High Power Proton LINACs

Part 1

JOINT UNIVERSITIES
ACCELERATOR SCHOOL

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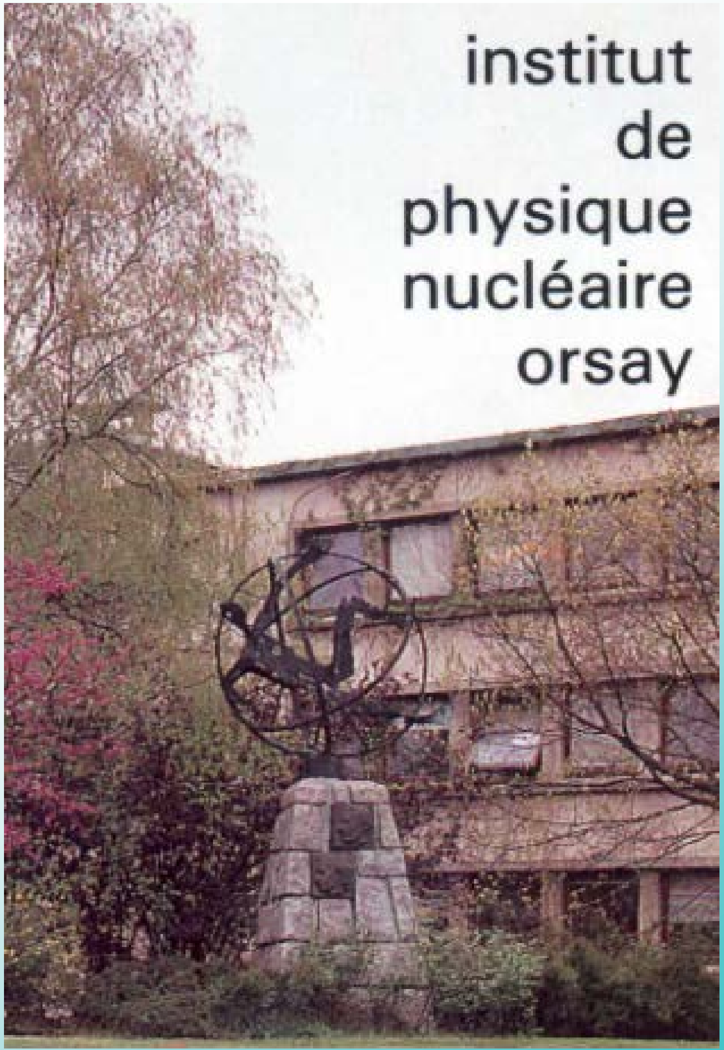


JUAS, Archamps, 9 March 2018

- 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

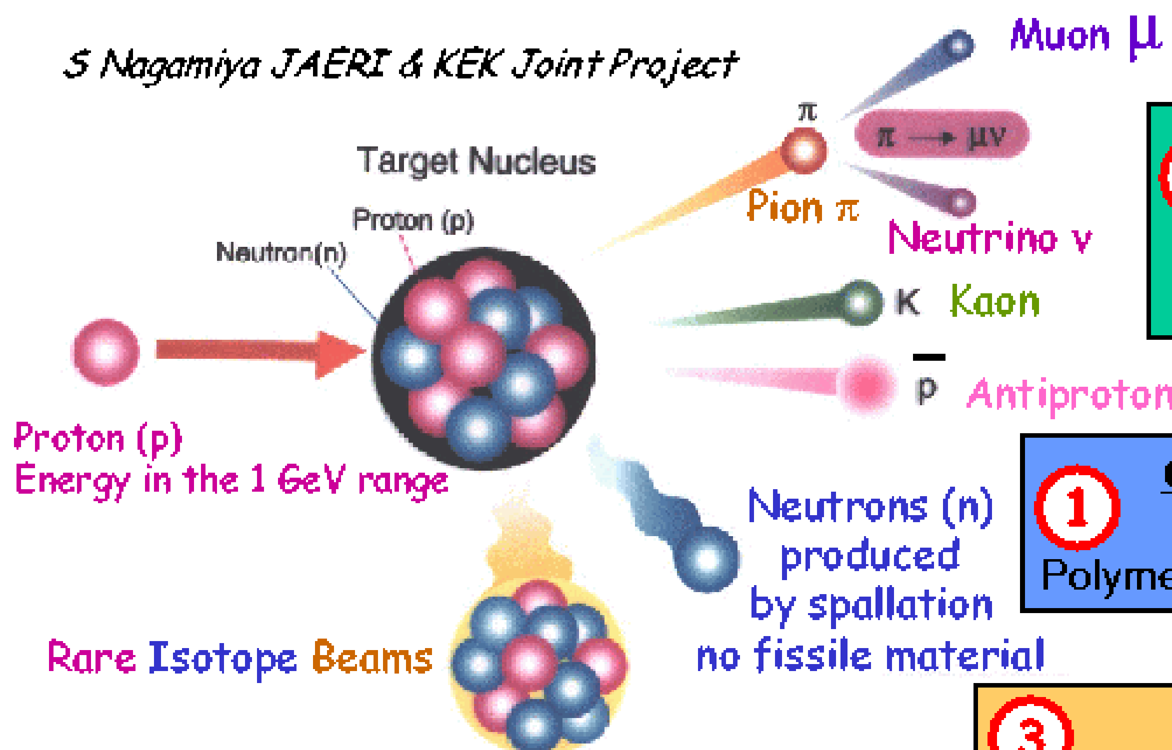
- « Definition » of a High Power Proton LINAC (HPPL) and range of applications
- HPPL for neutron source
- HPPL for Radioactive Ion beams production
- HPPL for Nuclear waste treatment

PART 2

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

Why high power proton accelerators ?

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



⑤ <u>Particle Physics</u>
μ colliders
μ Storage Rings
(ν factories)

① <u>Condensed Matter Study</u>
Neutron probe
Polymers, Fractals, Magnetism, Biology

③ <u>Transmutation</u>
of long-lived radioactive wastes

② <u>Nuclear Physics</u>
Beams of short-lived elements
super heavy elements

④ <u>Technical Irradiation Tool</u>
Tests of material

Specification for a High Power Proton Accelerator (HPPA)

	R.I.B. (EURISOL)	ν&μ (CERN)	Neutrons (ESS)	Transmutation (DEMO→Industriel)
$\hat{I}_{mA}$	0.1→ 30	10	30→100	10→100
$<I>_{mA}$	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%
$<P>_{MW}$	0.1→5	4	1→ 5	6 → 40

HPPA: Power ranging typically from 100 kW so several MW

Particle accelerator main components & where HPPA is specific

schematic view

Source → Accelerator → User

An accelerator is composed of the following main sub-systems:

- 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

$$W \geq E_0$$

$$E = E_0 + W$$

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

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

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

And:

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

Ultra-relativistic case $W \gg E_0$

$$\beta \approx 1 \qquad v \approx c$$

Different accelerator types

	Kinetic energy W	
	Electrons	Protons/ions
Electrostatic Van de Graaf &Tandems		20-35 MeV (Vivitron)
Betraton	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)

$= E_0 + W$

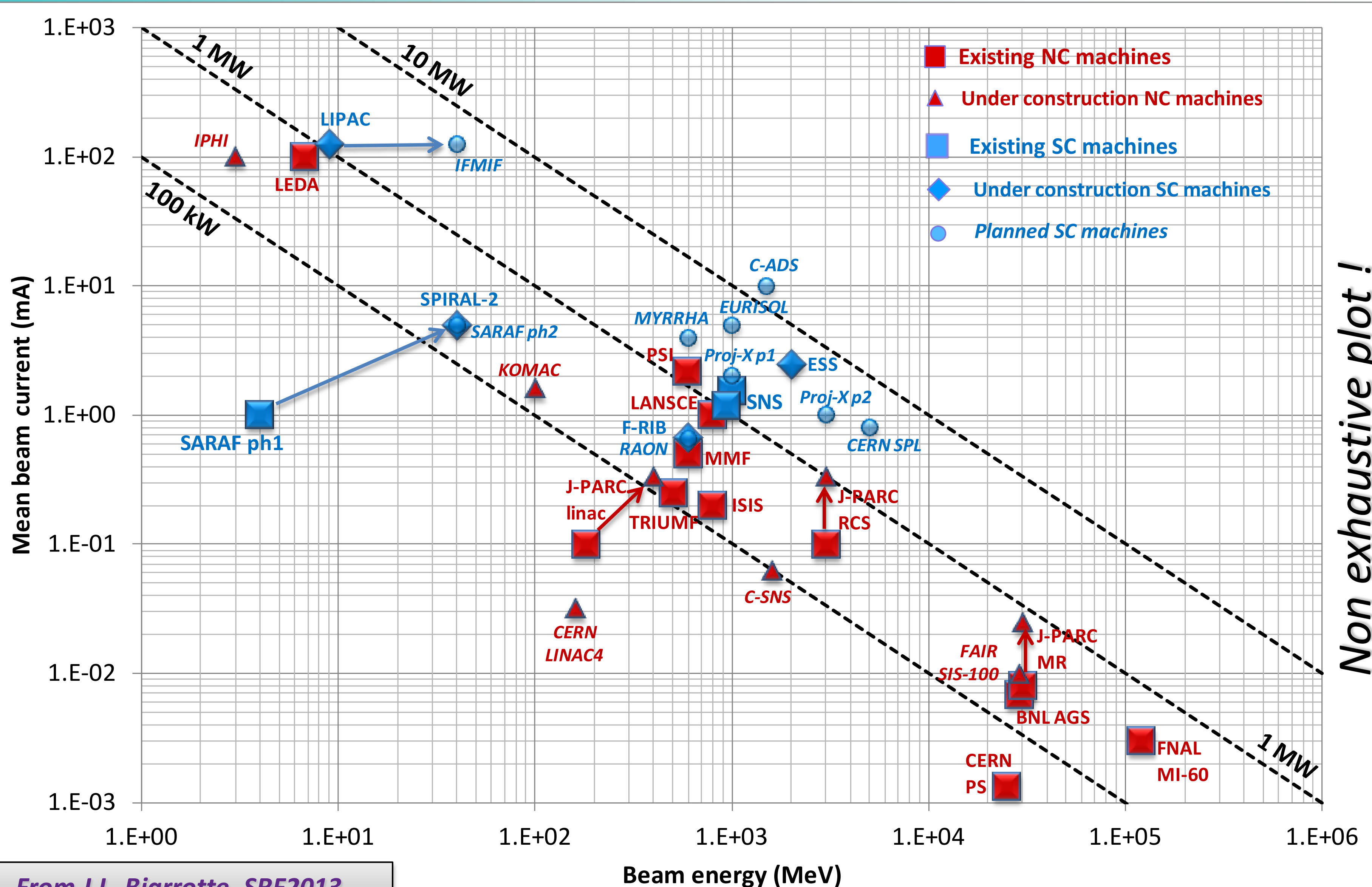
$E_0 = m_0 c^2$ ⇨ electron E_0= 0,511 MeV
protons E_0= 938 MeV

- 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 beam 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.

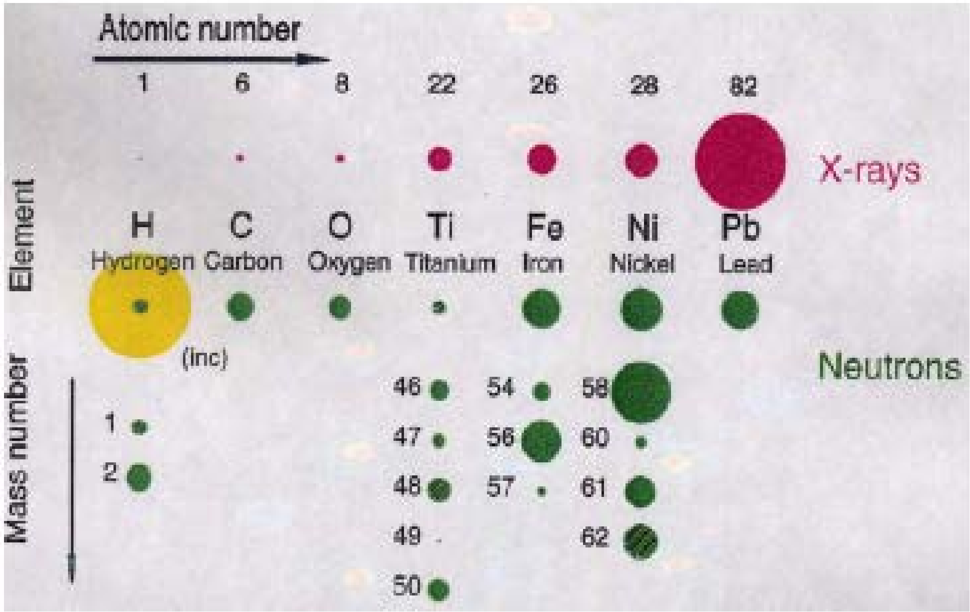
Installed or projected HPPA

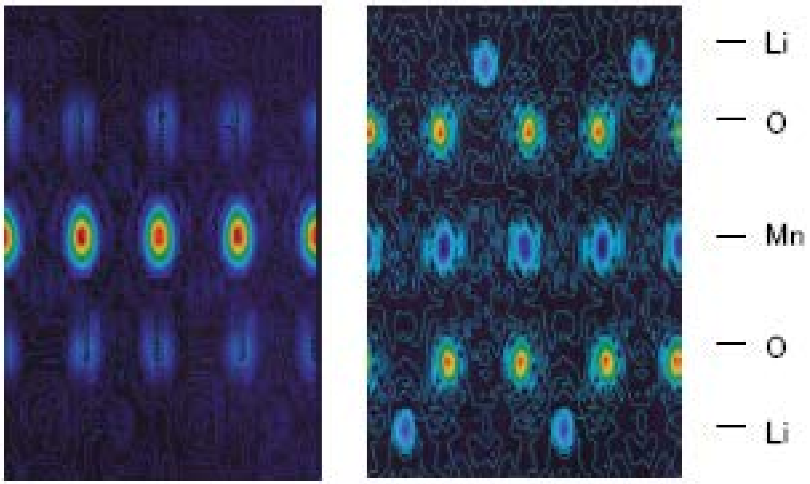


From J.L. Biarrotte, SRF2013

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

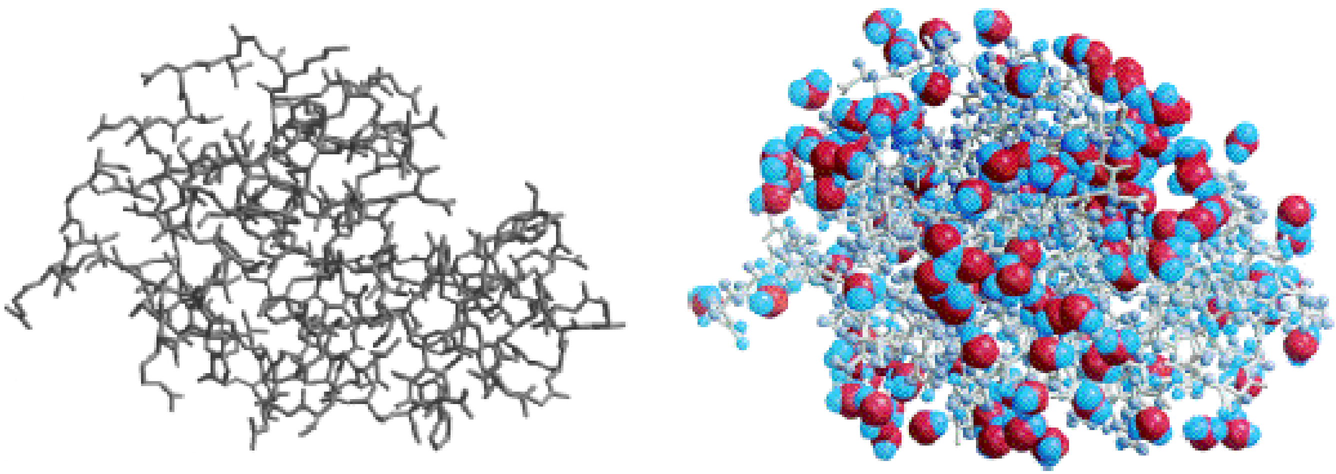
X rays (left) and

Neutrons (right)

T. Kamiyama, et al.

Condensed matter study: why neutrons ?

Hen Egg-White Lysozyme



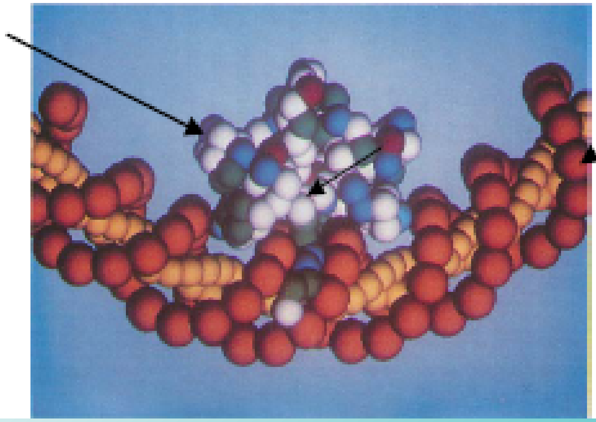
X-rays

Neutrons

Water molecules Observed with neutrons

N. Niimura, et al.

Protein



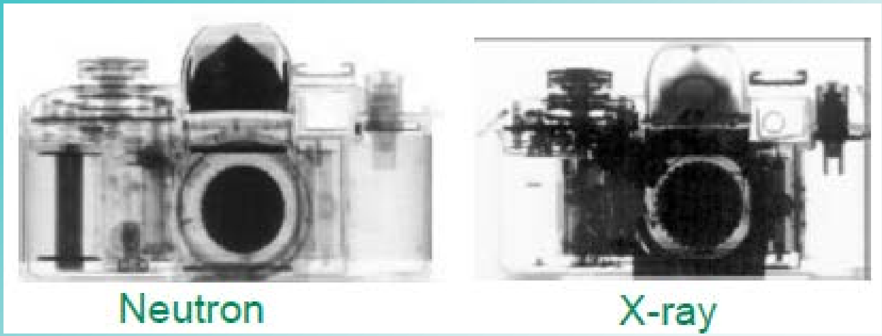
DNA

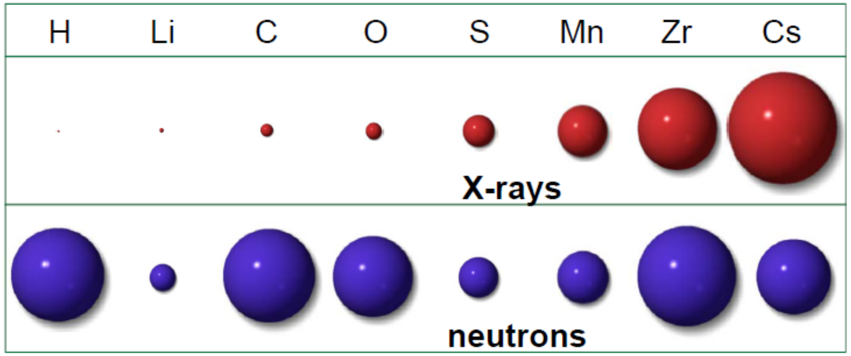
A proten molecule moving along the DNA chain

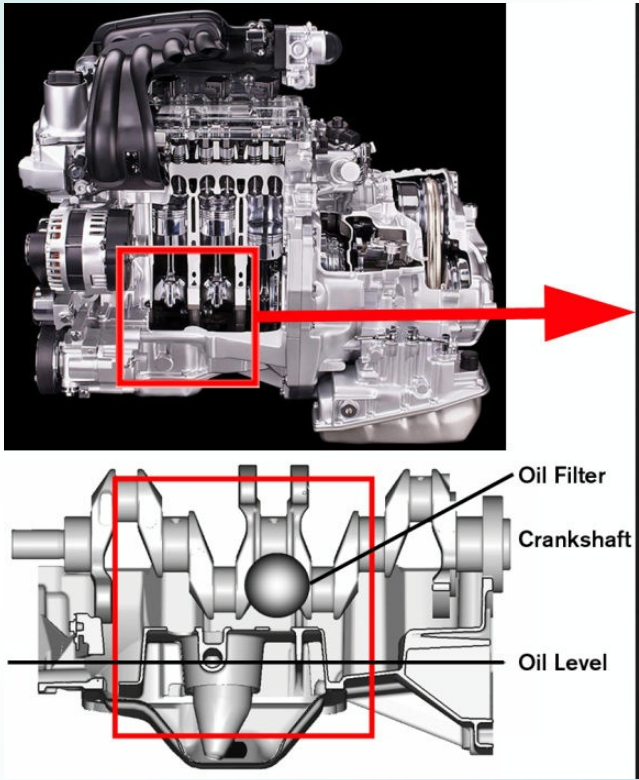
From structure to function

Courtesy of PSI

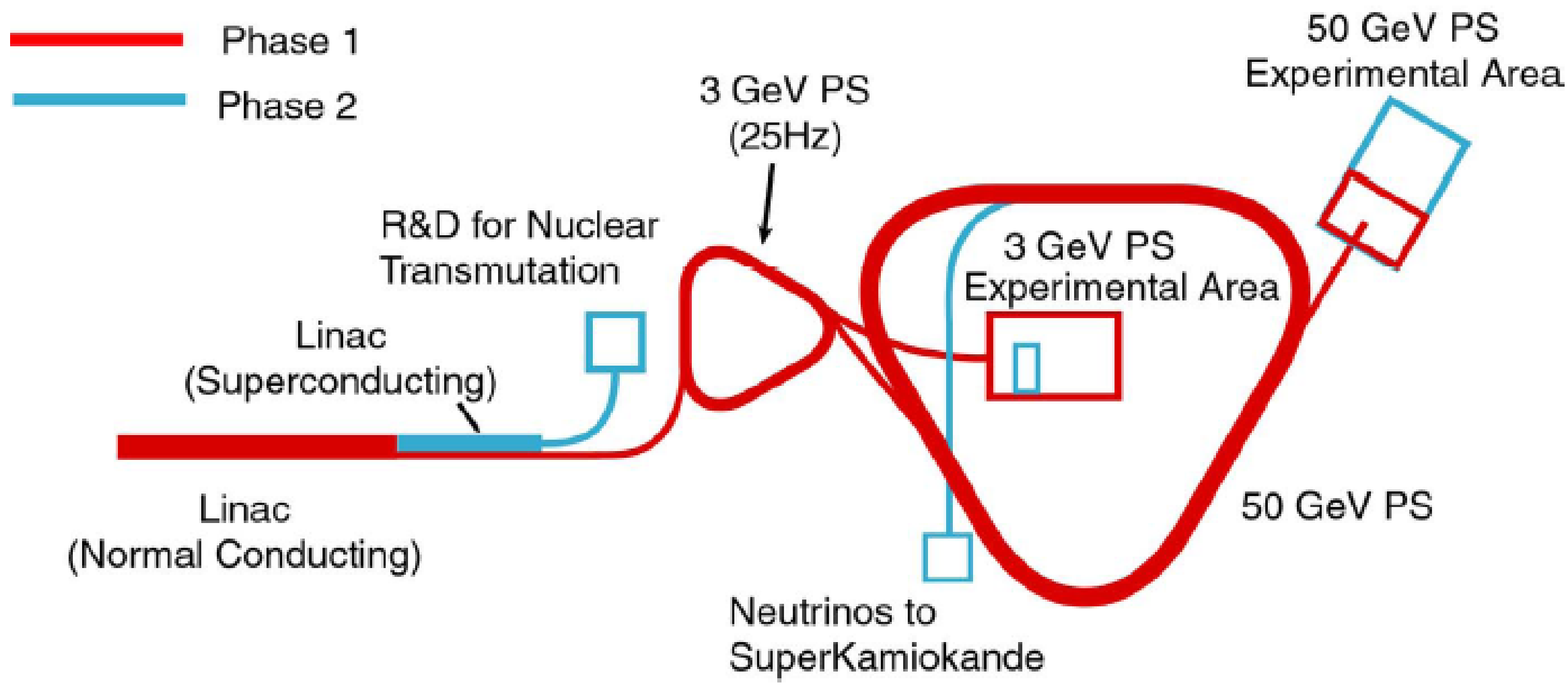
Condensed matter study: why neutrons ?





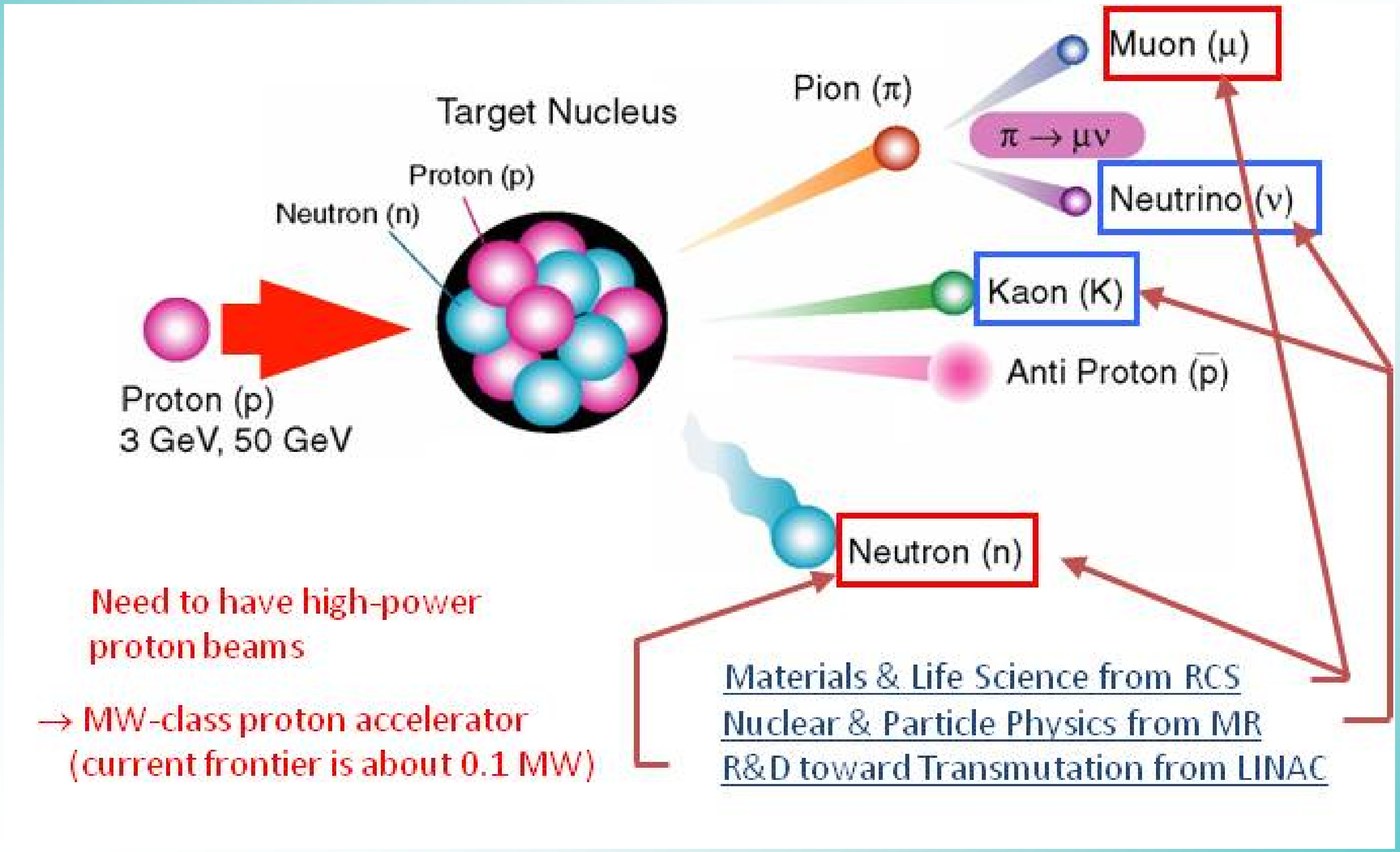


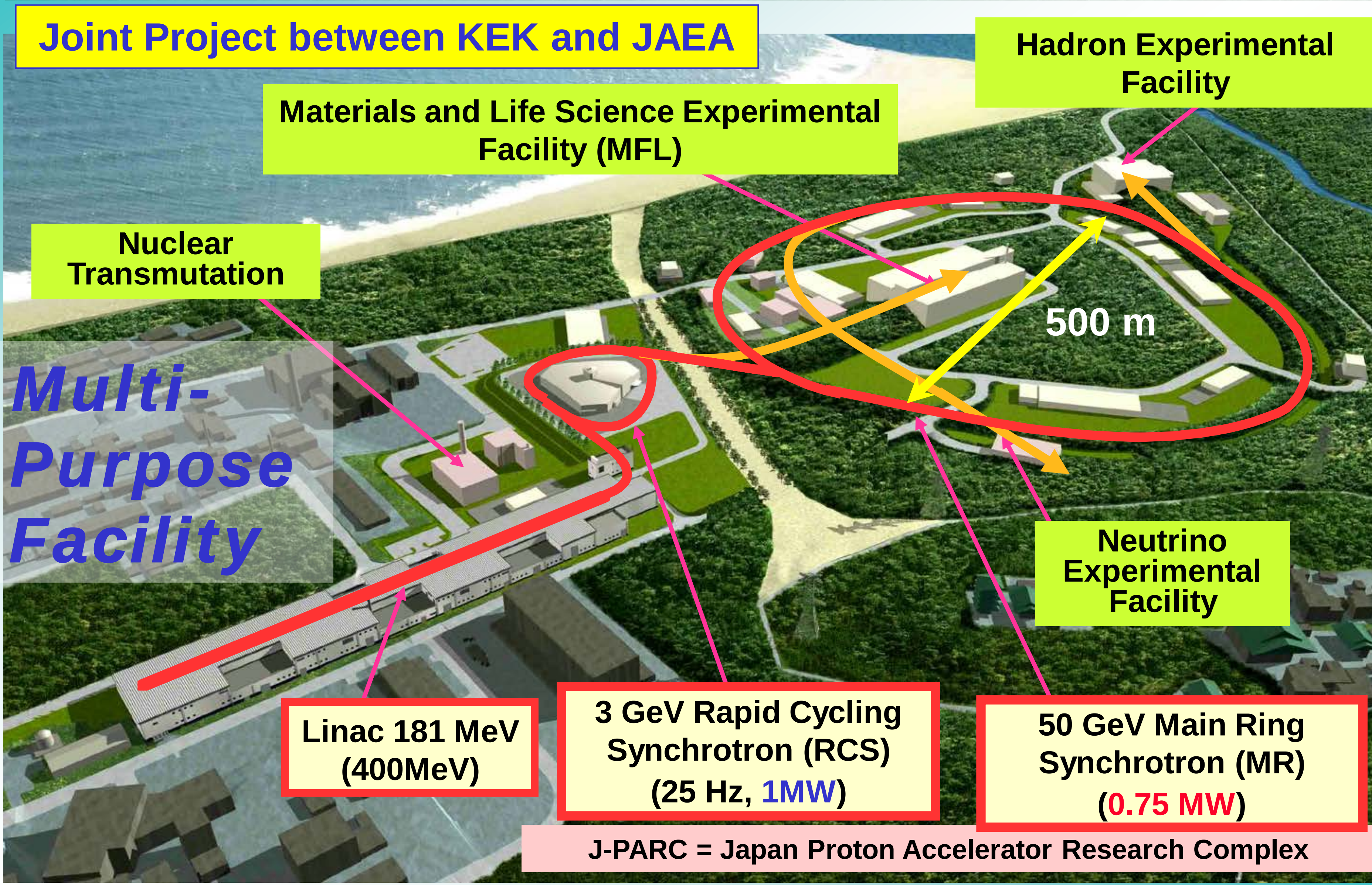
J-PARC : Japan Proton Accelerator Research Complex (construction achieved, close to commissioning completion)



