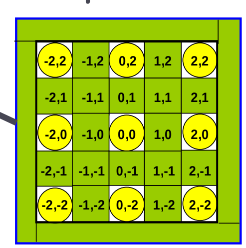
- Sub-Critical configurations:

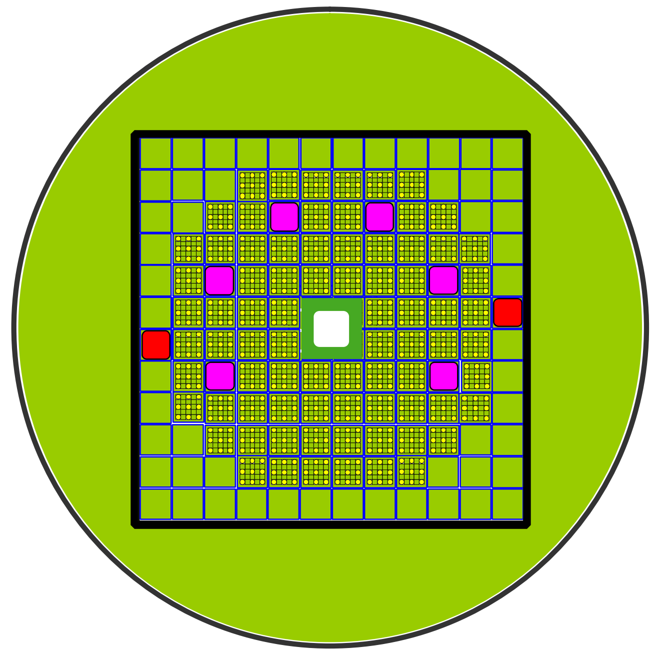
84 Fuel Assemblies

- **SC1 with k_{eff}= 0.97**
- SC2 with k_{eff}= 0.95
- SC3 with $k_{eff} \geq 0.99$
- SCL with k_{eff} = 0.85-0.95 (loading)
- SCR with different reflectors



FA pattern

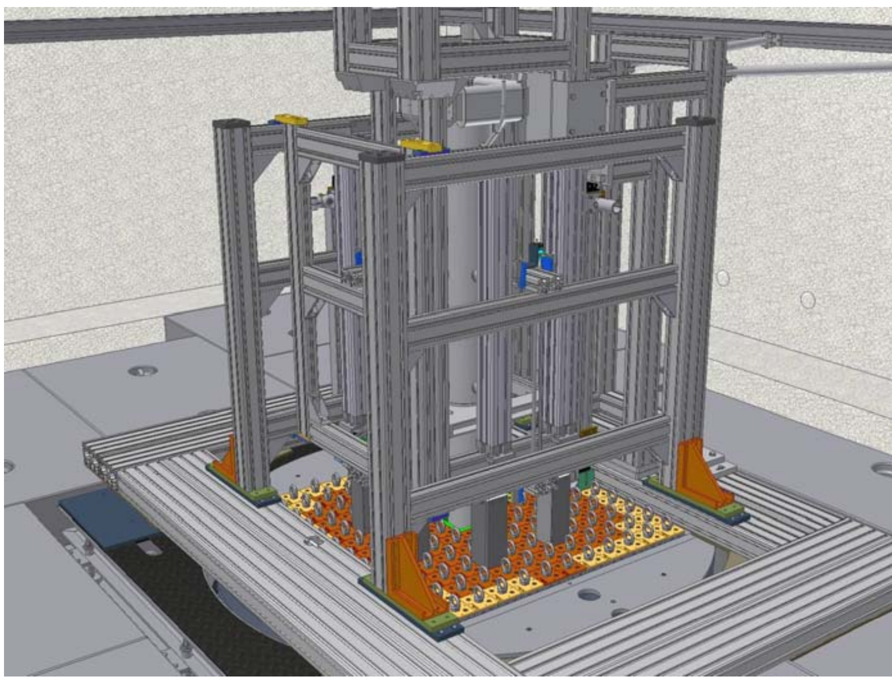


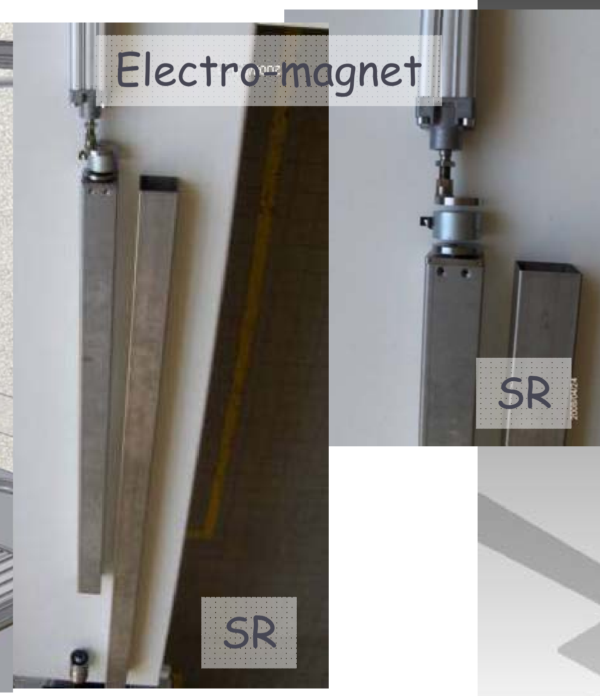


Safety and control rods

- Safety rod structure driving
  - 6 Safety Rods
  - 2 Control Rods (stand-alone units)

  ➔ installed

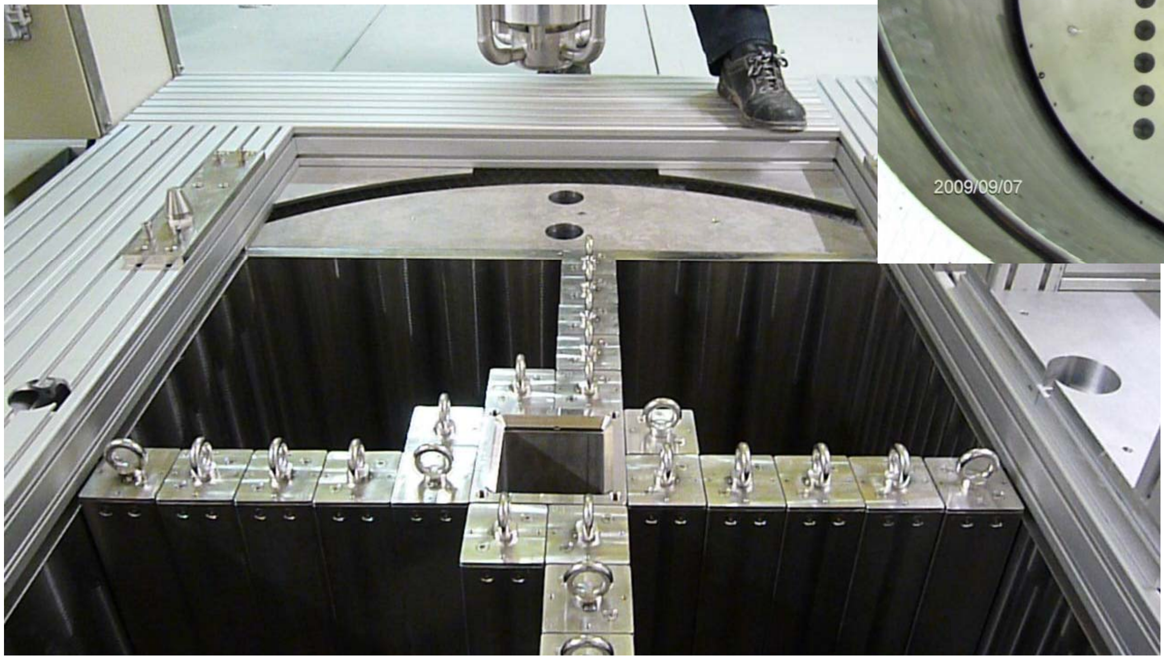


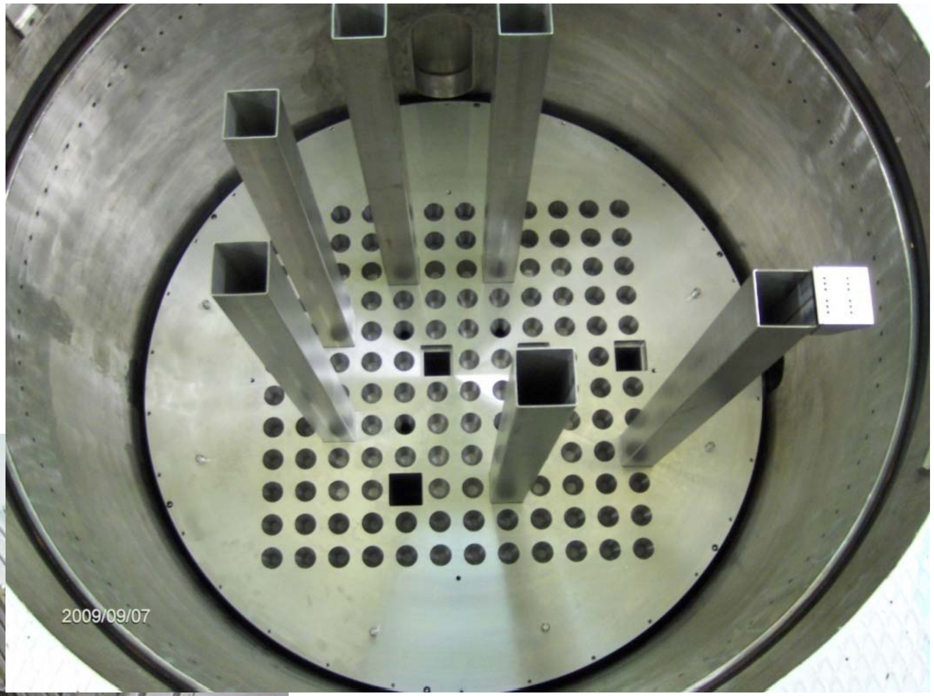


Reactor vessel

- Reactor vessel

➔ ready for core loading





Physics requirements for the accelerator - 1

- Intense pulsed mode

  similar as GENEPI-1

Energy	140 up to 240 keV
Peak current	40 mA
Repetition rate	10 Hz to 5 kHz
Mean current	190 μA at 4.7 kHz
Pulse FWHM	~ 0.7 μs
Pulse stability	~ 1%
Beam spot size	20-25 mm in diameter
Target	Tritium (Deuterium) /Titanium
Maximum neutron production	~8×10^{9} n/s at 4 kHz for Tritium
Neutron energy	14 MeV (2.5 MeV)

Physics requirements for the accelerator - 2

- Continuous modes
  - DC beam
  - DC beam with programmable interruptions

Mean current	160 μA to 1 mA
Beam trip rate	0.1 to 100 Hz
Beam trip duration	~ 20 μs to 10 ms
Transition (ON/OFF)	~ 1 μs
Beam spot size	20-40 mm (diameter)
Max neutron rate	~5×10^{10} n/s
Pulse stability	~1%

