RRCAT

Critical Aspects of Spallation Neutron Sources

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Outline

- Motivation – Spallation Neutron Source
- Why Neutron
- Neutron v/s X-ray
- Sources of Neutron
- SNS – world scenario
- Technology development
- Spallation Target
- Facility layout

Importance of Spallation Neutron Source

The proposed Indian Spallation Neutron Source (ISNS) will be a unique facility for neutron based multi-disciplinary research. The facility will compliment reactor based neutron research facility at BARC and synchrotron facility at RRCAT.

Motivation:

- Research in the fields of condensed mater physics, material sciences, chemistry, biology and engineering.
- Radiation therapy R&D using proton linac (~250 MeV)
- Nuclear physics experiments using 1 GeV proton (Exp. ADS)
- SCRF cavity infrastructure will be useful for domestic programs and International collaborations

Characteristics of neutron for material science

• No charge	Deep penetration through material
• Spin 1/2	Magnetism research
• Large cross sections for H, C…	Soft materials, life science
• Wave length 1.8 A at En=25.3meV	~Unit size of materials Crystal structure < 10eV
• Atomic mass ~ 1	Sensitive to material motion Dynamics

Nobel prize to neutron scattering studies in 1994.
C.Shull (Antiferromagnetism) &B. Brockhouse (Ineastic Scattering)

Neutrons as a Probe of Materials Vs X-rays and Electrons

- Thermal neutrons produced in the core of a reactor or through moderation in SNS, have a wavelength distribution peaked around 0.1 nm, ideally suited for studying atomic structure. Thermal neutrons having energy about 0.025 eV are incapable of disturbing even the most delicate materials, like biological materials.

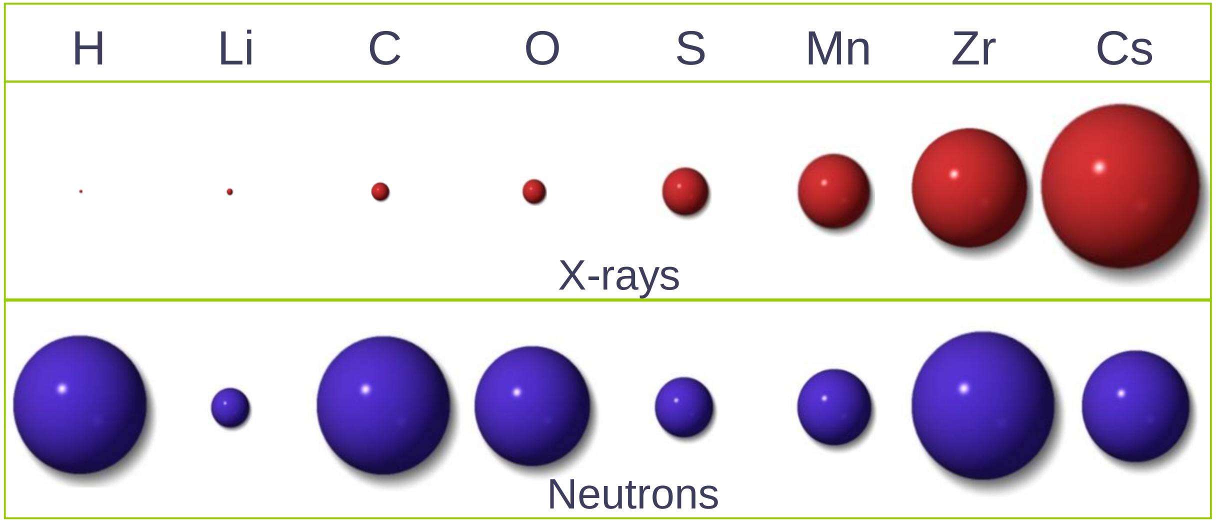
- A further consequence of the low energy of thermal neutrons is that in inealstic scattering events neutrons exchange energy with the sample, creating or destroying excitations (phonons, magnons etc.) in the process. The study of these disturbances provides a unique probe of the inter-atomic forces in the materials.

- Electrons of wavelength 0.1 nm have energies more than 3 eV, which is greater than typical bonding energies.

- X-rays with 0.1 nm wavelength have about 12 keV energy, capable of multiple ionization of the most robust chemical structures.

- Neutrons can determine magnetic structures of the solids.

Comparison of Neutron Characteristics with X-ray



X−rays interact with electrons.

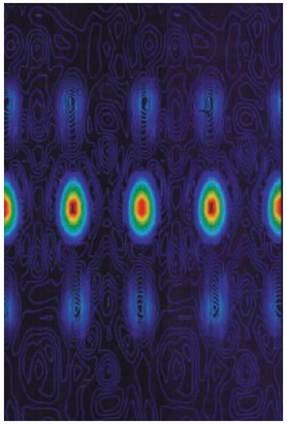
X−rays see high−Z atoms.

Neutrons interact with nuclei.

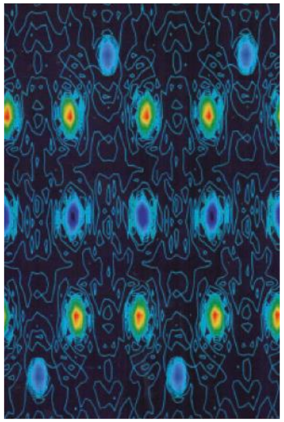
Mass dependence of neutron scattering cross section is small.

Neutrons see low−Z atoms.

Material for Li-battery seen by

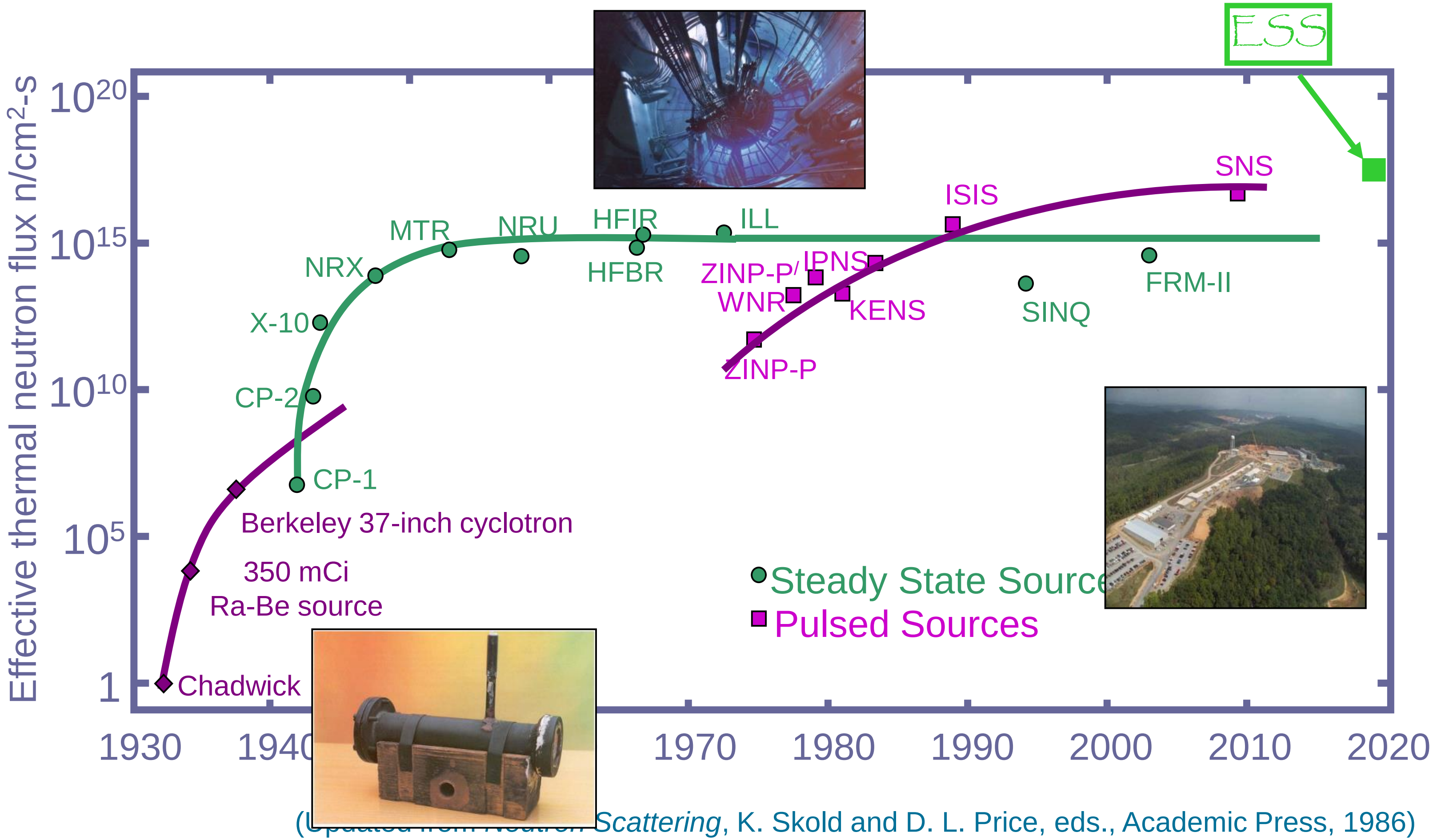


X-ray



Neutron

Evolution of Neutron Sources



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

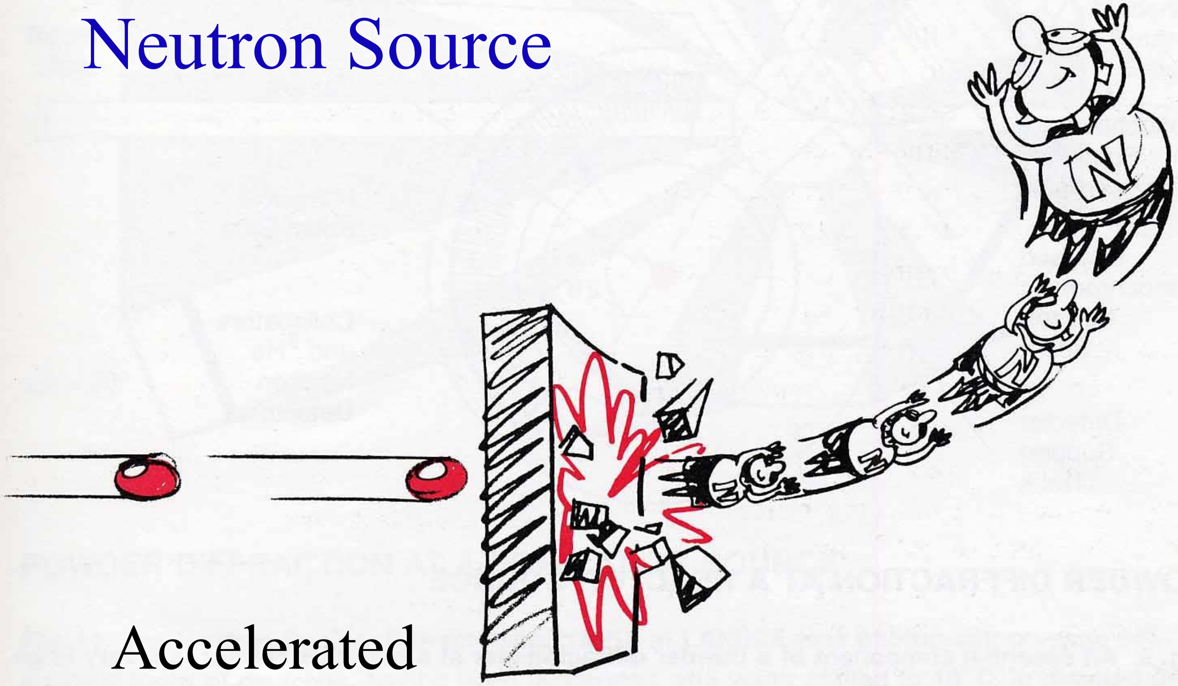
Comparison of neutron yield

Reaction	Example	Yield (n/process)	Energy deposition (MeV/n)	Yield/E-dep (n/MW)
d(T, n)	400 keV d+ T in Ti	4×10^{-5} n/d	10,000	6.3×10^{14}
Deutron stripping	35 MeV D on liq. Li	2.5×10^{-3} n/d	10,000	6.3×10^{14}
(γ, n)	100 MeV e- on ^{238}U	5×10^{-2} n/e	2,000	3.1×10^{15}
Fission	Fission reactor	1 n/fission	180	3.5×10^{16}
Spallation	800 MeV p on ^{238}U	30 n/p	55	1.1×10^{17}
DT CTR	Laser or ion-beam imploded pellet	1 n/fusion	3	2.1×10^{18}

N.B. Fission reaction emits 2-3 neutrons, but only one neutron is effective in order to self-sustain chain reactions in nuclear reactor.

