A Linear Accelerator for Proton Therapy.

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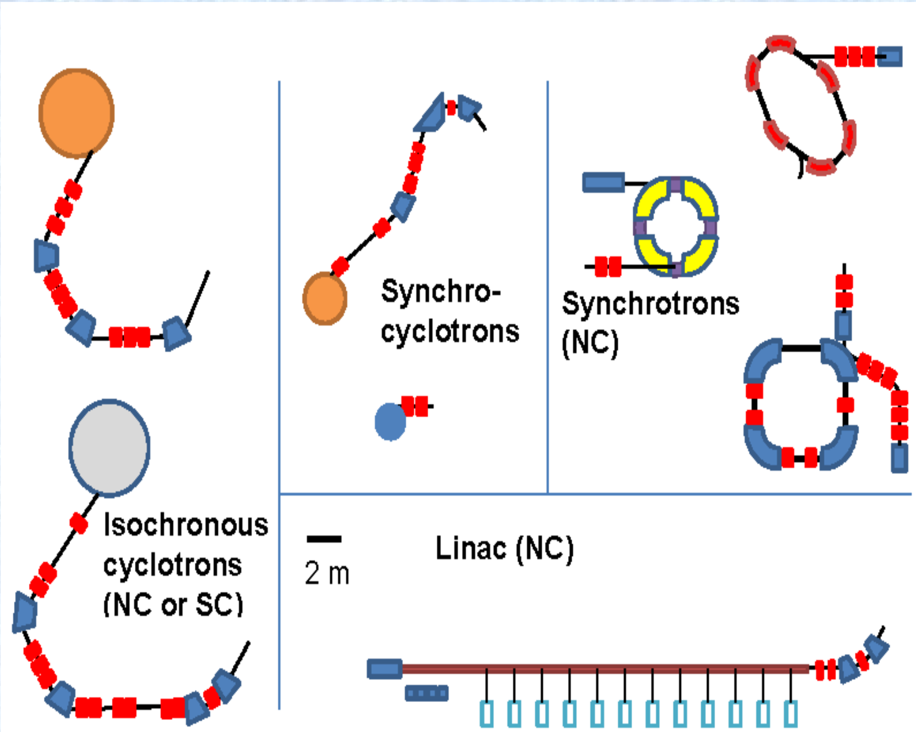
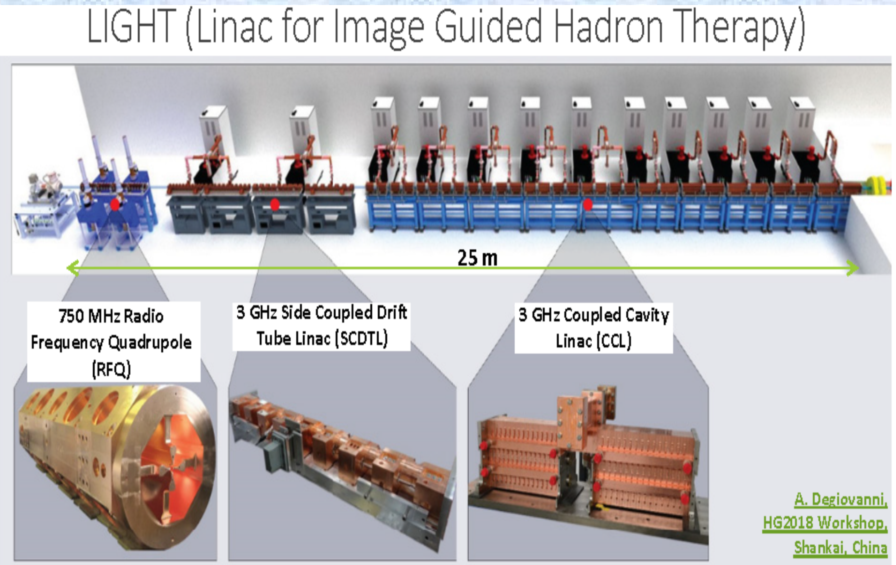
Accelerators for Proton Therapy

***LIGHT** is the mostly advanced linac project for today*





- Active energy modulation → no absorber and degrader
- Pulsed beam at 200 Hz → intensity and energy modulation in 5 ms
- Small beam emittance → small magnets aperture
- Almost no losses! → reduced shielding

→ beam suited for 3D spot scanning

Linac benefits

A. Degiovanni, NAPAC 2016.

Cornerstones for the design.

