Overview Linacs

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CSNS, IHEP

ICFA Mini-workshop on Beam Commissioning for High Intensity Accelerator, Dongguan, 8-10 June 2015

Challenges and Design Principles

- Beam loss control --- <1W/m
- Space-change effect --- Tune depression $\sigma_i/\sigma_0 > 0.5$
- Beam halo formation --- Matched beam

  $\sigma_0 < 90^0$

  K_r , K_l smooth change

  Equipartitionin/Fast cross

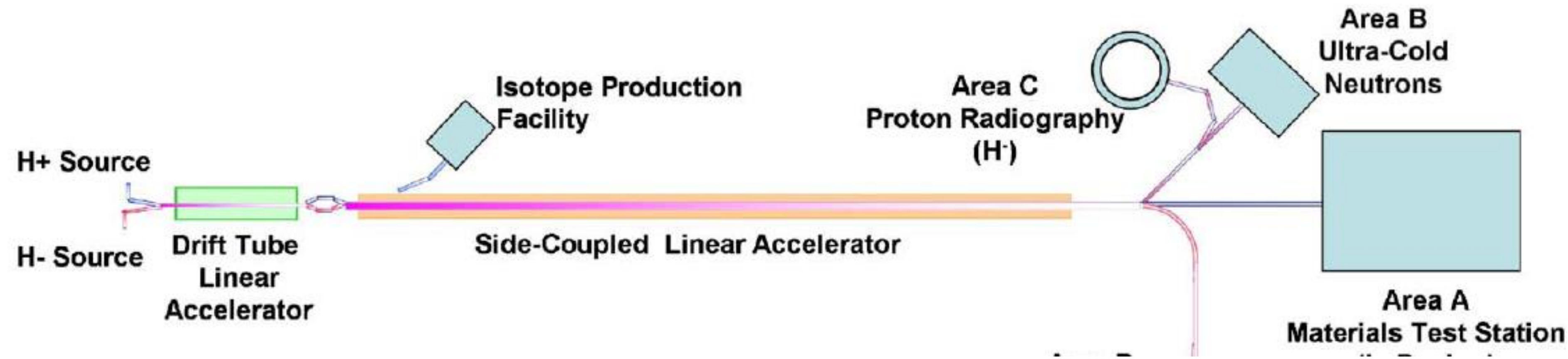
  $$\frac{\varepsilon_{nr} z_m}{\varepsilon_{nz} R} = 1$$
- High availability and reliability --- Redundancy, fault compensation

Some High Intensity Linacs

1. LANSCE
2. SNS
3. J-PARC
4. ISIS
5. CSNS
6. KOMAC
7. Linac4
8. ESS
9. MYRRHA
10. C-ADS
11. HIAF
12. FRIB
13. RAON

LANSCE Linac

Courtesy of R.E.Shafer



Four 201.25-MHz drift tube linac (DTL) tanks accelerate beam from 750 keV to 100 Me

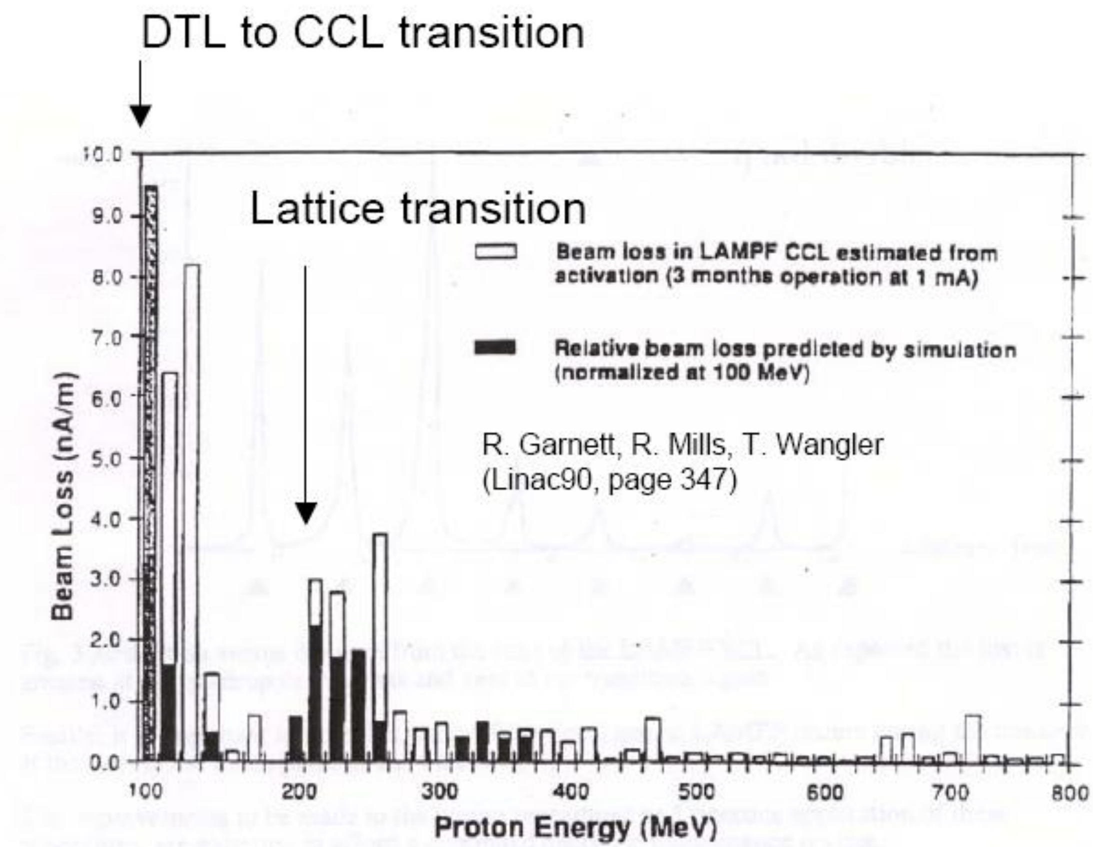
805MHz SCL linac of 800 MeV with 44 modules

Proton beam operation

~800 MeV
~6% duty cycle
60-Hz pulse rep rate
~ 1000 μs pulses
~ 15 mA peak current
~ 1 mA avg. current
~ 0.8 MW avg. beam power

Proton beam rms emittances (normalized)

100 MeV: ~ 0.30 π mm-mrad
800 MeV: ~ 0.70 π mm-mrad
(very large emittance growth between 100 And 800 MeV)

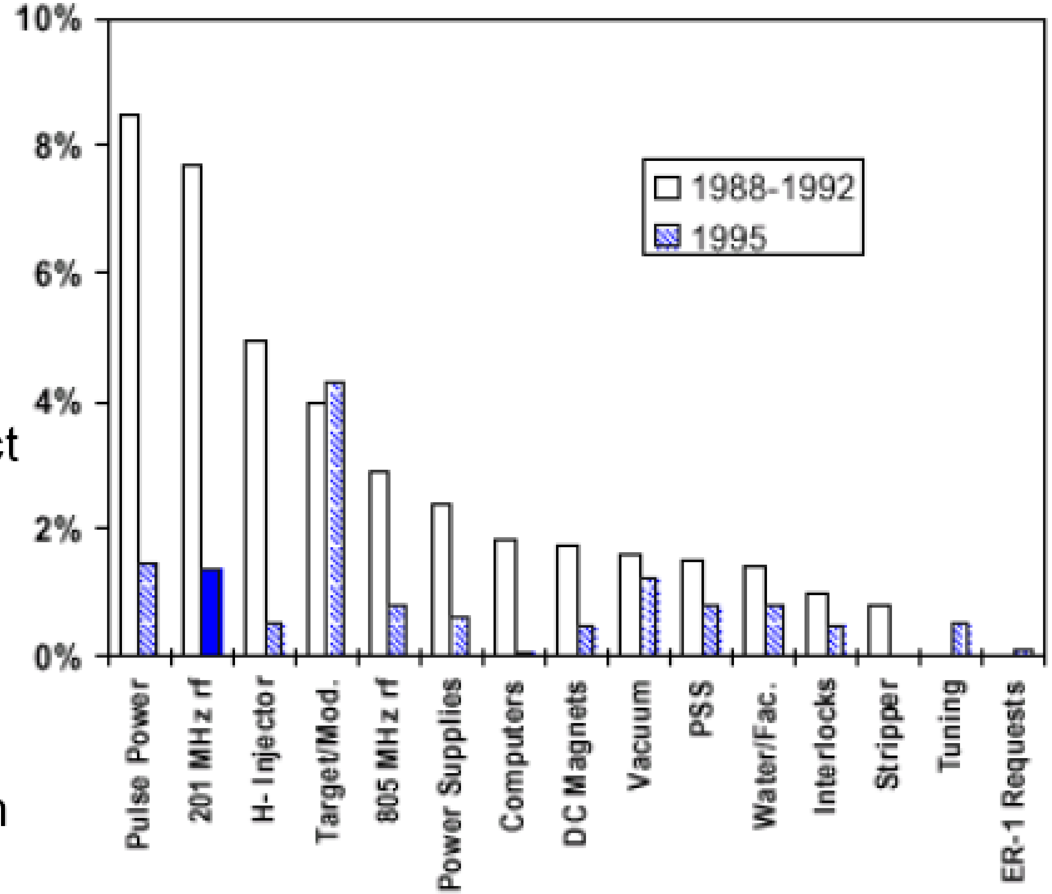


Major sources of beam losses are caused by

1) DTL to CCL transition at 100 MeV, including a 15' drift w/o RF bunching cavities.
2) Abrupt change in doublet lattice period at about 180 MeV.

Lack of ability to steer beam may also contribute (simultaneous H- and proton acceleration).

Because of the different type of users, with much shorter experiment durations (2-3 days instead of 2-3 months), the impact of availability and down time led to LRIP (LANSCE Reliability Upgrade Project).

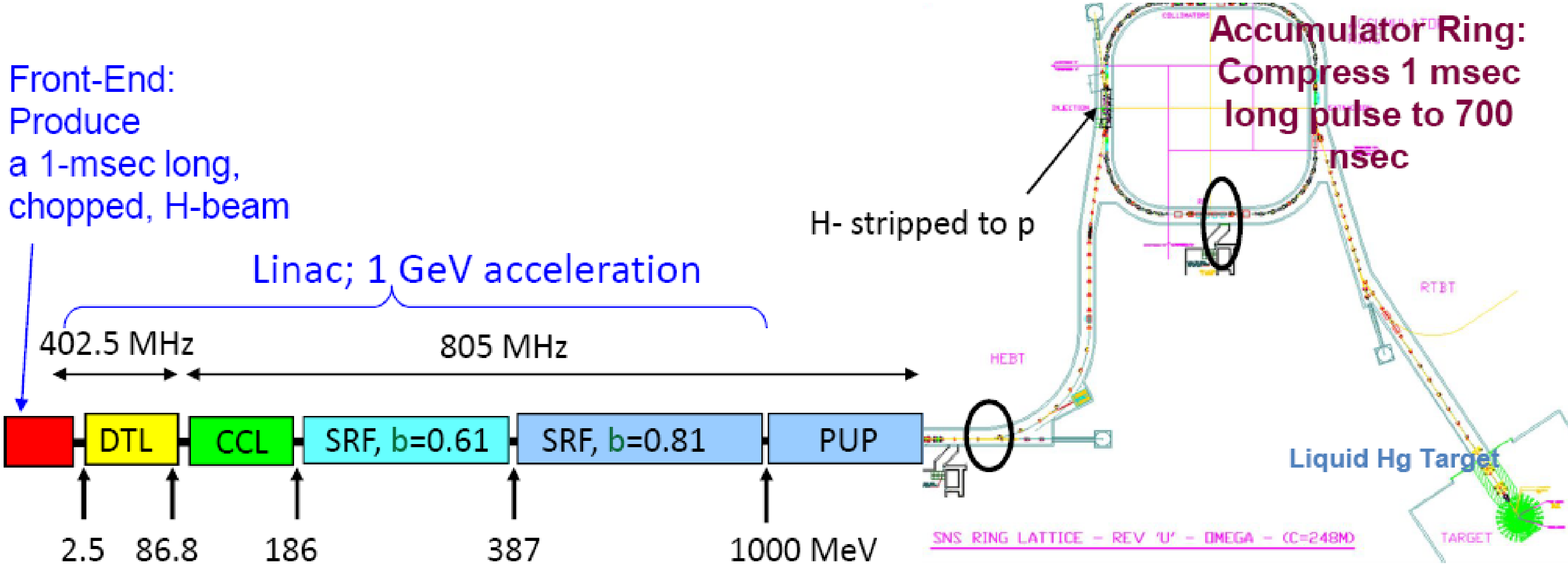


Recent improvements have improved neutron availability from < 75% to >85%.

LANSCE-R Project with $200M: Replacing radio-frequency equipment to achieve high reliability and providing adequate spare components; replacing hardware and software in the accelerator controls, data acquisition, and timing systems; refurbishing and replacing vacuum, cooling, and magnet power supplies for the accelerator and beam-transfer lines; and refurbishing and improving the beam-diagnostics systems; replacing some drift tubes.

Courtesy of J. Galambos

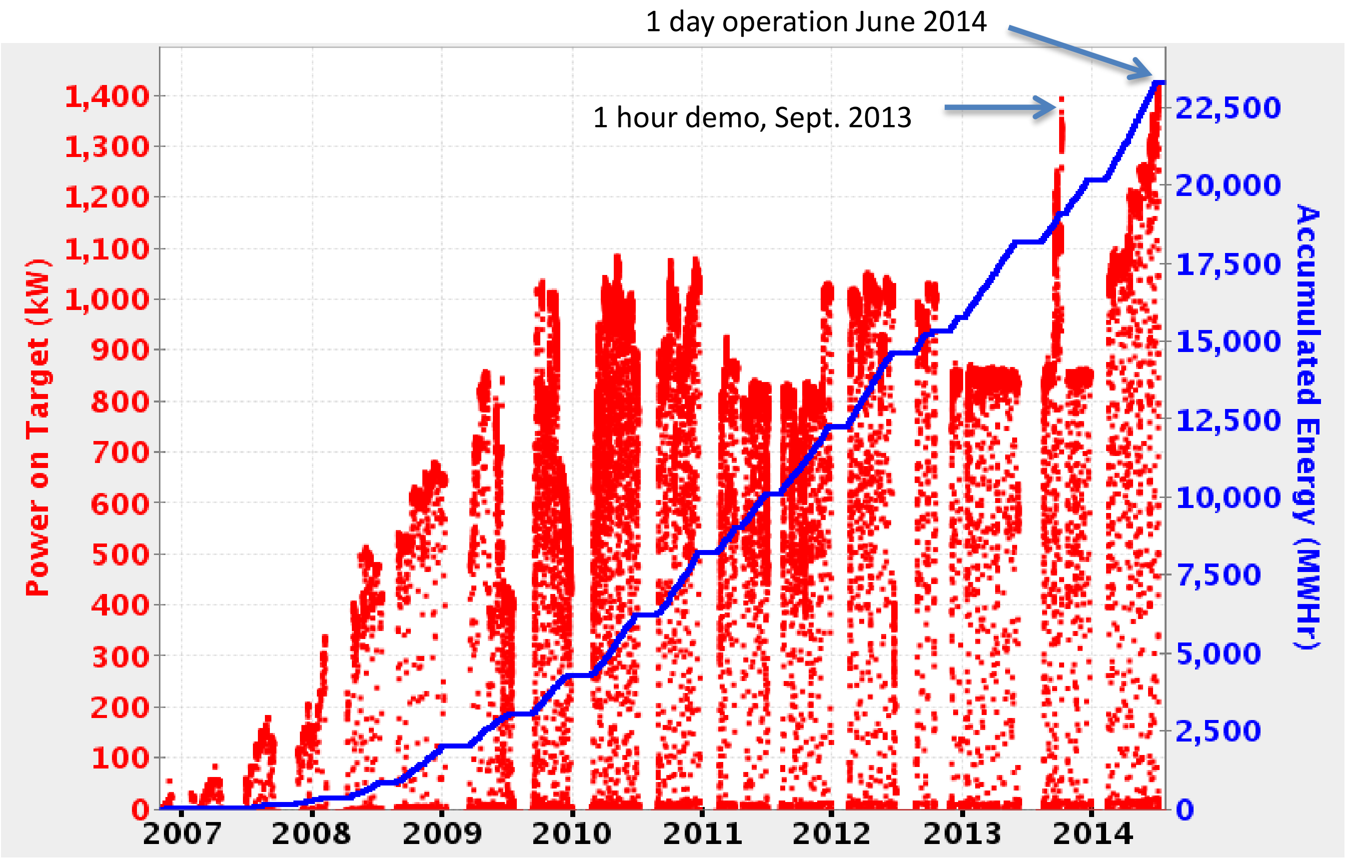
SNS Linac



Subsequent beam commissioning runs for the accelerator subsystems

Title of the run	Date for ARR permission to operate	Energy (MeV)		Intensity (H^-/pulse)	
		Design	Achieved	Design	Achieved
FES	10/29/2002	2.5	2.5	1.6×10^{14}	1.0×10^{14}
FES + DTL1	08/26/2003	7.5	7.5	1.6×10^{14}	1.3×10^{14}
FES—DTL3	04/08/2004	23	23	1.6×10^{14}	1.0×10^{13}
FES—CCL3	09/07/2004	157	157	1.6×10^{14}	1.0×10^{13}
FES—HEBT	07/25/2005	1000	950	1.6×10^{14}	8.0×10^{13}
FES—Ring extraction	01/05/2006	1000	932–950	1.5×10^{14}	1.3×10^{13}
FES—Target	03/15/2006	1000	860	1.4×10^{14}	2.5×10^{13}

