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# A LINEAR ACCELERATOR FOR PROTON THERAPY

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*Abstract*

For applications in Proton Therapy (PT), linear accelerators can provide beam performances not achievable with cyclic facilities. The results of the development of a proposal for a linac, operating in a pulsed mode, with the maximal proton energy of 230 MeV, are presented. Possibilities of fast, from pulse to pulse, adjustment of the output energy in the range from 60 MeV to 230 MeV, formation and acceleration to the output energy of a 'pencil-like' beam are shown. Optimized solutions, proposed for both the accelerating-focusing channel and the technical systems of the linac make it possible to create a facility with high both functional, economic and operational features. Special attention, due to the selection of proven in long-term operation parameters of the systems, is paid to ensuring the reliability of the linac operation. The feasibility of linac is substantiated on the basis of mastered, or modified with a guarantee, industrial equipment.

## INTRODUCTION

Advantages of linacs for PT are known and one can see it in reviews [1,2]. Now the mostly advanced, in the stage of construction, is the LIGHT project [3]. To meet the high requirements for such linacs for applied purpose, sometimes system parameters are set that are more suitable in record-breaking linacs for research purposes. In this report we present the physical justification for the proton linac with wide functional possibilities but conservative, well mastered systems parameters.

## RATIONALITY AND FEASIBILITY

The cornerstones of this linac proposal are:

- - wide functionality for both practical and research proton medicine;
- - operational reliability through conservative systems parameters, proven in long-term operation;
- - cost reduction, size reduction;
- - deep mutual optimization, balance and feasibility of proposals for beam dynamics, accelerating and focusing elements;
- - focus on well mastered level of technologies and elements parameters confidently mastered in high-tech industry (or with guaranteed parameters upgrade);
- - to be placed in regional PT centres.

To meet all requirements, everyone will come to the concept of high-frequency, multi-cavity, low-current, pulsed proton linac with pencil-like proton beam. The main solutions and features are briefly discussed below.

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## SCHEME AND PARTICULARITIES

The linac is built according to classical scheme for proton linear accelerators at medium, up to 200 MeV, proton energies, Fig. 1.

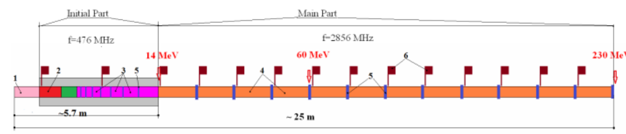


Figure 1: Linac scheme. 1 - proton source, 2 – RFQ, 3 – IH DTL structure, 4 – TW structure, 5 – focusing elements, 6 – RF sources.

The proton source provides 60 keV continuous proton beam with transverse emittance ~0.1 π mm mrad. Such beam can not be formatted, but confidently can be collimated from more powerful beam.

Further accelerator is in two parts. The initial part, operating with frequency 476 MHz, includes RFQ cavity, matching section and accelerating cavities. RFQ cavity provides pre-acceleration and formation of bunches with the small longitudinal emittance. Subsequent elements provide beam matching, allowing beam collimation at energies < 7 MeV, acceleration to energy ~14 MeV and preservation of emittance growth, both in transverse and in longitudinal directions. Operating frequency is selected as a compromise between beam dynamics requirements, parameters of accelerating elements and RF sources, taking into account further acceleration in the main part. As the result, at output of initial part we expect pencil beam with envelope of ~1 mm and extremely small, for such proton energies, phase length of bunches, ~4 degrees, see Fig. 2. In more details initial part of the linac is considered in [4].

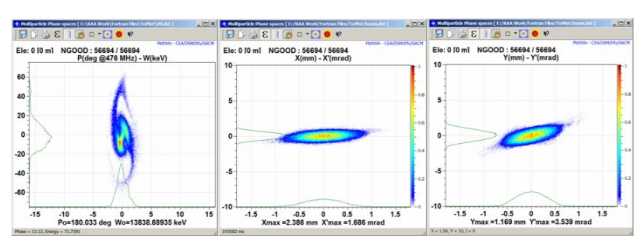

Figure 2: The phase space bunch portraits at the output of linac initial part.

