High Power Proton LINACs

Part 1

JUAS
Joint Universities Accelerator School

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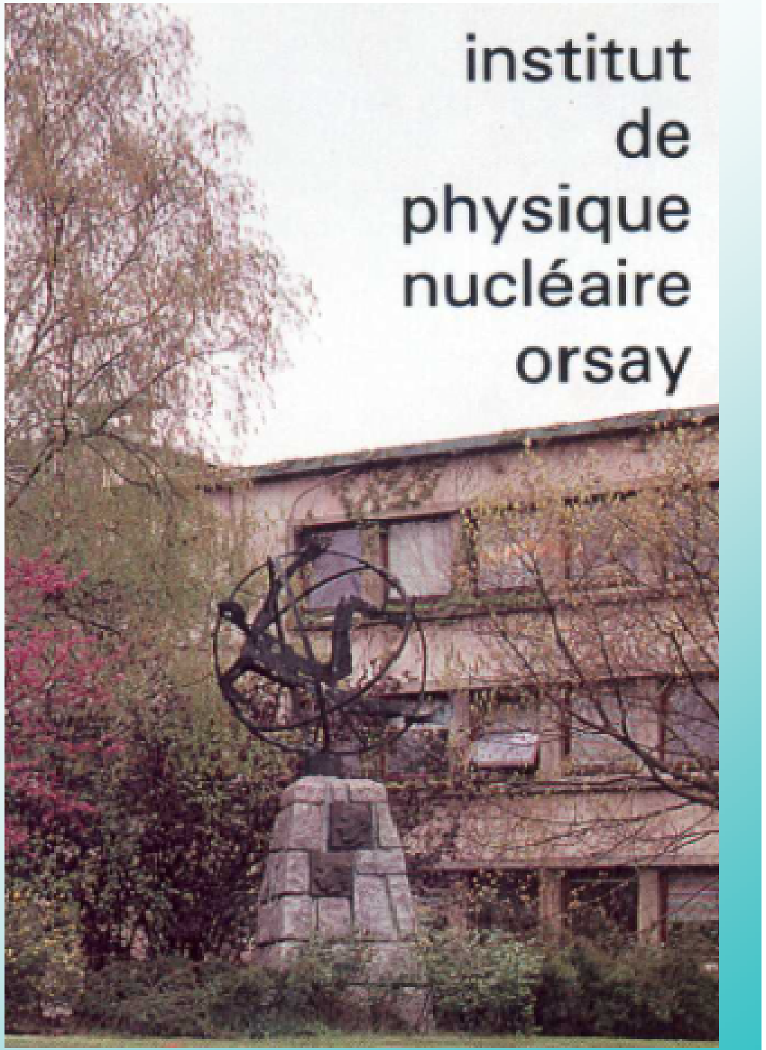


JUAS, Archamps, 8 March 2012

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

Lecture Outlook

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

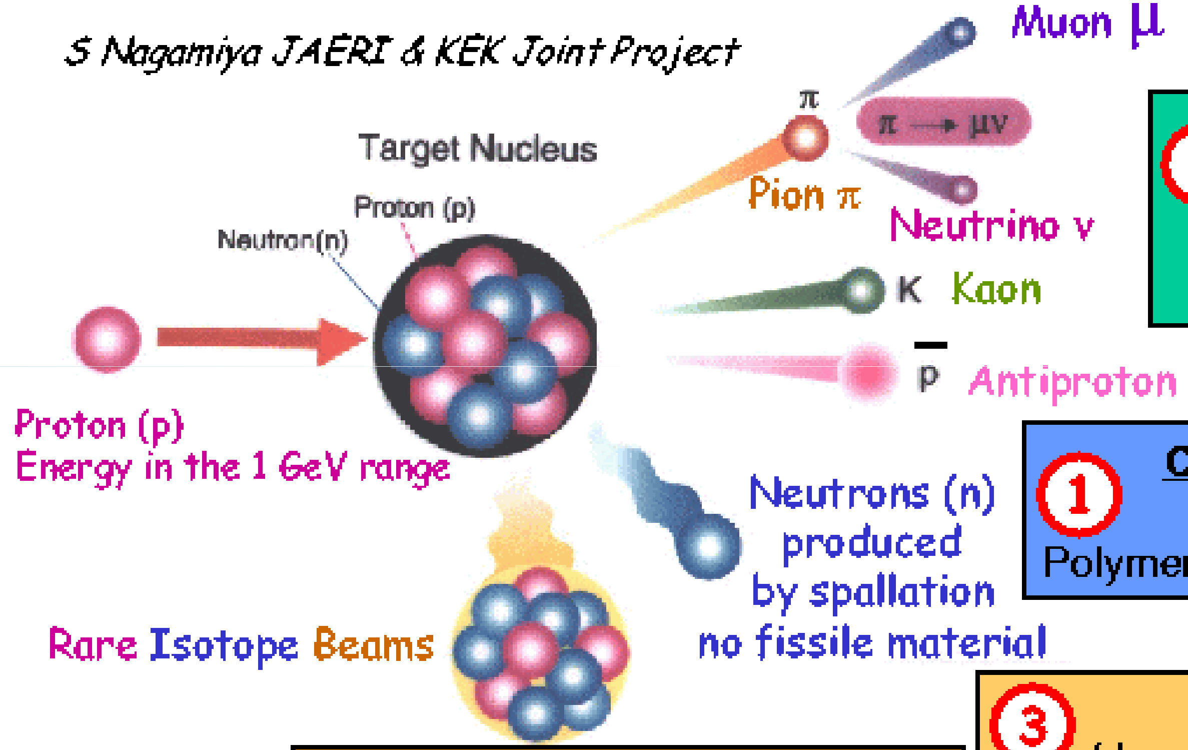
PART 2

- 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

S Nagamiya JAERI & KEK Joint Project



Muon μ

Pion π

Neutrino ν

Kaon

Antiproton

Proton (p)
Energy in the 1 GeV range

Neutrons (n)
produced
by spallation
no fissile material

Rare Isotope Beams

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)

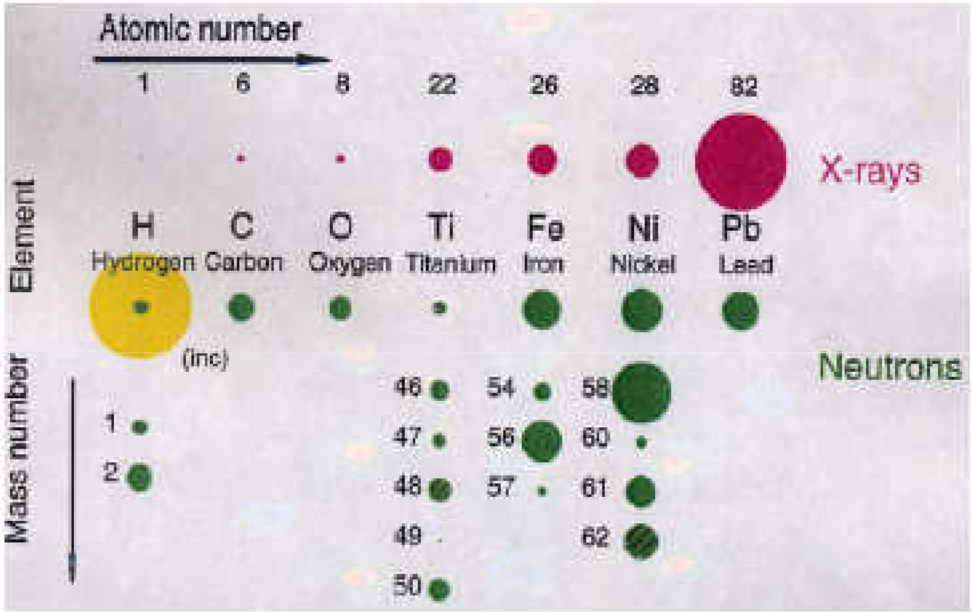
	R.I.B. (EURISOL)	ν&μ (CERN)	Neutrons (ESS)	Transmutation (DEMO→Industriel)
$\hat{I}_{mA}$	0.1→ 30	10	30→100	10→100
$\langle I \rangle_{mA}$	0.1→5	2	1→ 4	10→ 40
E_{GeV}	0.02→1-2	2	1→1.3	0.6-1
D.C.	100%	20%	6%	100%
$\langle P \rangle_{MW}$	0.1→5	4	1→ 5	6 → 40

HPPA: Power ranging from 100 kW so sevral MW

High Power Proton Accelerator used for neutron sources produced by spallation

Condensed matter study: why neutrons ?

Neutron Scattering

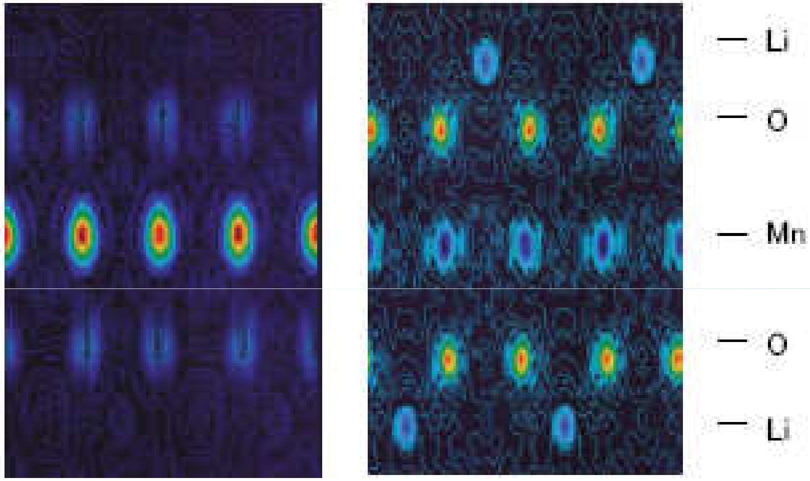


X-rays interact with electrons.

→ X-rays see high-Z atoms.

Neutrons interact with nuclei.

→ Neutrons see low-Z atoms.



Material for Li-battery seen by

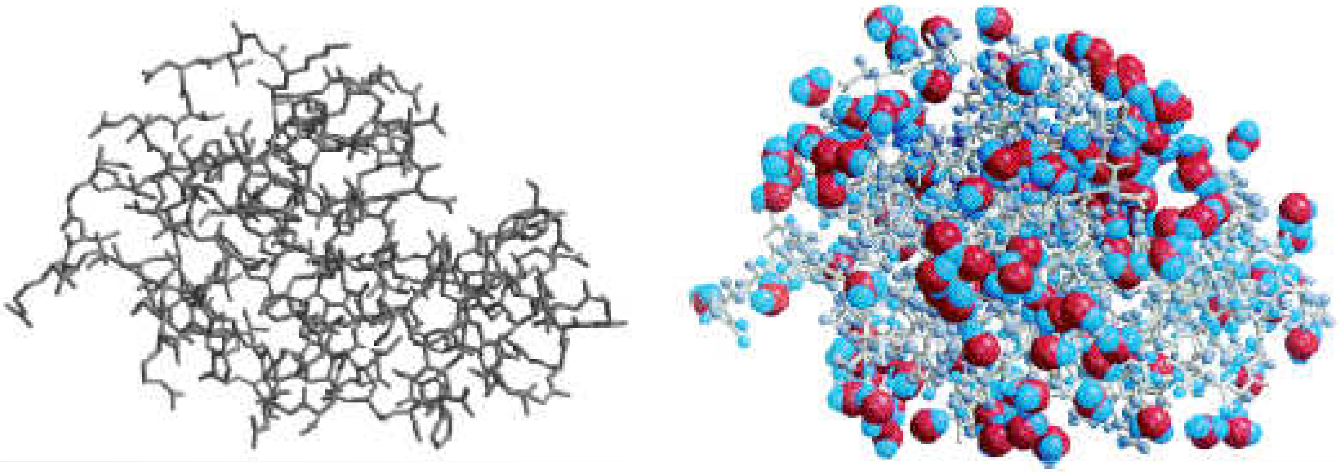
X rays (left) and

Neutrons (right)

T. Kamiyama, et al.

Condensed matter study: why neutrons ?

