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NEW TRENDS IN PROTON AND CARBON THERAPY LINACS

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Abstract

In the last years, many developments have contributed to make feasible an all linac solution for proton and carbon ion therapy, with typical output energies of about 200 MeV and 400 MeV/u, respectively. The efficient beam matching of the source to the high-energy linacs, operating at 3 GHz, represents one of the major challenges. With the successful test of a 750 MHz RFQ at CERN, this possibility starts to be a reality. At the same time CERN is testing a high-gradient S-band cavity, successfully exceeding the accelerating gradient goal of 50 MV/m - more than twice what has been obtained before - and paving the way to more compact medical facilities. In this paper, some of the most significant projects involving linear accelerators for hadron therapy will be presented.

INTRODUCTION

The energy gain ΔW across a RF cavity is proportional to:

$$\Delta W \propto \sqrt{ZTT \cdot P_d \cdot L} \tag{1}$$

where ZTT is the effective Shunt impedance of the cavity, P_d is the dissipated power on the cavity walls and L the cavity length. Eq. (1) shows that, for a given energy gain and cavity design, one can either increase the power consumption P_d and decrease the cavity length L, or vice versa. At the same time, it can be shown that the cavity design, so its ZTT, is a function of the maximum accelerating gradient achievable, and in particular the higher the accelerating gradient, the lower is the ZTT achievable. Hadron therapy linacs can be thus divided into high-gradient and high-efficiency designs. Though arbitrary, the separation bar between the two approaches can be set at 30 MV/m accelerating gradient; linacs designed for values lower or equal than this threshold can be referred as high-efficiency designs.

Proton therapy linacs have been designed in both high-gradient and high-efficiency solutions. Carbon ions linacs have been predominantly designed in high-efficiency solutions, to limit the RF power consumption [1]. However in recent years a researchers are working on a high-gradient design for carbon ions [2]. The different projects are listed in Table 1.

Two of the most important developments of recent years have been started at CERN. Those are the construction and test of a 750 MHz RFQ [3,4] and of a 50 MV/m accelerating gradient 3 GHz cavity for a relativistic beta of 0.38 [5], corresponding to approximately 70 MeV/u. The 750 MHz RFQ solved the issue of the efficient low energy acceleration and control of the beam, bridging the gap between the ion source and the 3 GHz accelerating cavities. The 3 GHz cavity designed for 50 MV/m accelerating gradient showed that more compact linac designs can be conceived.

LOW ENERGY BEAM ACCELERATION

The low energy beam acceleration is probably the most difficult part in a linac design. Space charge does not affect a medical linac design thanks to the low beam current - average of few nA - needed. However, the need to reduce the footprint as much as possible makes the design challenging in many different ways.

A key aspect in this regard is the choice of the operating frequency f_{RF}. The scaling law $ZTT \propto \sqrt{f_{RF}}$ [6] relates the cavity effective Shunt impedance ZTT with the resonating frequency f_{RF}, and it is valid if the cavity beam aperture is scaled accordingly with the frequency. This is not always possible due to beam dynamics constraints, and in addition different geometries, as the drift tubes in drift tube linacs (DTL) or the septum thickness in coupled cavity linacs (CCL) are bounded in the minimum dimension by mechanical and thermal limitations. For these reasons, while in principle it would be ideal to increase the cavity operating frequency, in reality an optimum has to be found. For hadron therapy linacs it has been historically chosen a frequency of 3 GHz [7], in order to profit of the availability of relatively cost-effective power supplies developed for radiotherapy linacs. In [8] it has been showed that for a proton therapy linac design a 3 GHz solution has to be preferred over a 6 GHz one.

Before 2014, existing RFQs did not have high enough operating frequencies to efficiently inject the beam into the longitudinal acceptance of 3 GHz linacs. In the 2011 TOP-IMPLART project [9, 10] a 425 MHz commercial injector, composed by a 3 MeV RFQ and a 7 MeV DTL, inject into a 3 GHz side coupled DTL (SCDTL), with losses. Researchers proposed the so called cyclinac design [7], where a commercial cyclotron provides the beam acceleration up to 20 to 30 MeV for protons, and around 150 MeV/u for carbon ions, followed by the 3 GHz linac. In this case even higher losses occurred at the injection in the 3 GHz linacs.

