INDUCTION LINACS

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Abstract
Induction linacs represent a somewhat unusual way of accelerating to medium energies particle beams of extremely high intensities. They generally operate in long-pulse mode where applications require high power beams. In this chapter we shall present the principle and main features of induction linacs and give information on the related problems of beam transport and the means to diagnose them. Some specific applications will be briefly reviewed.

1. INTRODUCTION

Development of induction linacs to accelerate very high current particle beams (multi kA) to energies in the tens of MeV range is a relatively recent outcome of a principle which was expressed before the last world war. In fact the idea was discussed by Bouwers in 1939 [1] but the first realization was achieved by N. Christofilos in 1964 at LLNL [2]. This Astron accelerator provides a 5 MeV, several hundred amperes electron beam to confine plasmas for the magnetic fusion program. During the early 1970's at the Lawrence Berkeley Laboratory (LBL) was built the Electron Ring Accelerator (ERA) for the goal of proton acceleration. Meantime significant technological development has also occured in the Soviet Union in the induction accelerator field [3]. Other machines were built during the seventies and the eighties at LLNL and among them the Experimental Test Accelerator (ETA) and the Advanced Test Accelerator (ATA). The last one, designed for beam propagation studies, was a 50 MeV, 10 kA, 50 nsec, device with burst-mode capability up to 1 kHz.

It must be noted that the LLNL has been during nearly twenty years a leading laboratory for linear induction accelerator development. This was closely related to the progress of the Free Electron Laser (FEL) program in this laboratory [4]. The last device built at LLNL is the ETA II/ETA III accelerator operated in an FEL experiment aimed towards high power microwave production for the MTX Tokamak magnetic fusion facility [5]. ETA III is a 6 MeV, 2 kA accelerator capable of multiburst operation (up to 50 pulses at 2 kHz) with improved characteristics (beam quality and reliability). During the same period other laboratories were involved in the development of induction linac technology and namely the Naval Research Laboratory (NRL) and the National Bureau of Standards (NBS) [6].

More recently, during the last decade, new developments have appeared in China and in Japan at ILE, KEK and JAERI[7,8,9]. In France, since 1988, the Commissariat a l'Energie Atomique (CEA) has undertaken an induction linac development program at the CESTA laboratory, first for FEL application with the LELIA facility (2.5 MeV, 1 kA, 50 ns) [10,11] and then for Flash - Radiography with the AIRIX project now under construction (16 MeV, 3.5 kA, 60 ns) [12]. Many papers have been published on the subject of designing induction linacs in conference proceedings or elsewhere. Some of them are listed in references [13–16].

2. PRINCIPLE OF OPERATION

In principle the accelerating unit consists of an induction cell that provides the particle beam passing through with an $eV$ energy increase and an electric generator supplying the cell with a High Voltage (HV) pulse of $V$ amplitude. By simply stacking $n$ induction cells (and $n$ HV pulse generators) the incoming beam with an $eV_o$ energy exits with an $e(V_o+nV)$ energy according to the schematic drawing (Fig. 1). Induction linacs allow beam acceleration up to several tens of MeV by using HV pulse generators operating at a few hundred kV voltage. As
we shall discuss further, the main advantage of induction linacs is their ability to accelerate long-pulse (tens of ns to μs) high-intensity (multi-kA) beams. Another specific feature is the total electrical insulation of the apparatus, the high voltage appearing only inside the induction cells.

Fig. 1 Schematic of an induction linac

An induction cell looks like a cylindrical metallic box with a hollow center where the beam is transported and accelerated under vacuum. As shown in Fig. 2 the HV from the electrical generator is applied to a circuit containing magnetic cores. The electrical insulation is obtained via a concentric gap area and a ring ensuring both electrical and vacuum insulation of the beam pipe, which is under vacuum, from the oil-cooled magnetic cores. Moreover a guiding magnet is enclosed in the box to allow beam focusing while two trim coils permit small beam position corrections.