Hen Egg-White Lysozyme



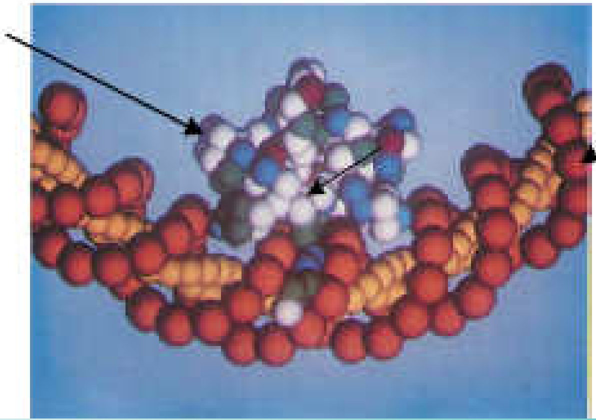
Water molecules Observed with neutrons

N. Niimura, et al.

X-rays

Neutrons

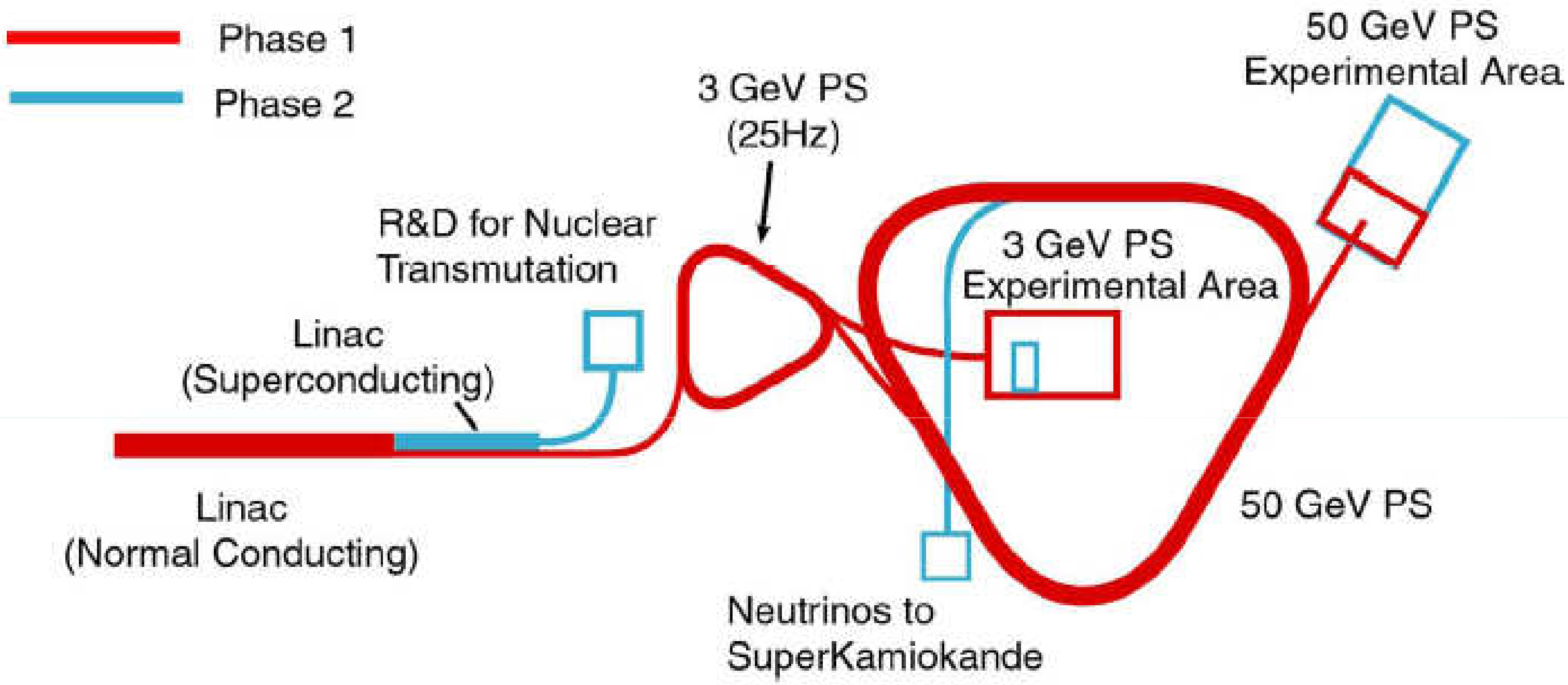
From structure to function



A proten molecule moving along the DNA chain

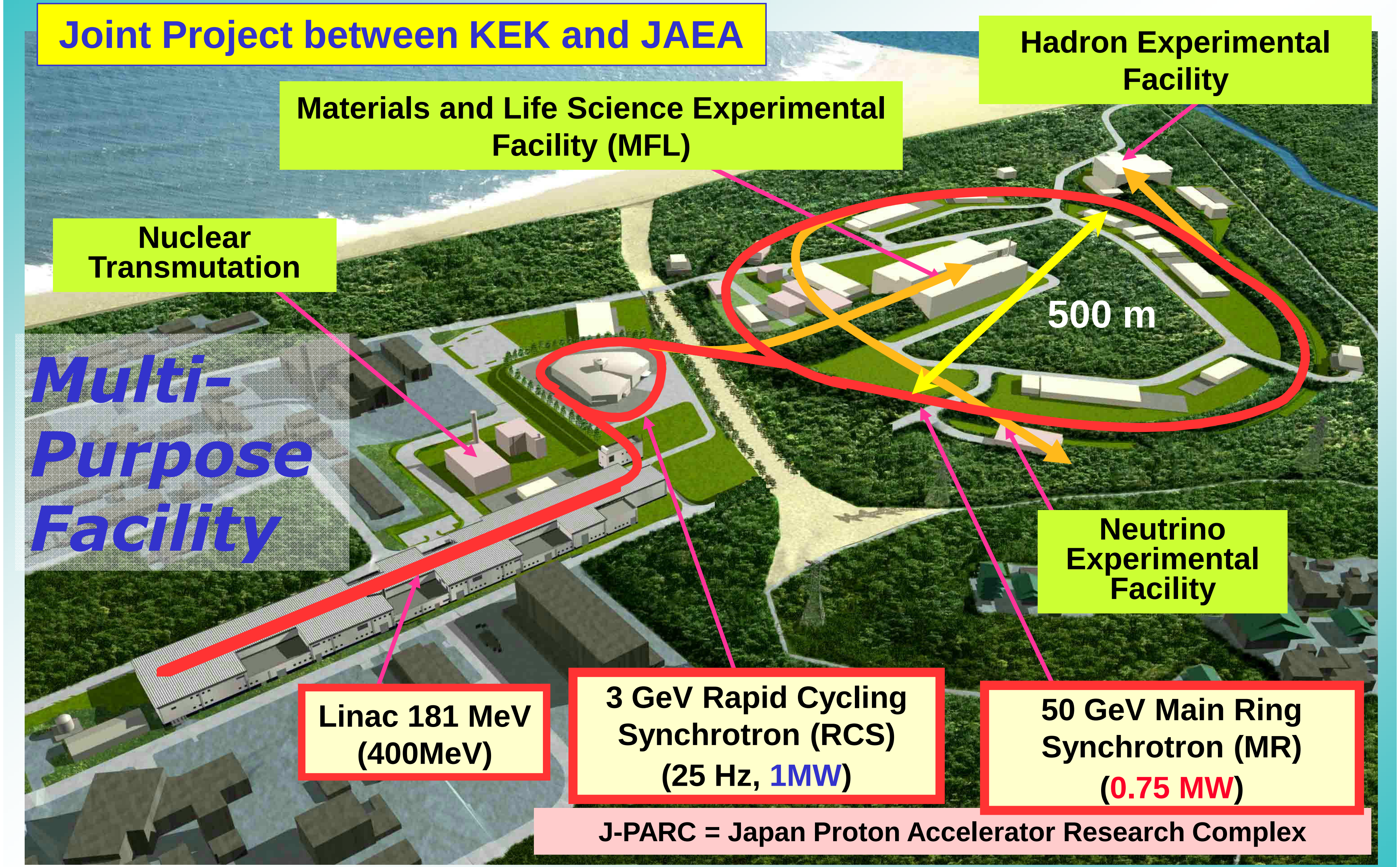
J-PARC : Japan Proton Accelerator Research Complex (under construction)

J-PARC (Japan) : Accelerator complex



- 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.

J-PARC : Overview



Joint Project between KEK and JAEA

Multi-Purpose Facility

Materials and Life Science Experimental Facility (MFL)

Hadron Experimental Facility

Nuclear Transmutation

Neutrino Experimental Facility

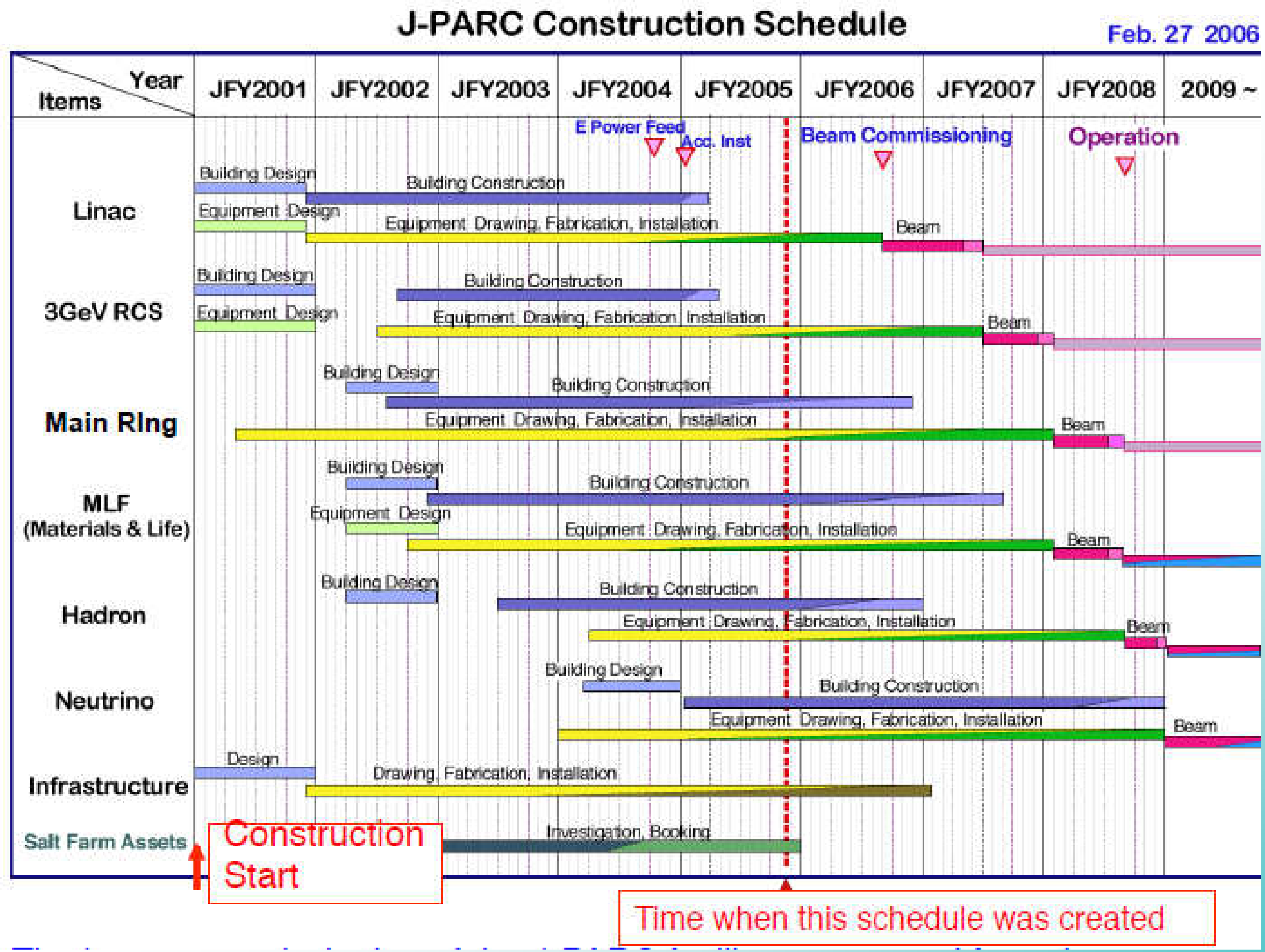
Linac 181 MeV (400MeV)