The 750 MHz CERN RFQ was explicitly designed to inject into 3 GHz cavities, accepting losses in the RFQ itself but preserving full transmission and a good beam matching in the transition from 750 MHz to 3 GHz, thus maintaining constant the normalized beam emittance. The CERN 750 MHz RFQ is now successfully in operation [11] in the ADAM bunker in the CERN ALICE area.

For low energy beam acceleration, three different type of linear accelerators are usually considered: RFQs, SCDTLs and H-mode DTL cavities. A qualitative assessment of their advantages and disadvantages is proposed in Fig. 1. Each accelerator has been ranked from one to three considering four aspects: the RF efficiency, the maximum accelerating

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Table 1: Main Projects of Hadron Therapy Linacs

Linac	E acc [MV/m]	Structures	Status	Where
Proton linacs				
TULIP	40	RFQ, IH, SCDTL, BTW	Design, cavity prototype	CERN, Switzerland
TOP-IMPLART	NA	RFQ, DTL, SCDTL, CCL	Under construction	ENEA, Italy
ADAM Light	16	RFQ, SCDTL, CCL	Under construction	Geneva, Switzerland
Carbon ion linacs				
CABOTO	30	RFQ, IH, SCDTL, CCL	Design	CERN, Switzerland
ACCIL	50	RFQ, DTL, BTW	Design, cavity prototype	ANL & RadiaBeam, USA

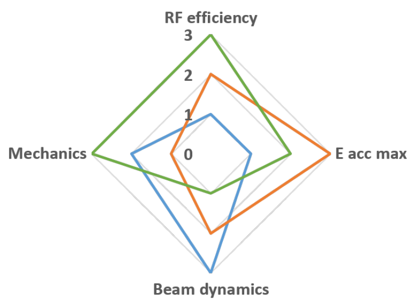

Figure 1: Qualitative assessment between RFQ, DTL and H-type cavities for low energy acceleration. RFQ in blue, DTL in orange, H-type cavities in green.

gradient E_{acc}, the beam dynamics control of the beam and the machinability.

RF Efficiency A simplified geometry, with constant drift tube thickness and stems radius independently on the geometric β, can be considered to preliminary assess the ZTT of different type of cavities using both TE and TM modes. If the structures cell gap is optimized at different geometric β_s, from 5 to 70 MeV/u, one obtains the results shown in Fig. 2.

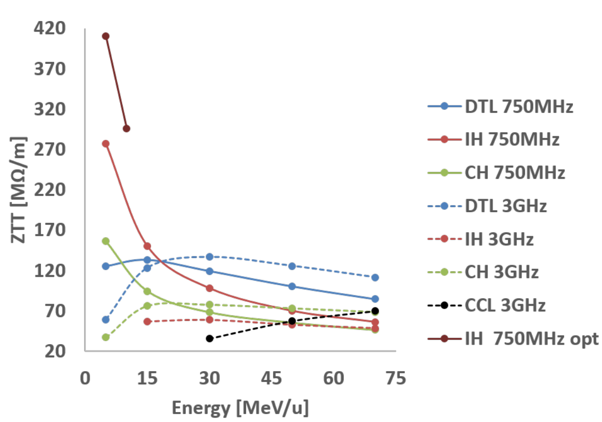

Figure 2: ZTT as a function of the RF cavity energy for different low energy RF cavities [12].

The bore aperture radius chosen is 2.5 mm. Promising cavities at 5 MeV/u are the 750 MHz IH and the 750 MHz CH. The 3 GHz DTL cavity, which is the most efficient choice for higher energies, has a cell length too small at 5 MeV/u, and it is ultimately not as efficient. If one considers only the ZTT, the crossing point between a 750 MHz solution and a 3 GHz solution is around 20 MeV/u.

The results of Fig. 2 hold for the TM mode cavities, as no current flows through the stems. Thus once the optimum gap is found, the thinner the drift tube and the drift stems are, the higher is the ZTT. TE mode DTL cavities have, on the other hand, current flowing through the stems. The induced Ohmic losses can be minimized by increasing the size of drift tubes and stems. However, this reduces the electric field concentration near the z axis. Ultimately, a detailed RF optimization is needed to find the optimum ZTT for a given cell length, taking into consideration machinability and thermal dissipation constraints. A more detailed discussion on the RF optimization of TE cavities can be found in [13]. The design of the optimized 750 MHz IH cavity for medical applications (dark red curve in Fig. 2) is discussed in [14].