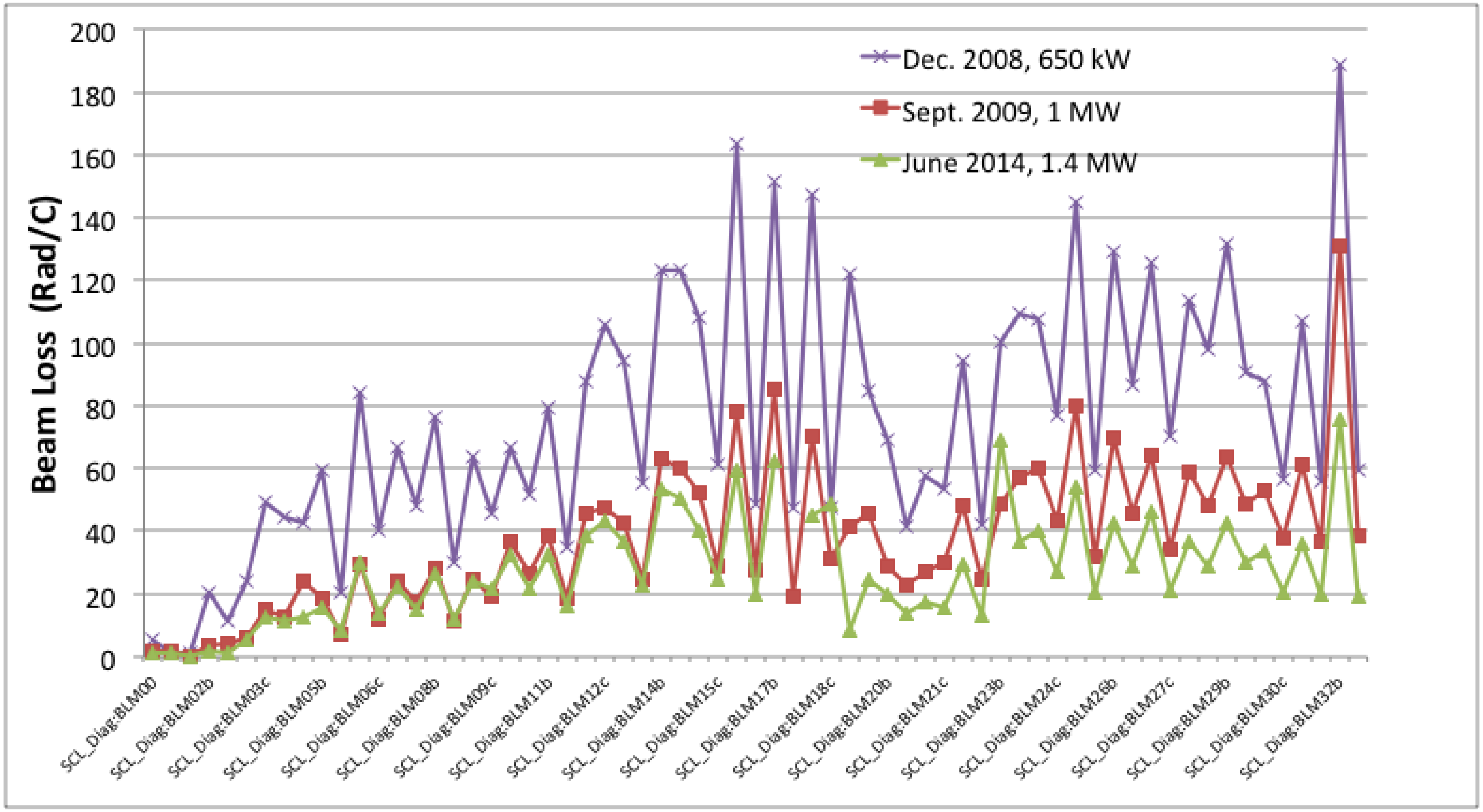
SNS Linac



- First neutron production at 1.4 MW: June 29, 2014
  - Sustained power increase during the 2014 run, increasing power from ~ 1. MW to 1.4 MW

SNS Linac

Superconducting Linac Beam Loss History



SNS Linac

STS Accelerator Scope:

Double the "power" (intensity/pulse)

	1.4 MW	STS	
		First Target	Second Target
Beam Energy (GeV)	.94	1.3^	1.3
Rep rate (Hz)	60	50	10
Average current (mA)	26	33	38
Energy / pulse (kJ)	23.3	40	46.6
Power (MW)	1.4	2.0**	0.47

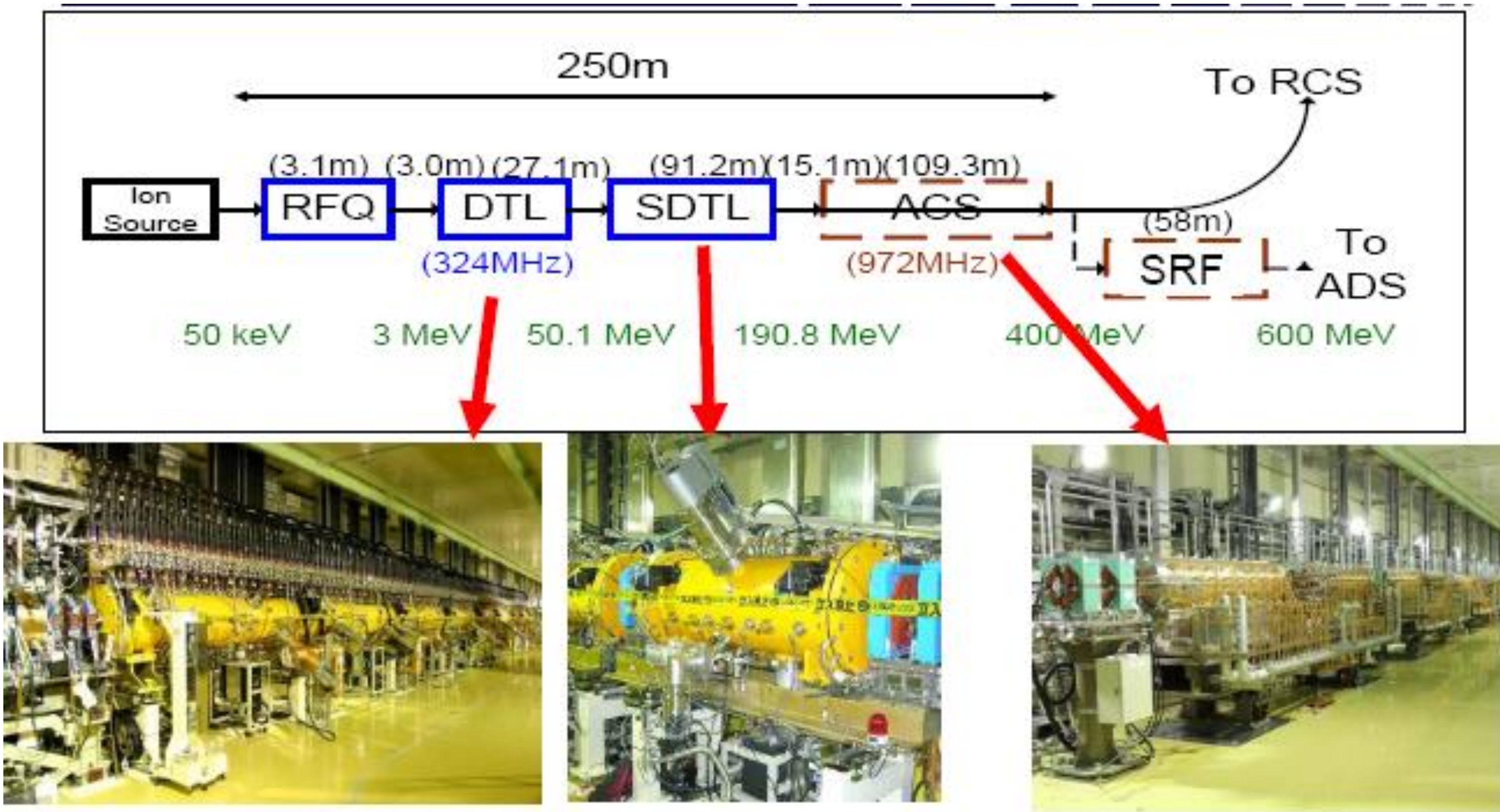
^ plasma-processing of the existing superconducting linac (SCL) cavities and additional 7 cryomodules.

* Use beam chopping (average current) to independently throttle FTS / STS power

** Shielding / target system limit, may be possible to increase.

J-PARC Linac

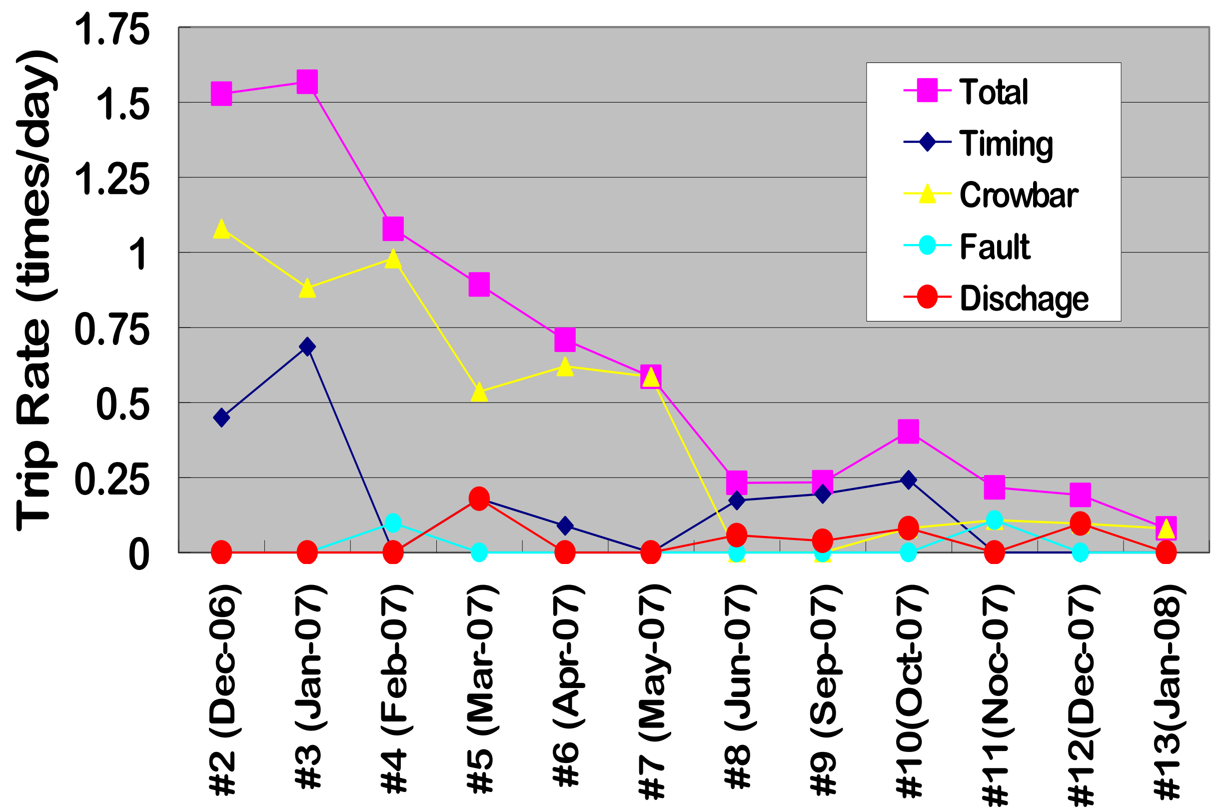
Courtesy of Hasegawa



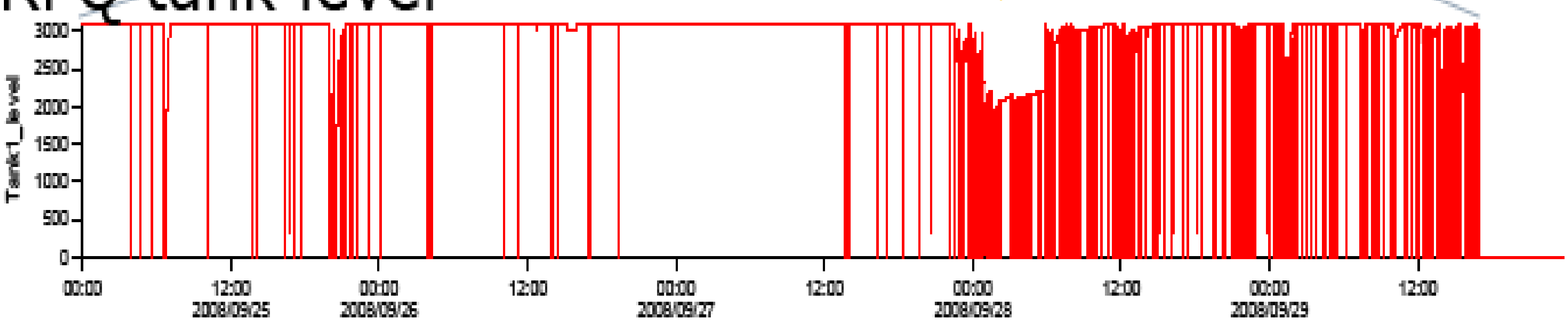
Drift-Tube Linac (DTL) Separated DTL (SDTL) ACS

J-PARC Linac

J-PARC Linac trip rate



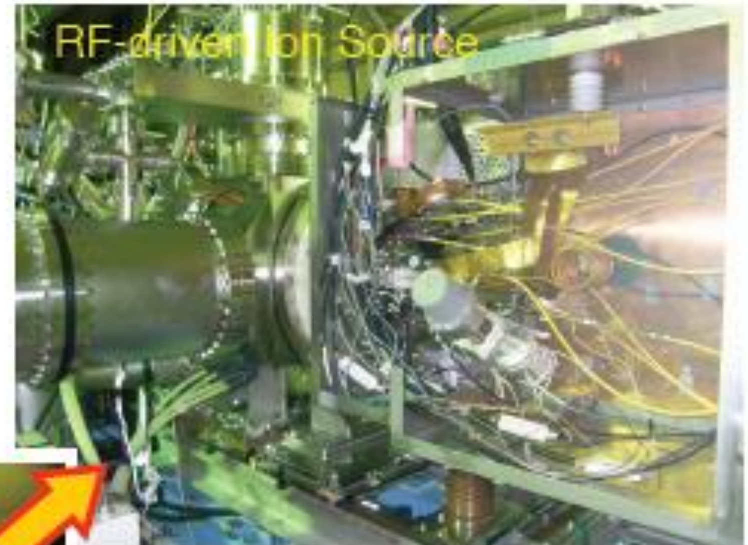
RFQ tank level

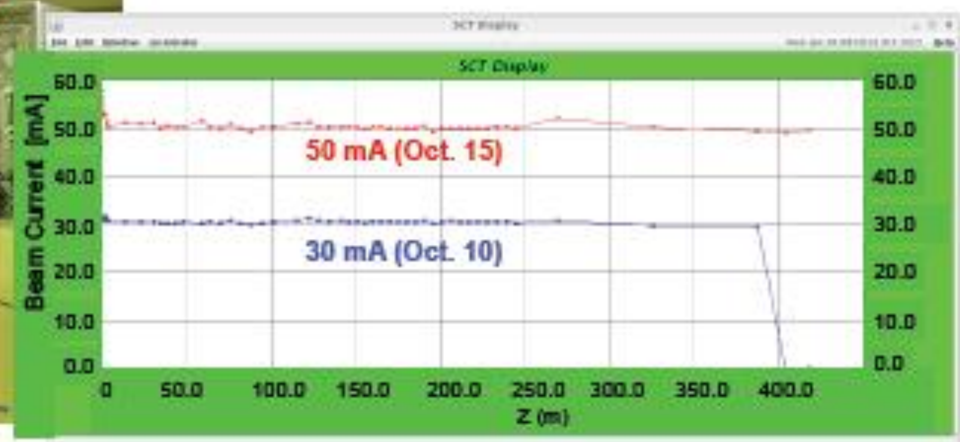


J-PARC Linac

New front-end system of the linac

During the 2014 summer shutdown period, the front-end system of the linac was replaced to increase the peak current to 50 mA.

