Chapter 2
Historical Perspectives

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2.1 Introduction

The main objective of this chapter is to provide an overall perspective on the historical evolution of induction accelerator technology, and the applications that motivated its initial development. Understanding the context of these early developments might help the reader appreciate why particular technical approaches were followed in the past, and why new applications might push induction accelerator developments in different directions in the future. However, the main emphasis in all cases is to provide historical perspectives on the technical features of the accelerator technology, and not a detailed history of the projects that motivated their development.

Because the authors have personal knowledge of many of the early pioneering linear induction accelerator developments in the USA, these will be covered in the greatest detail. We will attempt to balance this emphasis by also providing references and brief summaries of the parameters of various induction accelerators built in other countries throughout the world.

The Betatron also uses pulsed voltages on a magnetic core to generate an inductive acceleration field, and its development preceded linear induction accelerator developments by a couple of decades. As we noted in Chap. 1, the technology and beam dynamics of the Betatron are fundamentally different from the induction accelerators discussed in this book. Pulsed voltages many orders of magnitude smaller with pulse lengths many orders of magnitude longer than linear induction accelerators are used to accelerate the electrons that circulate around the transformer core of the Betatron, and the pulsed magnetic fields of the core are an integral part of the magnetic focusing system of the electrons. We therefore consider a detailed discussion of the history of the Betatron development, like the history of RF accelerators, to be outside the scope of this book.

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2.2 Invention of the Linear Induction Accelerator by Christofilos

The Astron controlled-fusion concept invented by N. C. Christofilos required very high pulsed currents of relativistic electrons [1, 2]. The objective was to create an intense enough electron ring for its self magnetic field on axis to be stronger than the applied solenoidal magnetic field. The resulting closed magnetic field lines would be an ideal magnetic bottle to confine a thermonuclear plasma. Radiofrequency accelerators could not provide the 100's of Amp currents required in this application. To explore this fusion concept, Christofilos conceived of, and developed, the linear induction accelerator technology to serve as the injector for the Astron.

The original Astron Injector shown in Fig. 2.1 began operation in 1963 [3]; it produced a 300 ns, 350 A electron beam at around 3.7 MeV. The upgrade to 6 MeV and 800 A shown in Fig. 2.2 was completed in 1968 [4]. Both of the Astron Injectors used commercial coaxial cables charged to 25 kV as the energy storage medium, switched by thyratrons, to deliver a 400 ns pulse to magnetic "transformer" cores constructed out of Ni–Fe tape. (See Sects. 6.2 and 6.3 for more details on the Astron Injector modules themselves). With individual core voltages of $\sim$12.5 keV (half the charge voltage on the energy storage cable), a large number of switch modules were required and the average acceleration gradient was relatively low (0.2–0.3 MeV/m). But these machines did have the remarkable capability to produce a burst of up to 100 electron pulses (limited by the energy stored in a rotating generator) at repetition rates of order 1 kHz. This burst output capability was required to study the build up of the electron ring by "stacking" successive electron beam pulses in the plasma confinement vessel on a fast enough time scale.

The Astron Injectors produced very repeatable and high quality electron beam pulses, and the energy variation within the pulse on the Astron Upgrade accelerator

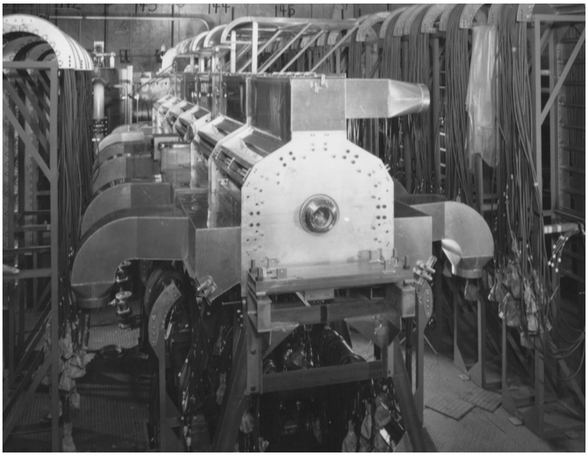

Fig. 2.1 Original Astron Injector (1963)