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

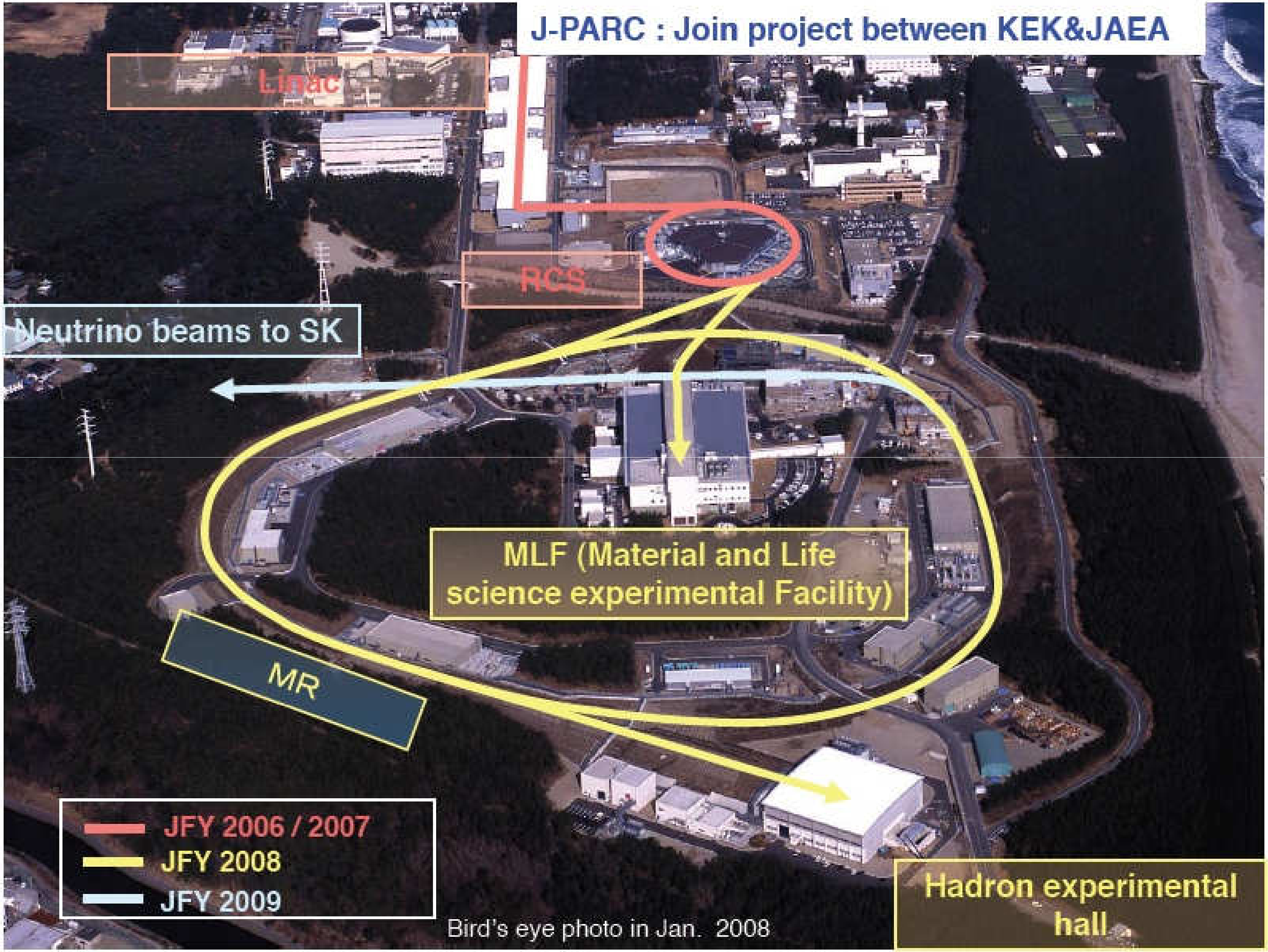

Linac building


December, 2003


3 GeV building

J-PARC : Pictures

J-PARC : Pictures


J-PARC : Join project between KEK&JAEA

Bird's eye photo in Jan. 2008

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.

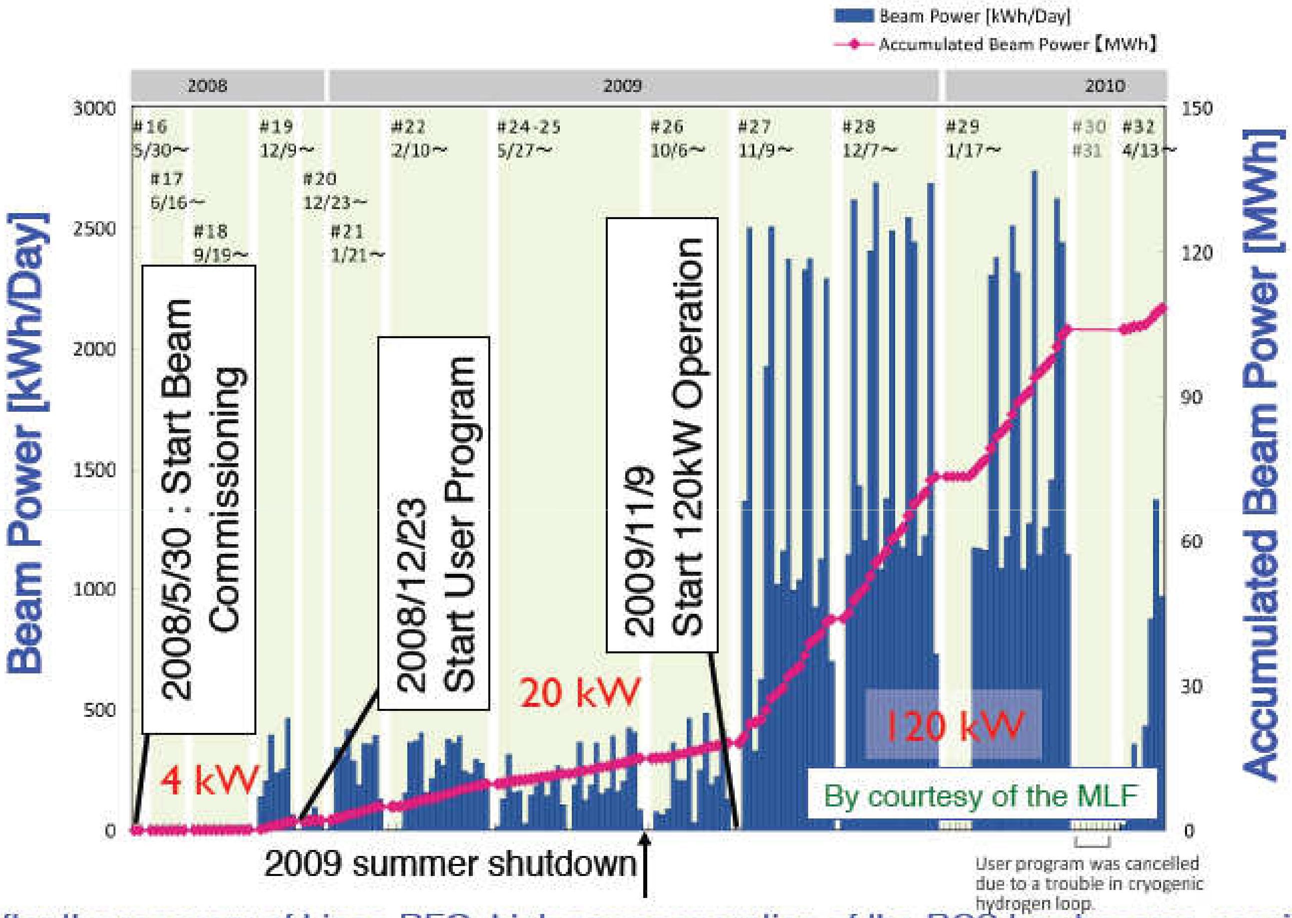
First proton beams reached to the Hadron target.

User operation of MLF started.

2009 First proton beams reached to the Neutrino target.

J-PARC : commissioning

History of beam delivery to MLF



User program was cancelled due to a trouble in cryogenic hydrogen loop.

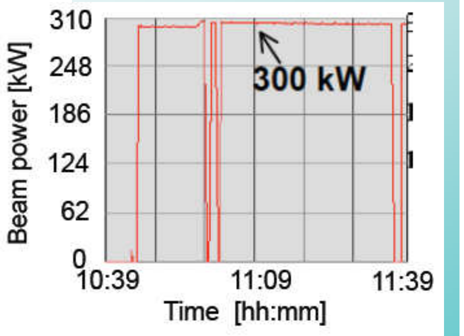
After the recovery of Linac-RFQ, high power operation of the RCS has became possible and 120 kW operation has started for the MLF users.

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.

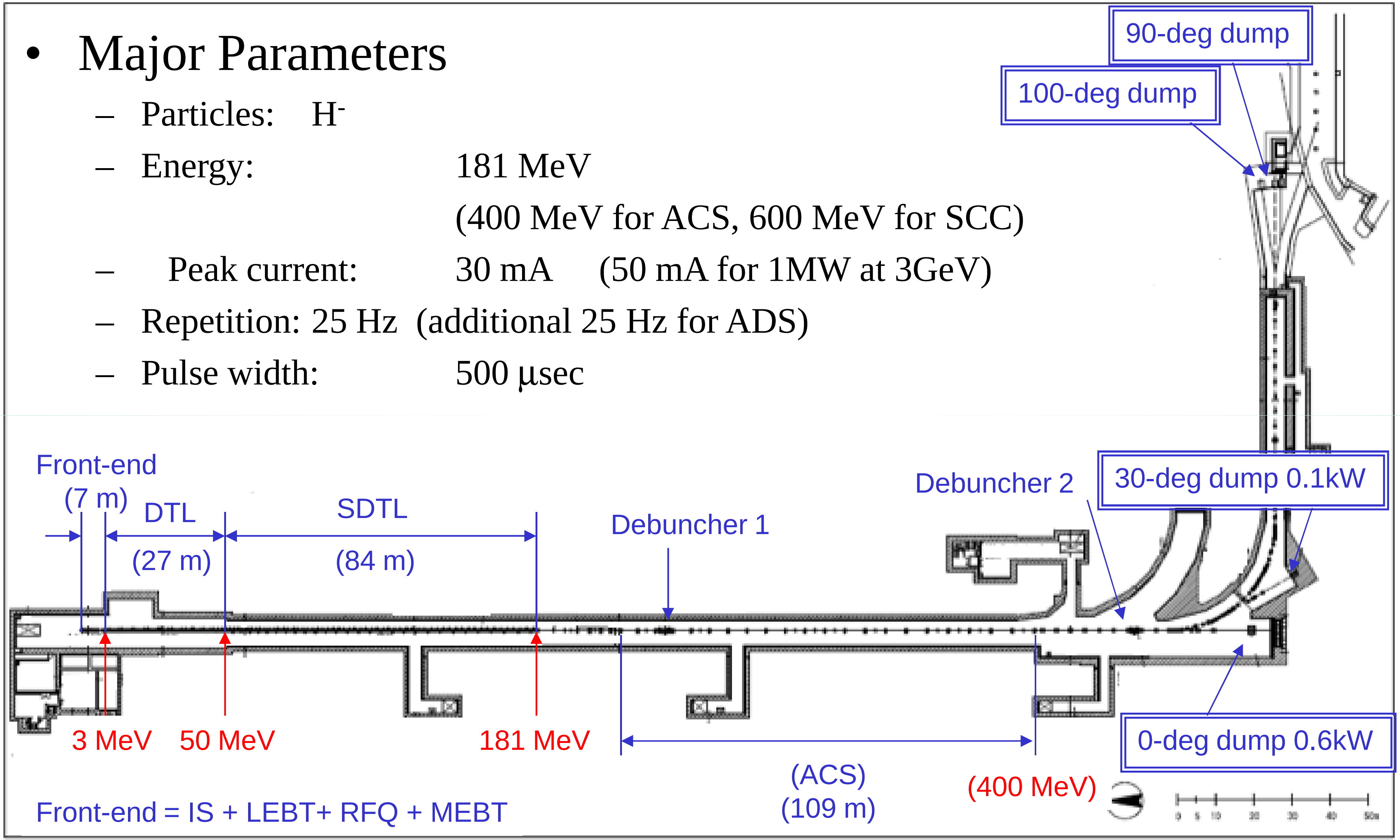
Dec. 2010:

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



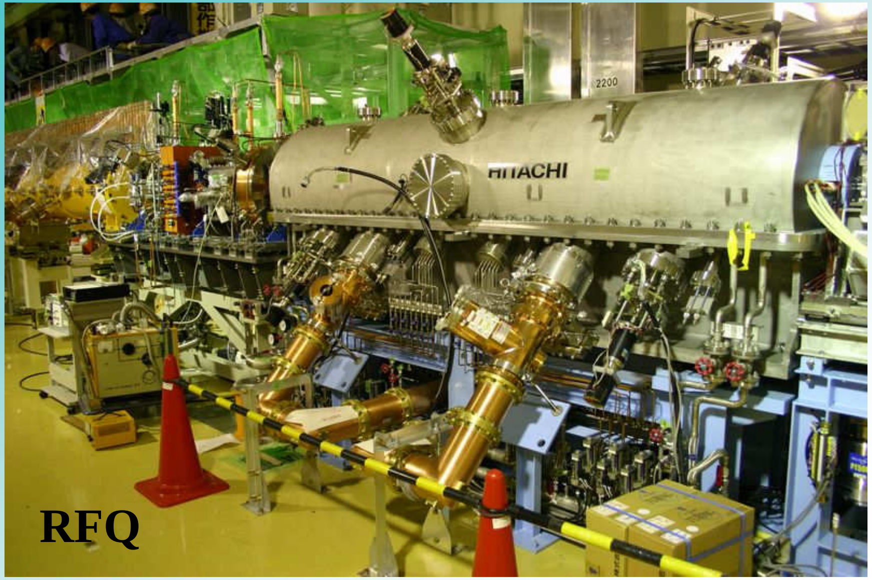
J-PARC : Linac parameters

- 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

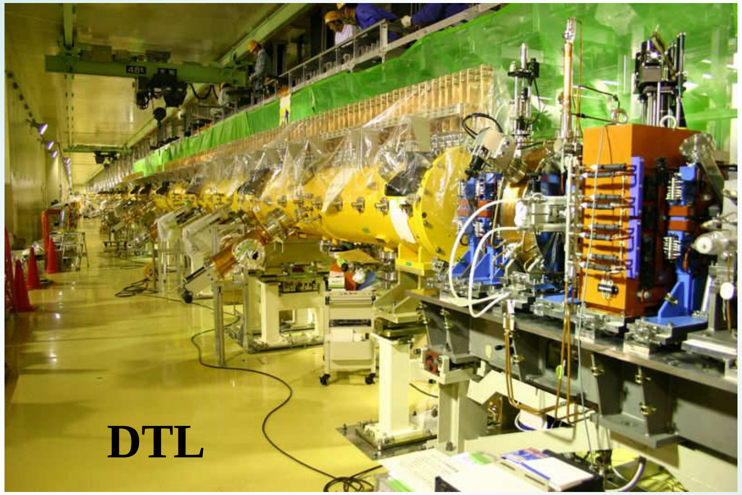


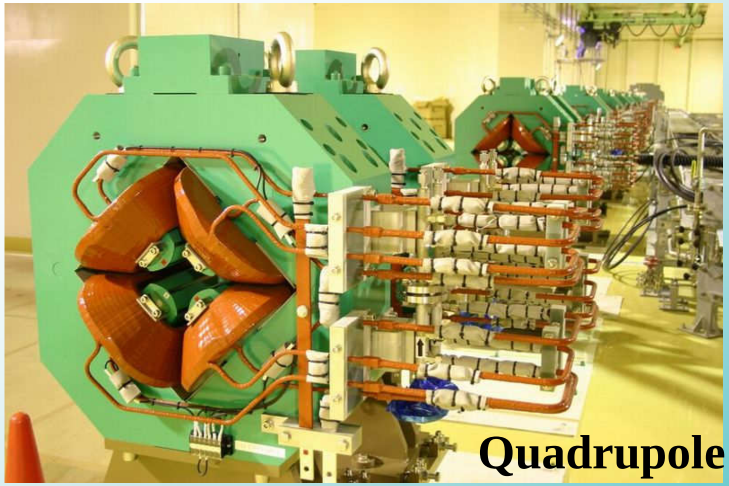
Front-end = IS + LEBT+ RFQ + MEBT

J-PARC : Linac pictures


RFQ


Klystron


DTL

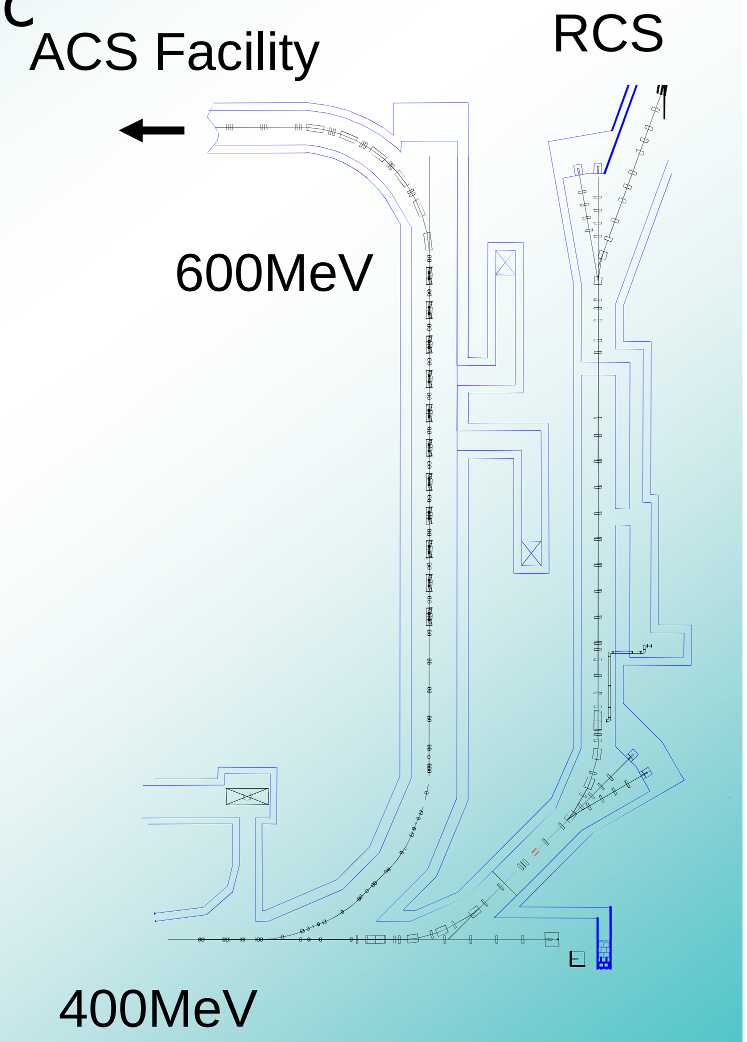

Quadrupole

J-PARC : The SC Linac parameters

Preliminary design of SC proton linac

Design Parameters

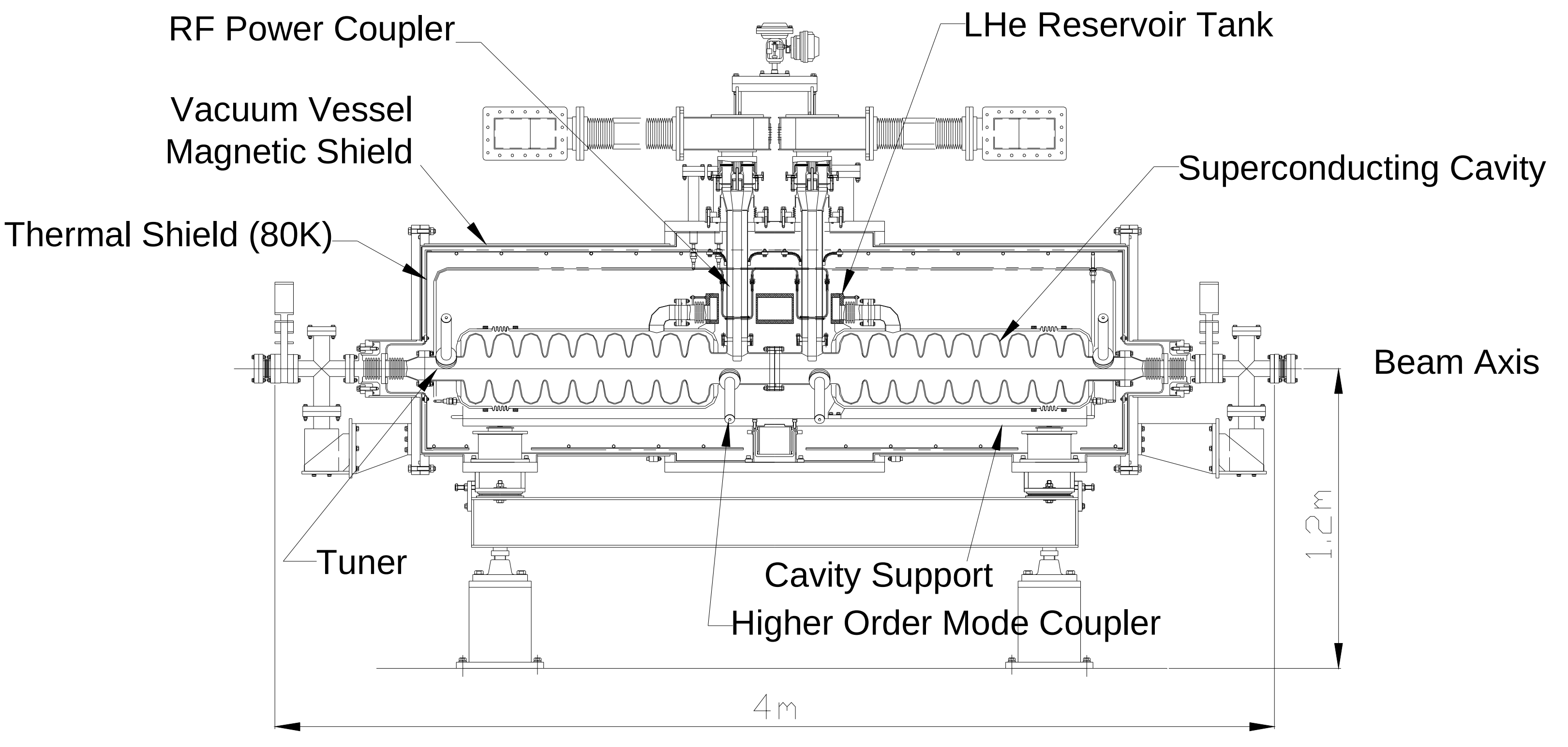
Energy	400-600 MeV
Frequency	972 MHz
β	0.71-0.79
No. of Cell	9 cell/cavity
No. of Cavity	2 cavity/cryomodule
No. of Cryomodule	11 cryomodules
Length	57.7 m
Surface Peak Field	30 MV/m
Accelerating Field	9.7-11.1MV/m
Synchronous Phase	-30 deg
No. of Klystron	11 klystrons
Total RF Power	10 MW
Loaded Q	~500,000