In the main part, operating at frequency of 2856 MHz, protons will be accelerated for the maximal energy of 230 MeV. The value of operating frequency is selected both from commercial availability of RF hardware and parameters of accelerating strictures. In the main part the output proton energy can be changed fast in the range from 60 MeV to 230 MeV.

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## RF CAVITIES

The relatively short, ~1 in length, RFQ has a good, ~8 MHz, separation in frequency with dipole modes and provides bunch formation and pre-acceleration to energy ~1.6 MeV with the maximal electric field strength at the electrodes surface up to 1.57 Ek, where Ek is Kilpatrick threshold value, and RF pulsed power consumption up to ~ 125 kW, [4].

The beam pulse length of the linac is defined mainly by RF pulse length of klystrons in the main part. As for initial part, the length of beam pulse is much less as compared to field rise time in accelerating cavities. To decrease rise time, which is necessary but not useful, in initial part we need an accelerating structure with relatively low quality factor Q but with high effective shunt impedance Ze. Different structures were compared in [5] and Inter-digital H-type structure was selected. In initial part 11 relatively short, $4\beta\lambda$, from 155 mm to 410 mm in length, IH DTL cavities are applied, [4].

In the main part Travelling Wave (TW) accelerating structure is applied. For protons acceleration we can not allow strong field decay, typical for constant impedance TW option and constant gradient TW option is strongly preferable from proton dynamics. TW structure represents the simple disk loaded waveguide with magnetic coupling. It decouples the control over group velocity $\beta_{gr}$ and Ze value. The simplest shape of cells confidently allows production with modern NC equipment realising required ~10 mm precision. There are 12 accelerating modules, consisting from accelerating structure, RF source and focusing elements. In the beginning of main part TW structure operates with n=-1 backward harmonic of accelerating field. Practical proposal for protons acceleration with n=-1 harmonic was formulated in 90-th of previous century, [6]. Particularities of n=-1 harmonic application for protons acceleration was analysed in [7]. Now there are a lot of papers dedicated to development and tests of such option. With the average accelerating rate over TW structure of ~13.2 MV/m the ration of maximal electric field at the surface Es all time is lower Kilpatrick threshold Ek~45 MV/m for frequency 2856 MHz, see Fig. 3.

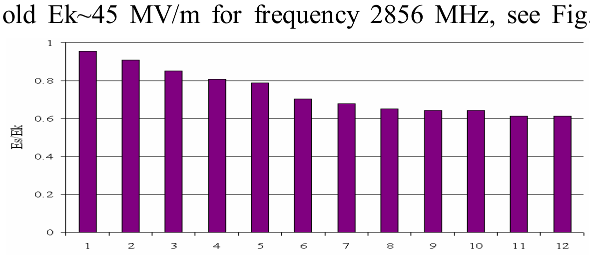


Figure 3: The maximal values of Es/Ek ratio for accelerating modules in the main linac part.

Such conservative Es value ensures, after short commissioning, stable structure operation without RF breakdowns. With such structure parameters we are far below from effects of pulsed RF heating, which can occur for higher accelerating gradient in the structure. Additionally, requirements for surface treatment during cells manufacturing are typical for S-band accelerations structures.

## RF SOURCES

With a reasonable, from practice, safety margins we need for initial linac part it total ~520 kW of pulsed RF power, with RF pulse length ~80 μs, non uniformly distributed between 12 RF channels. With duty factor value of ~250 the average RF power ~2 kW is rather low. Unified architecture and declared parameter limits of solid state RF amplifiers, described in [8], meet this specification.

For TW structure in the main linac part we need in total ~144 MW of pulsed, or ~ 220 kW average RF power. Multi Beam Klystrons (MBK) are very attractive due to lower cathode voltage ~60 kV. Commercially available are MBK with PMQ focusing and output RF power ~6 MW, [9]. But 24 klystrons for such short linac is not the best solution. Development of klystrons with different parameters is continuous process and MBK with 12 MW output RF power is quite realistic, [10]. For modulators there is interesting development of solid state units also with unified modular architecture, [11].