Accelerator Driven Neutron Source

Neutrons



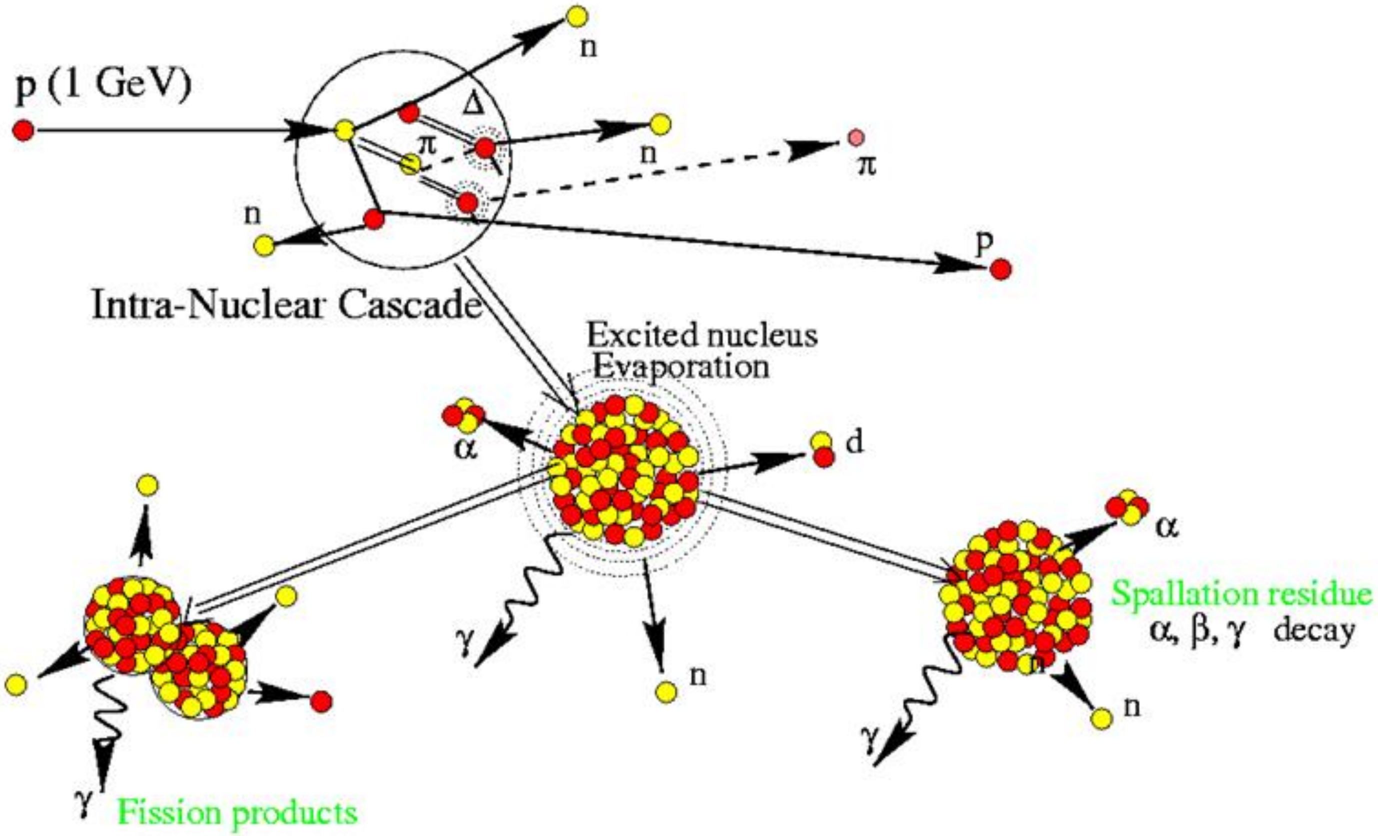
spallation neutrons

Neutrons generated at an accelerator by driving a highly energetic beam of particles, typically protons, into a target of heavy atoms, such as tungsten. The incident protons knock neutrons loose from the nuclei of the target, creating a pulse of highly energetic spallation neutrons.

Accelerated Protons

Spallation Reaction

Spallation Reaction



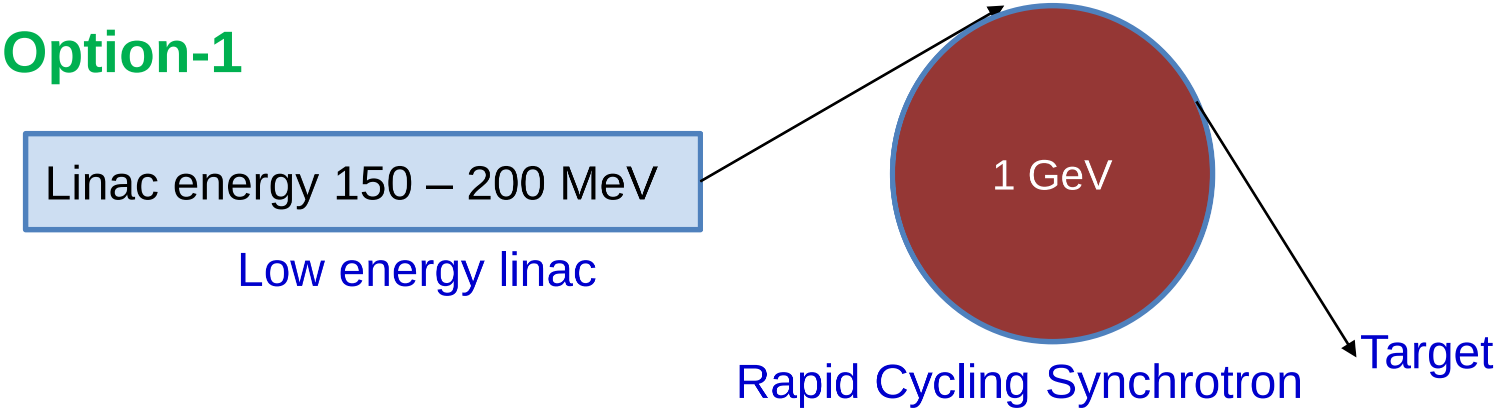
Major Sub-Systems of SNS Facility

- High power proton linac
- Proton synchrotron / Accumulator Ring
- Target station
- Beamlines and experimental stations

Configurations of
Proton Accelerator for SNS

Spallation Neutron Source

Option-1



Linac energy 150 – 200 MeV

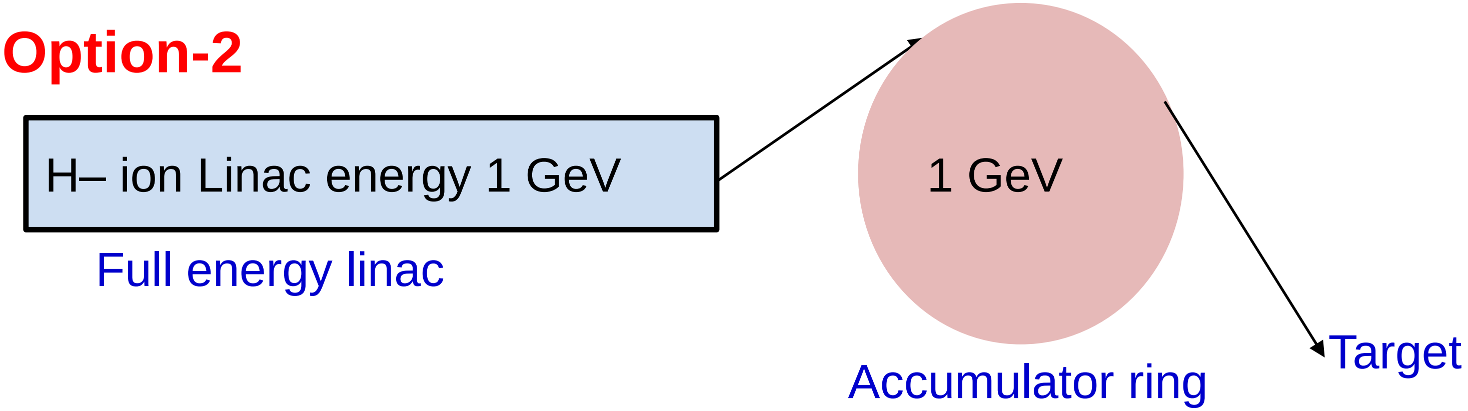
Low energy linac

1 GeV

Rapid Cycling Synchrotron

Target

Option-2



H– ion Linac energy 1 GeV

Full energy linac

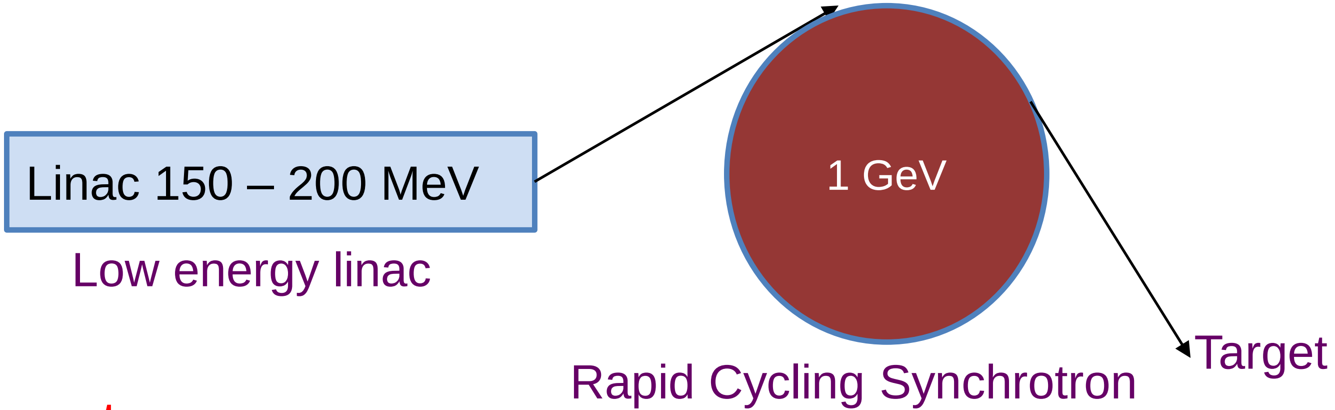
1 GeV

Accumulator ring

Target

Accumulates current and bunches the proton beam into short duration pulses of ~ 1 μs duration

