STUDIECENTRUM VOOR KERNENERGIE
CENTRE D'ÉTUDE DE L'ÉNERGIE NUCLÉAIRE

The MYRRHA/XT-ADS project

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on behalf of the MYRRHA Team

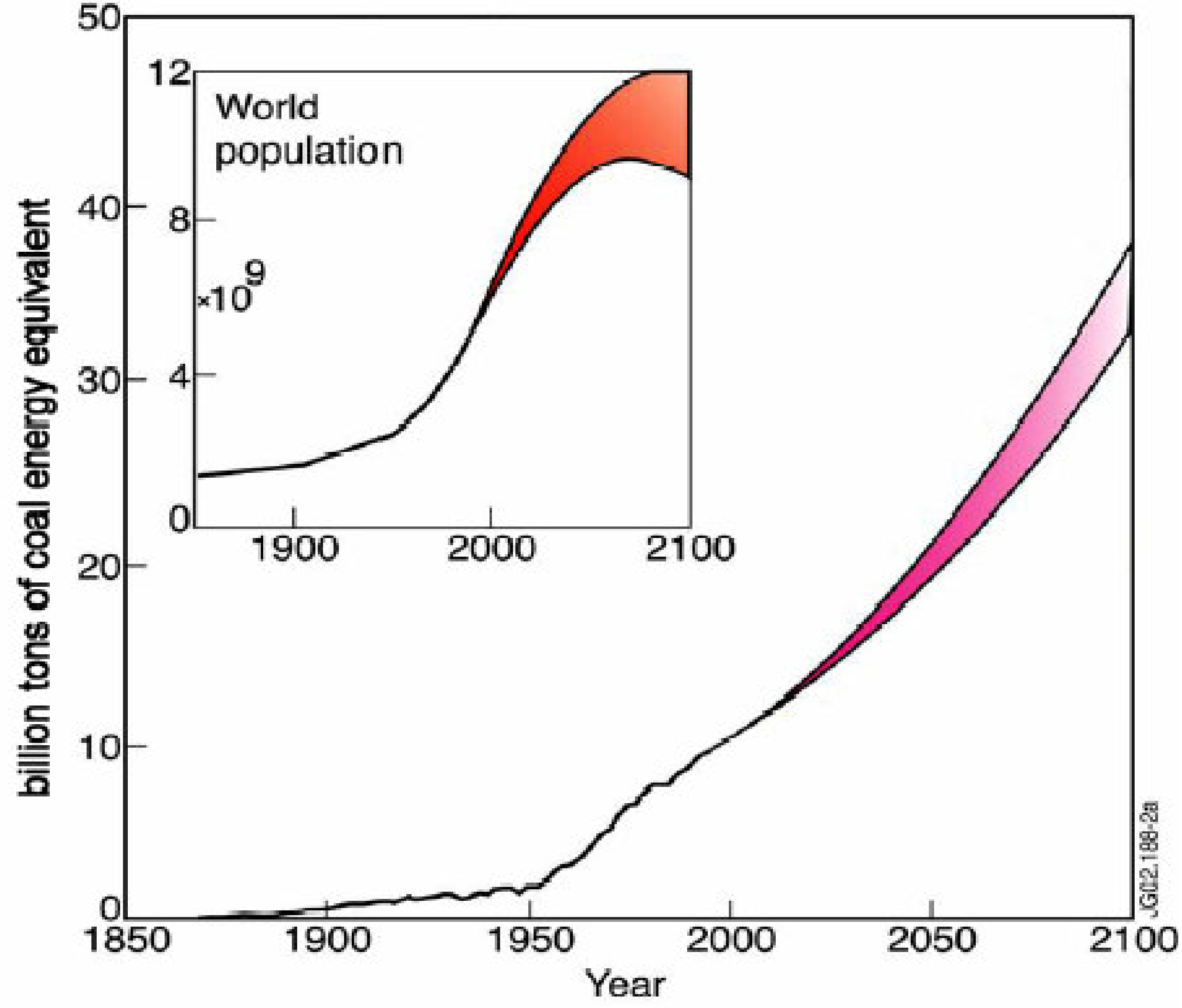
JAI Lecture Oxford May 3rd 2007

Summary

- Introduction
- Partitioning and transmutation
- Accelerator driven system
- MYRRHA/XT-ADS components
- Deployment

Energy problem

Doubling
in next 50 years



Solution?

- Reduce consumption
  - Zero growth
  - developing nations ?
- Renewable energy ?
  - 10-15% max in our region
  - back-up power
- Fossil fuels ?
  - Finite
  - $C0_2$
- Nuclear Fusion ?
  - Great, but when ? (@ t+50y, ∀t ?)

Go with nuclear (fission!)

Fission ?

- Our plants are safe

Yes, but within a “safety culture”

Risk = Probability * Consequences

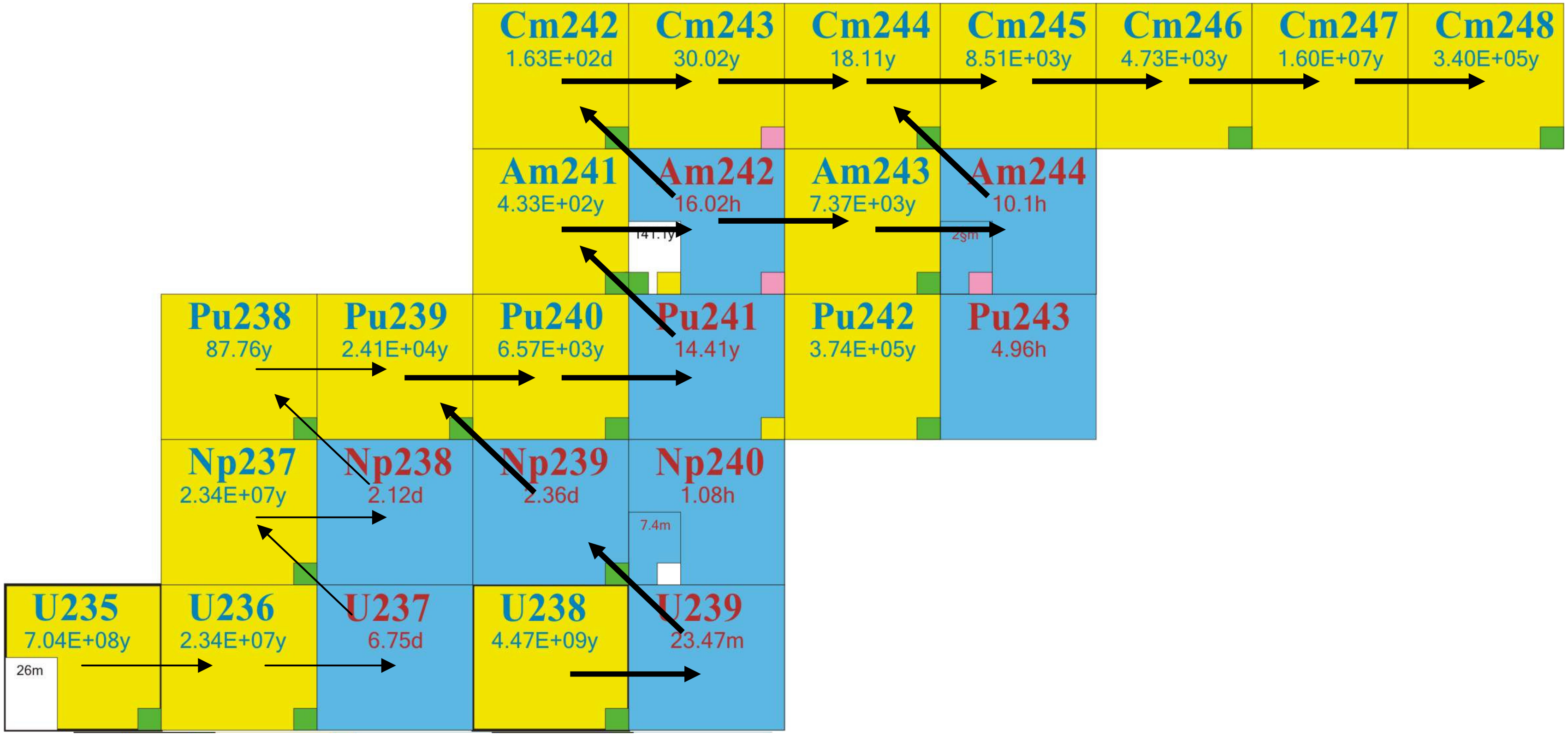
$R = 0 * \infty$

unstable risk

It explains the acceptability reluctance

And they generate
long-lived highly toxic radioactive products

Waste from fission



Solution : burn them !

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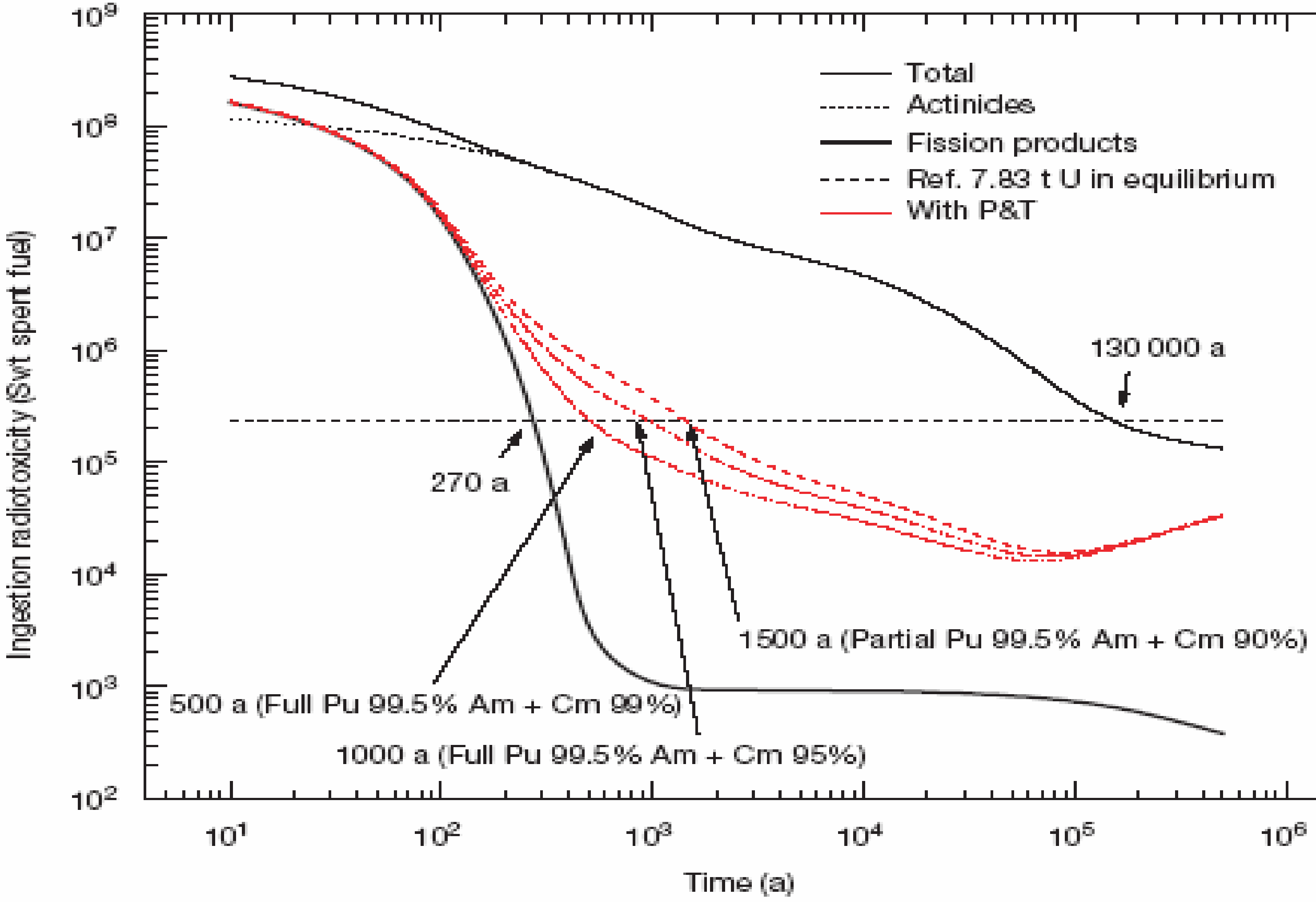
Nuclear Energy & waste

- Europe : 35% of electricity from nuclear energy
- This produces about 2500 t/y of spent fuel:
  - 25 t Pu
  - 3.5 t minor actinides
  - 3 t long lived fission products
- Worldwide : multiply by 4
- A technically, socially and environmentally satisfactory solution is needed for the waste problem.
- Partitioning & Transmutation (P&T) of MA and LLFP can lead to this acceptable solution by reducing time scales for waste storage.

