CSNS-II superconducting linac design

Jun Peng

On behalf of the CSNS Accelerator Team & Collaboration

Dongguan Campus, IHEP

Special thanks to: Yu-liang Zhang, Wen-zhou Zhou, Zhi-ping Li, Xin-yuan Feng, Yan-liang Han

Linac 2022, 2 Sept. 2022

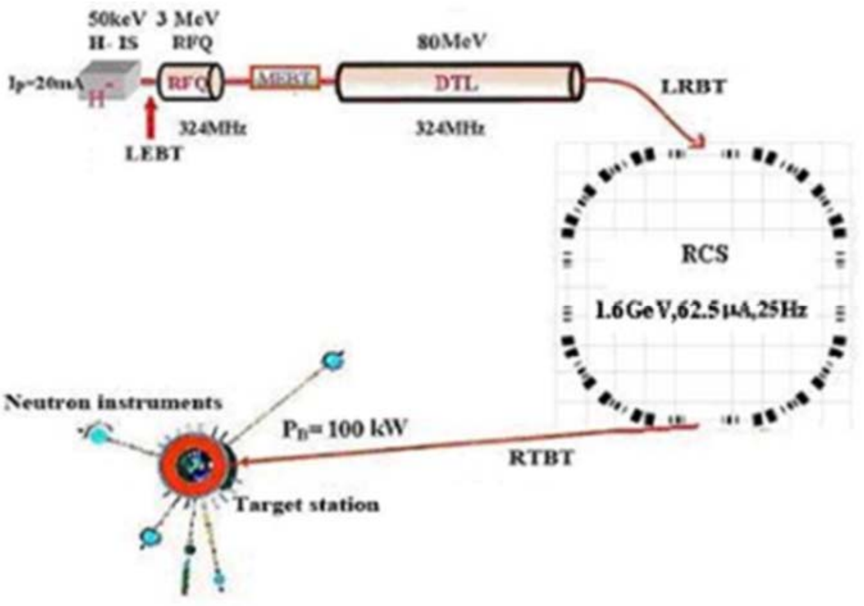
Outlines

1. Introduction
2. Accelerator status
3. Options of the linac for the CSNS power upgrade
4. Design of the superconducting linac
5. Summary

CSNS overview

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

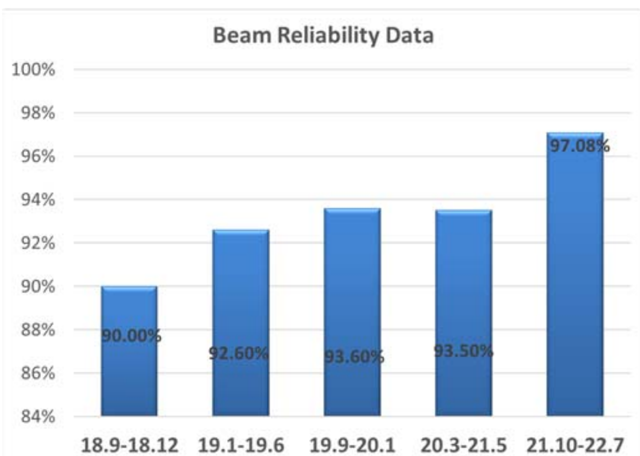
Project Phase	**I**	**II**
Beam Power on target [kW]	100	500
Proton energy [GeV]	1.6	1.6
Average beam current [μA]	62.5	312.5
Macropulse.ave current[mA]	15	40
Macropulse duty factor	1.0	1.7
Linac energy [MeV]	80	300
Linac type	DTL	Spoke+ Elliptical
Target	1	1
Spectrometers	3	20



CSNS accelerator performance

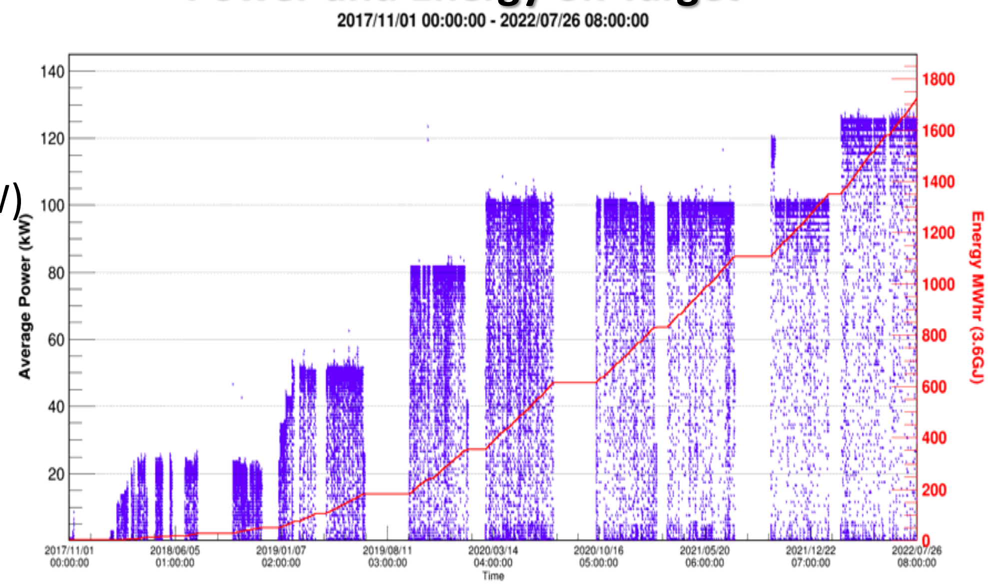
Key milestones(On schedule)

2015 start beam commissioning
2017 first beam on target
2018 end of beam commissioning
start operation for user program(20kW)
2020 Reach full power(100kW)



-Data from Yu-liang Zhang

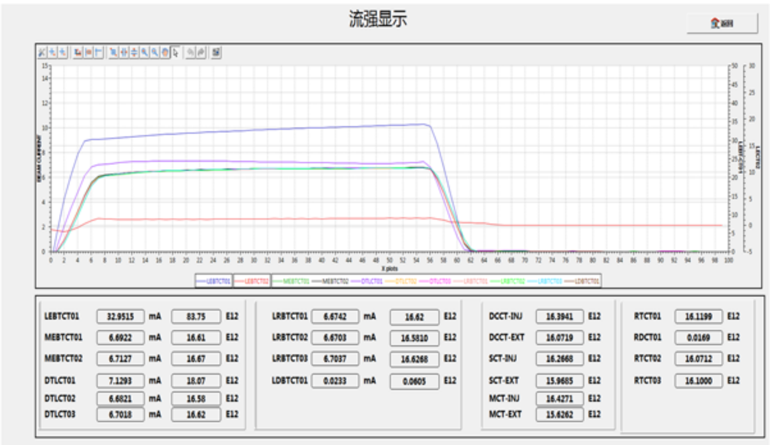
Power and Energy on Target



- ➢ The accelerator routinely operates with >90% availability in recent years
- ➢ From October 2021 to July 2022, the beam availability has been improved to more than 97%.