Linac + Synchrotron Driven SNS (Option – 1)



Linac 150 – 200 MeV

Low energy linac

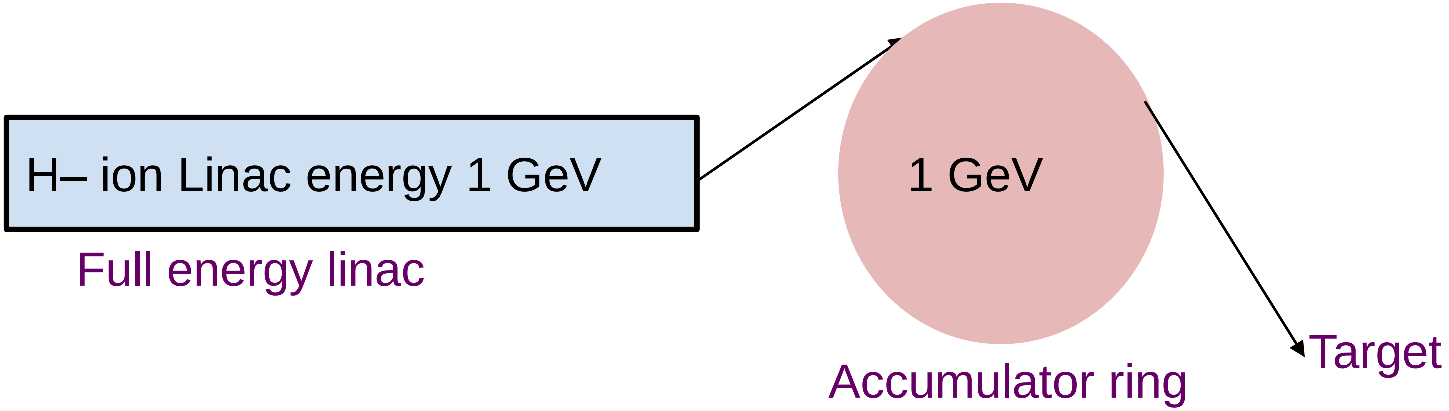
1 GeV

Rapid Cycling Synchrotron

Target

- Advantages:
  - Lower cost as compared to Linac based SNS
  - Lower radiation activity at injection point
- Disadvantages:
  - Complex magnet power supplies for synchrotron due to fast ramping/rapid cycling
  - Complex RF cavities in synchrotron due to change in beam energy
  - Linac energy (~ 150 MeV) space charge and accumulation issues
  - Ceramic chambers (eddy currents – fast cycling magnets)

Linac Driven SNS (Option – 2)



H– ion Linac energy 1 GeV

Full energy linac

1 GeV

Accumulator ring

Target

- Advantages:
  - High intensities possible
  - Ease of operation of accumulator ring
  - Linac can also be used for target experiments

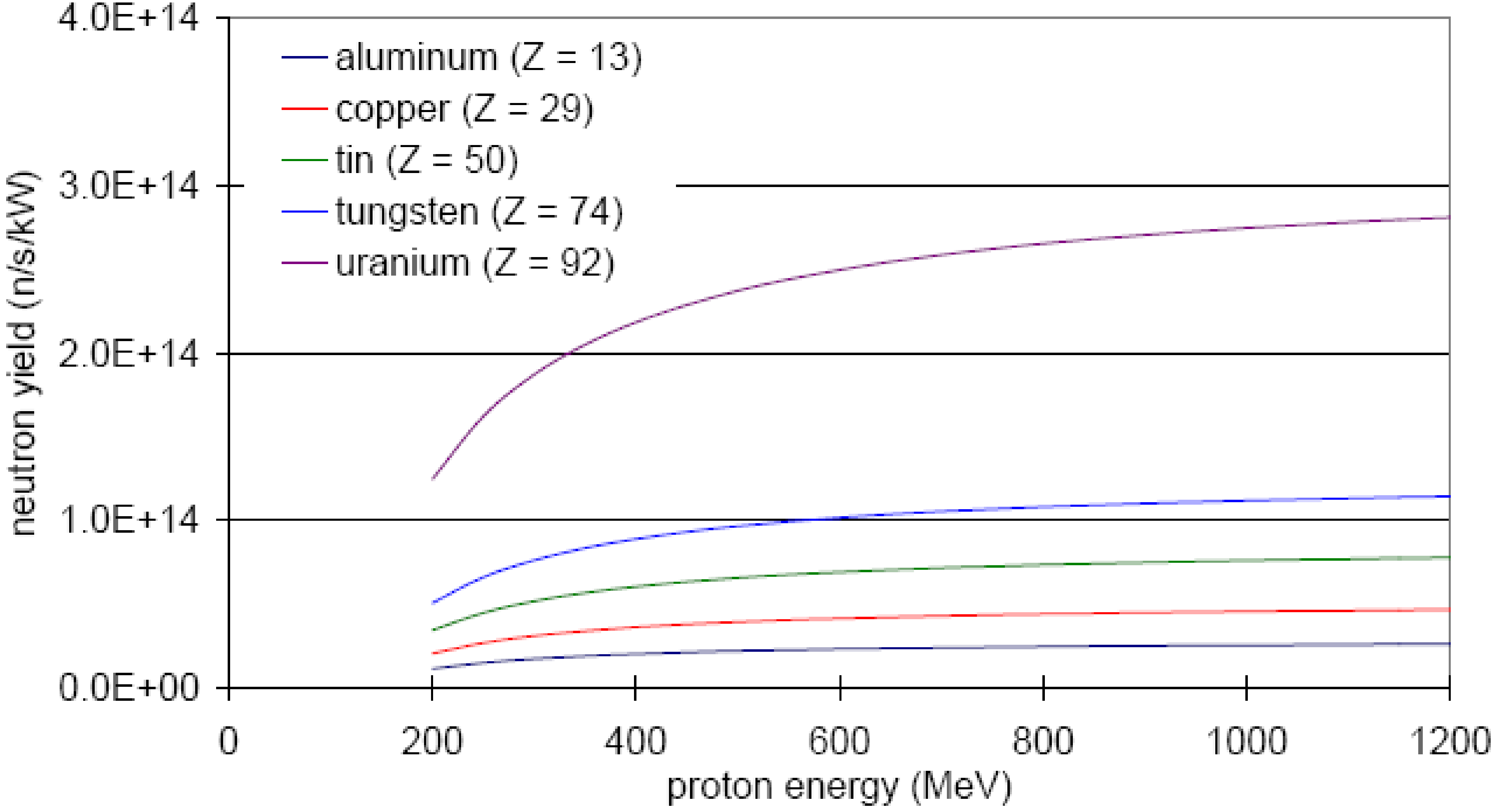
- Disadvantages:
  - High cost due to full energy linac
  - Higher operational cost
  - High radiation activity at injection point

Important Factors for Spallation Sources

SNS Linac

- Beam Energy – ~100 MeV to full energy
- Duty Factor % (DF=RF pulse duration x Rep rate x 100)
  - E.g. DF = 3% in JPARC and 6% in SNS
  - Heat dissipation in the linac
- Choice between Normal Conducting v/s SCRF
  - Front end – Normal Conducting (RFQ)
  - Lower energy part – (NC/ combination of NC+SCRF) depending on DF
- RF Frequency
  - (325 MHz – 402.5 MHz) Low energy Linac
  - 650 – 805 - 972 MHz for medium energy linac

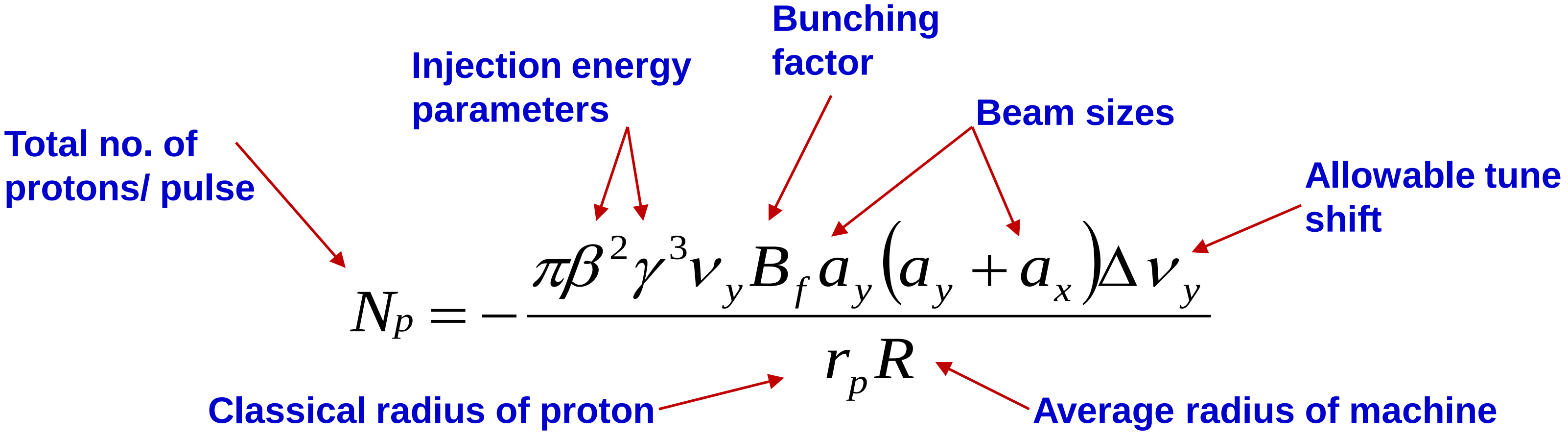
Choice of Proton Beam Energy



Limitation on Beam Current & Injection Energy

The Coulomb force between the charged particles of a high-intensity beam results in defocusing of the beam in transverse plane. The repulsive Coulomb forces between the particles cause the tune to be shifted from the design value that may induce beam instabilities and losses.

The number of particles that can be injected into the ring, keeping the tune shift within certain limit, is proportional to the beam energy and phase-space area of the beam.



