Physical design of the proton linac injector for the synchrotron based proton therapy system in China

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2. Optimization process
3. Error analysis
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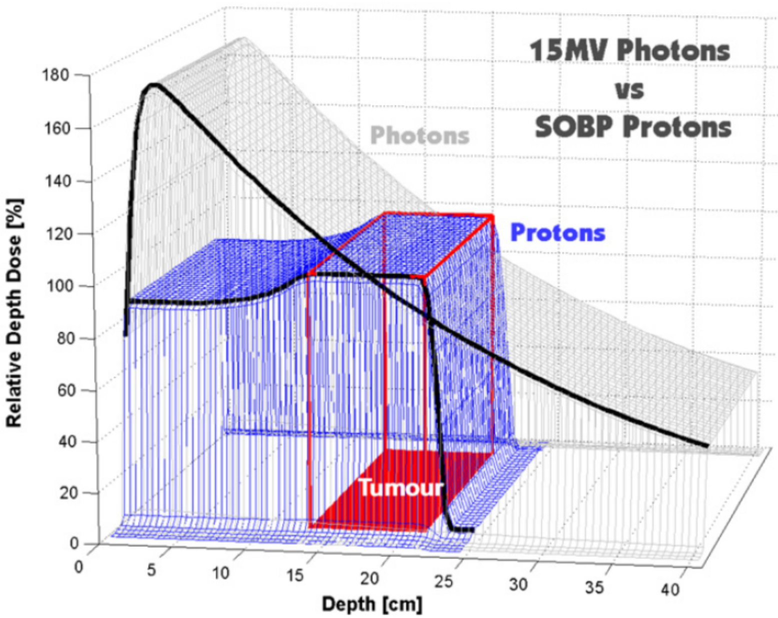
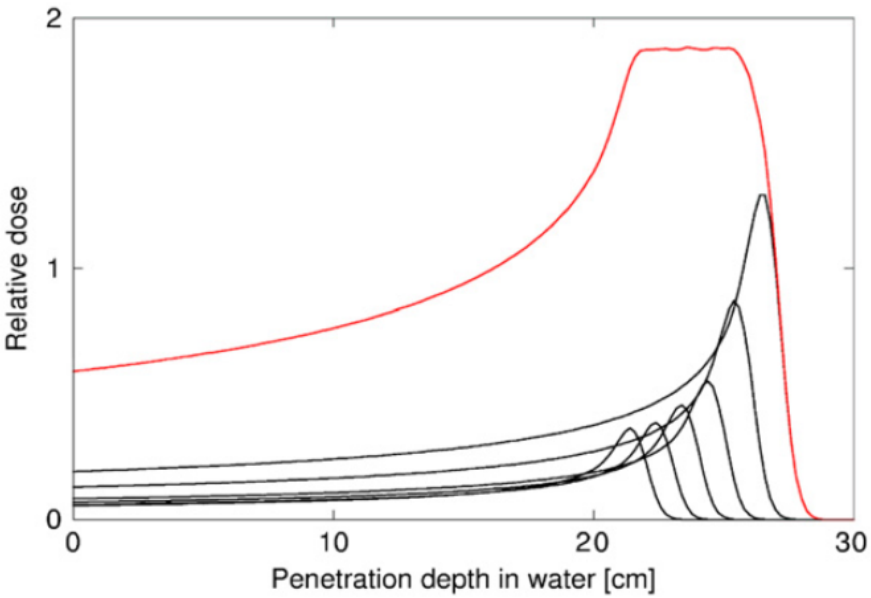
Introduction

■ Proton therapy

- ✧ One type of particle therapy techniques for cancer treatment
- ✧ Advantages over the traditional radiation therapy

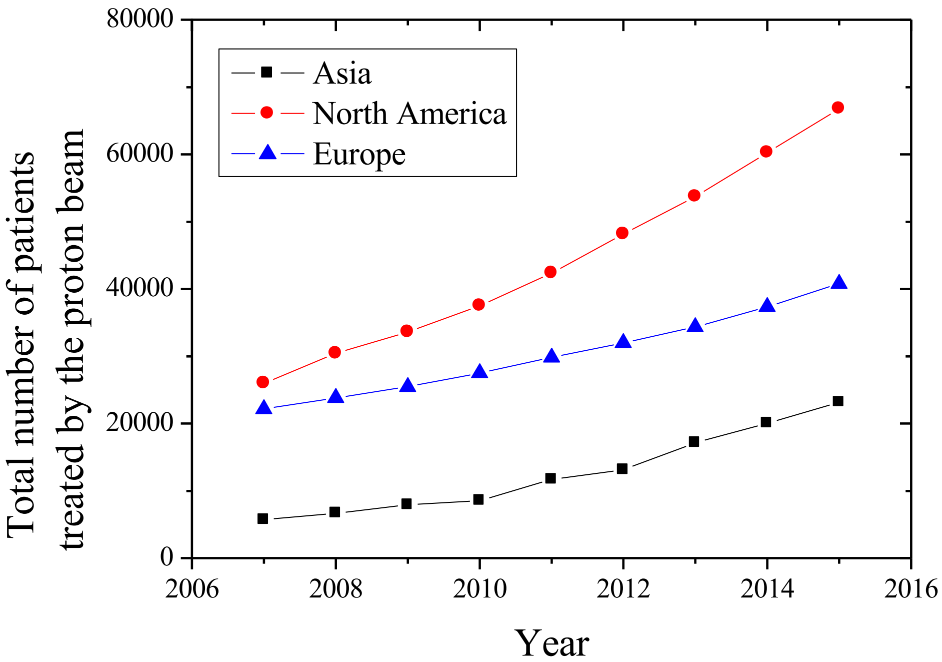
  - Bragg peak



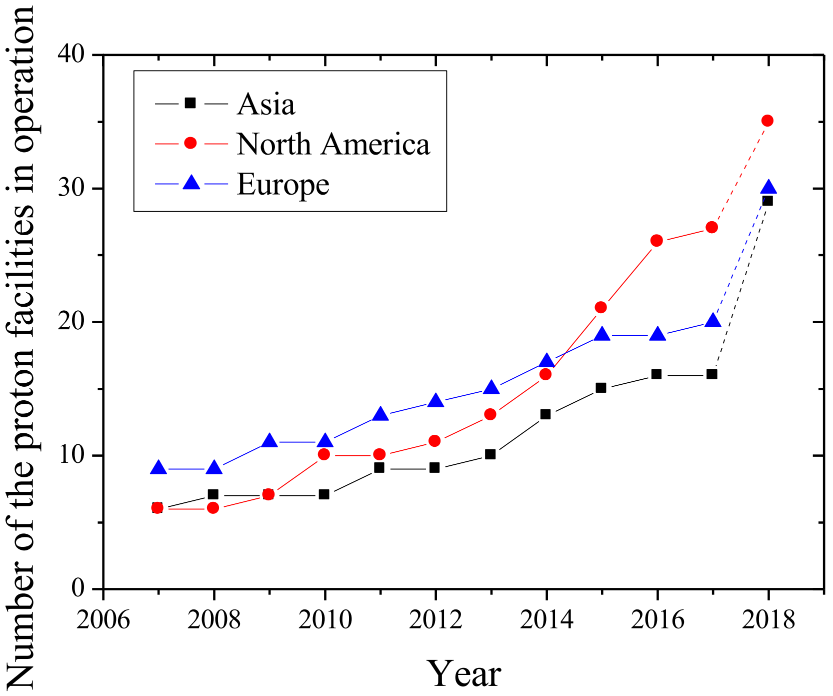


Alfred R Smith 2006 Phys. Med. Biol. 51 R491

Proton treatment



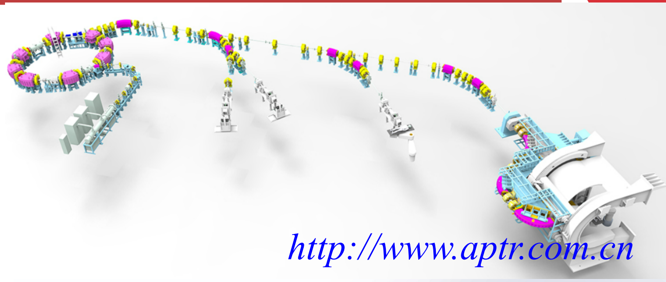
Number of the patients treated by the proton beam



