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CENTRE D'ÉTUDE DE L'ÉNERGIE NUCLÉAIRE

An Accelerator Driven System MYRRHA

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global framework

- nuclear energy
- CO_2 problems
- "sustainability" of nuclear energy
  - much better use of the energy vector
  - propose a solution for the very long living waste, esp. the actinides

- present generation of power reactors: thermal neutron spectrum typ. PWR
- spent fuel is entirely considered as waste
  - but still a lot of energy in it: NOT sustainable

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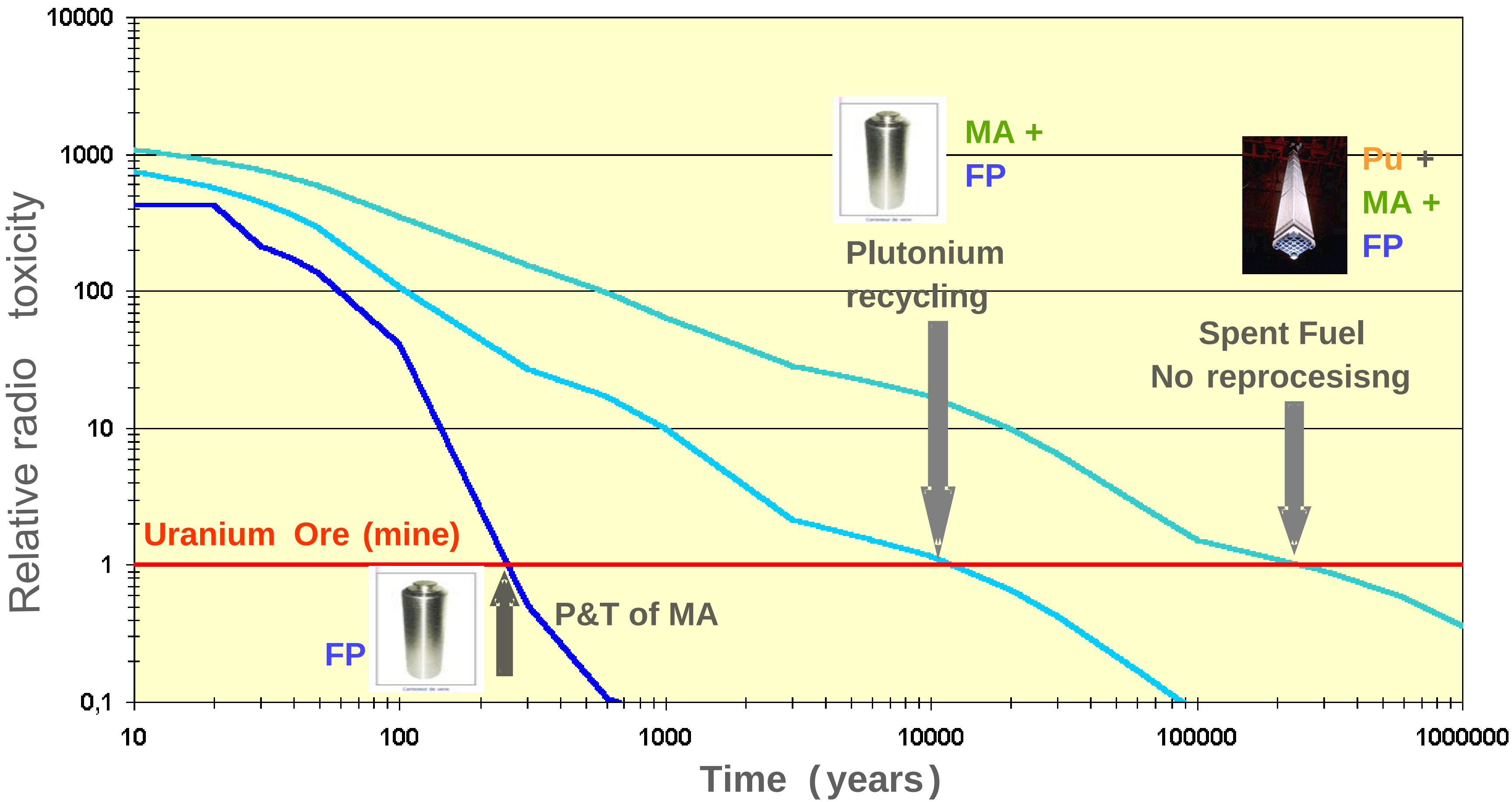
global framework

- use it → need for fast spectrum reactors
  - has been built: Phénix
  - GEN IV: different types: GFR, SFR, LFR, ...
- spent fuel → reprocessing: partitioning
  - fuel
  - fission products
  - actinides
    - Np
    - Am
    - Cm

these may be

- buried public acceptance ???
- "transmuted"

global framework



global framework

- needed for transmutation:
  - fast neutron spectrum
  - fuel containing actinides – how much ??? crucial question!

- 2 possibilities
  - critical fast power reactors: 2 problems
    - small concentrations
    - logistics
  - dedicated burners: basically solve the 2^{nd} problem, and possibly also the 1^{st}

global framework

- how then does a dedicated burner look like ?
- critical fast reactor ←→ small concentrations of actinides. Why ? Important safety reasons
  - delayed neutron fraction ←→ control by safety rods
  - insufficiently known cross sections
- NOT critical → go SUBCRITICAL !
  - need for an external source of neutrons
  - regulation of the reactor by this source

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global framework

- source ? how to produce neutrons ?

1. use an accelerator (protons)
2. use a spallation reaction → several neutrons per proton
3. the core plays the role of a multiplying medium

- what beam current do we need ?
  - thermal power 100 MW / per fission ~ 100 MeV
  - # fissions = 6.10^{18} s^{-1}
  - multiplication factor = $\frac{1}{1-k_s} \approx 20$
  - produce ~ 15 neutrons/proton
  - # protons ≈ 2.10^{16} s^{-1} ≈ 3 mA

ADS

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- thermal spectrum research reactor BR2
  - world class installaton in terms of thermal flux
  - end of life is getting close
- needs for research in future:
  - fusion
  - fast reactors (Gen IV): materials, fuel
  - ADS proof of principle (if belief in need for transmutation + double strata scheme)
- transmutation and ADS at EURATOM level: interest in FP5 (PDS-XADS) and FP6 (IP-EUROTRANS)

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- SCK•CEN's own ADS studies in parallel and embedded in FP's : MYRRHA

