DEVELOPMENT OF LINEAR INDUCTION ACCELERATORS AT JINR

G.V. Dolbilov, A.A. Fateev, I.I. Golubev, V.I. Kazacha, V.V. Kosukhin, N.I. Lebedev,
V.A. Petrov, V.P. Sarantsev, A.I. Sidorov, A.P. Sumbaev
Joint Institute for Nuclear Research, 141980 Dubna, Moscow Region, Russian Federation

Abstract

A review of current research activity in the field of linear induction accelerators (LIA) is presented. The tendencies of the LIA development at JINR are determined. The principal features of the modulators and induction systems, technical parameters and output characteristics of the electron beams are given.

Introduction

Linear induction accelerator technology has been developed at JINR in the frame of the collective method of acceleration research program which has defined the direction of the LIA development and significantly influenced on the accelerator parameters (see Table 1 and refs. [1]-[5]). LIA at JINR have been used for generation of the electron rings and further acceleration of these rings filled with multicharged ions. The present day applications of the LIA cover such regions as microwave electronics, FEL technique, two-beam acceleration and study of relativistic klystron.

Tendency of the LIA development at JINR

Classical schemes of the one-step modulator consisting of the energy storage, switch, and forming circuit, were used in the induction linacs of the first generation (LIA-3000, SILUND). Either capacitors (SILUND) or forming lines (LIA-3000) are used as energy storage, and powerful hydrogen thyratrons - as commutators. High voltage pulses on the accelerating modules - inductors are driven by either forming lines or sharping lines (leading edge) together with the inductors (trailing edge).

The first linear induction accelerator LIA-3000 was constructed at JINR in 1966. After several reconstructions of the modulator and focusing system, the accelerator has already been working for more than 25 years without interruption. It has served the program of the collective method of acceleration and now is used for the FEL and relativistic klystron research.

The further progress of the first LIA generation to increase the average power transferred into the beam, was limited by the traditional commutator techniques. The need in the electron beams of 15-20 ns pulse duration with current ~ 1 kA, caused the development of several accelerators (SILUND, SILUND-II, SILUND-10 and SILUND-20) where ferrite cores were used in the inductors.

The schemes of the magnetic pulse modulators including one or several compression chains, were realized in the induction linacs of the next generation. In these schemes the energy was stored in the capacitor banks and the hydrogen thyratrons operating in μs pulsed mode were used as primary switches. Compression of the electromagnetic power is performed in compression chains consisting of capacitors and nonlinear reactors. The power of the primary circuit is transferred in a resonance manner from the previous chain to the next one with compression in time. The nonlinear reactors fulfil the role of the power commutators for the following chains. As a result, the primary pulses of microsecond duration are transformed into the pulses of nanosecond duration with the higher peak power.

Accelerator SILUND-II was the first one of the second generation LIA and served as a prototype of the basic accelerator SILUND-20. Further the concept of the modulator and induction systems of accelerators SILUND-II and SILUND-20 was developed in the SILUND-10 accelerator to increase the power transferred into the beam by decreasing of the residual inductance and impedance matching of all the elements of the scheme. This problem was solved by using of the short grounded nonlinear ferromagnetic lines with distributed parameters as commutators. The lines are connected in a series in the preliminary compression chain and in parallel – in the final forming chain. All connections including the lines to the accelerating gaps, are manufactured as matched feeder lines. One modulator feeds induction section consisting of 6 inductors (of total length 38 cm) and provides integral accelerating voltage $U \sim 250$ kV at the loading equivalent to the electron beam with current $\sim$ 8000 A.

LUEK-20 accelerator is another accelerator of the second generation [5]. It has been designed to accelerate electron rings filled with heavy ions. Sufficiently low longitudinal velocity of the electron rings (which resulted in a large time of flight in the accelerating gaps) caused the development of a powerful modulator with pulse duration about of 50 - 70 ns. Later accelerating modules of LUEK-20 have been used for acceleration of conventional electron beams.

