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Advanced Beam Dynamics
Workshop on High-Intensity,
High Brightness and
High Power Hadron Beams

Present Status of the High Current Proton Linac at Tsinghua University and Its Beam Measurements and Applications

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CPHS Compact Pulsed Hadron Source
TSINGHUA UNIVERSITY

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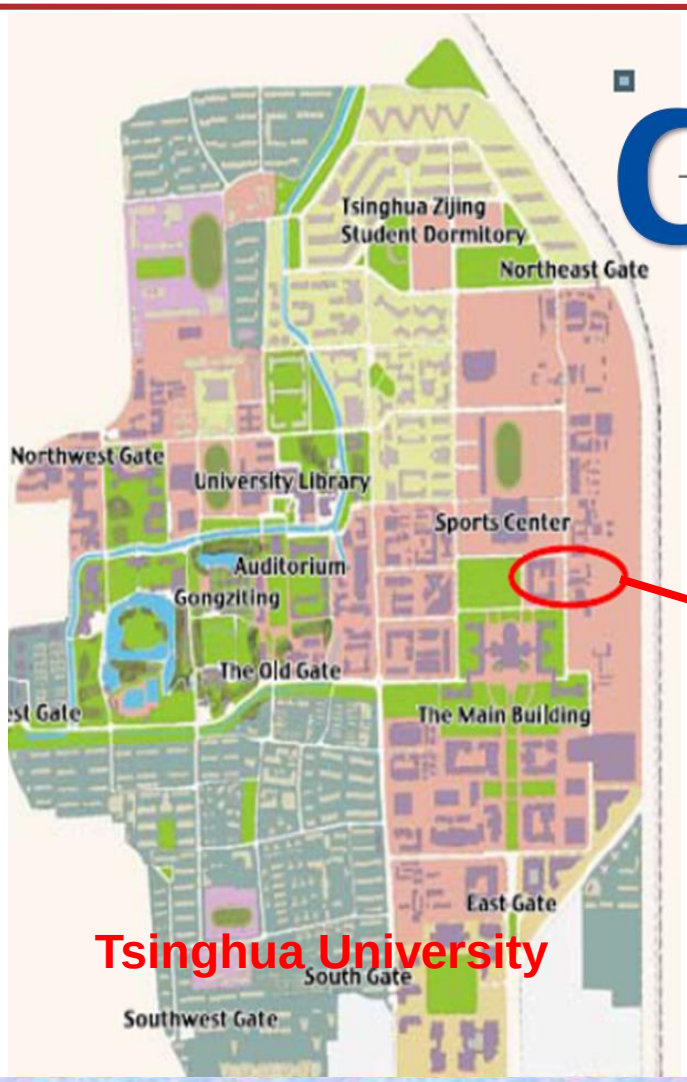
Introduction



CPHS 微型脉冲强子源
Compact Pusled Hadron Source
TSINGHUA UNIVERSITY

CPHS+TTX:

- Network of accelerator-driven proton, neutron, electrons, x-ray, and laser
- Experimental platforms for education, research, and innovative applications

TSINGHUA University 清华大学

Thomson scattering X-ray source 汤姆逊散射实验平台

CPHS (Compact Pulsed Hadron Source) project

CPHS project

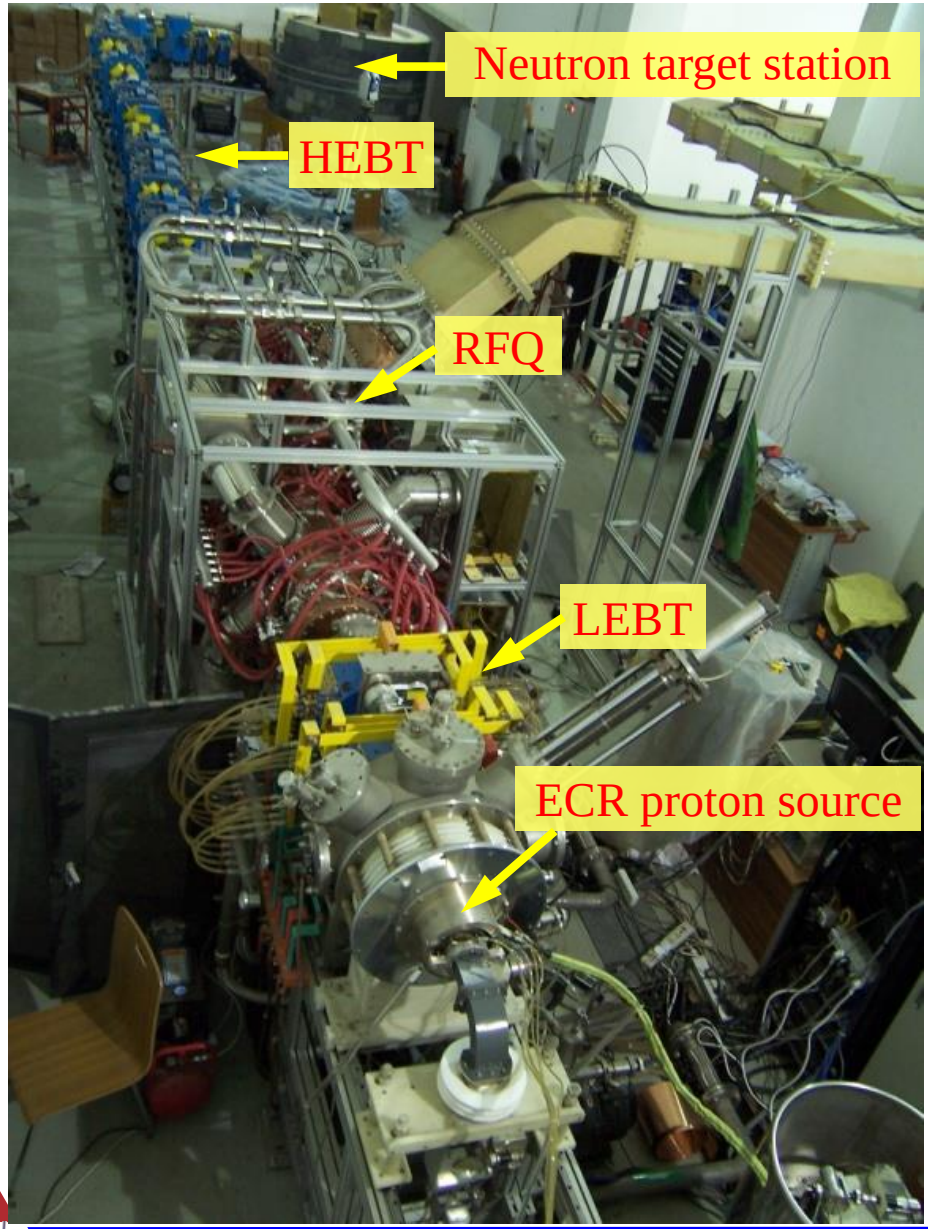
- Launched in June 2009
- Four neutron beam lines planned
- Neutron beam test line and neutron imaging beam line constructed
- Target station: Beryllium
- Expected neutron flux: ~5*10^{13} n/s

Proton linac requirement

Ion type	Proton	
Beam power	16	kW
Beam energy	13	MeV
Average current	1.25	mA
Pulse repetition rate	50	Hz
Uniform beam diameter on the target	5	cm

