KEK Report 92-10
July 1992
A

Proposal of a Separated-Type Proton Drift Tube Linac for a Medium-Energy Structure

Takao KATO

NATIONAL LABORATORY FOR
HIGH ENERGY PHYSICS

KEK Reports are available from:

Technical Information & Library
National Laboratory for High Energy Physics
1-1 Oho, Tsukuba-shi
Ibaraki-ken, 305
JAPAN

Phone:	0298-64-1171	
Telex:	3652-534	(Domestic)
	(0)3652-534	(International)
Fax:	0298-64-4604	
Cable:	KEKOHO	

PROPOSAL OF A SEPARATED-TYPE PROTON DRIFT TUBE LINAC FOR A MEDIUM-ENERGY STRUCTURE

Takao KATO
KEK, National Laboratory for High Energy Physics
Oho 1-1, Tsukuba-shi, Ibaraki-ken, 305, Japan

Abstract

A separated-type drift tube linac for medium energies from 150 to 300 MeV is proposed for a continuous-beam proton linac. The average effective shunt impedance increases by 55% compared with that of an alternating-periodic structure of the on-axis coupling type. Some technical difficulties in the manufacturing, alignment and cooling of the drift tube linac are greatly reduced by eliminating the focusing quadrupole magnets from the drift tubes. A modified design of a high-energy, high-average current 1-GeV proton linac with a continuous-beam is presented. It is pointed out that sudden transitions of focusing forces on both transverse and longitudinal motions, due to a change in the type of accelerating structure, are induced at two separated spots in the modified linac. On the contrary, they are induced simultaneously at the same spot in the originally proposed linac.

KEYWORDS: proton linac, drift tube linac, alternating-periodic structure, shunt impedance, high current, focusing force

1. Introduction

A high-energy, high-average current proton linac with a continuous beam has been proposed.[1] In the proposal, an operating frequency of around 400 MHz (432 MHz) was chosen for all types of the accelerating structures: a high-β linac, a drift tube linac (DTL), and an RFQ linac. A higher frequency in order to increase the shunt impedance was not chosen, emphasizing a minimization of the beam losses in a high-β linac with a large transverse acceptance. An alternating-periodic structure (APS) of the on-axis coupling type[2,3] was an attractive candidate for a high-β linac of the coupled-cavity linac type (CCL) because of a superior symmetry regarding structure. Since the wall thickness between two adjacent cells remains nearly constant in order to obtain sufficient mechanical strength and a cooling channel, and so does the length of the coupling cell in order to obtain stable rf properties, the ratio of the coupling cell length to the accelerating one increases as the energy decreases. Thus, the shunt impedance of the APS decreases rapidly in a low-energy region. Although a high-frequency structure, which could have a high shunt impedance proportional to the square-root of the frequency, was not chosen in the proposal, it is needless to say that an accelerating structure with a higher shunt impedance is desirable. The applications of a drift tube linac with some geometry modifications for a medium-energy structure were thus studied. It should be noted that the achievable maximum accelerating field for a normal-conducting, continuous-beam proton linac is determined not by the optimized value with a beam dynamics calculation, but by considering the cooling properties. The latter is generally lower than the former for a continuous-beam proton linac. As a result, it is reasonable to search for a structure with a high shunt impedance without taking much care concerning an increase in the maximum surface electric field.

In this paper a separated-type drift tube linac with a high shunt impedance is proposed for a medium-energy-type structure. A design with a separated-type DTL for proton energies ranging from 150 to 300 MeV is presented, compared with the APS in the originally proposed design. A modified scheme for a 1-GeV proton linac is also presented along with some comments concerning sudden transitions in focusing forces on both the transverse and longitudinal motions caused by changing the type of accelerating structure.

