Modern Linear Accelerators

Modern applications of linear ion accelerators include:

Injectors of high energy synchrotrons
Spallation neutron sources
Accelerator Driven Systems (ADS) for waste transmutation and power generation
Nuclear physics
Production of short-lived isotopes
Industry application

The figure of merit of accelerator facilities is the amount of secondary beams produced by the target, which primarily depend on beam intensity and target yield within optimum energy range.

The most important parameters that characterize operation of modern linacs are required RF power, required cooling, beam losses, operation reliability, elimination of beam trips.

High-Power Accelerators

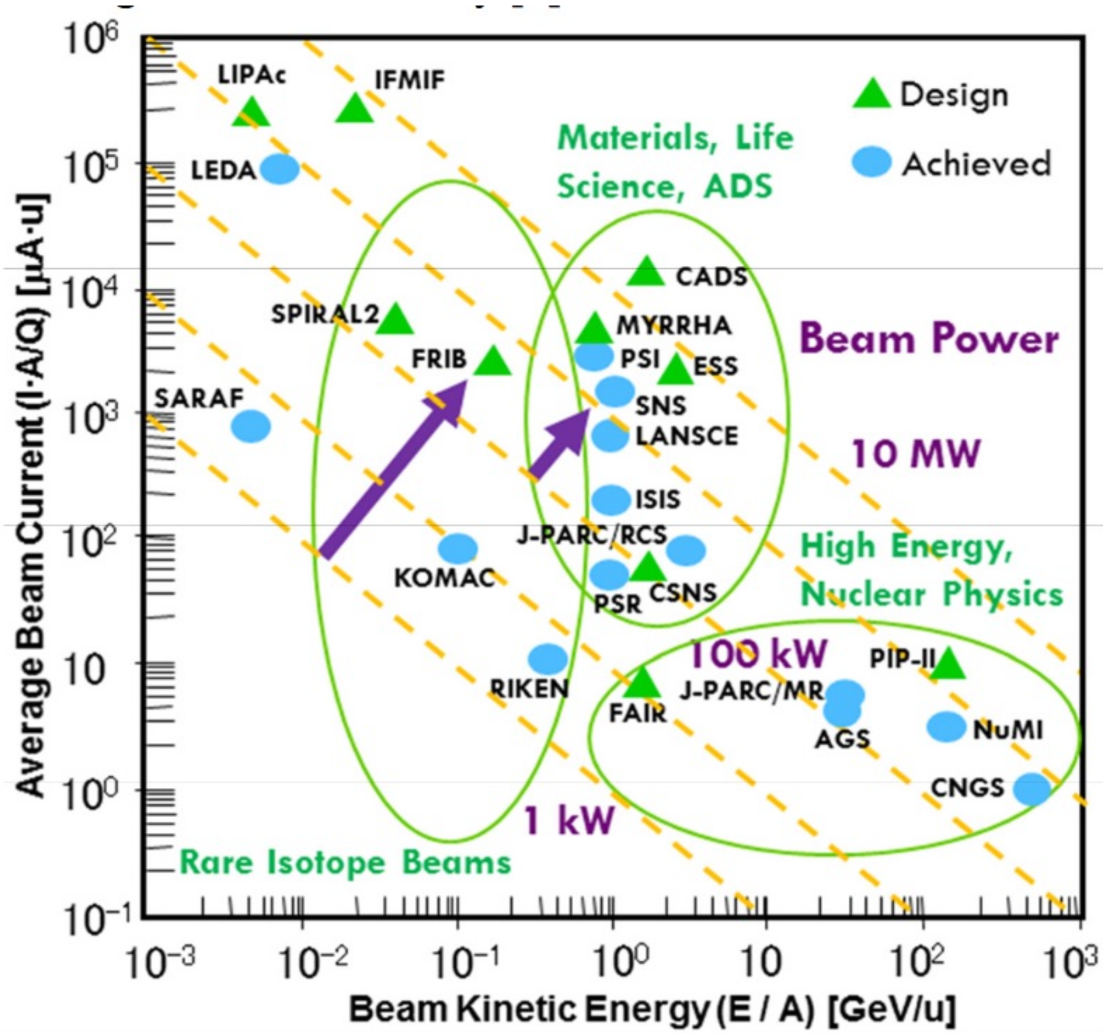


Figure 1: Hadron accelerator power frontier.

J.Wei (IPAC 2014)