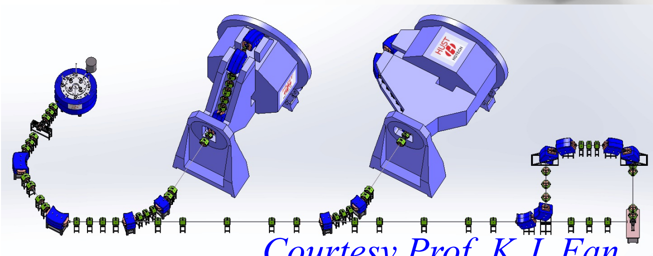
Number of the proton facilities in operation

Data from http://ptcog.web.psi.ch/

Proton facilities



http://www.aptr.com.cn



Courtesy Prof. K.J. Fan

- Two popular alternatives
  - Synchrotron-based
  - Cyclotron-based
- Proton facilities in mainland China
  - Only two proton therapy facilities in operation

    - WPTC(Wanjie Proton Therapy Center)/Zibo, cyclotron-based

    - SPHIC(Shanghai Proton and Heavy Ion Center)/Shanghai, synchrotron-based
  - Several under construction or planning

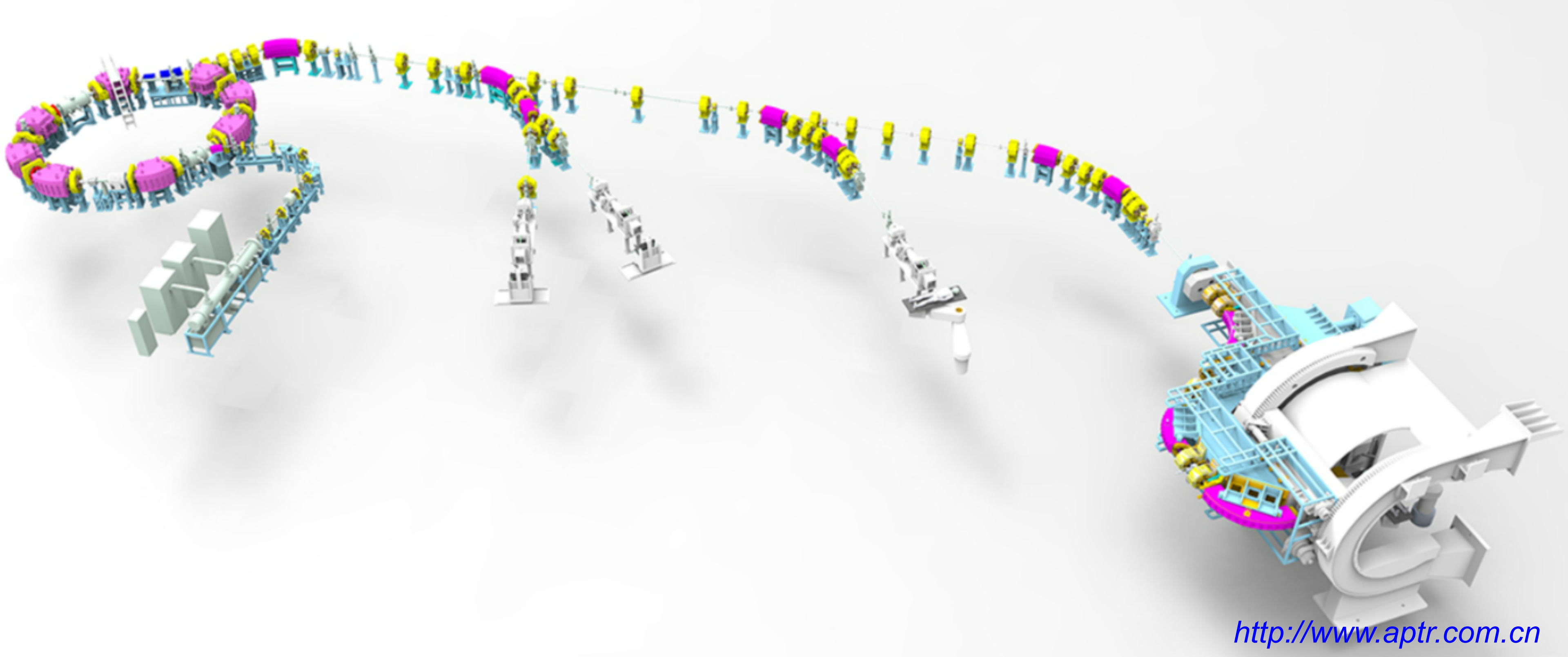
    - HIMC(Hefei Ion Medical Center), SC cyclotron-based, treatment in 2020

    - HUST-PTF(Huazhong University of Science and Technology-Proton Therapy Facility), SC cyclotron-based, treatment in 2021

    - ……

Synchrotron-based proton therapy facility

- Synchrotron-based proton therapy facility
  - ✧ Advantages of less radiation dose due to no energy degrader
  - ✧ One linac injector needed



Linac injector for the synchrotron

- Linac injector
  - ✧ Design: Tsinghua University
    - Approved by the government under National Key Research and Development Program
  - ✧ Adopting domestic mature technologies and cost control

Beam requirement of the linac injector

PARAMETER	VALUE
Ion type	Proton
Output beam energy	7 MeV
Output beam momentum spread	±0.3% (≥8 mA)
Output peak current	≥12 mA
Output normalized transverse emittance (90% particles)	≤1.2π mm•mrad
RF frequency	325 MHz
Repetition rate	0.5 Hz
Output beam pulse width	40~100 μs

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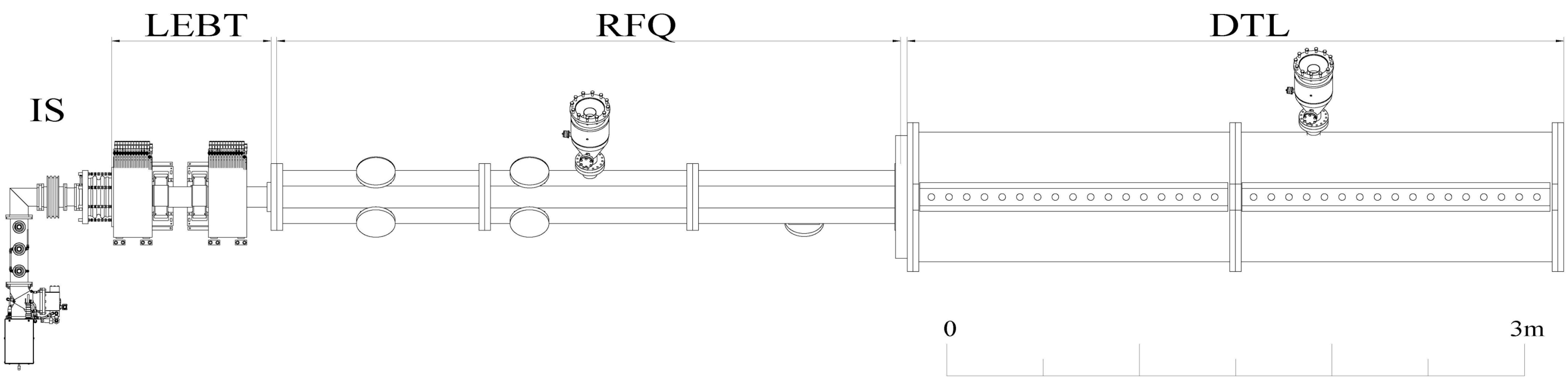
Optimization process

- Overall configuration
  - Ion source: ECR source
  - LEBT: magnetic LEBT; electric optional
  - RFQ: four-vane type, abundant manufacturing experiences in China
  - DTL: Alvarez-type DTL, instead of KONUS (Combined Zero Degree Structure) or APF (Alternating Phase Focusing) IH DTL