Bunching factor

Injection energy parameters

Beam sizes

Total no. of protons/ pulse

Allowable tune shift

$$N_p = -\frac{\pi\beta^2\gamma^3\nu_y B_f a_y (a_y + a_x)\Delta\nu_y}{r_p R}$$

Classical radius of proton

Average radius of machine

Dependence of Beam Power on Injection Energy

$$P_{beam} = q\, N_{p}\, f\, E = I_{avg}\, E$$

- P_{beam} : Beam power (W) at target
- q : Charge on proton (C)
- N_p : No. of protons/ pulse

- E : Final proton energy (eV)
- f : Repetition rate (Hz)
- I_{avg} : Average current at Target (A)

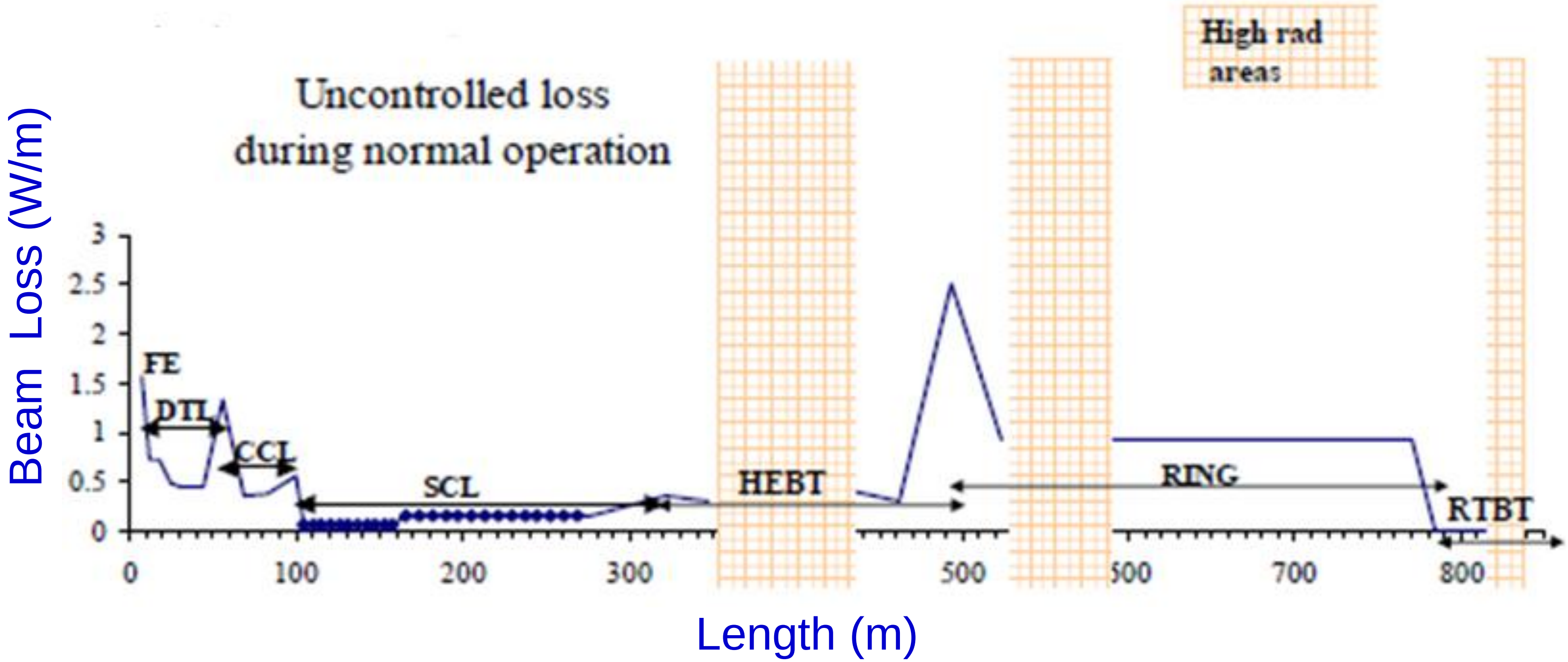
E (MeV)	β	γ	$\beta^2\gamma^3$
100	0.428	1.107	0.25
500	0.758	1.533	2.07
1000	0.875	2.066	6.75

Since N_p is proportional to $\beta^2\gamma^3$, high injection energy is required to achieve high beam power

Uncontrolled Beam Loss

- Hands-on maintenance : no more than 100 mrem/hour residual activation (4 h cool down, 30 cm from surface)
- 1 W/m uncontrolled beam loss for linac & ring
- Less than 10^{-6} fractional beam loss per tunnel meter at 1 GeV; 10^{-4} loss for ring

SNS @ ORNL



Accelerating Structures / RF Power

Super Conducting Cavities for Proton Linacs

- The SC cavities (Q ~ 10^9) have a large gain over NC cavities (Q~10^3-10^4). AC power consumption is therefore much lower using SC cavities.
- The savings in operating cost are estimated to be in the order of 3 M€/year for a 10-mA CW proton beam. This is somewhat offset by requirement of cryogenics.
- Choice of frequency has a trade-off between size and superconducting loss.

Size (Diameter)	α	1/f
Superconducting loss	α	f^2

- Multi-cell elliptical shape superconducting cavities are used for medium to high energy acceleration of protons.
- The elliptical shape is chosen for reducing multipacting and for ease of fabrication multicell structures

SCRF Cavities for Low β regime

- SC squeezed elliptical β=0.61 & β=0.81 have been adopted starting from 186 MeV at SNS Oak-Ridge
- SC squeezed elliptical cavities below <0.6 have certain technological limitations
- SC spoke cavities provide solution for low β (0.2 to 0.6) and has been a choice of designers for many proton accelerators
- SC spoke cavities have been proposed down up to 2.5 MeV (β=0.11) for Project-X FNAL

Klystron to Power Superconducting Cavities

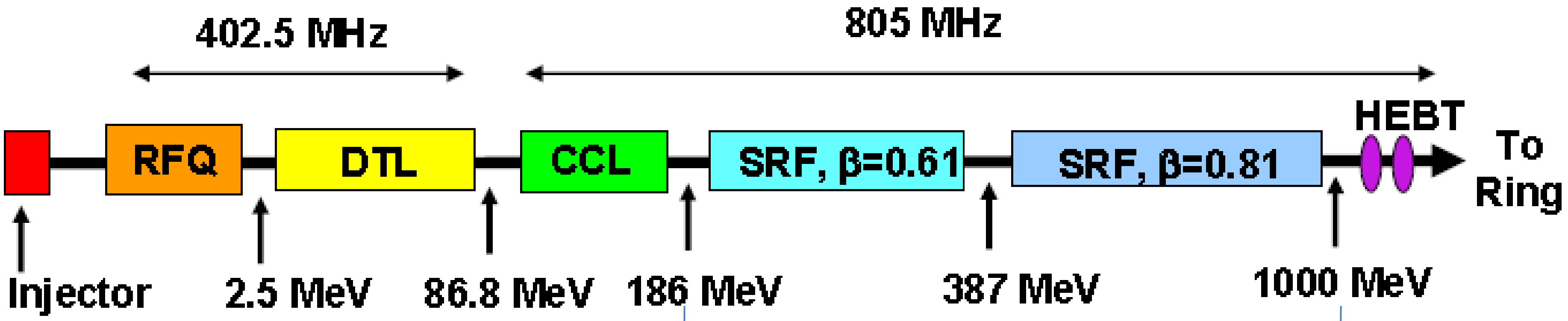
Frequency	User Laboratories	Klystron Suppliers
• 1500 MHz	Cornell design for CEBAF (J.Lab)	CPI (Communication and Power Industries)
750 MHz		
375 MHz		
• 1300 MHz	DESY (X-FEL), ILC (Proposed frequency), Fermilab (Project X)	CPI, Toshiba, Thales
650 MHz		
325 MHz	ISIS (upgrade), CSNS, Project X	Toshiba (Pulsed 324 MHz, which can be adjusted to 325 MHz)
• 972 MHz	J-PARC (NC + SC Linac)	Toshiba
324 MHz	J-PARC (RFQ, DTL, SFDTL)	Toshiba
• 805 MHz	SNS (ORNL)	CPI
402.5 MHz	SNS	Marconi
• 500 MHz	KEKB (B factory electron positron collider). DESY-PETRA (electron proton ring)	CPI, Toshiba, Thales
• 352 MHz	LEP(CERN : large electron positron collider), ESS (Planned)	Thales
704 MHz		CPI

Survey of Spallation Neutron Sources / Pulsed Proton Linacs

World-wide Spallation Neutron Sources

Country	Facility	Status	RCS /AR	Injection energy	Pulse duration	Rep rate (Hz)	Duty factor	Final energy	Current @target	Protons per pulse ($x10^{12}$)	Power
USA	IPNS	Closed (2007)	RCS	50 MeV	80 μs	30	0.24%	500 MeV	15 μA	3	7.5 kW
	PSR/ LANSCE	Operational (Since 1983)	AR	800 MeV	625 μs	20	1.25%	800 MeV	80 μA	25	64 kW
	SNS	Operational (Since 2006)	AR	1 GeV	1 ms	60	6%	1 GeV	1 mA	200	1 MW
Switzerland	PSI	Operational (Since mid-90's)	Isochronous Cyclotron (cw)					590 MeV	–	10^{14} n/cm^2/s	1.2 MW
U.K.	ISIS	Operational (Since 1985)	RCS	70 MeV	300 μs	50	1.2%	800 MeV	200 μA	25	160 kW
	ISIS Upgrade	Under Planning	RCS	800 MeV				3 GeV			
Sweden	ESS (H+)	Under Design	LINAC	2.5 GeV	2 ms	20	4%	2.5 GeV	2 mA	234	5MW
Japan	KEK-PSB/ KENS	Decommissioned 2006-07	RCS	40 MeV	–	20	–	500 MeV	4.6 μA	2.5	2.3 kW
	JPARC Phase 2	Operational since 2006 / Under development	RCS	200 MeV (400 MeV)	500 μs	25	3%	3 GeV	200 μA (333 μA)	50 (83)	600 kW (1MW)
China	CSNS	Under Construction	RCS	80 MeV	500 μs	25	1.05%	1.6 GeV	76 μA	19	120 kW
Korea	PEFP	Under Planning	LINAC	100 MeV	1.3 ms	60	8%	1 GeV	1.5 mA	–	150kW

