ACCELERATION MODULE IN LINEAR INDUCTION ACCELERATOR

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Abstract

Linear Induction Accelerator (LIA) is a unique type of accelerator, which is capable to accelerate kilo-Ampere charged particle current to tens of MeV. The LIA acceleration modules, filled with ferrite or ferromagnetic toroid cores, can be conveniently stacked to obtain high energy. During the evolution of LIA, several models for the LIA acceleration module and the function of the cores have been proposed. Authors of this paper surveyed these models and tried to bridged them to form a consistent understanding of the LIA acceleration module. The unified understanding should be helpful in the further development and design of the LIA acceleration module.

INTRODUCTION

Linear Induction Accelerator (LIA) is a special type of accelerator which can accelerate pulsed, high intensity current charged particles beam to several tens of MeV [1, 2]. The particle beam current in LIAs can be as large as 100 kilo-Amperes [3]. LIAs can be used to accelerate electrons and ions. The unique characteristics of LIA give it many special applications: radiography, high power microwave production, FEL, heavy-ion inertial fusion, etc.

The key component of a LIA is its accelerating cavity. LIA cavities are low-impedance, non-resonant devices which enables LIAs to accelerate kilo-Ampere charged particle current without severe instabilities problem. An other feature of LIAs is their accelerating cavities can easily stacked in series to continuously accelerate particles, which also limits the LIA's accelerating gradient.

Since the first LIA, ASTRON-I, was built in 1964 [1], several types of LIA accelerating cavity and corresponding model concepts have been developed. The transformer model is the first and most widespread model to introduce the LIA concept and explain the source of the accelerating voltage as the magnetic induced field integral of the magnetic flux change of the core. The transmission line model was brought about by Keefe [4]. The core and its housing is considered as a transmission line with one end shorted. The accelerating voltage is just the voltage between the inner and outer conductor of the transmission line when the beam is passing through the gap region until the high voltage pulse is reflected back from the shorted end of the core housing. Smith and others [5, 6] even denied the accelerating voltage to be inductive voltage of the magnetic core. Although transmission line model and accordingly designed cavities do provide accelerating voltage of better flat-top, other characters of LIA activities, like voltage-seconds, beam loading effect and voltage droop are still using meaning according to transformer model.

LIA technology is being exploited to provide new features and higher performance, like providing longer pulse, working under MHz busting mode. Authors feel it is necessary to clarify some issues to further develop LIA technology. We re-examined LIA cavity structures and models, discussed several important issues, tried to provide a more accurate understanding of LIA accelerating cavities.

ACCELERATING CAVITIES IN LIA

Introduction to LIA Cavities

Like Linacs with RF cavities, LIAs are composed of many power transmission lines, which are all driven in parallel and feed in power in to cavities where charged particles are accelerated while passes through them in series. Unlike RF accelerators, isolation between LIA cavities is achieved with the magnetic core of high permeability. An induction cavity is designed to be non-resonant, the low Q property makes it store neither the drive fields nor the beam's wake fields. This dramatically increases the practical operating current. While, LIAs are incapable of efficiently accelerating very low current beams.

In operating induction linacs that provide short pulses (~ 50 ns), the induction module is filled with ferrimagnetic material, ferrite; for long pulses (50 ns $\leq \tau_p \leq$ several μs) ferromagnetic materials or Metglas [7] are used. Ferrite is a ceramic like type of material. Ferrites exhibit a form of magnetism called ferrimagnetism. The saturate magnetic inductions of NiMn ferrite usually fall in the range of 0.2-0.4 T [8]. Ferrite is a very convenient choice of the magnetic material due to its very high resistivity. This resistivity ensures a skin depth of the order of many tens of cm for 50 ns pulse length.

There are two types of accelerating cavities using large volume of ferrites. They are Resonant Ferrite Core Cavities (RFCC), referred in this paper, used in synchrotrons and Non-Resonant Ferrite Core Cavities (NRFCC), referred in this paper, used in LIAs. In synchrotrons, the resonant frequency of accelerating cavity needs to keep up with particles' revolution frequency. RFCC uses shorted, DC-biased ferrite loaded coaxial transmission lines as inductances to resonate with the accelerating gap capacitance. The circuit is kept in tune with the required frequency by changing the bias current which in turn changes the permeability of the ferrite core and the resonance frequency. Only a small portion of the saturate Hysteresis loop is used at any moment of ramping. While, NRFCC in LIA is a non-resonant structure, used in a pulsed working mode. For each accelerating

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pulse, B-H variation of the ferrite cores covers most of the saturate Hysteresis loop to obtain the maximum ΔB, except in the case of bursting mode, where Hysteresis loop range is distributed among pulses. In both RFCC and NR-FCC, the ferrites allow the cavity to be small.