Fig. 2 Induction cell

2.1 The transformer analogy

In order to understand the induction cell principle, the analogy of the 1:1 transformer is usually presented as a first approach. In this comparison the primary winding is the metallic structure of the cell, the beam itself playing the part of the secondary winding. When a square
pulse of $V_o$ voltage and $\Delta t$ duration is applied to the cell a magnetic field is created into the cores that induces on the beam an accelerating voltage of the same amplitude and duration. When $n$ cells fed by identical electric pulses are coupled, the beam is given an $nV_o$ accelerating voltage as in a transformer with $n$ primary windings and a single secondary. With this analogy, represented in Fig. 3, we can understand how, in an induction linac, a high accelerating voltage can be reached by simply stacking along the beam axis many cells fed by a pulse of moderate voltage.

However only the gross electric balance is concerned by this approach. To go further in the design of the cell and the magnetic cores we have to study the current and voltage distribution in the accelerator.

![Fig. 3 The transformer analogy](image)

### 2.2 Current and voltage distribution

When the high voltage pulse ($V_o, \Delta t$) from the coaxial transmission line enters the cell, it meets on the one hand a capacitive element constituted by the accelerating gap, and on the other hand an inductive element constituted by the magnetic material. The $I$ supply current is then divided into an $I_b$ charging current flowing into the gap and the inner wall of the cell, and an $I_m$ magnetization current flowing around the magnetic cores (see Fig. 4). If these cores have been properly magnetized before the pulse, they present a large inductance $Z_m$ limiting the evolution of the $I_m$ current and preventing the line from being short-circuited on the electric ground.

The $I_b$ charging current equals the beam current and therefore is limited by its impedance which depends on the upstream diode characteristics. It has to be noticed that this current loops in the HV generators by the means of coaxial cables. It never surrounds the magnetic cores unlike the transformer analogy has assumed.

Let us now consider the voltage distribution at different places of the apparatus and to begin with, at the cable meeting point with the cell, assuming the HV generator and the cell are
impedance matched. The potential difference between the power supply point (A) and the ground (B) then equals the $V_o$ voltage delivered by the HV generator.

$$V_A - V_B = 0$$

The same potential difference is obtained by computing the line integral of the electric field along the loop along which the $I_m$ current flows.

$$V_o = \int \vec{E} \cdot d\vec{l}$$

According to the Faraday law

$$V_o = \oint \vec{E} \cdot d\vec{l} = \int_S \frac{\partial \vec{B}}{\partial t} \cdot d\vec{S} \quad (1)$$

where $S$ is the sectional area of the magnetic cores and $\vec{B}$ the magnetic induction produced by the $I_m$ current. This last equation shows that the $V_o$ cell voltage is linked with the magnetic and geometric characteristics of the cores. If we neglect the radial variations of $\vec{B}$ the integration of the Eq. (1) between $t_o$ and $t_o + \Delta t$ leads to:

$$V_o \Delta t \equiv S[B(t_o + \Delta t) - B(t_o)] \quad (2)$$

We know that the magnetic induction inside the cores varies according to a hysteresis cycle as shown in Fig. 5. Taking care to preset the cores at the $B_r$ remanence field before each pulse, it is possible to get a maximum variation

$$\Delta B_s = B_r + B_s$$
where $B_r$s is the value of $B$ at saturation.

Fig. 5 Hysteresis cycle of a ferrite core

Fig. 6 Characteristic dimensions of an induction cell

The equation (2) can be written as the following inequality:

$$V_o \Delta t \leq S. \Delta B_s$$

This can be used for the dimensioning of the magnetic cores according to the high voltage pulse characteristics.

2.3 Considerations for the design of magnetic materials

Ferrites are often used as magnetic material for their mechanical and magnetic characteristics. Other materials have been used and among them Fe-Ni alloys and Metglass (from Allied Chemical). We currently have used PE 11B Ni-Zn ferrites from TDK. The maximum $\Delta B_s$ for this material is 6 kG. New PE 16 ferrite allows larger $\Delta B_s$ of the order of 7 kG. For Metglass 2605 SC the $\Delta B_s$ value is much larger ($\sim$ 25 kG) but this material has to be used in ribbons of small thickness ($\sim$ 20 $\mu$m) with Mylar insulation between consecutive layers.