Major Parameters of Proton and Heavy Ion Accelerators

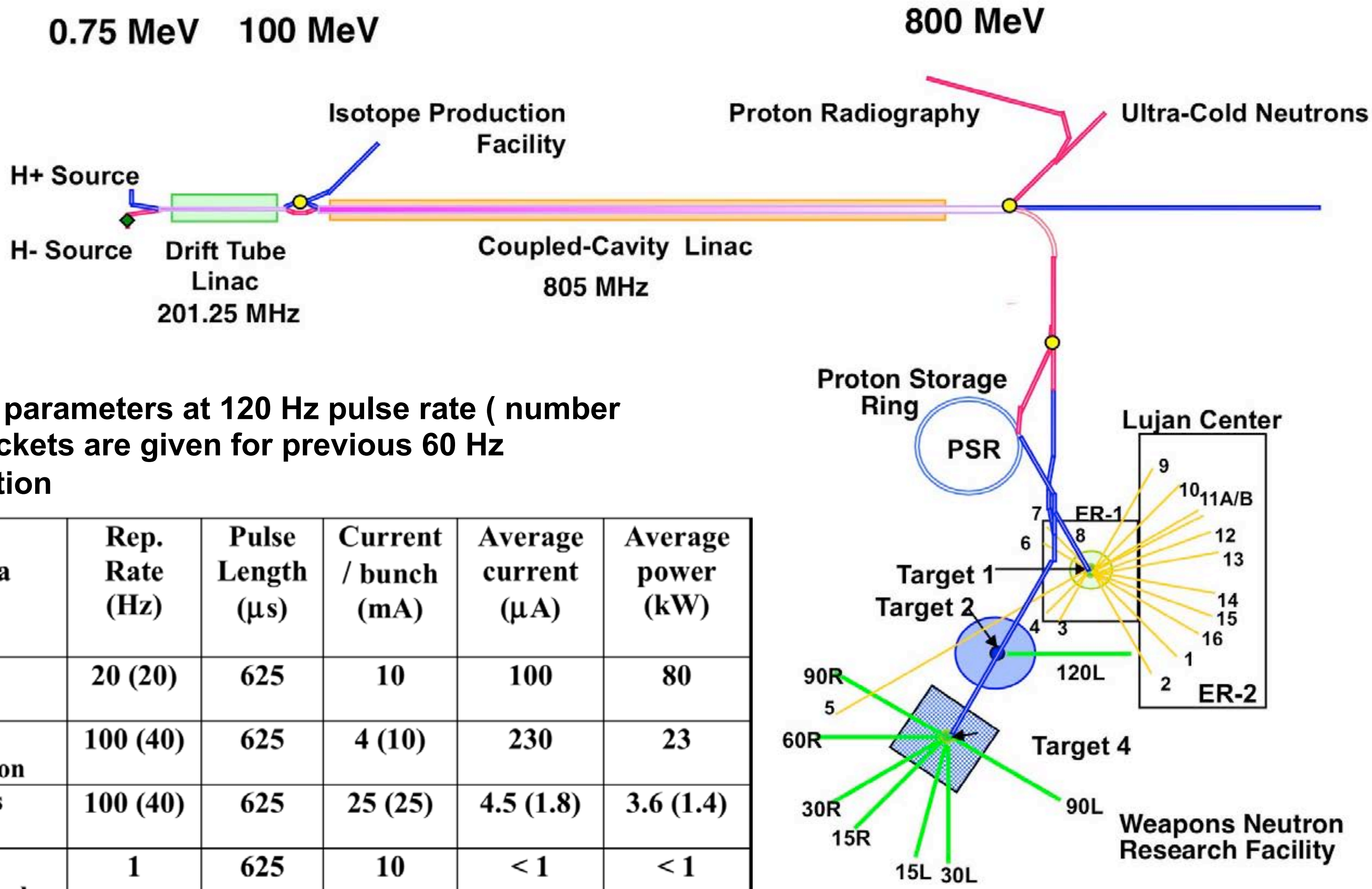
Project	Status	Primary Beam	Sec. Beam	Accel. Type	f_{rep} [Hz]	Beam Duty	Target Type	Energy [MeV/u]	Ave. Power [MW]
AGS	Achieve	p	μ, K	LN/SR	0.5	5e-7;.5 ^{t}	Ni; Pt	24000	0.1
SPS	Achieve	p	ν	LN/SR	0.17	3.5e-6 ^{t}	C	400000	0.5
MI	Achieve	p	ν	LN/SR	0.75	1.e-5 ^{t}	C	120000	0.4
J-PARC	Achieve	p	ν, K, π	LN/SR	0.4;0.16	2e-6;.3 ^{t}	C; Au	30000	0.2; 0.02
MR	Goal	p	ν, K, π	LN/SR	1; 0.16	5e-6;.3 ^{t}	C; M ^{r}	30000	0.75; > 0.1
LANSCE	Achieve	p, H^-	π, μ, n	LN	100	0.15	C ^{r}	800	0.8
PSR	Achieve	p	n	LN/AR	20	0.08 ^{i}	W	800	0.08
RIKEN	Achieve	d to U	RIB	LN/CY	CW	1	Be	345-400	0.007-0.002
	Goal	d to U	RIB	LN/CY	CW	1	Be	345-400	0.08 (U)
PSI	Achieve	p	n, μ	CY	CW	1	C ^{r}, Pb	590	1.4
SNS	Achieve	p	n	LN/AR	60	0.06 ^{i}	Hg ^{l}	>940	1.3
	Goal	p	n	LN/AR	60	0.06 ^{i}	Hg ^{l}	1300	2.8
J-PARC	Achieve	p	n, μ	LN/SR	25	0.02 ^{i}	Hg ^{l}	3000	0.3
RCS	Goal	p	n, μ	LN/SR	25	0.02 ^{i}	Hg ^{l}	3000	1
ISIS	Achieve	p	n, μ	LN/SR	40; 10	0.01 ^{i}	W	800	0.16; 0.04
	Goal	p	n, μ	LN/SR	40; 10	0.01 ^{i}	W	800	0.45; 0.05
SARAF	Achieve	p; d	n; -	LN	CW; 1	1	SST;Li ^{l}	3.9; 2.8	0.0039; -
	Goal	p, d	n, RIB	LN	CW	1	Li ^{l}; Be	40; 20	0.2
KOMAC	Achieve	p	-	LN	10	0.005	-	100	0.01
FRIB	Constru.	p to U	RIB	LN	CW	1	C ^{r}	>200	0.4
FAIR	Constru.	p to U	RIB, $\bar{p}$	LN/SR	0.2;0.5	<0.25 ^{i}	M ^{r}; Ni	1e3;3e4	0.012;0.001
SPIRAL2	Constru.	p,d,A/q$\le$3	RIB, n	LN/CY	CW	1	C ^{r}	33,20,14	0.2,0.2,0.04
CSNS	Constru.	p	n	LN/SR	25	0.01 ^{i}	W	1600	0.1
LIPAc	Constru.	d	n	LN	CW	1	Li ^{l}	4.5	1.1
PIP-II	Design	p	ν, μ	LN/SR	15	0.15 ^{i}	C; Al	1e5; 800	1.2; 0.1
ESS	Design	p	n	LN	14	0.04	W ^{r}	2000	5
IFMIF	Design	d	n	LN	CW	1	Li ^{l}	20	2 x 5
CADS	Design	p	n	LN	CW	1	G+He	1500	15 – 30
MYRRHA	Design	p	n	LN	CW	1	Pb-Bi ^{l}	600	1.5 – 2.4

Notation: LN for Linac; CY for Cyclotron; SR for Synchrotron; AR for Accumulator; C for graphite; M for metal; RIB for rare isotope beams; Superscripts r for rotating and l for liquid targets, i for linac beam duty and t for beam duty on target.

J.Wei (IPAC 2014)

The LANSCE Accelerator Provides Unique Flexible Time-Structured Beams From 100 to 800 MeV