- MYRRHA is intended to be
  - a replacement for BR2, but better and up-to-date
  - a demo ADS at 80 MW_{th}
  - a versatile irradiation facility
  - a production unit, e.g. radioisotopes for medical

- MYRRHA critical is foreseen from the start

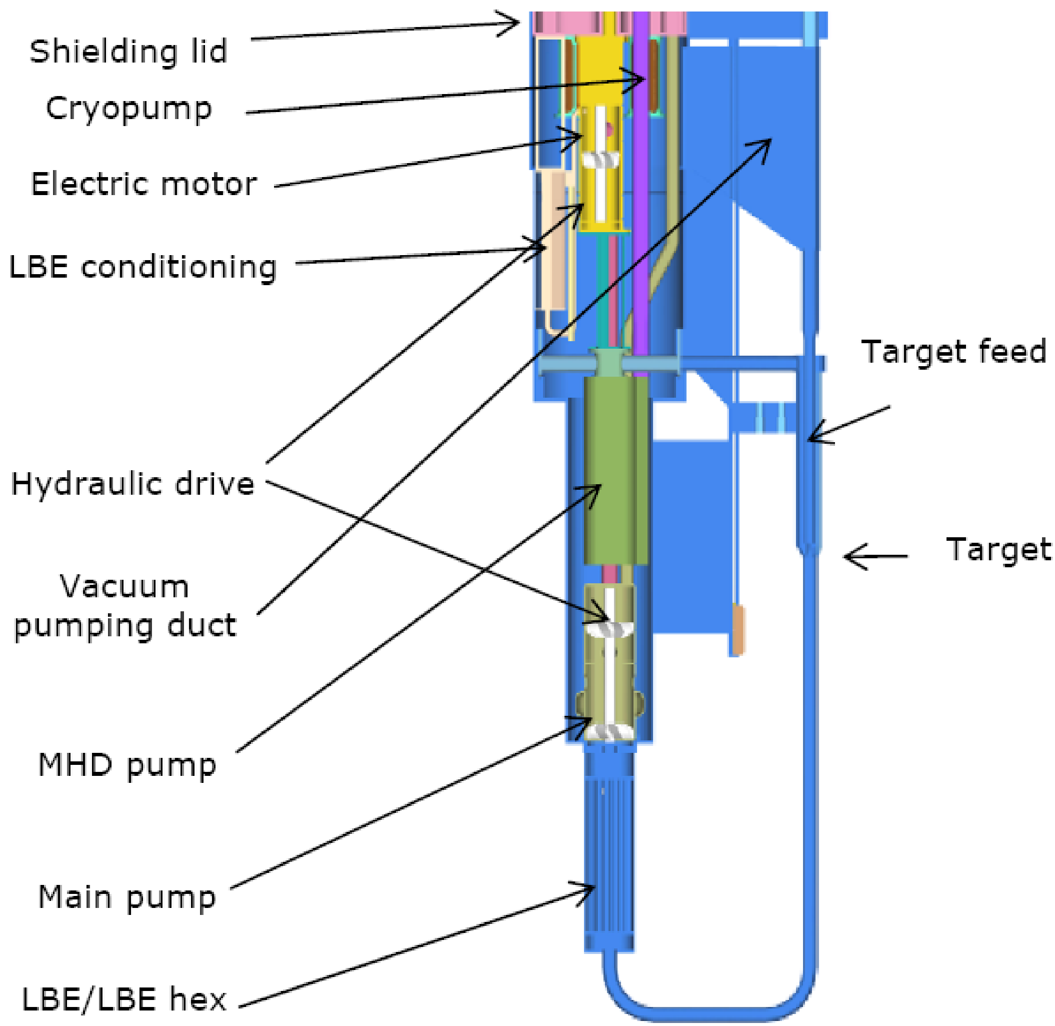
MYRRHA system description

- ADS
  - reactor 80 MW_{th}
  - accelerator 600 MeV, 4 mA
  - beam line
  - building(s)
  - land