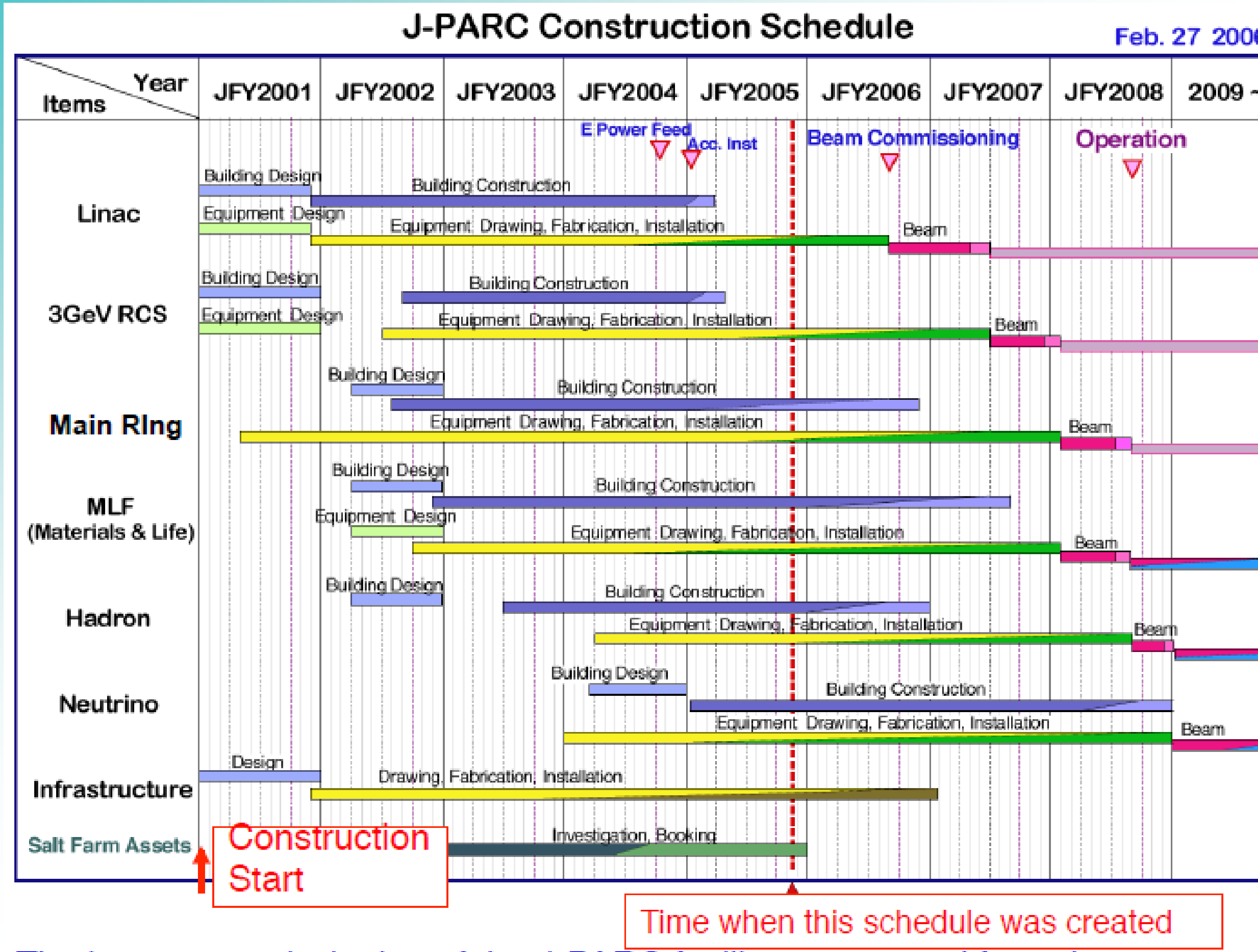
- Phase 1 + Phase 2 = 189 billion Yen (= \$1.89 billion if \$1 = 100 Yen).
- Phase 1 = 133.5 billion Yen for 6 years (= 2/3 of 189 billion Yen).
- Construction budget does not include salaries.

Secondary particle produced at J-PARC:




Joint Project between KEK and JAEA
Hadron Experimental Facility
Materials and Life Science Experimental Facility (MFL)
Nuclear Transmutation
500 m
Multi-Purpose Facility
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 : Planning



J-PARC : Pictures

J-PARC : Pictures

J-PARC : Pictures

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.

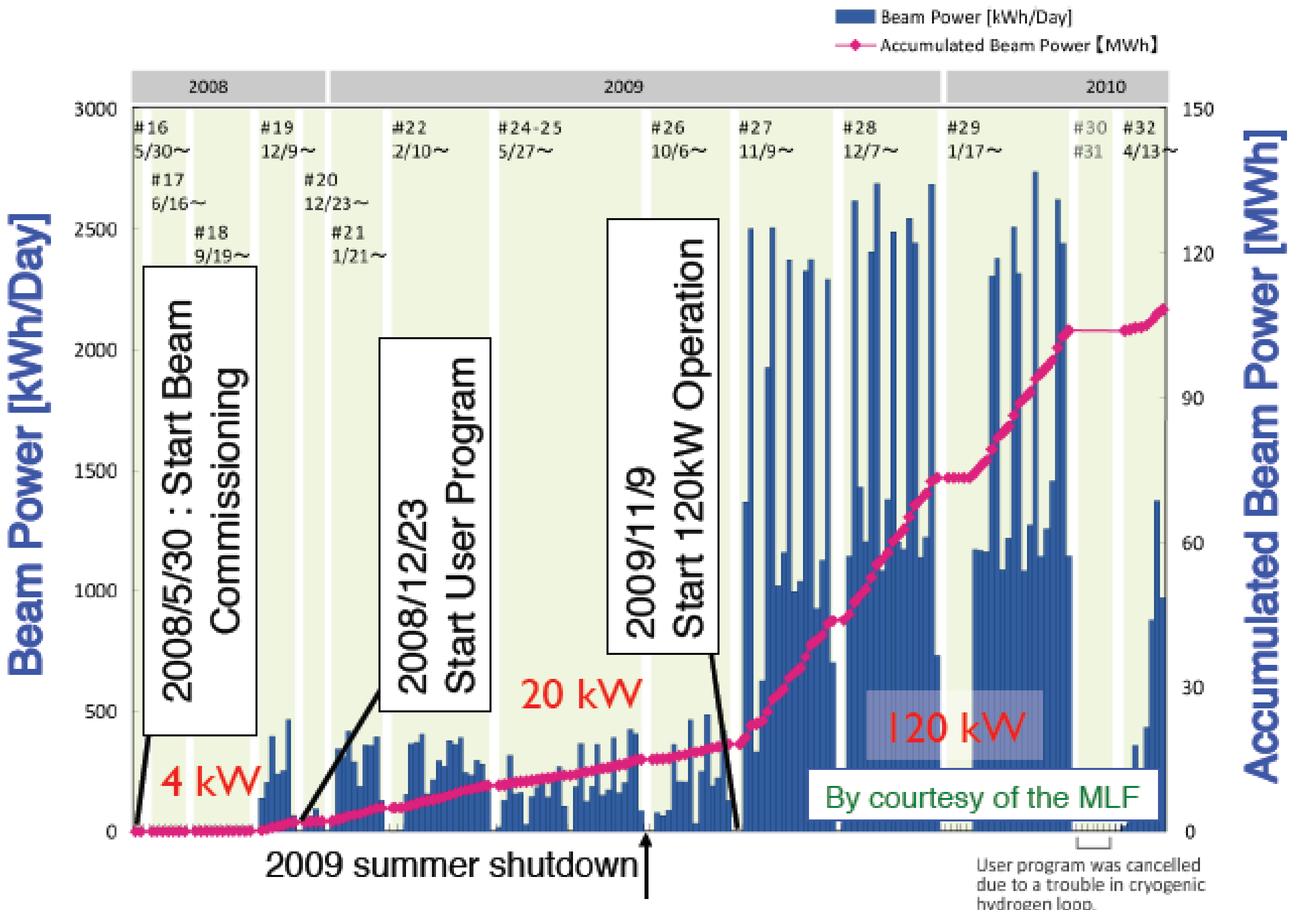
First proton beams reached to the Hadron target.

User operation of MLF started.

2009 First proton beams reached to the Neutrino target.

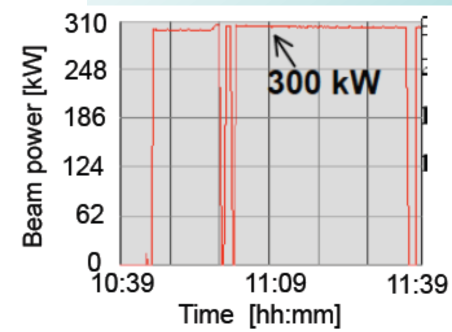
J-PARC : commissioning

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 became possible and 120 kW operation has started for the MLF users.

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

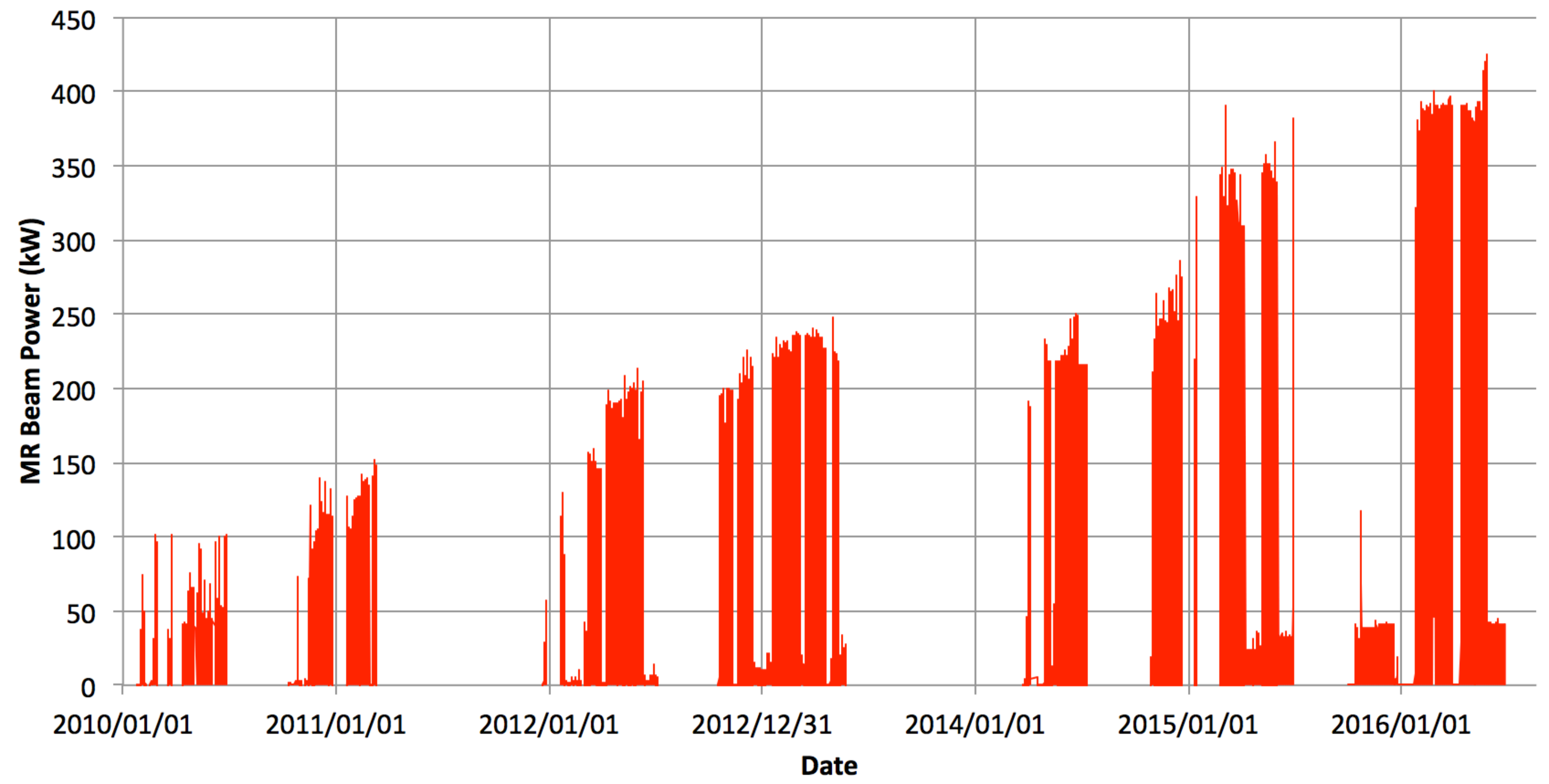
Muon beamline: The highest intensity beamline in the world with the 120 kW beam.

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

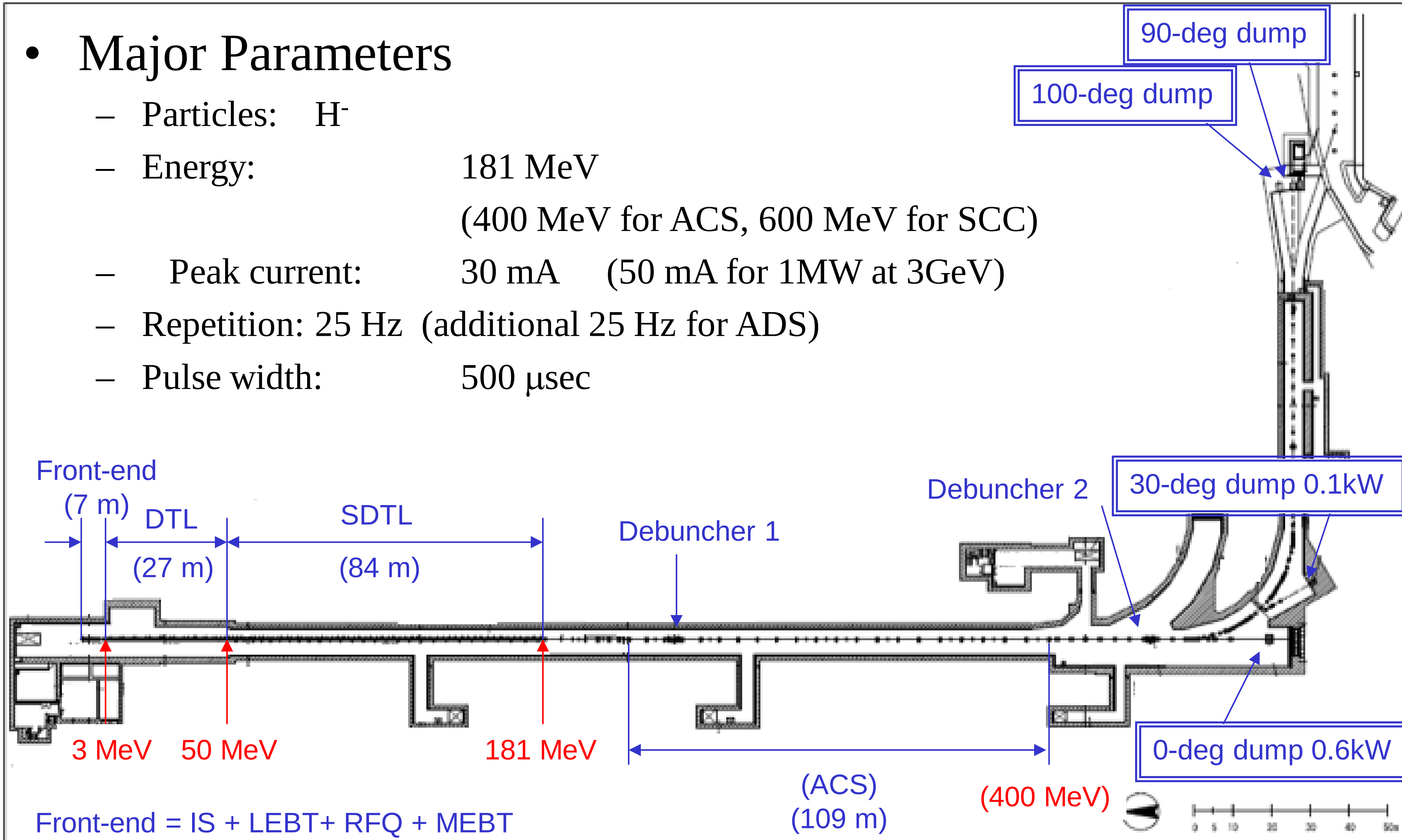
Full power (1 MW in RCS, 330 μA) achieved 27 Dec. 2015

Main Ring Beam Power History

- In the operation of Jan ~ May 2016, the beam power was mostly about **390 kW with 2×10^{14} protons per pulse**. The user operation of **415~425 kW** was successful in May 2016.

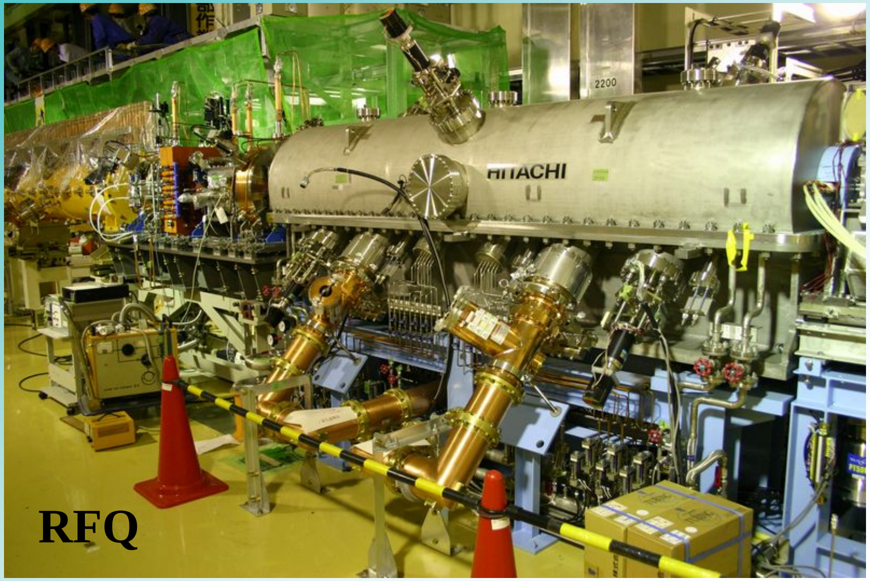


- Major Parameters
  - Particles: H^-
  - Energy: 181 MeV
    (400 MeV for ACS, 600 MeV for SCC)
  - Peak current: 30 mA (50 mA for 1MW at 3GeV)
  - Repetition: 25 Hz (additional 25 Hz for ADS)
  - Pulse width: 500 μsec

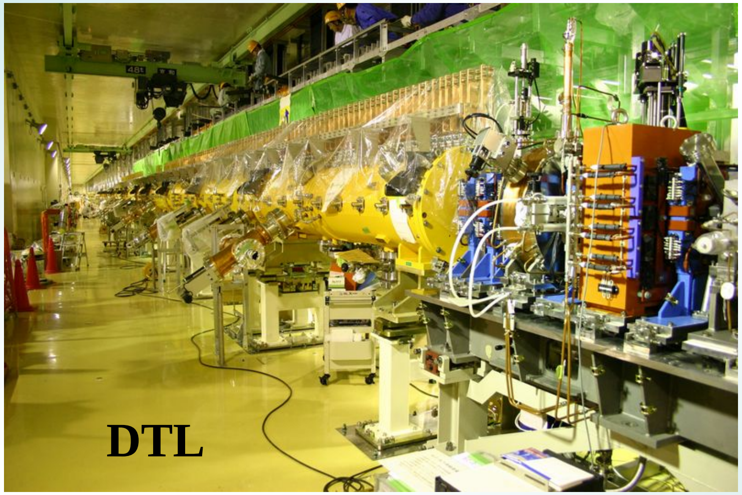


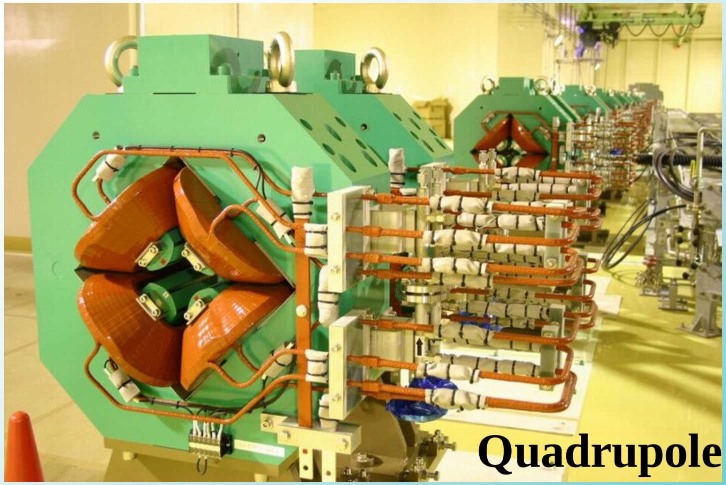
Front-end = IS + LEBT+ RFQ + MEBT

J-PARC : Linac pictures


RFQ


Klystron

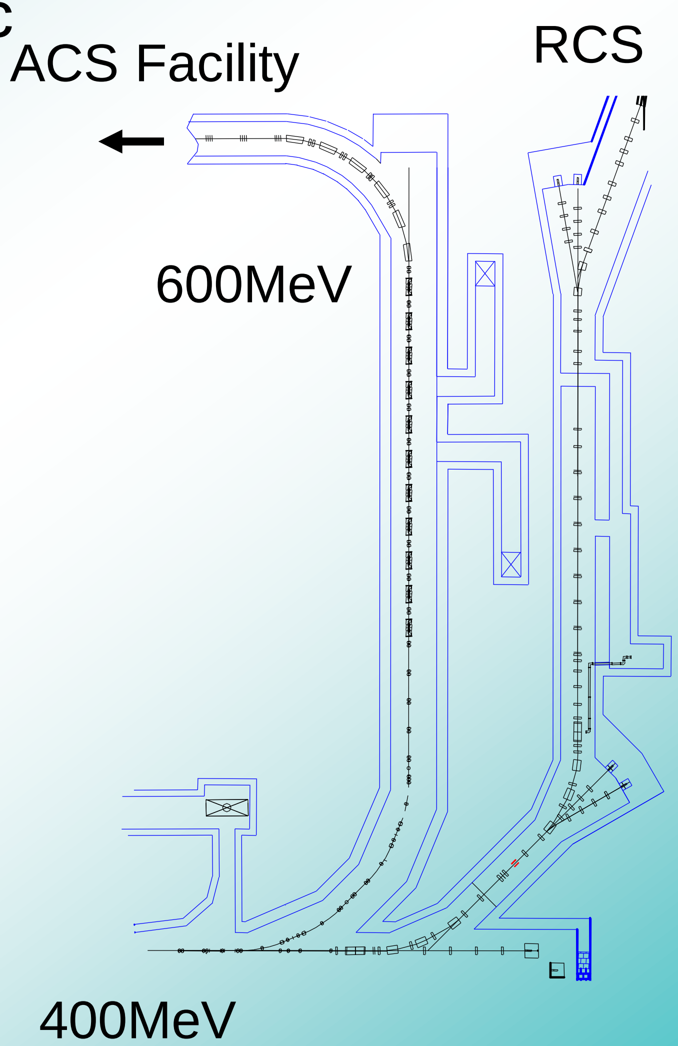

DTL


Quadrupole

Preliminary design of SC proton linac

Design Parameters

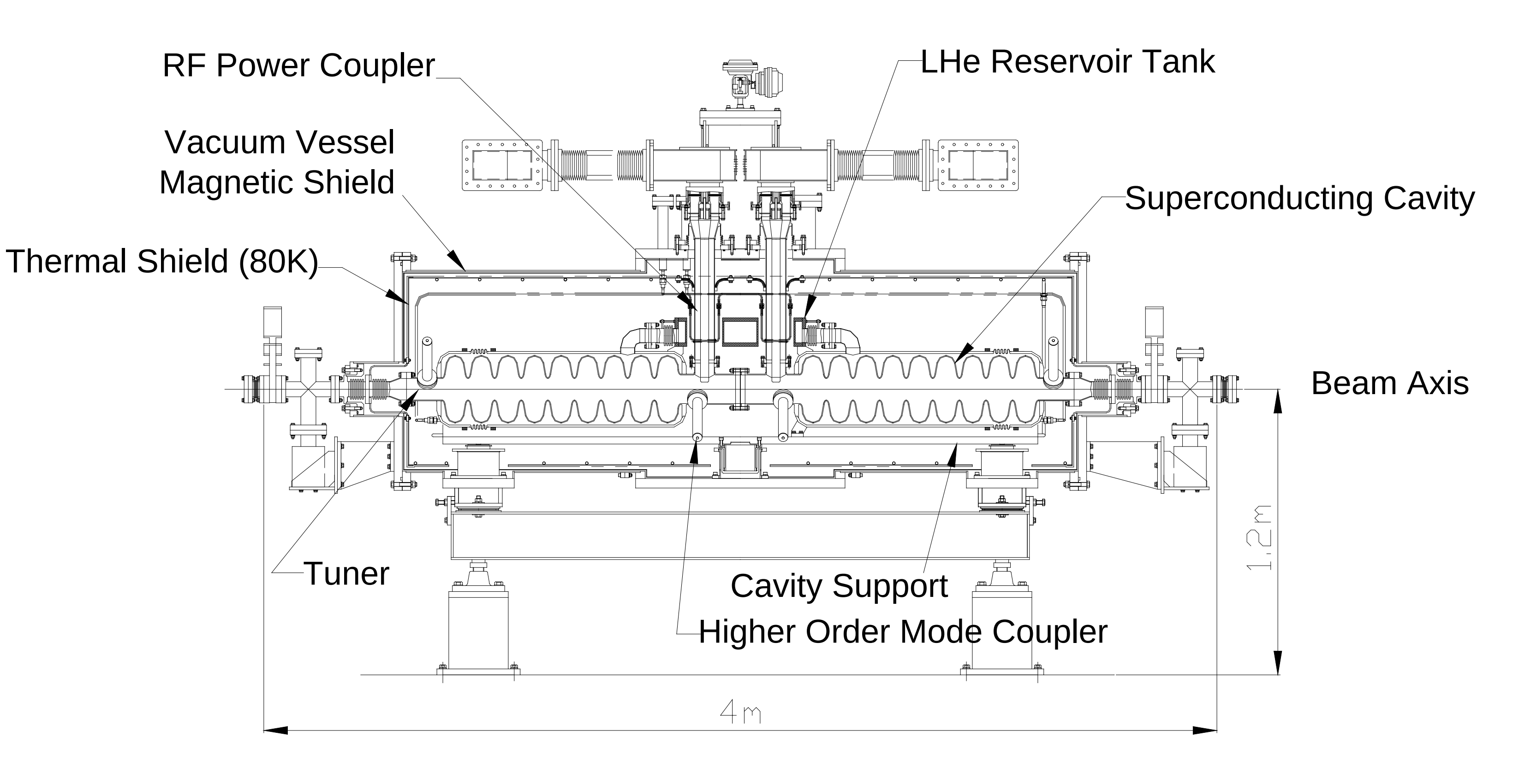
Energy	400-600 MeV
Frequency	972 MHz
β	0.71-0.79
No. of Cell	9 cell/cavity
No. of Cavity	2 cavity/cryomodule
No. of Cryomodule	11 cryomodules
Length	57.7 m
Surface Peak Field	30 MV/m
Accelerating Field	9.7-11.1MV/m
Synchronous Phase	-30 deg
No. of Klystron	11 klystrons
Total RF Power	10 MW
Loaded Q	~500,000



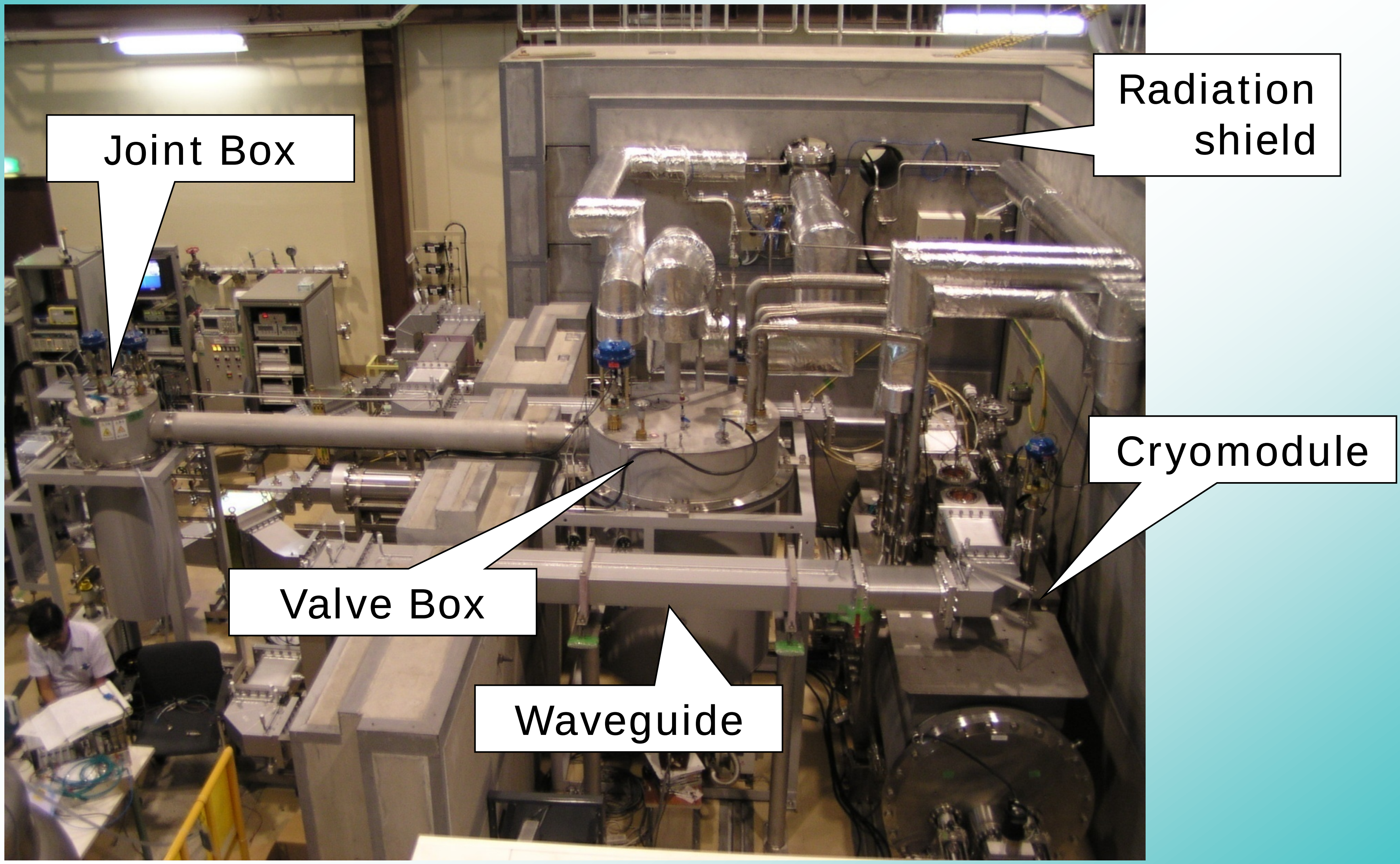
Amplitude and phase stability (±1% & 1deg) in pulsed operation

J-PARC : The SC Linac cryomodule

- Two 9-cell elliptical cavities of β=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



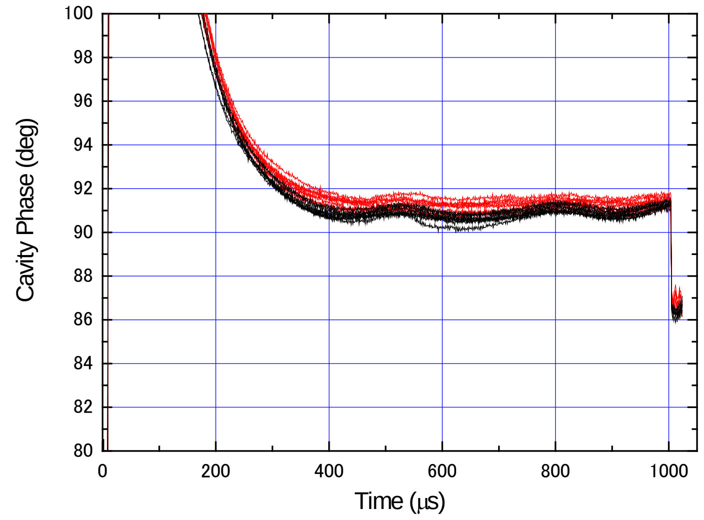
J-PARC SC Linac : R&D on 972 MHz cryomodule



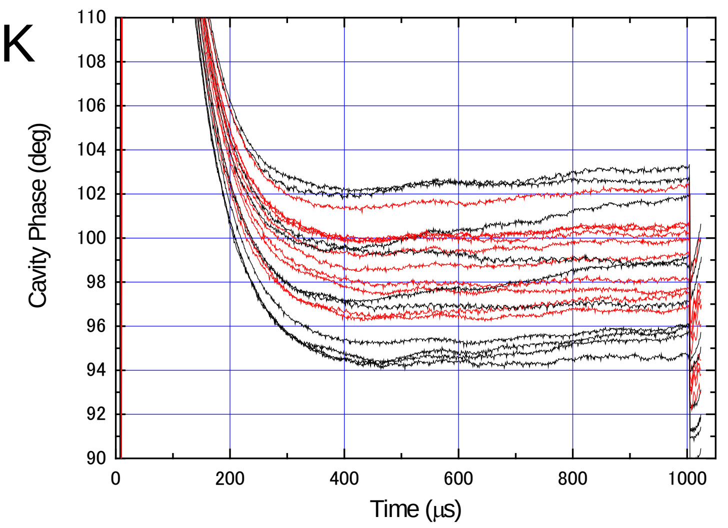
Cavity Phase for several pulses during ~1min

(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 ?)

