CSNS Front-end and Linac Commissioning

CHINESE ACADEMY OF SCIENCES

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Outline

- Project Overview
- Front End Commissioning
- DTL Commissioning
- Prospect
- Summary

1, Project Overview

CSNS completed its project construction in March 2018

Project duration 6.5 years

Design and Acceptance

Design Specification

Beam power	Rep. rate	Ave. Curr.	Beam Energy	Neutron Efficiency	Neutron Flux
100 kW	25Hz	63μA	1.6GeV	0.1(n/p/sr)	$2*10^7$

Acceptance Specification

Beam power	Rep. rate	Ave. Curr.	Beam Energy	Neutron Efficiency	Neutron Flux
10 kW	25Hz	6.3μA	1.6GeV	0.005(n/p/sr)	10^5

Acceptance Test

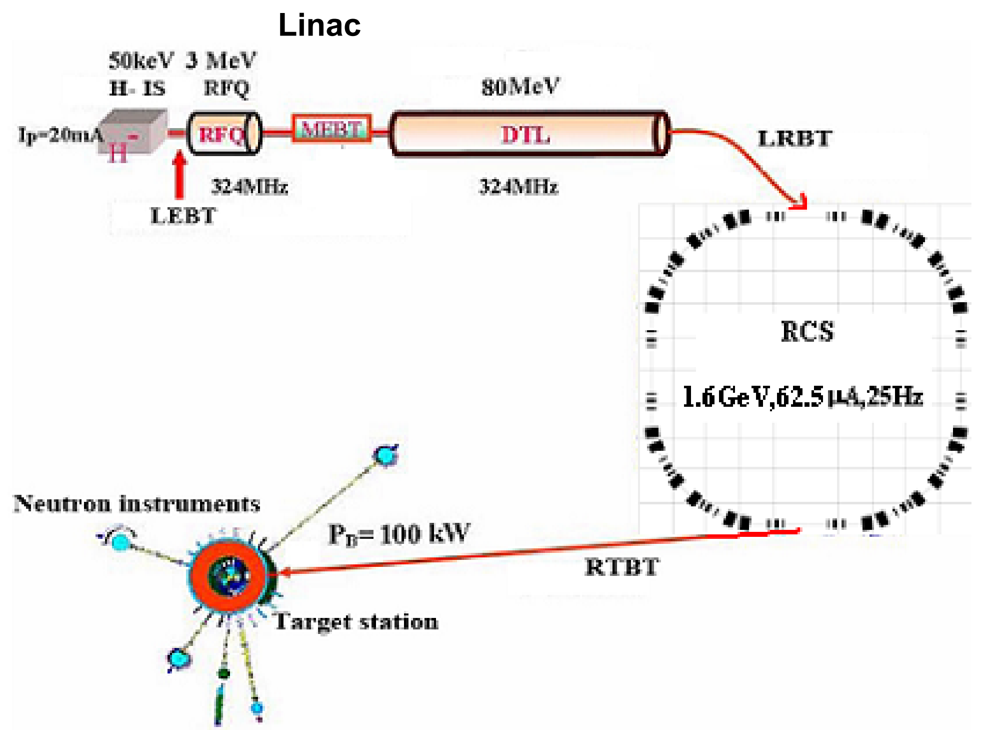
23 kW	**25Hz**	**14.5μA**	**1.6GeV**	**0.125**	**$2.5*10^6$**

- Measured data all reached to or higher than the acceptance specification.
- 3 spectrometers have completed sample test.
- Whole project completed ahead of the schedule.

Project Design

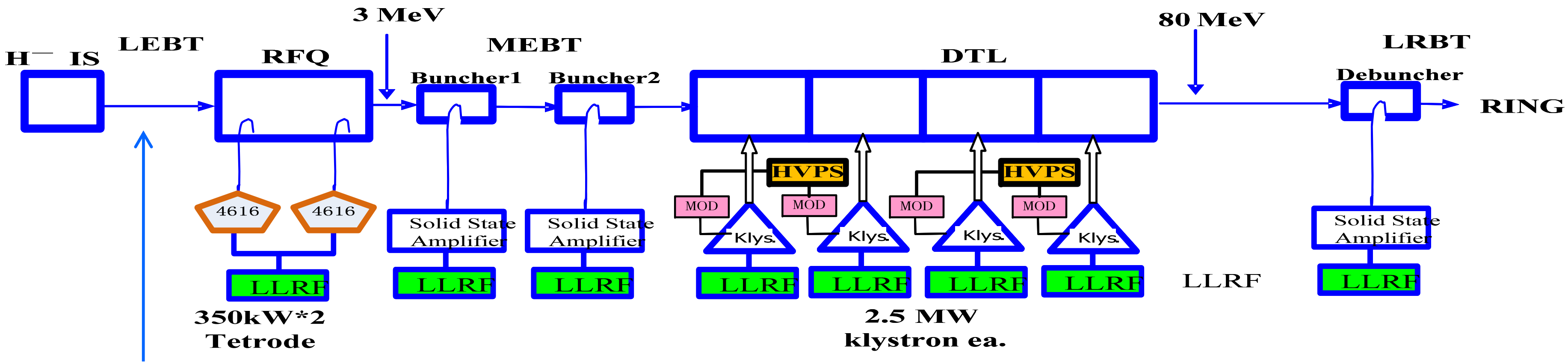
- **The phase-I CSNS facility consists of an 80-MeV H^- linac, a 1.6-GeV rapid cycling synchrotron(RCS), beam transport lines, a target station, and 3 instruments.**

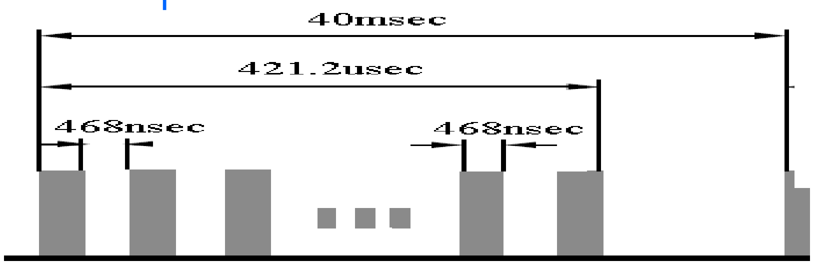
Project Phase	I	II
Beam Power on target [kW]	100	500
Proton energy [GeV]	1.6	1.6
Average beam current [μA]	62.5	312.5
Pulse repetition rate [Hz]	25	25
Linac energy [MeV]	80	300
Linac type	DTL	+Spoke/PIMS
Linac RF frequency [MHz]	324	324
Macropulse. ave current [mA]	15	40
Macropulse duty factor	1.0	1.7
RCS circumference [m]	228	228
RCS harmonic number	2	2
RCS Acceptance [πmm-mrad]	540	540
Target	1	1
Spectrometers	3	20