2. Separated-type drift tube linac

2.1 Concept of a separated-type drift tube linac

A drift tube linac, instead of an APS, is a promising candidate for a medium-energy-type accelerating structure with a high shunt impedance. In order to increase the shunt impedance, a separated-type drift tube linac is considered, in which the focusing quadrupole magnet, usually within a drift tube, is removed and placed between two drift tube tanks. This is a similar focusing method to that generally used for a high-β structure. In order to obtain a large transverse acceptance, a short-length drift tube tank as well as a large bore radius is required. Therefore, the separated-type DTL can be applied for a rather high-energy region, where the transverse focusing period can be set to be longer than the unit-cell length and the effects of the drift spaces between two tanks on a longitudinal motion can be kept small.

Many of the difficulties experienced in fabricating the usual-type drift tube linac can be greatly reduced, since there are no quadrupole magnets in the drift tubes. The alignment of both drift tubes in a tank and each tank on the beam line also becomes very easy, since the alignment tolerance is no longer limited by the required accuracy for transverse focusing, but by the accelerating field homogeneity in the drift tube gap. The cooling method becomes easier, since all of the inner parts of the drift tube can be used for a cooling channel.

2.2. Calculation of the unit-cell geometry

A SUPERFISH calculation was carried out in order to determine the optimum unit-cell geometry of the DTL at a frequency of 432 MHz. The radius of the drift tube is reduced, keeping both the 15-mm bore radius and the 200-mm outer radius of the tank constant. Since the drift tube does not hold a quadrupole magnet, the radius of the tube can be freely reduced as long as the shunt impedance increases and sufficient cooling around the surface of the drift tube can be achieved. Figure 1 shows the dependence of the effective shunt impedance on the radius of the drift tube for a cell length of 35.2 cm, corresponding to a proton energy of 150 MeV. The maximum surface electric fields are shown in Fig. 2. Comparing the results for drift tubes of 25 and 20 mm radii, the increase in the effective shunt impedance is about 3%, while the increase in the maximum surface electric field is about 40%. Therefore, a radius of 25 mm was chosen. Figure 3 shows the energy dependence of the effective shunt impedance. The calculated results for the APS are also plotted. It can be seen that the effective shunt impedance of the DTL is larger than that of the APS for an energy below 280 MeV. It should be noted that a 59-mm bore radius for the APS greatly decreases the shunt impedance compared with a similar structure with a 15-mm bore radius. However, a 15-mm radius of the APS is too small to obtain sufficient rf coupling through the beam hole between adjacent cells; a bore radius as large as 59 mm is thus required for the APS.

2.3. Comparison of the separated-type DTL with the APS

The principal accelerating parameters for the unit cell of the separated DTL and the APS are listed in Table 1. A significant difference between them arises from the operating mode; a DTL operates in the 2π-mode, while an APS usually operates in the π/2-mode. Here, the mode name for the APS indicates a phase shift between two adjacent cells. Therefore, the cell length of the DTL is $\beta\lambda$, while that of the APS is $\beta\lambda/2$, resulting in a difference in the transit time factor (T), where λ is the wavelength. Since the net accelerating energy in a unit-cell length (L) is given by $E_0TL\cos\phi$, where E_0 is the average accelerating field and ϕ is an rf phase angle, the effective accelerating field (E_0T) should be of the same order to produce the same accelerating energy per unit length. Therefore, the average electric field of the DTL at 300 MeV should be larger than that of the APS by 88% in order to obtain the same accelerating energy. In this case, the longitudinal focusing strength per unit cell is equal for both structures. Comparing the separated DTL with the APS, it is noted that the periods for longitudinal focusing are different from each other by a factor of two, while those for transverse focusing are equal.

One of the merits of the π/2-mode structure is stable operation against external perturbations, such as structure imperfections and beam loading.[4,5] On the contrary, such a character is not expected for DTL 2π-mode operation. However, since the unit-tank length of DTL is sufficiently short, in order to obtain a large transverse acceptance, the accelerating field tilt due to external perturbations is very small, as the result of the large separation between the accelerating mode and the near-by TM mode.