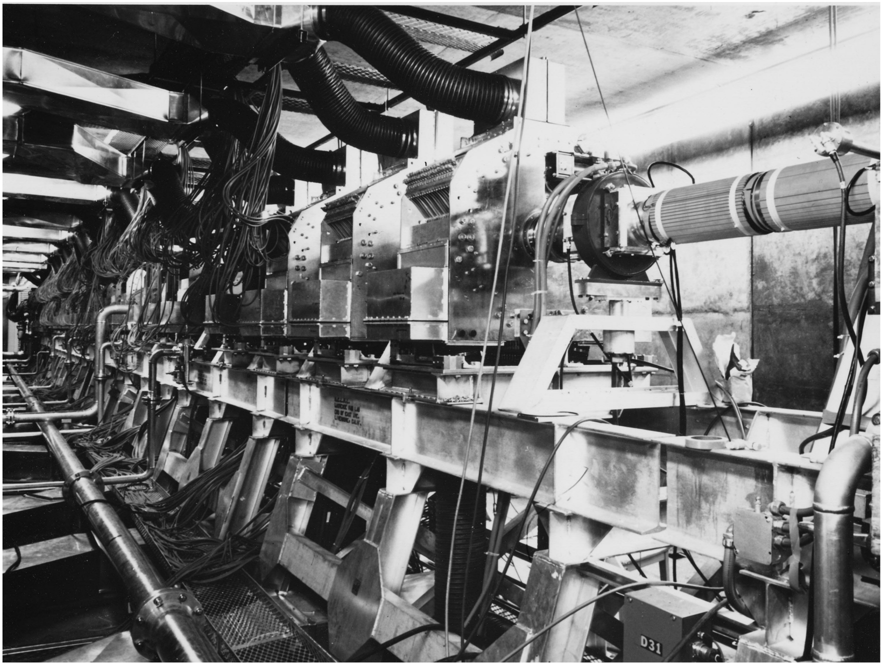

Fig. 2.2 Astron Injector upgrade (1968)

could be reduced to less than 0.1–0.2% with careful tuning of the pulse compensation networks in the drive system. This precision was felt to be important for controlling the trapping of the electron pulses injected into the confinement vessel.

It should be noted that the beam current in the Astron Upgrade, originally designed to produce a 1 kA beam, was limited to about 800 A by the beam breakup instability (BBU), and for a good quality beam the current needed to be less than 500–600 A [4]. The BBU instability in induction accelerators was poorly understood at that time but its observation in the Astron Injector did serve as a warning in the design of subsequent machines to study and to minimize cell resonances.

2.3 Early History of Short-Pulse Induction Accelerators at LLNL and LBNL

Lawrence Livermore National Laboratory (LLNL) and Lawrence Berkeley National Laboratory (LBNL; formerly denoted LBL) continued to pioneer the linear induction accelerator technology following its origination by N.C. Christofilos in the early 1960s. A summary of some of the key parameters of these accelerators and the Astron Injectors is given in Table 2.1. Switch modules listed drive the accelerator cells.

Table 2.1 Early history of induction accelerators in the USA

Accelerator	Kinetic energy [MeV]	Current [A]	Pulse length [ns]	Repetition rate [Hz]		Core type	HV modules	Number switch modules	Modulator voltage [kV] cell (core)	Length [m]
				Max. Avg.	Burst (pulses)					
Astron injector, LLNL (1963)	3.7	350	300	60	1,440 (100)	Ni–Fe tape	Thyratron	300	250 (12.5)	∼10
Astron upgrade, LLNL (1968)	6.0	800	300	60	800 (100)			550		30
NBS prototype, NBS (1971)	0.8	1 k	2,000	< 1	–	Steel tape	Spark gap	2	200 (40)	1.3
ERA injector, LBNL (1970)	4	1 k	30	5	–	Ferrite	Spark gap	17	250	14
ETA, LLNL (1979)	4.5	10 k	40	2	900 (5)	Ferrite	Spark gap	10	250	10
FXR, LLNL (1982)	18	3 k	70	0.3	–	Ferrite	Spark gap	54	250	40
ATA, LLNL (1983)	50	10 k	60	5	1,000 (10)	Ferrite	Spark gap	200	250	53