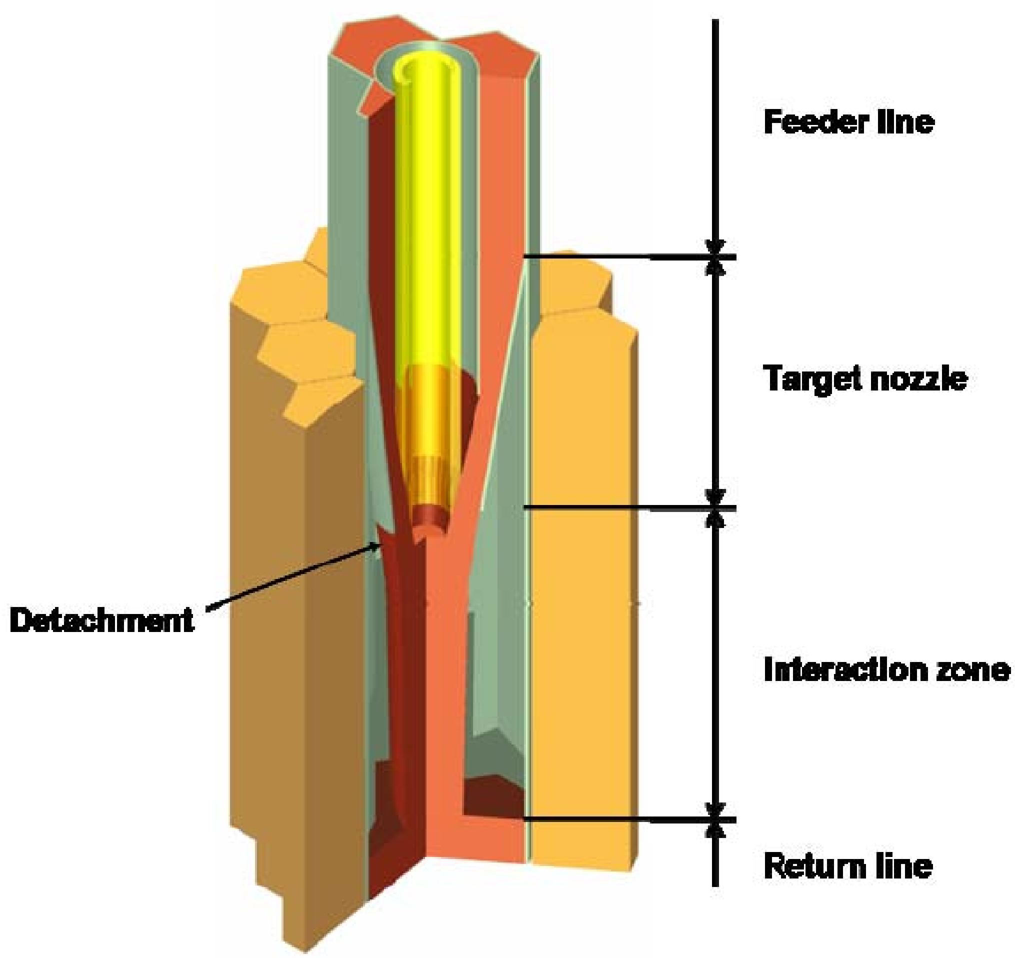
highlights for the reactor

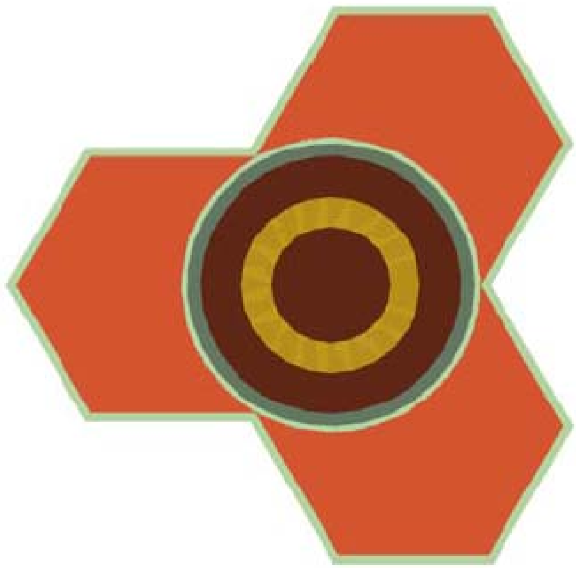
- performance
  - fast neutron flux: $\Phi_{>0.75\ MeV} > 10^{15}\ n/cm^2.s$
- coolant, compatible with high power density
  - liquid metal: LBE
  - temperatures: freezing 125 °C, core in 300 °C, core out 400 °C
- target
  - Pb-Bi circulating in a spallation loop
  - free surface
  - windowless

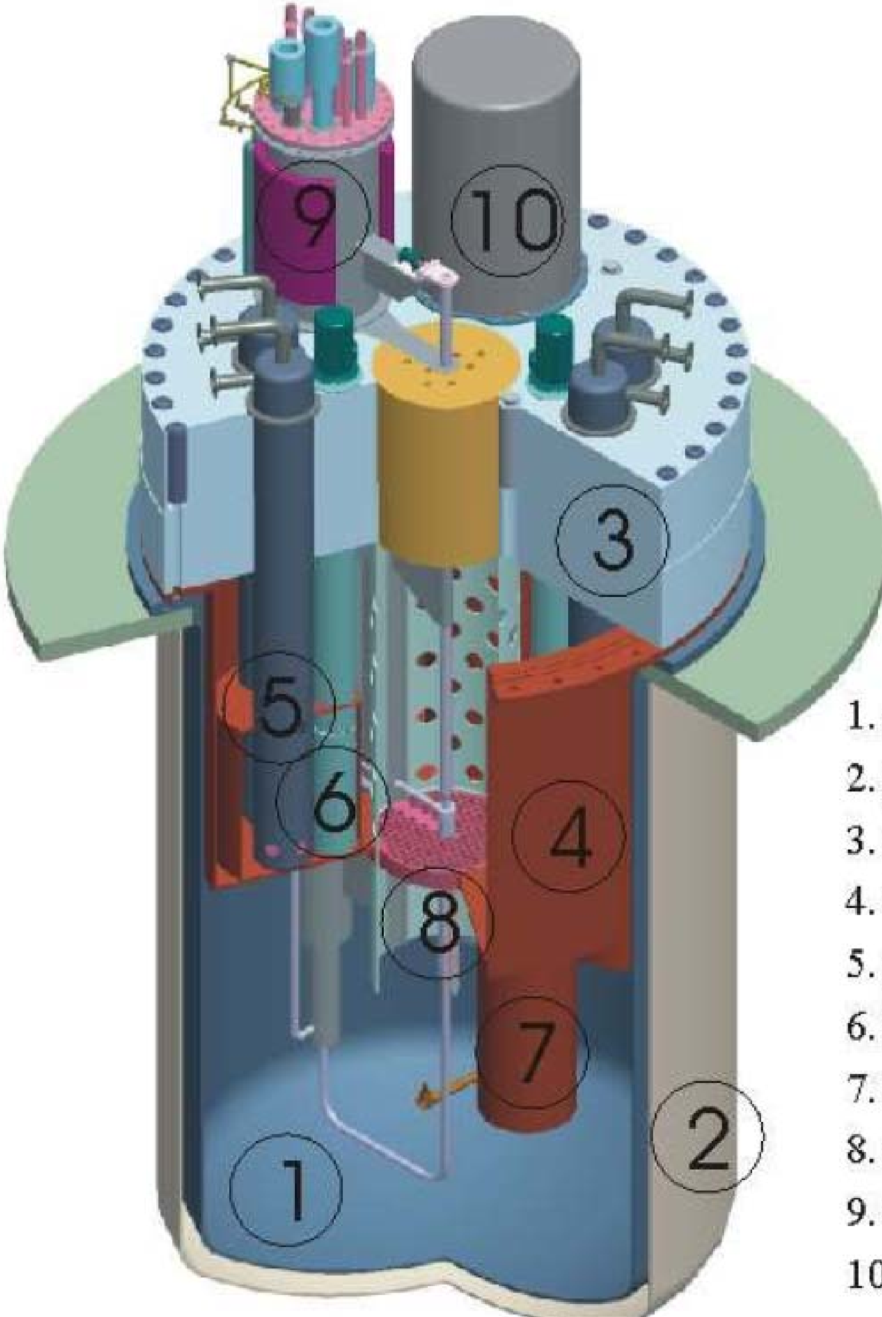
highlights for the reactor



highlights for the reactor







1. reactor vessel
2. guard vessel
3. cover
4. diaphragm
5. primary pumps
6. heat exchangers
7. fuel storage zone
8. windowless target and core
9. spallation loop
10. fuel manipulators

highlights for the reactor

- R&D program: extensive around use of HLM
  - compatibility with vacuum
  - compatibility with beam (surface heating)
  - fluid dynamics: free surface generation
  - materials: corrosion and embrittlement
  - instrumentation: visualisation under Pb-Bi
  - remote handling