Transmutation



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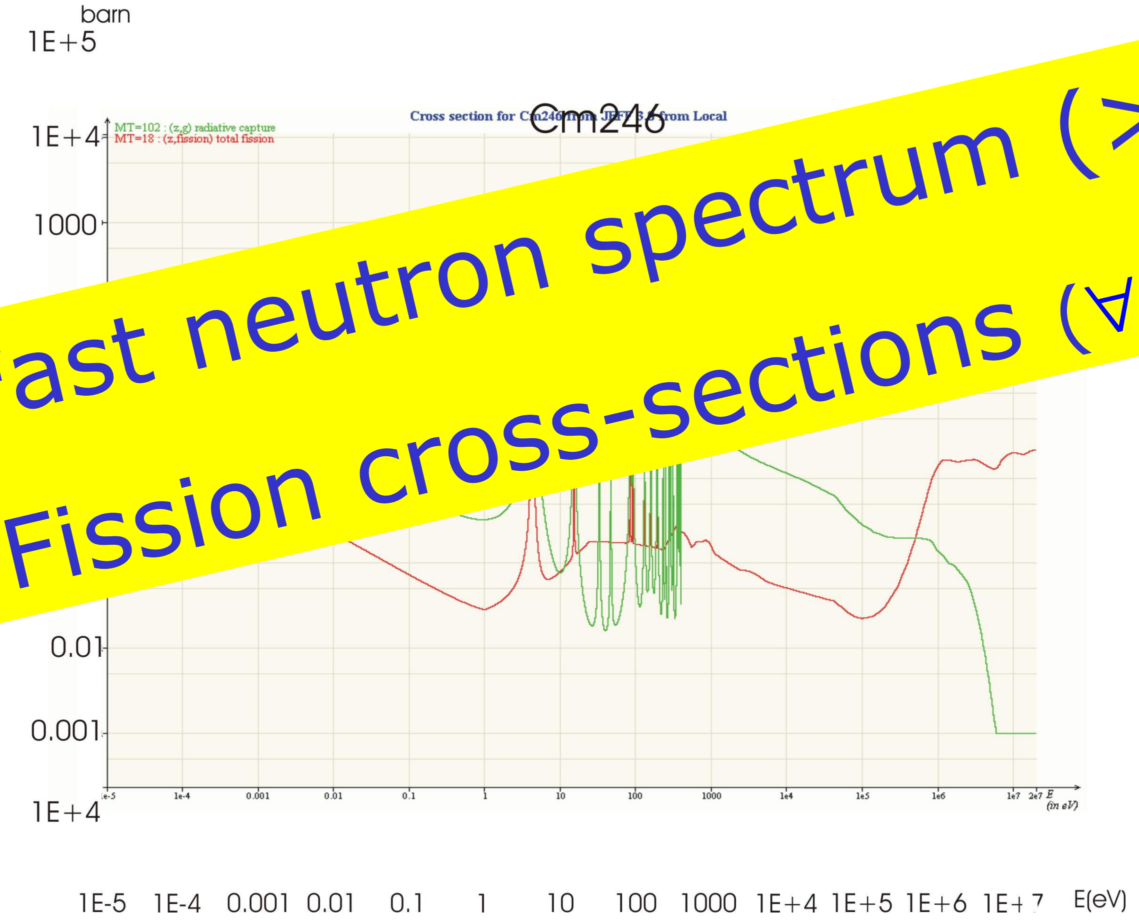
Fission of minor actinides



- Fast neutron spectrum (>1MeV)
- Fission cross-sections (∀ Energies)

Reactor dynamics

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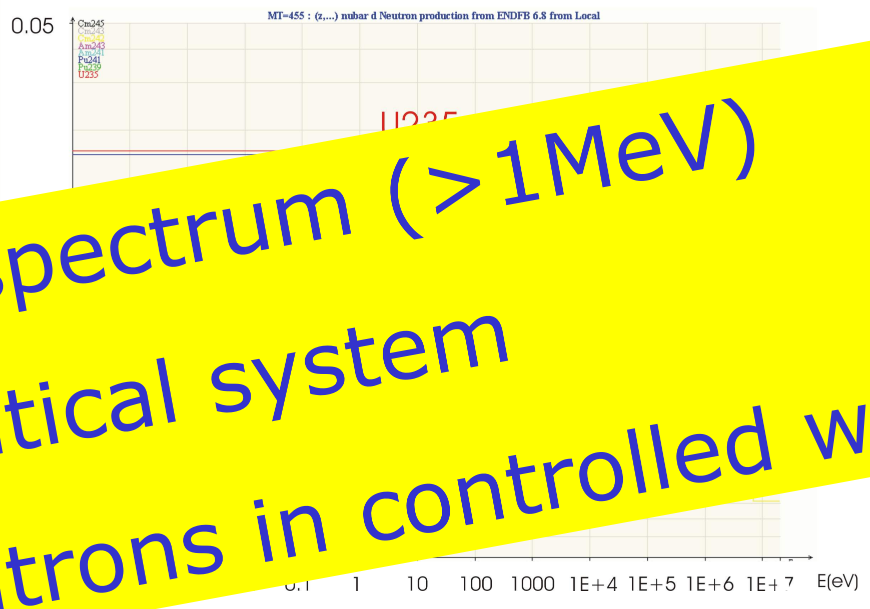
Fraction of delayed neutrons/fission



Fast neutron spectrum (>1MeV)

Sub-critical system

Feed lacking neutrons in controlled way

-
- T ... /fission ↑: Fraction of delayed n° ↓
- MA fuel makes reactor more difficult to handle (nervous)
- Maximum MA fuel load in critical fast reactor : 1-1.5%

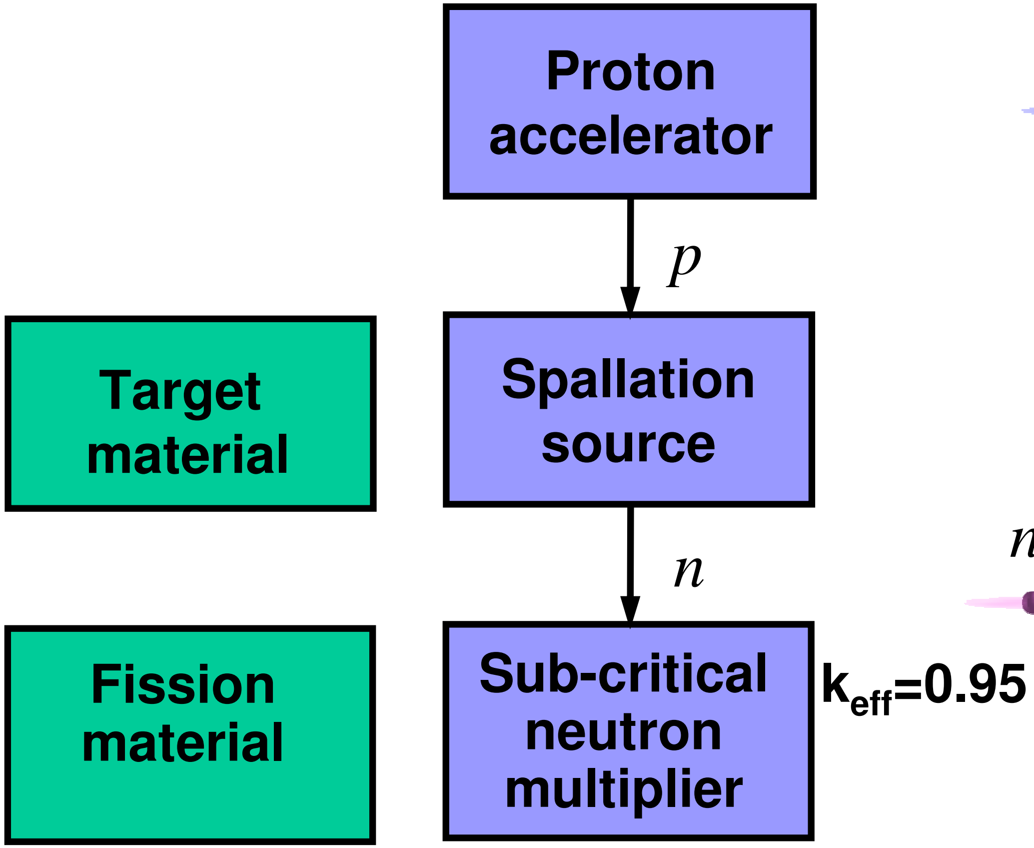
ADS Concept

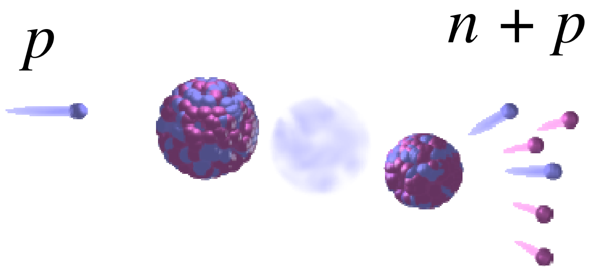
The idea of using accelerators to produce fissionable material was put forward by G.T. Seaborg in 1941. He produced the first human-made plutonium using an accelerator.

In the 1990s C. Bowman's group at LANL and C. Rubbia's group at CERN designed a transmutation facility using thermal neutrons (CB) and fast neutrons (CR), for burning both the actinides and long life fission products from spent LWR fuel.

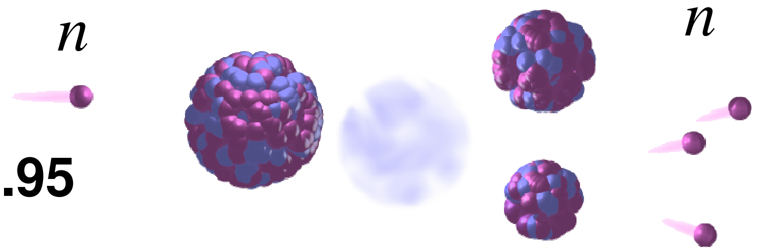
The facility, called an ADS, combines high intensity proton accelerators with spallation targets and a subcritical core.

Accelerator driven system Concept





Spallation

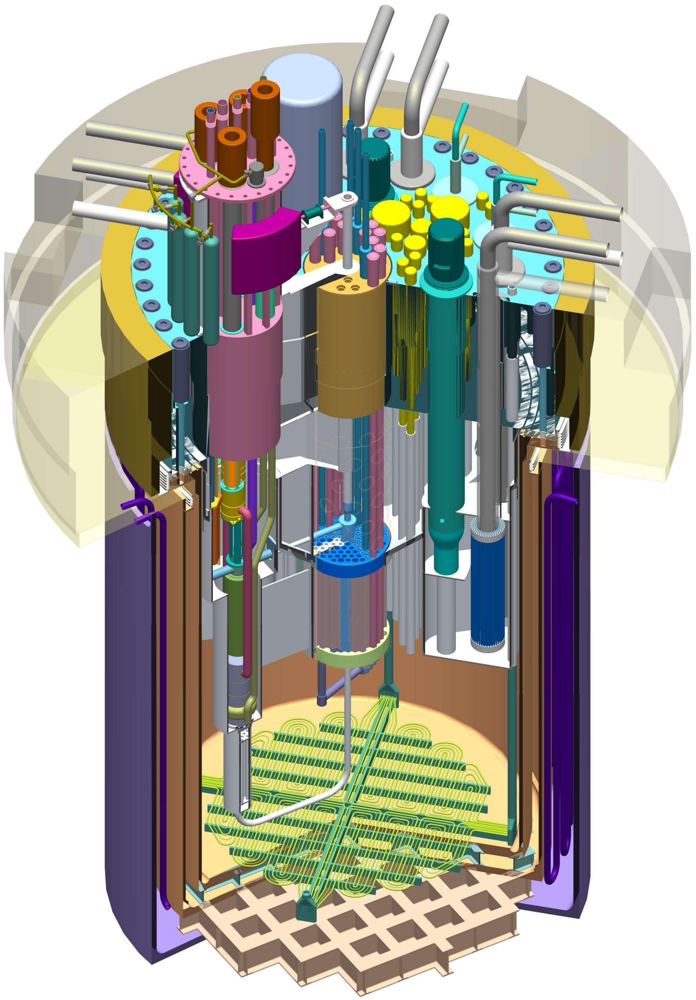


Fission

MYRRHA/XT-ADS

eXperimenTal-ADS: applications catalogue

- ADS first step demonstration facility
  - ➢ Coupling of three components at reasonable power level (~50-100 MWth)
  - ➢ ADS Operational and Safety studies
    - ⇒Operation with liquid metal coolant (Lead-Bismuth Eutectic)
    - ⇒Operation feed-back with sub-criticality monitoring and control
    - ⇒Beam trip mitigation and restart procedures after interruptions
    - ⇒Spallation products monitoring and control
  - ➢ P&T testing facility