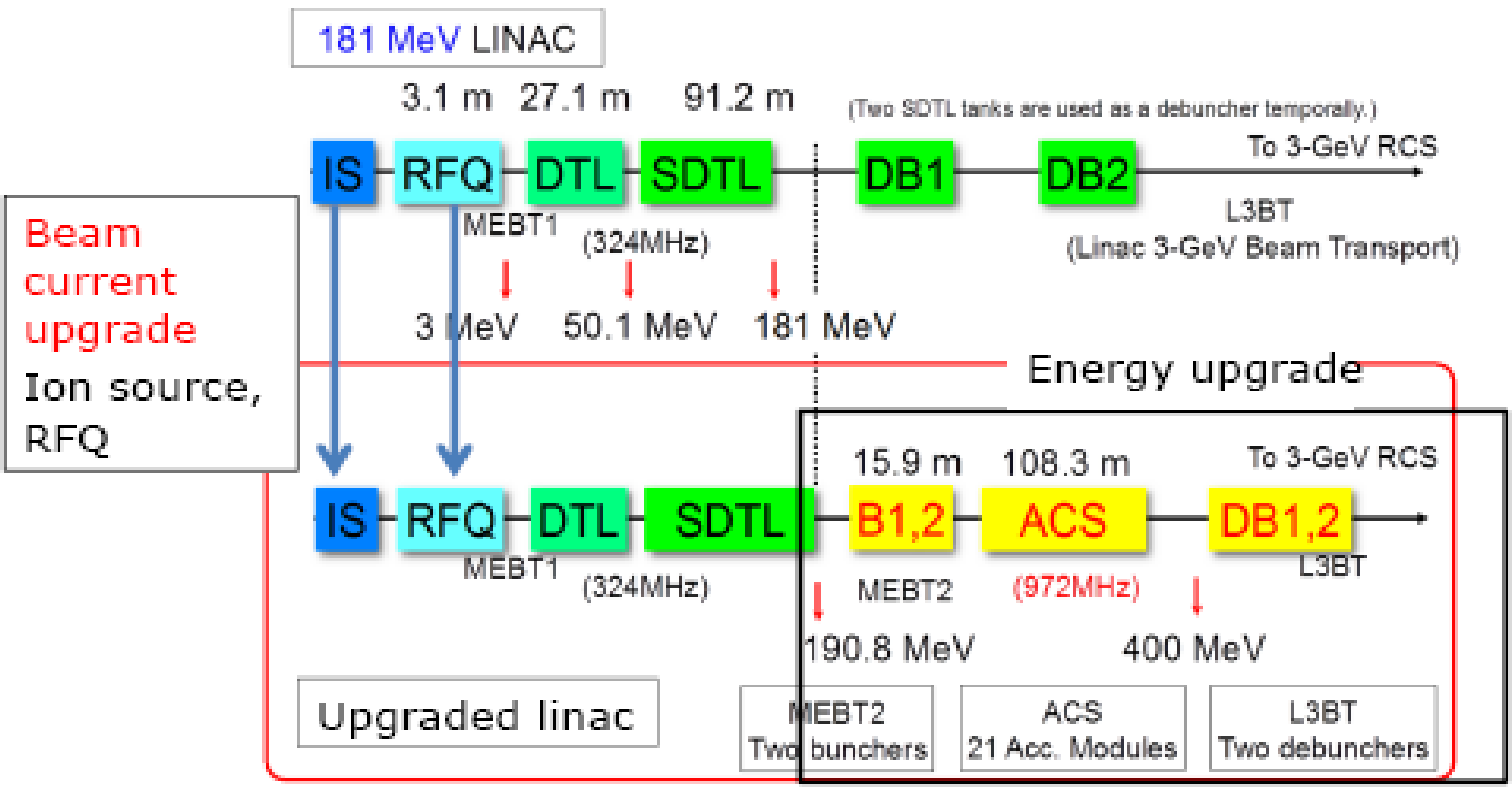




New front-end system in the tunnel.

J-PARC Linac

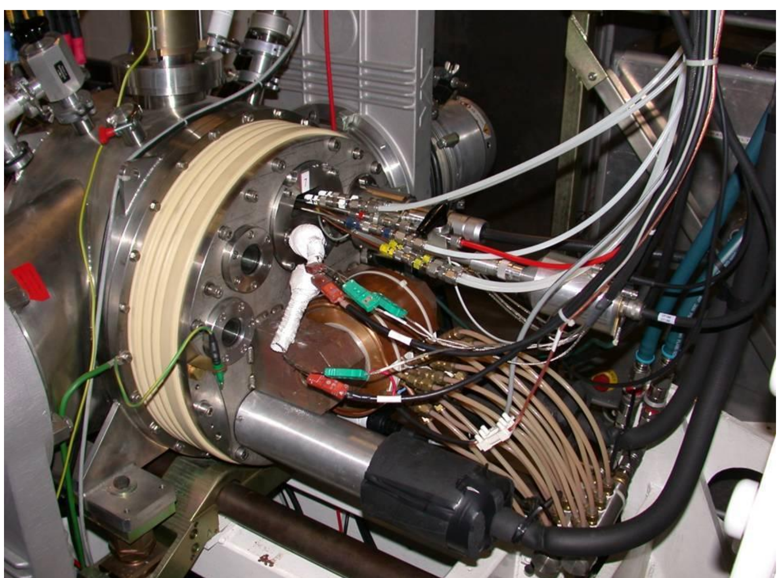
Replacing with the new IS, RFQ and adding ACS, the beam current can reach design value of 50mA and energy can reach design value of 400MeV. After the upgrade program, 1MW equivalent beam power with reduced repetition rate from the RCS ring has been demonstrated.



ISIS Linac

H⁻ ion source at −35 kV

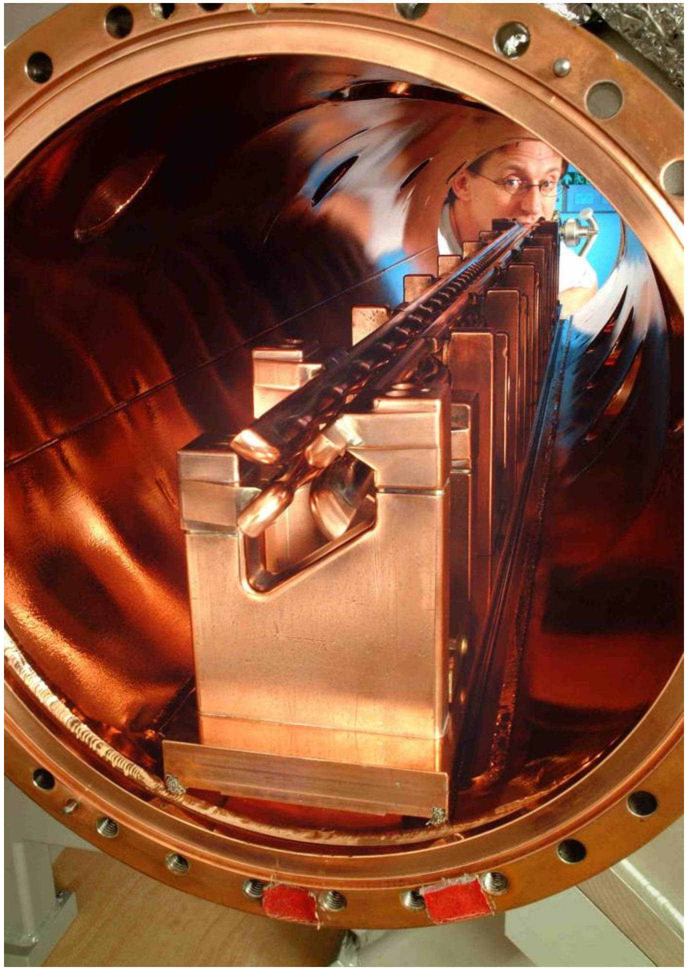
RFQ	35 keV	—	665 keV
Linac, 4 tanks	665 keV	—	10 MeV
	10 MeV	—	30 MeV
	30 MeV	—	50 MeV
	50 MeV	—	70 MeV
Beam current	ave.200uA, peak 22mA		



Penning IS: 30mA, 30day life time

Old Cockcraft-Walton accelerator of 665 keV

ISIS Linac



RFQ: 35 keV → 665 keV

70 MeV, 202½ MHz DTL linac

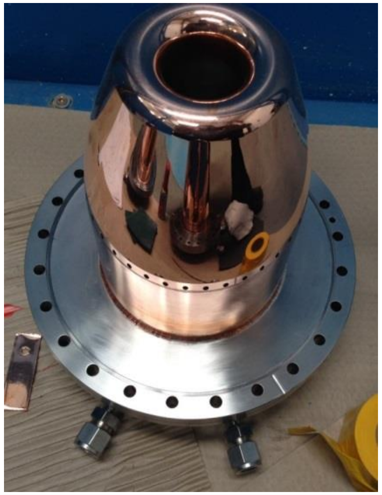
ISIS Linac

Courtesy of R. McGreevy

- Linac R&D Activity

VESPA: ion source test stand

Front end test stand: new RFQ



New Debuncher

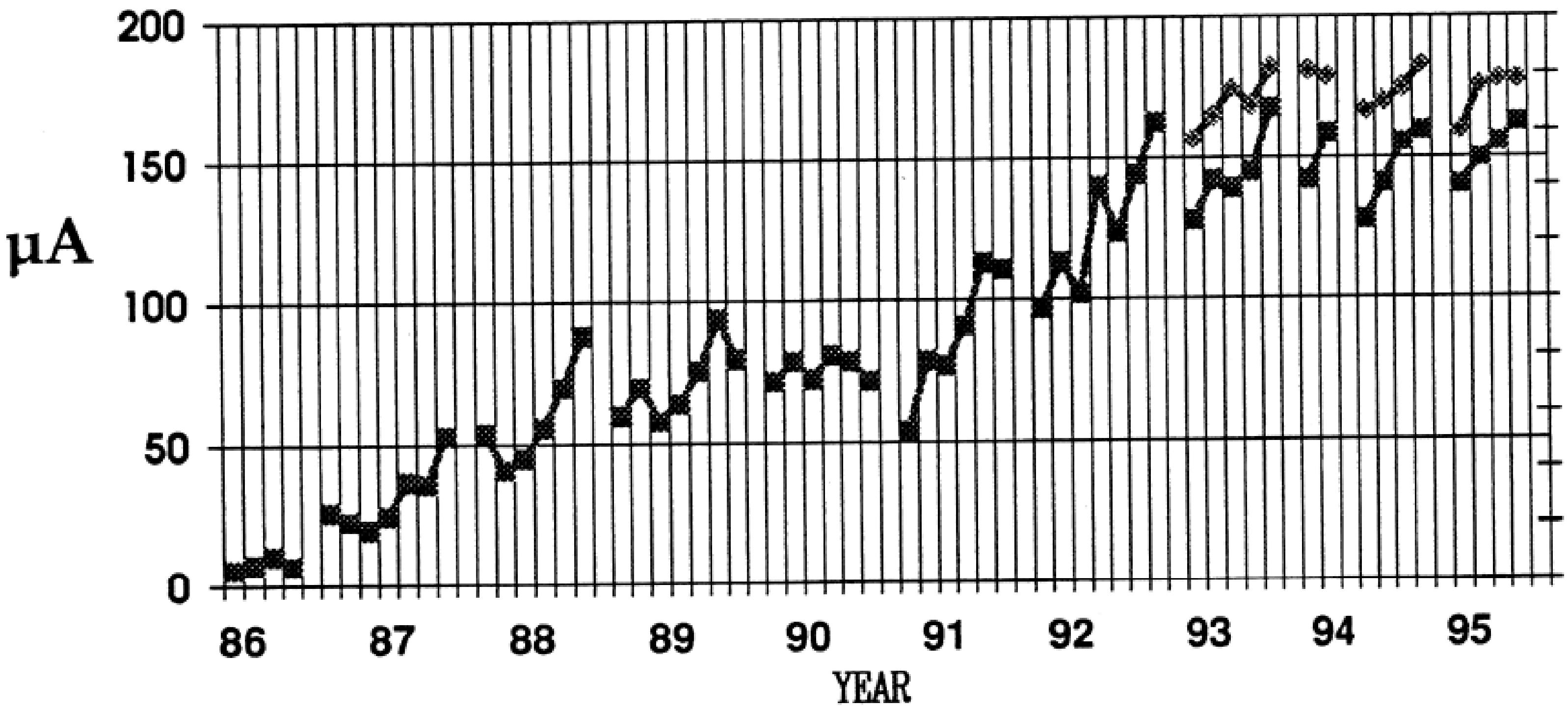
New Linac Tank 4 prototype and test stand