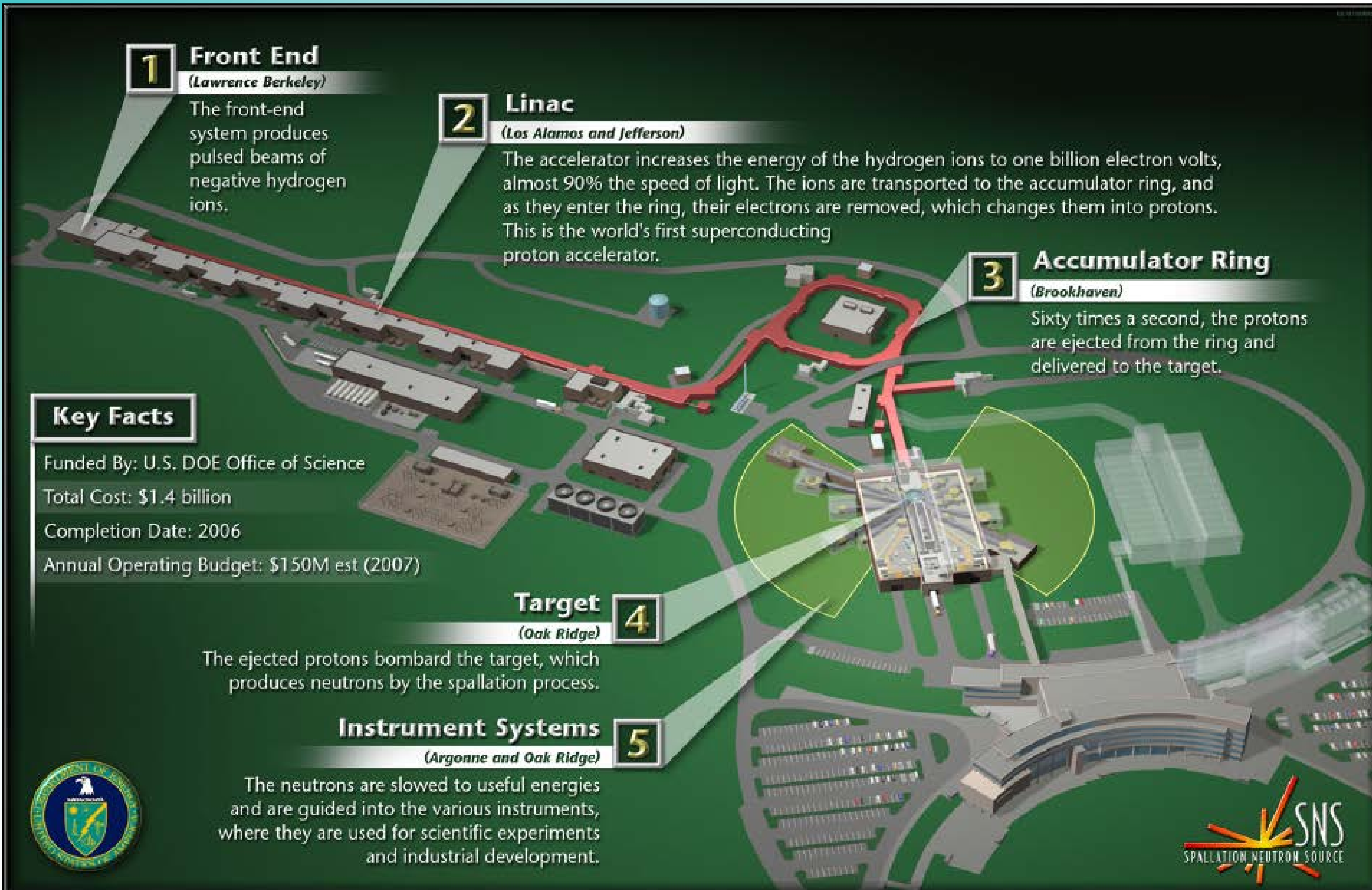
Phase stability of ±1deg is realized in 2K operation, impossible at 4.2 K

SNS : Spallation Neutron Source
Oakridge, Tennessee, USA

(commissioning completed, operationnal phase)

SNS : the US spallation neutron source

SNS layout



1
Front End
(Lawrence Berkeley)
The front-end system produces pulsed beams of negative hydrogen ions.
2
Linac
(Los Alamos and Jefferson)
The accelerator increases the energy of the hydrogen ions to one billion electron volts, almost 90% the speed of light. The ions are transported to the accumulator ring, and as they enter the ring, their electrons are removed, which changes them into protons. This is the world's first superconducting proton accelerator.
3
Accumulator Ring
(Brookhaven)
Sixty times a second, the protons are ejected from the ring and delivered to the target.
Key Facts
Funded By: U.S. DOE Office of Science
Total Cost: $1.4 billion
Completion Date: 2006
Annual Operating Budget: $150M est (2007)
Target
(Oak Ridge)
4
The ejected protons bombard the target, which produces neutrons by the spallation process.
Instrument Systems
(Argonne and Oak Ridge)
5
The neutrons are slowed to useful energies and are guided into the various instruments, where they are used for scientific experiments and industrial development.
SNS
SPALLATION NEUTRON SOURCE

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 μC
Energy per pulse on target	24 kJ
Proton pulse length on target	695 ns
Ion type (Front end, Linac, HEBT)	H minus
Average linac macropulse H- current	26 mA
Linac beam macropulse duty factor	6 %
Front end length	7.5 m
Linac length	331 m
HEBT length	170 m
Ring circumference	248 m
RTBT length	150 m
RTBT length	150 m
Ion type (Ring, RTBT, Target)	proton
Ring filling time	1.0 ms
Ring revolution frequency	1.058 MHz
Number of injected turns	1060
Ring filling fraction	68 %
Ring extraction beam gap	250 ns
Maximum uncontrolled beam loss	1 W/m
Target material	Hg
Number of ambient / cold moderators	1/3
Number of neutron beam shutters	18
Initial number of instruments	5

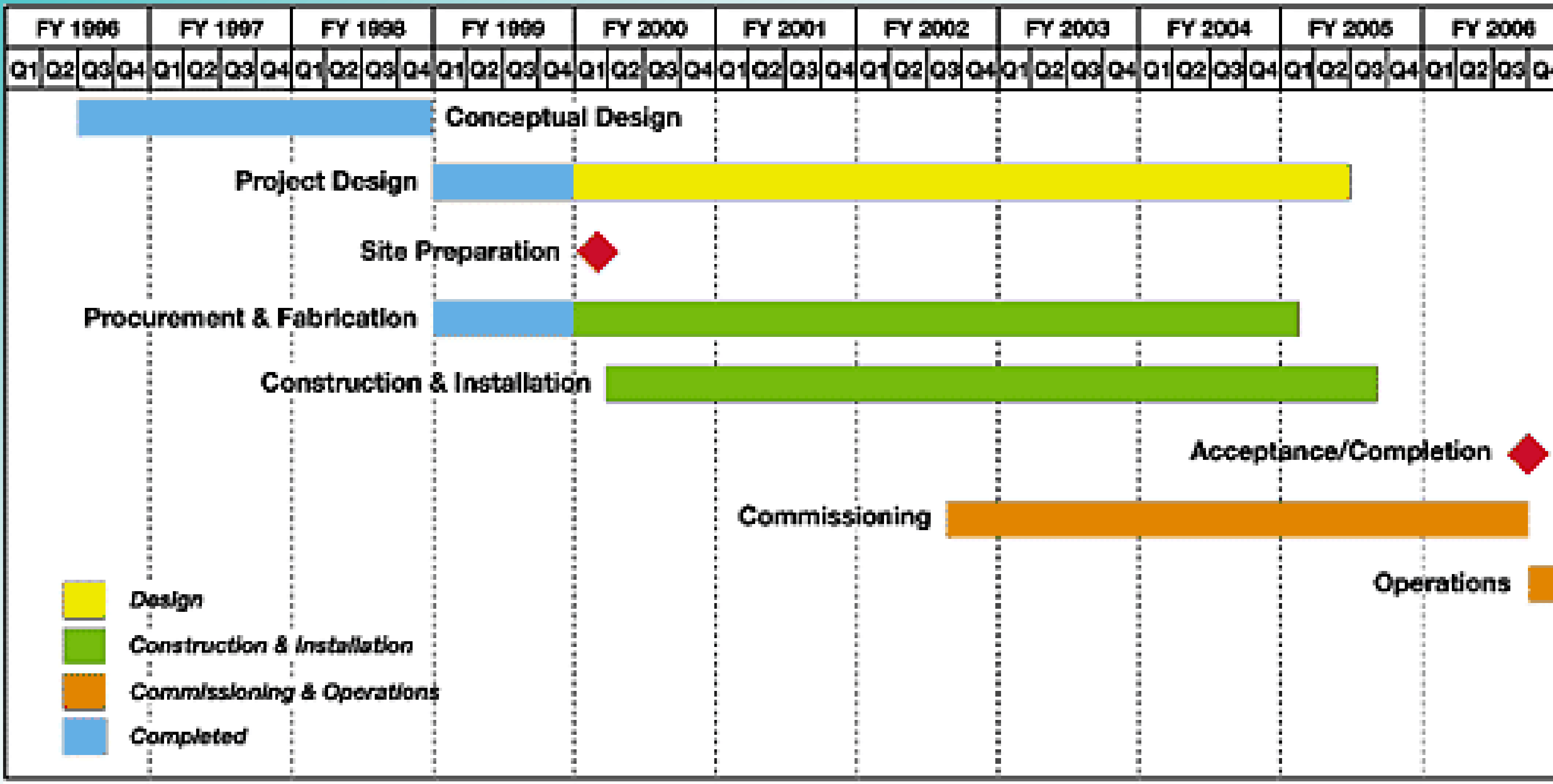
SNS : Main parameters

SNS Beam Evolution Parameters

	Front End			Linac				Ring			
	IS/LEBT	RFQ	MEBT	DTL	CCL	SCL (1)	SCL (2)	HEBT	Ring	RTBT	Unit
Output Energy	0.065	2.5	2.5	86.8	185.6	391.4	1000	1000	1000	1000	MeV
Relativistic factor □	0.0118	0.0728	0.0728	0.4026	0.5503	0.7084	0.875	0.875	0.875	0.875	
Relativistic factor □	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	πmm mr
Output H emittance (unnorm., rms)	17	2.9	3.7	0.75	0.59	0.41	0.23	0.26	24	24	πmm mr
Minimum vertical acceptance [g]			51	42	18	55	39	26	480	400	πmm mr
Output V emittance (unnorm., rms)	17	2.9	3.7	0.75	0.59	0.41	0.23	0.26	24	24	πmm mr
Minimum longitudinal acceptance			4.7E-05	2.4E-05	7.4E-05	7.2E-05	1.8E-04		19/□		πeVs
Output longitudinal rms emittance		7.6E-07	1.0E-06	1.2E-06	1.4E-06	1.7E-06	2.3E-06		2/□		πeVs
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	πmm mr
Output V emittance (norm., rms)	0.2	0.21	0.27	0.33	0.39	0.41	0.41	0.46	44	44	πmm 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

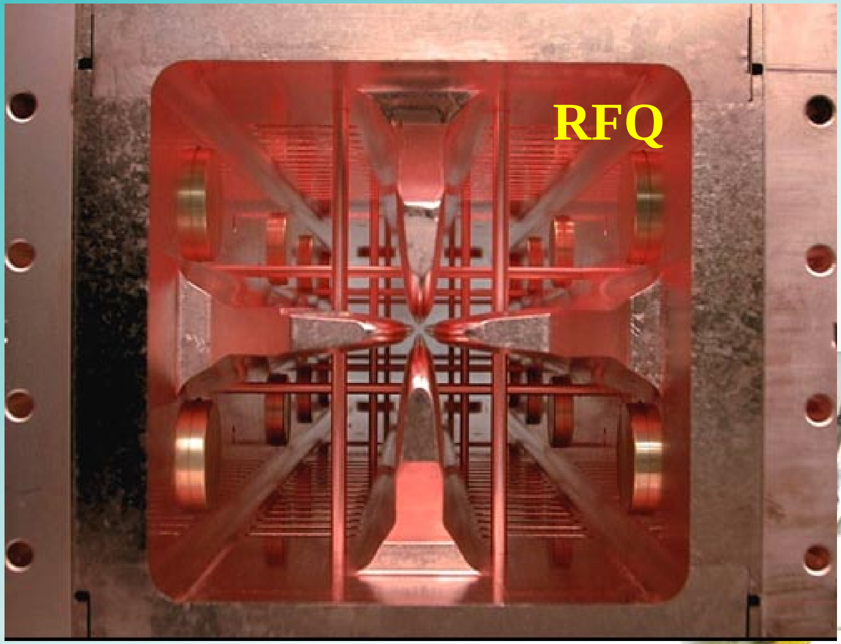


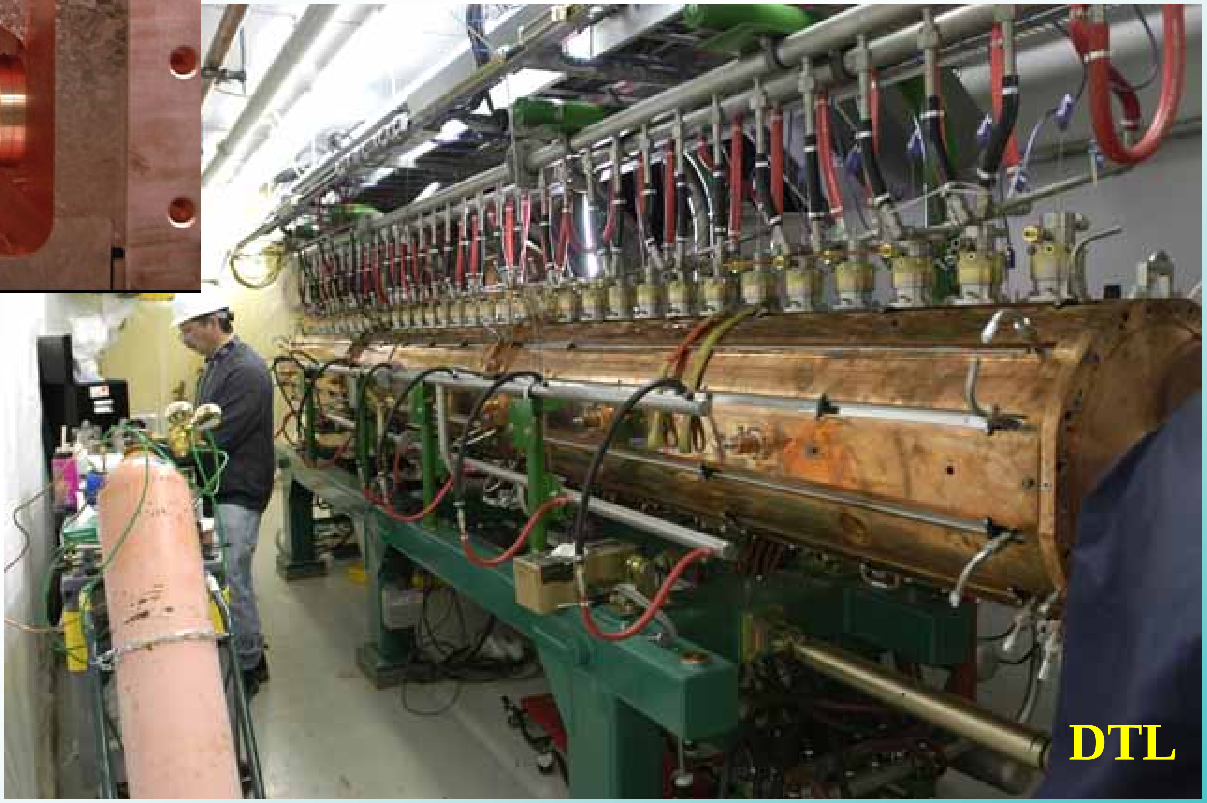
Commissioning of the accelerator at low power (10 kW) achieved in May 2006. Next phase is the power ramping up to 1. 4 MW. Present status is around 1 MW

SNS : aerial views

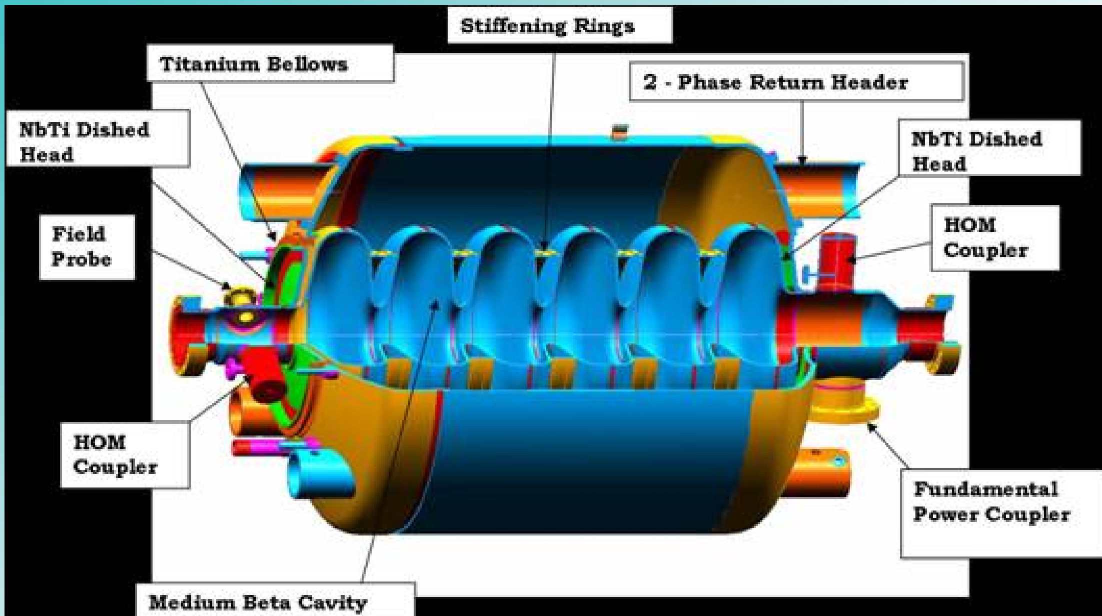
SNS : aerial views

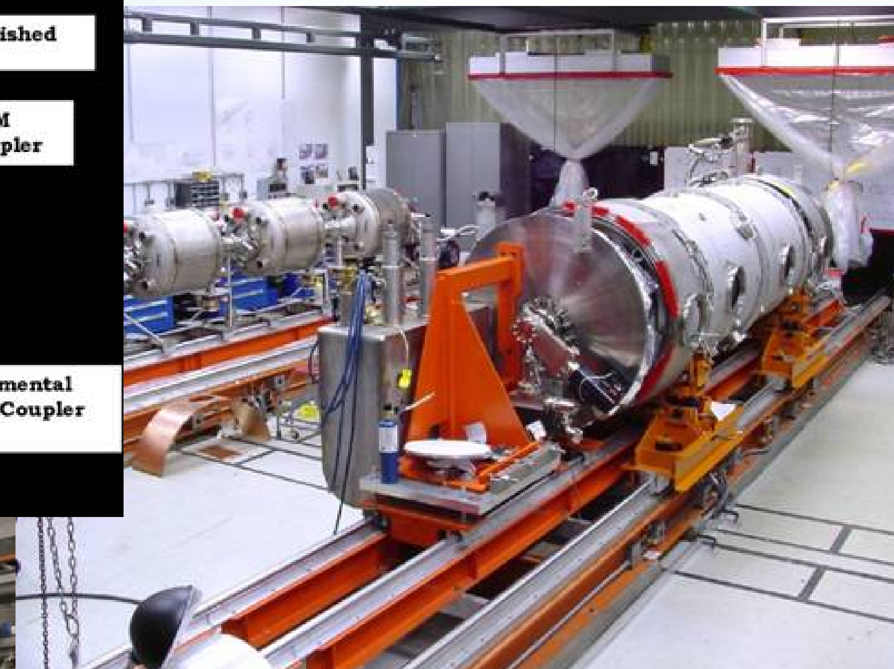
SNS : Linac pictures



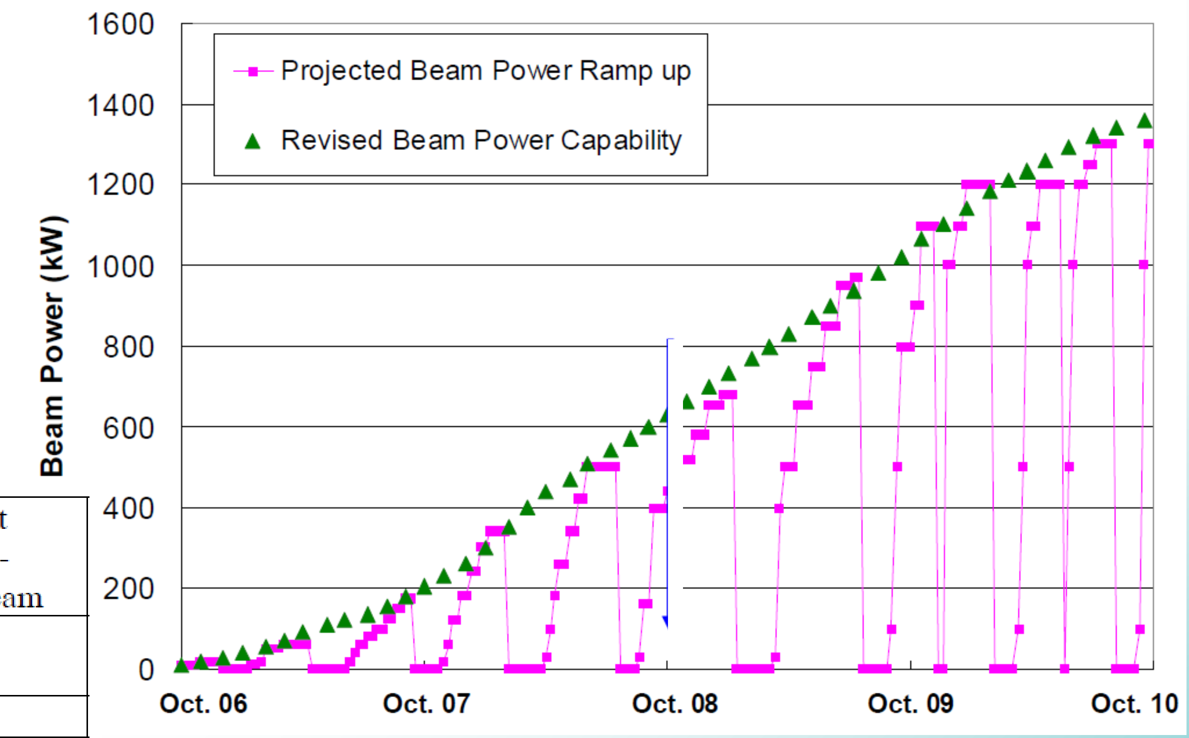


SNS : Linac pictures : SC cryomodules



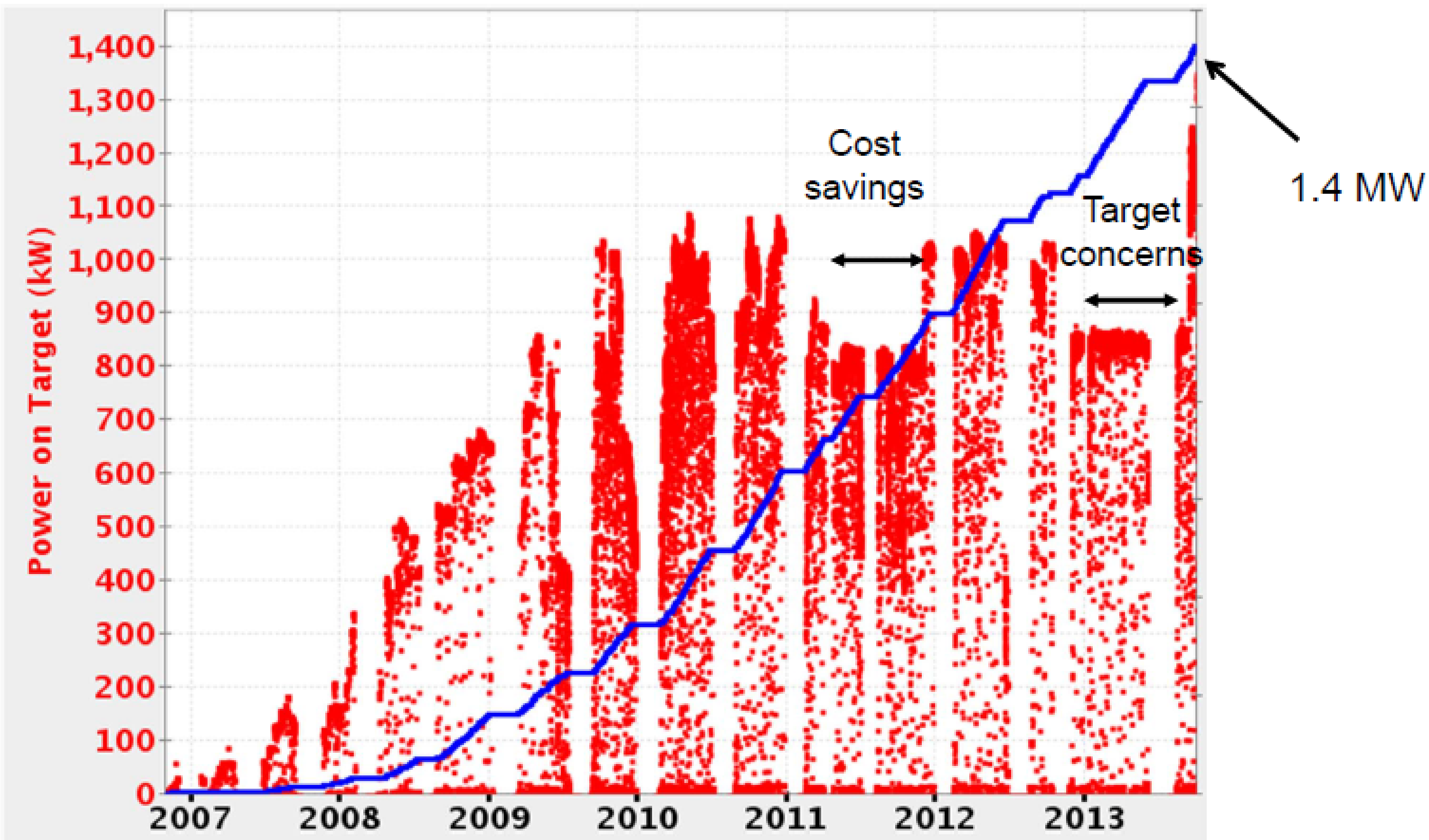


SNS : Design vs achieved parameters (oct. 2009)