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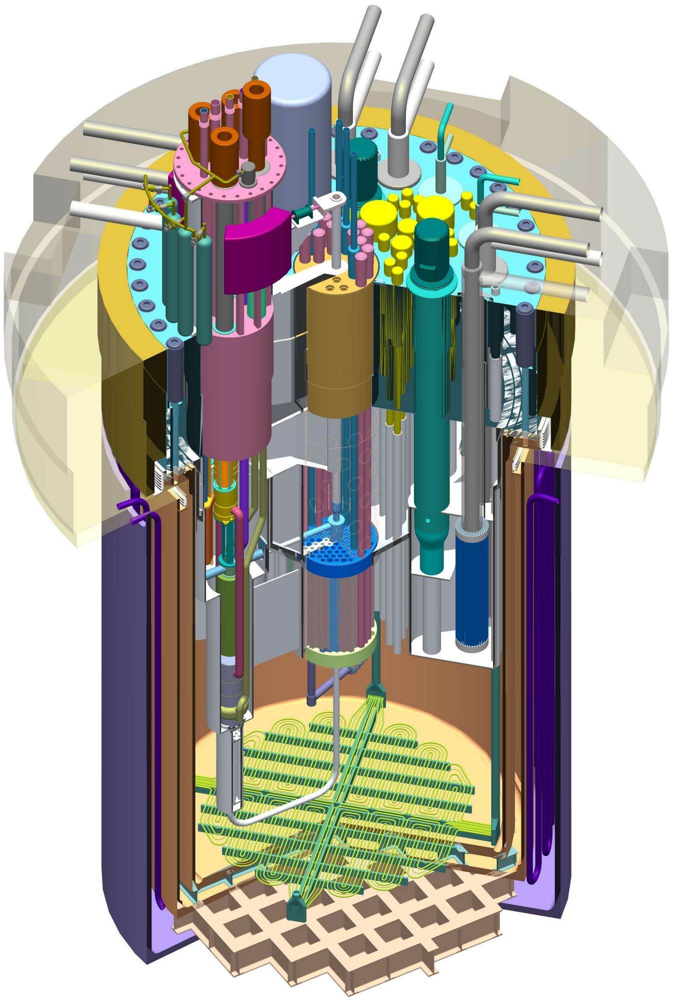
MYRRHA/XT-ADS
eXperimenTal-ADS: applications catalogue

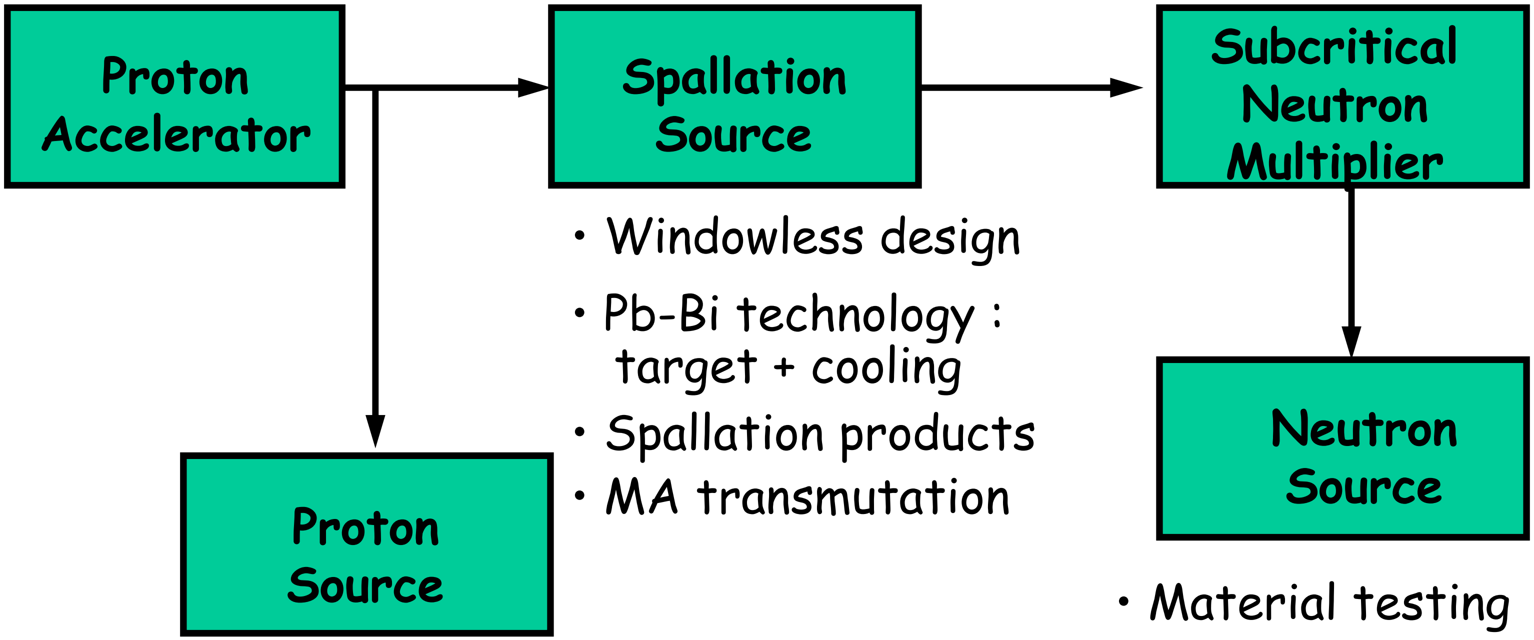
MYRRHA

- Flexible irradiation facility in Europe
  - Fast spectrum : complementary to Reactor Jules Horowitz (France)
  - GenIV applications
  - Materials research :PWR, BWR, Fusion, Fuel
  - Medical isotope production
  - Replacement of BR2 (100 MWth MTR at Mol)



Need for high performance core : high power density in limited volume
  - $\Phi_{>0.75\,MeV}$ ~10^{15} n/cm^2 .s)
  - Φ_{th} ~2.10^{15} n/cm^2 .s)

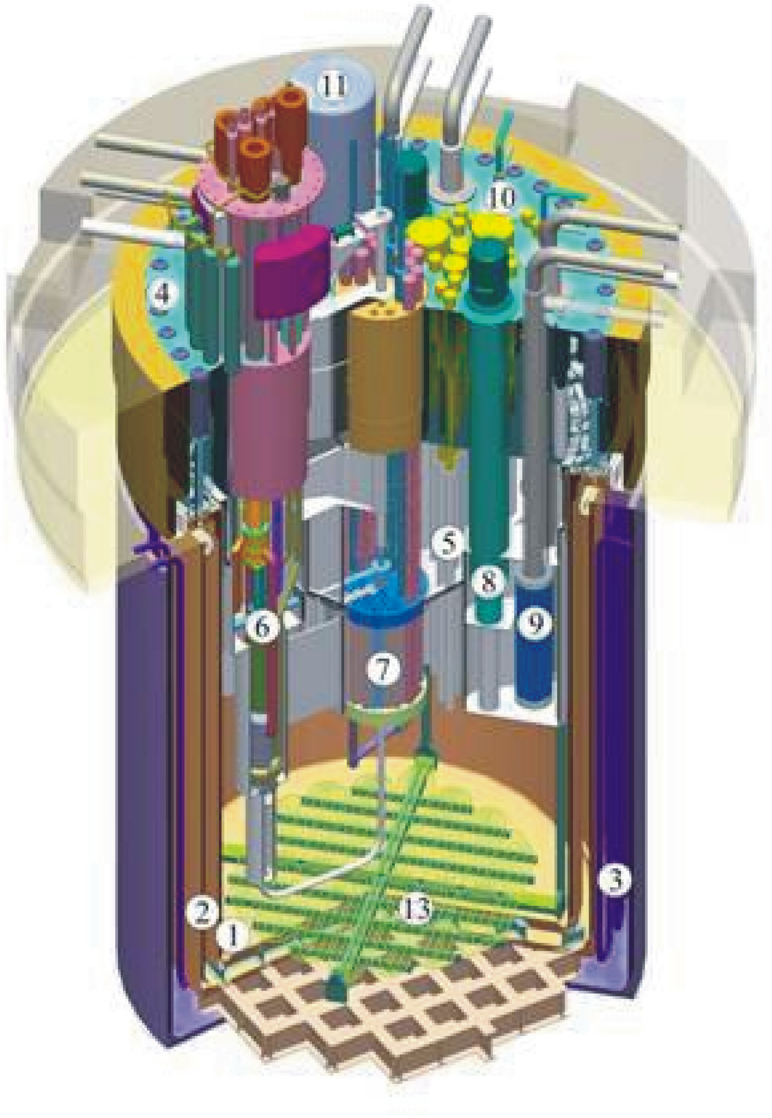
MYRRHA - concept
multipurpose experimental ADS



- Material testing
- Fuel irradiation
- MA & LLFP transmutation
- Radioisotope production

- Material testing
- Radioisotope production
- Proton therapy
- Nuclear physics

The MYRRHA machine



1. inner vessel
2. guard vessel
3. cooling tubes
4. cover
5. diaphragm
6. spallation loop
7. sub-critical core
8. primary pumps
9. primary heat exchanger
10. emergency heat exchanger
11. in-vessel fuel transfer machine
12. in-vessel fuel storage
13. coolant conditioning system

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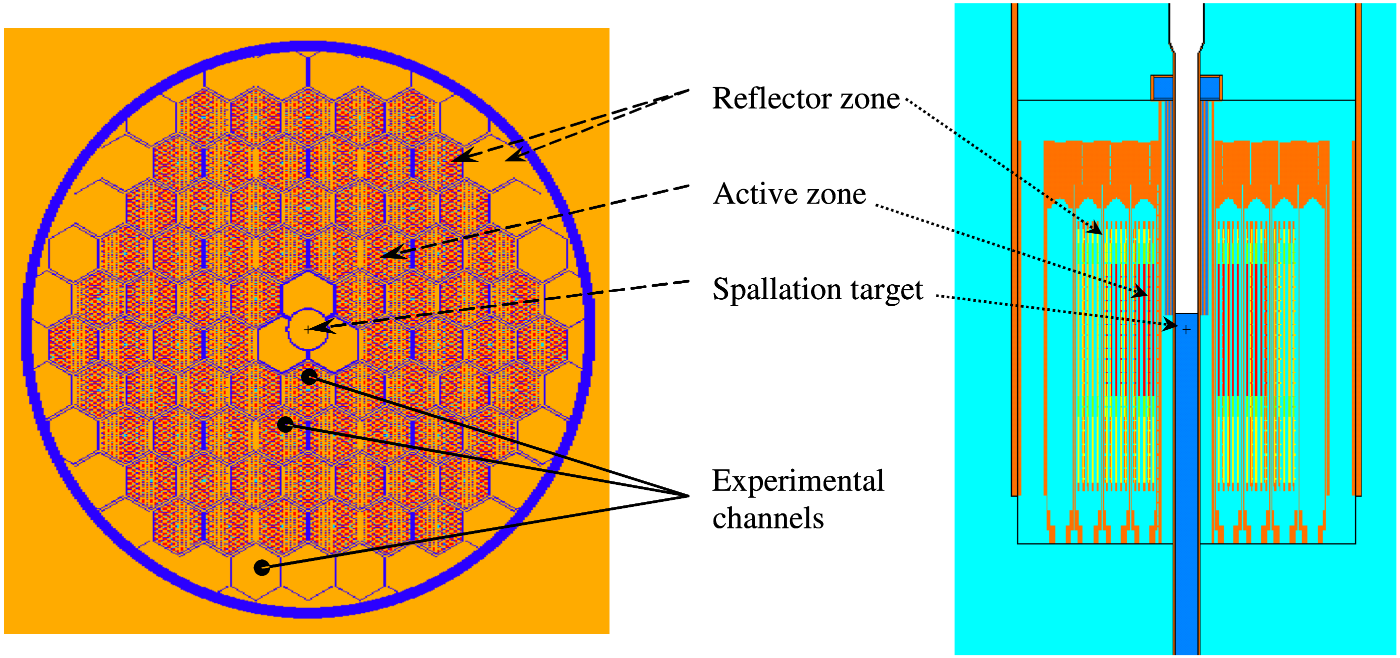
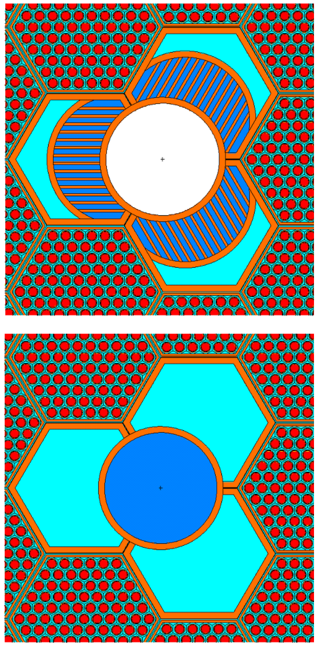
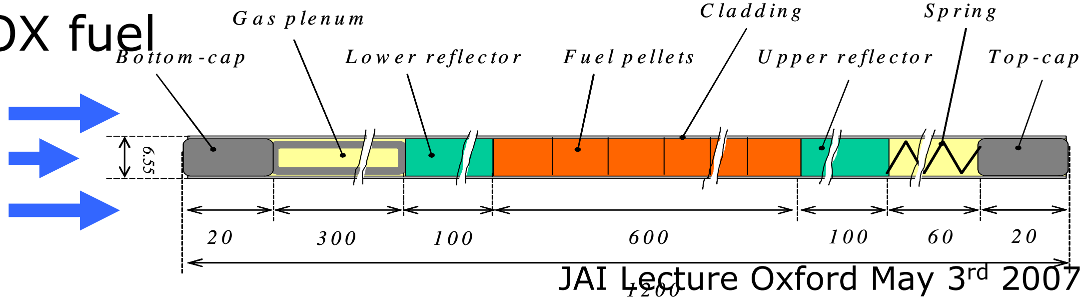
Core configuration