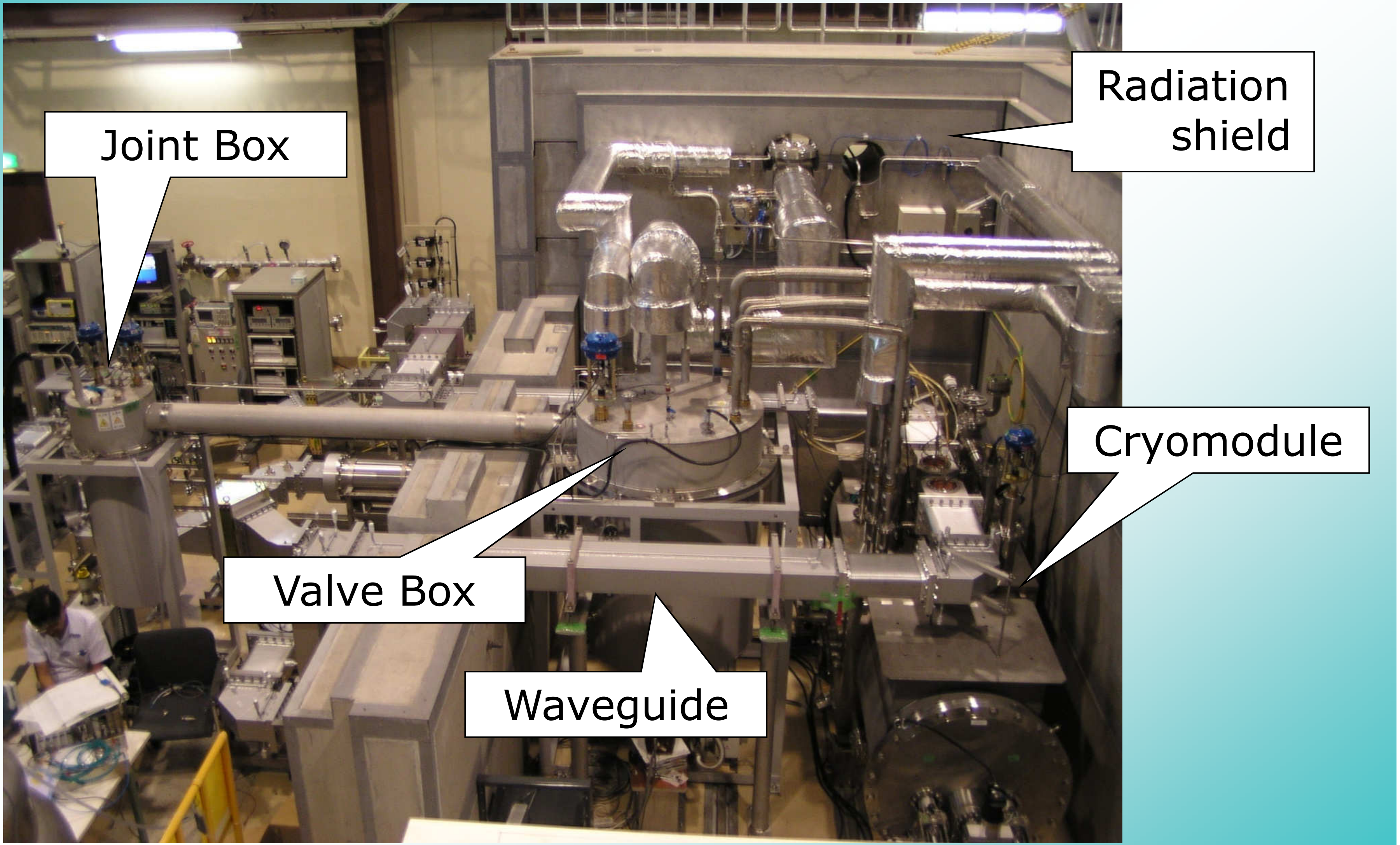
Amplitude and phase stability (±1% & 1deg) in pulsed operation

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



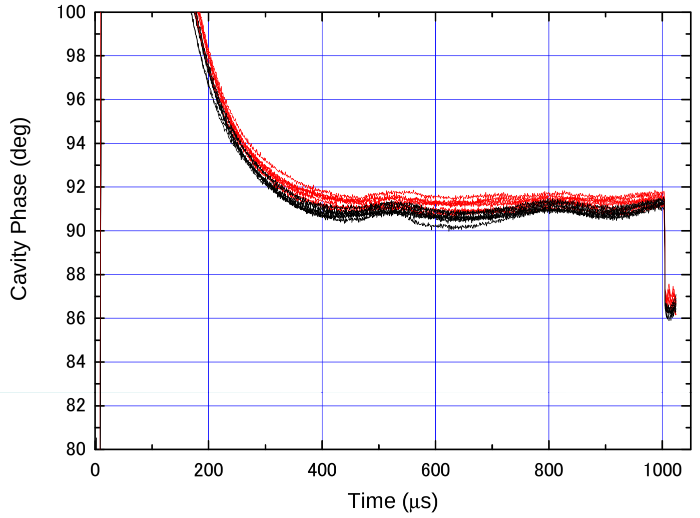
J-PARC SC Linac : R&D on 972 MHz cryomodule



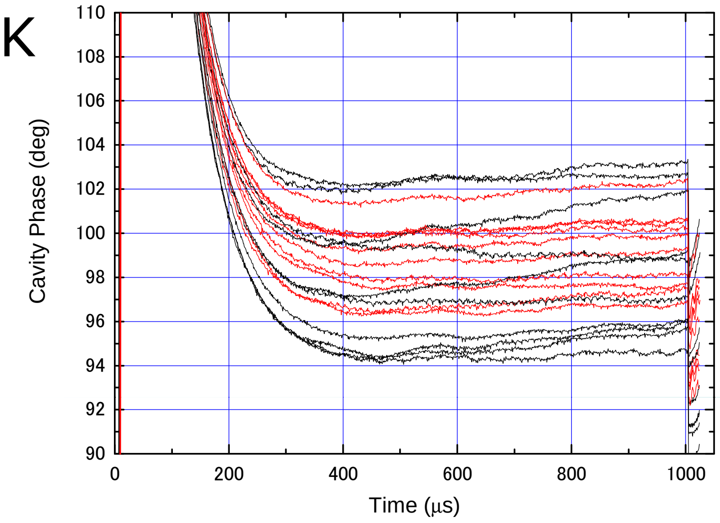
J-PARC SC Linac : R&D on 972 MHz cryomodule

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

(under commissioning)

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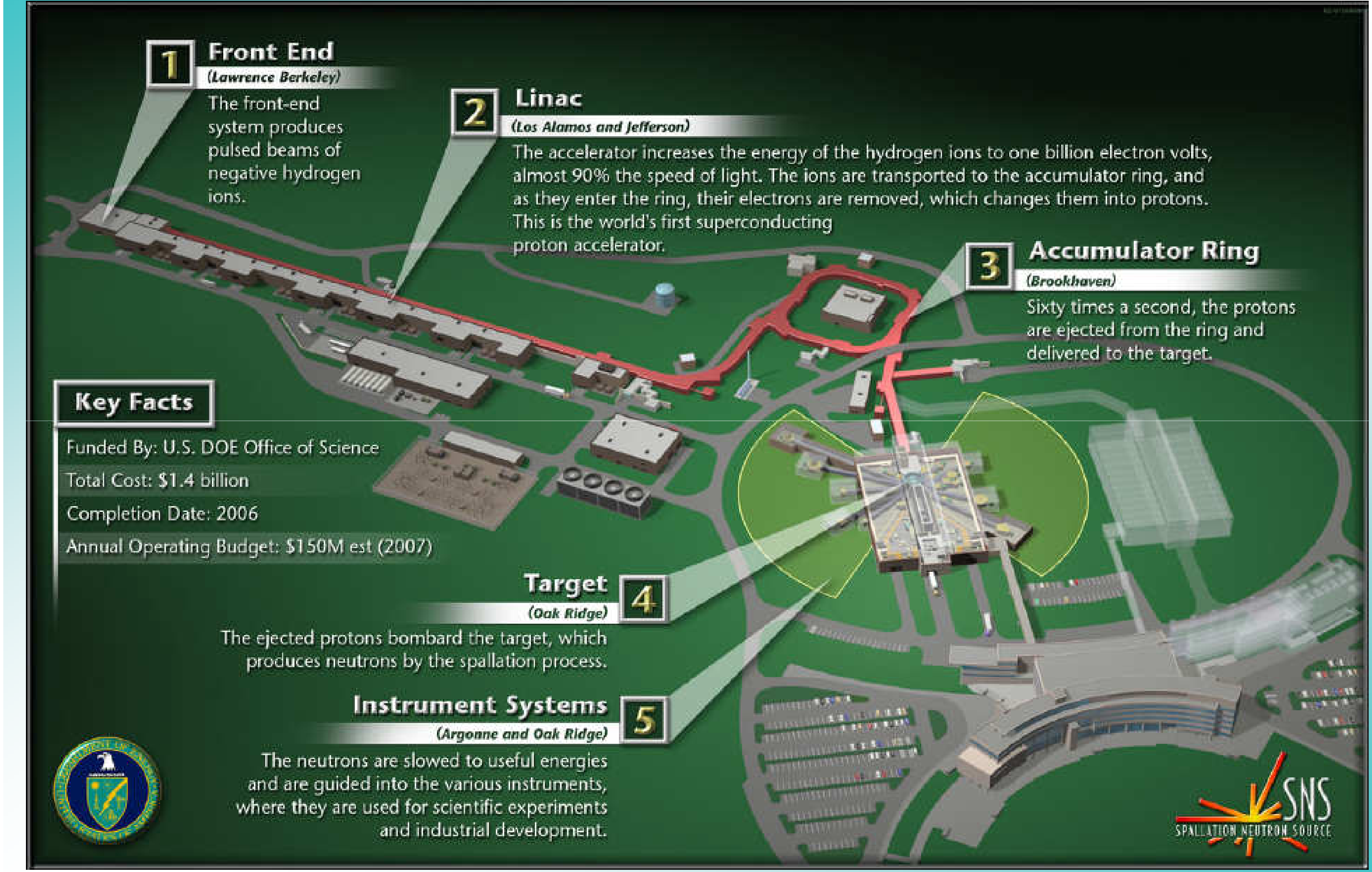
SNS : the US spallation neutron source

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 4

(Oak Ridge)

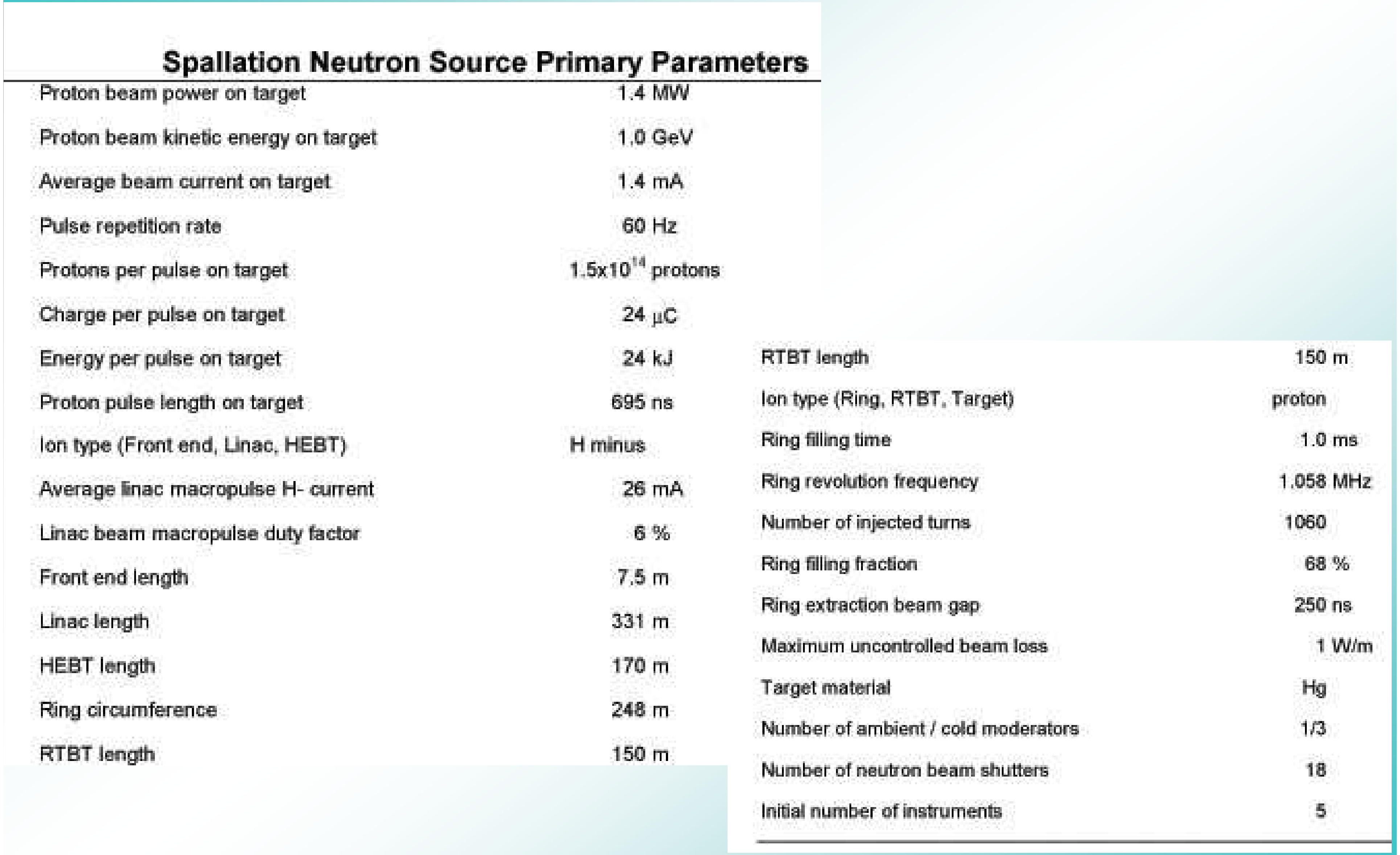
The ejected protons bombard the target, which produces neutrons by the spallation process.