## FOCUSING ELEMENTS AND LATTICE

Both in initial and in main linac parts as focusing elements PMQ lenses with SmCo5 permanent magnets are applied. Due to a small aperture radius ~4 mm, according simulations, focusing gradient G up to 260 T/m can be achieved. There is example of practical PMQ realisation with G~200 T/m, [12].

In initial part PMQ doublets are applied with 70 T/m < G < 120 T/m, [4]. For the main part lattice options are investigated in [13]. In any case for PMQ in main part G < 215 T/m, showing a sufficient reserve with respect to calculated values.

## FRONT-END SIMULATIONS

Front-end simulations for beam dynamics are performed from RFQ input to linac output by using TRANSIT code [14]. Phase space beam portraits at the linac output are shown in Fig. 4. The beam has a small pencil-like diameter trough the total linac. In the current option transmission from DTL input to TW output is of ~95%. The bottle-neck points for these small particle losses are fixed and transmission will be improved in further development.

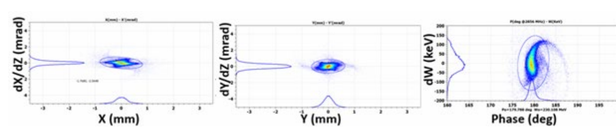


Figure 4: Phase space beam portraits at the linac output.

Space charge forces are essential in the linac beginning, especially RFQ, and affect mainly longitudinal motion. Short estimations have shown no essential changes in beam parameters for pulse beam current up to ~2 mA.

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## ENERGY REGULATION

The simplest method of proton energy regulation is the manipulations from RF pulse to pulse with the phase in one accelerating module, with switched off subsequent modules. This case from pulse to pulse we can get any energy between lower and upper energy limits for active module. The last module has wider control ability and even can decelerate protons, Fig. 5.

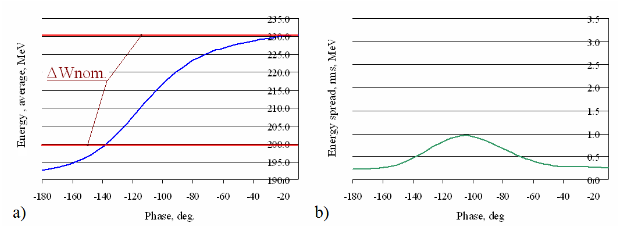


Figure 5: Dependencies of output energy , (a), and rms energy spread, (b), on the phase of RF field in the last accelerating module.

More sophisticated methods for output energy regulation are under development.

## MAIN FEATURES

Radiological effect of proposed linac has been estimated in [15]. With different operating modes, direct pencil-like or fluffy beams, short or long beam pulses and low, ~ µA scale, or medium, ~ mA scale, the dose both for practical PT and for FLASH mode can be delivered in required time. This parameters range is foreseen for proposed linac.

The summarized features of this linac proposal are:

- - wide functionality for both practical and research proton medicine;
- - the maximal proton energy – 250 MeV;
- - the total length ~ 25.5 m;
- - the range of output energy regulation – 60 MeV - 230 MeV;
- - the maximal time for energy regulation < 20 ms;
- - the maximal pulse beam current - up to 2 mA;
- - beam pulse length - up to 15 µs;
- - operational reliability through conservative systems parameters;
- - use of mastered level of technologies and elements parameters confidently mastered in high-tech industry (or with guaranteed parameters upgrade);

## SUMMARY

The physical substantiation of a proton linac for use in PT proton therapy is presented. The functional capabilities ensure its use in both practical and research medicine. To provide broad functionality, both traditional solutions are optimized and new proposals for accelerator systems are justified. Conservative, long-term proven system parameters ensure reliable stable operation. For the construction of linac 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. 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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