The accelerator

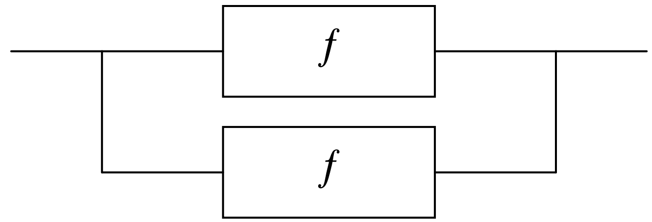
- performances for Myrrha
  - see table
  - challenging: CW reliability/availability
  - special requirements on reliability:
    - beam trip > 1s = failure
    - failure frequency < ~1/month
    - or: MTBF ≈ 500 h (typical 20 – best 100 h ?)
- principles for increased reliability
  - downrating, ample operational margins
  - redundancy: parallel vs. serial scheme

The MYRRHA beam

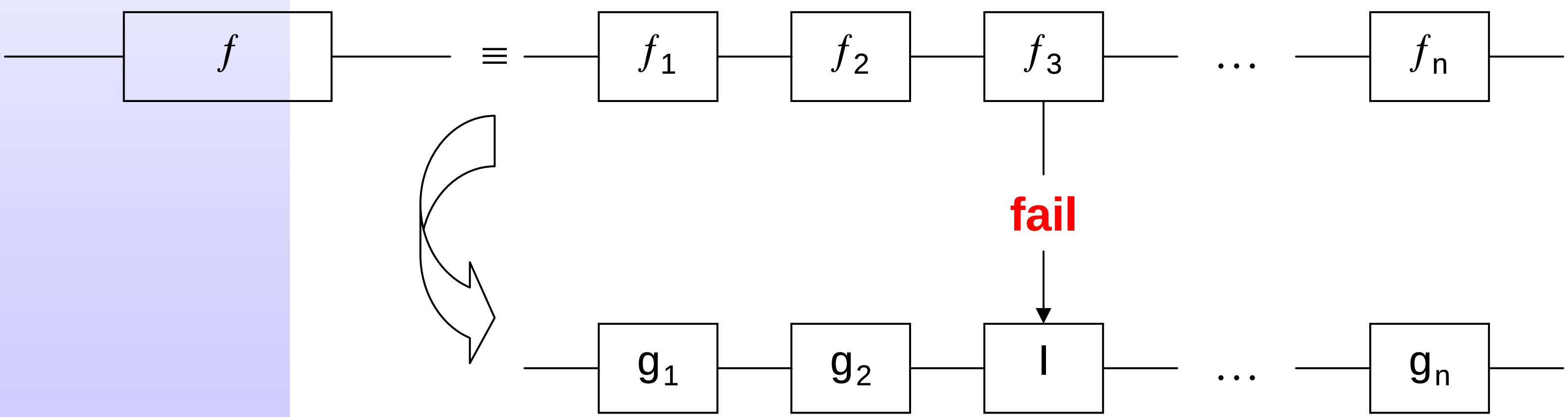
Proton energy	600 MeV
Beam intensity (CW)	4 mA
Beam entry	vertically from above
Beam stability	energy ±1% intensity ±2%, size ±10%
Footprint on target	"donut"-shaped, r_{in} 25 mm r_{out} 50 mm
Time structure	CW, I=0 holes 200 μs, 1 Hz pulsed mode capable (50 Hz)