At LBNL a program to investigate the electron ring collective ion accelerator (ERA) concept, following successful initial experiments in the USSR by Sarentsev and his group, led to the development of a new type of shorter pulse induction accelerator in the late 1960s [5]. In the electron ring collective ion accelerator concept, invented by V.I. Veksler, a small radius electron ring was loaded with a few ions by ionization of a background gas. The electron ring and its ion load were then accelerated along the axis of the ring; the ions trapped within the ring could be accelerated at a much higher gradient than in conventional accelerators. To create the electron ring, an injected electron beam pulse of 10's of ns at beam currents of a few 100 Amps was required. Following successful initial experiments using the Astron Injector, the 4 MeV ERA Injector at LBNL shown in Fig. 2.3 was built to study the formation of these electron rings. It introduced the use of ferrite tiles for the magnetic core material, and it used much higher voltage pulsers driving each core than the Astron Injector (the electrical energy storage was based on oil-filled Blumleins operating at 250 kV, as described in Chap. 4). The current through the accelerator was generally around 1–1.5 kA, but collimation systems were used to separate out a high quality beam of a few 100 Amps.

Fig. 2.3 Electron Ring Accelerator Injector, the first induction linac to use ferrite cores (1970)

A program aimed at the study of electron beam propagation in air for directed energy weapon applications lead to the development and construction of similar shorter pulse machines at LLNL in the late 1970s and early 1980s. The predicted requirements for stable propagation of a self-focused beam in air was a peak current of order 10 kA or more, and a one kHz "burst mode" capability was needed to explore the creation of rarefied channels in the air to extend the propagation range. A 4.5 MeV Experimental Test Accelerator (ETA) was constructed to develop the technologies required for this high current, high burst repetition-rate operation [6]. Individual cores in both the ETA and the 50 MeV Advanced Test Accelerator (ATA) shown in Fig. 2.4 were driven by 250 kV Blumleins switched by spark gaps. These pulse power units were capable of 1 kHz burst operation [7], and the Blumleins used water with its high dielectric constant as the energy storage medium to produce the required output current of 20 kA. The gradient in the 50 MeV ATA was on the order of 1 MeV/m, considerably higher than the earlier longer pulse machines. These accelerators were used to study self-focused beam propagation in air, and also to investigate high gain Free Electron Laser (FEL) amplifiers in the mm and infrared wavelength bands (discussed in Chap. 8).

The requirement for an intense pulsed X-ray source for radiography in non-nuclear hydrodynamic experiments supporting nuclear weapons research (see Chap. 8) lead to the construction of the 18 MeV FXR machine at LLNL [8]. FXR was built in the same timeframe as ATA, with a design based on the ERA injector and ETA. It has been a workhorse in "flash radiography" of hydro experiments for the last several decades. The 20 MeV first axis of DARHT-I built at Los Alamos National Laboratory (LANL) in the early 1990s [9] made several improvements on the FXR design, and it has been providing an even more robust radiography capability.

