ACCELERATOR COMPONENTS

DEVELOPMENT OF ALTERNATIVES FOR ACCELERATING STRUCTURE IN THE RANGE OF INTERMEDIATE PROTON ENERGY

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A scope of the linear accelerating structures for acceleration proton high rower beams in energy range 5… 100 MeV is presented. Main task lies in a possibility to use superconductive equipment. The results are given for +original desgn of accelerating structures of alternating segments being excited on E_{11}-wave on π/2-mode. A possibility is discussed about the use of focusing blocks with the RF–quadrupoles which uniformly fit into the chain of accelerating cells.

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1. INTRODUCTION

Development and construction of powerful proton linear accelerators is currently the most topical line of accelerating industry. A number of important research and design and tasks is set up which can be solve with powerful proton beams accelerated to 1...2 GeV. The problem of safe and effective nuclear energetics is put in the forefront. Accelerator driven nuclear energetic based on the accelerator-reactor complex gives a possibility to operate in the subcritical and, therefore, to ensure safe nuclear energetic. Such a reactor on fast neutrons allows also incinerate the most harmful radiotoxic long lived decay products in nuclear waste such as plutonium and other transuranic elements; with this extra energy will be produced. The rigid neutron spectrum allows using in the fuel cycle thorium which is abundant in the earth's crust or depleted ^{238}U; this will solve the problem of fuel once and for all.

The proton accelerator used in accelerator driven nuclear energetic complex to compensate the neutron deficiency in the subcritical reactor should produce a proton beam with the power to 30 MW and energy of 1...1.5 GeV and current of 25...30 mA in the continuous mode. The task of the development of such an accelerator was set up in the middle 90ties in the works of CERN team [1] that immediately attracted researchers in different countries. It was supposed that presentation samples the EA complexes would have been constructed by 2015. However, according to known sources no project of this type has been funded yet; but the question on creation of Pan-European powerful linacs is still open. Presently, several projects of conservative approach and more distant terms of construction and putting into operation are discussed. These accelerators are expected to be multi-purpose. Practically, proton beams of different energies and power are directed to experimental installations for solving problems in physics of high energies and nuclear physics, biology, medicine, material engineering, transmutation of nuclear waste. It is assumed to create neutron fluxes in the spallation-reaction of higher intensity and more flexible pulsed operational mode than research nuclear reactors. Problems of creation of intense fluxes of secondary particles such as mesons and neutrinos directed on targets located at distances of hundreds and thousands kilometers with intensity of 10^{20} annually will be being solved which are the most important from scientific viewpoint.

2. PROJECTS OF POWERFUL LINACS

These are the projects under intensive science and technological development such as European spallation neutron generator (ESS) on the energy of 1.3 GeV with the duty factor of 15% and average beam power of 5 MW [2]. The SPL project (superconducting linac) on the energy of 2.2 GeV with the duty factor of 14% and beam power of 4 MW [3]; the EURISOL project – 1(2) GeV, 5 MW [4]; the SNS project – 1 GeV, 1.5 MW [5]; JAERY-KEK – 600 MeV [6]. The two last projects are already funded, and the time of putting them into operation is fixed, 2006 and 2007, respectively.

The works on projects of powerful proton linear accelerators which imply the creation of presentational samples for accelerator driven nuclear energetics are being continued. Such are the TRASCO project [7], Italy, COMAK [8], Korea, AAA, Los Alamos, [9], ITEP, Russia, [10]. These projects are rated for continuous operational mode with the average beam power of tens of MW. Their implementation meets with a series of unsolved technical problems; though, in principle, the modern technological level of accelerating technique will allow to overcome them.

3. THE CONCEPTUAL SCHEME

General architecture of the mentioned above linacs is approximately the same. There is the common opinion that an accelerator should be divided in the following sections:

1. A proton or H^- source with intensity to 100 mA of the ICR type. Currently, the highest parameters of proton beams are achieved. With such a current, the emittance is about 0.2 π mm mrad. At the frequency of 2.4 GHz and high voltage of 100 kV the RF discharge is stable. Very high reliability is achieved [11].