Astron and Transformer Model

Astron is the first LIA, and the transformer model of the acceleration principle was clearly stated with Astron [1]. For the purpose of comparison with later developed LIA cavities and transmission line model, we will briefly restate the transformer model and Astron cavity here.

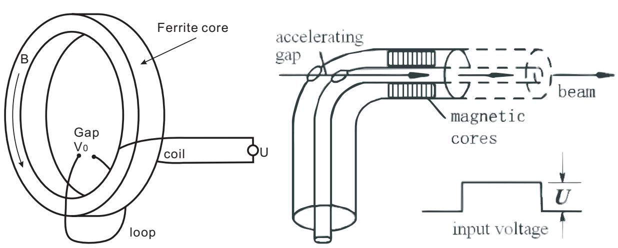

Figure 1: Diagrams of transformer model and transmission line model.

The geometry of the accelerating structure is shown diagrammatically in Fig. 1. A toroidal ring core of magnetic material surrounds of the beam pipe, and the change in flux in the magnetic core induces an electric field between the gap electrodes, which is the accelerating field.

$$V_0 = \oint \vec{E} \cdot d\vec{l} = -\int_s \frac{\partial \vec{B}}{\partial t} \cdot d\vec{S} \qquad (1)$$

The accelerating units consists of 48 cores each. Each core is threaded by primary straps. The case of each core forms the secondary coil. Electrodes are connected to the plate of the case. Each core contributes an average of 12 keV to the beam.

The energy uniformity during the beam pulse was provided by the pulsing system maintaining a constant dB/dt during the useful part of the pulse. This was done by providing a current ramp in the primary pulse. A specially designed pulse shaper circuit was used to produce the required current ramp. The primary and secondary voltage pulses are copied here in Fig. 2

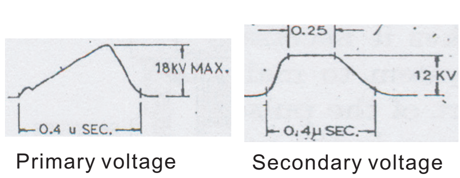

Figure 2: Astron's primary and secondary voltages.

The Astron's experiments and transformer model is perfect and convincing.

Later developed Induction Cavities and Transmission Line Model

In Astron's case, the dependence of constant voltage on dB/dt is clearly explained and demonstrated. But, the relationship of the flux swing ΔB to H and the drive current I is complicated, being nonlinear and time dependent for the pulse durations of interest. The insulation problem in the assembly of Astron required considerable attention during the development of Astron. During the journey to higher accelerating gradient, more magnetic cores are placed in single case while magnetic isolation concept is developed. And, the LIA cavity structure has subtly changed.

Figure 3 shows the schematics of later developed LIA cavities. Although the high voltage conductor of the power feed-in cable is connected with the outer conductor through the conductor surrounding the cores, it is inductive isolated because of the large inductance of the core for the high voltage pulse. At the same time, the beam still senses the accelerating field at the gap. This process is called inductive isolation.

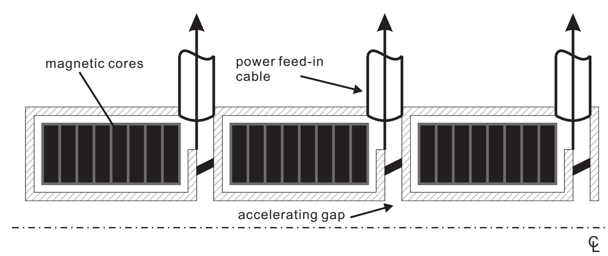

Figure 3: Schematics of later developed LIA cavities.

In such kind of structure, transformer model is challenged for the explanation of the acceleration mechanism. The coupling from the pulsed power system in Fig. 3 is by hard connection, and the view that dB/dt causes the acceleration seems inappropriate [5]. Whether there is a hard connection from the high voltage conductor to the gap is the key difference between the two accelerating structures. The loss current that flows from high voltage to ground through this connection path is limited to a level low enough by aforementioned inductive isolation.