CPHS facility

CPHS layout - linac

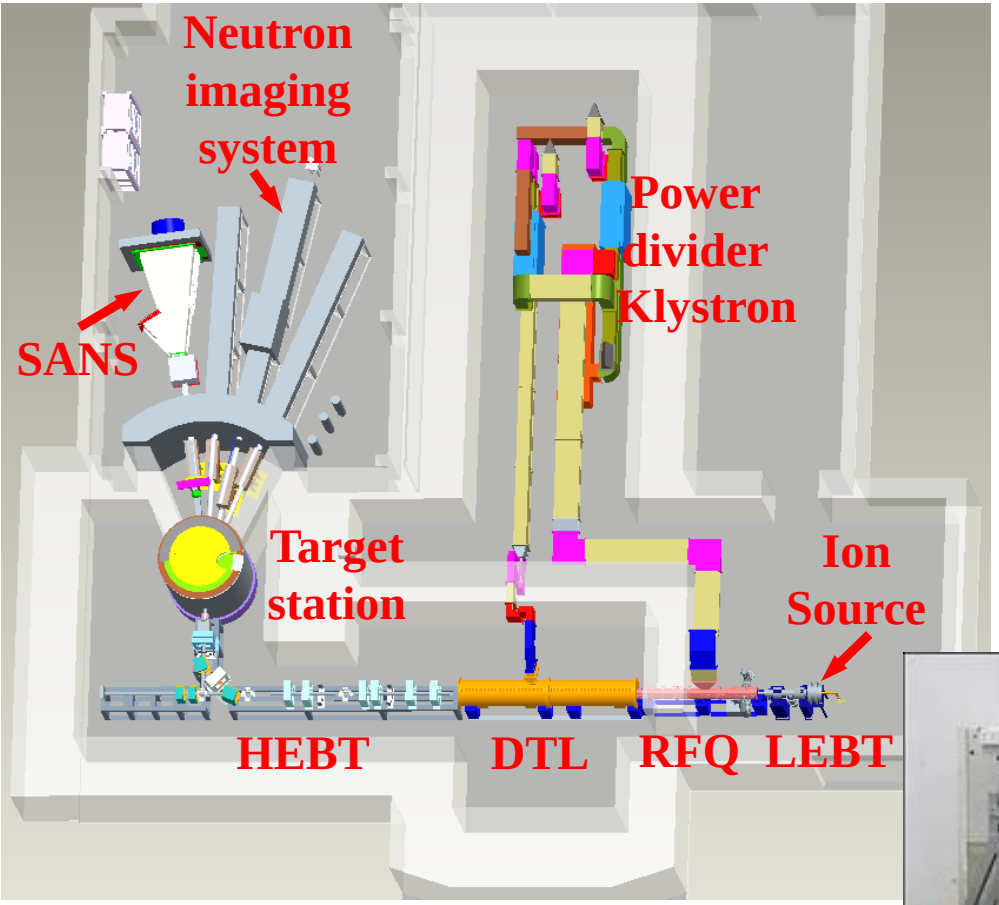



CPHS linac power system

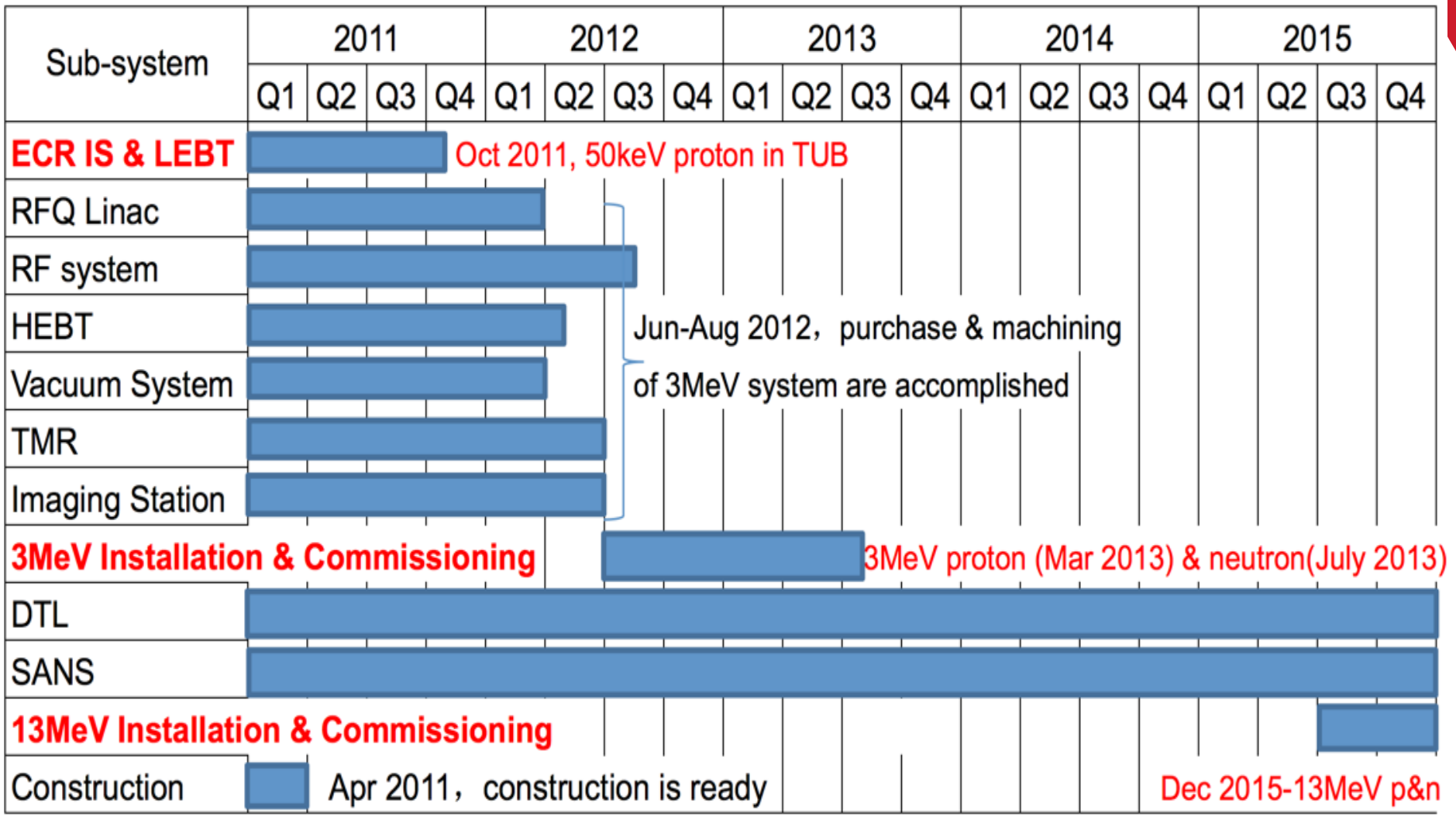
Proton linac design parameters

Ion type		**Proton**	
Beam energy		**13**	MeV
Peak current		**50**	mA
Pulse length		**500**	μs
Pulse repetition rate		**50**	Hz
RF frequency		**325**	MHz
Output energy	Ion source	**50**	keV
	RFQ	**3**	MeV
	DTL	**13**	MeV

CPHS layout – target station and neutron beam line



CPHS project schedule



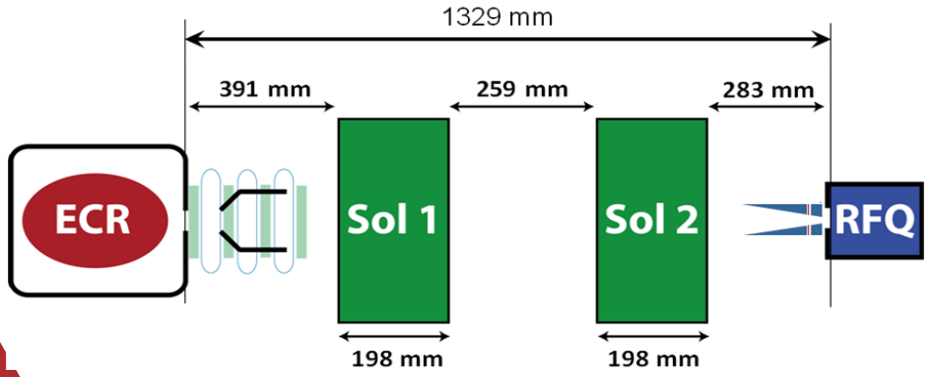
Operation status – CPHS milestones

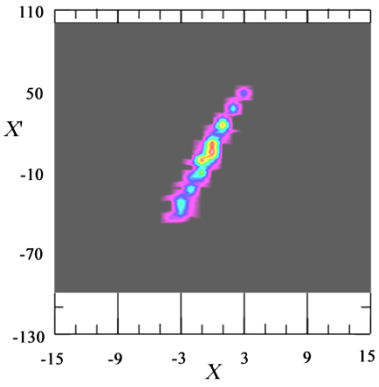
- RFQ conditioned to 550kW/50Hz/40μs on 2013/02
- First beam of RFQ on 2013/03/25
- Highest transmission of RFQ (88%, input 50mA, output 44mA) on 2013/03/27
- First neutron beam on 2013/07/18 (**mid-term objective achieved**)
- First neutron imaging on 2013/07/26
- Highest transmission of HEBT (> 90%) on 2013/08/13
- RFQ conditioned to 442kW/50Hz/500μs on 2014/04

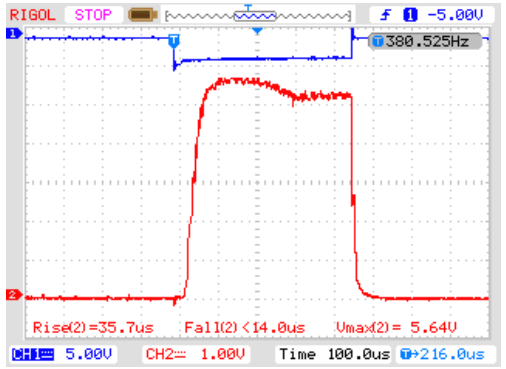
Parameter	Designed	Achieved
Beam Energy	13 MeV	**3 MeV**
Beam Current	50 mA	**23 mA**
Pulse Length	500 μs	**100 μs**
Repetition Rate	50 Hz	**20 (50) Hz**

Operation status – ECR source & LEBT

Output energy	50	keV
Output current	60	mA
Microwave frequency	2.45	GHz
Microwave average power	1.5~2.0	kW
Normalized RMS emittance	0.2	π mm·mrad



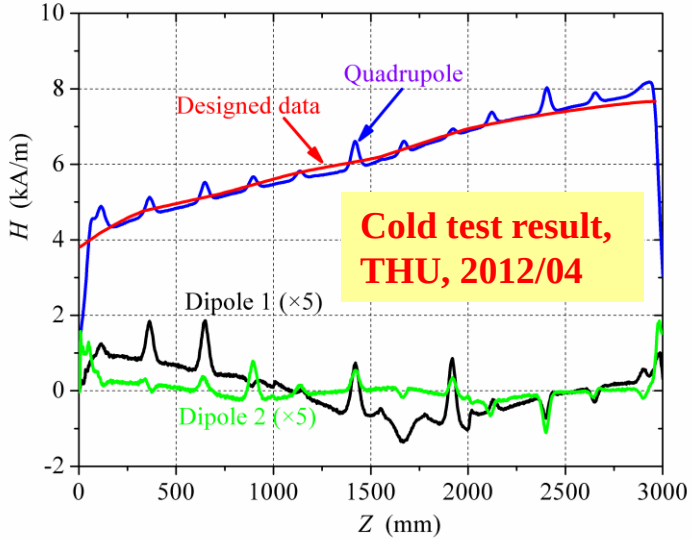




Phase space and proton pulse measured at the end of the LEBT.