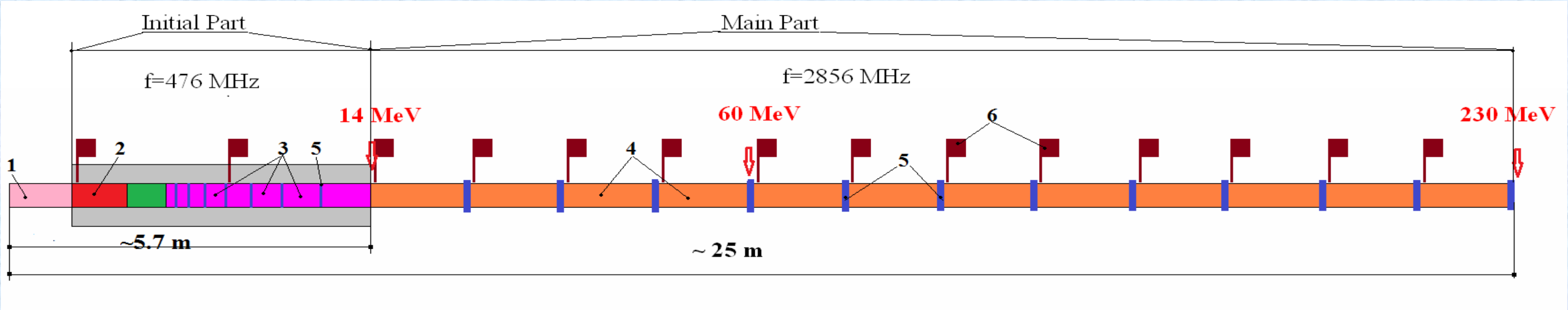
1. - wide functionality for both practical and research proton medicine;
2. – operational reliability, conservative systems parameters proven in long-term operation;
3. – the concept of a high-frequency multi-cavity low-current pulsed linac;
4. – pencil-like beam;
5. – mutual optimization, balance and feasibility of solutions for beam dynamics, accelerating and focusing elements;
6. - cost reduction, size reduction;
7. - the use of technologies and elements confidently mastered by the high-tech industry (or with guaranteed parameters upgrade);
8. - one button start with a minimal wake-up time,
9. – to be installed in regional PT centers.

Our development assistants.

1. - long-term experience in the operation and modernization of operating multi cavity linear proton accelerators;
2. - accumulated experience in understanding and managing interrelated processes in the accelerator;
3. - long-term experience in the development of both equipment for linear accelerators and projects for both national and foreign laboratories.

Linac scheme.

A classical proton linac scheme with some non classical proposals and operating modes.



1 - proton source, 2 – RFQ, 3 – DTL, 4 – TW structure, 5 – focusing elements, 6 – RF sources.

Functional purpose and particular features

Proton source ***- 60 kV pulsed proton beam with peak current up to 3 mA and emittance 0.1*** π ***mm mrad.*** *Formation is not possible. Beam collimation is possible.*

RFQ ***- pre-acceleration, bunches formation with small longitudinal emittance.***

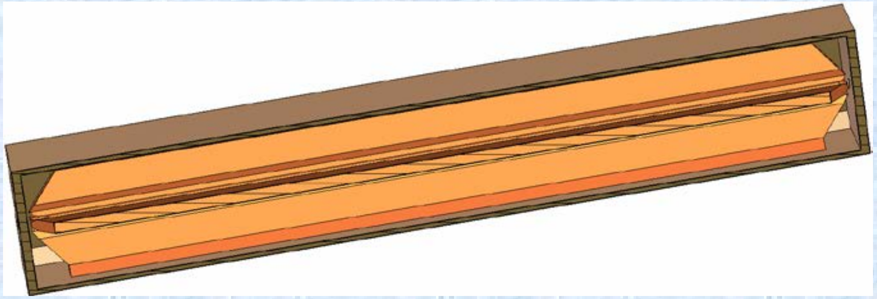
Initial Part ***- acceleration, collimation (below 7 MeV) and conservation of longitudinal emittance.***

Main Part ***- main acceleration, energy regulation, traveling wave structure.***

RFQ

Main RFQ parameters.