The first high-energy high-intensity proton accelerator in China

H⁻ Linac Design



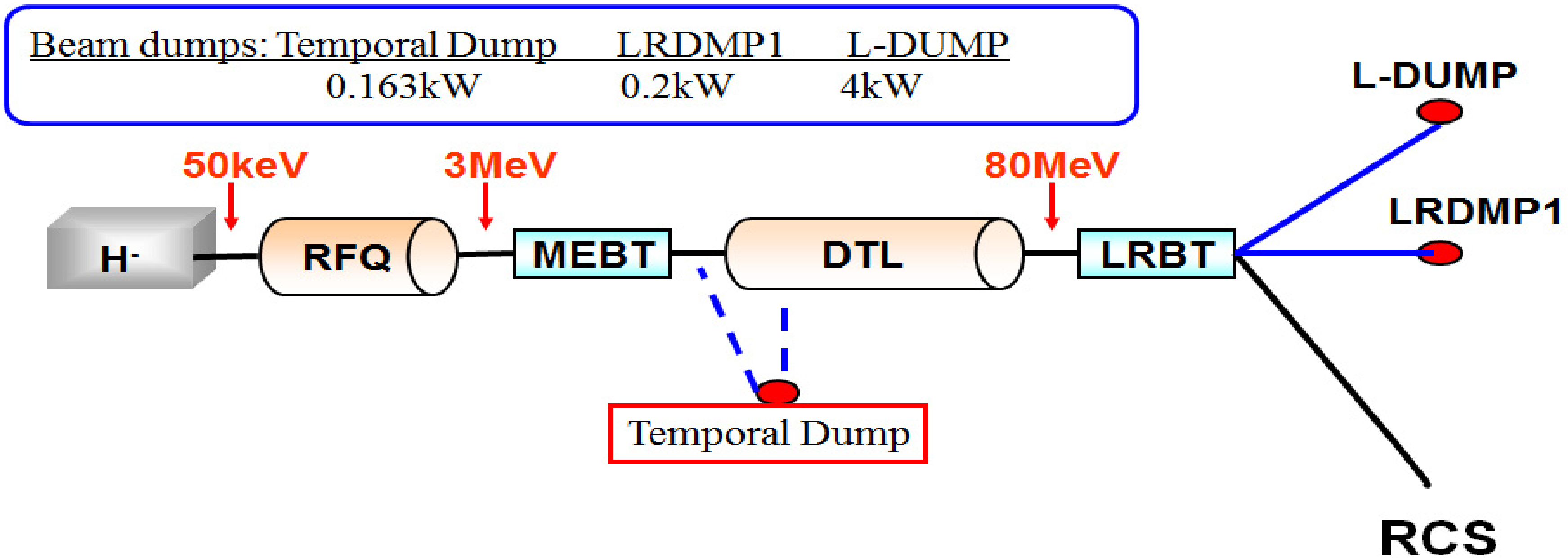


EMQ option in FFDD lattice for DTL. DT has no room for diagnostics

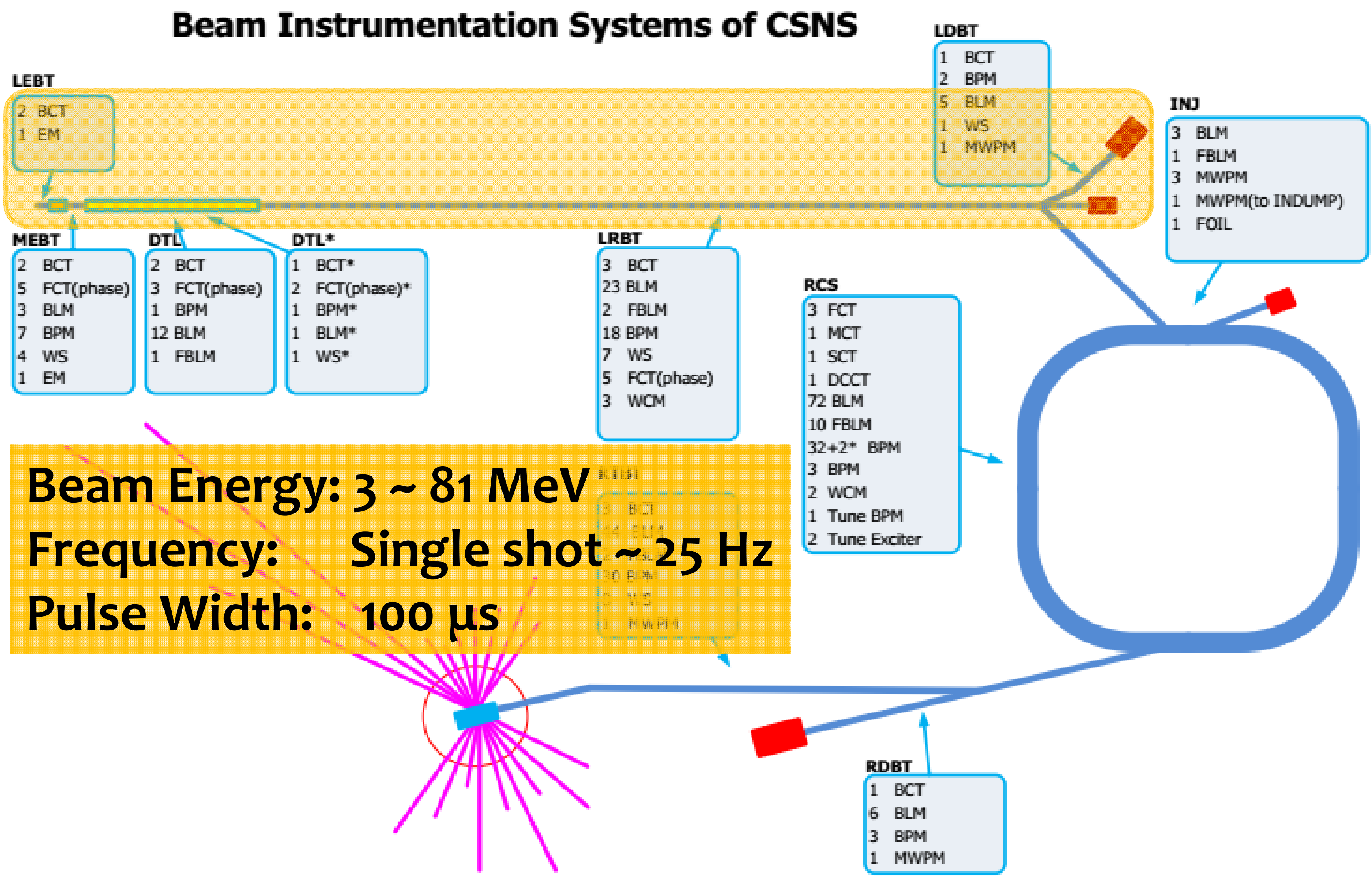
Electrostatic chopper in LEBT

	Ion Source	RFQ	DTL
Input Energy（MeV)		0.05	3.0
Output Energy(MeV)	0.05	3.0	80
Pulse Current (mA)	20/40	15/30	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

Linac beam dumps for beam commissioning



LINAC diagnostics for beam commissioning



Beam Energy: 3 ~ 81 MeV
Frequency: Single shot ~ 25 Hz
Pulse Width: 100 μs

Key Milestones(on schedule)

Feb. 2001	idea of CSNS discussed
June 2005	proposal approved in principle by the central government (CD0)
Jan. 2006	prototyping R&D started
Sept. 2008	proposal approved
Oct. 2009	feasibility study report reviewed
April 2010	site preparation start
Feb. 2011	feasibility study report approved (CD-1)
May 2011	preliminary design report approved (CD-2) （1.67B RMB）
Sept. 2011	construction started (CD-3), component fabrication started
May 2012	civil construction started
Oct. 2014	Frontend and LRBT started installation in Linac tunnel
April 2015	the RCS magnets started installation in RCS tunnel
May 2015	the Helium Vessel of the target station installed
Mar. 2016	preliminary design adjustment report approved （1.87B RMB）
May. 2017	RCS commissioning start
Aug. 2017	first beam on target
Mar. 2018	project complete/operation start (6.5 years from start)

Baseline Budget and Support

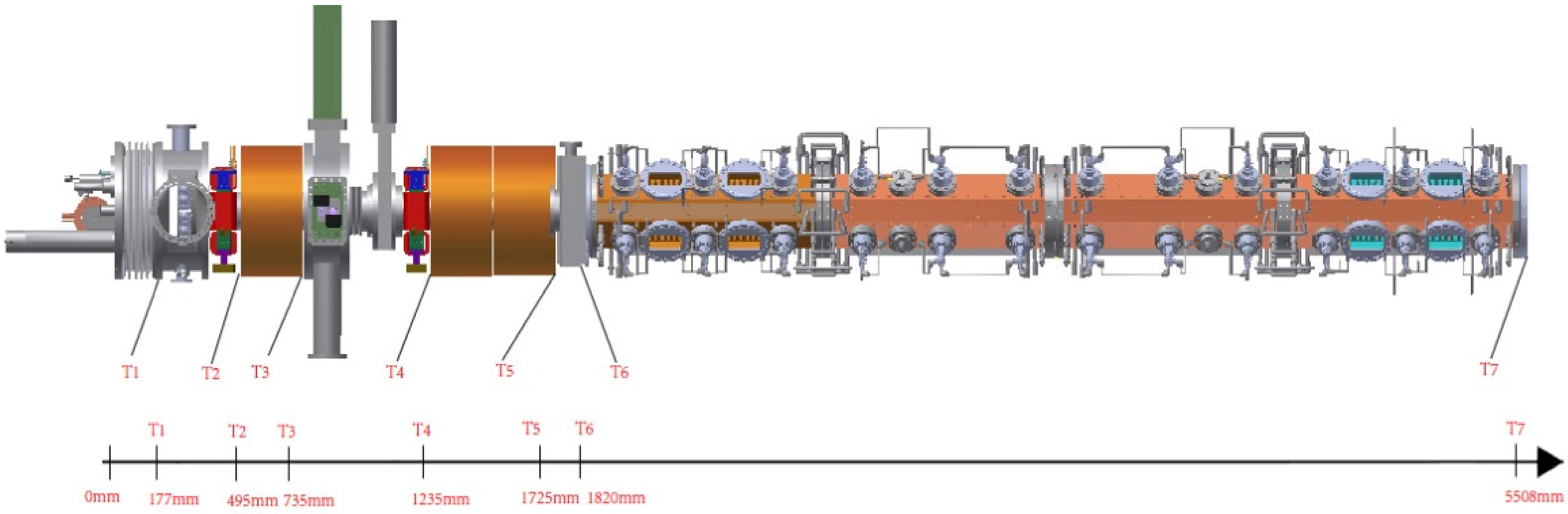
- Approved budget
  - 1.87B CNY from central government for project construction
  - 0.5B CNY from Guangdong/Dongguan local government for additional support
  - ~0.5B CNY from Dongguan local government for the site preparation and infrastructure
  - 30M CNY from CAS for initial R&D
  - Personnel salary provided by CAS (now ≈350 staff, finally to 400)

Accelerator budget: 0.72 B CNY (reduced to 0.62B, completed within the new budget – 0.36% error)

Human Resources

No.	Division	Employees
1	Accelerator	149
2	Experiment	116
3	Conventional Facility	36
4	Administration	49
Total		350

2, Front End Commissioning

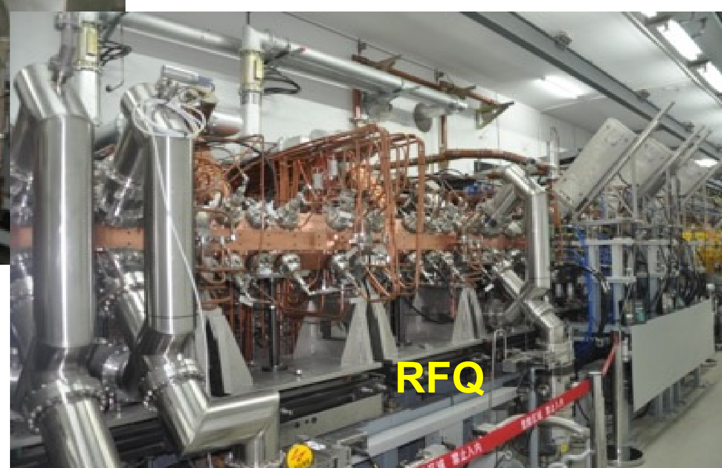


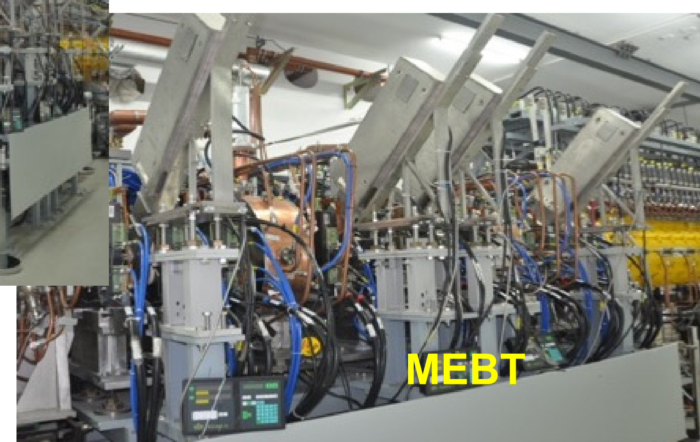
Front end commissioning milestone

Oct. 2014: H- ion source and LEBT, as the first facility, was installed into the linac tunnel and then started beam commissioning;

Dec. 2014: RFQ moved into the tunnel, and then the field tuning of the RFQ cavity and high power conditioning;

April 2015: MEBT assembled following the RFQ and then the initial beam commissioning of the RFQ started.