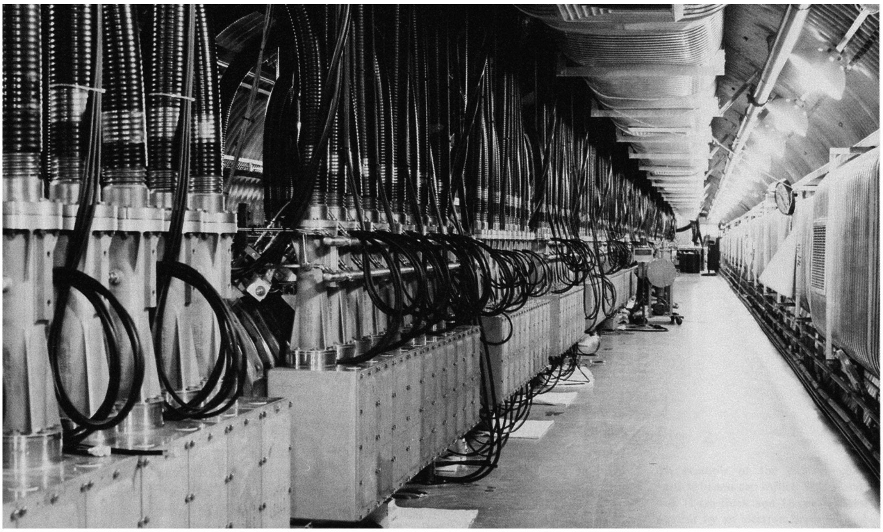

Fig. 2.4 Advanced Test Accelerator, the highest energy induction linac (1983)

2.4 Long-Pulse Induction Accelerators

At the same time that the LBNL/LLNL programs were developing the short-pulse ferrite core induction technology, a program was initiated at the National Bureau of Standards (NBS, now NIST) to extend the induction linac technology to much longer pulse lengths (∼2 μs) to get higher total charge per pulse [10]. It was recognized that much longer pulse length induction accelerators extended to higher energies would require a more cost effective way to construct induction cores with a larger energy gain per module. Cost considerations lead to the choice of thin mild-steel foil wound with Mylar sheet insulation into tape-wound cores, and radial segmentation to enhance the acceleration gradient (see Chap. 6). The prototype modules constructed at NBS accelerated a 1 kA beam by 400 keV, held constant within a few percent over the full 2 μs pulse (see Table 2.1).

The legacy of this long-pulse induction linac development continued in the Heavy Ion Fusion Program at LBNL. In the mid 1970s, it was recognized by Maschke and others that an intense multi-GeV beam of heavy ions could be an attractive driver for inertial fusion energy (see Chap. 10). Because very high intensity beams are required in this application, the USA Heavy Ion Fusion (HIF) program has focused on driver concepts based on linear induction accelerator technology for the past three decades. The heavy ion beam must be eventually compressed to pulse lengths of order 10 ns at the target, but space charge limitations in the beam transport in the earlier sections of the linac lead to multi-μs induction cores for much of the accelerator. In the late 1980s, a 1 MeV heavy ion induction accelerator test bed (MBE-4) was built to accelerate four parallel 10 mA Cesium ion beams through the same induction cores [11]. The Astron cores were reused in the MBE-4, and the beam pulse lengths varied from 2.0–0.5 μs.

The recent construction of a long-pulse electron induction linac for multiple pulse radiography at LANL, the ∼18 MeV second axis of DARHT (DARHT-II), represents a significant advance in the long-pulse induction technology [12]. The DARHT-II cell design and its application to radiography are both discussed in the later chapters of this book (Chaps. 6 and 8).

2.5 High Repetition-Rate Induction Technology Developments

Motivated by applications requiring high average power, like microwave power sources for heating of magnetically confined plasmas, and short-wavelength FELs for directed energy weapon applications, the technology of magnetic modulators for induction accelerators was pioneered at LLNL by the late Dan Birx in the early 1980s. A watershed in this development was the construction of the MAG-I-D modulator in the early 1980s [13]. Using thyratrons as the primary switch, this pulsed power system produced 125 kV, 8 GW peak, 70 ns pulses at a 5 kHz repetition-rate (quasi-CW) for an average power of ∼3 MW. The efficiency of this multistage magnetic pulse compression system exceeded 90%; this made it a viable candidate for induction linac pulsed power systems in applications where high conversion efficiencies were needed.