Travelling wave LIA (LIA-TW) is a special type of LIA producing the accelerating voltage pulse in the accelerating module spreading from one inductor to another on the front of the shock wave injected into the forming line which is the part of the accelerating module. LIA-TW was developed to accelerate charged clusters with a very short length, moving with the velocity $\beta z \ll 1.0$ (electron rings, heavy

TABLE 1
Survey of JINR Induction Accelerators

name	date of design	E MeV	core material	τ *ns*	f Hz	cathode types	I_b A	references
LIA-3000 *1	1966-67	1.5	permalloy	200	1	BaO(thermoionic)	300	[1]
SILUND	1971-73	1,7	ferrite	15	1	plasma	700	[2]
SILUND-II	1977-78	0,8	ferrite	20	50	plasma	1000	[3]
SILUND-10	1979-80	0,25	ferrite	20	1	—	8000	
SILUND-20	1981-82	2,0	ferrite	20	50	plasma	1000	[4]
		2,5			1	explosive, carbon fibre	600	
		2,5			1	explosive, graphite	600	
LUEK-20 *2	1985-86	10kV/cm	permalloy	60	20	—	e.r.	[5]
	1989-91	1,5	permalloy	60	1	explosive	800	
LIA-TW *2	1979-80	6,0kV/cm	ferrite	5	20	—	e.r.	
SILUND-21	project	8-10	permalloy	60	1	explosive	1000	[6]
					50	plasma	1000	

*1 - constructed at the Efremov-Institute (S-Petersburg), *2 - developed for electron ring acceleration (e.r.)
E - beam energy, τ— pulse duration, f - repetition rate, I_b - beam current

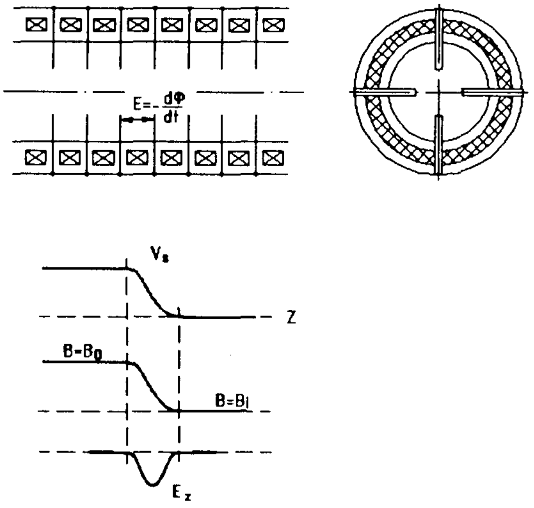

Fig. 1: Travelling-wave LIA (LIA-TW)

ions). Fig.1 shows the simplified scheme of the accelerating induction system and time diagram of the $E-z$-wave forming process. Such a system operates only when the velocity of the wave coincides with the velocity of accelerated particles. It is provided by the change of the initial magnetization of the ferromagnetic cores in the accelerating module. Scaling model of accelerating module of this type has been constructed. The field amplitude of E_z-wave has reached the value of 6 kV/cm and the velocity of the wave has been changed in the limits $\beta_z = 0.05 - 0.2$. On these results we conclude that accelerating gradient up to 20 kV/cm can be achieved in the LIA-TW.

Parameters of the beams

The electron beams of the JINR induction accelerators possess two peculiar features. First, there always exist the transverse drift of the beams off the accelerator axis. Second, the normalized emittance is growing in the process of acceleration.

As for the transverse drift of the beams, it is a consequence of the fact that the geometrical and magnetic axes of the focusing solenoids do not coincide which results in a finite value of transverse component of the magnetic field. Even a small value of this field ($B_{\mathrm{tr}} \sim 2-4$ Gs) is sufficient to provide transverse displacement of the beam $\Delta r \sim 10-20$ mm in the accelerator with the length ~ 5 m and the value of the focusing field $B \sim 1$ kGs.

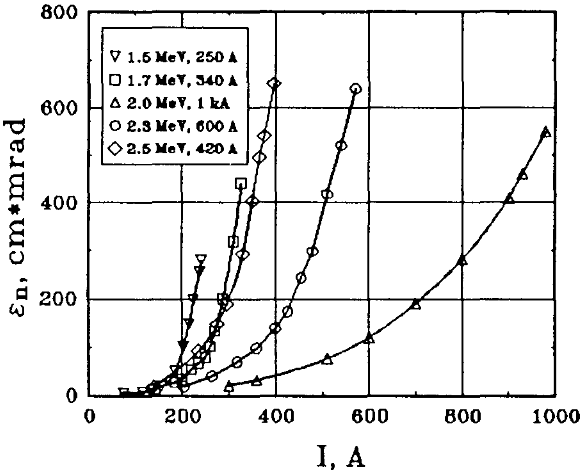

Fig. 2: Normalized emittance versus the beam current

The process of the emittance growing is defined with nonlinearities in the focusing fields and the space charge fields. Figs.2 and 3 present the results of emittance measurements at the JINR accelerators. Several electron sources have been used: with the hot BaO, plasma and explosive (graphite and graphite-fibre) cathodes. Our investigations have shown that there is no visible dependency

