Institute of High Energy Physics

Beam Dynamics and Beam Commissioning of 10 MeV CW Proton Superconducting Linac Based on Spoke Cavities

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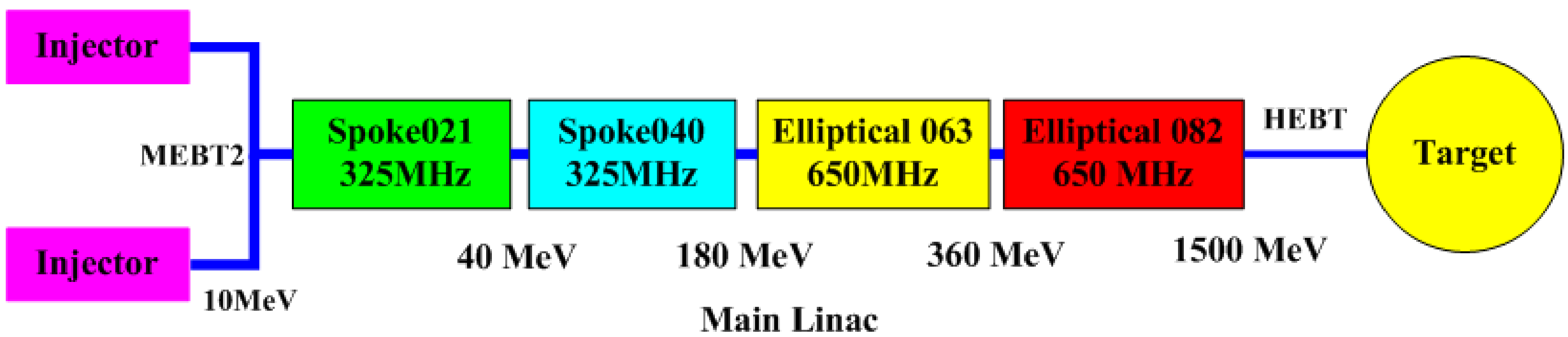
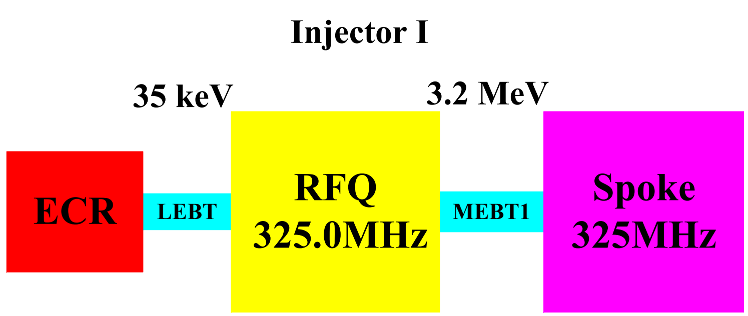
Outline

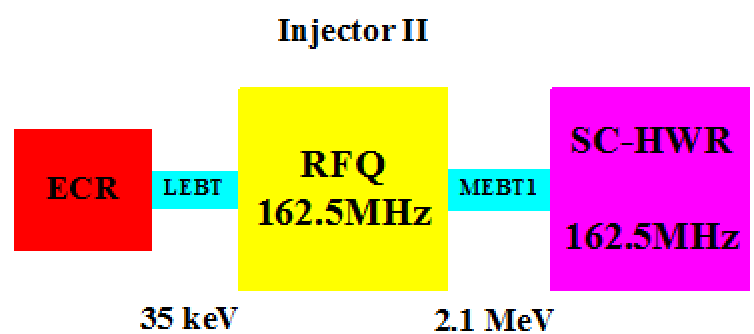
1. Introduction
2. Injector-I commissioning status
3. Injector-I beam performance
4. Beam loading effect
5. Summary

1. Introduction

Schematic figure of ADS driver linac

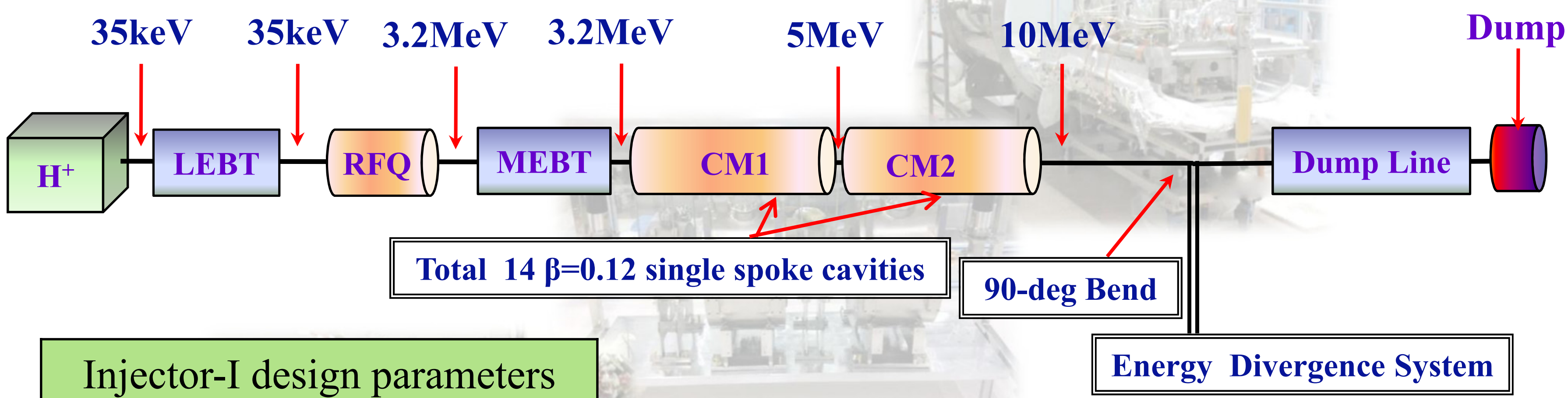






1. Introduction

The layout and specifications of ADS Injector-I testing facility



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

Injector-I consists of:

- ECR source providing with 35keV proton
- LEBT: including a chopping system
- 4-vane type copper structure RFQ: 3.2MeV
- MEBT
- SC section: including two cryomodules → **5**/10MeV
- Energy divergence system & beam dump line

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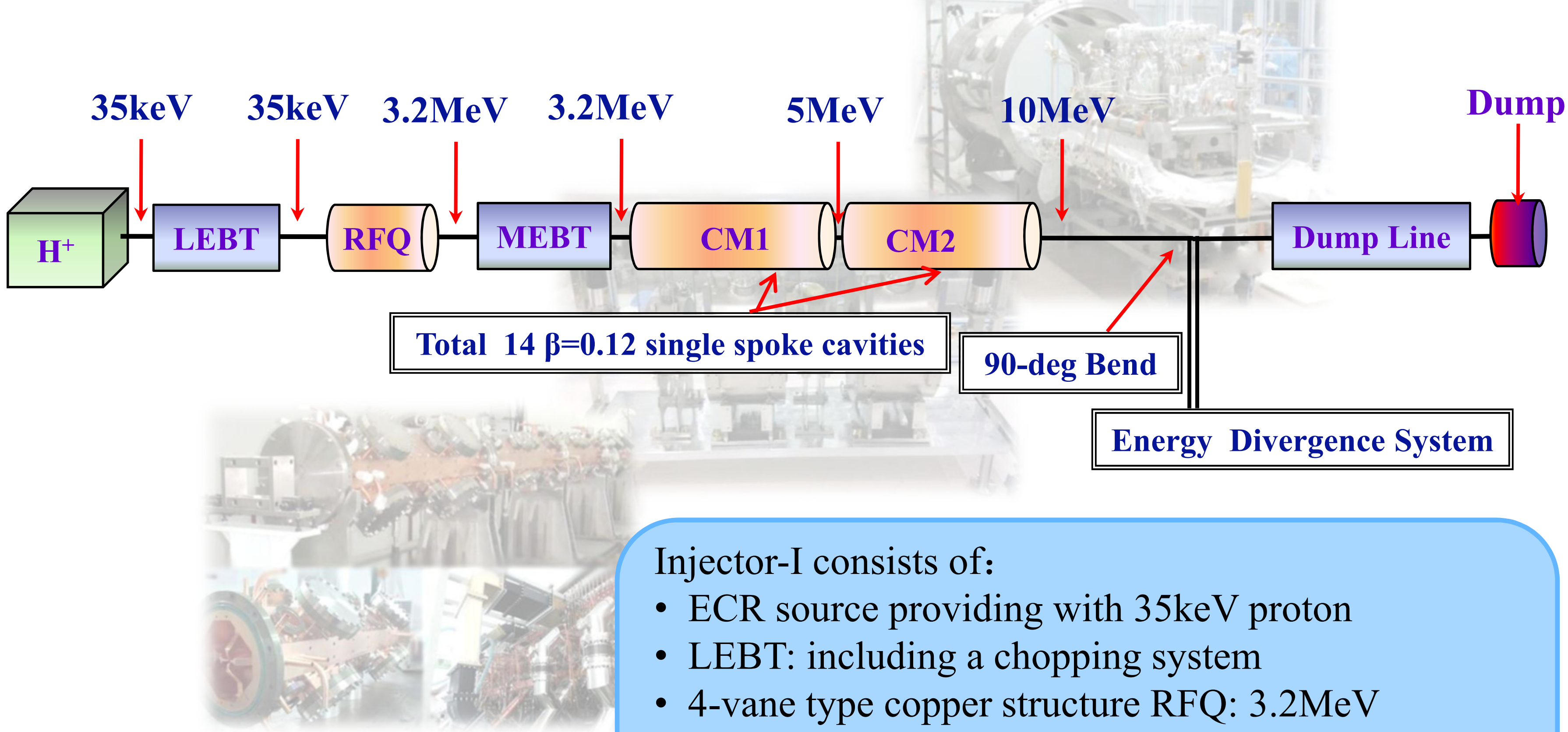

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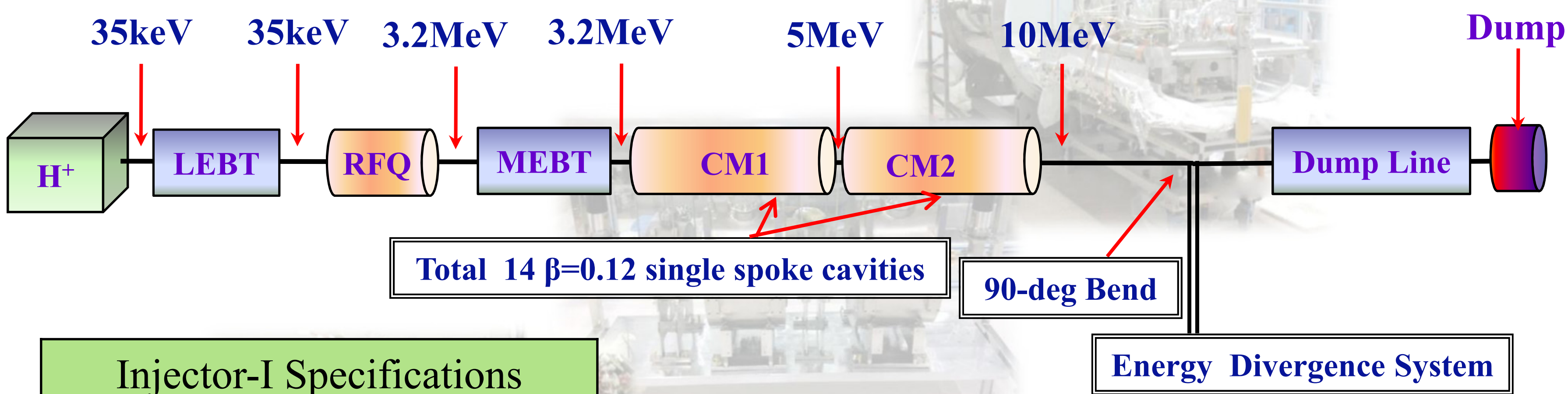

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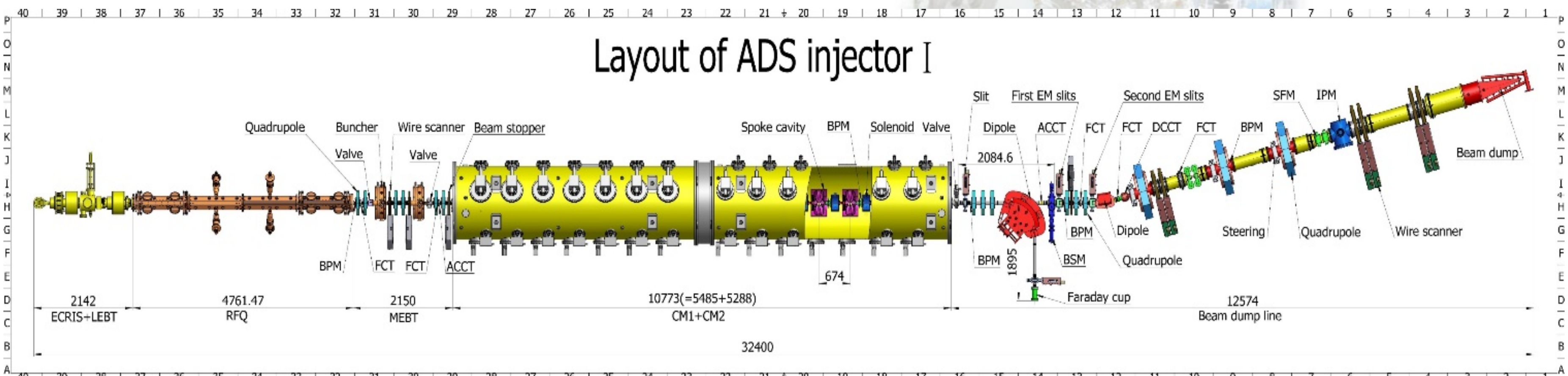


- **2011, Injector-I key components design completed, fabrication started.**
- **2012, manufacture of the key hardware finished.**
- **2013, testing of the key components completed & supporting facilities fabrication finished, integration began.**
- **2014~2016, periods commissioning according to the integration stages.**

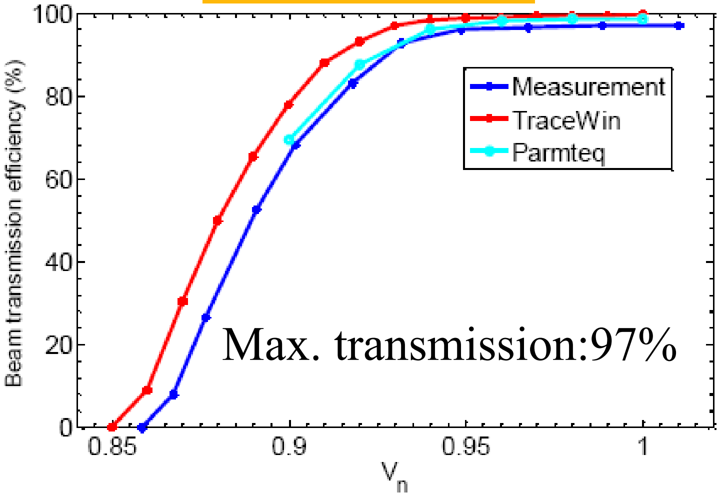
2. Injector-I commissioning status ➡ RFQ

325 MHz RT high intensity RFQ

—Key technology of the CW injector-I

- **The max. beam transmission measured out of RFQ is 97% in pulse mode V.S. the designed beam transmission of 98.7%**
- **90% beam duty cycle: 90% beam transmission was obtained @20140925**
- ***Send through CW beam with average current of 1-2mA at the beginning of 2017!***

@20150715



@20140925

RFQ input current: 12.2mA;
Output current: 11.0 mA.