Parameter	Value
Frequency, MHz	476
Voltage, kV	75
Input energy, MeV	0.06
Output energy, MeV	1.56
E_{smax}/E_k	1.57
Length	1.48 λ



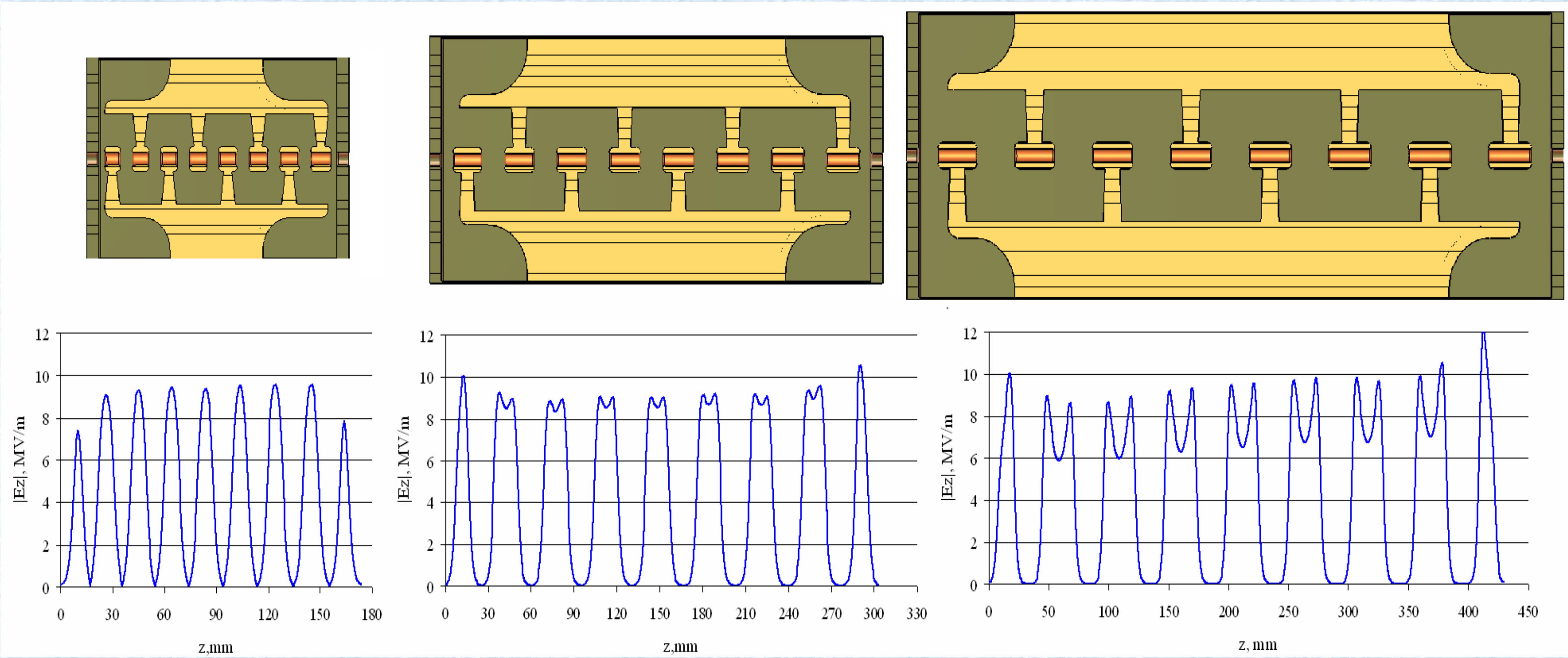
Particles distribution at RFQ output.

Low longitudinal emittance of the output bunches.