Ion source 3 commissioning modes:

3 modes are design to meet accelerator commissioning require.

1, Linac commissioning mode:

1Hz&100 μs ; 10mA; 50keV

2, RCS commissioning mode:

Single shot: one pulse beams &1Hz&100 μs ; 10mA; 50keV

3, Other mode(Neutron physics):

5Hz&100 μs and 25Hz&100 μs

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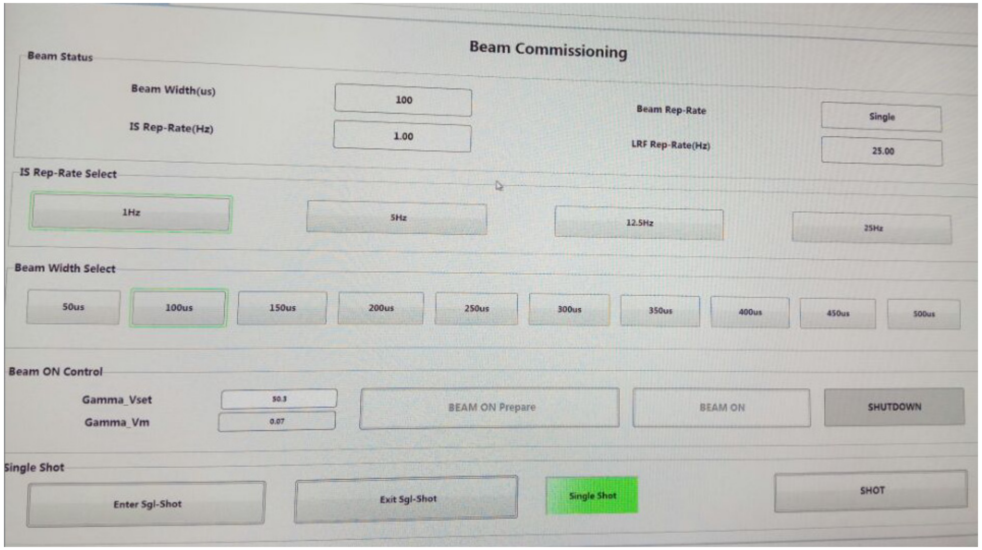


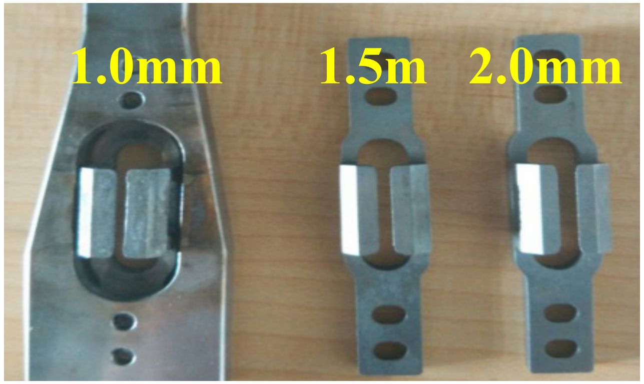
Ion source operation modes

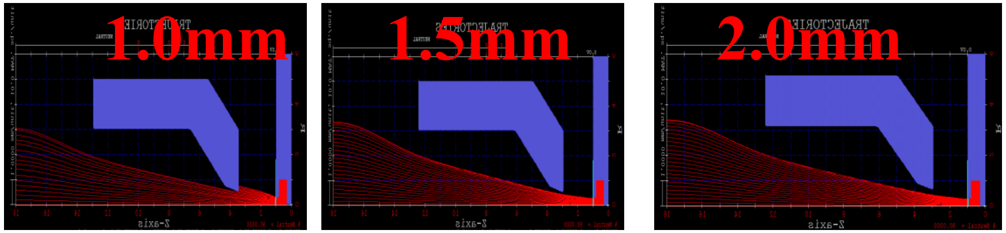
All of modes can be switched quickly

Ion source commissioning:

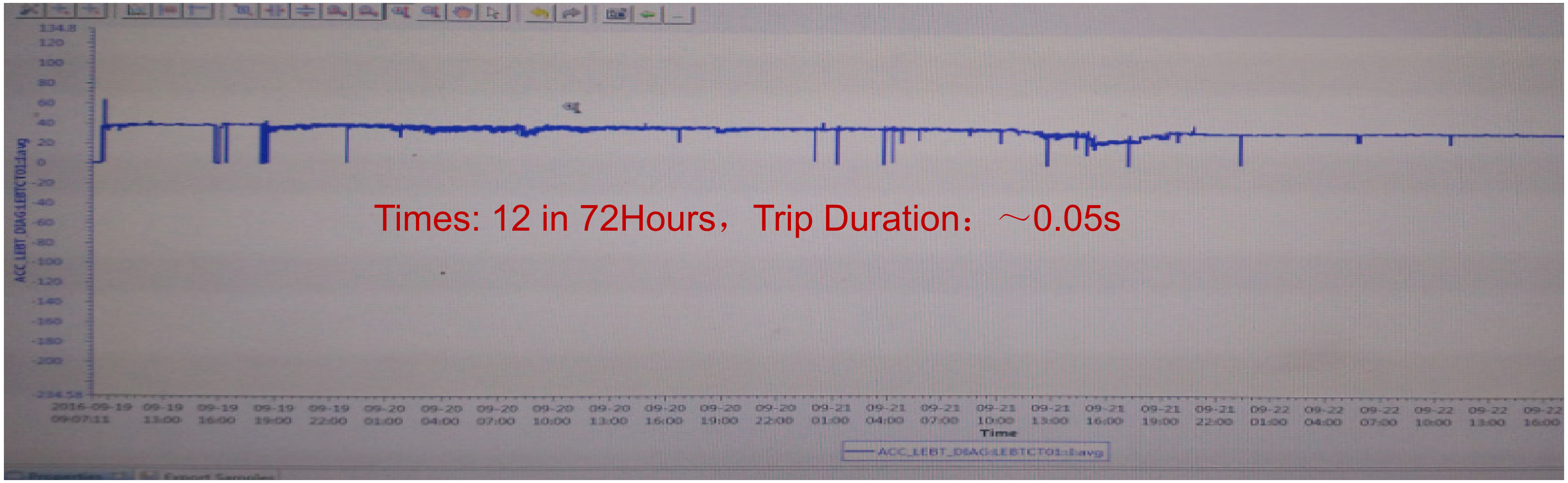
- Commissioning from a low duty factor of 50us&1Hz first, and then increase to 500us&25Hz.
- Beam current can be adjusted in a range of 10 – 50 mA by an aperture plate together with a collimator at the end of the LEBT. The resulted LEBT beam transmission rate becomes low about 50% .
- Larger emittance (0.75-0.9 π mm.mrad) from ion source can be collimated to 0.2 π mm.mrad for matching with RFQ acceptance.
- Ion source stability is better at higher duty factor, owing the cleaning function of the extracted beam to the extractor surface.

After some improvement, now the beam interruption duration becomes very short: about tens of ms for each spark, and the spark numbers are several times a day, satisfying user operation.



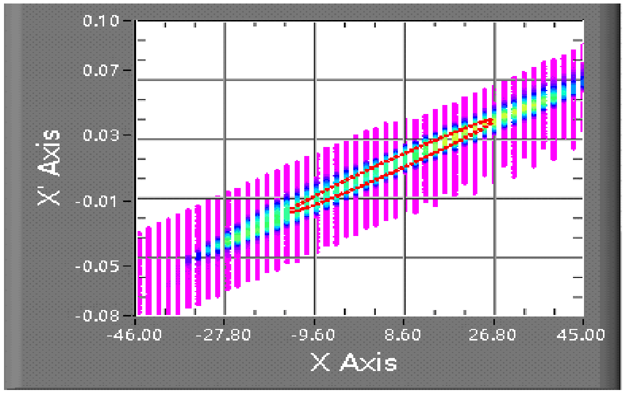


PBGUN Simulation. various extraction jawing gaps

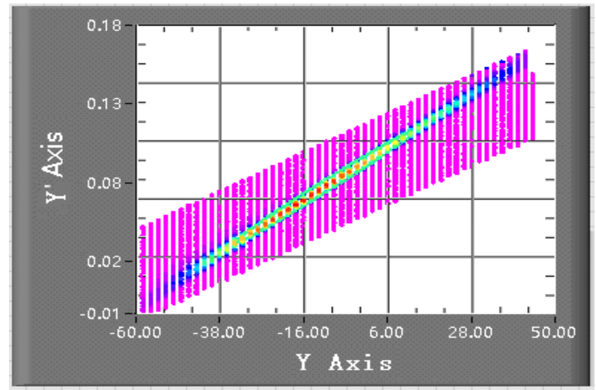


Ion source and LEBT- emittance

Horizontal and vertical emittance of H^- beam at 53mA

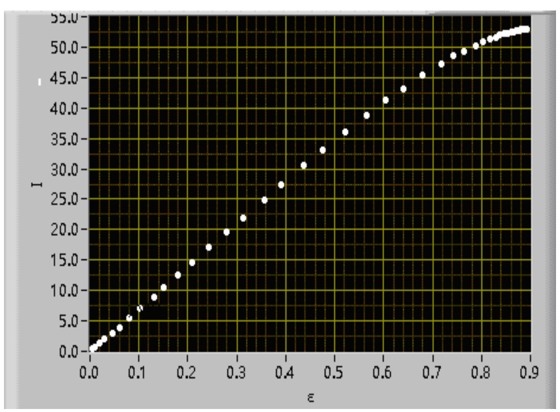


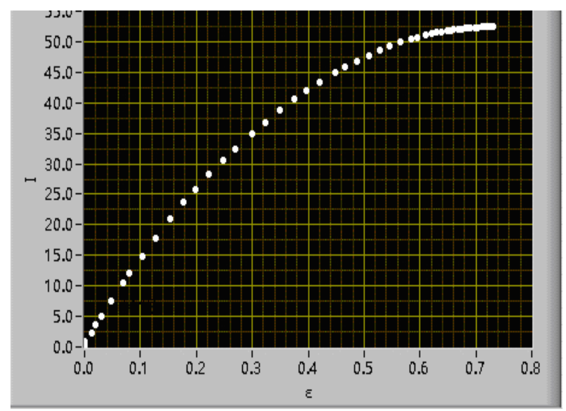
X-plane: 0.892πmmmrad



Y-plane: 0.742πmmmrad.