CSNS Linac Status

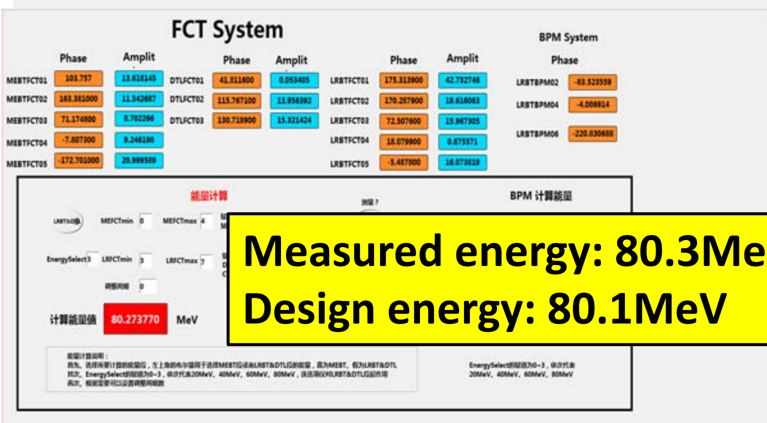
With 50% chopping



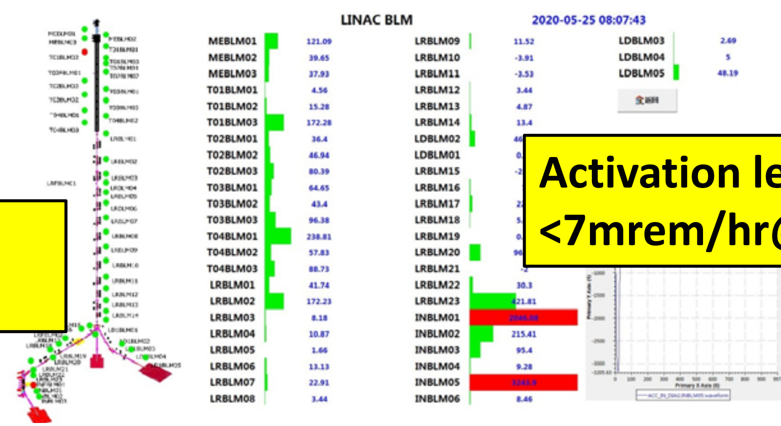
CT Display

2020–05–25 08:06:29

LEBT CT01	32.63	mA	RTBT CT02	1.585	E13
LEBT CT02	0.83	mA	RTBT CT03	1.587	E13
MEBT CT01	6.56	mA	MEBT Trans	100.3	%
MEBT CT02	6.58	mA	DTL Trans	99.6	%
LRBT CT01	6.55	mA	LRBT Trans	100.2	%
LRBT CT02	6.54	mA	EXT Trans	100.5	%
LRBT CT03	6.57	mA	RCS Trans	98.5	%
DCCT-INJ	1.608	E13	RTBT Trans	99.7	%
DCCT-EXT	1.584	E13	Linac Energy	80.271	MeV
RTBT CT01	1.591	E13	Beam Power	101.44	kW

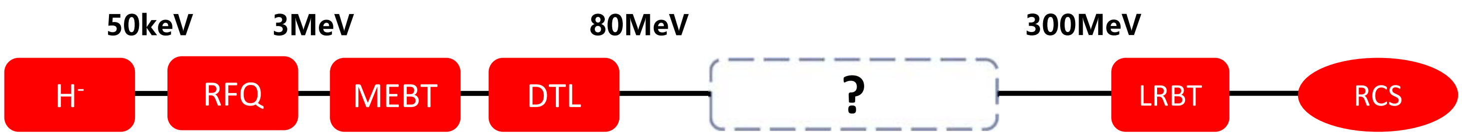


Measured energy: 80.3MeV
Design energy: 80.1MeV



Activation level: <7mrem/hr@30cm

Options of linear accelerator for CSNS Ⅱ



Main constraints:

- The tunnel length reserved for linac energy upgrade is 92m.
- To reduce space-charge effect in the RCS, beam energy output from the linac should be more than 300MeV.

The energy gain per meter>2.4MeV/m

Special requirements for linac energy upgrade

- Stable output beam energy, energy jitter $\Delta E/E<0.04\%$
- High availability (>95%)
- Quick installation, device and beam commissioning, recover user operation
- Technical risk/local expertise

Mini Workshop on CSNS Upgrade Program
Sept. 20, 2018, Beijing, China

Scheme 1、Pi mode structure

324MHz

DTL

28 *7cell PIMS

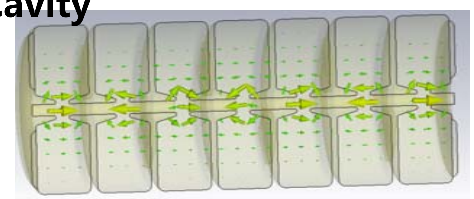
12*6cell PIMS

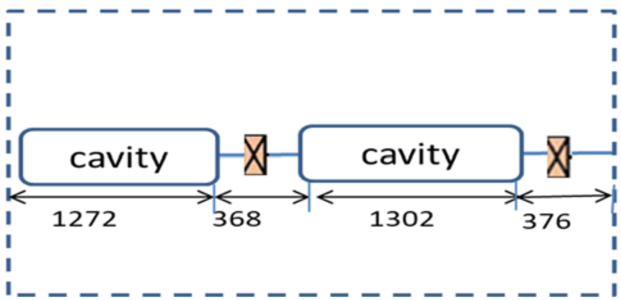
80MeV

83m

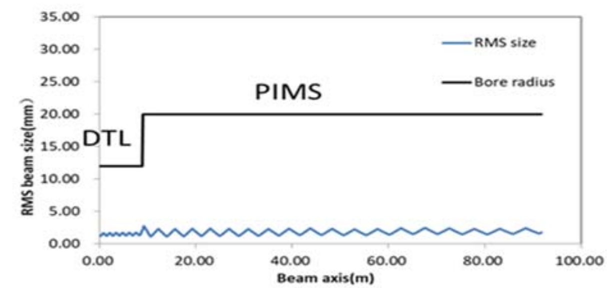
311MeV

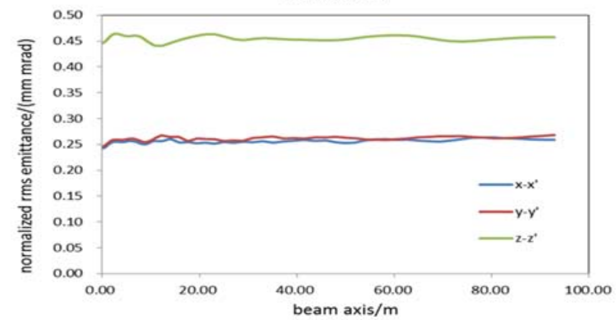
Cavity





Module





Superconducting linac

Scheme 2:

50keV — 3MeV — 80MeV — 174MeV — 300MeV

H⁻ — RFQ — MEBT — DTL — Low β Elliptical cavities — Medium β Elliptical cavities — LRBT — RCS

Low β Elliptical cavities: β_g=0.47, 648MHz, 11cryomodules, 2 cav/cryomodule

Medium β Elliptical cavities: β_g=0.6, 648MHz, 7cryomodules, 4cav/cryomodule

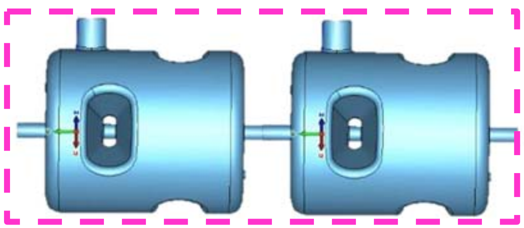
Scheme 3:

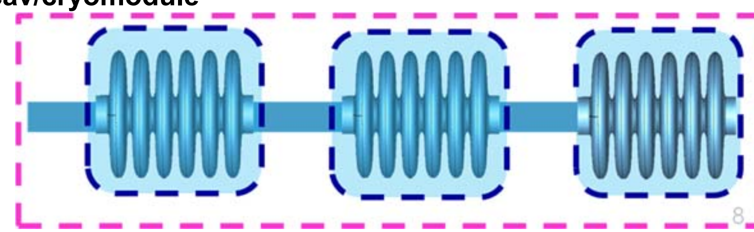
50keV — 3MeV — 80MeV — 165MeV — 300MeV

H⁻ — RFQ — MEBT — DTL — Double-Spoke cavities — Elliptical cavities — LRBT — RCS

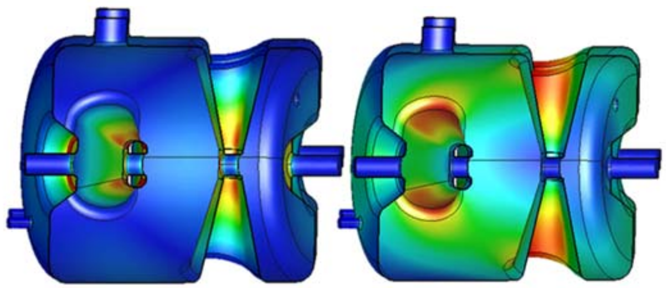
Double-Spoke cavities: β_0=0.5, 324MHz, 10cryomodules, 2 DSR/cryomodule

Elliptical cavities: β_g=0.62, 648MHz, 8cryomodules, 3cav/cryomodule

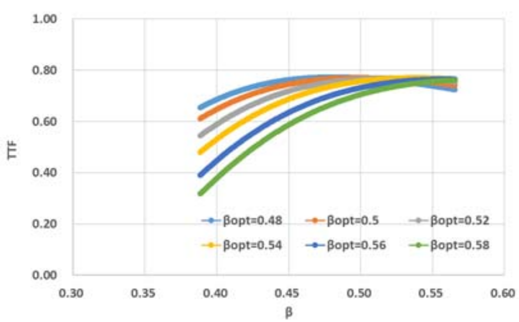


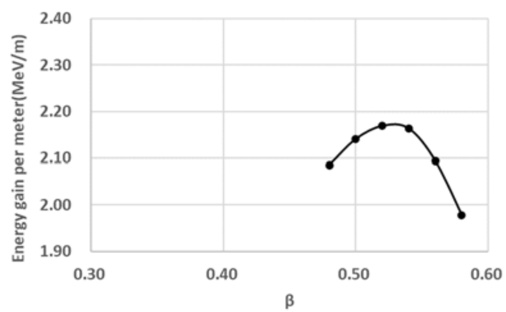


Spoke cavities for CSNS Ⅱ linac



electric field (left)and magnetic field(right)





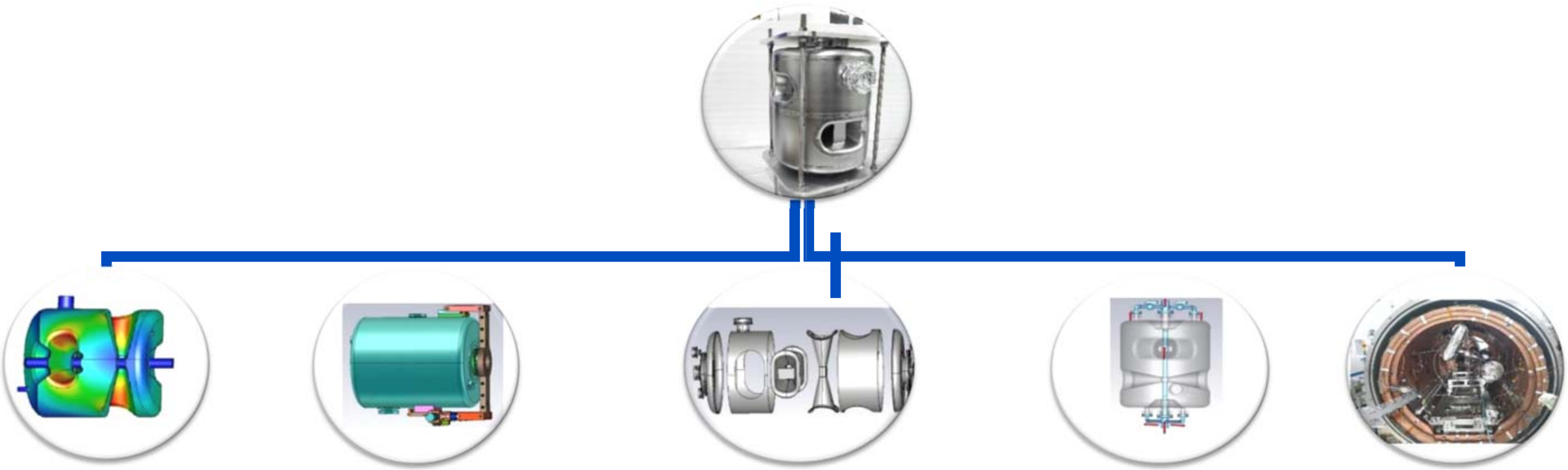
Spoke section
from 80MeV to 180MeV

The Main Parameters

Parameter	Design value
Frequency(MHz)	324
Beam tube aperture (mm)	50
Ep/Eacc	4.1
Bp/Eacc(mT/MV/m)	9.2
β_0	0.5
G(Ω)	120
R/Q(Ω)	410
Eacc(MV/m)	9

-Data from Wen-Zhong Zhou

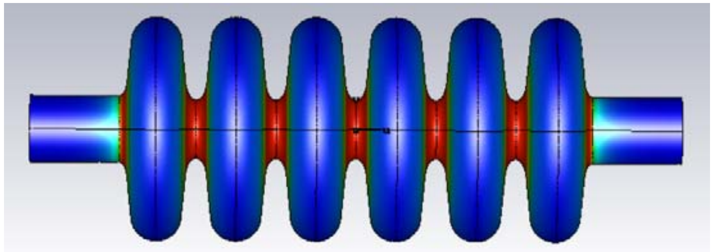
Status of Prototyping



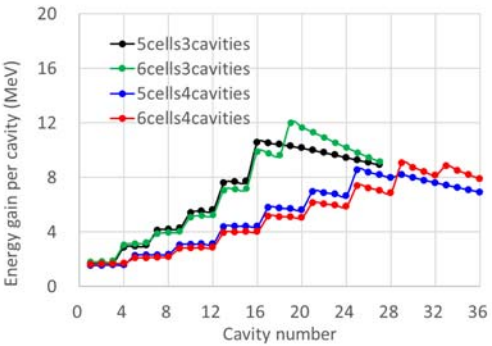
EM Design	Machine Design	Manufacturing Technique	Postprocessing	Vertical Testing
2021.2-2021.6	2021.6-2021.8	2021.9-2022.3	2022.4-2022.6	2022.6-