SNS Linac Configuration at ORNL, USA



1 RFQ
6 DTL Tanks
4 CCL Modules

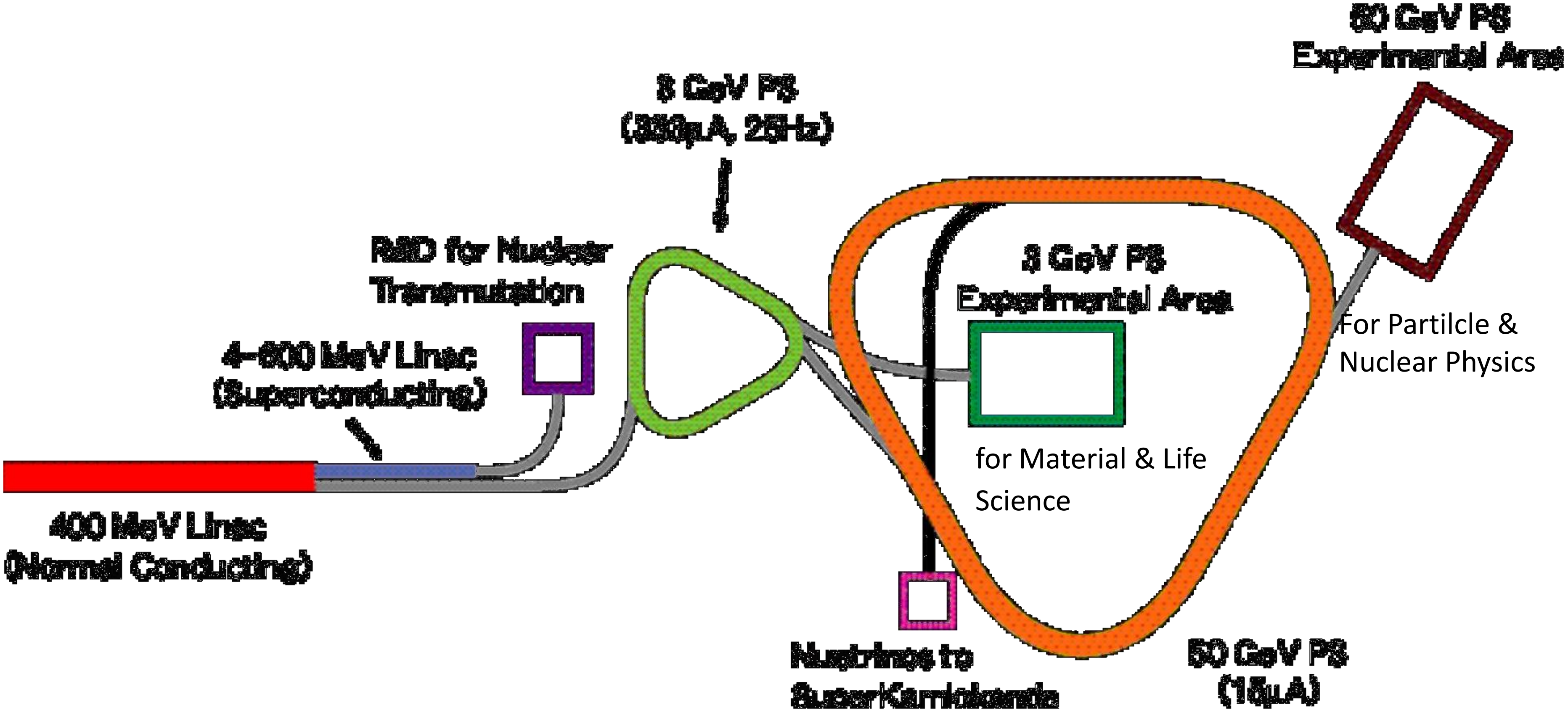
11 Medium-β Cryomodules - 3 Nb cavities each
12 High-β Cryomodules - 4 Nb cavities each

Normal conducting linac structure

SCRF cavity based linac

SNS Site at ORNL, USA

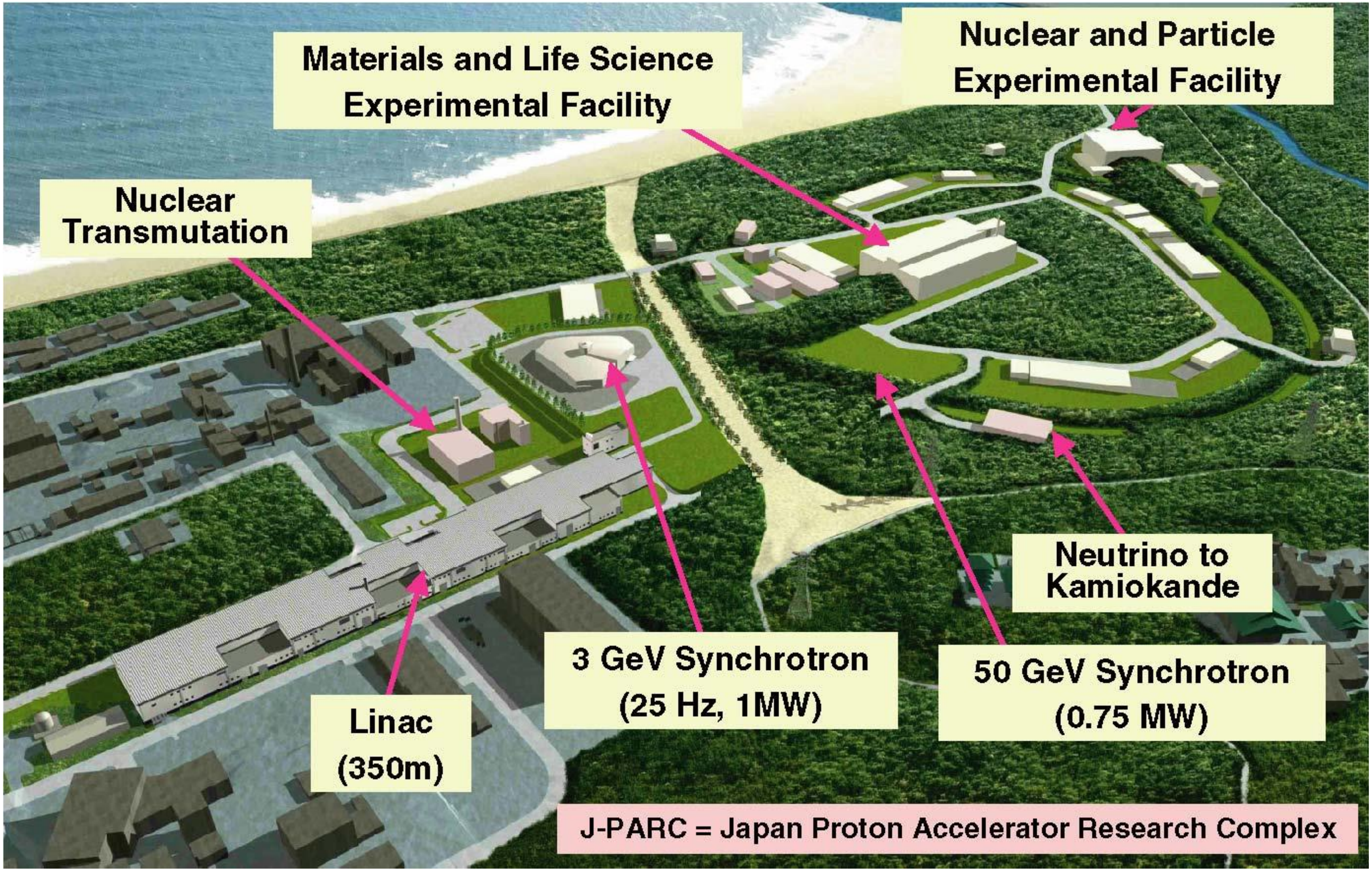
Schematic of J-PARC Project



For Partilcle &
Nuclear Physics

for Material & Life
Science

Site View of the J-PARC Project



Materials and Life Science Experimental Facility

Nuclear and Particle Experimental Facility

Nuclear Transmutation

Neutrino to Kamiokande

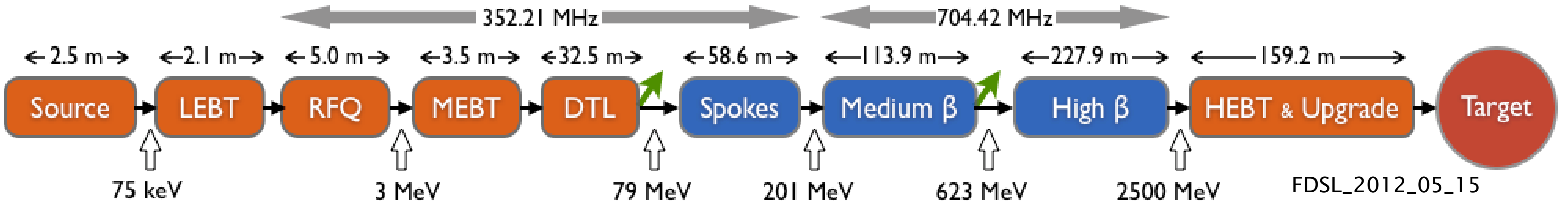
Linac (350m)

3 GeV Synchrotron (25 Hz, 1MW)

50 GeV Synchrotron (0.75 MW)

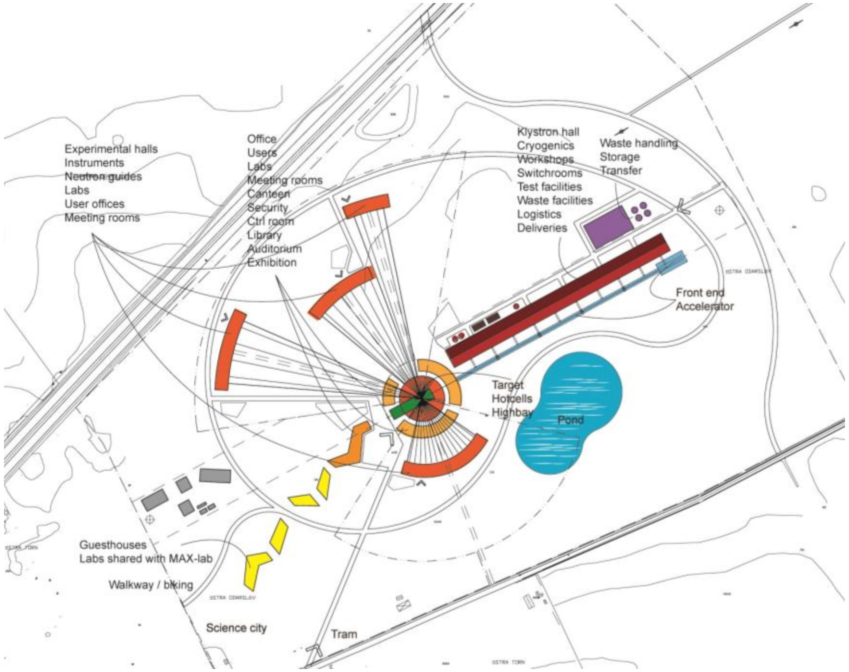
J-PARC = Japan Proton Accelerator Research Complex

ESS Linac Parameters

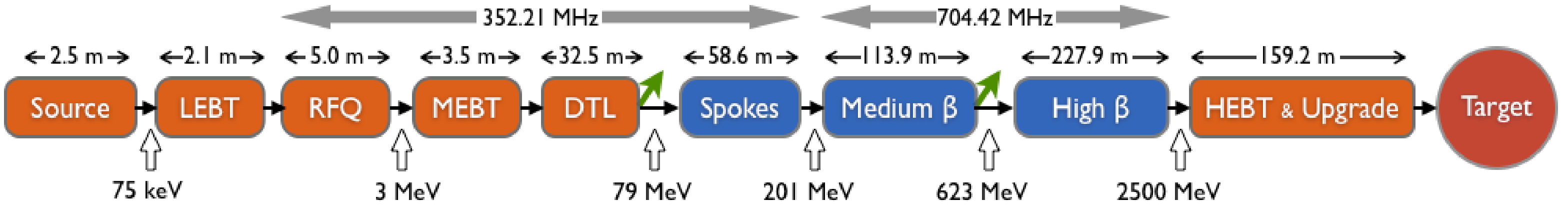


FDSL_2012_05_15

Particle species	p
Energy	2.5 GeV
Current	50 mA
Average power	5 MW
Peak power	125 MW
Pulse length	2.86 ms
Rep rate	14 Hz
Max cavity surface field	40 MV/m
Operating time	5200 h/year
Reliability (all facility)	95%



