R&D FOR LINEAR INDUCTION ACCELERATOR IN CHINA

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Abstract

It has been more than three decades since the researches and developments of key technologies and components for the linear induction accelerator (LIA) started at the Institute of Fluid Physics, China Academy of Engineering Physics (CAEP), The first LIA was built in 1989 with beam parameters of 1.5 MeV, 3 kA and pulse width of 90 ns. Later the SG-I LIA (3.3 MeV, 2 kA, 90 ns) was developed for FEL in 1991. The first Linear Induction Accelerator X-Ray Facility (LIAXF, 10 MeV, 2 kA, 90 ns, spot size about 6mm in diameter) was built in 1993 and upgraded to 12 MeV with higher performance (LIAXFU, 12 MeV, 2.5 kA, 90 ns, spot size about 4mm in diameter) in 1995. The Dragon-I LIA with the best quality in the world (20 MeV, 2.5 kA, 70 ns, and spot size about 1 mm in diameter) was finished in 2003. The smallest novel LIA with double pulses separated by 300ns (MiniLIA, 240 keV, 1 A, 80 ns) was developed in 2007 for double-beam physics studies.

INTRODUCTION

The linear induction accelerators have been used in many research fields in the past four decades such as radiography, free electron laser, high power microwave, heavy ion fusion and so on. The researches and developments of key technologies and components for linear induction accelerator have been conducted at Institute of Fluid Physics, China Academy of Engineering Physics (CAEP) since 1970's such as ferrite toroids and metglass toroids with high performance and high voltage switches with low jitter, multi-pulse technologies and so on which will be presented in the second section. In the third section, a series of induction accelerators with energies ranging from hundreds keV to 20 MeV which have been built in China [1, 2, 3,4] are described briefly such as the Dragon-I LIA and novel smallest LIA called mini-LIA. The Dragon-I was built at Institute of Fluid Physics, the world best quality LIA which can produce an electron beam of 2.5 kA, 20 MeV with pulse width of 80 ns (FWHM). The Mini-LIA was built at Tsinghua University which can generate double pulses electron beams with 240keV,1A and pulse width of 80ns.The time interval of the double pulses could be less than 300ns and adjustable very conveniently. In the forth section, diagnostics technologies for measurements of beam parameters such as beam energy, beam current, emittance and spot size are presented. Emittance measurements have been conducted using two different methods and good agreement has been achieved. Time-resolved measurement of beam envelop has been made by Cerenkov radiation method. All these diagnostic technologies have been used for measurements of the beam parameters on the Dragon-I LIA. In the last section is the summary of the paper.

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R&D OF KEY TECHNOLOGIES AND COMPONENTS FOR LIA

Development of Magnetic Cores

The magnetic core is one of the key components for linear induction accelerator. There are two kinds of magnetic core have been developed in China. One is the ferrite toroid with outer diameter up to 900mm and thickness about 25mm. The B_s and B_r of the ferrite core were more than 4000 Gauss and 3400 Gauss respectively. The other is the metglass core with similar dimension but higher magnetic performance with B_s and B_r of 1.5T and 1.2T respectively.

R&D of High Voltage Switches With Low Jitter

The stability and reliability of the linear induction accelerators highly depends on the performance of the switches used in the LIA system. Therefore, the high voltage switch is the most important active device in the pulsed power system for LIA. Different types of switches have been designed and studied for LIA. The typical switch applied for the Marx generators is the coaxial spark gap gas switch with working voltage of 200kV and jitter of 2ns. The cylindrical gas switch working at voltage of 300kV-400kV with time jitter of less than 1ns was used for the Blumlein pulse forming line.