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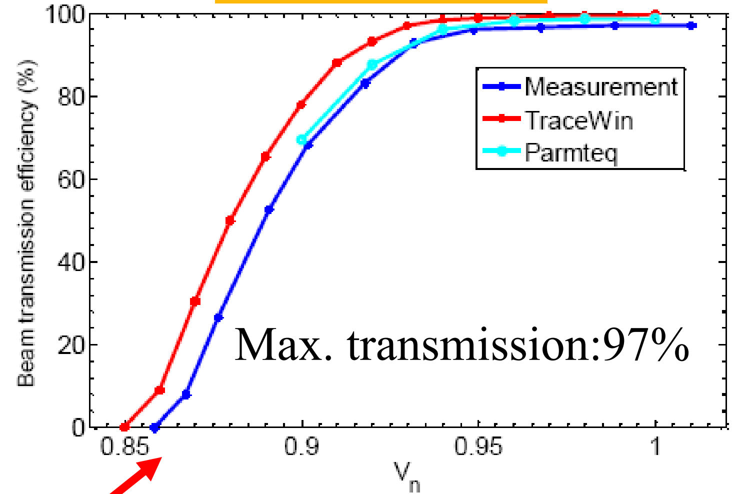

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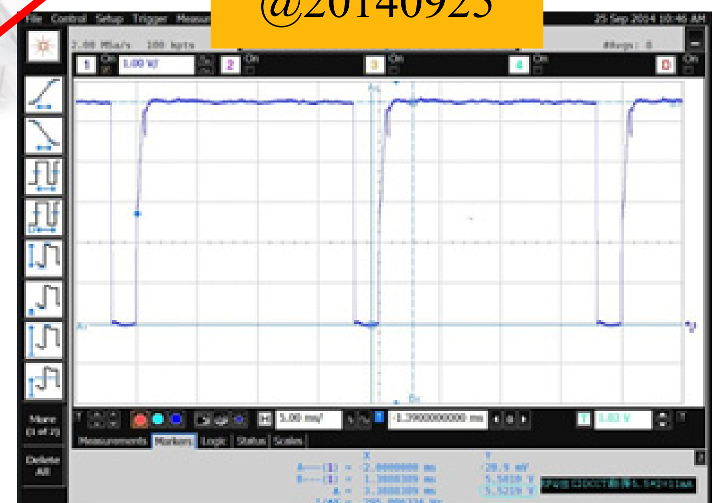

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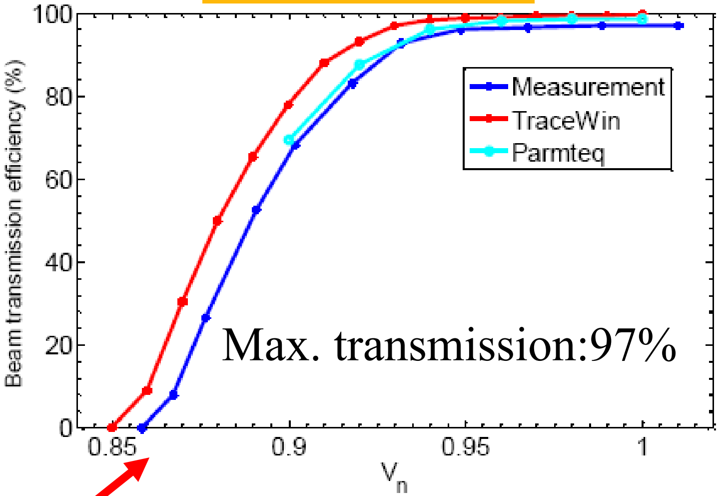

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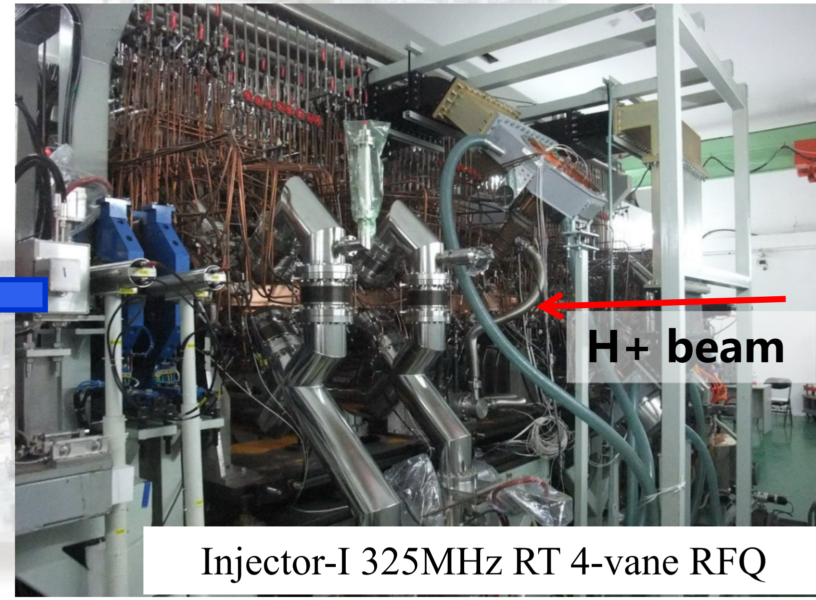
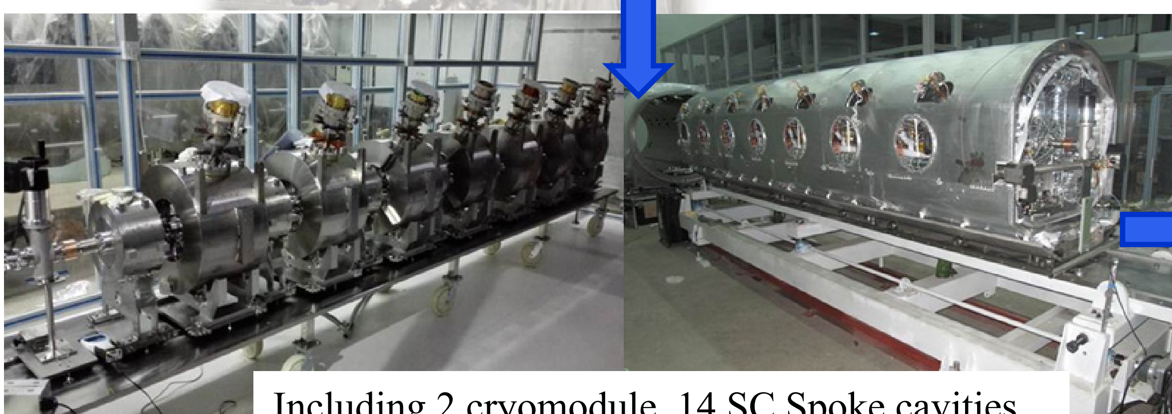
SC section tested by pulsed mode

Injector-I SC section in the tunnel



Injector-I 325MHz RT 4-vane RFQ



Including 2 cryomodule, 14 SC Spoke cavities

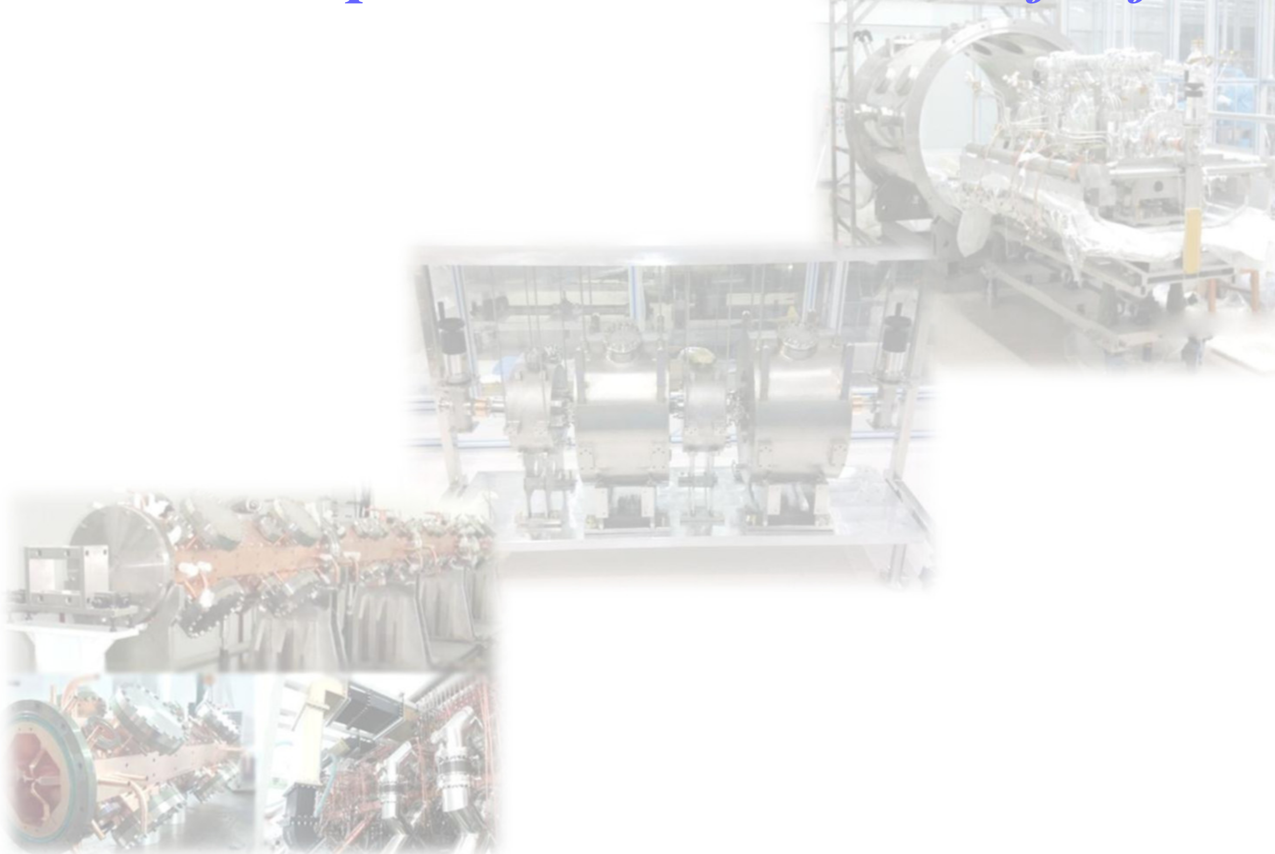
Obtained @ 2016.7.19:
- 10.67MeV
- 10.6mA

Pulsed beam

中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

Tested by CW beam

Obtained 1-2mA CW proton beam at the end of Injector-I SC linac



2. Injector-I commissioning status → SC section

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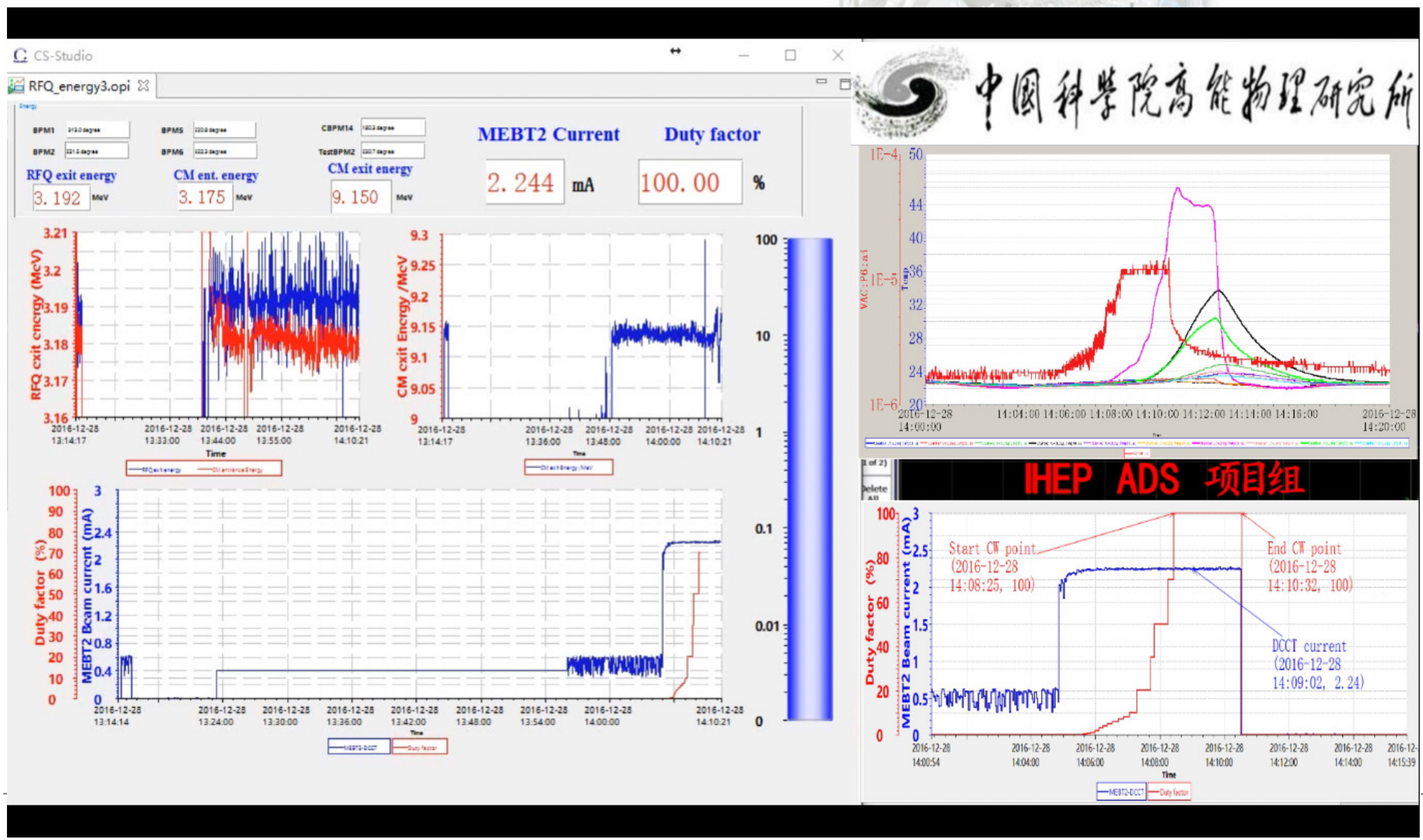