Accelerating Structure in the Initial Part

Low Q high Ze accelerating structure -, 11 IH DTL cavities

DTL 1, ***DTL 6,*** ***DTL 11.***



Esmax/Ek 0.96 -1.5

RF sources for the Initial Part

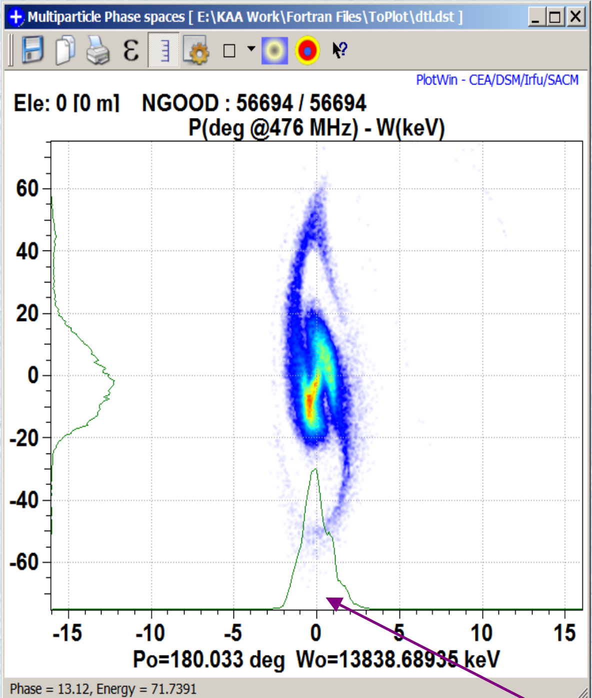
Pulsed RF sources, frequency 476 MHz, RF pulse length 80 μs, duty cycle ~250, full reflected power.

Cavity	Pimp
RFQ	124
DTL 1	15
DTL 2	18
DTL 3	22
DTL 4	25
DTL 5	33
DTL 6	35
DTL 7	38
DTL 8	43
DTL 9	48
DTL 10	55
DTL 11	62

G.B. Sharkov, LaPLAZ, Moscow, 2021

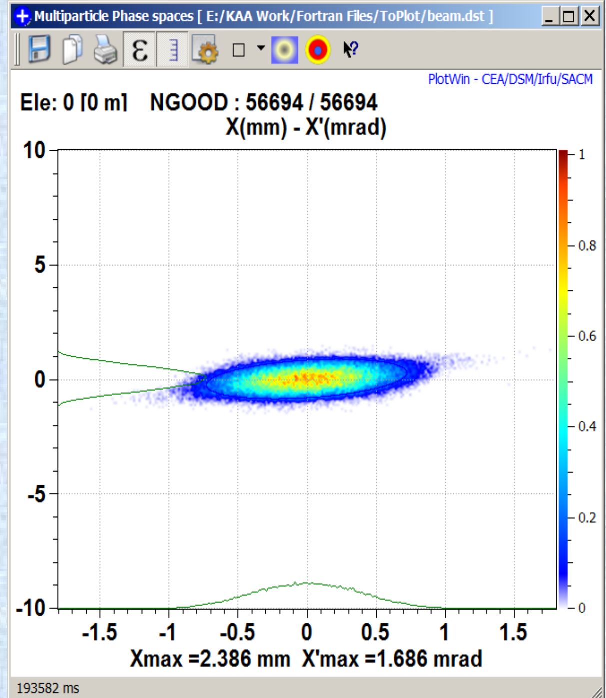
The total pulsed RF power ~520 kW, the total average RF power ~ 2 kW.

As the result at Initial Part output we expect:



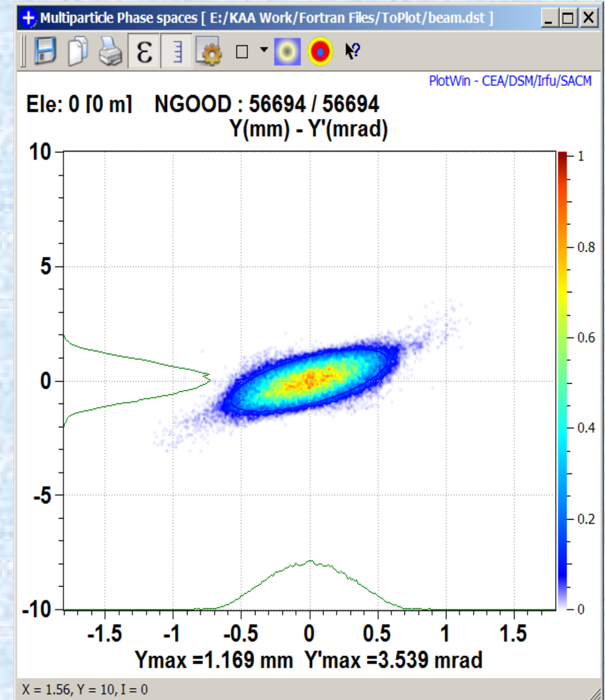
εz (rms) = 14.3709 π.deg.keV

εz (98.41%) = 100.5962 π.deg.keV



εx (rms) = 0.0258 π.mm.mrad

εx (96.41%) = 0.1032 π.mm.mrad



εy (rms) = 0.0258 π.mm.mrad

εy (96.41%) = 0.1032 π.mm.mrad

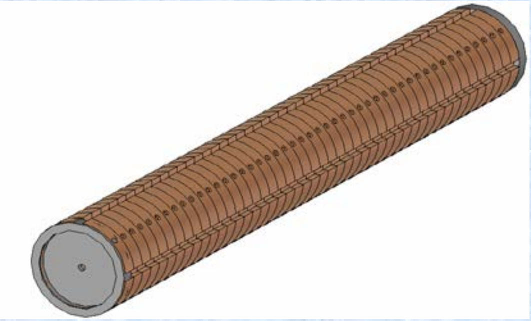
Transmission	*(MEBT-1 + DTL)*	*99.1%;*
Longitudinal emittance rise	*(DTL/RFQ)*	*1.20;*
Transversal emittance rise	*(DTL/RFQ)*	*1.01;*

The phase length of the bunch of ~ 4 degrees -

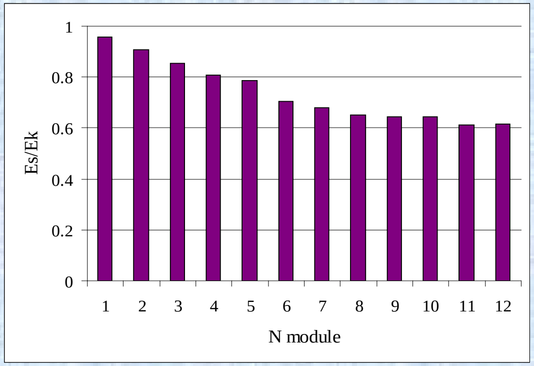
is extremely small for such proton energy;

A frequency jump of 6 times is possible!

Accelerating Structure in the Main Part

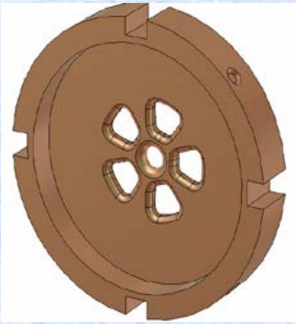


TW structure



Esmax/Ek ratio

1. – frequency 2856 MHz;
2. -traveling wave accelerating structure;
3. – constant gradient mode;
4. - 12 accelerating modules;
5. – application (as accelerating) backward (n= -1, at the beginning) and direct (n = 0, further) field harmonics;
6. the simple shape of magnetically coupled cells,
7. short filling time;
8. average accelerating rate (over the structure) of 13.2 MV/m;
9. moderate surface field;
10. sufficient vacuum conductivity.



Cell

Mastering the level of surface treatment with NC equipment and reliable operation in the future.

RF sources for Main Part

We need in total 144 MW of pulse RF power (average240 kW) .
Klystrons:

Parameter	***Mastered***	***Wishes***
Frequency, MHz	***2856***	***2856***
Output power, MW	***>5.5***	***12***
Pulse length, mks	***7-16***	***7-16***
Duty cycle	***>240***	***>600***
Efficiency	***>40%***	***>55%?***
Voltage, kV	***<55***	***< 65?***

https://toriy.ru/upload/iblock/e49/KIU_268.pdf

From experience of INR 600 MeV proton linac operation, we like MBK (KIU 40). But 24 klystrons looks extra. We have wishes, (realistic *)

Yu. Paramonov, private communications.