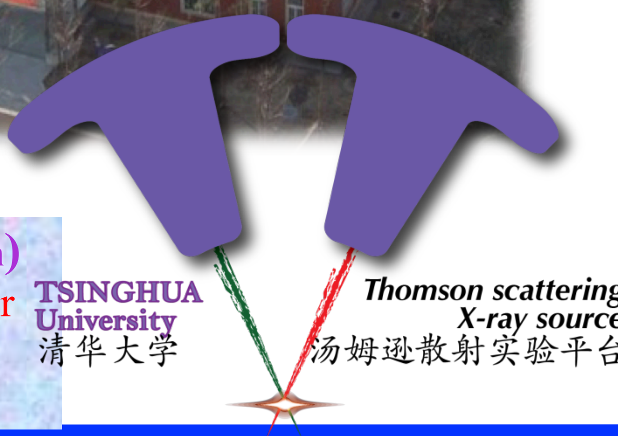


Experiences on Alvarez-type DTL

- Alvarez-type DTL in China
  - CPHS(Compact Pulsed Hadron Source)/Beijing, PMQ
  - XiPAF(Xi’an Proton Application Facility)/Xi’an, PMQ
  - CSNS/Dongguan, electro-magnetic (EM) quadrupole

Compact Pulsed Hadron Source (CPHS)

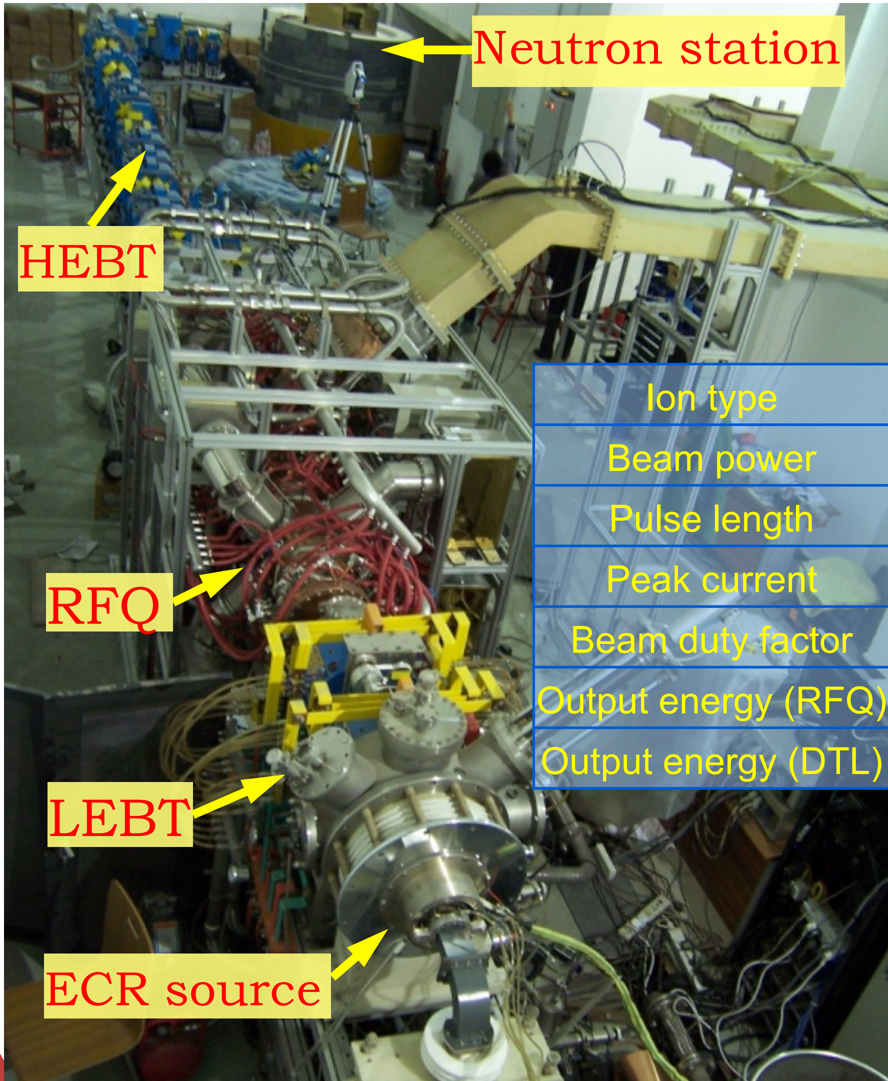
CPHS 微型脉冲强子源
Compact Pusled Hadron Source
TSINGHUA UNIVERSITY



CPHS+TTX: (**Laboratory for Advanced Radiation Sources and Application**)

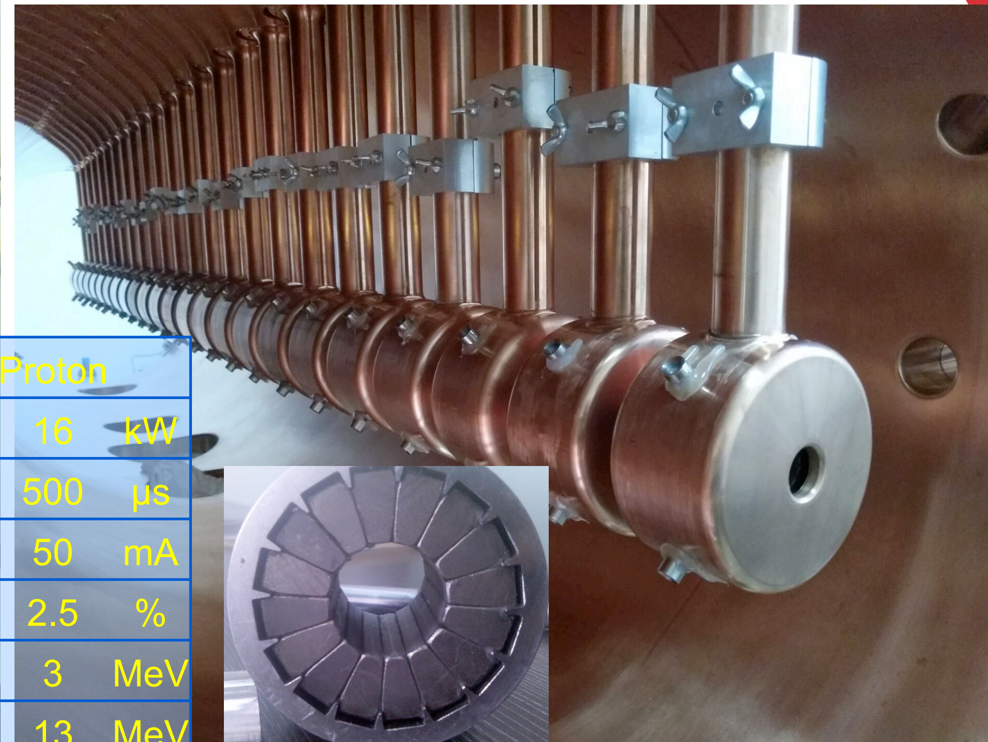
- Network of accelerator-driven proton, neutron, electrons, x-ray, and laser
- Experimental platforms for education, research, and innovative applications

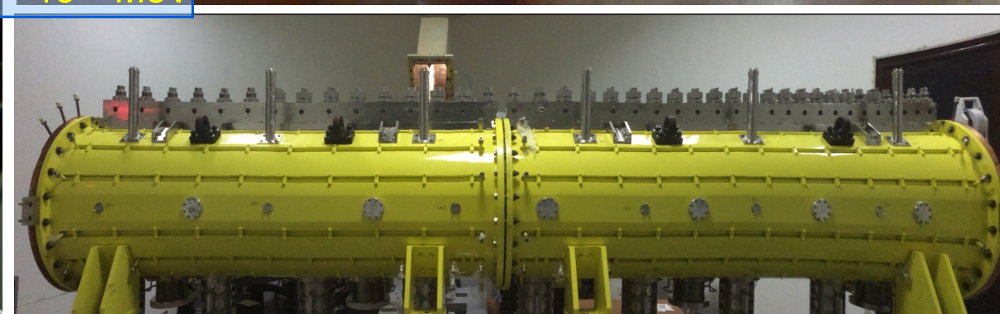
Compact Pulsed Hadron Source (CPHS)



CPHS at Tsinghua University. 3MeV proton and thermal neutrons to users for ~2000hrs.

