

High Power Proton LINACs

Part 1



JOINT UNIVERSITIES
ACCELERATOR SCHOOL

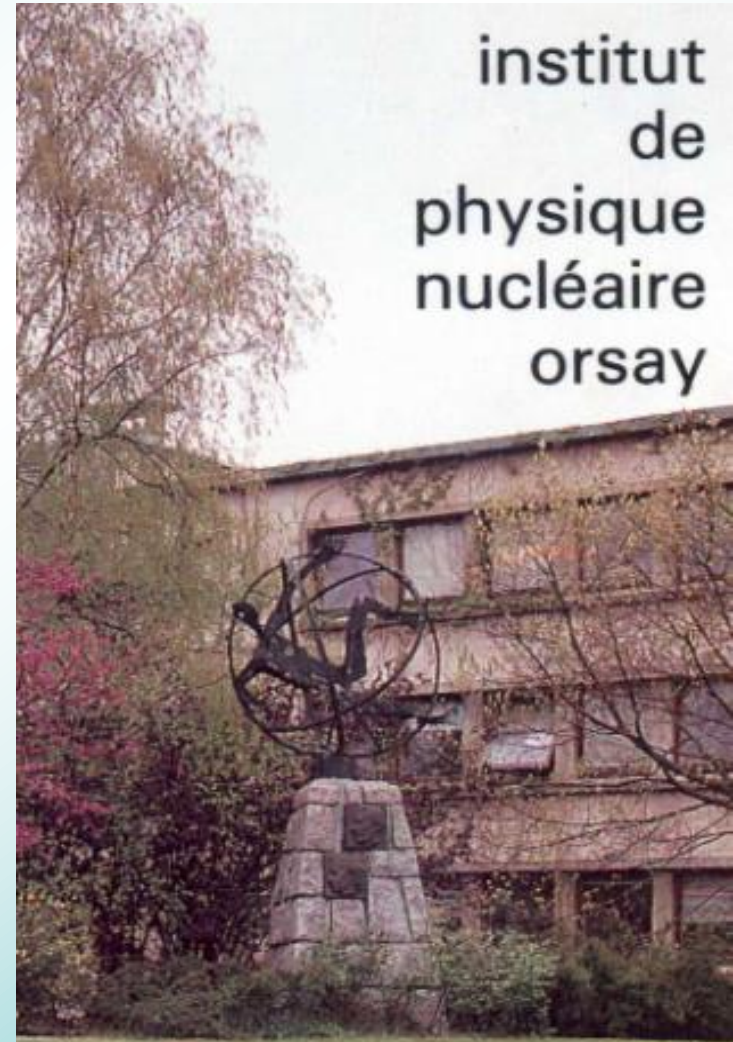
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Acknowledgment

- Relies on preceding lectures, and particularly on Alex Mueller's course at previous JUAS
- Selected information with some emphasis on applications according to personal taste
- Some of the material was developed with Jean-Luc Biarrotte (IPN Orsay) for a seminar on superconducting cavities

PART 1

- ➡ « Definition » of a High Power Proton LINAC (HPPL) and range of applications
- ➡ HPPL for neutron source
- ➡ HPPL for Radioactive Ion beams production
- ➡ HPPL for Nuclear waste treatment

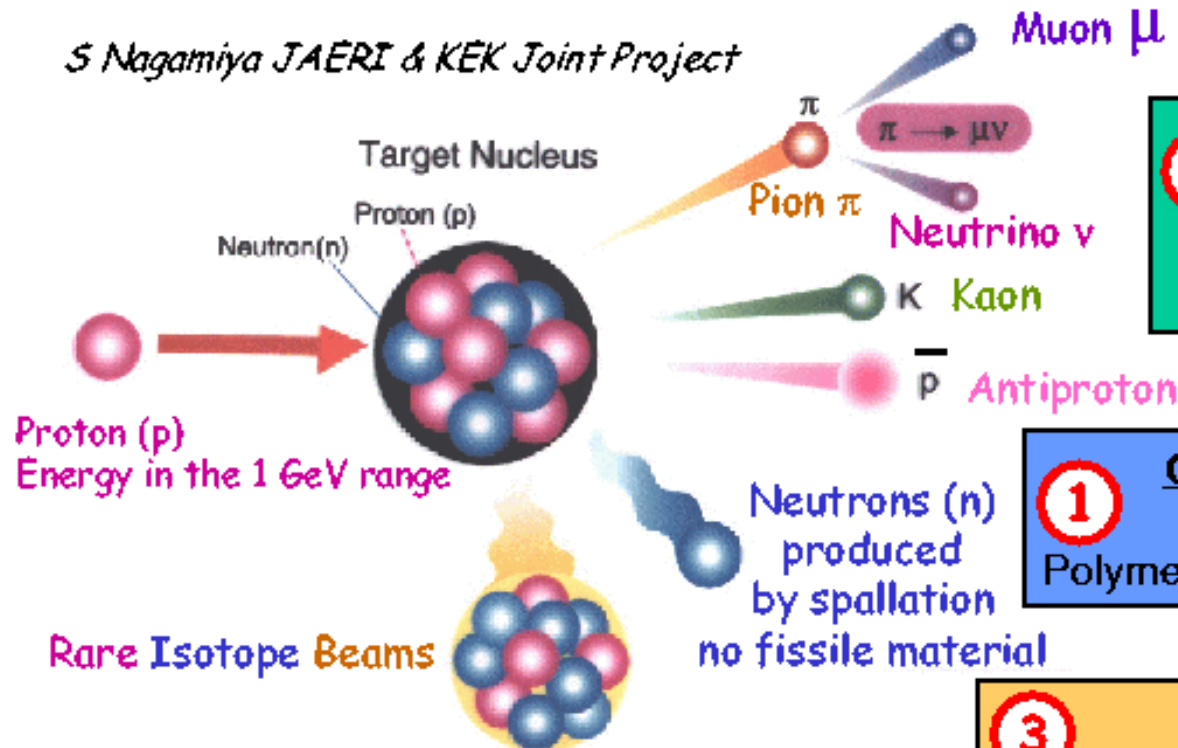
PART 2

- ➡ Superconducting cavities for HPPL : basics, advantages, performances overview and technological challenges

Why high power proton accelerators ?

Secondary Beams produced by a
high energy proton in a target
5 applications in fundamental and applied Research

S Nagamiya JAERI & KEK Joint Project



5

Particle Physics

μ colliders
 μ Storage Rings
(ν factories)

1

Condensed Matter Study

Neutron probe
Polymers, Fractals, Magnetism, Biology

3

Transmutation

of long-lived radioactive wastes

4

Technical Irradiation Tool

Tests of material

2

Nuclear Physics

Beams of short-lived elements
super heavy elements



Specification for a High Power Proton Accelerator (HPPA)

	R.I.B.	ν&μ	Neutrons	Transmutation
	(EURISOL)	(CERN)	(ESS)	(DEMO→Industriel)
\hat{I}_{mA}	0.1→30	10	30→100	10→100
$\langle I \rangle_{mA}$	0.1→5	2	1→4	10→40
E_{GeV}	0.02→1-2	2	1→1.3	0.6-1
D.C.	100%	20%	6%	100%
$\langle P \rangle_{MW}$	0.1→5	4	1→5	6 → 40

HPPA: Power ranging from 100 kW so sevral MW

Particle accelerator main components & where HPPA is specific

schematic
view



An accelerator has the following principal components:

- a source of charged particles: e^- , p^+ , heavy ions; special case: e^+ & anti-protons
- accelerating elements
electrostatic columns or **radiofrequency cavities** which provide the **electric fields** giving the energy to the particle (beam)
- beam guiding elements
mainly magnetic, in order to maintain (**focus**) the beam on the wanted **trajectory** and to provide the **orbit** in the case of a **circular** machine
- as most important ancillary systems vacuum and beam diagnostics
high vacuum is needed to avoid perturbation of the beam by **collisions with residual gas**, and beam diagnostics for the **monitoring of the beam trajectories**
- the user installation
(complex) experimental set-ups including **targets, spectrometers, detectors**
special case: **secondary beams** produced by a nuclear reaction (e.g.: neutrons) or an electromagnetic process (e.g.: photons by Bremsstrahlung/synchrotron Rad.)



Classical Dynamics

$$W < E_0$$

In this case, the energy of the particle is purely kinetics:

$$E = \frac{1}{2} m_0 v^2$$

The particle momentum is

$$p = m_0 v$$

Relativistic Dynamics

$$W \geq E_0$$

$$E = E_0 + W$$

$$E = mc^2 \quad E_0 = m_0 c^2$$

$$m = \gamma m_0 \quad E = \gamma E_0$$

$$\gamma = \frac{1}{\sqrt{1 - \beta^2}} \quad \beta = \frac{v}{c}$$

And:

$$p = mv \quad E^2 = E_0^2 + p^2 c^2$$

Ultra-relativistic case $W \gg E_0$

$$\beta \approx 1 \quad v \approx c$$



Different accelerator types

	Kinetic energy W	
	Electrons	Protons/ions
Electrostatic Van de Graaf & Tandems		20-35 MeV (Vivitron)
Betatron	10-300 MeV	
Microtron	25-150 MeV	
Cyclotron		10-100 MeV
Synchro-cyclotron		100-750 MeV
Synchrotron	1-10 GeV	1-1000 GeV
Storage ring	1-7 GeV (ESRF)	
Collider ring	10-100 GeV (LEP)	1-7 TeV (LHC)
Linacs	20 MeV-50 GeV (SLC)	50-800 MeV (LAMPF)
Linear collider	50-1000 GeV (TESLA)	

*At PSI: p+ of
600 MeV, 2,2 mA*

Total Energy (E) = Rest energy (E_0) + Kinetic Energy (W)



$$= E_0 + W$$



$$E_0 = m_0 c^2 \rightarrow$$

electron $E_0 = 0,511$ MeV
protons $E_0 = 938$ MeV



RF Linacs compared to other accelerator types

- In DC accelerators the energy gain is limited by the maximum applied voltage, which is limited by electric breakdown.
- In RF accelerators (linacs, synchrotrons, cyclotrons) the final energy can exceed the maximum voltage, which can be applied repeatedly to the beam. **The final energy is limited only by economics.**
- Synchrotrons are limited to low beam currents by beam instabilities associated with the repetitive cycling of the beam from turn to turn through unavoidable focusing lattice errors.
- Cyclotrons are not pulsed but are limited to low beams currents by weak focusing and same inherent circular machine instabilities.
- Linacs can deliver high beam currents because they can provide strong focusing to confine the beam and are not subject to circular machine instabilities.



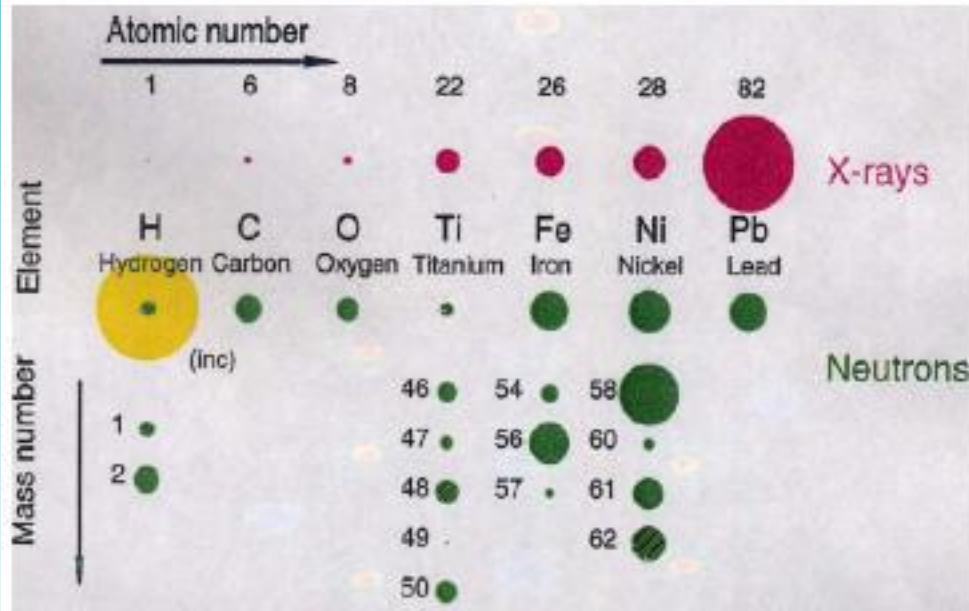
In summary : Linacs are capable of delivering beams with high energy, high intensity and good beam quality (small emittance)

- Maximum energy not limited by electric breakdown.
- Strong focusing can be provided.
- Single pass device means beam is not subject to repetitive error conditions which cause destructive resonances as in circular machines.
- No power loss from synchrotron radiation for electron linacs.
- Natural orbit is a straight line making injection and extraction easier.
- No limit to duty factor.



High Power Proton Accelerator used
for neutron sources produced by spallation

Neutron Scattering

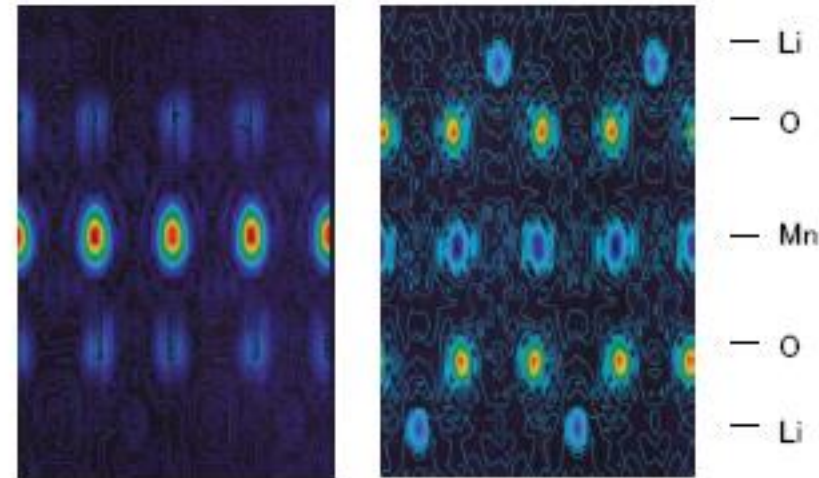


X-rays interact with electrons.

→ X-rays see high-Z atoms.

Neutrons interact with nuclei.

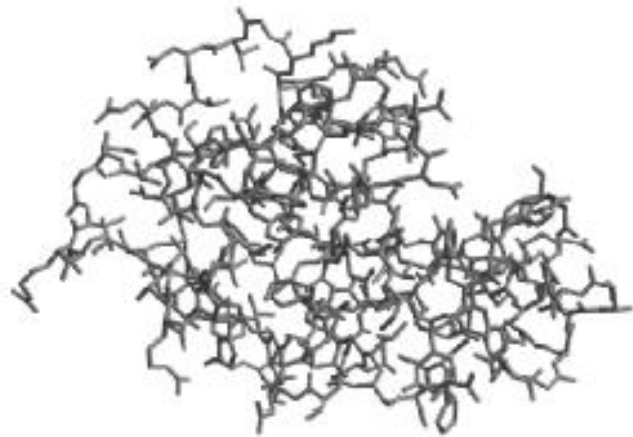
→ Neutrons see low-Z atoms.



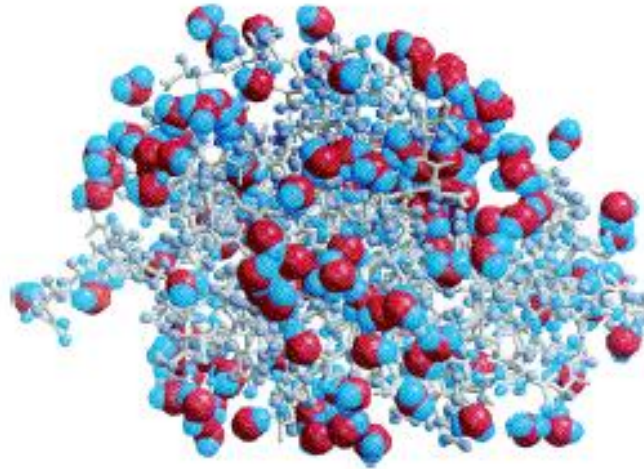
Material for Li-battery seen by
X rays (left) and
Neutrons (right)

T. Kamiyama, et al.

Hen Egg-White Lysozyme



X-rays

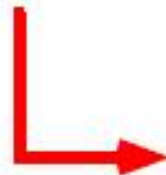


Water molecules
Observed with
neutrons

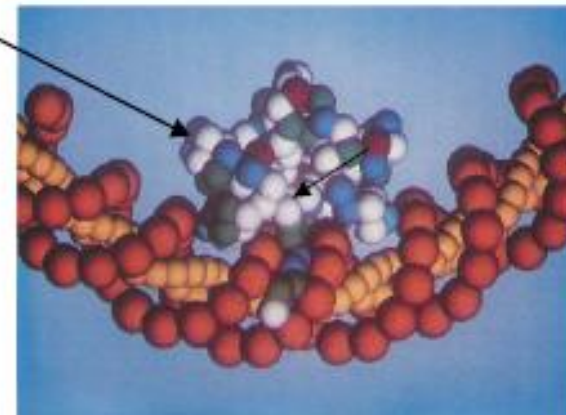
N. Niimura, et al.

Neutrons

Protein



From structure to function

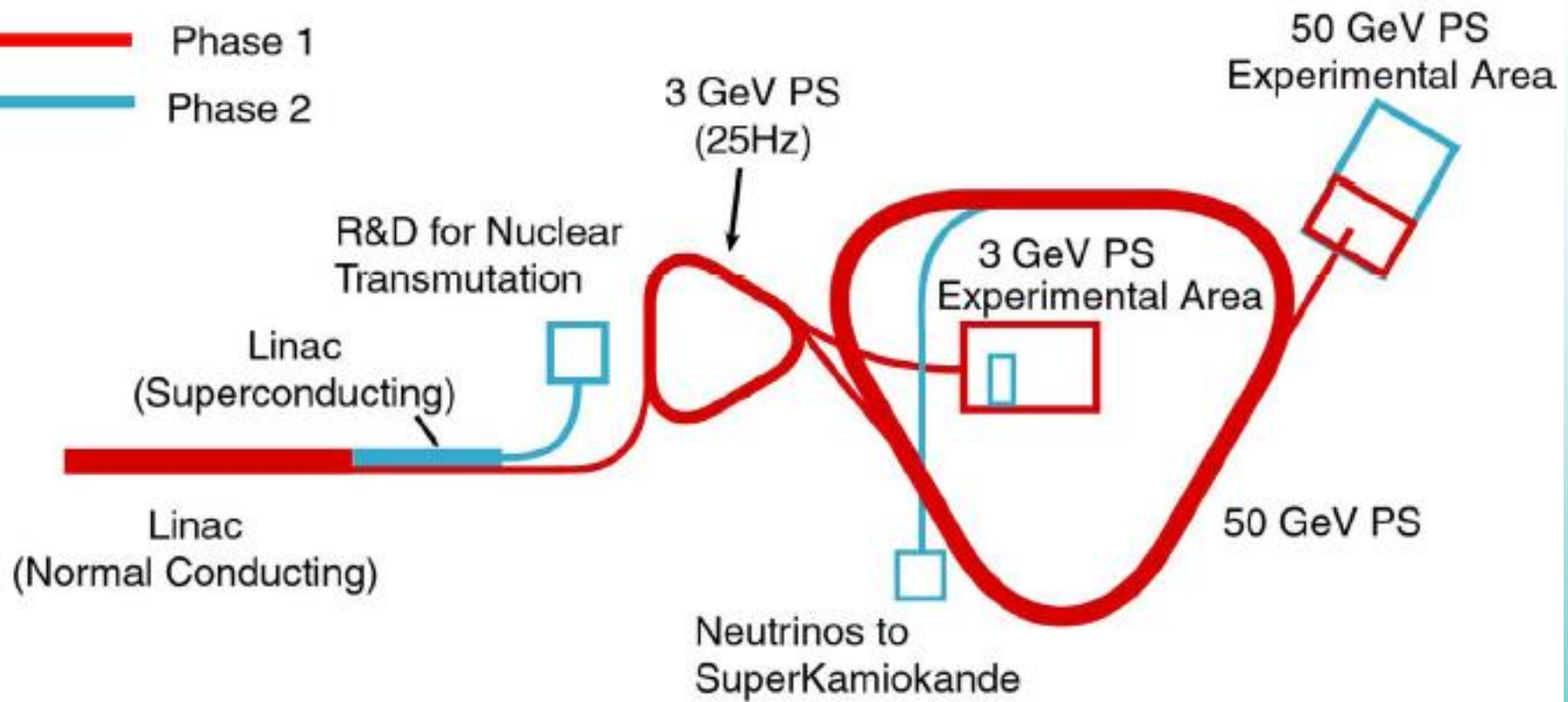


DNA

A protein
molecule
moving along
the DNA chain

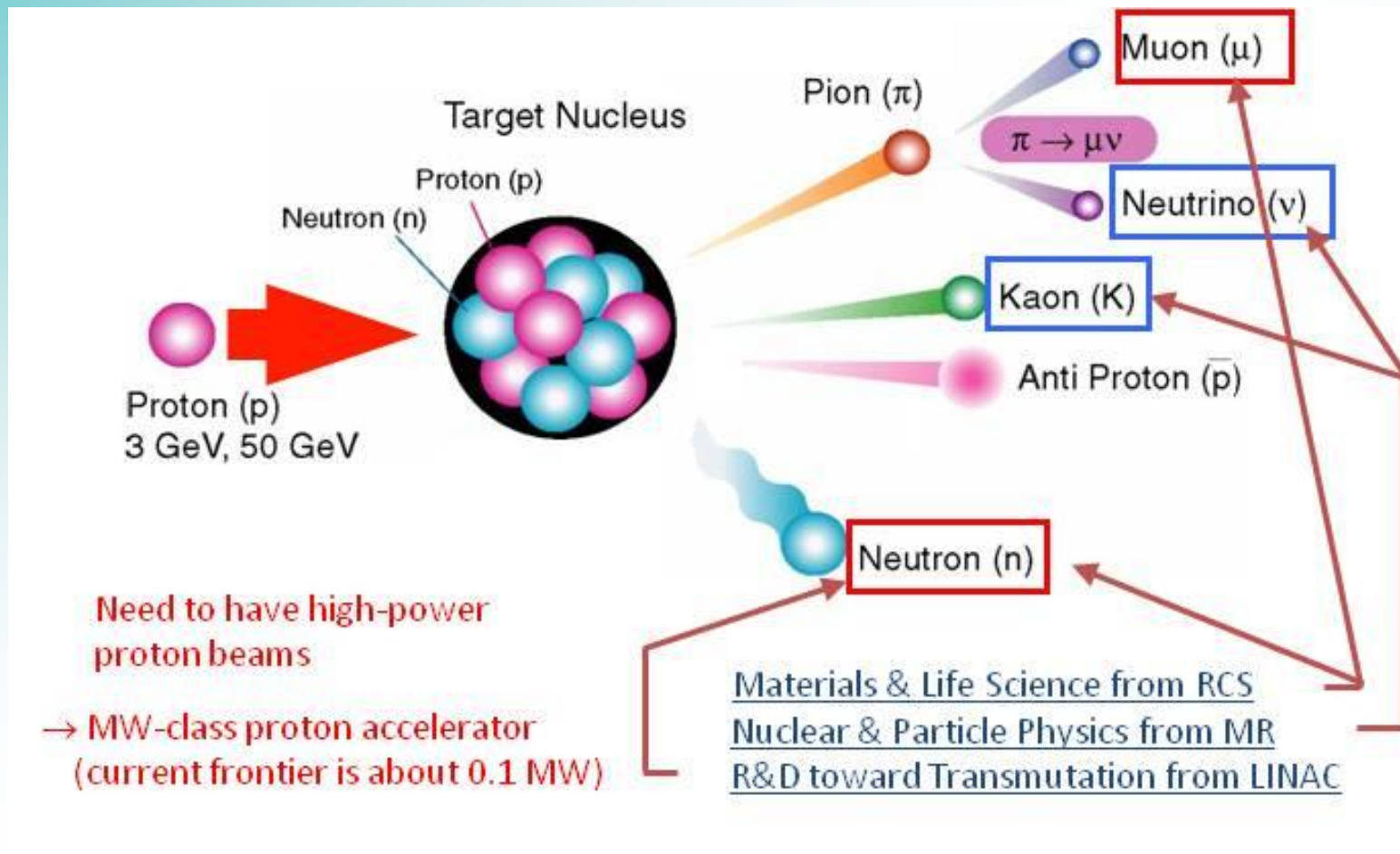


J-PARC : Japan Proton Accelerator Research Complex (under construction)



- Phase 1 + Phase 2 = 189 billion Yen (= \$1.89 billion if \$1 = 100 Yen).
- Phase 1 = 133.5 billion Yen for 6 years (= 2/3 of 189 billion Yen).
- Construction budget does not include salaries.

Secondary particle produced at J-PARC:





J-PARC : Overview

Joint Project between KEK and JAEA

Materials and Life Science Experimental Facility (MFL)

Hadron Experimental Facility

Nuclear Transmutation

Multi-Purpose Facility

500 m

Neutrino Experimental Facility

Linac 181 MeV
(400MeV)

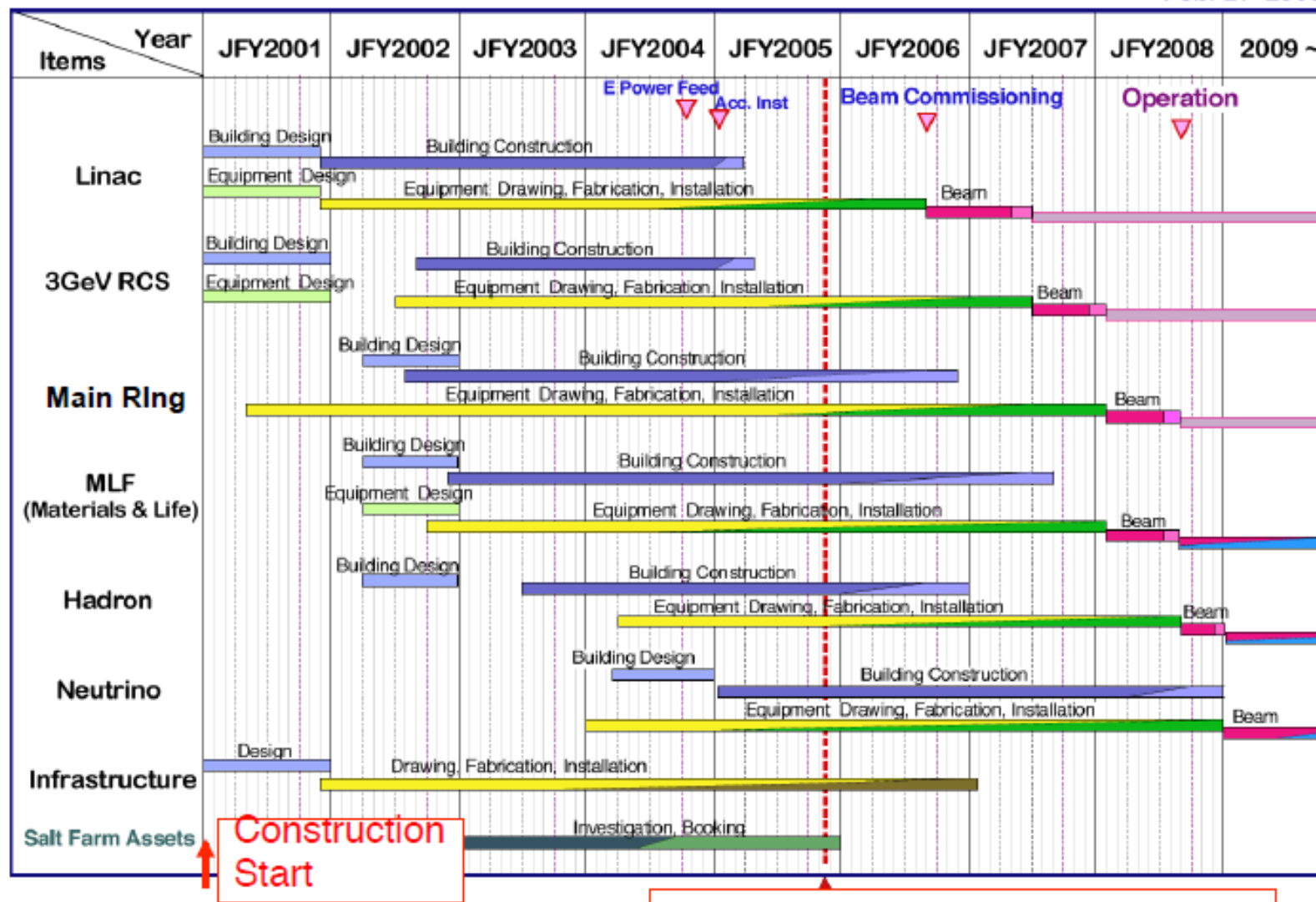
3 GeV Rapid Cycling
Synchrotron (RCS)
(25 Hz, 1MW)

50 GeV Main Ring
Synchrotron (MR)
(0.75 MW)

J-PARC = Japan Proton Accelerator Research Complex

J-PARC Construction Schedule

Feb. 27 2006





J-PARC : Pictures

Linac building



3 GeV building





J-PARC : Pictures

J-PARC Photo







History of beam commissioning

2001 Construction started.

2006 Linac beam commissioning started.

2007 Linac beam energy of 181 MeV was achieved.

RCS beam commissioning started.

RCS beam energy of 3 GeV was achieved.

2008 MR beam commissioning started.

First proton beams reached to the neutron target.