- Aim for a single source for pulsed & DC mode operation

  ➔ Required important developments on the ion source

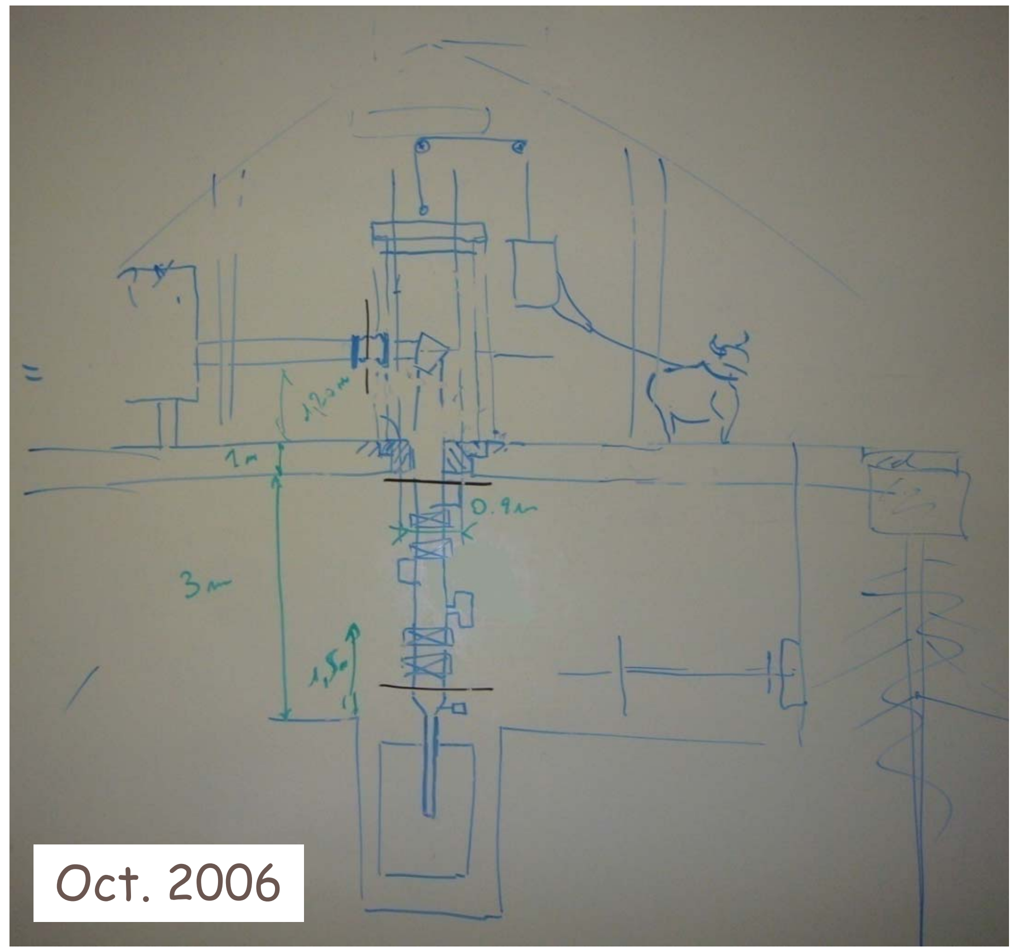
Machine design : version 2006

- Preliminary discussions with SCK•CEN : 2006

  feasibility, machine implementation

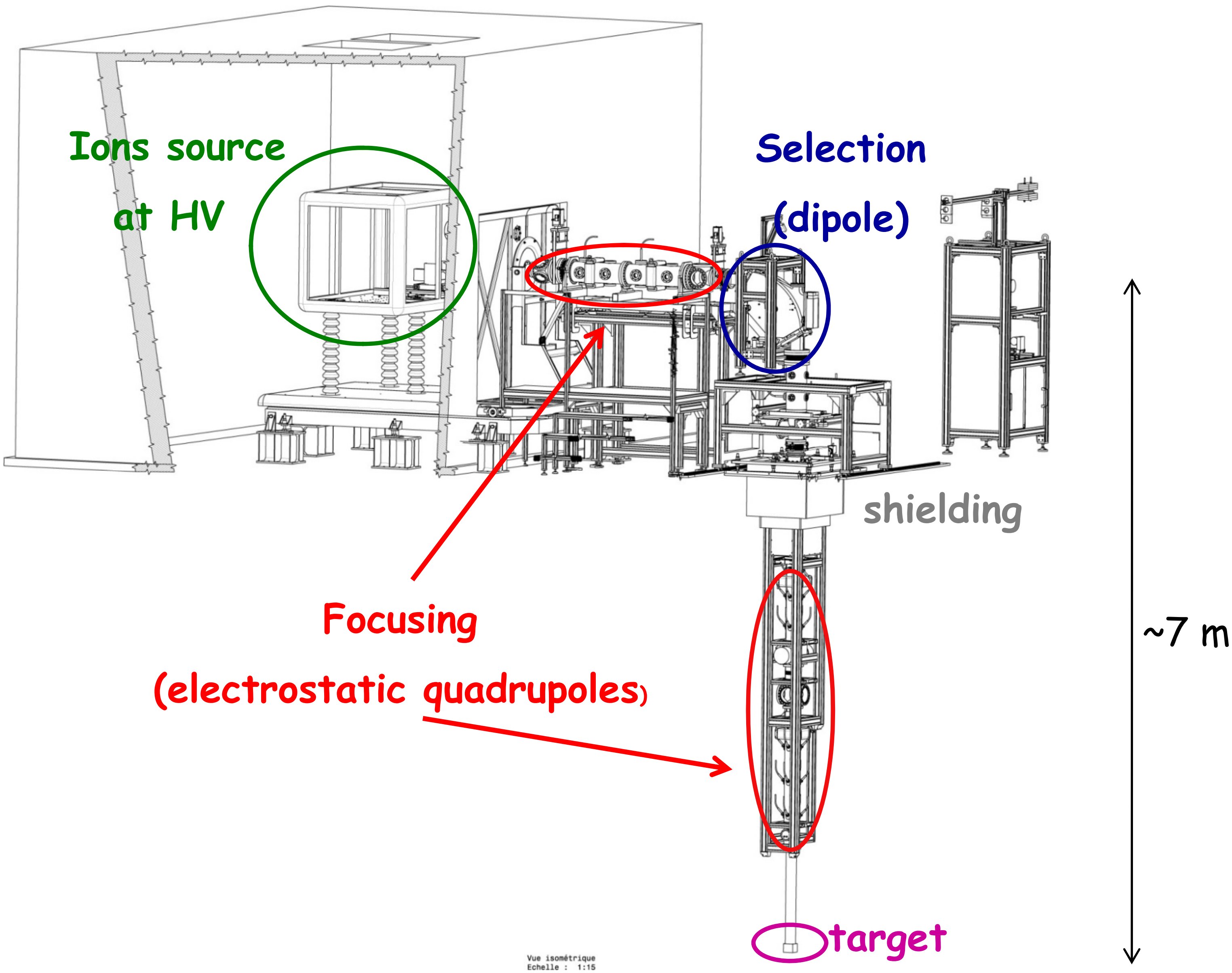
- Financing approved : Dec 2006

- French collaboration within the IN2P3 institute of CNRS
  - LPC Caen
  - IPN Orsay
  - IPHC-DRS Strasbourg
  - LPSC Grenoble



Oct. 2006

Machine design : version 2008

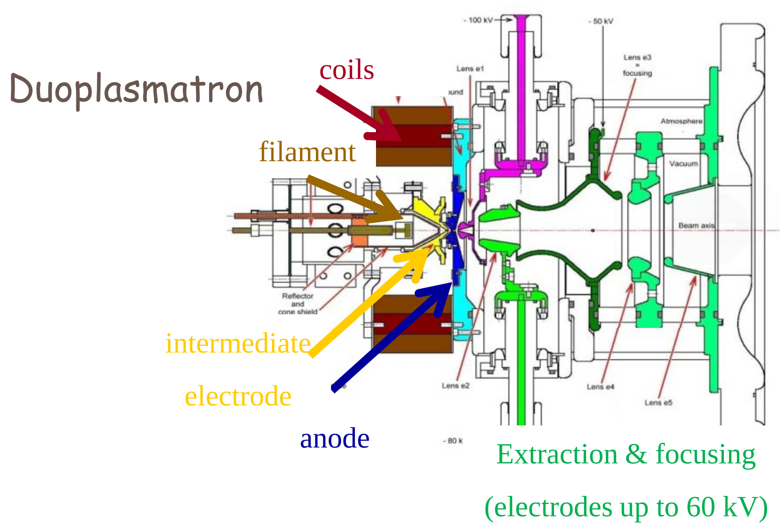


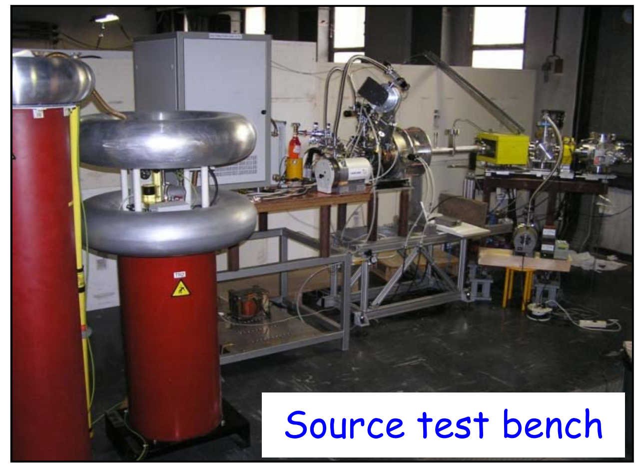
Ion source

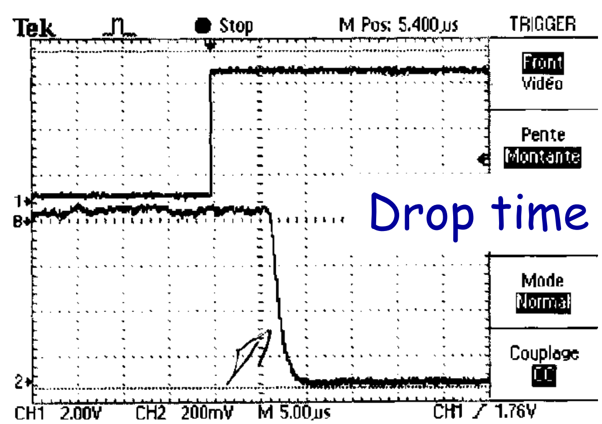
- Duoplasmatron : production of Deuterons : well adapted to pulsed mode
- Developments for DC operation : ionization efficiency D+ ~ 40%

  ➔ 60% beam lost before target

- DC mode specifications mostly reached
  - ✓ 1 mA D^+
  - ✓ Programmable interruptions
  - ✓ ON/OFF transitions ~ few µs







Drop time ~ 2-3 µs

Dipole magnet - 1

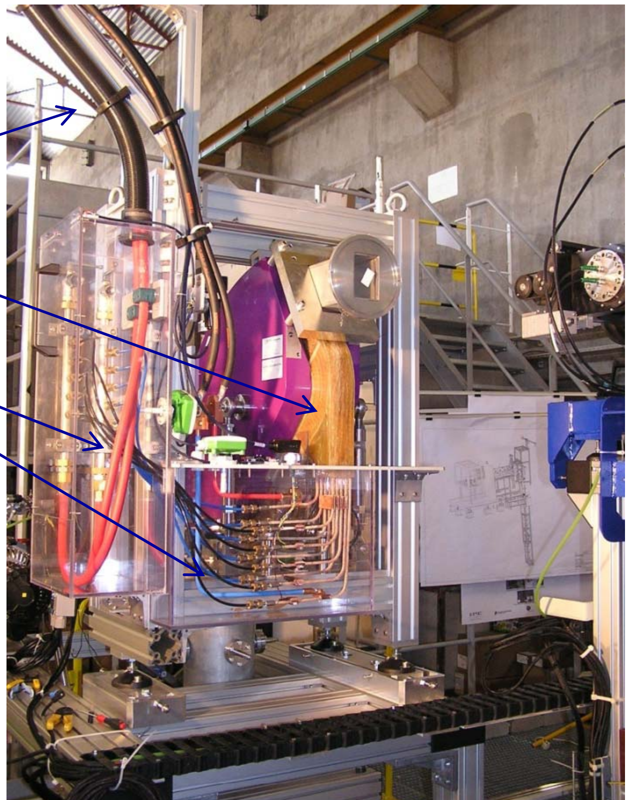
- Deflect the beam towards core & perform magnetic separation
- Magnet features : C design, 0.5 m radius, 0.2 T, 30° faces
- Translation system for dipole + short V line
- Water cooled with stringent precautions against leaks
  - Deported cooling unit

  away from bunker penetration
  - Coil, cooling system waterproof

  fiber glass ribbon & epoxy resin body
  - Water & electrical connections

  waterproof casing with leak detection

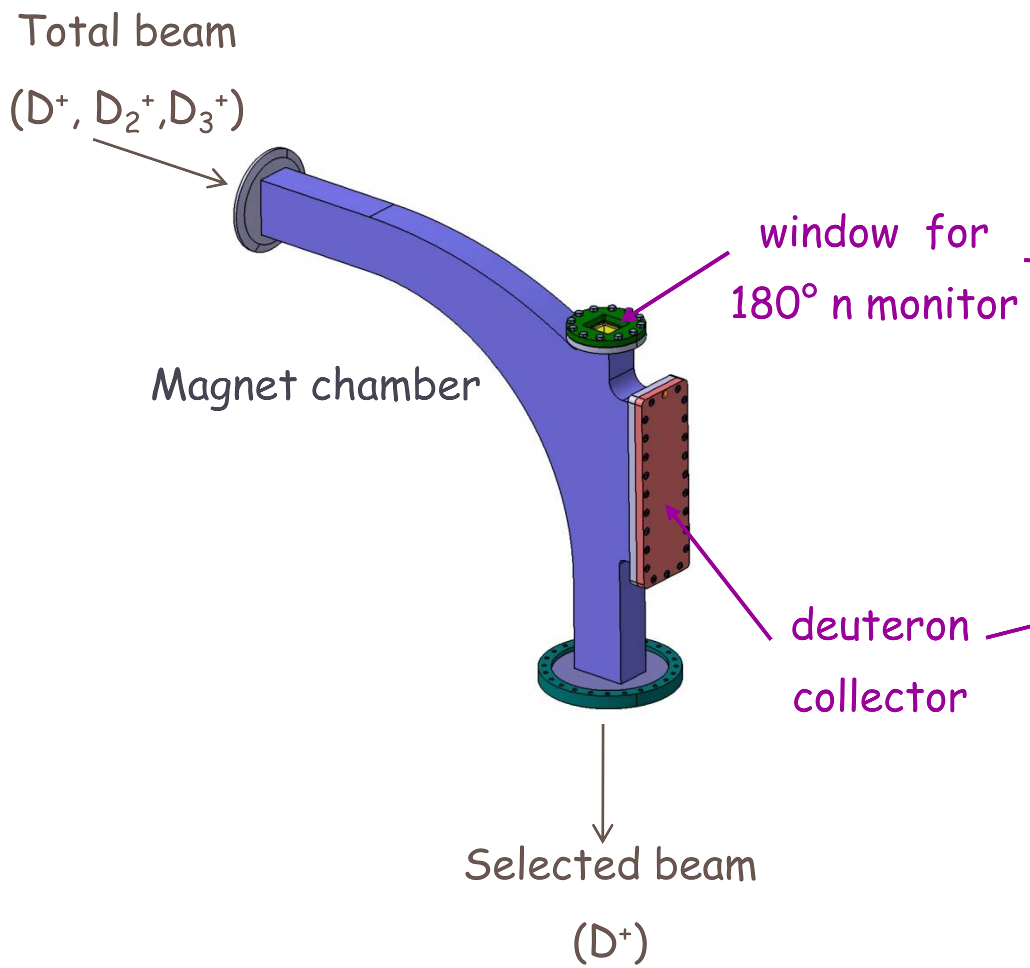
Dipole magnet (in position)