2. Beam transportation systems (LEBT) providing ion and optical diagnostics and transportation and beam matching at the input of the RFQ structure.

3. RFQ accelerating structure. In many laboratories in the world RFQ structures are so highly developed that there is doubtless that it is possible to achieve the required beam parameters with energy of several MeV and intensity of tens of mA.

4. The range of intermediate energies of a proton beam from 5 to 100 MeV. For different projects upper and lower figures are differs essentially. This range will be discussed later. It is the most vulnerable area as in electrodynamical characteristics and in the costs and complexity of development.

5. The range of high energies is the main part of an accelerator. During last years, there was disagreement on the choice of accelerating structure and on the choice between the conventional and superconductive alternatives. However, by the present time as EPAC-2002 proceedings show the general opinion is elaborated: the high-energy section of the accelerator should be superconductive.

4. SUPERCONDUCTIVE ACCELERATING STRUCTURES

Application of superconductive cavities offers great advantages. Extremely low losses of RF-power in surfaces allow considerable energy saving, especially in the continuous operational mode of an accelerator. Practically, the RF-power is only used for beam acceleration. The corresponding decrease in the number of generators would considerably reduce the cost of the accelerator. From the technologic point of view, application of superconductive cavities allows to increase apertures that will give a chance to reduce essentially the beam losses due to halos and, therefore, to reduce activation. Here, we have to do with a possibility to achieve zero losses even in a high current beam. Besides that, the length of high-energy part is less almost three times in comparison with a 'warm' alternative due to high surface and middle gradients of the electric field. Again, the short superconductive structures give a chance to realize the flexible operational mode providing the necessary reliability and availability. The drawback is that the use of cryogenics, but this technique is already successfully put into action in a few large installations.

By the present time, the superconductive structures are sufficiently elaborated and studied and are already used in the large accelerating installations with β=1. Those are TRISTAN [12], HERA [13], CEBAF [14], LEP-2 [15], and others. Due to superconductivity the average operational gradient of the accelerating field of about 4...6 MV/m is achieved, and in individual cases (CEBAF) - 7 MV/m, and even 14 MV/m.

For each case of the superconductive cavities several conditions should be met; failing to meet them would complicate the operation:

To achieve a high quality factor ($Q \sim 10^{11}$) it is necessary to maintain the surface resistance not higher than 0.2 nOhm [16].

1. On the metallic surfaces secondary emission may arise with high electric fields. This phenomenon may be caused with nonuniformity on working surfaces of all kinds; therefore their especially careful finishing under conditions of extreme purity is necessary.

2. High-gradient quench is caused with thermomagnetic breakdown of superconductivity. The theoretical limit in magnteic field for Nb is rather high (up to 190 mT at 2K). However, the experimental values are much lower (50 mT) owing to surface defects. Electric polishing allows to achieve 130 and even 170 mT at individual cells (KEK, Desy, CERN, Sacle) [17]. Under laboratory conditions accelerating fields up to 40 MV/m are achieved. However, to perform this in full scale is very difficult.

3. The extra losses in the surfaces are caused with oxygen diffusion into niobium. Experiments on heating at temperatures of 80–150ºC demonstrated the possibility to avoid the drop in Q.

4. The multipactor resonance discharge in a cavity. The elliptic shape of the cavities decreases a probability of multipaction. However, there is a number of other reasons for its initiation.

5. Lorentz forcedetuning and microphone effect. Cavities working in the pulsed mode undergo mechanical influence of the electromagnetic field causing a shift in frequency and mechanical vibrations. With very high Q this influence is essential. To avoid these effects high-speed auto-tuning system is used.

Superconductive cavities reached the high level and are widely used in accelerating technology. Its application for proton linacs stimulates further modernization. In this respect, a considerable contribution to further development of SC technology will be the SNS complex which presently is being built in which SC cavities are used [18].