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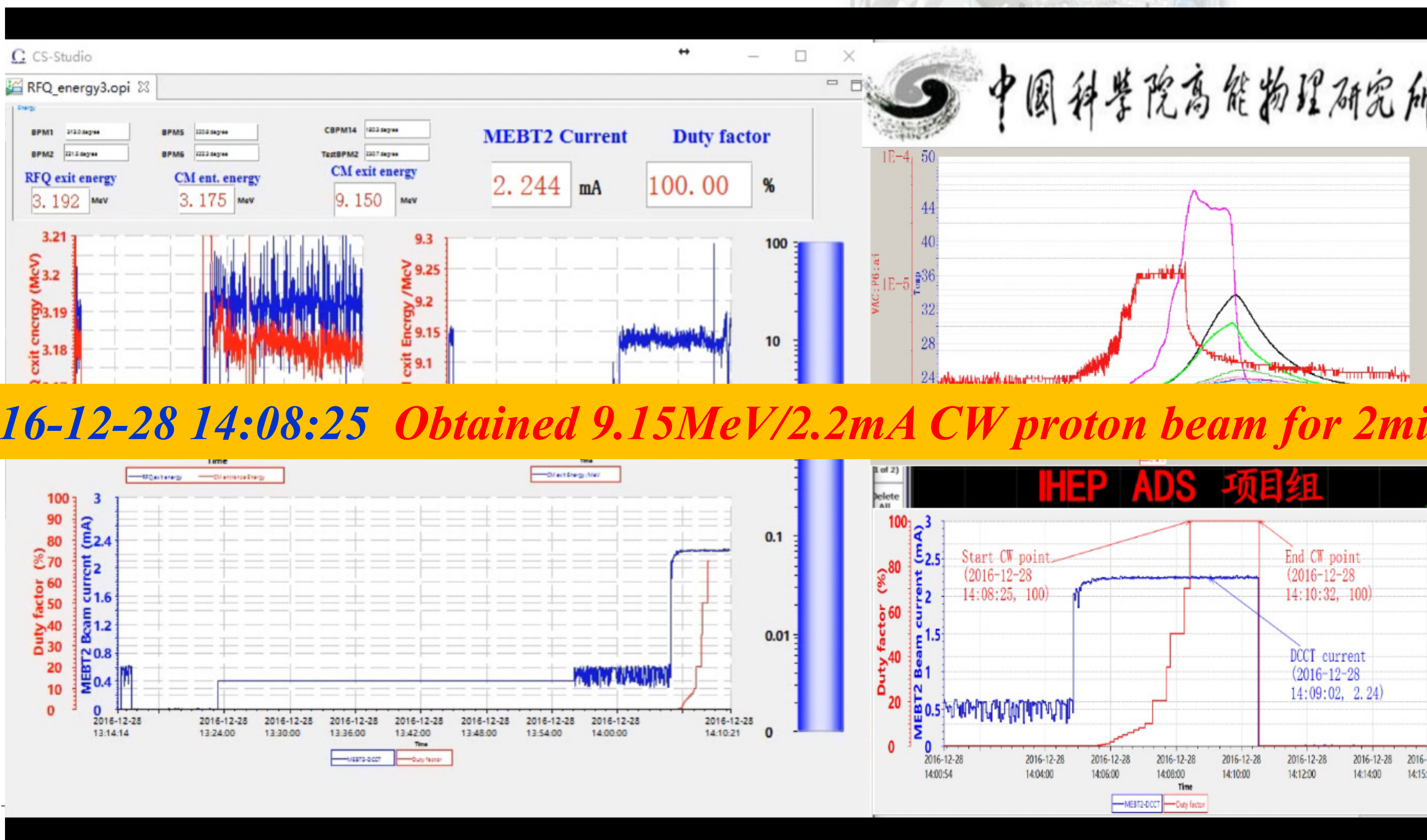
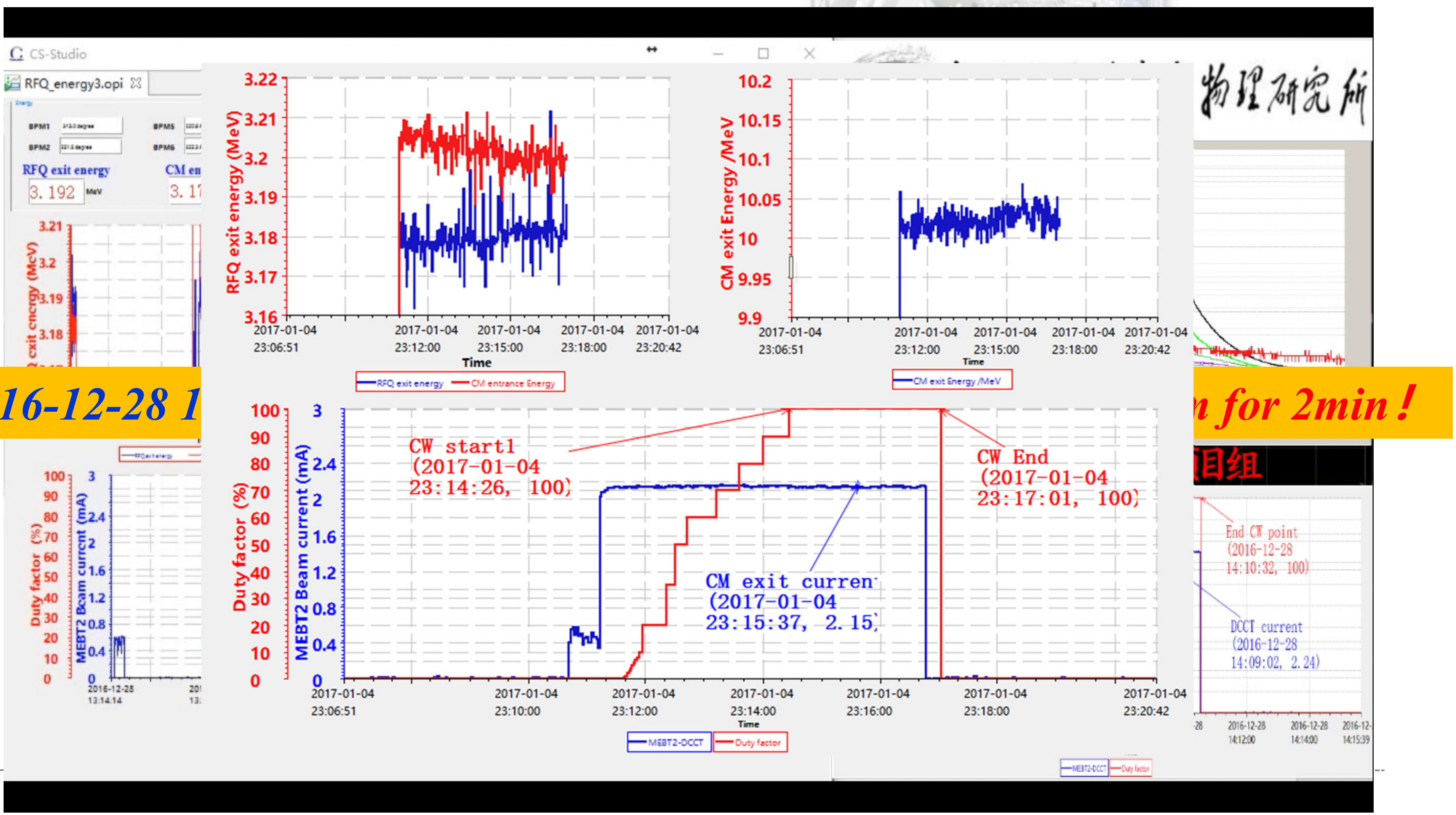


2016-12-28 14:08:25 ***Obtained 9.15MeV/2.2mA CW proton beam for 2min!***

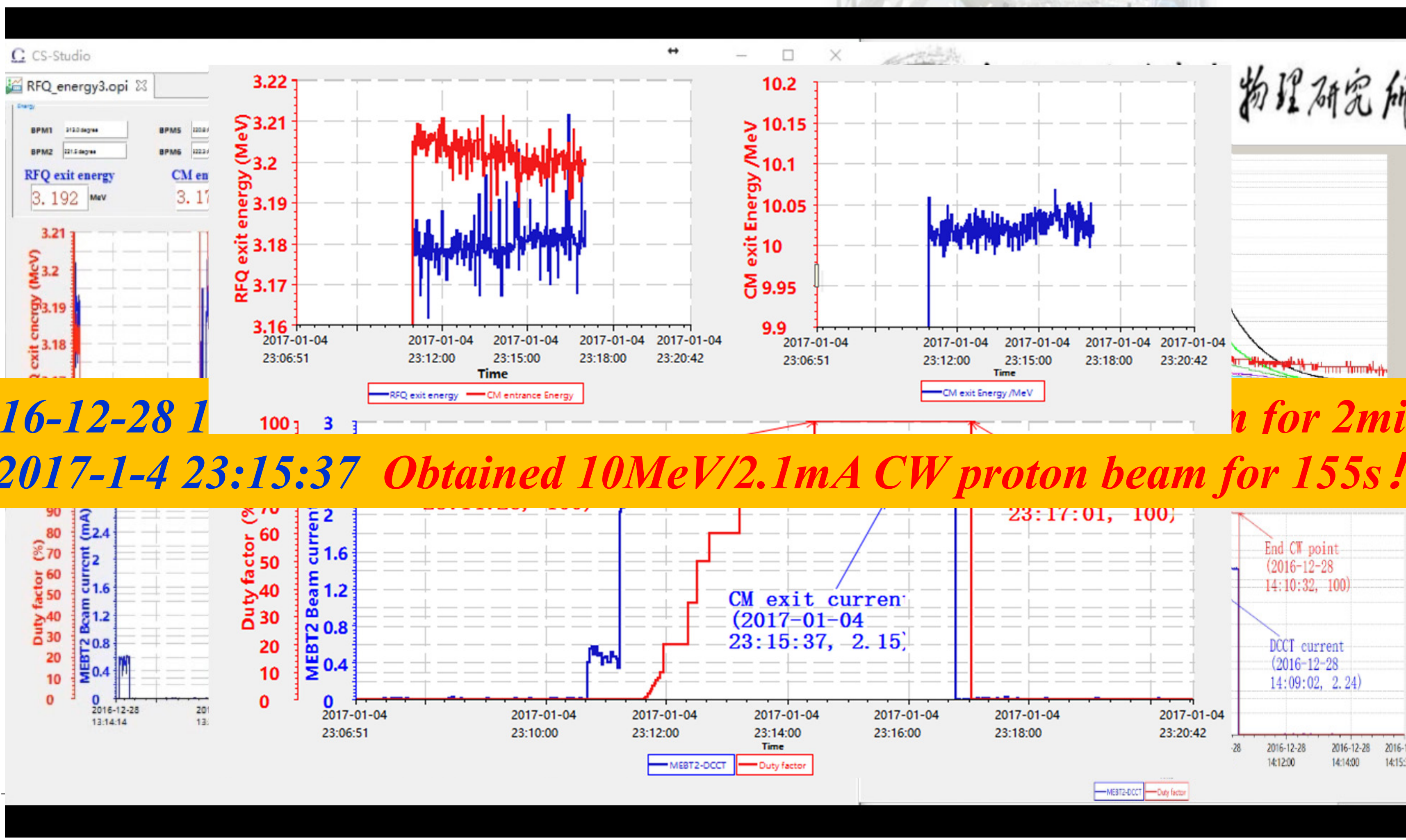
Tested by CW beam

Obtained 1-2mA CW proton beam at the end of Injector-I SC linac



Tested by CW beam

Obtained 1-2mA CW proton beam at the end of Injector-I SC linac



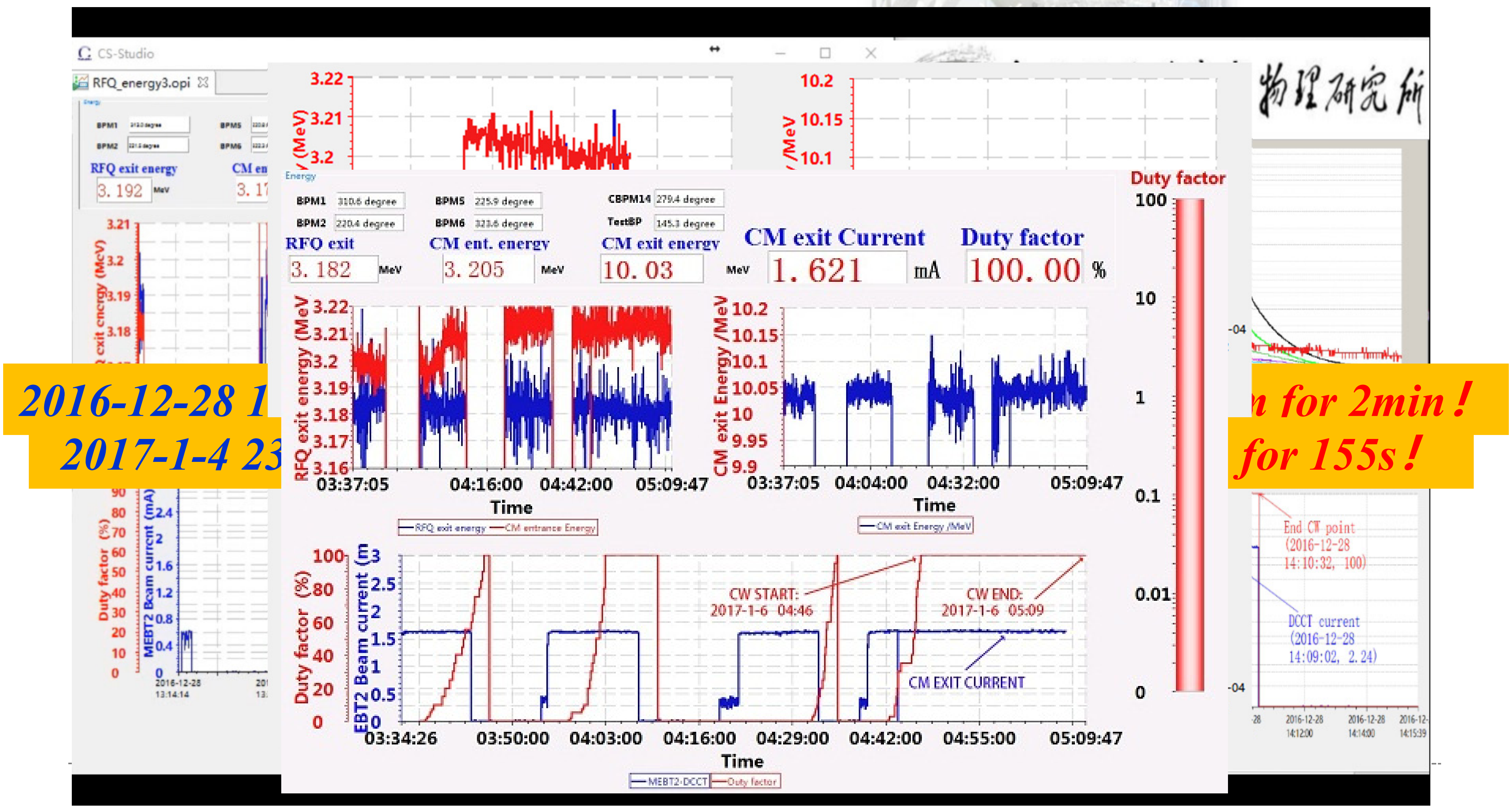
2016-12-28 1 ... n for 2min!