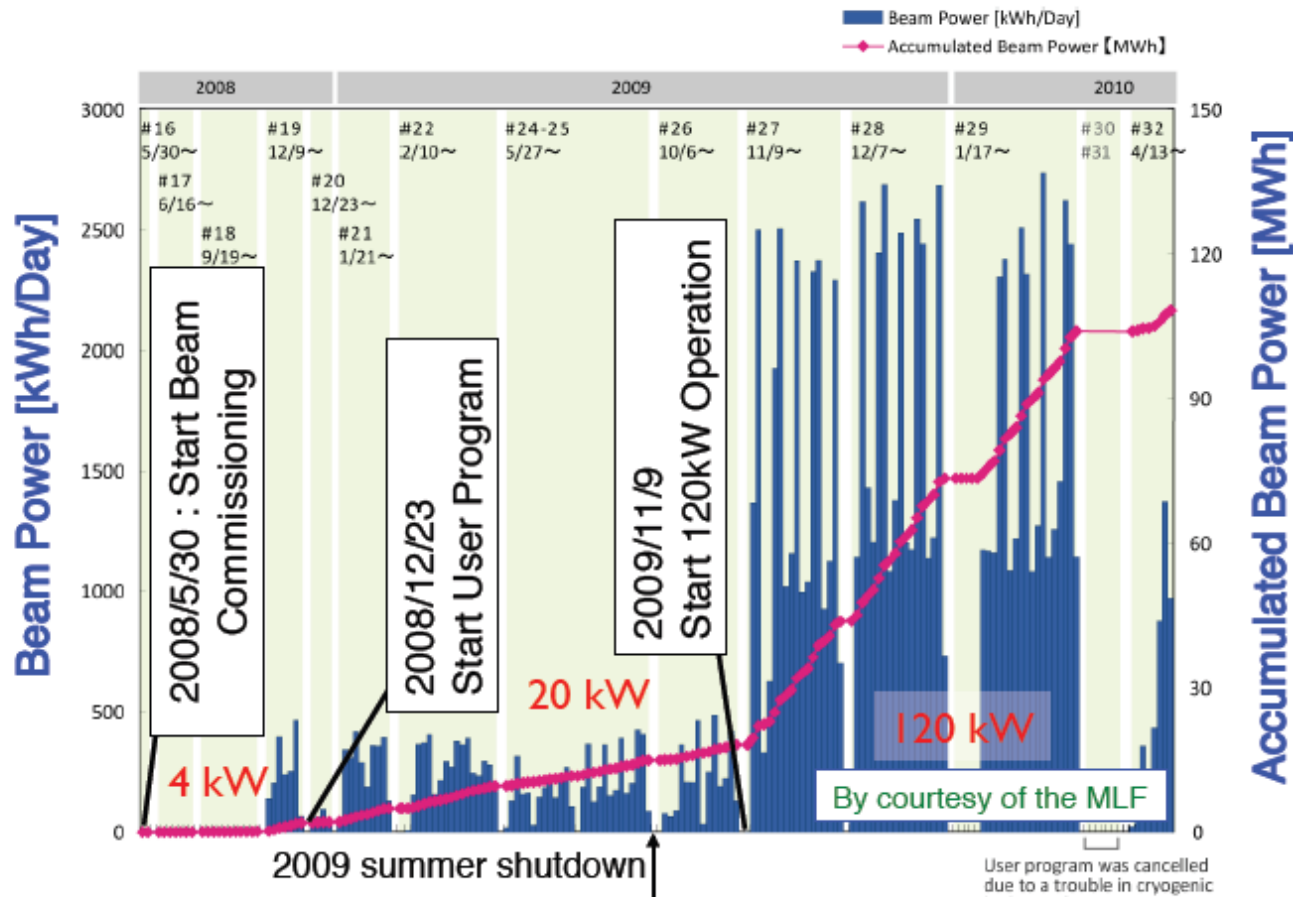
MR beam energy of 30 GeV was achieved.

First proton beams reached to the Hadron target.

User operation of MLF started.

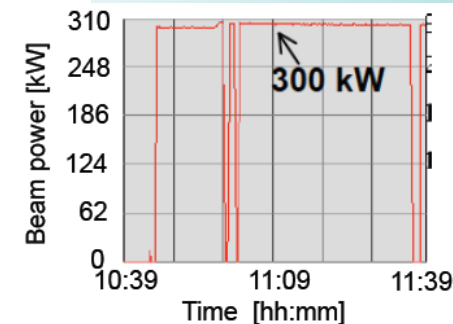
2009 First proton beams reached to the Neutrino target.

History of beam delivery to MLF



Dec. 2010:

300 kW during 1 hour of beam power issued from the RCS



After the recovery of Linac-RFQ, high power operation of the RCS has become possible and 120 kW operation has started for the MLF users.

Neutron beamline : 12 beamlines are now under commissioning and open for users.

Muon beamline: The highest intensity beamline in the world with the 120 kW beam.

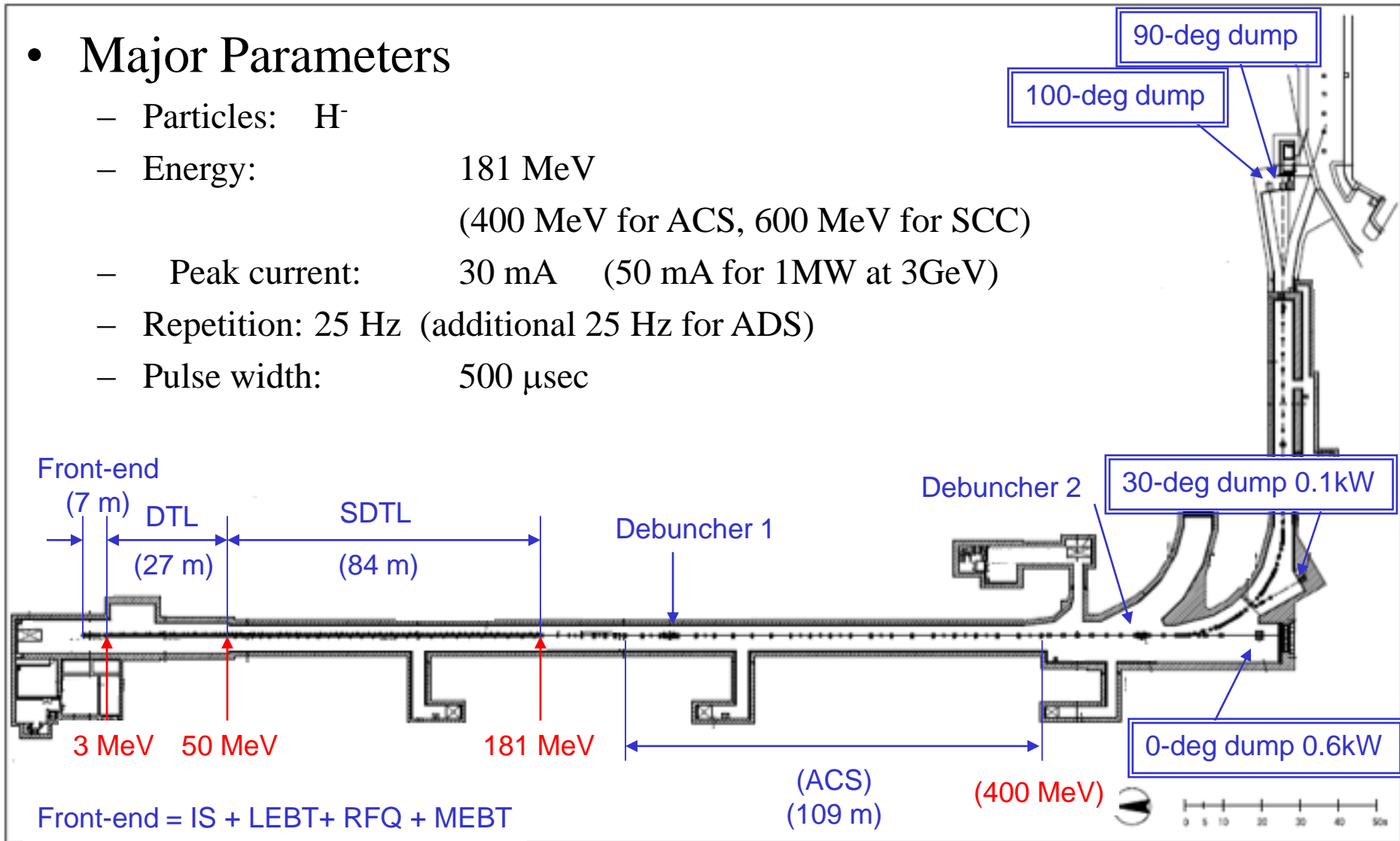
11 Mars 2011: M 9 Earthquake & consecutive Tsunami: damages to JPARC



Expected full power (1 MW) early 2015

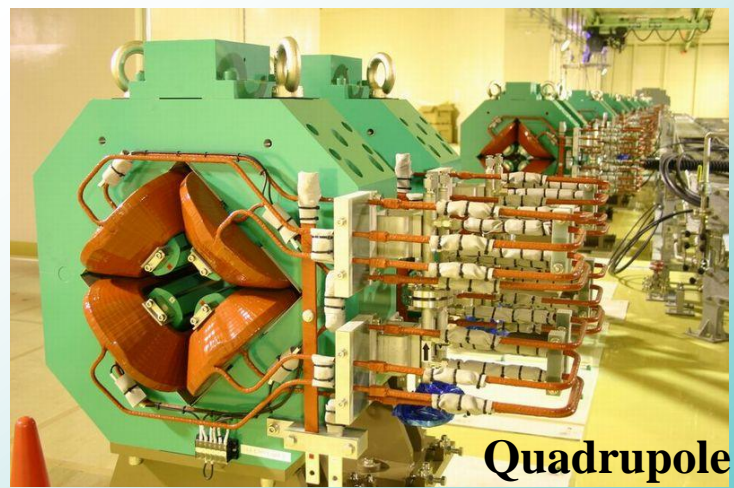
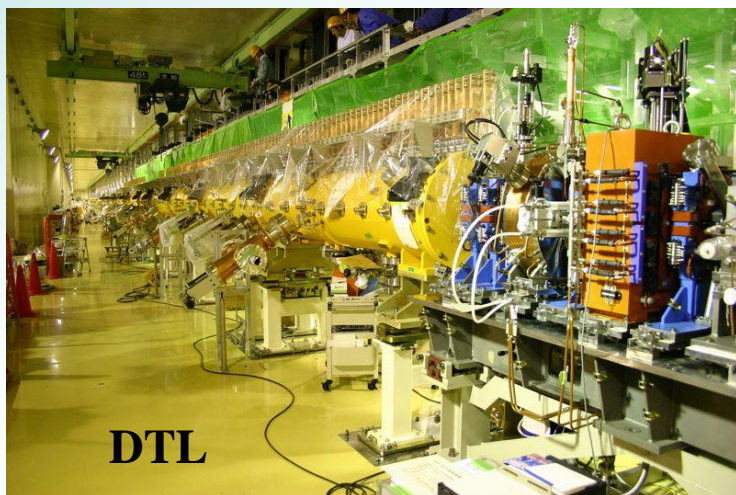
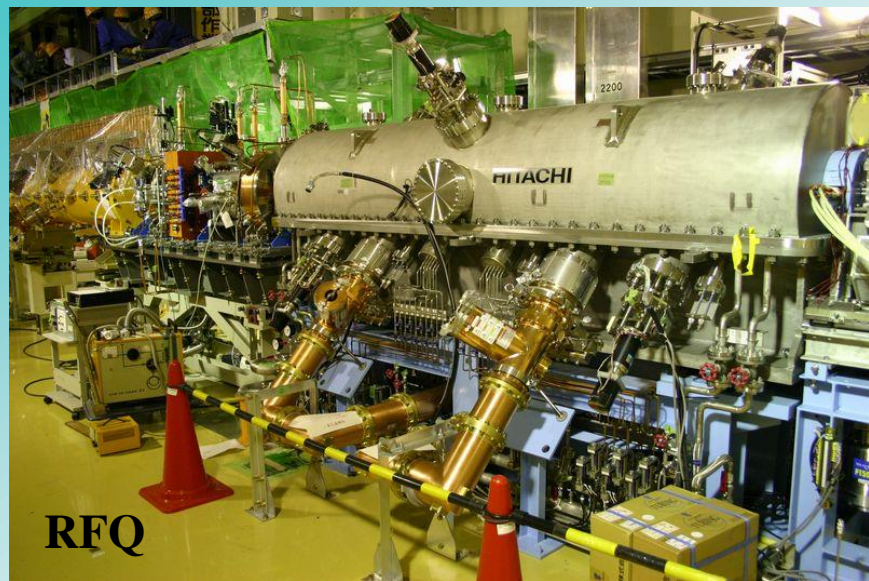
Major Parameters

- Particles: H^-
- Energy: 181 MeV
(400 MeV for ACS, 600 MeV for SCC)
- Peak current: 30 mA (50 mA for 1MW at 3GeV)
- Repetition: 25 Hz (additional 25 Hz for ADS)
- Pulse width: 500 μ sec





J-PARC : Linac pictures



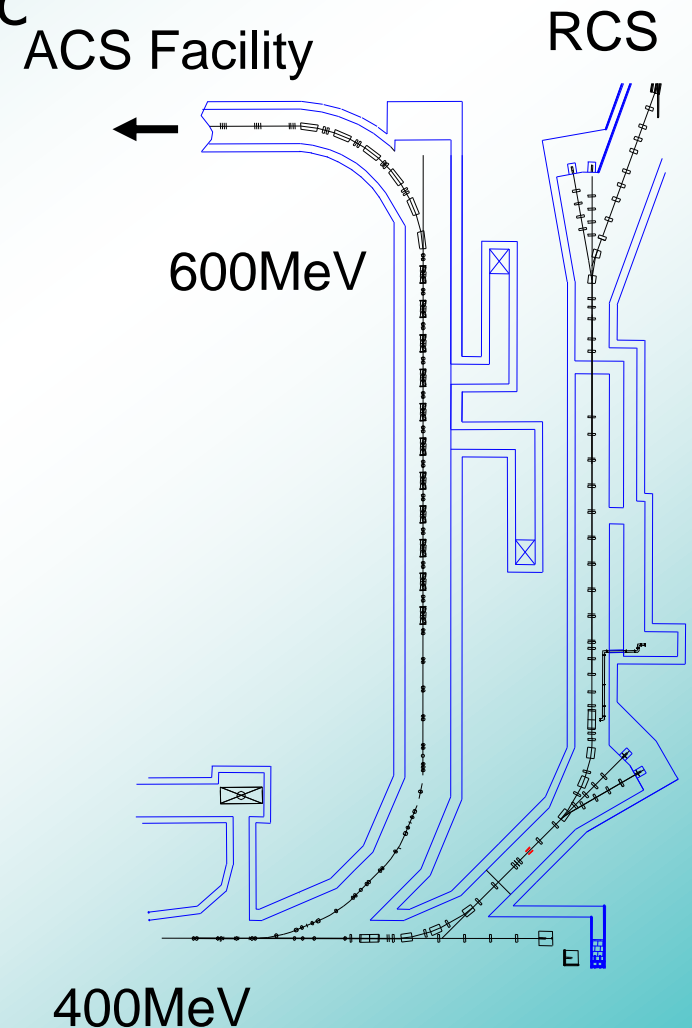


J-PARC : The SC Linac parameters

Preliminary design of SC proton linac

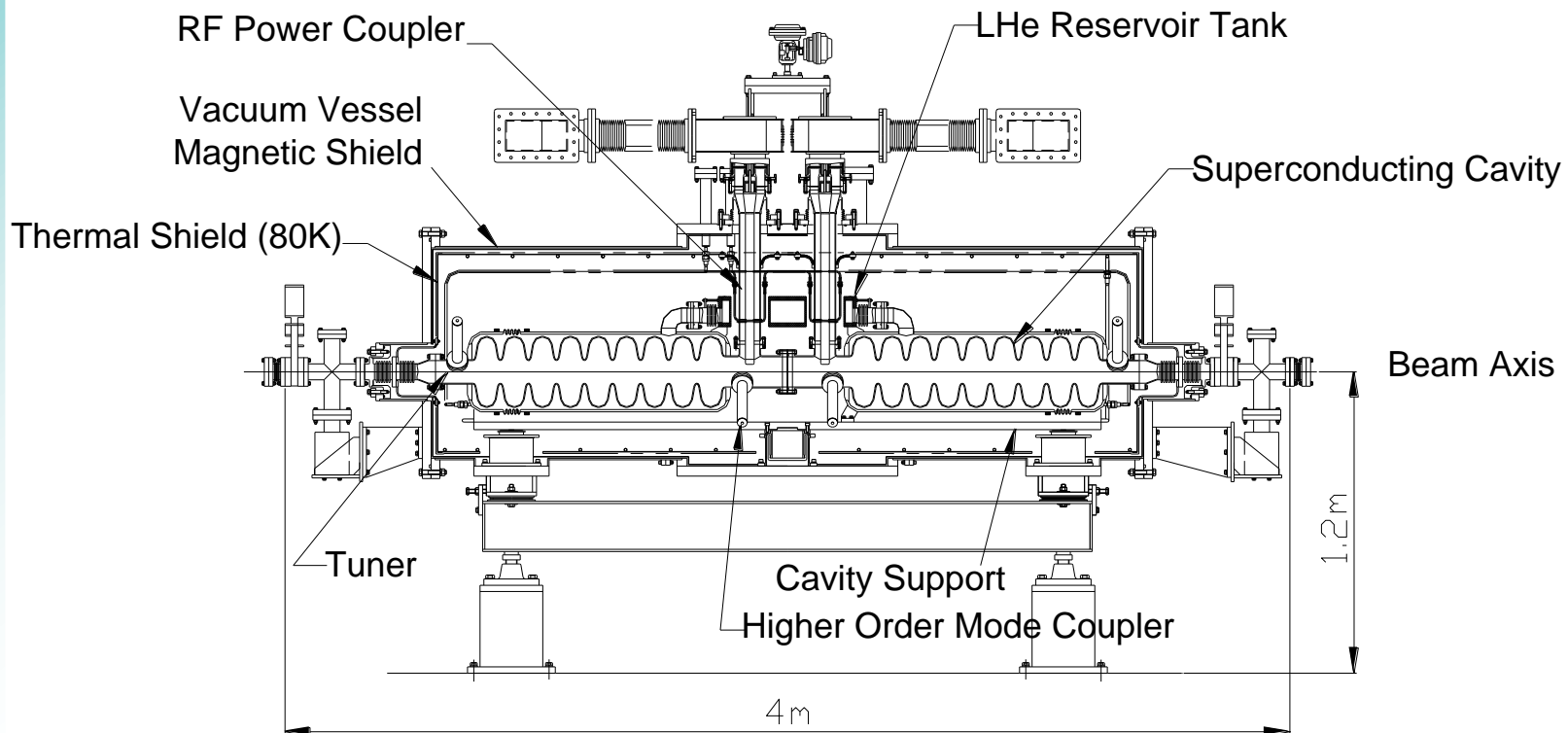
Design Parameters

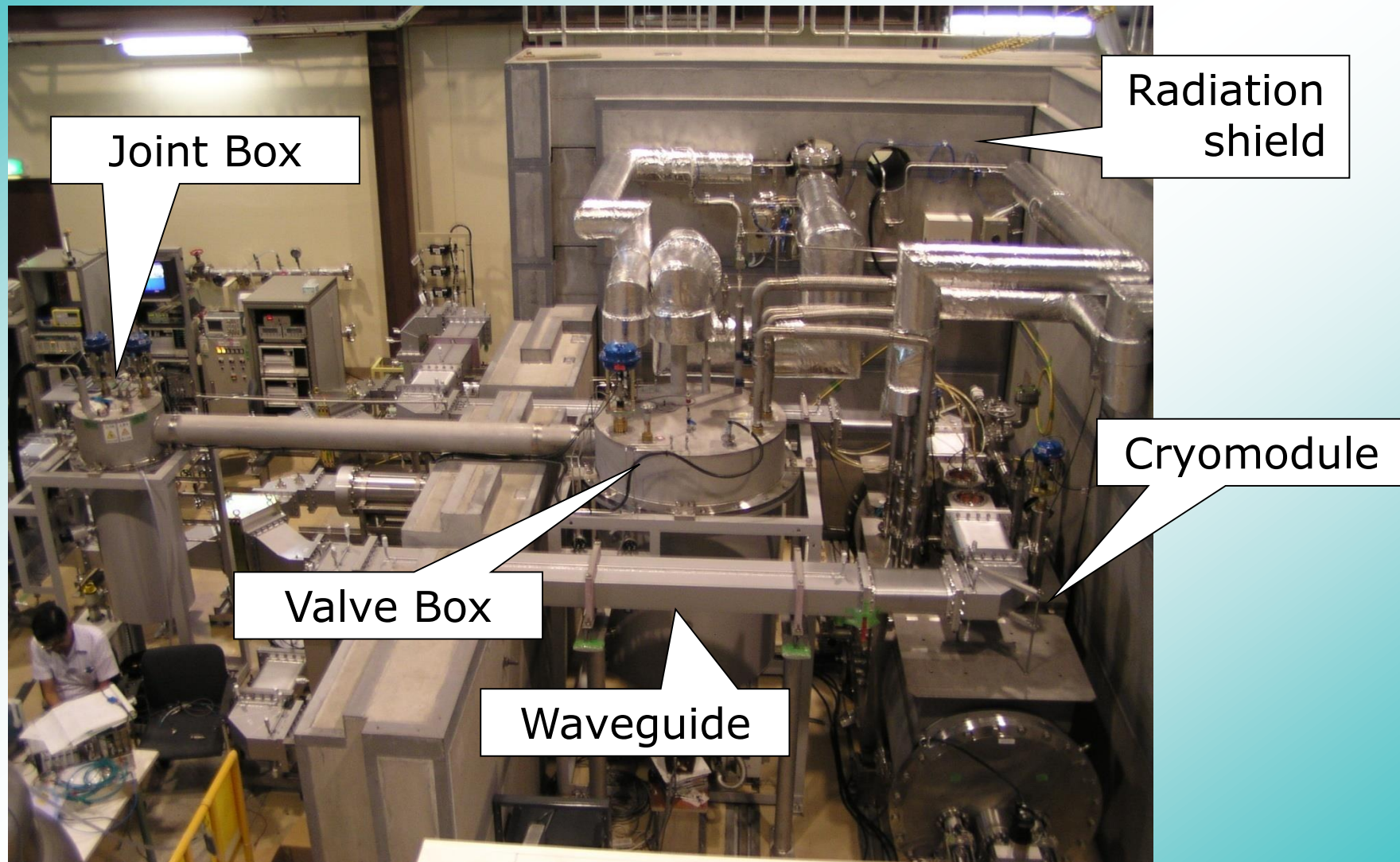
Energy	400-600 MeV
Frequency	972 MHz
β	0.71-0.79
No. of Cell	9 cell/cavity
No. of Cavity	2 cavity/cryomodule
No. of Cryomodule	11 cryomodules
Length	57.7 m
Surface Peak Field	30 MV/m
Accelerating Field	9.7-11.1 MV/m
Synchronous Phase	-30 deg
No. of Klystron	11 klystrons
Total RF Power	10 MW
Loaded Q	~500,000



Amplitude and phase stability ($\pm 1\%$ & 1deg) in pulsed operation

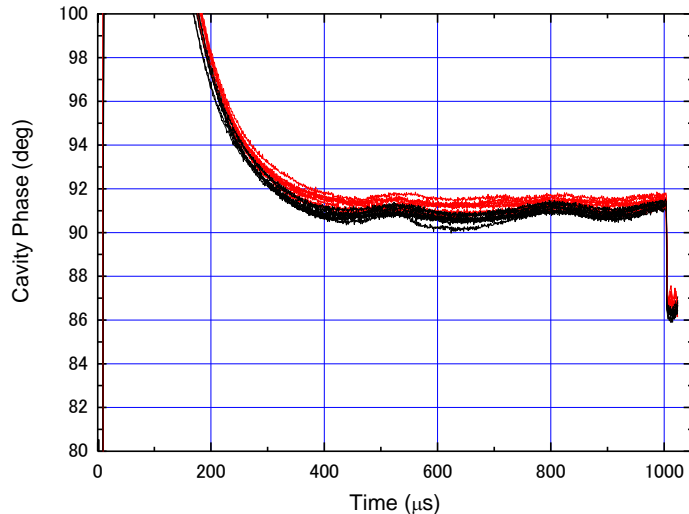
- Two 9-cell elliptical cavities of $\beta=0.725$ at 2K (972 MHz)
- Stiff structure for cavity and tuner to reduce Lorentz force detuning
- 80K thermal shield by LN_2 and 5K thermal intercept by LHe



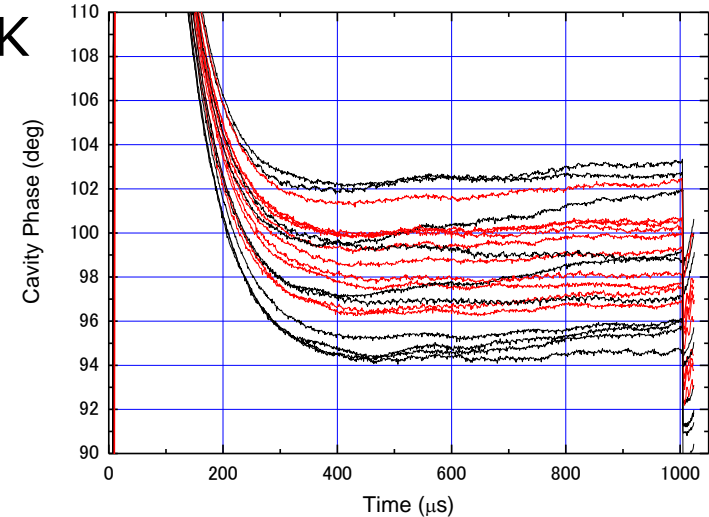


Cavity Phase for several pulses during ~1min
(Eacc~10MV/m, Pulse length:1ms, Repetition:25Hz)

@2.1K



@4.2K



- Phase stability < ± 1 deg
- Changing slowly
→ Control of LHe vessel pressure & automatic tuning system

- Phase stability < ± 5 deg
- Scattering significantly
(Microphonics ?)
(Bubbling of He ?)

Phase stability of ± 1 deg is realized in 2K operation, impossible at 4.2 K



SNS : Spallation Neutron Source
Oakridge, Tennessee, USA

(under commissioning)

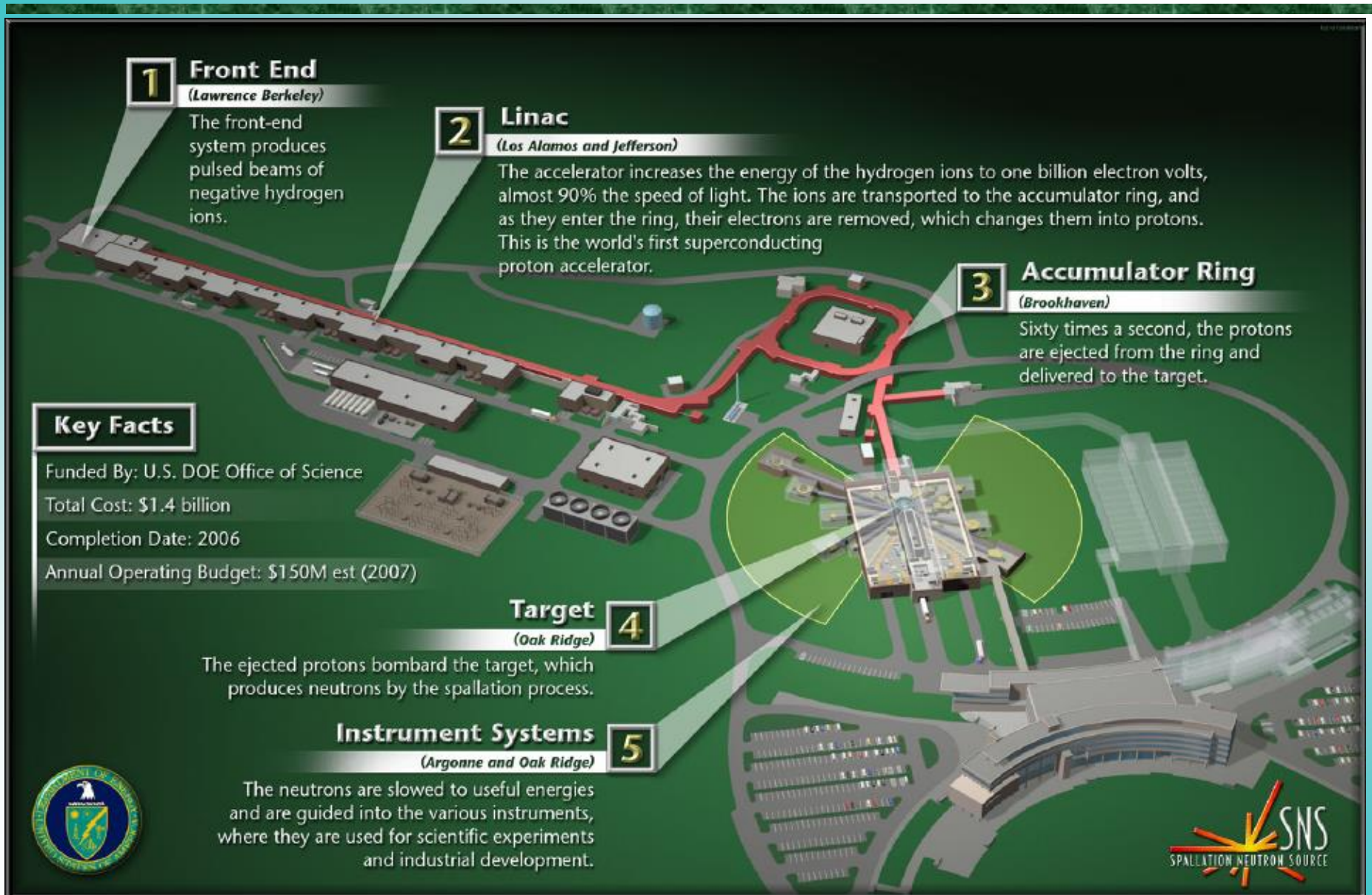


SNS : the US spallation neutron source





SNS layout





SNS : Main parameters

Spallation Neutron Source Primary Parameters

Proton beam power on target	1.4 MW		
Proton beam kinetic energy on target	1.0 GeV		
Average beam current on target	1.4 mA		
Pulse repetition rate	60 Hz		
Protons per pulse on target	1.5×10^{14} protons		
Charge per pulse on target	24 μ C		
Energy per pulse on target	24 kJ	RTBT length	150 m
Proton pulse length on target	695 ns	Ion type (Ring, RTBT, Target)	proton
Ion type (Front end, Linac, HEBT)	H minus	Ring filling time	1.0 ms
Average linac macropulse H- current	26 mA	Ring revolution frequency	1.058 MHz
Linac beam macropulse duty factor	6 %	Number of injected turns	1060
Front end length	7.5 m	Ring filling fraction	68 %
Linac length	331 m	Ring extraction beam gap	250 ns
HEBT length	170 m	Maximum uncontrolled beam loss	1 W/m
Ring circumference	248 m	Target material	Hg
RTBT length	150 m	Number of ambient / cold moderators	1/3
		Number of neutron beam shutters	18
		Initial number of instruments	5



SNS : Main parameters

SNS Beam Evolution Parameters

	Front End		Linac				Ring				Unit
	IS/LEBT	RFQ	MEBT	DTL	CCL	SCL (1)	SCL (2)	HEBT	Ring	RTBT	
Output Energy	0.065	2.5	2.5	86.8	185.6	391.4	1000	1000	1000	1000	MeV
Relativistic factor γ	0.0118	0.0728	0.0728	0.4026	0.5503	0.7084	0.875	0.875	0.875	0.875	
Relativistic factor β	1.00007	1.0027	1.0027	1.0924	1.1977	1.4167	2.066	2.066	2.066	2.066	
Peak current	47	38	38	38	38	38	38	38	9×10^4	9×10^4	mA
Minimum horizontal acceptance ^g			250	38	19	57	50	26	480	480	π mm mr
Output H emittance (unnorm., rms)	17	2.9	3.7	0.75	0.59	0.41	0.23	0.26	24	24	π mm mr
Minimum vertical acceptance ^g			51	42	18	55	39	26	480	400	π mm mr
Output V emittance (unnorm., rms)	17	2.9	3.7	0.75	0.59	0.41	0.23	0.26	24	24	π mm mr
Minimum longitudinal acceptance			4.7E-05	2.4E-05	7.4E-05	7.2E-05	1.8E-04		19/ \square		π eVs
Output longitudinal rms emittance		7.6E-07	1.0E-06	1.2E-06	1.4E-06	1.7E-06	2.3E-06		2/ \square		π eVs
Controlled beam loss; expected	0.05 ^a	N/A	0.2 ^b	N/A	N/A	N/A	N/A	5 ^c	62 ^d	58 ^e	kW
Uncontrolled beam loss; expected	70	100 ^f	2	1	1	0.2	0.2	<1	1	<1	W/m
Output H emittance (norm., rms)	0.2	0.21	0.27	0.33	0.39	0.41	0.41	0.46	44	44	π mm mr
Output V emittance (norm., rms)	0.2	0.21	0.27	0.33	0.39	0.41	0.41	0.46	44	44	π mm mr