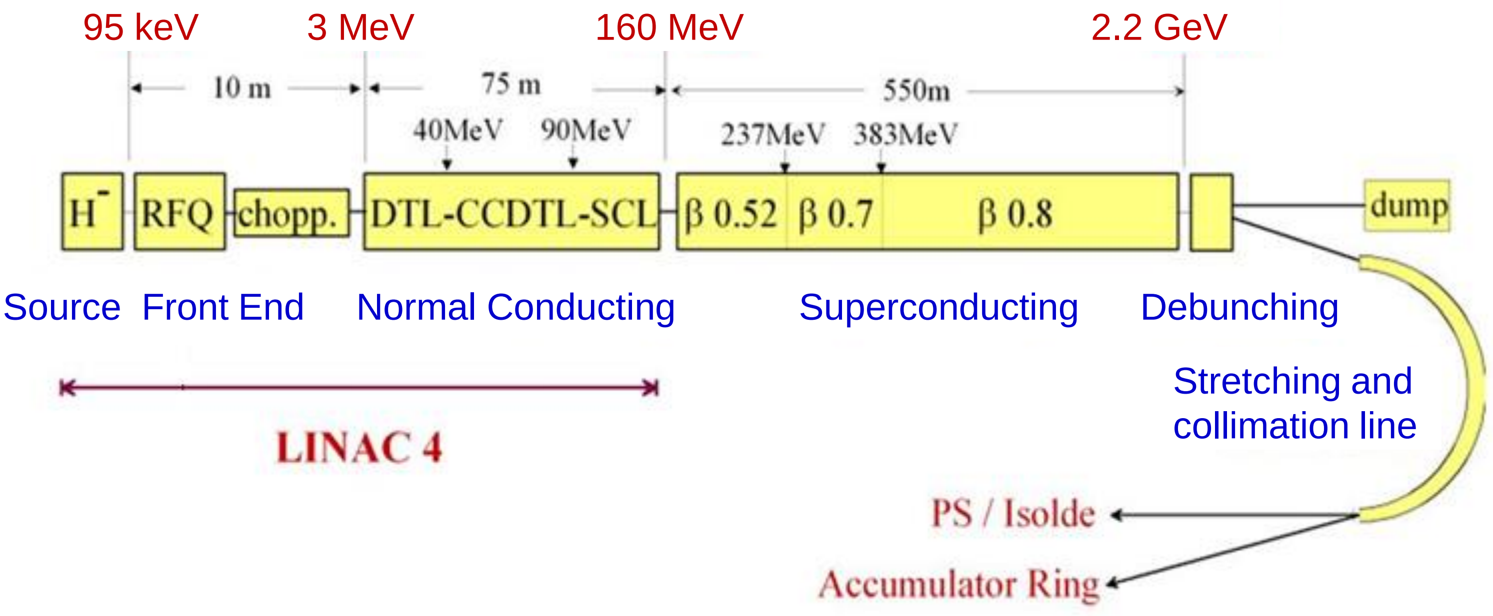
Linac Layout



	Lab	E_{out} (MeV)	$Beta_{out}$	Length (m)	Temp (K)	Freq (MHz)
Ion source + LEBT	Catania	0.075	0.01	4.6	300	–
RFQ	Saclay	3	0.08	5.0	300	352.21
MEBT	Bilbao	3	0.08	3.5	300	352.21
DTL	Legnaro	79	0.39	32.5	300	352.21
Spoke cavities	Orsay	201	0.57	58.6	2	352.21
Medium-beta ellipticals	Saclay	623	0.80	113.9	2	704.42
High-beta ellipticals	Saclay	2500	0.96	227.9	2	704.42
HEBT	Aarhus	2500	0.96	159.2	300	–

	Spoke resonators	Medium-beta ellipticals	High-beta ellipticals
Cells per cavity	3	5	5
Cavities per cryomodule	2	4	4
Number of cryomodules	14	15	30

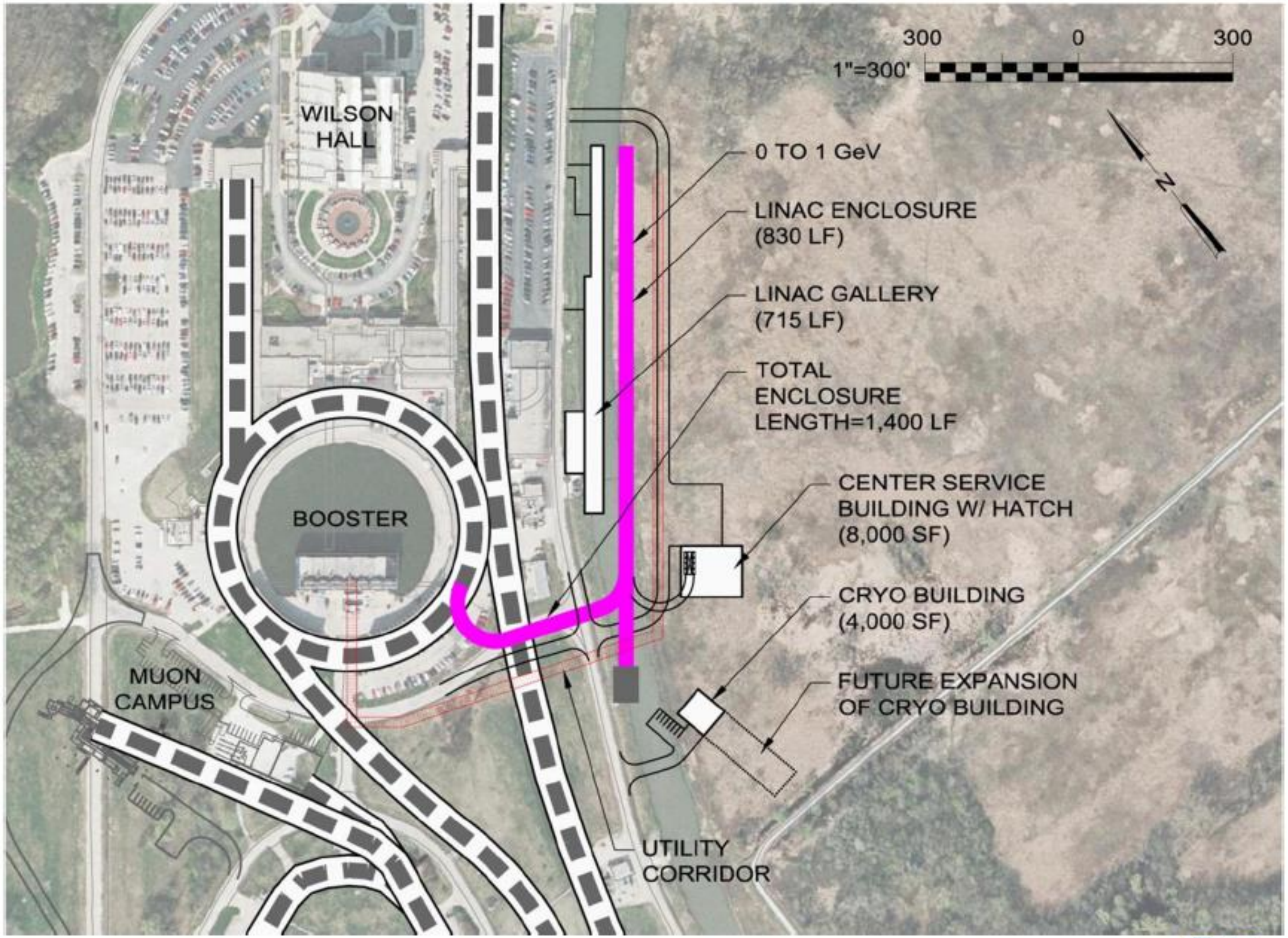
Superconducting Proton Linac Project at CERN



We have participated and contributed to :

- 352 MHz modulator development
- Development of wave guide components for WR 2300
- 1MW test bench for modulator for 2Hz repetition rate

PIP-II Site Layout (provisional) at Fermilab, USA



0 TO 1 GeV

LINAC ENCLOSURE
(830 LF)

LINAC GALLERY
(715 LF)

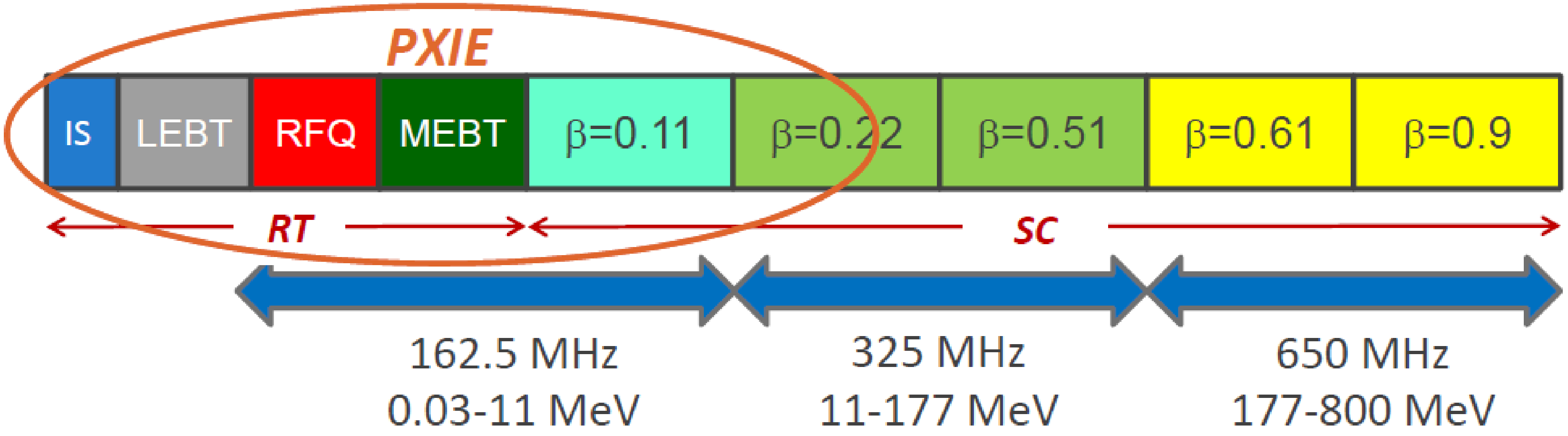
TOTAL
ENCLOSURE
LENGTH=1,400 LF

CENTER SERVICE
BUILDING W/ HATCH
(8,000 SF)

CRYO BUILDING
(4,000 SF)

FUTURE EXPANSION
OF CRYO BUILDING

PIP-II Linac Technology Map



Section	Freq	Energy (MeV)	Cav/mag/CM	Type
RFQ	162.5	0.03-2.1		
HWR (β_{opt}=0.11)	162.5	2.1-11	8/8/1	HWR, solenoid
SSR1 (β_{opt}=0.22)	325	11-38	16/8/ 2	SSR, solenoid
SSR2 (β_{opt}=0.51)	325	38-177	35/21/7	SSR, solenoid
LB 650 (β_G=0.61)	650	177-480	30/20/5	5-cell elliptical, doublet
HB 650 (β_G=0.9)	650	480-800	24/10/4	5-cell elliptical, doublet