2017-1-4 23:15:37 Obtained 10MeV/2.1mA CW proton beam for 155s!

2. Injector-I commissioning status → SC section

Tested by CW beam

Obtained 1-2mA CW proton beam at the end of Injector-I SC linac



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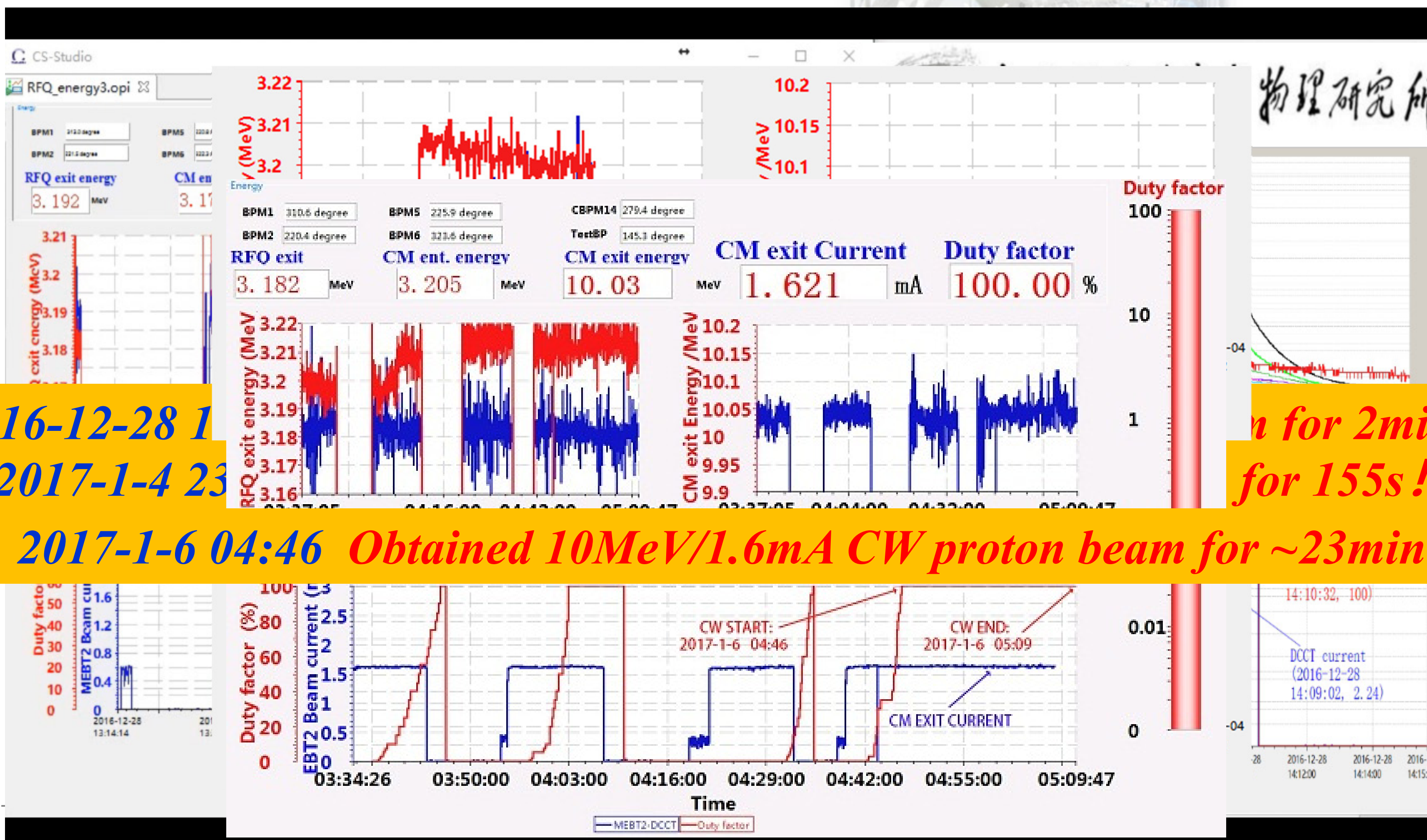
Obtained 1-2mA CW proton beam at the end of Injector-I SC linac



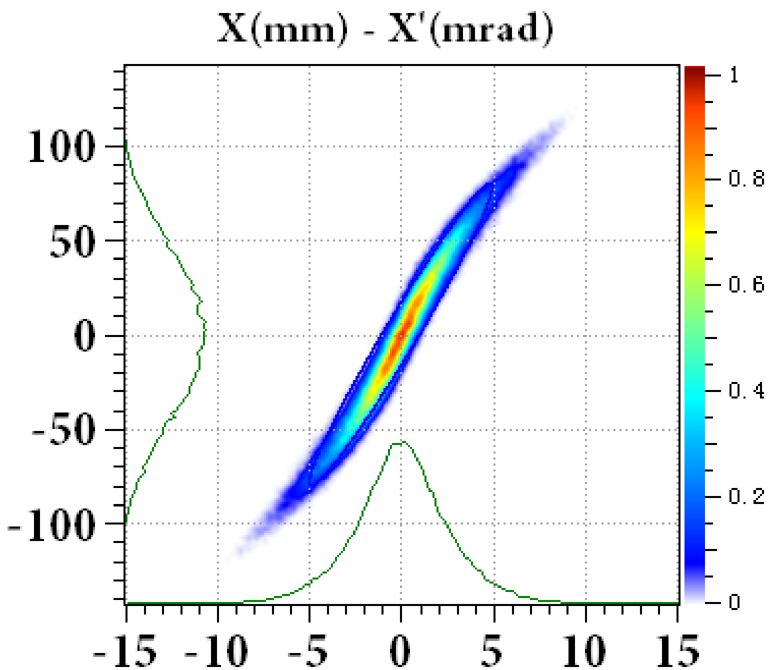
2016-12-28 1… …n for 2min!

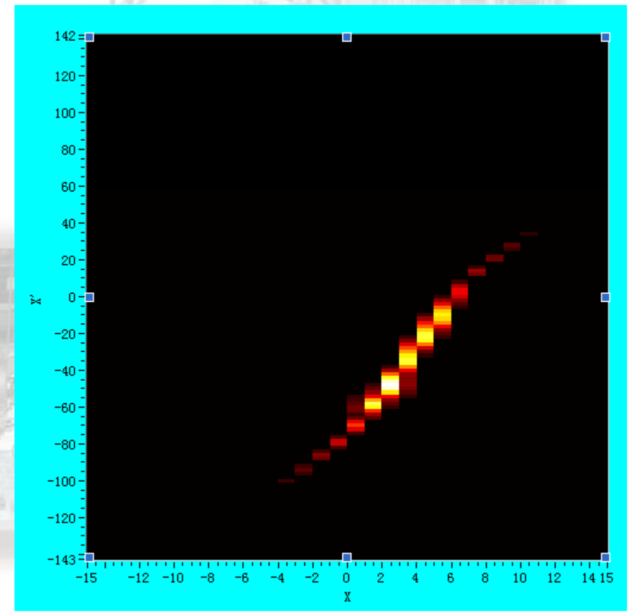
2017-1-4 23… for 155s!

2017-1-6 04:46 Obtained 10MeV/1.6mA CW proton beam for ~23min!

3. Injector-I beam performance → at the entrance of RFQ

- **Beam phase space at the measured location (8.8cm drift downstream the LEBT exit): left for simulation and right for measurement.**





Beam performance at the LEBT exit

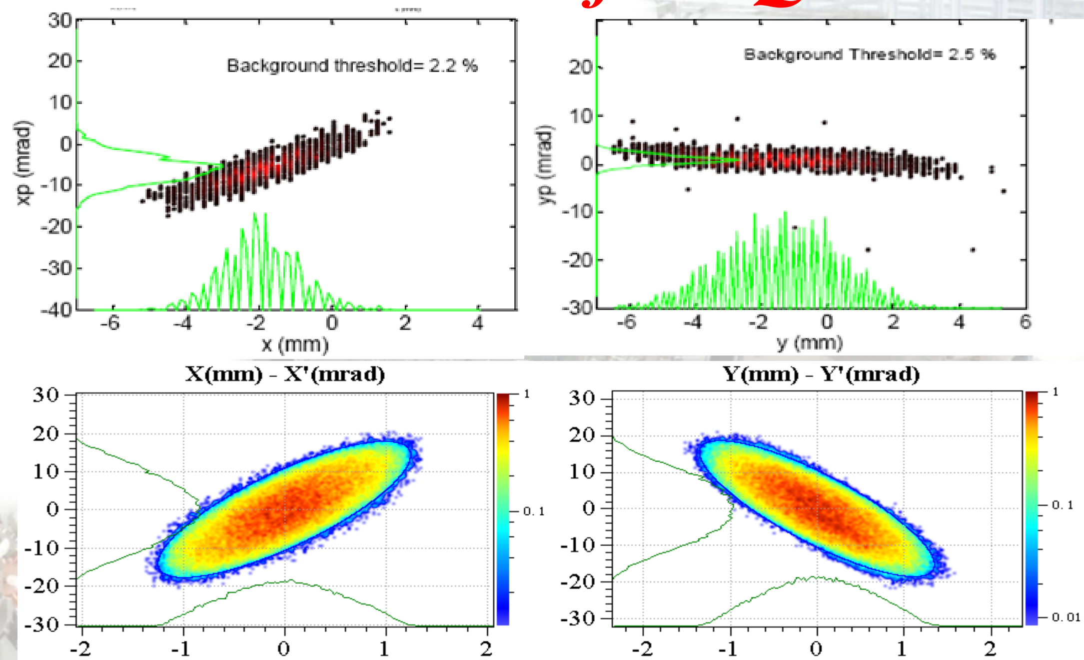
Parameters	I_{beam} (mA)	α	β (mm/mrad)	$E_{n, ms}$ (π mm.mrad)
Design goal	10	2.41	0.0771	<0.20
Measurement (backward deduced from the measured location)	11.5	2.18	0.0774	0.14

Alison detector: 5% background

Emittance measurement results V.S simulation at the exit of RFQ

Measured

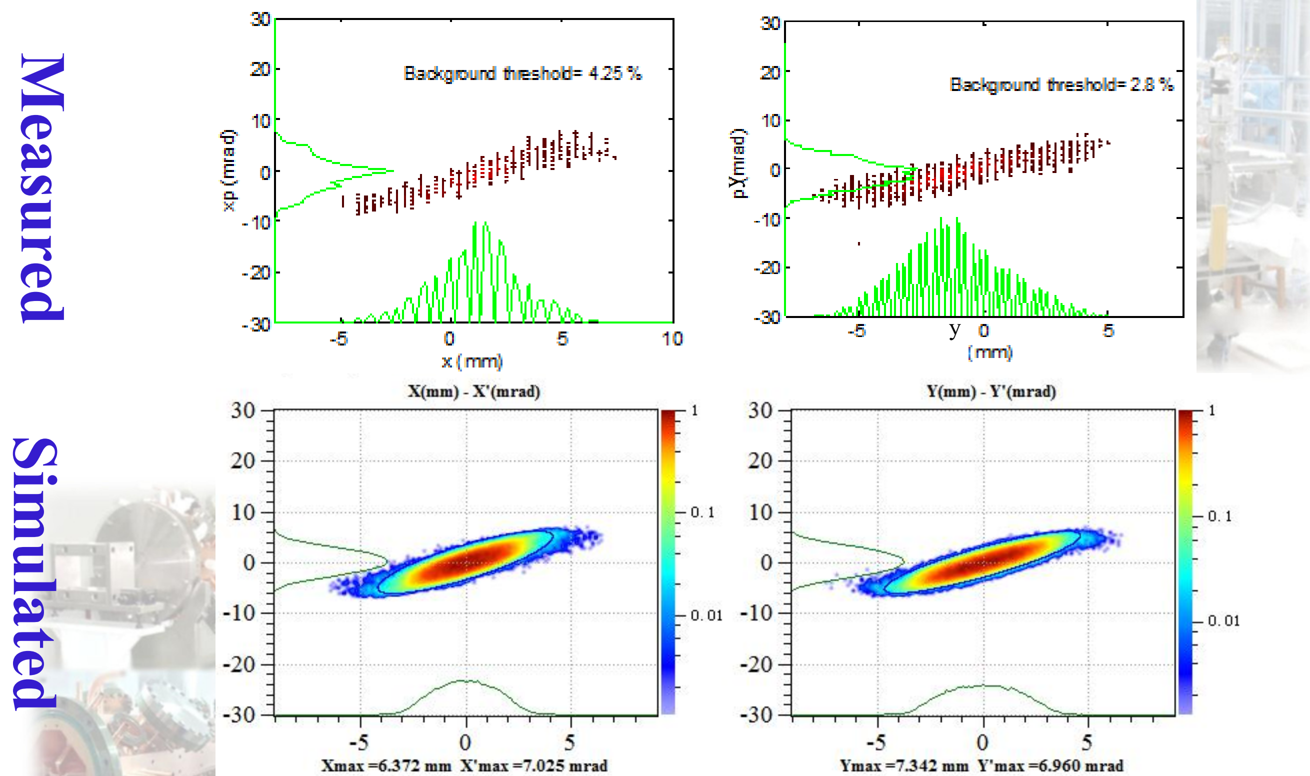
Simulated



Beam performance at the MEBT entrance

Parameters		αx/αy	βx/ βy (mm/mrad)	$E_{n,rms,x/y}$ (π mm.mrad)
Simulation results		-1.3/1.46	0.12/0.13	0.21/0.20
RFQ exit (backward deduced from the measured location)	Quad. Scan with MATRIX	-1.09/2.15	0.12/0.19	0.19/0.27
	Quad. Scan with MOGA	-1.27/1.10	0.16/0.10	0.16/0.24
	Double slits	-1.78/0.65	0.46/1.85	0.14/0.14

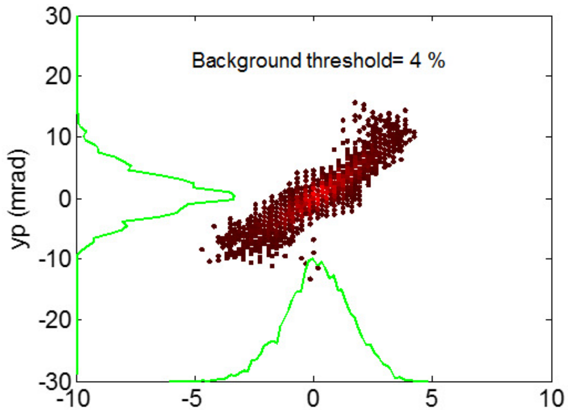
Emittance measurement results V.S simulation at the exit of CM1 with nominal design (@5MeV)