Note a) corresponding to 27% chopped beam

b) corresponding to 5% chopped beam

c) beam loss on the transverse and momentum collimators

d) including total 4% of beam escaping foil and 0.2% beam loss on collimators

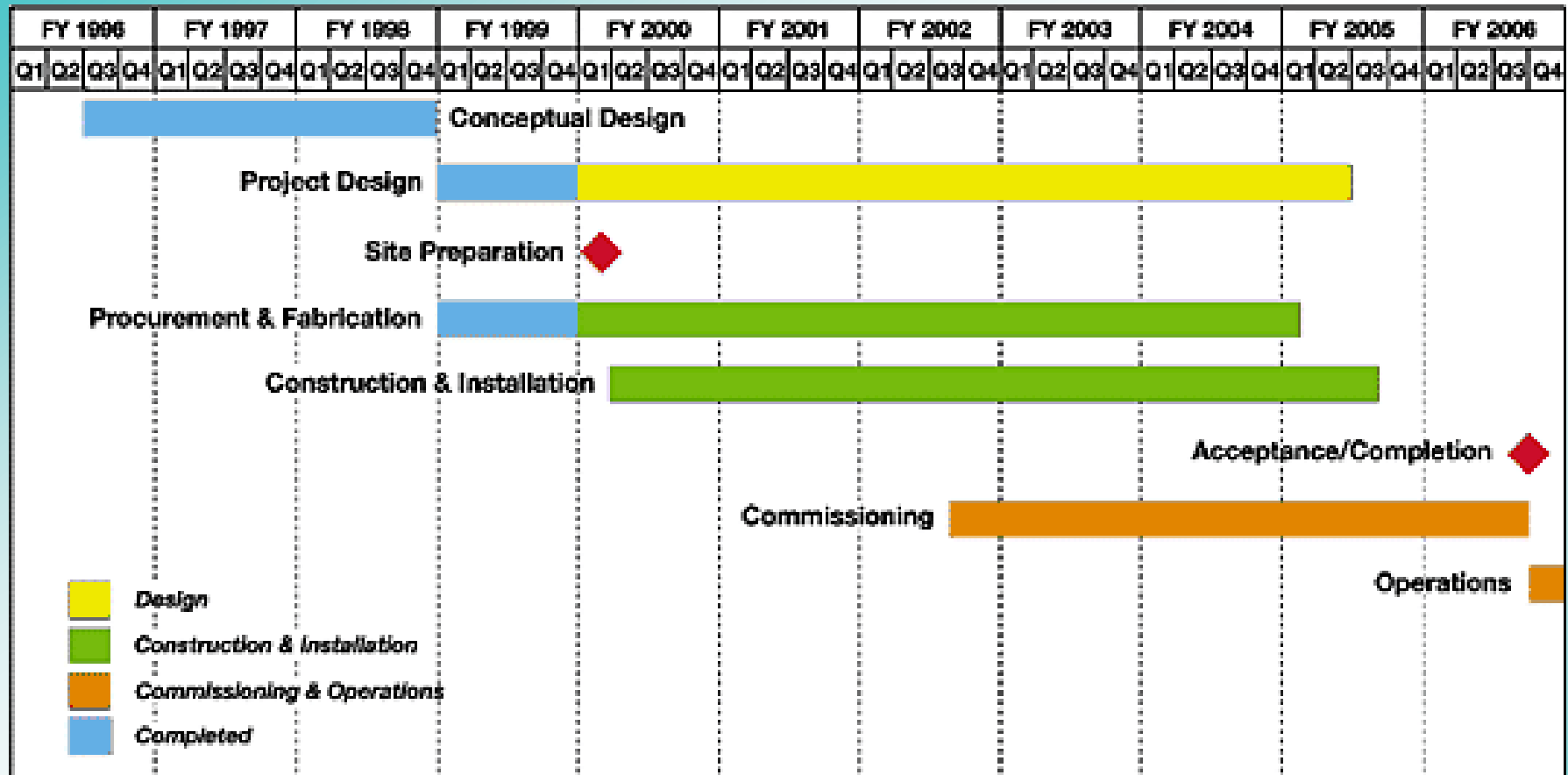
e) including 4% beam scattered on the target window

f) corresponding to 20% beam loss averaged over RFQ length

g) full acceptance without collimation



SNS : Planning




➡ Commissioning of the accelerator at low power (10 kW) achieved in May 2006. Next phase is the power ramping up to 1.4 MW. Present status is around 1 MW



SNS : aerial views



End 1999



End 2000

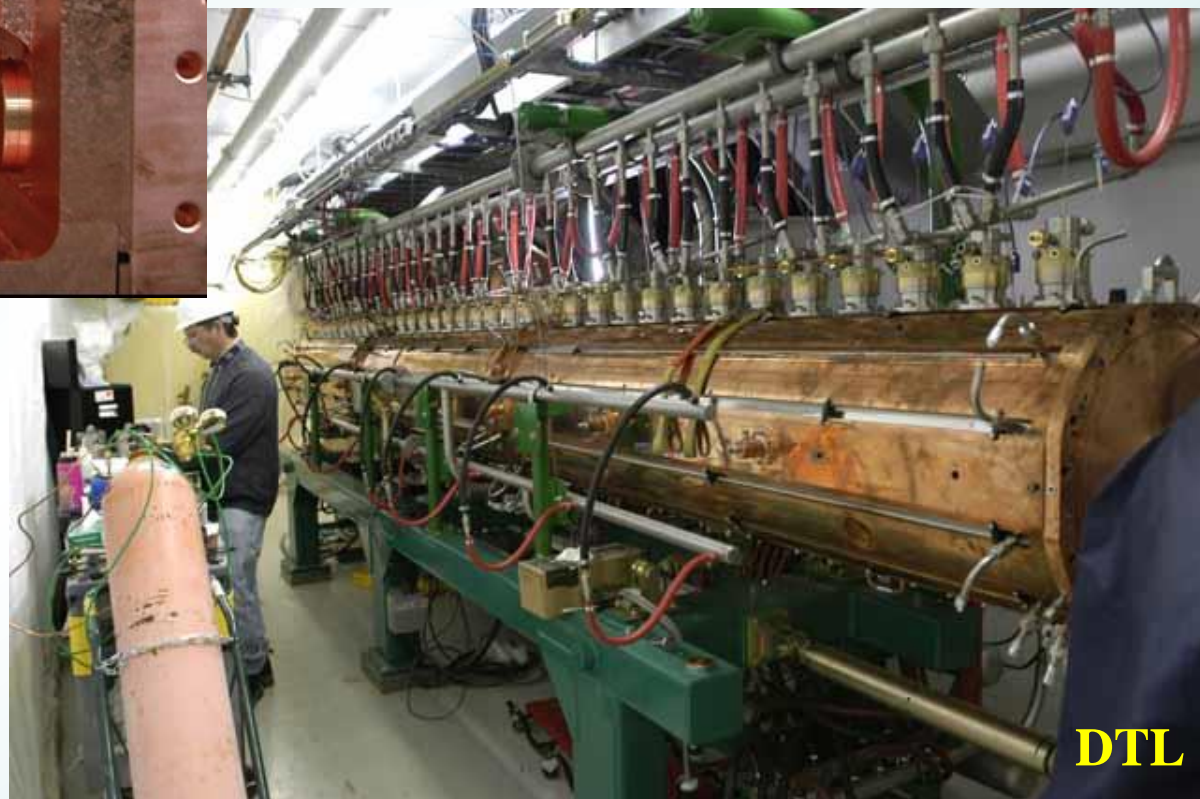
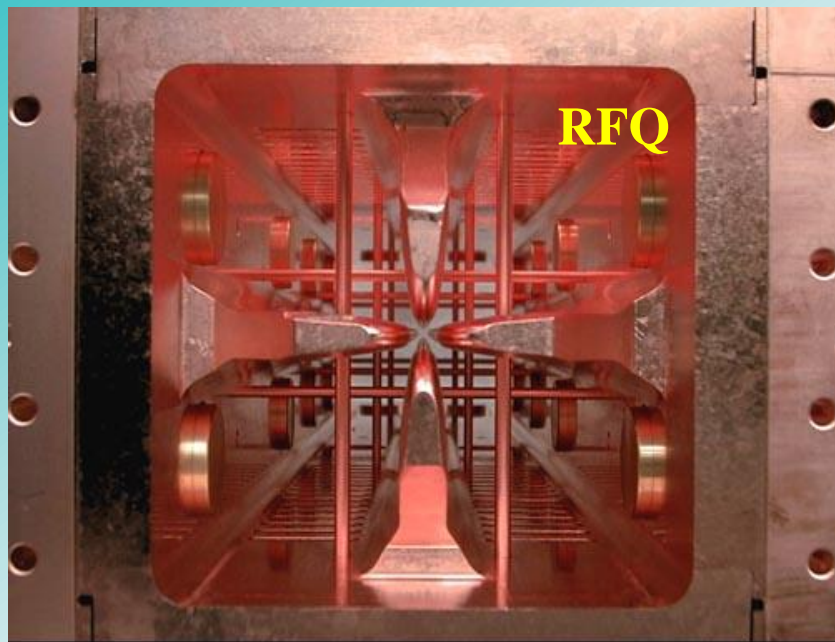


SNS : aerial views



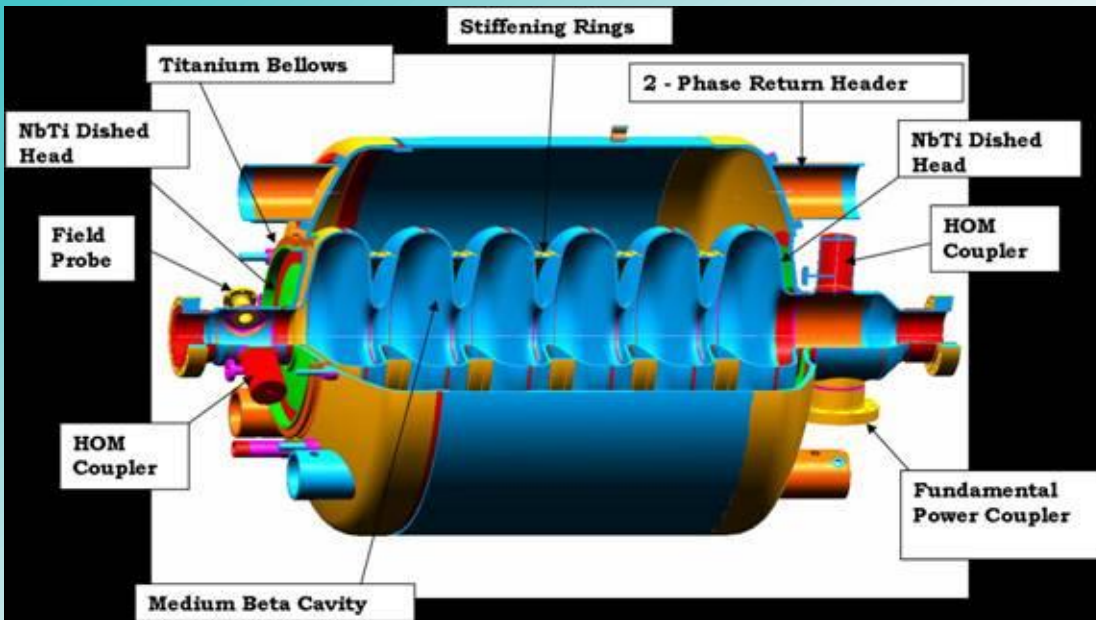


SNS : Linac pictures



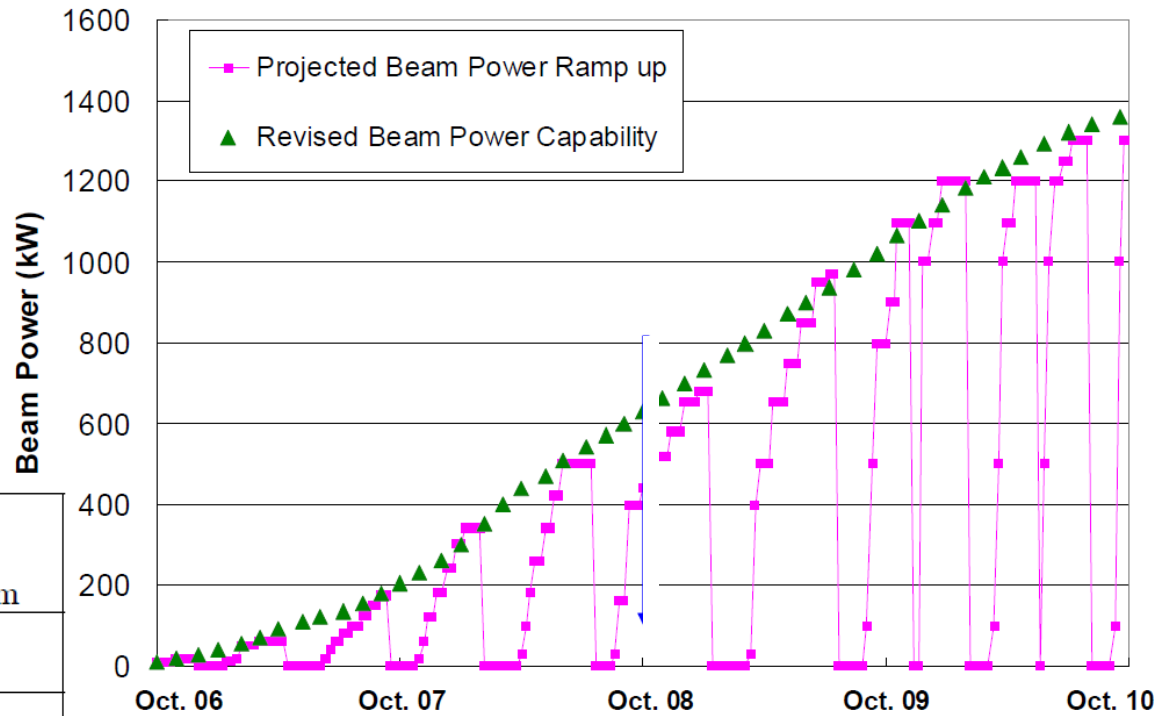


SNS : Linac pictures : SC cryomodules



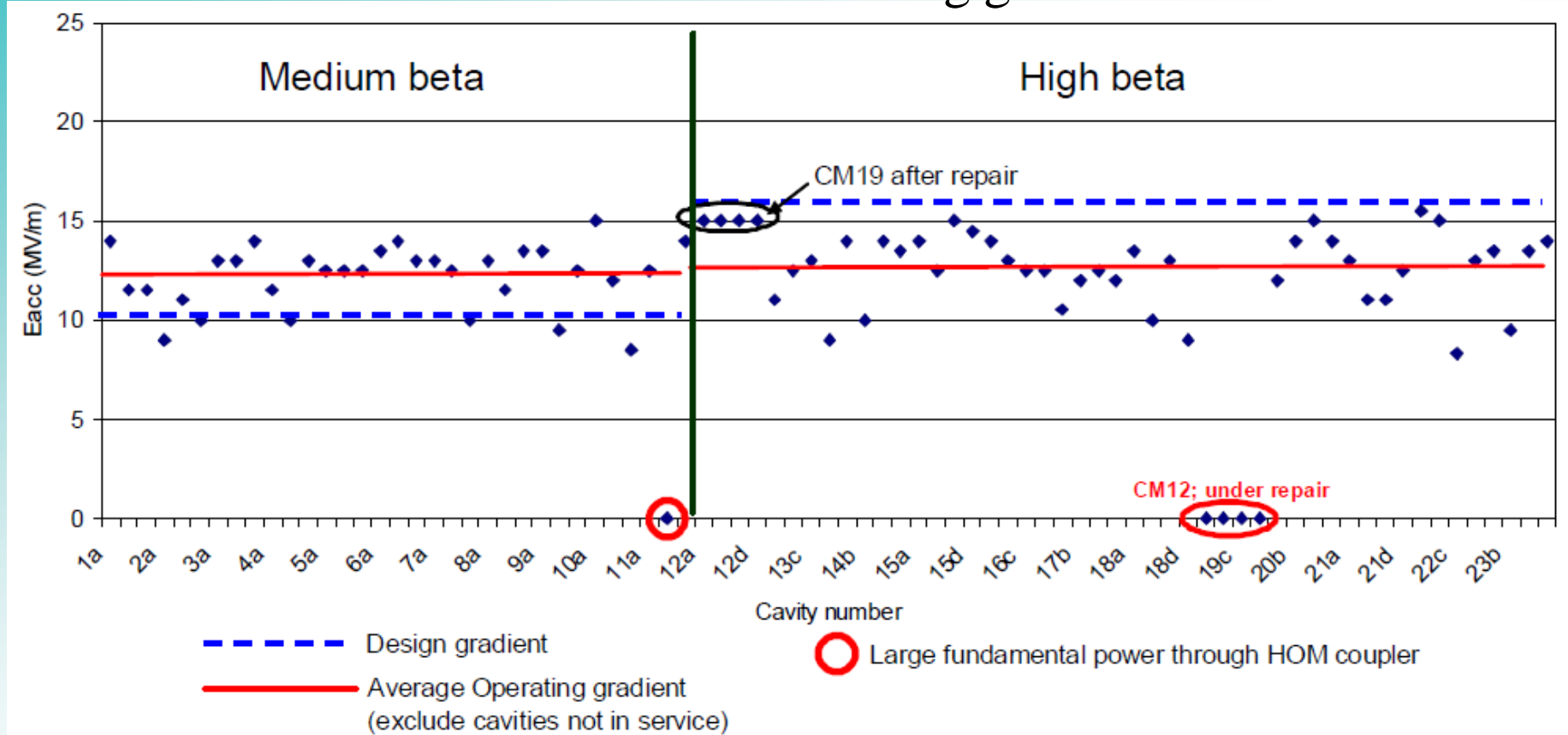


SNS : Design vs achieved parameters (oct. 2009)



Parameters	Design	Highest Production Beam
Beam Energy (GeV)	1.0	0.93 + 0.01
Peak Beam current (mA)	38	40
Average Beam Current (mA)	26	24
Beam Pulse Length (ms)	1000	670
Repetition Rate (Hz)	60	60
Beam Power on Target (MW)	1440	1.01
Linac Beam Duty Factor (%)	6	4.0
Beam intensity on Target (protons per pulse)	1.5×10^{14}	1×10^{14}
SCL Cavities in Service	81	80

SNS Linac : Achieved accelerating gradients in SC cavities



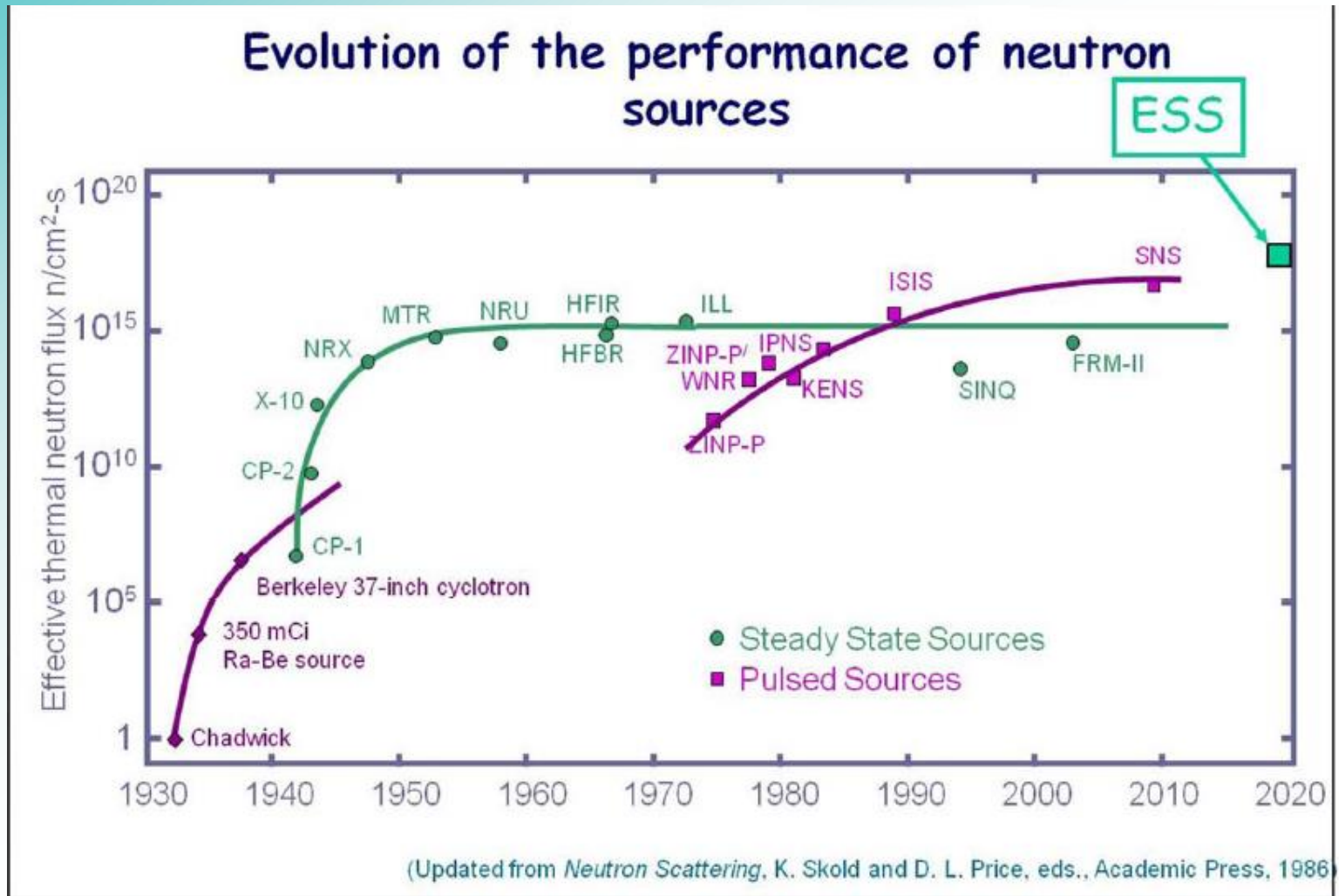
Future : finish commissioning up to 1.4 MW.

Upgrades plans: beam power upgrade to 3 MW with increasing beam energy from 1.0 GeV to 1.3 GeV (adding 9 additional high-beta cryomodules) and by increasing beam current from 38 mA to 59 mA.



ESS : European Spallation Source
(Lund, Sweden)

(project approved in 2009)

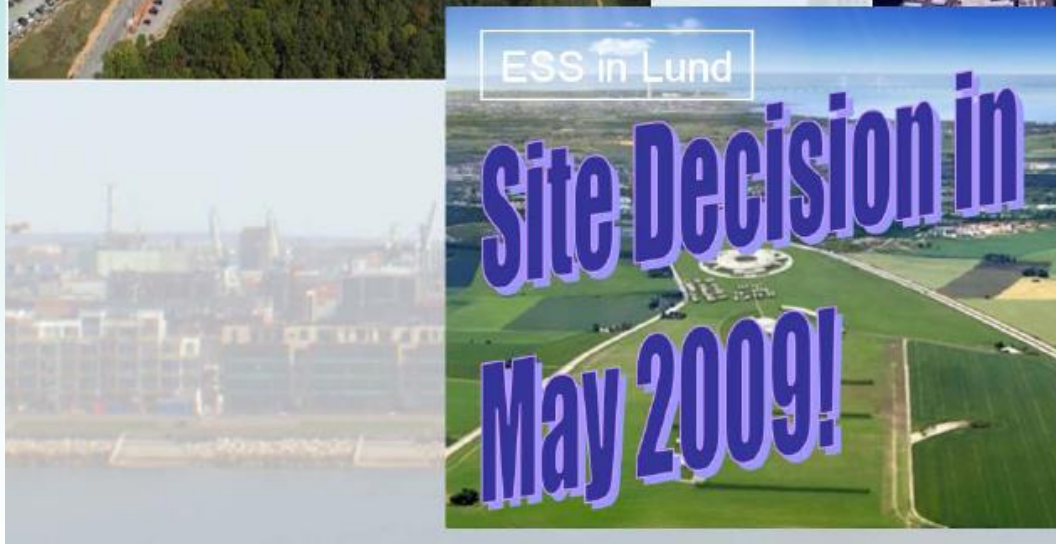


OECD: « a high power spallation source in each global region »





ESS : the European Spallation Source





ESS : the European Spallation Source





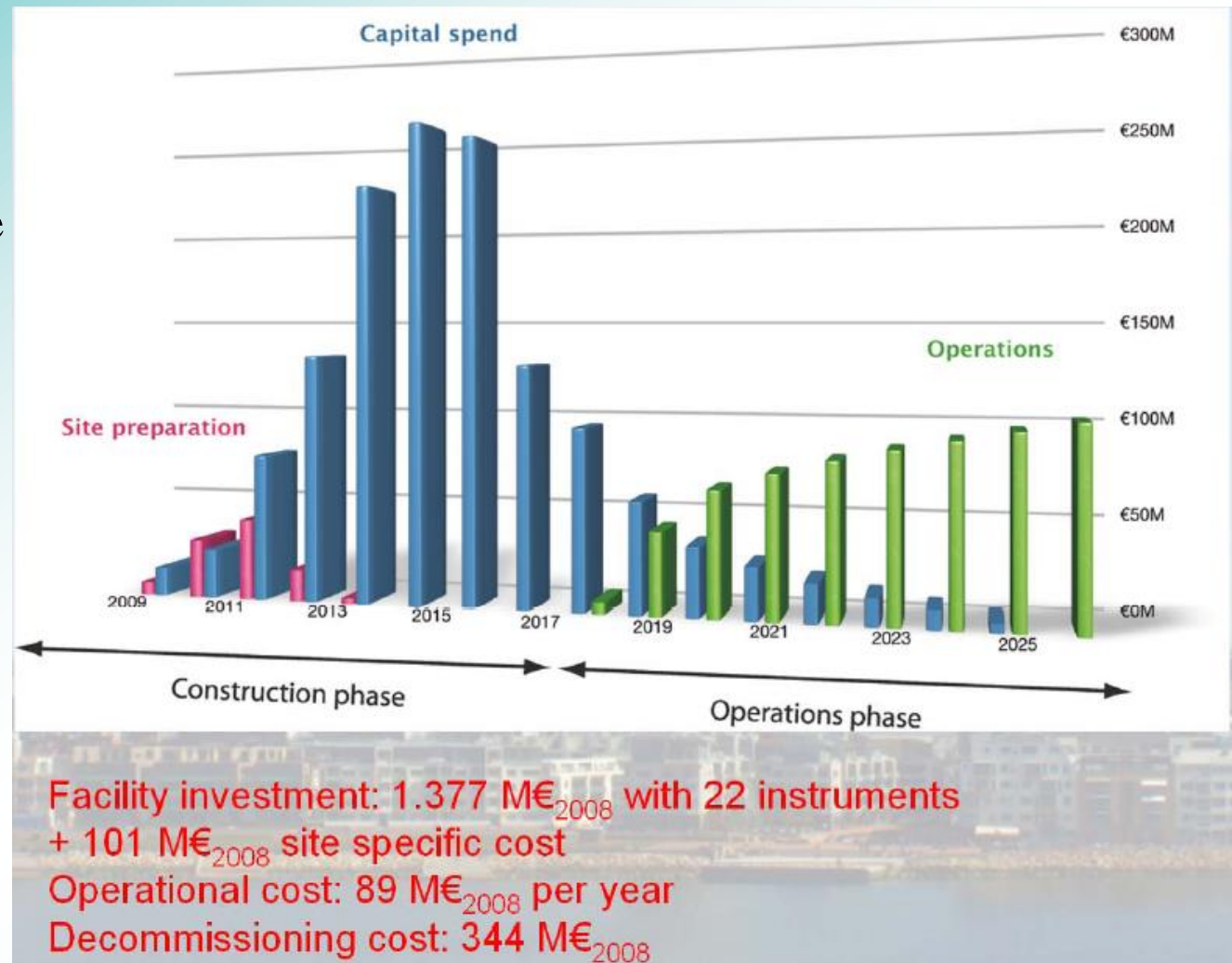
ESS : the European Spallation Source

Technical objective:

5 MW long pulse source
(Upgrade 7.5 MW)

Long pulse (2.86 ms)
14 Hz rep rate
Protons beam

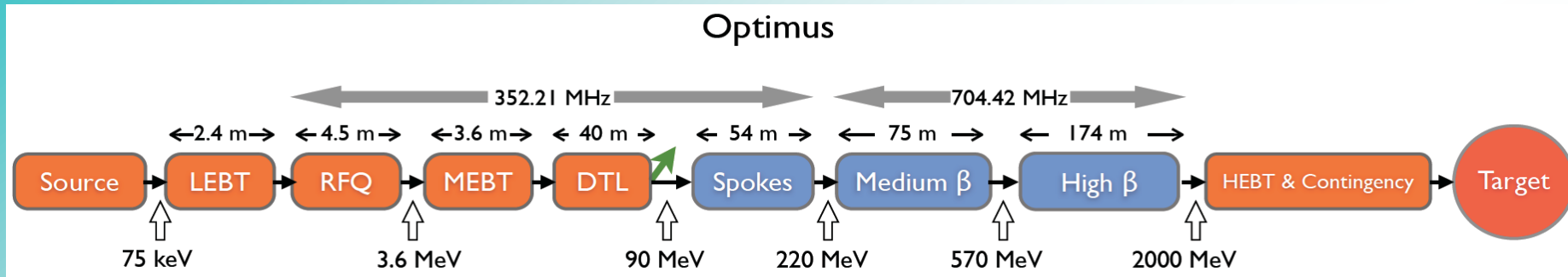
High reliability (>95%)
Low losses



Facility investment (cost re-evaluated in 2013) : 1850 M€



ESS : the European Spallation Source

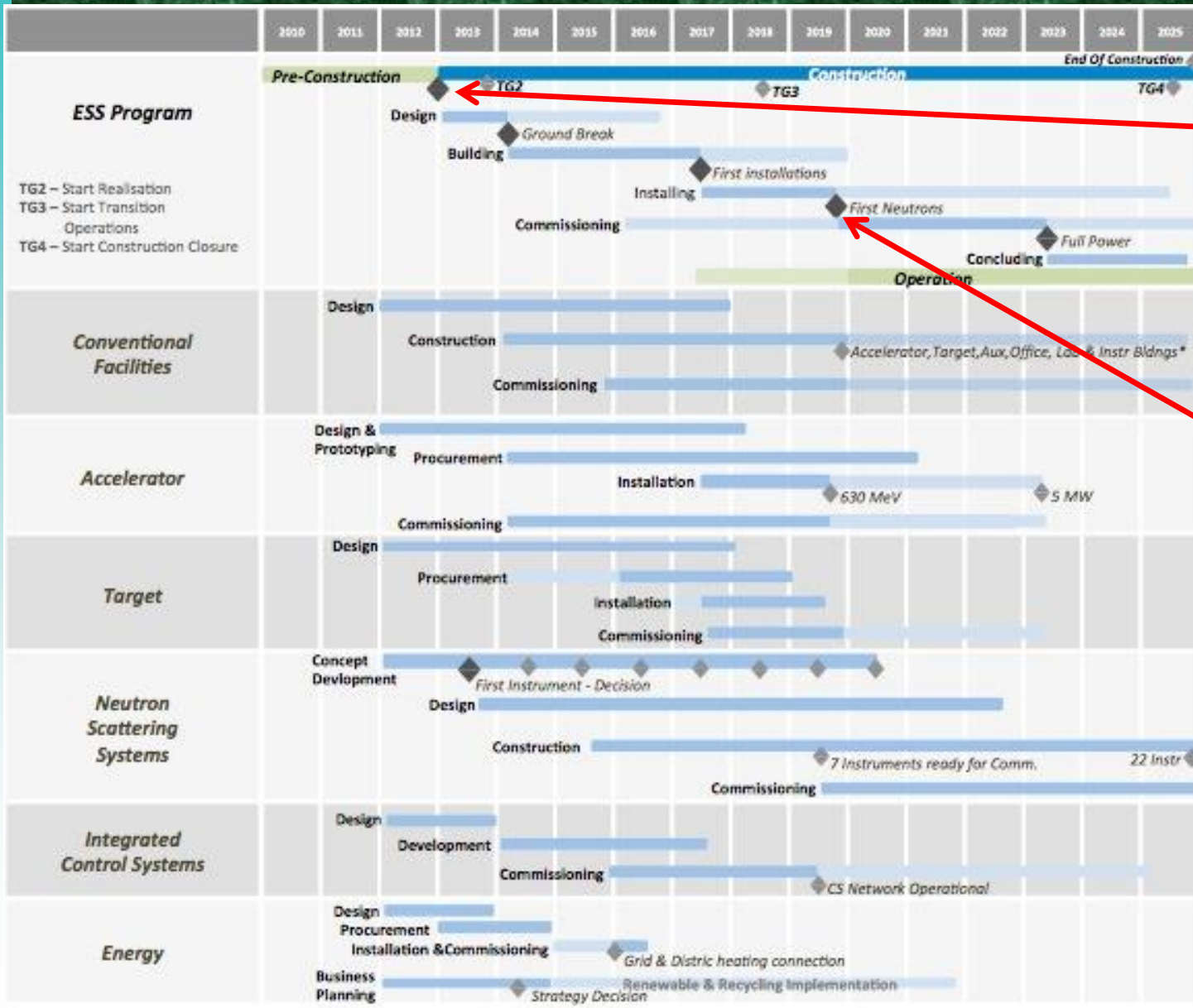


Section	Cavity β	Total number of Modules	Cavity frequency	# Cavity per module	# Cavity per section	Cryomodule length	Section length
Spoke	0.50	13	352 MHz	2	26	~ 2.9 m	54 m
Medium-beta	0.67	9	704 MHz	4	36	~ 6.7 m	75 m
High-beta	0.92	21	704 MHz	4	84	~ 6.7 m	174 m
Total		43			146		~ 300 m

- This architecture is mainly an evolution of the SNS linac with less critical subsystems: H- source, fast chopping, Pils RFQ, ring injection.
- Main innovation (risk?): Spoke Resonators are used to enhance the flexibility and the accelerating efficiency at medium energy.
- More robust than 2003 design: lower peak current for the same power (higher energy) without any extra length (power coupler limitation) and no funnelling.