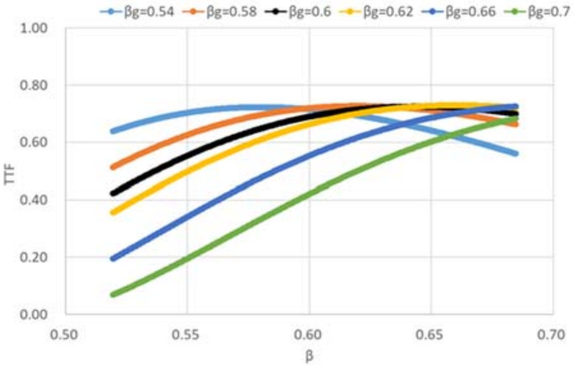
10

Elliptical cavities for CSNS Ⅱ linac



electric field





6 cells per cavity, 3 cavities per cryomodule

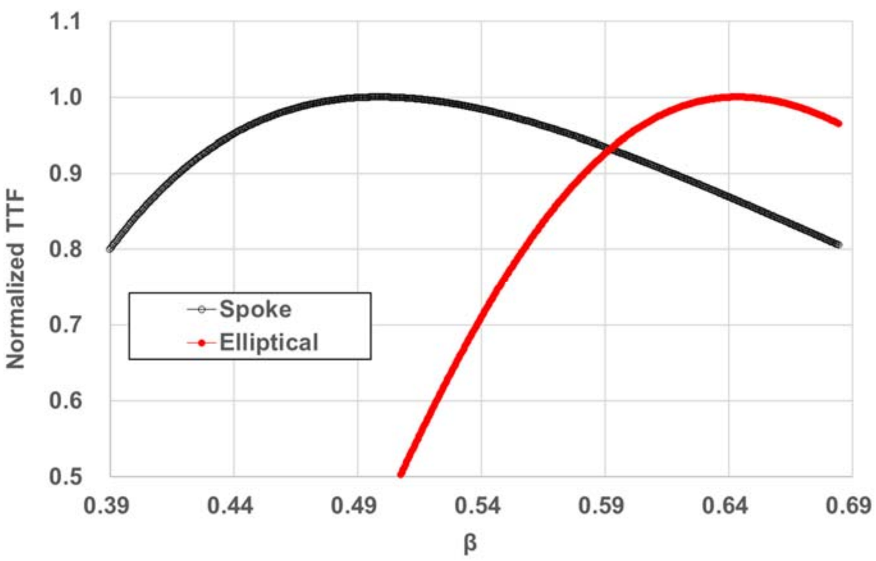
The Main Parameters

Parameter	Design value
Frequency(MHz)	648
N cell	6
βg	0.62
Beam aperture(mm)	105/120
R/Q （βg）(Ω)	309
Ep/Eacc （βg）	2.53
Bp/Eacc （βg） (mT/(MV/m))	5.53
G(Ω)	177
Coupling Kcc%	1.35
Eacc(MV/m)	15.8

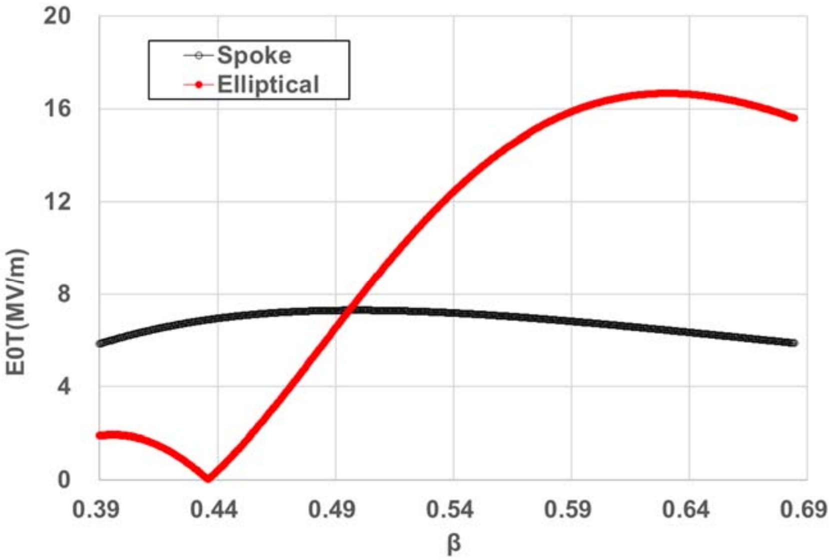
-Data from Wen-Zhong Zhou

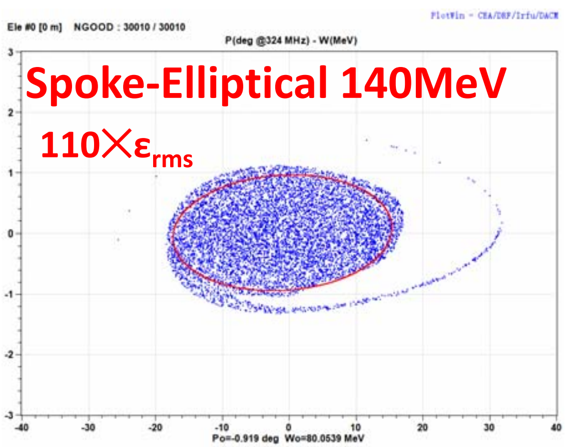
Spoke – Elliptical energy transition

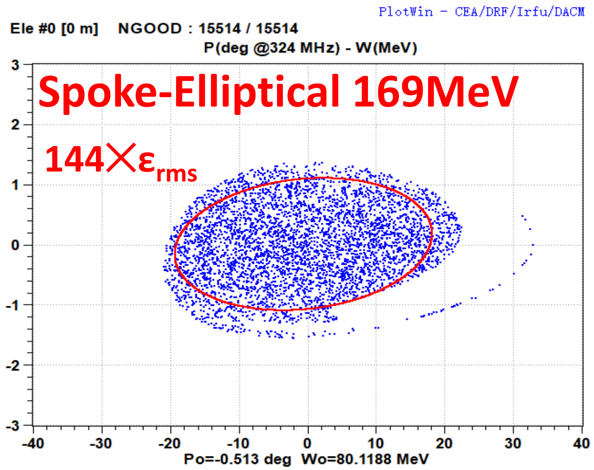
Normalized TTF curve， the intersection point is at β=0.592(~226MeV),

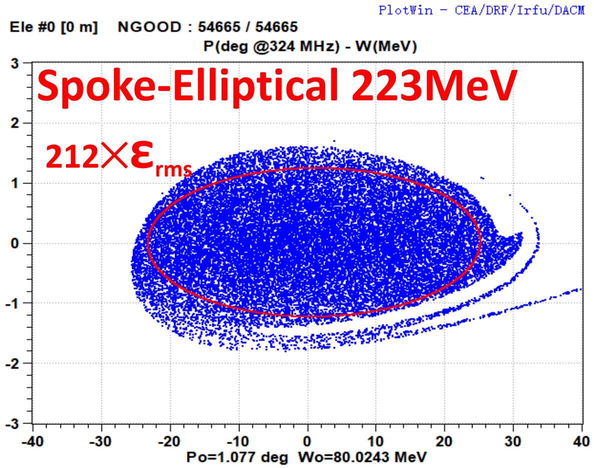


Accelerating field curve, the intersection point is at β=0.496(~142MeV)