The relation between beam current and emittance



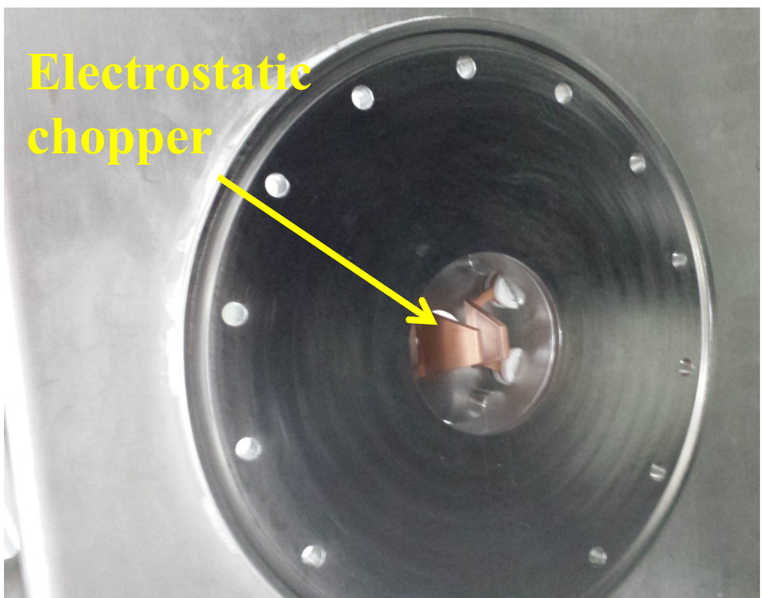


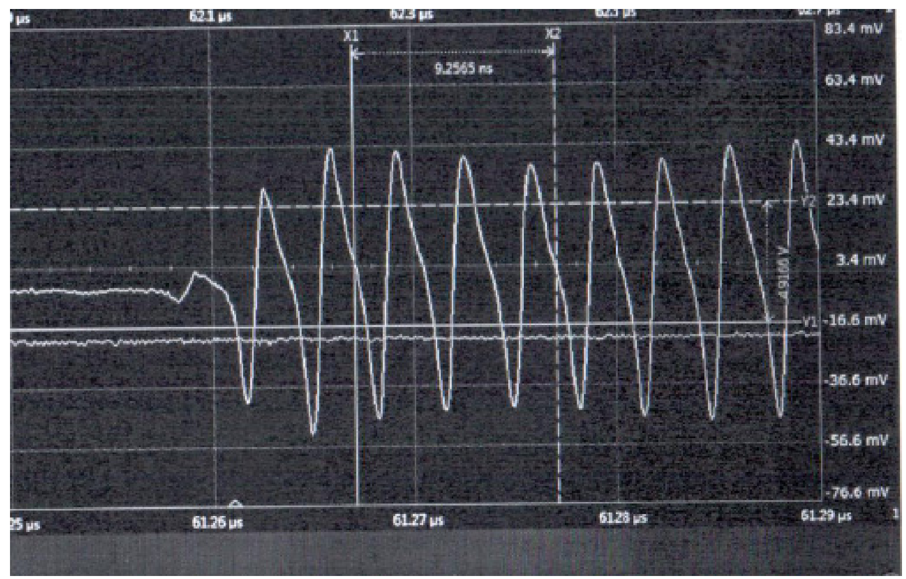
X plane: 15mA and Y plane: 25mA at 0.2πmmmrad

Chopper

In the space-charge neutralized LEBT an electrostatic chopper is located in front of the RFQ. The deflected beam is partially dumped on the entrance plate of the RFQ and majorly dumped in the RFQ cavity.

The rise and falling time of the chopper is so fast (about 10ns) that we do not need additional fast chopper in the MEBT.



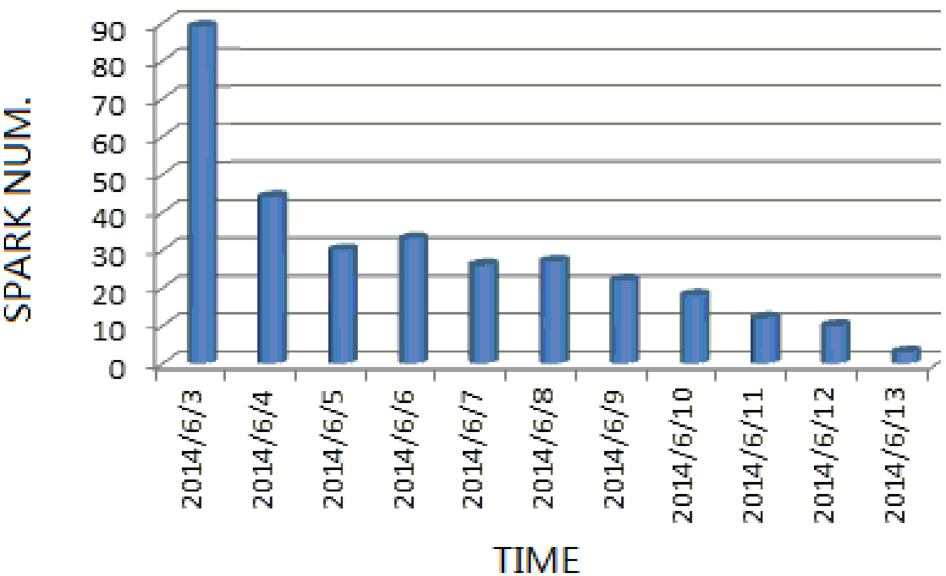


BPM signal after chopping at the exit of RFQ

RFQ Commissioning

RFQ major parameters

Frequency (MHz)	**324**
Injection Energy (keV)	**50**
Output Energy (MeV)	**3.0**
Pulsed beam current (mA)	**40**
Beam duty factor	**1.05%**
RFQ length （m)	**3.62**
Emittance (πmm.mrad)	**0.2**
Inter-vane voltage V (kV)	**80**
Maximum surface field (MV/m)	**31.68(1.78Kilp)**
Average bore radius: r0 (mm)	**3.565**
Vane-tip curvature: ρｔ(mm)	**3.173**
Cavity Power dissipation (kW)	**410**



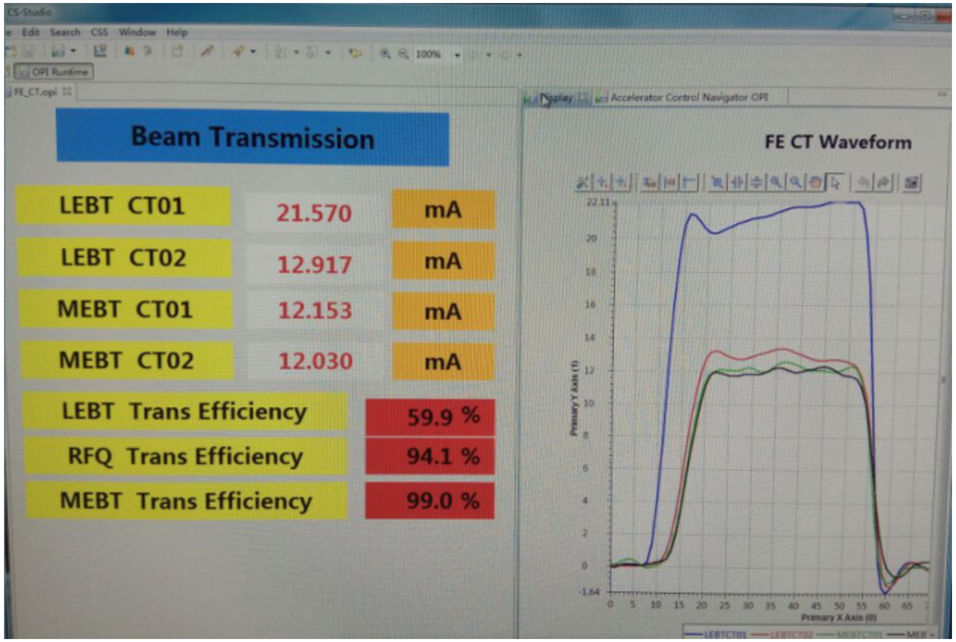
High power conditioning progress in 11 days at a duty of 700us and 25Hz and input RF power of 470kW

RFQ-beam commissioning

The first beam from RFQ in April, 2015, and then run the front end at different beam duty factor.

In general the beam transmission efficiency for RFQ is range 75-85% due to a larger input beam emittance than RFQ acceptance. The best value was about 94% with only core part after collimation.

But sparks appear in the case of the high beam duty factor and with beam chopping.