5. ACCELERATING STRUCTURES OF THE INTERMEDIATE ENERGY RANGE

In linear accelerators rated for acceleration of proton beams with high duty factor, and even in continuous mode, new problems arise of fundamental and technologic nature. The Alvaretz accelerating structures having long cavities stuffed with tens of drift tubes which contain magnetic quadrupoles that are most often used for this energy range are unfit got new conditions. The enormous amount of RF-power absorbed in cavity walls and drift tubes less pronounced in the structures with a small duty factor may exceed the permissible level of 10...15 kW/m. The value of shunt impedance is determined largely by drift tube diameters [19]. The use of drift tubes with magnetic quadrupoles in structures with high operating frequency results in the sharp drop in the shunt impedance. Accelerating structures with tubes without focusing devices allow to achieve the effective shunt impedance about 55 MOhm/m. With the use of quadrupoles with constant magnets R_s drops to 48 MOhm/m, which is still acceptable, therefore a few projects of proton linear accelerators with high duty factors are rated for this alternative in the range 5...50 MeV. However, the drawback of such a structure lies in the fact that the constant magnets are impossible to control and in for their replacement large efforts would be necessary.

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A structure with focusing devices brought out into the gaps between short section in this energy range should not exceed 5...6 βλ for radial beam stability. Hence, in this case there should be many short cavities, each of them being supplied from an individual generator. The acceleration rate is also low due to the known periodical structure of L=βλ. This results in a complicated system of auto-regulation and the total effect of errors leads to the rise in the radial emittance. In this connection, the search is under way for an effective structure possessing high R_s and high accelerating rate and, at the same time, which would allow to combine several cavities in one module with common power supply.

Development of accelerating structures for the intermediate energy range until recently was focused on a side coupling cavity linac, SCCL. This structure is realised at Los Alamos meson factory [20] for π/2-wave. In the side coupling cavities nodes of variations of electric field are localised, therefore performing and power transportation from one cavity to another this cells practically do not cause its losses. Accelerating cells are excited with RF-power similarly to π-structure providing high accelerating rate. High resolution of modes typical for π/2-wave provides stable electrodynamic characteristics. This structure is used widely in the energy range above 100 MeV. However, in the lower energy range it is ineffective owing to the small cell lengths.

In this connection, an alternative CCDTL (Coupled Cell Drift Tube Linac) [21] was developed in which into the accelerating cell a drift tube is inserted that elongates it by βλ. Such cavity contains two gaps; its total length is 3/2 βλ. The accelerating cavities are joined by side coupling cavities. The beam focusing is achieved with magnetic quadrupoles brought out outside the cells.

CCDTL structure is acknowledged as the most effective in the 'warm' variant in the energy range of 20...100 MeV. Its use in the superconductive alternative is complicated because of large transverse dimensions due to the side coupling cavities. Besides that, the small cell length in the range of small β assumes the close arrangement of magnetic quadrupoles.

In the last years, new modifications of accelerating structures designed for SC were proposed for intermediate energy range. Beside CCDTL the most developed structures are 're-entrant' cavity structures. Another modification is the 'spoke-cavity' structure based on two-gap half-wave cavity.

The 're-entrant' cavity structure forms the basis for intermediate part of the TRASCO project (Italy) [22, 23]. It is being developed as a superconductive variant at the frequency of 350 MHz. It is assumed also to locate SC quadrupoles in the cryostat. A low coupling coefficient between cells assumes the small length of sections and very branched system of RF-power supply.

The structure of 'spoke cavity' type is under development at IPM, Orsey, France for European of EURISOL, XADS linac projects. Drift tubes are placed at the maximum of potential difference of half-wave rod. In the contrast to CCDTL, in neighbouring gaps the electric field strength corresponds to π-wave. The structure is designed to be operated as the SC variant. It possesses low R_s when it is 'warm'. Each of single-cell cavity is supplied with power from an individual generator. Focusing is carried out with SC quadrupoles inside the cryostat.