The RF efficiency is strictly related with the cost of the facility, which for medical linacs is mostly given by the cost of the RF power sources. Preliminary discussions [15] quantifies in one order of magnitude the cost per peak power of a 750 MHz Inductive Output Tube (IOT) over a 3 GHz Klystron-modulator. This is the main argument to choose a 3 GHz cavity for the low energy acceleration of the beam. For a hadron therapy linac, even considering the cost argument, the crossing point between an high-efficiency 750 MHz H-mode DTL and a 3 GHz structure is at 10 MeV/u [12].

Beam Dynamics DTL cavities use a FODO focusing system to transversally control the beam. When the overall cavity dimension allows it, the focusing quadrupole are inserted in the drift tubes themselves. In the case of high-frequency designs the quadrupoles are placed in drift spaces between accelerating tanks, formed by more than one RF drift tube cell, and DTLs are then called SCDTL. From a beam dynamics point of view, a DTL is a good choice after an RFQ as one can preserve a FODO focusing system, and just needs to rematch the beam to the different transverse phase advance.

H-mode DTL are rather complicated structures from a beam dynamics point of view. In the end-cells takes place a

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transition from the TE mode of regular cells to a TM mode, due to the end walls. This decreases significantly the quality factor and thus the ZTT. For this reason, to fully exploit the RF advantages of H-mode DTL, those have to be composed by many RF cells. In this way the detrimental effect of end-cells is minimized. To transversally control the beam, the solution is to accelerate it at a low synchronous phase, either with a KONUS solution [16] or by simply choosing a low synchronous phase and adapting the RF cell with the relativistic β [14]. For this reason, a triplet focusing system is usually adopted, to maximize the acceleration length. The use of PMQs inside the drift tube of H-mode DTL [17] and hybrid RF accelerating-focusing systems were also studied [1]. In addition, in case of cavity designs with a small beam aperture, a dipole kick component is present and this has to be properly controlled [14].

In general, for the same operating frequency, the DTL beam control solution is considered to be simpler to design than for H-type cavities. However, if a 3 GHz SCDTL is compared to a 750 MHz IH, the latter proved to be a better choice. This argument was explicitly studied for a proton solution, where after the 5 MeV 750 MHz RFQ a 3 GHz SCDTL and a 750 MHz IH were compared [12].

It is interesting to discuss the equation of the RF defocusing [18], which is proportional to:

$$\Delta p_r \propto \frac{V_{gap} \cdot f_{RF}}{(\beta\gamma)^2} \tag{2}$$

Eq. 2 shows that, for a gap accelerating voltage V_{gap}, the RF defocusing increases with the RF cavity frequency f_{RF}, while it decreases with the square of the beam momentum $\beta\gamma$. Thus switching to higher frequencies increases the RF defocusing, but this is mitigated by the momentum scaling if done at higher energy. If for instance one chooses to accelerate at 3 GHz at 10 MeV/u instead that at 5 MeV/u, the RF defocusing decreases by 30%.

Maximum E_{acc} The maximum accelerating gradient E_{acc} that can be reached is not limited by breakdown (BD) phenomenon as in high-energy linacs. The two main constraints are instead the thermal RF power dissipation and the need to ensure a good matching with the RFQ output beam. DTL and H-mode DTL are critical in terms of power dissipation due to the bottleneck represented by the drift stems. DTLs were proposed with cooling channel inside the drift tubes, also in the 3 GHz SCDTL design [10]. H-mode DTLs have an advantage in this regard thank to the higher ZTT, however the cavity dimensions are too small and to the author knowledge no one has proposed an IH solution with cooled drift tubes. At the same time, a too high accelerating gradient immediately after the RFQ is unwise due to the longitudinal beam phase space shape at the RFQ output, that requires a smooth acceleration to avoid filamentation [1, 12]. In conclusion, it can be argued that a DTL can be designed with the highest accelerating gradient, as the stems can be made larger and with internal cooling without loosing too much ZTT as in a H-type solutions.