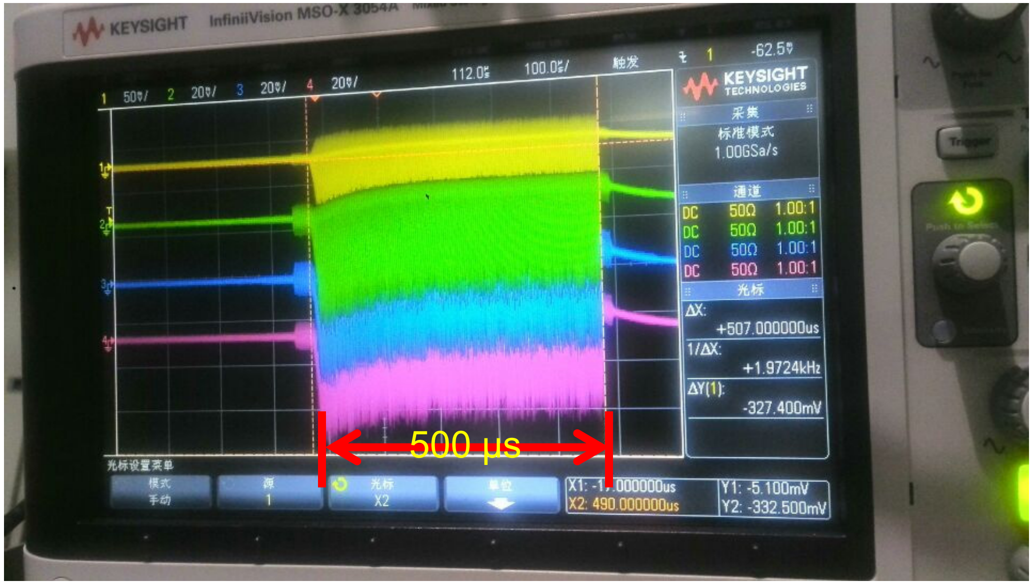
MEBT-beam commissioning results

- Beam commissioning means for 2 ends: Beam measurement and diagnostics instruments confirmation.
- Magnet fields set to design value and no power for 2 bunchers, The transmission kept near to 100% in all the commissioning time .

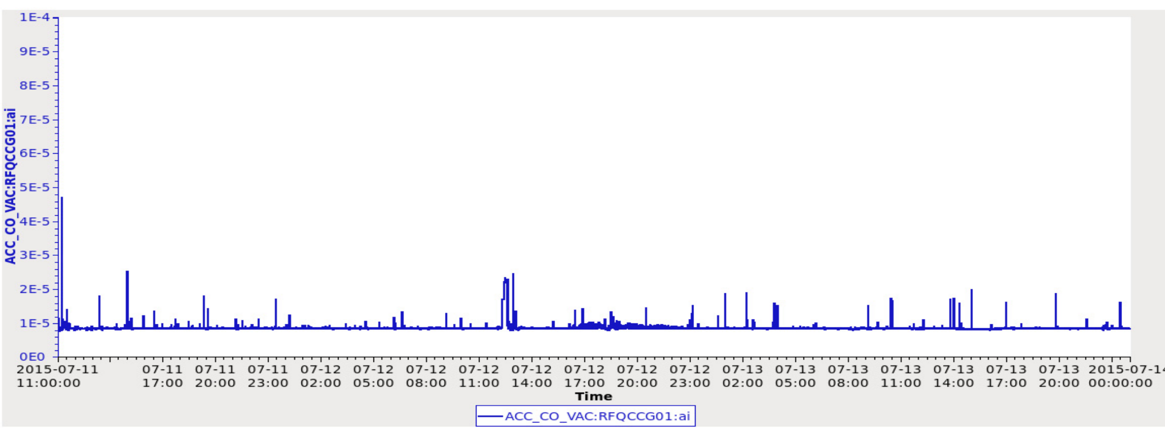
Beam Twiss parameters at exit of RFQ

	α	β [mm/mrad]	Emittance rms, normalized [πmm mrad]
Horizontal Measured Simulated	 -1.716 -1.773	 0.256 0.233	 0.215 0.215
Vertical Measured Simulated	 1.944 0.639	 0.173 0.074	 0.211 0.212

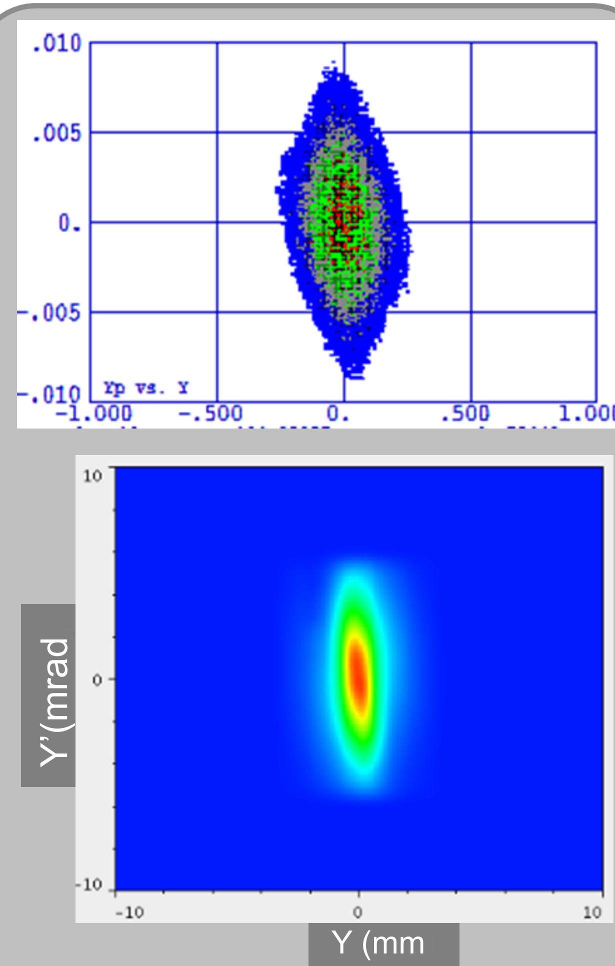
Measured results



Beam pulse duration measured from MEBT FCT



RFQ vacuum



Emmitance: (π mm mrad)

simulated=0.2
measured=0.201

Emittance

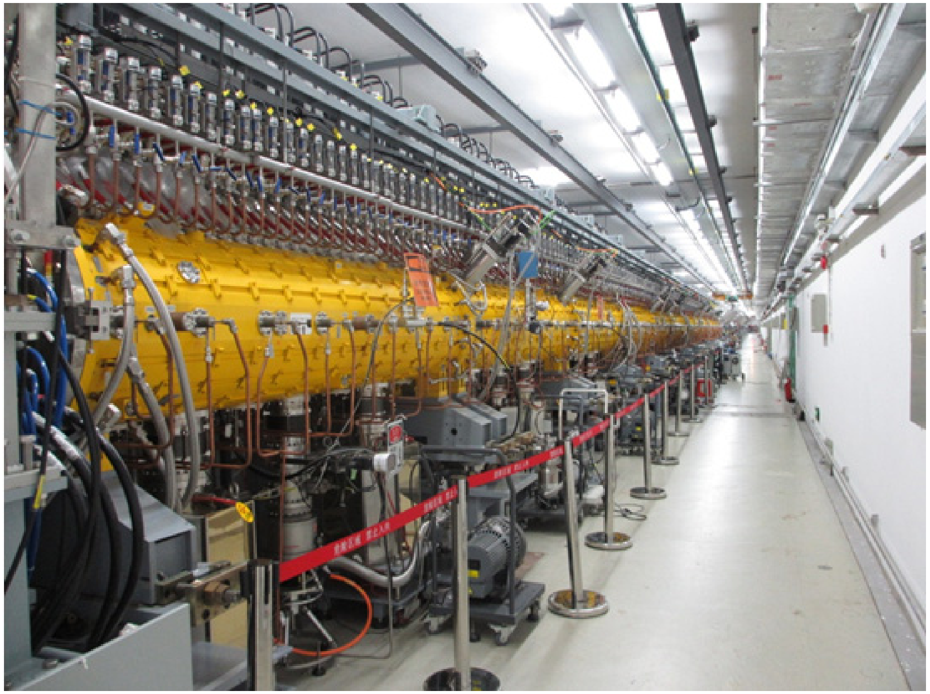
MEBT-beam commissioning results

parameters	Baseline Design or Goal	Achieved
Pulse width [μs]	420	500
Pulse repetition rate [Hz]	25	25
Chopping rate [%]	50	50
LEBT peak current [mA]	20	31
MEBT peak current [mA]	15	21
MEBT horiz emittance [π mm mrad (rms, norm)]	0.22	0.27
MEBT vertical emittance [π mm mrad (rms, norm)]	0.22	0.27
MEBT Beam Energy[MeV]	3.0258	3.02±0.015

3， DTL Commissioning

DTL commissioning milestone

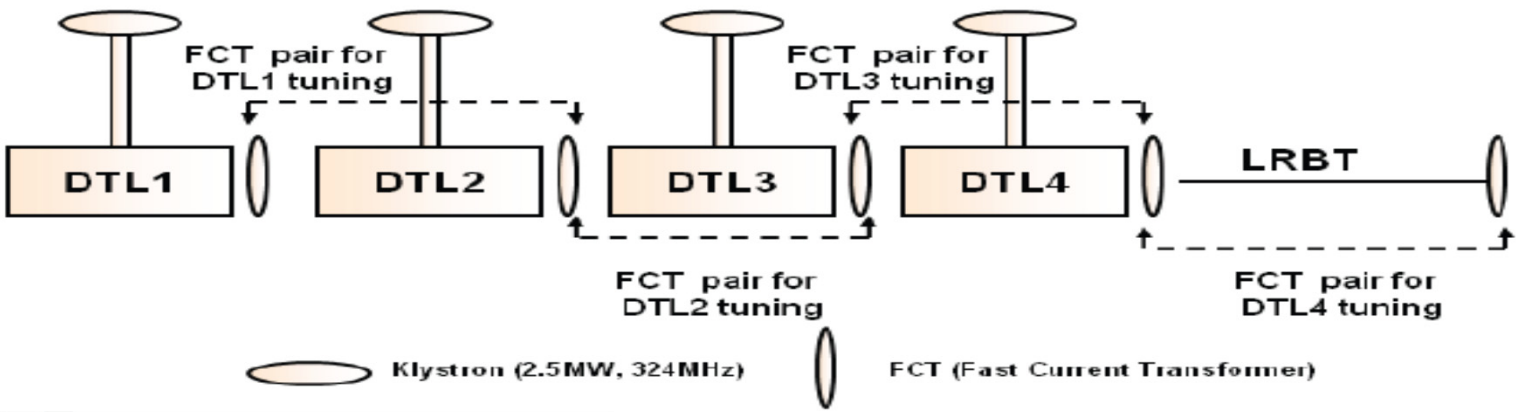
- Jan. 2016: DTL-1 started beam commissioning with beam energy of 21MeV;
- Oct. 2016: DTL2-4 completed installation in the tunnel and then high power conditioning started;
- Nov. 2016: DTL-2 started beam commissioning with beam energy of 41MeV;
- April 2017: DTL-3 started beam commissioning with beam energy of 61MeV;
- July 2017: Linac beam of 61MeV was injected into the ring for RCS beam commissioning and then first neutron came from CSNS;
- Jan. 2018: DTL-4 started beam commissioning, reaching linac energy of 81MeV.