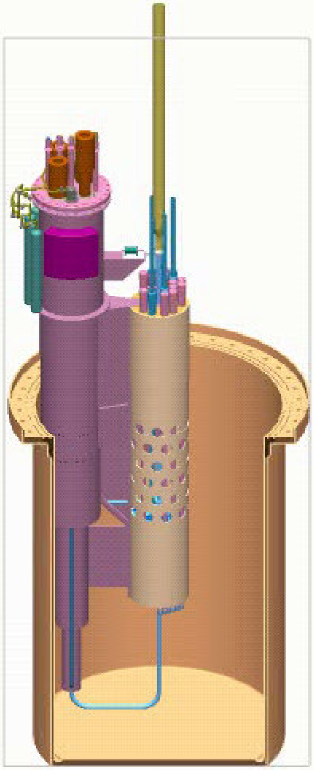




- hexagonal cells ("macro-cells")
- Target-block hole : 3 FA removed
- Surrounding active zone : MOX fuel
- Outer reflector zone

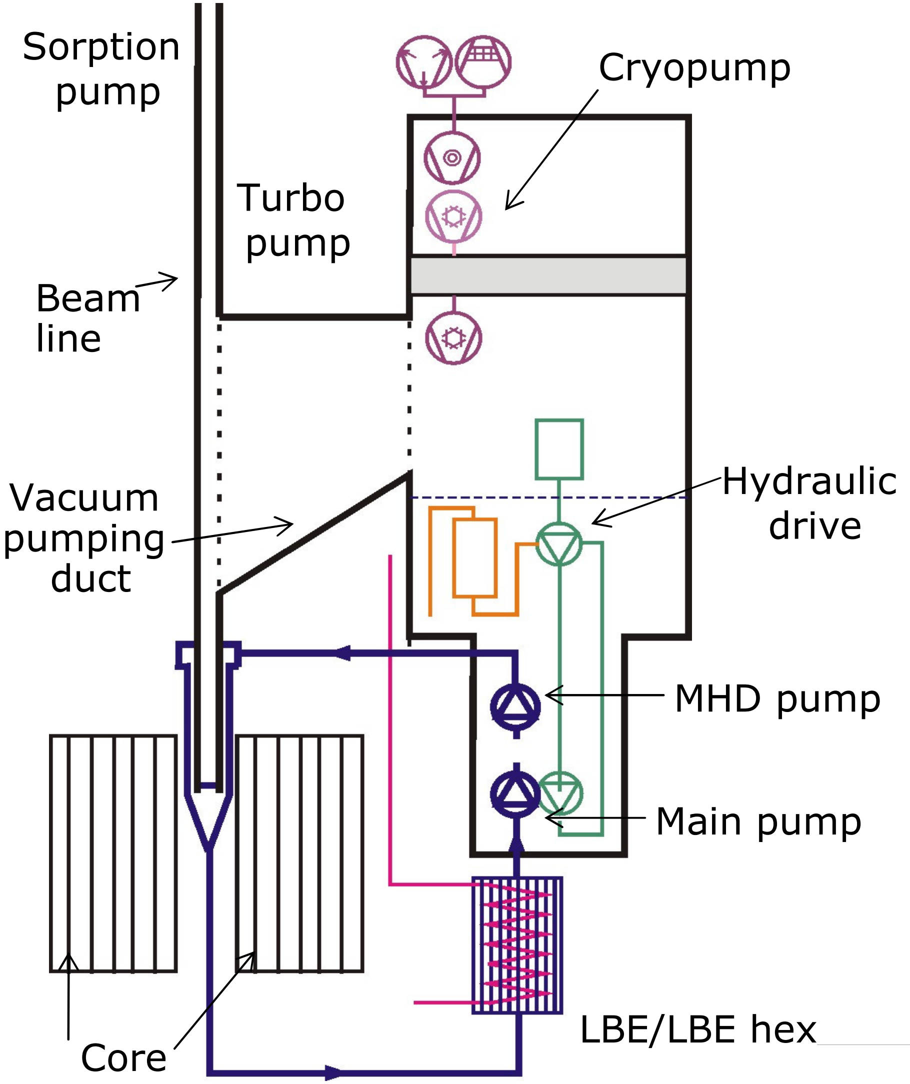


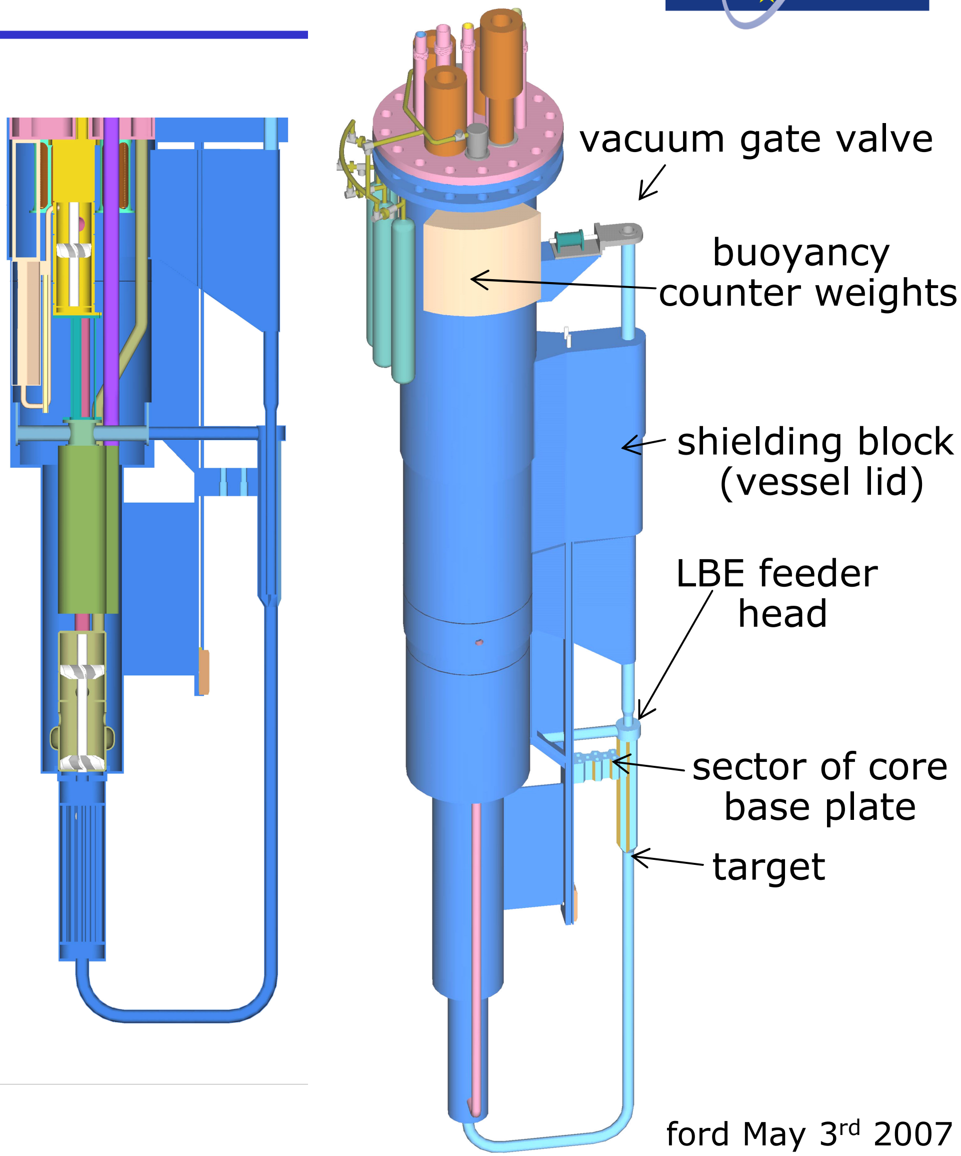
Spallation target



- Tasks
  - Produce 10^{17} neutrons/s to feed subcritical core @ k_{eff}=0.95
    - heavy target material
  - Accept megawatt proton beam
    - 600 MeV, 2.5-4 mA
    - liquid metal & forced convection
  - Fit into central hole in core
    - compact target
    - Off-axis geometry
  - Match MYRRHA purpose as experimental irradiation machine
    - flexible remote handling
  - Survive (lifetime)

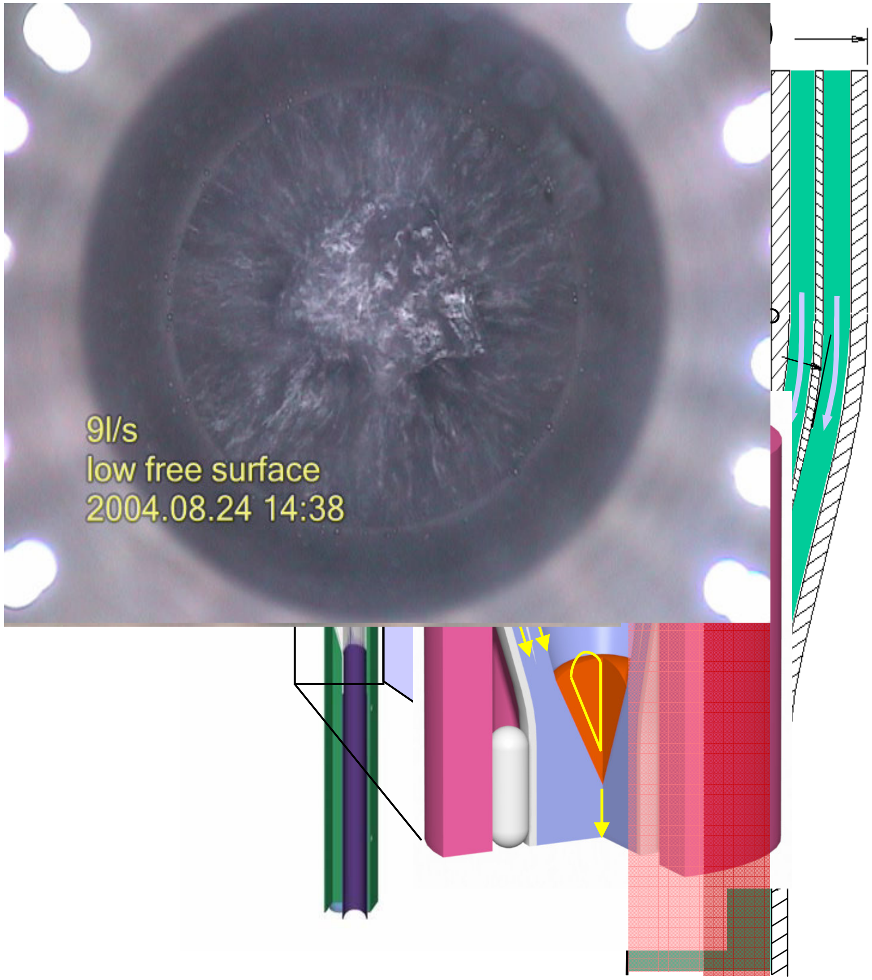
MYRRHA/XT-ADS components
Spallation target