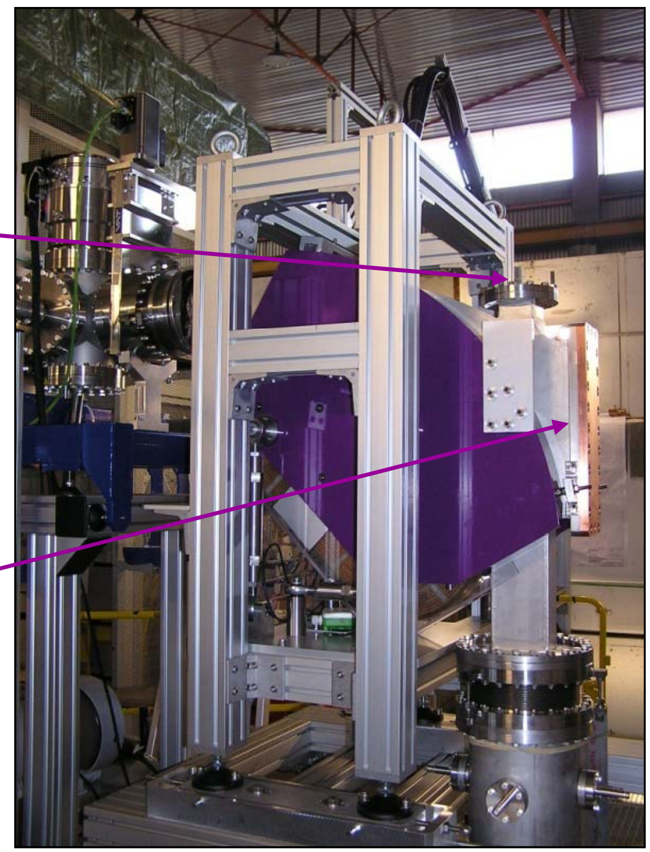


Dipole magnet (out position)

Dipole magnet - 2

- Ion collector connected to the chamber (D_2^+, D_3^+ out of source)
- Recoil telescope facing the target
- Shielding against neutron production (protection of upper level)

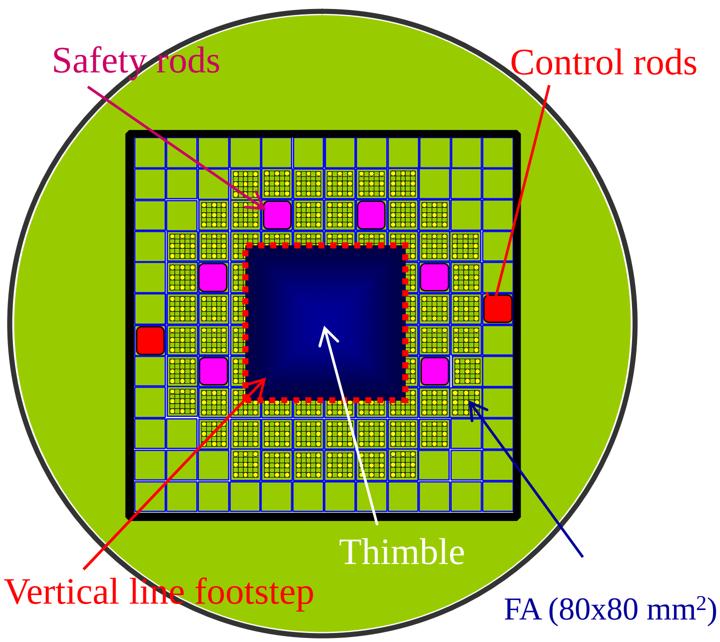




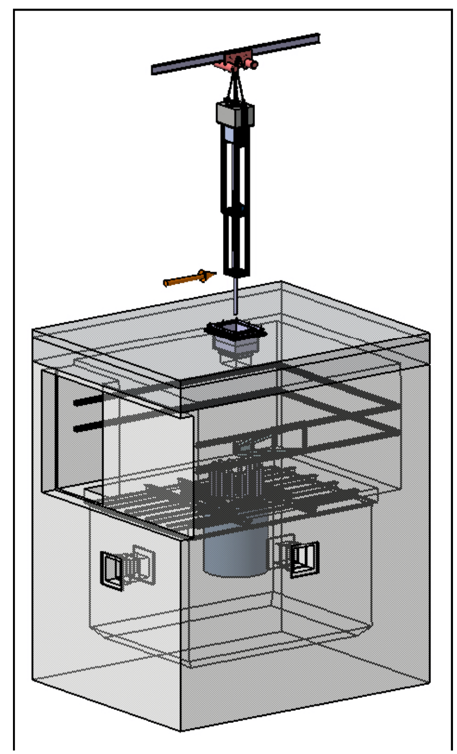
Dipole magnet

Vertical beam line insertion

- Target within the thimble to be inserted at core center
- Machine sections mobile for periodic target changes & core maintenance
  - Dipole magnet to grant access to the V line
  - Vertical beamline to be lifted up
- V line & shielding embedded in support structure, guided at upper & lower level

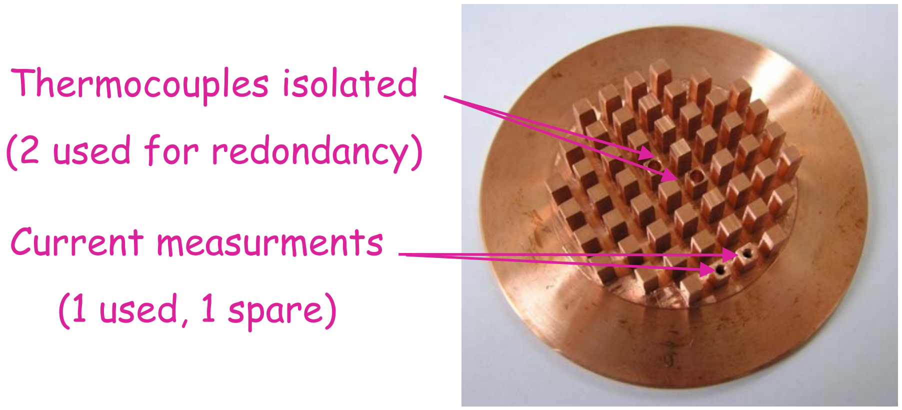


Top view



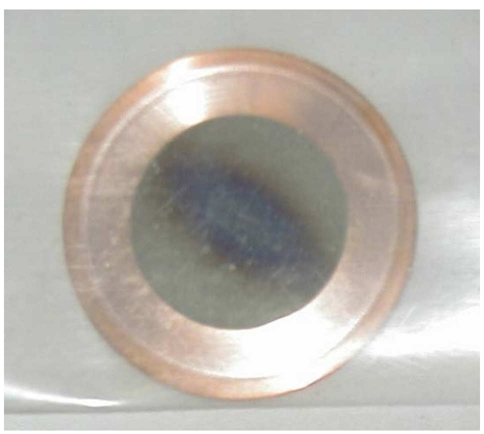
Tritium target

- Target holder : copper disk



- Material: high purity copper OFHC
- Diameter: 60 mm
- Thickness: 1.5 mm
- Back side:
  - Pin fin size: 2.4x2.4x7 mm3
  - Diameter of pin area: 40 mm

- Thin layer of TiT (12 Ci)

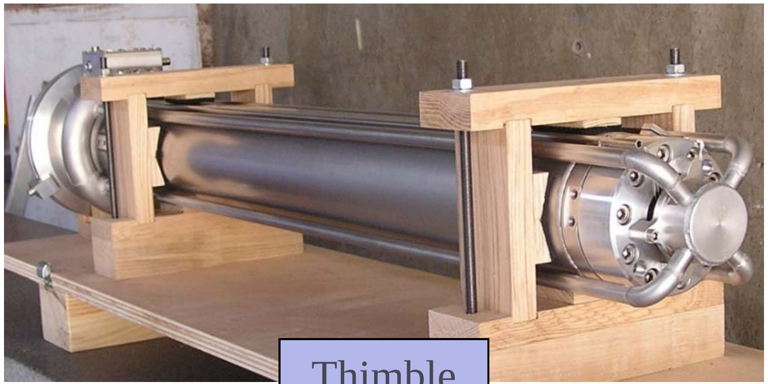


- Titane deposit: 1100 $\mu g/cm2$, diameter: 40 mm
- Tritium loading (by impregnation): 12 Ci
- Titanium hydride ρ=4.2 g/cm2
- T/Ti ~ > 1.5

- Mounted on beamline termination (thimble)

Target cooling

- Requirements
  - Beam power to be evacuated up to 250 W (DC mode), reactor not cooled
  - Temperature to be kept minimal to limit Tritium desorption : T < 60 ° C
  - No Hydrogen within core (neutron slowdown in fast core)
  - Limited room available for cooling (2x2 FA)



Thimble

Diffuser

Air conditionning

- Cooling system developed based on compressed air
  - Cooler & drier system (6 bars)
  - Diffuser at target's back fed by 4 inlets

Neutron monitoring - 1

- Neutron production

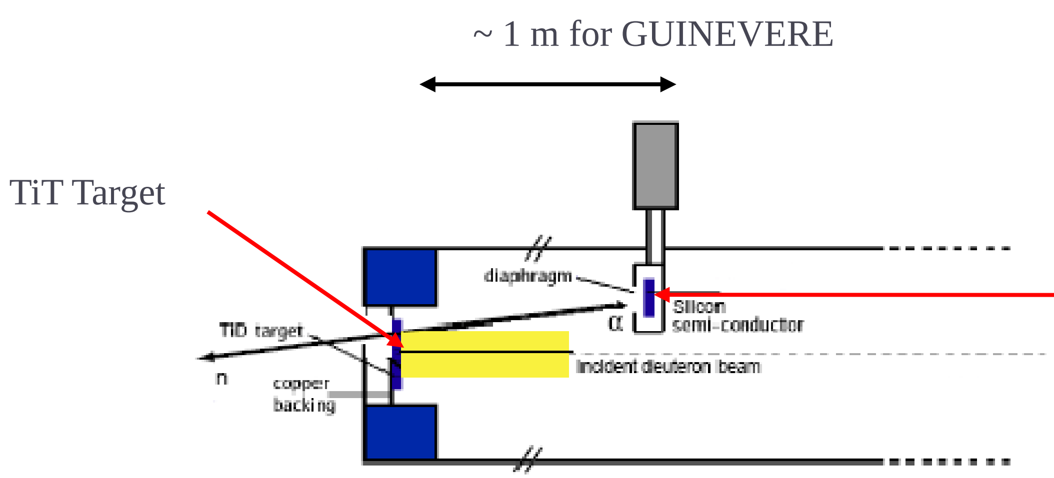
  d + T -> n (14 MeV) + α

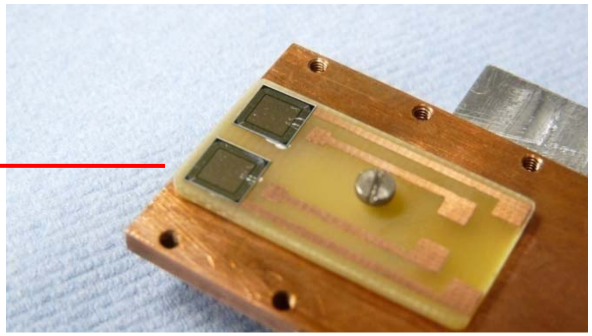
- Monitoring of alpha particles associated to neutron production