The maximum output proton beam reaches 60 mA

Operation status – RFQ



Quadrupole error: ±3%; Dipole component: ±4%

Parameters	Value	Unit
Type	Four vane	
Frequency	325	MHz
Input beam energy	50	keV
Output beam energy	3.0	MeV
Peak beam current	50	mA
Emittance (norm. rms)	0.2	πmm· mrad
Maximum surface field	32.1	MV/m
Pulse length	0.5	ms
Pulse repetition rate	50	Hz
RF peak power	537	kW
Beam duty factor	2.5	%
Section number	3	

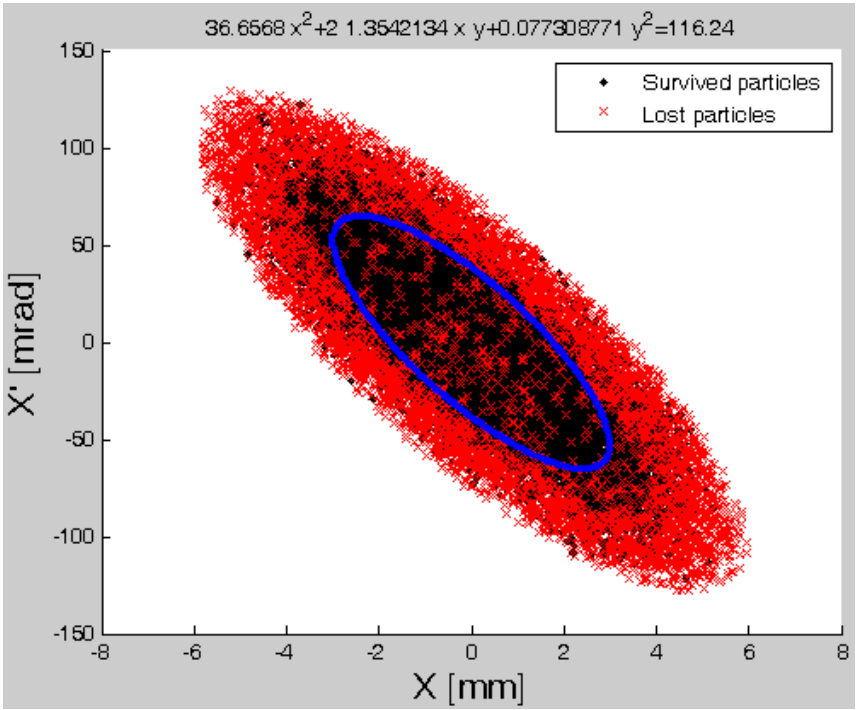
Main characteristics：

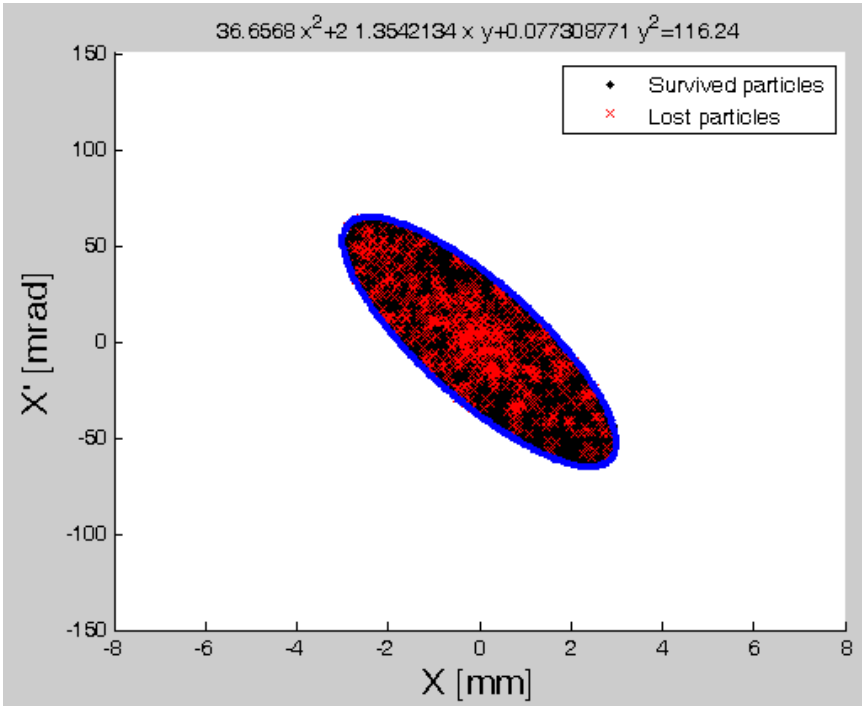
1）High transmission with shorter length: without coupling plates;

2）Optimization design of the peak field and the multipole field: vane-tip geometry tailored as a function of longitudinal position;

3）No MEBT.

Operation status – RFQ





Peak current: 60 mA
Macroparticle number: 2×10^4
$\varepsilon x=0.8\ \pi$ mm•mrad
$\varepsilon y=0.0001\ \pi$ mm•mrad
$\alpha x, \beta x, \alpha y, \beta y$: matched values

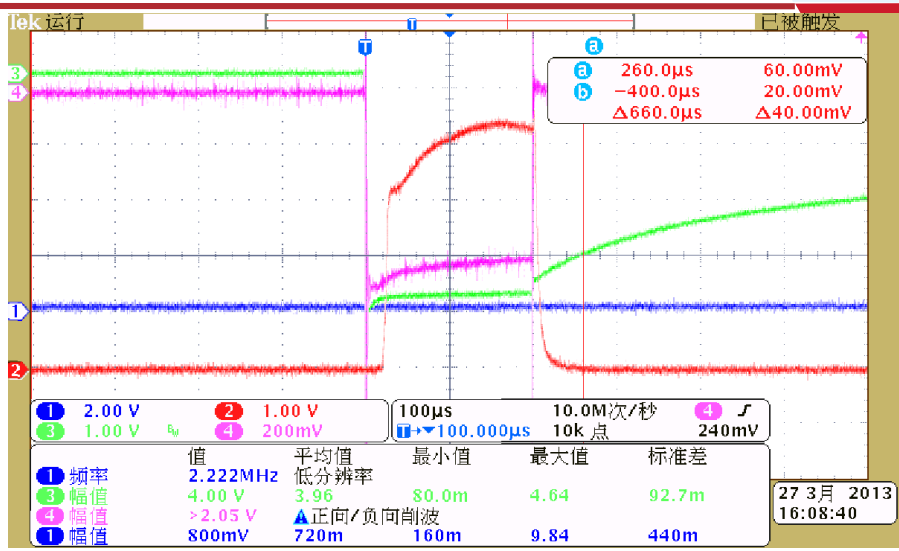
Peak current: 60 mA
Macroparticle number: 2×10^4
$\varepsilon x=0.2\ \pi$ mm•mrad
$\varepsilon y=0.2\ \pi$ mm•mrad
$\alpha x, \beta x, \alpha y, \beta y$: matched values
Transmission rate: 97%(total), 95.8%(accelerated)

Matched values for Twiss parameters:
$\alpha x = \alpha y = 1.35$; $\beta x = \beta y = 0.0773$ mm/mrad
(obtained from ParmteqM with input peak current of 60 mA)

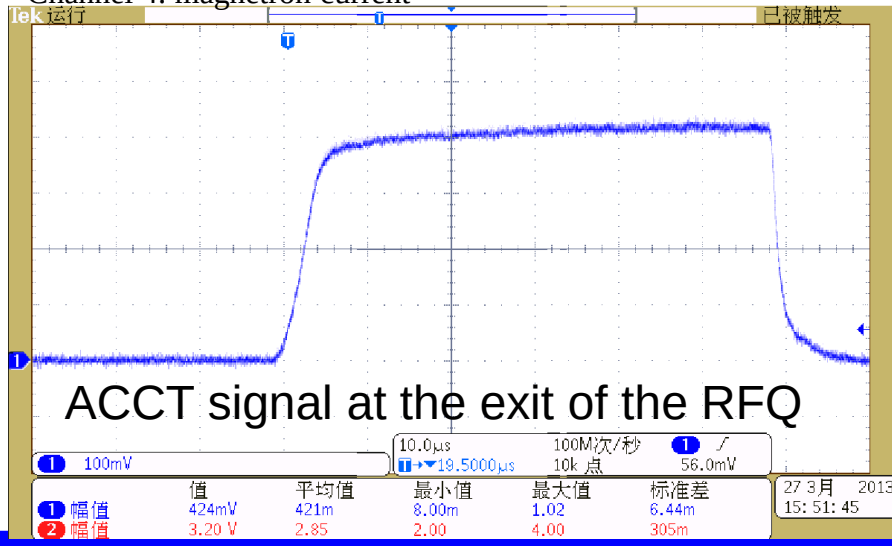
Operation status – RFQ commissioning-1

First 3MeV proton beam on 2013/03/25

RFQ input current: **50 mA**
RFQ output curren: **44 mA**
Repetition rate: **50 Hz**
Pulse length: **50us**