ISIS Linac

History and Future

Historical Performance of ISIS Accelerator

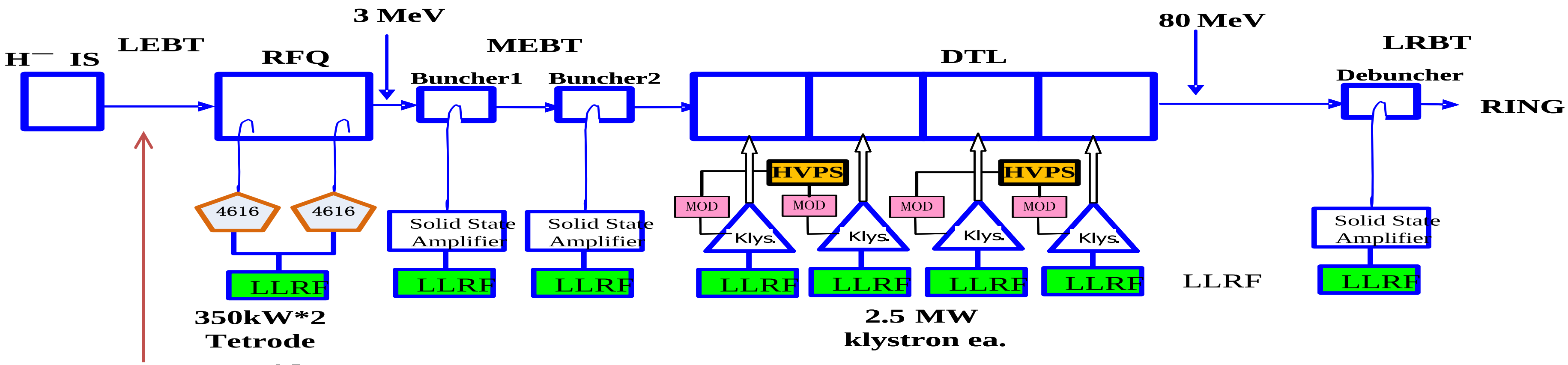
85-90 % operation efficiency

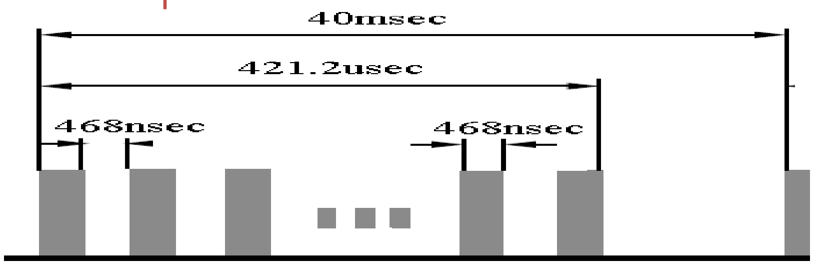


By 2020: will be running at double current capacity

By 2030: Build a new (international) facility: ISIS-II

CSNS Linac





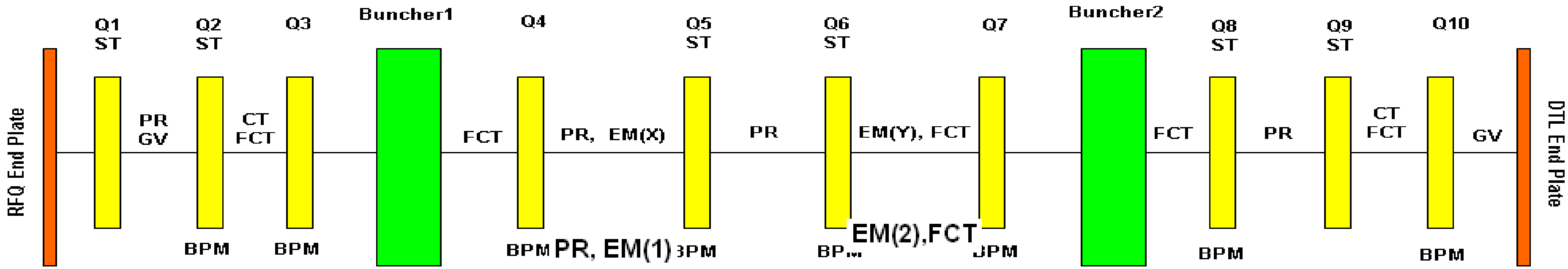
EMQ option in FFDD lattice for DTL

Electrostatic chopper in LEBT

	Ion Source	RFQ	DTL
Input Energy（MeV)		0.05	3.0
Output Energy(MeV)	0.05	3.0	80
Pulse Current (mA)	20/40	20/40	15/30
RF frequency (MHz)		324	324
Chop rate (%)		50	50
Duty factor (%)	1.3	1.05	1.05
Repetition rate (Hz)	25	25	25

CSNS Linac

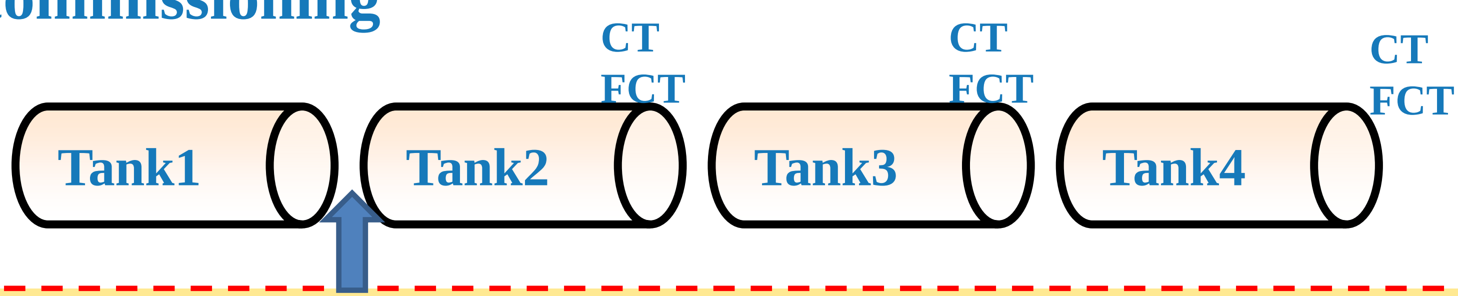
RFQ&MEBT commissioning



PR, EM(1)

BPM=beam position monitor
PR=profile monitor
FCT=fast current monitor
CT=current monitor
Q=quadrupole magnet
EM=emittance monitor
GV=gate vale
ST=steering magnet
DR=drift space

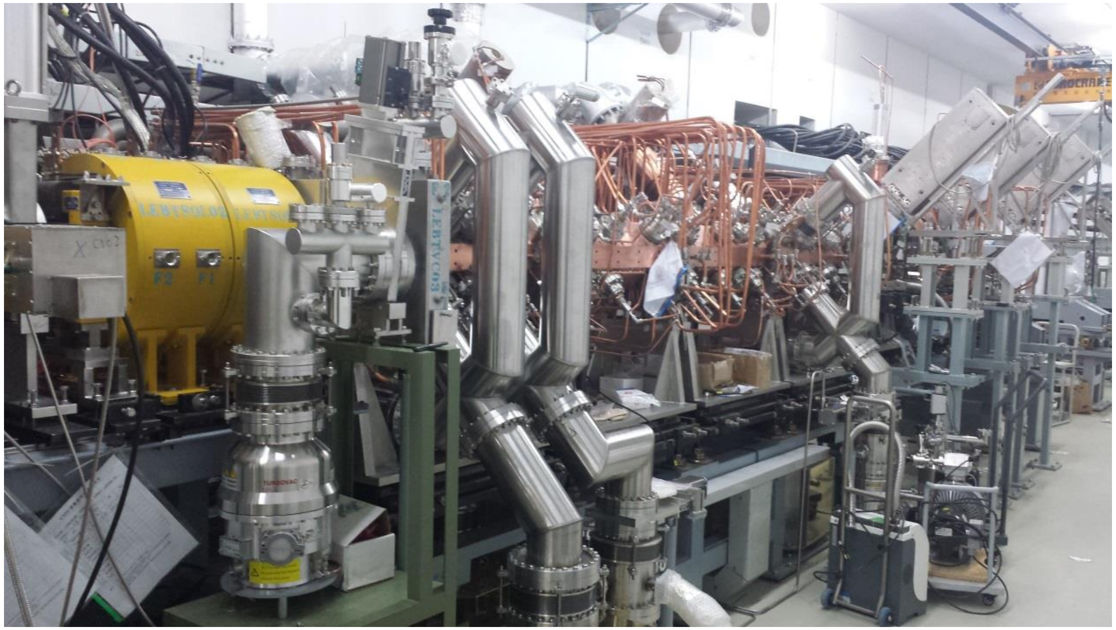
DTL commissioning

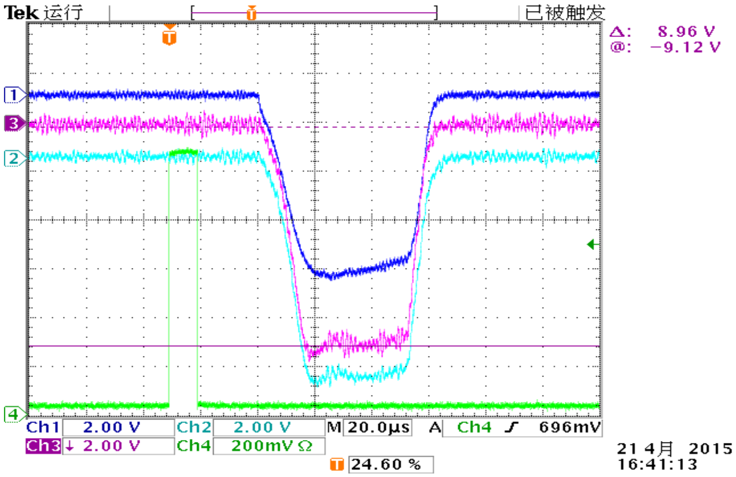


Temporal Beam Diagnostic system:
1BPM,1CT,2FCT,1 QEM,1 x-y steering magnet,1EM,1WS
1 Energy degrader /Faraday cup,1 Beam dump(0.163kW)

CSNS Linac

FE is under beam commissioning



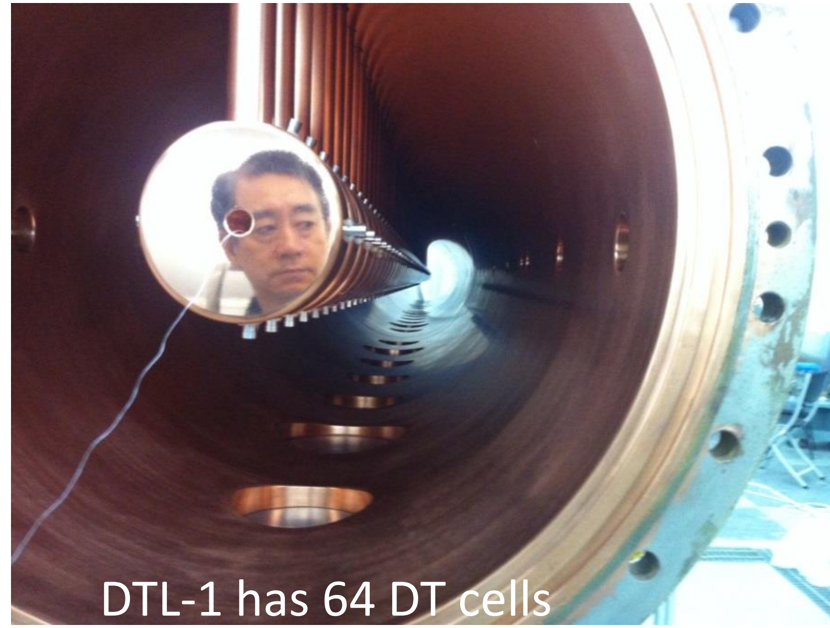


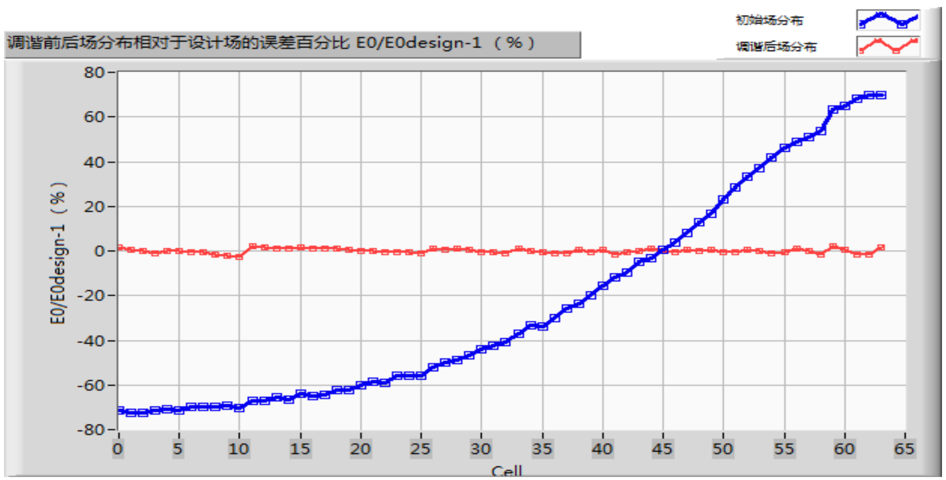
Beam current on CT

	IS	LEBT	RFQ	MEBT
Peak Current (mA)	40	30	20	20
Transmission rate		75%	67%	100%

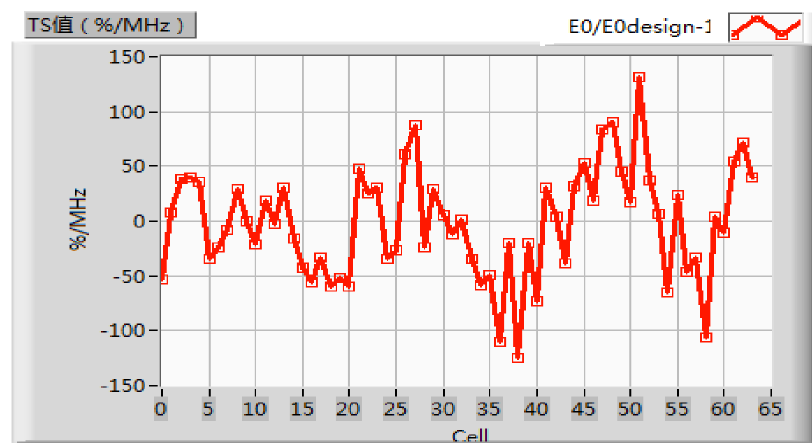
Pulse length is 100 μs and 1 Hz. Emittance from IS is lager than acceptance of RFQ. There is a collimator in the LEBT

CSNS Linac



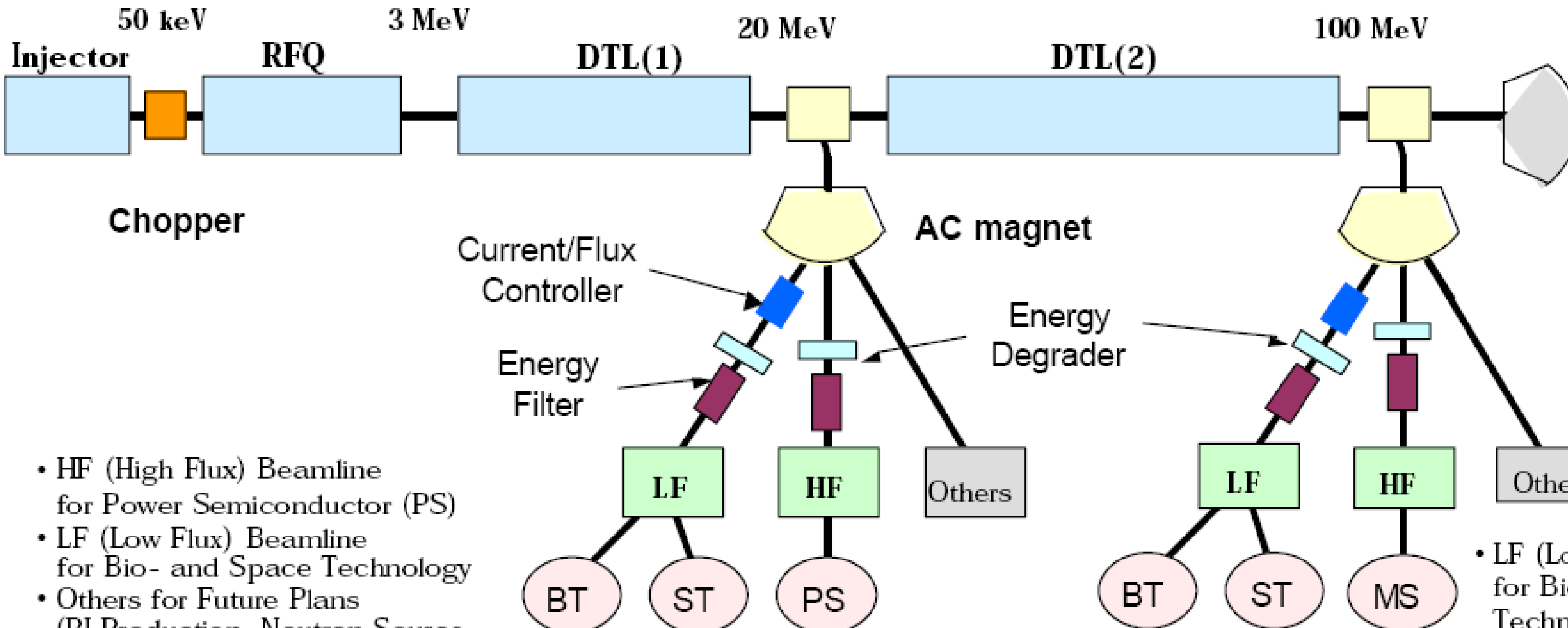


Achieved field flatness <2%



Achieved field stability < 130%/MHz

KOMAC Linac



- HF (High Flux) Beamline for Power Semiconductor (PS)
- LF (Low Flux) Beamline for Bio- and Space Technology
- Others for Future Plans (RI Production, Neutron Source, BNCT Research, etc.)