ESS : the European Spallation Source



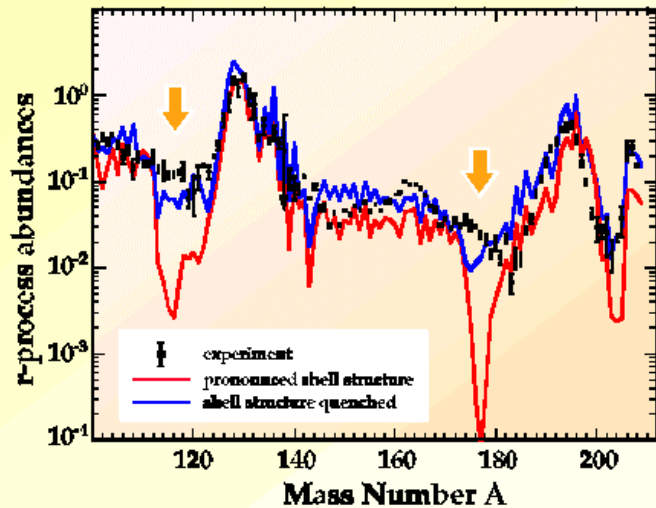
Since Feb. 2013:
Construction
phase

End 2019:
1st neutrons with
linac @ 570 MeV

In 2025:
ESS @ full power
&
22 instruments

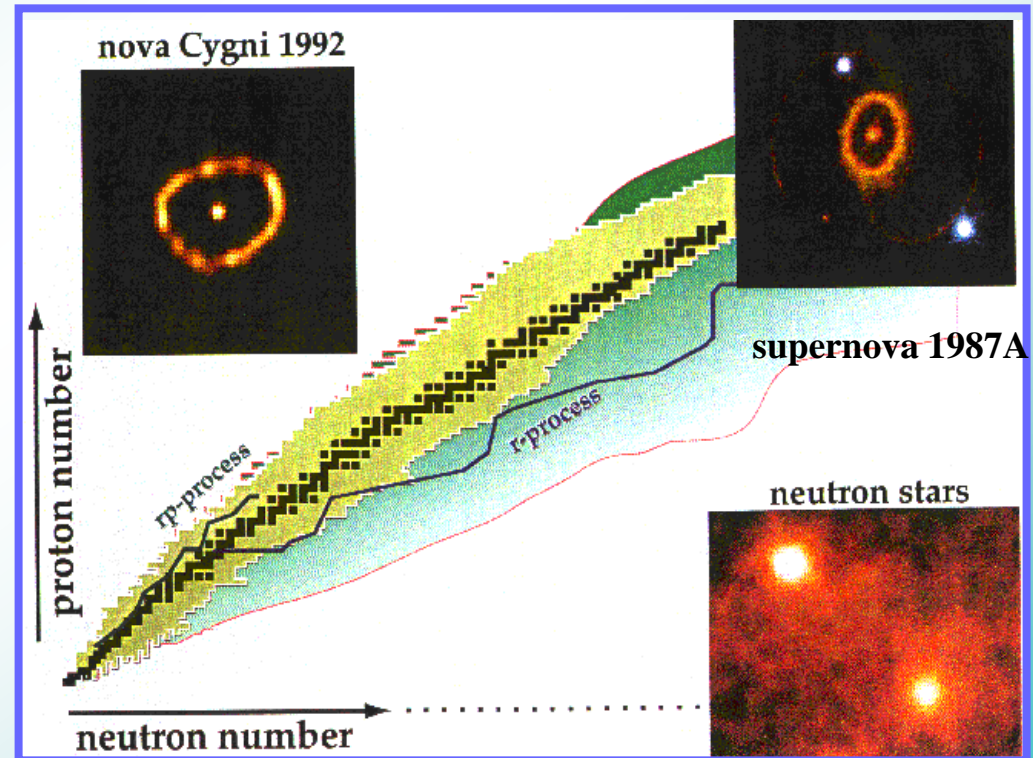


High Power Proton Accelerator for Radiative Ion Beam Production



- nuclear astrophysics studies the **nuclear reactions** which happen in **stars**
- the reactions give rise to the energy production and make the chemical elements, "isotopic abundance", our world is made of
- the left figure shows, e.g. the abundance produced in the r-process, believed to happen when **supernovae explode** (black = measured abundance)

- the rapid proton (rp) and neutron (r) capture generate **very short-lived nuclei**
- the nuclear structure properties of these nuclei are often **unknown**.
- yet their masses, decay-properties, reaction cross sections critically **determine** the isotopic abundance (in the figure, note the difference between **normal** and **quenched** shell structure)
- this is a very important physics goal for accelerators, like **GANIL-SPIRAL, GSI...** or the future projects **RIA** or **EURISOL**
- the high-intensity EURISOL accelerator has remarkably similar **specifications** as the one of the XADS!



$$I = \sigma \times \Phi \times N \times \varepsilon_1 \times \varepsilon_2 \times \varepsilon_3 \times \varepsilon_4 \times \varepsilon_5$$

σ : cross-section, Φ : primary-beam intensity,

N : target thickness,

ε_1 : product release and transfer efficiency

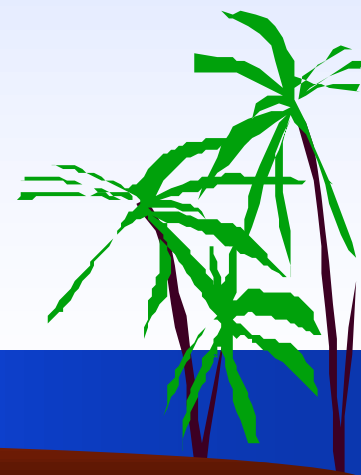
ε_2 : ion-source efficiency,

ε_3 : efficiency due to radioactive decay losses

ε_4 : the efficiency of the spectrometer

ε_5 : the post-acceleration efficiency

$$\Phi \times N = \text{Luminosity}$$



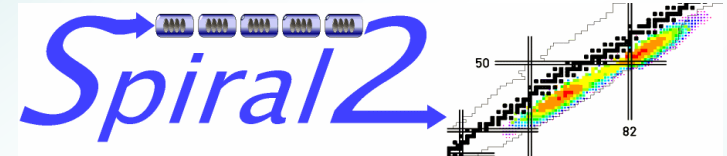
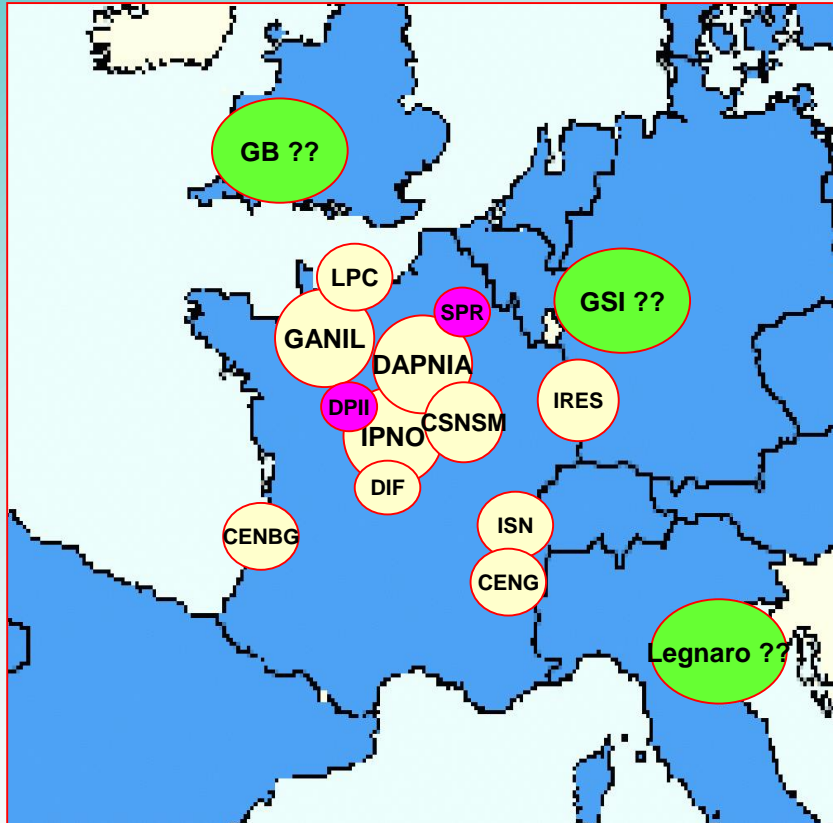


SPIRAL-2 : Radioactive ion beam production
GANIL, Caen, France

(under construction)



Spiral - 2



SPIRAL II Project:
13 French Laboratories
International Collaborations
135 M€ total cost (inc. manpower)

Project approved in May 2005
Construction phase has started

First beam in 2012

Existing GANIL

SP2 beam time : 44 weeks/y
ISOL RIB beams : 28-33 weeks/y
SP2 users : 400-500/y
GANIL+SP2 Users : 700-800/y

CIME cyclotron
 $E < 25$ A.MeV - RI Beam

DESIR Facility
Low energy RIB

HRS and RFQ cooler

RIB production cave : up to 10^{14} fiss./s

S3 : Super
Separator
Spectrometer

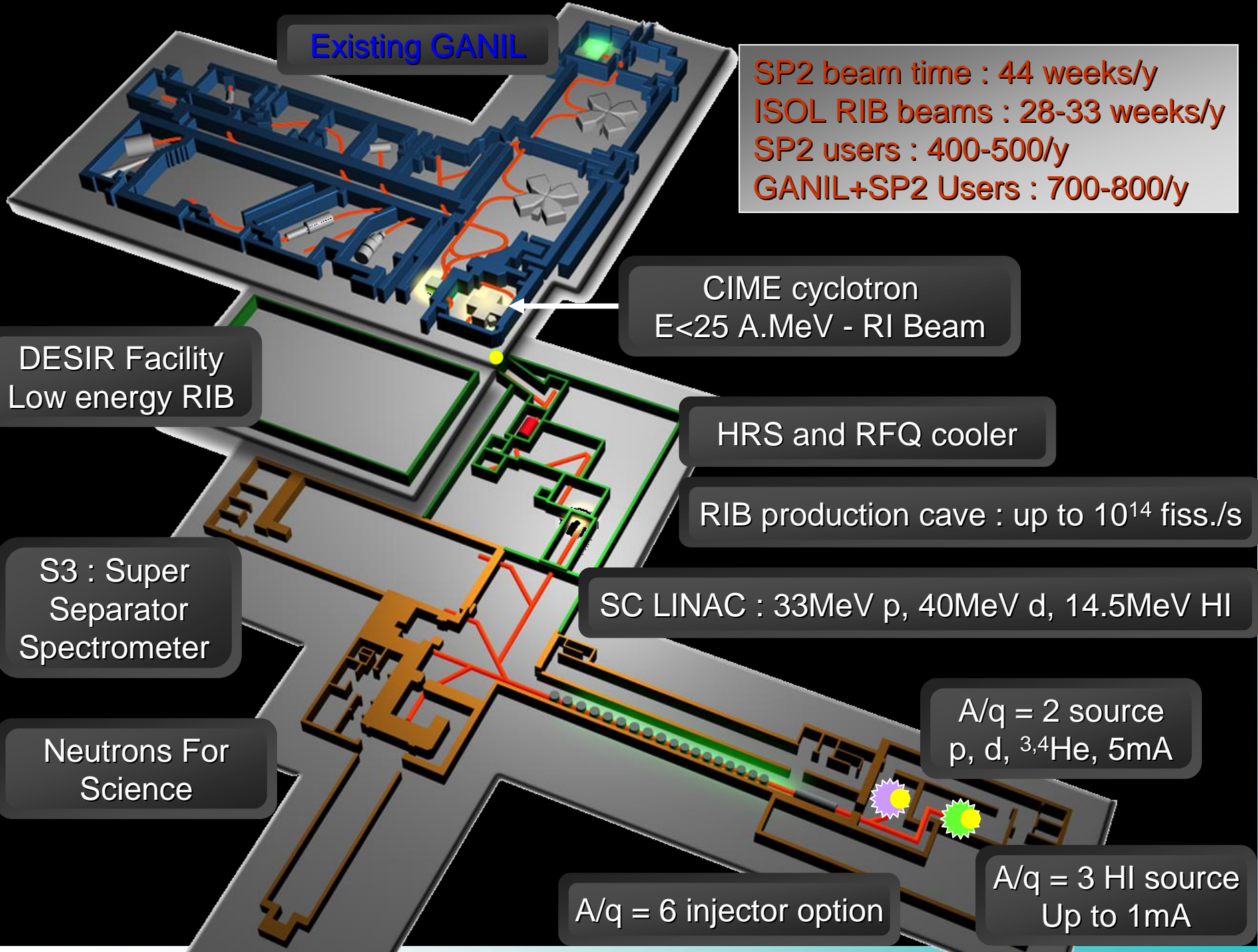
SC LINAC : 33MeV p, 40MeV d, 14.5MeV HI

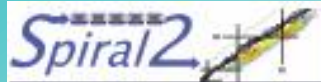
Neutrons For
Science

$A/q = 2$ source
p, d, ^3He , 5mA

$A/q = 6$ injector option

$A/q = 3$ HI source
Up to 1mA



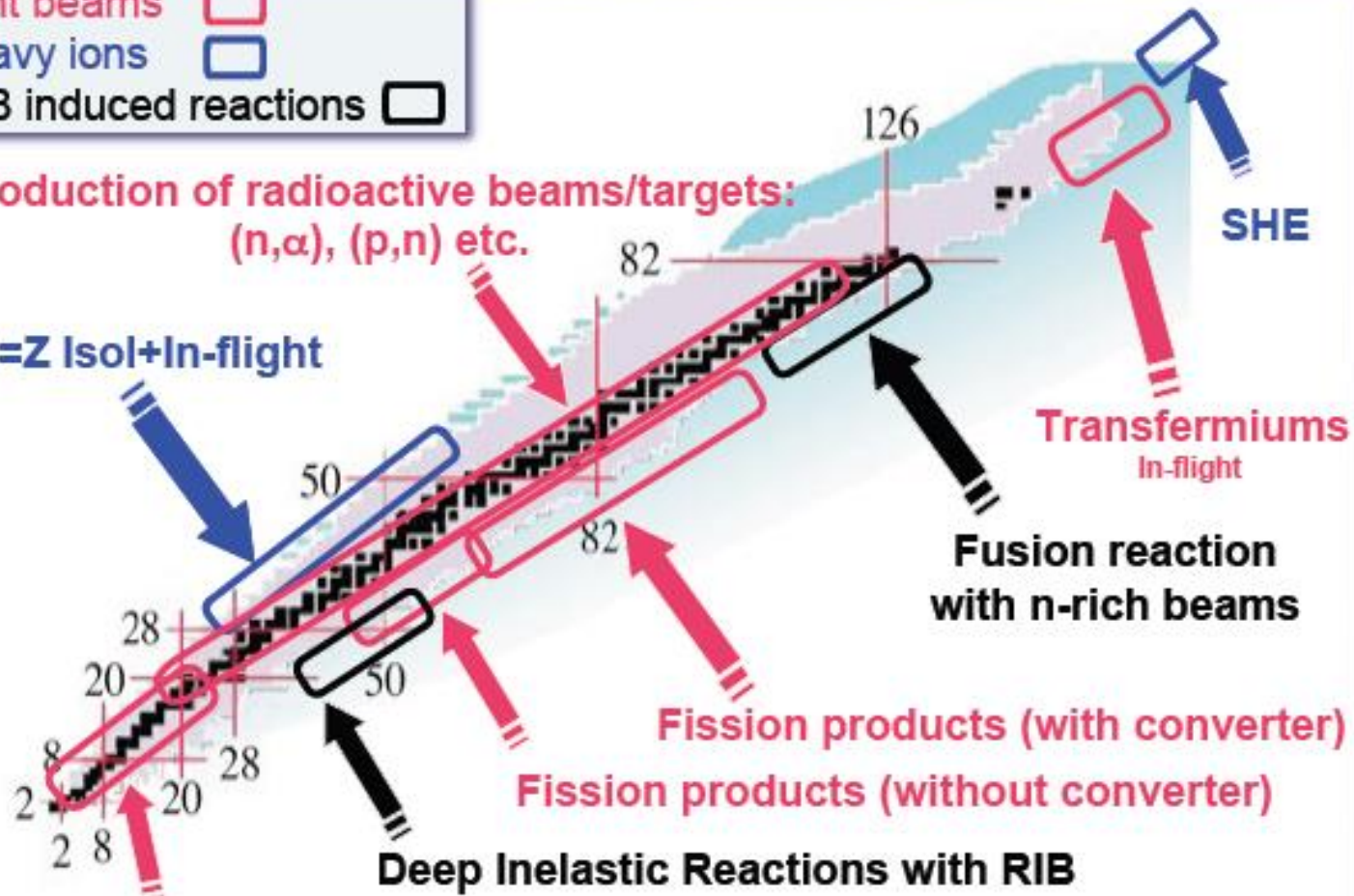


Regions of the Chart of Nuclei Accessible with SPIRAL 2 Beams

- ⇒ light beams
- ⇒ heavy ions
- ⇒ RIB induced reactions

Production of radioactive beams/targets:
(n,α), (p,n) etc.

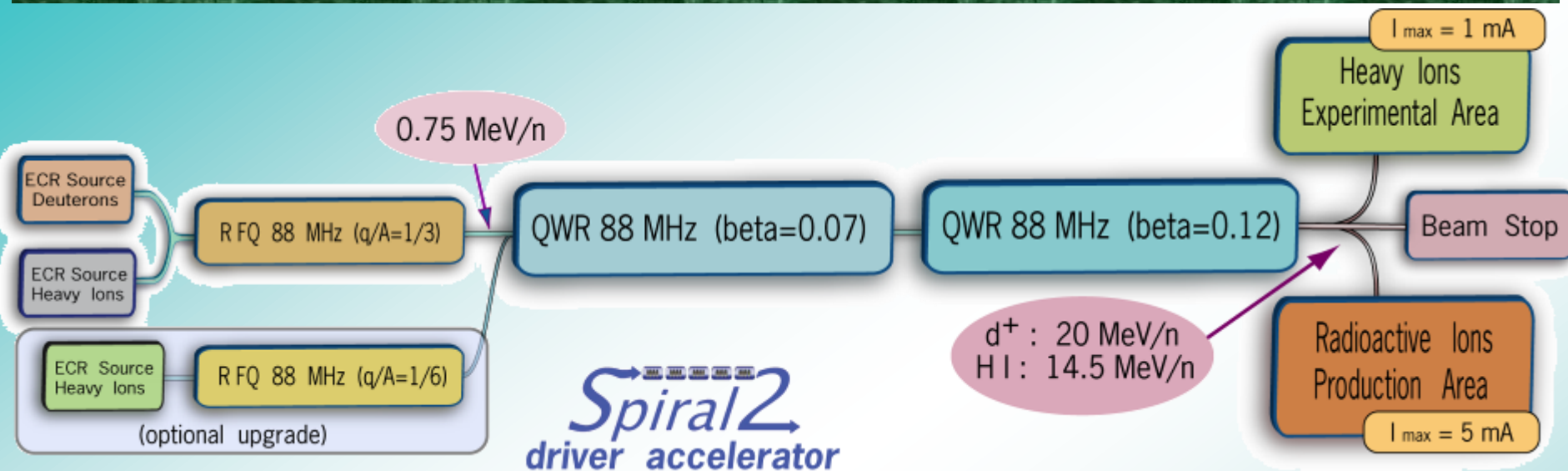
N=Z Isol+In-flight



High Intensity Light RIB



Spiral - 2 : the accelerator baseline configuration



Total length: 65 m (without HE lines)

D^+ : ECR ion source

Heavy Ions : ECR Ion Source

Slow and Fast Chopper

RFQ (1/1, 1/2, 1/3) & 3 re-bunchers

12 QWR beta 0.07 (12 cryomodules)

14 (+2) QWR beta 0.12 (7+1 cryomodules)

1 kW Helium Liquifier (4.2 K)

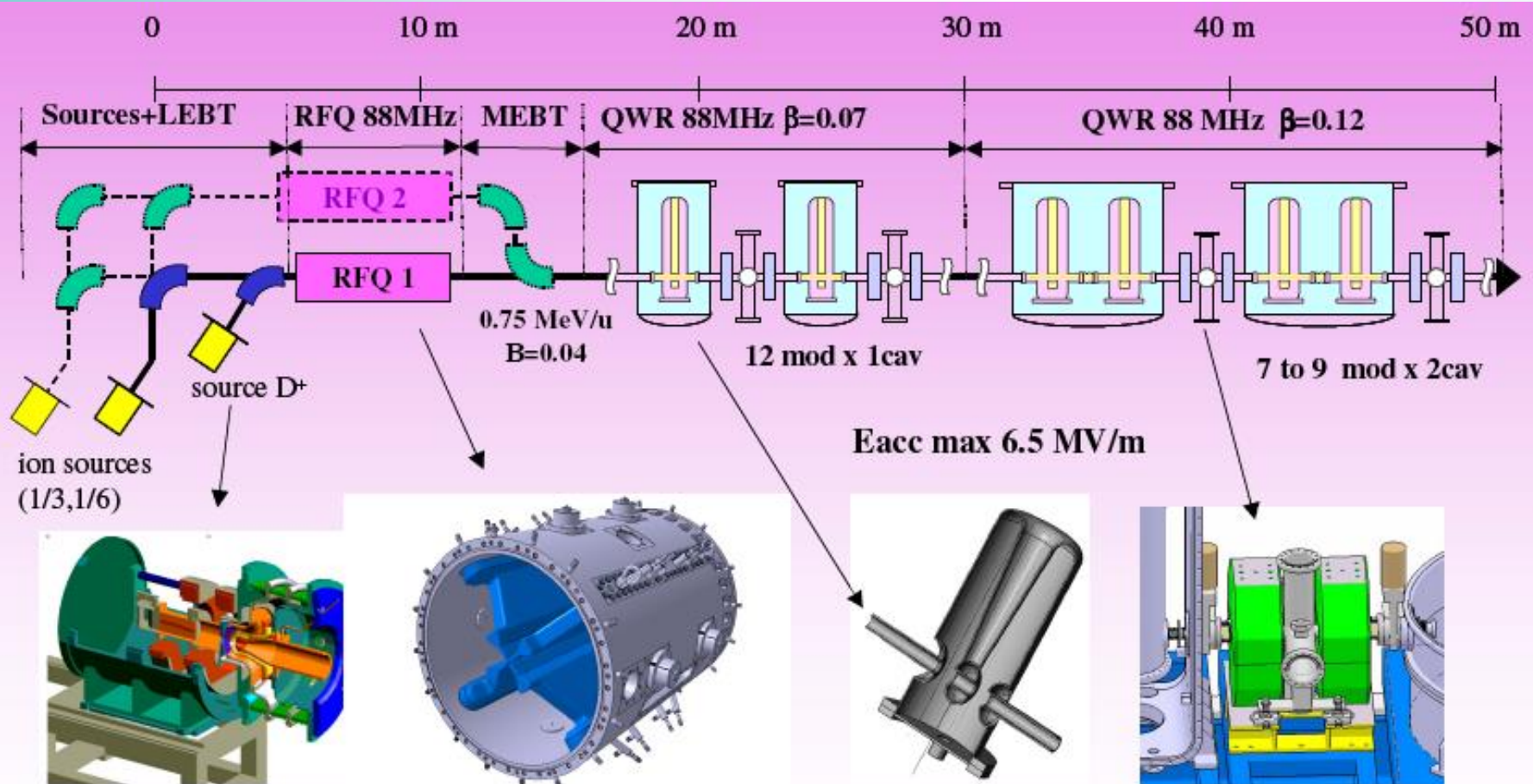
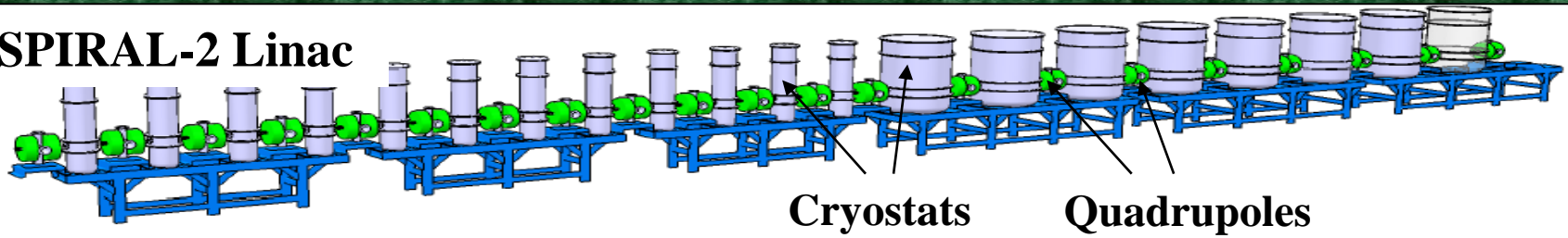
Room Temperature Q-poles

Solid State RF amplifiers (10 & 20 KW)

6.5 MV/m max $E_{\text{acc}} = V_{\text{acc}}/(\beta_{\text{opt}}\lambda)$ with $V_{\text{acc}} = \int E_z(z) e^{i\omega z/c} dz$.