Instrument Systems 5

(Argonne and Oak Ridge)

The neutrons are slowed to useful energies and are guided into the various instruments, where they are used for scientific experiments and industrial development.

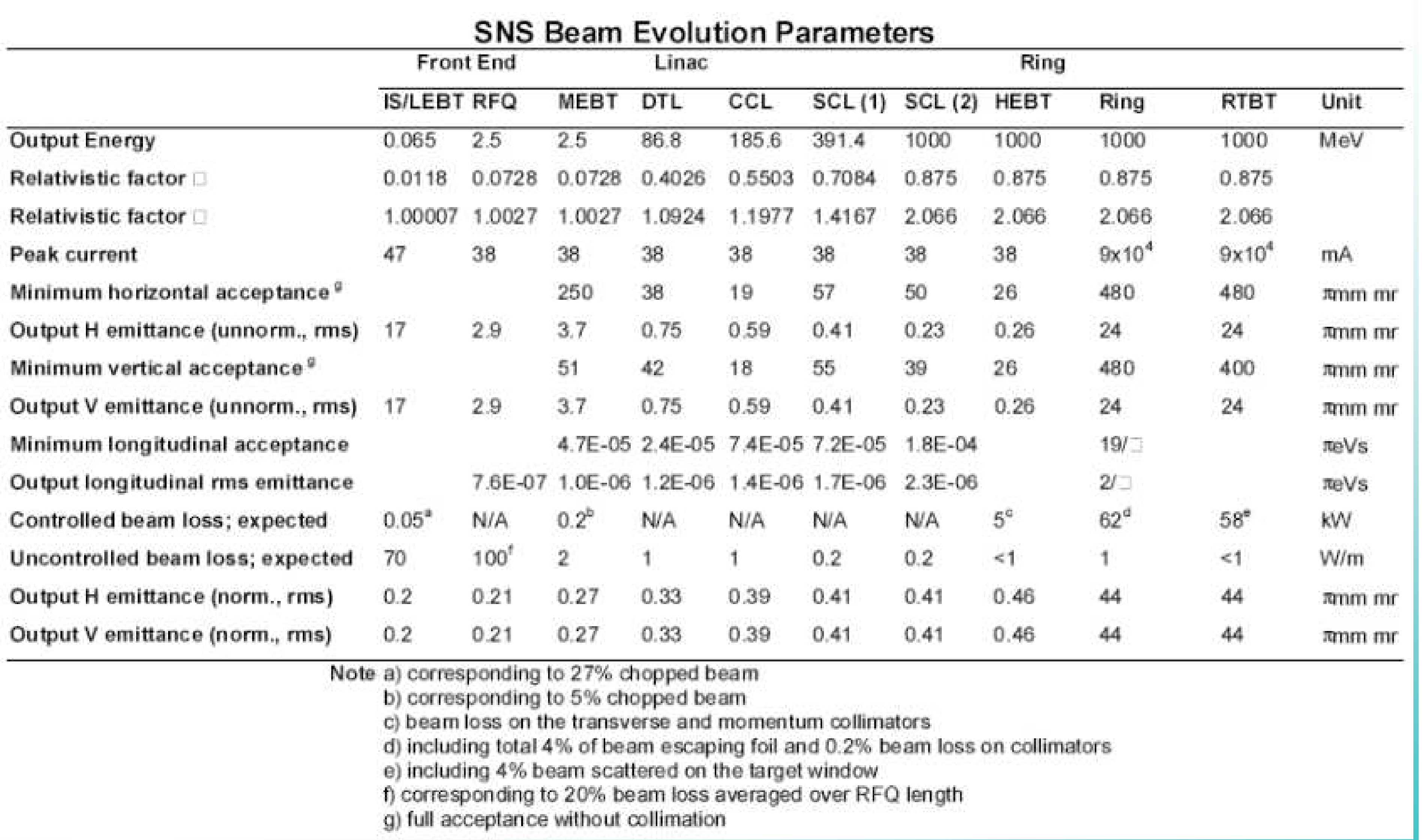
SNS : Main parameters



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

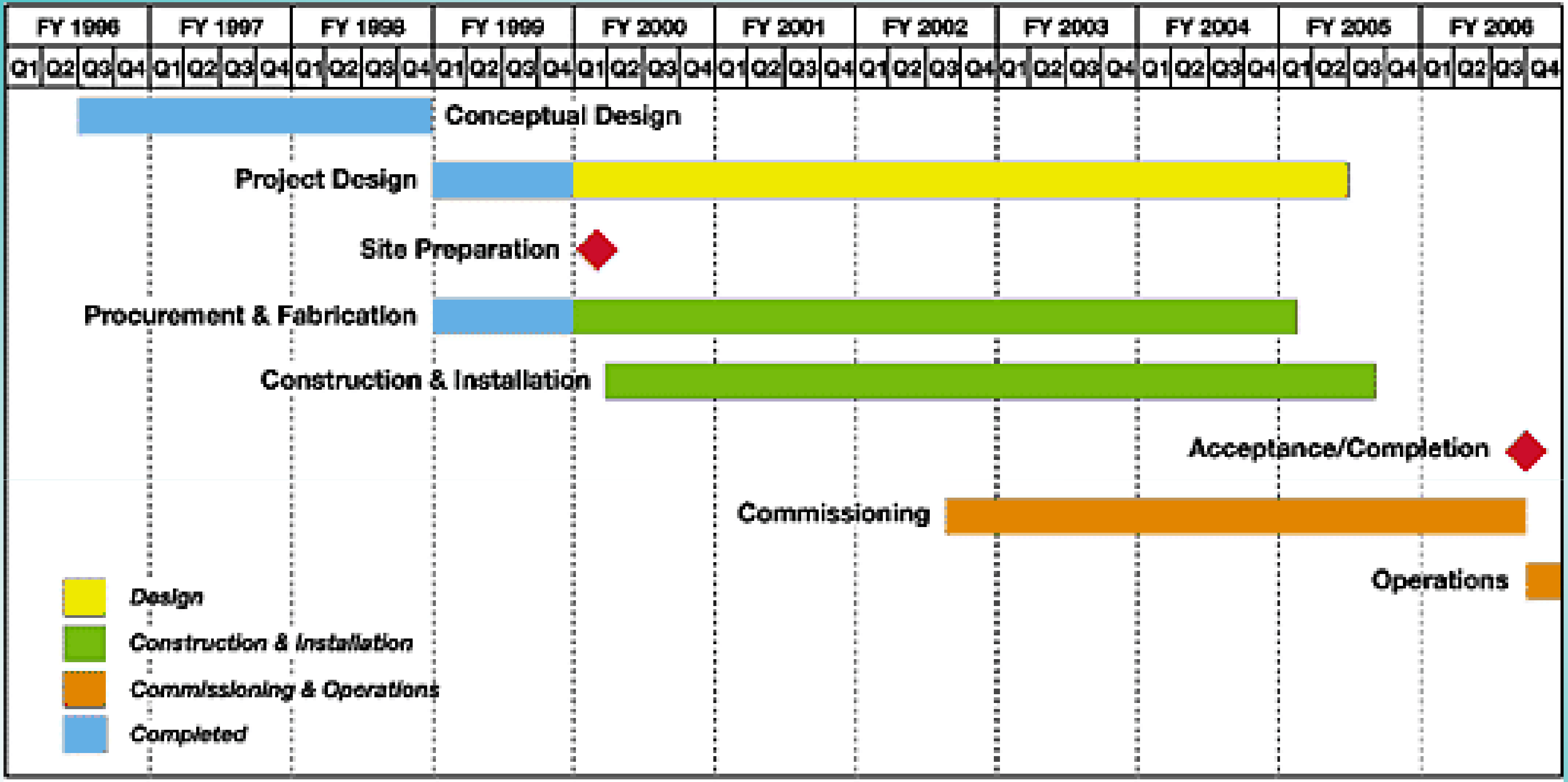


SNS Beam Evolution Parameters

	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	9x10^4	9x10^4	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