2.4 Calculation of the separated-type DTL configuration

A beam dynamics calculation code, called PROEND, that can be used to generate a π/2-mode proton linac and to simulate three-dimensional beam behavior, was written[6] in order to study a high-intensity, high-energy proton linac for the Japanese Hadron Project (JHP).[7] Some modifications were added in order to calculate the 2π-mode structure for the DTL-type high-β structure. A doublet focusing scheme between two tanks was adopted in the calculation. The results are summarized in Table 2. Part of the design of the 1-GeV proton linac for JHP (a pulsed 20-mA beam, 3% duty factor) is also shown for a comparison. The linacs were designed with a constant-β structure, keeping the unit-cell length in a tank constant. The maximum phase slip from the stable rf phase within a tank is only -2.4° for the DTL; this is negligibly small. As can be seen from Table 2, the average effective shunt impedance of the DTL is larger than that of the APS by 55%. The transverse acceptance of the DTL is much smaller than that of the APS due to a rather small beam hole radius of 15 mm. However, it is larger than that of the ACS (a high-β linac for JHP) by about 50%.

Figure 4 shows the length of the accelerating structure and the rf excited power for both the separated DTL and the APS as a function of the average accelerating field (E_0). This is useful for considering the cost optimization problem, depending on the two principal parameters: rf power consumption and length of the accelerating structure.

3. Modified design of the 1-GeV continuous-beam proton linac

The proposed 1-GeV proton linac[1] comprises three types of structures: an RFQ (3 MeV), a DTL (148 MeV), and an APS (1 GeV). If part of the APS section is replaced by a separated DTL structure, the modified 1-GeV continuous-beam proton linac is divided into four accelerating structures: an RFQ (3 MeV), a DTL (148 MeV), a separated DTL (304 MeV), and a APS (1 GeV). Table 3 and Fig. 5 show summarized parameters of the modified design. Table 4 shows the results of a comparison between the modified and original linacs for a high-β accelerator part.

4. Discussion

There are three advantages in using a separated DTL for a medium-energy structure in a 1-GeV proton linac: an increase in the rf power efficiency, an improvement in the ease to manufacture the structure, and a change in the focusing scheme.

An increase in the shunt impedance of the separated DTL is achieved as shown in Table 2 and Fig. 3; the average effective shunt impedance increases by 55% compared with that of an APS of the on-axis coupling type. It is important that the fabrication of the separated DTL is very simple. In addition, it is very easy to align the drift tubes that do not contain any focusing quadrupole magnets, since the required accuracy is reduced by more than one order. This is also true for the alignment of many successive tanks. The cooling ability is expected to be an important technical problem for a continuous-beam proton linac. Owing to the simple structure, the cooling efficiency of the separated DTL can be made to be excellent.

Another important point regarding the introduction of a modified DTL is the effects on the beam dynamics. Generally speaking, a sudden transition in the focusing force as small as possible is preferable for a high-energy proton linac from the viewpoint of beam quality in a high-energy part. The originally proposed scheme, using the same frequency for all accelerating structures from 3 MeV to 1 GeV, cures any sudden transition of the longitudinal focusing force due to multiplication of the operating frequency. A factor from three to five has usually been selected. However, a sudden transition in the longitudinal focusing force, due to a change in the operating mode from 2π to $\pi/2$, remains. Therefore, sudden transitions in the focusing forces, both for the transverse and longitudinal motions, are expected at an energy of 150 MeV for the originally proposed design. Upon introducing the separated DTL, a sudden transition for the longitudinal focusing force shifts to a higher energy of 300 MeV, while that for the transverse focusing force remains at an energy of 150 MeV. Further detailed beam simulations are required in order to determine which scheme is more suitable for a high-intensity continuous-beam proton linac.

The separated DTL scheme can be applied to a low-energy structure below 100 MeV with carefully designed transverse and longitudinal focusing systems.

5. Summary

A separated-type drift tube linac for medium energies from 150 to 300 MeV is proposed for a continuous-beam proton linac. The average effective shunt impedance increases by 55% compared with that of an alternating-periodic structure of the on-axis coupling type. Some technical difficulties in the manufacturing, alignment and cooling of the drift tube linac are greatly reduced by eliminating the focusing quadrupole magnets from the drift tubes. A modified design of a high-energy, high-average current 1-GeV proton linac with a continuous-beam is presented. It is pointed out that sudden transitions of focusing forces on both transverse and longitudinal motions, due to a change in the type of accelerating structure, are induced at two separated spots in the modified linac. On the contrary, they are induced simultaneously at the same spot in the originally proposed linac.