The described cavities promise SC application in the intermediate proton energy range. However, they will demand complicated RF-systems. Besides that, the location of SC quadrupoles inside cryostat requires new constructional innovations, their tuning and replacement if malfunctions occur. Presently, development and testing of these systems are under way.

In connection with the above, it is pertinent to cite J. D. Schneider [26] "Distribution of superconductive structures on the low energy range will probably be continued as superconductivity in RF-systems promises considerable operating advantages, especially for accelerating continuous beams. For the range of low β we should demonstrate cavity configurations which differ from traditional elliptic niobium structures".

6. MULTI-CELL ACCELERATING STRUCTURES

The drawbacks of the accelerating structures of Alvaretz type specified above with respect to acceleration of powerful proton beams, especially in the continuous mode made researchers develop accelerating structures in the form of separated cells coupled in RF-power or completely supplied from individual generators. Such a solution that was complicated beforehand was made with the purpose to increase the acceleration rate with the transition on the mode of π or π/2 waves. This required the separation of accelerating and focusing units. With that the beam focusing in all cases was carried out with a magnetic quadrupoles laced between accelerating cavities with the FODO and sometimes FOFDOD focusing periods or focusing doublets FDOFD. Such focusing devices were set rather closely in the range of low (intermediate) energies; this decrease the accelerating rate essentially.

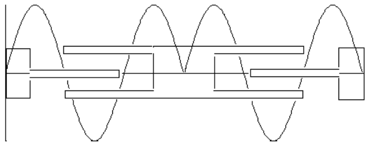
We searched a possibility to go back to multi-cell structure in the variant free from these drawbacks. The backgrounds for this were two elaborated approaches:

1. The use of RF-quadrupole modification instead of magnetic system for beam focusing.
2. The use of a new variant of multi-cell accelerating structure on the π/2 wave.

6.1. BEAM FOCUSING WITH RF-QUADRUPOLE UNITS

The principle of focusing of a proton beam being accelerated that was proposed earlier with RF-quadrupoles in the structure of 'horned' drift tubes [27,28] and a variant of RF-quadrupole focusing realized by the team of V.A. Teplyakov [29] has opened up new opportunities for accelerating high current beams. The URAL proton accelerator built on the basis of this principle operates successfully accelerating proton beams to the energy of 30 MeV and the current of 100 mA [30]. In this variant based on the accelerating structure on H_{01}-wave effective focusing is achieved at the cost of essential decrease in accelerating rate, therefore, despite considerable beam current limit, developers of linacs do not take this principle into consideration. At the same time, the principle of focusing with RF-quadrupoles possesses high capabilities.

In the Fig. a layout of RF-quadrupole block (RFQB) exhibiting an accelerating and focusing doublet which consists of two two-gap cells of the CCDTL type.



RF-quadrupole block of two-gap cells of the CCDTL type

The total length of paired cells is 3 βλ. The central part of the unit is a drift tube that is symmetrical relatively to the dividing wall and with long ‘horns’ forming two focusing quadrupoles in two planes. The location of the quadrupoles corresponds to the space in the structure where the drift tubes are located that screen the particles being accelerated from the hindering effect of the electric field. Thus, a section of βλ/2 in each cell that is equal to 1/3 of the cell length is saved beside the fact that in each of two planes where the ‘horns’ are placed there are two accelerating gaps.

A value of focusing gradient in RFQB and its place in the chain of accelerating cells is determined from radial dynamics of bunches being accelerated along the cells. Efficiency of beam focusing with such doublets is high therefore their number is less than in the structure of a focusing period with spaced quadrupoles.

The variant of RFQB focusing described above may be successfully applied for instance to a CCDTL structure where the cells are separated and the coupling is performed through side cells. Their application is efficient both in ‘warm’ and in SC variants. CCDTL structure is being developed for accelerating protons in the intermediate energy range under few projects. The length of SC module is limited, from one hand, with a small coefficient of coupling carried out through side cells and usually do not exceed 3...5%. From the other, the imposed limitation on the module length is due to the length of the focusing period when magnetic quadrupoles are located outside the cryomodule, therefore, in the range of low energies a large number of short cryomodules are required that makes the structure more complicated.