Particles	p^+	D^+	Ions	
Q/A	1	1/2	1/3	1/6
I (mA) max.	5	5	1	1
W_0 min. (Mev/A)	2	2	2	2
W_0 max. (Mev/A)	33	20	14.5	8.5
CW max. beam power (KW)	165	200	44	48

SPIRAL-2 Linac

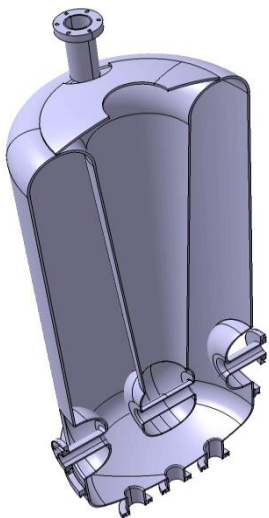




Spiral - 2 : final site appearance

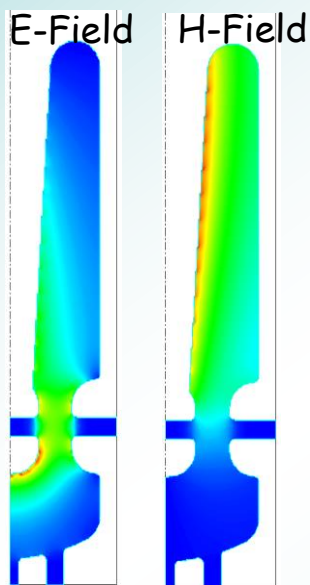


Spiral - 2 Linac : High beta SC cavities

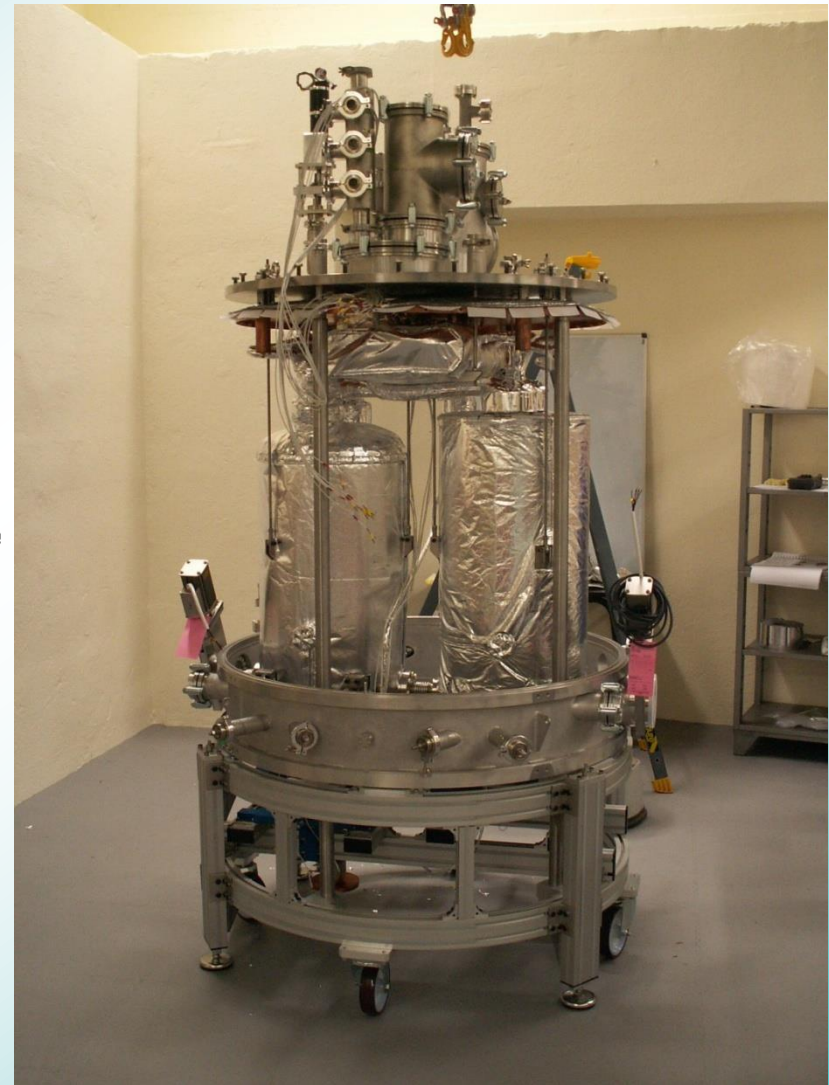
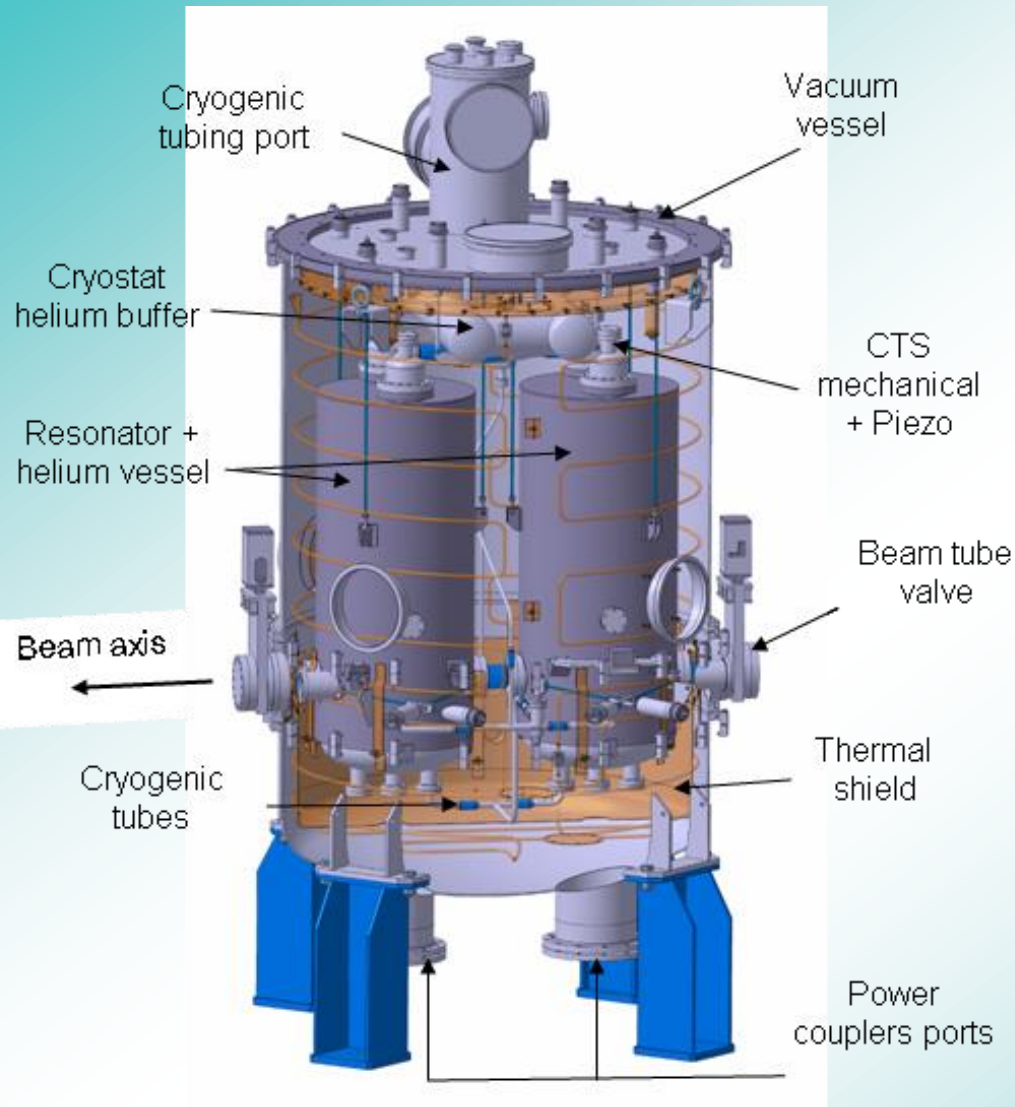


Frequency [MHz]	88.05
β_{optimal}	0.12
$E_{\text{pk}}/E_{\text{acc}}$	5.56
$B_{\text{pk}}/E_{\text{acc}}$ [mT/MV/m]	10.18
r/Q [Ω]	518
V_{acc} at 6.5 MV/m & b_{opt} [MV]	2.65
G [Ω]	38
Beam ϕ [mm]	38
Cavity ext. ϕ [mm]	380
Q_{ext}	$1.2 \cdot 10^6$

QWR 88 MHz SC Cavities

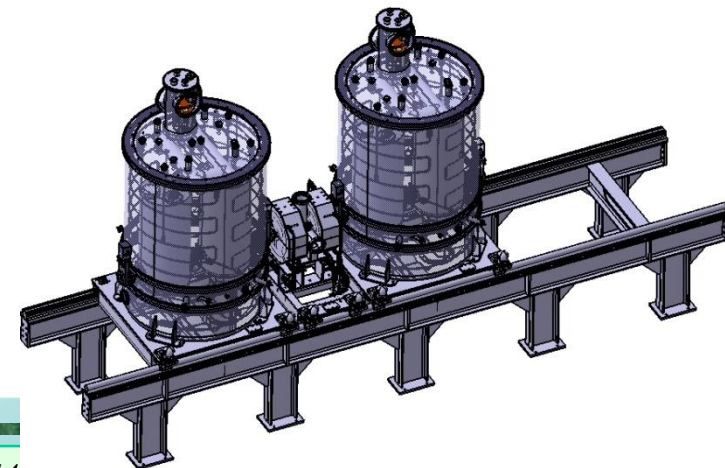
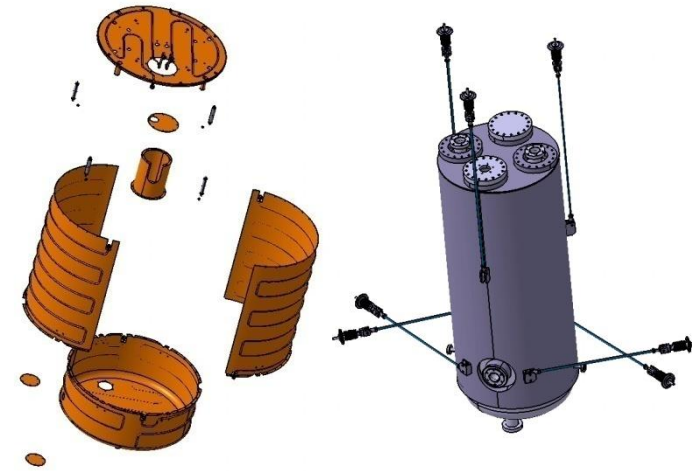
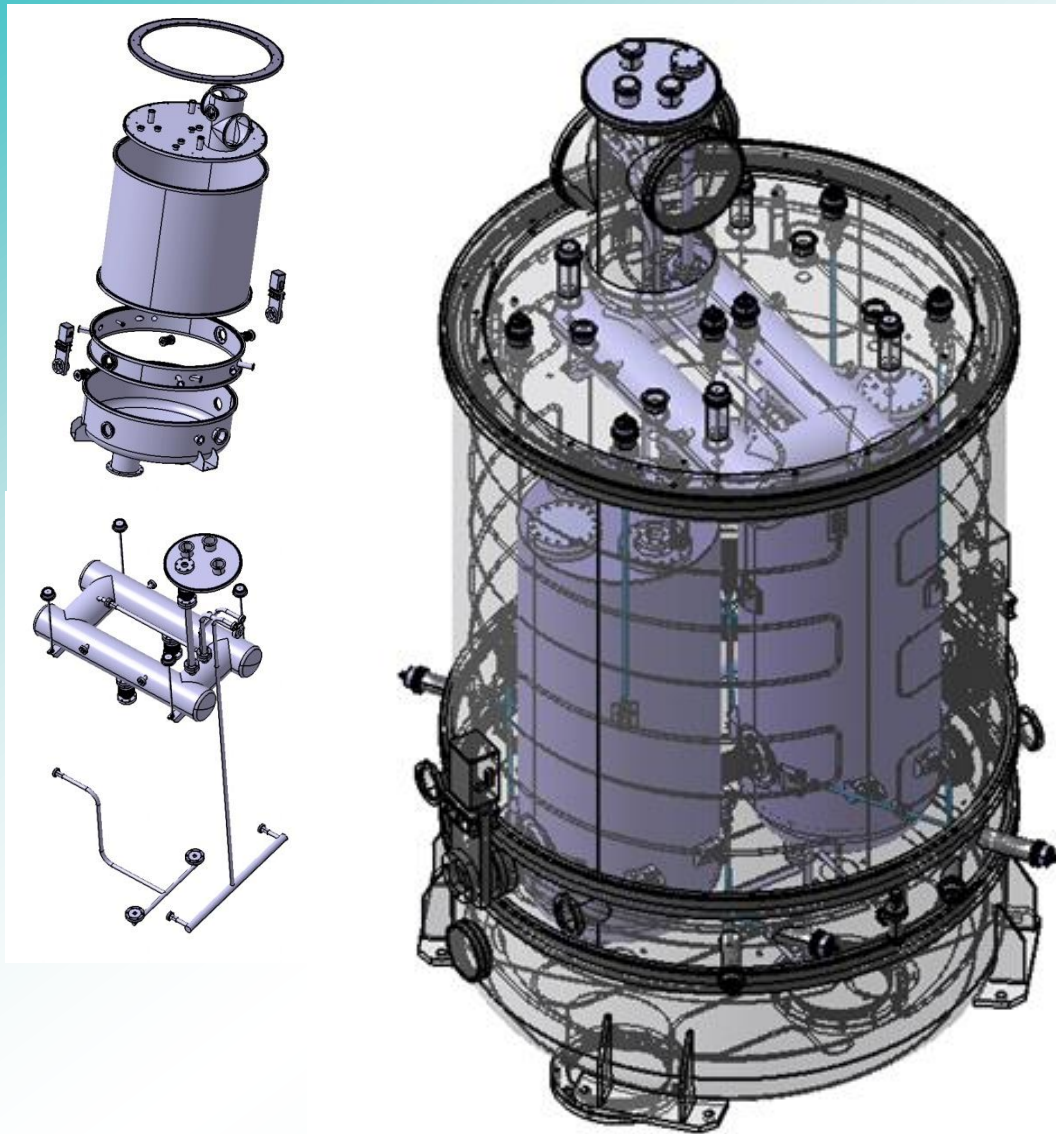


Spiral - 2 Linac : High beta SC cryomodule





SPIRAL-2 : high energy section cryomodule

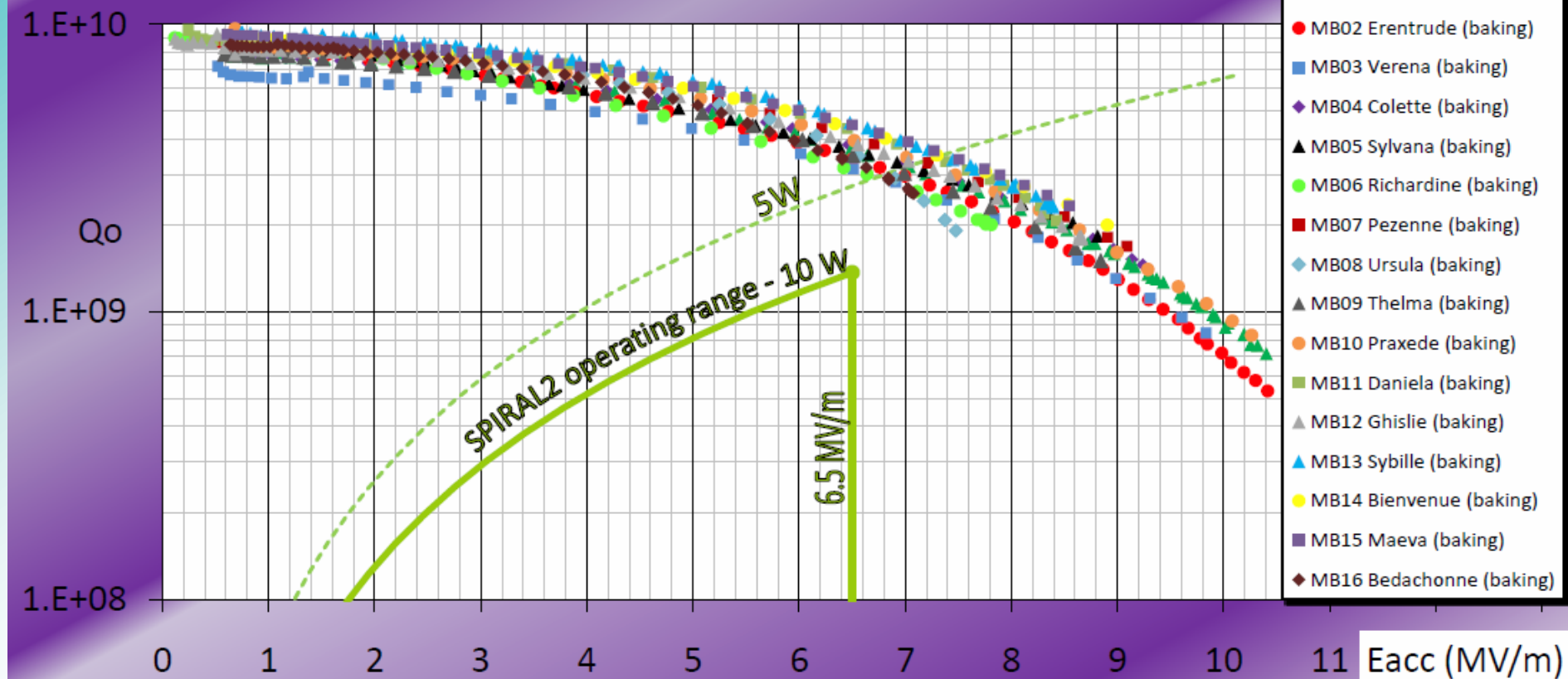




SPIRAL-2 : High Beta Cavity RF Performances



QWR B, beta 0.12
Vertical test results - T=4.2K





EURISOL : Radioactive ion beam production
(Project phase - site not yet chosen)

Under Design Study

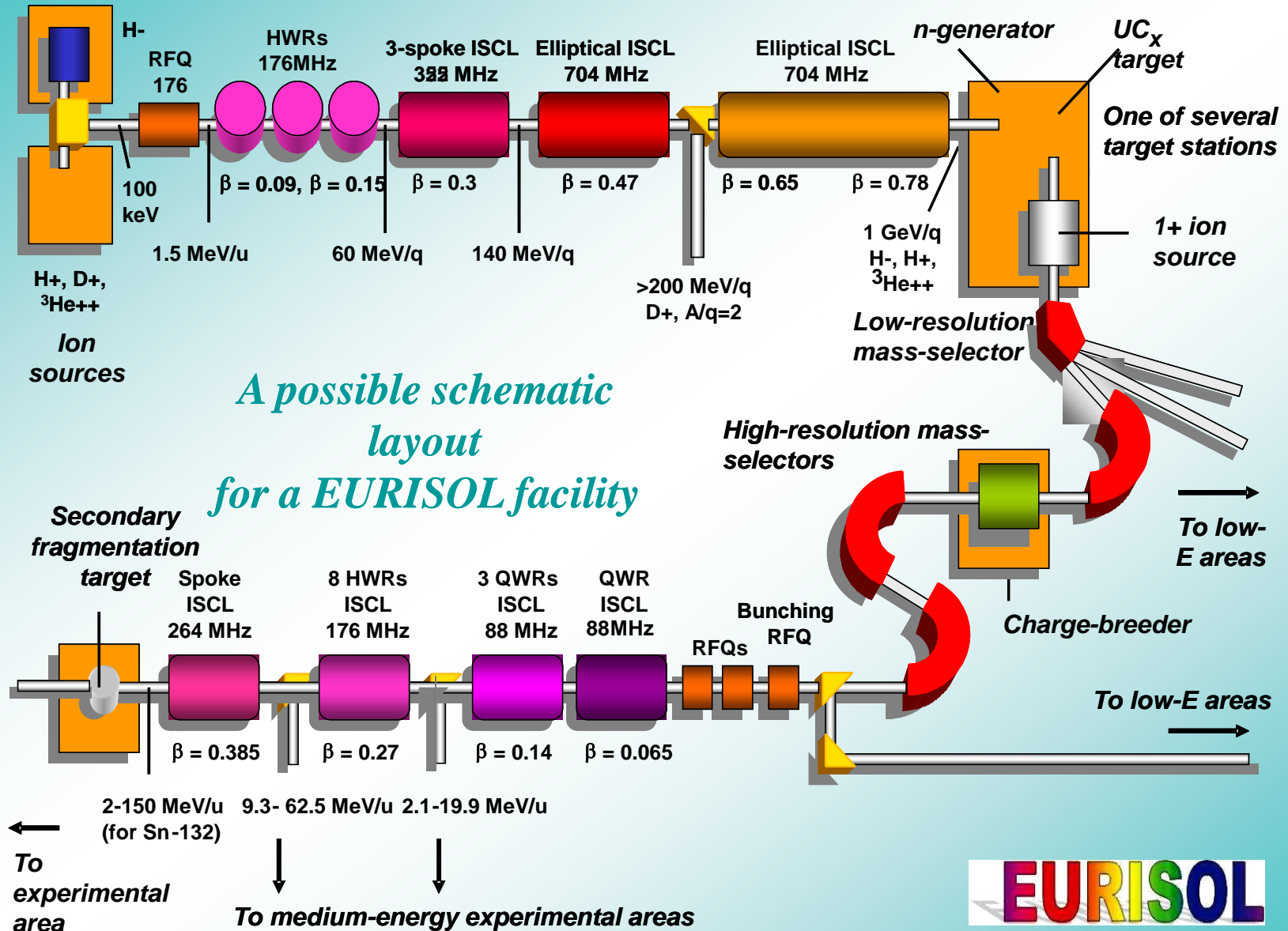


EURISOL is the « next step after Spiral-2 » - Today, it's an European Research Program for a design study of a 5 MW radioactive ion beam production facility.

1 GeV proton, 5 mA, 5 MW total power
Capabilities to accelerate also Deuterons and He3



EURISOL PROJECT



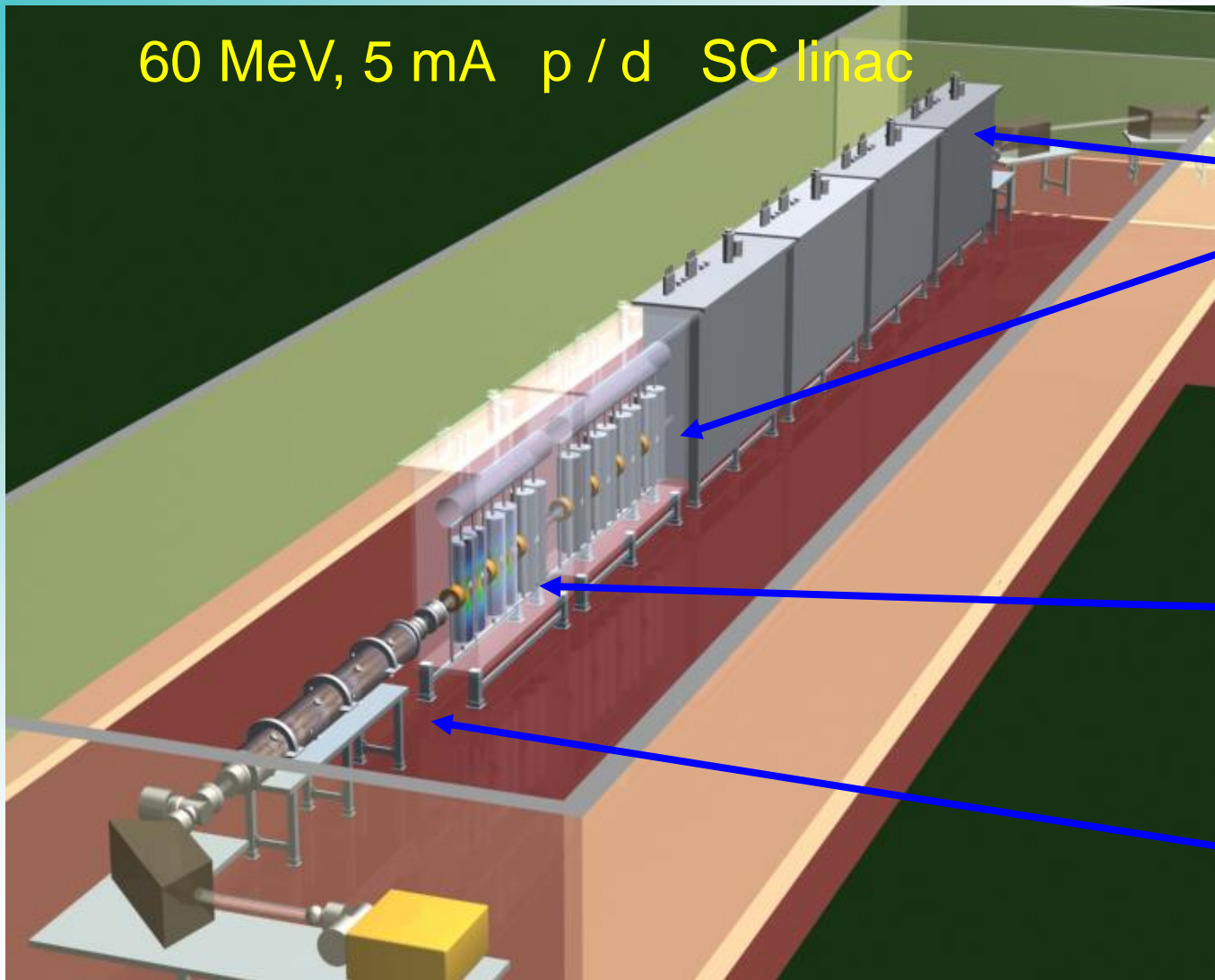
Cost comparison

Option	beams in operation	length, m	extras required	cost M€	Δcost
#1 proton only	1 GeV p, 4 MW or 100 kW	203		199	+0 %
#2 p + 100 MeV d	1 GeV p, 4 MW or 100 kW or 100 MeV d, 50 kW	203	176 MHz RFQ instead of 352	199	+0 %
#3a p + 250 MeV d	1 GeV p, 4 MW or 100 kW or 200 MeV d, 125 kW	218	as #2 + low-β to 140 MeV	211	+6 %
#3b p+ ³ He	1 GeV p, 4 MW or 100 kW or 2 GeV ³ He ⁺⁺ , 4 MW	223	as #2 + more β=0.47 cavities	220	+11 %
#4 p+ ³ He+d	1 GeV p, 4 MW or 100 kW or 200 MeV d, 100 kW or 2 GeV ³ He ⁺⁺ , 2 MW	231	as #3a + #3b	230	+16 %
#5 p+ ³ He+d + multi-user p	1 GeV p, 1× 4 MW and 3×100 kW or 200 MeV d 125 kW or 2 GeV ³ He ⁺⁺ , 2 MW	231	H- injector+ 4 stripping stations	+3%	+19 %



EURISOL : Low energy section : SARAF Scheme (Israel)

60 MeV, 5 mA p / d SC linac



Linac Length:
~32 m

3rd– 9th cryostats
7×8 SC HWR
 $\beta_0=0.15$

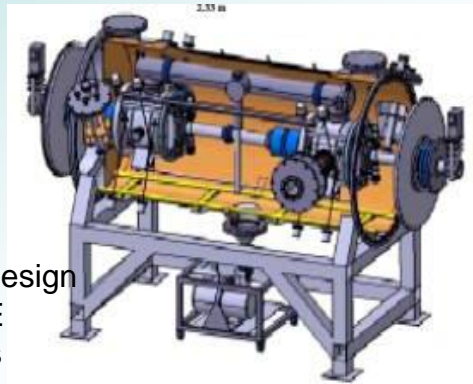
1st, 2nd cryostat
2×6 SC HWR,
 $\beta_0=0.09$

176 MHz RFQ
1.5 MeV/u $A/q=2$
3.8 m

$$60 \div 140 \text{ MeV}/q, 1 \leq A/q \leq 2$$

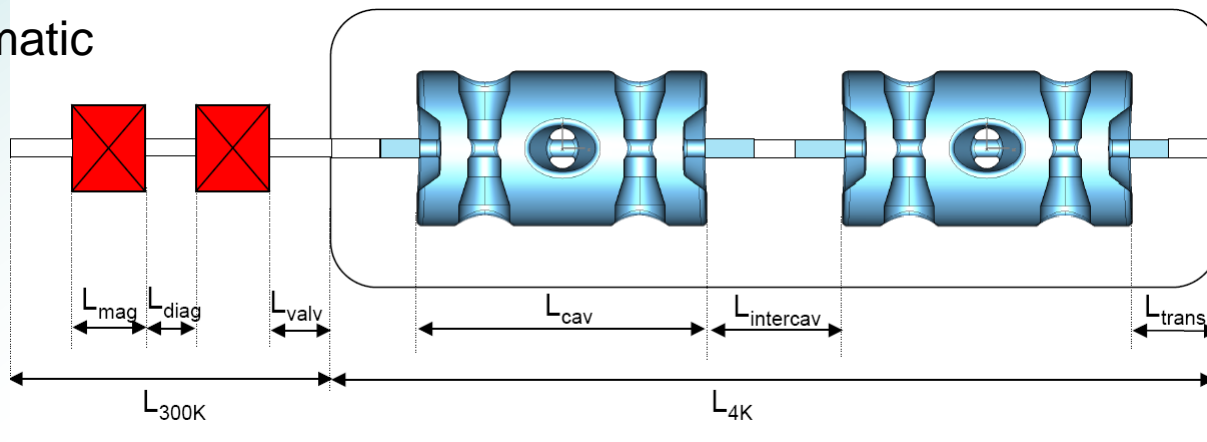
- superconducting Triple-SPOKE cavities $\beta=0.3$
- $E_{\text{in}} = 60 \text{ MeV}/q$
- $E_{\text{out}} = 140 \text{ MeV}/q$
- length $\sim 30 \text{ m}$

IPNO cryostat design
for SPOKE
resonators



ANL 3-Spoke cavity

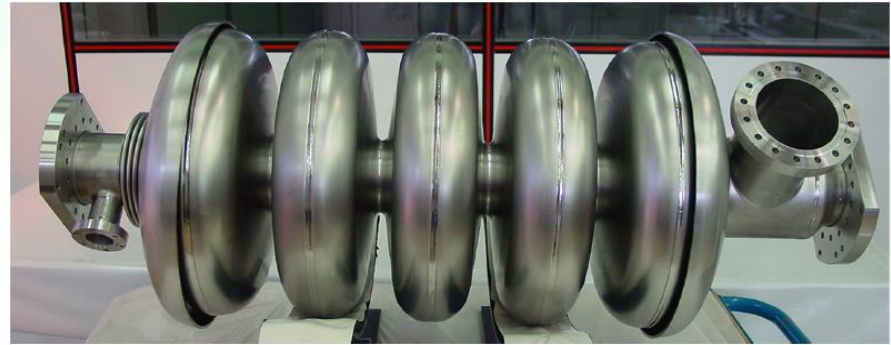
3-spoke
cryomodule
schematic



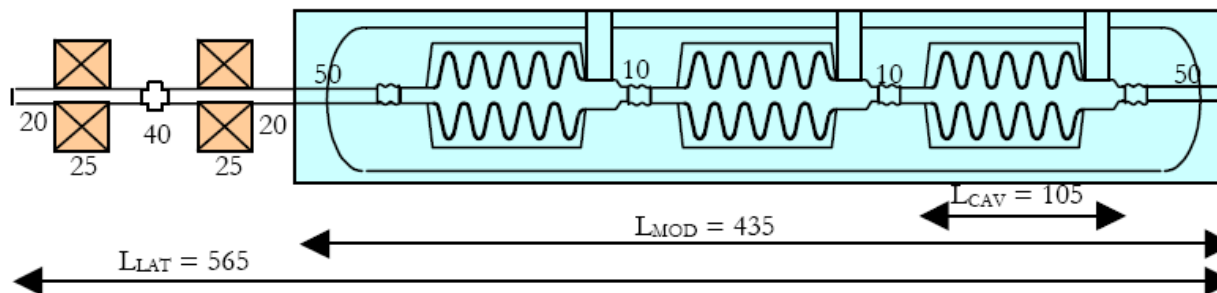


$140 \div 250 \text{ MeV}/q, 1 \leq A/q \leq 2$
 $250 \div 1000 \text{ MeV}/q, 1 \leq A/q \leq 1.5$

- superconducting elliptical cavities
- $\beta = 0.47, 0.65, 0.78$
- $E_{\text{in}} = 140 \text{ MeV}/q$
- $E_{\text{out}} = 1000 \text{ MeV}/q$
- section III+IV length $\sim 160 \text{ m}$