Modulators, promising development: ***Modular compact solid-state modulators for particle accelerators. Journal of Physics: Conf. Series 941 (2017) 012095***

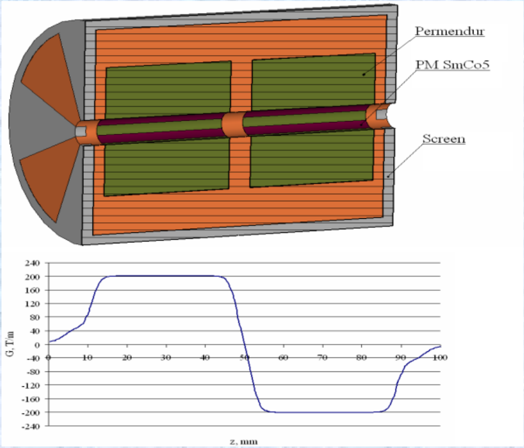
Upgrade is possible.
A. Zavadtsev, private communications.

Focusing Elements and Lattice

PMQ lenses with SmCo5 magnets.
Due to a small aperture of r < 4 mm the high focusing gradient can be achieved up to 260 T/m (simulations).

Initial Part,
PMQ doublets,
76 T/m <G<120 T/m

Main Part,
PMQ ,
G<215 T/m

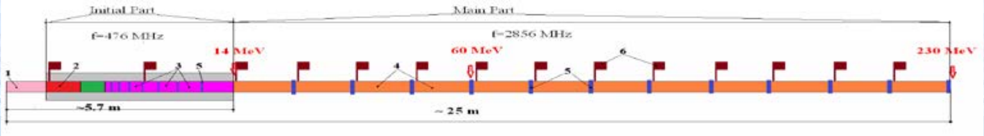


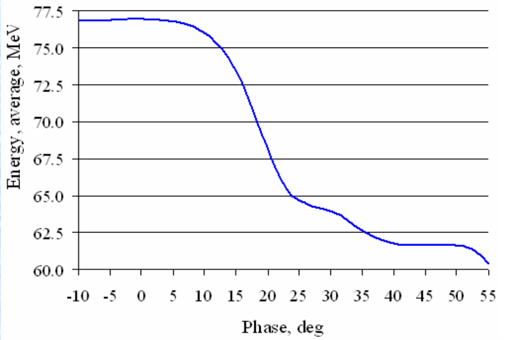
For details see A. Durkin et. al., LaPLAZ 2021, Moscow, v.2, p. 311

Reserve is sufficient. Not so easy, but possible.

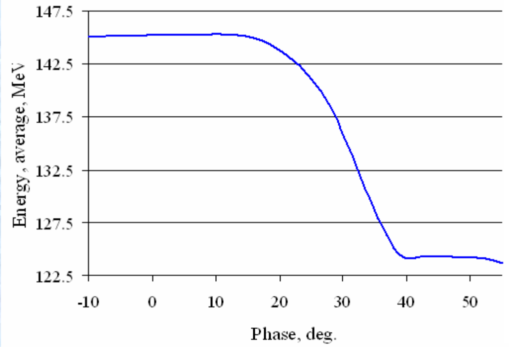
A. Picardi et. al., PRAB, 23, 020102 (2020)