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 Power History

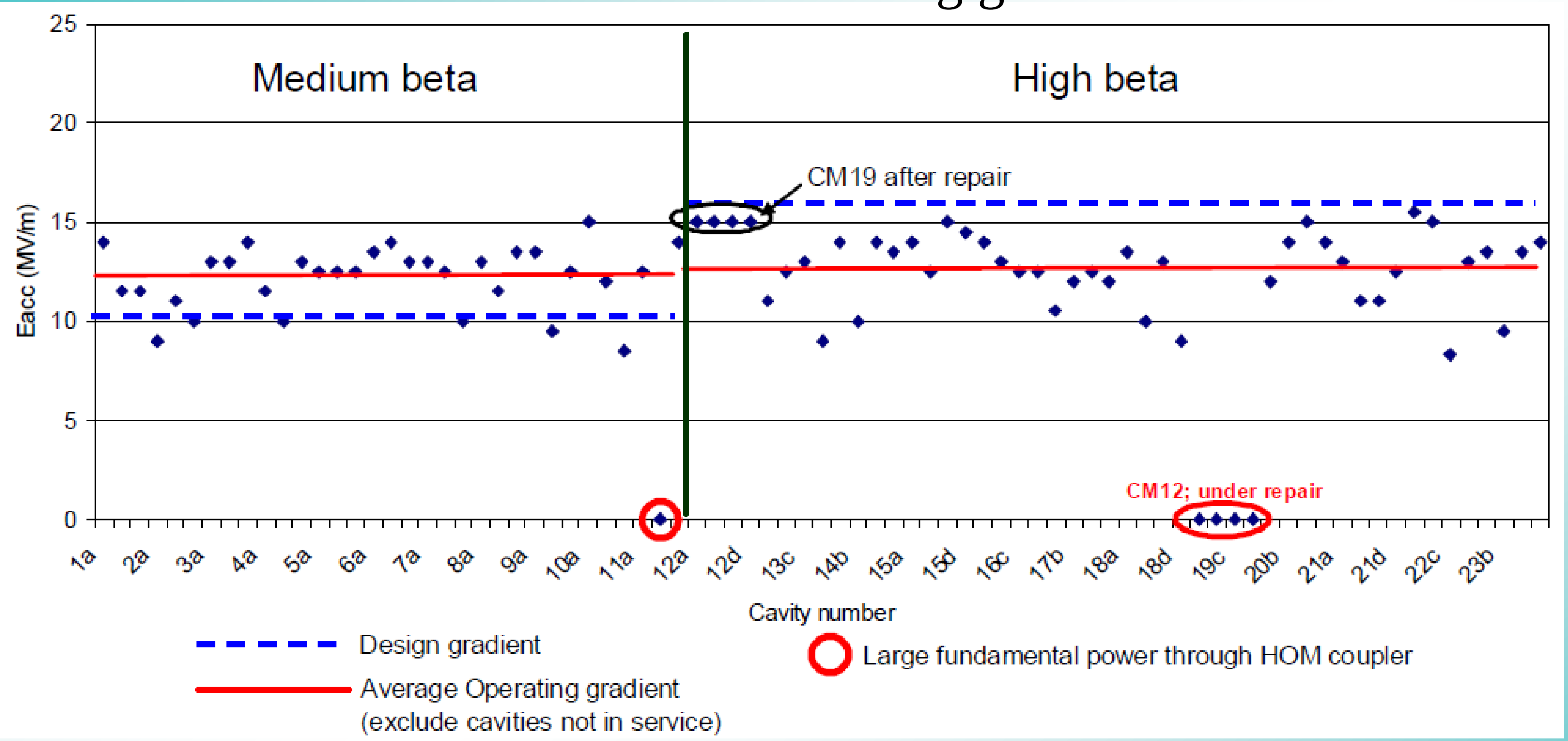


- SNS has run at ~ 1 MW for the past 3-4 years
  - Not accelerator limited
  - Recently operated up to 1.4 MW

J. Galambos

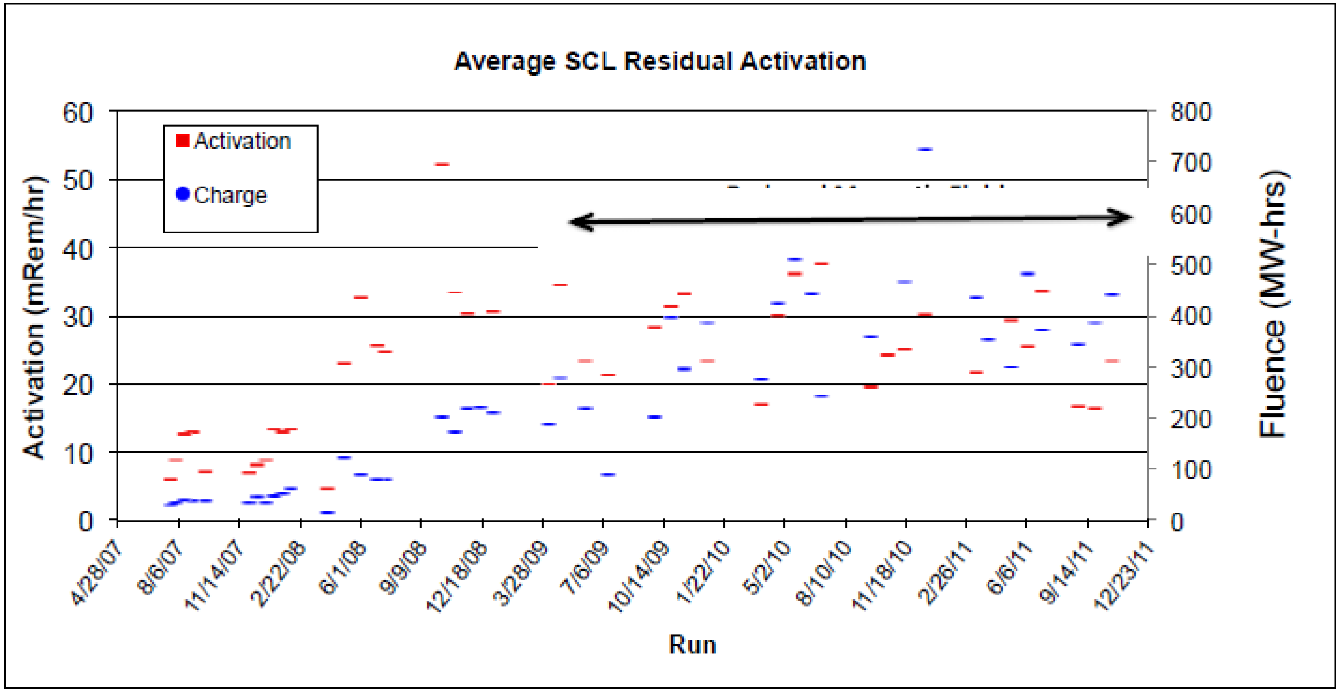
43 Managed by UT-Battelle

SNS Linac : Achieved accelerating gradients in SC cavities



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.

Beam Loss in the Superconducting Linac

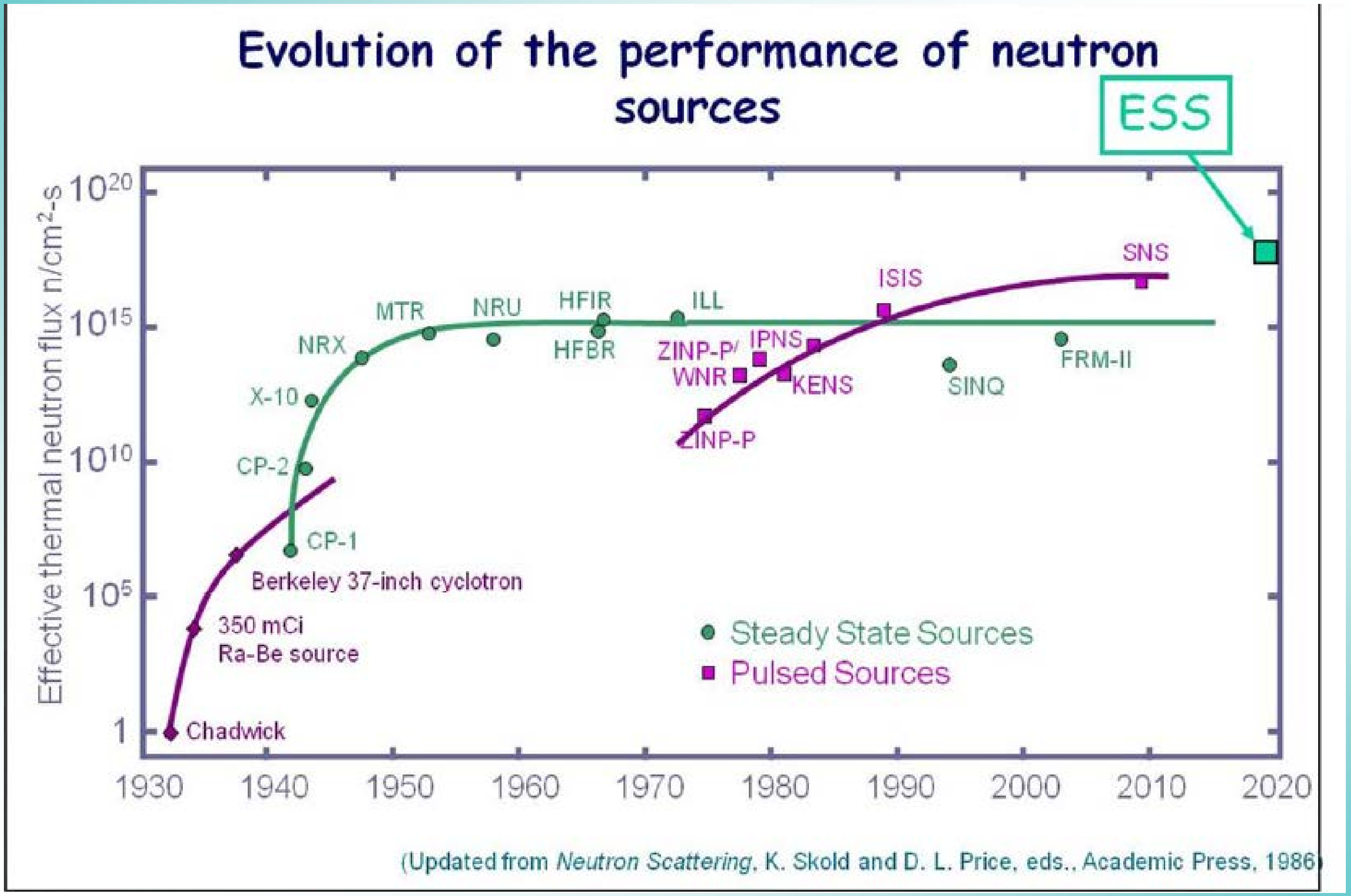


- High power proton beam operational loss limit: 1 W/m
  - 1 part per million at full energy!
- SNS observed a low level of beam loss / machine activation
  - Unexpected – not predicted in design stage!
  - OK for 1 MW – trouble for 10 MW

J. Galambos

ESS : European Spallation Source (Lund, Sweden)

(Under construction)



Evolution of the performance of neutron sources
ESS
Effective thermal neutron flux n/cm²-s
10^20
10^15
10^10
10^5
1
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020
SNS
ISIS
ILL
HFIR
NRU
MTR
NRX
HFBR
ZINP-P/
IPNS
WNR
KENS
X-10
ZINP-P
SINQ
FRM-II
CP-2
CP-1
Berkeley 37-inch cyclotron
350 mCi
Ra-Be source
Chadwick
Steady State Sources
Pulsed Sources
(Updated from Neutron Scattering, K. Skold and D. L. Price, eds., Academic Press, 1986)

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

ESS : the European Spallation Source

17 nations committed to build ESS

Cash contributions from Sweden, Denmark and Norway
50% of construction and 15-20% of operations costs

In-kind contributions from the other 14 nations

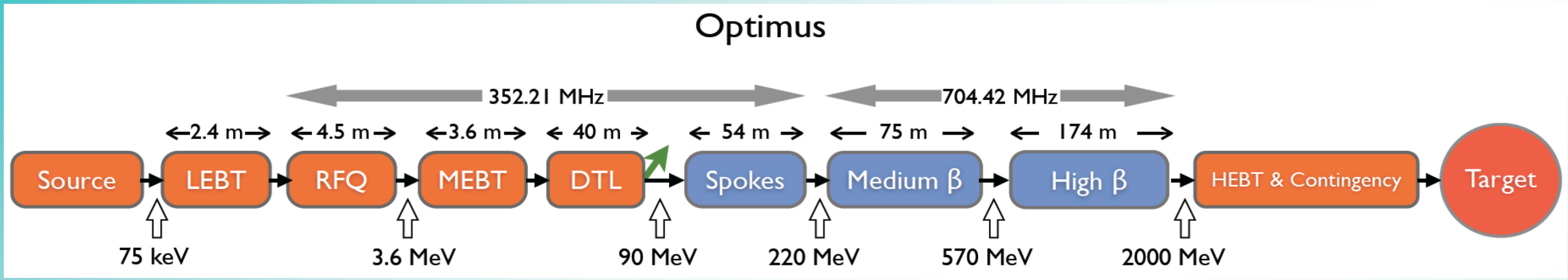
Construction cost: 1843 M€
Operation cost: 140 M€
Decommissioning cost: 177 M€

ESS AB in 2014, 250 people, 32 nationalities

ESS Linac: Hig hPower Proton Accelerator: 5 MW of beam power

- Protons (H+), 2,0 GeV
- Pulse 2.86 ms, 62 mA
- Rep. rate.: 14 Hz
  -> duty cycle 4 % (125 MW peak)
- Low loss
- High reliability > 95%
- Modular design to allow future upgrade

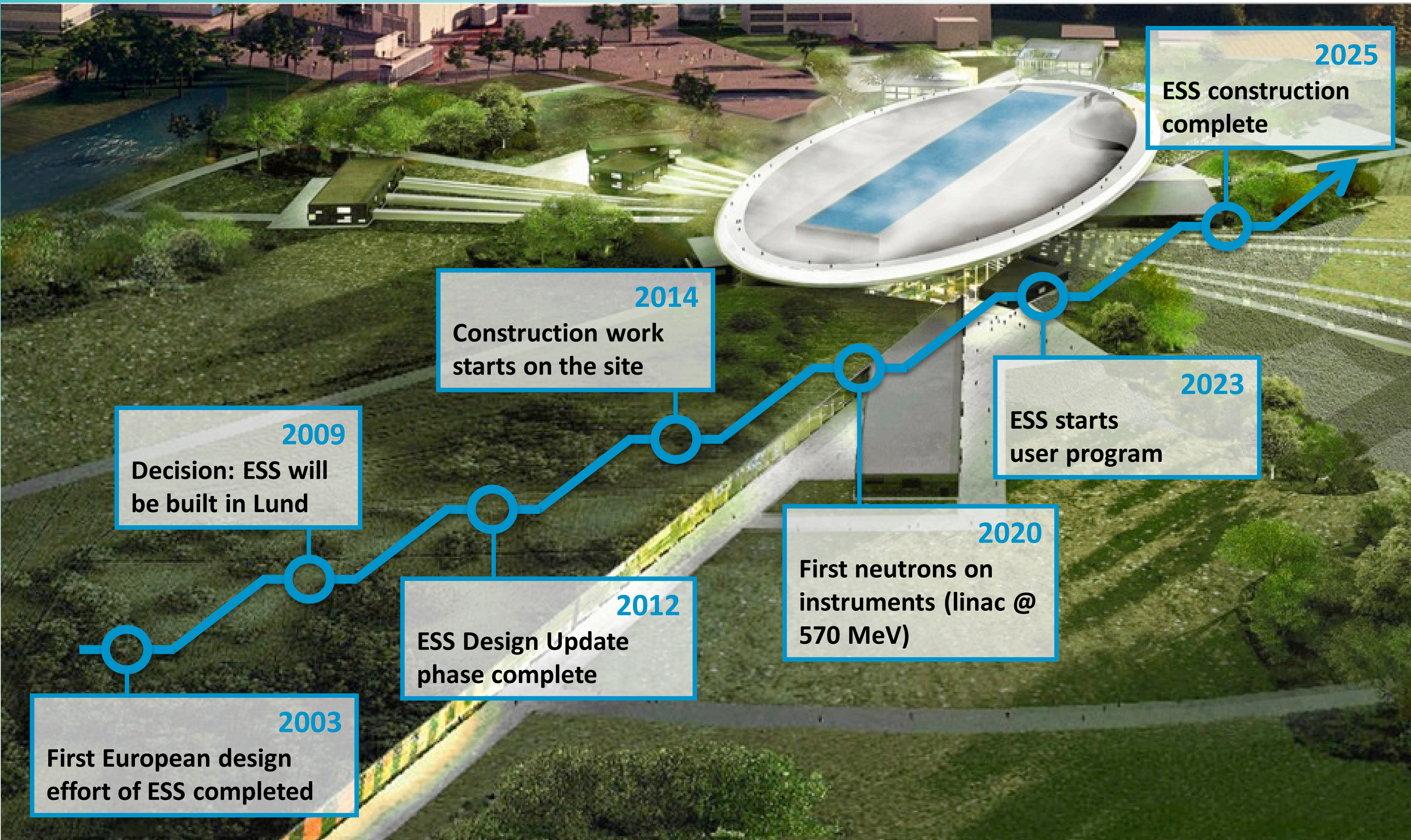
ESS : the European Spallation Source



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.

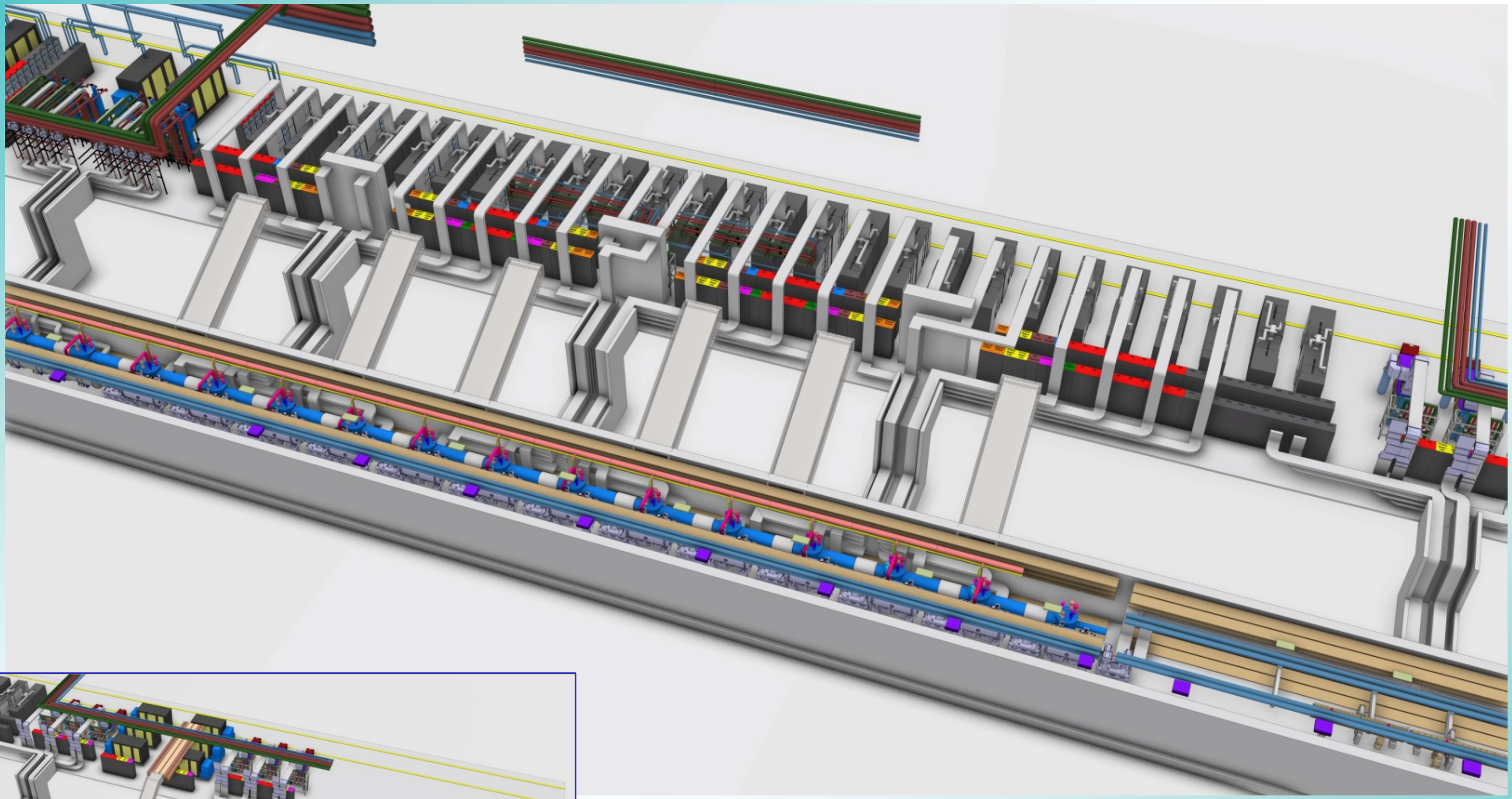
ESS : the European Spallation Source

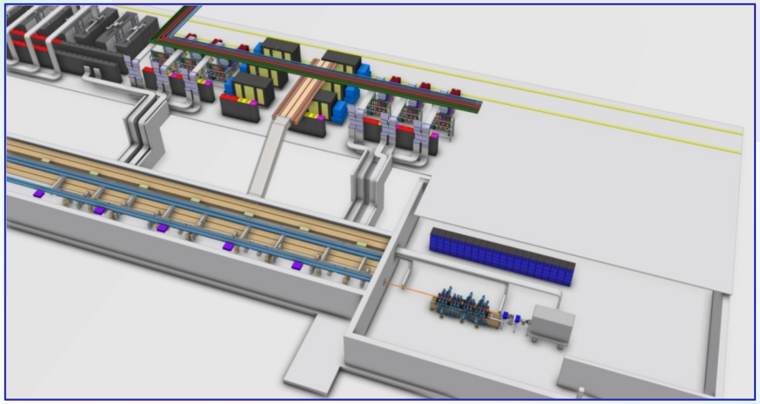


ESS : the European Spallation Source

Status (February 2017): linac tunnel completed, target building under preparation (pillars, monolith…)

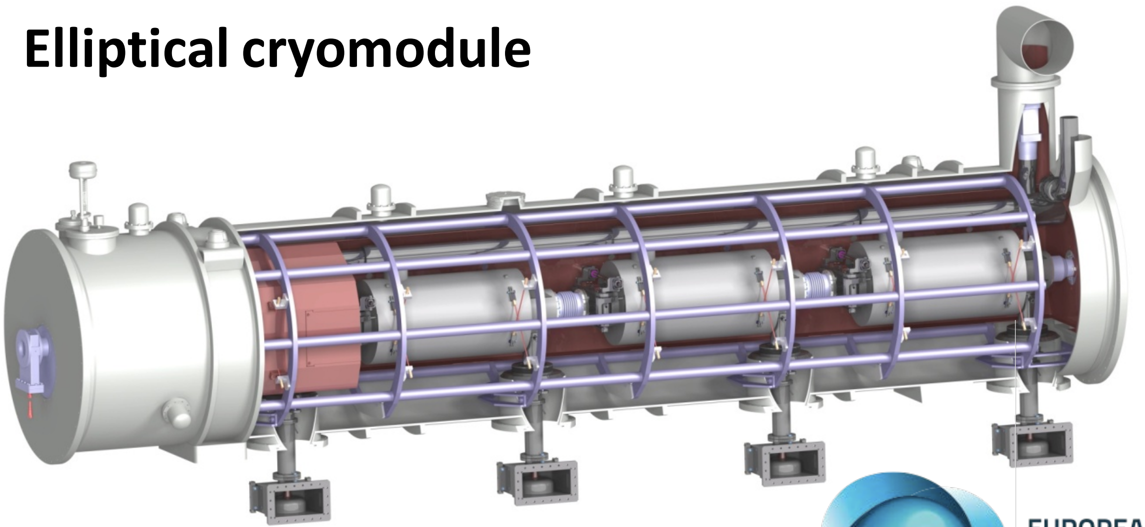
ESS : the European Spallation Source





ESS : the European Spallation Source

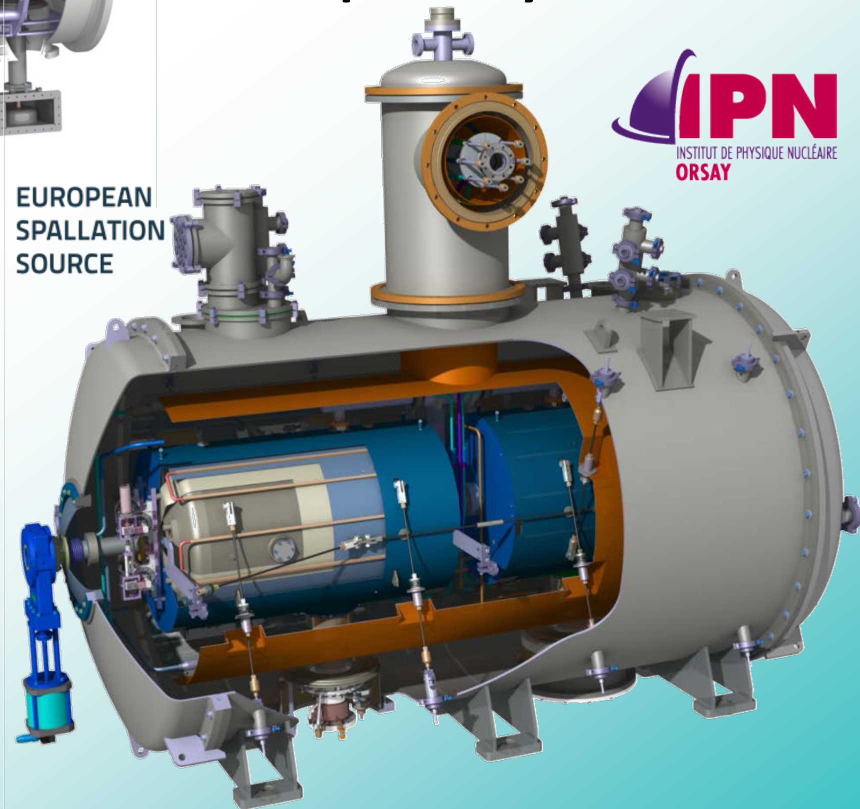
Elliptical cryomodule



EUROPEAN SPALLATION SOURCE

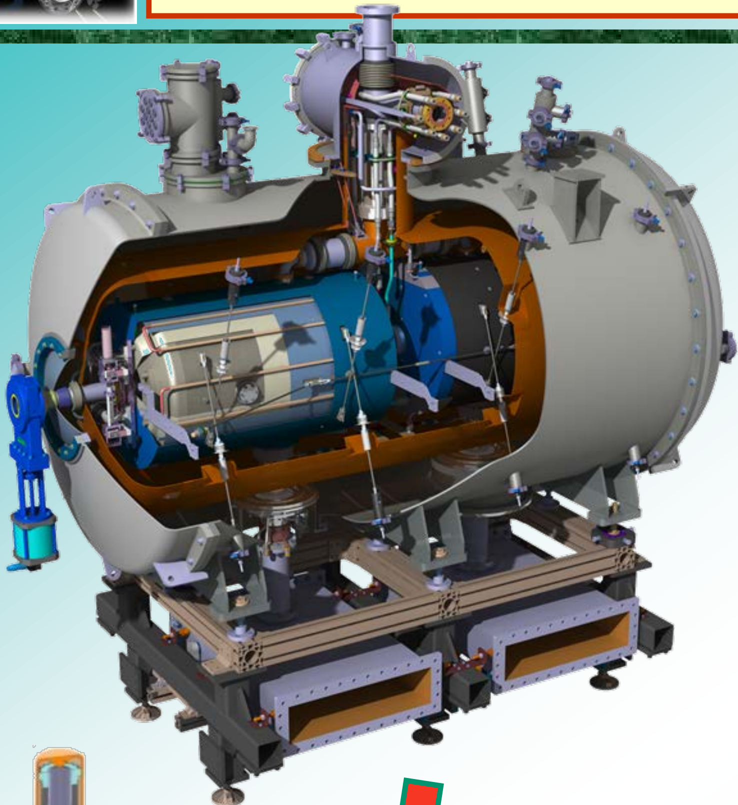
INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

Spoke cryomodule

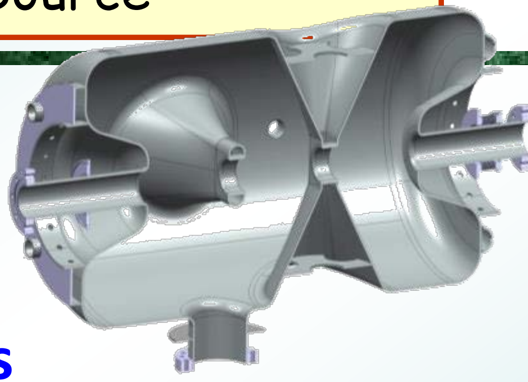


INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

All the linac sub-systems are currently in the prototyping phase

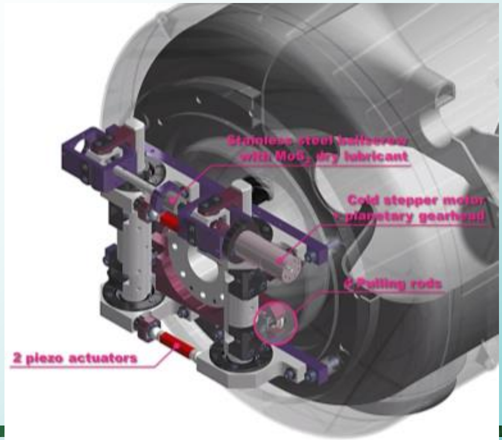


Double Spoke SRF Cavities



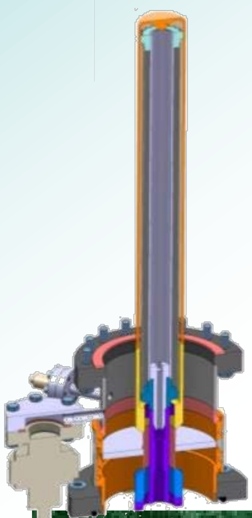
- Double spoke cavity (3-gaps), 352.2 MHz, β=0.50
- **Goal: Eacc = 9 MV/m** *[Bp= 62 mT ; Ep = 39 MV/m]*
- 4.2 mm (nominal) Niobium thickness
- Titanium Helium tank and stiffeners
- Lorentz detuning coeff. : ~-5.5 Hz/(MV/m)^2
- Tuning sentivity $\Delta f/\Delta z$ = 130 kHz/mm