R&D of Multi-pulse Technologies for LIA

High rep-rate LIA is of great interest in some applications. Several novel ideas to generate high rep-rate pulses up to MHz at burst mode based on conventional high power gas switch have been proposed and studied both theoretically and experimentally. Very good results have been achieved. One of the novel ideas to generate double pulses (See Fig.1) on the induction cavity is by means of cable delay method [5]. Another novel idea to produce multi-pulses (see Fig. 2) [6] is the so-called controlled pulse adder which runs multiple Marx-PFLs at different controlled time and add together to drive the induction cavity. Multi-pulse electron beams have been also achieved (see Fig.3 CH4) [7].

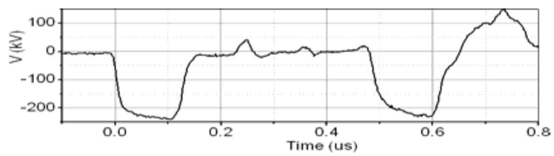


Figure 1: Double pulses by cable delay method

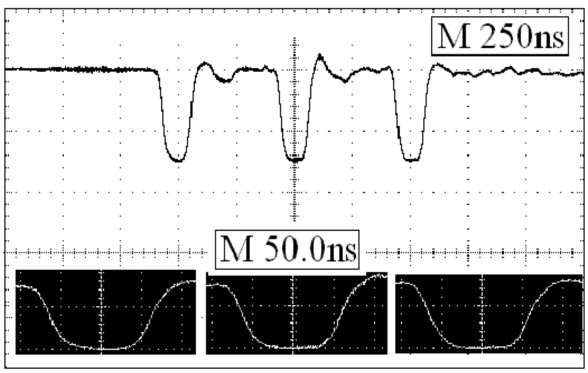
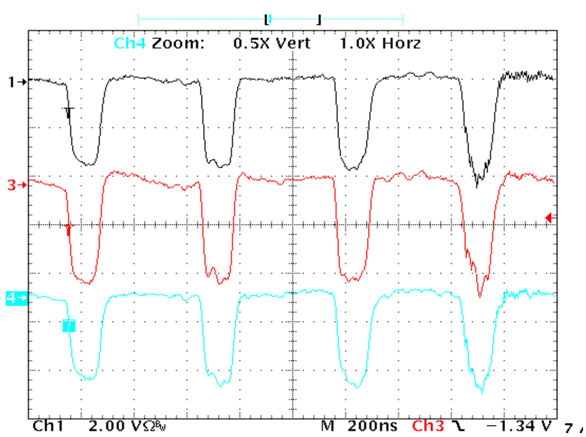


Figure 2: Triple pulses (250kV) by controlled adder method



CH1 &CH3 Voltage pulses
CH4 Beam pulses

Figure 3: Waveform of multi-pulse beams

DEVELOPMENTS OF LINEAR INDUCTION ACCELERATORS

In the mean time of the researches and developments of key technologies and components, the prototype of the induction module was developed and tested in 1985. After that, a series of linear induction accelerators were built in later year. The first linear induction accelerator (1.5MeV, 3kA, 60ns) in China was built in 1988, which consisted of 1MeV induction adder injector and two cavities for post acceleration [1]. The SG-I LIA (3.5MeV, 3kA, 60ns) was constructed in 1990 for free electron laser research [2]. The Linear Induction Accelerator X-ray Facility (LIAXF,10MeV, 2kA, 60ns, spot size 6mm) was built at Institute of Fluid Physics in 1993 and upgraded to LIAXFU (12MeV, 2.7kA, 60ns, spot size 4mm) in 1995 [3]. Recently, a higher quality LIA, Dragon-I (20MeV, 2.5kA, 70ns, spot size 1mm) [8] and a novel smallest LIA, Mini-LIA (240keV,1A, 80ns, double pulses) [9] were developed in 2003 and 2007 respectively.

1.5MeV Linear Induction Accelerator and SG-I LIA

The first linear induction accelerator in China was built in 1988, which consisted of 1MeV injector and two cavities for post acceleration each provided the beam with 250keV energy. The output beam parameters were 1.5 MeV, 3kA with pulse width of 90ns.The injector was made of a velvet cathode and tungsten mesh anode and four-cavity inductive adder which generated –1MV high voltage pulse to drive the diode.