Ongoing Projects/Activities in India

Ongoing Projects/Activities in DAE & IUAC

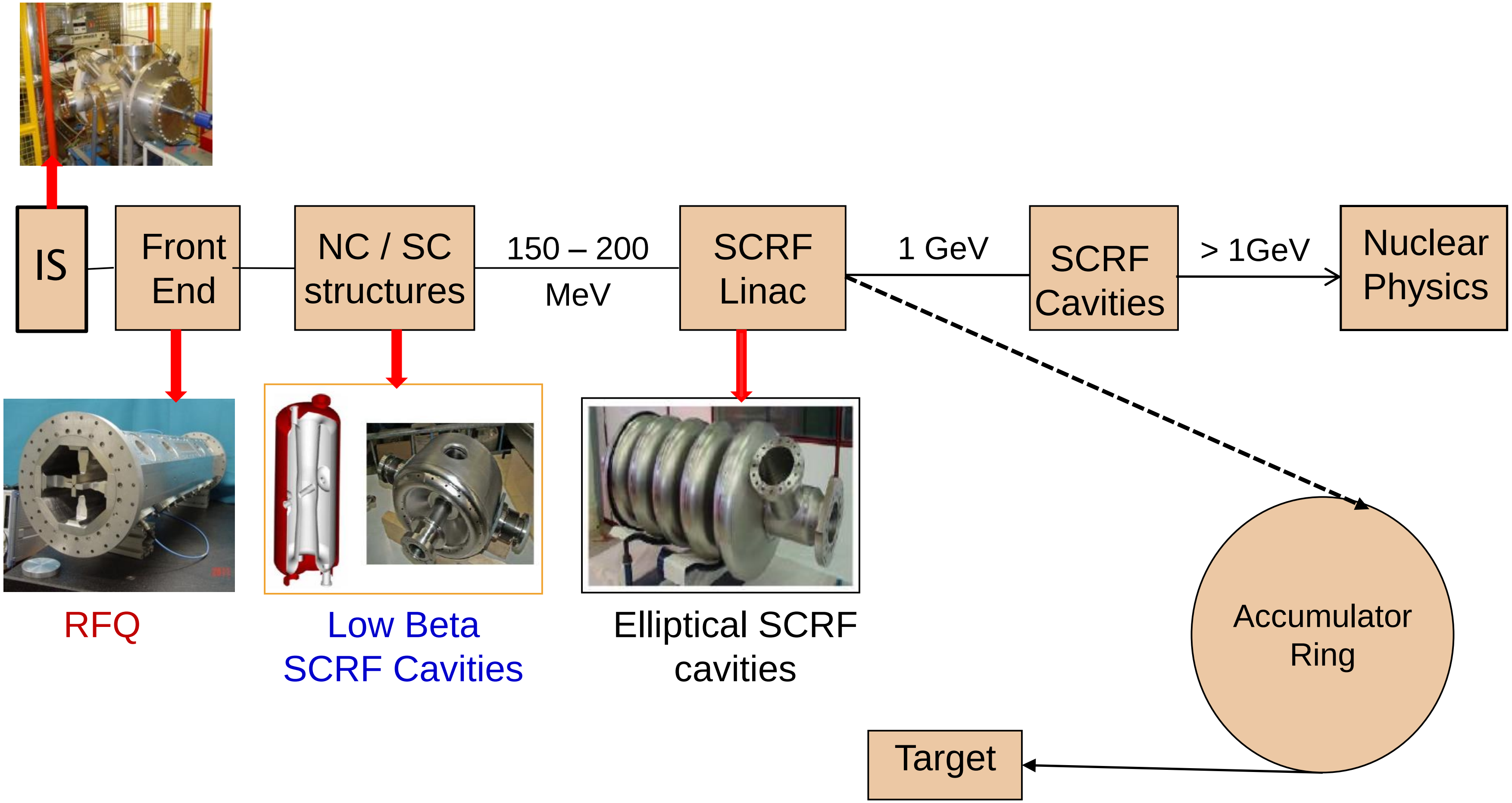
Design and development work for proton accelerator and support technologies viz superconducting cavities, cryogenics, RF power, magnets is going on at RRCAT, BARC, VECC, IUAC

- LEHIPA (BARC)
- R&D Activities of high energy Proton Linac for SNS (RRCAT)
- SCRF Cavities, Test stands, RF Power and Control Instrumentation (RRCAT, BARC, VECC, IUAC)

International Collaborations

- Fermilab (Project X)
- CERN (Linac 4)

Schematic Layout of Proposed ISNS Facility



IS

Front End

NC / SC structures

150 – 200 MeV

SCRF Linac

1 GeV

SCRF Cavities

> 1GeV

Nuclear Physics

RFQ

Low Beta SCRF Cavities

Elliptical SCRF cavities

Accumulator Ring

Target

R&D Activities related to concept building, design, simulation and development of various technologies are being pursued.

Schematic Layout of ISNS Facility

RRCAT

IS

Front End

NC / SC structures

150 - 200 MeV

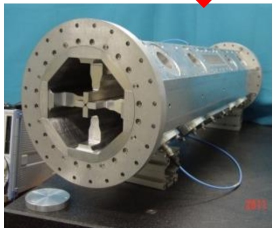
SCRF Linac

1 GeV

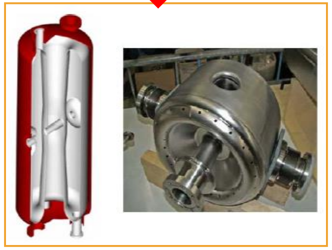
SCRF Cavities

> 1GeV

Nuclear Physics



RFQ



Low Beta
SCRF Ca es

Elliptical SCRF
cavitie

Accumulator Ring

Ta

Frequency
Output Energ
Length
RF Power

Frequency
Output Energ
MeV
Length
meters
RF Power

Circumference ~
meters
Output Energy :

Material : Mercury
Quantity : ~
20 Tons
Flow rate : ~ 325
kg/s

Accumulator Ring at SNS Facility, ORNL

Output Energy	1 GeV
Circumference	248 m
RF Peak Power (per PA)	200 kW/PA
Dipole Magnets	32
Arc regular quadrupoles	28
Arc large quadrupoles	8
Straight section long quadrupoles	8
Staright section short quadrupoles	8
Dipole & multipole corrector	28+8+8
Sextupole & Octupole corrector	8+8

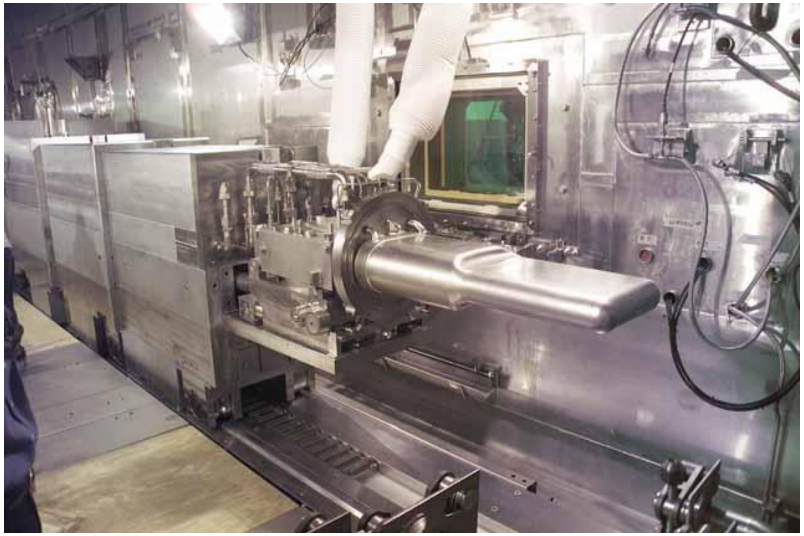
Spallation Target at SNS, Oak Ridge

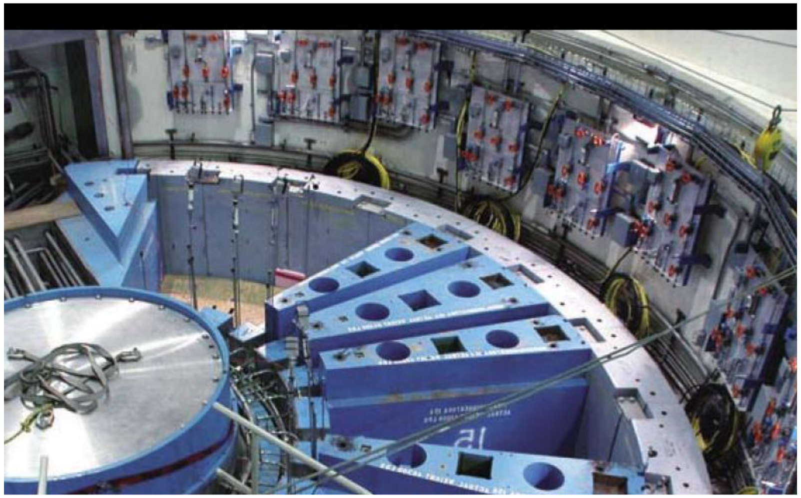
RTBT Beamline

Length	150.75
No of magnets	23 + 5

Target System

No of Target stations	1
No of neutron shutters	18
No of neutron beamlines	24
Target material	Mercury
Quantity of target	19 tons
Circulation rate	325 kg/s
Ambient moderator	Light water
Cryogenic moderator	Liquid Hydrogen

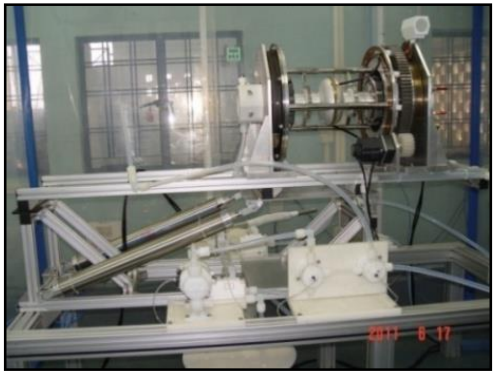




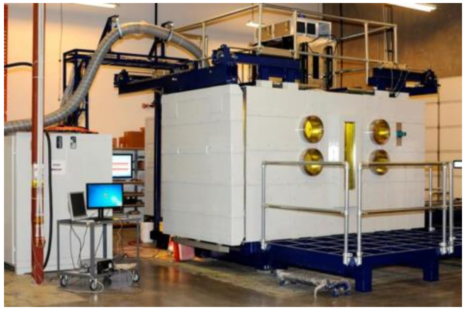
SCRF Cavity Fabrication, Processing Facilities at RRCAT