Cold Tuning System



- Slow tuning (stepper motor):
  Max stroke: ~ 1.3 mm
  Tuning range: ~ 170 kHz
  Tuning resolution: 1.1 Hz
- Fast tuning (piezo-actuator):
  Applied voltage up to +/- 120V
  Tuning range at 2K: 675 Hz (min)

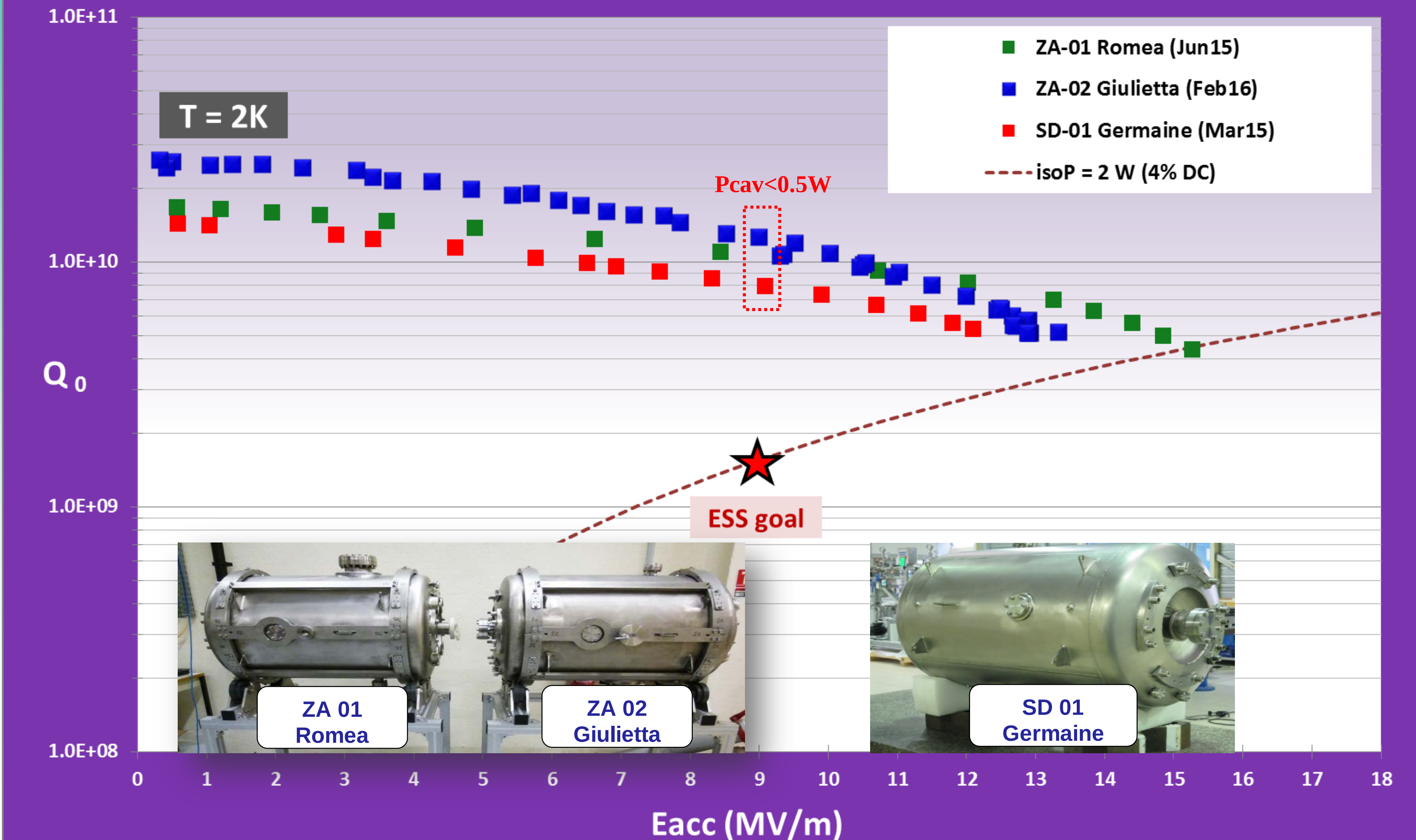
Power Coupler



- Ceramic disk, 100 mm diameter
- 400 kW peak power (335 kW nominal)
- Antenna & window water cooling
- Outer conductor cooled with SHe
- Doorknob transition from coaxial to ½ height WR2300 waveguide

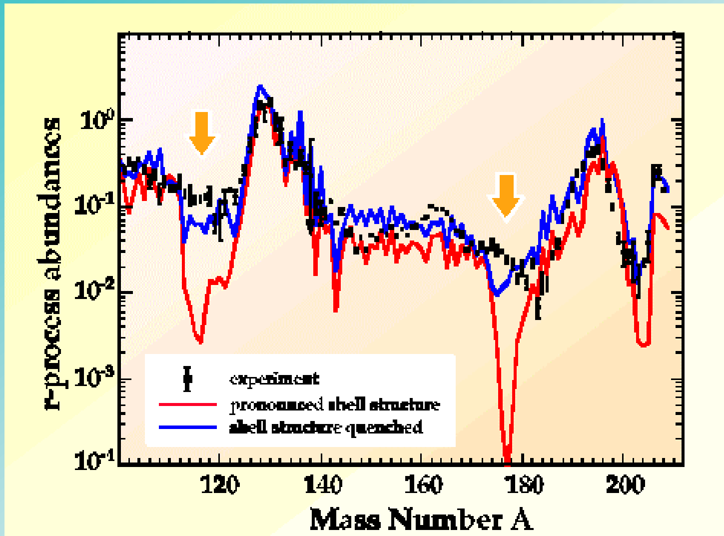
ESS : the European Spallation Source

ESS Double-Spoke prototype cavities
ZA-01 Romea, ZA-02 Giulietta & SD-01 Germaine

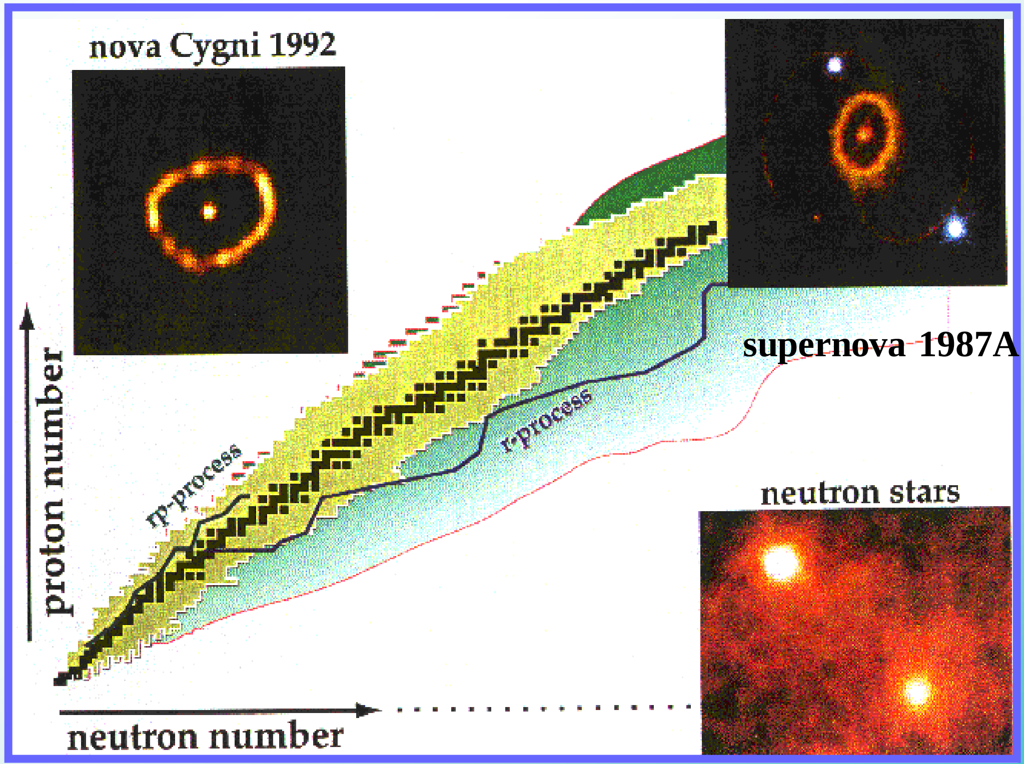


High Power Proton Accelerator for Radiactive Ion Beam Production

Nuclear studies with Radiactive Ion Beams



- 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!

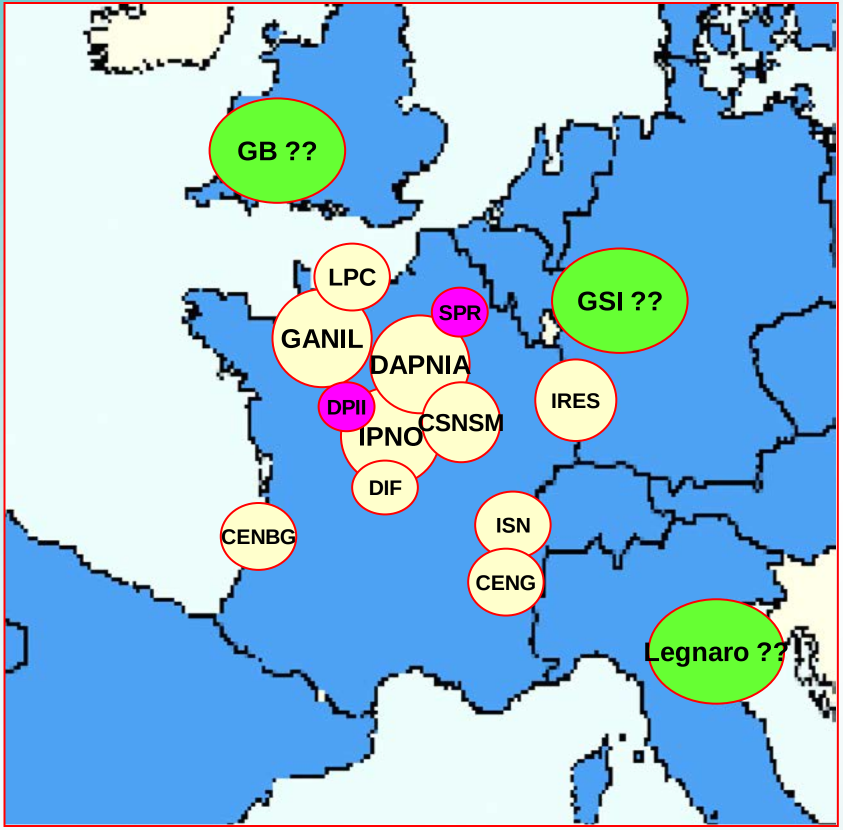
$$I = \sigma \times \Phi \times N \times \varepsilon 1 \times \varepsilon 2 \times \varepsilon 3 \times \varepsilon 4 \times \varepsilon 5$$

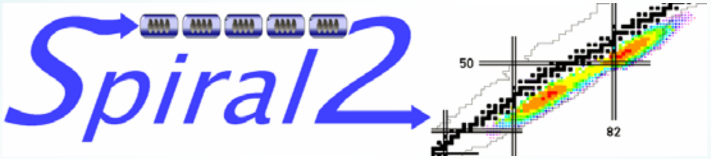
σ : cross-section, Φ : primary-beam intensity,
N: target thickness,
$\varepsilon 1$: product release and transfer efficiency
$\varepsilon 2$: ion-source efficiency,
$\varepsilon 3$: efficiency due to radioactive decay losses
$\varepsilon 4$: the efficiency of the spectrometer
$\varepsilon 5$: the post-acceleration efficiency

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

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

(under construction)



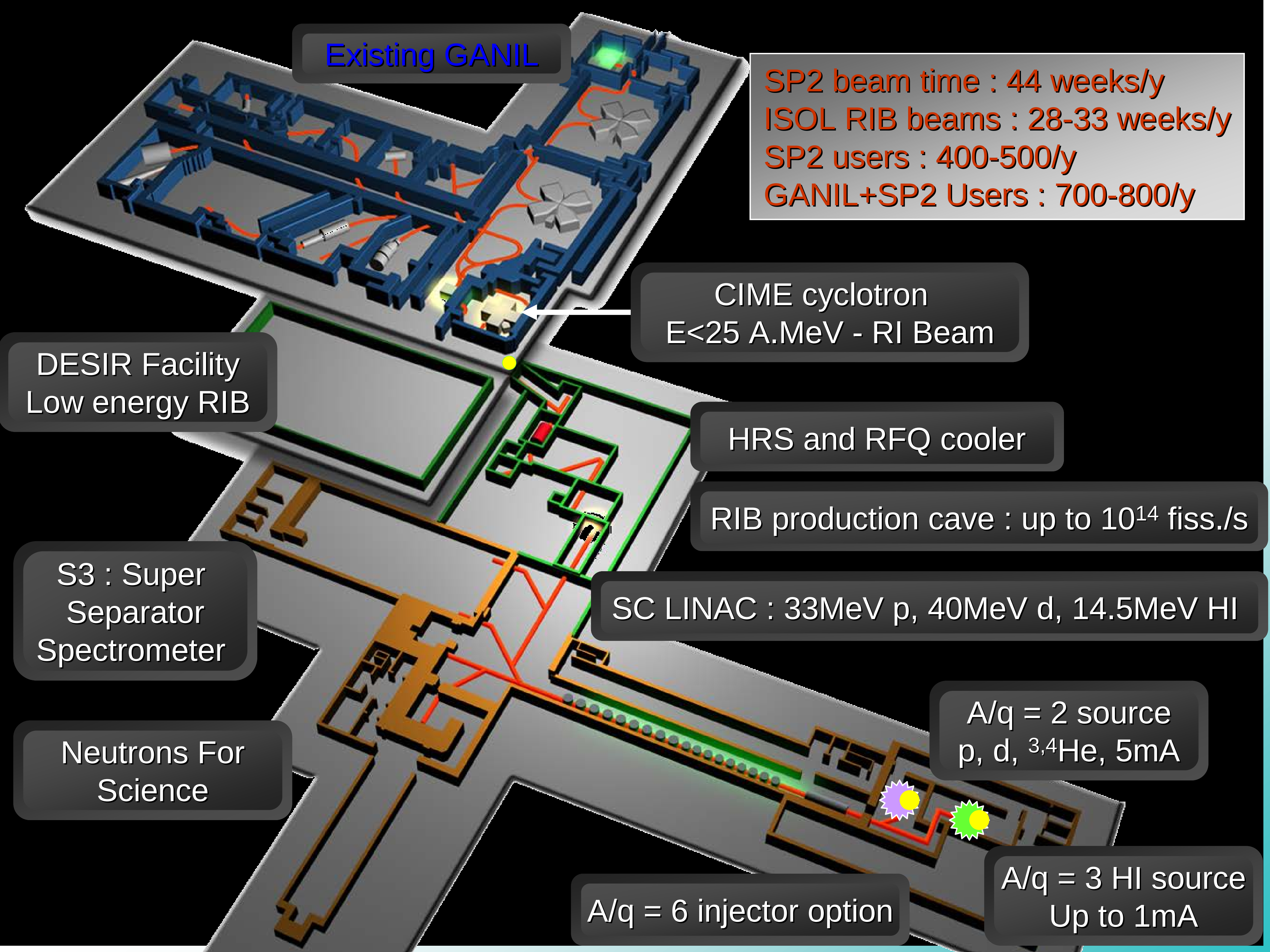


SPIRAL II Project:
13 French Laboratories
International Collaborations
135 M€ total cost (inc. manpower)

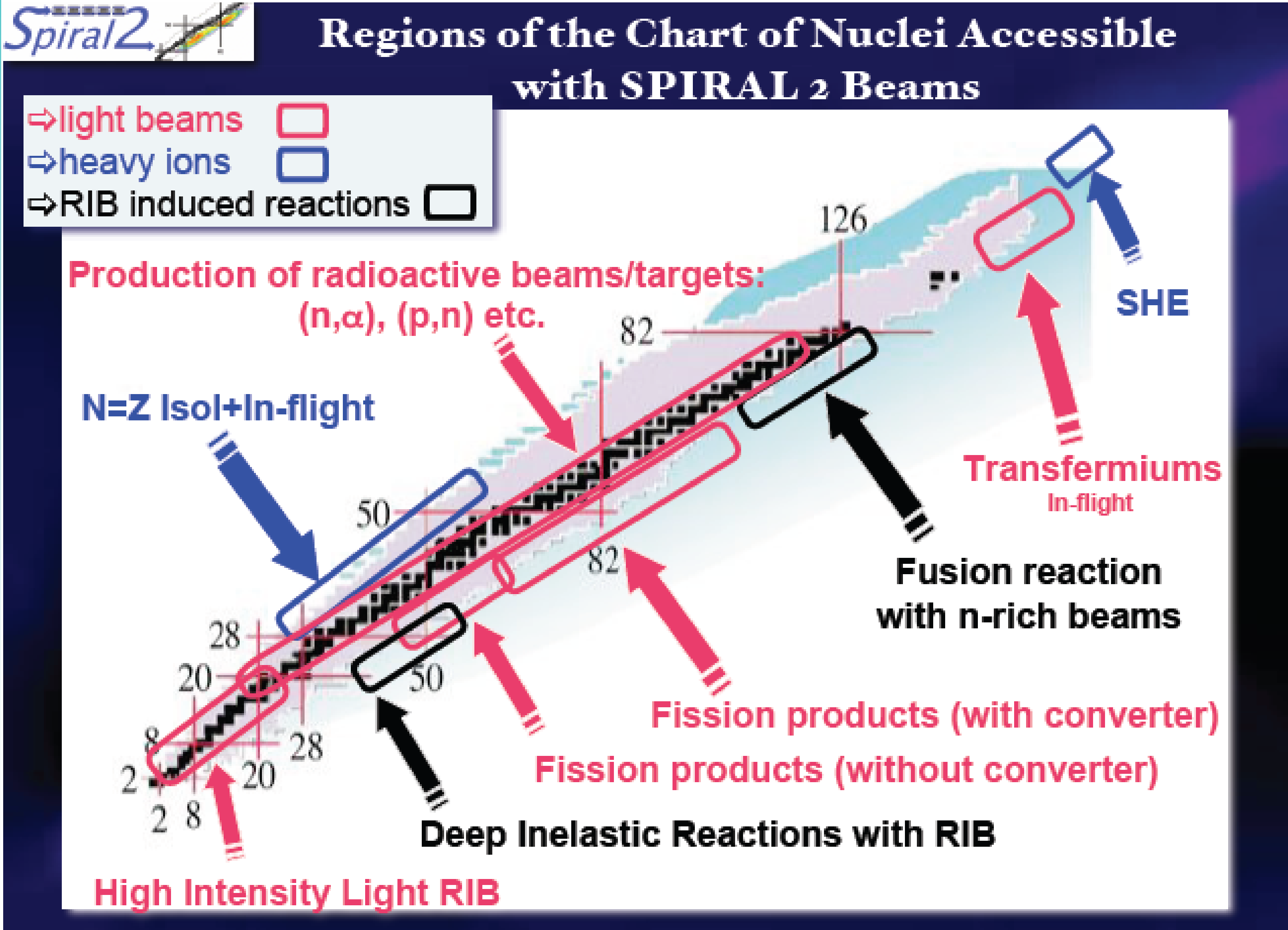
Project approved in May 2005
Construction phase close to completion

First beam (injector) in 2014

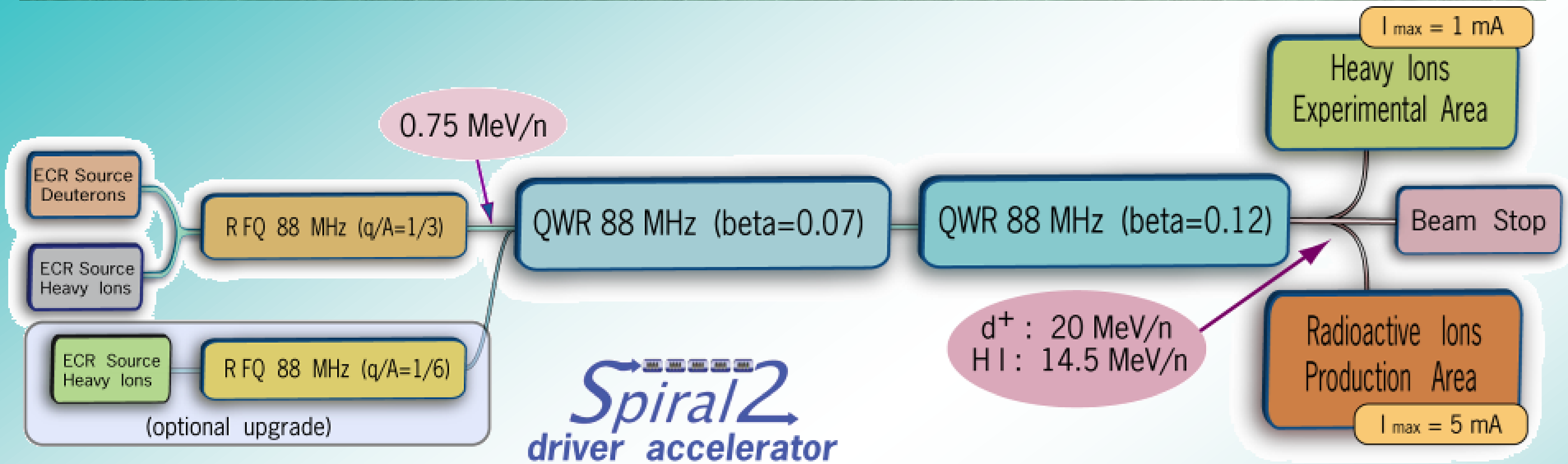
First beam at the end of the linac expected for end 2016


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
A/q = 2 source
p, d, 3,4He, 5mA
Neutrons For Science
A/q = 3 HI source
Up to 1mA
A/q = 6 injector option

Spiral – 2 : accessible elements



Spiral – 2 : the accelerator baseline configuration



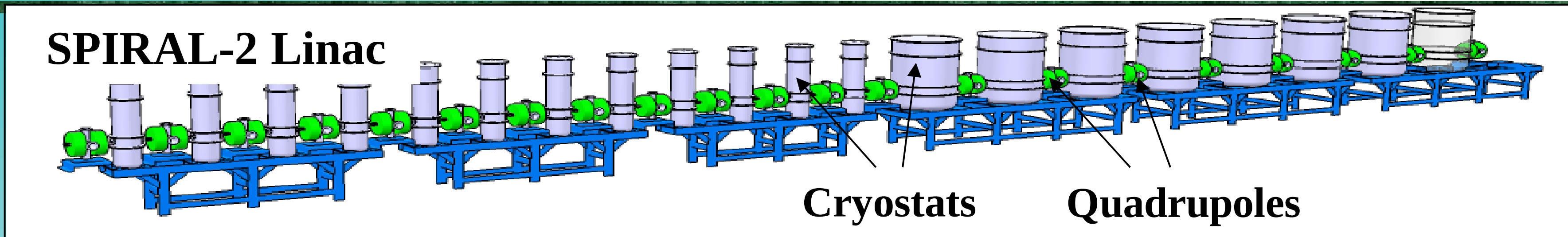
Particles	p^+	D^+	Ions	
Q/A	1	1/2	1/3	1/6
I (mA) max.	5	5	1	1
W_O min. (Mev/A)	2	2	2	2
W_O max. (Mev/A)	33	20	14.5	8.5
CW max. beam power (KW)	165	200	44	48

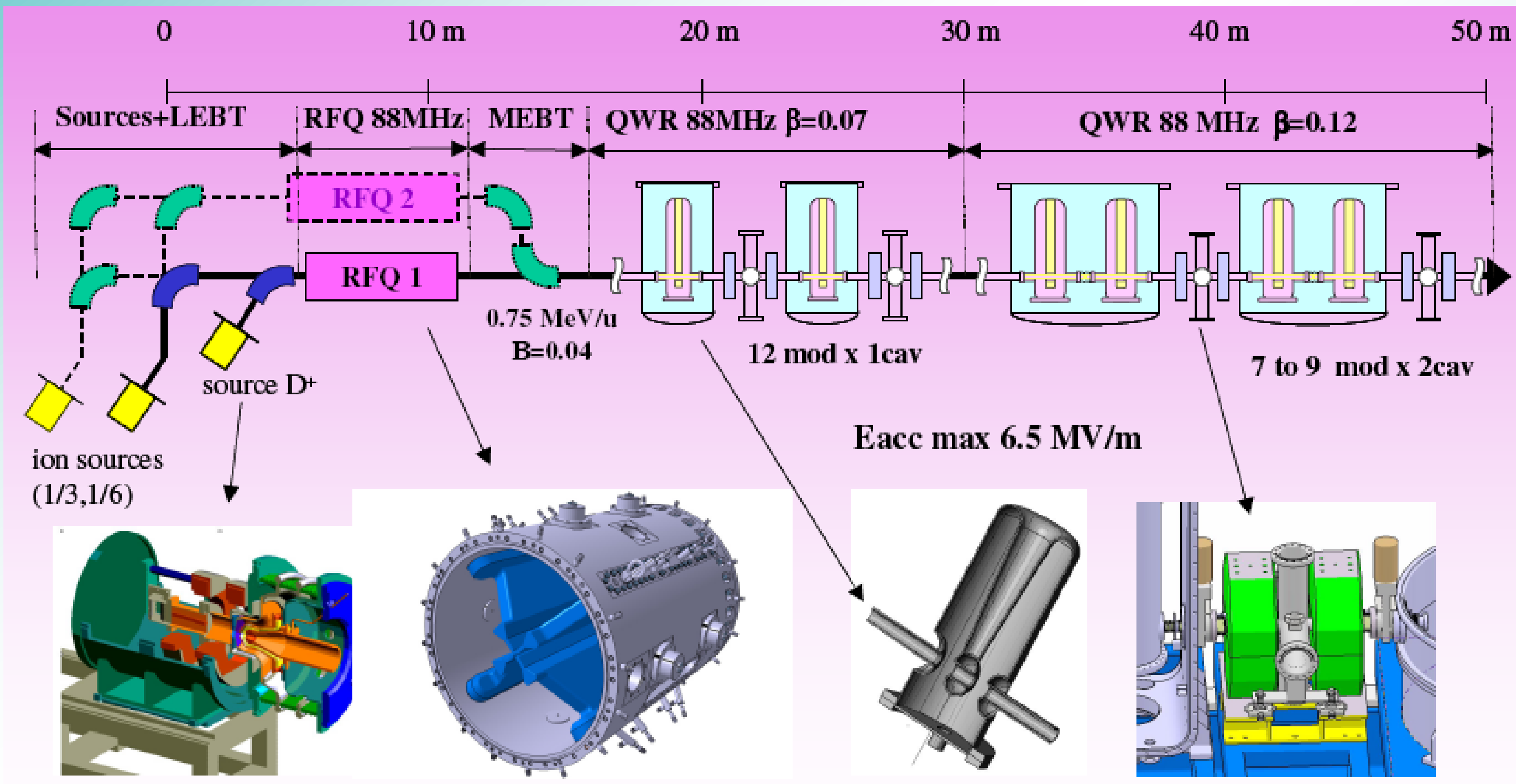
Total length: 65 m (without HE lines)

D^+ : ECR ion source
Heavy Ions : ECR Ion Source
Slow and Fast Chopper
RFQ (1/1, 1/2, 1/3) & 3 re-bunchers

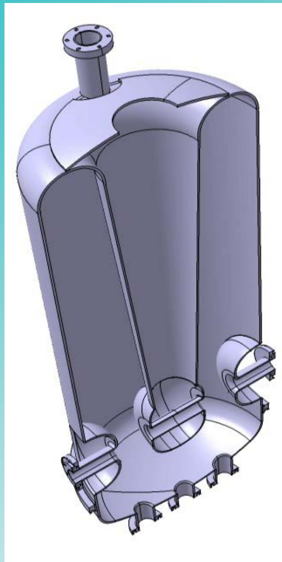
12 QWR beta 0.07 (12 cryomodules)
14 (+2) QWR beta 0.12 (7+1 cryomodules)
1 kW Helium Liquifier (4.2 K)
Room Temperature Q-poles
Solid State RF amplifiers (10 & 20 KW)
6.5 MV/m max $E_{acc} = V_{acc}/(\beta_{opt}\lambda)$ with $V_{acc}=\int E_z(z)e^{i\omega z/c}dz$.