Redundancy

parallel scheme



serial scheme: IF

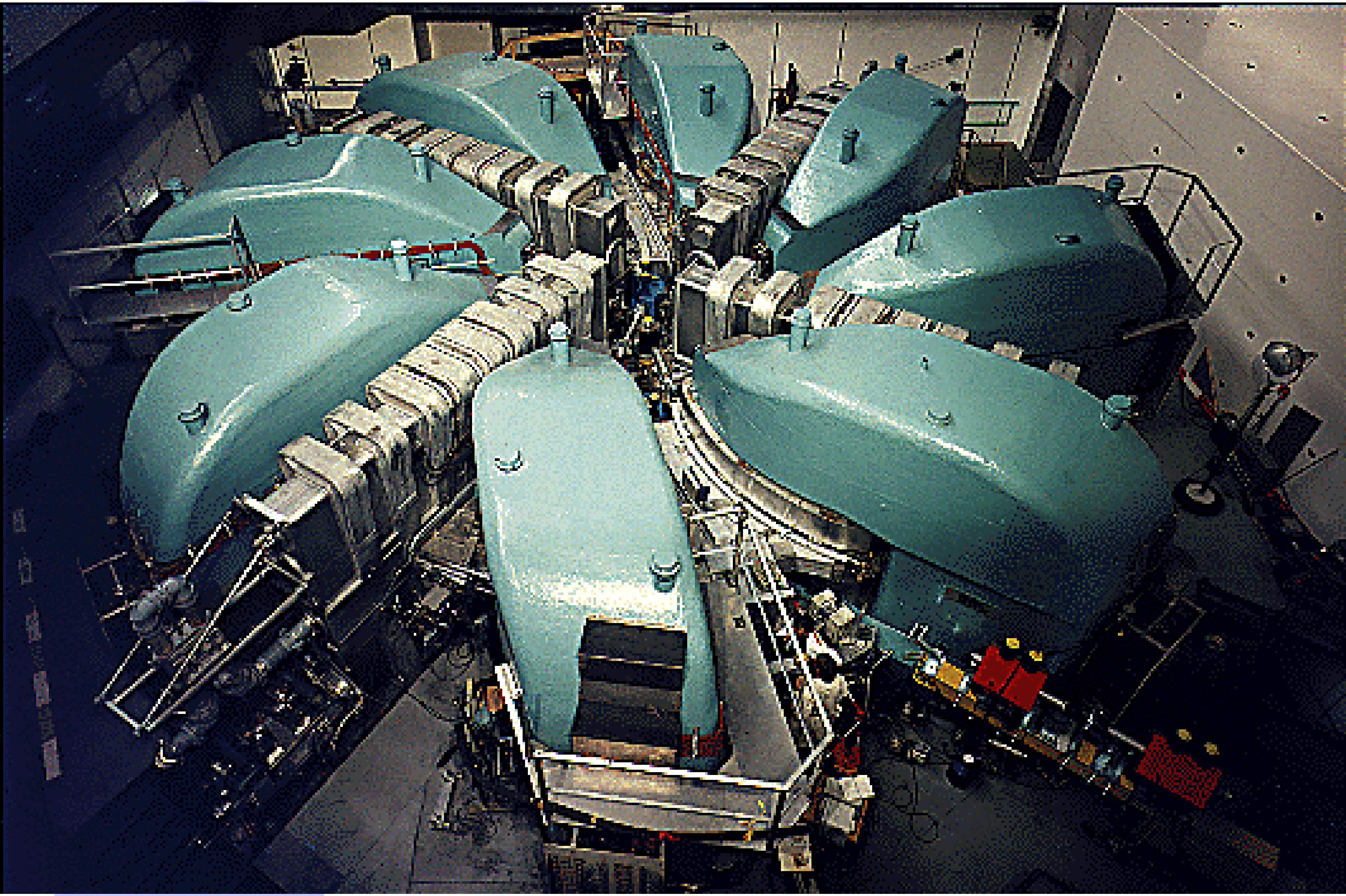


modularity

Choice of accelerator type

- CW beam →
  1. cyclotron: naturally CW (isochronous), but "at the limits"
  2. linac: "straightforward" for performances, mostly pulsed
  3. (FFAG)

- fundamental differences:
  - monolithic ←→ modular
  - extraction ←→ "not an issue", beam quality
  - ~fixed ←→ flexible and expandable



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Choice of accelerator type

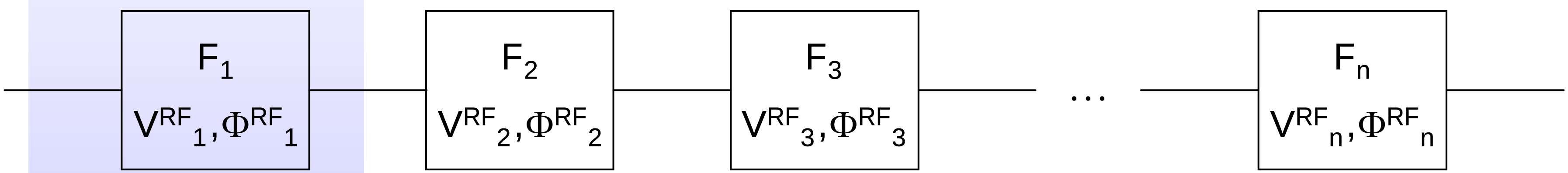
- in terms of redundancy
  - monolithic → only parallel
  - modular → correct topology for serial redundancy, or

fault tolerance

- linac: NC or SC ?
  - clear advantages for SC: shorter, more beam clearance, temperature stability, modularity
- R&D program (FP6, FP7) is focused around fault tolerance, and optimised MTBF and MTTR

Fault tolerance

serial redundancy applicable to (part of) a linac ?



If this is possible →

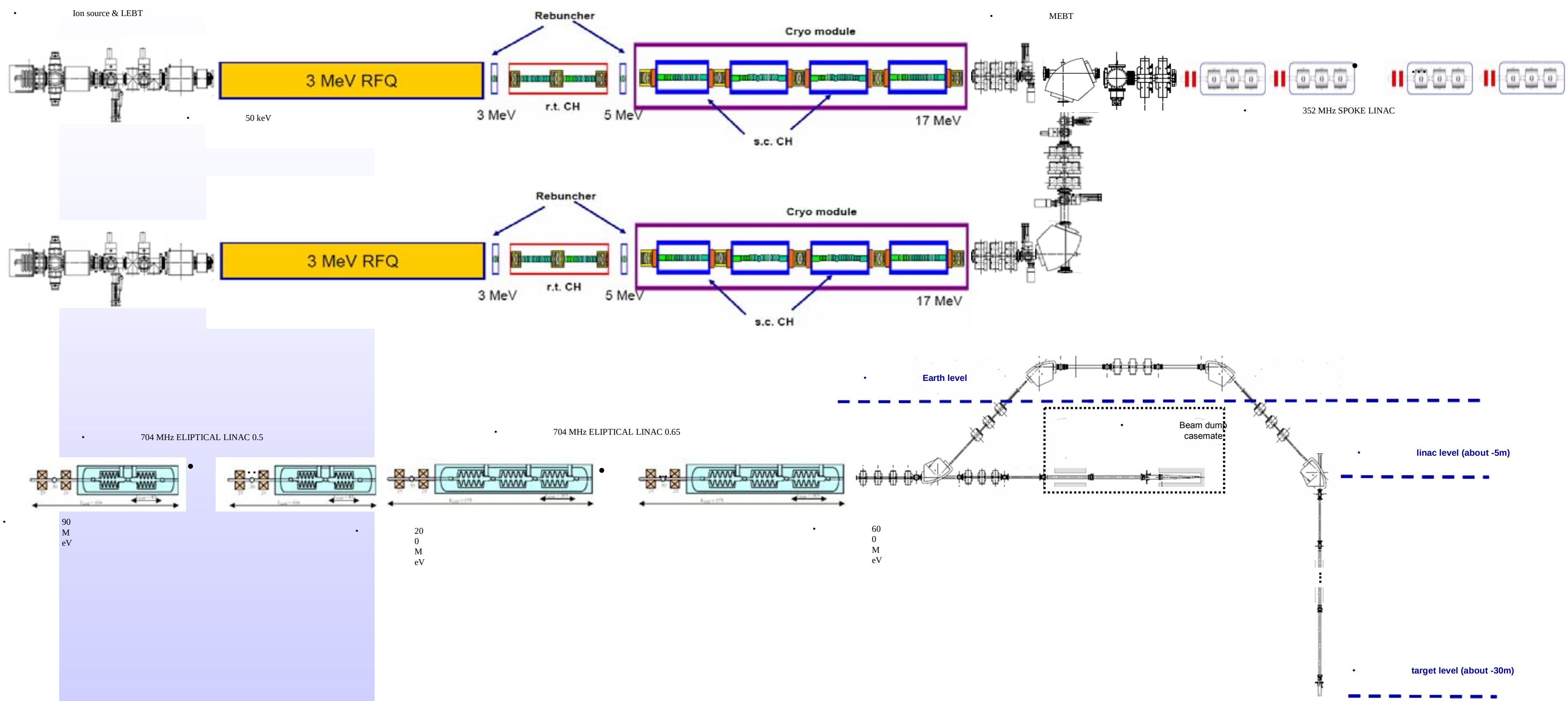
major step in reliability increase to be expected !