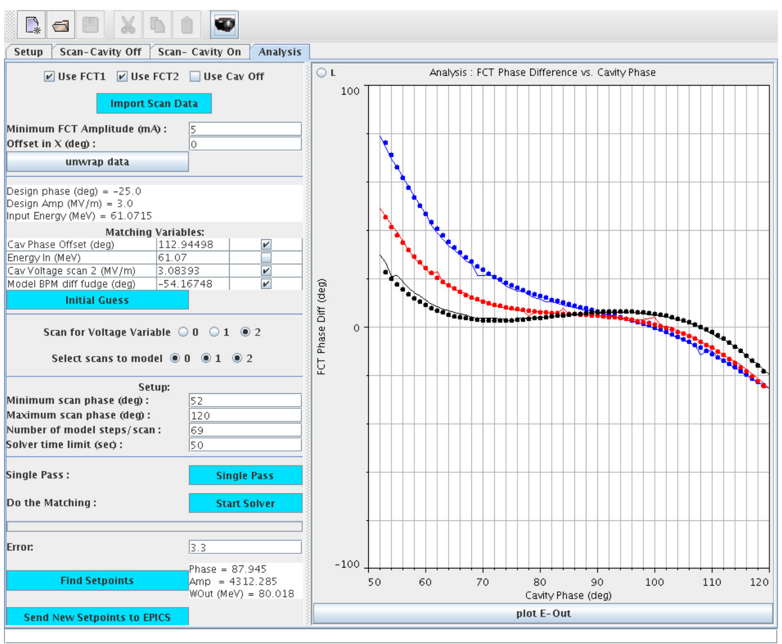


DTL commissioning methods:

1, Longitudinal: Phase scan with FCT pair and PASTA software.

2, Transversal: set all Q magnets as design.





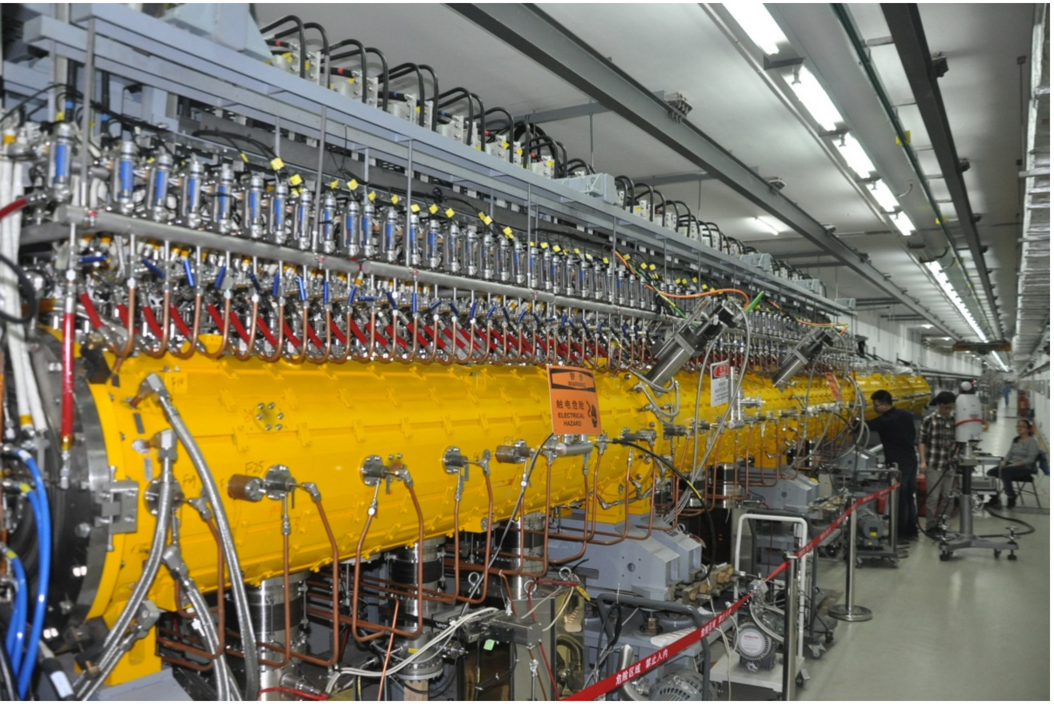
	TOF [MeV]	Phase scan [MeV]	Design [MeV]
DTL1	21.73±0.01	21.67	21.67
DTL2	41.54±0.01	41.45	41.41
DTL3	61.36±0.02	61.05	61.07
DTL4	80.34±0.01	80.17	80.09

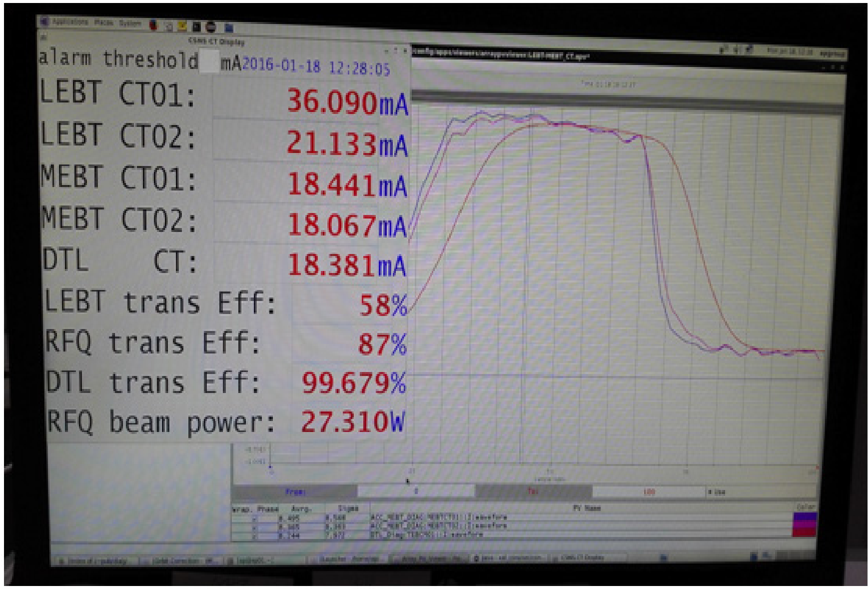
Energy deviation < 1%

DTL beam commissioning

- Jan. 2016 DTL-1 started beam commissioning with output beam 18mA, higher than designed 15mA. Transmission rate reached nearly 100%.
- 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)

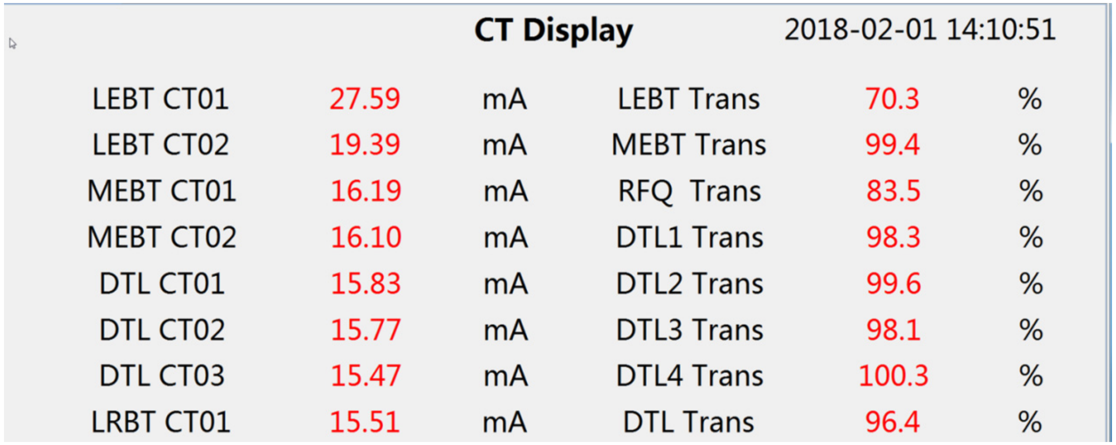




CT measured beam current

■ Following DTL tanks

- **DTL 2-3 ：Apr. 2017, Tank-3 output 15mA beam @60MeV.**
- **DTL4：Jan. 2018, 80MeV beam.**