  Performed within beam pipe and under direct solid angle

  Semiconductor Silicon dectector, mounted on thimble above the reactor

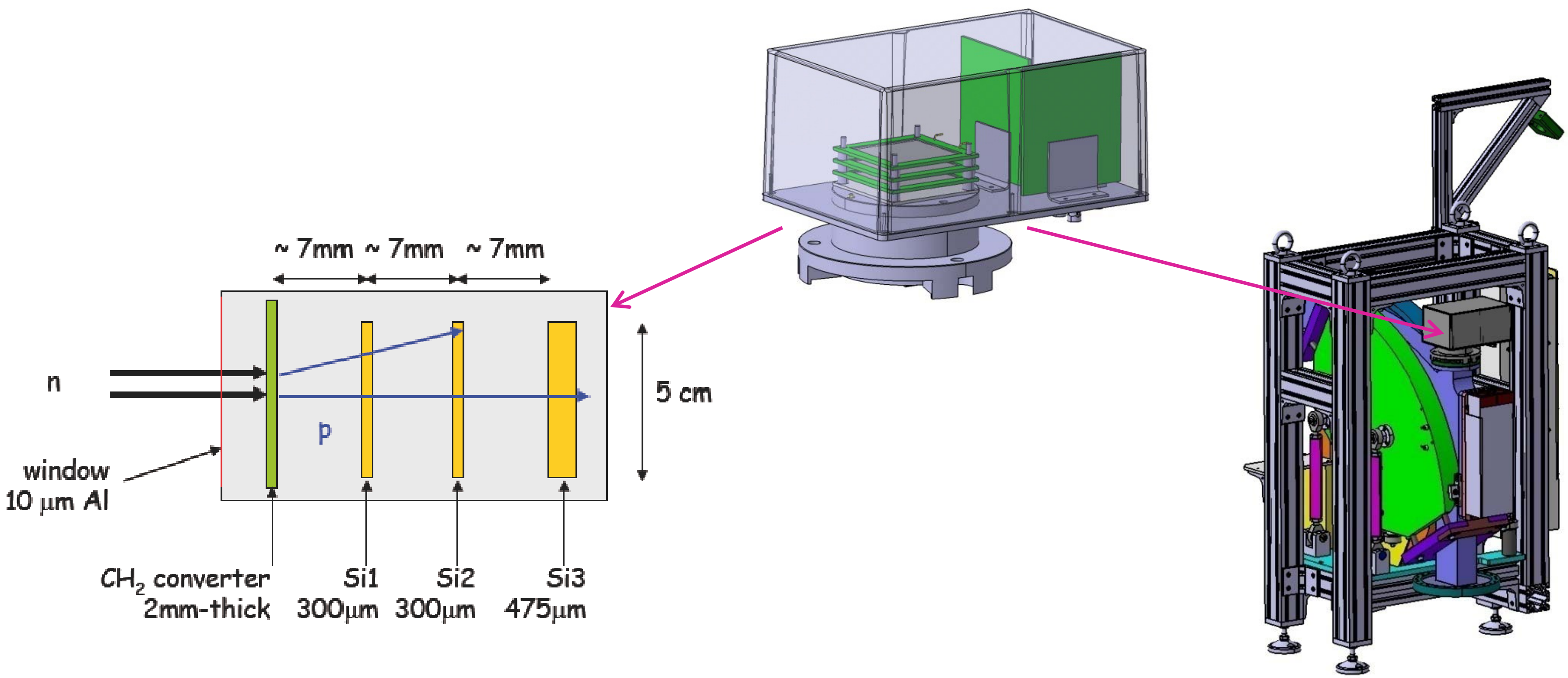
  Provides absolute neutron monitoring





Neutron monitoring - 2

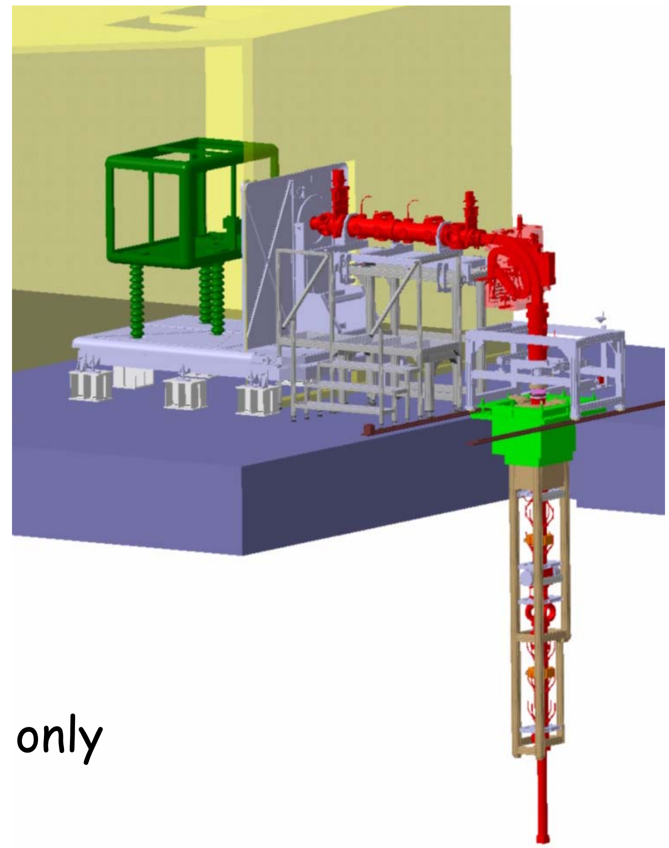
- Direct monitoring of 14 MeV neutrons
  - To detect neutrons : conversion into proton via (n,p) reactions in an H material
  - Consisting of 3 Silicon detectors, located atop the dipole magnet
  - High energy protons stop in 3rd detector
    - ➔ triple coincidence for identification
    - ➔ discriminated from reactor fission neutrons



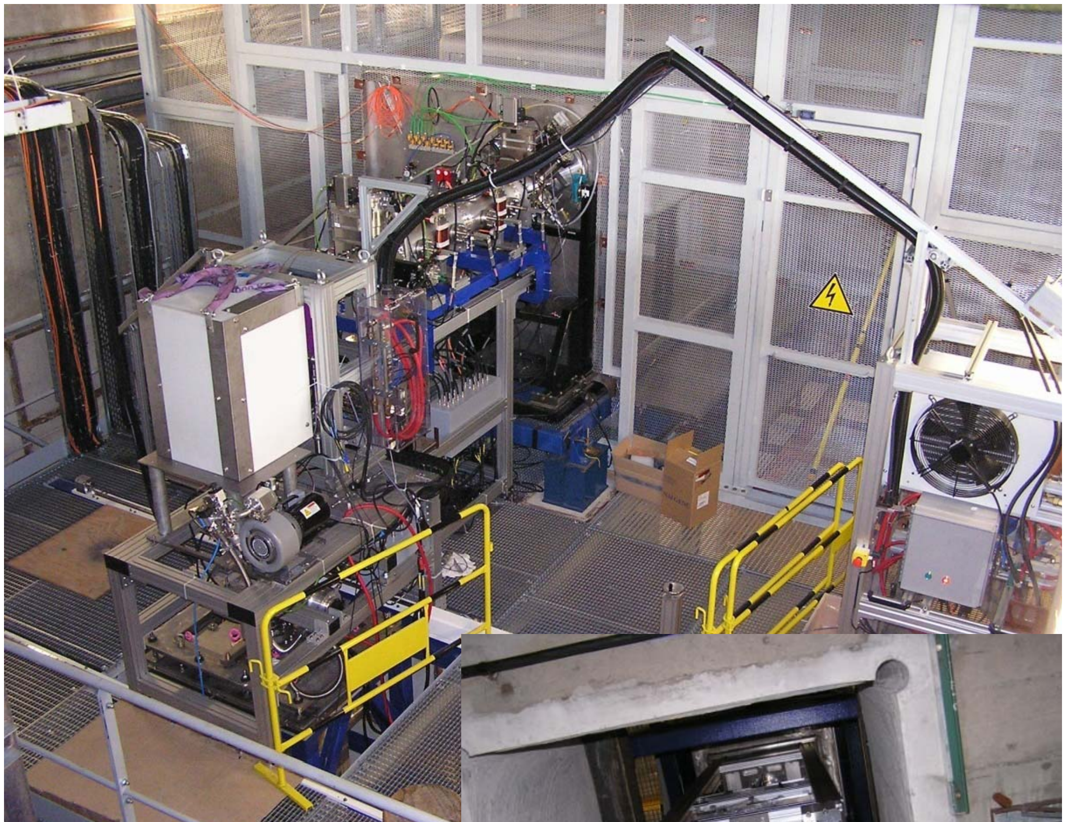
GENEPI-3C commissioning @ LPSC

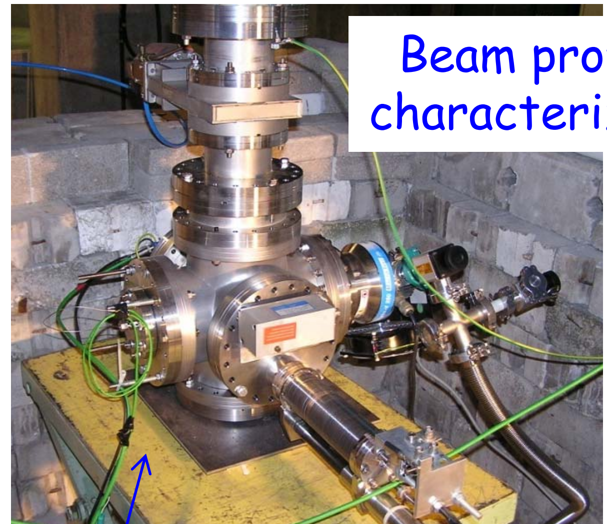
- Machine fully assembled and tested at LPSC before transfer to Mol

- Validate motions & guiding of mobile sections
  - Magnet horizontal translation
  - Vertical beam line lift
- Validate safety interlock system
- Validate machine operation
  - Individual equipment and remote control
- Validate beam dynamics
  - Beam transport through the machine
  - Beam size on target (emittance), dummy targets only
- Validate target cooling
  - Reactor core mock-up at expected operating temperature

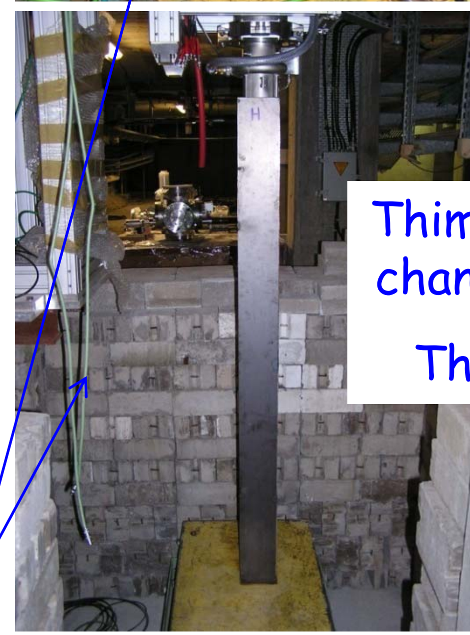


Commissioning at LPSC – July, August 2009





Beam profiler : characterizations



Thimble, insertion channel mock-up :

Thermal tests

Alternative terminal setups

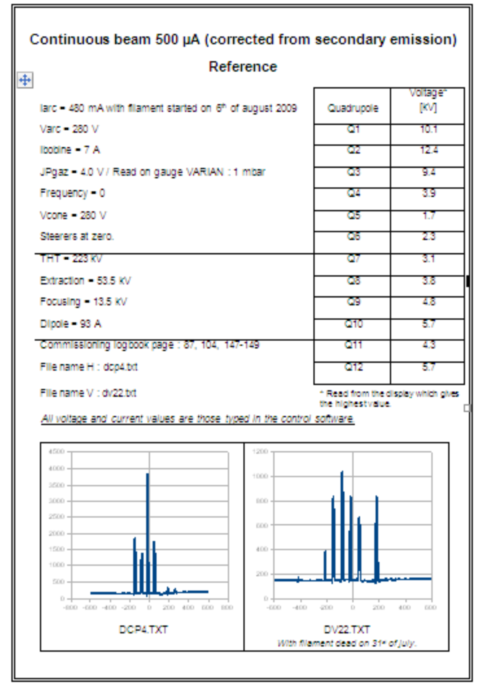
Beam transport

- Beam transported for
  - Intense pulsed beam : ~40 mA on target
  - DC beam: 150 µA to ~ 1.2 mA

with optimization : 8 reference settings

- Some beam diagnostics commissioned

- Beam profile measured on profilometer at line end



Continuous beam 500 µA (corrected from secondary emission)

Reference

Iarc = 480 mA with filament started on 6th of august 2009
Varc = 280 V
Ibobine = 7 A
JPgaz = 4.0 V / Read on gauge VARIAN : 1 mbar
Frequency = 0
Vcone = 280 V
Steerers at zero.