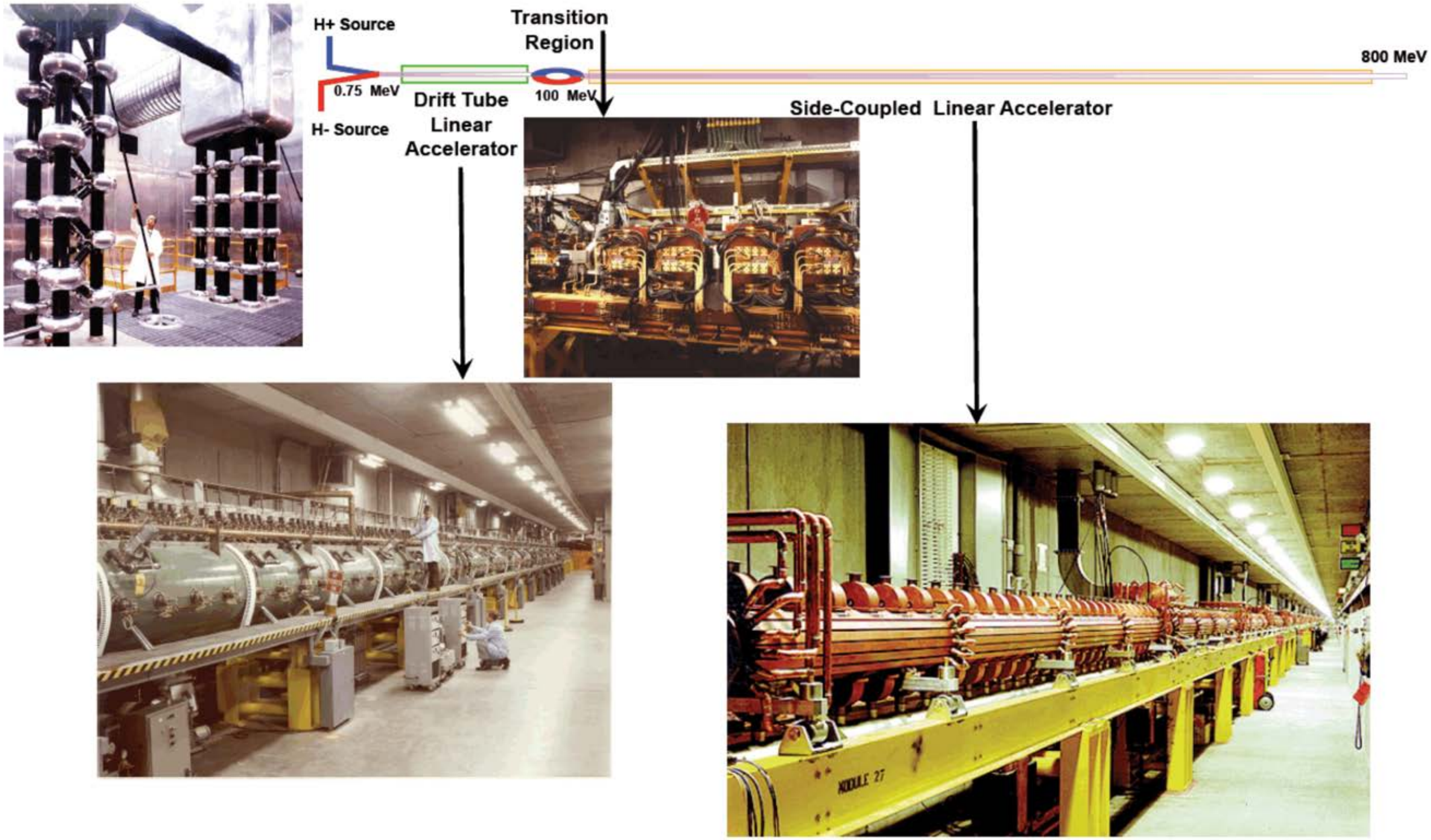
LANSCE Facility Overview



Beam parameters at 120 Hz pulse rate (number in brackets are given for previous 60 Hz operation

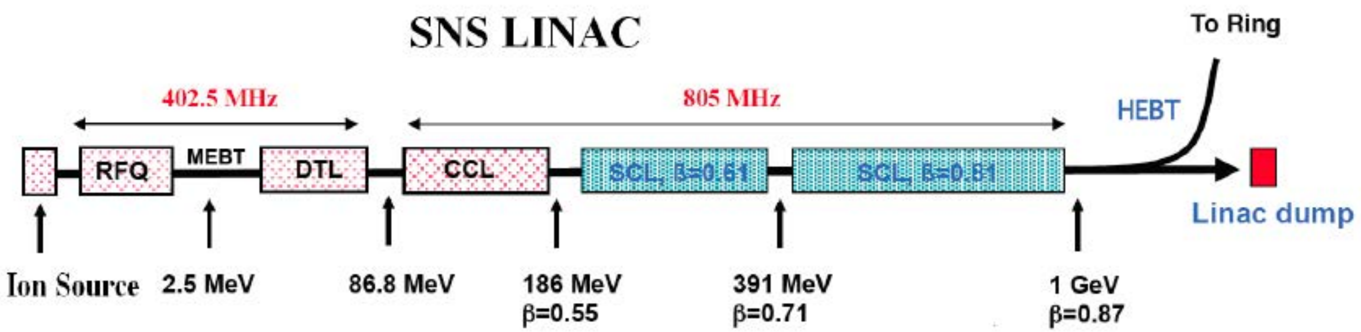
Area	Rep. Rate (Hz)	Pulse Length (µs)	Current / bunch (mA)	Average current (µA)	Average power (kW)
Lujan Center	20 (20)	625	10	100	80
Isotope Production	100 (40)	625	4 (10)	230	23
Weapons Neutron	100 (40)	625	25 (25)	4.5 (1.8)	3.6 (1.4)
Proton Radiography	1	625	10	< 1	< 1
Ultra-Cold Neutrons	20 (20)	625	10	10	8

LANSCE Accelerating Structures



Spallation Neutron Source Linac

SNS Linac Structure



DTL – Drift Tube Linac
CCL – Coupled Cavity Linac
SCL – Super Conducting Linac

H^- linac
Length: 330 m (Superconducting part 230 m)

Production run parameters:
Peak current: 38 mA
Repetition rate: 60 Hz
Macro-pulse length: 0.8 ms
Average power: 1 MW

3/20 Managed by UT-Battelle
for the Department of Energy

Beam Dynamics Issues in the SNS Linac

J-PARC Accelerator Facility

The J-PARC accelerator consists of a 400-MeV injector linac, a 3-GeV Rapid Cycling Synchrotron (RCS) and a 50-GeV main ring synchrotron. A high intensity proton beam is delivered to the materials and life science facility, the hadron experimental hall and the neutrino beam line.

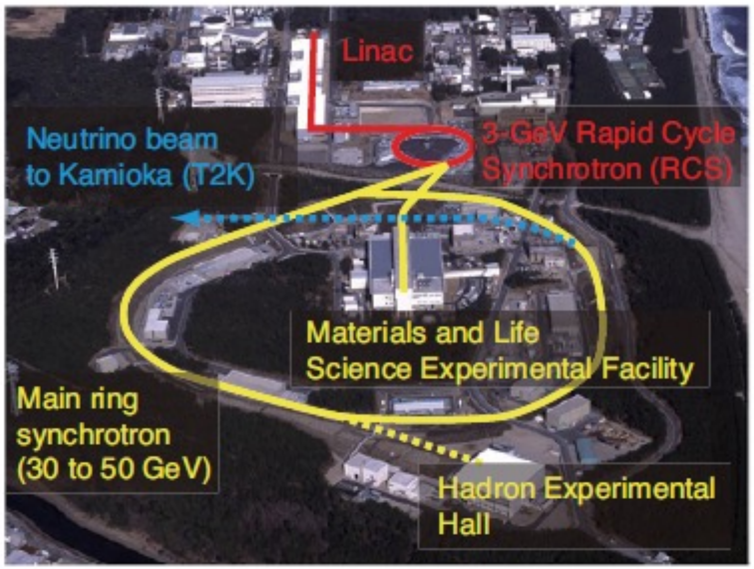


Figure 1: Bird's eye view of the J-PARC.

The 400-MeV energy upgrade of the J-PARC linac started from March 2009. The linac beam energy is at present 181 MeV, limiting the beam power of the 3-GeV Rapid-Cycling Synchrotron (RCS) to 600 kW at most by the space-charge effect. The 400-MeV injection is therefore vital for its 1-MW operation. This energy upgrade requires 25 modules of Annular-ring Coupled Structure (ACS) in total, 25 high-power RF sources, low-level RF

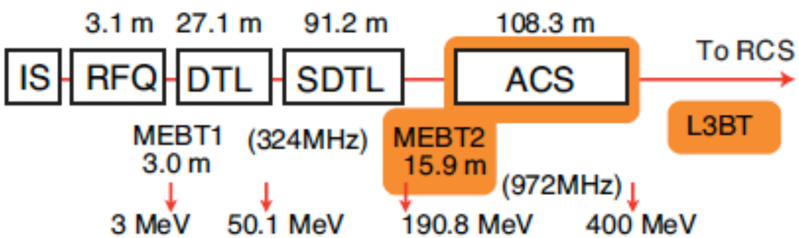


Figure 2: Schematic configuration of the linac.

