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The development of room temperature Radio Frequency Quadrupole linear accelerator

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Abstract. Room temperature linear accelerators are commonly used in the field of nuclear physics. The main categories include Radio Frequency Quadrupoles (RFQ) and Drift Tube Linac (DTL). Simulation design of room temperature linear accelerators can provide a powerful experimental platform for isotope production, material modification, semiconductor injection and other research, and effectively promote the rapid development of nuclear science and other related disciplines. This article identify different kinds of room temperature linear accelerators, for instance, four-vane and four-rod RFQ, IH DTL and CH DTL. Besides, it also identify the accelerators' development status of RFQ. Last but not least, the simulation and design softwares of RFQ are introduced.

Keywords: linear accelerator, RFQ, DTL, design softwares

1. Background of the room temperature linear accelerators

Room temperature linear accelerators are commonly used in the field of nuclear physics. The main categories include Radio Frequency Quadrupoles (RFQ) and Drift Tube Linac (DTL).

RFQ [1] is a compact strong current and low-energy ion accelerator. It is characterized by the use of a single high-frequency quadrupole electric field to achieve horizontal focusing and longitudinal acceleration of the beam current at the same time. RFQ can be regarded as an evolution of electrostatic quadrupole lens. Electrostatic quadrupole lens only has a focusing effect and cannot achieve particle acceleration. When the electrode is longitudinally wave-shaped which called "electrode modulation", an electric field that can accelerate particles will appear in the z direction. Continuous synchronous acceleration of particles can be achieved by replacing the electrostatic field with a radio frequency electric field. The common structural types of RFQ are four-vane type and four-rod type. Different structures lead to different electromagnetic working modes of the two. For four-rod RFQ accelerator [2], its characteristics are: suitable for accelerating low-velocity heavy ions at low frequencies (below 200 MHz); frequency and electric field distribution are not sensitive to external changes, and for four-vane RFQ, it is characterized by the following features: small cavity size at high operating frequency, suitable for accelerating light ions; high mechanical strength, convenient water cooling, and suitable for high duty cycle or CW operation mode.

The DTL can accelerate the beam energy to hundreds of MeV/u. There are two types of H-type DTL, one is IH type and the other is CH type. Compared to the CH structure, the IH DTL [3] has a smaller cavity size for the same operating frequency. The operating frequency of IH DTL is generally less than 300 MHz, and the effective shunt impedance can reach 100~300 MΩ/m or even higher. In general, IH structures accelerate better at speeds below about $\beta = 0.1$. In addition, the asymmetry of the IH DTL accelerator structure will cause the dipole field component of the electric field, which causes the beam to generate a center offset during transmission, and the influence of the dipole field can be reduced by optimizing the shape of the drift tube. The CH DTL has better acceleration effect in the speed range of about β=0.1 to β=0.5, and is suitable for higher frequency cases (150 MHz~ 800 MHz), its effective shunt impedance is about 50~100 MΩ/m. The CH structure has high stability, good symmetry, and even distribution of power consumption of the cavity, and is more stable and easier to water cooling than the IH structure, and therefore has great prospects for CW operation. For the H-shaped structure, lateral focus can be provided by a Quadrupole Triplets or magnetic solenoid. The advantages of these two H-mode structures are high shunt impedance and high acceleration efficiency. Both structures can be connected in series after the RFQ, or accelerate the particles directly without RFQ. In principle, they can be used for both light ion acceleration and heavy ion acceleration, both as room temperature cavity and superconducting cavity.

Simulation design of room temperature linear accelerators can provide a powerful experimental platform for isotope production, material modification, semiconductor injection and other research, and effectively promote the rapid development of nuclear science and other related disciplines. Up to now, CW accelerators are the hot spot and development direction of ion linear accelerators research. However, the long-term stable operation with high current intensity is a difficult problem that has not yet been overcome. Only a few CW RFQs have been built in the world, and the design of CW DTLs is even rarer. Therefore, the design of stable CW RFQ and DTL linear accelerators remains a challenge.