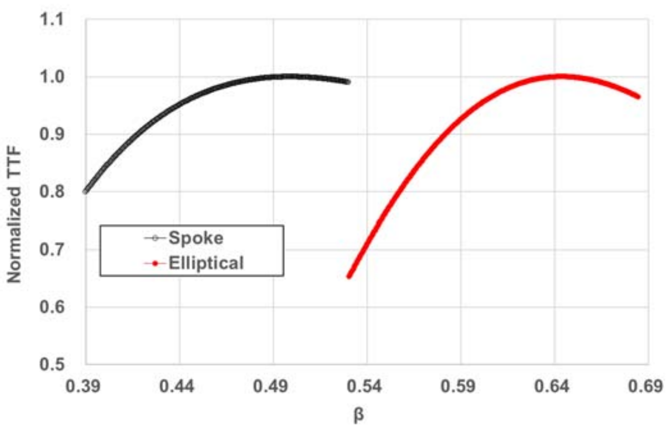




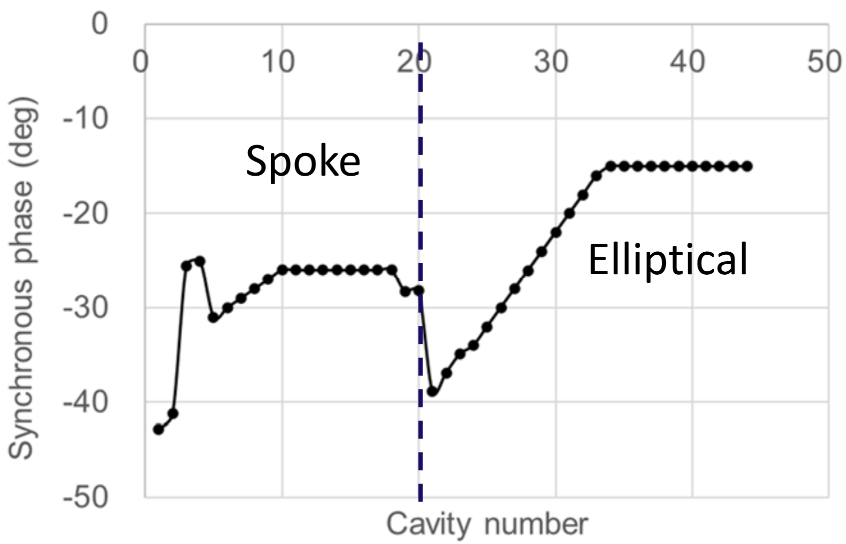


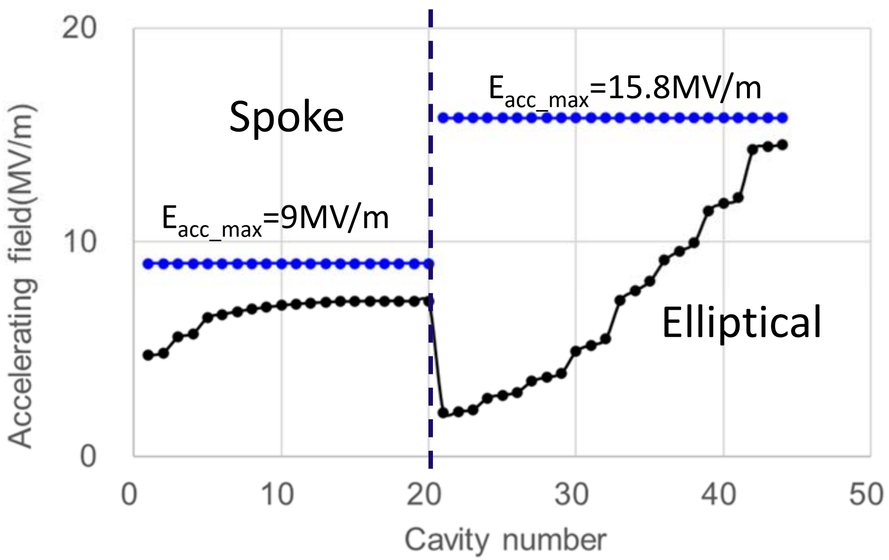


Transition energy is 169MeV(β=0.53)



Beam dynamics-ϕ_s and E_{acc}

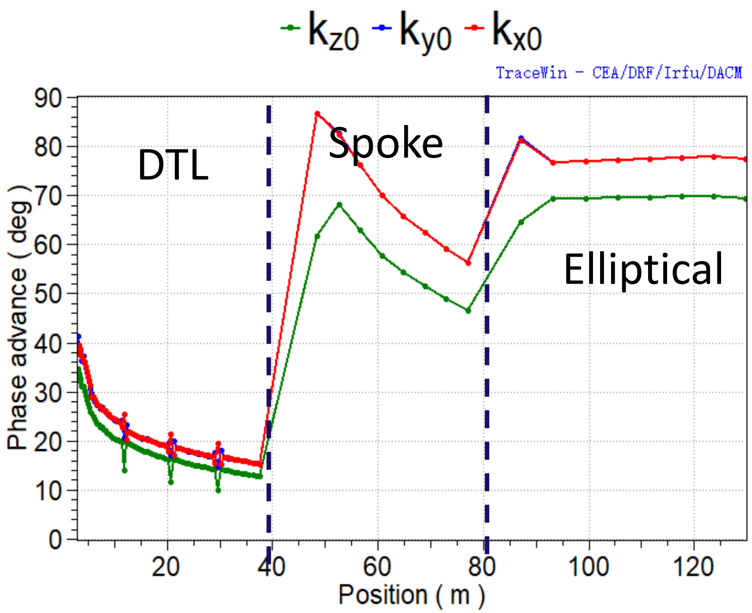


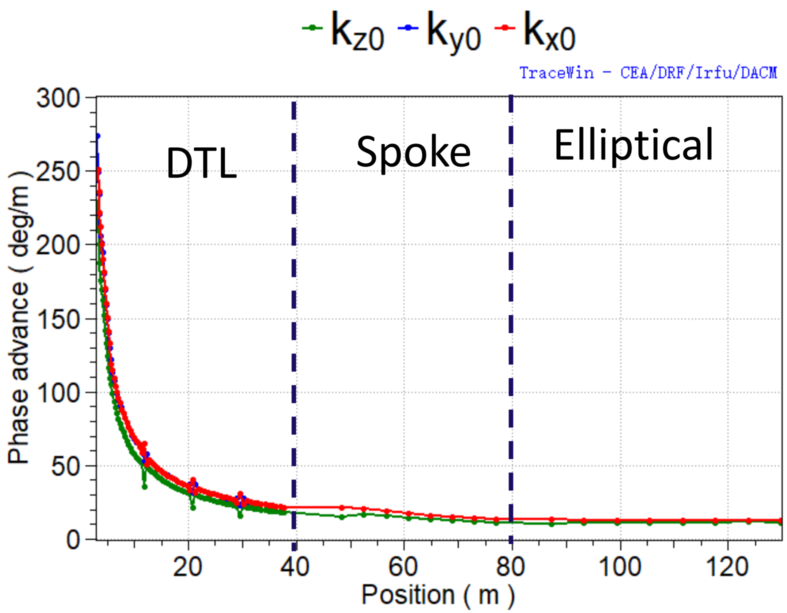


$$(\phi_s)_{648MHz} = 2 \times (\phi_s)_{324MHz}$$

$$k_{l0}^2 = \frac{2\pi q E_0 T sin(-\phi_s)}{mc^2 \beta_s^3 \gamma_s^3 \lambda}, \qquad maximum\ variation\ per\ period < 2deg/m$$

Beam dynamics-*phase advance*

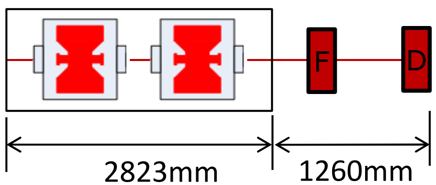




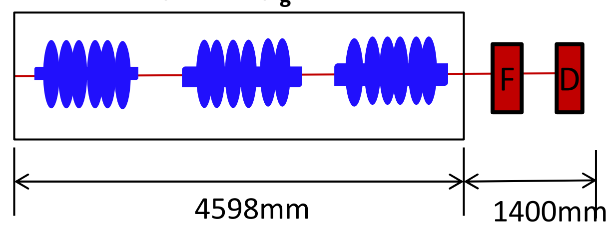
- Maximum zero-current phase advance per period is less than 90 degrees to avoid parametric resonances.
- Average phase advance per meter must be continuous.