The 1.5 MeV LIA was upgraded to 3.5MeV LIA for free electron laser research in 1990 by adding 6 more cavities for acceleration to increase beam energy from 1.5MeV to 3.5MeV. The output electron beam was adjusted through a conditioning section and put into wiggler to generate FEL.140MW output power of FEL was obtained and power gain of 26dB/m was achieved in 1993.

Linear Induction Accelerator X-ray Facility

In 1993, the Linear Induction Accelerator X-ray Facility （LIAXF）was built at Institute of Fluid Physics. The parameters of the electron beam were 10MeV, 2kA, 60ns with spot size about 6mm in diameter (FWHM). It consists of 1MeV injector same as 1.5MeV LIA and 28 induction modules for acceleration. There are total five Marx generators, 32 Blumlein PFLs and 32 induction cavities. Each Marx generator charges six or seven Blumlein PFLs and discharges through a gas filled spark gap switch. Each Blumlein PFL drives one induction cavity. The Spark gap switches are triggered in turn by a two stage triggering system which includes one first stage triggering switch and five second stage triggering switches, the first stage switch triggers five second switches in turn and then each second switch triggers six or seven Blumlein switches in turn. Each induction cavity provides about 350keV energy to the electron beam.

The LIAXF was upgraded to LIAXFU (12MeV, 2.7kA, 60ns) with smaller spot size of about 4mm in diameter by adding four more induction modules and other improvements in 1995.

The Dragon-I LIA

The Dragon-I linear induction accelerator is a new accelerator being built in 2003 at Institute of Fluid Physics (see Fig.4) [8]. It is an electron linac and consists of a 3.6 MeV injector, 72 accelerating cavities, pulsed-power system, beam-transport, control and auxiliary systems. It can produce an electron beam of 3 kA, 20 MeV with pulse width of 70 ns (FWHM).

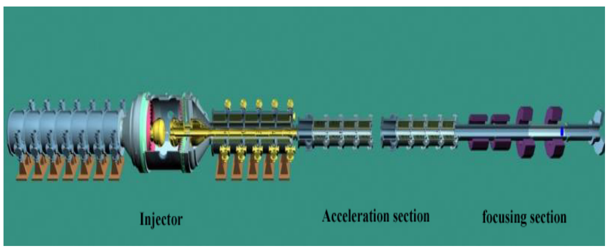


Figure 4: Schematic of the Dragon-I LIA

The injector of the Dragon-I LIA is based on the principle of inductive adder and composed of 12 induction cavities each can generate 300 kV high voltage with pulse width of 90 ns (FWHM)[10]. The voltages of the first seven cavities are added through a cathode stem and provide -2.1 MV on the velvet cathode of the diode. Likewise the voltages of the other five cavities are added through an anode stem and provide +1.5 MV on the foilless anode. So the total voltage of the diode of the injector is 3.6 MV. The injector is powered by two Marx generators each charges six Blumlein pulse forming lines (PFLs) through high voltage cables. Each Blumlein PFL drives one induction cavity.

In order to reduce the beam energy spread and get high beam quality, the output of electron beam from the injector is designed to be synchronized with the flattop of the accelerating voltages, i.e. the beam pulse is just put in the middle of the accelerating voltage pulses. Therefore the designed pulse width of the accelerating voltage for each cavity in the accelerating section is 120 ns (FWHM). The accelerating cavity is designed to generate 250 kV voltage pulse with 60 ns flattop with +/-1% variation. The accelerating section consists of 72 cavities and is divided into 18 subsections by four cavities plus one multi-function cavity. The multi-function cavity is designed for bridging the beam transporting magnetic field between adjacent accelerating subsections, vacuum pumping, monitoring the beam current and position, and detecting the beam profile.

The accelerating section is energized by six Marx generators each powers six Blumlein PFLs. Each Blumlein PFL is designed to drive two cavities through a pair of HV cables in the accelerating section.