2. Development status of RFQ accelerator

Research the development of RFQs at home and abroad, and summarize as follows:

2.1. FRIB

FRIB [4] was built at the University of Michigan in the United States and is a large isotope generation device. It can accelerate from protons to uranium ions. The frequency of the RFQ in the FRIB project is 81.25MHz, it adopts a four-vane structure, and the voltage change is 60-112 kV, which can accelerate the beam from 12 keV/u to 500 keV/u.

2.2. HIAF

HIAF [5] is a new generation of strong current heavy ion accelerator facility under construction by the Institute of Modern Physics of the Chinese Academy of Sciences. A RFQ with a frequency of 81.25 MHz is an important component of the injection segment of this project, which can accelerate the pulse beam 238U 35+ from 0.014 MeV/u to 0.8 MeV/u within a length of about 9.7 m. The dynamic design transmission efficiency is as high as 99.3%.

2.3. Spiral-II

Spiral- II [6, 7] is an upgraded version of the radionuclide generation device Spiral-I of the French GANIL Institute. Its front-end four-vane RFQ working at a frequency of 88MHz, adopted a variable voltage design of 100-113 kV, and the CW beam through the length of 5.1 m can be accelerated from 0.02 MeV/u to 0.75 MeV/u. The transmission efficiency of dynamic simulation reaches 99.9%.

3. Simulation and design software of RFQ

At present, the most widely used RFQ beam dynamics simulation program is ParmteqM written by LANL. The software uses an octal potential function to describe the distribution of electric fields and can generate electrode data directly for processing. The parameters of RFQ dynamics design include: synchronization phase φs, vane voltage V, modulation coefficient m, focusing intensity B, and minimum aperture a. In the process of RFQ dynamics design, the above parameters need to be optimized until the transmission efficiency and output beam quality and the electrode length meet the requirements. The classical "four-stage" method, first proposed by LANL, is used for the dynamics design of RFQs. This method divides the RFQ electrodes into the Radial Matching Section (RMS), the Shaper Section (SH), the Gentle Buncher Section (GB) and the Accelerator Section (ACC):

(1) RMS (Matching Section): This section usually has only 2-5 unmodulated cells, which are gradually narrowed in the shape of a flare, so that the injected beam can be effectively captured by the RFQ high-frequency field in the transverse direction;

(2) SH (Shaping Section): The initial synchronous phase is -90° to improve the capture ability of the RFQ on the beam, and the electrode modulation coefficient is gradually increased from m=1, and the longitudinal accelerating effect causes the continuous beam to form the beam cluster structure;

(3) GB (Gentle Buncher Section): This section keeps the length of the cluster unchanged while gradually widen the distance between the clusters, and reduce the transverse emittance growth and loss of particles caused by space charge effect by keeping the charge density of the clusters unchanged.

(4) ACC (Acceleration section): After the stable cluster structure enters this region, the synchronous phase φs and modulation coefficient are kept unchanged to maintain efficient acceleration until the energy meets the design requirements.

In addition to ParmteqM, there are also some programs used to calculate and verify simulation design results, such as Toutatis developed by CEA in France; Track developed by ANL in the United States and Tracewin programs developed in France, but these programs rely on the electrode structure generated by ParmteqM.

In the process of RFQ accelerator dynamics simulation design, shortening the electrode length as much as possible, improving the transmission efficiency of particles, controlling the emittance growth of the outlet beam, and reducing the risk of cavity power consumption and electrode surface peak electric field are the goals that need to be comprehensively considered and repeatedly optimized.

The RF structure simulation of RFQ is based on CST (Computer Simulation Technology) Microwave Studio software. CST is a professional 3D electromagnetic field simulation software, widely used in electromagnetic compatibility, antenna design, high-speed interconnect, microwave devices and other fields. The software provides complete full-wave electromagnetic algorithms in time and frequency domains, as well as high-frequency algorithms, covering electromagnetic simulation needs from DC to optical frequency bands. The main modules of CST include:

(a) CST Microwave Studio: for the simulation of high-frequency passive devices, such as antennas and filters.