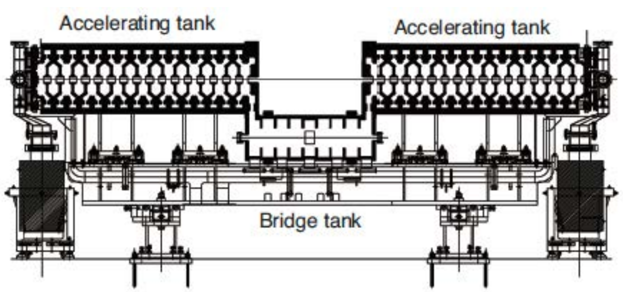
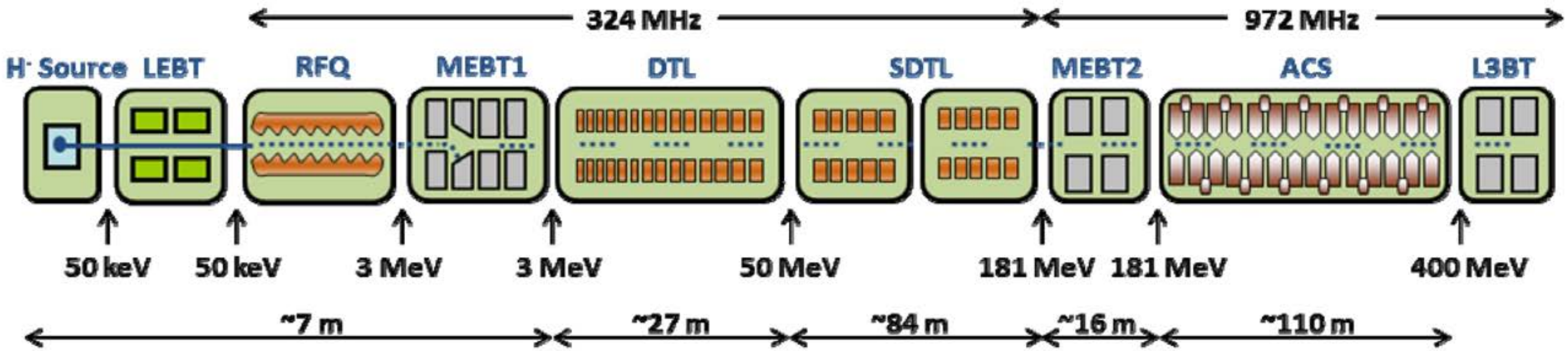


Figure 3: Layout of an ACS accelerating module. Two ACS tanks are coupled by one bridge tank.

J-PARC Linear Accelerator



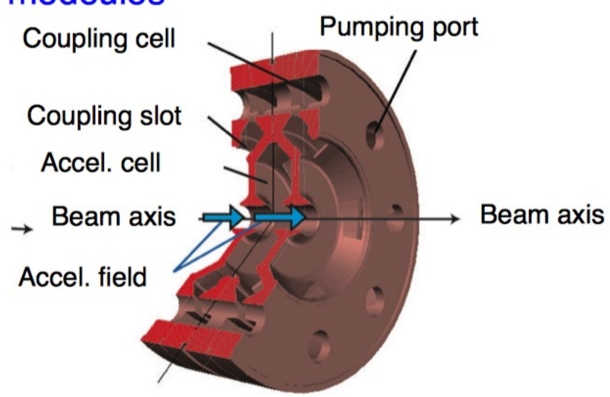
Schematic layout of j-PARC linac.

Table 2.1.1.2 Parameters of the 400-MeV linac.

	RFQ	DTL	SDTL	ACS	
Output energy	3	50	191	400	MeV
Frequency	324	324	324	972	MHz
Total length	3.1	27.1	91.2	108.3	m
Structure length	3.1	26.7	65.7	68.2	m
Number of tank	1	3	32	46	
Number of cell		146	160	690	
Number of Klys.	1	3	16	23	
Accelerating field		2.5~2.9	2.5~3.7	4.2~4.3	MV/m
Stable phase	-30	-30	-27	-30	deg
Vane voltage	82.9(1.8KL)				kV
Drive power	0.336	3.3	16.6	33.3	MW
Beam power	0.148	2.4	7.0	10.5	MW
Total power	0.484	5.7	23.6	43.8	MW

The ACS (Annular-ring Coupled Structure linac) system

- Frequency : 972 MHz
- 21 accelerating modules
- 4 debuncher modeules



European Spallation Source

Table 1: ESS Accelerator Main Parameters

Average beam Power	5 MW
Peak beam power	125 MW
Pulse Length	2.86 ms
Peak beam current	62.5 mA
Repetition rate	14 Hz
Duty cycle	4%

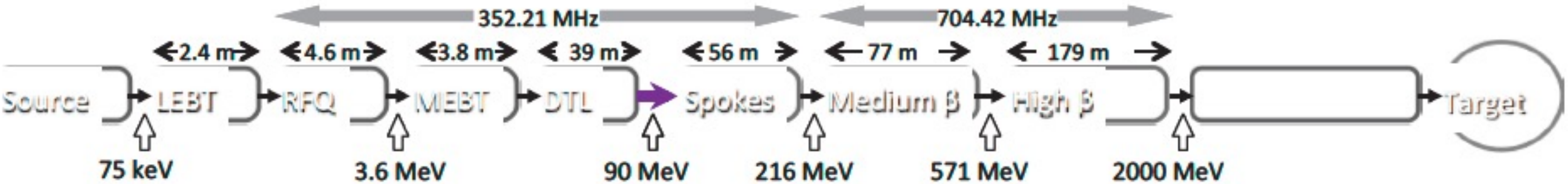


Figure 2: A block diagram of the ESS accelerator.

Linac 4 at CERN

Table 1: Main Linac4 design parameters

Output Energy	160	MeV
Bunch Frequency	352.2	MHz
Repetition Frequency	1.1 (max. 2)	Hz
Beam Pulse Length	0.4 (max. 1.2)	ms
Beam Duty Cycle	0.08	%
Chopper Beam-on Rate	62	%
Linac pulse current	40	mA
N. of particles per pulse	1.0	$\times 10^{14}$
Transverse emittance	0.4	π mm mrad
Maximum RF duty cycle	10	%

As the first step of a long-term programme aiming at an increase in the LHC luminosity, CERN is building a new 160 MeV H^- linear accelerator, Linac4, to replace the ageing 50 MeV Linac2 as injector to the PS Booster (PSB). Linac4 is an 86-m long normal-conducting linac made of an H^- source, a Radio Frequency Quadrupole (RFQ), a chopping line and a sequence of three accelerating structures: a Drift-Tube Linac (DTL), a Cell-Coupled DTL (CCDTL) and a Pi-Mode Structure (PIMS).

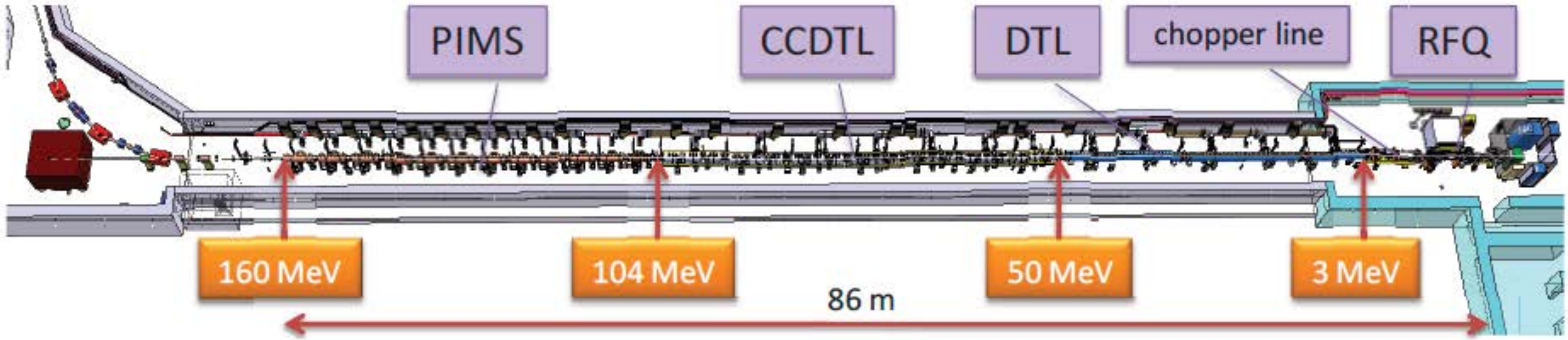


Figure 1: Linac4 layout.