6.2. THE ACCELERATING STRUCTURE OF THE TYPE OF ALTERNATING ARRANGEMENT OF SEGMENTS ASAS

Another situation is formed when RFQB may be used for beam accelerating. Their little difference from the accelerating cells does not impose limitations on the length of cryomodule; in this case the length will be determined by the power of RF-generator and other constructional considerations.

In this connection, we considered a possibility to use adequate accelerating structures. The most favorable in this respect was a accelerating structure of alternating segments (ASAS) type [31,32]. This structure did not found practical use because at that time creation of powerful proton linear accelerators was not considered.

The ASAS structure is two chains of identical cells combined in the same cylindrical cavity and being excited on E_{11}-wave; one of them is accelerating cell, and the other is the coupling one. Distribution of the electric field of the E_{11}-wave is two antinodes the centers of which are at the distance of 0.46 of the radius from the axis of the cavity. Drift tubes of the accelerating and coupling cells are located along the antinodes. In the second art as in other π/2 structures the stored power is practically absent so there are no power losses. At the same time, the coupling coefficient is high. As the model investigations showed the diameter of a cavity loaded in this way will be about 60 cm at 600 MHz. The coupling coefficient is about 30% that offers unlimited opportunities to lengthen the cavity. The structure possesses the high shunt impedance therefore it is suitable for operation in the ‘warm’ variant. From the other hand, the immediate contact of internal elements of the accelerating structure with a cylindrical wall of the cavity allows to perform rather effective heat-removal providing the operation under SC mode.

7. CONCLUSIONS

Proton linear accelerators are being really constructed. The use of superconductivity allows increasing essentially the efficiency of acceleration due to considerable reduction of accelerators length and decreasing in operational costs. In the energy range from 100 to 1000 MeV SC accelerating structures are elaborated. For the first time such an SC section is utilized in the SNS project. In the range of intermediate energies yet there is no general opinion about selecting the most effective accelerating structure. The variant of RF-quadrupole focusing presented in the report allows to solve a large part of problems. In combination an accelerating structure of alternative arrangement of segments, there is a possibility to create an effective variant of a proton accelerator in the intermediate energy range. More theoretical and experimental investigations of electrodynamics of cavities and dynamics of beams being accelerated are necessary.

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РАЗРАБОТКА ЭФФЕКТИВНЫХ МОДИФИКАЦИЙ УСКОРЯЮЩИХ СТРУКТУР В ДИАПАЗОНЕ ПРОМЕЖУТОЧНЫХ ЭНЕРГИЙ ПРОТОНОВ

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Приводится обзор разработок конструкций структур линейных ускорителей протонов с большой мощностью пучка в диапазоне энергий 5...100 МэВ. Главная задача заключается в возможности использования сверхпроводящей техники. Описаны результаты оригинальных разработок ускоряющей структуры типа встречных сегментов, возбуждаемой на E_{11}-волне, и возможность применения фокусирующих блоков с ВЧ – квадруполями, которые однородно вписываются в цепочку ускоряющих ячеек.

РОЗРОБКА ЕФЕКТИВНИХ МОДИФІКАЦІЙ ПРИСКОРЮЮЧИХ СТРУКТУР В ДІАПАЗОНІ ПРОМІЖНИХ ЕНЕРГІЙ ПРОТОНІВ

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Приводиться огляд розробок конструкцій структур лінійних прискорювачів протонів з високою потужністю пучка в діапазоні енергій 5...100 МеВ. Основна вимога полягає в можливості використання надпровідної техніки. Описані результати оригінальних розробок прискорюючої структури типу зустрічних сегментів, що збуджується на E_{11}-хвилі, а також можливість застосування фокусуючих блоків з ВЧ-квадруполями, які однорідно вписуються в цепочку прискорюючих комірок.