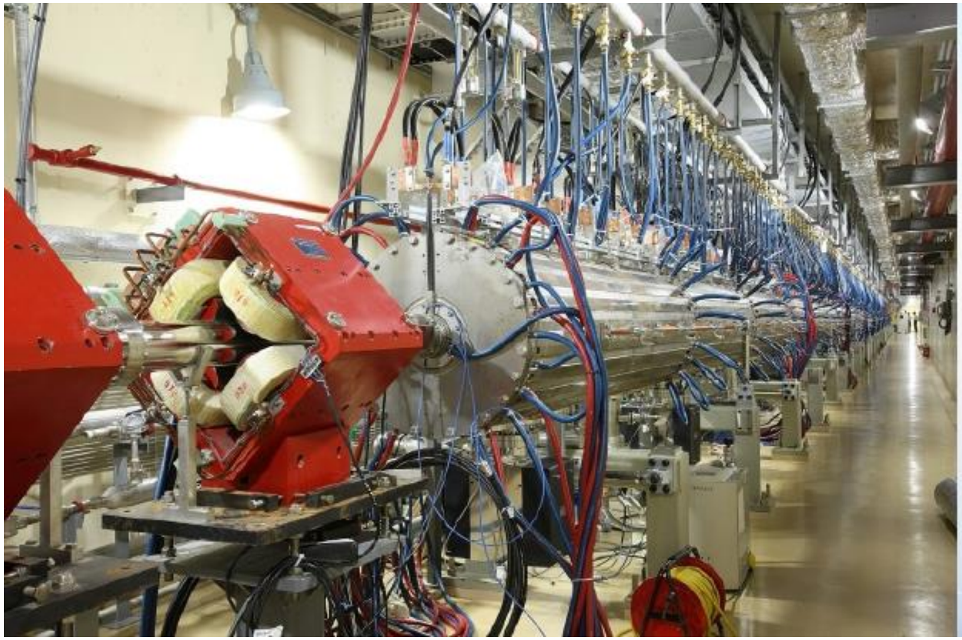
- LF (Low Flux) Beamline for Bio- and Space Technology
- HF (High Flux) Beamline for Material Science (MS)
- Others for Future Plans Material Irradiation, RI Production, Low Energy Proton Therapy, etc.)

❑ **Remarks**

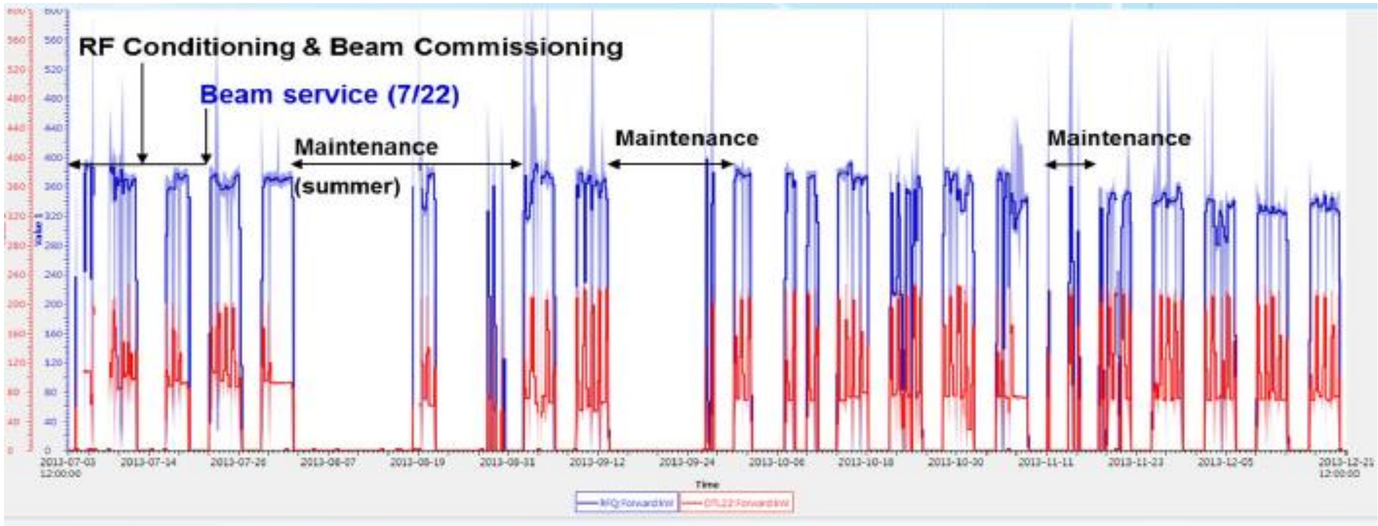
- The PEFP Accelerator compose of 50keV Proton Injector, 3MeV RFQ and 100MeV DTL.
- It extracts protons at 20MeV and 100MeV.
- A chopper & AC magnets to distribute beams for each beam line s imultaneously.
- It has energy degraders & filters to change and select proton e nergy.

KOMAC Linac

Linac commissioned for user operation in July 2013 @1kW beam power



Key Parameters		
Output energy (MeV)	20	100
Peak beam current (mA)	20	20
Beam duty (%)	24	8
Avg. beam current (mA)	4.8	1.6
Pulse length (ms)	2	1.33
Repetition rate (Hz)	120	60
Avg. beam power (kW)	96	160



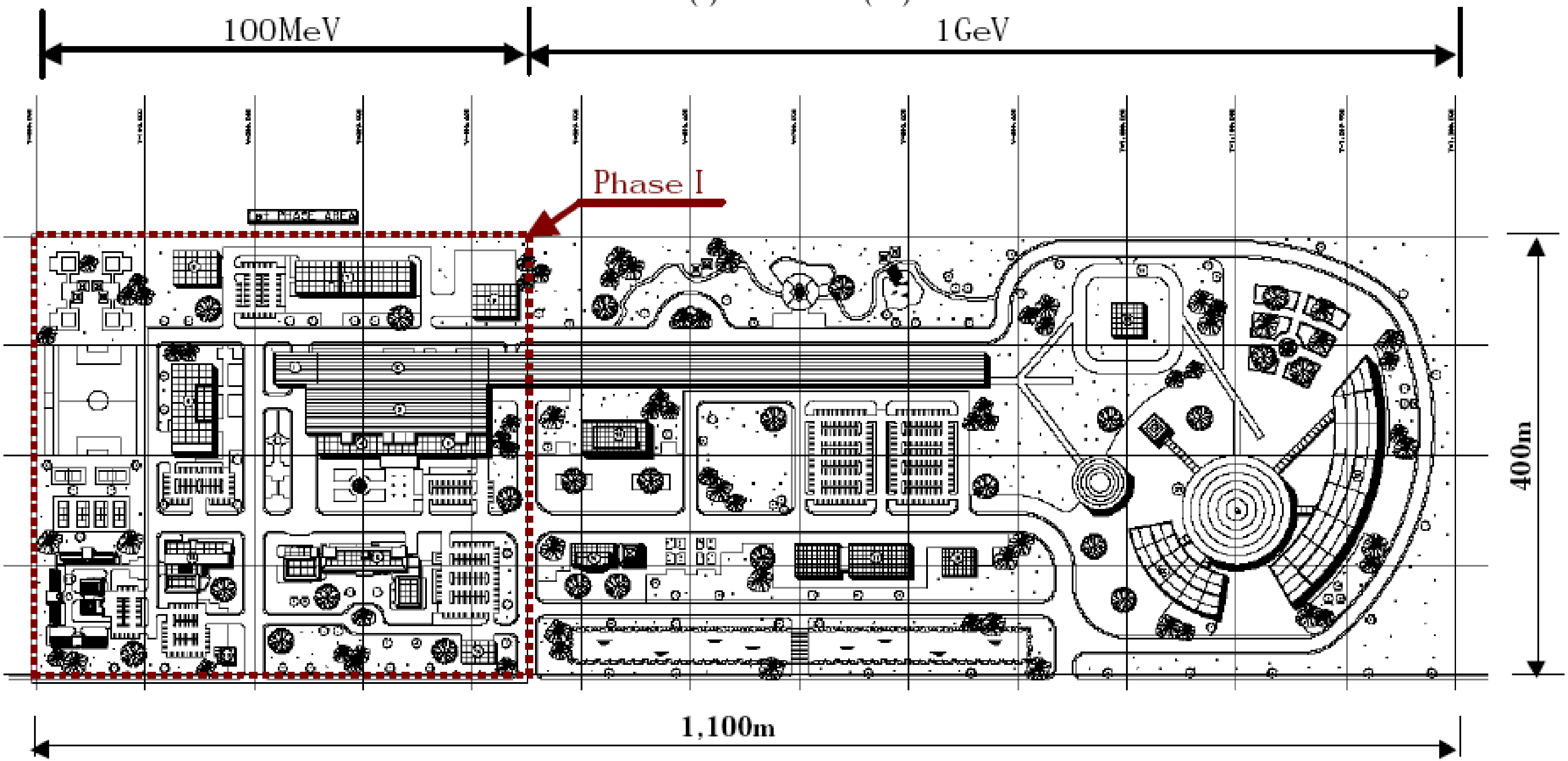
Availability ~ 82%

KOMAC Linac

Upgrade to 1GeV for spallation neutron source

- Construction of 100MeV accelerator complex (Phase I) is under way
- Land will be prepared for future extension (1GeV and Spallation Neutron Source etc.)

▶ For 100MeV Accelerator : 450m(L) X 400m(W)



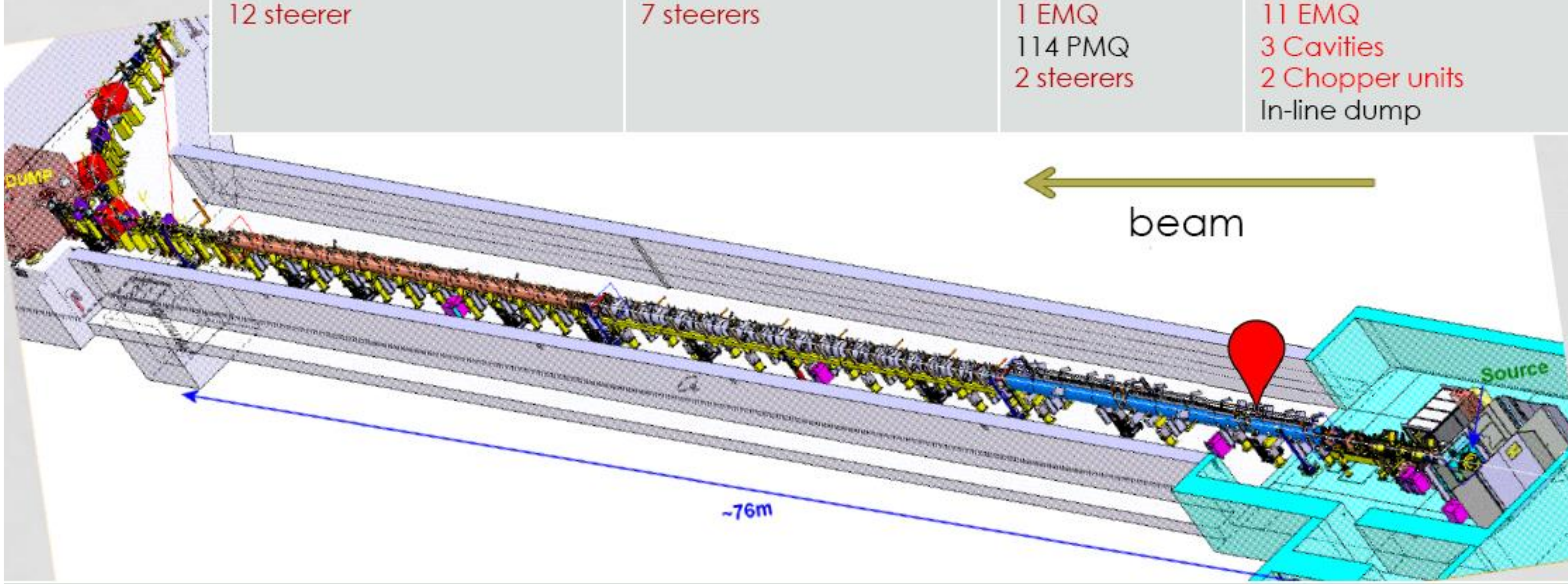
▶ For upgrading of Accelerator, land will be prepared about 1,100m(L) X 400m(W)

Linac4

Courtesy of A. Lombardi

LINAC4 machine layout- 352MHz

Π-mode	CCDTL	DTL	Pre-injector
160 MeV	100 MeV	50 MeV	3MeV
23 m 12 Modules 8 Klystrons: 12MW 12 EMQ 12 steerer	25 m 7 Modules 7 Klystrons : 7 MW 7 EMQ + 14 PMQ 7 steerers	19 m 3 Tanks 3 Klystrons : 5 MW 1 EMQ 114 PMQ 2 steerers	9 m Source(s) 2 solenoids RFQ 11 EMQ 3 Cavities 2 Chopper units In-line dump

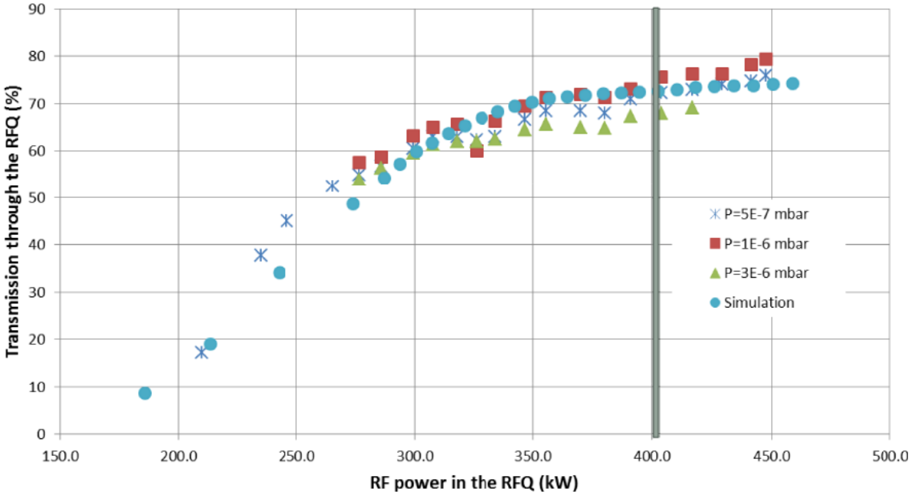


Commissioning stages

160 MeV	105 MeV	50 MeV	12 MeV	3 MeV	45 keV
End 2015	August 2015	May 2015	Well advanced	Chopping demonstrated	Not the final source