Side-Coupled DTL and Pi-Mode Structure (PIMS)

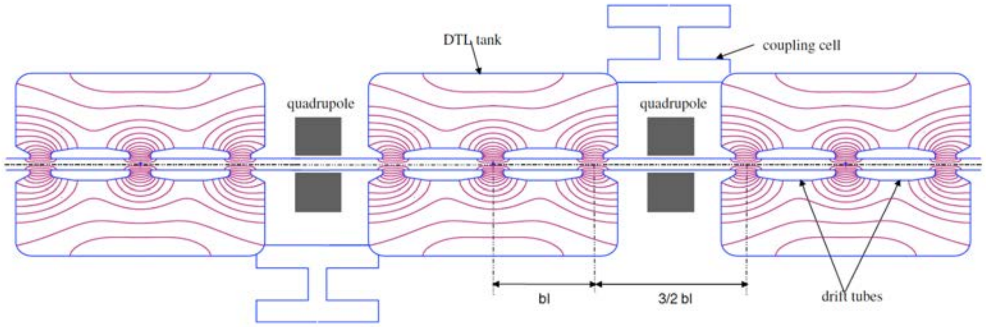


Figure 2.27: Scheme of a CCDTL module showing electric field lines

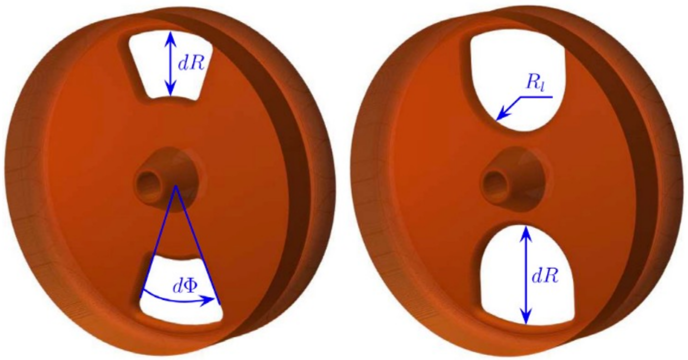


Figure 2: Different coupling slot shapes: left: standard shape, right: modified shape.

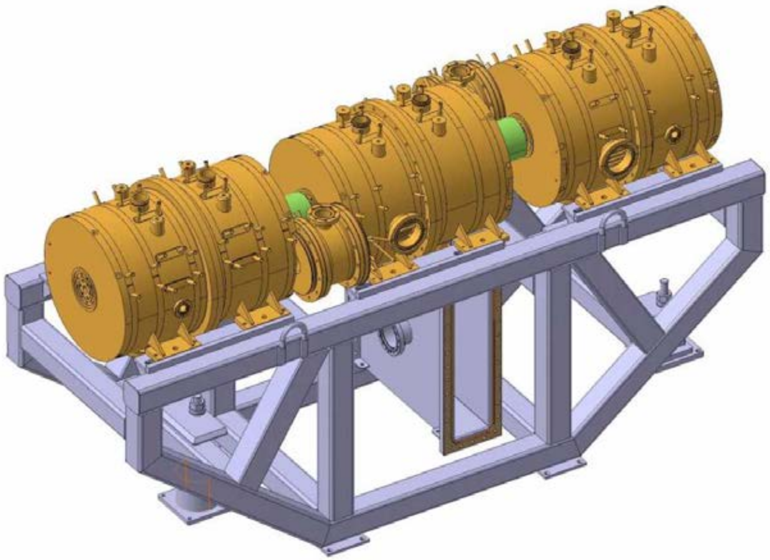


Figure 2.29: 3D view of a CCDTL module with support and waveguide coupler

CHINA SPALLATION NEUTRON SOURCE

Table1: CSNS Design Parameters

Project Phase	I	II
Beam Power on target [kW]	100	500
Proton energy t [GeV]	1.6	1.6
Average beam current [μ A]	62.5	312.5
Pulse repetition rate [Hz]	25	25

The accelerator complex of China Spallation Neutron Source (CSNS) mainly consists of an H- linac of 80 MeV and a rapid-cycling synchrotron of 1.6 GeV. It operates at 25 Hz repetition rate with an initial proton beam power of 100 kW and is upgradeable to 500kW. The project will start construction in September 2011 with a construction period of 6.5 years. The CSNS accelerator is the first

The approved budget from the central government is increased to $ 260 M from $ 215 M in 2010. The local government will support additional $ 77 M, free land and some infrastructure. CSNS will be located at Dong Guan

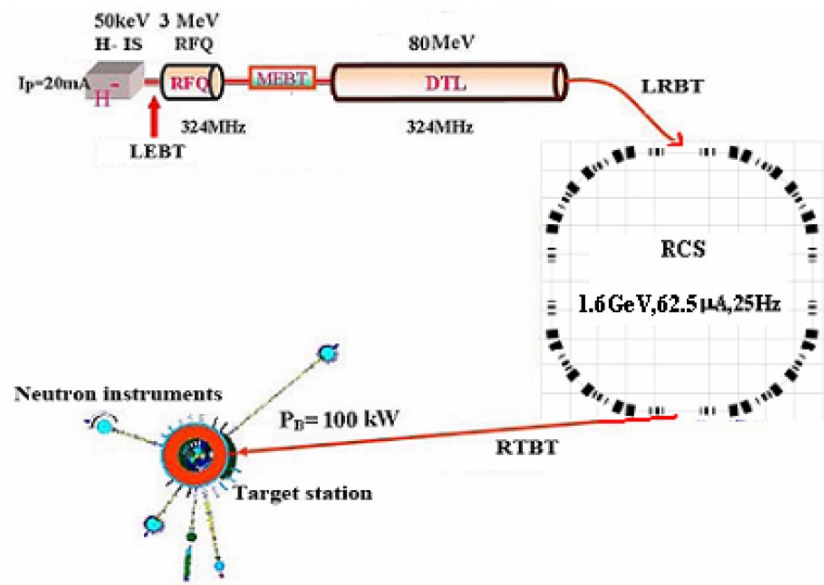


Figure 1: Schematics of the CSNS complex.

COMMISSIONING OF CSNS ACCELERATORS

Figure 8: DTL-1 installed in the tunnel.