Ion type	Proton	
Beam power	16	kW
Pulse length	500	μs
Peak current	50	mA
Beam duty factor	2.5	%
Output energy (RFQ)	3	MeV
Output energy (DTL)	13	MeV

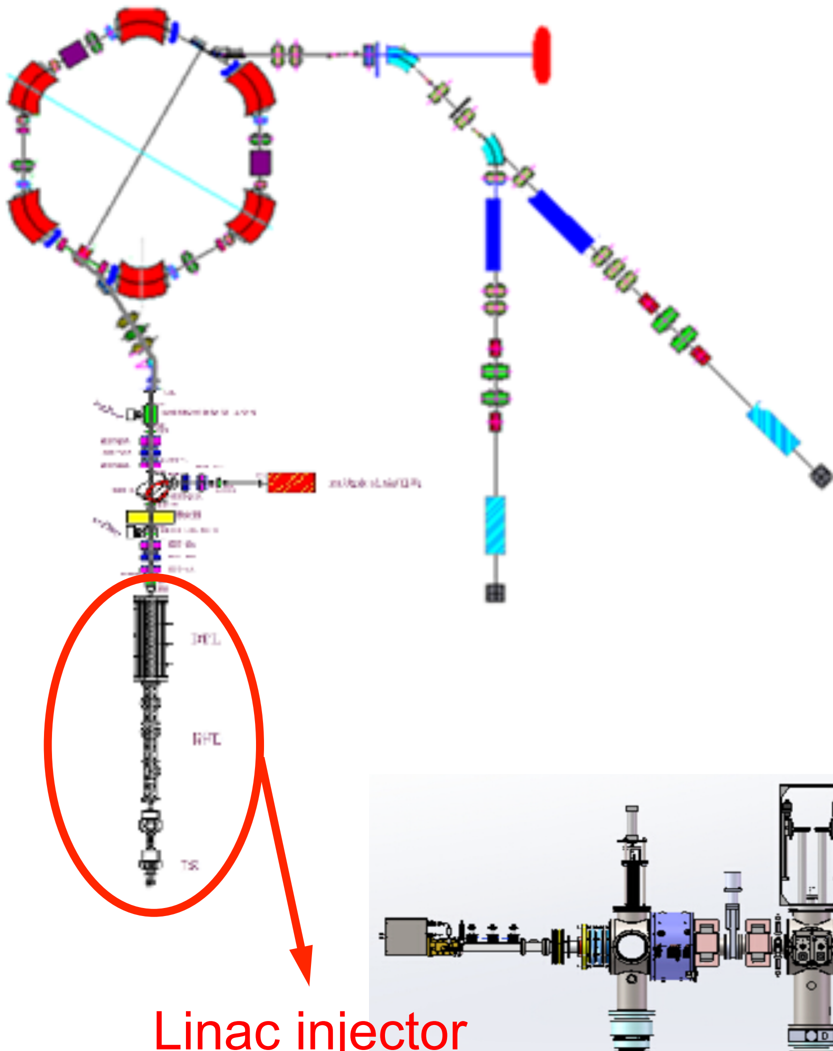


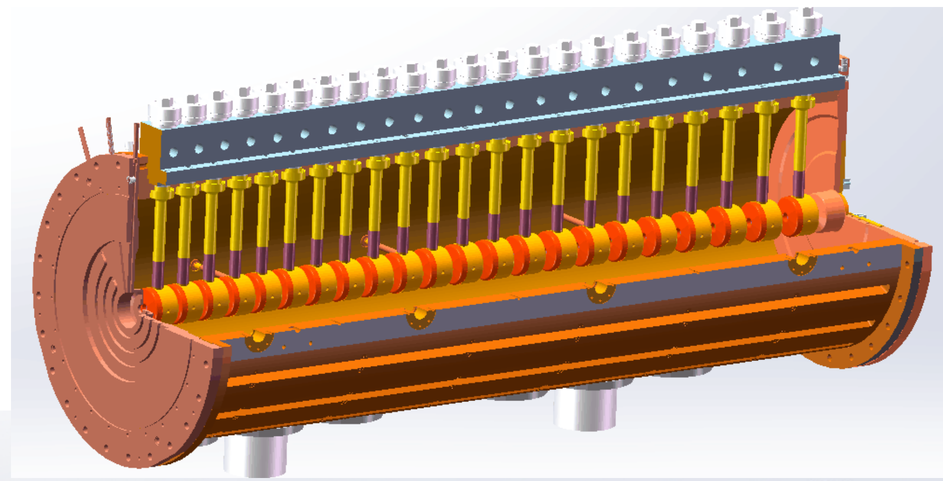


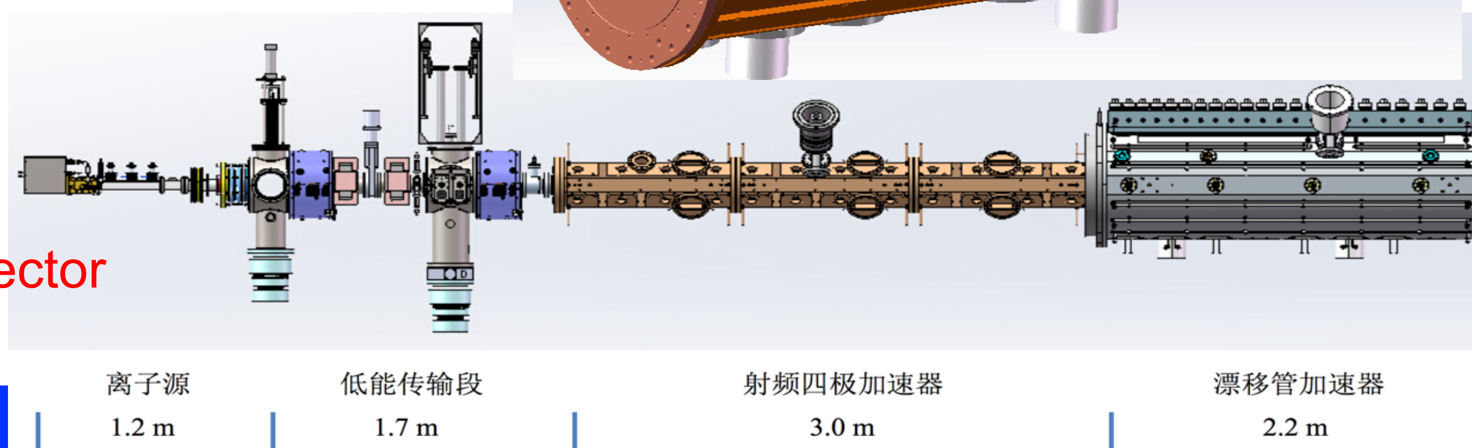
Assembly finished on Dec 2017

Linac injector of Xi'an Proton Application Facility (XiPAF)

Parameter	Value	Unit
Ion type	H^-	
Beam energy	7	MeV
Peak current	5	mA
Maximum repetition rate	0.5	Hz
Beam pulse width	10~40	μs
Normalized RMS emittance	<0.24	π mm•mrad







Design criterion & RF source consideration

Design criterion

- ✧ Control of capital cost

  - RF power source for the RFQ and DTL

  - Linac length

RF power source consideration

- ✧ Tetrode: the cheapest solution

  - 352 MHz with peak power of 350kW, duty factor of 4.9% for spoke cavities at ESS and FREIA（R. Yogi, Acc. Phys. & Inst., 2012）

  - Latest result of the high power test of the 4616V4 tetrode in Beijign: 500kW/peak power, 1 Hz/rep. rate, 150 μ /pulse width achieved (XiPAF)

- ✧ Required power consumed in the RFQ and DTL

  - <395kW (Considering a RF loss of 10% and a control margin of 15%)

DTL design

■ Transfer energy between RFQ & DTL

✧ Limited by the minimal injection energy into DTL

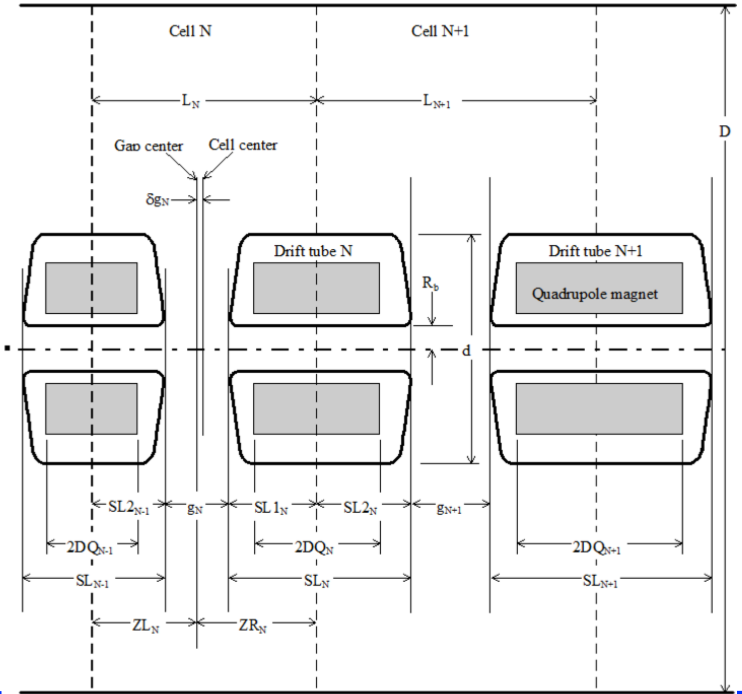
- Total length of the linac can be reduced by shortening the length of the conventional low-acceleration-gradient RFQ