Schematics of the SC linac

- The accelerator layout design comes from a collaboration initiated in the EURATOM FP5 project “PDS-XADS”, and continued in the EURATOM FP6 “IP-EUROTRANS”, with main partners
  - CNRS (France)
  - CEA (France)
  - INFN (Italy)
  - Univ. Frankfurt (Germany)

- base frequency is 352 MHz

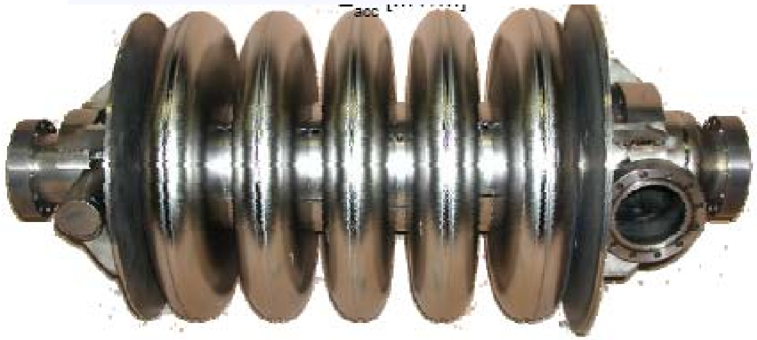
Schematics of the SC linac

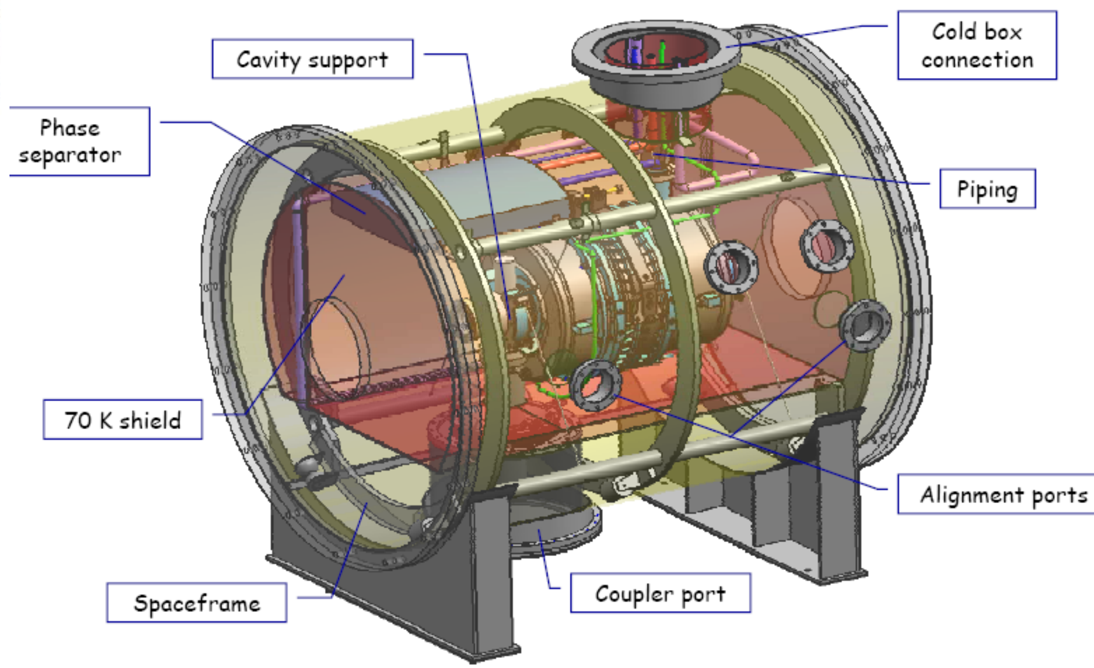


linac components: HE

elliptical cavity section > 90 MeV INFN Milano

- 2 or 3 geometrical families according to β
- arranged in cryomodules, 2 or 3 cavities / module