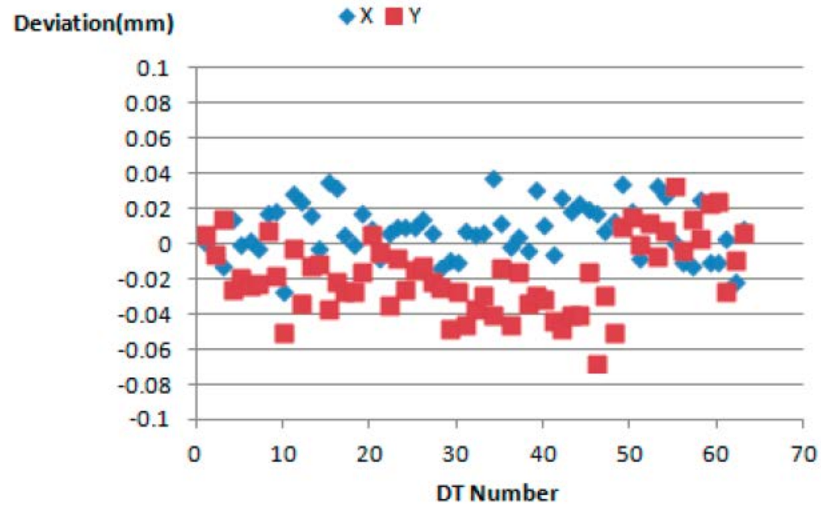


Figure 6: Alignment error of DTL-1 drift tubes.

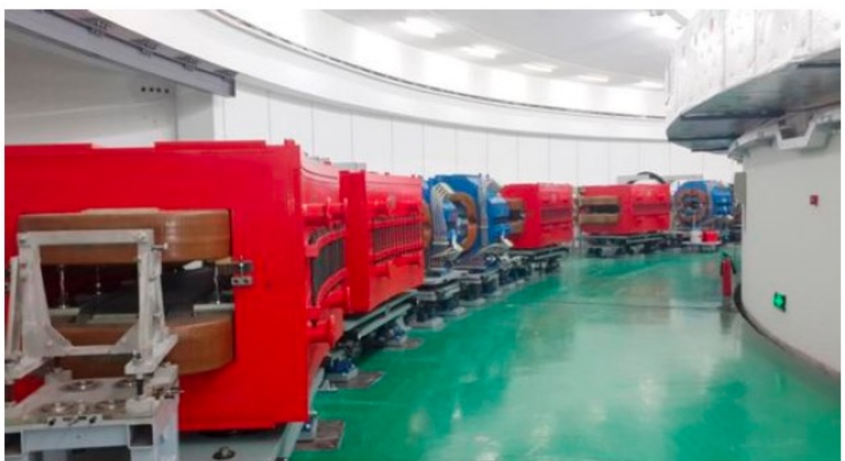
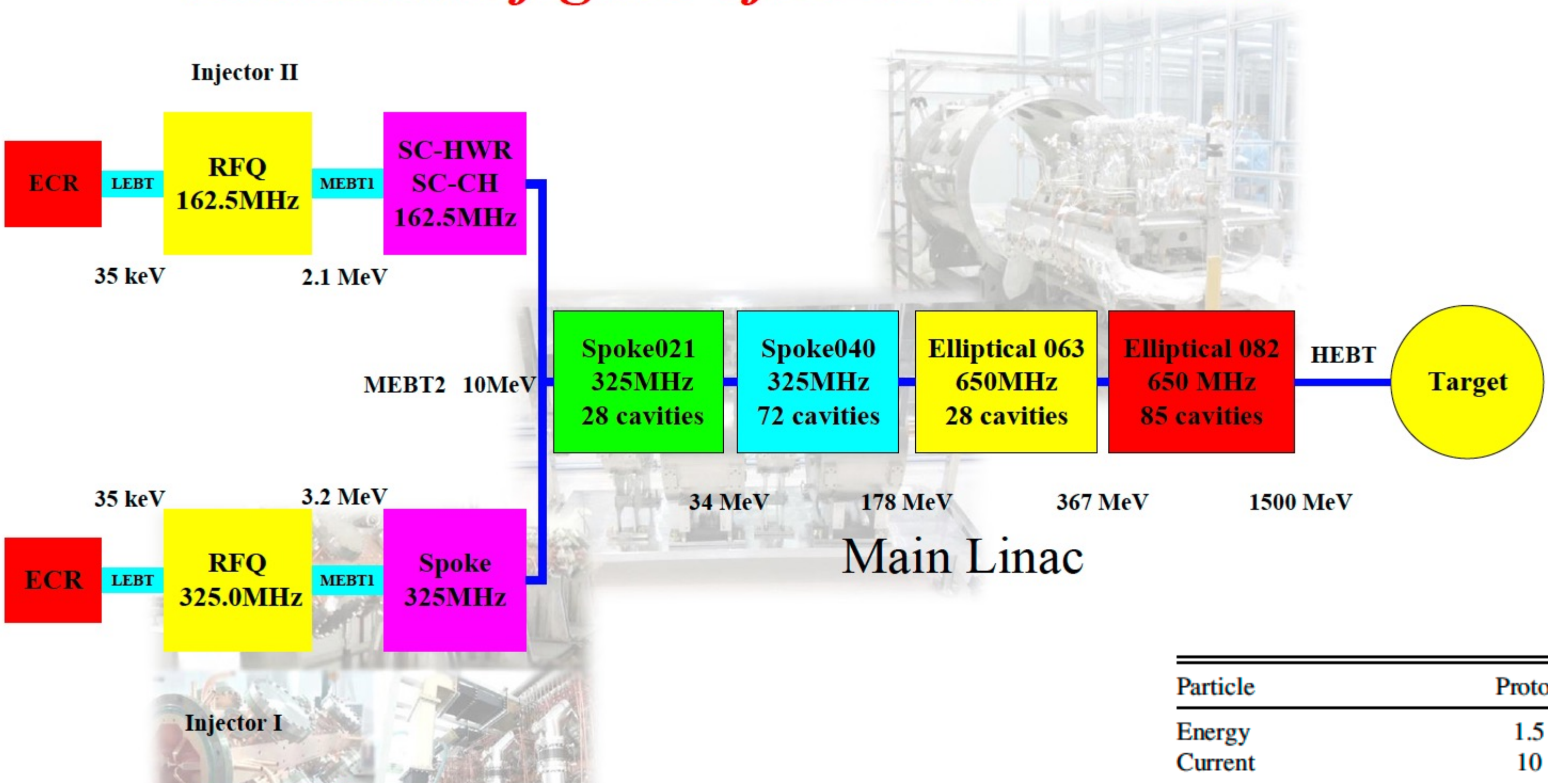


Figure 10: The dipoles and quadrupoles installed in the tunnel.

CHINA-ADS FACILITY

Schematic figure of ADS driver linac



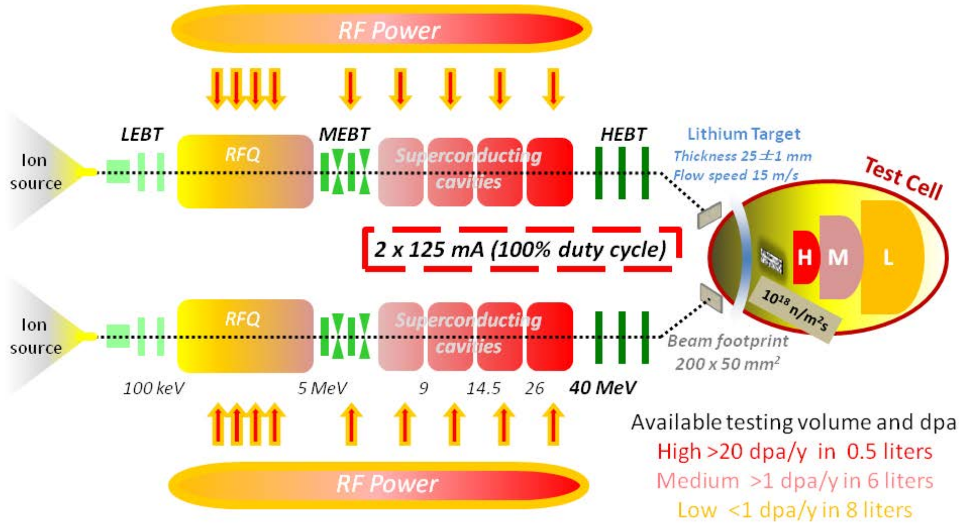
Particle	Proton	
Energy	1.5	GeV
Current	10	mA
Beam power	15	MW
rf frequency	(162.5)/325/650	MHz
Duty factor	100	%
Beam loss	<1	W/m
Beam trips/year [1]	<25000	$1\ s < t < 10\ s$
	<2500	$10\ s < t < 5\ m$
	<25	$t > 5\ m$