Acknowledgments

The author wishes to express his gratitude to Prof. Y. Yamazaki regarding his careful reading of the manuscript.

References

1) Y. Yamazaki and T. Kato, "A Proposal for a High-Intensity, High-Energy, Continuous-Beam Proton Linac," Atomic Energy Industry Radioactive Wastes Handling Problems, Moscow, p.65 (1991); KEK Preprint 91-11.

2) T. Nishikawa, S. Giordano, and D. Carter, " Dispersion Relation and Frequency Characteristics of Alternating Periodic Structure for Linear Accelerators," Rev. Sci. Instr. 37, 652(1966).

3) Y. Yamazaki, T. Higo, and K. Takata, "Study of Alternating Periodic Structure Cavities with a Disc Loaded Waveguide Model," Part. Accel. 22, 273 (1988).

4) E. A. Knapp, B. C. Knapp, and J. M. Potter, "Standing Wave High Energy Linear Accelerator Structures," Rev. Sci. Instr. 39, 979 (1968).

5) Y. Yamazaki, "Stability of the Standing-Wave Accelerating Structure Studied with a Coupled Resonator Model", Proc. of the XIV International Conference on High Energy Accelerators, 1989, Japan; Part. Accel. 32, 39(1990); KEK Preprint 89-122.

6) "Report of the Design Study on the Proton Linac of the Japanese Hadron Project [I]," (in Japanese), JHP-10 or KEK-Internal 88-8 (1988), Section 7, p.137.

7) M. Kihara, "Outline of the Japanese Hadron Facility," Proc. International Workshop on Hadron Facility Technology, 1987, Los Alamos, LA-11130-C p.67; KEK Preprint 86-106.

Table 1 Comparison between the accelerating parameters for the DTL and APS structures. An average accelerating filed is chosen so that the accelerating energy per unit length may be equal for both structures.

		DTL	APS	
at 150 MeV				
	T	0.60	0.79	
	E_0	2.2	1.7	MV/m
	ZTT	30.2	8.6	MΩ/m
at 300 MeV				
	T	0.41	0.77	
	E_0	3.6	2.0	MV/m
	ZTT	12.4	14.0	MΩ/m

Table 2 Calculated parameters for three kinds of linac, DTL, APS, and ACS. ACS (annular coupled structure) is used in a 1-GeV linac for JHP.

	DTL	APS	ACS	
Frequency	432	432	1296	MHz
Bore radius	15	50	15	mm
Operating mode	2π	π/2	π/2	
Injection energy	148	148	148	MeV
Output energy	304	303	309	MeV
Eo	2.2-3.6	1.7-1.9	3.6-3.9	
Tank length	126	126	64.3	m
Rf power	14.2	21.7	14.3	MW
Beam power (50mA)	7.8	7.8	8.1	MW
Number of cells	312	626	952	
Number of tanks	78	79	38	
Unit tank length	1.4-1.8	1.4-1.8	1.1-2.1	m
Average effective shunt impedance	18.1	11.7	37.6	MΩ/m
Transverse acceptance	4.3	41.4	2.8	πcm·mrad

Table 3 Parameters of the modified 1-GeV proton linac.

RFQ		
Input energy	100	keV
Output energy	3	MeV
Frequency	432	MHz
DTL		
Output energy	148	MeV
Frequency	432	MHz
Total length	132	m
Number of cells	593	
Accelerating field	1.7	MV/m
Power dissipation	5.1	MW
Separated DTL		
Output energy	304	MeV
Frequency	432	MHz
Tank length	126	m
Total length	179	m
Bore radius	15	mm
Number of cells	312	
Number of tanks	78	
Accelerating field	2.2-3.6	MV/m
Power dissipation	14.2	MW
APS		
Output energy	1	GeV
Frequency	432	MHz
Tank length	462	m
Total length	630	m
Bore radius	50	mm
Number of cells	1694	
Number of tanks	203	
Accelerating field	2.0-2.5	MV/m
Power dissipation	76	MW

Table 4 Comparison of the accelerating parameters between the modified linac and the original one for an energy range of 148 MeV to 1 GeV.