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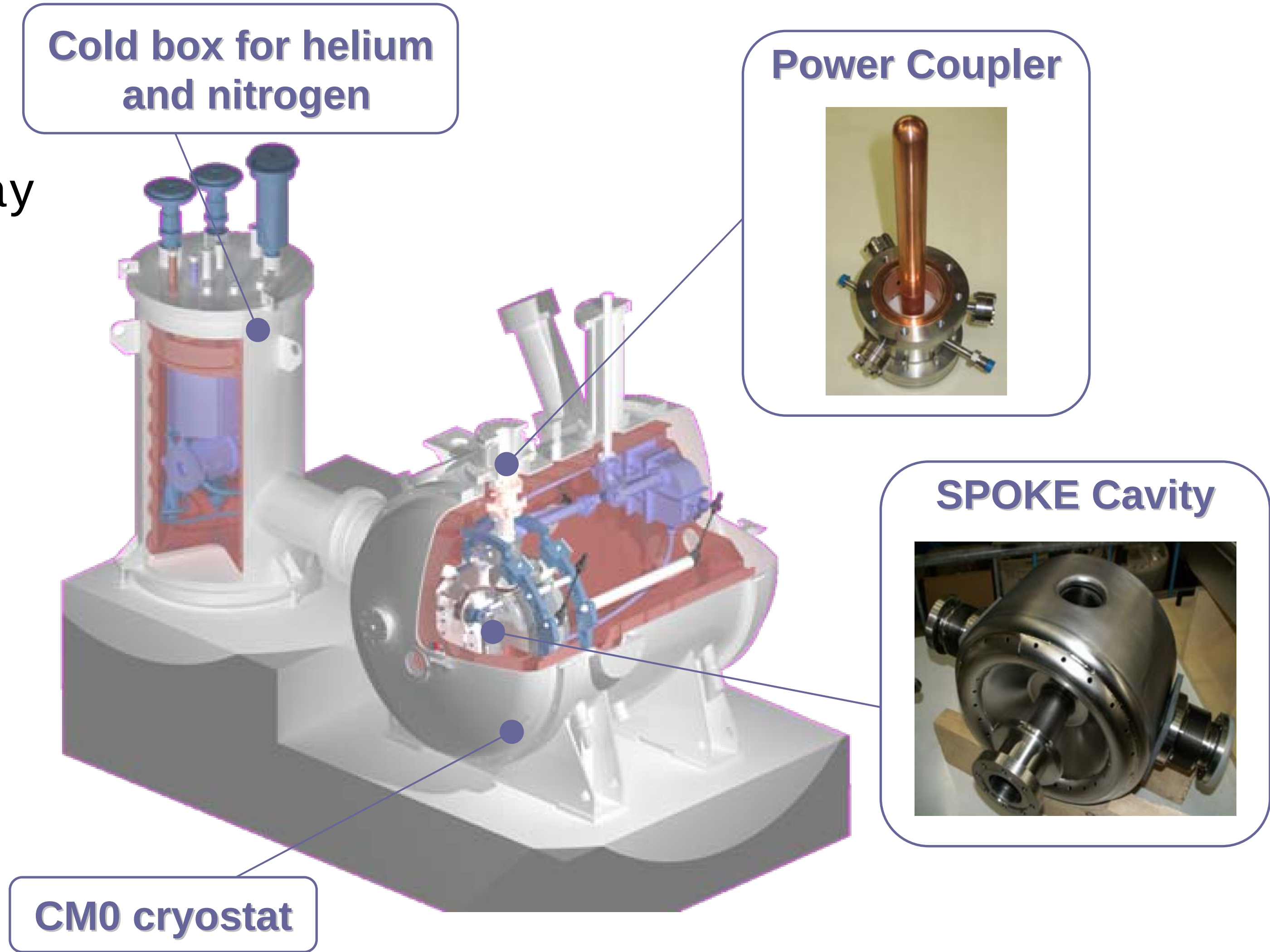
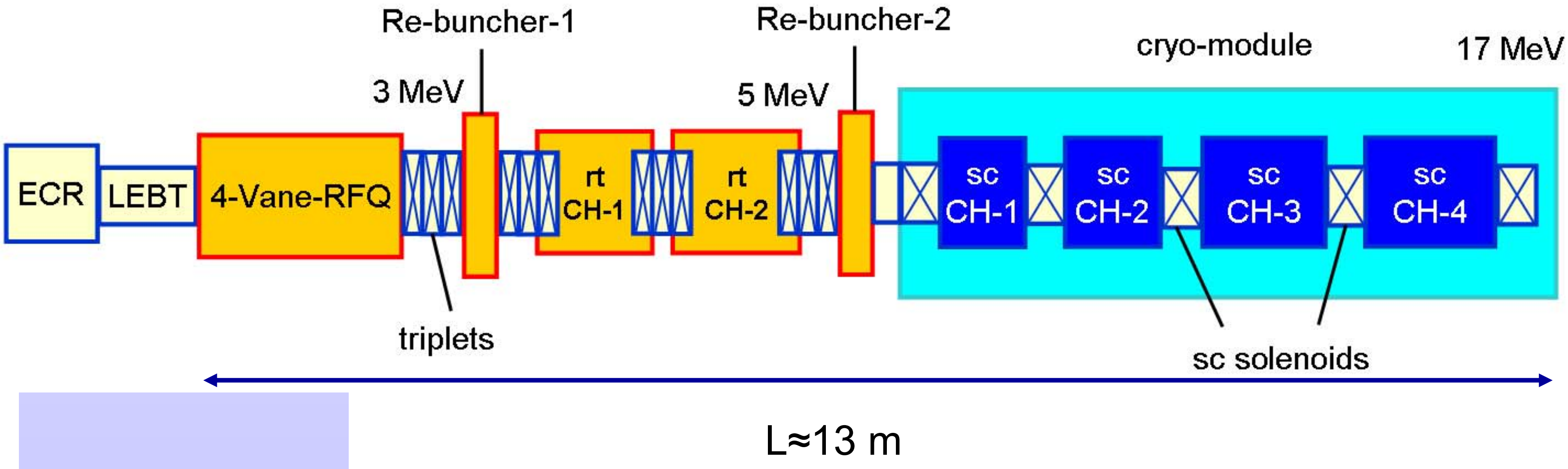
linac components: IE

spoke section
17 – 90 MeV
CNRS-IPN Orsay



linac components: FE

- → 17 MeV: quick variation in β
- not modular anymore → parallel redundancy
  - multicell cavities: Univ. Frankfurt
  - RFQ
  - ion source: SILHI at CEA Saclay