Mechanics Being 0 mode structures, DTLs are very prone to frequency perturbations. For this reason, post couplers are inserted in the geometry, and their resonator band is coupled to the main TM_{01} one [19]. A problem arises when the operating frequency increases: the small dimensions of the tank makes the tuning of the post couplers more difficult. In addition, the bandwidth of the cavity gets smaller at higher frequencies, thus it is more challenging to reach confluence between the post-couplers and the cavity dispersion curves. As a final note, post couplers affect the Q factor of the cavity due to surface currents, thus the ZTT of the DTL cavity is lower than the RF regular cell one. H-mode DTLs are easier to tune and to build. In a preliminary discussion, for the IH 750 MHz medical cavity [14], it was envisaged a similar construction and brazing procedure as for the 750 MHz RFQ [3].

FACILITY SIZE

A major research direction in the field of linear accelerators for hadron therapy is represented by the facility size. In the late 2000s, both researchers and private companies understood that compact, later called single-room, facilities would have been more flexible, patient-friendly, and would have helped in saving infrastructural costs. In 2013 Mevion treated the first patient with its S250 superconducting synchrocyclotron and the first single-room proton linac concept was presented [20]. In the past three years, one half of the 18 proton therapy centres that went into operation were single-room facilities [21].

The TULIP Project

TERA Foundation first proposed a single-room facility based on a cyclinac concept in 2013 [20], called TULIP (TUrning LInac for Proton therapy) [22]. The original idea was to have a commercial cyclotron on the floor, which injects into a linac mounted on a rotating structure around the patient (Fig. 3). As in the original design the linac had an accelerating gradient of 30 MV/m, TERA launched a high gradient research campaign, in collaboration with the CLIC group at CERN, to investigate the high gradient limit of S-Band accelerating structures [8, 23]. Based on the results of these tests, a high gradient (HG) backward travelling wave (BTW) accelerating structure for β=0.38 - approximately 70 MeV/u - with a 50 MV/m design accelerating gradient was built at CERN and is under-going testing [5, 24, 25]. This development allowed to reduce by a factor of two the length of the linac that has to be mounted on the rotating structure, saving size, weight and ultimately costs. The construction of the 750 MHz RFQ permitted to modify the initial cyclinac TULIP design to propose an all-linac high-gradient design (see Fig. 3), reducing the losses and improving the output beam quality.

The TULIP (Fig. 3) all-linac design [12] can be split into a low gradient section, to be placed on the ground, and a high gradient section, to be mounted on a rotating structure, called gantry. The footprint of the facility is driven by the

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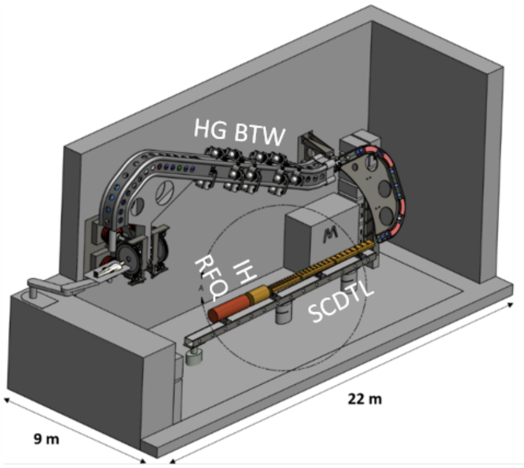

Figure 3: Sketch of TULIP all-linac solution (courtesy of M. Vaziri—TERA Foundation).

rotating structure, that has to integrate, together with the high gradient linac, also the high energy beam transport (HEBT) line and the beam diagnostic. As a result, about 10 meters are available on the ground to install the linacs that have to boost the particles up to 70 MeV. This length has been fully exploited, in order to minimize the power consumption for a given energy gain according to Eq. (1).

The design is based on a first acceleration up to 10 MeV in 750 MHz structures: the CERN RFQ [3, 4] and the newly designed Inter digital H-mode DTL cavity [14]. Particles are then injected into a 3 GHz linac chain composed of an SCDTL up to 70 MeV, and a HG BTW up to 230 MeV. The beam dynamics linac design downstream of the RFQ features full transmission and minimized emittance growth, and it has been accomplished with full tracking of the particles from the RFQ output up to 230 MeV. Misalignment studies were performed for the first time on a medical linac design validating the beam dynamics studies.