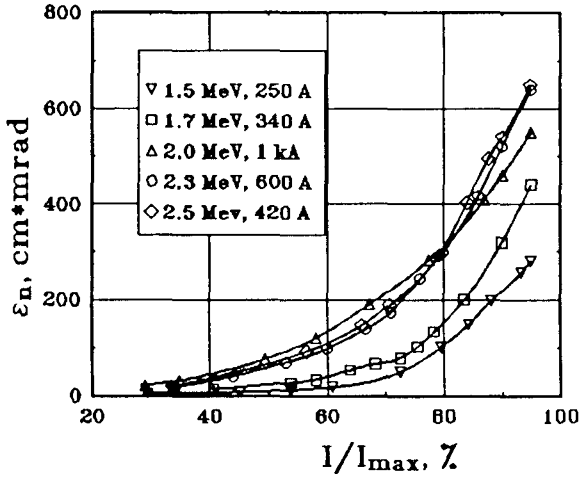

Fig. 3: Normalized emittance versus relative value of the beam current

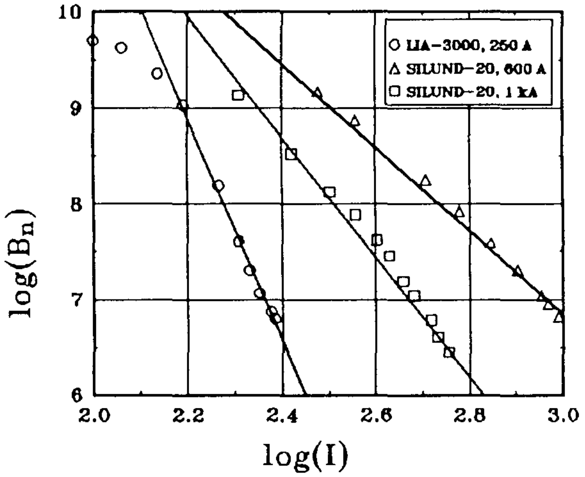

Fig. 4: Beam brightness versus the beam current (Here B_n is in $\mathrm{Am}^{-2}\mathrm{rad}^{-2}$ and I is in A units)

between the output beam parameters and the cathode type. On the other hand, there is a general tendency of the normalized emittance growing in the process of acceleration. The rate of the emittance growing is decreased with the energy increase.

One more peculiar feature of the beams is that the phase density of the particles and the beam brightness ($B_n = I/(\pi\epsilon_n)^2$) of the central core of the beam are increased with the increase of the total beam current. In Fig.4 we present the corresponding plot for the normalized brightness versus the beam current in the central core for several accelerators with different total beam currents. At $B_n < 10^9$ $\mathrm{Am}^{-2}\mathrm{rad}^{-2}$, these dependencies can be approximated with the simple formula $B_n = \alpha \times I^{-b}$, where factor b is inversly proportional to the logarithm of the total beam current I_{tot}, $b \propto 1/\log(I_{\mathrm{tot}})$.

SILUND-21 project

Silund-21 accelerator is constructed in the framework of experimental program to study microwave electronics, FEL physics and a problem of two-beam acceleration [6]. SILUND-21 will provide the electron beam with the following parameters: energy up to 10 MeV, peak current ~ 1 kA and pulse duration 50-70 ns. Instant energy spread will be less than 1 % and the energy spread averaged over pulse duration will be 2-3 %. The accelerator consists of seven accelerating modules. Each module is 1.8 m long and provides 1.5 MeV accelerating voltage at 1 kA beam load. The first accelerating module is combined with the electron source. Accelerating voltage of the electron source is equal to 500 kV – 1/3 of the total accelerating voltage of the module. The electron gun with graphite cathode and gridded anode will be used at the low repetition rate (~ 1 cycle per second) and a plasma electron source without anode grid – at the high repetition rate (~ 50 cycles per second). The value of magnetic field at the cathode will be controlled by the magnetic lens minimizing the value of the electron beam emittance. We may expect to obtain the value of the normalized emittance to be equal to $0.4\pi \times cm \cdot rad$ at 90 % of the nominal value of the beam current.

Conclusion

Linear induction accelerators of the 1-10 MeV energy range can be considered as effective energy transforming devices of the net electrical power into the energy of the high current electron beam. The main advantages of the LIA against another types of accelerators are: a high efficiency at high currents, sufficiently long macropulse duration, high peak power and simplicity of manufacturing. We believe that the linear induction accelerators have not exhausted their potential and can be used for a wide range of scientific and industrial applications.

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