(b) CST Electromagnetic Studio: for the simulation of electrostatic field, static magnetic field and low-frequency electromagnetic field.

(c) CST Particle Studio: for the simulation of charged particles interacting with electromagnetic fields, applicable to particle accelerators and other fields.

(d) CST Design Studio: to provide system-level active and passive circuit simulation, supporting the co-simulation of electromagnetic fields and circuits.

(e) CST Multi-physics Studio: used for electromagnetic loss-induced thermal effects and heat-induced structural stress analysis.

To ensure the accuracy of the simulation results, a mesh convergence analysis is performed before starting the RF EMF calculations.

When designing the RF structure, the following requirements need to be met: large frequency intervals between different modes, good electrical stability; large Q value, so that high electromagnetic field energy can be obtained with less RF power; strong heat dissipation capability, and small frequency drift due to thermal deformation.

In practice, the operating conditions of the ion source and the design of the low-energy transmission line affect the beam distribution into the RFQ. Non-ideal distribution can lead to mismatch at the input, and RFQ machining and assembly errors can result in uneven and asymmetric electric field distribution, and the RFQ power supply error can result in the difference between the actual voltage and the designed voltage. All of these errors have an impact on the beam transmission efficiency, so detailed error calculations are needed to analyze the redundancy of the design with respect to the errors.

4. Throw down the gauntlet

In the process of learning writing, the main obstacles are problems such as unfamiliar topic, difficulty in reading and understanding references, and redundant content and difficulty in clarifying. Moreover, the physical knowledge learned before does not fully match with the knowledge in the research process. On the one hand, the tutor patiently explained and focused on the introduction, which made me understand the role and structure of RFQ and DTL accelerator; on the other hand, it helped me streamline the content, highlight the key points, remove unnecessary data and tables, and make the scientific research context clearer, the logic smoother, and the article structure more reasonable. Finally, I got some preliminary understanding of various accelerators and a better understanding of the study of basic physics.

5. Lessons learned

Through this study, I found that the project is more about summarizing the research results of predecessors, making a highly condensed generalization, and putting forward my own unique understanding. In the face of unfamiliar projects, we should calm down, understand the field as much as possible with a humble attitude, conduct thorough research on reference materials, and carefully listen to the guidance of the tutor. Secondly, in order to better study elementary particles, physicists have proposed and built a considerable number of accelerators with different principles and forms, and have studied accelerators of various configurations. Researchers from different research institutions around the world have also built accelerators with their own characteristics. Finally, the research of basic science should be long and arduous but not lacking in harvest. On the basis of the research of our predecessors, we must constantly overcome difficulties and have the courage to innovate and invent in order to make new breakthroughs.

References

[1] Kapchinsky, I. M., & Teplyakov, V. A. (1969). A linear ion accelerator with spatially uniform hard focusing. ITEP-673.

[2] Klein, H. (1983). Development of the different RFQ accelerating structures and operation experience. *IEEE Transactions on Nuclear Science*, 30(4), 3313-3322.

[3] Pottier, J. (1969). A new structure for heavy-ions linacs. *IEEE Transactions on Nuclear Science*, 16(3), 377-379.

[4] Maruta, T. (2021, January 25). Beam Commissioning at FRIB. [PDF]. Retrieved October 12, 2023, from https://agenda.ciemat.es/event/1229/contributions/2854/attachments/2215/3364/ARIES_maruta_ver2.pdf

[5] Liu, G., et al. (2013). Design of a CW high charge state heavy ion RFQ for SSC-LINAC. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 701, 186-193.

[6] Gales, S. (2011). GANIL-SPIRAL2: a new era. In *Journal of Physics: Conference Series* (Vol. 267, No. 1, p. 012009). IOP Publishing.

[7] Orduz, A. K., Di Giacomo, M., Ferdinand, R., et al. (2021). Beam Commissionning SPIRAL2. In *12th International Particle Accelerator Conference (IPAC 2021)*, 2540-2543.