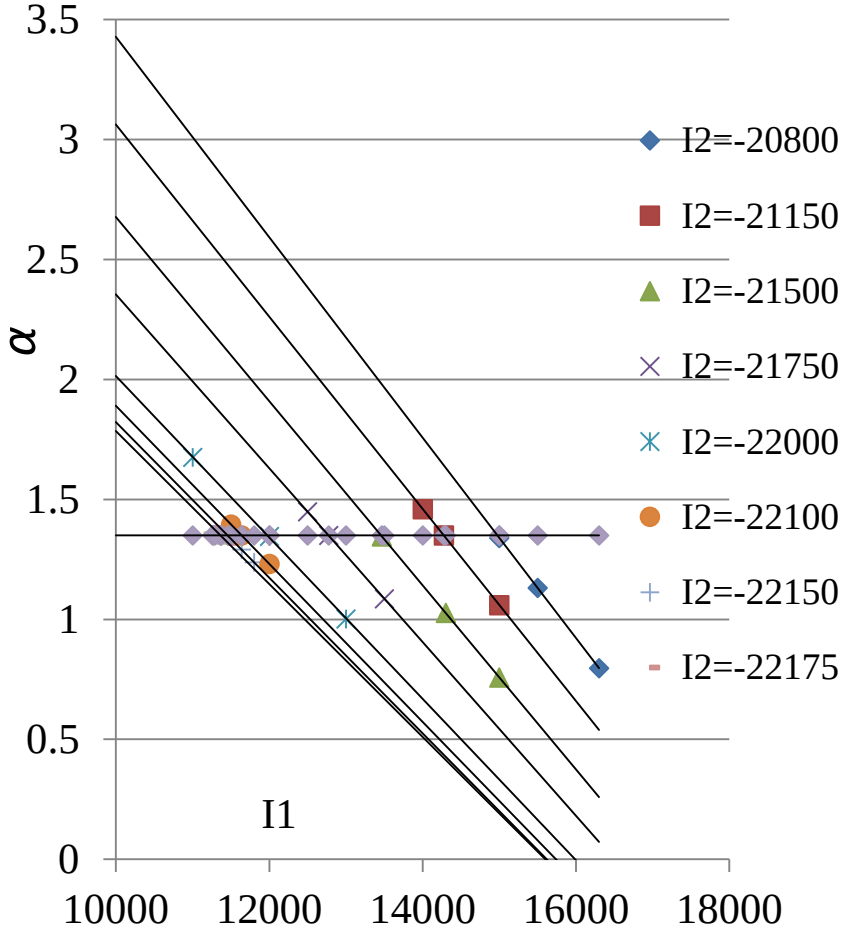


Channel 1: Current of the faraday cup at the exit of ECR source;
Channel 2: ACCT signal at the entrance of the RFQ;
Channel 3: magnetron voltage;
Channel 4: magnetron current

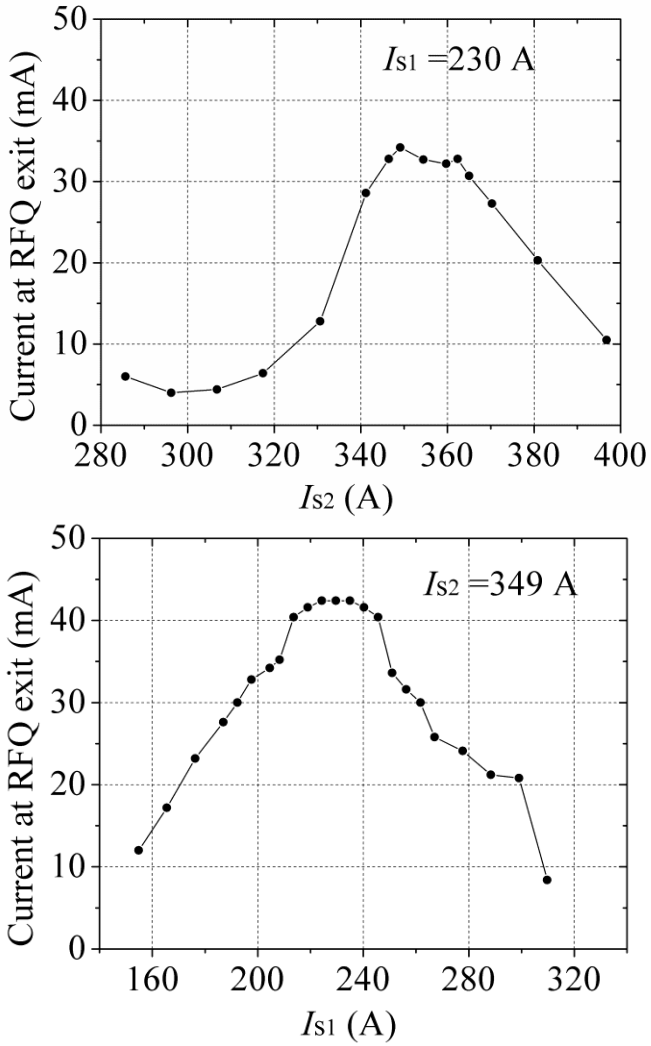


Operation status – RFQ commissioning-2

- Match between the LEBT and RFQ



With the **prediction** of TRACK code, highest transmission of 94% is obtained with I_{s1} =**202 A** and I_{s2} =**396 A** (input current of RFQ is 50 mA).



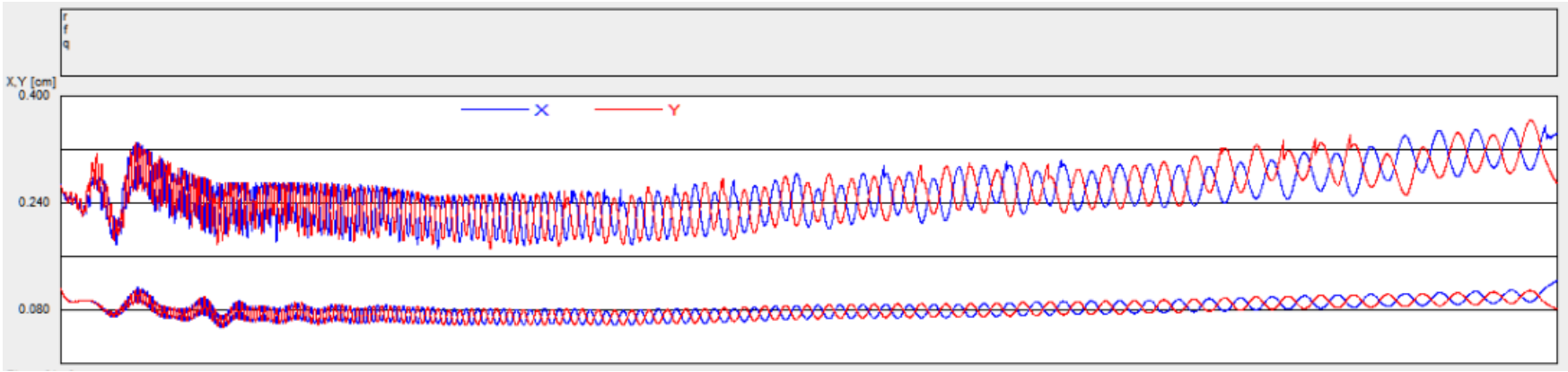
Current **measured** by ACCT at RFQ exit with currents of the first (left) and second (right) solenoids.

Operation status – RFQ commissioning-3

LEBT--->RFQ--->DTL: TSTEP --> TOUTATIS --> PARMILA

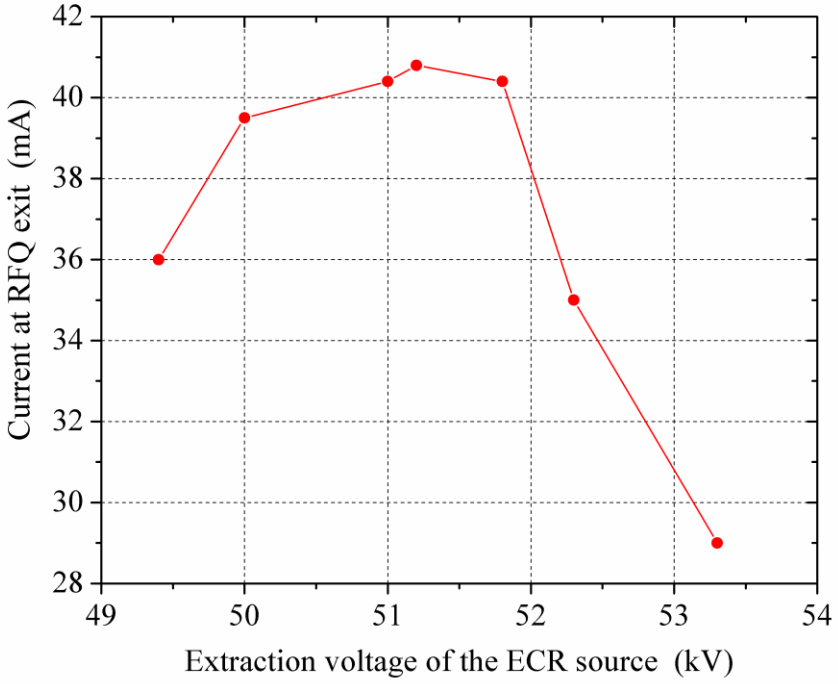
	Output particle number	Transmission rate
TSTEP (LEBT)	65099	
TOUTATIS (RFQ)	55529 (Accelerated)	85.3%
PARMILA (DTL)	55467 (Accelerated)	99.9%