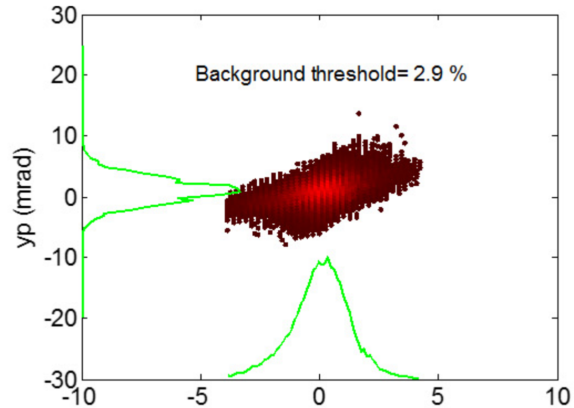
Parameters	αx/αy	βx/ βy (mm/mrad)	$E_{n,rms,x/y}$ (π mm.mrad)
The RFQ exit para. used for simulations are set by meas. results of Quad. Scan with 30% long. mismatch at RFQ exit	-1.44/-1.75	1.18/1.53	0.22/0.21
Measurement (Double slits)	-2.12/-1.97	1.56/1.81	0.29/0.27

Transverse Emittance measurement results

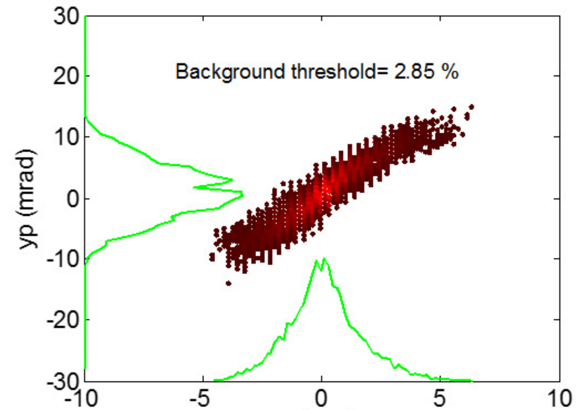
Phase advance ratio of 0.4



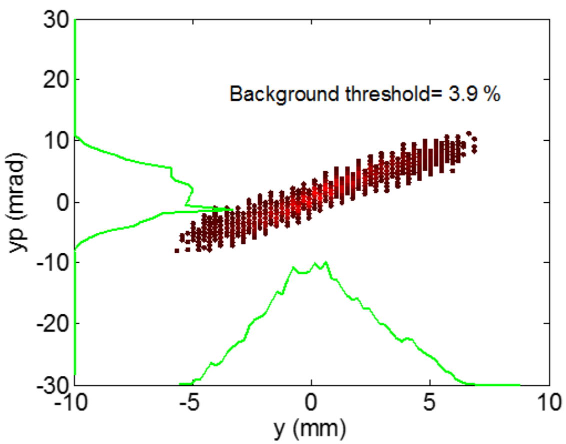
Phase advance ratio of 0.5



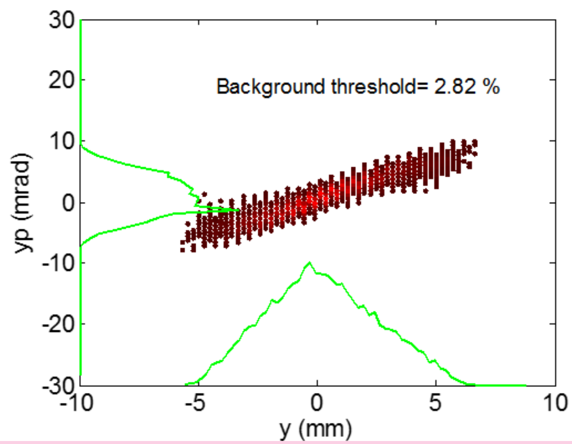
Phase advance ratio of 0.6



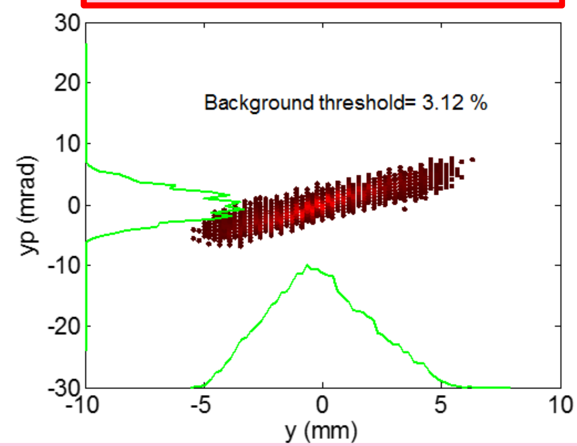
Phase advance ratio of 0.7



Phase advance ratio of 0.72

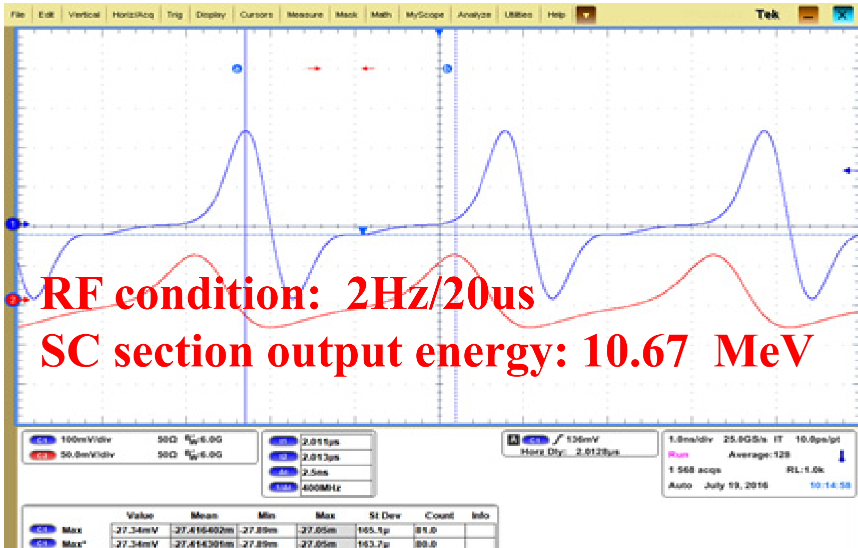


Nominal design



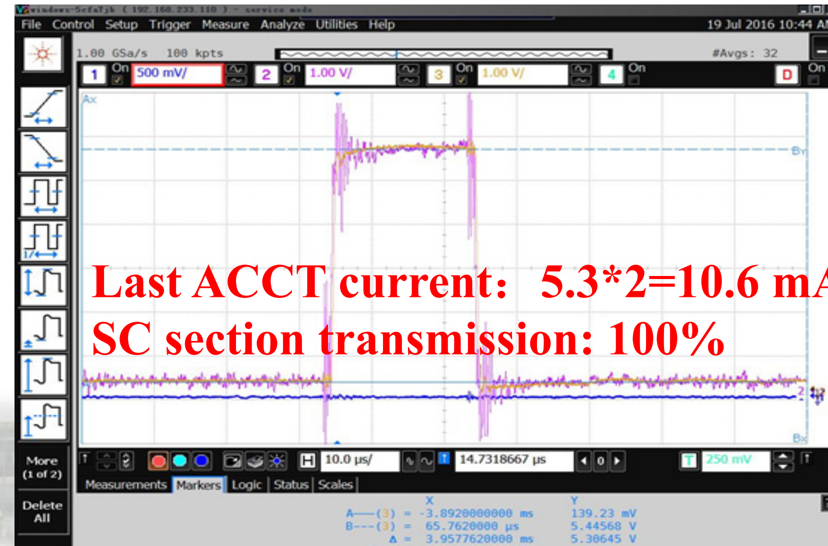
Change the solenoid fields while keep the longitudinal setting to be the same

3. Injector-I beam performance → energy divergence



RF condition: 2Hz/20us

SC section output energy: 10.67 MeV



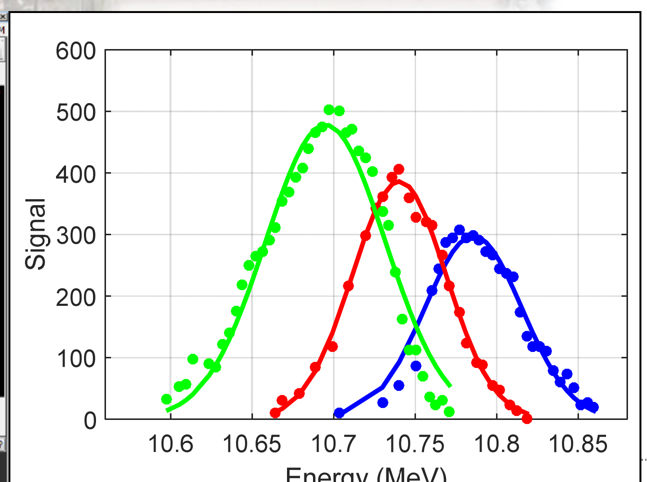
Last ACCT current: 5.3*2=10.6 mA

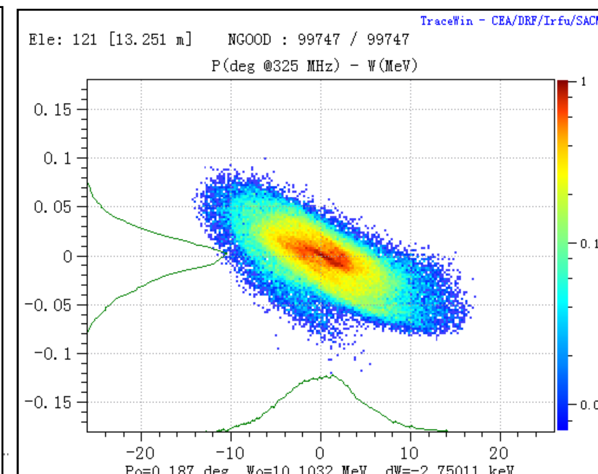
SC section transmission: 100%

Energy divergence results @10.67MeV/10.6mA

Measurement results: 0.32% (RMS)

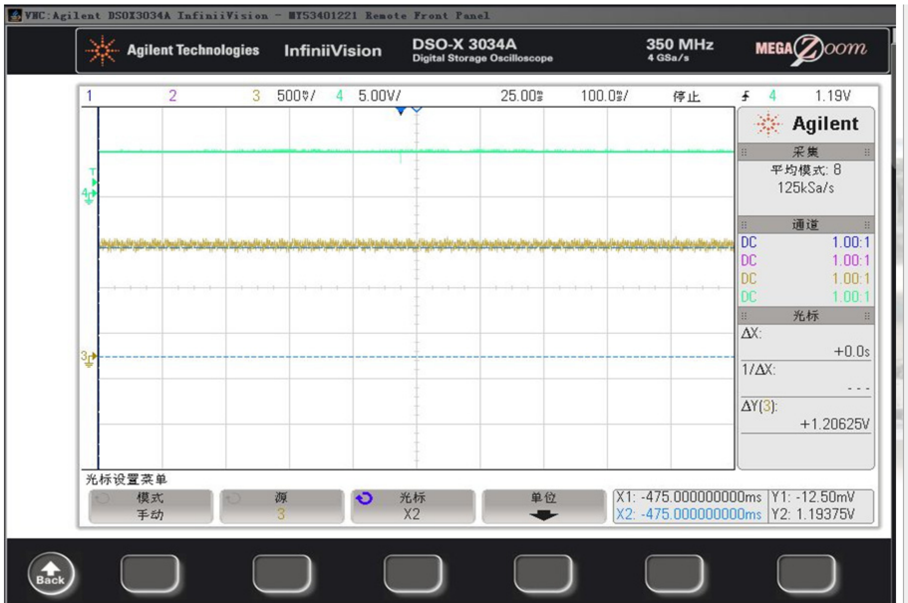
Beam dynamics results: 0.28% (RMS)



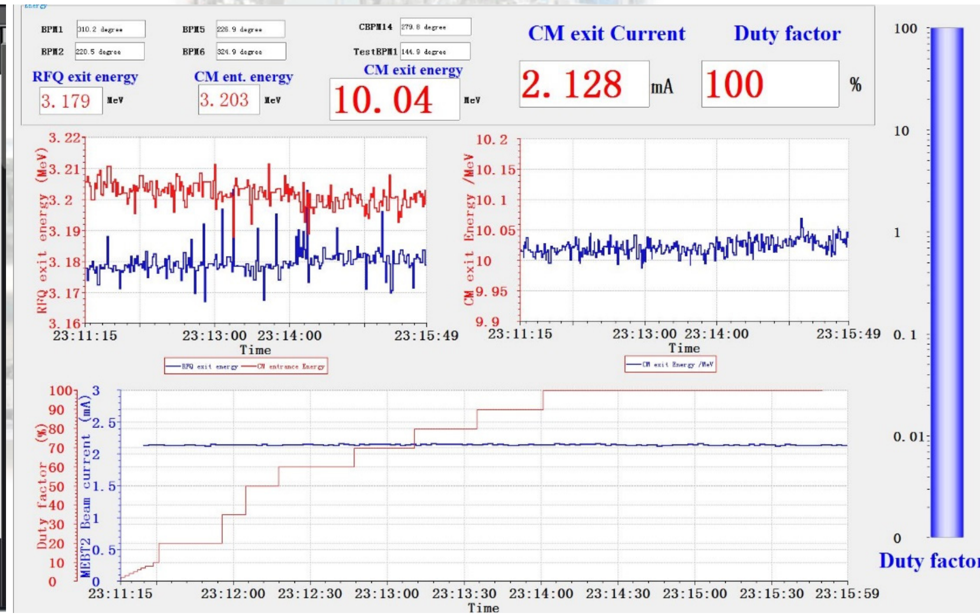


CW Beam transmission from LEBT to the exit of SC section

LEBT DCCT signal



DCCT at the exit



Transmission on CW operation @10MeV：

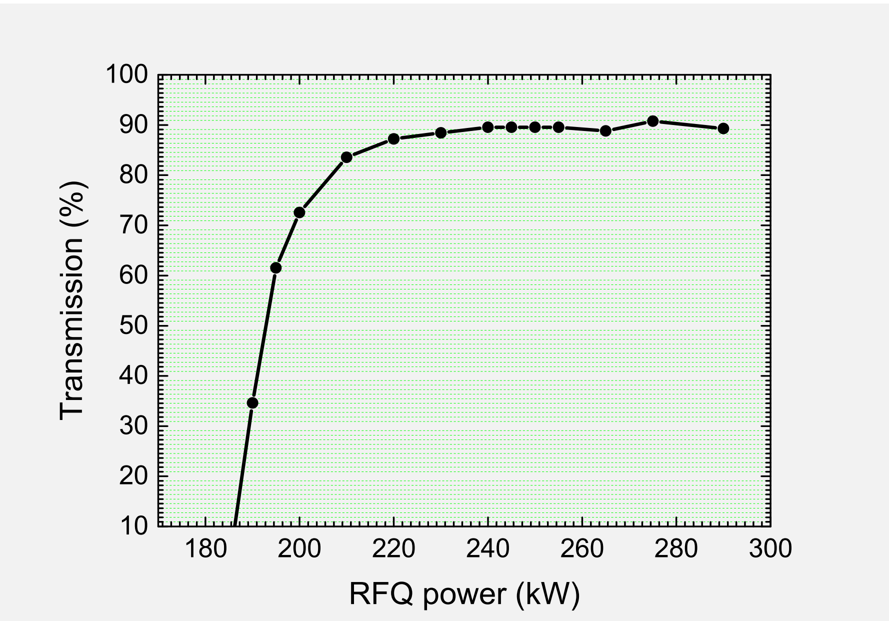
◆**DCCT signal on LEBT DCCT：1.206*2=2.412 mA**