There are ninety solenoids arranged periodically in the accelerating section to confine the beam in the accelerating section. In the focusing section several solenoids and two thin magnetic lenses are used to focus the beam to the targets. Each solenoid is supplied by a DC current source.

Mini-LIA

The mini-LIA consists of a thermo-cathode injector with beam energy of 80eV and two induction cavities for acceleration each provides the beams with energy of 80eV. The injector produces two electron beams with current of 1A and adjustable time interval. Double pulses are generated based on controlled pulse adder design. This work was done by collaboration with Tsinghua University.

TIME-RESOLVED DIAGNOSTIC TECHNOLOGIES

In order to measure the main parameters such as energy, beam current, beam envelop, beam centroid, emittance, Different kinds of time-resolved diagnostic technologies and systems have been developed and applied on Dragon-I LIA [11].

Time-resolved Energy Measurement

The time-resolved energy of the injector was measured by two methods [12]. One is measuring the voltage cross the diode. The other is using magnetic analyzer combined with quartz screen and streak camera. Cerenkov radiation light emitted from the screen was recorded by streak camera (see Fig. 5). Both results are in good agreement. The energy of the injector was measured at 3.5 MeV. The total energy at the exit of the accelerator was 19.4 MeV by adding the voltage of each cavity.

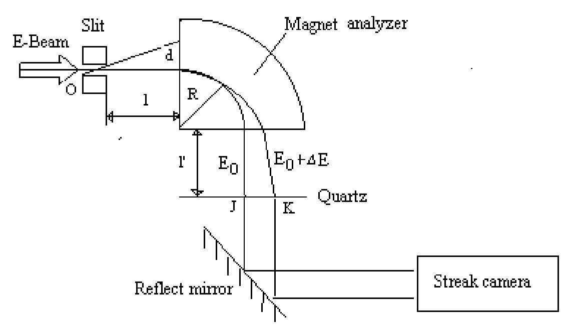


Figure 5: Schematic of time-resolved energy measurement

Beam Current Measurements

The emitting current is measured by B-dot probe. The beam current and beam centroid are measured by current view resistor (CVR). There are twenty CVRs along the accelerator to monitor the beam current transportation. Each CVR is located in the multi-function cavity to monitor the current after 4-cell transportation and provide information for magnetic field tuning.

The emitting current is measured at 2.65kA with pulse width of 90 ns, the output beam current at the exit of the accelerator is 2.6 kA and the beam current at the target is 2.54 kA with pulse width of 70 ns.

Time-resolved Emittance Measurements

The emittance of beam was measured with two different methods, modified three gradient method and OTR method. Fig. 6 is the schematic of the modified three gradient method. By measuring the time-resolved beam envelop at different magnetic fields, the time-resolved emittance can be obtained according to the beam envelop equation Eq. (1)

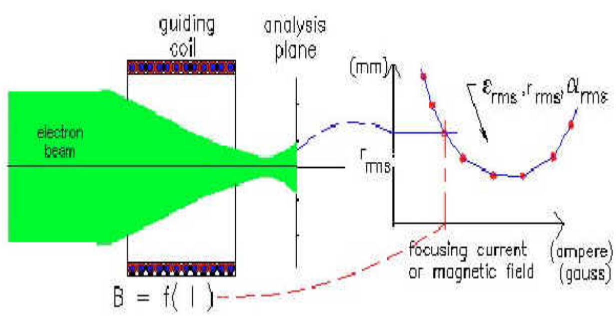


Figure 6: Schematic of the modified three gradient method

$$R'' + \frac{k^2}{4}R - \frac{K}{R} - \frac{\varepsilon^2}{\beta^2\gamma^2R^3} = 0 \qquad (1)$$

Here $K = \dfrac{2I}{17.045\beta^3\gamma^3}$ (I, kA), $k = \dfrac{ecB_z}{\beta\gamma mc^2}$

According to the experiment data, the measured normalized edge emittances during the flat-top of the beam pulse are about the same as 2060π.mm.mrad.