Energy regulation

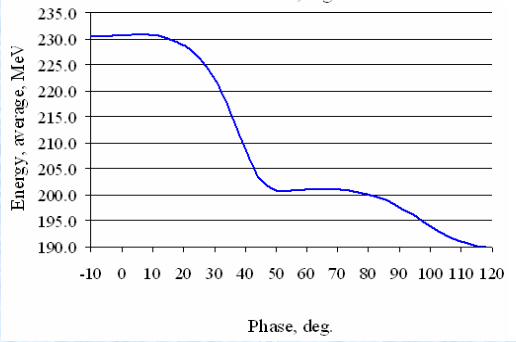




Modules 7-12 off



Modules 11-12 off



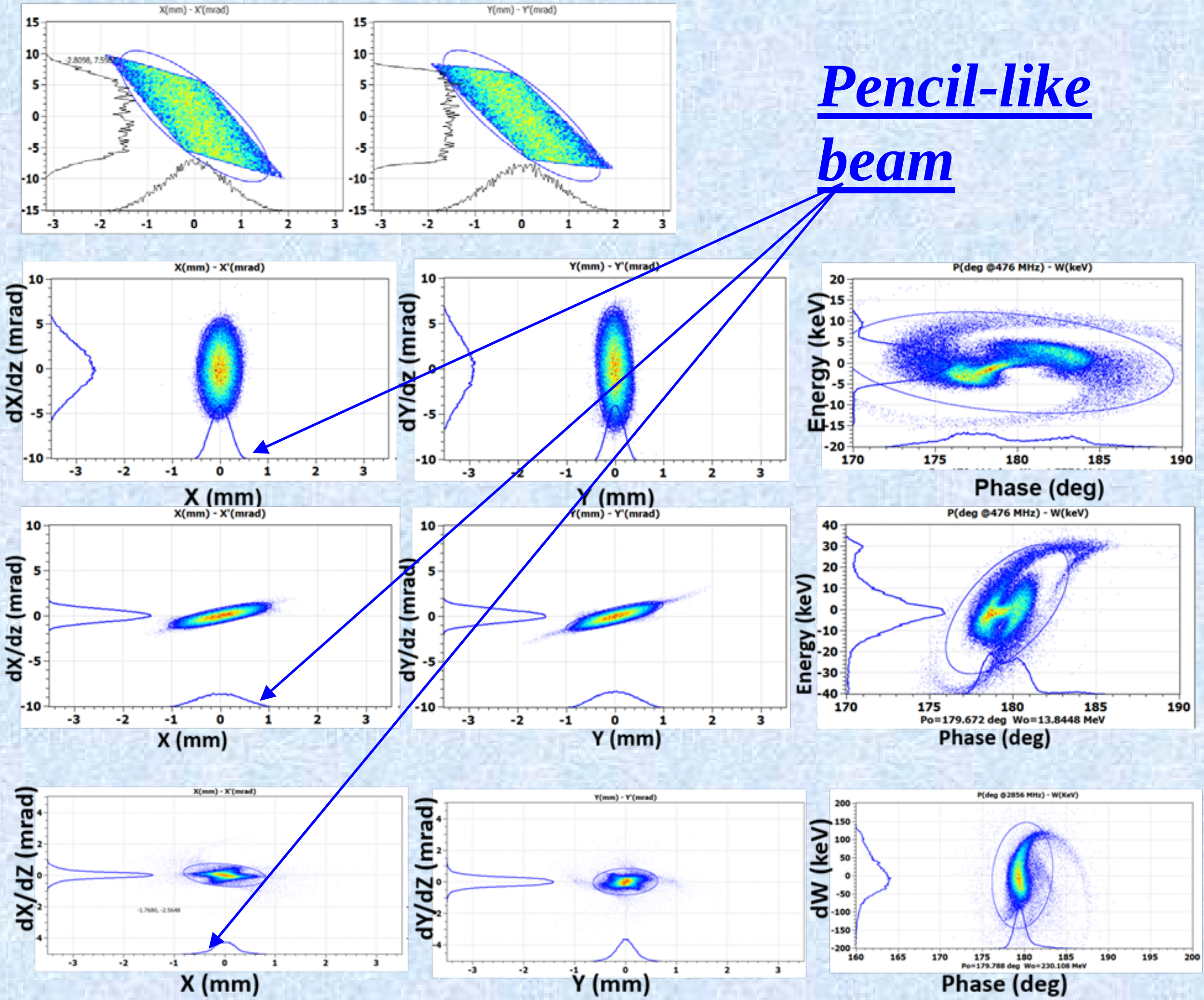
Last module – much more flexible.

The maximal energy changing time is from one RF pulse to another. The simplest option is manipulation with a RF phase in one module (subsequent ones are disabled). All time the beam envelope along the Main Part is within 1.0 mm.

Another options for energy regulations are under study.