◆**DCCT at the exit of SC section：2.128 mA**

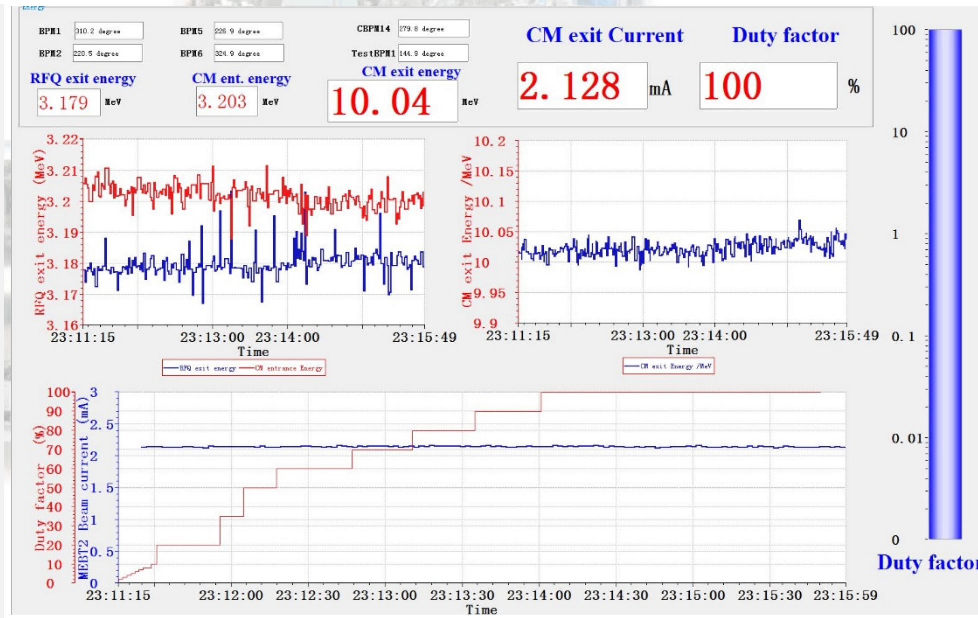
◆**Beam transmission from LEBT to the end of the linac: 2.128 / 2.412= 88.2%**

CW Beam transmission from LEBT to the exit of SC section

LEBT DCCT signal



DCCT at the exit



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Pursuing the final goal of ADS applications

- The pulsed mode commissioning results and preliminary CW commissioning results:
  - ✓ *Verified the basic beam lattice design;*
  - ✓ *Verified the possibility of using Spoke-type SC cavity (325MHz) with low entrance energy starting from 3.2MeV;*
- However we still have a long way to go for:
  - ✓ *Pursuing the final beam current goal of* ***10mA*** *average beam current operated on CW mode;*
  - ✓ *And most importantly, pursuing the stability goal for ADS applications;*
- The major obstacles for preventing raising the operated beam current:
  - ✓ *Beam loading effect of the SC cavities.*

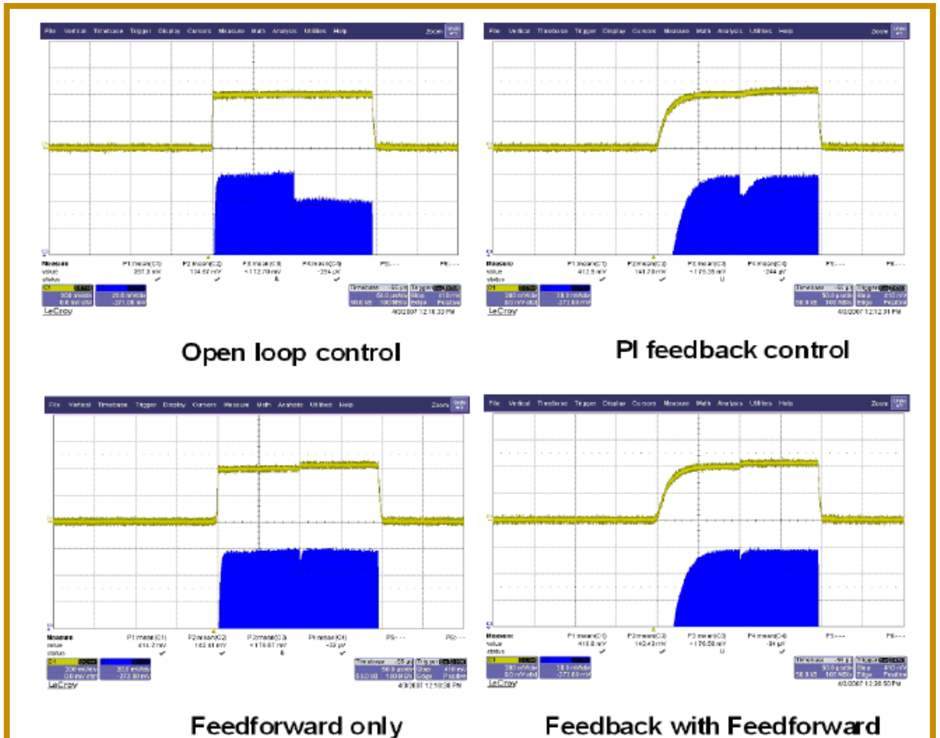
Operation Conditions

- Accelerator: 14 SC cavities; E_{in}: 3.2 MeV, E_{out}: 10MeV;
- V_c=300~650kV;
- Synchronous phase: -35º~-25º;
- Q_e: 7e5~9e5;
- Q_0=2~4e10;
- Cavity coupling factor: β=3e4~6e4;
- Cavity filling time: $T_f=2Q_L/w_0$~700μs;
- Passage time between bunches: T_b=1/f=3ns;
- ***These are the parameters of our SC cavities, and they are used to reproduce the cavity conditions and the transient beam loading effect of the beam.***

Transient beam loading of 20 μs pulsed beam @10mA

- *During the commissioning stage of Injector-I, the beam pulse spread of 20μs is used, amplitude Loop control (ALC) and phase loop control are applied.*

Comparison of various control schemes for PEFP proton linac



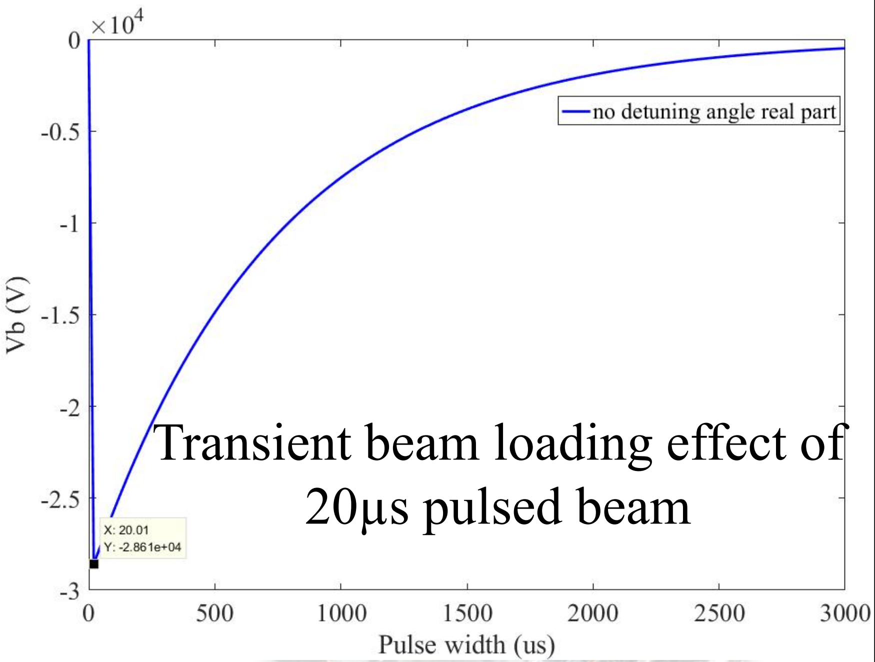
The yellow trace is forward rf power and the blue one is cavity field signal:

- The field recovery time after perturbation was about 3.1μs with feedforward and feedback control simultaneously;
- The field recovery time was about over 20μs for only feedback control.

* Courtesy of H. S. Kim, Beam loading effect and its compensation in the PEFP proton linac.

Transient beam loading of 20 μs pulsed beam @10mA

- *20 μs pulsed beam is used during the commissioning stage*
- *Amplitude Loop control (ALC) and phase loop control*



Transient beam loading effect of 20μs pulsed beam

- ➢ The amplitude and the syn. Phase of the beam is set by averaging the beam bunch of 20 μs;
- ➢ For simplify the problem, assume no detuning angle is set;
- ✓ The beam loading evolution is linear over the 20 μs beam bunch as shown in the left figure;
- ✓ Take the 1st cavity for example, the beam loading effect leading to :
  - amplitude variation of -7%~5%
  - phase variation of: -1.5º~2º.

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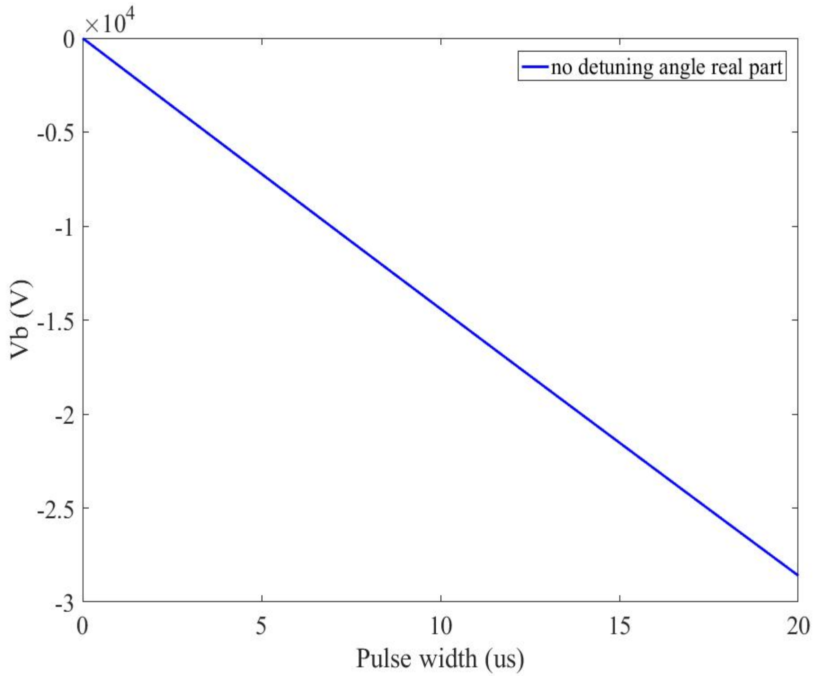

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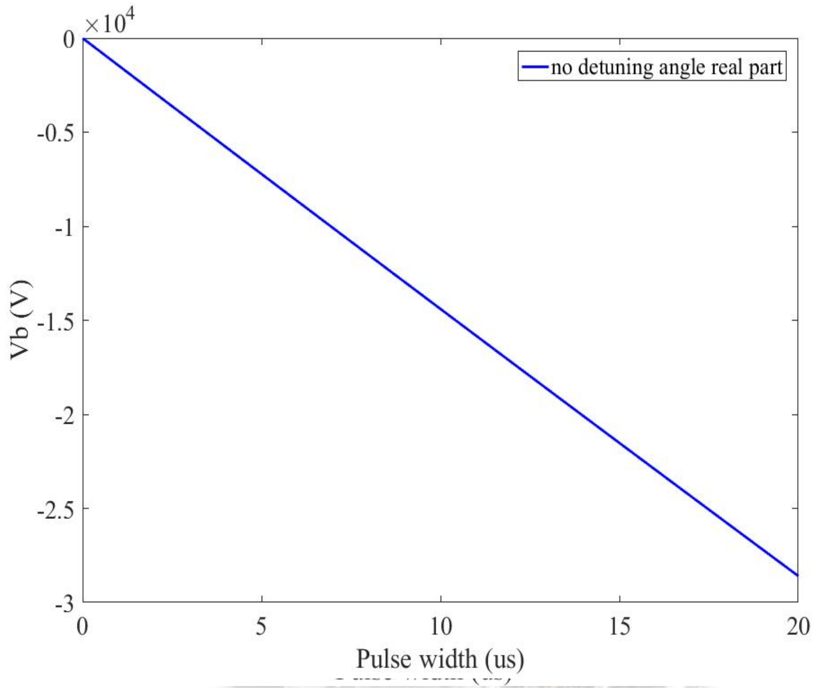

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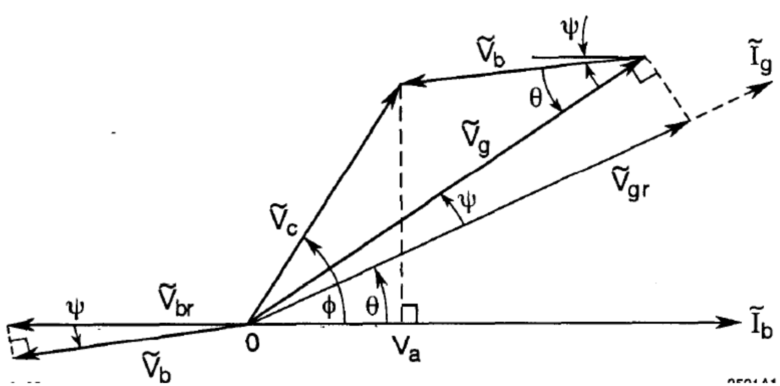
The smaller of operated voltage in the cavity, the worse of the amplitude and phase variation will be. Feedforward control is necessary to solve this problem.