THT = 223 kV
Extraction = 53.5 kV
Focusing = 13.5 kV
Dipole = 93 A

Commissioning logbook page : 87, 104, 147-149
File name H : dcp4.txt
File name V : dv22.txt

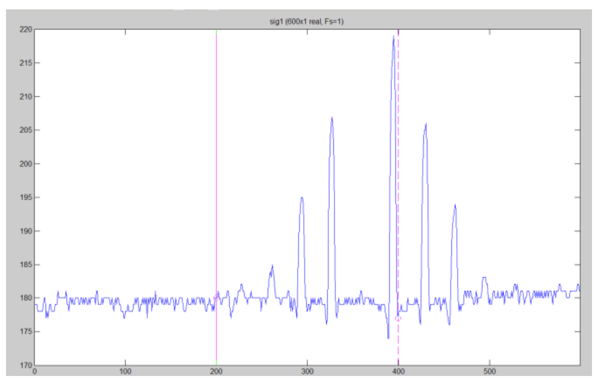
Quadrupole	Voltage* [kV]
Q1	10.1
Q2	12.4
Q3	9.4
Q4	3.9
Q5	1.7
Q6	2.3
Q7	3.1
Q8	3.8
Q9	4.8
Q10	5.7
Q11	4.3
Q12	5.7

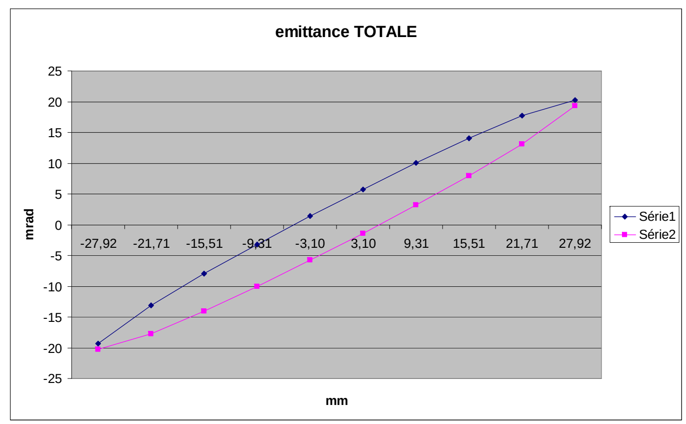
* Read from the display which gives the highest value.

All voltage and current values are those typed in the control software.

DCP4.TXT

DV22.TXT
With filament dead on 31st of July.

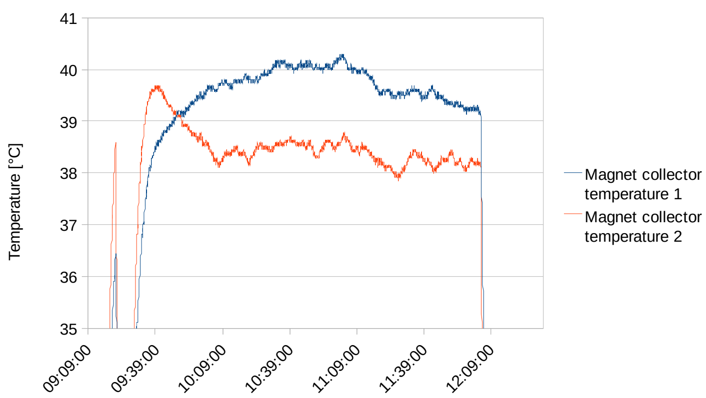


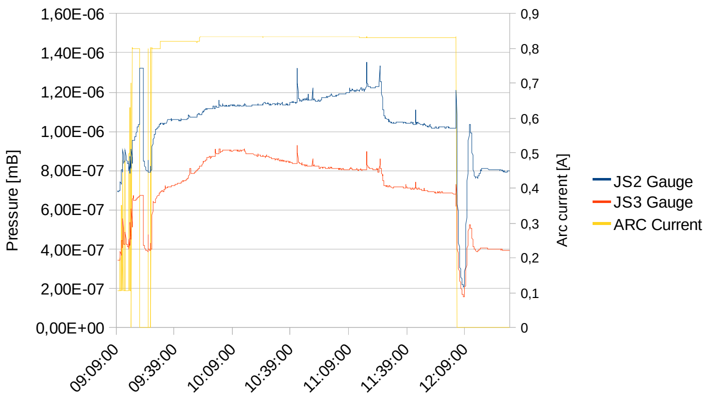


✓ reference settings ready for operation at SCK•CEN

High current DC beam : operation

- Validation of
  - Target cooling (P~ 250 W air-cooled)
  - Magnet collector cooling (P_{lost} ~ 400 W air-cooled)
- Vacuum chamber pressure
  - measurements consistent with design values
- High voltage operation
  - some discharges occurred



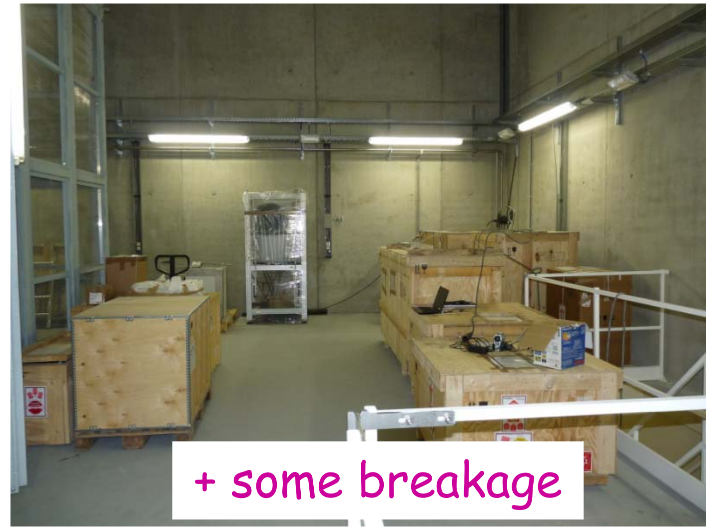


✓ no major problem detected

Dismantle and transfer

- Dismantling & packing of whole machine : sep. 09
- Transfer to SKC•CEN, Mol (Belgium) : oct. 09
  - 3 trucks
  - 16 tons of equipment
  - Estimated cost ~ 1 M€