Three MAG-I-D units were used to power the 60-cell ETA-II accelerator constructed at LLNL in the late 1980s [14]. This accelerator was built as a testbed for the development of high average power, high brightness electron beams. ETA-II produces a 6 MeV, 2 kA, 40 ns flat-top, very high brightness electron beam. It was used as the electron beam source to drive a mm wavelength FEL for heating a Tokamak plasma (discussed in Chap. 8). It has been used in recent years as a test bed for advanced radiography development.

A smaller induction accelerator, SNOMAD-II, used solid state primary switches to drive the magnetic pulse compressors [15]. The more recent advances in solid state switching technology and their application to induction accelerator modulators are described in Chaps. 4 and 11.

2.6 Recirculating Induction Linacs

Since linear induction accelerators (LIAs) generally have relatively low gradients, around one MeV per meter with short-pulse LIA's like ATA and even lower with long-pulse LIA's, the idea of recirculating the beam through the cores several times with independent beam transport lines has often been considered. The main objective is to obtain significant savings in cost, size, and weight of a high energy induction accelerator. Note that this "recirculating linac" architecture is very different from the induction synchrotron discussed in Chaps. 11 and 12, or a Betatron. The approach discussed here is more closely related to the Microtron, a "recirculating RF linear accelerator."

With a long-pulse electron beam (multi-μs, hundreds of meters in length) of "modest" current (a few kA), passing the beam several times through a few modules during the time of one voltage pulse on the induction cores can significantly reduce the number of modules required for a given final beam energy. The large bore of long-pulse induction cores and the low impedance of the pulsed power drivers are key here, since the bore must accommodate the simultaneous presence of several beam transport sections at once, and the total beam current load on the induction module (over most of the pulse length) is increased by the number of recirculations. This approach was considered at NBS, and experimental studies of electron beam recirculation through long-pulse induction cores with a two-pass facility delivering 20 keV per pass were carried out [16].

With shorter electron beam pulses a more reasonable recirculation scheme is to apply voltage pulses lasting slightly longer than the duration of a single beam pulse on a set of induction modules. The cores would then be reset during the recirculation time, and the pulse reapplied when the beam pulse comes around again. This approach, with a novel beam transport system utilizing static magnetic guide fields on the separate beam transport lines, was developed at PSI [17]. The spiral shape of the transport lines motivated its name, the Spiral Line Induction Accelerator (SLIA). Transport and acceleration of a 10 kA, 30 ns beam pulse around one turn of a SLIA with minimal emittance growth was demonstrated, and a 2 kA beam was accelerated around two turns to 9 MeV.

The Heavy Ion Fusion (HIF) program has also considered beam recirculation to reduce the cost of a heavy ion beam driver (see Chap. 10). In a conceptual inertial fusion power plant design, the induction acceleration stages would be relatively long and circular, and the beam pulse would occupy less than half the circumference. The cores would have fast resets, and the (burst) repetition rate of the pulsed power systems would be very high ($\sim$10–100s of kHz). An experimental test bed to study the beam transport in a heavy ion recirculator was constructed at LLNL, but only 1/4 turn of a 80 mA beam with 5 induction cells were completed before the project was terminated [18]. Recirculation of an intense space-charge dominated beam has continued to be studied using a low energy electron beam at the University of Maryland (UMER) [19].

2.7 Former USSR Induction Accelerators and "Coreless" LIA's

A number of "magnetic core-type" induction accelerators were constructed and operated in the former USSR during the same general time frame as the developments in the USA discussed in the previous sections. The first machine, the 1.5 MeV LIA-3000 at JINR, was completed around 1966 [20]. It was similar in many respects to the original Astron Injector, with Permalloy cores and a thermionic BaO cathode, and it operated at similar beam currents. As mentioned in Sect. 2.3, the collective ion acceleration results with an electron ring accelerator using this machine as the injector were a major stimulus for the initiation of the ERA program at LBNL.