High-gradient S-band BTW Cavity

A HG BTW accelerating structure was designed and built at CERN [5, 24]. The main goal of the project is to define the high gradient limits of S-band cavities in terms of breakdown rate (BDR). In the RF design of the prototype a modified Poynting vector model was used [26]. The prototype cavity is 20 cm long and is designed for β=0.38. The cavity successfully reached accelerating gradients above 60 MV/m, as shown in the conditioning history plot of Fig. 4, thus exceeding the design goal of 50 MV/m. The asymptotic BDR at 60 MV/m is $4 \cdot 10^{-6}$ break-down per pulse (bpp) [25] at 1.2 μs pulse width.

CARBON ION LINACS

The use of carbon ions in radiotherapy oncology is motivated by their higher radio-biological effectiveness - RBE - in treating radio-resistant tumours. The downside is the higher mass per unit charge than protons, so carbon ion linacs are bigger, and more expensive, than proton linacs. Specifically,

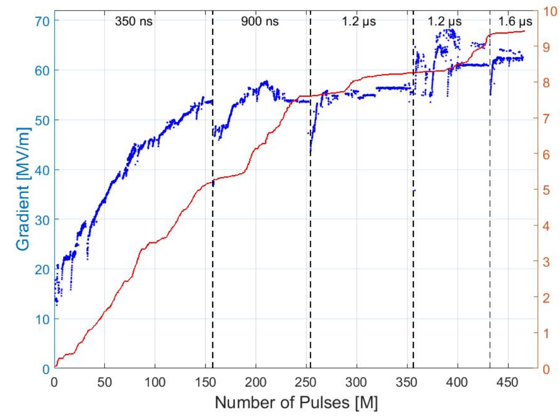

Figure 4: Conditioning history of the first BTW prototype, tested at CERN Sbox [25].

carbon ions require twice as much kinetic energy per nucleon than protons to travel the same distance through matter, and twice as much voltage, in the most favourable case of fully stripped ions, to reach the same energy per nucleon. Thus, a factor four lies between the overall voltage gain per nucleon of a carbon ion therapy linac over a proton one.

The CABOTO Project

As for the TULIP project, the CABOTO project [27] was initially conceived in a cyclinac design [28], with a cyclotron delivering a beam of fully stripped carbon ions at 150 MeV/u and a 24 m long linac boosting the beam up to 410 MeV/u [29]. In this initial study, the linac was designed with a resonant frequency of 5.7 GHz. In [8] a 3 GHz frequency linac is instead proposed and compared with the 5.7 GHz one, and a 70 MeV/u cyclotron was considered. In CABOTO, the beam losses at the cyclotron to linac injection are more critical than in TULIP due to the higher beam energy, 150 MeV/u with respect to the 24 MeV proposed for TULIP.

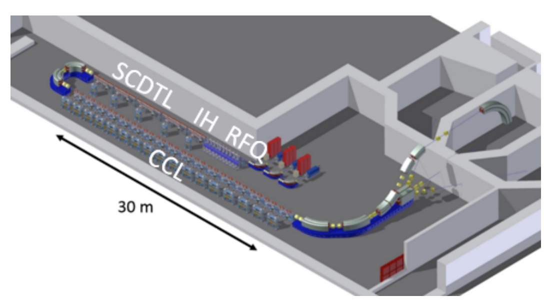

Figure 5: Sketch of CABOTO all-linac solution (courtesy of M. Vaziri—TERA Foundation)

An all-linac solution for fully stripped carbon ions acceleration is proposed in [1], with a final energy of 430 MeV/u (Fig. 5). To reduce the footprint, the linac is split into two branches of equal length. The ion sources, RFQ, IH and SCDTL form one branch, and a CCL the other one. The bottleneck is represented by the CCL section, that has to boost the C^{6+} ions

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from 100 MeV/u to 430 MeV/u, therefore a total voltage of 660 MeV. The 100 MeV/u bend was chosen on purpose. In fact, modulation of the beam energy should start at this level, which is equivalent to 70 MeV for protons [30] in terms of penetration in water equivalent tissues. This is convenient, since the beam momentum will change just after the 180 deg bend, thus the dipoles and quadrupoles of the bending can have a static field, and be more cost-effective. For the CCL, an average accelerating gradient of 30 MV/m was chosen, considered an optimum between facility size and power consumption. This choice results in a 30 m long CCL section, which then represents the target for the other branch. Given that ion sources, RFQ and IH cavities are more driven by beam dynamics and power consumption optimization, the length constraint reflects mostly in the accelerating gradient of the DTL linac, resulting in an average value of 15 MV/m.