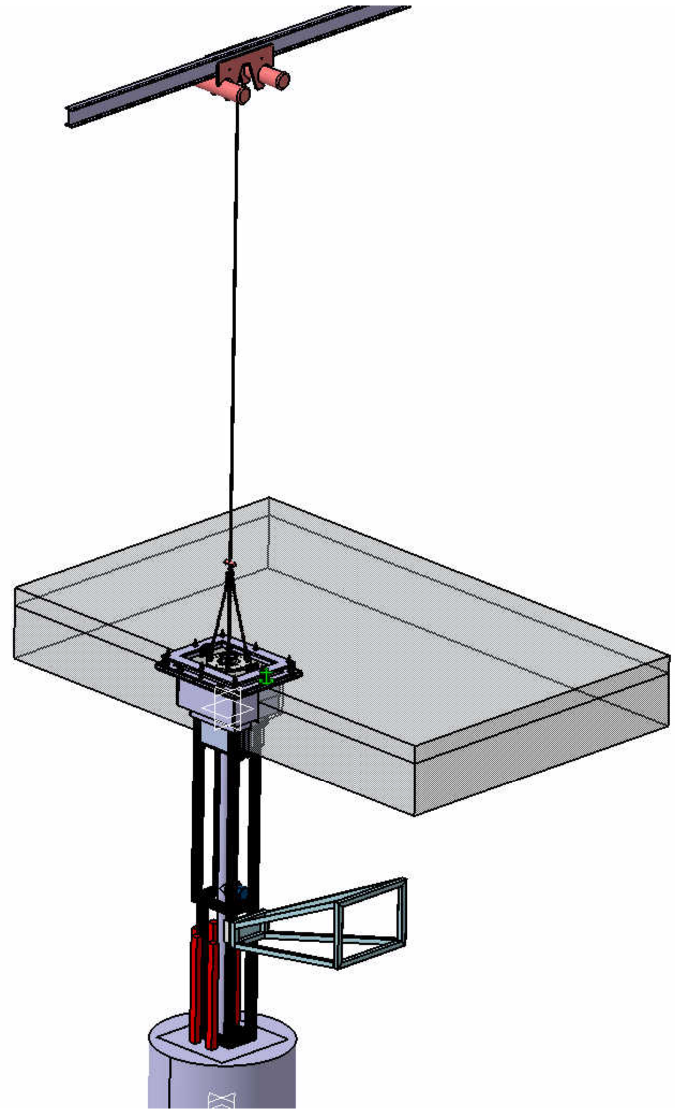
Delivery and re-assembly at SCK•CEN



Vertical beam line handling

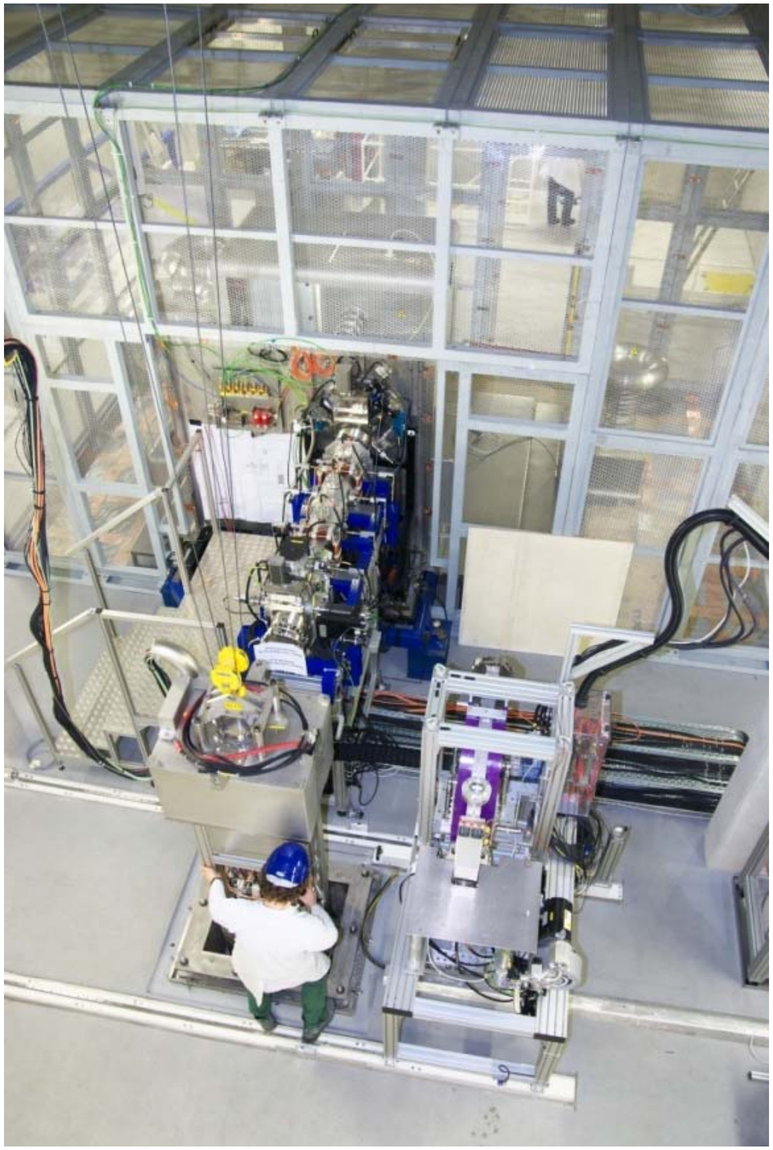
Vertical beam line storage

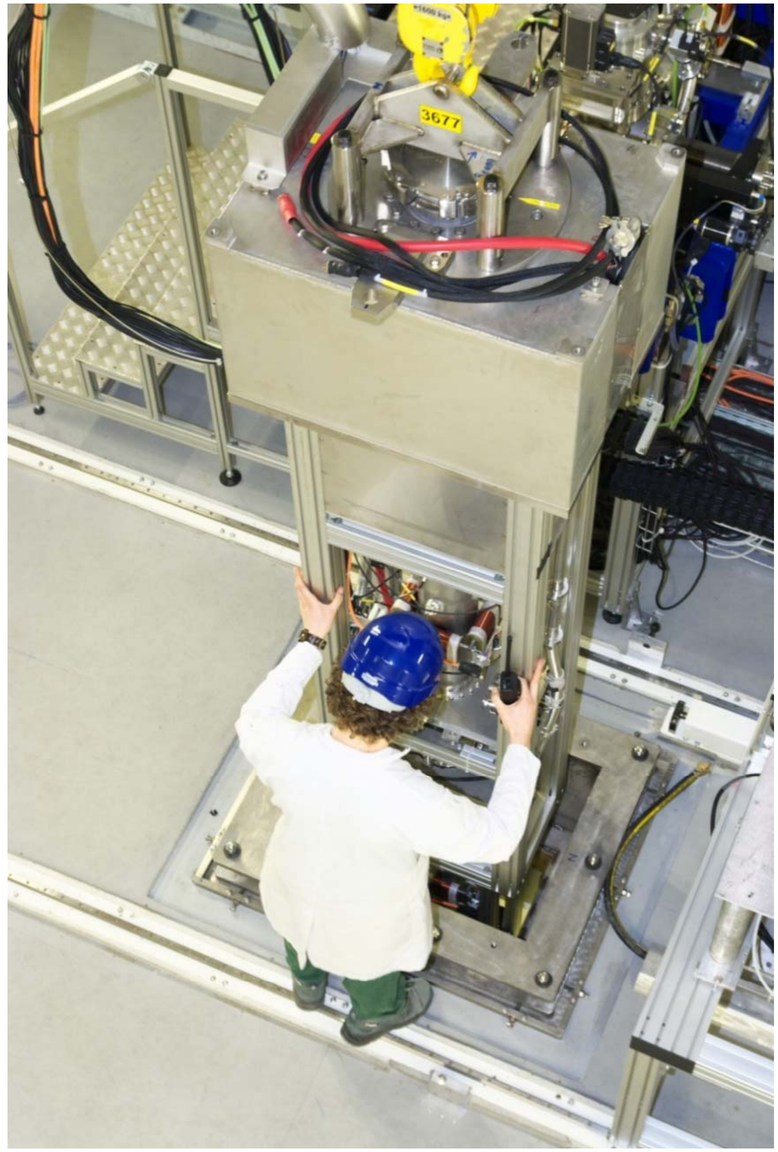
Vertical beam line motion



Accelerator – upper level

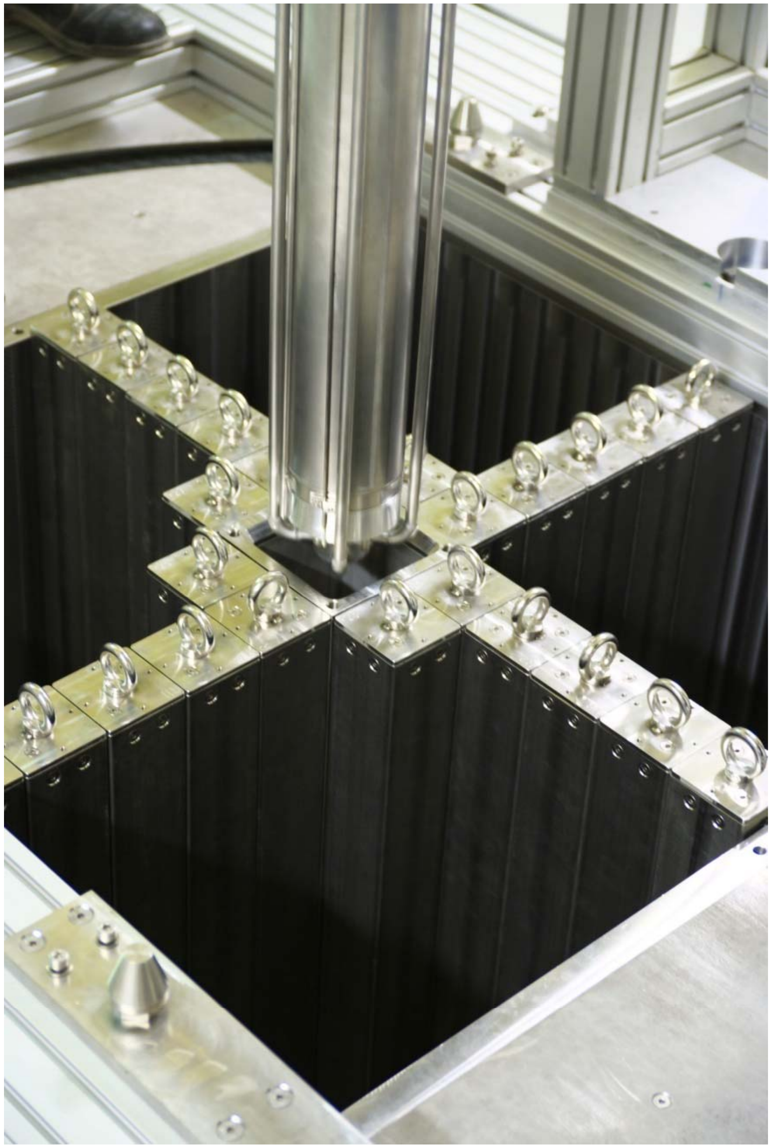
Beam line insertion into the core upper level

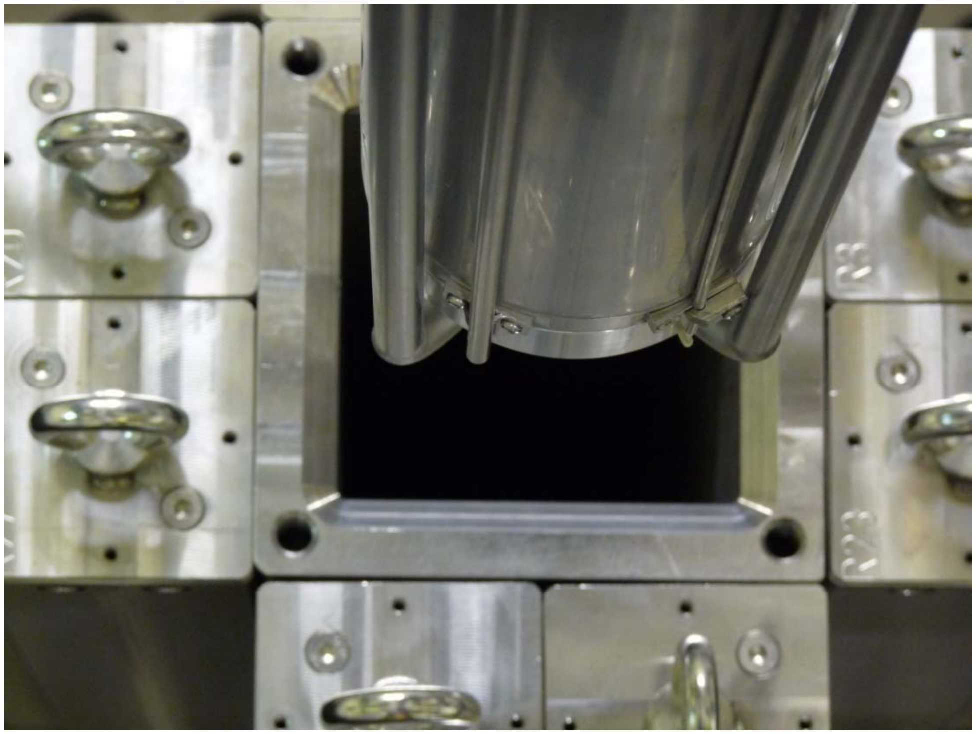




Beam line insertion into the core

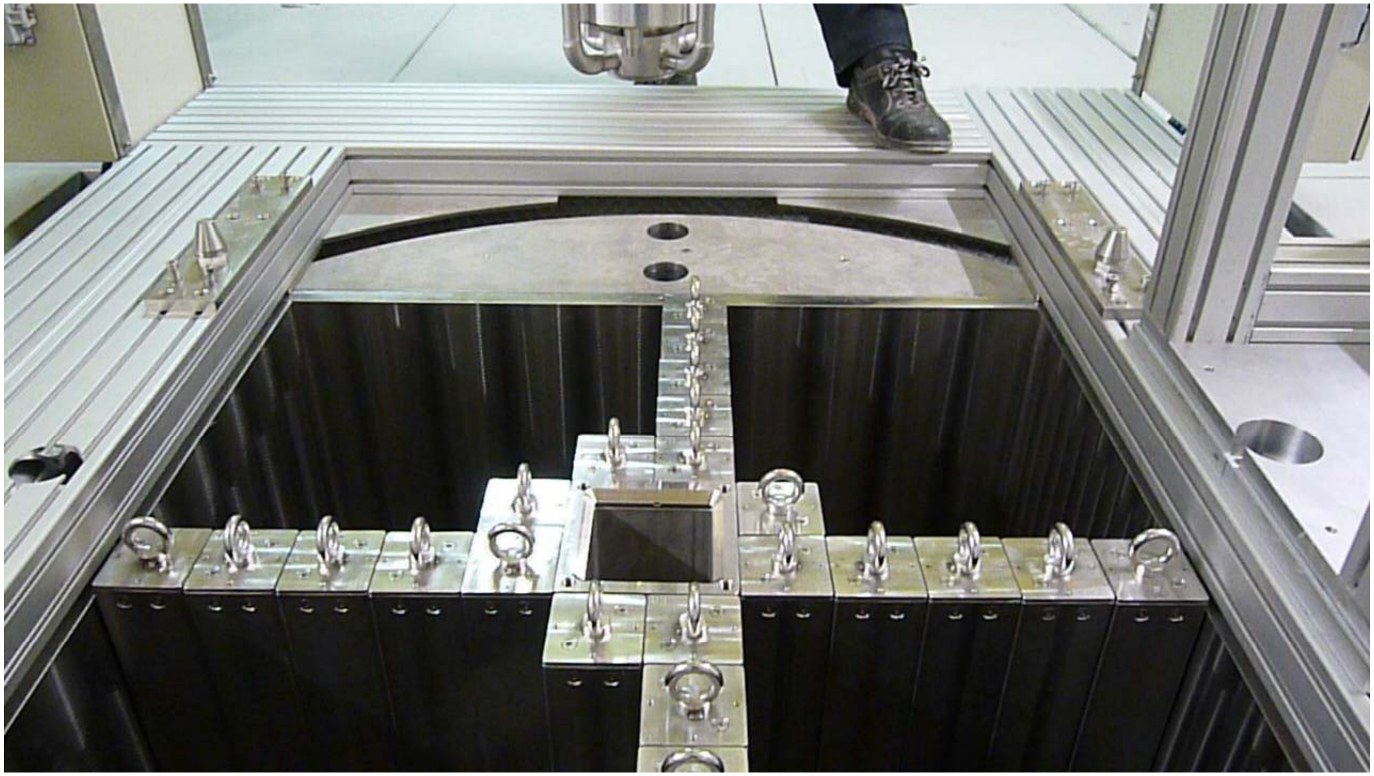
Beam line insertion into the core lower level





VENUS-F bunker and beamline

Motion picture



Official inauguration : March , 2010

GENEPI-3C commissioning at SCK•CEN

- Safety report for accelerator operation at SCK•CEN obtained by steps :
  Jan-Aug 2010