	Modified design			Original design	
RF structure	Separated DTL	APS	(total)	APS	
Tank length	126	462	588	590	m
Number of cells	312	1694	2006	2328	
Number of tanks	78	203	281	268	
Power dissipation	14.2	76	90.2	97.7	MW

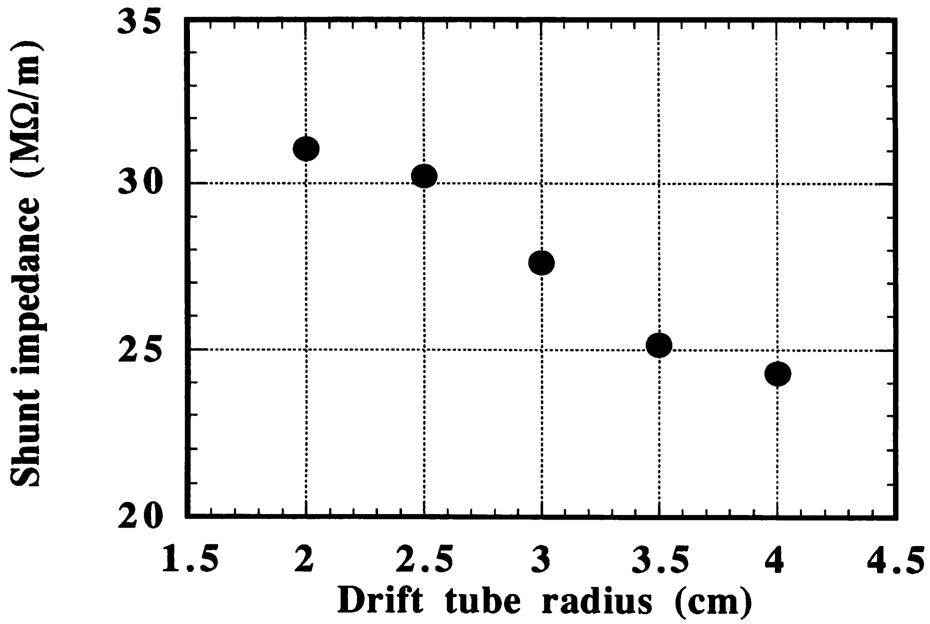

Fig.1 Effective shunt impedance of the DTL versus radius of the drift tube at a frequency of 432 MHz and a proton energy of 150 MeV.