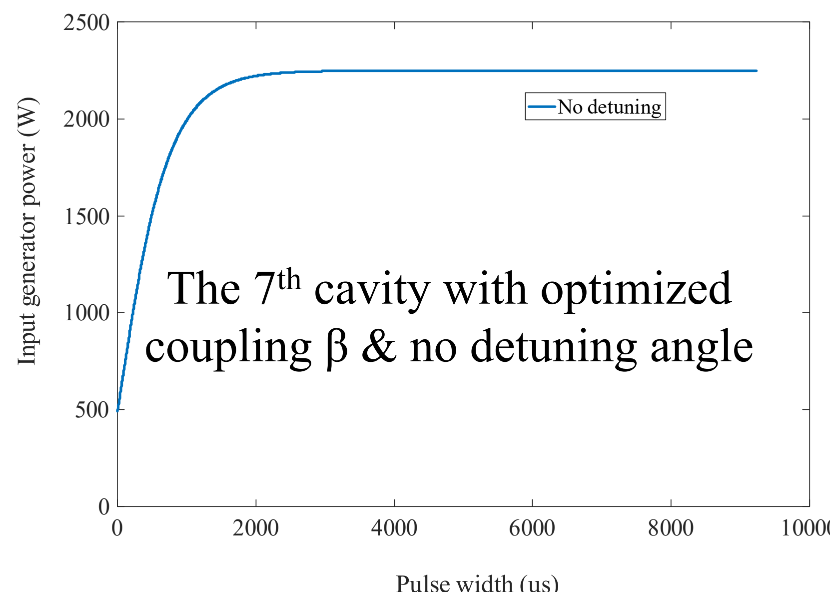
4. Beam loading effect ➡ Injector-I SC section

Transient beam loading @10mA

- *After 20 μs, the field is recovered with feedback and phase loop control, the cavity voltage (V_c) and Syn. Phase (ϕ) controlling are realized by variation of the generator power and angle (V_{gr} & θ);*
- *With the increasing of the beam loading effect along the bunches, the generator power has to be increased by 3 times more input power*



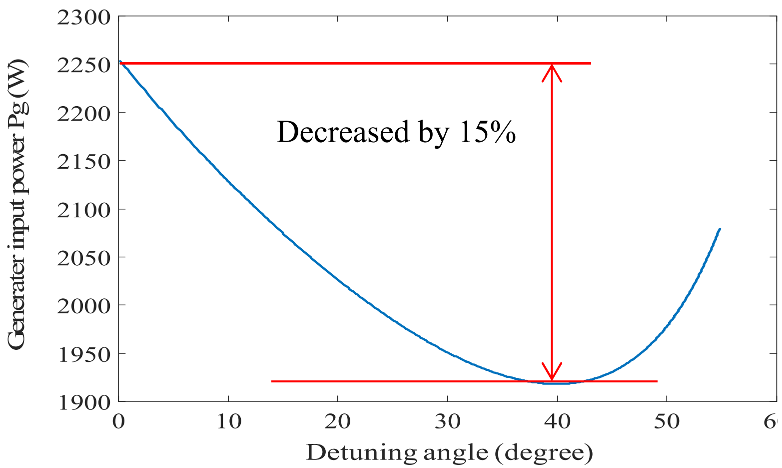
*Courtesy of P.B.Wilson, “fundamental mode rf design in e+ e- storage ring factory” , SLAC-PUB-6062, March, 1993.

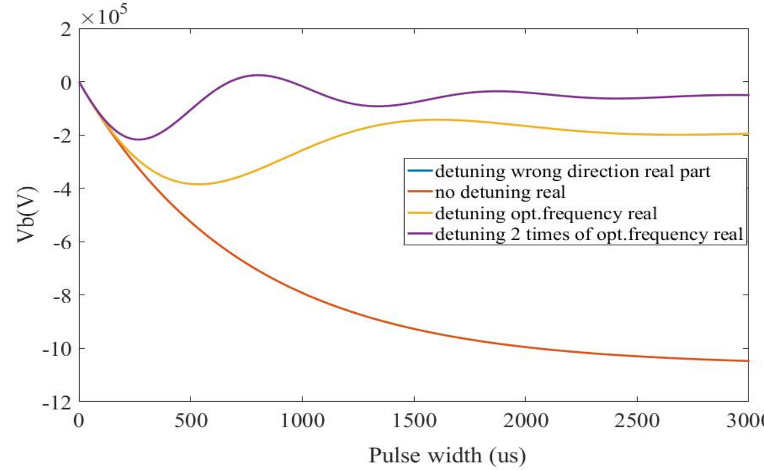


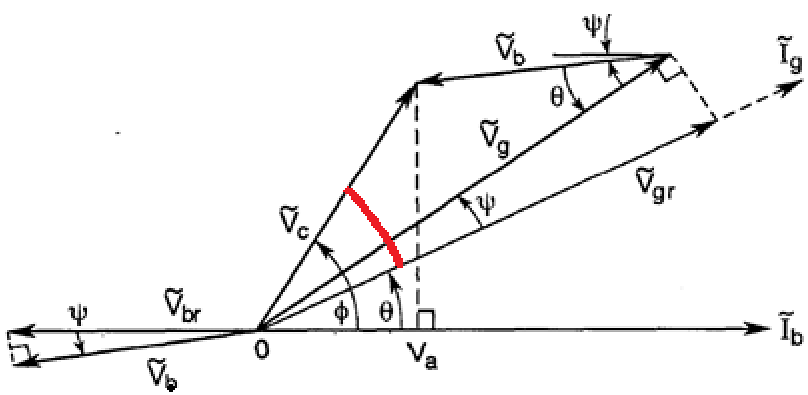
3. Beam loading effect ➡ Injector-I SC section

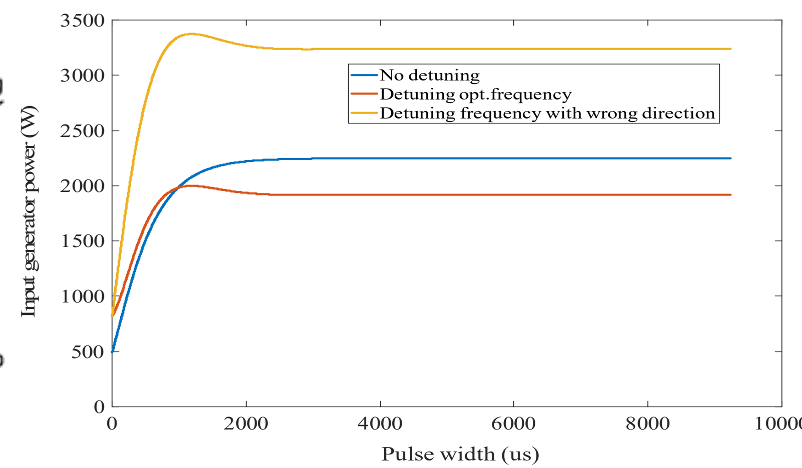
Transient beam loading @10mA

7th Cavity With Optimized Beta





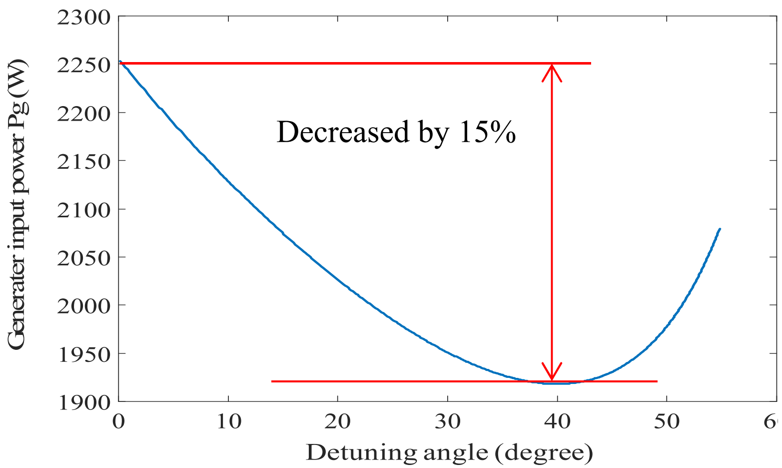


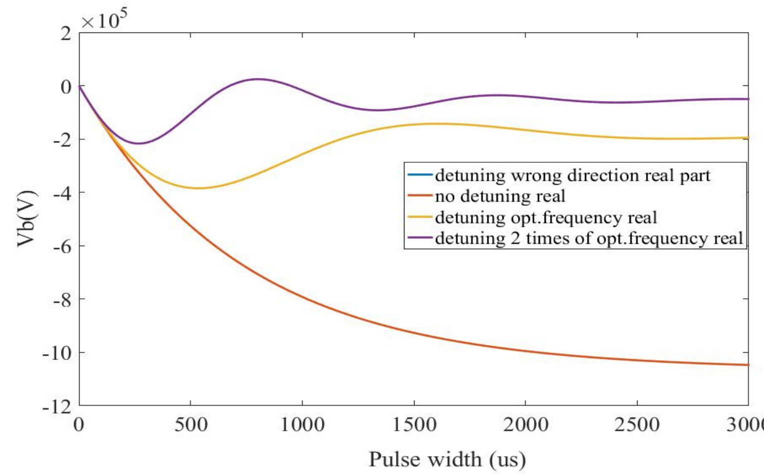


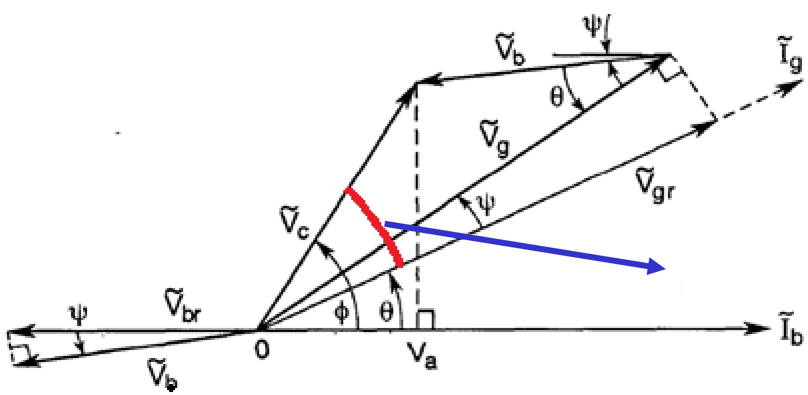
- *The frequency loop control is necessary to be added by adjusting the phase "Ω" to keep the cavity voltage and syn. Phase constant.*

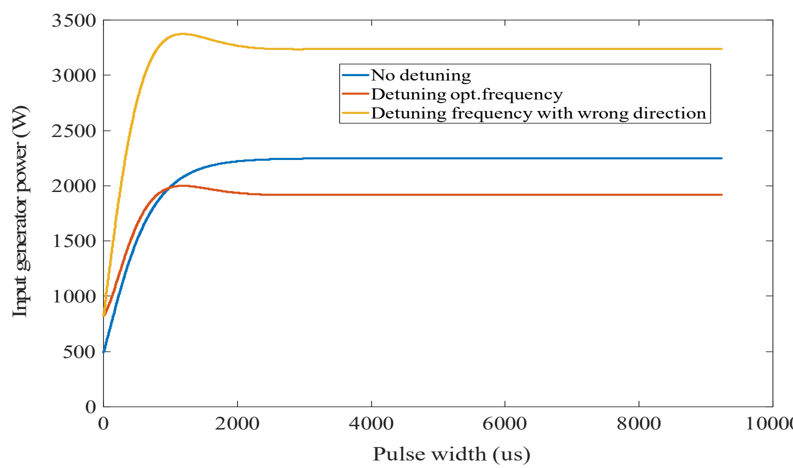
Transient beam loading @10mA

7th Cavity With Optimized Beta







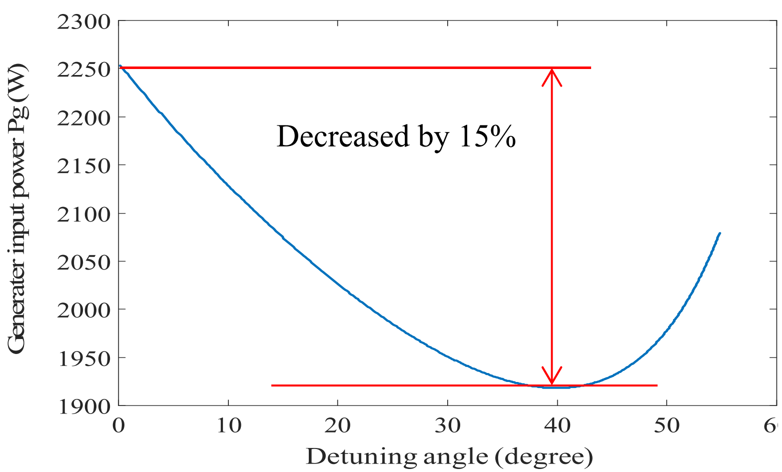


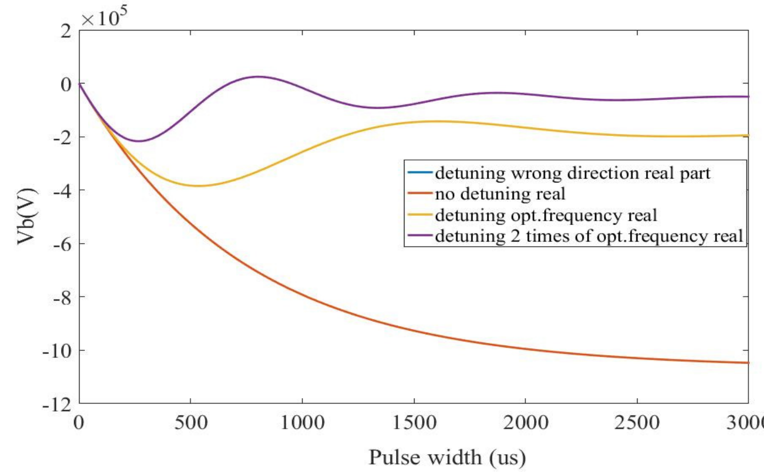
➢ *The frequency loop control is necessary to be added by adjusting the phase "Ω" to keep the cavity voltage and syn. Phase constant.*

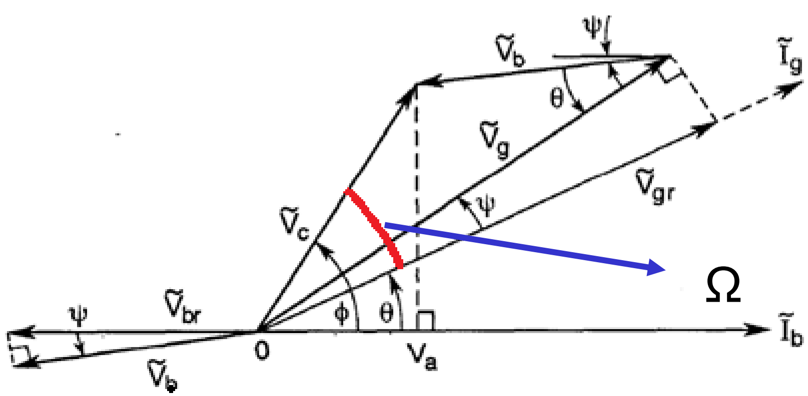
3. Beam loading effect ➡ Injector-I SC section