- Some debug : incorrect connections, fix breakages

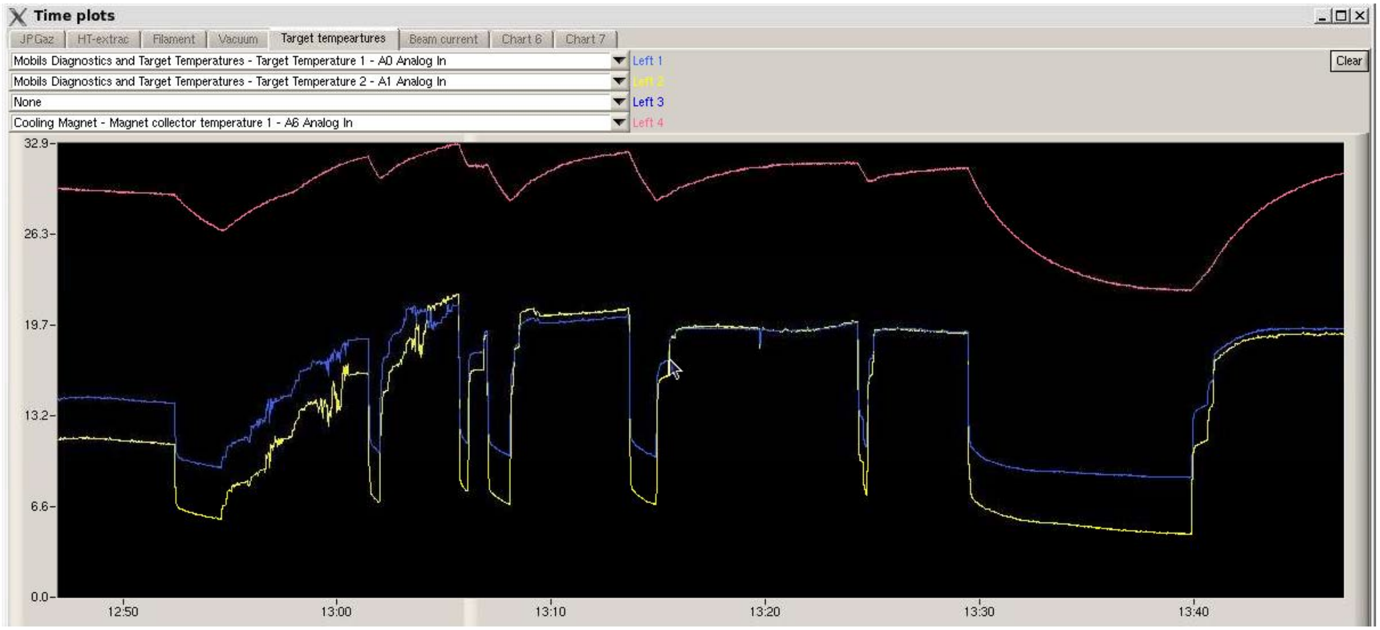
- Transported beam through the machine with mostly LPSC settings
  - DC mode : 1 mA on target
  - Pulsed mode : ~ 25 mA

- Some instability on long high current runs
  - Discharges ➔ to be investigated

- Maximum beam current in pulsed mode too low
  ➔ To be investigated

GENEPI-3C commissioning at SCK•CEN

- Target and collimator cooling validated



- Neutron production
  - First neutron production : Sep 2010
  - Preliminary measurements analysis

    few 10^9 n/s as expected!

Main key dates

- *Stop of VENUS reactor: 1-4-2007* ✔
- *Removal of internal parts of VENUS: 1-7-2007* ✔
- *Conceptual design of core: 1-10-2007* ✔
- *Transport of fuel from CEA to SCK-CEN: 1-11-2007* ✔
- *Accelerator room construction: 1-9-2009, Final stage 1-4-2009* ✔
- *Building and commissioning of GENEPI at LPSC: 01-6-2009* ✔
- *Transfer of GENEPI from CNRS to SCK-CEN: 1-10-2009* ✔
- *Installation new components in VENUS: 1-11-2009* ✔
- *Royal Decree for GUINEVERE-experiment: January-2010* ✔
- *Fuel assembly construction: May-2010* ✔
- *Commissioning accelerator: September 2010* ✔
- Commissioning reactor (non-nuclear): September- October 2010
- Criticality: October-November 2010
- Coupling with sub-critical core: December 2010

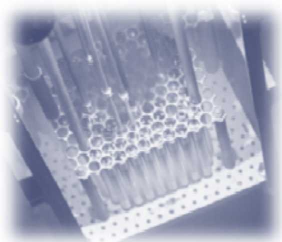
GUINEVERE outlook

- Experimental program to follow within framework of European programs FP7 FREYA (physics) & MAX (accelerator)
- GUINEVERE will provide a unique experiment with a continuous beam coupled to a fast (sub)critical assembly allowing
  - Validation of the methodology for measuring the sub-criticality level
  - Investigation and validation of the operational procedures for an ADS
  - Validation of neutronic codes
  - Safety and licensing issues related to a fast spectrum ADS
- It provides a zero power experimental facility (critical as well) for fast lead system studies and related further developments
- In particular it can act as a zero-power facility for the further design of the MYRRHA project

➔ **GUINEVERE as a mini-MYRRHA**

Multipurpose fast spectrum irradiation facility

MYRRHA



Multipurpose

h**Y**brid

Research

Reactor for

High-tech

Applications

SCK•CEN

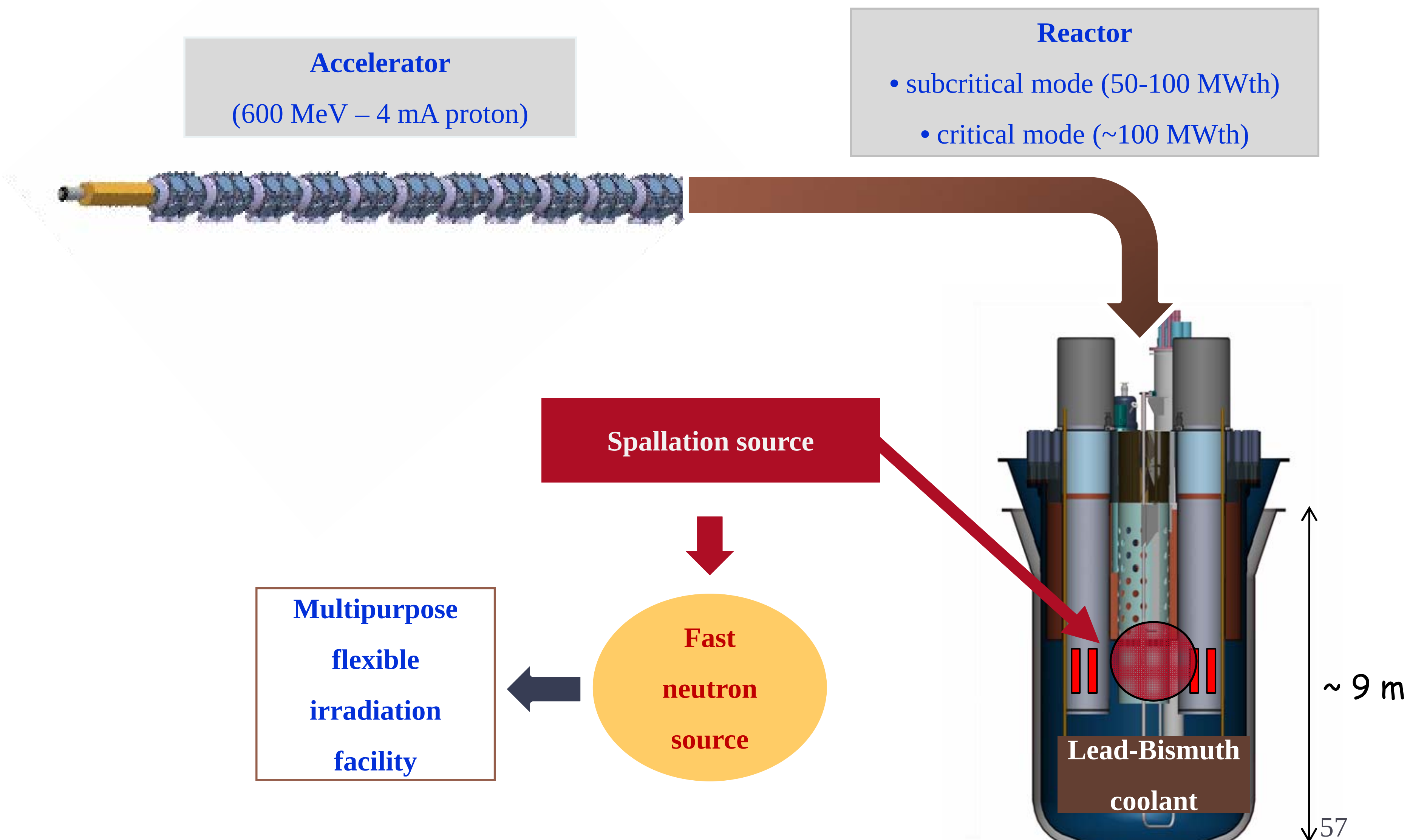
Courtesy of Prof. Baeten, SCK•CEN, pbaeten@sckcen.be or myrrha@sckcen.be

Applications of MYRRHA

	Challenge	Solution	MYRRHA contribution
Fission	High radiotoxic level waste	Transmutation	ADS demo
Fission GEN IV	Demonstrate concept	Build demonstrators	LFR ETPP Fast spectrum irradiation facility
Fusion	Extreme operating conditions	Material testing & development	Fast spectrum irradiation facility
Fundamental research	Pushing the limits of knowledge	Access to proton beam	Long term experiments with radioactive ion beams (RIB)
Renewable energies	Efficient power electronics	High efficiency transistors (NTD-Si)	Securing NTD-Silicon production
Healthcare	Ageing population	A long term source of medical radioisotopes	Securing radioisotopes production (existing and new ones)

Courtesy of Prof. Baeten, SCK•CEN, pbaeten@sckcen.be or myrrha@sckcen.be

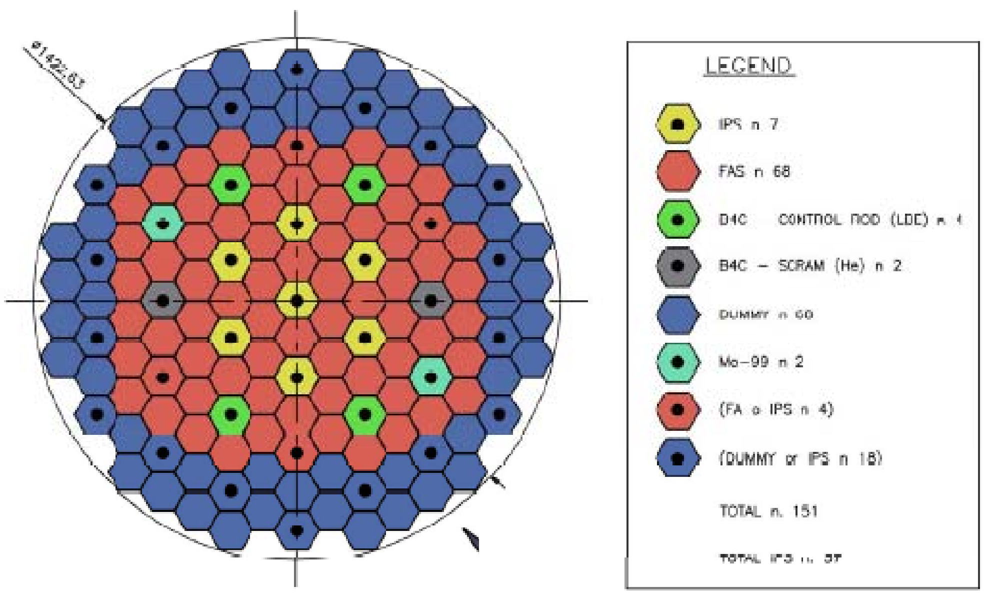
MYRRHA: innovative and unique



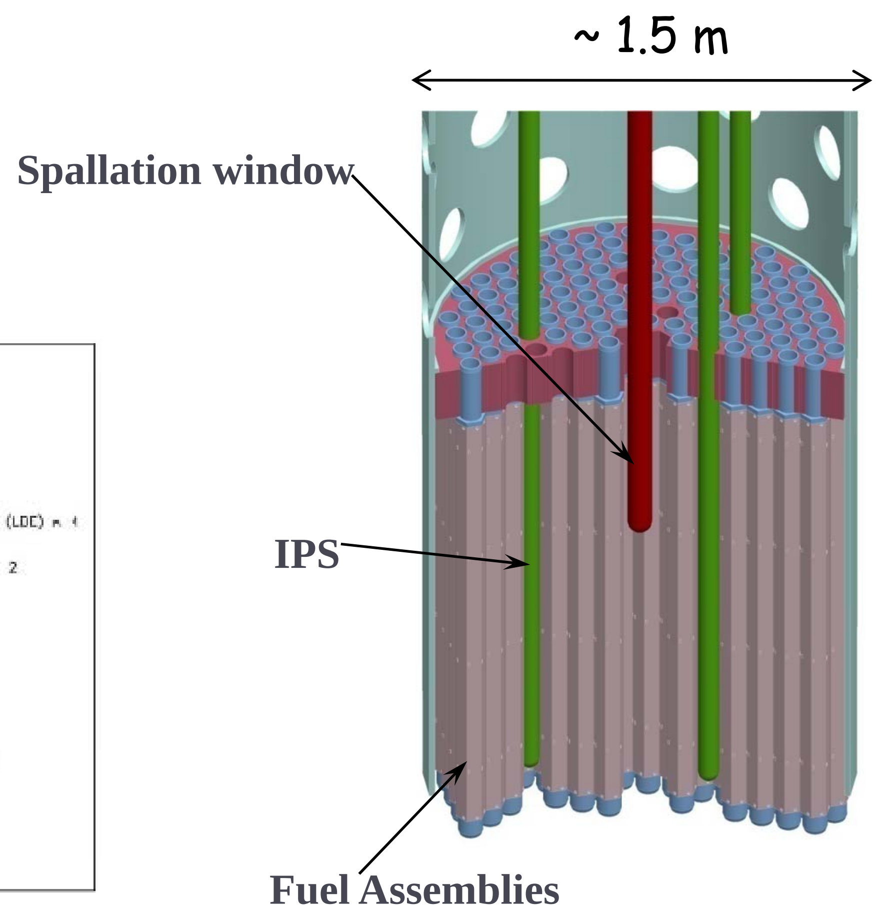
Courtesy of Prof. Baeten, SCK•CEN, pbaeten@sckcen.be or myrrha@sckcen.be