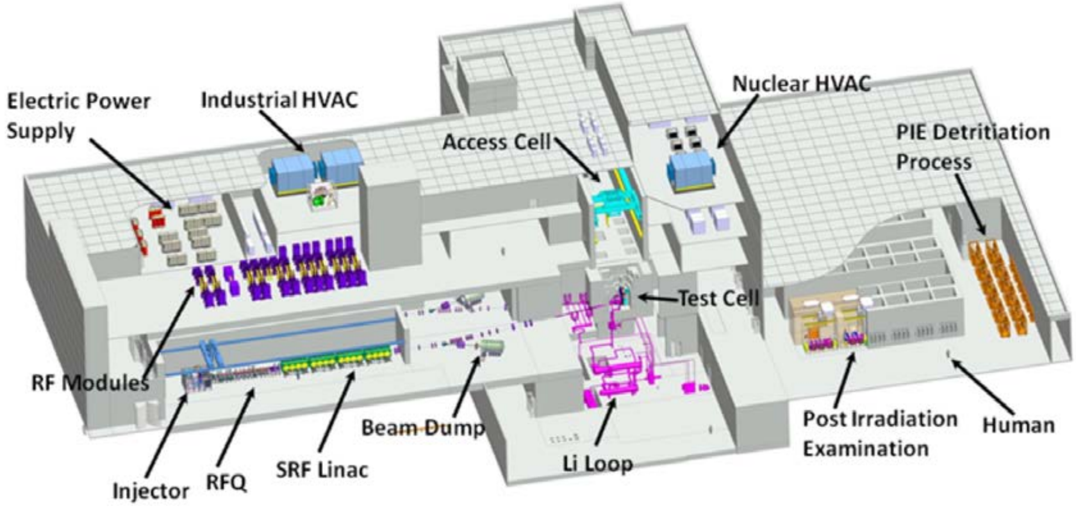
COMMISSIONING OF THE CHINA-ADS INJECTOR-I TESTING FACILITY

Injector-I Specifications	
Particle	H^+
Output Energy (MeV)	10
Current (mA)	10
Beam power (kW)	100
Duty factor (%)	100
RF frequency (MHz)	325

IFMIF/EVEDA Project

IFMIF, the International Fusion Materials Irradiation Facility, is an accelerator-based neutron source that will use Li(d,xn) reactions to generate a flux of neutrons with a broad peak at 14 MeV equivalent to the conditions of the Deuterium-Tritium reactions in a fusion power plant. (EVEDA: Engineering Validation and Engineering Design Activities).





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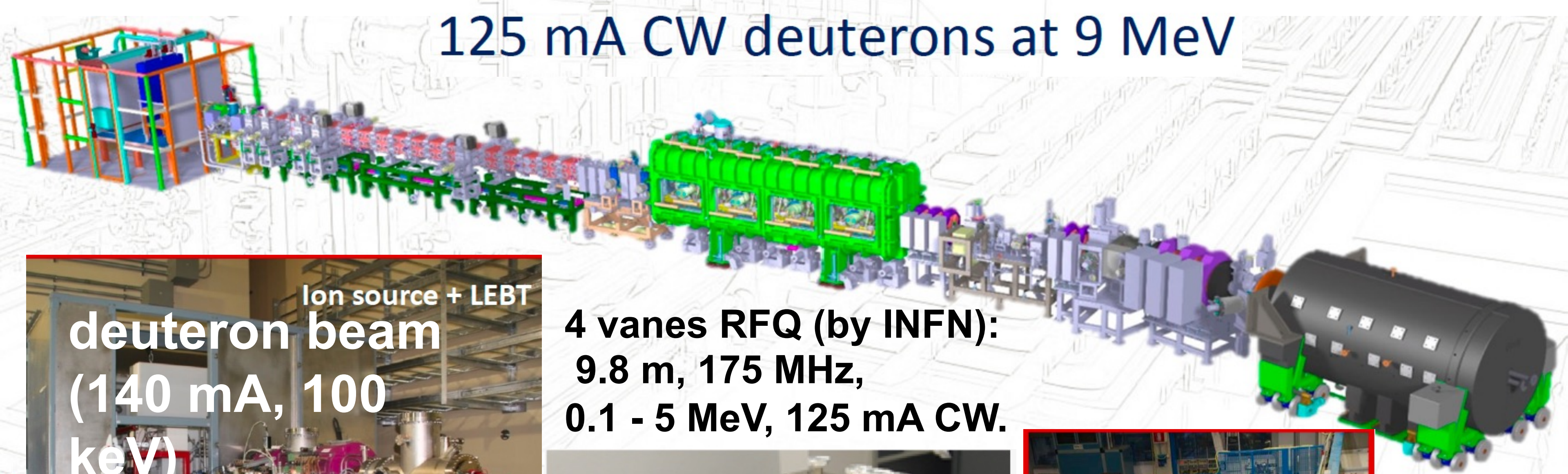
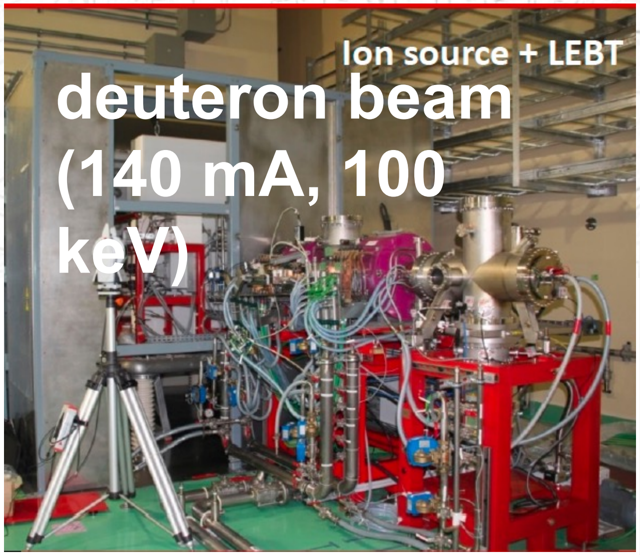
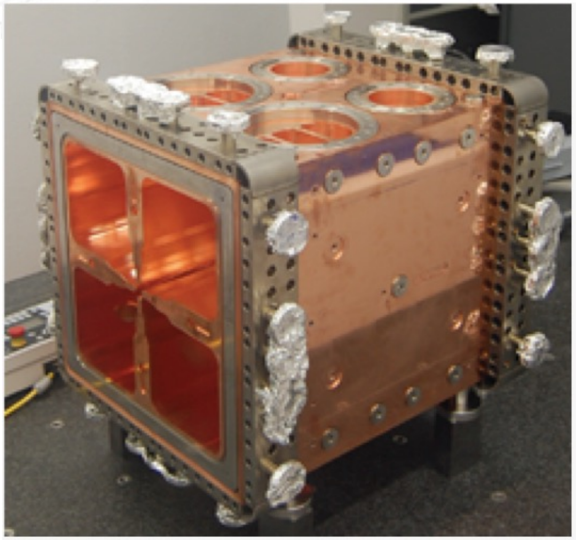
HIGH CURRENT PROTOTYPE ACCELERATOR OF IFMIF/EVEDA