Front – end simulations

Beam portraits in phase space



Pencil-like beam

RFQ input

RFQ output

DTL output

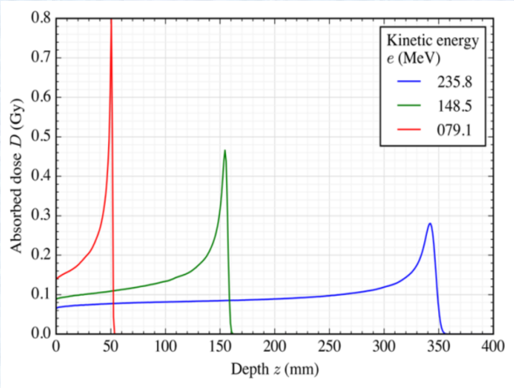
TW output

Main features

1. Output proton energy, max, MeV - 230,
2. Total length, m ~25.5,
*3. Pulsed operation, repetition rate, ~50 Hz,**
4. RF pulse length, μs, up to 16,
5. Energy regulation, range, MeV 60-230,
6. Time for energy change, ms, <20 (maximal – from RF pulse to pulse)
*7. Pulse beam current, mA up to 1.6, *,***
8. Number of protons in the bunch, up to $2.1*10^7$
** - to be defined at the stage of technical development;*
***- the concept works to the current up to 3 mA.*

Radiation effect estimates.

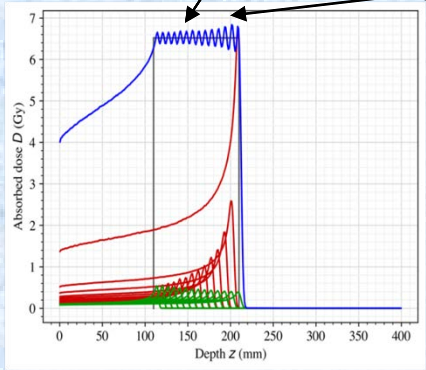
Poster MOPSC01 for details.

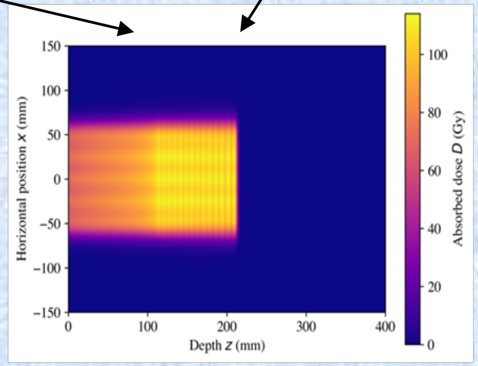


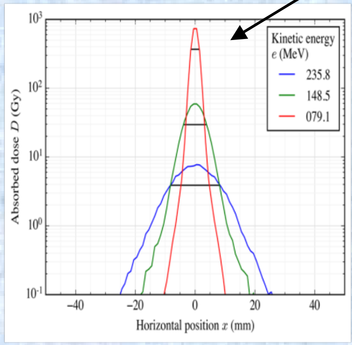
*For estimations – water phantom 10*10*10 cm^3*

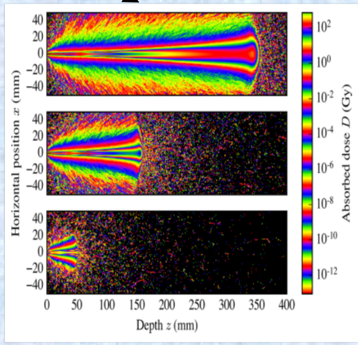
Mode

Therapy	*FLASH*	*Ultra FLASH*









Therapy	FLASH	Ultra FLASH
Spot scanning direct beam, reduced current,	*Fluffy spot 1.6 mA beam*	*Restricted volume direct beam, one pulse,*
t~15 sec.,	*t~ 0.5 sec.,*	*t ~ 15 μs*

SUMMARY

1. The physical substantiation of a proton linac for use in proton therapy is presented.
2. The functional capabilities of the linac ensure its use in both practical and research medicine.
3. To provide broad functionality, both traditional solutions are optimized and new proposals for accelerator systems are justified.
4. Conservative, long-term proven system parameters ensure reliable stable operation.
5. For the construction of the accelerator equipment, the mastered level of technologies and the characteristics of the equipment, achieved in the national high-tech industry are sufficient. The feasibility of the desired improvements is beyond doubt.
6. In terms of a complete set of functional, economic and operational parameters, the proposed linac surpasses both cyclic facilities and advanced foreign competitors.

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Thank You for attention!