A list of the other core type induction accelerators in the former USSR that the authors are aware of, and their key parameters, are given in Table 2.3. Detailed information on these accelerators was in general not publicly available until recently, and gaps still remain.

The so-called "coreless" or "line-type" induction accelerator was pioneered in the former USSR starting in the late 1960s [21, 22]. The accelerator modules in a "core-less" induction accelerator do not contain magnetic material; instead, short-duration acceleration voltage pulses are generated (for example) by firing closing switches on one side of a radial Blumlein configuration charged to several MeV. These modules are generally very low impedance, operate at a very high voltage per stage, and can accelerate extremely high electron beam currents. For example the highest energy accelerator (the LIA-30) accelerated 50–100 kA, 25 ns beam pulses to 40 MeV [23]. The applications that motivated these developments were not known at the time they were first reported, but were thought to be nuclear weapons effects simulation and radiography.

The initial reports of these developments at VNIEF (former USSR, presently Sarov, Russia) stimulated the development of high current radial line accelerators in the USA. The RADLAC-I accelerated a 25 kA, 15 ns pulse length electron beam to 9 MeV using 4 radial line stages operating at around 1.75 MeV each [24, 25]. Issues with beam transport at these high currents lead to the development of a follow-on machine (RADLAC-II) reconfigured into an Inductive Voltage Adder (IVA) – basically, a single stage high voltage diode with a ∼12 MeV stalk voltage generated by inductive addition of the stages [26].

As mentioned in Chap. 1, these "coreless" induction accelerators represent significant technological achievements but we do not cover their designs in detail in this book. We should note, however, that there is recent interest in the development of very short pulse length "coreless" induction linacs with extremely high gradients [27].

2.8 Summary Tables of Induction Accelerators World-Wide

To give an overall perspective on the development of induction accelerator technology over the past decades throughout the world, summary tables with references are provided in this section. The accelerators included in these tables are all the machines we are aware of that have been constructed and operated. The parameters listed are the energy, current, pulse length, and repetition rate of the output beam. In cases where the information was available, the repetition rate is qualified with the burst rate value and the number of shots (in parenthesis) that the burst rate could be maintained. The authors made a "best effort" to determine these beam parameters from published descriptions, but caution should be exercised by the reader. For example, pulse lengths are often not measured consistently and it is generally not clear whether quoted parameters are "typical" operating conditions or the occasional "best shot." Table entries where parameters could not be determined are indicated with dashes. The beam particles are electrons unless otherwise indicated.

In Table 2.2 the "core type" induction accelerators in the USA are listed. For completeness, this table includes the machines already discussed in some detail in the earlier sections. A major objective of the HBTS, SNOMAD-II, and ETA-II accelerators, for example, was the development of high average power capability of induction linacs. The recirculator was intended as an induction based ring with modulators capable of rapid pulse bursts as the beam pulse circulated in the ring.

The "core type" induction accelerators in the former USSR are listed in Table 2.3. Most of these accelerators operated at relatively modest beam voltages, with the exception of the LIA-30/250. This machine reportedly had the unique combination of a high beam voltage (30 MeV) and a relatively long pulse length.

Several "coreless" (also referred to as "radial line" type) induction accelerators are listed in Table 2.4. As discussed in Sect. 2.7, the development of this type of