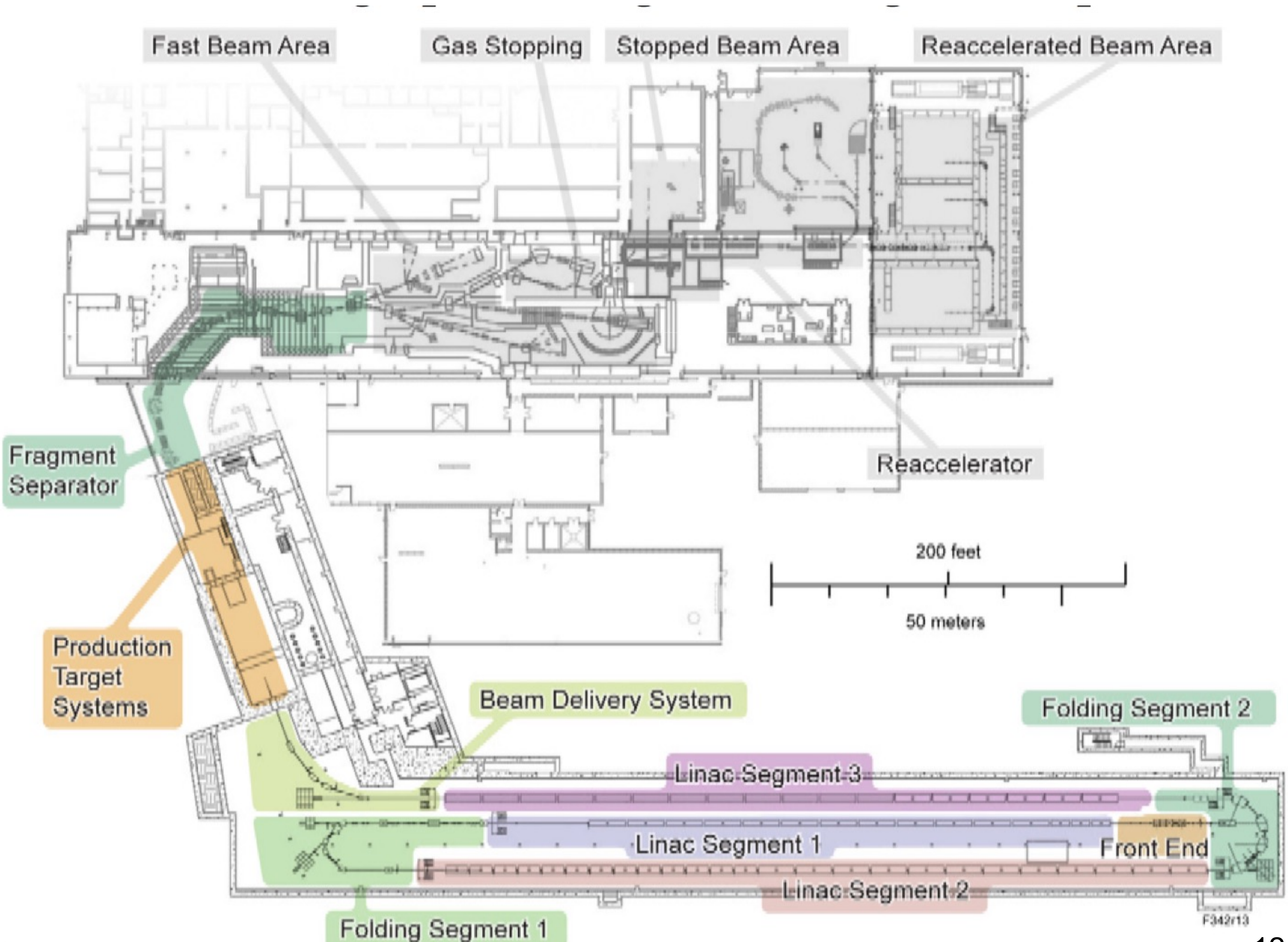


4 vanes RFQ (by INFN):
9.8 m, 175 MHz,
0.1 - 5 MeV, 125 mA CW.



First RFQ module completed (Module 16)

FACILITY FOR RARE ISOTOPE BEAMS (FRIB, MSU)



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FACILITY FOR RARE ISOTOPE BEAMS (FRIB, MSU)

Table 1: FRIB Driver Accelerator Primary Parameters

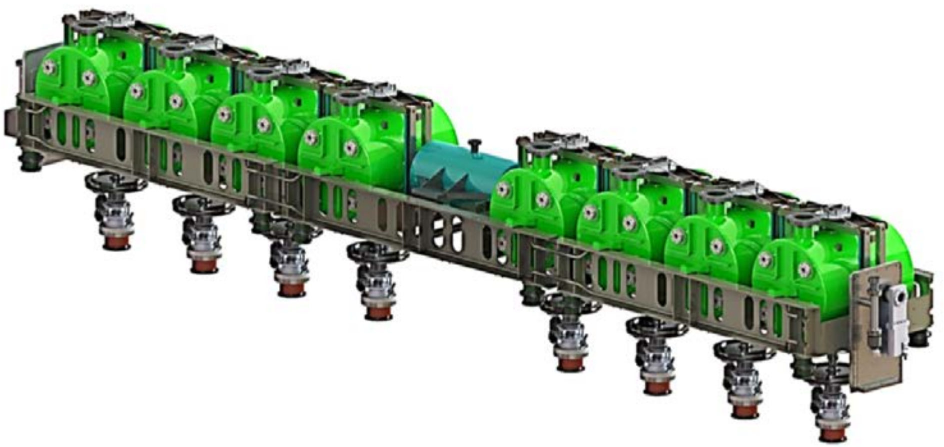
Parameter	Value
Primary beam ion species	H to ^{238}U
Beam kinetic energy on target	> 200 MeV/u
Maximum beam power on target	400 kW
Macropulse duty factor	100%
Beam current on target (^{238}U)	0.7 emA
Beam radius on target (90%)	0.5 mm
Driver linac beam path length	517 m
Average uncontrolled beam loss	< 1 W/m

FRIB Resonators

FRIB Resonator Parameters

Parameter	Segment 1		Segment 2	
Cavity type	$\lambda/4$	$\lambda/4$	$\lambda/2$	$\lambda/2$
Optimal β	0.041	0.085	0.29	0.54
Frequency, MHz	80.5	80.5	322	322
Effective voltage at optimal β	0.81	1.8	2.1	3.7
Aperture diameter, mm	36	36	40	40

Cryomodule with eight β =0.085 cavities and there superconducting solenoids in Linac Segment 1.



Cryomodule with eight β =0.54 cavities and one superconducting solenoids in Linac Segment 2.

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