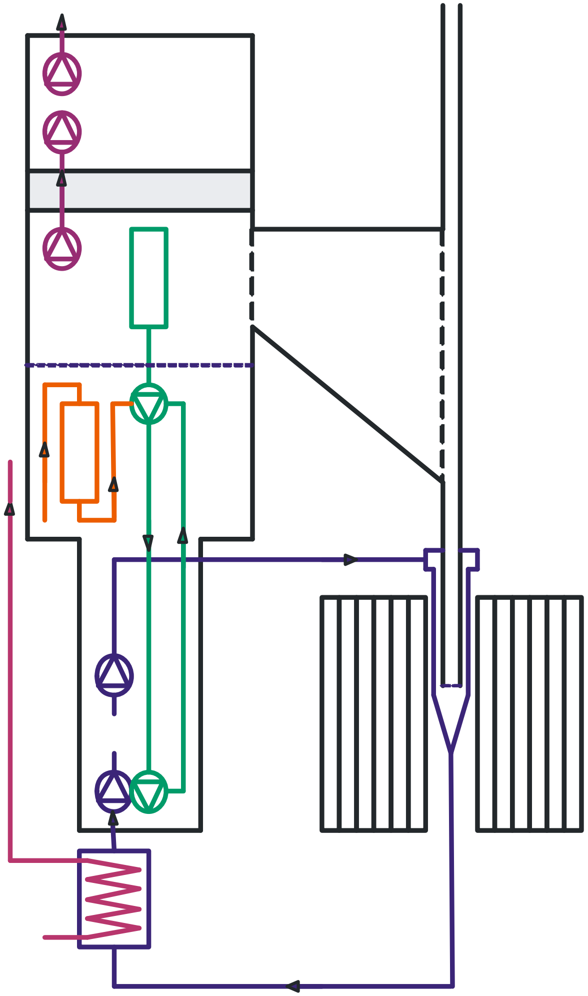
ford May 3rd 2007

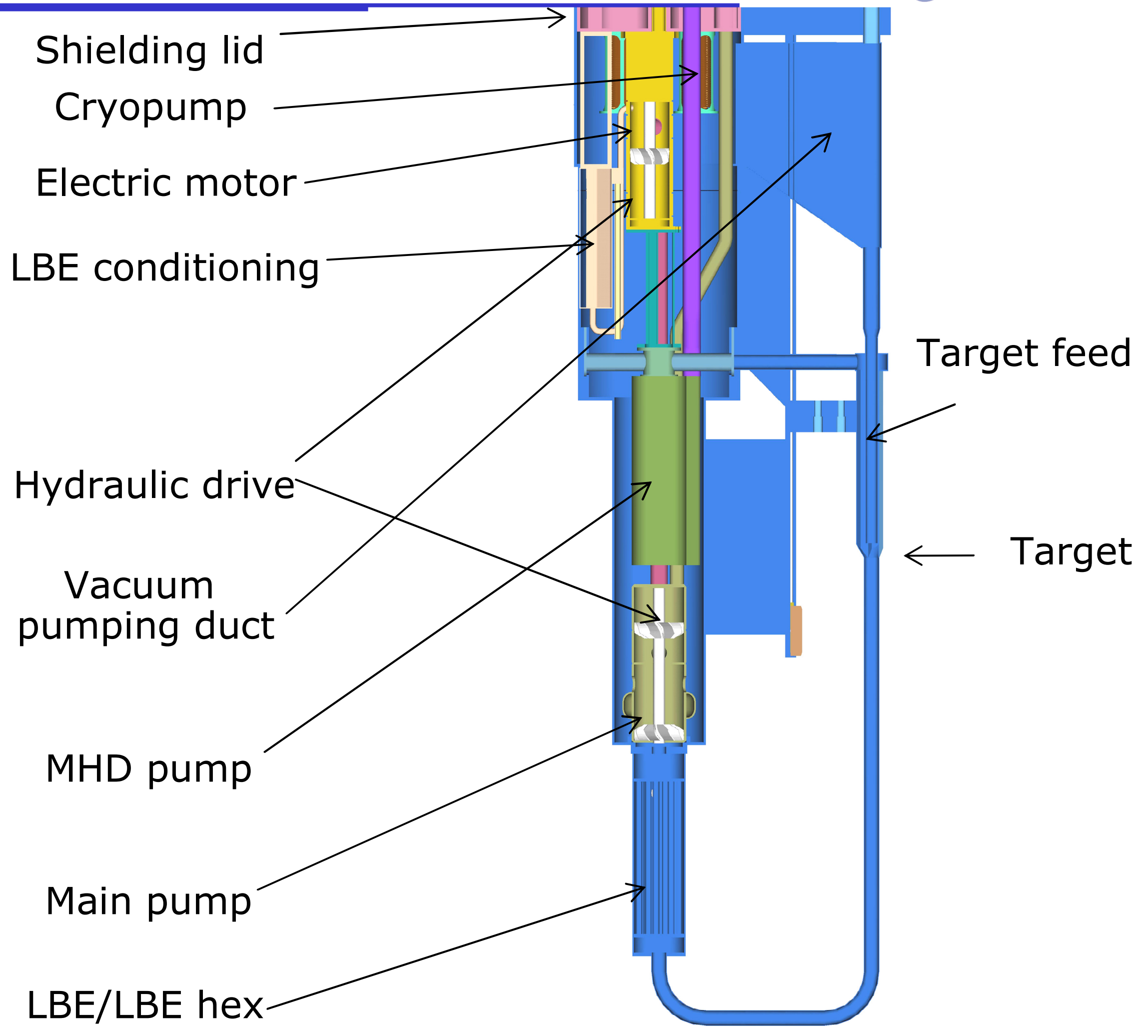
Spallation target



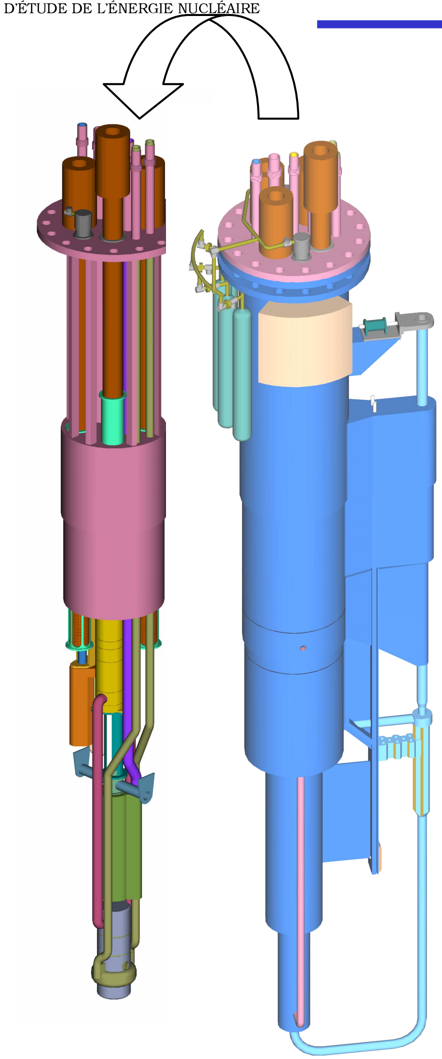
- Windowless target
  - space considerations
  - beam density
- Formation of target free surface
  - Confluence of Vertical coaxial flow
  - Driving force : gravity
  - Level : balance inlet-outlet flow
  - Recirculation zone : in check
  - Feedback necessary
  - Proton beam distribution
    - Avoid recirculation zone heating

Layout schematics





Remote handling compatibility



- Service by remote handling
  - Entire spallation unit removable from main vessel after core unloading
    - ♣ avoid criticality issues
    - ♣ safety
    - ♣ in situ commissioning
  - Separate sub-unit with all active elements
    - ♣ servicing without removal of spallation loop
  - Closed outer housing
    - ♣ replacement of spallation zone (embrittlement)
    - ♣ replacement of HEX
- Remote handling requirements
  - handling : machine; instrumentation
  - cutting; welding; ...

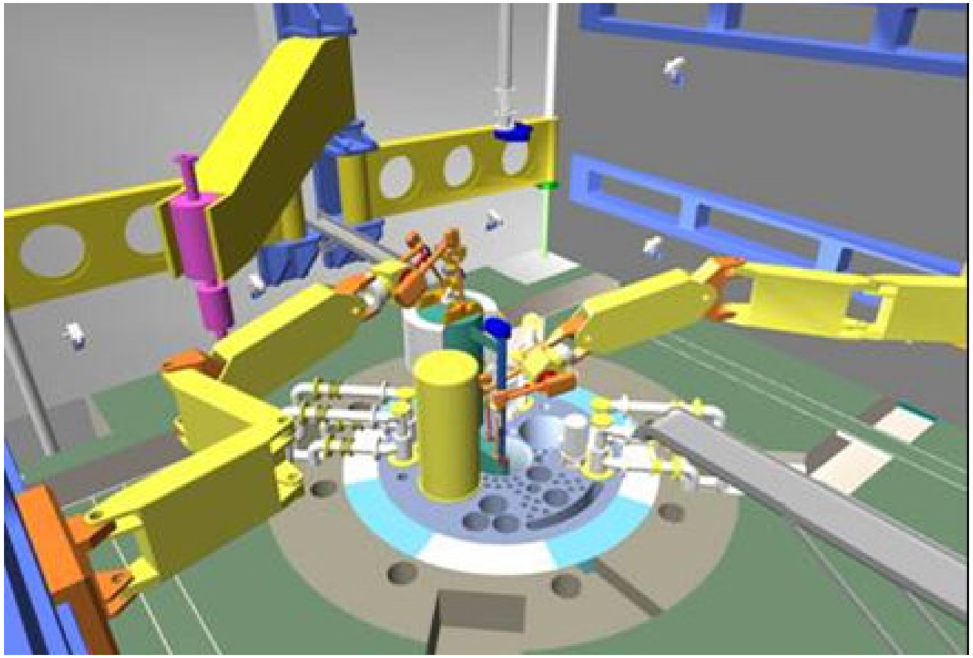
Maintenance, inspection and repair

- Operation and maintenance of MYRRHA with remote handling systems
  - High activation on the top of the sub-critical reactor,
  - α-contamination due to ^{210}Po when extracting components from the reactor pool,
  - non-visibility under Pb-Bi,
- Develop appropriate “In Service Inspection and Repair” (ISIR) and ultrasonic (US) visualisation systems.
- Maintenance schedule

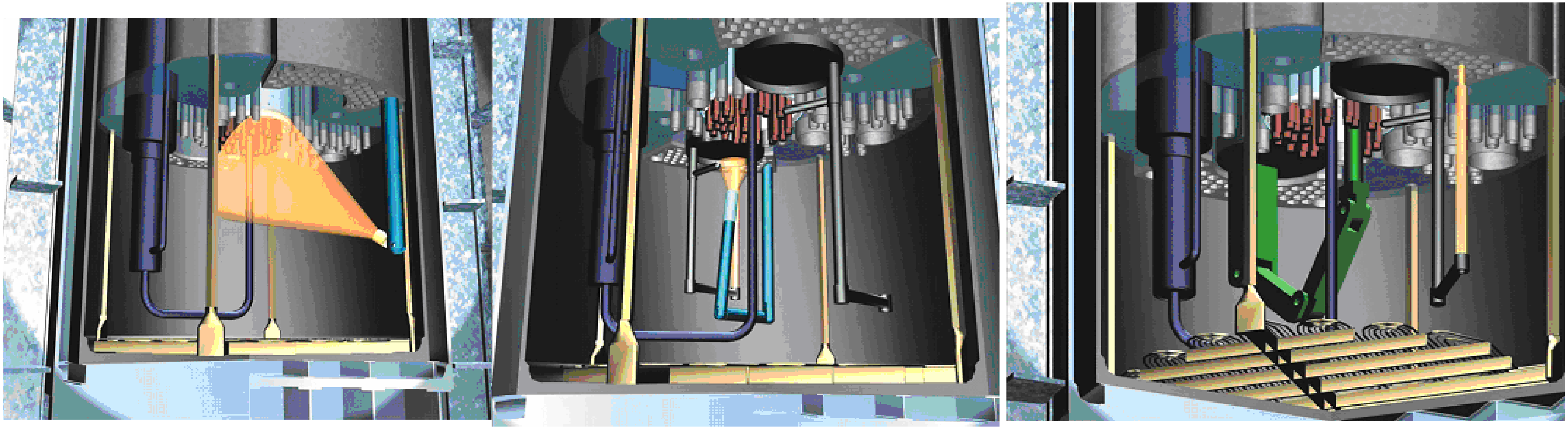
Remote handling

All MYRRHA maintenance operations on the machine primary systems and associated equipment are performed by remote handling, which is based on the *Man-In-The-Loop principle*:

- force reflecting servomanipulators
- Master-Slave mode: the slave servo-manipulators are commanded by remote operators using kinematically identical master manipulators
- supported with closed-cycle TV (CCTV) feedback



In-service inspection and repair



- Two permanent *inspection* manipulators
    - ➢US camera : *overview*.
- Second inspection manipulator close to critical components
    - ➢Detailed inspection
- Repair manipulator
    - ➢Recovery of debris
    - ➢Deployment of specialised tooling for repair

ADS Accelerator : Requirements

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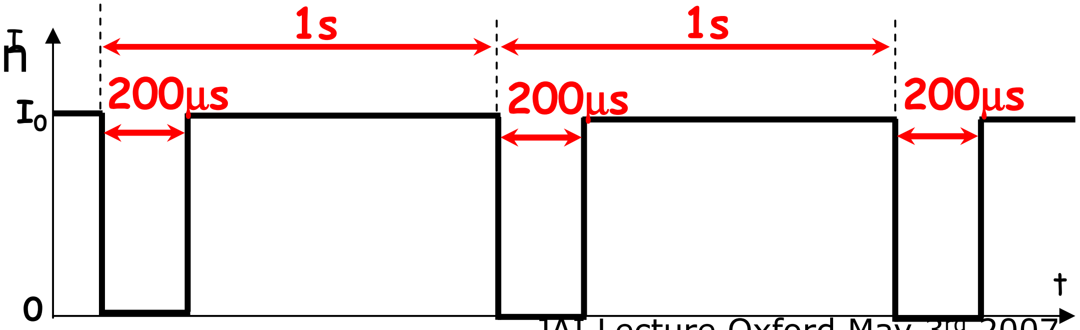
Proton Beam Specifications:

- 600 MeV*4 mA max for operation of XT-ADS
- High reliability :
  - **Less than 5 beam Trips > 1sec per cycle**
  - Power stability ±2%
  - Energy stability ±1%
  - Intensity stability ±2%
  - Beam footprint dimensions ±10%
- Additional requirements:
  - 200μs beam holes for on-line sub-criticality level measurement
  - Safety grade shut down



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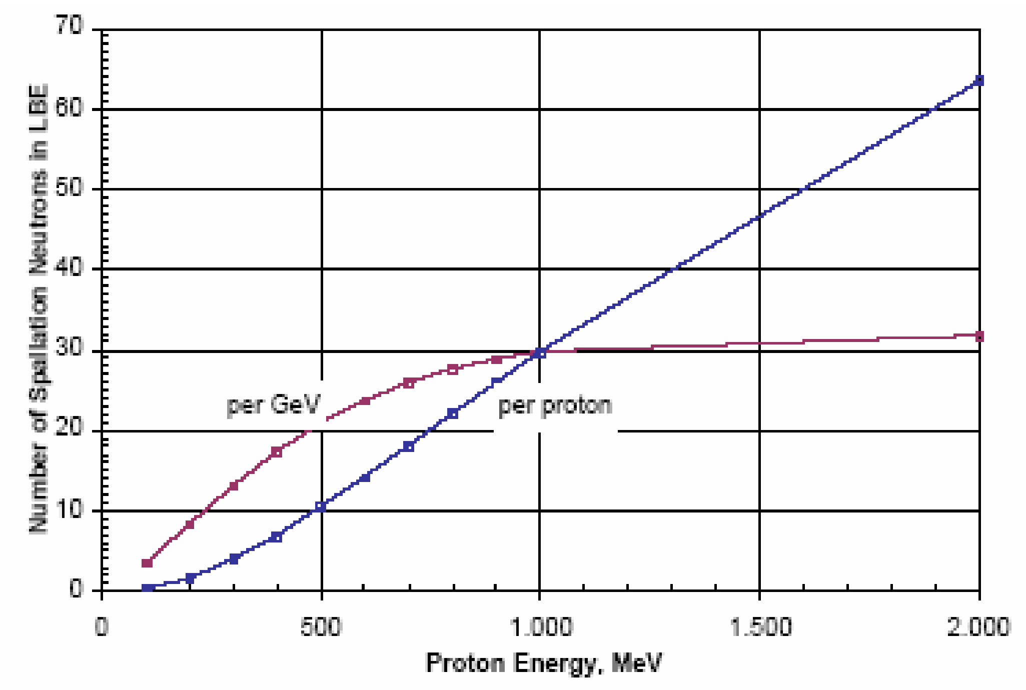
Accelerator

MYRRHA

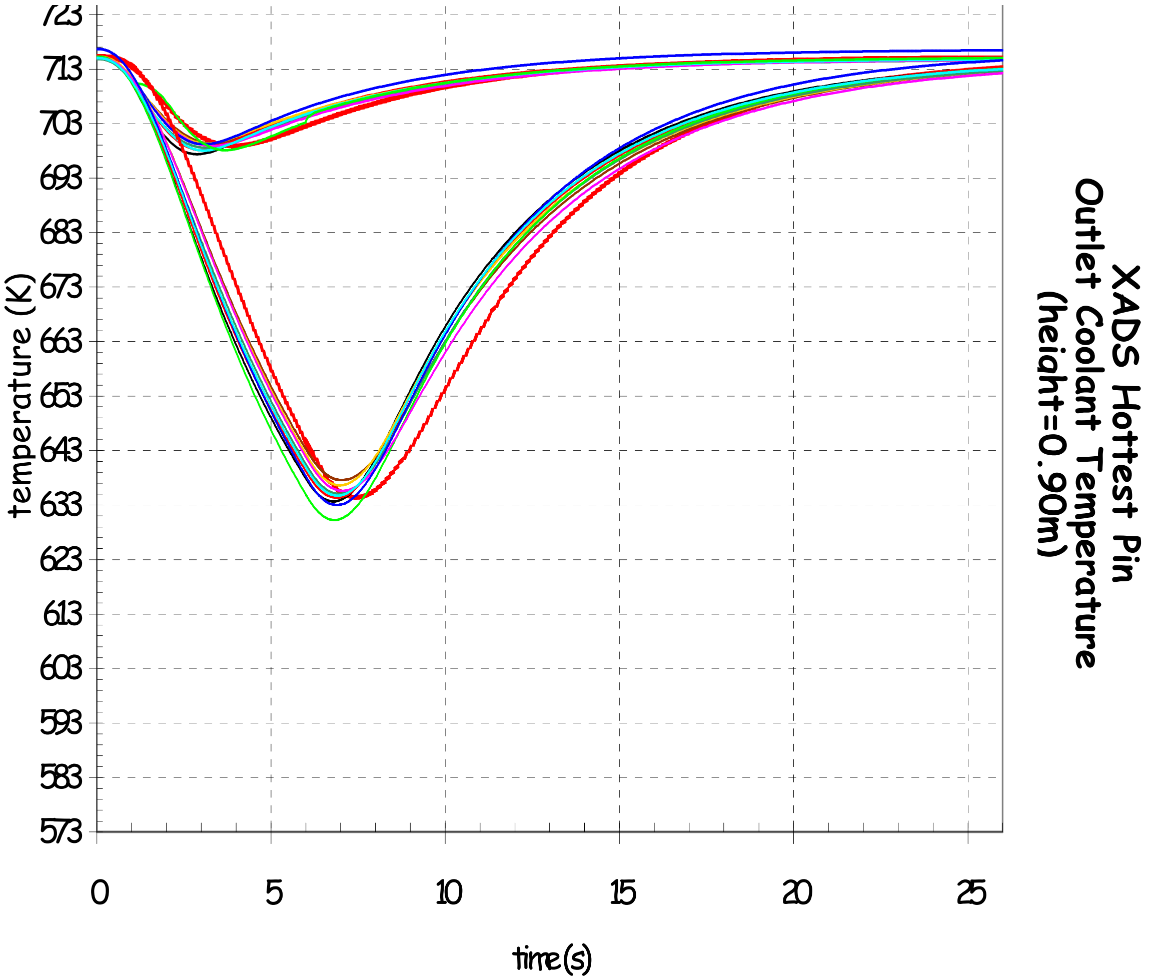
- Performance
  - ➢ energy E_p & intensity i_p
  - ➢ neutron yield per proton and per unit of energy
  - ➢ fraction of energy deposited at target entrance



➔E_p : 600 MeV → 1 Gev

➔i_p : 4 mA → 25 (40) mA

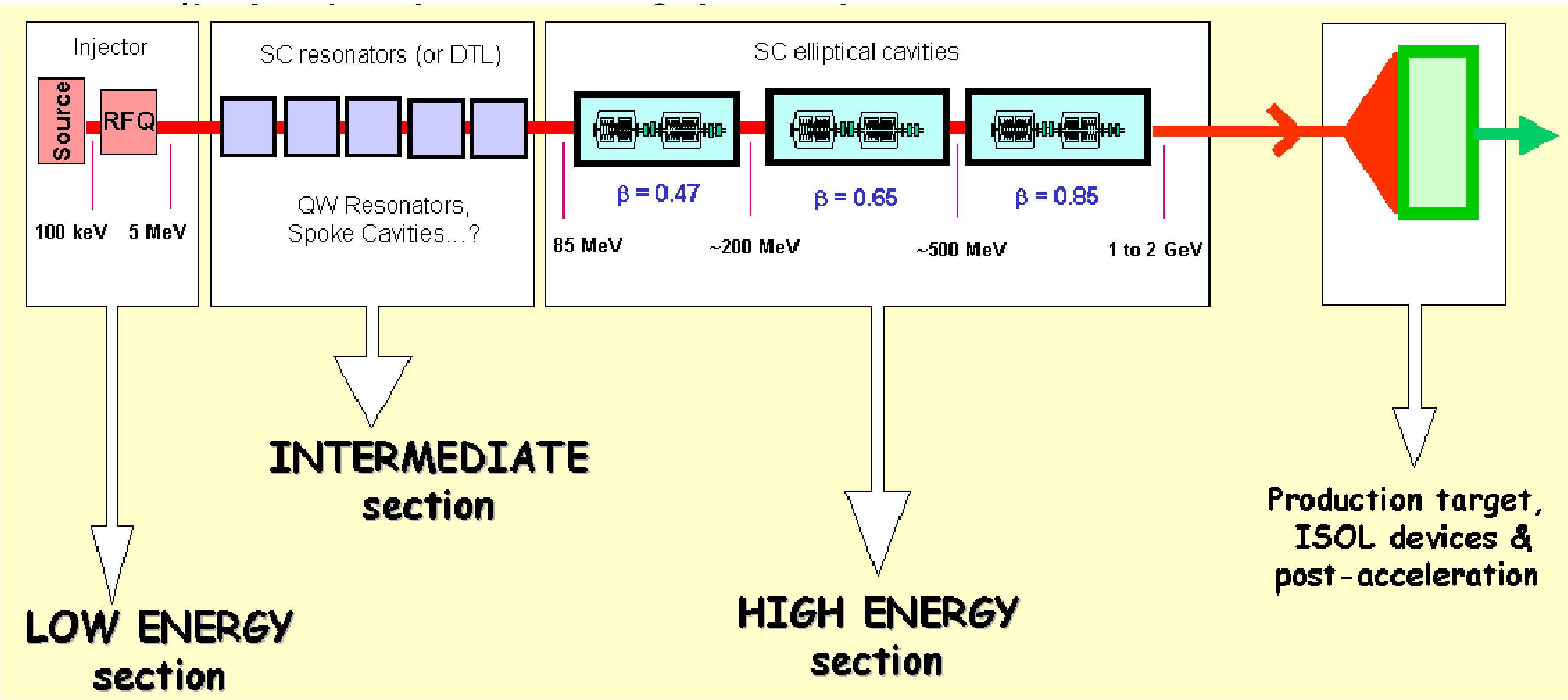
Accelerator



- Reliability and safety
  - ➢ beam trips → significant damage to
    - ♣ reactor structures
    - ♣ spallation target
    - ♣ fuel
  - ➢ beam shutdown system

The choice of the Generic Accelerator Type

- LINAC



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The low-energy section

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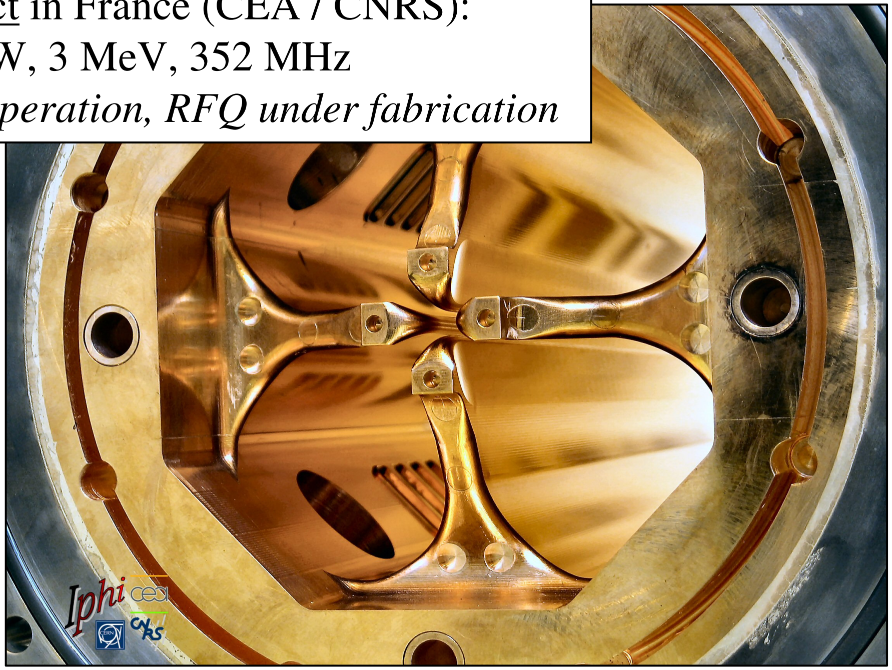
High-intensity proton injectors are quite straightforward: ECR source + RFQ

<u>TRASCO project</u> in Italy (INFN):
30 mA CW, 5 MeV, 352 MHz
source in operation, RFQ under fabrication

<u>LEDA project</u> at Los Alamos:
100 mA CW, 6.7 MeV, 350 MHz
in full operation (now stopped)

<u>IPHI project</u> in France (CEA / CNRS):
100 mA CW, 3 MeV, 352 MHz
source in operation, RFQ under fabrication

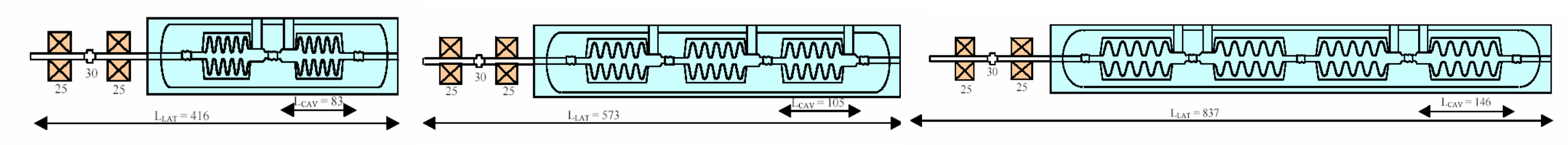


The high-energy section (1)

<u>General agreement for using **SC multi-cell elliptical cavities** @700 MHz:</u>

- **High performance** (gradients, efficiency, security, reliability, modularity…)
- **“Well-established” solution** (TTF, SNS…)
- **Comfortable margins can be chosen on critical values to ensure a design as robust as possible**: it consists in limiting, in a reasonable way, the minimum beam apertures, the fields in the cavities, the phase advances along the linac, the sensibility to beam mismatch, or the possibility of halo creation.