✧ Minimal injection energy for DTL: determined by the first cell

$$\beta\ \lambda \geqslant L_1+2L_2+L_3$$

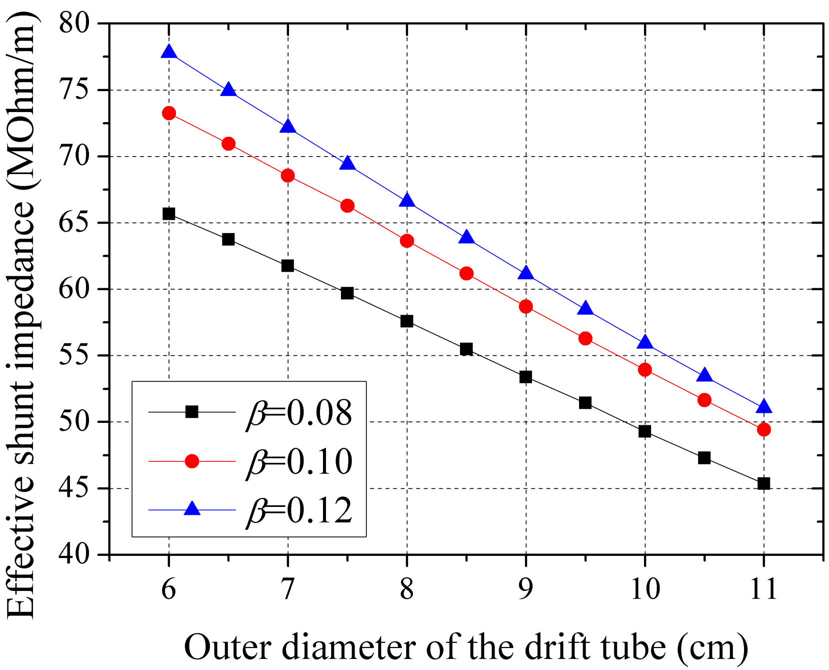
L_1 =40 mm: length of the PMQs
L_2 =10 mm: wall thickness of the dirft tubes
L_3: minimum distance between two adjacent tubes

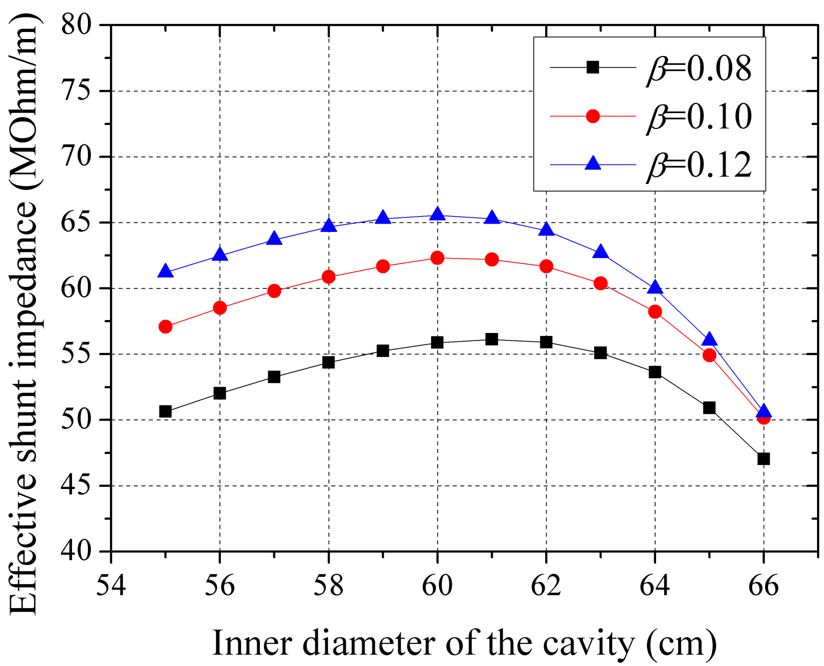
- $\beta \geqslant 0.076$ at 325MHz
- Minimal injection energy: 2.7MeV



DTL design

- Minimization of the dissipated peak power P in DTL
  - $P=(\Delta W)^2/(ZTT \bullet L)$ - ZTT: effective shunt impedance
  - Outer diameter of drift tubes: 8.4 cm

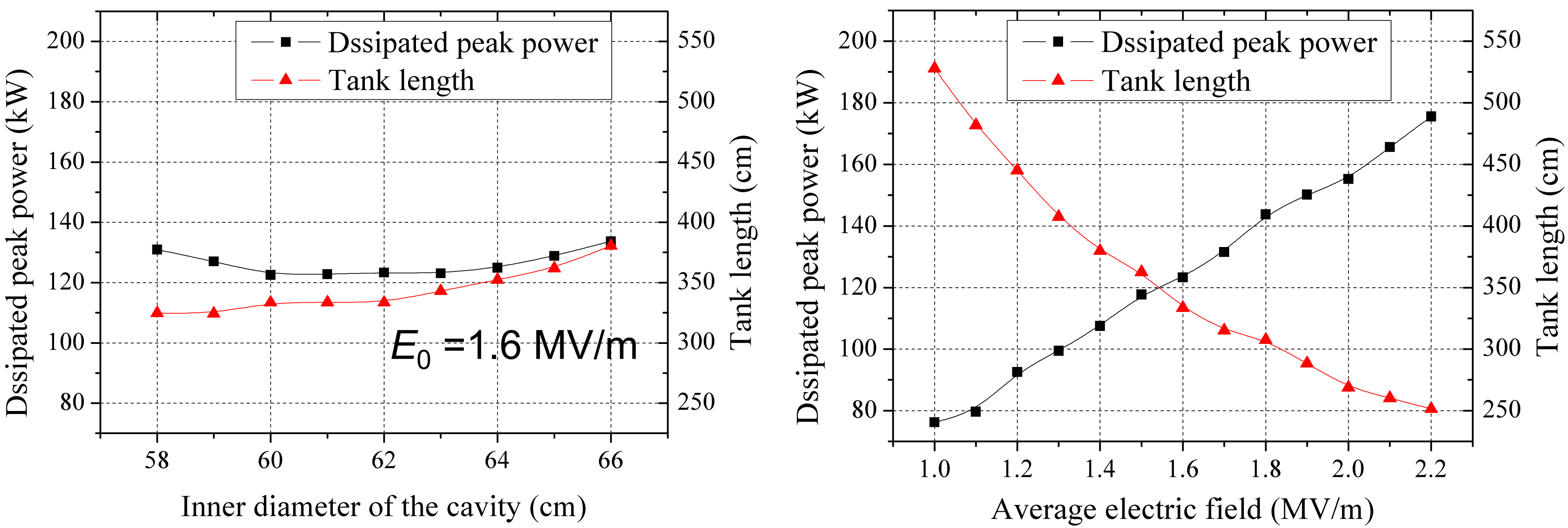




Effective shunt impedance of single cells with the outer diameter of the drift tube and inner diameter of the cavity by Superfish