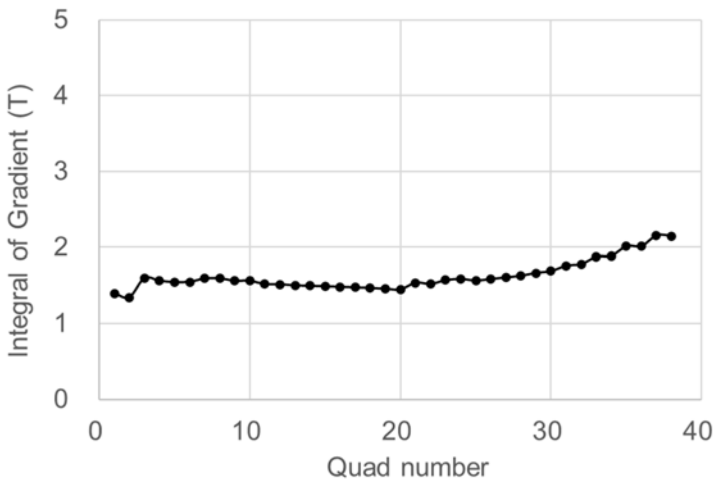
Beam dynamics-*lattice design*

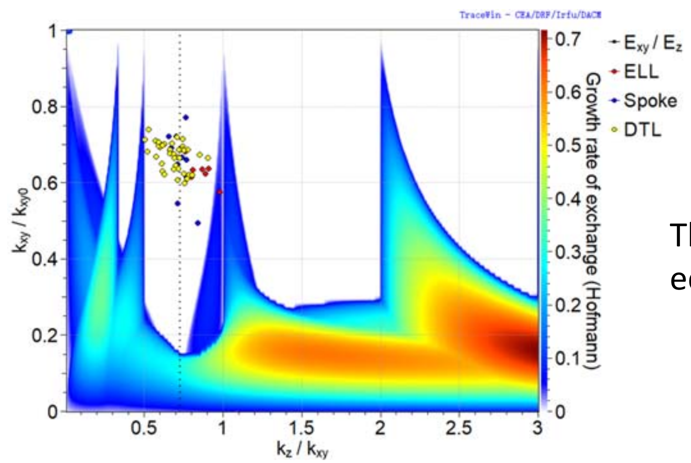
Spokes, β_{opt}=0.5



Elliptical, β_g=0.62



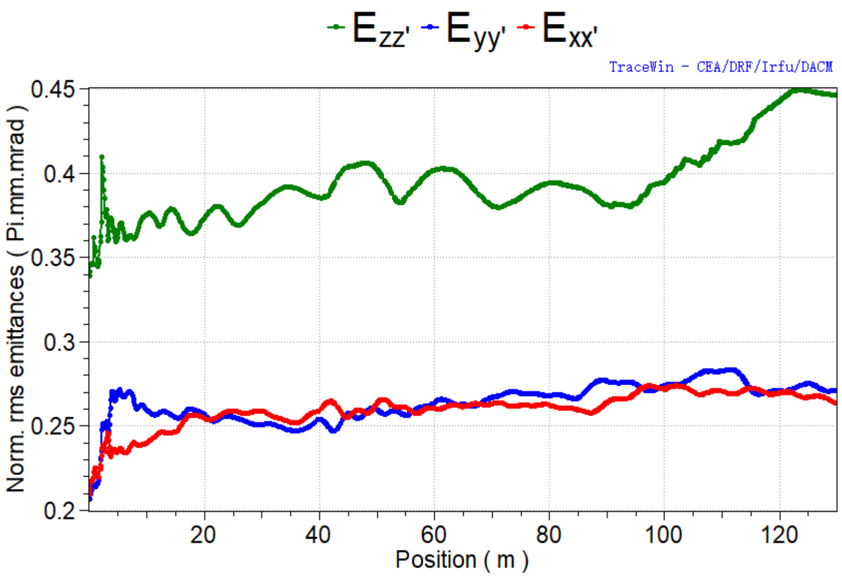


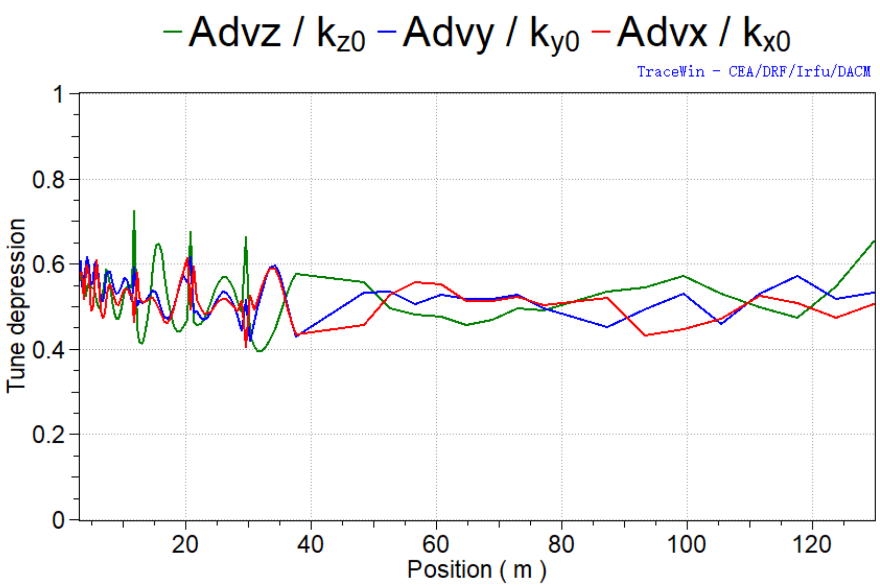


The beam is equipartitioned when:

$$\frac{\epsilon_{nx} k_x}{\epsilon_{nz} k_z} = 1$$

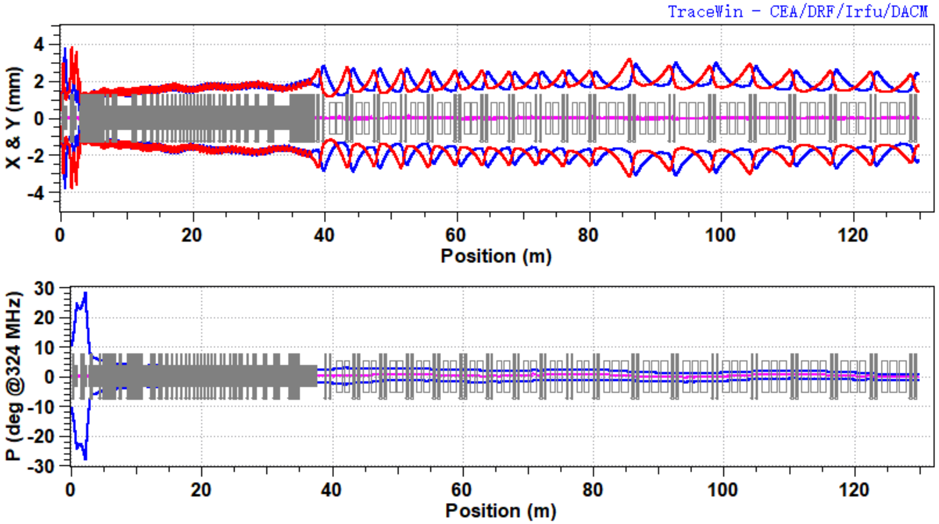
Beam dynamics-*Emittance*

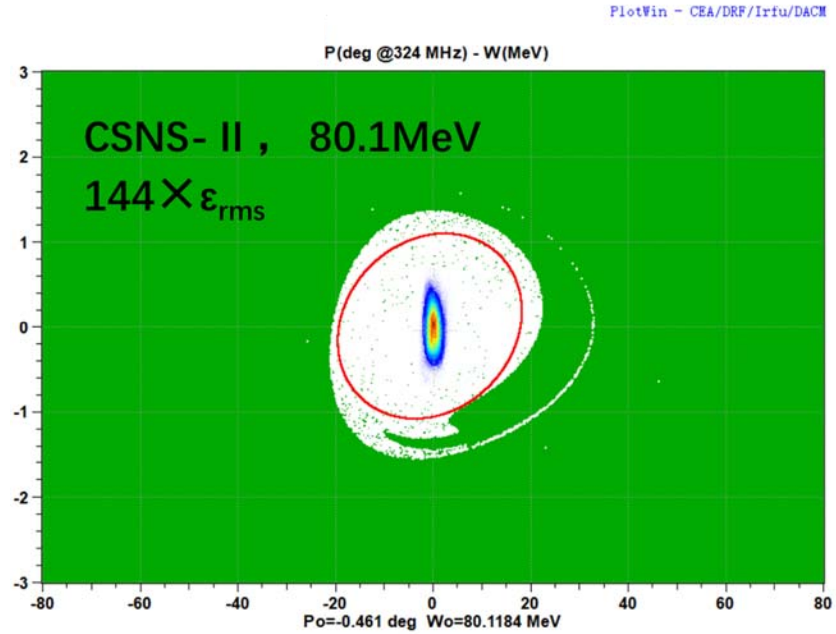




- The RMS emittance growth through MEBT+DTL+Spoke+Elliptical is 26%(horizontal), 32%(Vertical) and 32%(longitudinal).
- Tune depression is bigger than 0.4

Beam dynamics-*Acceptance*





- In the normal conducting linac, the bore radius/RMS beam size is over 5.5.
- In the superconducting linac , the bore radius/RMS beam size is over 8.5.
- For the superconducting linac, the longitudinal acceptance is more than 144 times the area of the matched rms beam emittance at spoke injection.