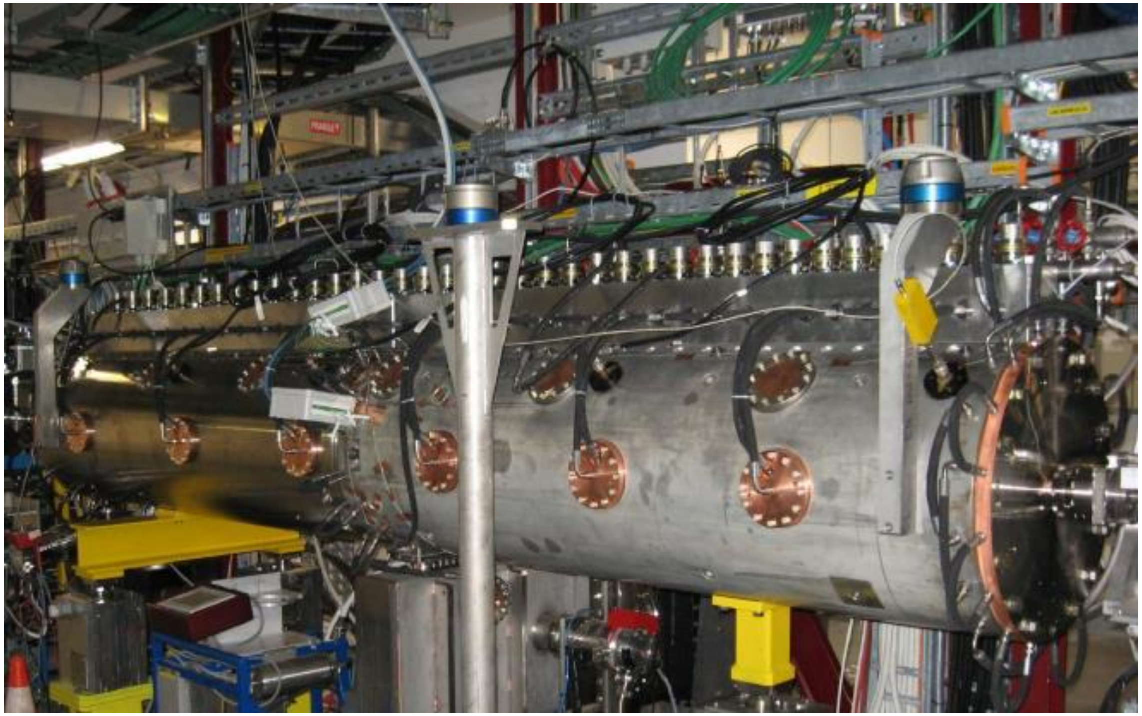
Linac4

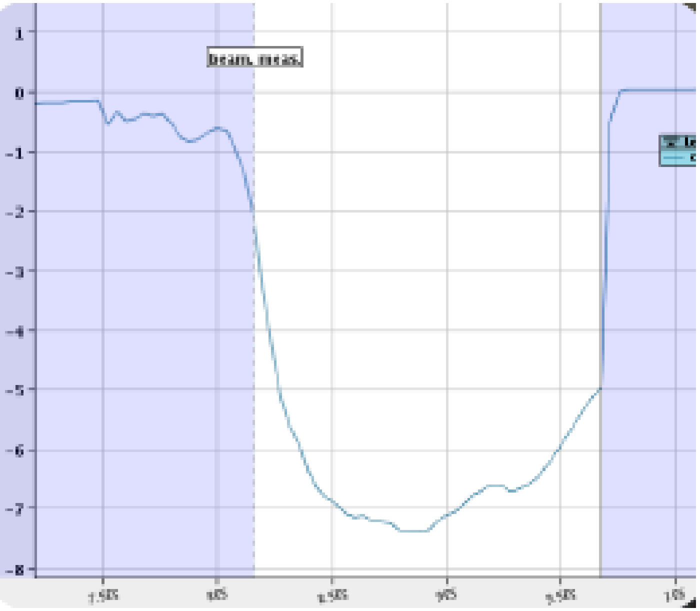
10 mA H- beam was accelerated to 3MeV by RFQ in March 2013 first time



Beam transmission rate is 75%

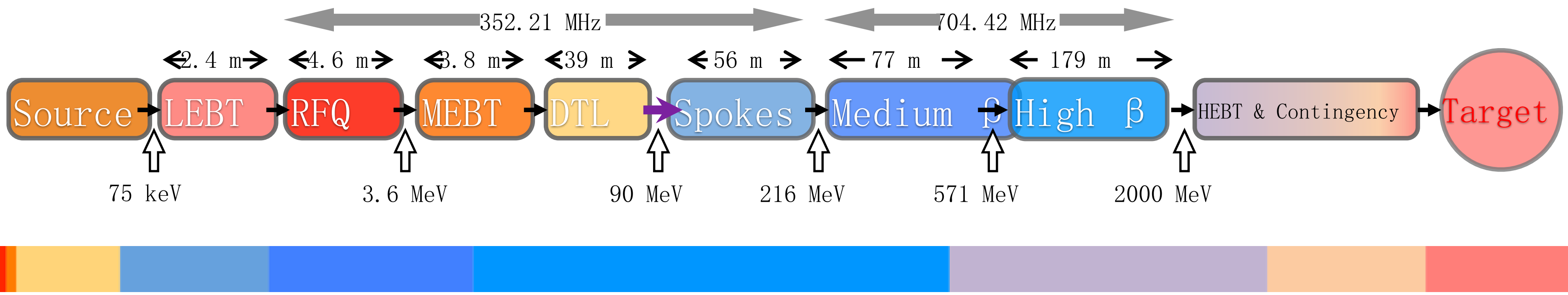
Linac4





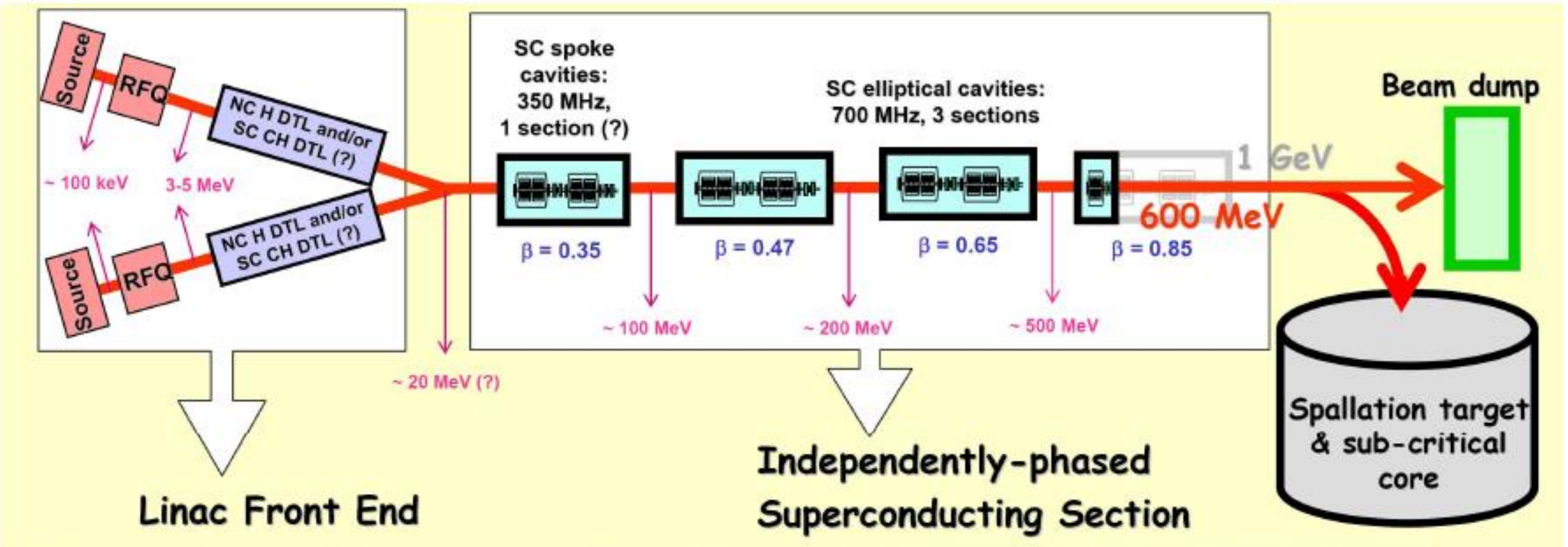
DTL accelerate 7.5mA H- beam from 3MeV to 12MeV with 100 % transmission rate in August 2013.

ESS Linac

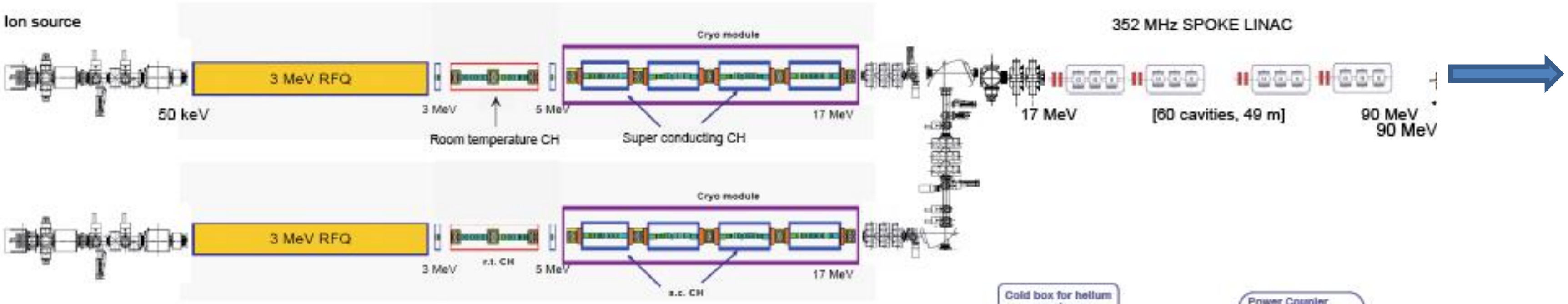


	Length (m)	W_in (MeV)	F (MHz)	β Geometric	No. Sections	T (K)
LEBT	2.38	0.075	--	--	1	~300
RFQ	4.6	0.075	352.21	--	1	~300
MEBT	3.81	3.62	352.21	--	1	~300
DTL	38.9	3.62	352.21	--	5	~300
LEDP + Spoke	55.9	89.8	352.21	0.50 (Optimum)	13	~2
Medium Beta	76.7	216.3	704.42	0.67	9	~2
High Beta	178.9	571.5	704.42	0.86	21	~2
Contingency	119.3	2000	704.42	(0.86)	14	~300 / ~2

MYRRHA



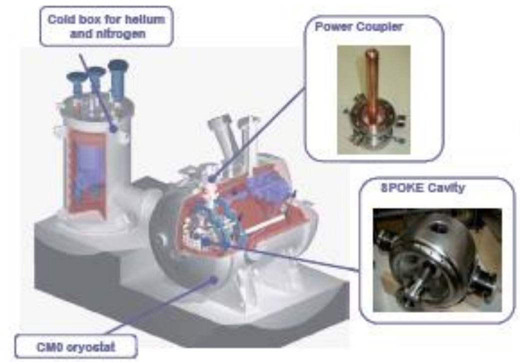
	Transmuter demo (XT-ADS / MYRRHA project)	*Industrial transmuter (EFIT)*
Proton beam current	2.5 mA (& up to 4 mA for burn-up compensation)	~ 20 mA
Proton energy	600 MeV	~ 800 MeV
Allowed beam trips (>1 sec) nb	< 5 per 3-month operation cycle	~ < 3 per year
Beam entry into the reactor	Vertically from above	
Beam stability on target	Energy: ± 1% - Current: ± 2% - Position & Size: ± 10%	
Beam time structure	CW (w/ low-frequency 200μs zero-current beam holes for sub-criticality monitoring)	