Minimization of the dissipated peak power in DTL

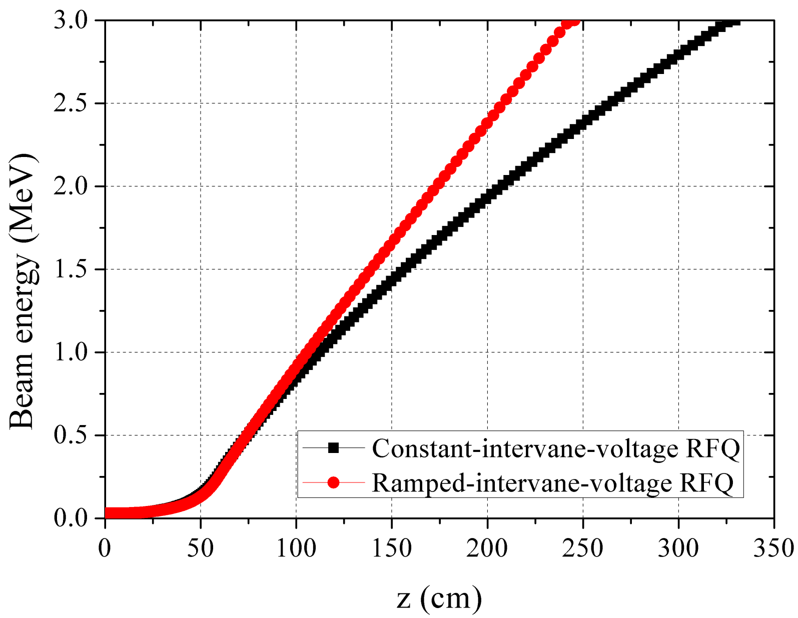
- Inner diameter of the cavity: 62cm
- Average electric field: 1.6MV/m
- Consumed peak power: 201kW (including beam power) by Superfish

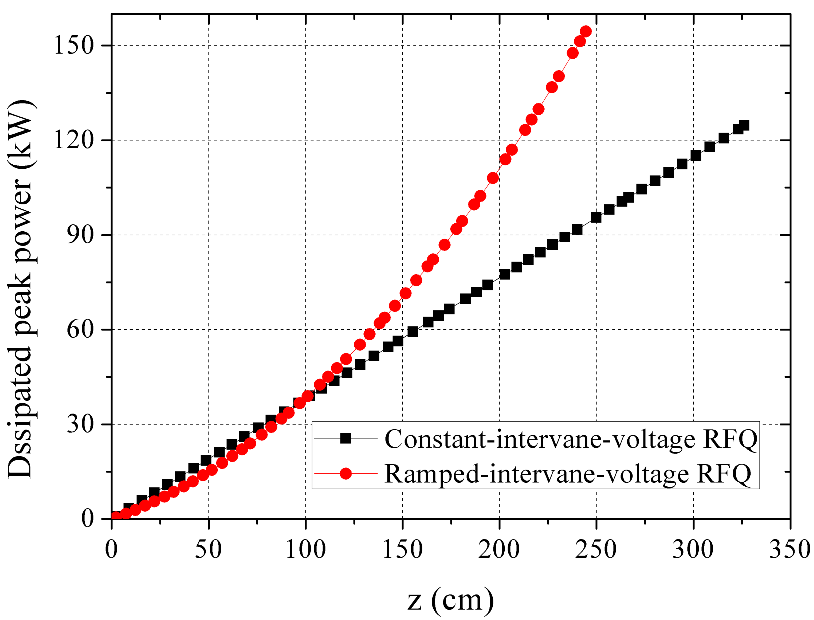


Dissipated peak power inside the DTL cavity (excluding the power loss on the end covers) and the tank length with the inner diameter of the cavity and average electric field by Parmila

RFQ design

- Minimization of the dissipated peak power in RFQ
  - Intervane voltage profile: constant vs ramped intervane voltage
  - Input beam energy



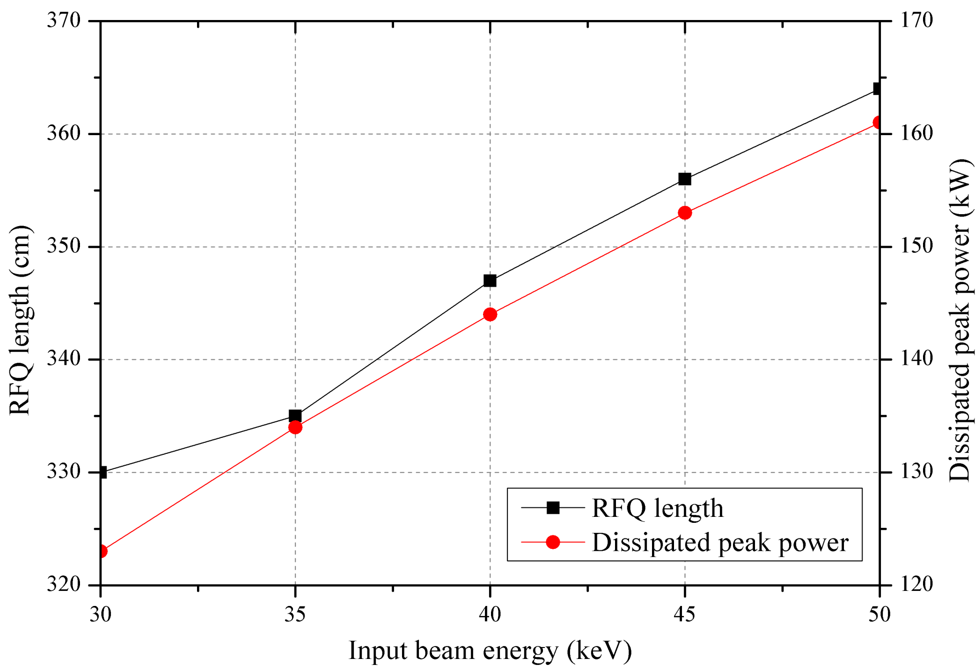


Comparing of two RFQ designs with constant and ramped intervane voltage. The input beam energy is 30keV. The intervane voltage is 50 kV for the constant profile and 36~107 kV for the ramped profile.

Minimization of the dissipated peak power in RFQ

- Input beam energy

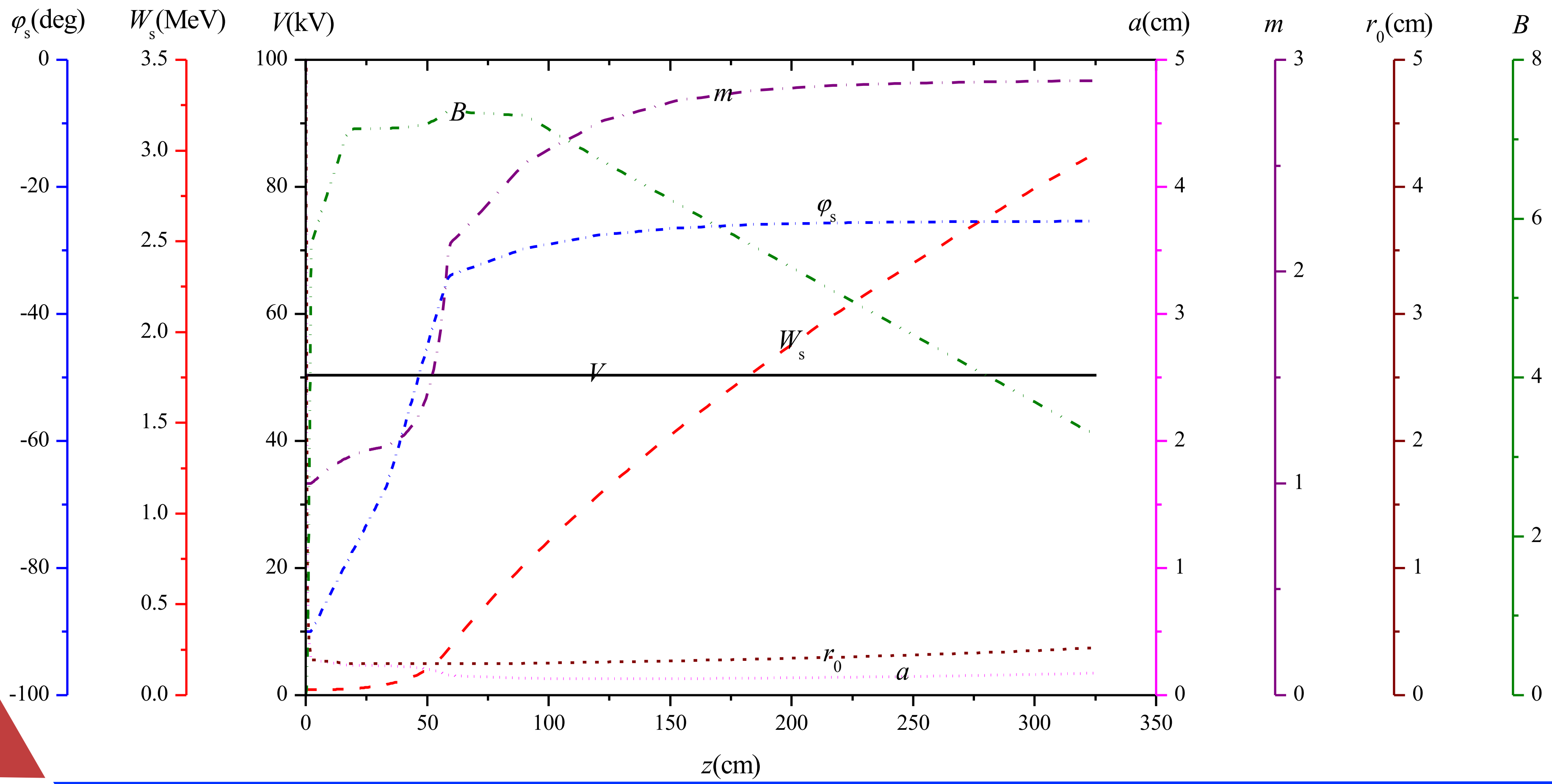
  - Lower energy leads to less length and less dissipated peak power
  - But space charge effect is stronger for lower input energy in LEBT
  - 30keV is selected