Spiral – 2 Linac : schematic view



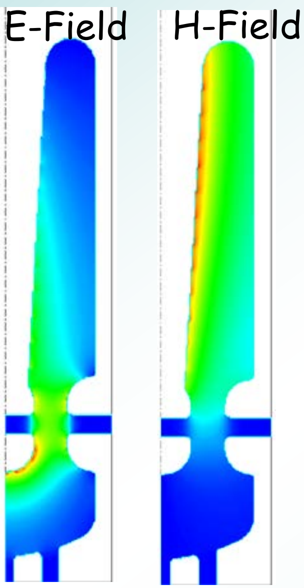


Spiral – 2 Linac : High beta SC cavities

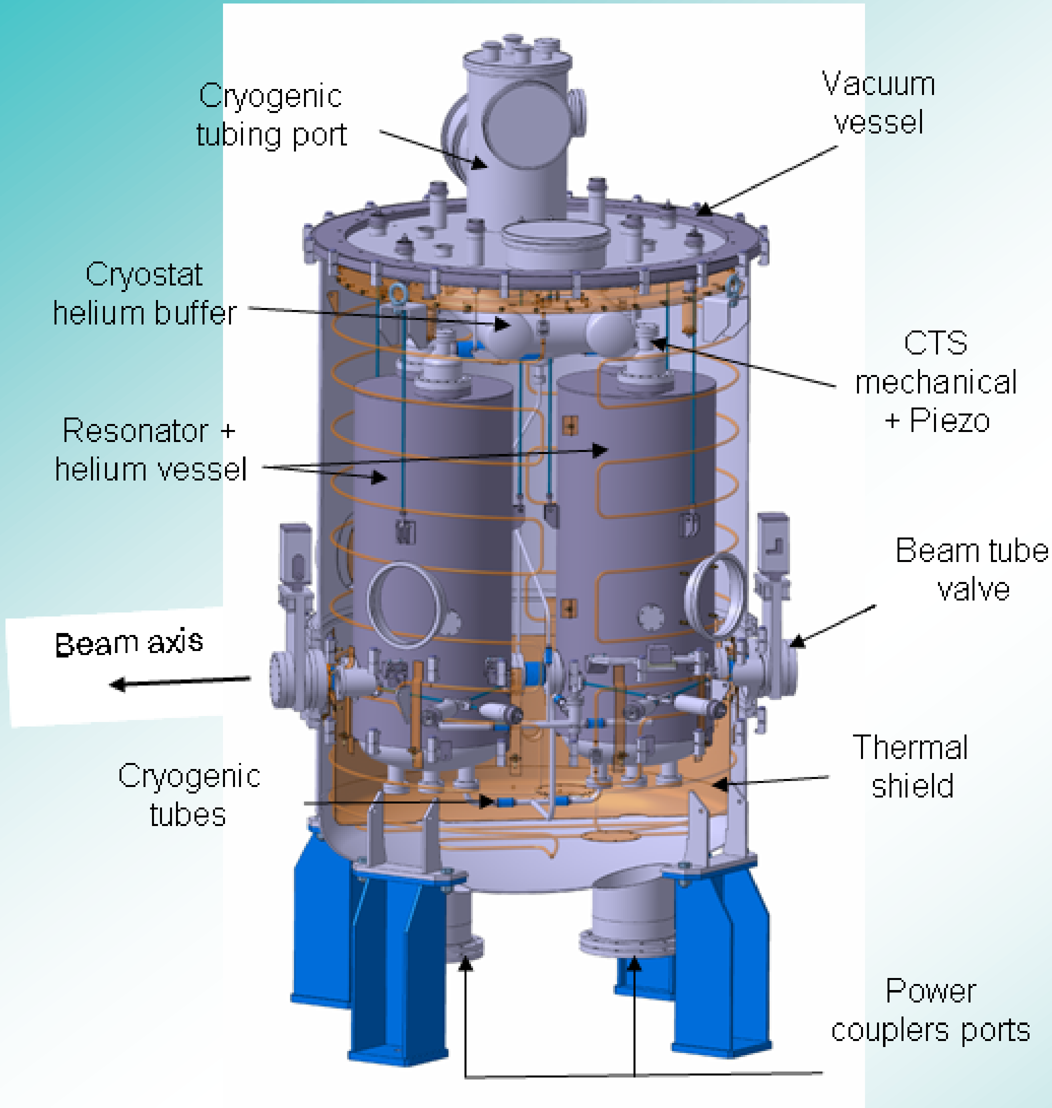


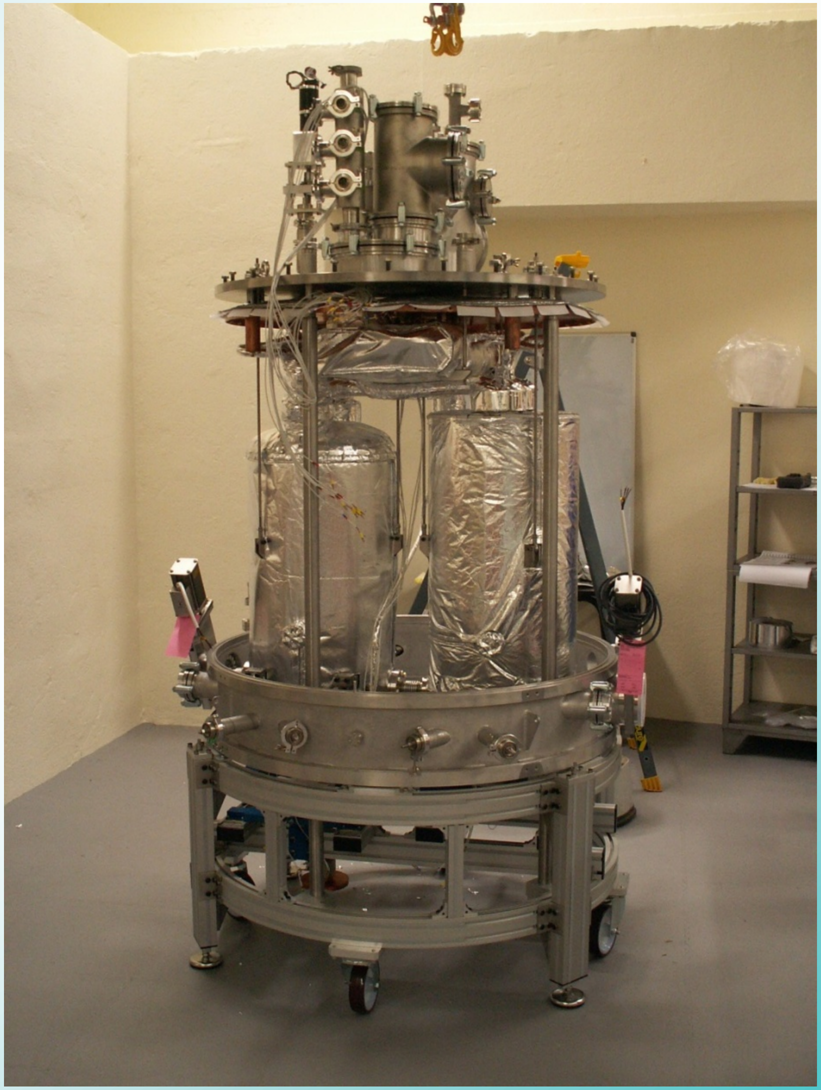
Frequency [MHz]	88.05
$beta_{optimal}$	0.12
E_{pk}/E_{acc}	5.56
B_{pk}/E_{acc} [mT/MV/m]	10.18
r/Q [Ω]	518
V_{acc} at 6.5 MV/m & b_{opt} [MV]	2.65
G [Ω]	38
Beam ϕ [mm]	38
Cavity ext. ϕ [mm]	380
Q_{ext}	$1.2\ 10^6$

QWR 88 MHz SC Cavities

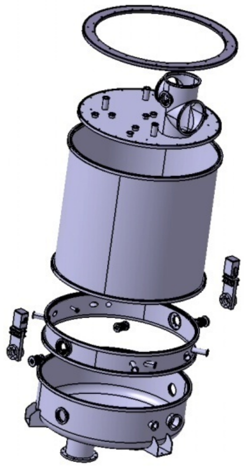


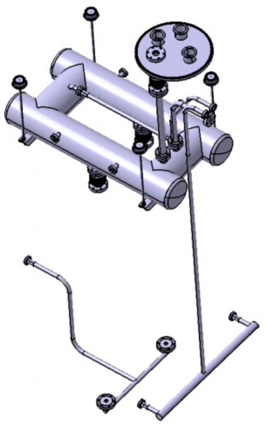
Spiral – 2 Linac : High beta SC cryomodule

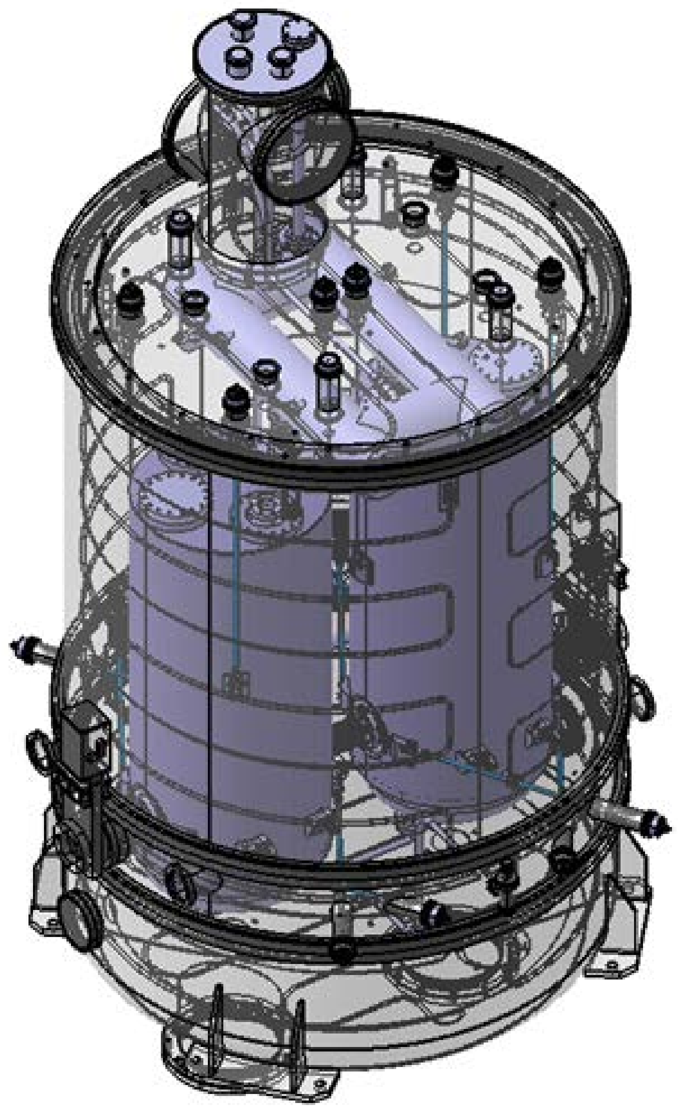


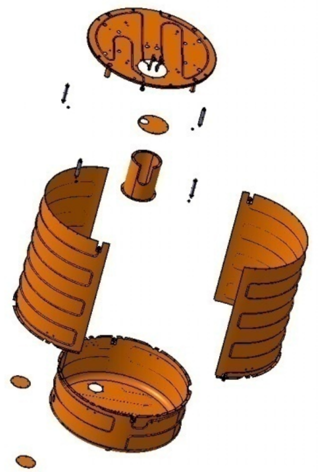


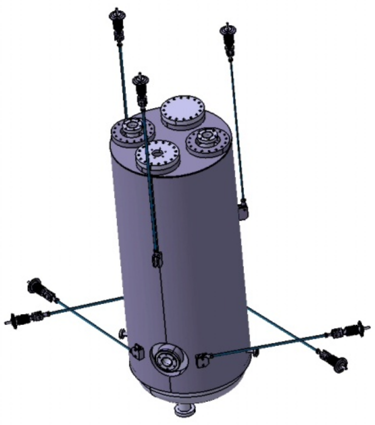
SPIRAL-2 : high energy section cryomodule

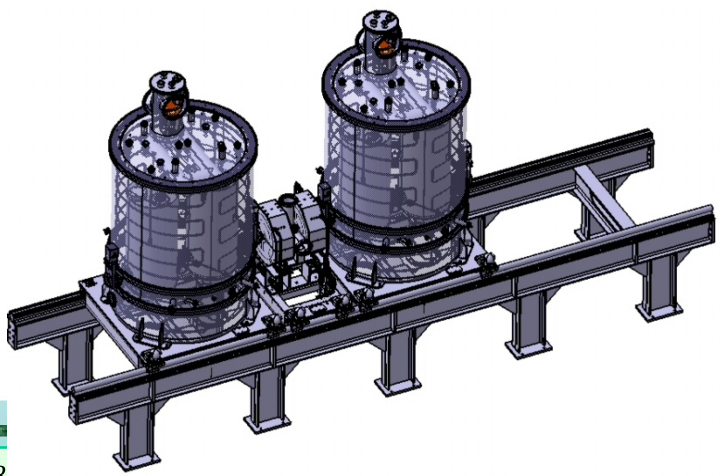




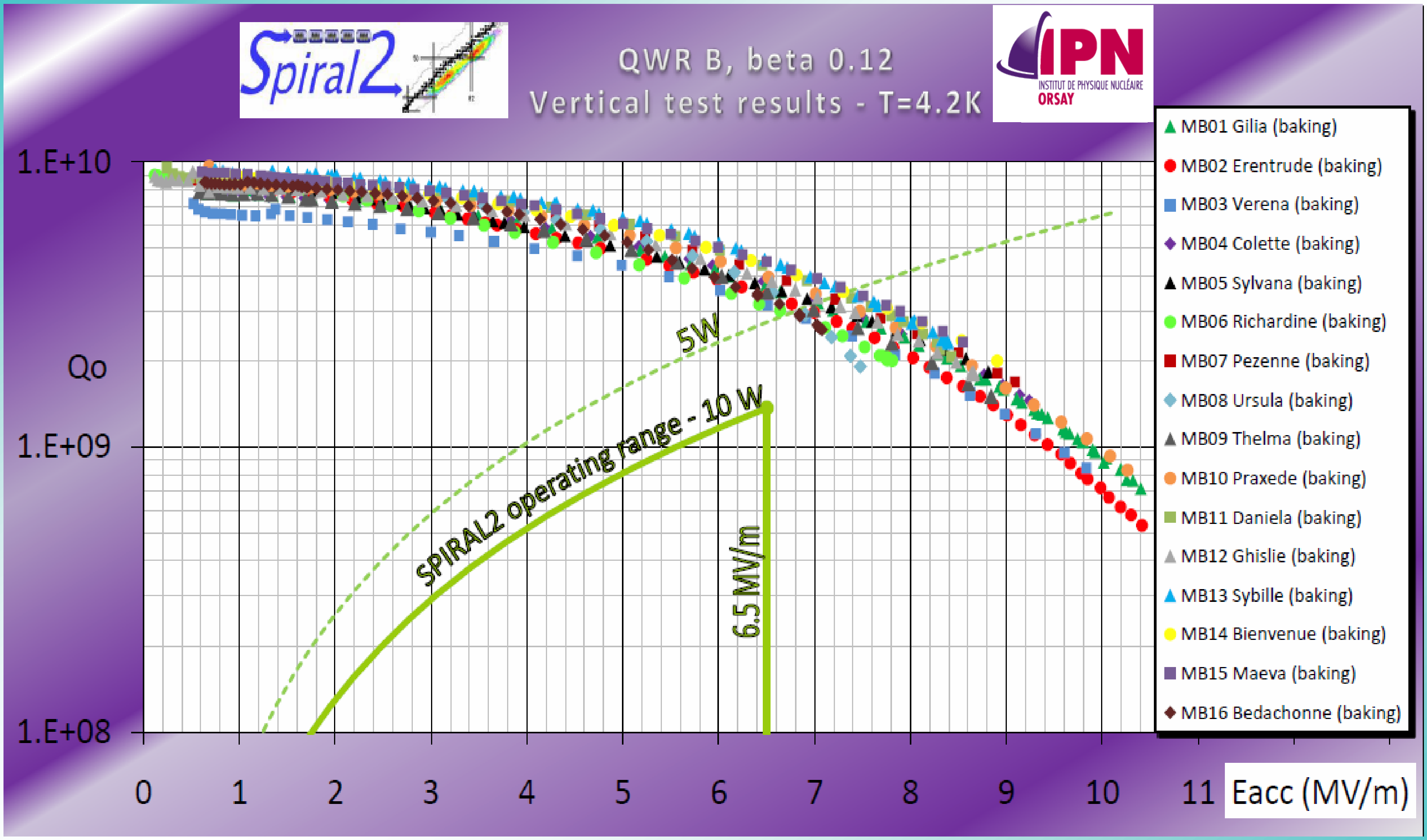


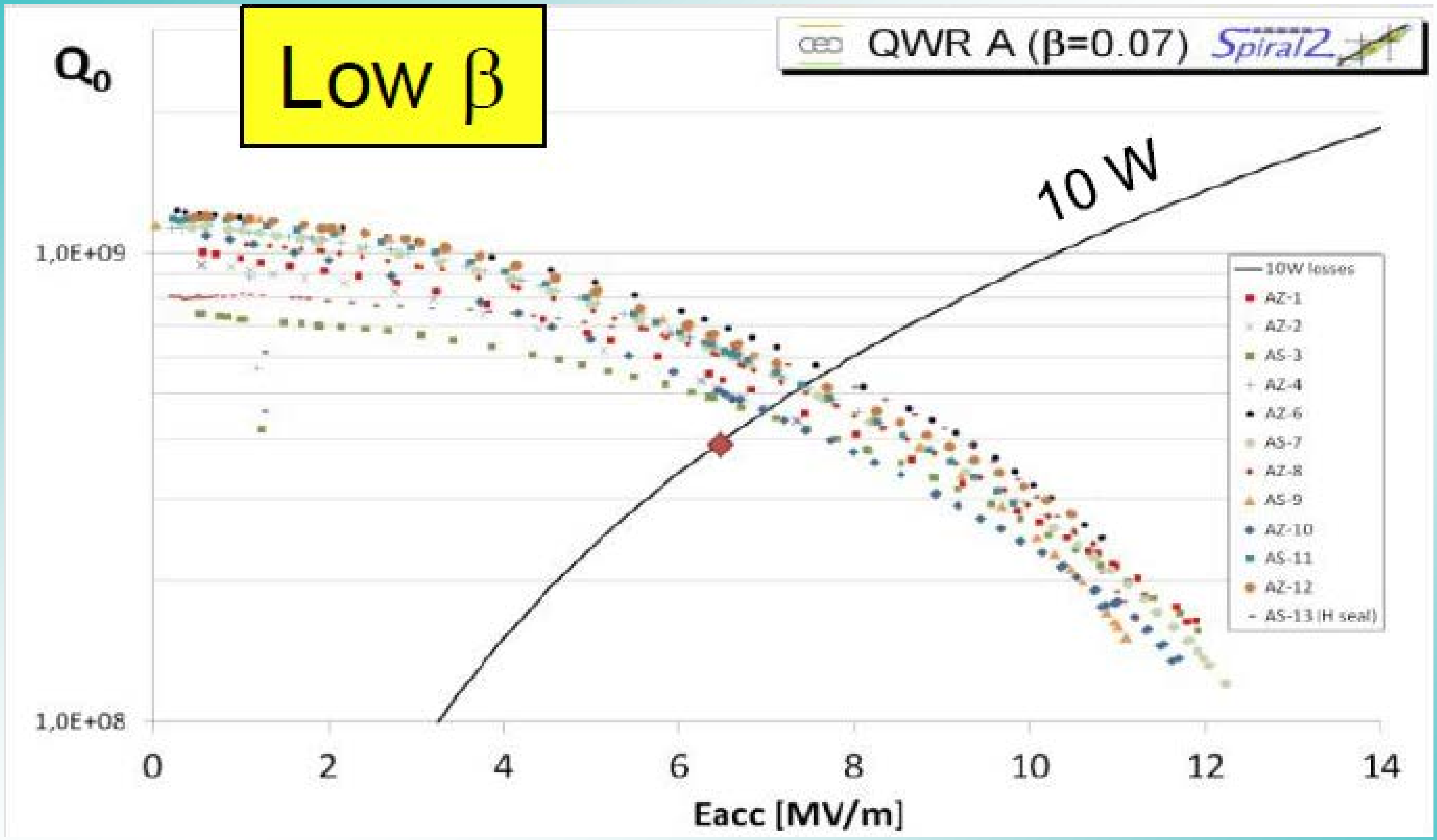






SPIRAL-2 : High Beta Cavity RF Performances




Q0
Low β
QWR A (β=0.07) Spiral2
10 W
1,0E+09
1,0E+08
0
2
4
6
8
10
12
14
Eacc [MV/m]
10W losses
AZ-1
AZ-2
AS-3
AZ-4
AZ-6
AS-7
AZ-8
AS-9
AZ-10
AS-11
AZ-12
AS-13 (H seal)

SPIRAL-2 : Linac tunnel pictures

SPIRAL-2 : Linac tunnel pictures

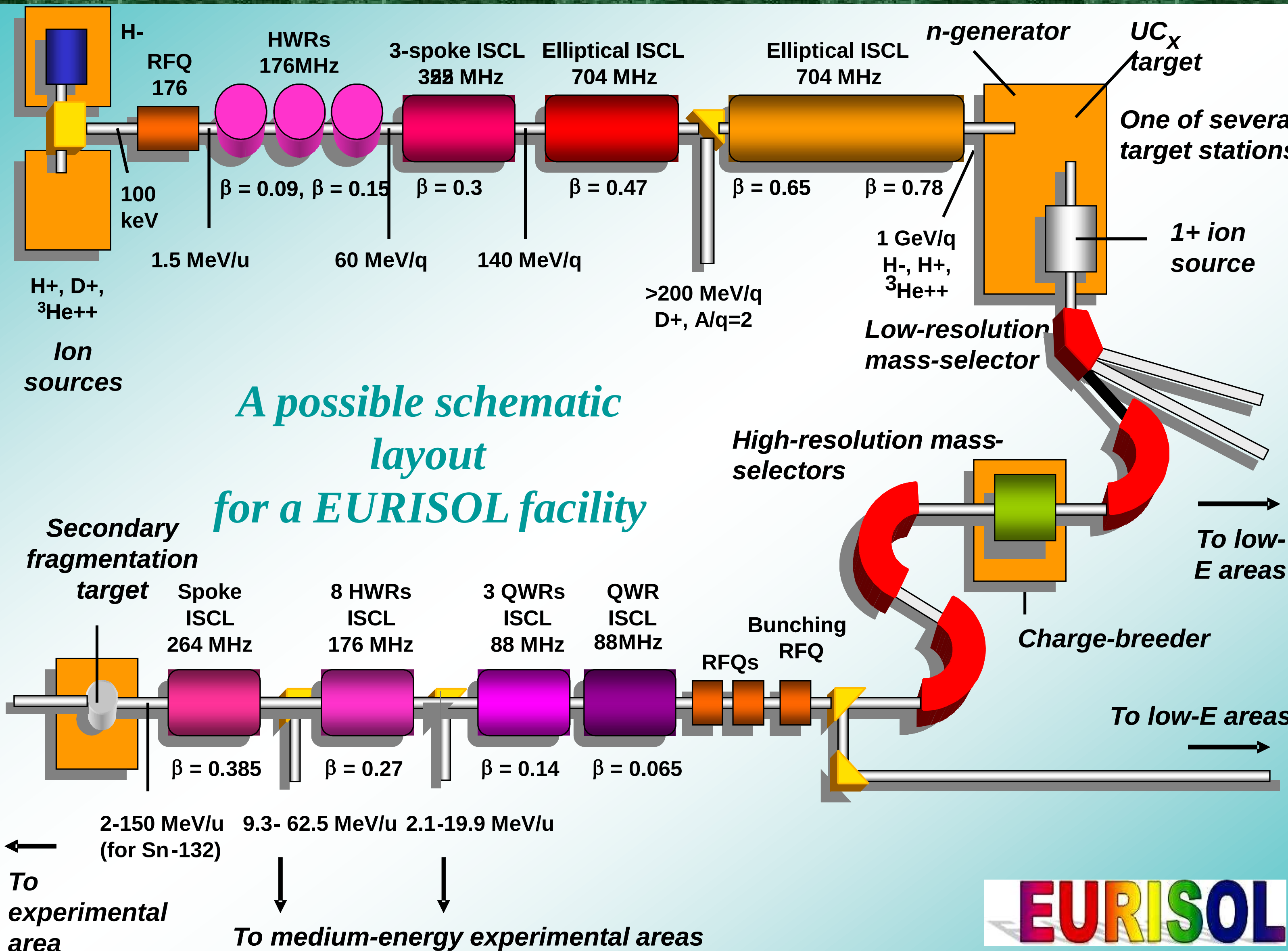
EURISOL : Radioactive ion beam production
(Project phase - site not yet chosen)

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.

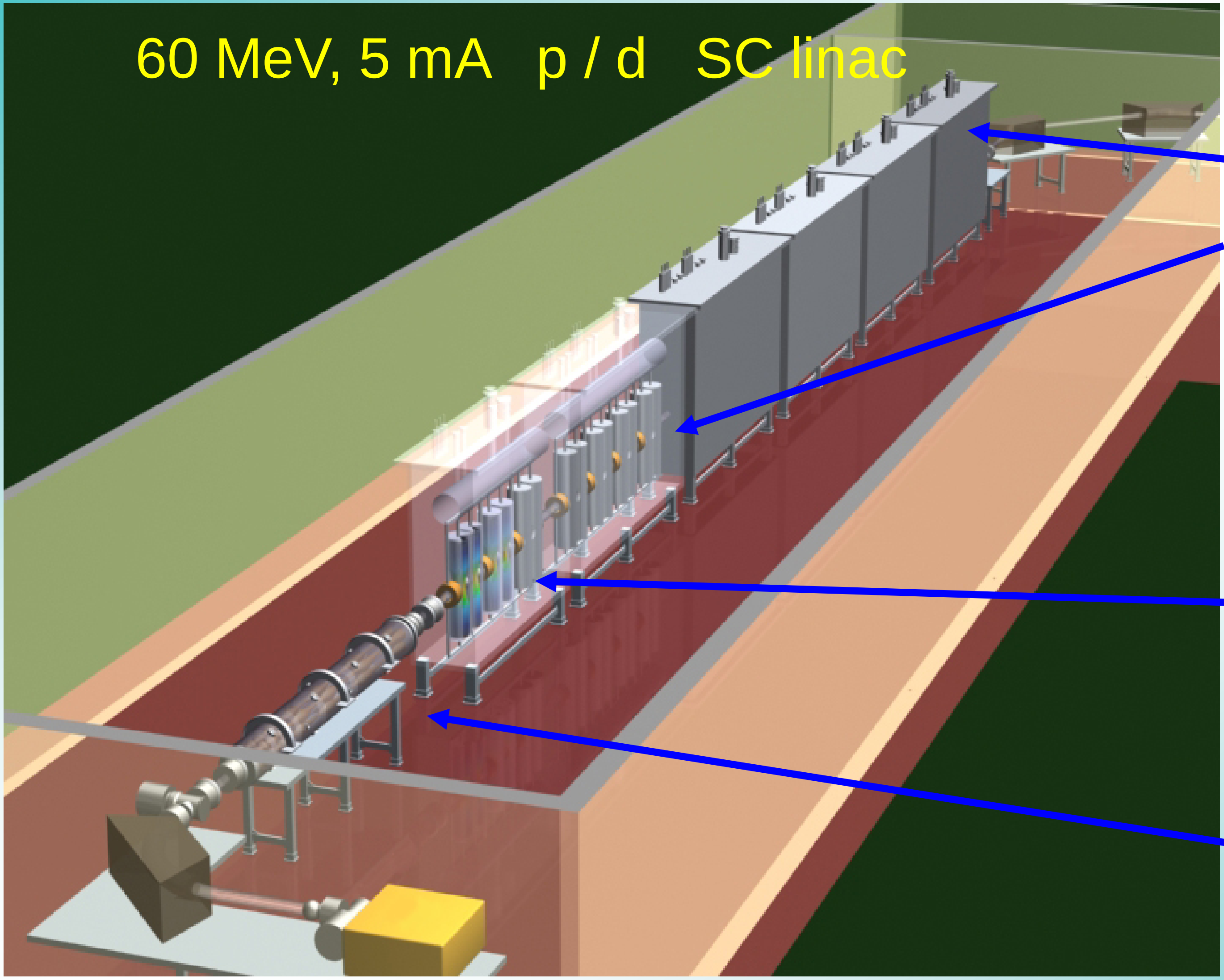
1 GeV proton, 5 mA, 5 MW total power

Capabilities to accelerate also Deuterons and He3


H-
RFQ
176
HWRs
176MHz
3-spoke ISCL
352 MHz
Elliptical ISCL
704 MHz
Elliptical ISCL
704 MHz
n-generator
UC_x
target
One of several
target stations
100
keV
β = 0.09, β = 0.15
β = 0.3
β = 0.47
β = 0.65
β = 0.78
1.5 MeV/u
60 MeV/q
140 MeV/q
1 GeV/q
H-, H+,
$^3He^{++}$
1+ ion
source
H+, D+,
$^3He^{++}$
Ion
sources
>200 MeV/q
D+, A/q=2
Low-resolution
mass-selector
A possible schematic
layout
for a EURISOL facility
High-resolution mass-
selectors
To low-
E areas
Secondary
fragmentation
target
Spoke
ISCL
264 MHz
8 HWRs
ISCL
176 MHz
3 QWRs
ISCL
88 MHz
QWR
ISCL
88MHz
Bunching
RFQ
RFQs
Charge-breeder
To low-E areas
β = 0.385
β = 0.27
β = 0.14
β = 0.065
2-150 MeV/u
(for Sn-132)
9.3- 62.5 MeV/u
2.1-19.9 MeV/u
To
experimental
area
To medium-energy experimental areas

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 **$^3He^{++}$** , 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 **$^3He^{++}$** , 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 **$^3He^{++}$** , 2 MW	231	H- injector+ 4 stripping stations	**+3%**	+19 %



Linac Length: ~32 m

3rd– 9th cryostats

7×8 SC HWR

β_0=0.15

1st, 2nd cryostat

2×6 SC HWR, β_0=0.09

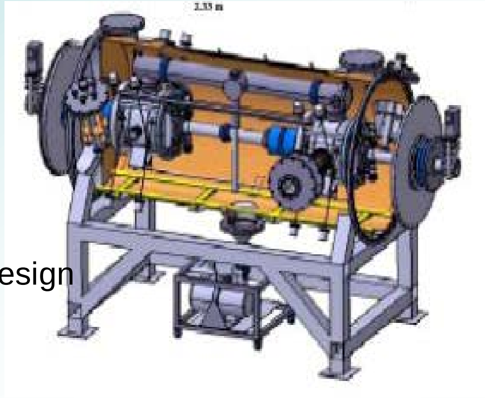
176 MHz RFQ

1.5 MeV/u A/q=2

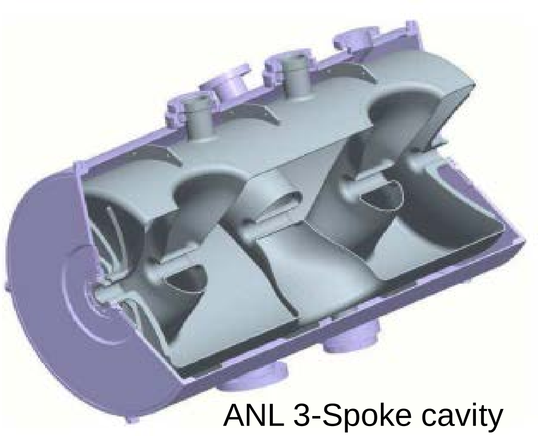
3.8 m

60÷140 MeV/q, $1 \leq A/q \leq 2$

- superconducting Triple-SPOKE cavities β=0.3
- E_{in}= 60 MeV/q
- E_{out}=140 MeV/q
- length ~30 m