Reactor : core layout

- $k_{eff} \approx 0.95$ (sub-critical mode)
- MOX fuel
- 30-35 % enrichment Pu
- 7 IPS positions (irradiation volume)



critical mode



sub-critical mode

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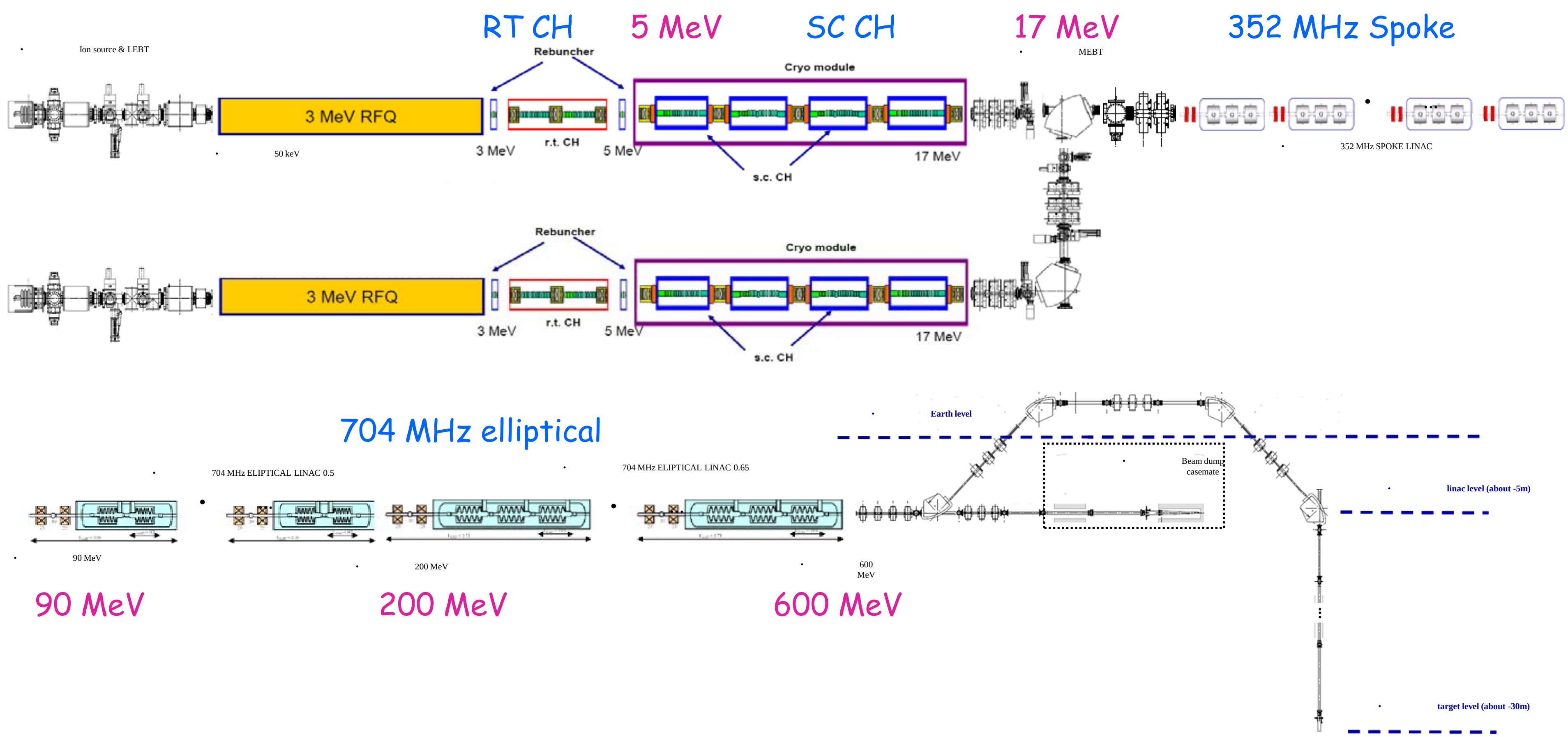
Accelerator - layout



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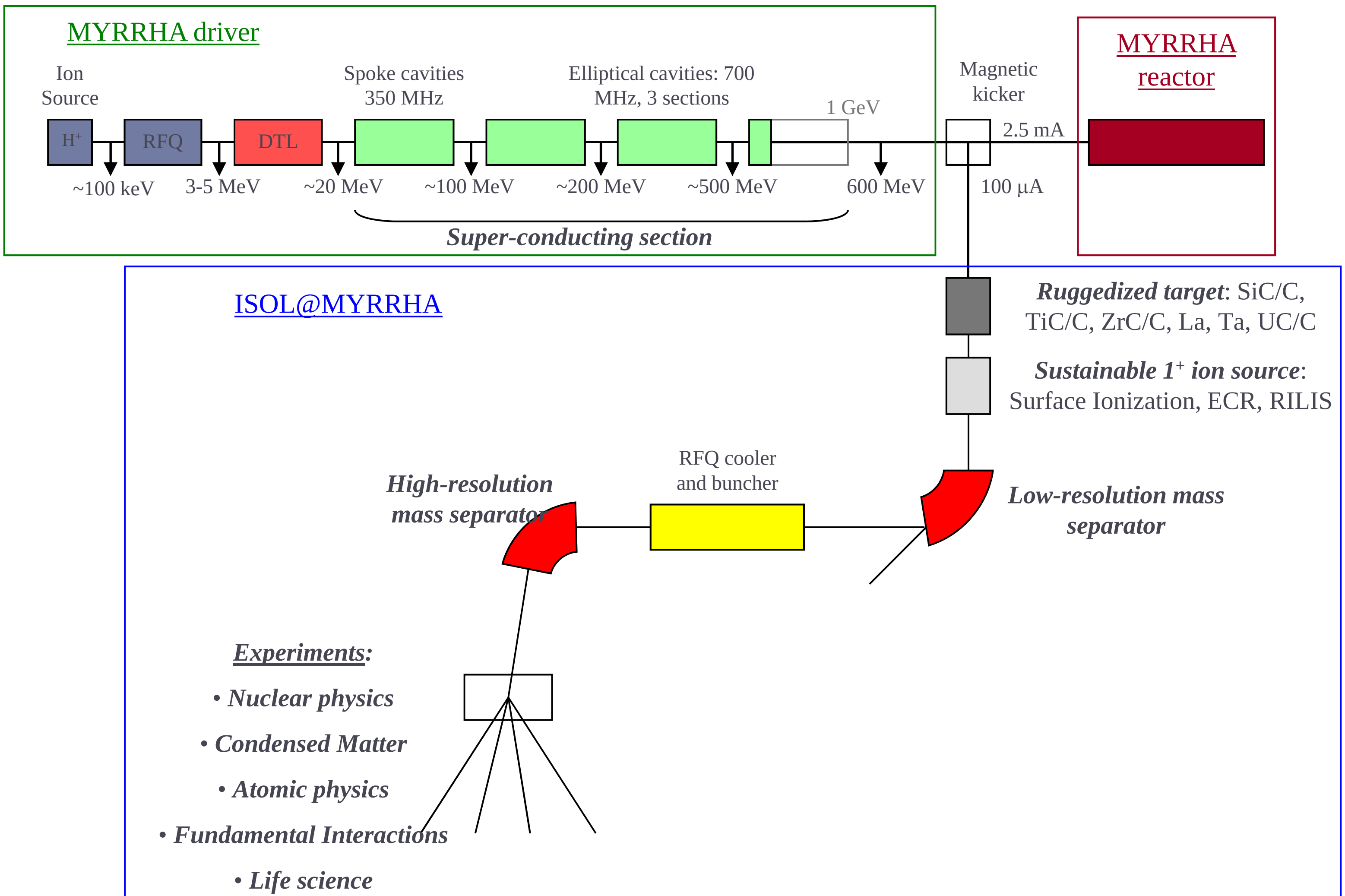
ISOL@MYRRHA lay-out



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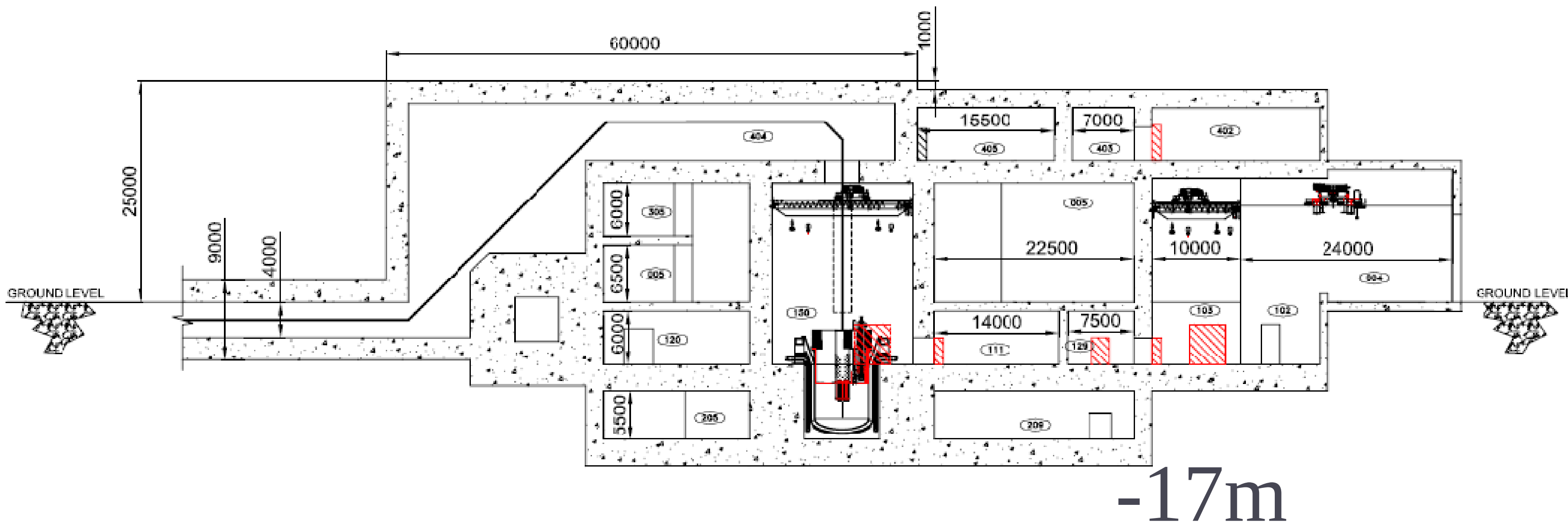
Building layout and reactor hall
Vertical section in the reactor building



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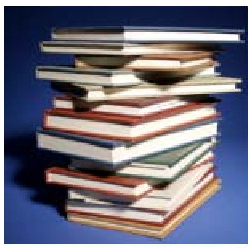
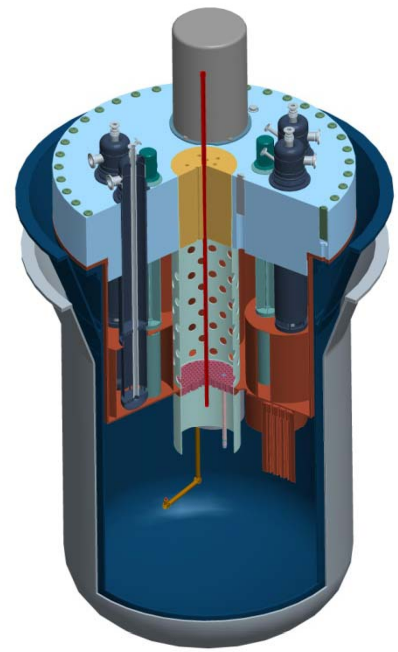
Project schedule

2010-2014	2014-2015	2016-2018	2019	2020-2022	2023	2024-
Front End Engineering Design	Specifications Drafting & Tendering	Construction of components & Civil engineering	On site assembly	Commissioning	Progressive start-up	Full exploitation





For more information on MYRRHA : http://myrrha.sckcen.be

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Thanks for your attention