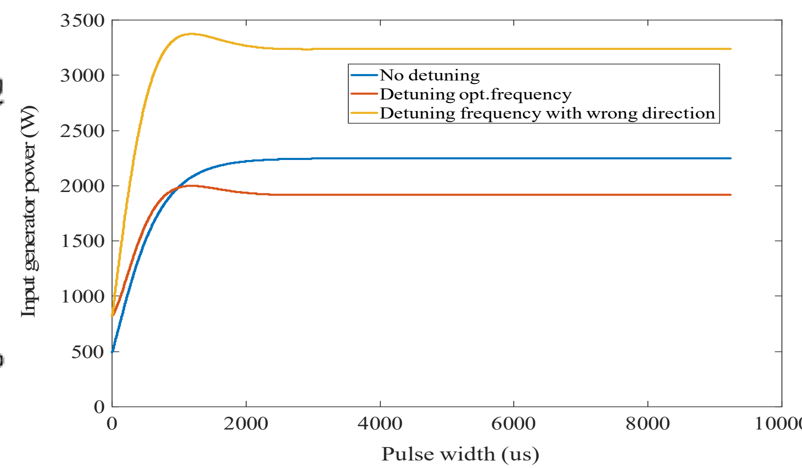
Transient beam loading @10mA

7^{th} Cavity With Optimized Beta







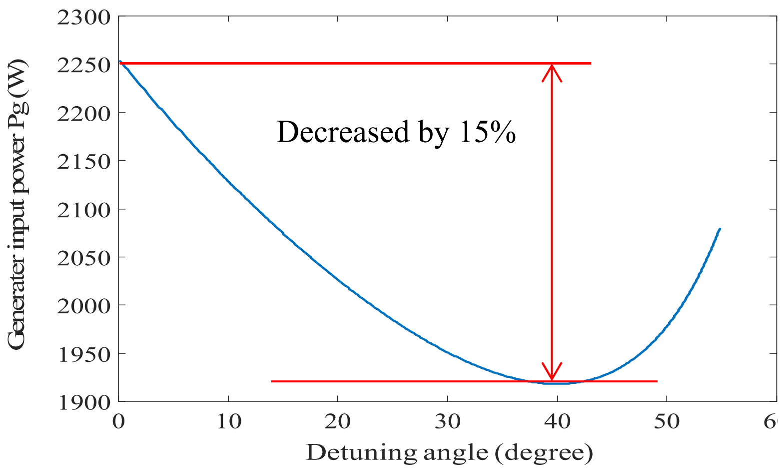


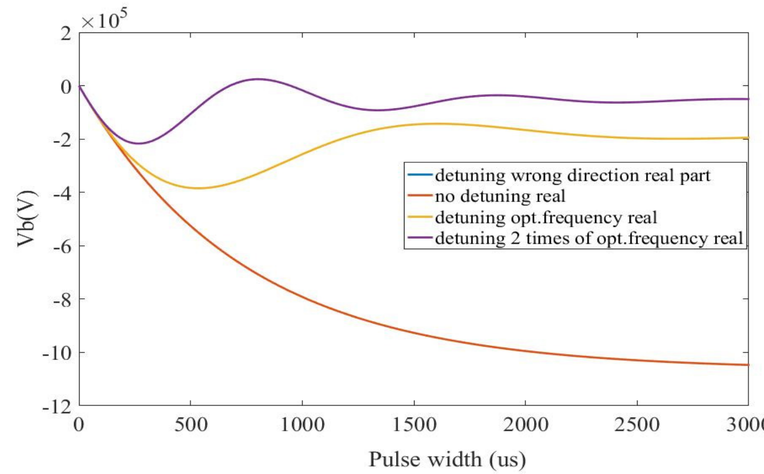
- *The frequency loop control is necessary to be added by adjusting the phase "Ω" to keep the cavity voltage and syn. Phase constant.*

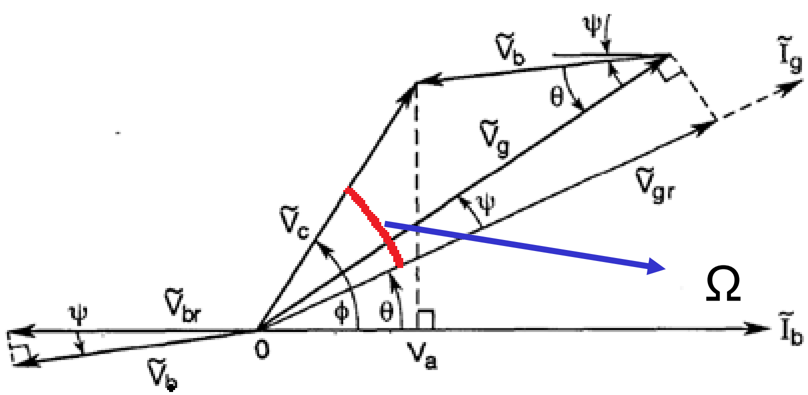
3. Beam loading effect ➡ Injector-I SC section

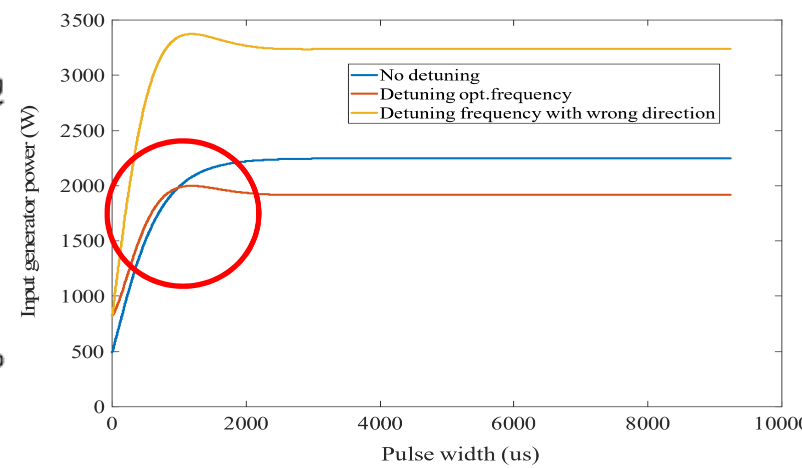
Transient beam loading @10mA

7th Cavity With Optimized Beta





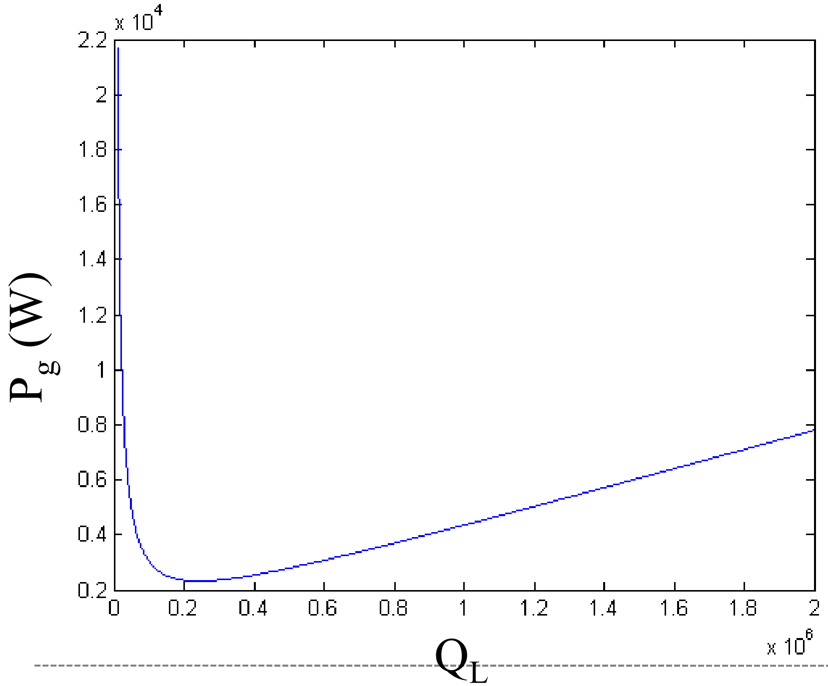


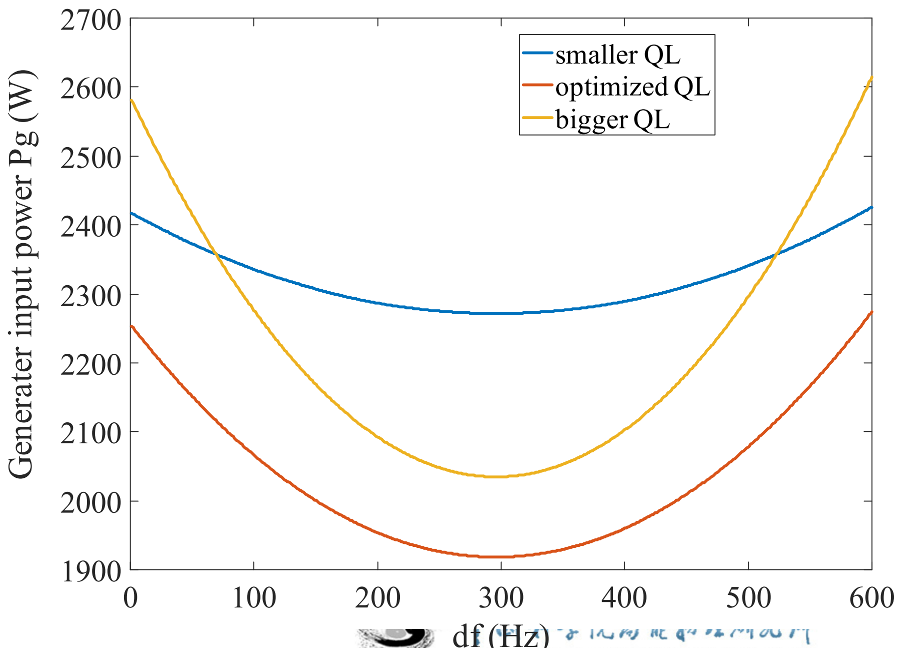


- *The frequency loop control is necessary to be added by adjusting the phase "Ω" to keep the cavity voltage and syn. Phase constant.*

Transient beam loading @10mA

- *For the cavities with* *not optimized coupling coefficient (β),* *more generator power are needed for establish required field in the cavities;*
- *But for cavities with bigger β / smaller Q_L, the cavity is less sensitive to the frequency change as it is benefit from bigger bandwidth (f/ Q_L) for this cavity.*

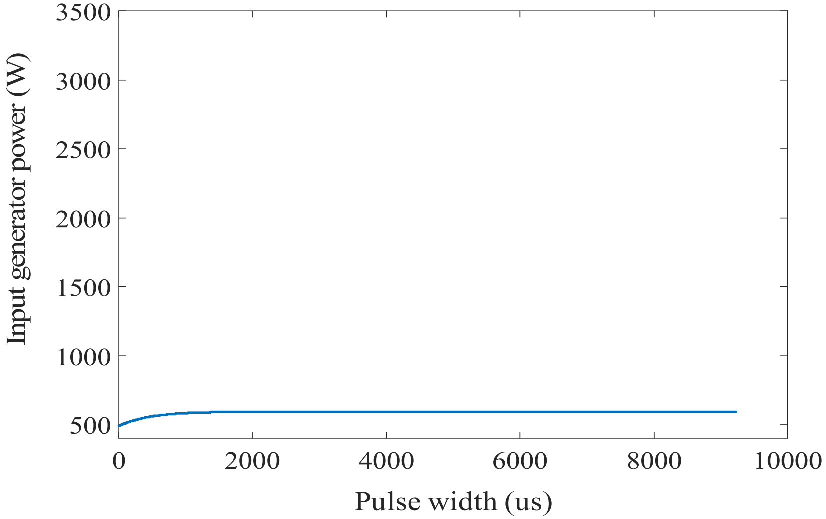


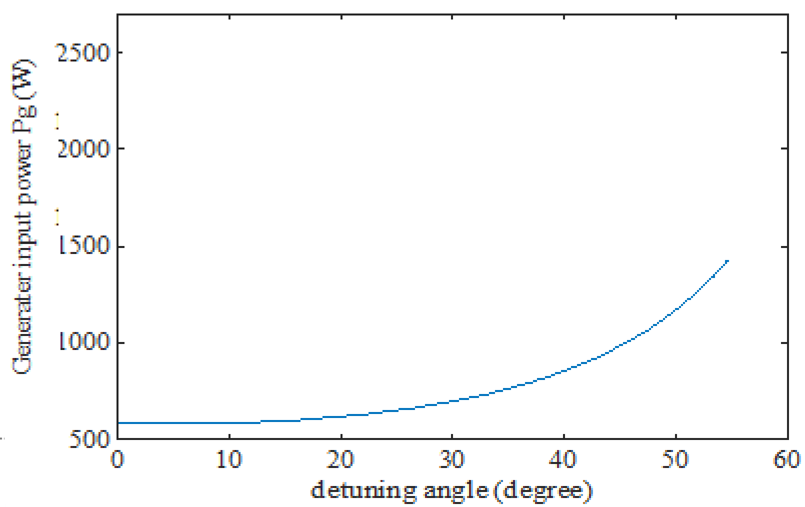


Transient beam loading @1mA

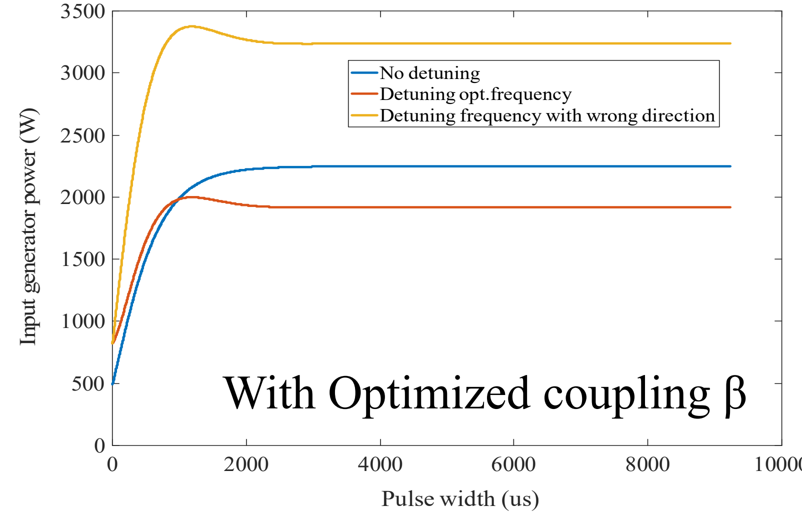
➢ *With Amplitude Loop control (ALC) and phase loop control*

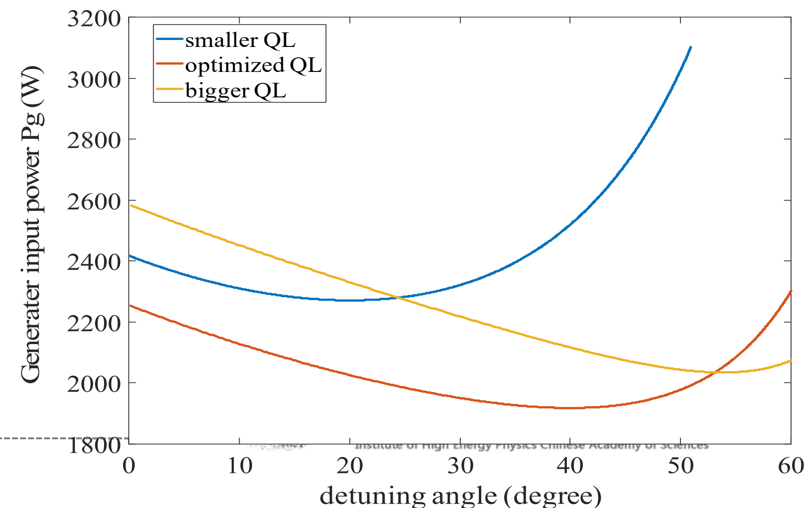
1mA





10mA





7. Summary

The China ADS injector-I testing facility has been commissioned using pulsed and CW beam:

- The maximum energy achieved at the exit of the Injector-I is 10.67 MeV with beam current of 10.6 mA on pulsed mode.
- CW proton beam with energy of 10 MeV and average beam current of 1.6~2.1 mA have been obtained at the exit of the linac.
- There are still some room from LLRF control point of view to improve the beam quality and stability & raise the beam current to be higher by adding frequency control and feedforward control.
- The beam loading effect of each cavity will be analysed to reproduce the beam behaviour during the commissioning and find the dominant factor for impacting the stability of the beam.

Thanks for your attentions!!