RFQ length and dissipated peak power as a function of the input beam energy. The intervane voltage is 50 kV.

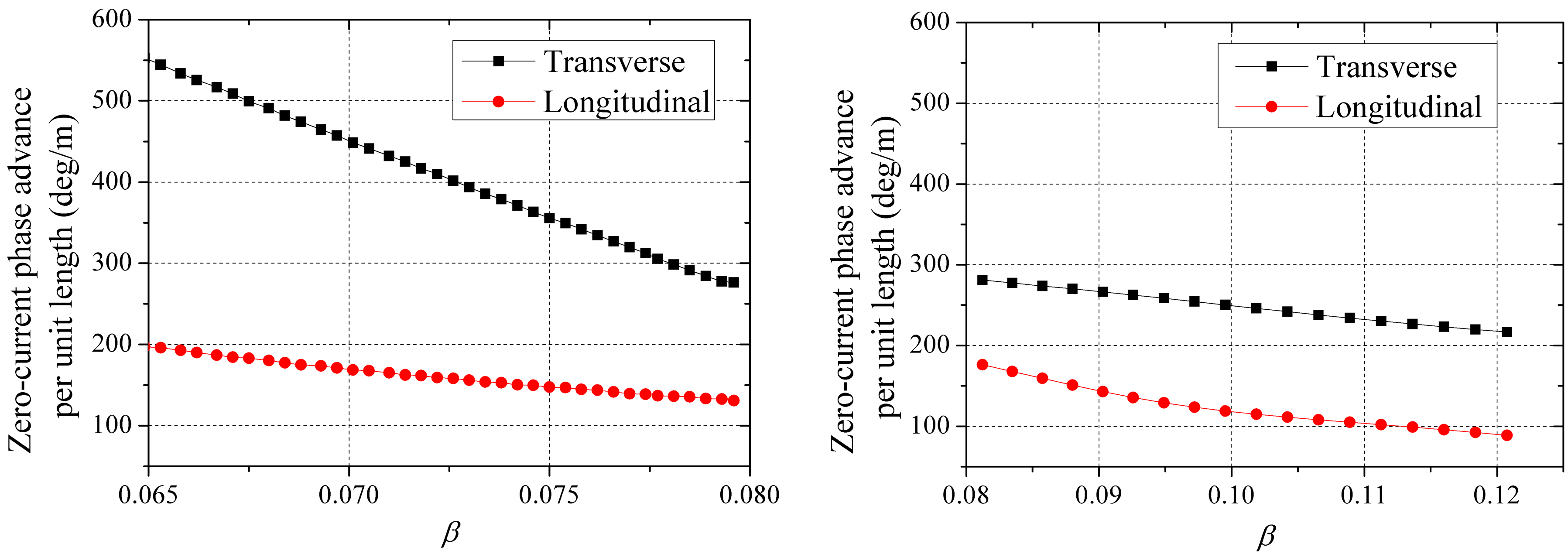
RFQ design

- Dynamics design of the RFQ by RFQGen
  - ✧ Consumed peak power: 177kW (including beam power) by Superfish



Match between RFQ & DTL

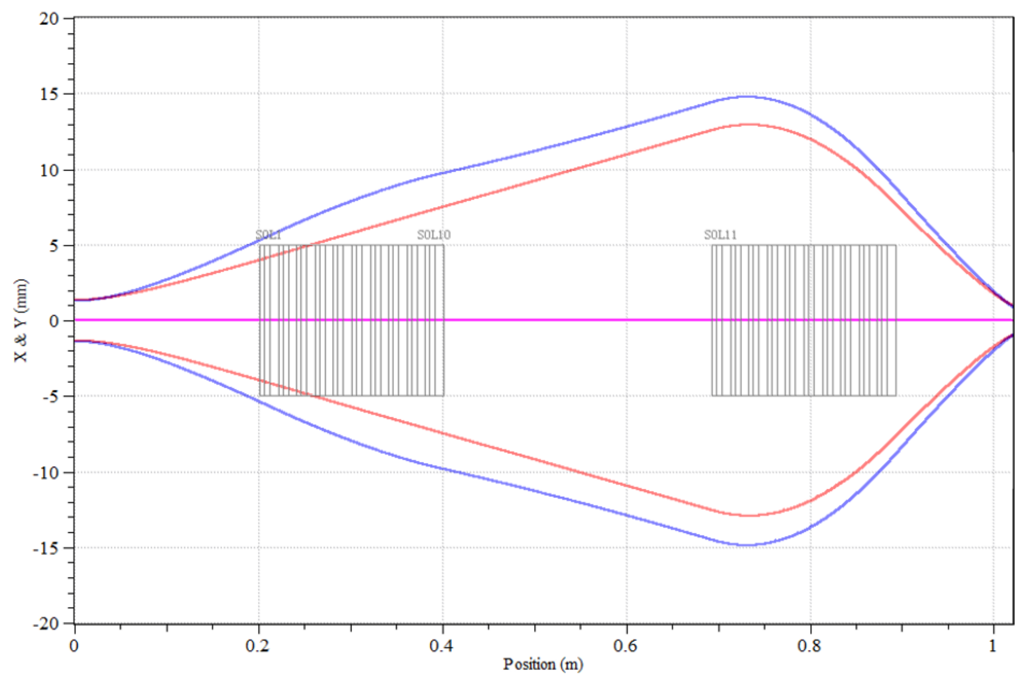
- **No-MEBT design**
  - Focusing strength B reduced at the high-energy part of the RFQ
  - $B=qV\lambda^2/(mc^2r_0^2)$, constant V leads to inconstant r_0
  - Constant gradient PMQs in DTL



Transverse and longitudinal zero-current phase advance per unit length with the relative velocity of the particle inside the RFQ and DTL cavities.