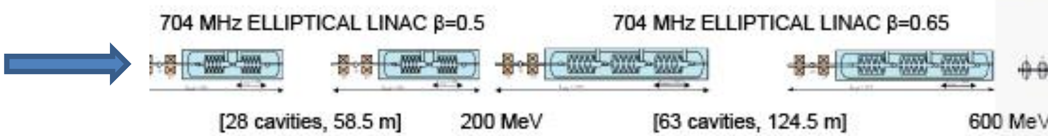


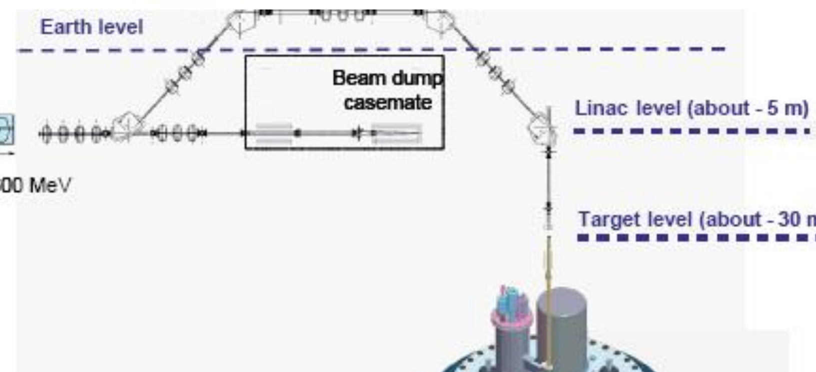

RFQ element


Copper CH RF cavity


Superconducting CH cavity design

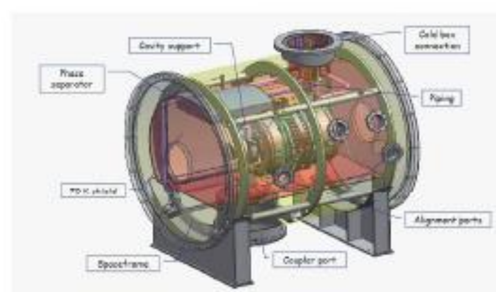


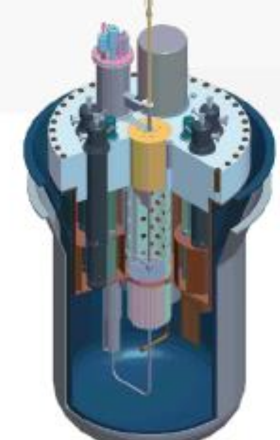




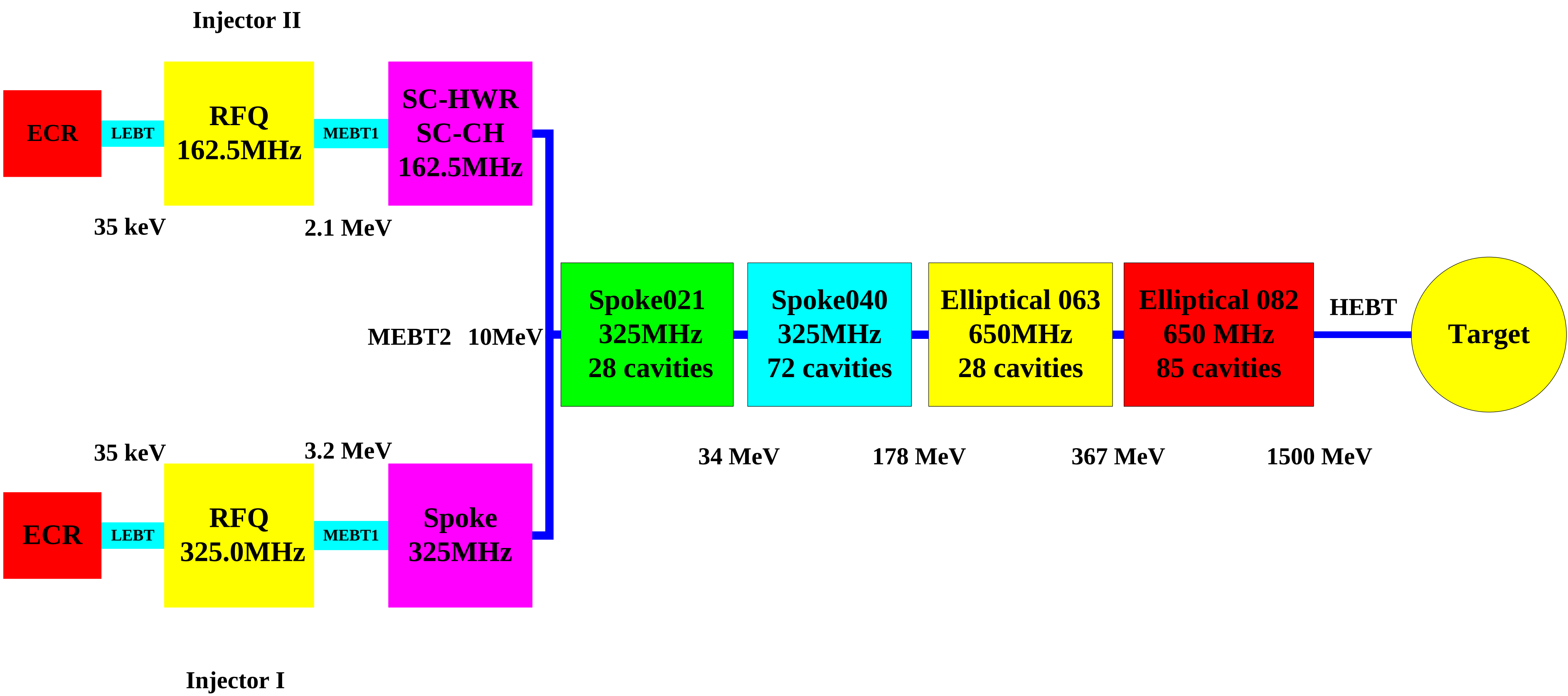

5 element elliptical cavity


Elliptical cavity envelope

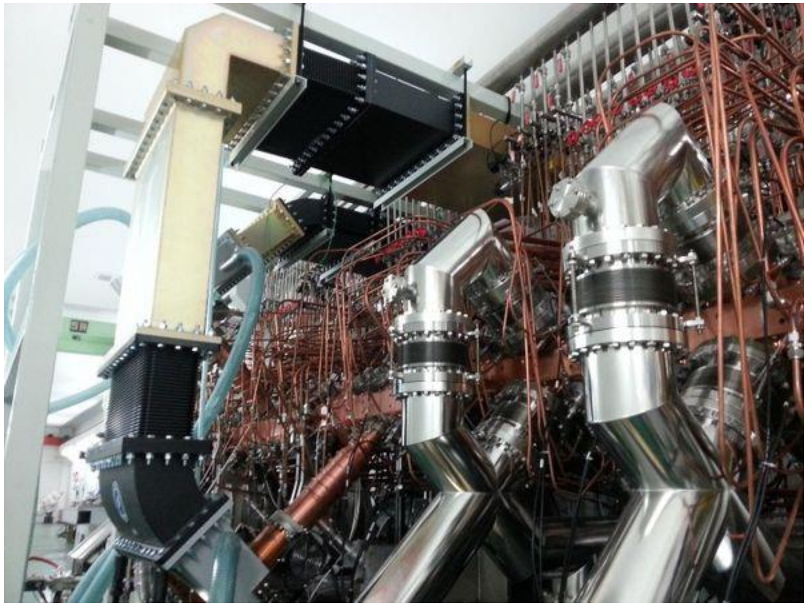

Cryomodule for the elliptical cavities

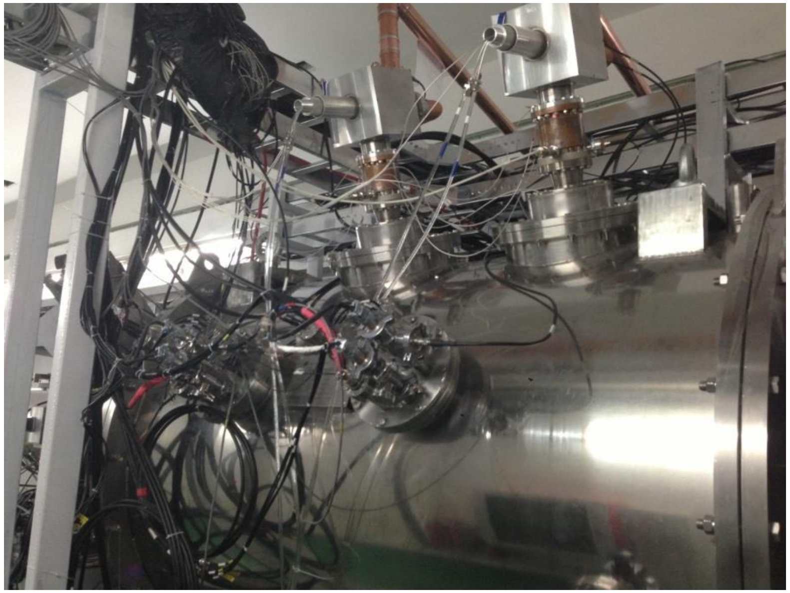

MYRRHA reactor

C-ADS Linac


Injector II
ECR
LEBT
RFQ
162.5MHz
MEBT1
SC-HWR
SC-CH
162.5MHz
35 keV
2.1 MeV
MEBT2
10MeV
Spoke021
325MHz
28 cavities
Spoke040
325MHz
72 cavities
Elliptical 063
650MHz
28 cavities
Elliptical 082
650 MHz
85 cavities
HEBT
Target
34 MeV
178 MeV
367 MeV
1500 MeV
35 keV
3.2 MeV
ECR
LEBT
RFQ
325.0MHz
MEBT1
Spoke
325MHz
Injector I

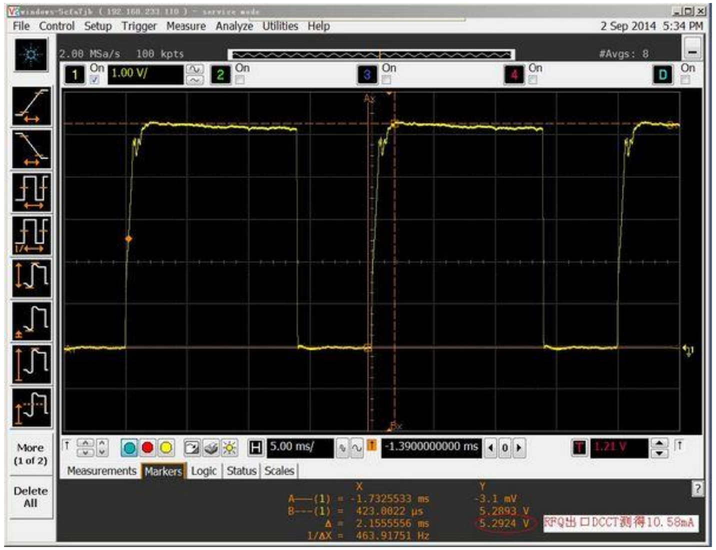
C-ADS Linac (IHEP)

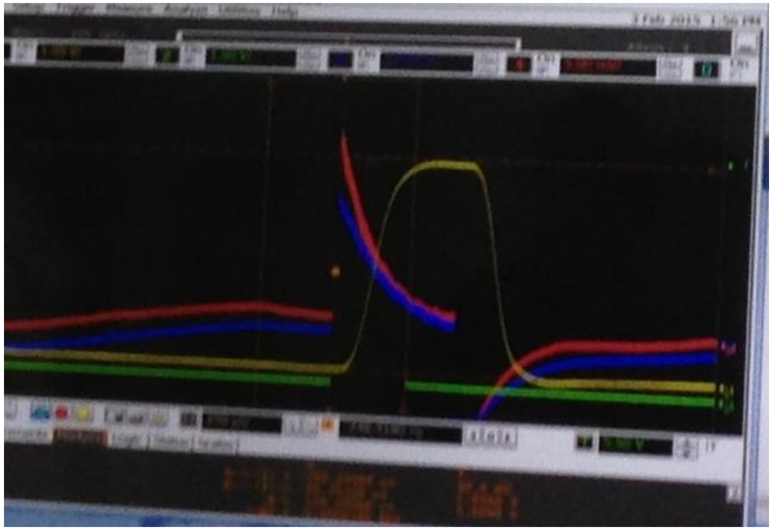




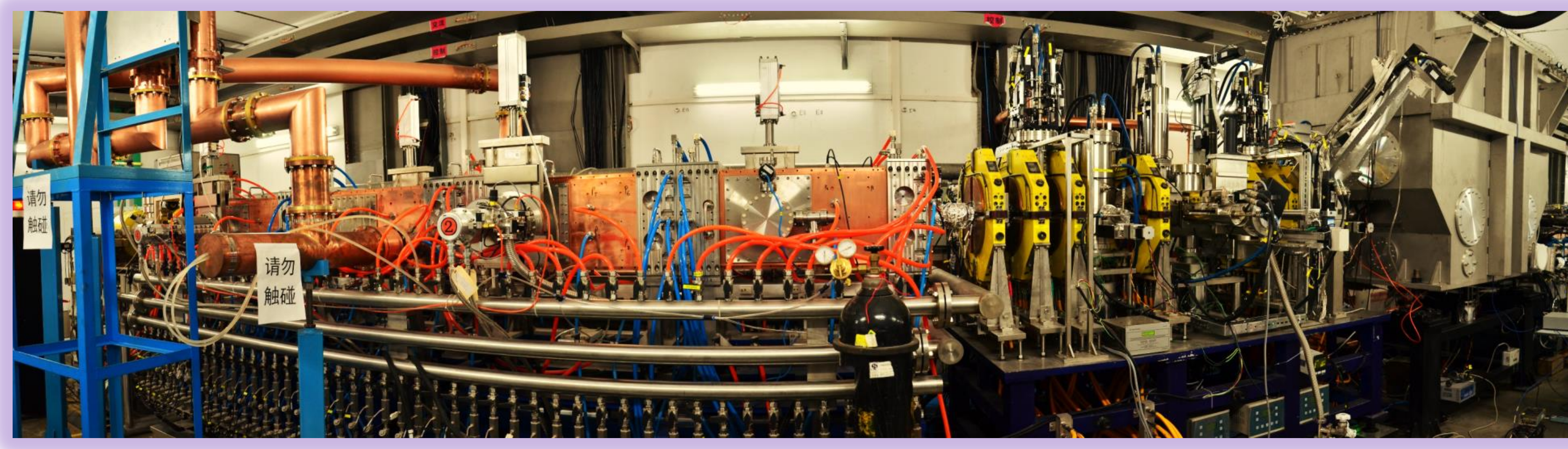
10 mA beam from 3.2MeV RQF at 70% duty

Pulse beam of 10mA from 2 spokes of β=0.14

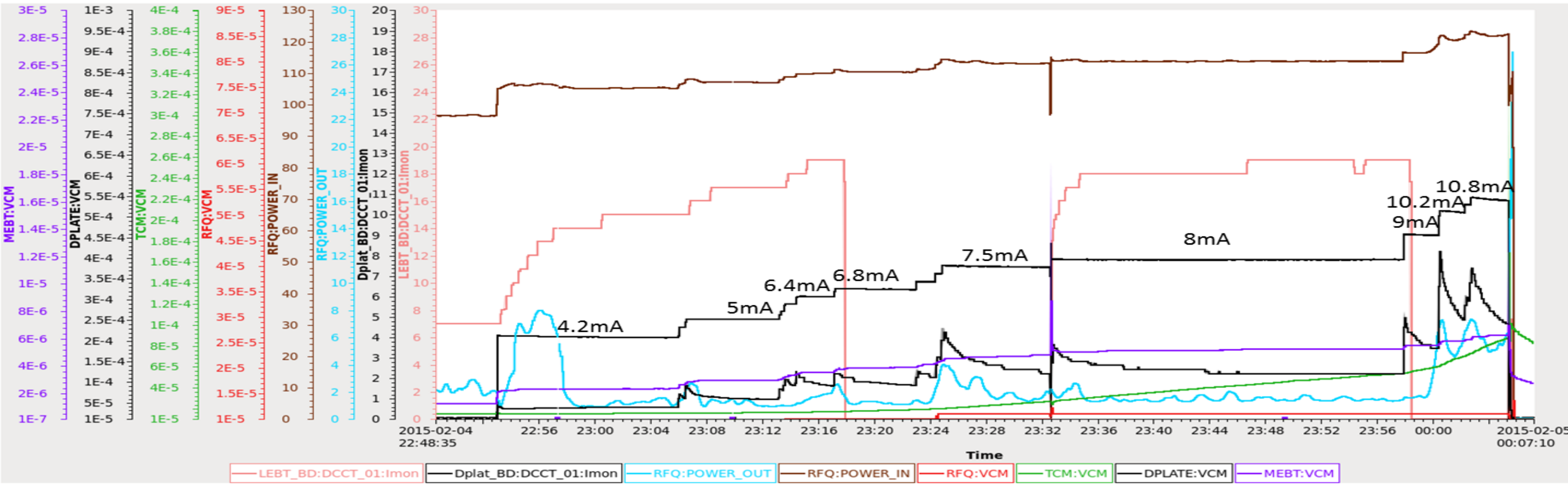




C-ADS Linac (IMP)



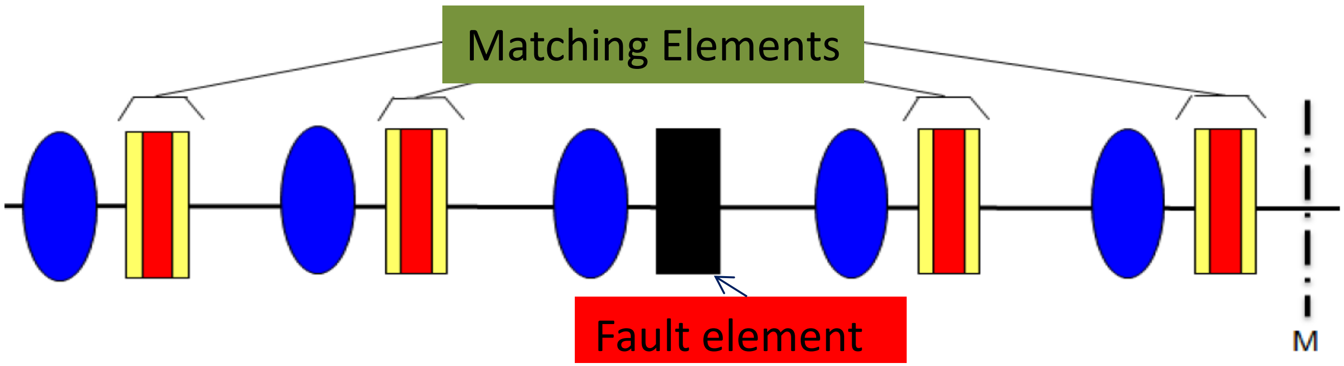
RFQ and HWR accelerate CW proton beam of 10mA to 2.5MeV.



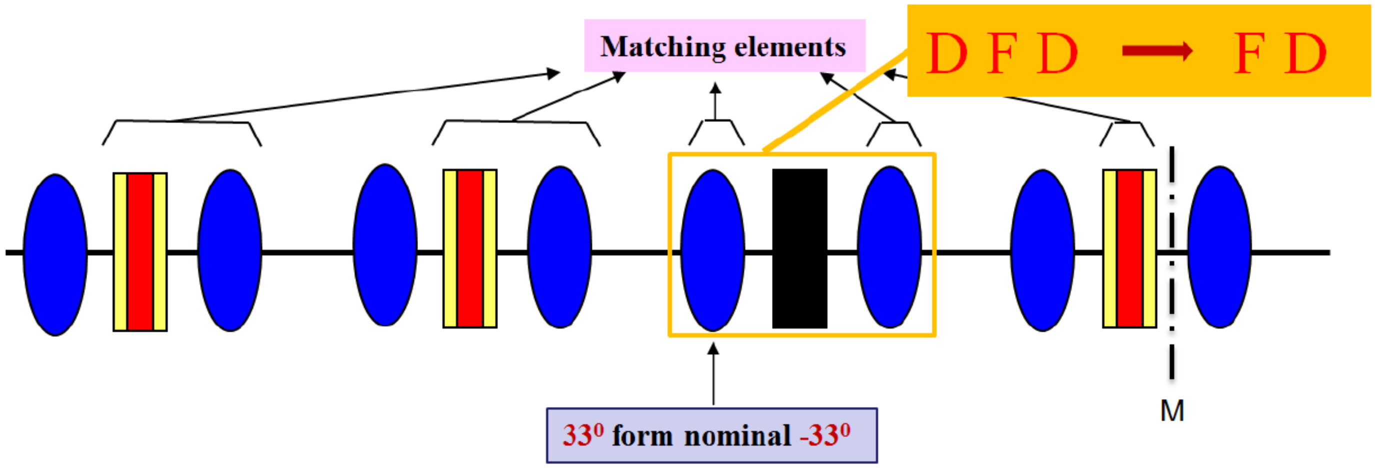
C-ADS Linac

•Local compensation scheme was proposed in design for high reliability in operation.