As long as the distribution of OTR is measured (see Fig. 7), the integrated emittance can be obtained (see Fig. 8) at 2935π.mm.mrad.

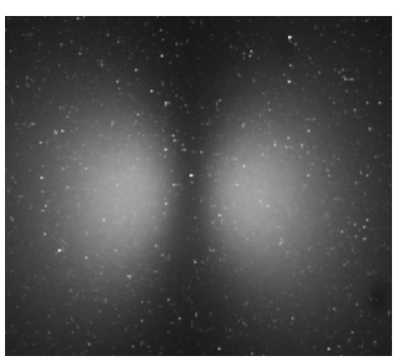


Figure 7: Experiment image of OTR

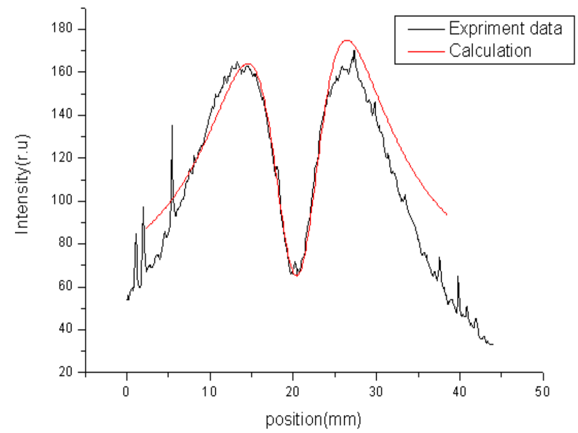


Figure 8: Scanned and fitted distributions of Fig. 7

Time-resolved Beam Centroid measurement

The time-resolved beam profiles were taken by fast frame camera with time interval of 10 ns and exposure time of 3 ns (see Fig.9). Fig. 10 are the eight pictures taken in one shot [13]. The fourth picture to the eighth picture correspond to the flat-top of the pulse. The variation of the beam centroid during the flat-top is in the range of 0.5 mm.

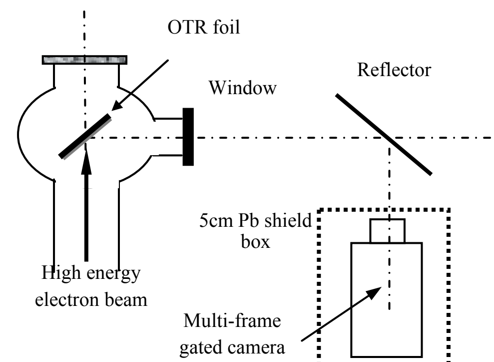


Figure 9: Experiment setup for beam centroid measurement

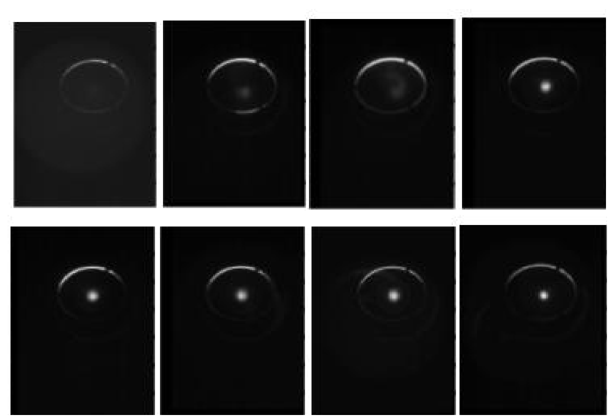


Figure 10: Beam profiles taken with frame camera

SUMMARY

The research activities for development of linear induction accelerator in China in the past thirty years are overviewed in the paper. The history of LIA development in China and most recent progresses have been introduced. Some results of the Dragon-I LIA are also presented in the paper.

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