There is an image current accompany the beam current in the inner conductor and forms a current loop with the beam current. At the accelerating gap, the image current flows into the power supply cable. Hence, the power supply current is divided into an charging current flowing into the gap, and an magnetization current flowing around the magnetic cores. The image current loads the charging current, so the charging current equals the beam current. The loop formed with the image current and charged particle current never surrounds the magnetic cores to behave as the secondary coil unlike the transformer model has assumed.

In Astron type accelerating cavity, the core is thin, the inductive impedance of the core is comparatively low in the circuit, the magnetizing current is easily controlled by external power supply, hence, constant dV/dt can be used to obtain constant flux change in the core and constant gap voltage in turn. In later developed cavities, the core inductance is increased greatly with much larger core in the cell. And the supplied high voltage is directly applied to the gap. So, constant V, instead of constant dV/dt, is pursued. The large core inductance and compensation circuits are used to minimize the voltage droop.

In the accelerating structure shown in Fig 3, magnetic cores and the housing can be viewed as either an large inductance or a short transmission line depending on the electric length of the core cell compared with the rising time of the high-voltage pulse. When the electric length of the core cell is longer than the rising time of the high-voltage pulse, it behaves like a short transmission line, and a constant resistive impedance is seen from the input port. The gap voltage flatness in this situation is determined by the high-voltage pulse shape and beam load variation. The transmission line model was brought about by Keefe [4], see Fig 1. Transmission line model is straight forward in explaining the accelerating structure in Fig 3. And we can see both Transmission line model and transformer model are good in explaining their corresponding structure.

SEVERAL ISSUES ABOUT TRANSMISSION LINE TYPE CAVITIES

The Inductive Field

In later developed cavities, when the core can be considered as a lump element, the inductive field around the core is the back-EMF, like in an inductance case. When the transmission line model can be applied, the wave front travels inside the core region for some period before it reaches the shorted end. During this period, there is an internal field distribution inside the core region, the induced field is localized in the wave front region, and move toward the shorted end. In regions before and after the wave front in the core, there is no flux change, hence, no induced field. In this case, although the accelerating voltage at the gap is not the magnetically induced field, the induction of the core does sustain the gap voltage, so we can still call it induction accelerator.

Wave's Reflection inside the Core Housing

In core transmission line, the voltage pulse will be reflected back by the shorted end. When this reflected and flipped voltage arrives at the input end of the core transmission line, it won't cancel the input pulse at the gap. This is because the impedance of the core transmission line is much higher than the combined impedance of the feed in power cable and the beam load, only a very small part of the reflected voltage is transmitted to the gap, the rest dominant part is reflected again. Hence, the voltage pulse is locked inside the core housing with small leakage as long as the core is not saturate [10].

Volt-Seconds

The Voltage-Second is a basic design criteria in determining the dimension of the magnetic cores. And it is derived from the transformer model by treating the cores as a single lump element:

$$V_0 \tau \leq \Delta B S \tag{2}$$

where, τ is the pulse length, S is the core transection area. In the transmission line model, twice of the voltage pulse traveling time in the transmission line must larger than the pulse length. That is

$$\frac{2L}{\frac{c}{\sqrt{\varepsilon_f \mu_f}}} \geq \tau \tag{3}$$

where L is the core housing length. In the core area, with the pulse traveling forward, the magnetized area increasing speed is $\frac{c(r_o - r_i)}{\sqrt{\mu_f \varepsilon_f}}$. The pulse voltage equals to the induced voltage,

$$V_0 = \Delta B \frac{\delta S}{\delta t} = \Delta B \frac{c(r_o - r_i)}{\sqrt{\varepsilon_f \mu_f}} \tag{4}$$

$(r_o - r_i)$ must be larger enough to support needed V_0. Substitute Eq.(3), into Eq.(4), we get

$$V_0 \tau \leq 2 \Delta B S \tag{5}$$

There is a factor of 2 difference between Eq.(5) with Eq.(2), which comes from the additional magnetization by the reflected current. The reflected current has same direction as the input current and make the total current double. So, the factor of 2 will be absorbed by ΔB and we get Eq.(2) again. In the above derivation process according to transmission line model, we can see that the dimension of the core, L and $(r_o - r_i)$ are determined separately because of separate physics requirements behind them.

SUMMARY

Transformer model and transmission line model for LIA cavities are reviewed for their corresponding structure, some unclear knowledge points are clarified.

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