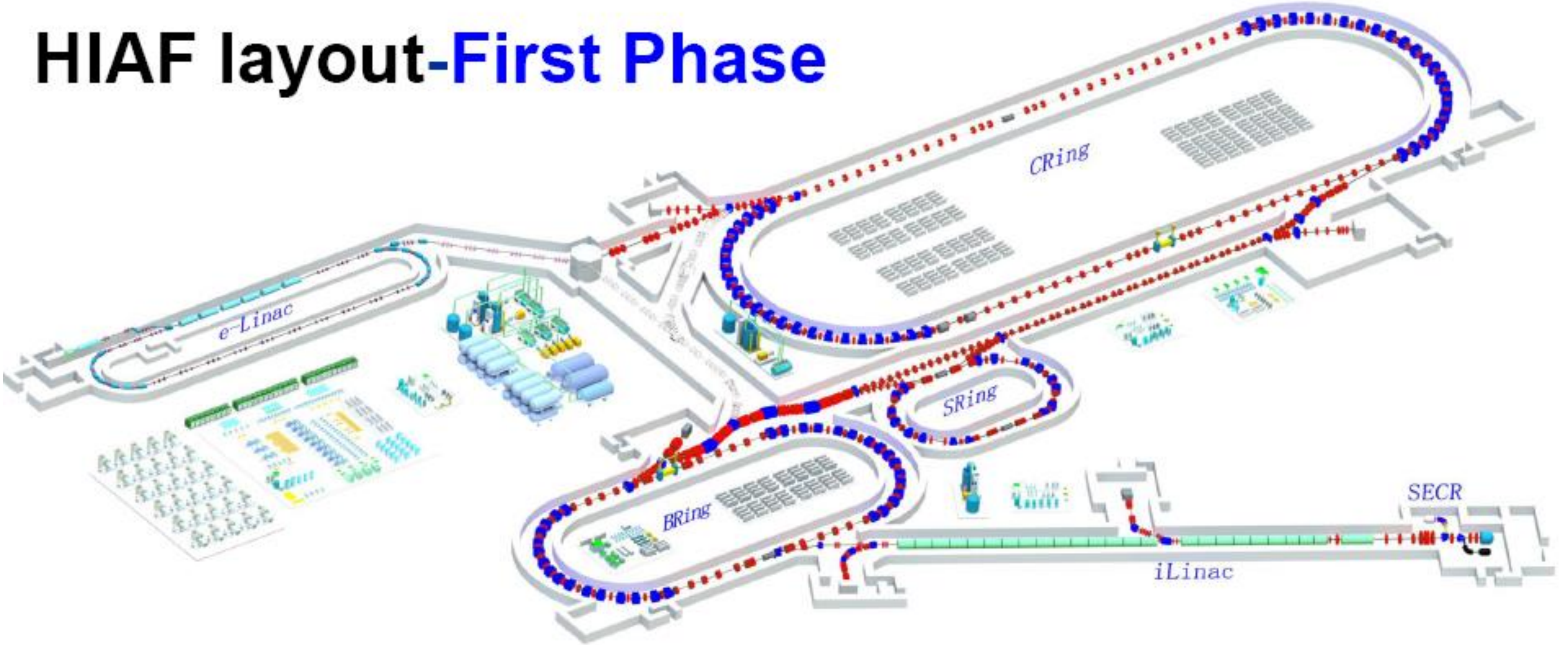
For high energy section:



For low energy section:



HIAF layout-First Phase



SECR: ECR ion source

iLinac: Superconducting ion linac

BRing: Booster ring

CRing: Compression ring

eLinac: Electron linac

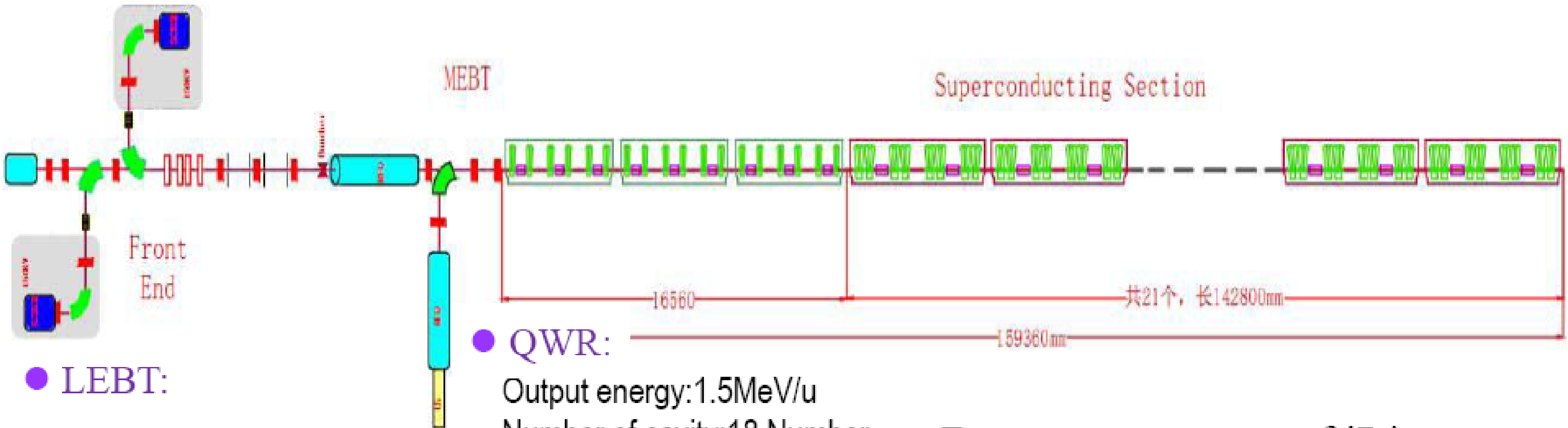
SRing: High precision spectrometer

Accelerator		Ions	Energy	Intensity
Ion source	ECR	U^{34+}	14 keV/u	0.05 pmA
	H_2^+	H_2^+	14 keV/u	2.0 pmA
iLinac		U^{34+}	25 MeV/u	0.028 pmA
		H_2^+	54 MeV/u	1.0 pmA
BRing		U^{34+}	0.8 GeV/u	~3.3×10^{11} ppp
		p	9.5 GeV/u	~2.3×10^{12} ppp
CRing		U^{34+}	1.1 GeV/u	**~1.0×10^{12} ppp**
		U^{92+}	4.1 GeV/u	~2.0×10^{11} ppp
		p	12.0 GeV/u	~4.5×10^{12} ppp

iLinac

550M Yuan
Commissioning in 2020

Features: SC, high charge state, high pulse current



- LEBT:
- RFQ:
  Input energy:0.014MeV/u
  Output energy:0.5MeV/u
  RFQ length:6m
- HWR1:
  Output energy:5MeV/u
  Number of cavity:42
  Number of solenoid:21
  Number of CM:7
  Length:38.43m
- QWR:
  Output energy:1.5MeV/u
  Number of cavity:18 Number of solenoid:9
  Number of CM:3
  Length:14.94m
- HWR2:
  Output energy:25MeV/u
  Number of cavity:96
  Number of solenoid:24
  Number of CM:12
  Length:80.88m

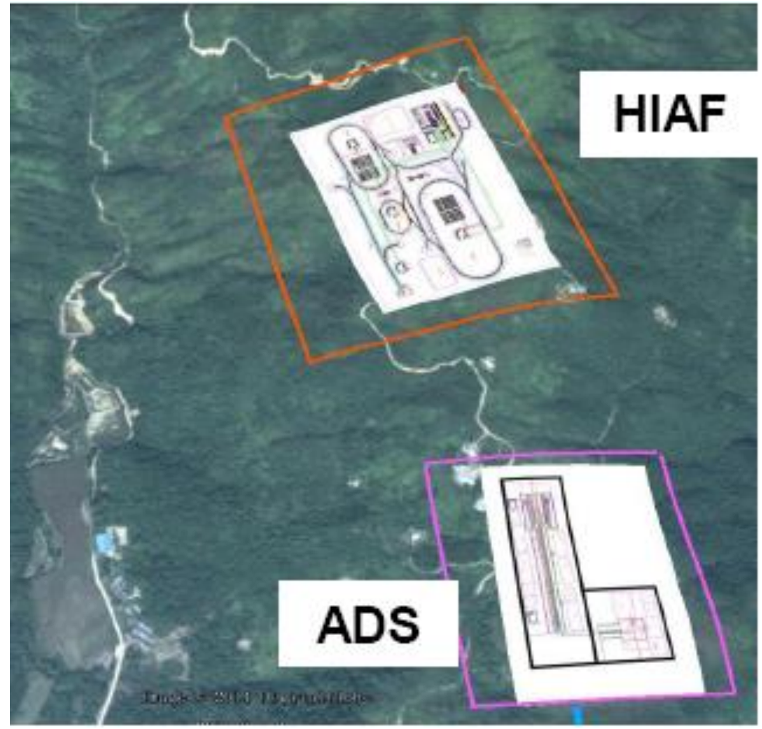
Beam parameters of iLinac

Ions	Charge to mass ratio	Energy (MeV/u)
$^{238}U^{34+}$	1/7	**25**
$^{78}Kr^{19+}$	19/78	45
$^{18}O^{6+}$	1/3	57
H_2^+	1/2	**70**

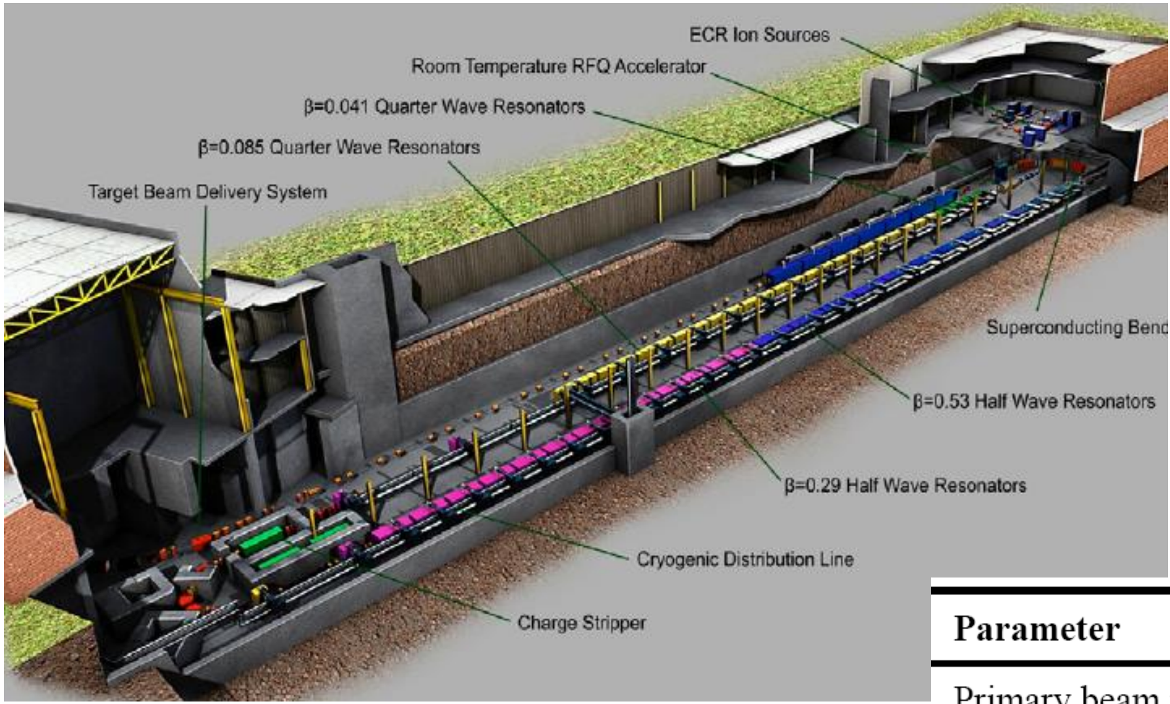
Future:

$^{238}U^{34+}$	1/7	**100**

Site selection: Huizhou, Guangdong



FRIB Drive Linac



Parameter	Value	Unit
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	mA
Beam radius on target (90%)	0.5	mm
Driver linac beam-path length	517	m
Average uncontrolled beam loss	< 1	W/m

RISP Linac : RAON

Courtesy of Dr. H.J.Kim

- **Goal**: To build a world class heavy ion accelerator RAON, for rare isotope science research in Korea
- **Project period**: 2011. 12 - 2021. 02
- **High intensity rare isotope beam with ISOL and IF methods**
  - 70 MeV, 1 mA proton beam, ^{238}U target: 70 kW ISOL system
  - 200 MeV/u, 8.3 pμA, ^{238}U beam and other SI beam: 400 kW IF system, 600 MeV for proton
- **High current high purity neutron-rich RI beam**
  (For example, ^{132}Sn : ~250 MeV/u, ~ 10^8 pps)
- **Production of exotic beams combining ISOL and IF methods**
- **Simultaneous operation of IF and ISOL systems**

Layout of driver linac

ECR	LEBT	RFQ	MEBT	SCL11	SCL12	STRIP	SCL21	SCL22
				QWR (81.25MHz)	HWR (162.5MHz)		SSR1 (325MHz)	SSR2 (325MHz)

CAV QF QD — 22 cryomodules → Output 2.5 MeV/u

22 β=0.047 QWRs, 44 quadrupoles

CAV CAV CAV QF QD — 13 cryomodules → Output 7.4 MeV/u

CAV CAV CAV CAV CAV CAV QF QD — 14 cryomodules → Output 18.5 MeV/u

123 β=0.12 HWRs, 54 quadrupoles

Stripper: charge state 33, 34 → 77,78,79,80,81 for Uranium

C C C C QF QD — 21 cryomodules → Output 70.9 MeV/u

84 β=0.30 SSR1, 42 quadrupoles

C C C C C C C C QF QD — 18 cryomodules → Output 200 MeV/u

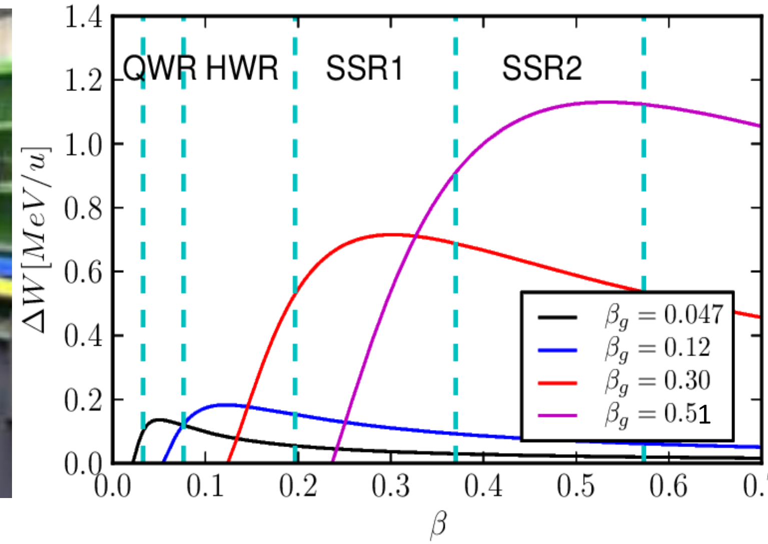
144 β=0.51 SSR2, 36 quadrupoles

Total 373 cavities, 88 cryomodules, 176 quadrupoles, 106m (LEL), 186m (HEL)

RAON Prototype

28GHz ECR IS

81.25MHz RFQ



QWR Beta=0.047

HWR Beta=0.12

Spoke cavity Beta=0.51

Thank you very much
for your attention