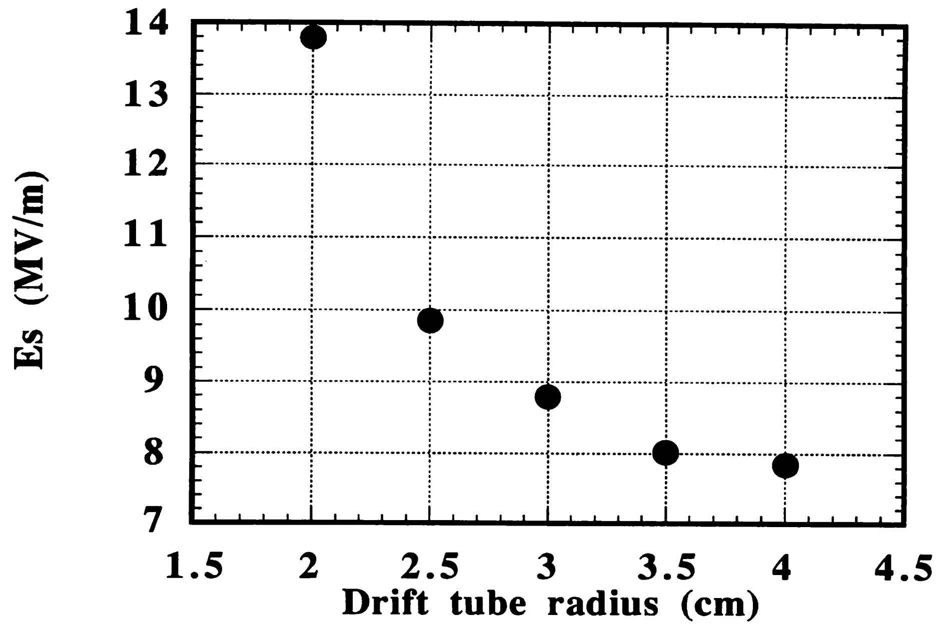

Fig.2 Maximum surface electric field of the DTL versus radius of the drift tube at a proton energy of 150 MeV. An accelerating field of 1 MV/m is assumed.

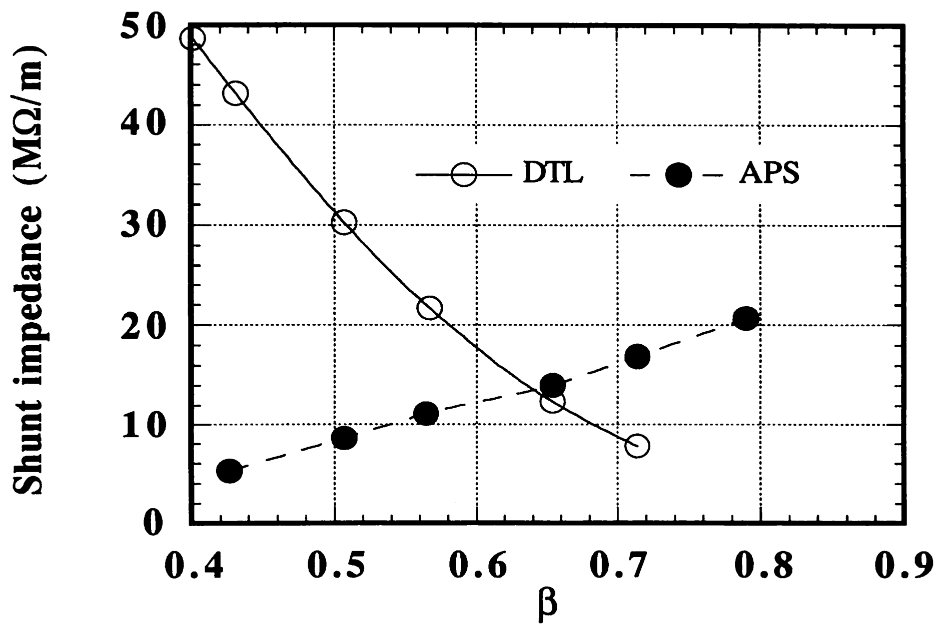

Fig.3 Effective shunt impedances of the DTL and the APS versus β (v/c), where v is the velocity of protons and c the velocity of light.