Layout of the XADS high-energy section :



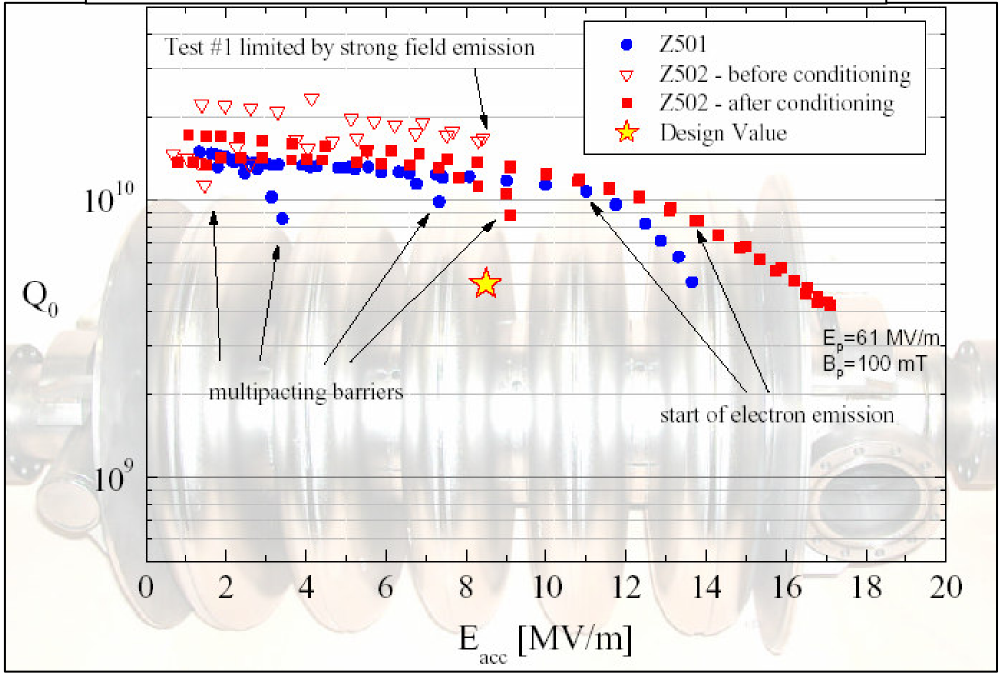
β=0.47 (90-192 MeV), β=0.65 (192-498 MeV) & β=0.85 (498 MeV – 600 MeV or 1 GeV)

(14 modules / 59 m) (17 modules / 99 m) (3 or 12 modules / 26 or 101 m)

The high-energy section (2)

Active R&D and prototyping are going on successfully at CEA Saclay, CNRS / IPN Orsay & INFN Milano

Test results @2K of 5-cell β=0.5 prototypes (INFN Milano)



A 5-cell β=0.65 prototype (CEA Saclay / IPN Orsay)

The intermediate section (1)

Two concepts have been retained:

1. Extend the injector philosophy towards high energies using **DTL-type structures**
2. Extend the high-energy SC linac philosophy towards low energies using **low-beta superconducting resonators**

The SC cavities solution as compared to **a room-temperature DTL solution**

- Roughly same length & construction cost
- Excellent "RF to beam" efficiency

  => **Significant operation cost savings (7 MW AC, i.e. 1.5 M€/year for a 4 mA beam)**

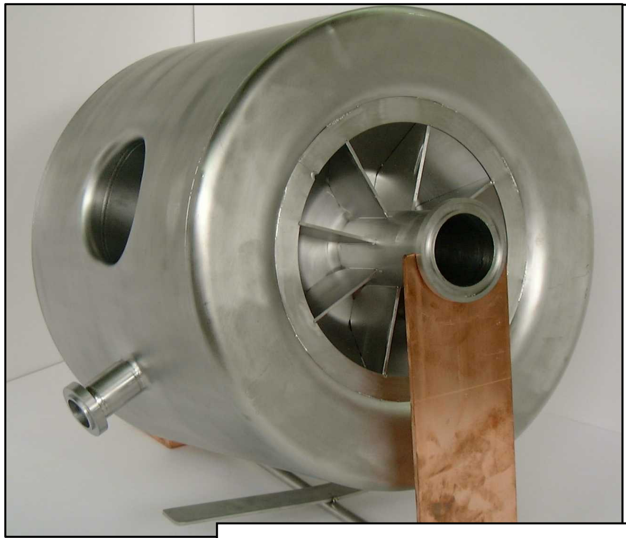
- Very large beam aperture => **High safety** (less structure activation)
- Independant RF structures => **High flexibility** (power adjustments)

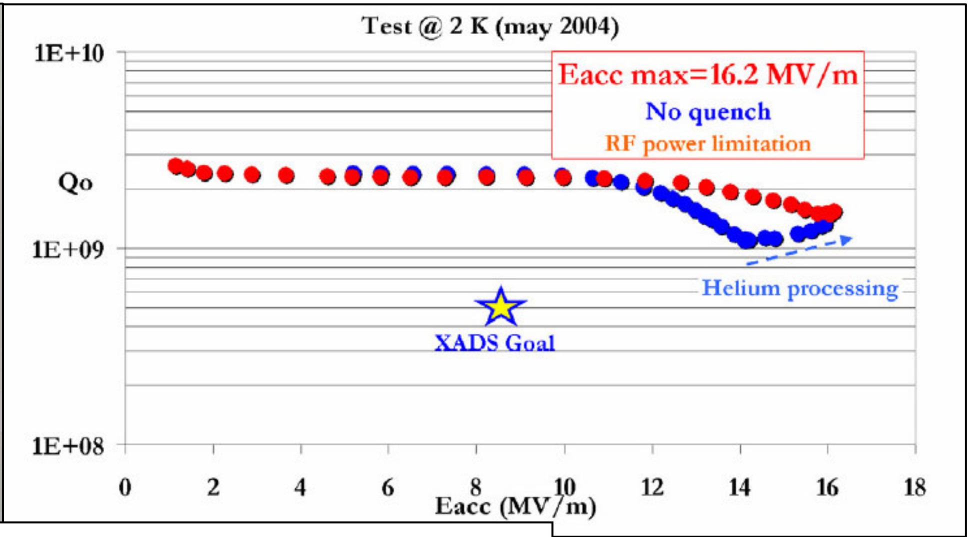
  => **High reliability** (low power RF components, fault tolerance capability)

- **Poor real estate gradient at very low energies** (< 20 MeV)

The intermediate section (2)

- **The independently-phased SC option is agreed** from "X" MeV (X still to be defined between 5 and 50 MeV), especially because of it allows to implement the **fault-tolerance concept** *(see later)*
- **352 MHz Spoke cavities,** developed by CNRS / IPN Orsay, are used in this region (high shunt impedance, good mechanical stability & tunability, no steering effect, possibility to design multi-gap structures if needed, excellent test results)





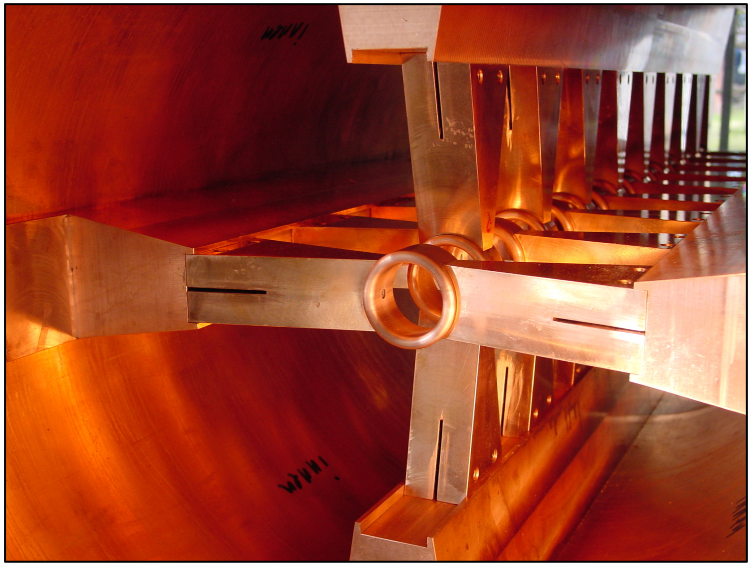
Test result on a β=0.35 spoke cavity (IPN Orsay)

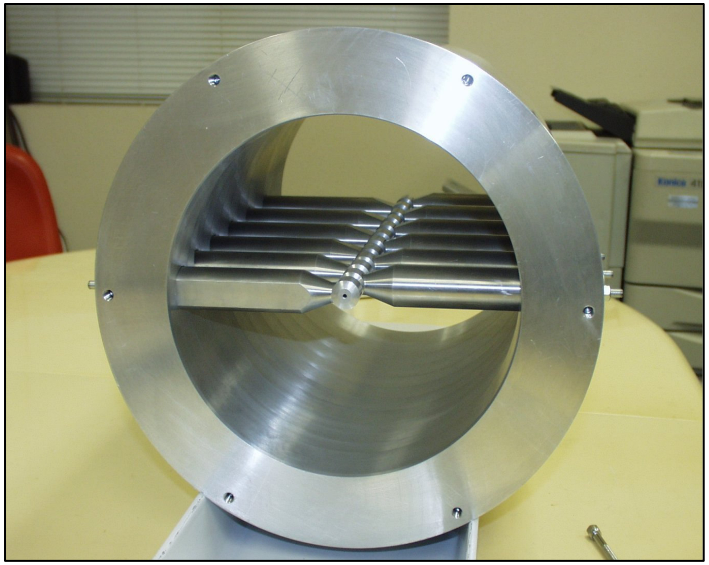
The intermediate section (3)

- Between 5 MeV and 20 MeV, the β=0.15 spoke solution is not so efficient in terms of real estate gradient; DTL-type solutions are also explored:

  - **Superconducting CH-DTL structure**, developed by IAP Frankfurt

  - **Room-temperature IH-DTL structure**, developed by IBA

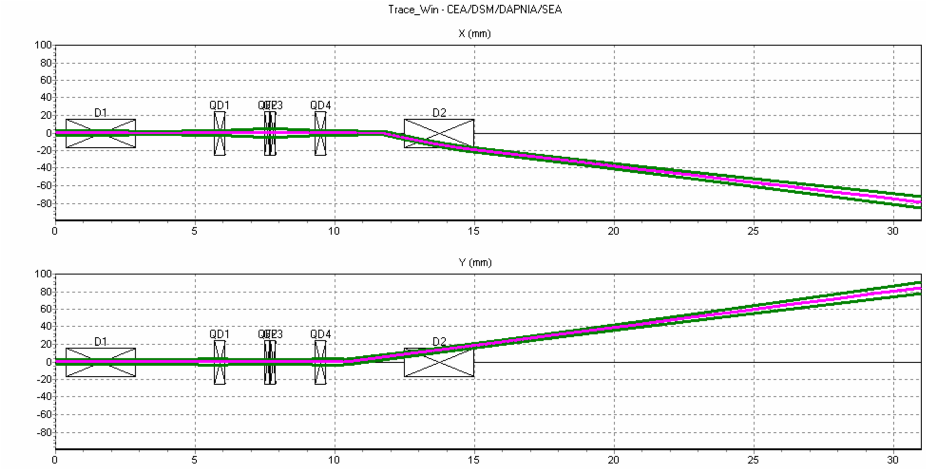


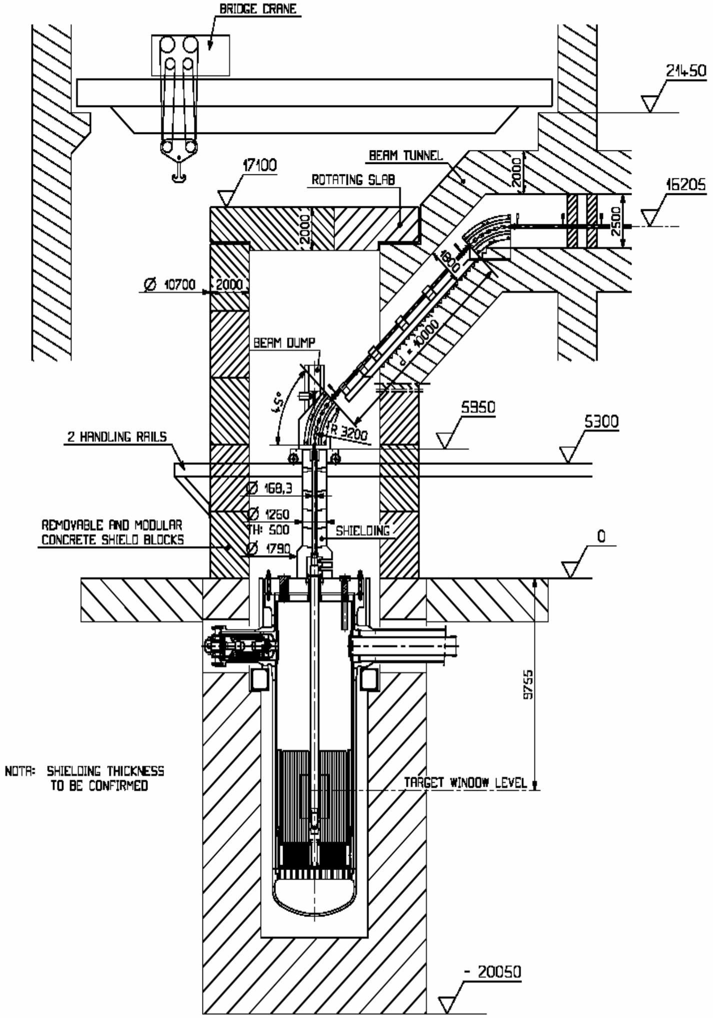


Prototyping on SC CH-DTL & IH-DTL (U.Fra & IBA)