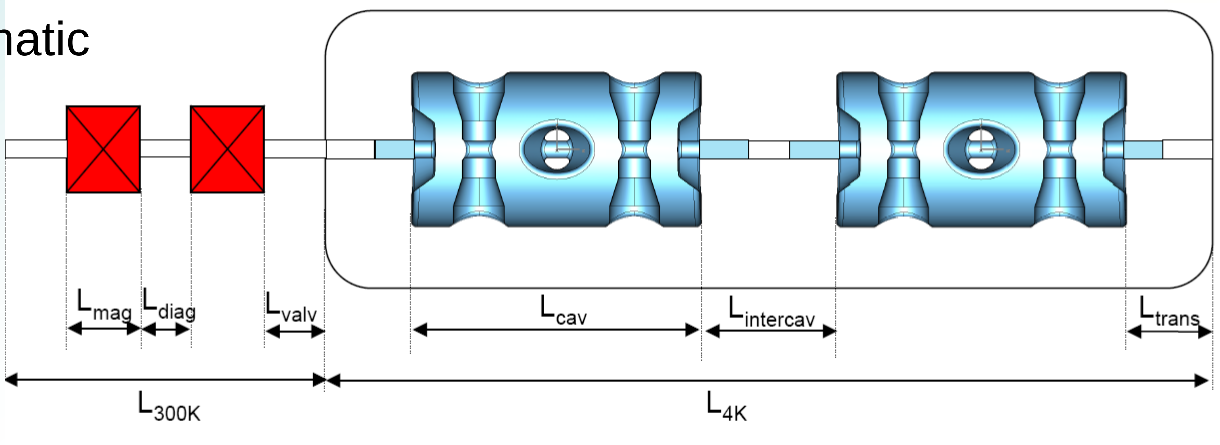


IPNO cryostat design for SPOKE resonators



ANL 3-Spoke cavity

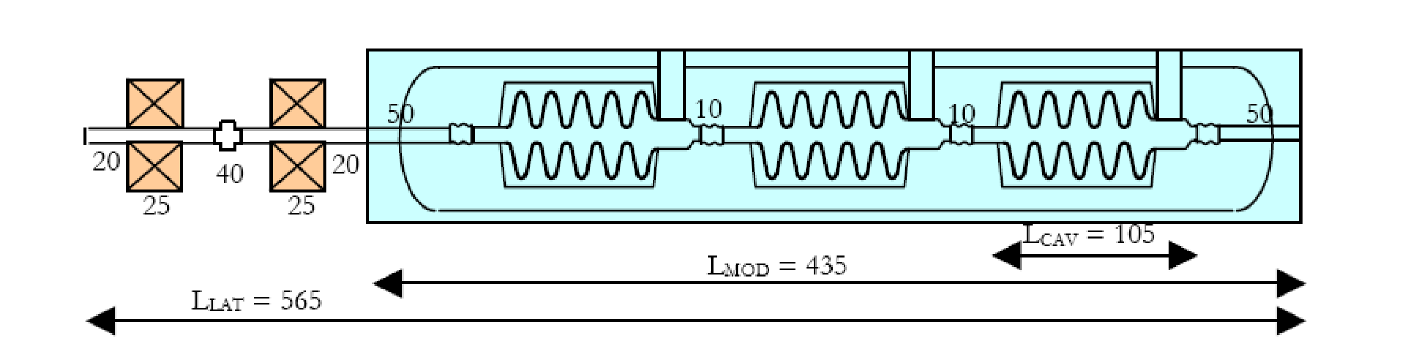
3-spoke cryomodule schematic



140÷250 MeV/q, $1 \leq A/q \leq 2$
250÷1000 MeV/q, $1 \leq A/q \leq 1.5$

- superconducting elliptical cavities
- β=0.47, 0.65, 0.78
- E_{in}= 140 MeV/q
- E_{out}=1000 MeV/q
- section III+IV length ~160 m

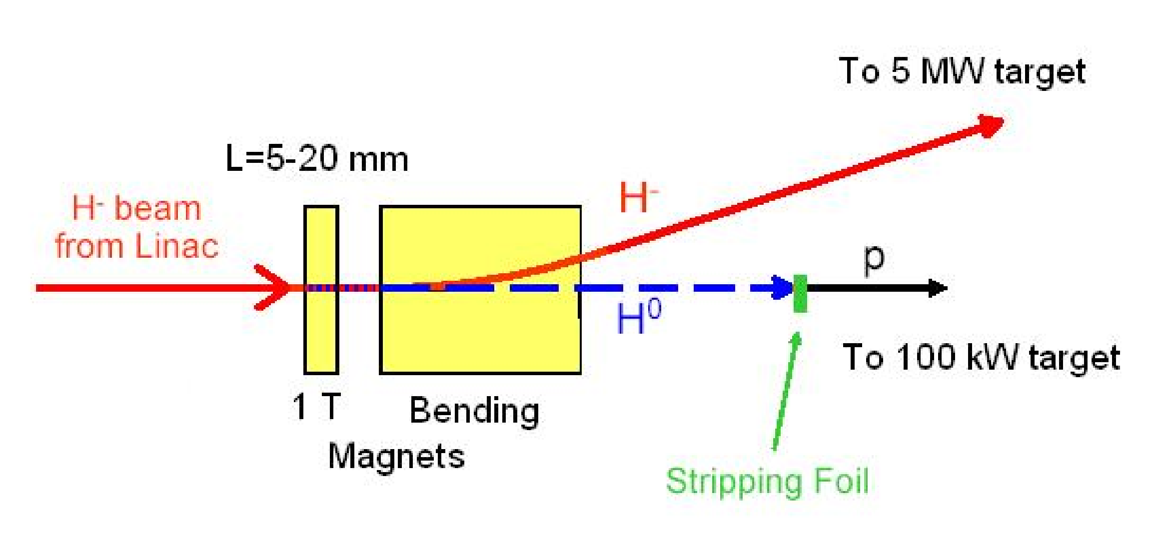
β = 0.65, 704 MHz elliptical cavity



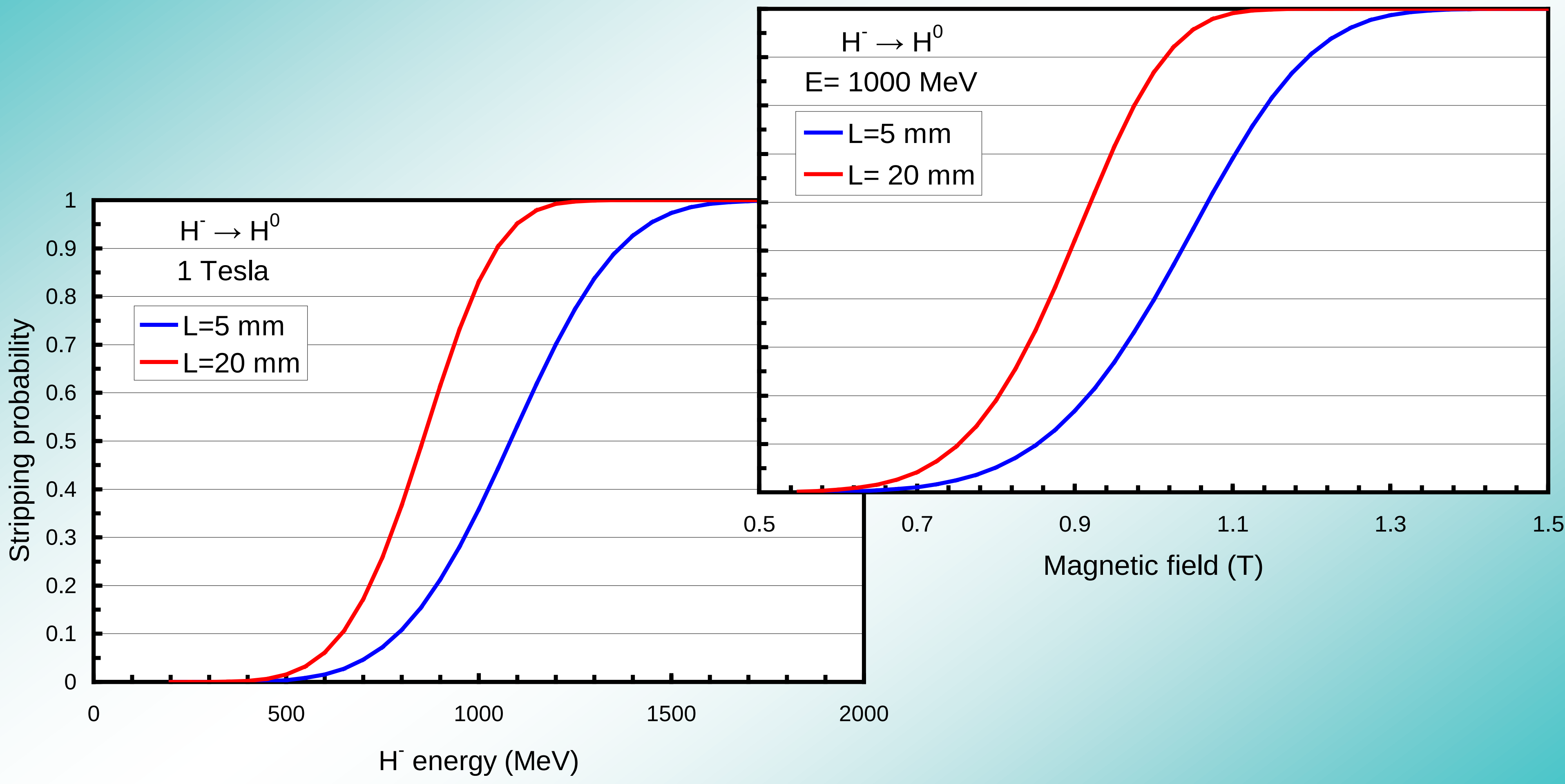
schematic of the β=0.47 cryomodule

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.



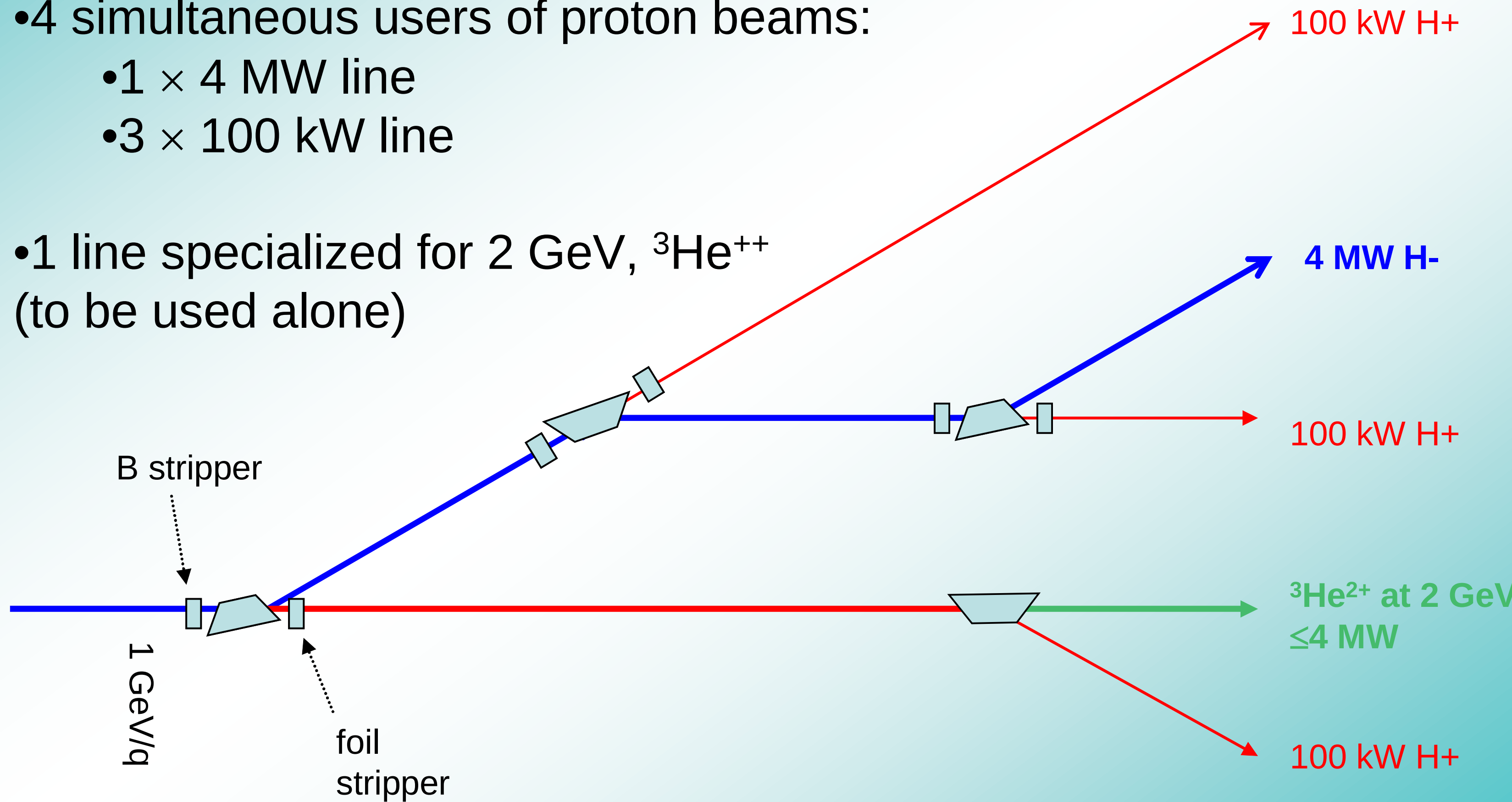
Magnetic stripping probability



1 GeV Extraction possible scheme

- 3 splitting stations
- 4 simultaneous users of proton beams:
  - 1 × 4 MW line
  - 3 × 100 kW line

- 1 line specialized for 2 GeV, $^{3}He^{++}$ (to be used alone)



High Power Proton Accelerator for Nuclear Waste Transmutation

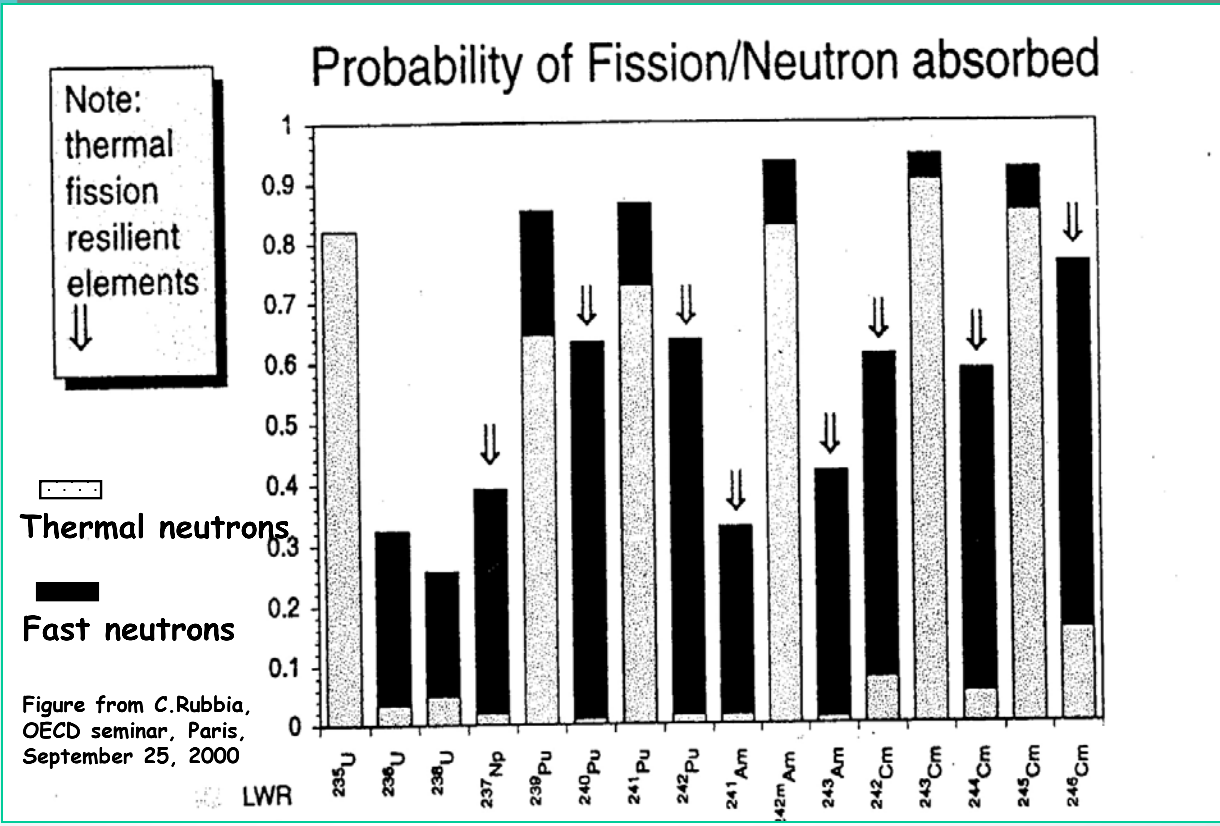
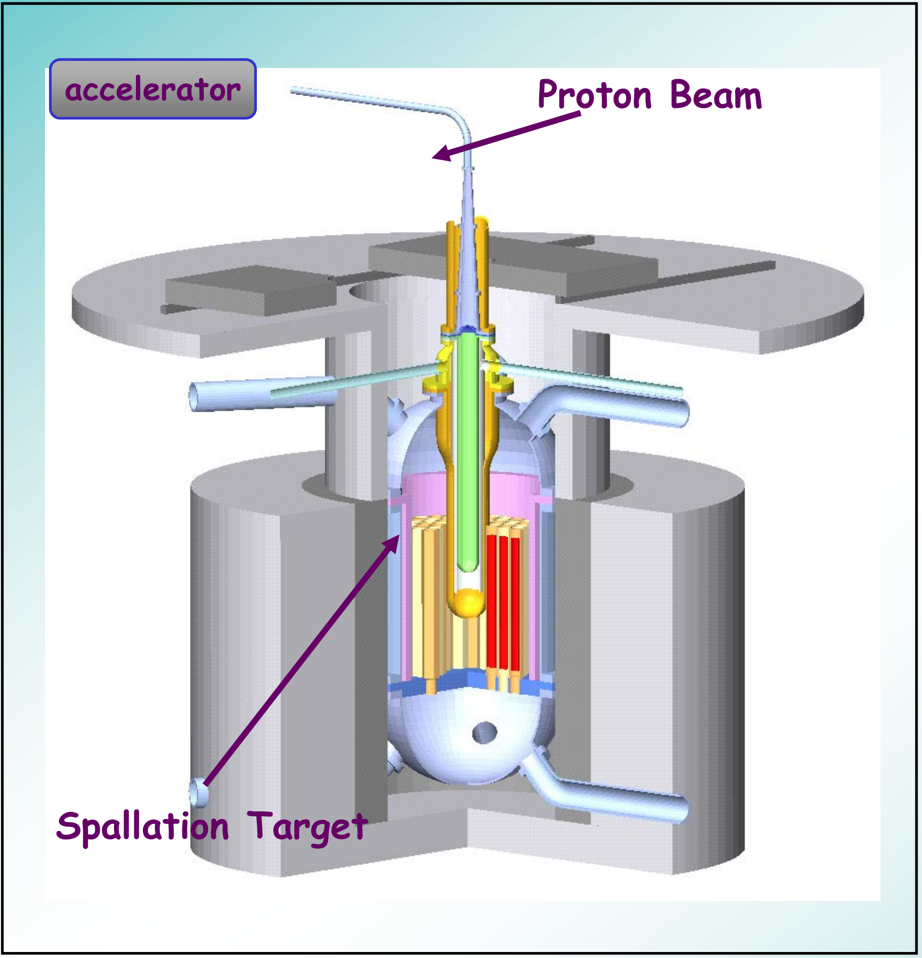


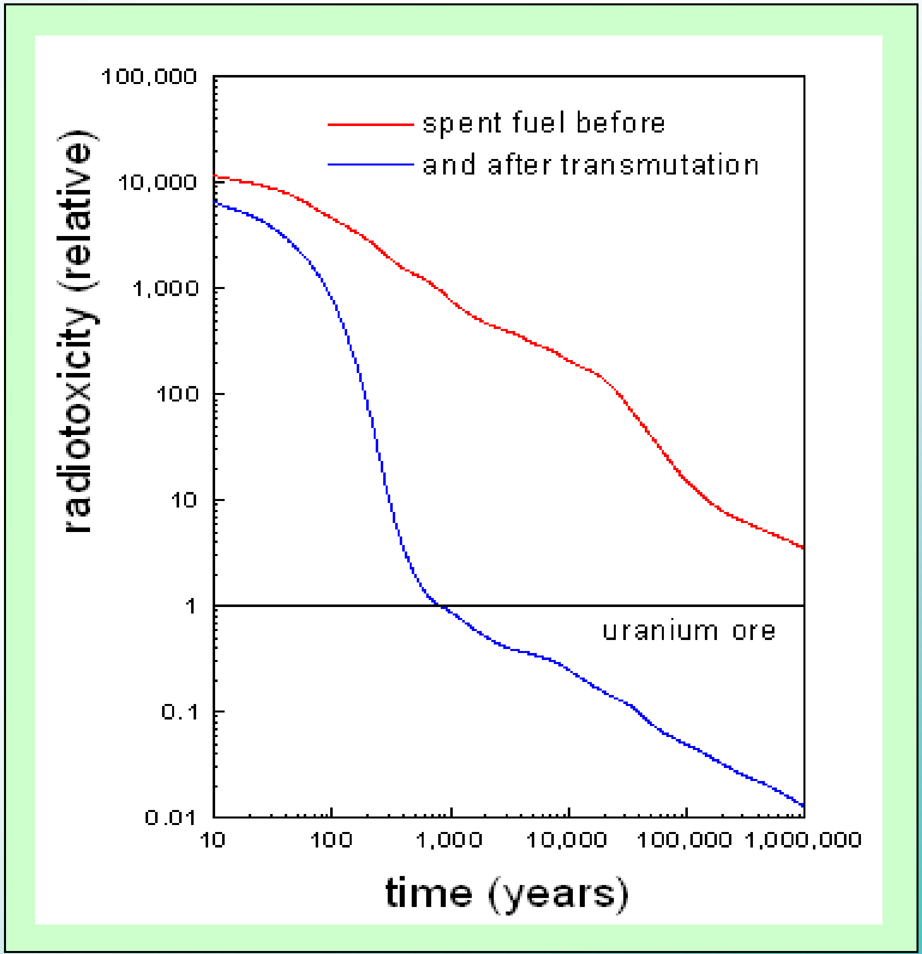
Figure from C.Rubbia, OECD seminar, Paris, September 25, 2000

- 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 transmution needs fast neutrons
- fast breeder reactors like "SUPERPHENIX" ????

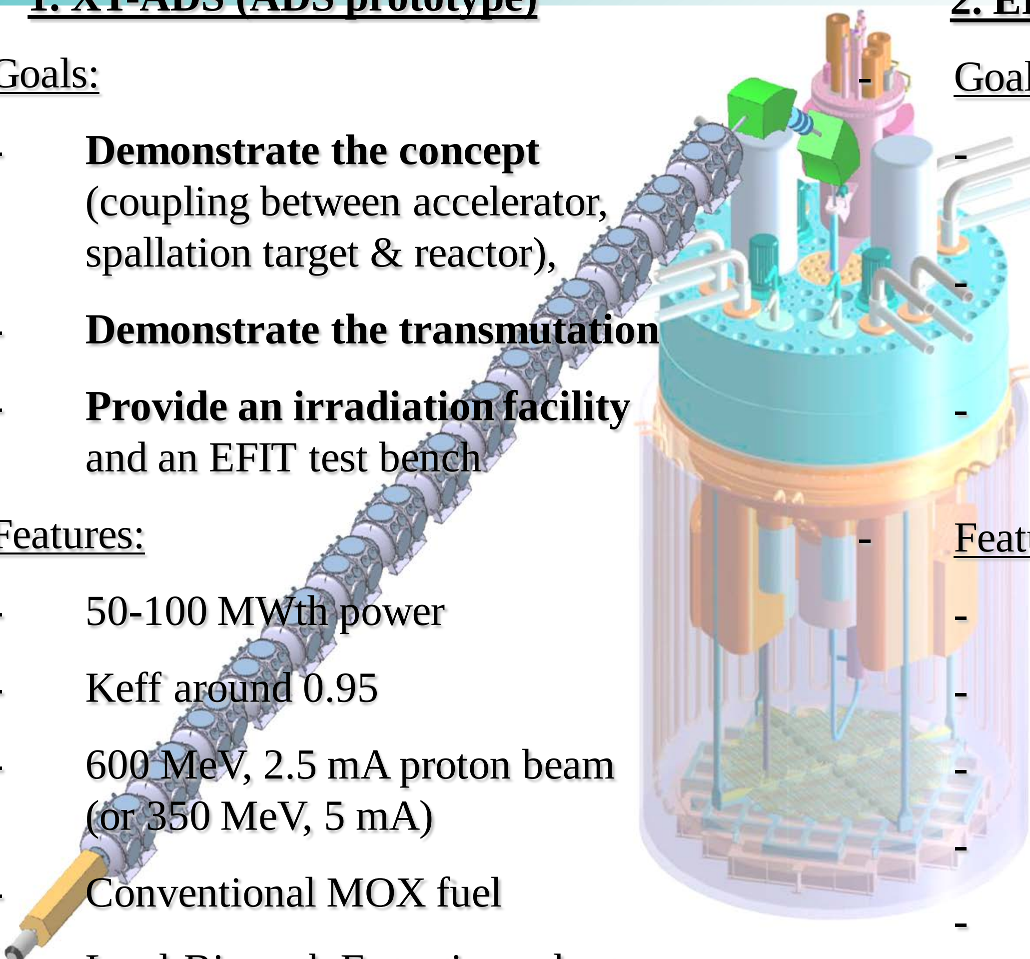
Alternative: use, for higher flexibility, safety and efficiency, (very) fast neutrons, produced by an accelerator, in combination with a subcritical reactor !

Note: Subcriticality is not virtue but necessity!





European Transmutation Demonstration



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

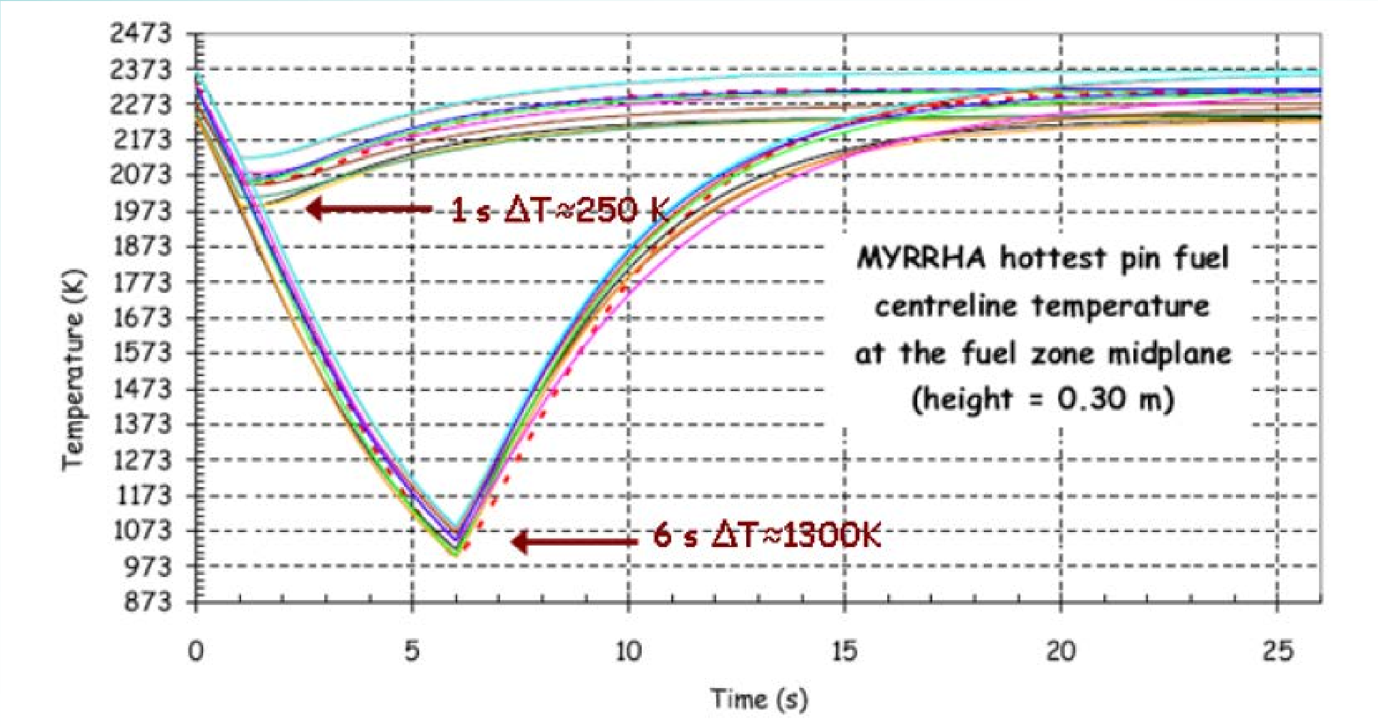
	XT-ADS	EFIT
Maximum beam intensity	2.5 – 4 mA	20 mA
Proton energy	600 MeV	800 MeV
Beam entry	Vertically from above	
Beam trip number	< 20 per year (exceeding 1 second)	< 3 per year (exceeding 1 second)
Beam stability	Energy: ± 1 %, Intensity: ± 2 %, Size: ± 10 %	
Beam footprint on target	Circular ∅ 5 to 10 cm, "donut-shaped"	An area of up to 100 cm² must be "paint-able" with any arbitrary selectable intensity profile
Beam time structure	CW, with 200 μs 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

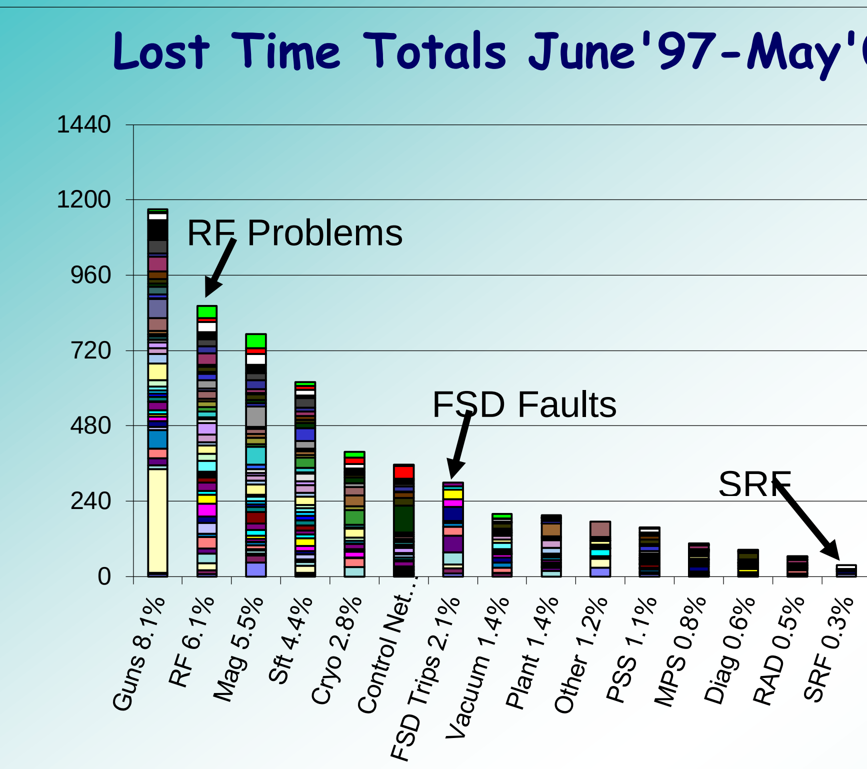
- **Linacs**
  - LAMPF/LANSCE (~1970)
    - 800 MeV
    - 1 mA H^+ average current
    - Peak H^+ current 16.5 mA @ 100 Hz and 625 μs pulse length
    - NC accelerator
- **Cyclotrons**
  - PSI – separated sector (1974)
    - Original design was for 100 μA
    - From 72 to 590 MeV
    - 1.8 mA average current
    - Beam losses at extraction < 1 μA
    - 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