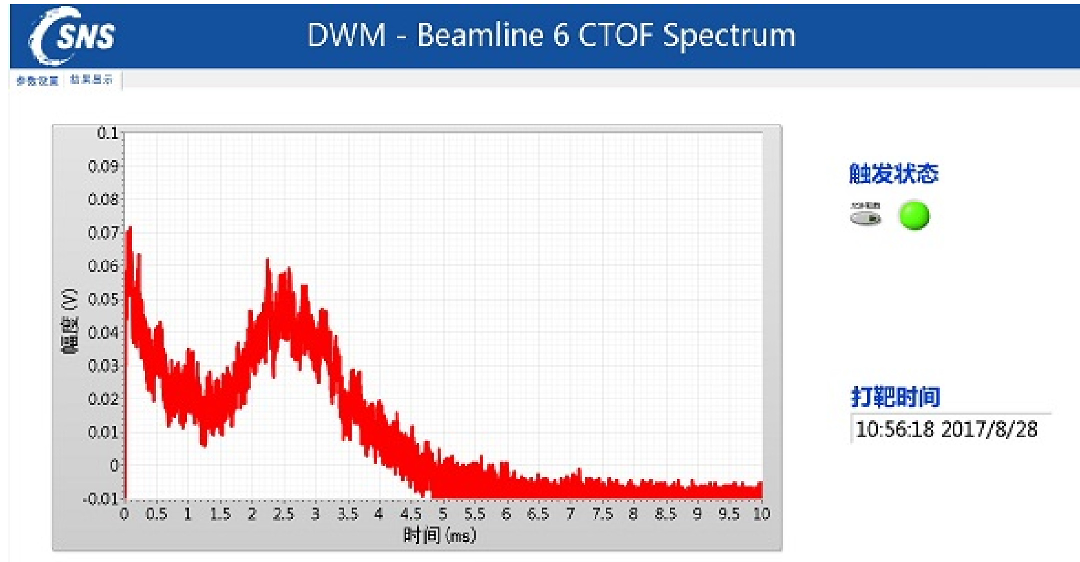


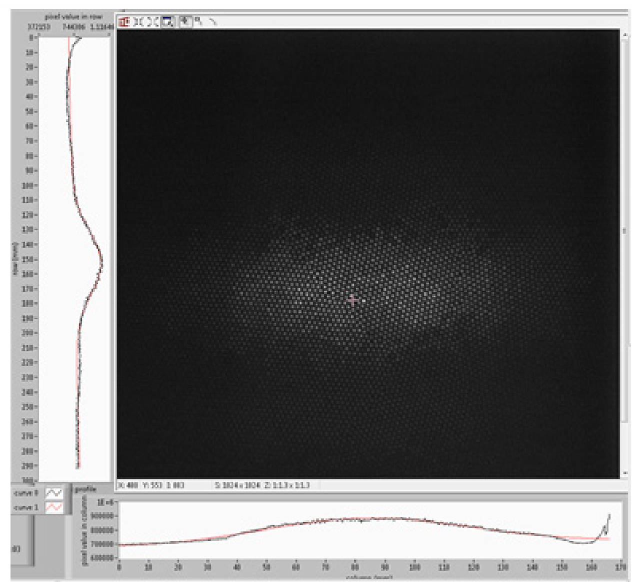
CT Display 2018-02-01 14:10:51

LEBT CT01	27.59	mA	LEBT Trans	70.3	%
LEBT CT02	19.39	mA	MEBT Trans	99.4	%
MEBT CT01	16.19	mA	RFQ Trans	83.5	%
MEBT CT02	16.10	mA	DTL1 Trans	98.3	%
DTL CT01	15.83	mA	DTL2 Trans	99.6	%
DTL CT02	15.77	mA	DTL3 Trans	98.1	%
DTL CT03	15.47	mA	DTL4 Trans	100.3	%
LRBT CT01	15.51	mA	DTL Trans	96.4	%

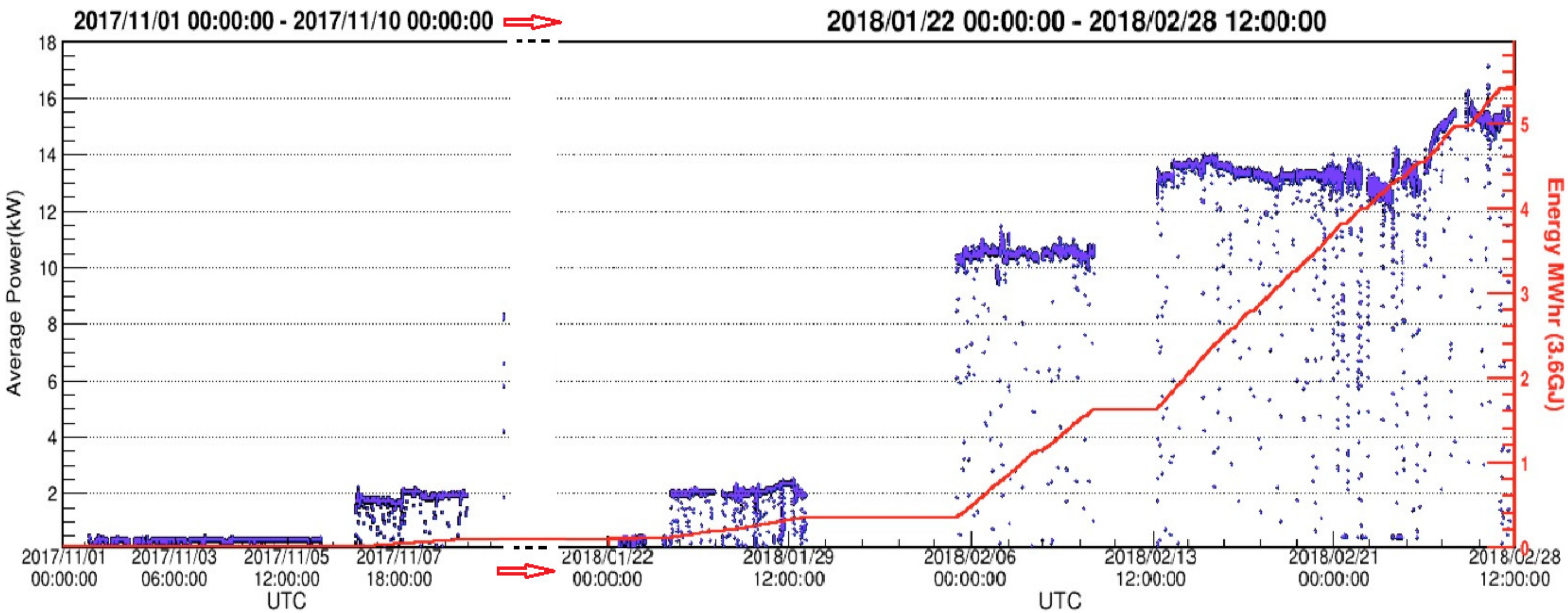
■ First beam on target on schedule

- **August 2017 the first proton beam hit on the target and produced spallation neutrons. This a important milestone for CSNS project.**
- **Beam commissioning is so fast which confirms a good performance in design, manufacture and commissioning.**