ECR source & LEBT

- ECR proton source
  - Peak current of proton: 15~25mA adjustable
  - Normalized RMS emittance: <0.2π mm•mrad
- LEBT
  - Two solenoids to match beam with the RFQ
  - Two steering magnets
  - One electric chopper provide desired pulse length of 40~100μs

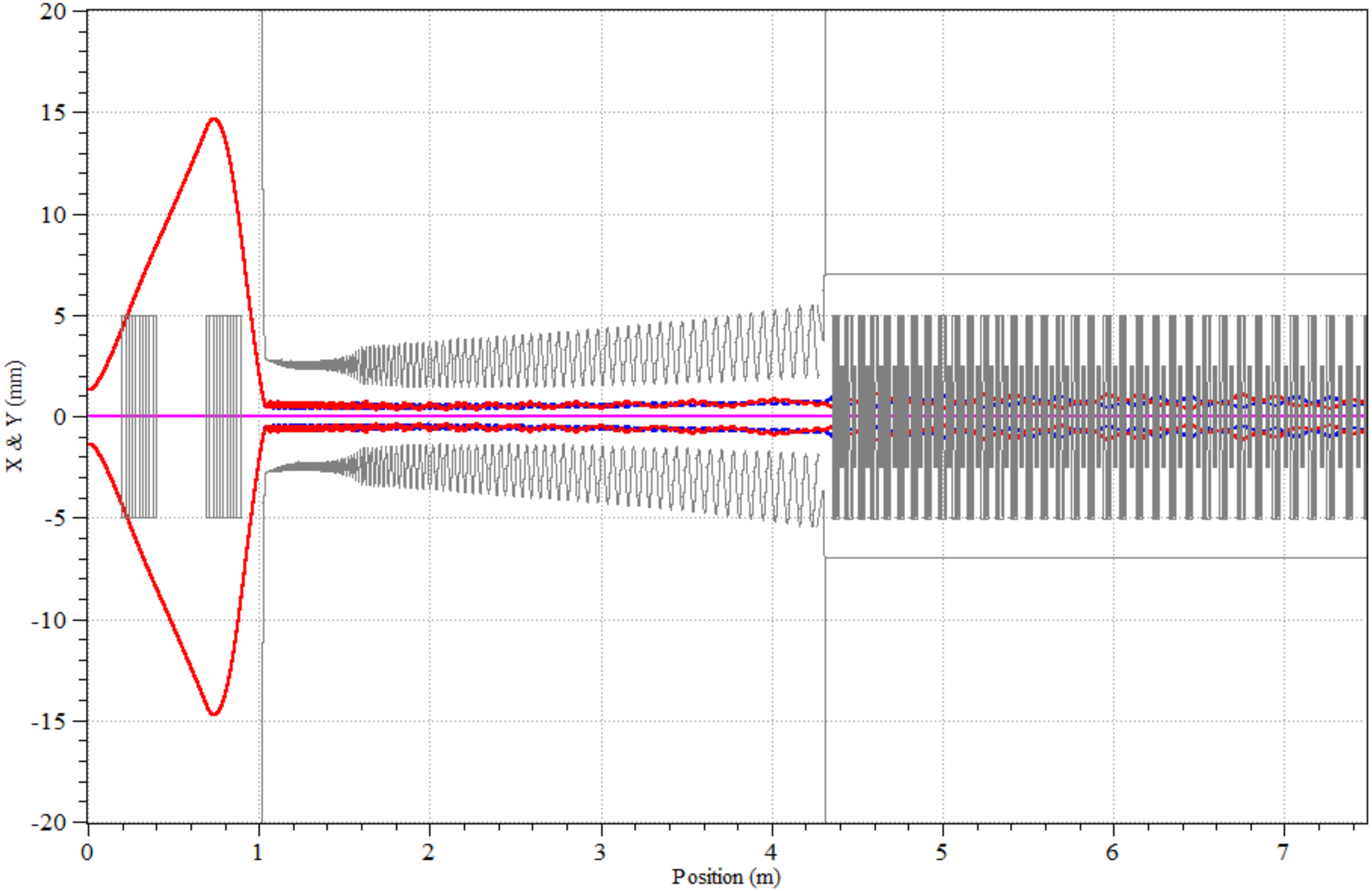


RMS envelop of the proton beam from exit of of the ECR source to the LEBT exit by Tracewin. Space charge compensation degree is 1 for the blue line and 0.7 for the red line.

Physical design result

PARAMETER	VALUE
Output energy of the ECR source	30 keV
Output energy of the RFQ	3 MeV
Output energy of the DTL	7 MeV
Output beam momentum spread of the DTL	±0.3% (14.5 mA)
Output peak current of the DTL	16.4mA
Output normalized transverse emittance (90% particles) of the DTL	0.91π mm•mrad
Dissipated RF peak power for the RFQ	177 kW
Dissipated RF peak power for the DTL	201 kW
Total RF peak power for the RFQ & DTL	378 kW
Length of the ECR Source and LEBT	1.42 m
Length of the RFQ	3.30 m
Length of the DTL	3.41 m
Total length	8.13 m

Start-to-end simulation



RMS envelop of the proton beam from the beam waist at the exit of the ECR source to the exit of the DTL by Tracewin (blue line: x direction; red line: y direction)

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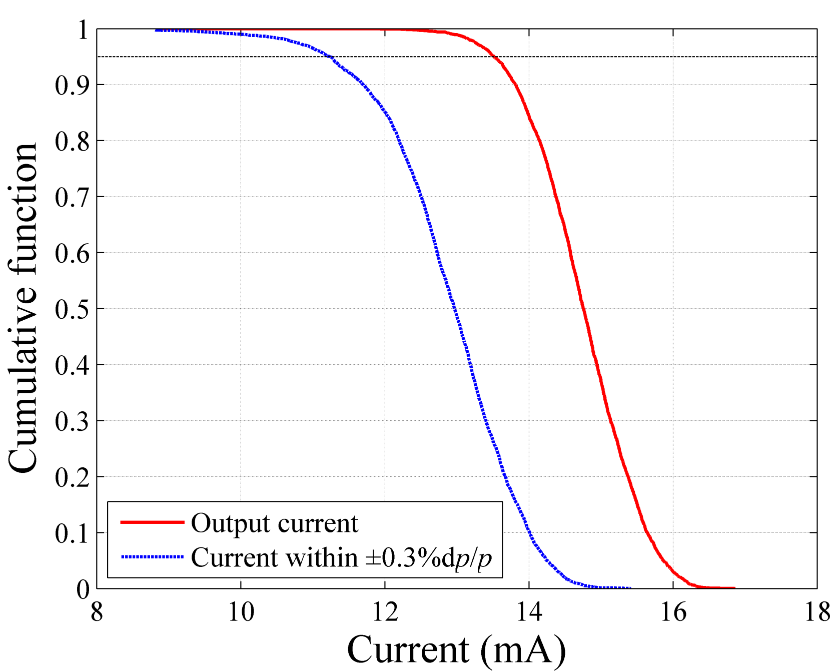
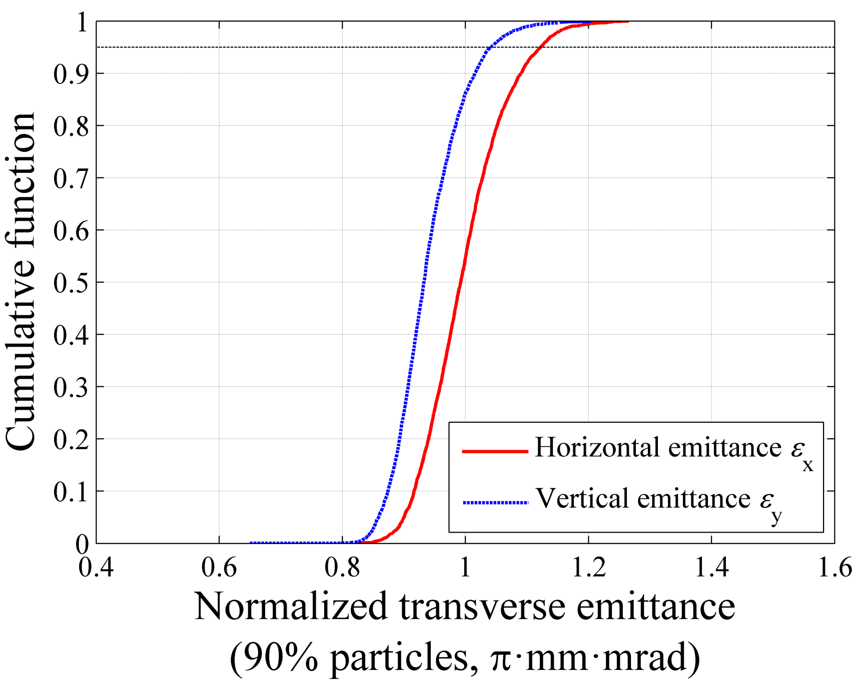
Error analysis

Error analysis

- Errors considered
  - Parameter errors of the input beam
  - Field errors of solenoids, quadrupoles and RF power
  - Machining errors of the RFQ vane-tip
- Simulation of 3500 times with uniform random error distribution
- Probability higher than 95% reached with the requirement of the peak current and the transverse emittance at DTL exit





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Summary

- One 7MeV proton linac injector being designed for the synchrotron-based proton therapy system
- Domestic mature technologies and cost control adopted
- Experience from CPHS and XiPAF project is beneficial
- One tetrode feeds the RF power to RFQ & DTL

谢 谢！

Thank you for your attention!