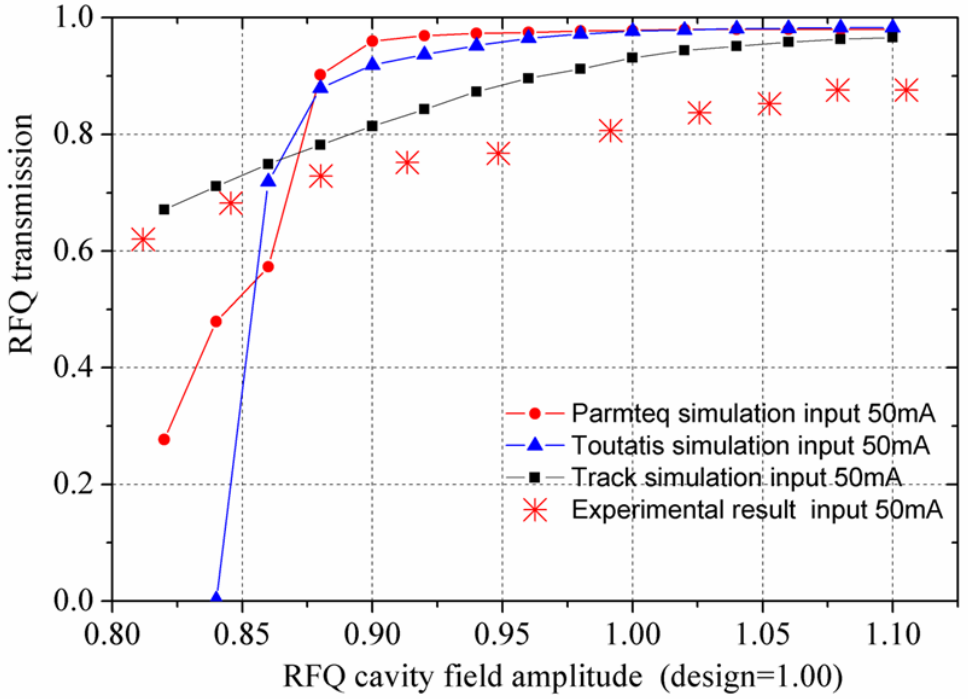
Beam loss: most of the lost particles locate in the drift and the first four DTL cells



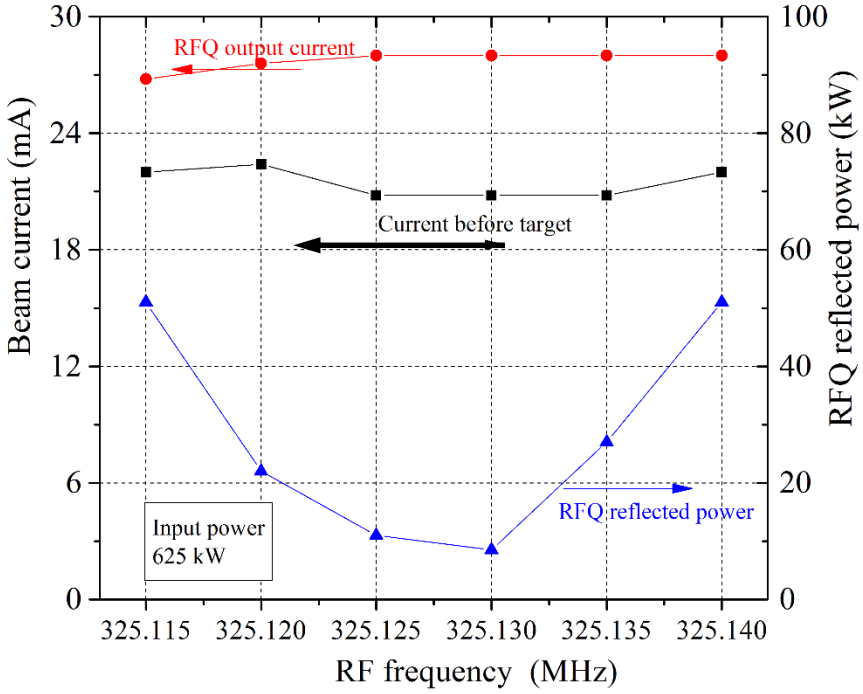
Simulation result of beam envelop by Track (LEBT output distribution is adopted as input. Solenoid currents are optimized by THU): Transmission rate of 91.8% for 60mA input and 94% for 50 mA input