Thanks to the low RFQ output emittance, in the CABOTO all-linac design it was possible to propose a peculiar beam dynamics design with beam aperture tapered from 2.5 mm to 2 mm in the SCDTL linac, and constant 2 mm in the CCL linac, increasing by 15 % the average ZTT. As a result, the all-linac CABOTO design [1] has the same power consumption of the cyclinac design [8]. As for the TULIP project, a full transmission with a negligible emittance growth is accomplished, with 430 MeV/u output energy, and misalignment studies were performed.

TwinEBIS and the 750 MHz C^{6+} RFQ

TwinEBIS is an Electron Beam Ion Source (EBIS) recently made operational at CERN [31] with a 2 T solenoidal field strength. Goal of the project is to provide a C^{6+} source with 300-400 Hz repetition rate, and 10^8 C^{6+} within 1.5 μs pulse [32]. As such, an ideal injector for high-frequency carbon ion linac as CABOTO, allowing to deliver final beam currents more than ten times larger than state-of-art carbon therapy synchrotron [1]. At the time of writing, beam measurements on the ionising electron beam are under way [33], and beam emittance measurements are being set.

At CERN, the same group that built the 750 MHz proton RFQ is working on a C^{6+} carbon ion RFQ operating at the same RF frequency. Two solutions have been considered, a 2.5 MeV/u design and a 5 MeV/u one with approximately double length and power consumption. For both the two designs, the transmission and output normalized emittances are similar to the already built proton RFQ [34].

The ACCIL Project

The Argonne National Laboratory (ANL), in collaboration with RadiaBeam Technologies, is studying a compact carbon ion linac, named Advanced Compact Carbon Ion Linac (ACCIL) [2]. Two main differences exist with respect to the CABOTO project:

- the use of a commercial ECR ion source, delivering C^{5+}, that are further accelerated by a 476 MHz RFQ until 3 MeV/u and then stripped to C^{6+};
- the choice of a high-gradient solution for the high-energy linac, operating at a 50 MV/m accelerating gradient.

A travelling wave cavity similar to the one developed for the TULIP project [12] has been considered for the high-energy linac - from 45 MeV/u to 450 MeV/u - and is being built [35].

HIGH-ENERGY PROTON THERAPY

With high-energy proton therapy (HEPT) one can treat and at the same time produce a radiography of the patient. A 350 MeV proton beam has a range of more than 60 cm in water equivalent tissue (WET), so it traverses a patient body and can be used for proton radiography. From a treatment point of view, the smaller lateral penumbra of an high-energy beam permits to treat the critical boundaries of the tumour volume, such as the ones near a critical healthy structure.

The IMPULSE project, started at PSI in collaboration with TERA Foundation in 2011 [36] proposed a high-energy cyclotron for this purpose. In [37] it is proposed to couple the PSI proton therapy cyclotron to a 3 GHz linac to accelerate the protons from 250 MeV to 350 MeV.

Similarly, in [38] is proposed a similar approach considering as a starting point the 250 MeV Christie Hospital cyclotron in Manchester, UK.

COMMERCIAL DEVELOPMENTS

The CERN spin-off company ADAM is constructing and testing the first commercial linear accelerator for proton therapy [11, 39], called LIGHT (Linac for Image-Guided Hadron Therapy). Based on the original design presented in [7], LIGHT is composed by an ECR source, followed by the CERN 750 MHz RFQ, a 3 GHz SCDTL and a 3 GHz CCL. At the time of writing, the machine commissioning is ongoing, with reported results of beam acceleration up to 16 MeV, at the output of the second SCDTL module.

SUMMARY

The research on hadron therapy linacs produced significant breakthroughs over the past years. CERN had a leading role in the field, with the test of a high frequency RFQ and of a high-gradient accelerating cavity. These developments solved two of the biggest challenges: the efficient acceleration of low energy beams and the size of the facility. All-linac designs for proton and carbon therapy linacs have been designed, and two projects are currently under construction, the ADAM Light in Geneva and the TOP-IMPLART in Rome. The research effort is now focused on carbon therapy linacs, where the biggest advantages over state-of-art synchrotrons is present.

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