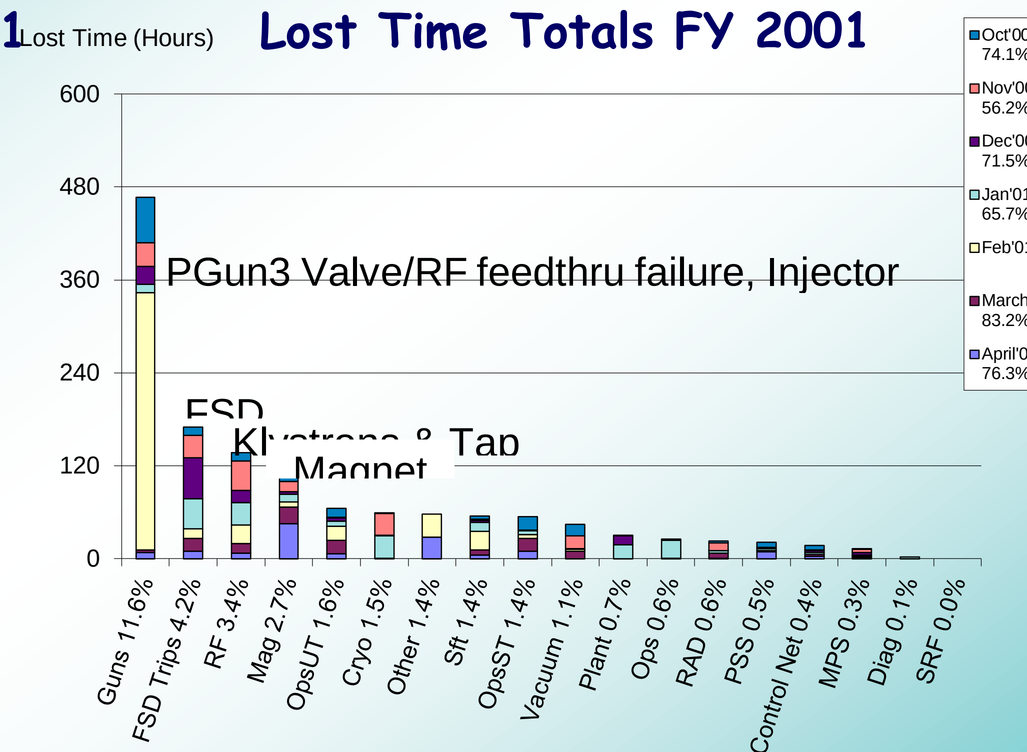
- A reactor should not have more than a hundred "scram's" in its life time
  - ➔ only "some" accelerator trips per year !!
  - ➔ a performance gain of 2 -3 orders of magnitude is needed !
- The beam losses in the accelerator should be very low in order to avoid activation
  - ➔ max some 10 µSv/h, one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

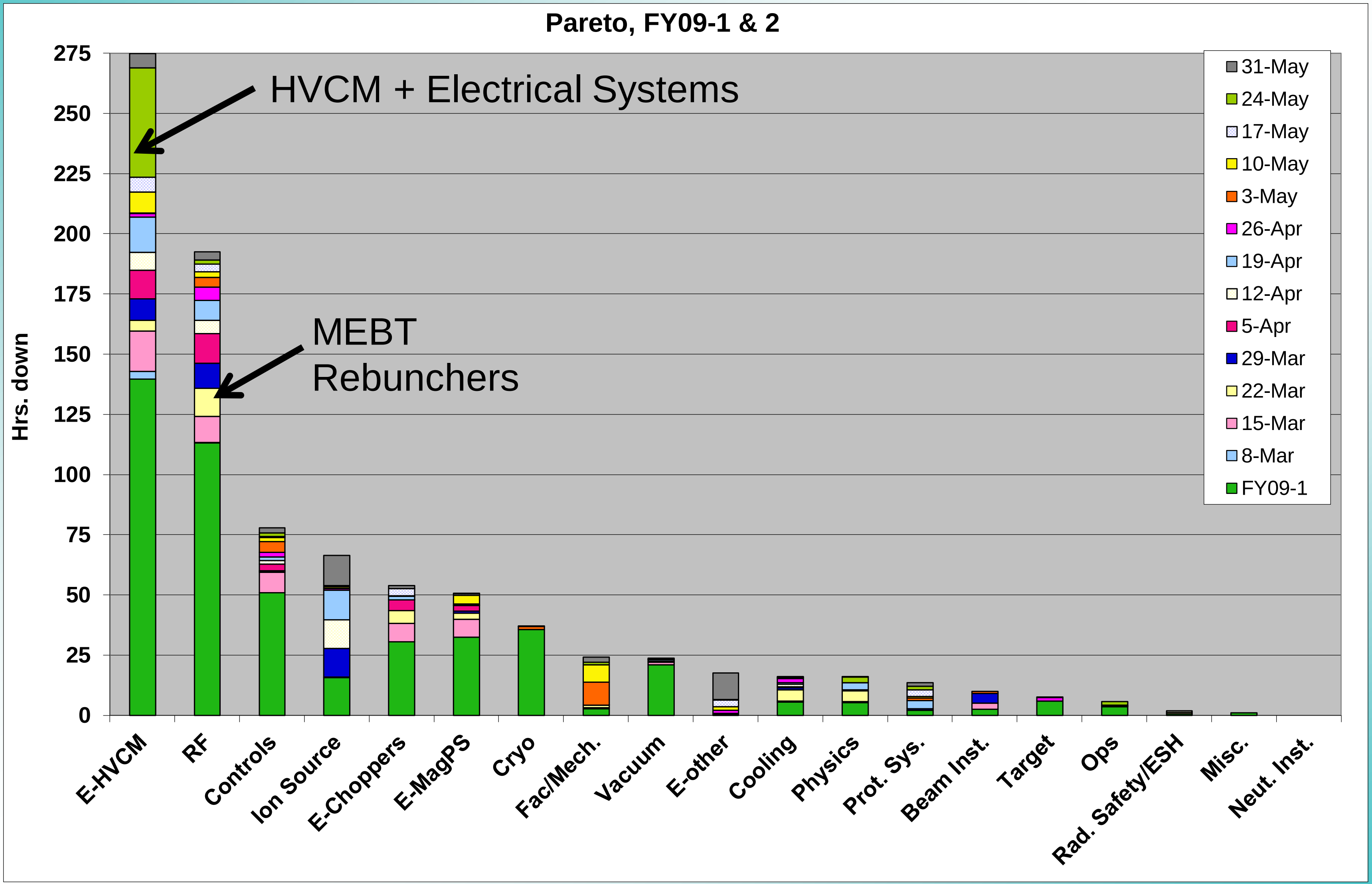




- Reliability must be improved for ADS applications
- The SC linac is modular and allows: overdesign, redundancy and “spare-on-line”
- Fast dedicated control electronics is crucial
- Beam can stay “on” when the linac is resetting itself to use spere-on line
- SC cavity technology proved to be the minor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

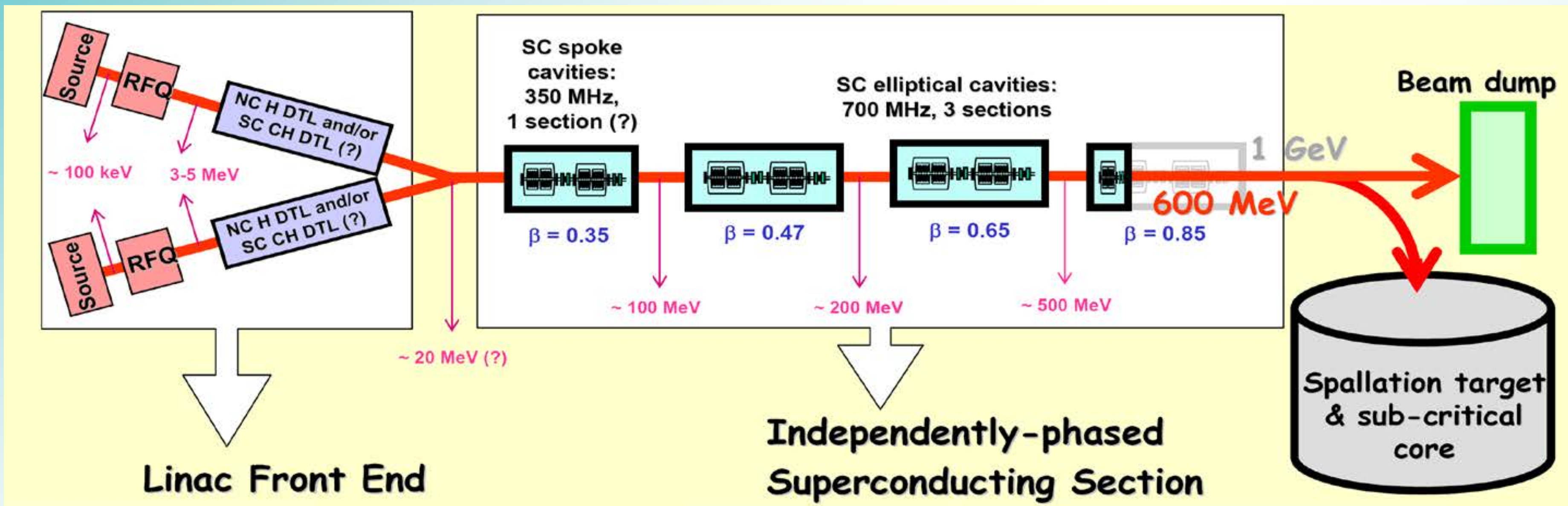
Reliability Example - SNS

Down Time – Pareto Chart for FY09-1 & 2



Experimental ADS : reference design

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



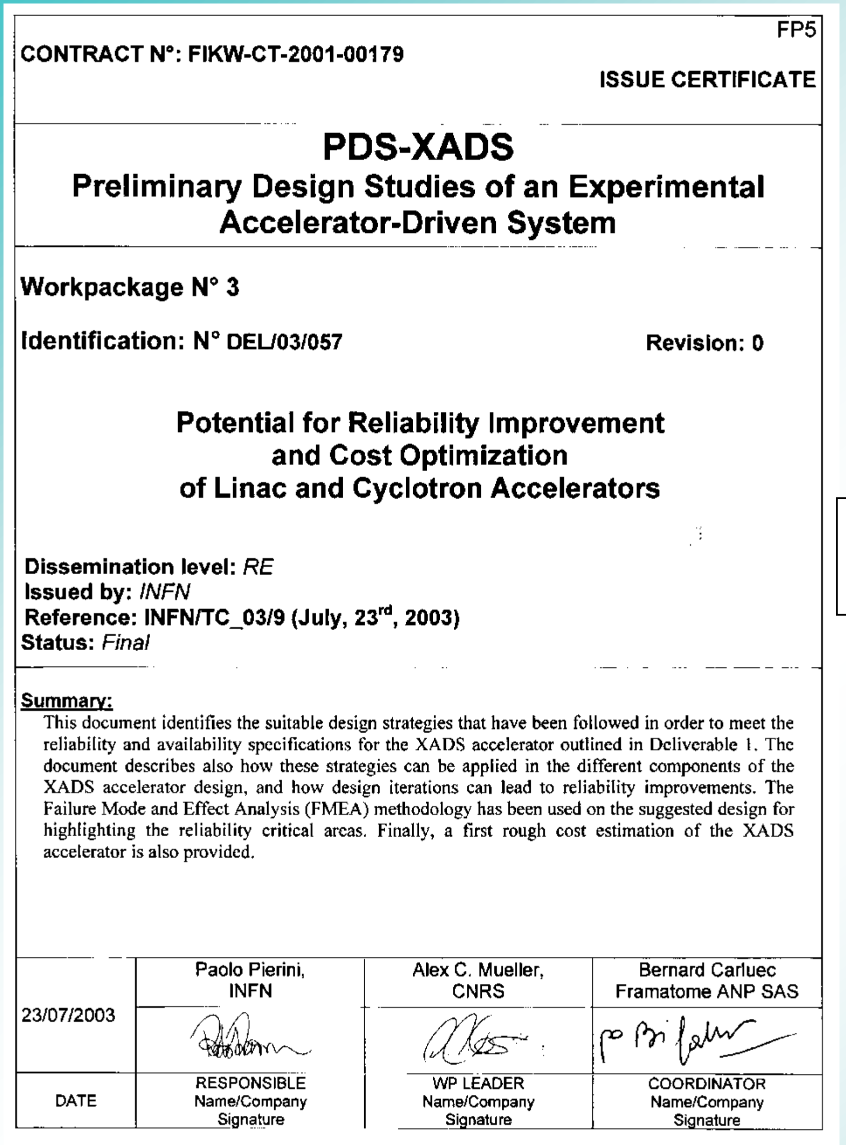
Realibility guidelines

- **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



FP5

CONTRACT N°: FIKW-CT-2001-00179

ISSUE CERTIFICATE

PDS-XADS

Preliminary Design Studies of an Experimental Accelerator-Driven System

Workpackage N° 3

Identification: N° DEL/03/057 **Revision: 0**

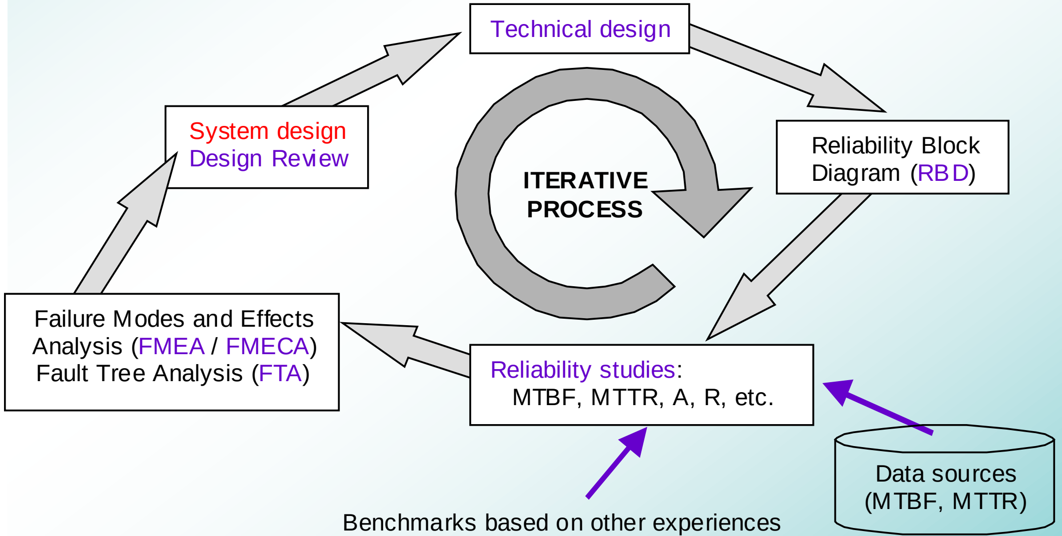
Potential for Reliability Improvement and Cost Optimization of Linac and Cyclotron Accelerators

Dissemination level: *RE*
Issued by: *INFN*
Reference: INFN/TC_03/9 (July, 23rd, 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.

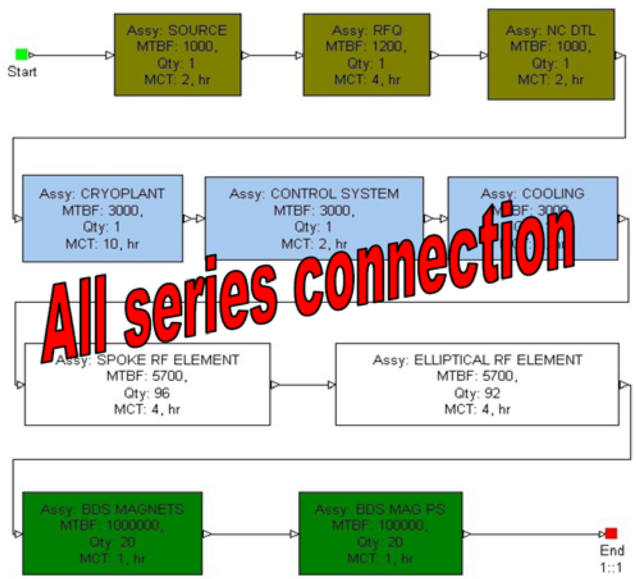
23/07/2003	Paolo Pierini, INFN	Alex C. Mueller, CNRS	Bernard Carluec Framatome ANP SAS
DATE	RESPONSIBLE Name/Company Signature	WP LEADER Name/Company Signature	COORDINATOR Name/Company Signature

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



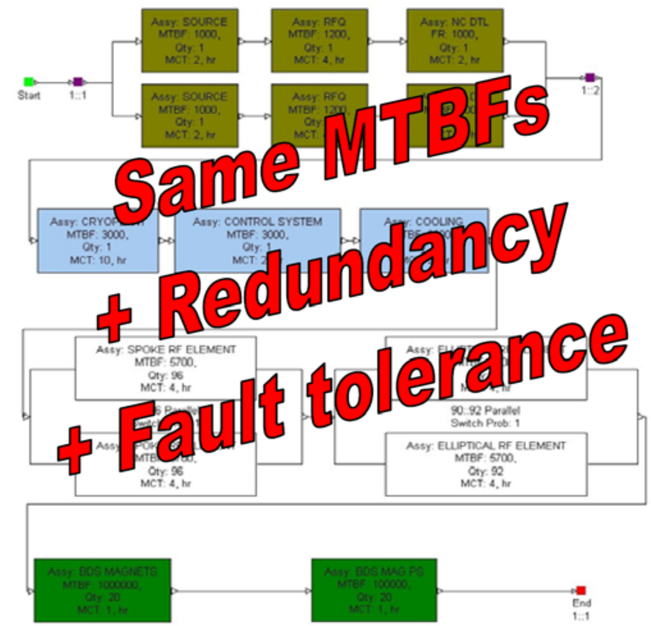
- Reliability engineering is a discipline for estimating, predicting and controlling the probability of occurrence of system faults

Classical linac



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

ADS linac, optimized for reliability

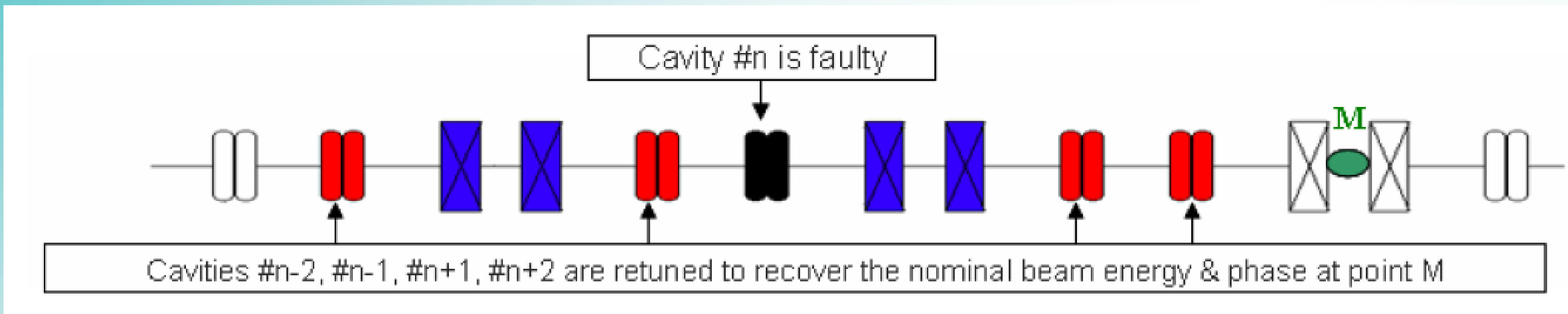


System MTBF	757.84 hours
Nb of failures (3 months)	**2.89**
Steady State Availability	99.5 %

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 ΔEacc (%)	Max E_{pk} (SP) or B_{pk} (EL)	Max ΔPower (%)	# 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 (<< 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 <u>digital LLRF control systems</u>**
  - 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

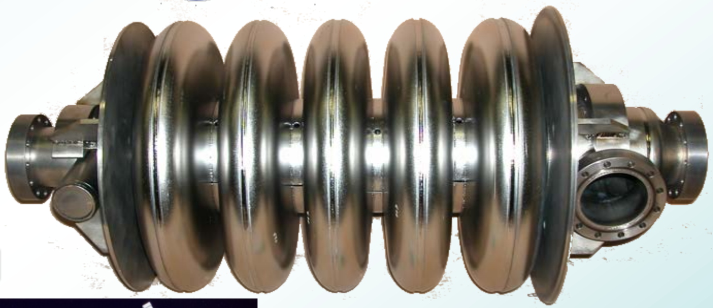
PDS-XADS-WP3 Deliverable 48 Chapter 4 4.3.1 H+ source	Severity Ranking Tables	
	Local effect	**Effect on beam**
	0: No effect	0: Beam with nominal parameters on targ
	1: Functionning with reduc	1: Beam with wrong parameters on target
	2: Loss of function	2: No beam on target

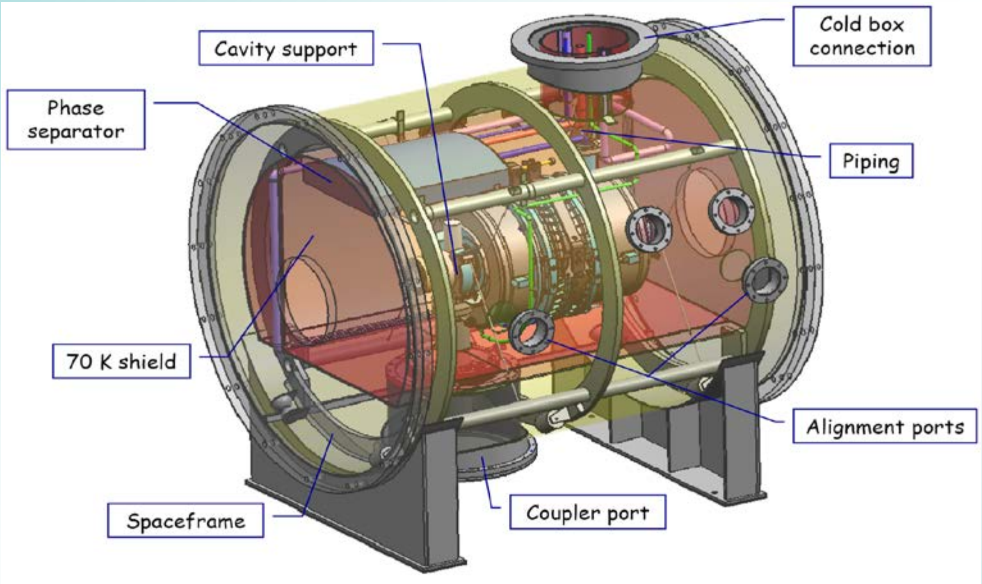
Main Items	Function	Failure Mode	verity rank		Preventive action			Curative action		Rem.
			local	beam	action	freq.	time of int.	action	time of int.	
Boron nitride discs		Wear	1	1	Replace	6 months	24 H	Replace	24H	
Vacuum pumps		Wear	1	2	Regenerate	24 months				
		Out of order	2	2	-			Replace	8H	
Power 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	

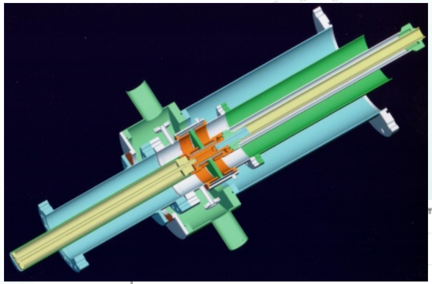
EUROTRANS: prototyping of accelerator components

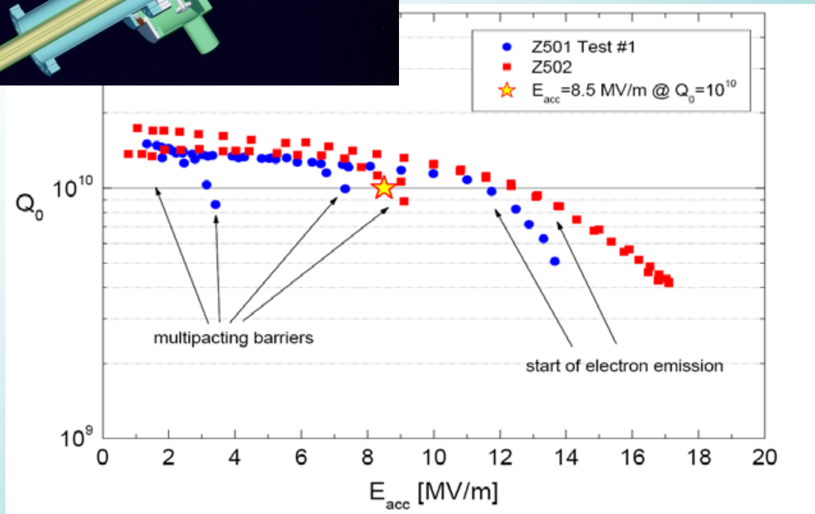
Design, fabrication & test of an elliptical module at nominal power & temperature

- β =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



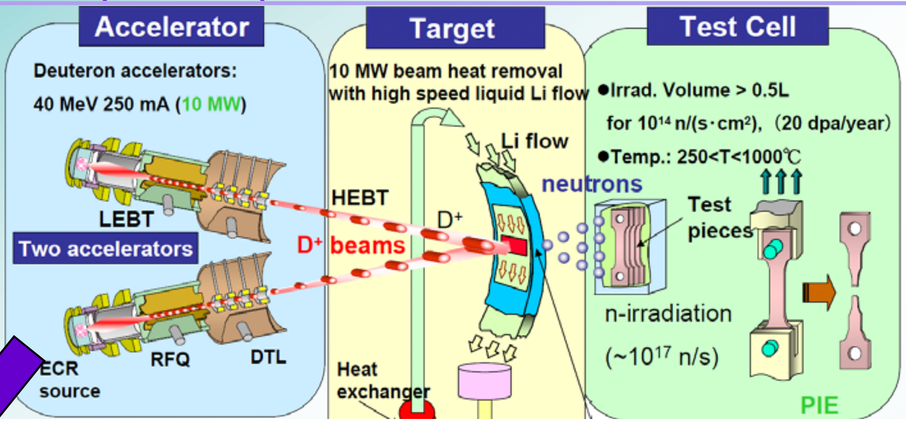


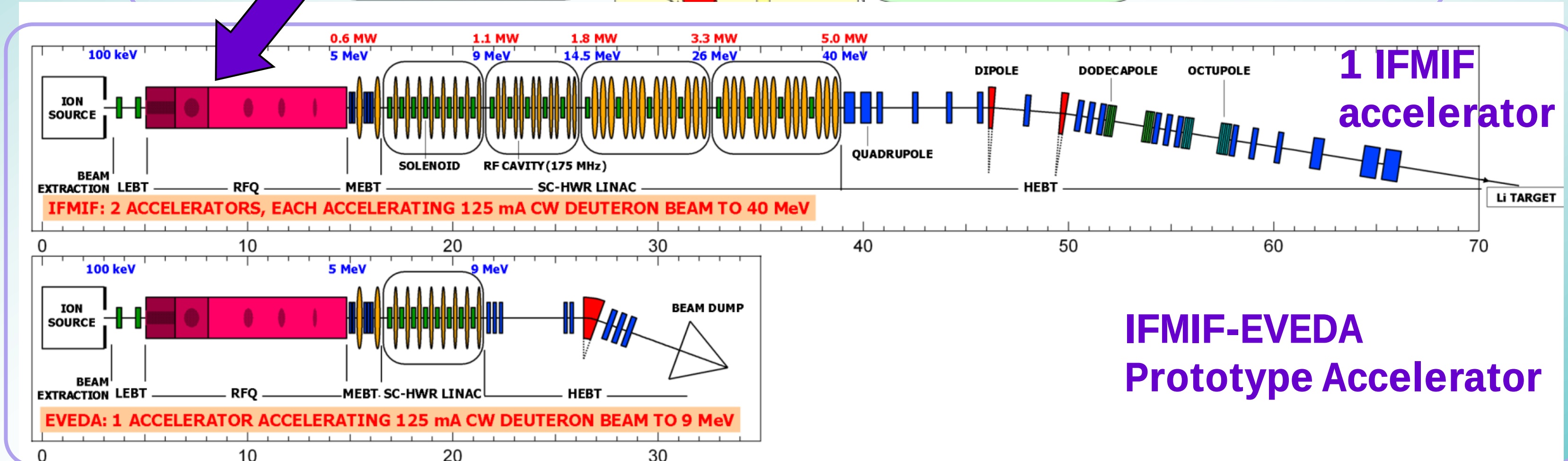




High Power Proton Accelerator as an irradiation tool for material testing: the IFMIF project

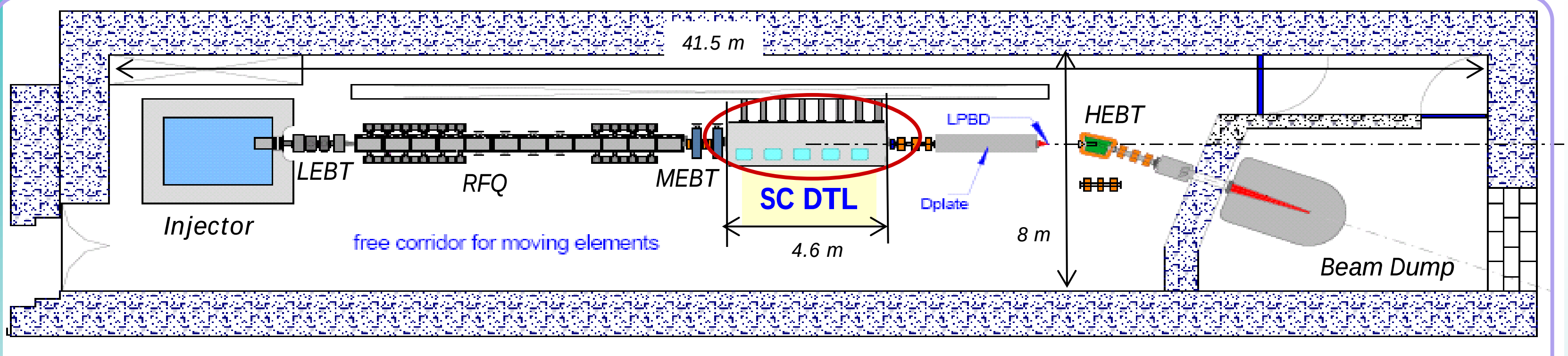
Objective of the IFMIF project: characterization of materials with intense neutrons flux (10^{17} n/s) for the future Fusion Reactor DEMO (~150 dpa)





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



EVEDA General layout

Objectives of the SC Drift Tube Linac

- Transport and accelerate a deuton 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-β = 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