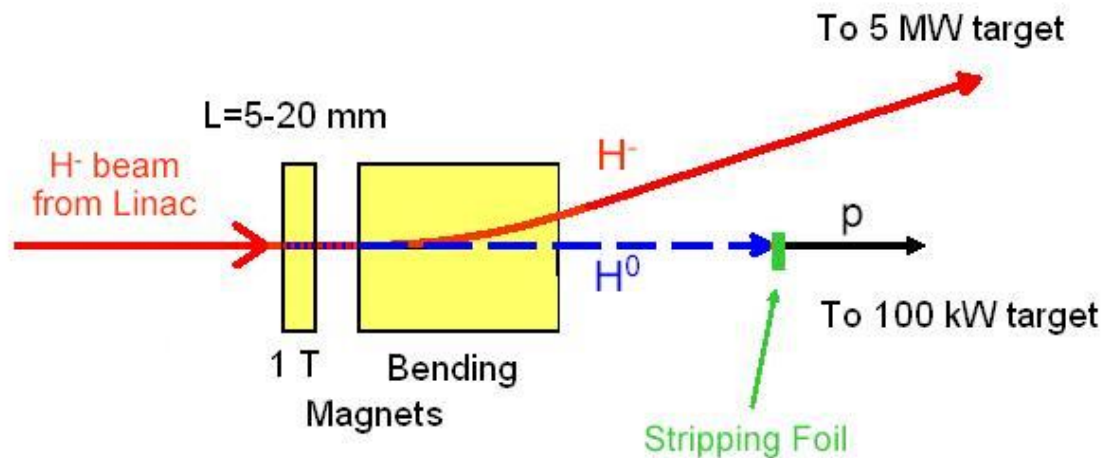
$\beta = 0.65, 704 \text{ MHz}$ elliptical cavity



schematic of the
 $\beta = 0.47$
 cryomodule

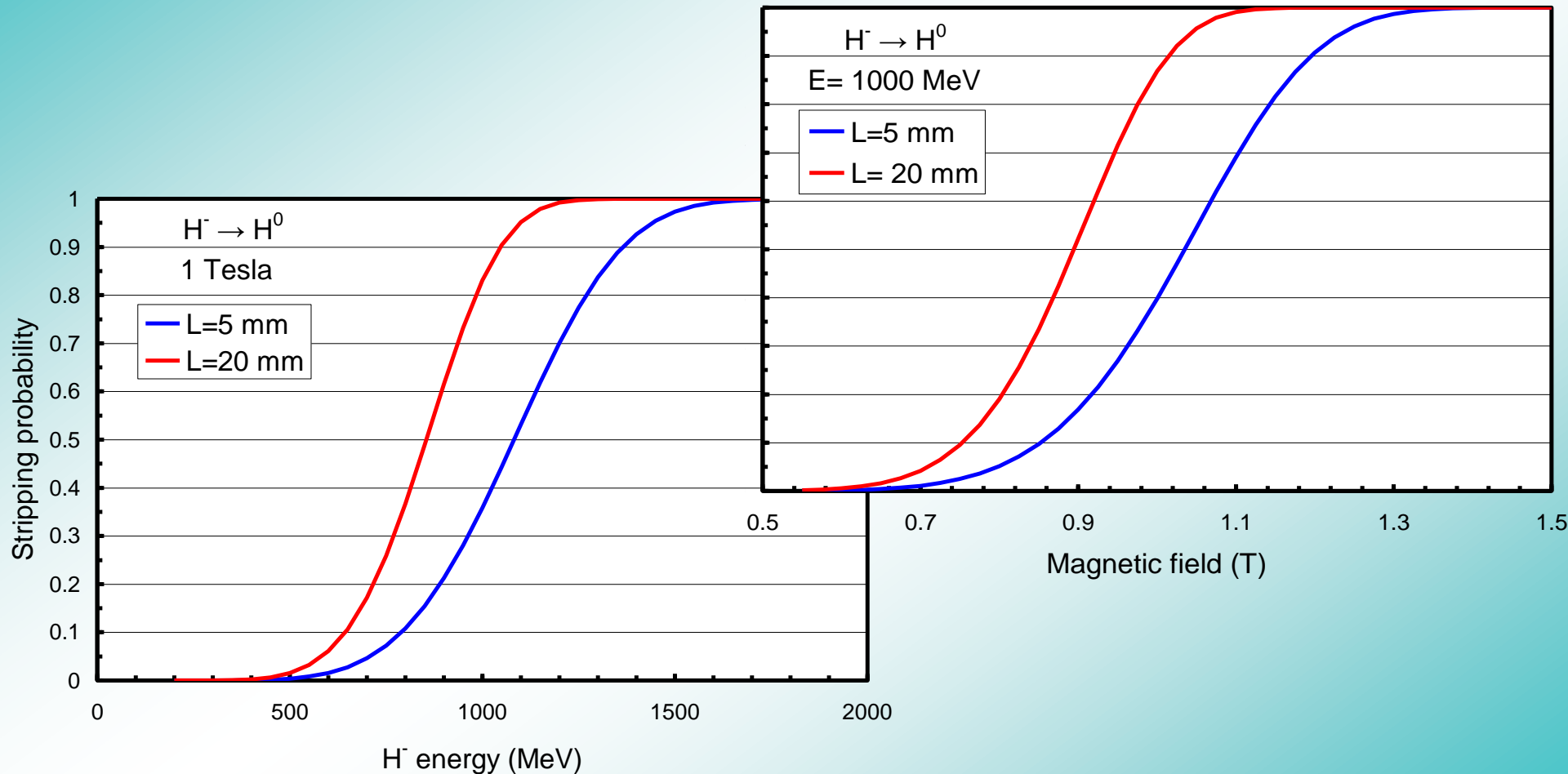
High energy beam splitters

- magnetic stripping at 1 GeV of a small part of the H^- beam to H^0
- bending of H^- with a magnetic dipole
- stripping of H^0 to H^+ by means of a stripper foil
- H^- to target 1 and H^+ to target 2(3,4).
- The spilled beam intensity can be controlled by adjusting the field strength of the magnetic stripper.



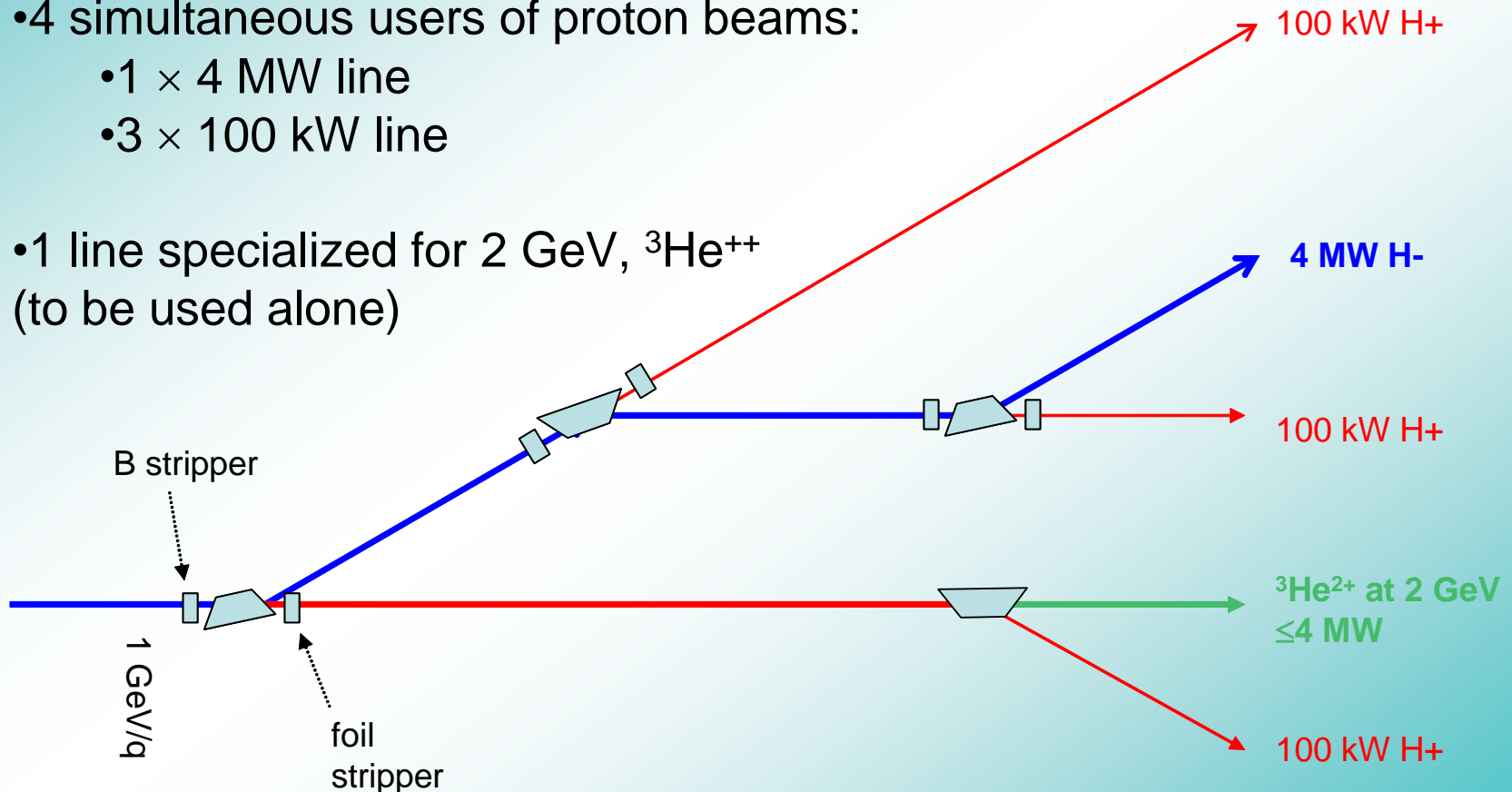


Magnetic stripping probability



1 GeV Extraction possible scheme

- 3 splitting stations
- 4 simultaneous users of proton beams:
 - 1 \times 4 MW line
 - 3 \times 100 kW line
- 1 line specialized for 2 GeV, $^3\text{He}^{++}$ (to be used alone)



Spoke cavities prototypes developments



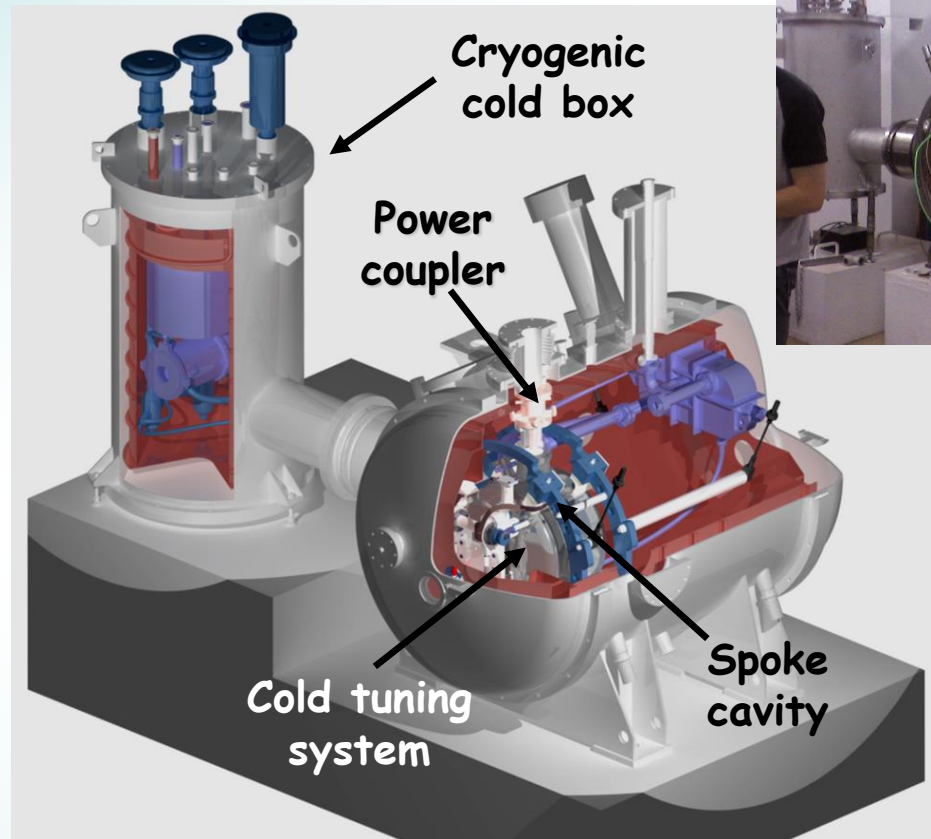
Spoke resonators

Two prototypes @ 352 MHz
(β 0.15 and β 0.35)
fabricated and tested.



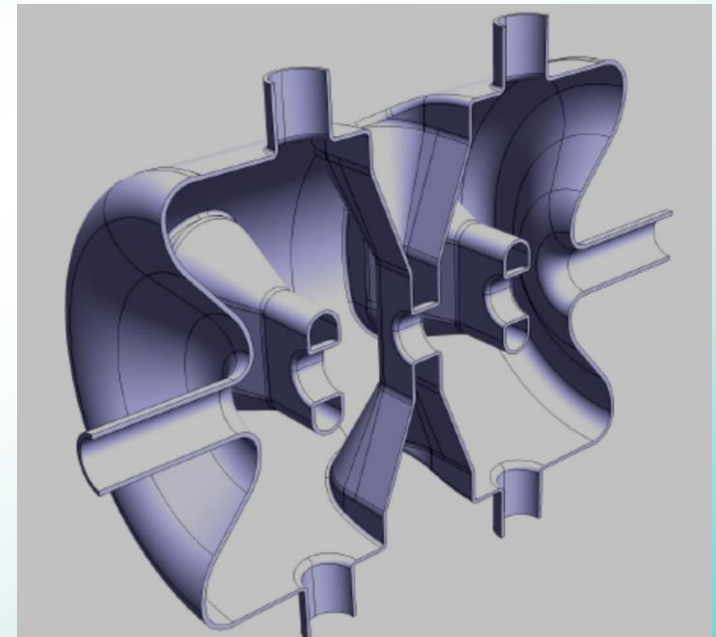
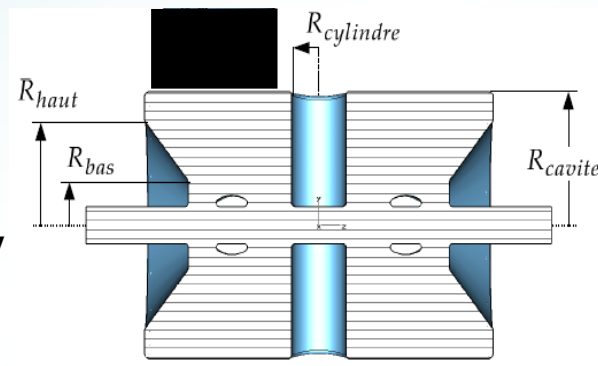
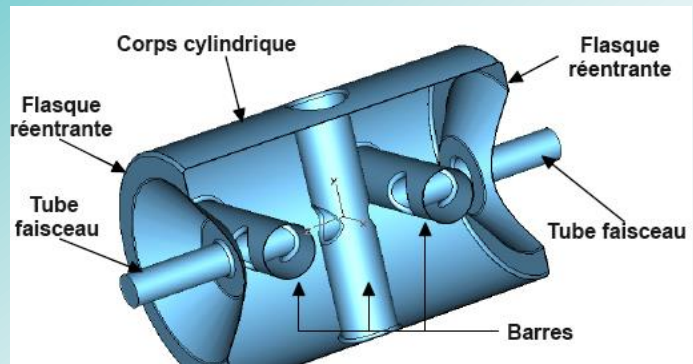
Horizontal cryostat

Adapted to spoke cavities for 4K and 2K tests



Triple spoke cavity for Eurisol

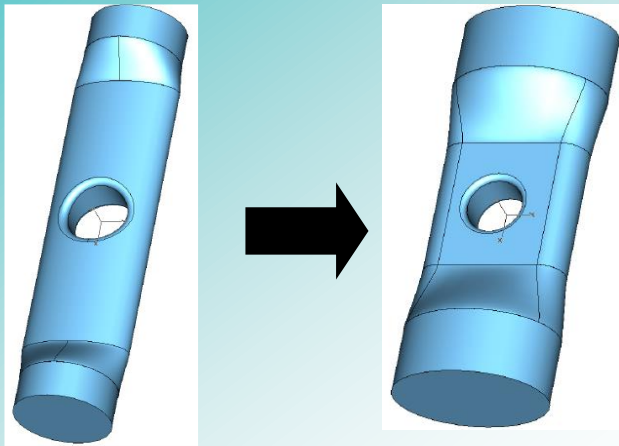
- Optimization of the beta 0.30, 352 MHz, 3-spoke cavity geometry
 \Rightarrow minimize the E_{pk}/E_a & B_{pk}/E_a ratios
 \rightarrow Full 3D model, 13 main parameters, more than 300 models



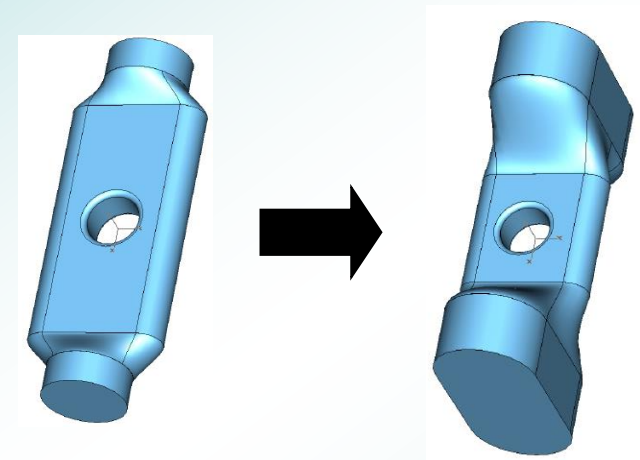
Optimized geometry

Aurélien Ponton, Guillaume Olry

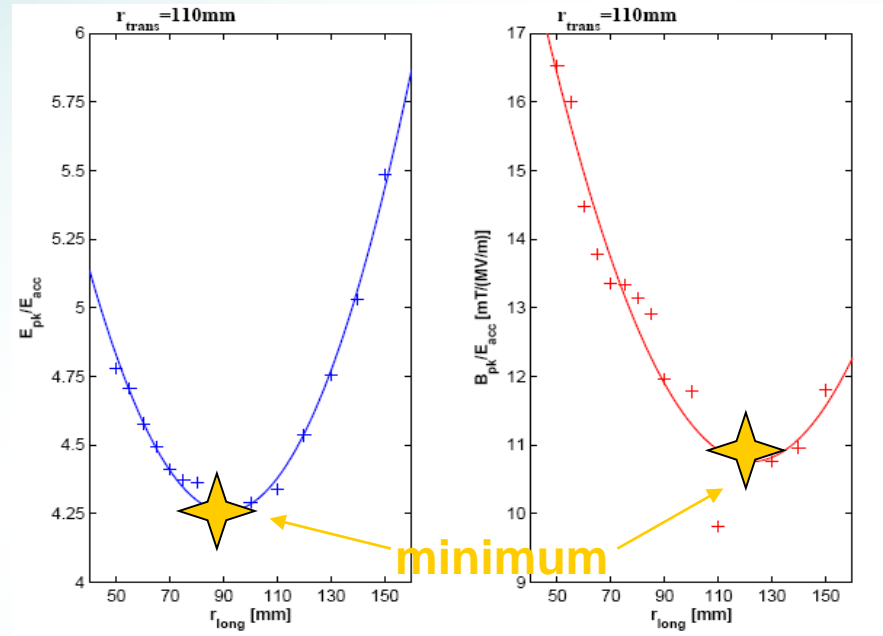
- Example: optimization of the spoke bars



Elliptical shape



Racetrack shape



Design goals

$$\frac{E_{pk}}{E_{acc}} \leq 5$$

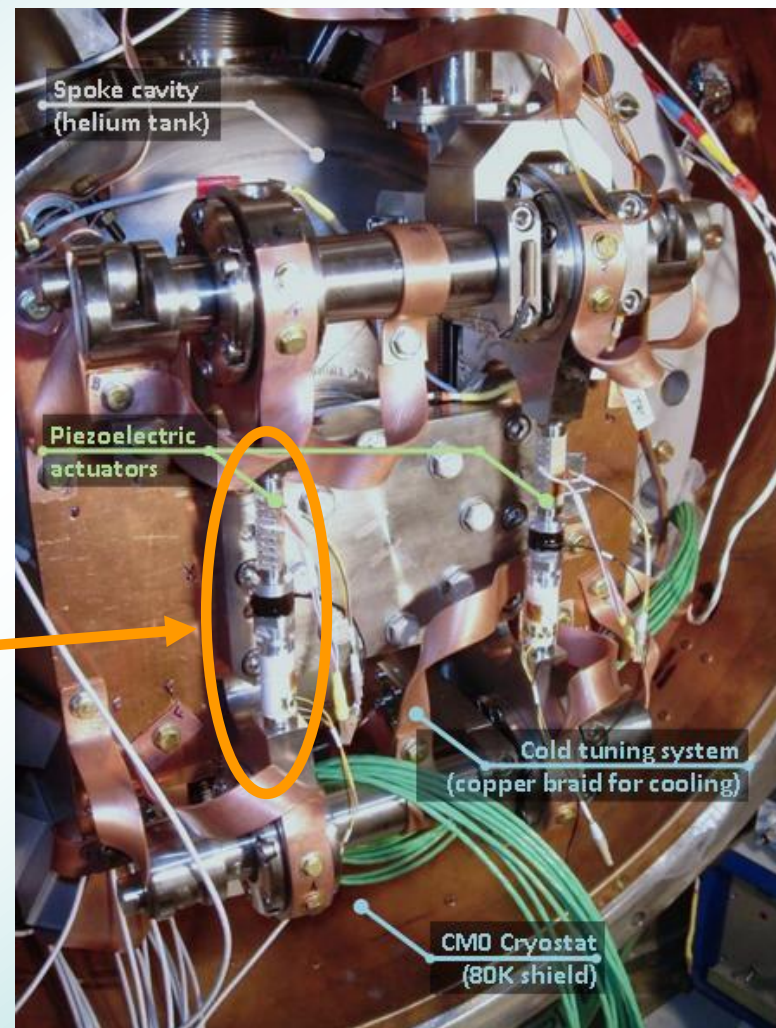
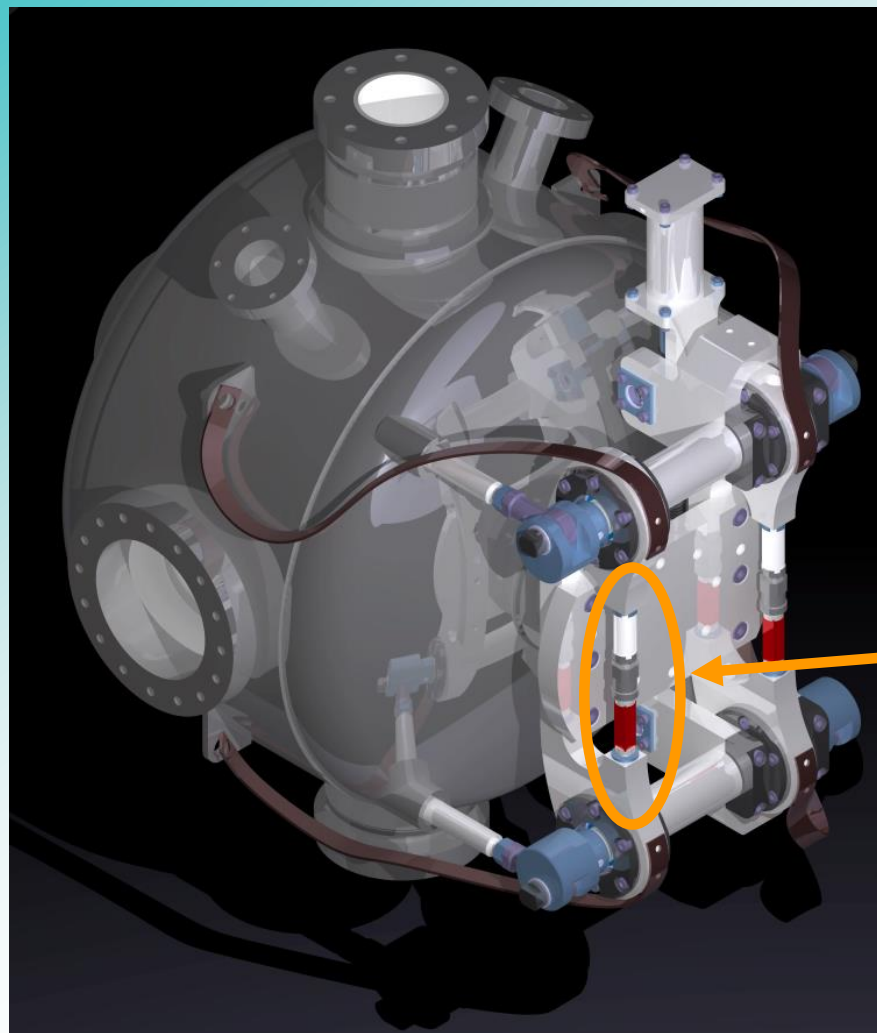
$$\frac{B_{pk}}{E_{acc}} \leq 10\text{mT}/(\text{MV}/\text{m}).$$

Results

$$\frac{E_{pk}}{E_{acc}} = 4.12$$

$$\frac{B_{pk}}{E_{acc}} = 9.05\text{mT}/(\text{MV}/\text{m})$$

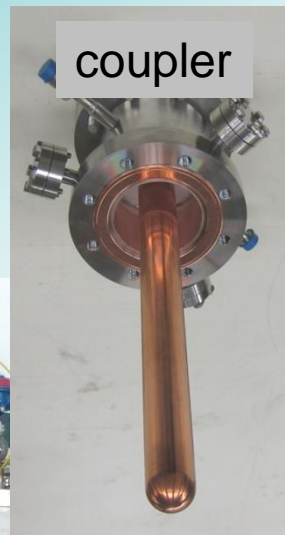
Cold tuning systems for Spoke cavities



Integrated tests



Tuning system



coupler

10 kW



RF amplifier



cavity



Digital LLRF



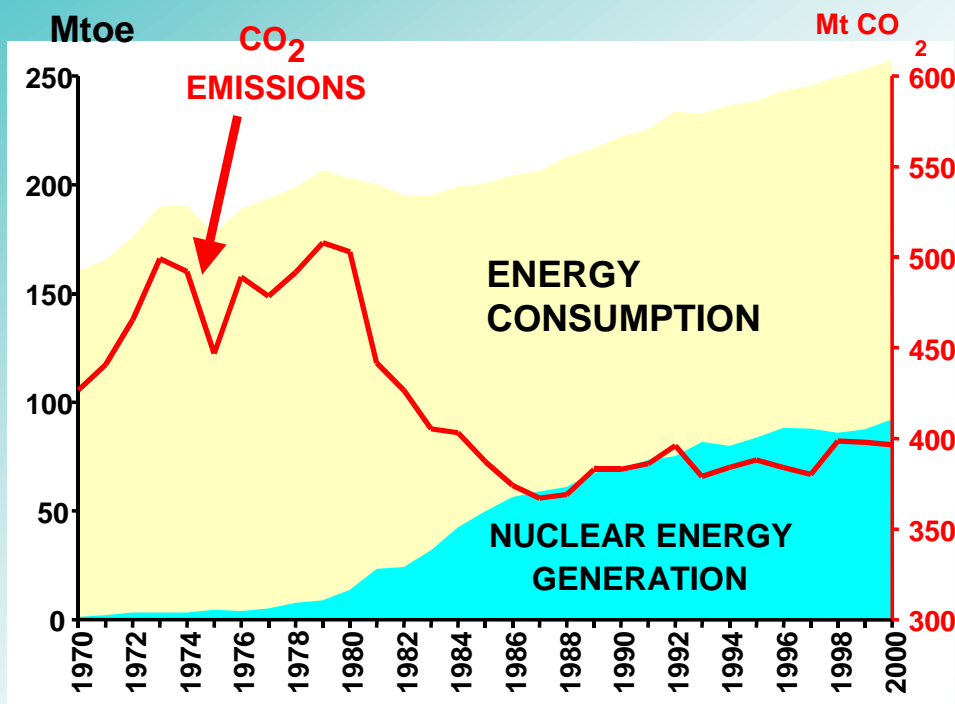


High Power Proton Accelerator for Nuclear Waste Transmutation

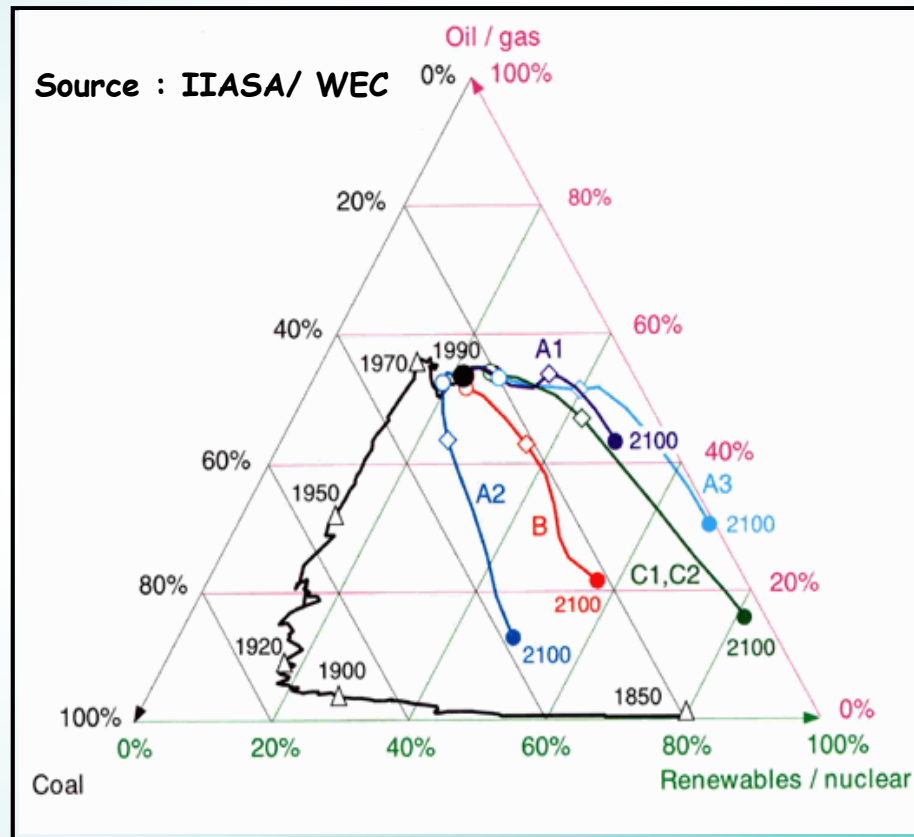


Energy & CO₂ Production in France, Scenarii for the long-term future:

Massive Use of Nuclear & Renewable Energy can stabilize CO₂ Generation !