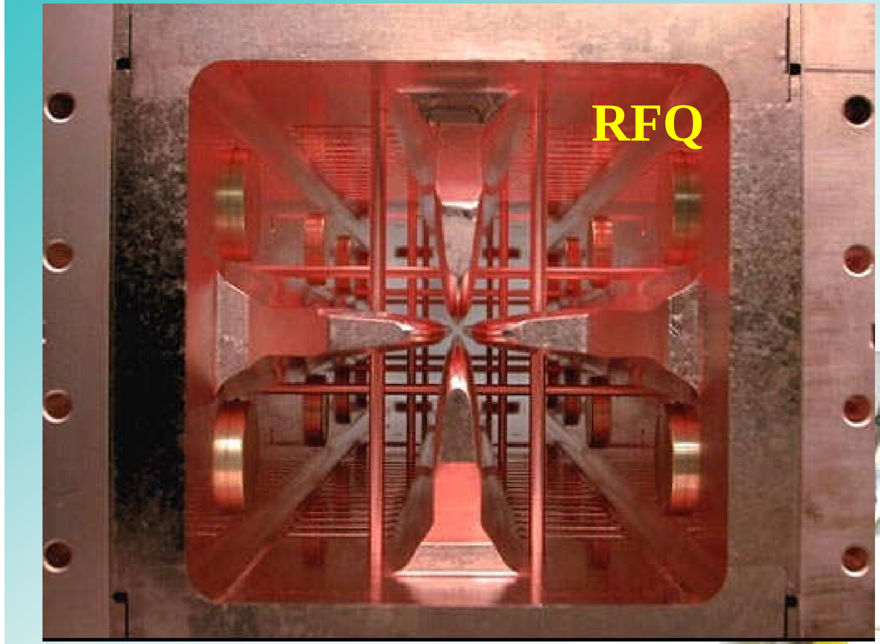
SNS : aerial views

End 1999

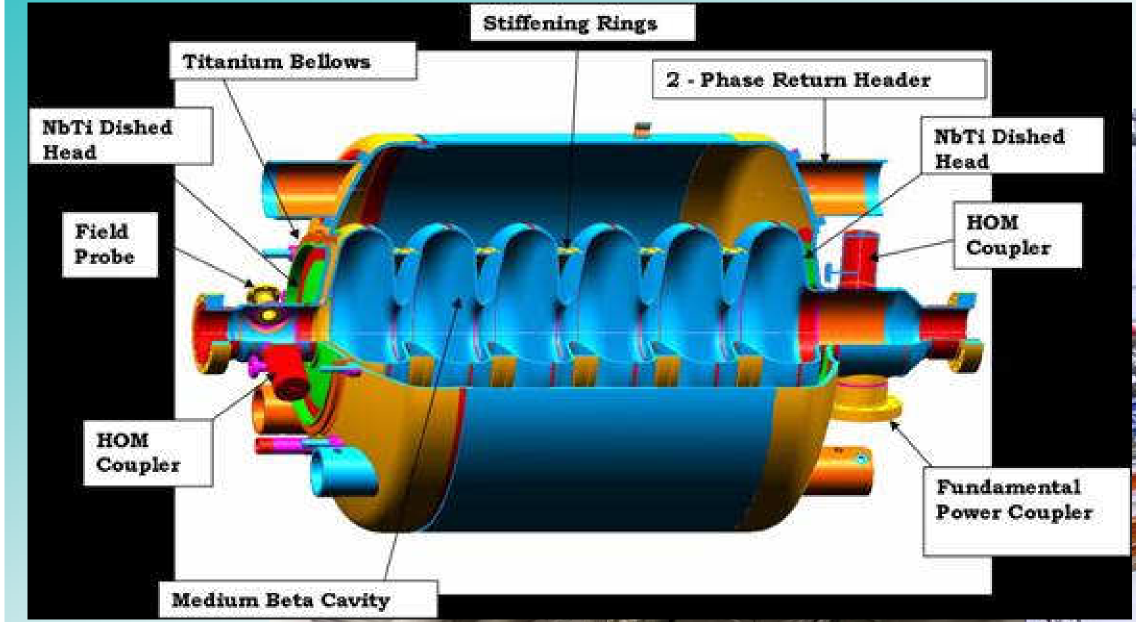
End 2000

SNS : aerial views

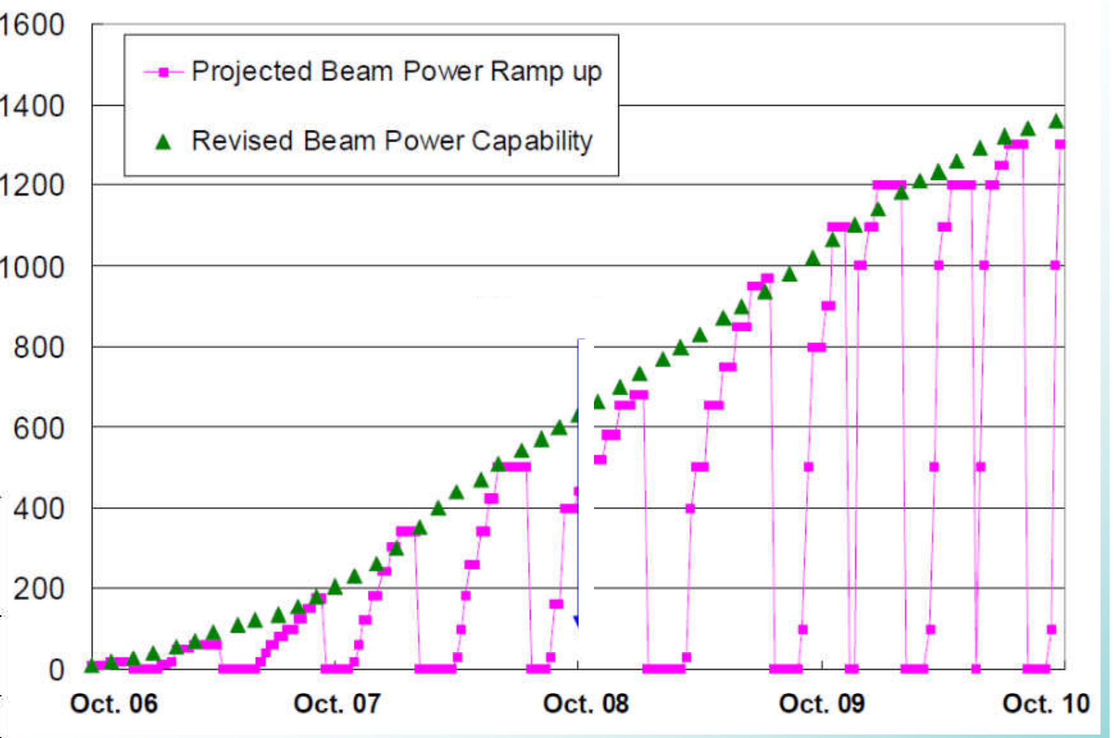
SNS : Linac pictures

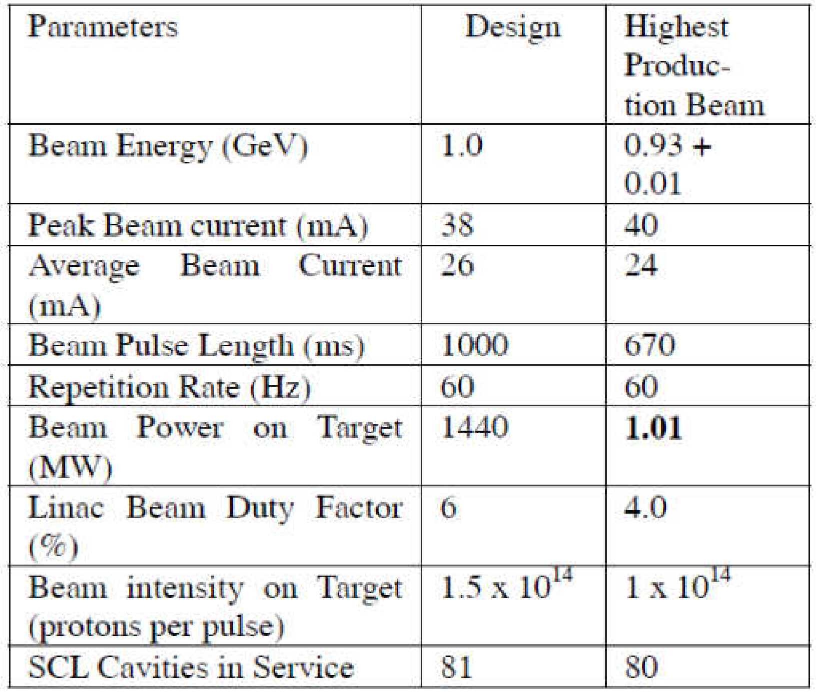


SNS : Linac pictures : SC cryomodules



SNS : Design vs achieved parameters (oct. 2009)

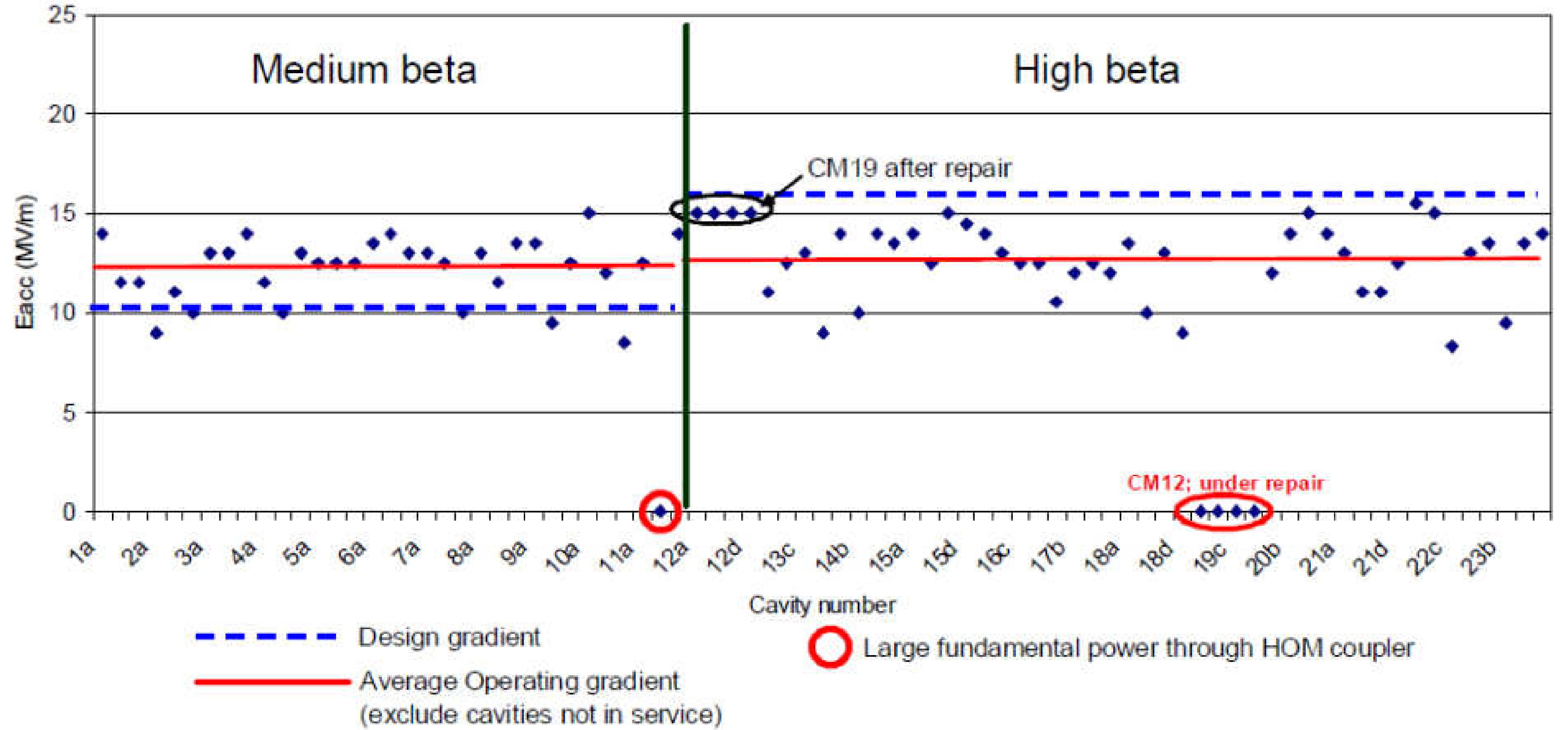




Parameters	Design	Highest Production Beam
Beam Energy (GeV)	1.0	0.93 + 0.01
Peak Beam current (mA)	38	40
Average Beam Current (mA)	26	24
Beam Pulse Length (ms)	1000	670
Repetition Rate (Hz)	60	60
Beam Power on Target (MW)	1440	**1.01**
Linac Beam Duty Factor (%)	6	4.0
Beam intensity on Target (protons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

SNS : Design vs achieved parameters

SNS Linac : Achieved accelerating gradients in SC cavities



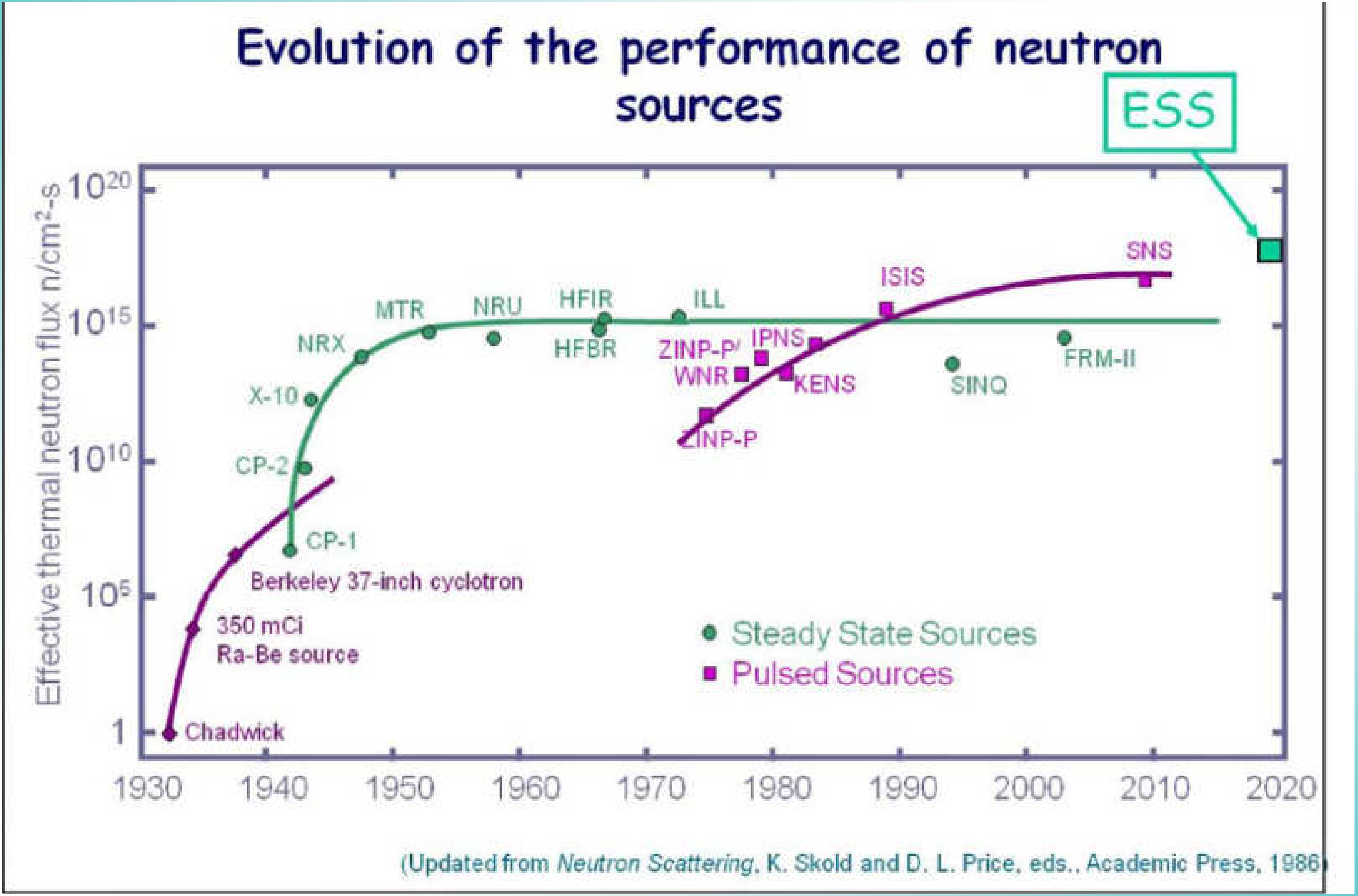
Future : finish commissioning up to 1.4 MW.