The final beam transport line

- Doubly achromatic beam line concept
  (non-dispersive optical system + energy monitoring)
- Beam scanning method to paint the target
  (very reliable: used for protontherapy)





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Accelerator reliability analyses

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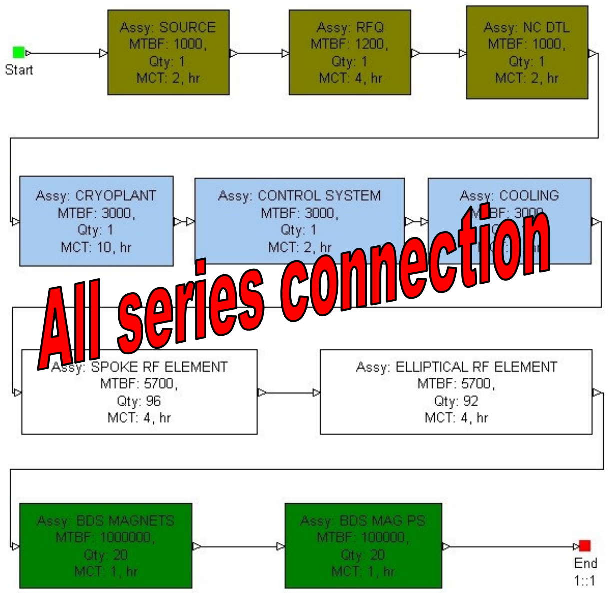
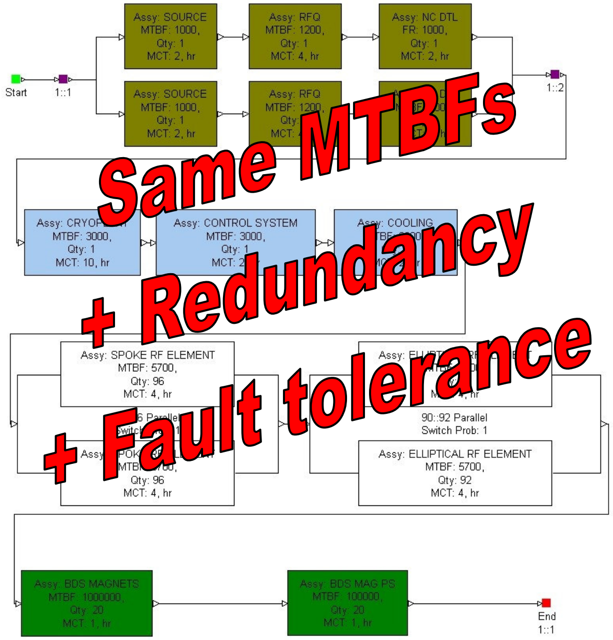
Classical linac



System MTBF	31.19 hours
Nb of failures (3 months)	**70.23**
Steady State Availability	86.6 %

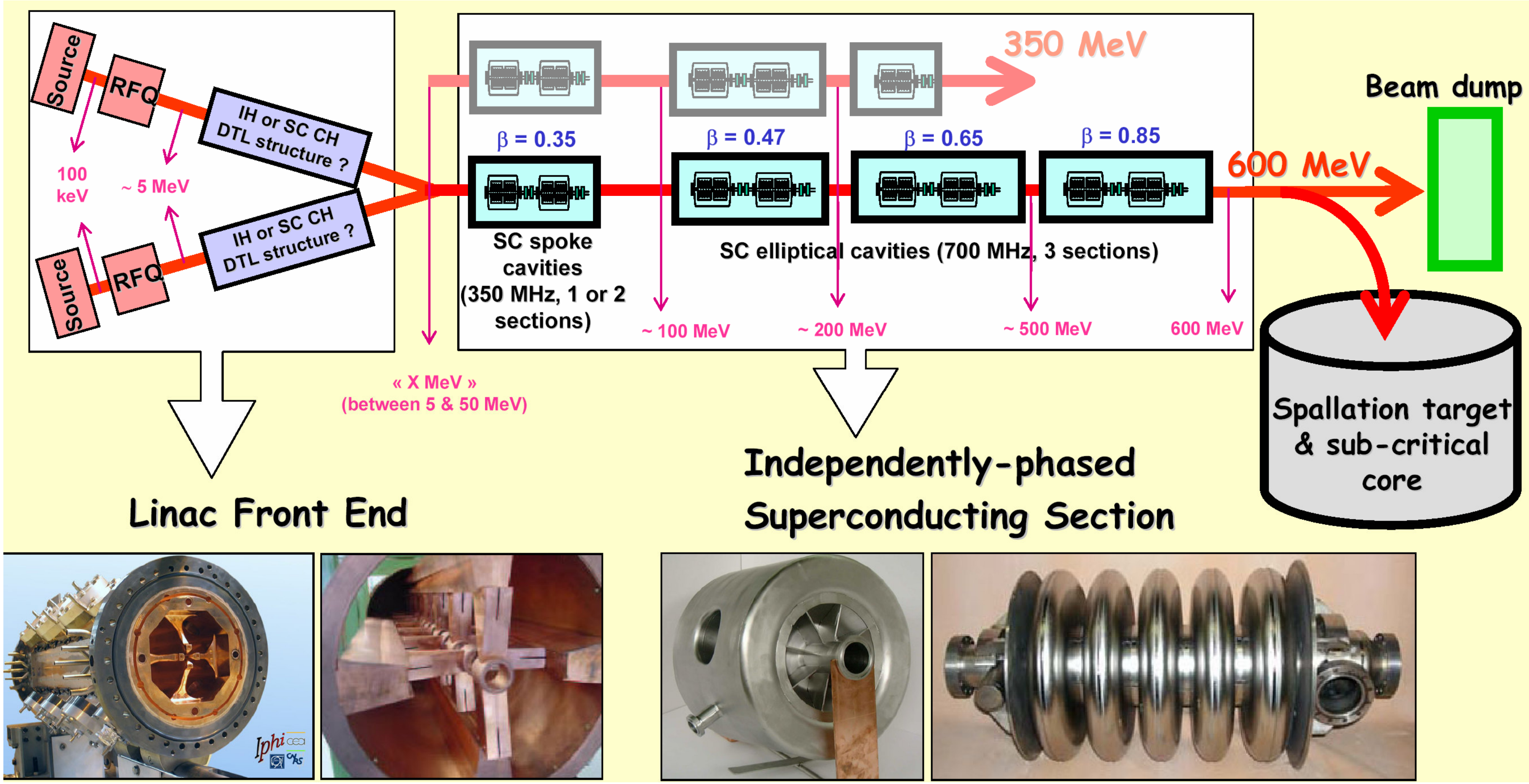
XADS linac, optimized for reliability



System MTBF	757.84 hours
Nb of failures (3 months)	**2.89**
Steady State Availability	99.5 %

Preliminary reliability estimations by P. Pierini, INFN

The choice of the Generic Accelerator Type



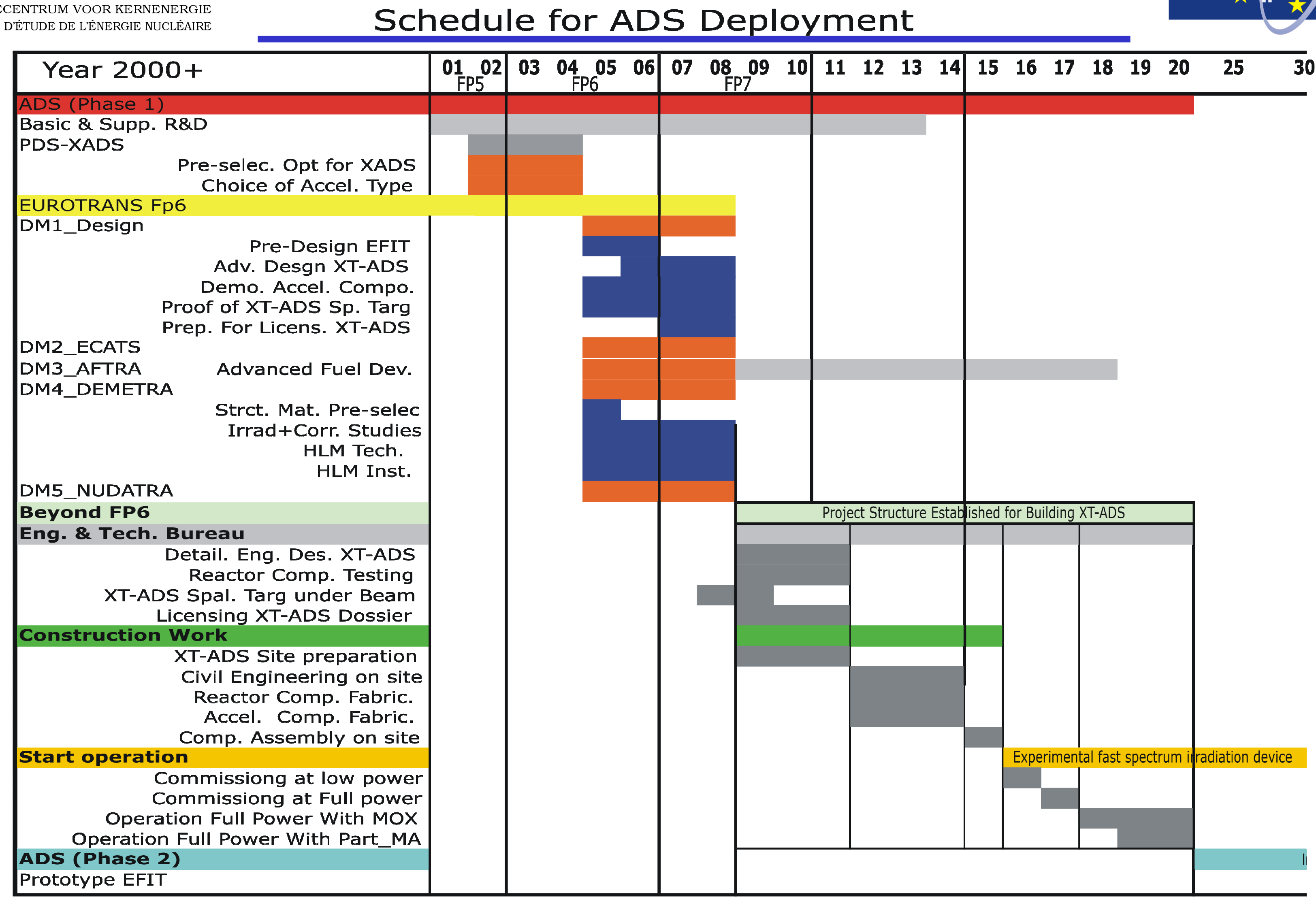
Roadmap of an XT-ADS at Mol

- 2005-2008 FP6 : EUROTRANS Period
  - Advanced Pre-design File of XT-ADS
  - Potential show stoppers in Basic Technological research (material, HLM technology, instrumentation) should be answered
  - Key Accelerator components will be demonstrated
  - Spallation module hydraulic design will be accomplished
  - Realise a coupling of the ADS components

Roadmap of an XT-ADS at Mol

- Beyond FP6,
  - technical issues addressed
  - project funding addressed
  - Multi-lateral Integrated Project structure
  - **Phase 1: 2009-2011**
    - Detailed Engineering design and Mol site preparation
    - Reactor components testing (IHX, PP, Fuel Assembly,…)
    - Spallation module testing under beam
    - Licensing procedure
  - **Phase-2 : 2012-2016**
    - Construction at Mol : 3 to 4 years
    - 2 years for commissioning before **Full power operation**

Roadmap for ADS deployment



One picture is better than a thousand words, we are in 2016