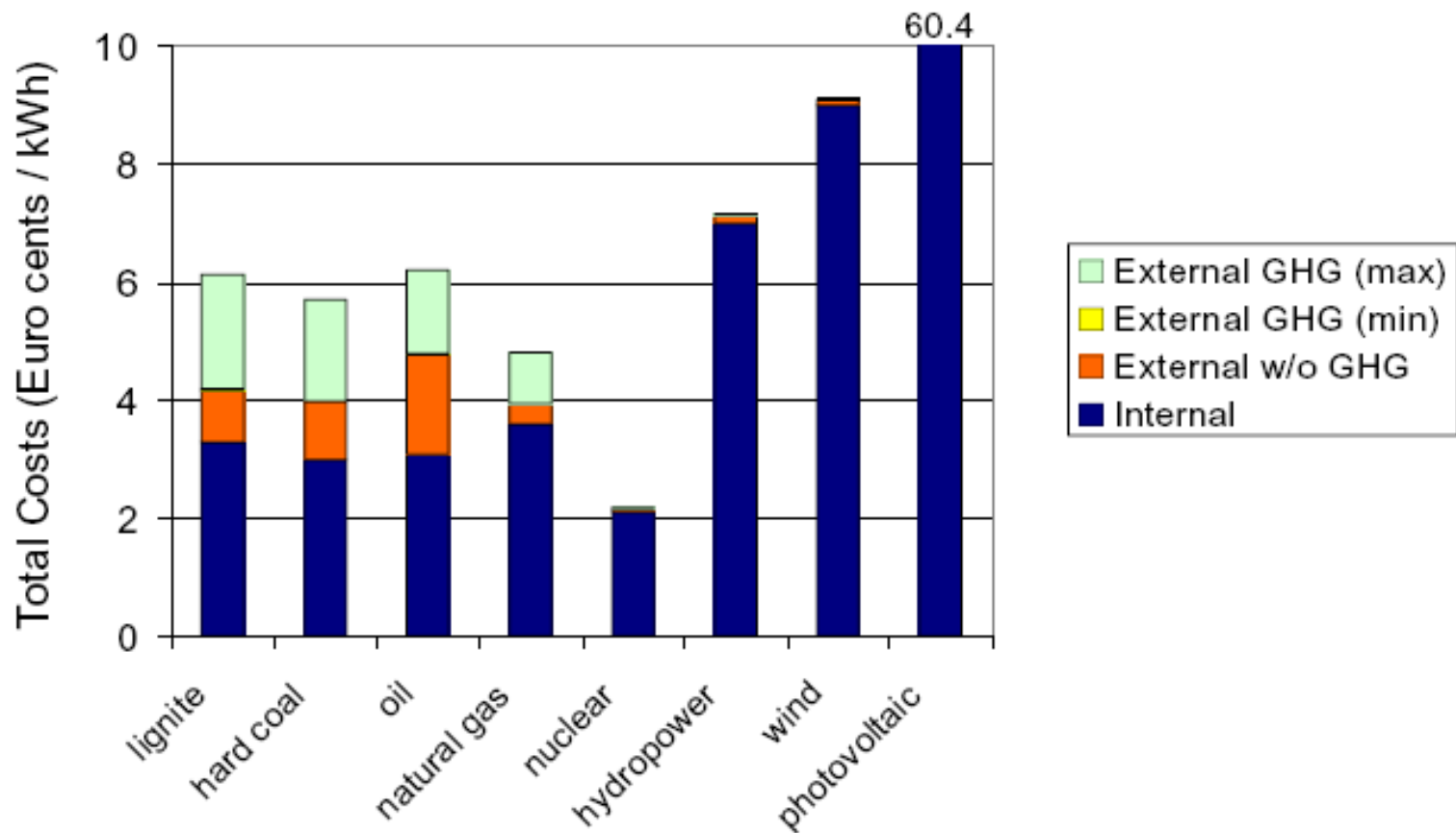


- electric cars with fuel cells using hydrogen generated by nuclear power are today a realistic perspective to fight pollution and global warming



- another future problem is the huge energy need for making drinkable water (desalination)

Total Costs of *Current Average* Technologies (Germany)



Source: Hirschberg et al., November 2003

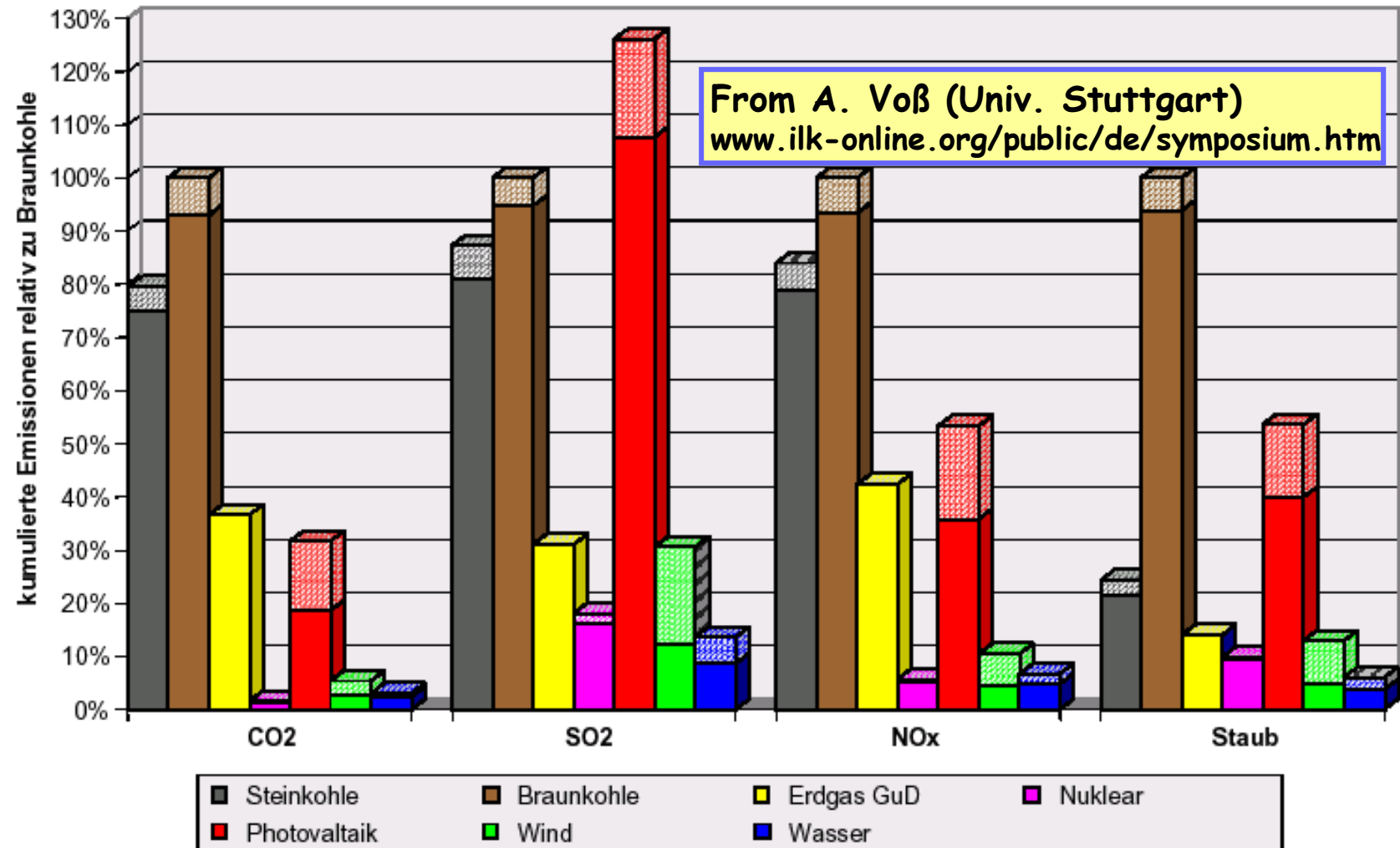


Abbildung 1: Kumulierte Emissionen von Stromerzeugungssystemen



The Nuclear Waste Issue : some selected facts

- **Nuclear Energy is (presently) important in Europe (e.g. EU "Green Paper")**
 - 145 operating reactors (127 GW_{el}) produce 850 TWh/y = 35% of EU electricity
 - A 1 GW_{el} reactor produces 1000 tons of waste in 30 years
 - n.b. the world has 330 (1 GW equivalent) reactors, producing 6% of the electricity
- **Europe has mastery of the entire nuclear fuel cycle, with the exception of waste management**
 - *"for this reason focusing on waste management has to be continued" (European Commissions Green Paper)*
- **Nuclear Waste from present LWR's (Light Water Reactors)**
 - is highly radiotoxic (10^8 Sv/ton)
 - at the end of nuclear deployment about 3×10^{13} Sv (0.3 Mio tons), compare to radiation workers limiting dose (EU Directive: < 20 mSv)
 - the initial (uranium) radiotoxicity level is only reached after more than 1 Mio years
- **Geologic time storage of spent fuel is heavily debated**
 - leakage in the biosphère ?
 - expensive (1000 €/kg), sites? (Yucca mountain would hold 0.07 Mio tons)
 - public opposition
- **Long term Energy Concerns**
 - availability of oil, gas, coal (and uranium!)
 - global warming induced by fossile fuels

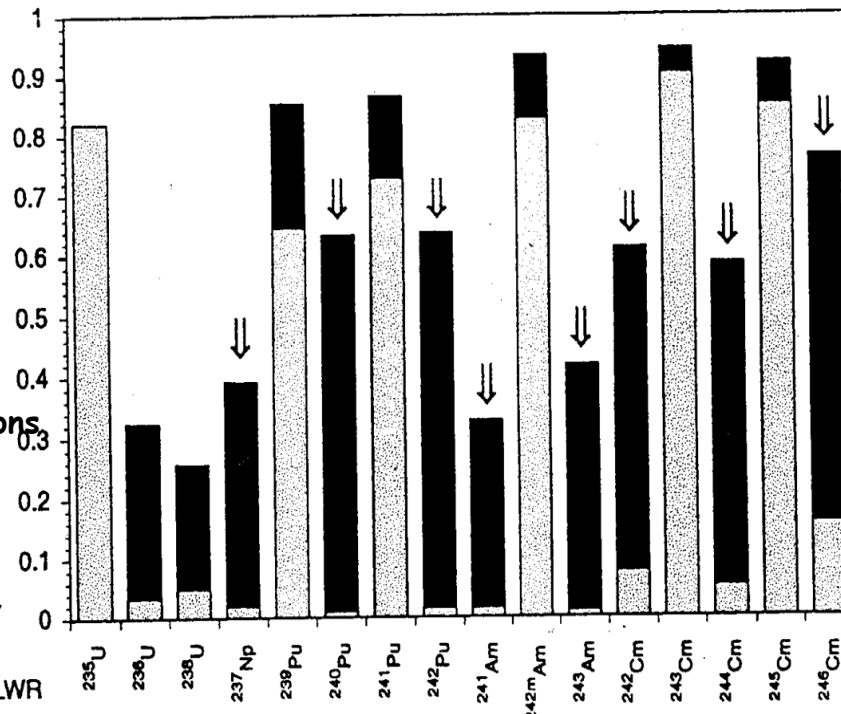
Probability of Fission/Neutron absorbed

Note:
thermal
fission
resilient
elements
↓

Thermal neutrons
Fast neutrons

Figure from C. Rubbia,
OECD seminar, Paris,
September 25, 2000

LWR

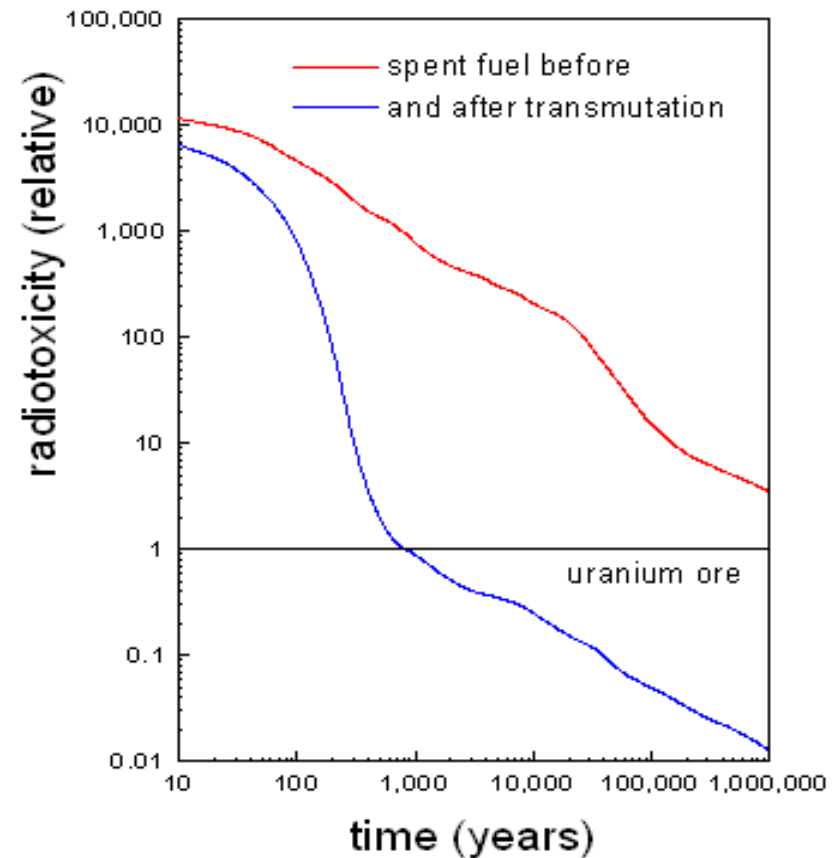
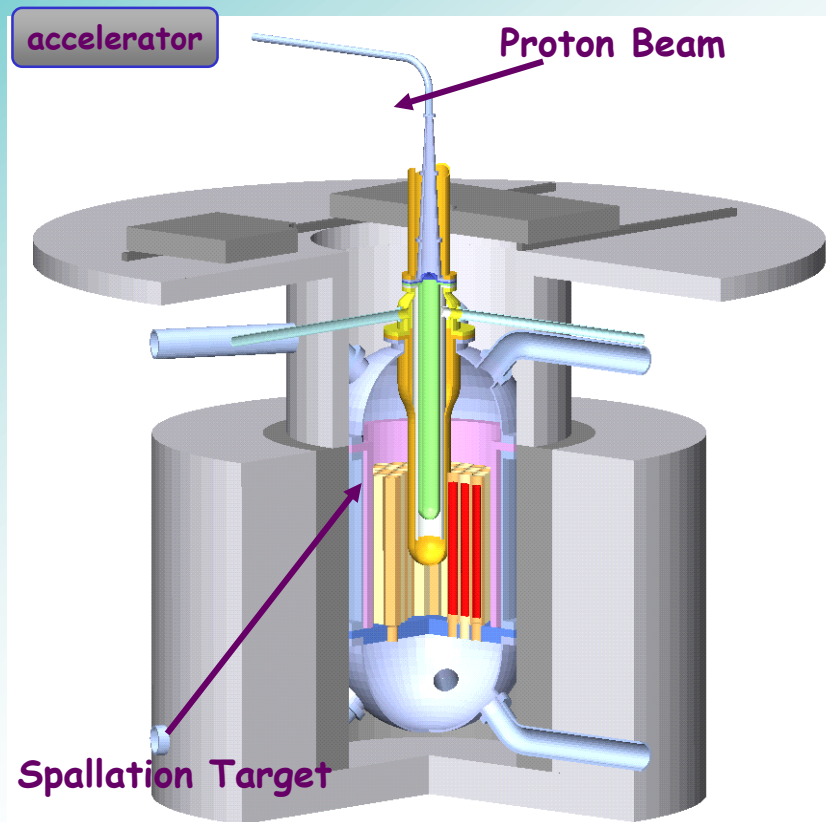


- 99.995% of the > 500 years lasting radiotoxic isotopes are concentrated in a few elements representing 1% of the spent fuel (300 kg/y/ 1GW_{el} reactor)
- most of these are resilient to further burning in a LWR
→ full transmutation needs fast neutrons
- fast breeder reactors like "SUPERPHENIX" ????

Alternative: use, for higher flexibility, safety and efficiency, (very) fast neutrons, produced by an accelerator, in combination with a subcritical reactor !

ADS: **A**ccelerator **D**riven (subcritical) **S**ystem for transmutation

Note: Subcriticality is not virtue but necessity!



1. XT-ADS (ADS prototype)

Goals:

- **Demonstrate the concept** (coupling between accelerator, spallation target & reactor),
- **Demonstrate the transmutation**
- **Provide an irradiation facility** and an EFIT test bench

Features:

- 50-100 MWth power
- Keff around 0.95
- 600 MeV, 2.5 mA proton beam (or 350 MeV, 5 mA)
- Conventional MOX fuel
- Lead-Bismuth Eutectic coolant

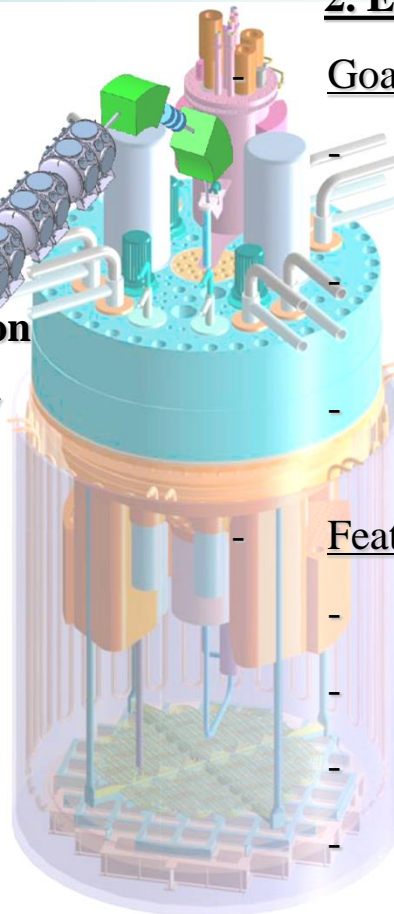
2. EFIT (Industrial Transmuter)

Goals:

- Maximise the transmutation efficiency
- Easiness of operation and maintenance
- High level of availability for a cost-effective transmutation

Features:

- Several 100 MWth power
- Keff around 0.97
- 800 MeV, 20 mA proton beam
- Minor Actinide fuel
- Lead coolant (gas as back-up solution)





Accelerator for an ADS : main specifications

High-power proton CW beams

Table 1 – XT-ADS and EFIT proton beam general specifications

	XT-ADS	EFIT
Maximum beam intensity	2.5 – 4 mA	20 mA
Proton energy	600 MeV	800 MeV
Beam entry	Vertically from above	
Beam trip number	< 20 per year (exceeding 1 second)	< 3 per year (exceeding 1 second)
Beam stability	Energy: $\pm 1\%$, Intensity: $\pm 2\%$, Size: $\pm 10\%$	
Beam footprint on target	Circular \varnothing 5 to 10 cm, “donut-shaped”	An area of up to 100 cm ² must be “paintable” with any arbitrary selectable intensity profile
Beam time structure	CW, with 200 μ s zero-current holes every 10 ⁻³ to 1 Hz, + pulsed mode capability (repetition rate around 50 Hz)	

Extrememely high reliability is required !!!



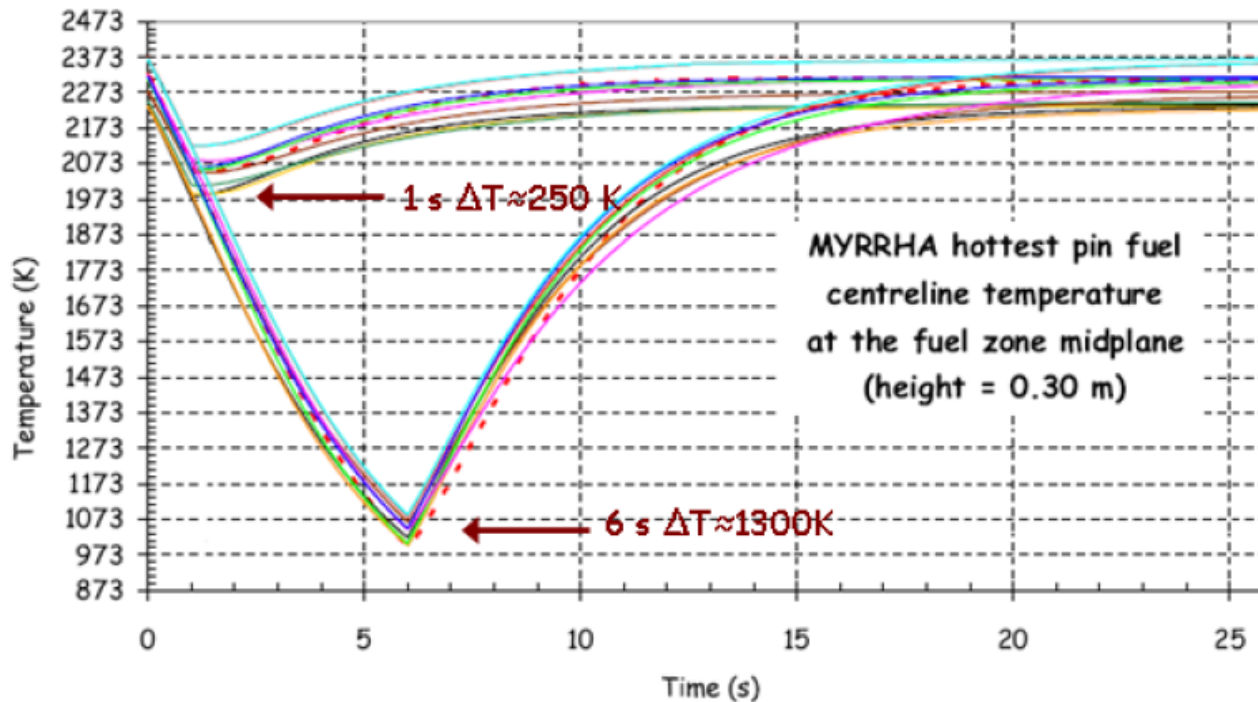
Most powerful proton accelerators

- **Linacs**
 - **LAMPF/LANSCE (~1970)**
 - 800 MeV
 - 1 mA H^+ average current
 - Peak H^+ current 16.5 mA @ 100 Hz and 625 μs pulse length
 - NC accelerator
- **Cyclotrons**
 - **PSI – separated sector (1974)**
 - Original design was for 100 μA
 - From 72 to 590 MeV
 - 1.8 mA average current
 - Beam losses at extraction $< 1 \mu A$
 - Plans for further upgrade (new cavities)
- **Both linac and cyclotrons were considered as possible ADS drivers**
 - **No fundamental obstacles** have been found so far **for a linac** to deliver ~ 100 mA at 1 GeV or more
 - **1 GeV and few mA** are considered as limiting values **for a cyclotron** (multistage): **possible for the demonstrator, not for the burner**



"Unusual" Features needed by ADS-class accelerators

- A reactor should not have more than a hundred "scram's" in its life time
 - only "some" accelerator trips per year !!
 - a performance gain of 2 -3 orders of magnitude is needed !
- The beam losses in the accelerator should be very low in order to avoid activation
 - max some $10 \mu\text{Sv/h}$, one hour after shutdown, for hands-on maintenance
 - $\Delta I/I = 10^{-8} - 10^{-9} / \text{m} !!$

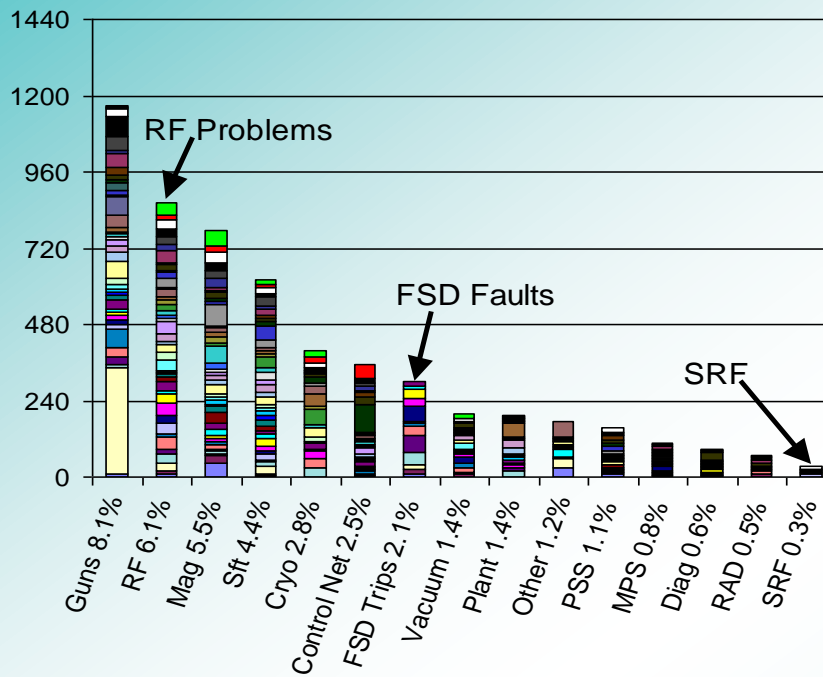


■ All the reliability requirements for the ADS accelerator is linked to the need to avoid high thermal stresses in the reactor materials to minimize the fatigue and keep reasonable lifetime

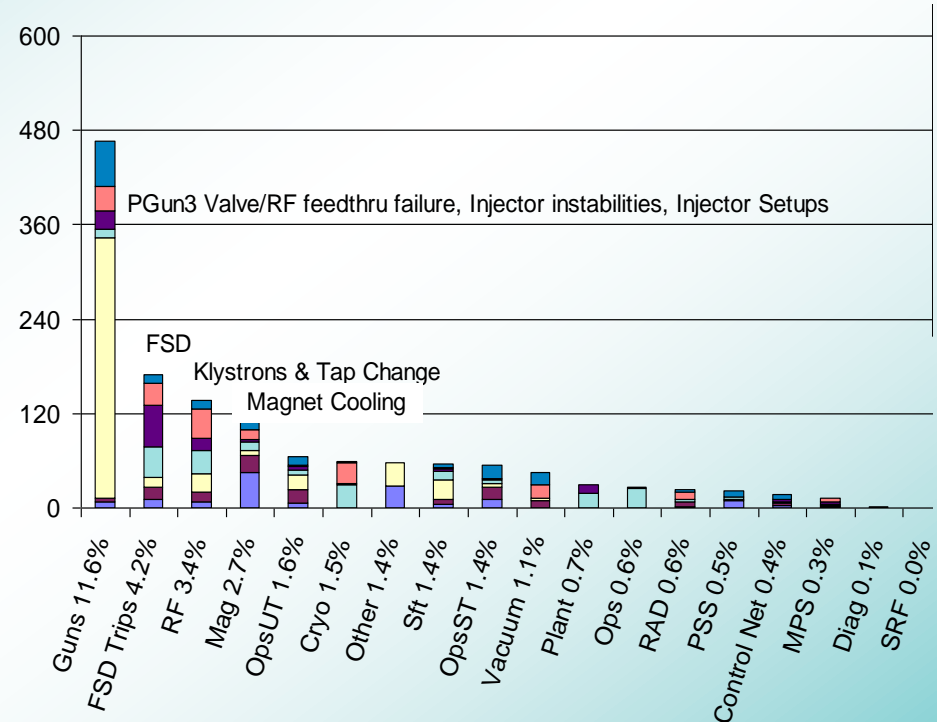


Reliability Example - CEBAF

Lost Time Totals June '97-May '01



Lost Time Totals FY 2001

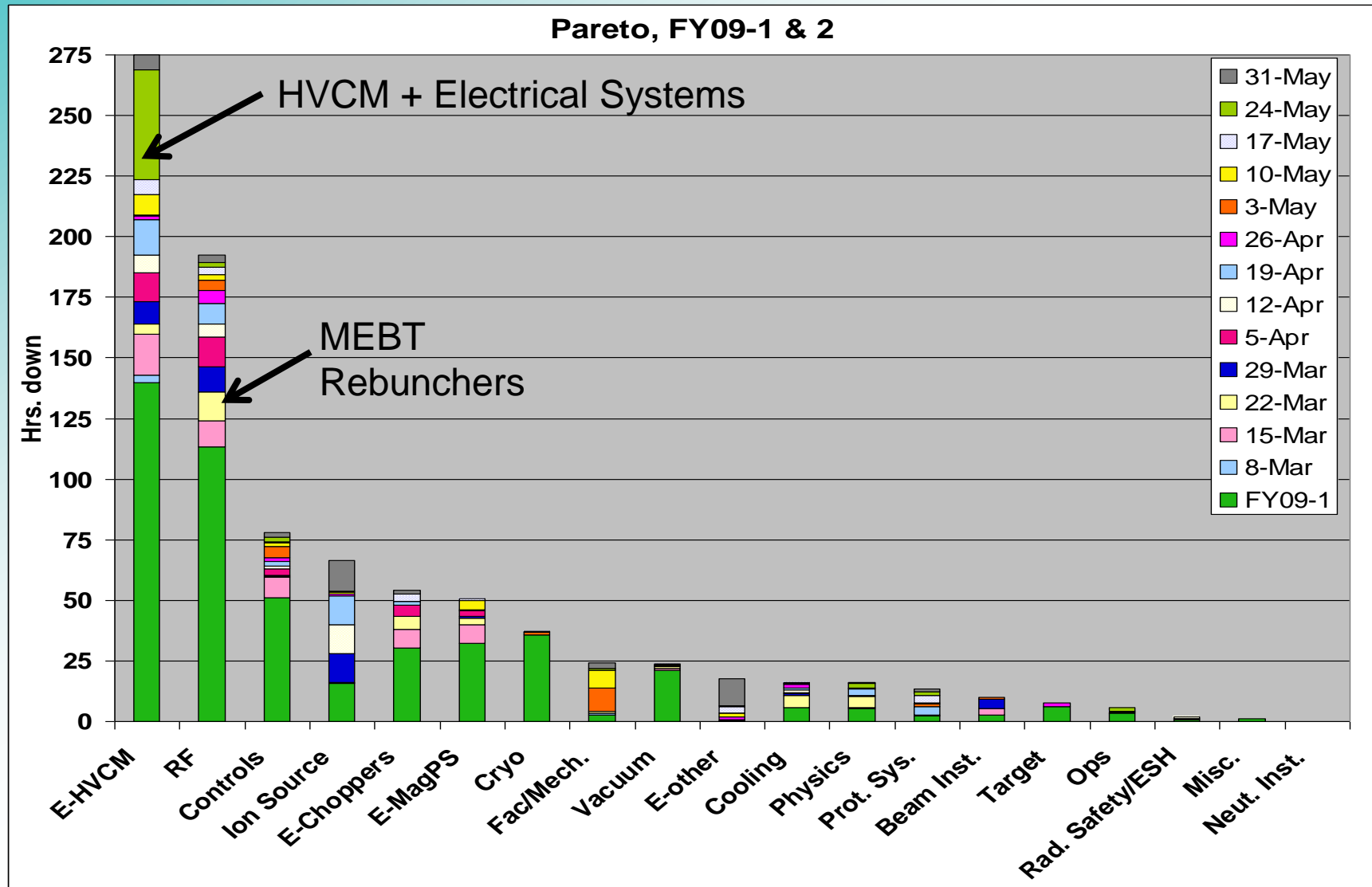


- Reliability must be improved for ADS applications
- The SC linac is modular and allows: overdesign, redundancy and "spare-on-line"
- Fast dedicated control electronics is crucial
- Beam can stay "on" when the linac is resetting itself to use spare-on line
- SC cavity technology proved to be the minor concern