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 just approuved)

ESS : the European Spallation Source



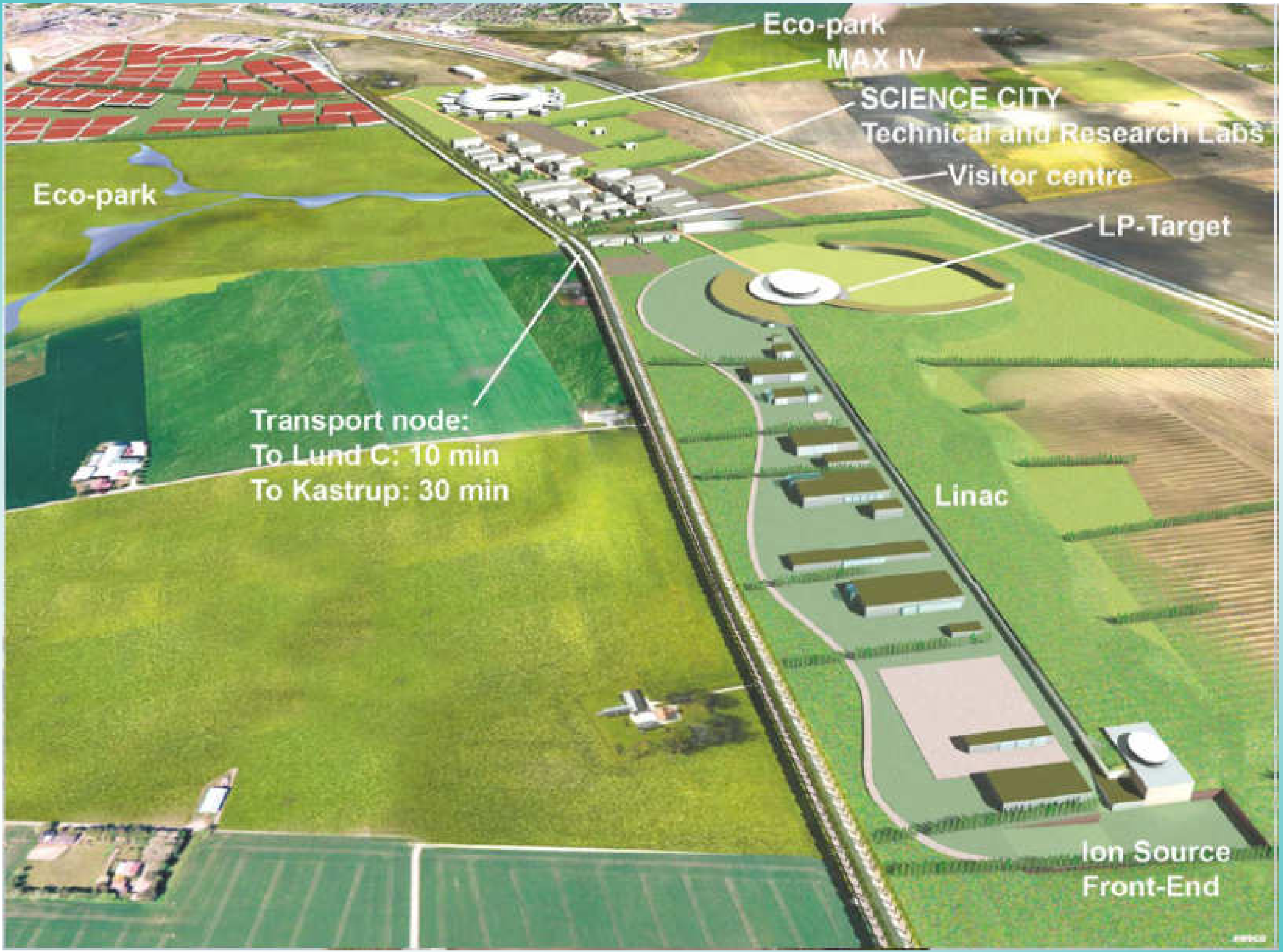
(Updated from *Neutron Scattering*, K. Skold and D. L. Price, eds., Academic Press, 1986)

ESS : the European Spallation Source

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

ESS : the European Spallation Source

ESS : the European Spallation Source



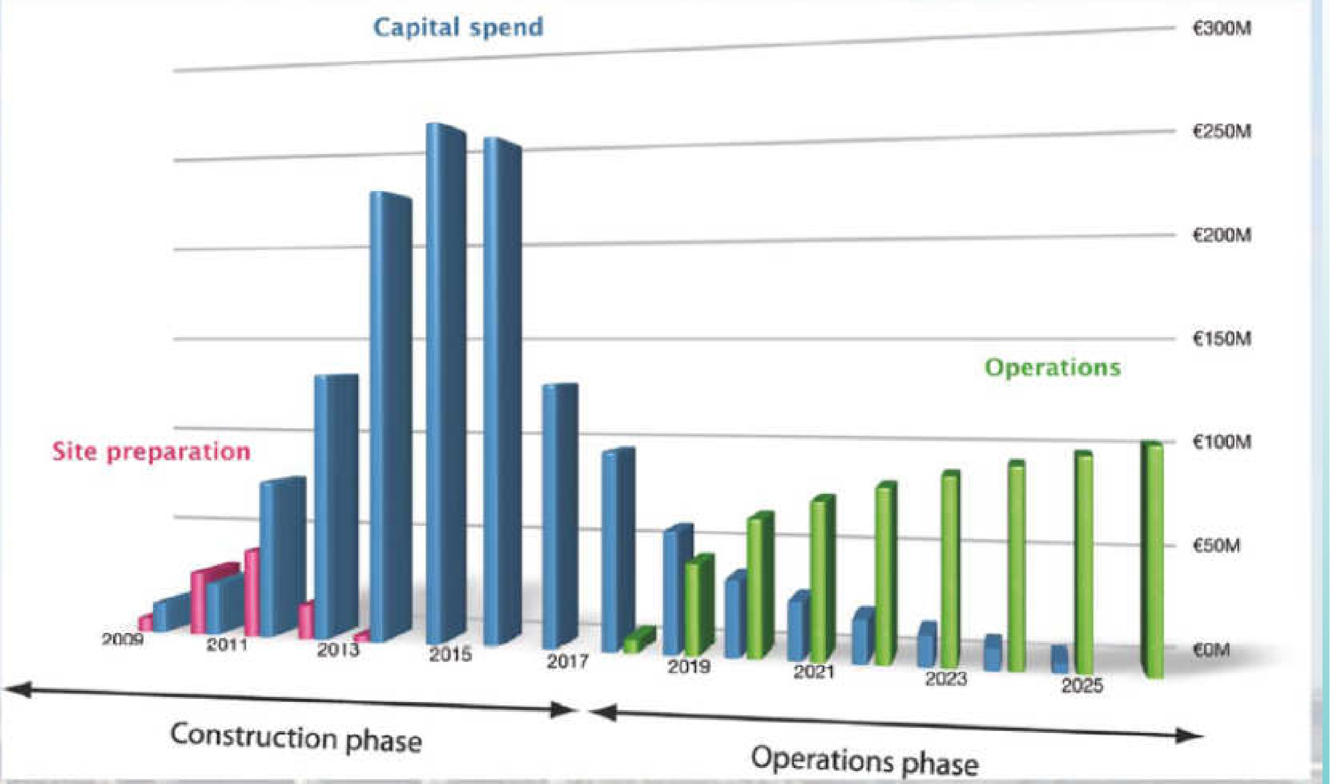
ESS : the European Spallation Source

Technical objective:

5 MW long pulse source
(Upgrade 7.5 MW)

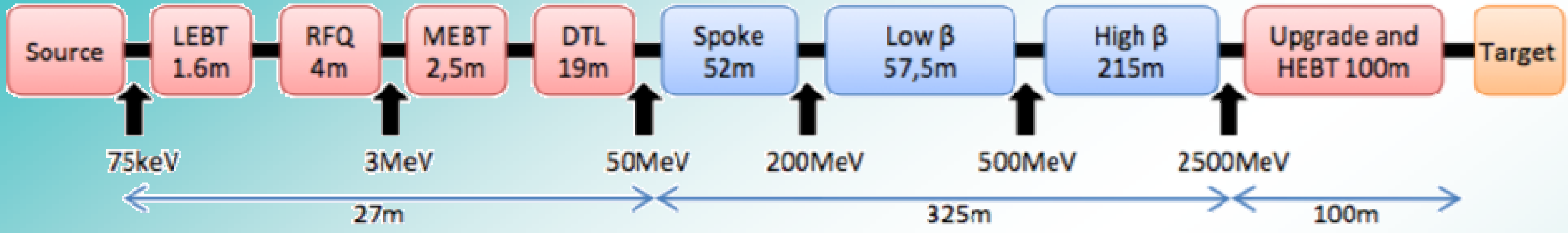
Long pulse (~2 ms)
20 Hz rep rate
Protons beam

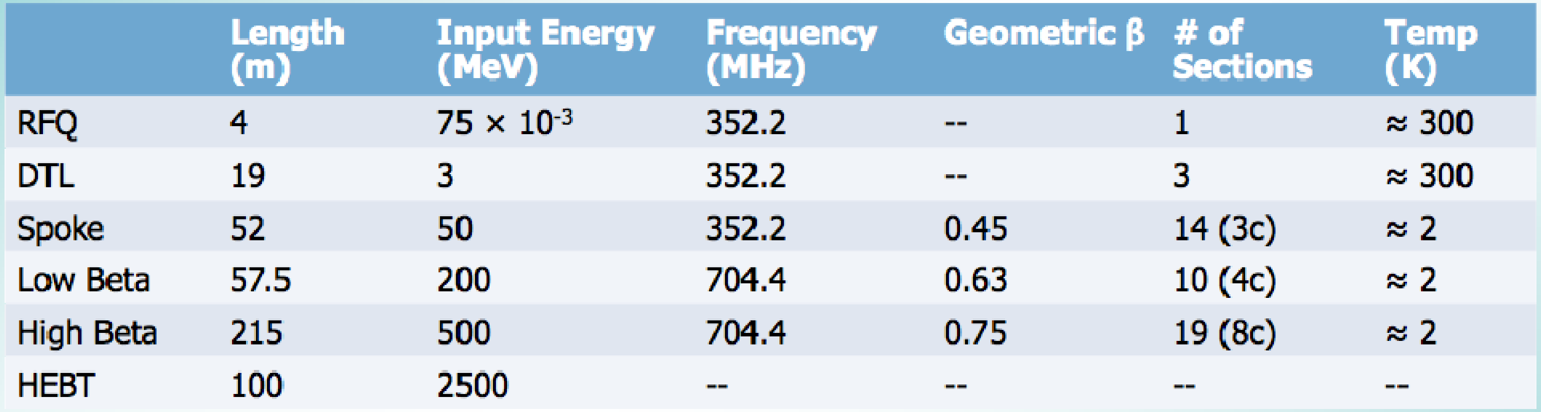
High reliability (>95%)
Low losses



Facility investment: 1.377 M€$_{2008}$ with 22 instruments
+ 101 M€$_{2008}$ site specific cost
Operational cost: 89 M€$_{2008}$ per year
Decommissioning cost: 344 M€$_{2008}$

ESS : the European Spallation Source





	Length (m)	Input Energy (MeV)	Frequency (MHz)	Geometric β	# of Sections	Temp (K)
RFQ	4	75×10^{-3}	352.2	--	1	≈ 300
DTL	19	3	352.2	--	3	≈ 300
Spoke	52	50	352.2	0.45	14 (3c)	≈ 2
Low Beta	57.5	200	704.4	0.63	10 (4c)	≈ 2
High Beta	215	500	704.4	0.75	19 (8c)	≈ 2
HEBT	100	2500	--	--	--	--

- 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

Project planning