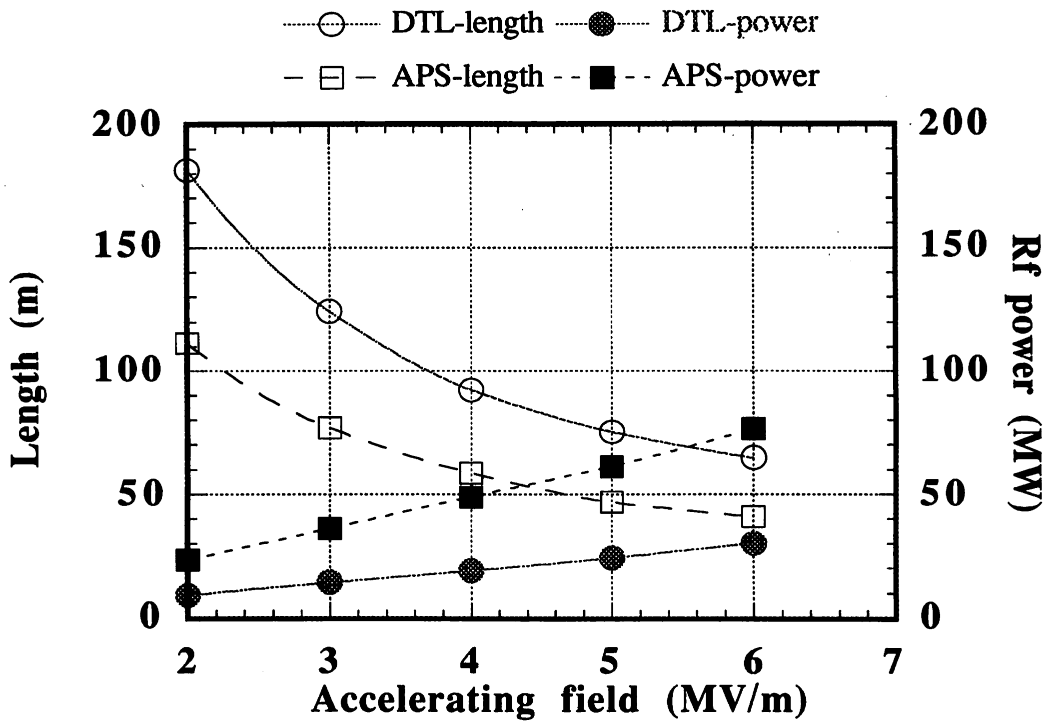

Fig.4 Tank length (without length for transverse focusing) and required rf power for the separated DTL and the APS versus the average accelerating field. The input and output energies are 150 and 300 MeV, respectively.

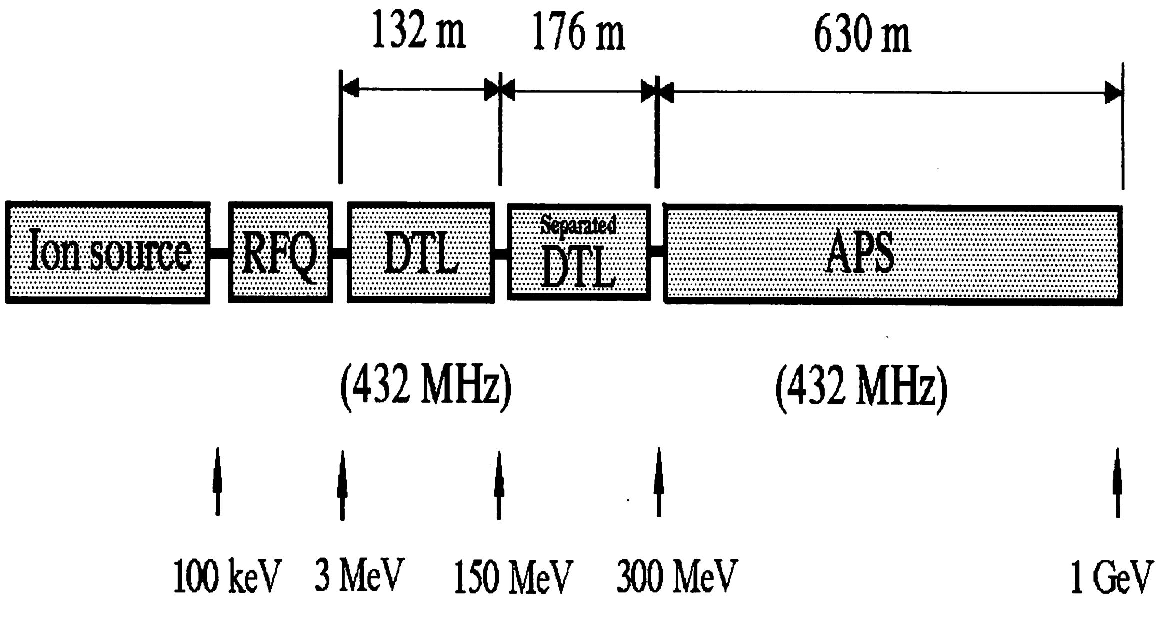

Fig. 5 Modified scheme of a 1-GeV continuous beam proton linac.