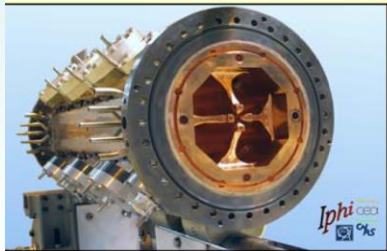
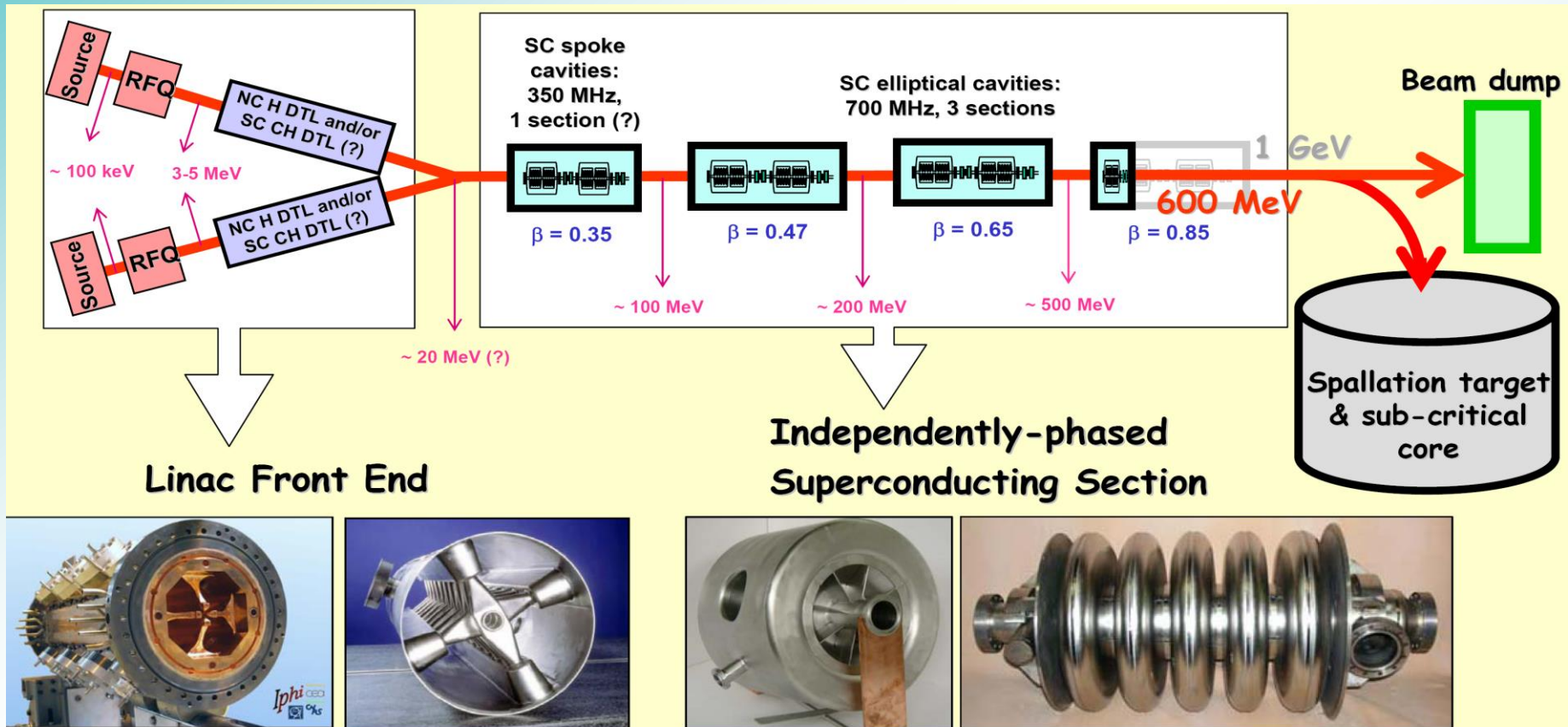


Reliability Example - SNS

Down Time – Pareto Chart for FY09-1 & 2



Superconducting linac: Highly modular and upgradeable (same concept for prototype & industrial scale) ; Excellent potential for reliability ; High efficiency (optimized operation cost)





Realibility guidelines

- **Beam trips longer than 1 sec are forbidden** to avoid thermal stresses & fatigue on the ADS target, fuel & assembly : less than 5 per 3-month operation cycle (XT-ADS)

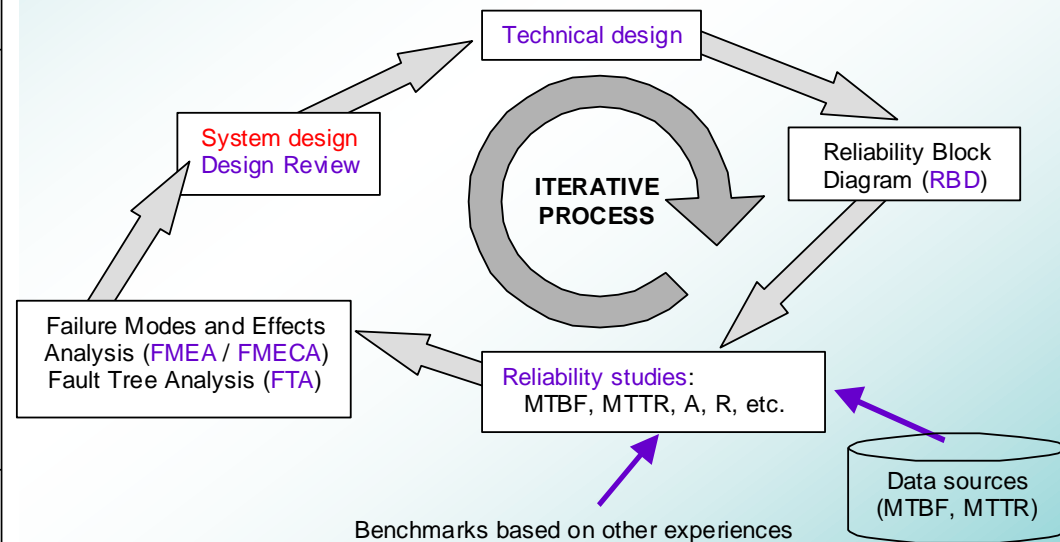
- **Reliability guidelines have been followed during the ADS accelerator design**
 1. Strong component design & derating
 - All components are derated with respect to technological limitations
 - For every linac main component, a prototype is being designed, built and tested within the EUROTRANS programme
 2. Inclusion of redundancies in critical areas
 - Front-end duplication, solid-state RF power amplifiers where possible...
 3. Capability of fault-tolerant operation
 - Expected in the highly modular superconducting RF linac (from ~20 MeV)
 - Implies reliable and sophisticated digital RF control systems with preset set points for implementation



Reliability Analysis in PDS-XADS

CONTRACT N°: FIKW-CT-2001-00179		FP5	
ISSUE CERTIFICATE			
PDS-XADS Preliminary Design Studies of an Experimental Accelerator-Driven System			
Workpackage N° 3			
Identification: N° DEL/03/057		Revision: 0	
Potential for Reliability Improvement and Cost Optimization of Linac and Cyclotron Accelerators			
Dissemination level: RE Issued by: INFN Reference: INFN/TC_03/9 (July, 23 rd , 2003) Status: Final			
Summary: This document identifies the suitable design strategies that have been followed in order to meet the reliability and availability specifications for the XADS accelerator outlined in Deliverable 1. The document describes also how these strategies can be applied in the different components of the XADS accelerator design, and how design iterations can lead to reliability improvements. The Failure Mode and Effect Analysis (FMEA) methodology has been used on the suggested design for highlighting the reliability critical areas. Finally, a first rough cost estimation of the XADS accelerator is also provided.			
23/07/2003	Paolo Pierini, INFN 	Alex C. Mueller, CNRS 	Bernard Carlucci, Framatome ANP SAS
DATE	RESPONSIBLE Name/Company Signature	WP LEADER Name/Company Signature	COORDINATOR Name/Company Signature

- Assessments using the « **Failure Modes and Effects Analysis** » (FMEA) method

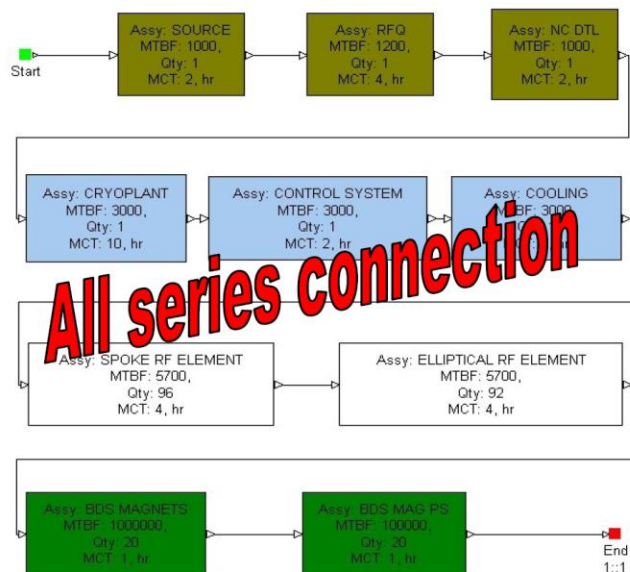


- Reliability engineering is a discipline for **estimating, predicting and controlling** the probability of occurrence of system faults



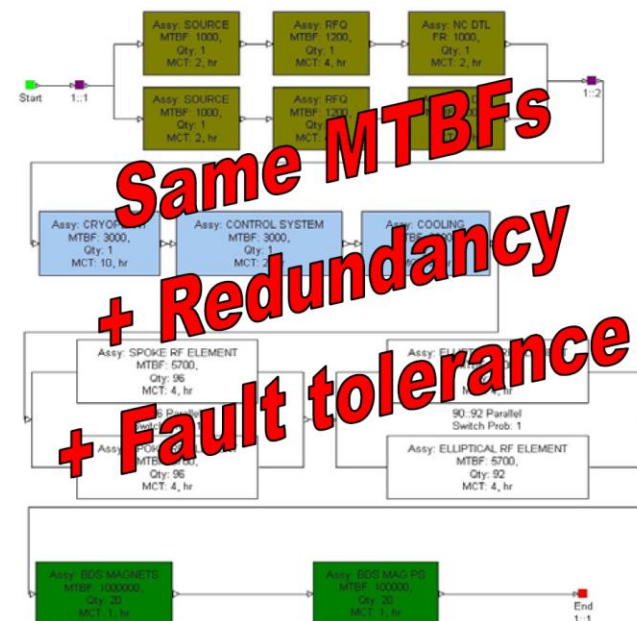
Reliability Analysis going on in EUROTRANS

Classical linac



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

ADS linac, optimized for reliability

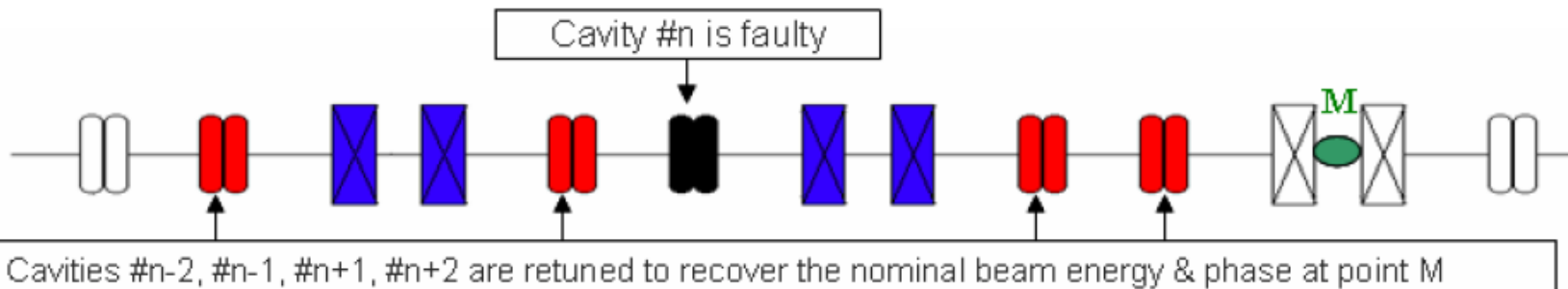


System MTBF	757.84 hours
Nb of failures (3 months)	2.89
Steady State Availability	99.5 %

Preliminary reliability estimations by P. Pierini, INFN

Fault-tolerance = ability to loose a RF cavity (or Q-pole) without loosing the beam

- Based on a fast local **compensation method**, possible thanks to the independently-phased linac



# faulty cavity	section	Final energy	Emittance growth (%)		# of retuned cavities (before + after)	Max ΔE_{acc} (%)	Max E_{pk} (SP) or B_{pk} (EL)	Max $\Delta Power$ (%)	# retuned quads (before + after)
			Trans.	Long.					
0	-	Nominal	+ 5 %	0 %	-	-	-	-	-
1	SP 0.15	Nominal	+ 7 %	+ 4 %	0 + 4	+ 67 %	19 MV/m	+ 67 %	0 + 4
4	SP 0.15	Nominal	+ 9 %	+ 4 %	3 + 3	+ 46 %	15 MV/m	+ 35 %	2 + 4
62	SP 0.35	Nominal	+ 6 %	0 %	2 + 2	+ 26 %	31 MV/m	+ 28 %	2 + 2
63	SP 0.35	Nominal	+ 5 %	+ 1 %	3 + 2	+ 25 %	31 MV/m	+ 27 %	2 + 2
98	EL 0.47	Nominal	+ 6 %	0 %	3 + 2	+ 23 %	62 mT	+ 31 %	4 + 2
109	EL 0.47	Nominal	+ 6 %	0 %	3 + 3	+ 20 %	60 mT	+ 28 %	4 + 2
174	EL 0.65	Nominal	+ 5 %	0 %	3 + 3	+ 18 %	59 mT	+ 22 %	4 + 2
175	EL 0.65	Nominal	+ 5 %	0 %	4 + 4	+ 17 %	59 mT	+ 18 %	4 + 2
186	EL 0.85	Nominal	+ 7 %	0 %	6 + 1	+ 21 %	61 mT	+ 33 %	2 + 2
187	EL 0.85	Nominal	+ 6 %	0 %	7 + 0	+ 25 %	63 mT	+ 37 %	2 + 2

Capability of fault-tolerant operation due to the highly modular superconducting RF linac (from ~20 MeV) and due to the availability of reliable and sophisticated digital RF control systems



The Fault Tolerant Accelerator

- Two **fast failure recovery scenarios** ($\ll 1$ sec) have been identified & checked on the beam dynamics point of view, both based on:
 - Fast fault detection
 - Fast update and tracking of the field/phase set-points (preset)
 - Adequate management of the tuner of the failed cavity
- Requires up to 30% **margins** on RF fields and powers
- **Requires the use of digital LLRF control systems**
 - Heavy R&D on-going on this topic

Note -> Fault recovery system in real operation at the SNS SC linac (US)
(global compensation method, “high” energies, “slow” retuning)



**FPGA
based
DIGITAL
SYSTEM**



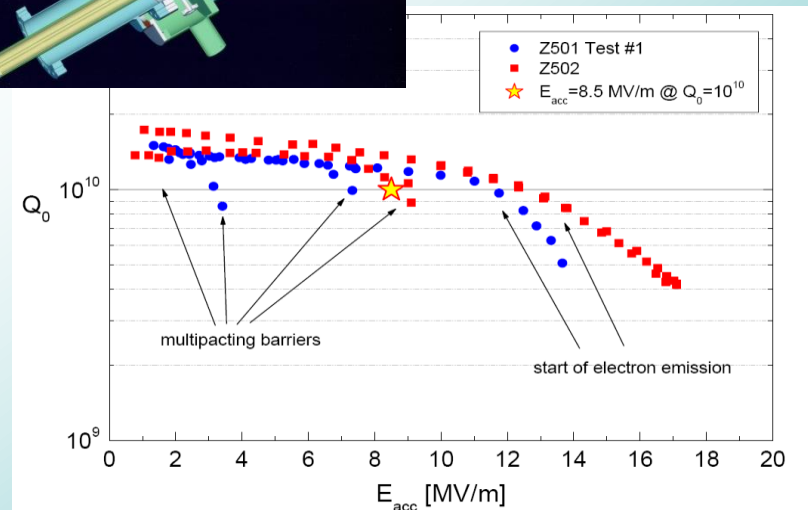
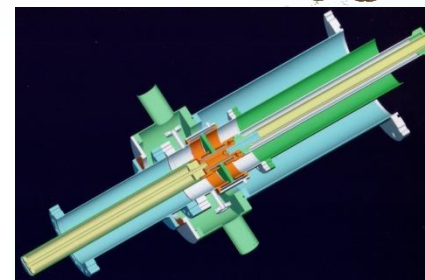
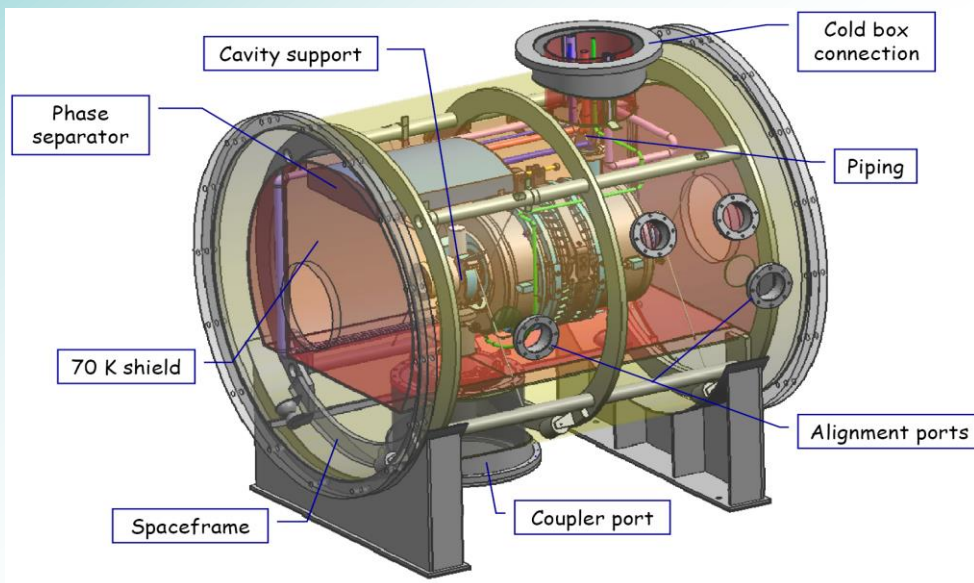
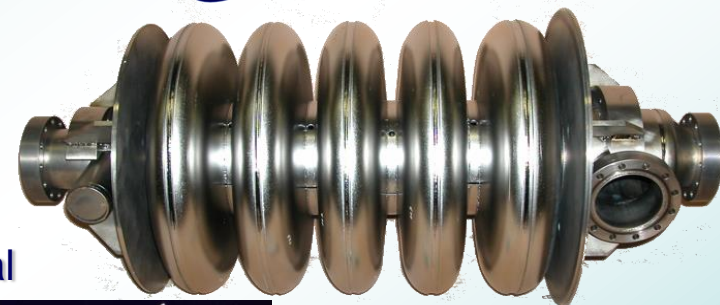
ADS : Reliability & Maintenance

- The maintenance strategy is presently under investigation, assuming 3 months of operation / 1 month of maintenance

PDS-XADS-WP3 Deliverable 48 Chapter 4 4.3.1 H ⁺ source		Severity Ranking Tables									
		Local effect			Effect on beam						
		0: No effect			0: Beam with nominal parameters on target						
		1: Functioning with reduced performance			1: Beam with wrong parameters on target						
		2: Loss of function			2: No beam on target						
Main Items		Function	Failure Mode	Severity rank		Preventive action			Curative action		Rem.
				local	beam	action	freq.	time of int.	action	time of int.	
Boron nitride discs			Wear	1	1	Replace	6 months	24 H	Replace	24H	
Vacuum pumps			Wear	1	2	Regenerate	24 months				
			Out of order	2	2	-			Replace	8H	
Power supply filters			Get dirty	0	0	Clean	3 months	few min			
Power supply			Aging	0	0	Overhaul	24 months	few weeks			Use spare while overhauling
Cooling (water): filters, pumps...			Wear / dirty	0	0	Clean					
Plasma electrode			Aging	1	1	Replace	12 months	24H			
Magnetron			Out of order	2	2	Replace	24 months	2H	Replace	2H	Replace "before MTBF"
HV power supply			Out of order	2	2	Oil changing	24 months	8H	Replace	8H	
Extraction electrodes			Aging	1	1	Replace	24 months	48H			
Security devices :											
Water flow controller			get dirty			cleaning	12 months	30 min	Replace	2H	
Temperature controller			Out of order			Systematic tests	12 months	few min	Replace	8H	could be doubled
Emergency stop			Out of order			Systematic tests	12 months	1 H	Replace	1 H	
DGPT			Out of order			Systematic tests	12 months	1 H	Replace	8 H	

Design, fabrication & test of an elliptical module at nominal power & temperature

- $\beta = 0.47$ prototype constructed and tested
- Vessel & valve box under construction
- CW RF power coupler just fabricated
- 700 MHz RF 80 kW power source received and operational

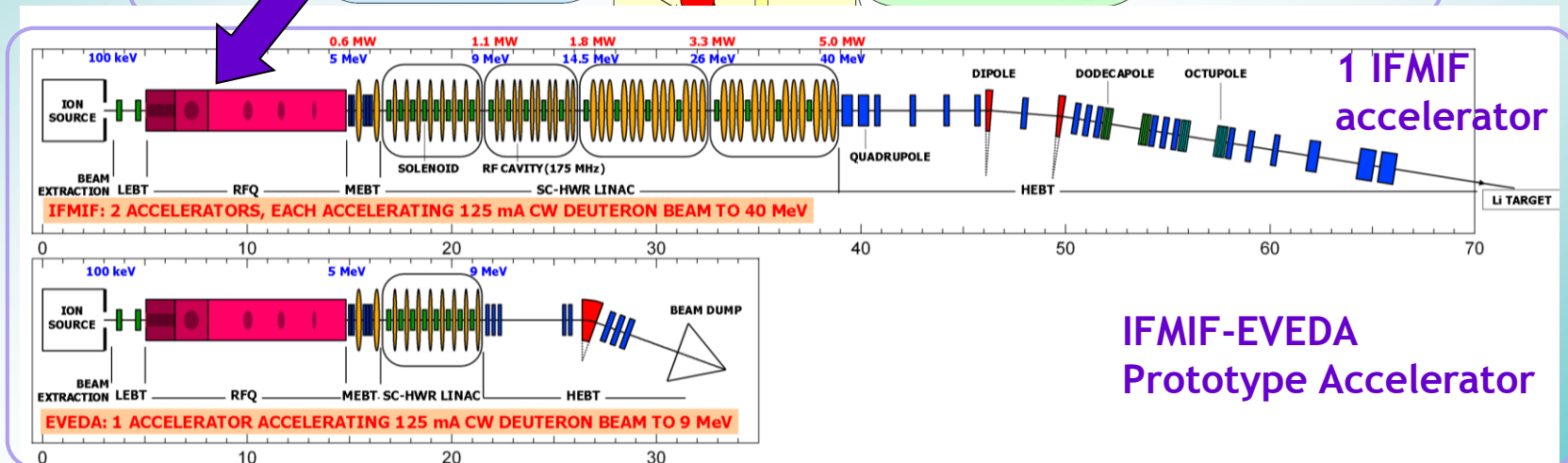
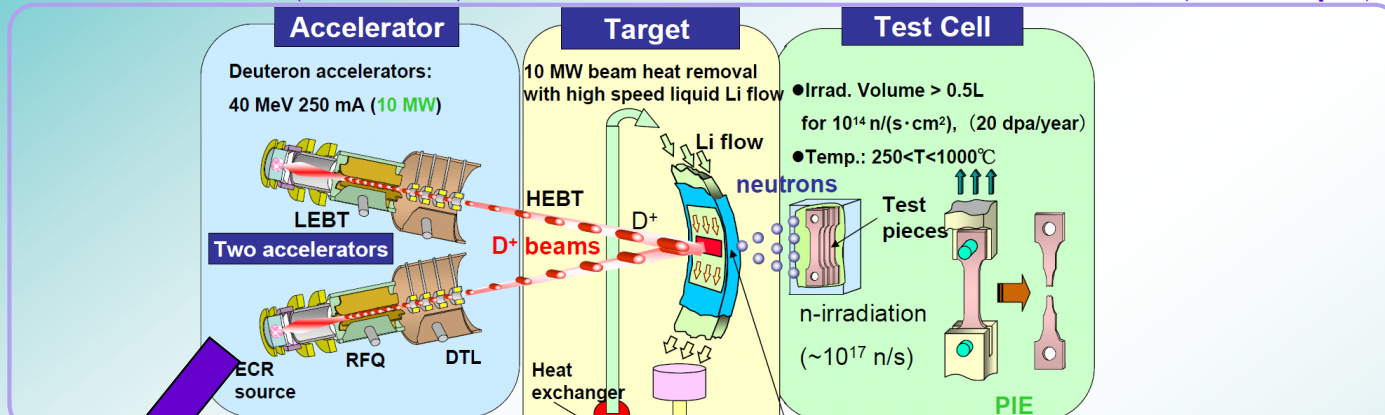




High Power Proton Accelerator as an irradiation tool for material testing: the IFMIF project

The IFMIF accelerator

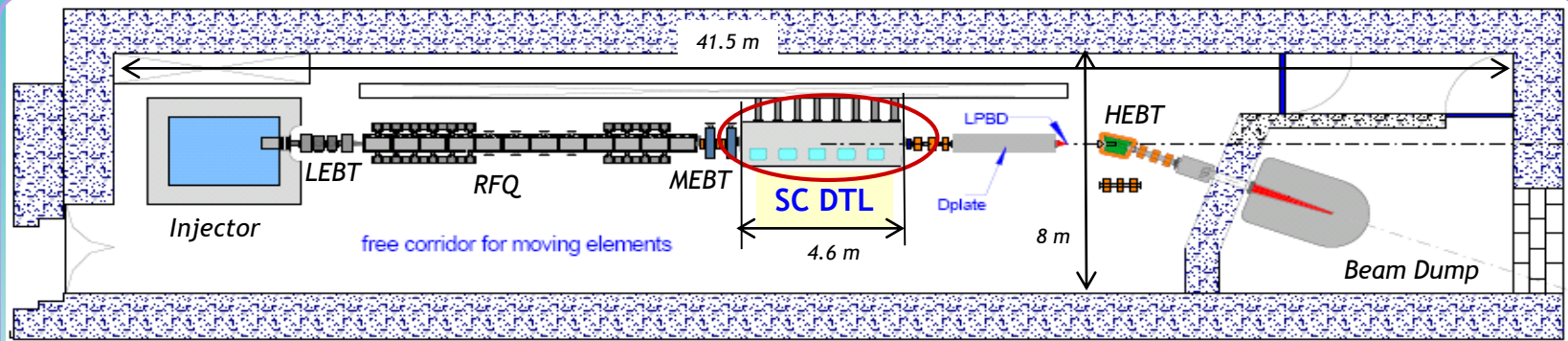
Objective of the IFMIF project: characterization of materials with intense neutrons flux (10^{17} n/s) for the future Fusion Reactor DEMO (~150 dpa)



Collaboration for Accelerator: CEA (FR), INFN (IT), CIEMAT (SP), SCK-CEN (BE), JAEA (JA)

*In the framework of an agreement between Euratom & Government of Japan,
the program IFMIF/EVEDA has been launched in June 2007*

The IFMIF accelerator



EVEDA General layout

Objectives of the SC Drift Tube Linac

- Transport and accelerate a deuteron beam of $I=125$ mA @ 175 MHz, CW,
- Energy from 5 MeV up to 9 MeV for EVEDA Acc. prototype, and up to 40 MeV for IFMIF,
- Good performances in terms of transverse and longitudinal emittances and w/o beam loss

⇒ SC DTL of 4.6 m long, equipped with:

- 8 superconducting Half Wave Resonator (HWR low- $\beta = 0.094$), working at 4 K, with a moderate accelerating field ~ 4.5 MV/m max, and an appropriate tuning system (frequency range ± 50 kHz)
- 8 RF power couplers, working in TW, and providing to HWRs the RF power of 70 kW per coupler (EVEDA cryomodule) and 200 kW per coupler for IFMIF cryomodules
- 8 Solenoids Packages, including focusing solenoid, H&V steerers and Beam Position Monitors (BPMs)
- Cryostat: supports, cryogenic distribution, alignment, vacuum, shielding, instrumentation, etc ...



The IFMIF accelerator

Vacuum tank
Thermal shield
cooled by LN₂

Tuning system

Helium
phase
separator

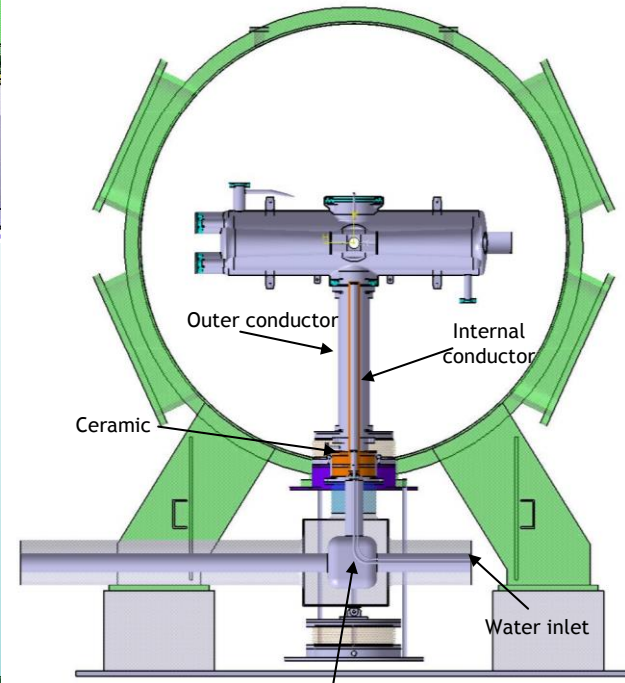
Acces
traps

Solenoid package

HWR

RF Couplers

External RF transition



External RF transition