Table 2.2 USA "core-type" induction accelerators

	Institute	Energy [MeV]	Current [A]	Pulse [ns]	Rep.-rate [Hz]	Operational years	References
Astron	LLNL	3.7	350	250	60 Burst 1.4 k (100)	1963–1967	[3]
Astron upgrade	LLNL	6	800	300	60 Burst 0.8 k (100)	1968–1975	[4]
ERA	LBNL	4	3 k	30	∼1	∼1970	[5]
NBS prototype	NBS	0.8[a]	1 k	2,000	< 1	∼1975	[10]
ETA	LLNL	4.5	10 k	30	2 Burst 900 (5)	1977–1987	[6]
FXR	LLNL	17	3 k	60	0.3	1980–Present	[8]
ATA	LLNL	45	10 k	75	5 Burst 1 k (10)	1983–1995	[7]
HBTS	LLNL	3	2 k	50	∼100 Burst 5 k	1984–1990	[28]
MBE-4	LBNL	1	0.04[b] Cs^+	500	< 1	1984–2000	[11]
ETA-II	LLNL	6.5	3 k	50	∼1 Burst 2 k (50)	1989–Present	[14]
SNOMAD-II	MIT	0.5	500	50	∼1 Burst 5 k	∼1991	[15]
SLIA	PSI	5.5	10 k	∼30	? Burst 10 M	∼ 1996	[17]
CLIA	PI	0.75	10 k	100	100 (5 k) 1 k (5)	∼1993	[29]
RTA	LBNL	1	1.2 k	250	4	1998–2001	[30]
Recirculator	LLNL	0.08[c]	0.002[b] K^+	4,000	0.1 Burst 100 k (100)	∼1999	[18]
DARHT-I	LANL	19.8	2 k	60	< 1	1999–Present	[9]
DARHT-II	LANL	17	2.1 k	1,600	< 1	2003–Present	[12]

Abbreviations: LLNL – Lawrence Livermore National Laboratory (formerly LRL-Livermore), LBNL – Lawrence Berkeley National Laboratory (formerly LRL-Berkeley), NBS – National Bureau of Standards (presently NIST), MIT – Massachusetts Institute of Technology, PSI – Pulse Science Inc., San Leandro, CA, PI – Physics International Company, San Leandro, CA.

[a]Induction cells boosted injector voltage by 400 kV.

[b]Current of ion machines are distinguished by listing the ion and charge state with the current.

[c]Only one quarter turn installed. Energy boost by 5 induction cells was 500 V.

accelerator was pioneered in the former USSR, culminating in the construction of a 40 MeV, 100 kA accelerator (LIA-30). The USA RADLAC machines are also included in this table.

A number of linear induction accelerators were constructed in Japan for FEL and Two Beam Accelerator (TBA) research projects (see Table 2.5). The application of induction accelerator technology to high energy synchrotrons is included in the table. This technology has been pioneered at KEK in Japan and is discussed in detail in Chaps. 11 and 12.

Table 2.3 Former USSR "core-type" induction accelerators

	Institute	Energy [MeV]	Current [kA]	Pulse [ns]	Repetition-rate [Hz]	∼Start year	References
LIA-3000	JINR	1.5	0.25	250	5	1967	[20]
SILUND	JINR	1.7	0.7	15	1	1973	[20]
SILUND-2	JINR	0.8	1.0	20	50	1978	[20]
SILUND-10	JINR	0.25	8	20	1	1980	[20]
SILUND-20	JINR	2	1	20	50	1982	[20]
LEUK-20	JINR	1.5	–	60	20	1985	[20]
LIA-30/250	JINR	30	0.25	500	50 Dual pulse	–	[31]
LIA-5/5000	ITEP	4	2	200	1 K design	1977	[32]
LIA-0.8/5000	MRTI	0.8	5	80	100	–	[31]
LIA-0.4/10000	NPI	0.4	10	100	10 Burst 50 (2 k)	–	[31]
LIA-0.5/5000	NPI	0.5	5	100	100 Burst 1 k (10)	–	[31]
LIA-4/2	NPI	4	2	80	100	–	[31]
SILUND-21	JINR	10(5)	1	60	–	1995	[33]

Abbreviations: JINP – Joint Institute for Nuclear Research, Dubna, NPI – Nuclear Physics Institute at Tomsk Pollytechnic University, Tomsk, MRTI – Moscow Radio Technical Institute, Moscow, ITEP – Institute for Theoretical and Experimental Physics, Moscow.