Cavity forming facility

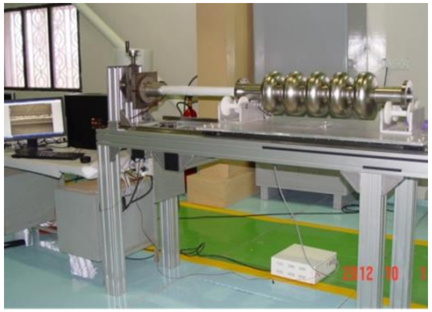

Centrifugal barrel polishing machine

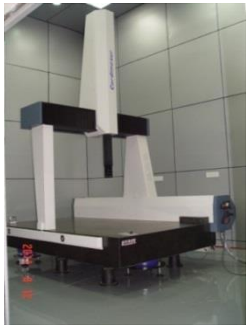

Electro-polishing setup


High pressure rinsing Set up


15 kW e-beam welding machine

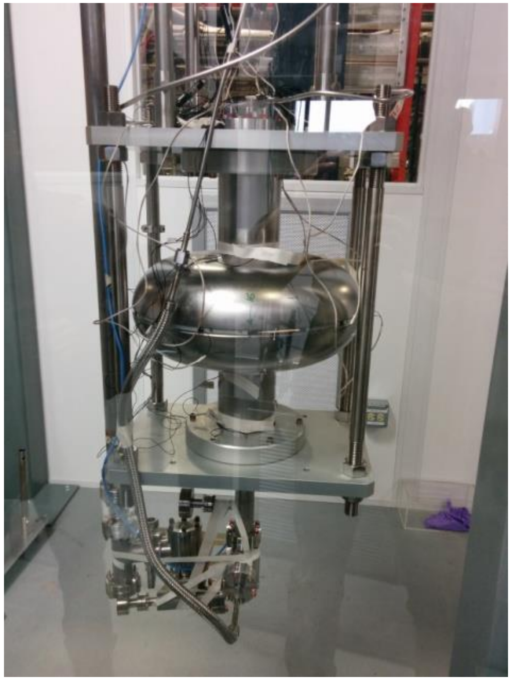

SIMS setup

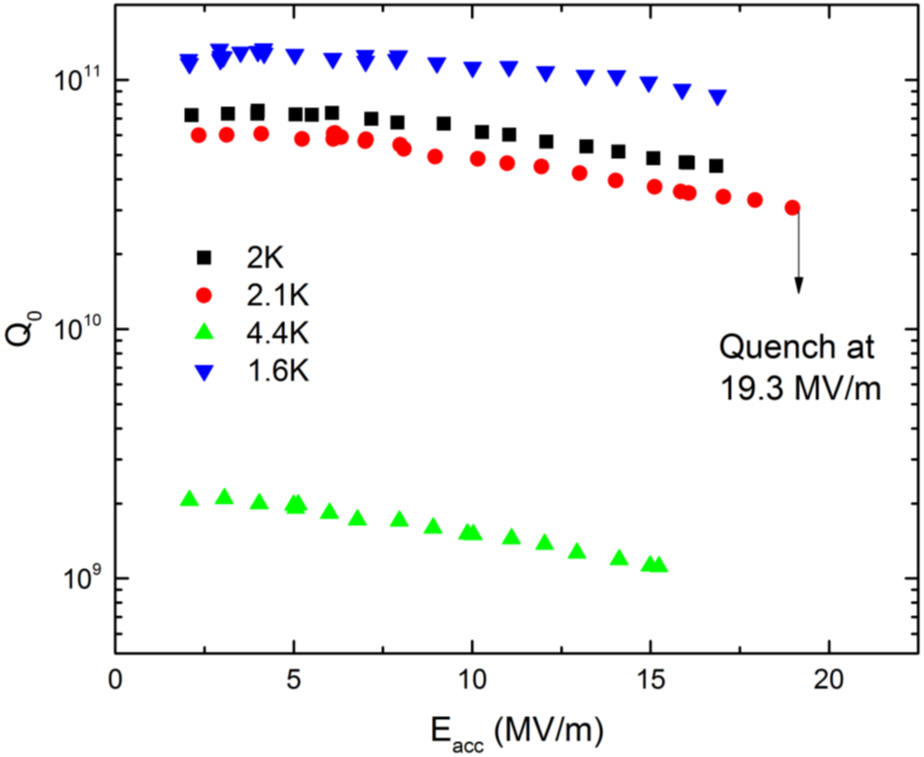

Optical bench setup


3D CMM

First 650 MHz Single-cell Niobium Cavity

- First 650 MHz single-cell niobium cavity fabricated by RRCAT and IUAC was processed and tested at Fermilab.
- It reached E_{acc} of 19.3 MV/m and Q_o of of $7x10^{10}$ at 2K. This performance exceeds the design parameters.



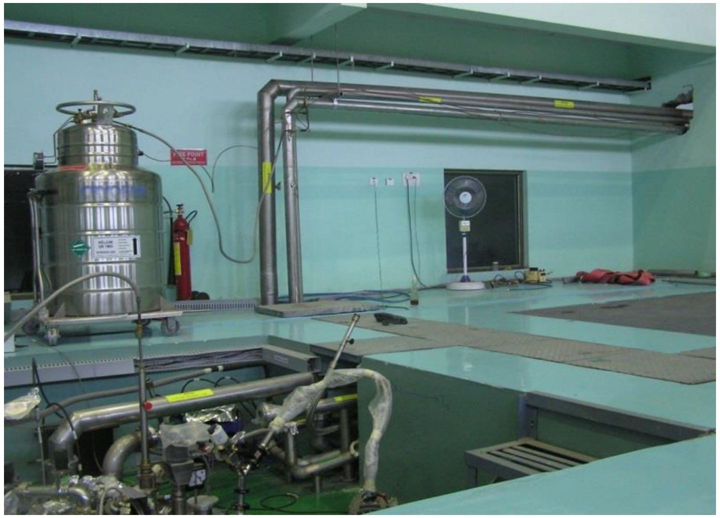


RRCAT

Insert assembly and Cryogenic Transfer lines for VTS

Cavity Insert assembly

Lowering of cavity insert in VTS cryostat

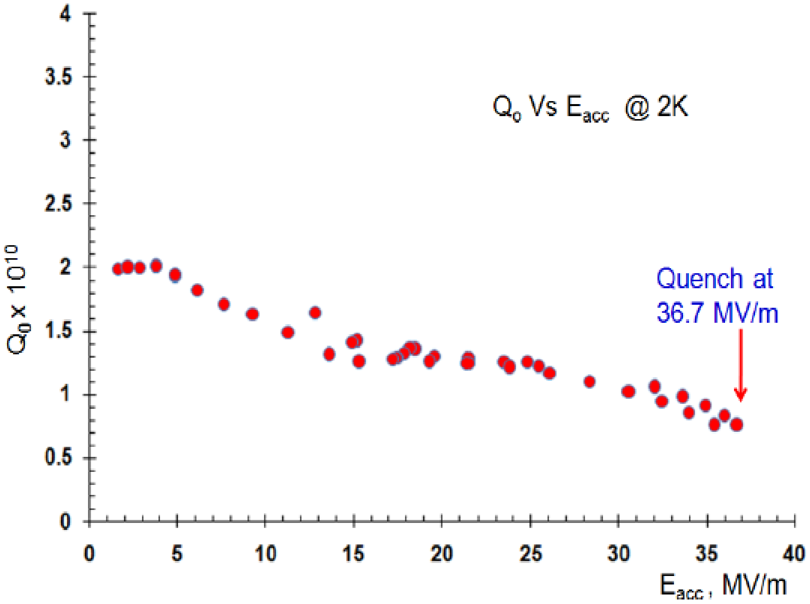


Cryogenic Transfer lines for VTS

Vertical Test Stand Facility for SCRF Cavity

A vertical test facility for RF characterization of SCRF cavities at 2 K was commissioned. Nearly 1400 liters of liquid helium was transferred and a single-cell 1.3 GHz cavity has been successfully tested using the facility.

Transfer of liquid helium in the VTS cryostat



Testing of single-cell 1.3 GHz SCRF cavity in the VTS facility at RRCAT

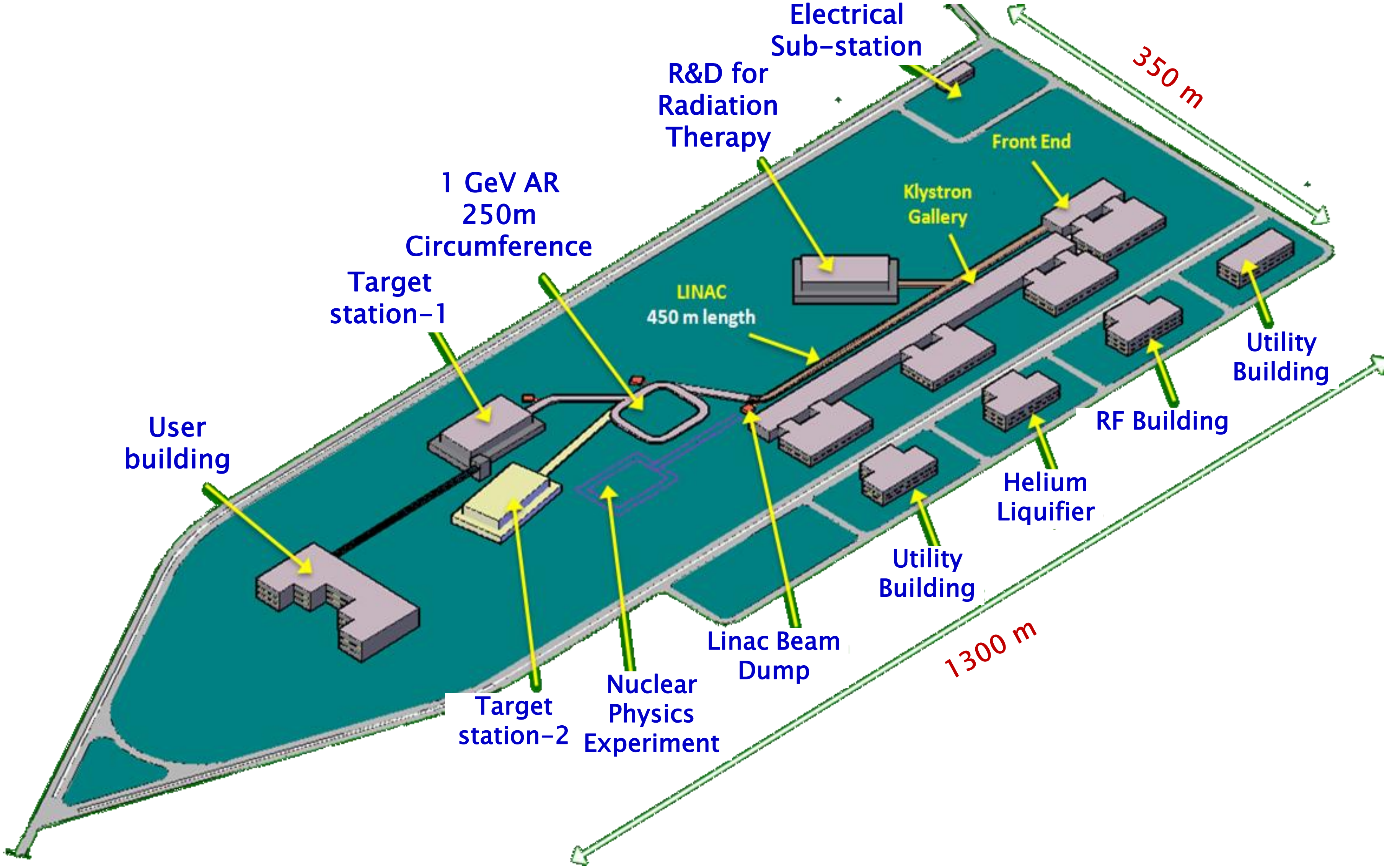
Challenging Tasks Ahead

- Radiation shielding and Beam dump design (linac+AR)
- Large size LHe plant and cryomodule test stand facility
- Sub-system development for 1 GeV AR
  - Beam Injection system, Magnets, RF cavities, vacuum chambers, beam diagnostic extraction
- Spallation target and moderator system
- Building design for linac + AR + target + beam lines
- Site evaluation and approval from AERB
- Infrastructure design + planning for civil works, electric power, water & utility services
- Development of Indian industry

International Collaborations

- Fermilab : Indian Institution –Fermilab Collaboration for Project X
- DAE – CERN Collaboartion – for NAT and Grid Computuing Activities (SPL/Linac 4, CLIC/CTF3)
- KEK : MoU has been signed for cooperation in the areas of Accelerator science and technologies
- J.Lab : Development of SCRF cavities using large grain niobium material & study of SC materials

Layout for ISNS Facility



Satellite view of ISNS layout

Thank You