Error studies

- The start-to-end error analysis is performed – (MEBT, DTL, SC Linac)
  - Beam error from RFQ
  - MEBT & DTL
  - Super-Conducting Linac
- Nominal & 2*Nominal Errors are studied

Beam Errors @ RFQ Output

Errors		Values
Trans. Offset	△X, △Y (mm)	0.5
Angle	△X', △Y' (mrad)	1
Phase	△phi (deg)	1
Energy	△E(MeV)	0.01
Emittance	△EmitX, △EmitY, △EmitZ	10%

Cavity & Quads Errors from the MEBT and DTL

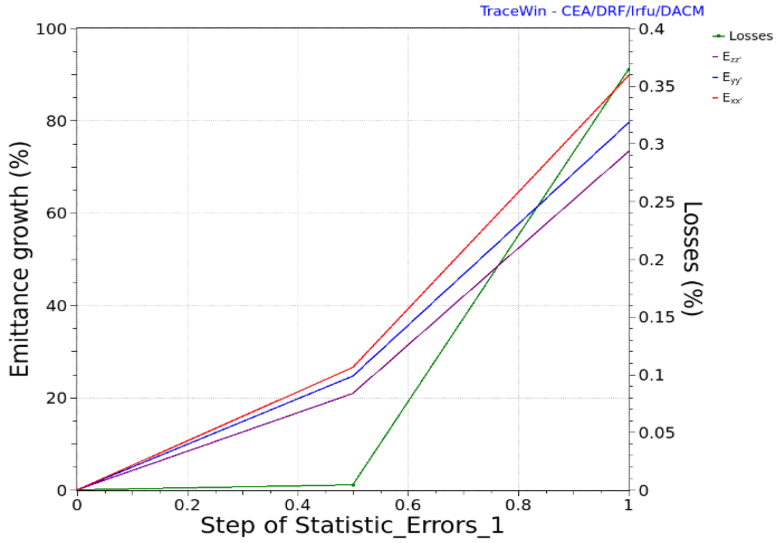
Errors		Values	
		Cavity	Quads
Trans. Offset	△X, △Y (mm)	0.05	0.05
Angle	Rx, RY, Rz (mrad)	3	3
Gradient	△G (%)	1	1
Phase	△phi (deg)	1	
Long. Offset	△z (mm)	0.1	

Cavity & Quads Errors from the SC linac

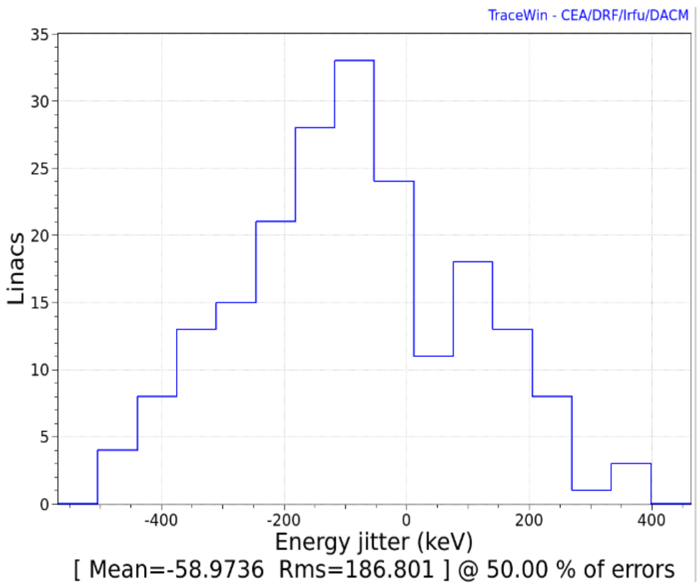
Errors		Values	
		Cavity	Quads
Trans. Offset	△X, △Y (mm)	1	0.1
Angle	Rx, RY, Rz (mrad)	2	2
Gradient	△G (%)	0.5	0.5
Phase	△phi (deg)	0.5	
Long. Offset	△z (mm)	0.5	0.5

Error Analysis Results

- Emittance growth rates are about 25%
- Beam loss rates are <0.01%
- RMS Energy jitters are 187keV(**0.063%@300MeV**) . (Debunchers are needed to compress the energy jitter)