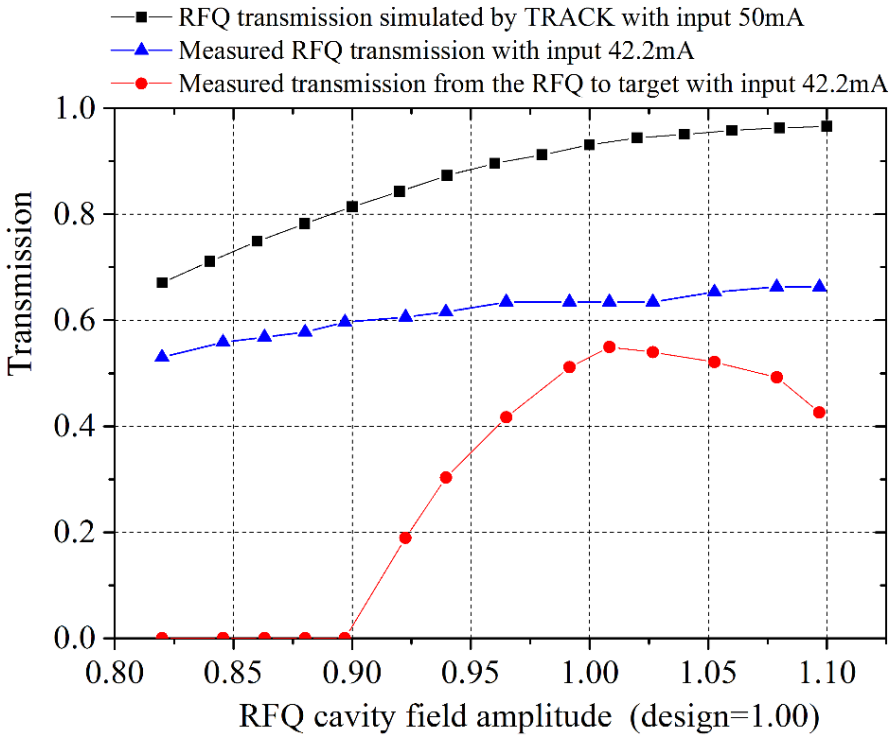
Operation status – RFQ commissioning-4



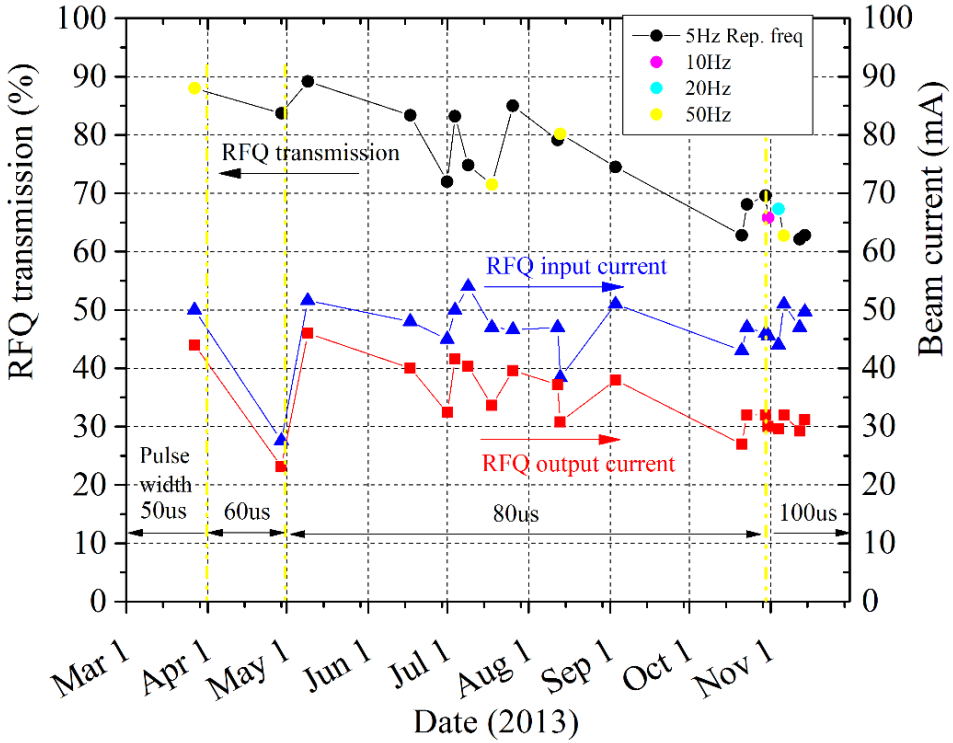


Operation status – RFQ commissioning-5

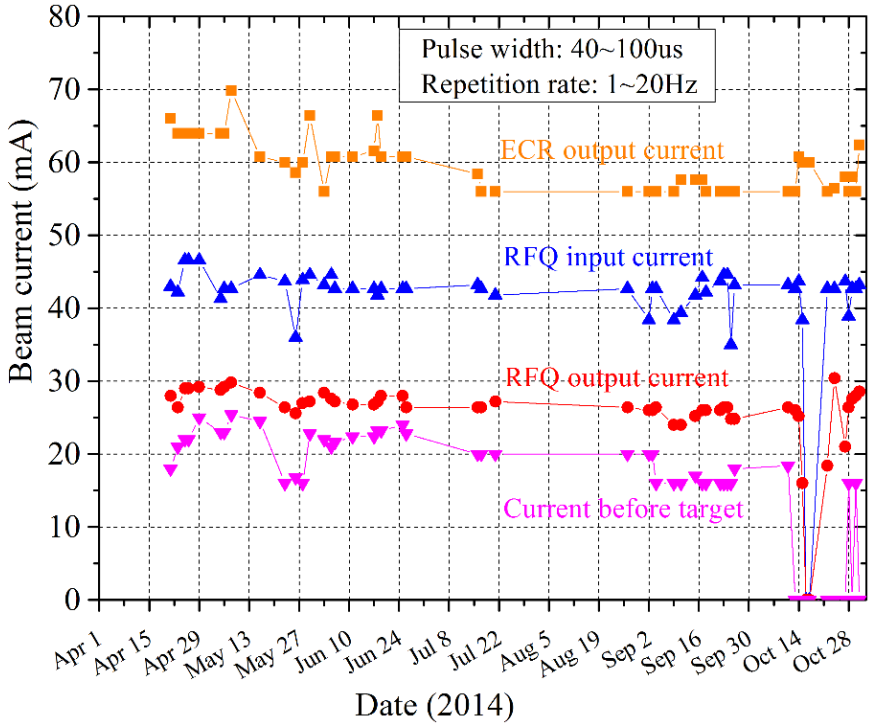




Operation status – history in 2013~2014



Operation history of the 3 MeV linac in 2013

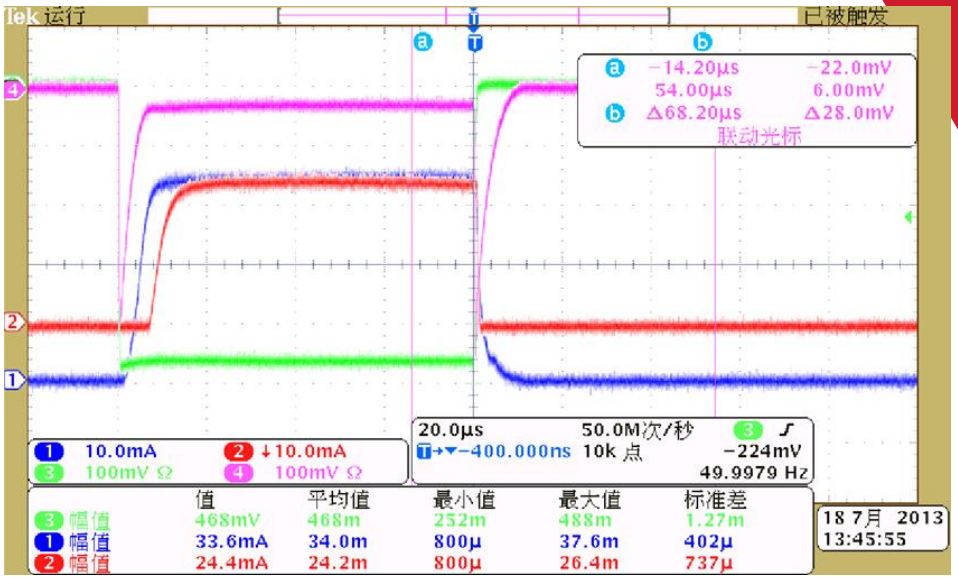


Operation history of the 3 MeV linac in 2014

Frequency shift problem of the RFQ:

- 325.021 -> 325.124 MHz during Jan.~Feb. 2013
- 325.120 -> 325.165 MHz on Oct. 15, 2014

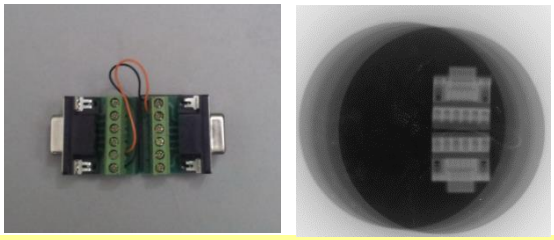
Operation status – first neutron beam



Channel 1: ACCT signal at the output of the RFQ;
Channel 2: ACCT signal after the beam bends 90°;
Channel 3: input power to RFQ;
Channel 4: reflected power from RFQ

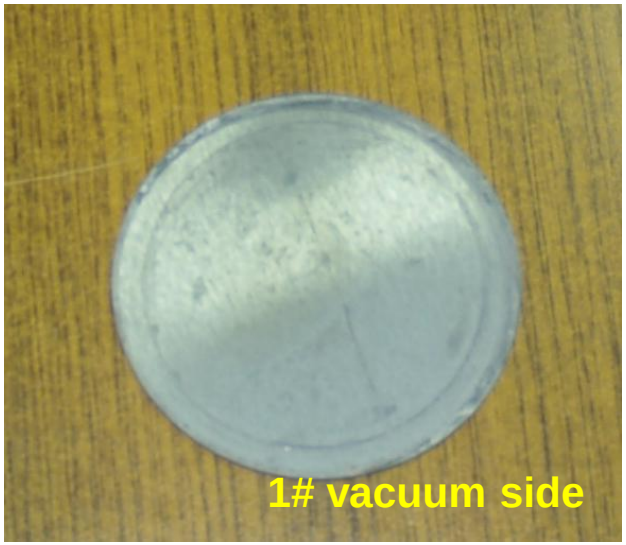
First neutron beam on 2013/07/18

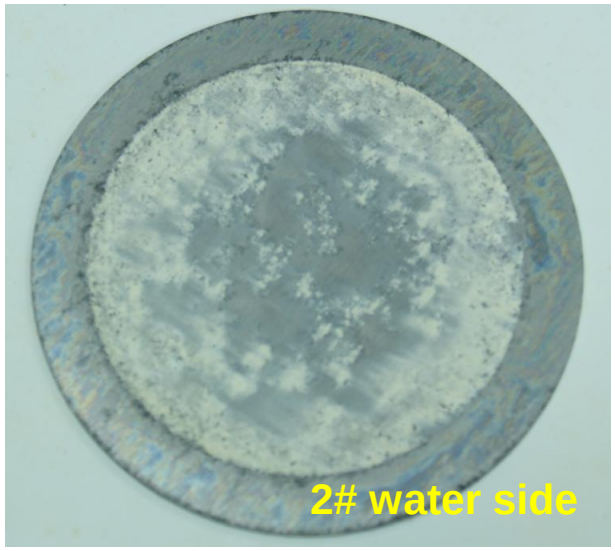
Repetition rate: **50 Hz**
Pulse length: **80us**
Beam current after bending 90°: **22.4 mA**
Neutron flux (~10meV ~a few hundred meV): **1.9e9**
Total calculated neutron flux: **2.8e10** (neutron efficiency of 5e-5)

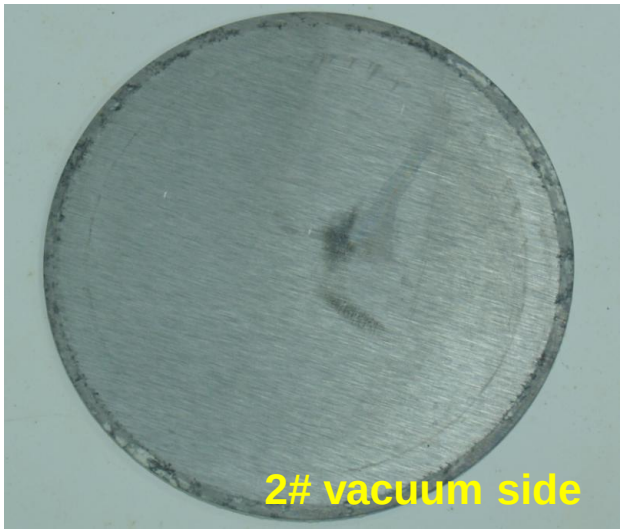


First image on 2013/07/26

Operation status – Be target problem

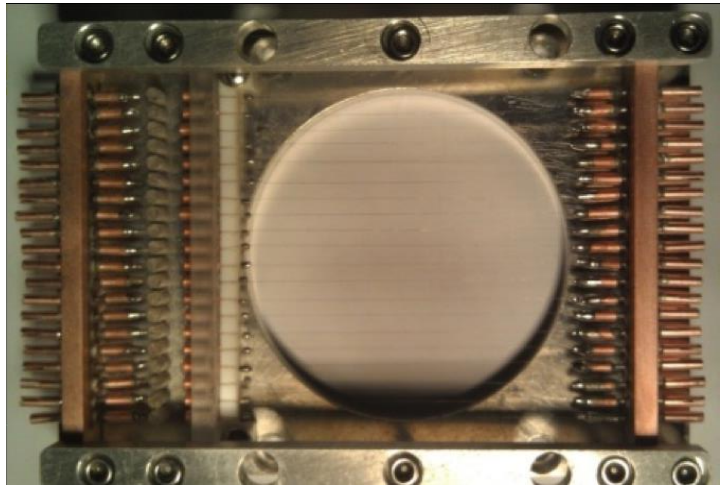


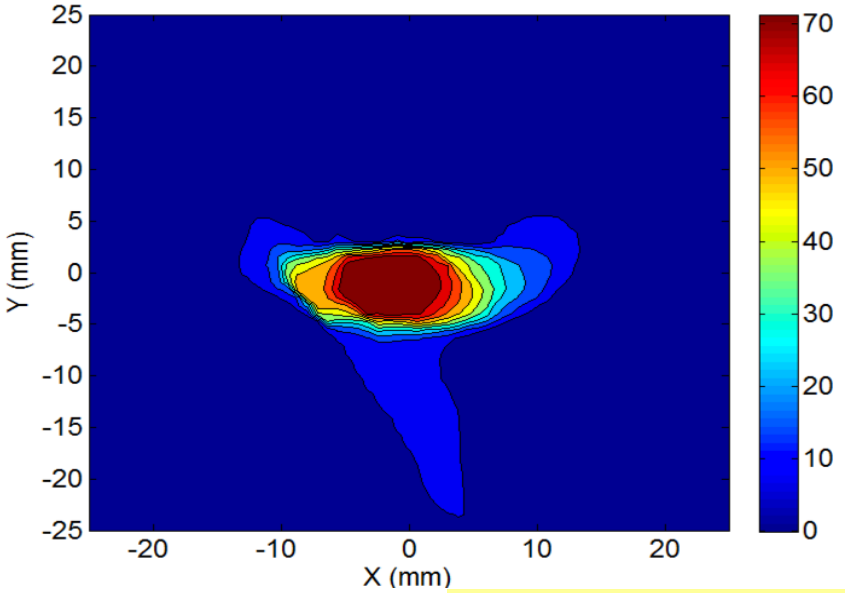




Two Be targets have been broken (2013/07/19, 2013/08/13)