Table 2.4 Former USSR and USA coreless ("radial line") induction accelerators

	Institute	Energy [MeV]	Current [kA]	Pulse [ns]	Rep.-Rate [Hz]	∼Start year	References
LIA-2	VNIEF	2	25	35	$\ll 1$	1967	[34]
LIU-10	VNIEF	14	40	20	$\ll 1$	1977	[34]
Copy of LIU-10	NIIP	14	40	20	$\ll 1$	–	[34]
LIU-30	VNIEF	40	50–100	∼25	$\ll 1$	1988	[34, 23]
I-3000	VNIEF	3.5	20	16	$\ll 1$	–	[34]
STAUS	VNIEF	2.7	15	40	$\ll 1$	–	[34]
STRAUS-2	VNIEF	3.3	50	40	$\ll 1$	–	[34]
LIU-10M	VNIEF	20	50	20	$\ll 1$	1994	[34]
RADLAC-I	SNL	9	25	15	$\ll 1$	1981	[24]
RADLAC-II	SNL	9	40	20	$\ll 1$	1984	[25]

Abbreviations: VNIEF – All-Russian Scientific and Research Institute of Experimental Physics (formerly Arzamas, presently Sarov), NIIP – Lytkarino (built for use by radiation researchers), SNL – Sandia National Laboratory, Albuquerque, NM.

The linear induction accelerators built in France are listed in Table 2.6. The 20 MeV AIRIX accelerator was built for flash radiography. Its design is similar to DARHT-I, and it achieved record-setting performance in the combination of beam current (dose) and emittance (spot size). China is the most recent country to construct a major linear induction accelerator for flash radiography, the DRAGON-I accelerator in Table 2.7.

Table 2.5 Japanese "core-type" induction accelerators

	Institution	Energy [MeV]	Current [A]	Pulse [ns]	Rep.-rate [Hz]	~Start year	References
FEL–KEK	KEK	1.6	3 k	80	0.1	1987	[35]
KEK+JLA	Naka, JAERI	4	1 k	80	1	1997	–
LAX-1	Naka, JAERI	1	3 k	100	1	1991	[36]
JLA	Naka, JAERI	2.5	3 k	100	1	1988	[37]
ETIGO-III	Nagaoka Univ.	8	5 k	30	< 1	1997	[38]
12 GeV PS Ring	KEK	0.01/Turn	0.48[a]	500–100	1 M	2006	[39]
RAIDEN	ILE	4	1.2 k	100	< 1	1990	[40]

Abbreviations: KEK – National Laboratory for High Energy Physics, Tskuba, JAERI – Japan Atomic Energy Research Institute, ILE – Institute for Laser Engineering, Osaka University, Osaka.
[a]Proton current.

Table 2.6 French "core-type" induction accelerators

	Institution	Energy [MeV]	Current [kA]	Pulse [ns]	Rep.-rate [ns]	Operational	References
LELIA	CESTA	3	1	80	~1 (~1k burst)	1991–2002	[41]
PIVAR	CESTA	8	3.5	80	< 1	2000–2002	[42]
AIRIX	B3–M/PEM	20	4	80	< 1	1999–Present	[43]

Abbreviations: CESTA – Centre d'Etudes Scien. et Tecniques d'Aquitaine, Le Barp, B3–M/PEM – Institute at Pontfaverger–Moronvilliers.

Table 2.7 Chinese "core-type" induction accelerators

	Institution	Energy [MeV]	Current [kA]	Pulse [ns]	Rep.-rate [Hz]	Operational	References
LIAXF (LIAXFU)	Institute of Fluid Physics	12	2.6	90	< 1	~1990–Present	[44, 45]
DRAGON-I	Institute of Fluid Physics	20	3	90	< 1	~2007–Present	[46]

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