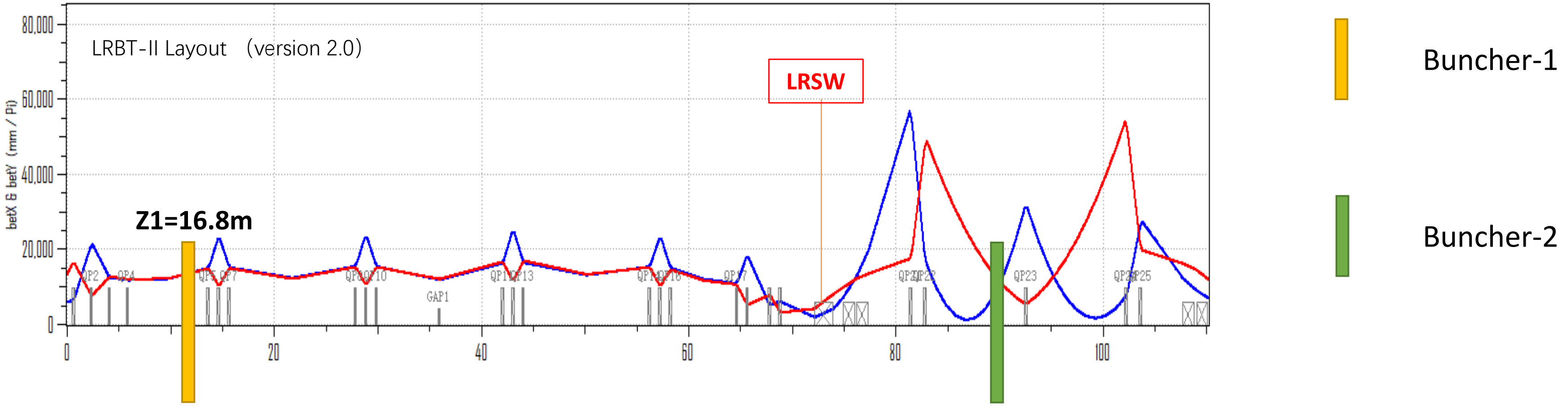
-Data from Yan-liang Han



Study of Debuncher System for CSNS-II Linac

2-Cavity Debuncher System

-Data from Zhi-ping Li



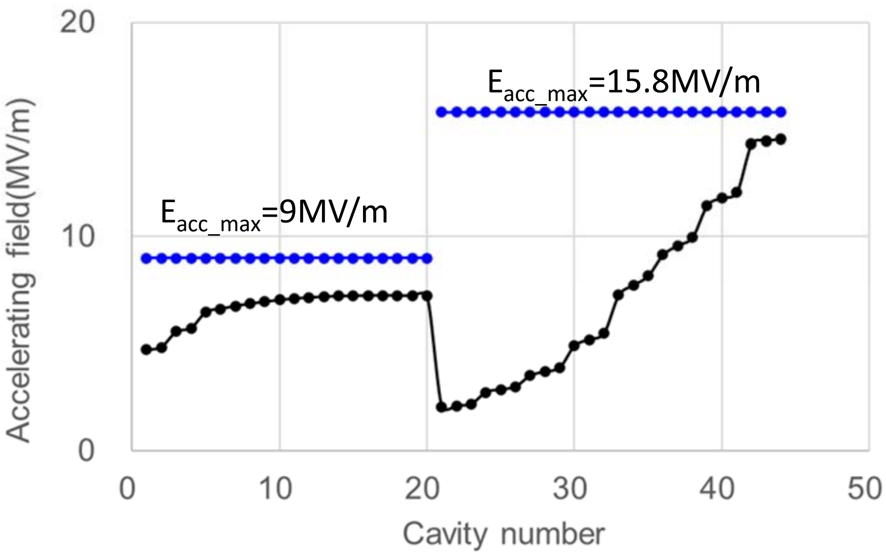
Principle：

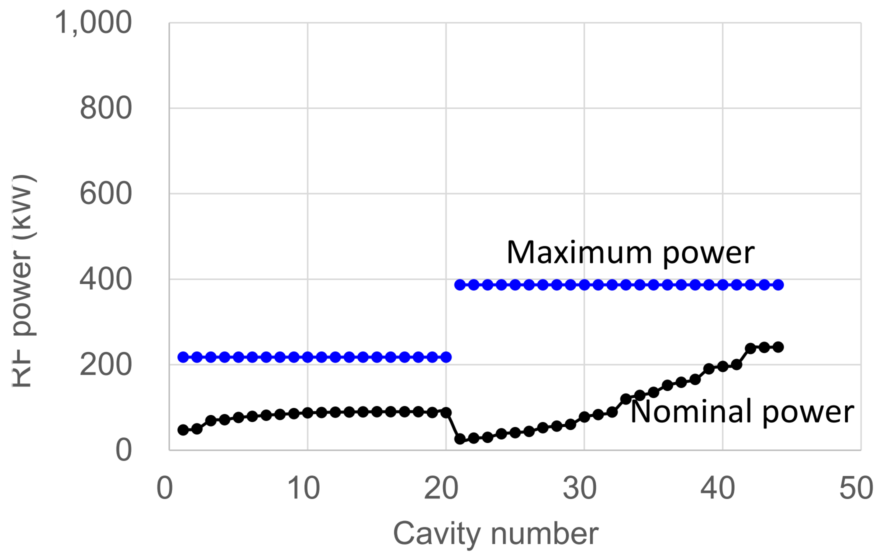
1. Small Aperture
2. Small *L1/L2*
3. Voltage of debuncher available(*L1* not too small)

Momentum Jitter Compactor Ratio：

$$\delta_{p1}/\delta_{p0} = -\frac{l_1}{l_2} \sim -\frac{1}{4}$$

Fault-compensation scheme for CSNS Ⅱ linac

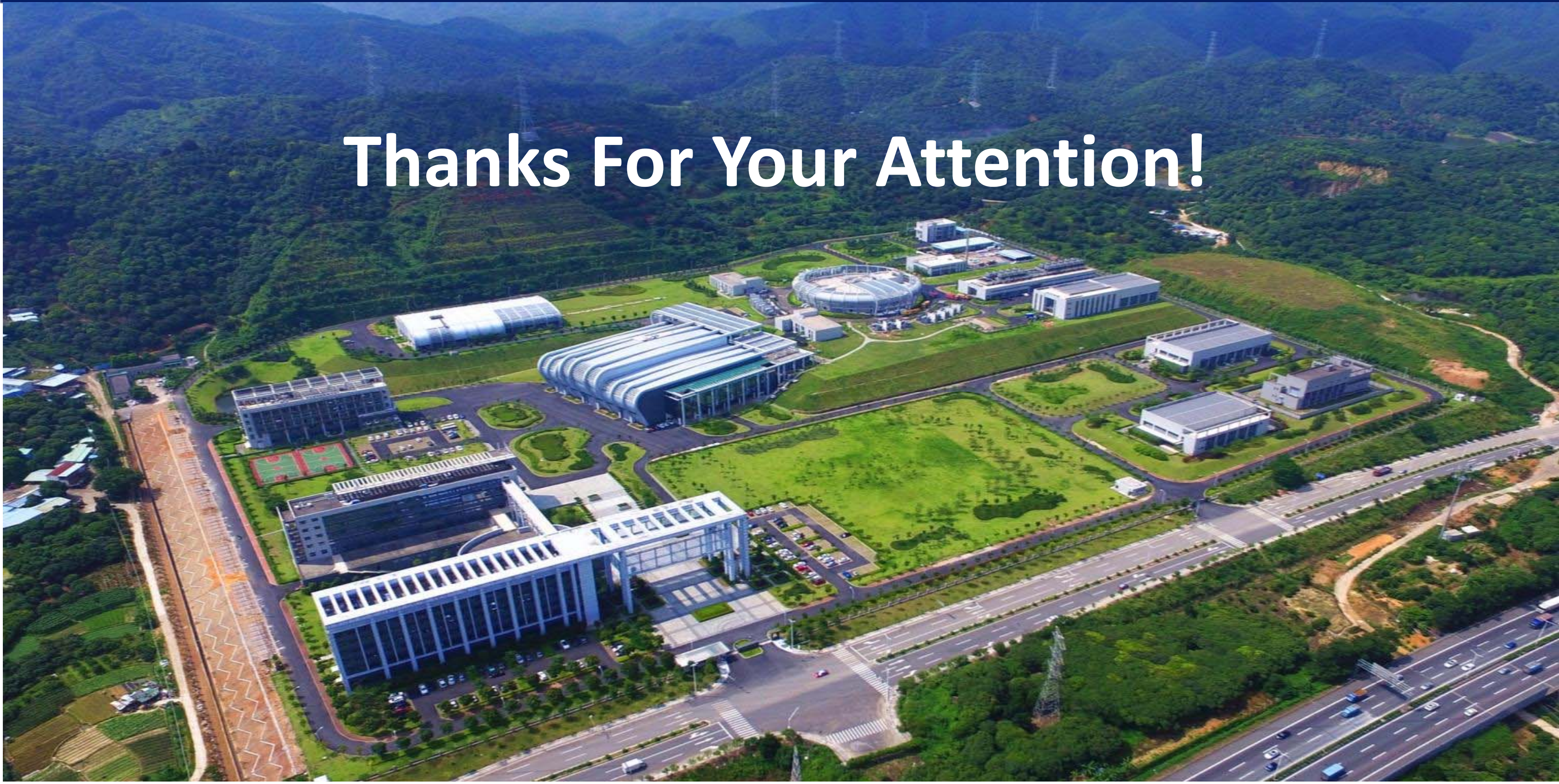




- The accelerating fields have about 25% margins for fault-recovery.
- The RF powers have nearly 100% margins for fault-recovery.
- The cavities are powered independently for retuning the ϕ_s and the E_{acc}.

Summary

- The CSNS is operating reliably at 125kW and is launching the power upgrade project.
- A superconducting linac has been designed for the CSNS power upgrade project.
  - The prototype of spoke cavity is under vertical testing. The design of the elliptical cavity begins.
  - 2 cavity debuncher system is adopted to compress the energy jitter.
  - A fault-compensation scheme is used to keep the linac energy stable. Dedicated algorithm is under developing.


Thanks For Your Attention!