Proton beam – 2D profile measurement

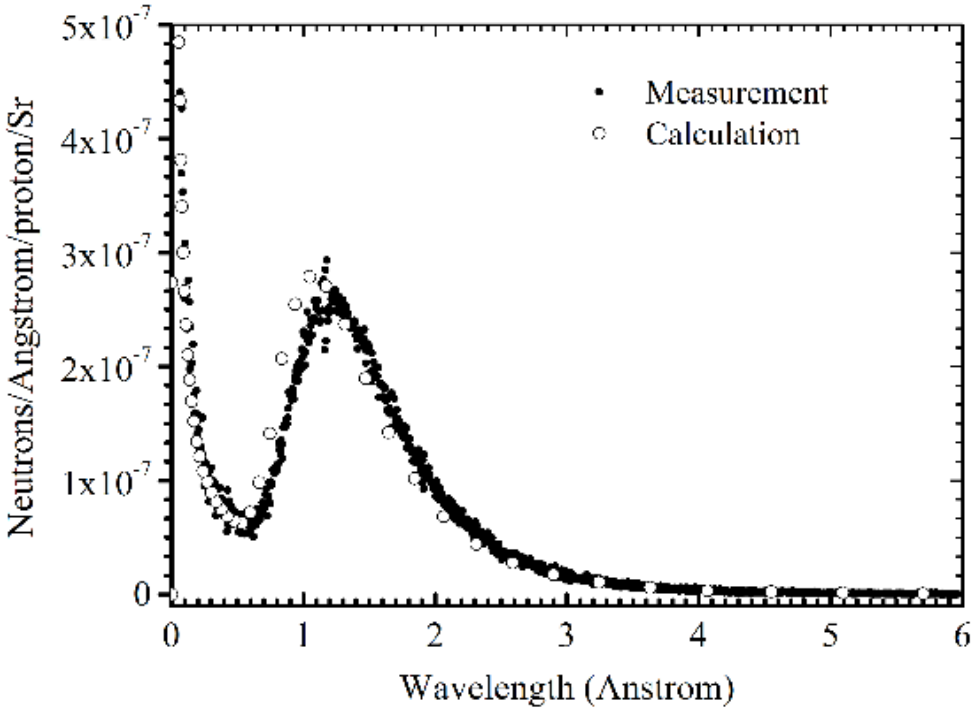




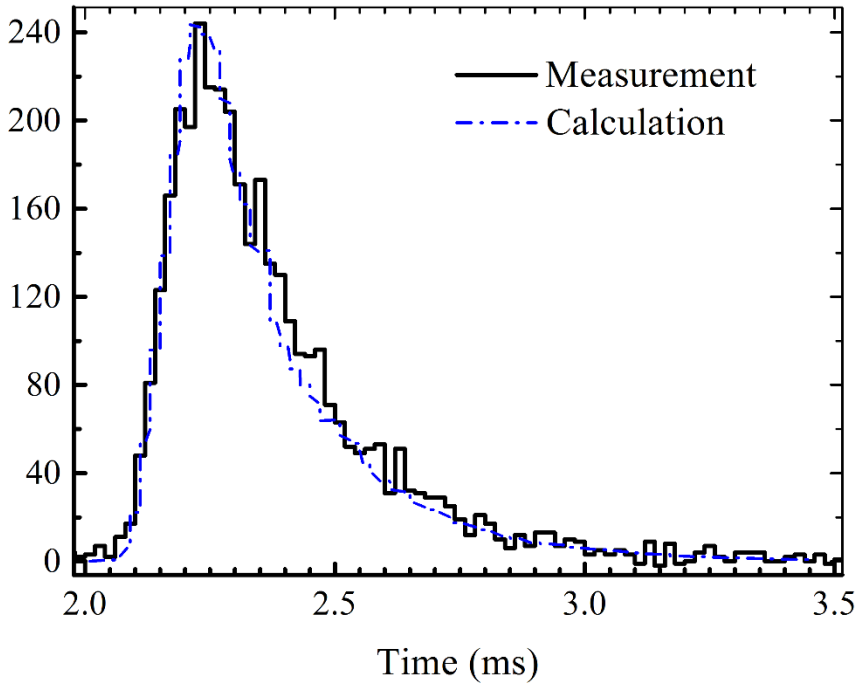
- 2D profile measurement by the CT algorithm
- Twenty carbon wires rotatable with the diameter of 30 μm
- Primary experiment done with only one wire
- The electronics system for the measurement of the twenty wires simultaneously will be ready at the end of this year

Lei Du, THO2LR02

Neutron beam measurement



The wavelength spectrum of the first neutron production

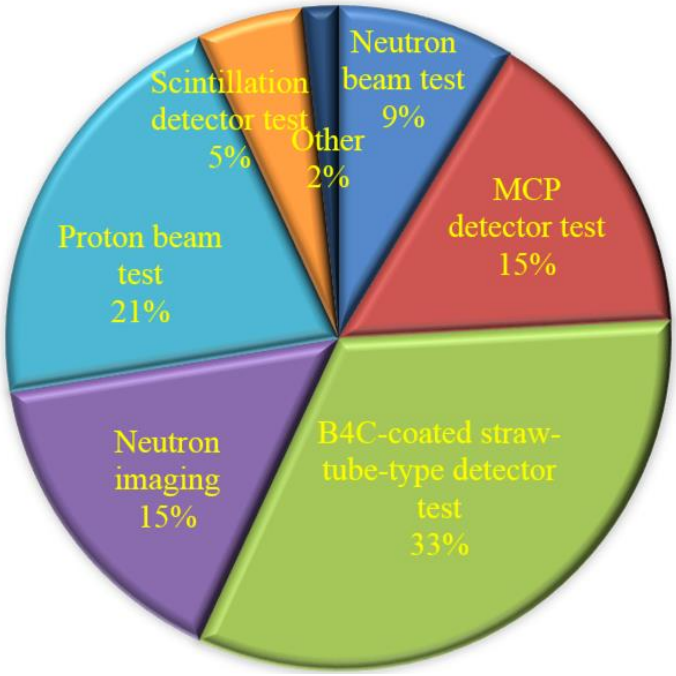


The time structure of the neutron with the wavelength of 1.17 Å measured by the time-of-flight method

- Flux of neutron below 1eV was measured to be 403 n/cm^2/s at the position 6.625 m away from the centre of the target station, which agrees with the value simulated within ±15%

Courtesy S.L. Wang

Neutron application



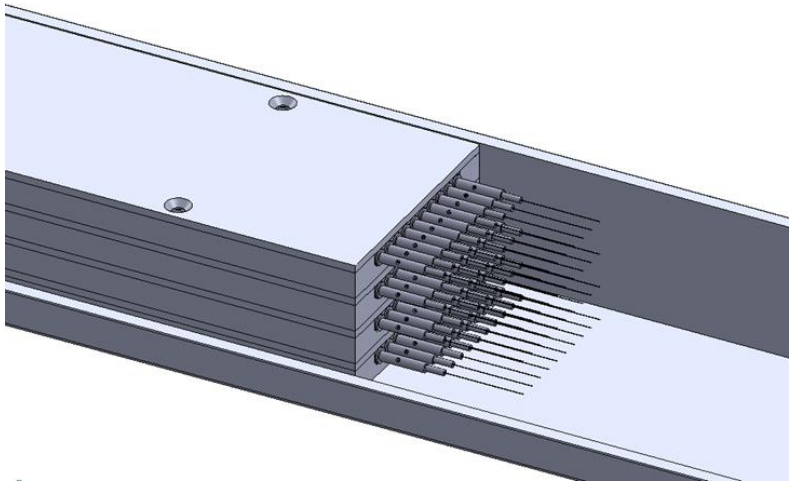
Time percentage of the CPHS operation for different applications of the beam at THU in 2014（Total operation time：~500 hrs）

Plan of CPHS:

- 2014: stable operation of the 3MeV beam
- 2015: stable operation of the 3MeV beam and 13 MeV beam commissioning
- 2016: providing the 13 MeV proton and neutron beams