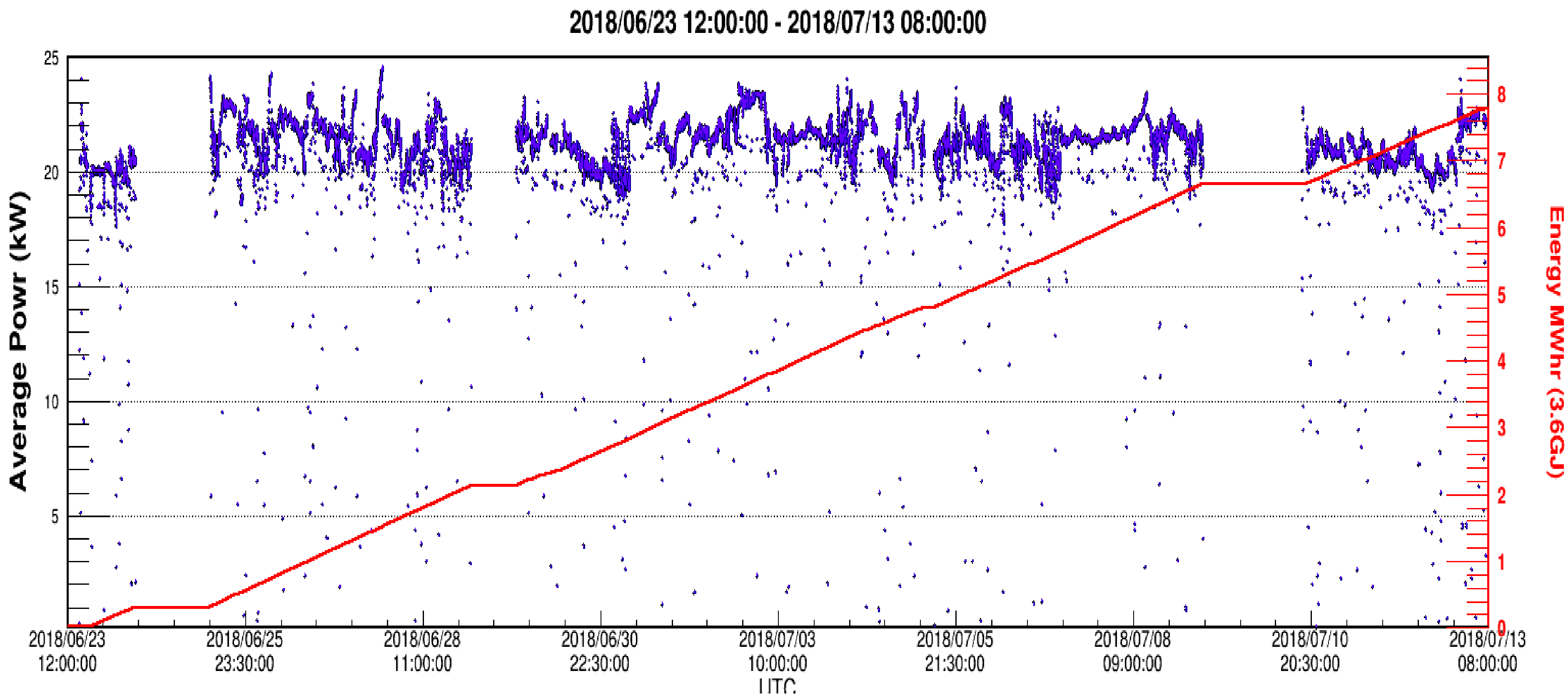




Beam power growth



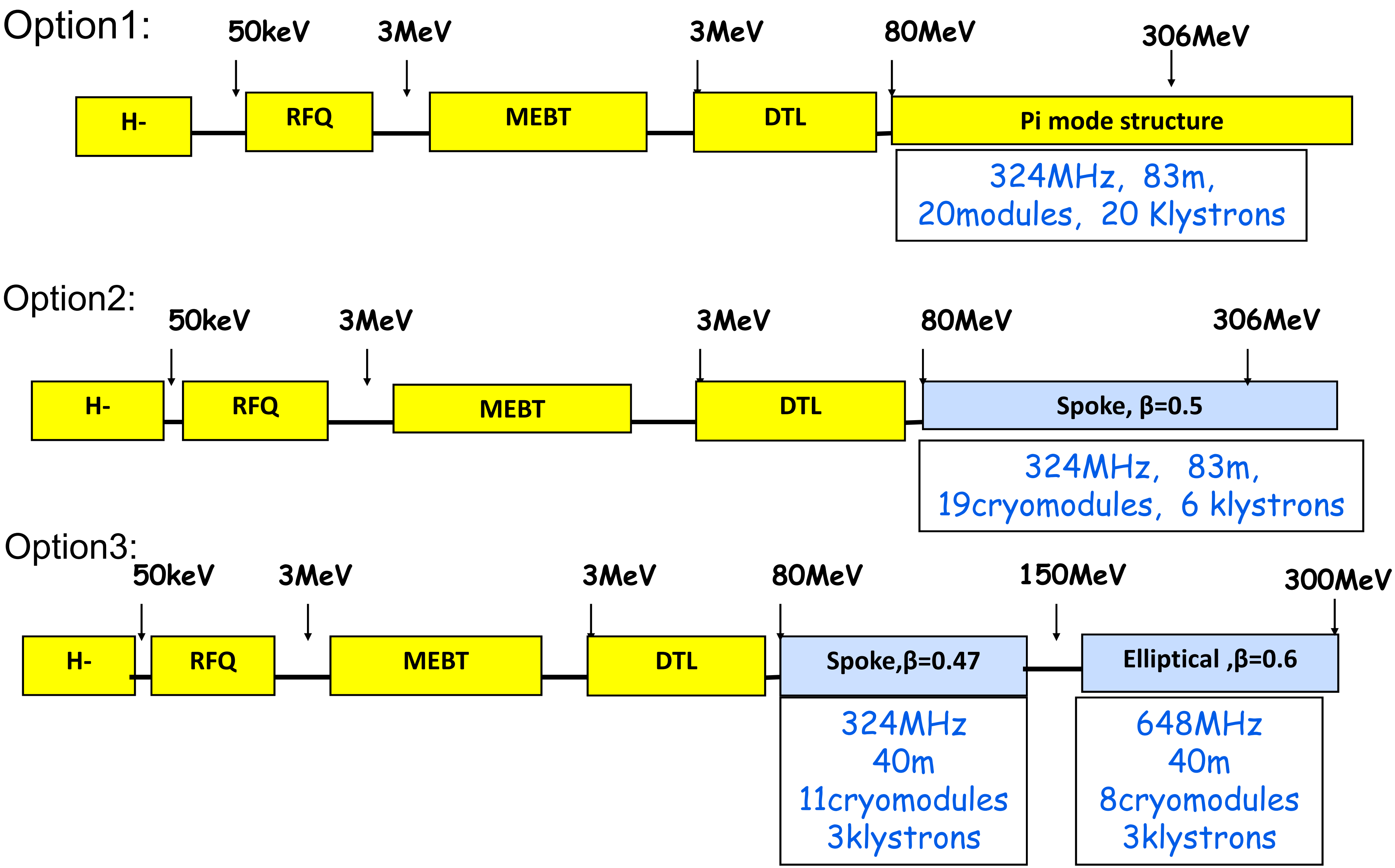
User Operation Status



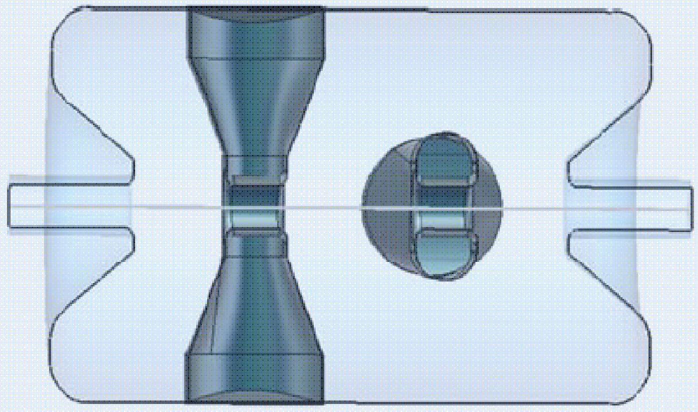
- **In March 2018, we increase the beam power up to 22kW, double of the acceptance value.**
- **Before summer shunt down, we operated at higher than 20kW with 90% availability after we had solved the spark problem of RFQ.**

4, Prospect

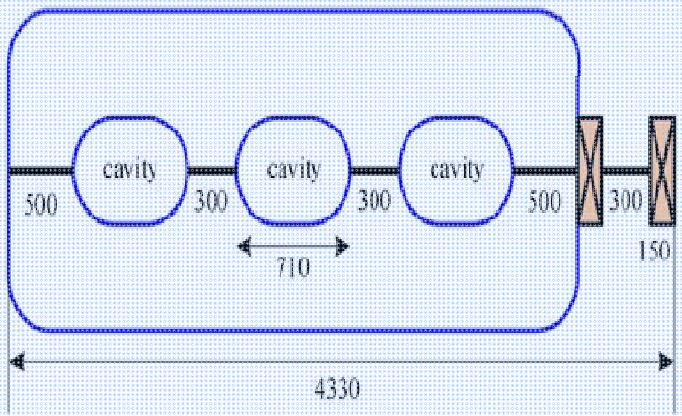
Layout of the CSNS Linac



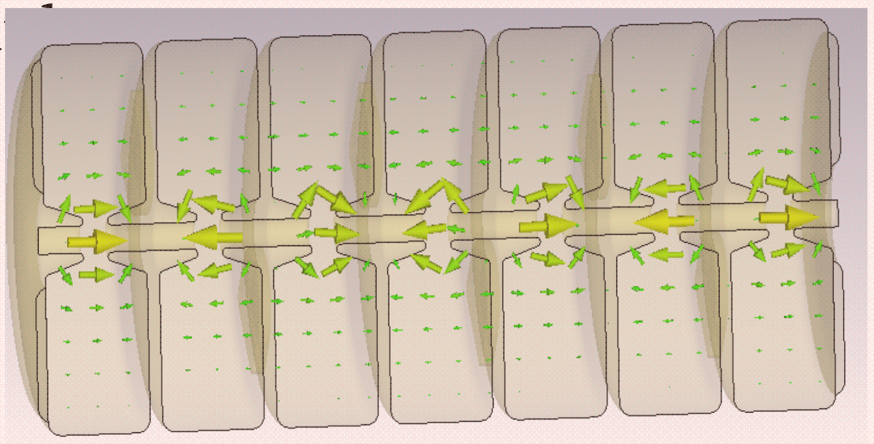
SC Spoke Cavity and its Module



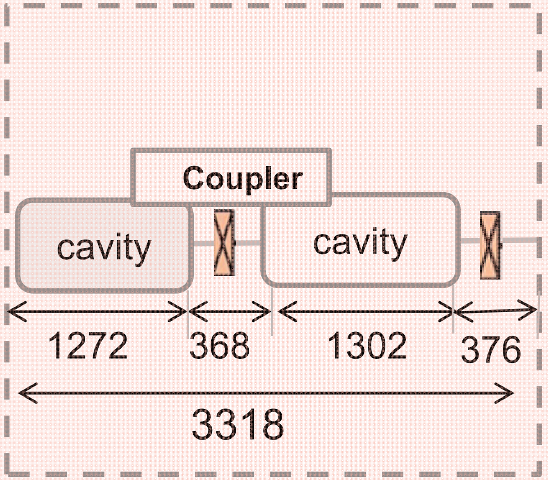
Spoke Cavity Energy Gain 3.7MeV



RT PI-Mode Structure and its Module



PIMS Cavity Energy Gain 4.2 – 6.7MeV



Linac Parameters

Spoke

parameters	value
Frequency/MHz	324
Energy range/MeV	80-306
Length/m	82.9
Cavity number	57
Cryomodule number	19
Cells per cavity	3
Energy gain per cavity/MeV	3.7
Quad. number	38+3
Lattice structure	R^3FD
Aperture/mm	60
Cavity length/mm	710
Filling factor	0.5
Cavity diameter/mm	512
Voltage(E_{peak}=30MV/m)/MV	3.9
B_{peak}(E_{peak}=30MV/m)/mT	73

PIMS

parameters	value
Frequency/MHz	324
Energy range/MeV	80-306
Length/m	83
Cavity number	40
Module number	20
Cells per cavity	7
Energy gain per cavity/MeV	4.3~6.65
Quad. number	40+2(matching)
Lattice structure	FD
Aperture/mm	40
Cavity length/mm	1273~2119
Filling factor	0.8
Cavity diameter/mm	610
E0/MV/m	3.7-4.0 (<1.8Kilpatrick)

A new project China South Light Source is strongly promoted by Guangdong government, as a complementary tool to CSNS.

It consists of both synchrotron light source and free electron laser.

Summary

- Accelerator machine and beam commissioning has been completed with a good results.
- We reached 22kW beam power on target, much higher than the acceptance specification 10kW.
- CSNS started user operation and meanwhile will gradually rise beam power to 100kW in 2 years.
- 500kW upgrade is under consideration, and the upgrade project will be launched as soon as we realize 100kW.
- CSNS accelerator construction finished successfully within budget and on time. A week ago, CSNS project past the government acceptance.
- As a complementary tool, China South Light Source is under planning nearby the CSNS.

THANK YOU VERY MUCH!

CSNS Contributed Papers in LINAC2018

ID	Title
MOPO108	Design and Performance of the Digital LLRF Control System for the CSNS
MOPO080	The manufacturing of the CSNS DTL tank
TUPO115	Beam parameters measurement and correction in CSNS linac
TUPO114	Beam dynamics studies for the CSNS Linac due to a quadrupole fault
THPO028	Magnetic Field Measurement and Analysis for Drift Tube Linac of CSNS
THPO029	Quality Factor and Power Loss of the CSNS DTL
THPO030	Operation experience of the CSNS DTL
THPO031	RF Conditioning and Beam Commissioning Status of CSNS DTL
THPO032	CSNS linac beam commissioning tools and experience
THPO038	Status of the power couplers for the CSNS DTL
THPO039	The status of CSNS Front End