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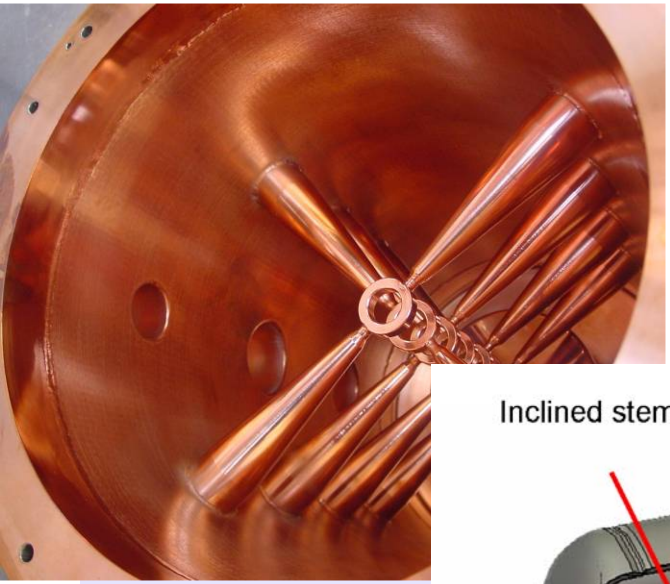
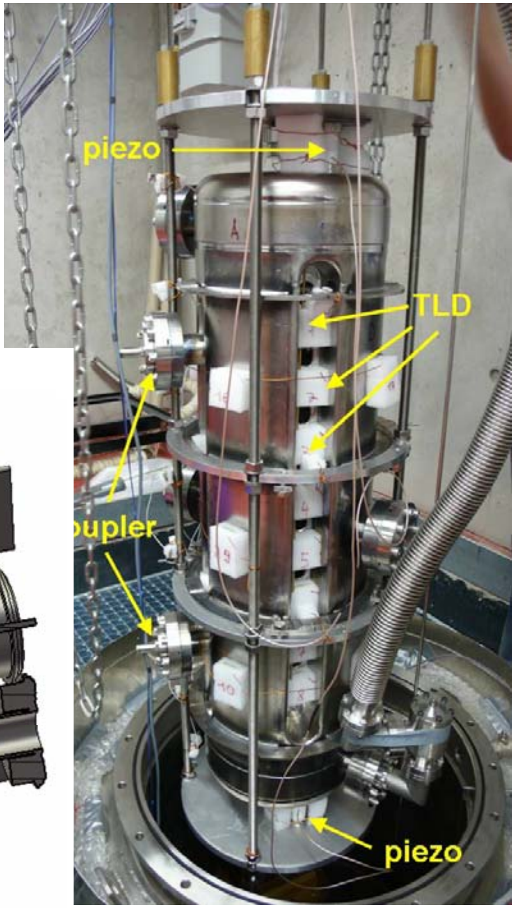
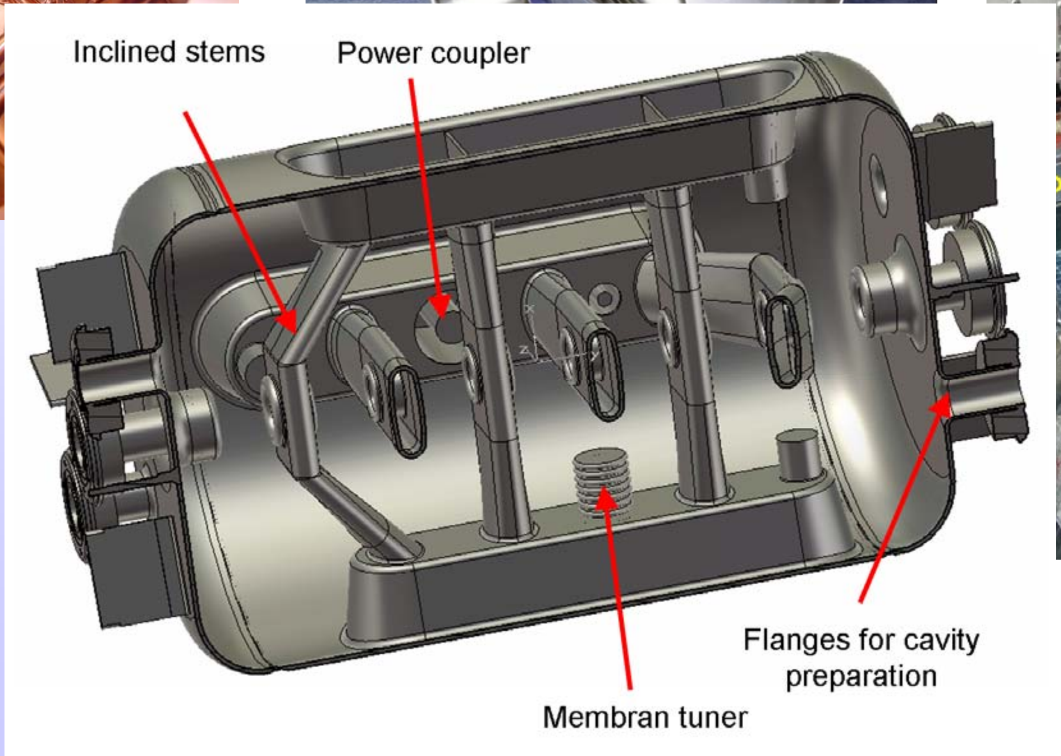
linac components: FE







linac components: IS

ECR ion source (SILHI)

- operational
- 100 mA proven
- 30 mA during 162 h
- compatible with 200 μs holes

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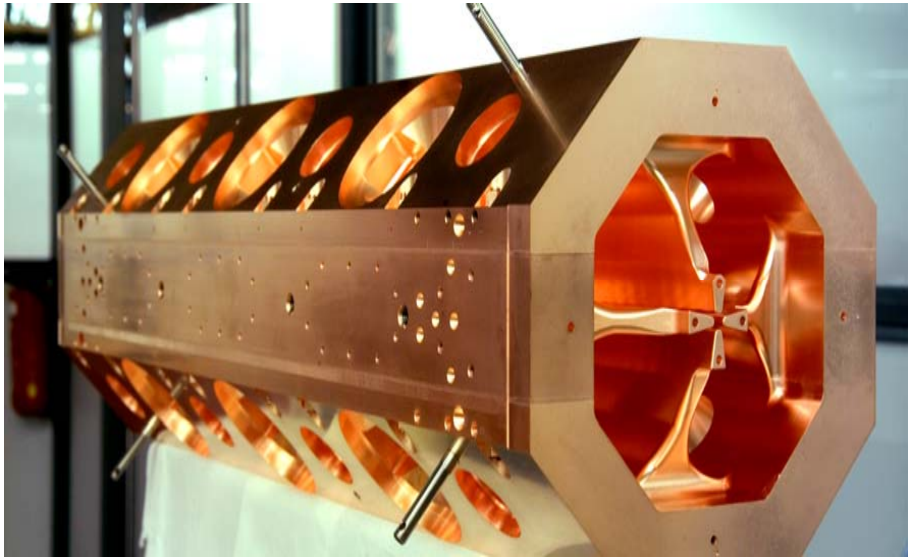
linac components: RFQ

- probably the most delicate component (CW)
- presently the least known component

  - 352 MHz
  - 50 keV – 3 MeV
  - 4-vane copper cavity



Fault tolerance issues

- the scheme
  - global ← shown to work at SNS
  - local OK in simulations, with typ. 4 surrounding cavities
- the scenario
  - fault detection
  - switch off beam
  - detune faulty cavity
  - retune neighbour cavities, < tables
  - reinject beam

< 1 s

Fault tolerance issues

- the tools
  - LLRF, entirely based on fast digital programmable components
  - tests with prototypes are foreseen on cold cavities
- reliability model studies

Beam line and beam delivery

- conceptual design phase
- important issues
  - no dispersion at target position → achromatic 90° bend
  - 600 MeV p → $B\rho = 4.07\,\mathrm{Tm}$
  - 45° bending magnet ~15 t
  - last magnet, right above the reactor, may be challenging
    - removable, by remote handling
    - high radiation environment
  - scanning magnets, few mrad, 250 Hz, very reliable
    - removable, by remote handling
    - high radiation environment

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Conclusion

- if sustainable nuclear energy is chosen by society as one of the pillars for satisfying future energy demands, then transmutation and partitioning are fundamental ingredients
- if a double strata scenario is privileged, then ADS is the technology to apply
- there is presently a relatively cool but worldwide interest in ADS

Conclusion

- at SCK•CEN we consider that research in this domain is useful and necessary, and that a research irradiation facility based on ADS technology is the logical next step, and one giving many new possibilities in its field
  → Myrrha project

- the accelerator physicist's standpoint: the development of high reliability accelerators is a necessity for all future applications, both in research and in industry