Neutron application - B_4C-coated straw-tube-type detector

One B4C-coated
Straw-tube module

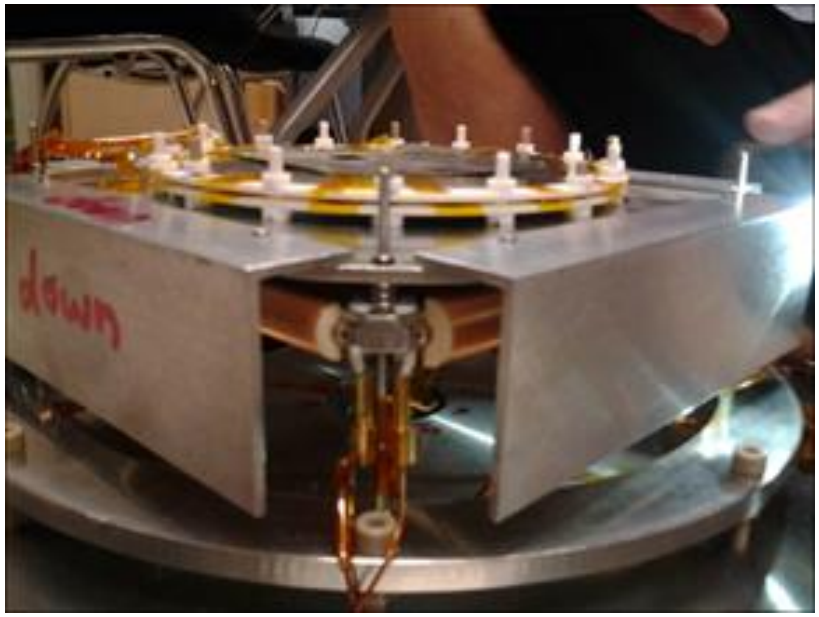


TEST RESULT

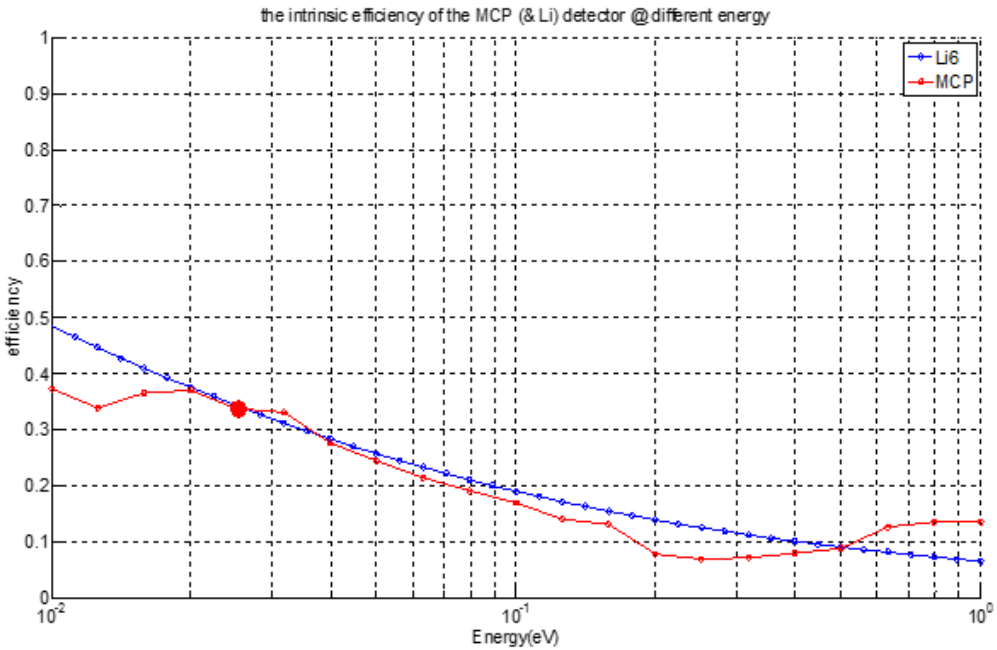
- Sensitive length longer than 1000 mm
- Resolution of the tube module is 4 mm in the radial direction
- Resolution of the tube module is better than 8 mm in the axial direction
- Detection efficiency of the thermal neutron for single tube is larger than 7% (at 25.3 meV)

Courtesy H. Gong

Neutron application - gadolinium-doped MCP detector



One gadolinium-doped Micro-Channel Plate (MCP) detector

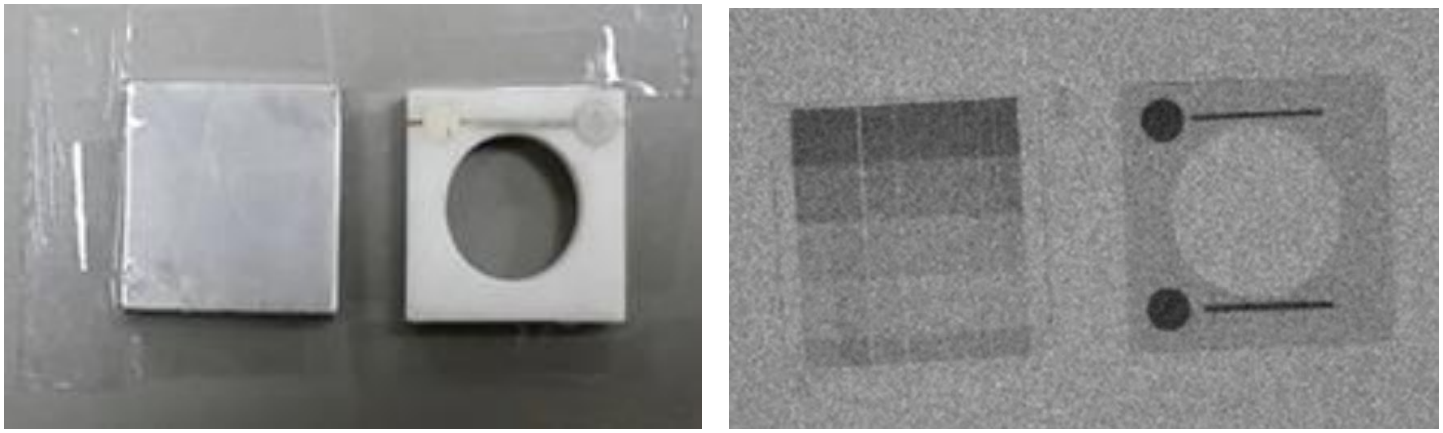


TEST RESULT

- Detection efficiency of MCP detector is larger than 30% (at 25.3 meV)

Courtesy Y.G. Yang

Neutron application - imaging



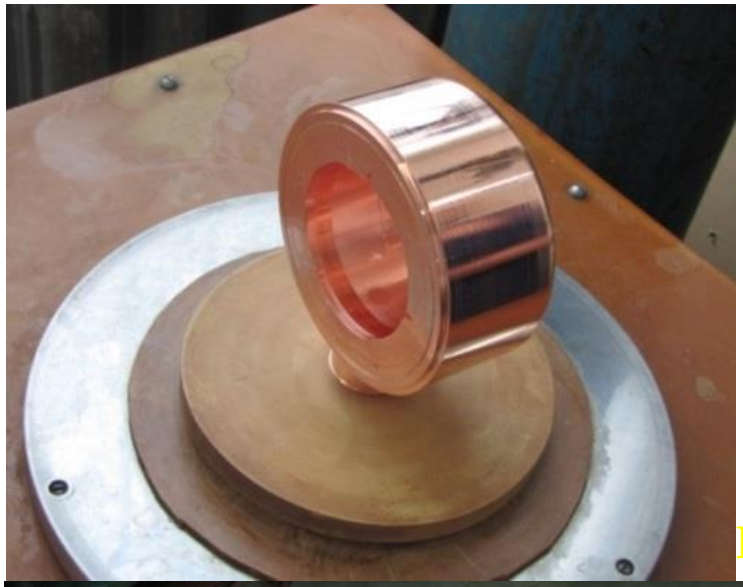
Test piece (left) and neutron imaging (right) after 10 hrs at the end of the neutron beam line

TEST RESULT

- Imaging IP board positioned at the end of the neutron beam line
- Alignment of the beam line is good because the efficient scattered neutrons are reduced sufficiently
- Contribution of the gamma ray is relatively low
- Transverse distribution of the neutron beam is uniform

Courtesy Y.S. Xiao

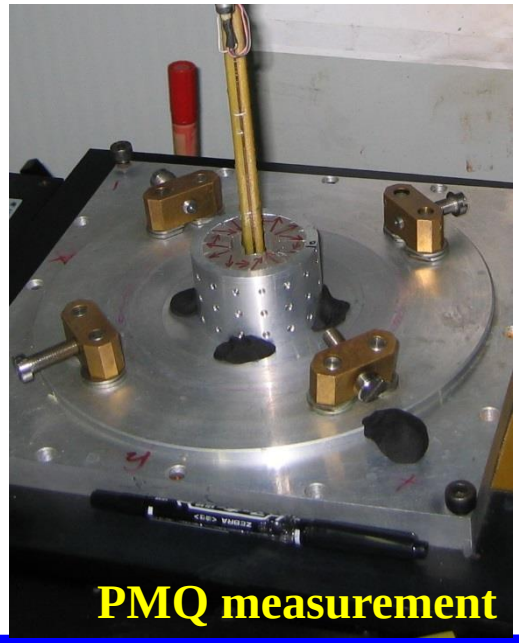
DTL development



Drift tube

Input/output energy	3.0/13	MeV
Peak current	50	mA
Synchronous phase	-30→-24	Degree
Accelerating field	2.2→3.8	MV/m
Peak power	1.2	MW
Lens gradient	84.6	T/m
Lens effective length	4	cm
Cell number	40	
Total length	4.37	m

DTL cavity model



PMQ measurement

Summary

- CPHS facility achieved its mid-term objective: delivering the 3 MeV proton beam to the Beryllium target
- Measured highest transmission rate of the RFQ agrees with the prediction of simulation codes
- Simulation result contributes to the beam commissioning
- Transmission degradation and frequency shift of the RFQ need to be physically explained
- Proton beam measurement continues (BPM/TOF, infrared camera for the beam profile on the target)
- Project aims at reaching its designed performance, stable operation, and providing the proton and neutron beams to the users


谢 谢!
Thank you for your attention!