The role of the magnetic material is essential in the induction cell operation. Let us try to see how it is possible to dimension these cores. If we consider the area they fill in the cell, it could be regarded as a coaxial transmission line of length $l$ ended by a short circuit Fig. 6. The internal conductor of the line is formed by the cylinder of radius $r_i$, the external conductor by the cylinder of radius $r_e$ and the short circuit by the SC plate. In this line, at point A, enters the voltage wave $(V_o, \Delta \tau)$ associated with current $I_m$ such that:

$$I_m = \frac{V_o}{Z_m}$$

$Z_m$ forming the characteristic impedance of the line.

As in a classical line, as the wave advances in the magnetic material, the $V_o$ supply voltage is propagated lengthwise along the internal cylinder whereas the external cylinder and the SC plate are kept at the ground potential. When the wave reaches the plate, the whole
cylinder is virtually held at the $V_o$ voltage. At this time the wave is reflected by the short circuit with a polarity change for the voltage. As it comes back, the internal cylinder voltage goes progressively to zero up to the A feeding point. Accordingly the $V_o$ voltage can be held at the line terminals no longer than the time of a journey there and back for the wave along the cell at the velocity $1/\sqrt{\varepsilon\mu}$.

In these conditions a pulse of $\Delta t$ duration will be used to best advantage by imposing a magnetic core length such as

$$\Delta t \leq 2l\sqrt{\varepsilon\mu} \quad (5)$$

where $\varepsilon$ and $\mu$ are respectively the dielectric constant and permeability of the magnetic material.

On the other hand the pulse duration must not be shorter than a single transit time of the wave, otherwise some magnetic cores would not see the pulse and would be useless. This condition can be expressed by

$$\Delta t \geq l\sqrt{\varepsilon\mu} \quad (6)$$

It must be pointed out that Eqs. (5) and (6) hold only when the $I_m$ magnetization current remains smaller than the $I_s$ saturation current. If not, a saturation wave is created with a velocity larger than the electromagnetic wave velocity, and the magnetic cores get saturated in a time shorter than the pulse duration.

This condition $I_m \leq I_s$ can as well be written as

$$H_m = \leq H_s \quad (7)$$

$$H_m = \frac{I_m}{2\pi} \frac{\log(r_e/r_i)}{r_e - r_i} \quad (8)$$

If the magnetic cores can be considered as an ideal inductance $L$

$$L = \frac{\mu l}{2\pi} \log(r_e/r_i) \quad (9)$$

then

$$V_o = L \frac{dI_m}{dt} \quad (10)$$

and Eq. (10) leads to

$$V_o \cdot \Delta t \leq L \cdot I_s$$

$$V_o \cdot \Delta t \leq \mu \cdot H_s \cdot l \cdot (r_e - r_i)$$

Considering the hysteresis cycle of the magnetic core

$$\mu \approx \frac{B_r + B_s}{H_s}$$

we obtain again Eq. (3)

$$V_o \cdot \Delta t \leq S \cdot \Delta B_s$$
The meaning of Eq. (3) is now clearer: when cells are dimensioned in such a way that this condition is fulfilled, then saturation of the magnetic cores is prevented during the high-voltage pulse by keeping the magnetization current lower than the saturation current.

To sum up, the transmission line analogy allows a better understanding of the phenomena occurring in the magnetic cores which play a double part:

- holding the gap at the charging potential by delaying the cell short circuit,
- keeping the cell external structure at the ground potential during the whole high voltage pulse.

The previous considerations are helpful in dimensioning the magnetic ($\Delta B_s$) and geometrical ($l, r_e - r_i$) characteristics of the cores. We shall give in another way information about $\mu$ and the internal radius $r_i$.

2.4 Cell coupling efficiency

During the flat top of the voltage pulse, the current from the HV pulse generator is divided into two lines in the cell. The efficiency can be expressed as:

$$\eta = \frac{I_b}{I_b + I_m}$$

Assuming the cores to be properly simulated by an inductance $Z_m$ and the beam by a resistance $R$, then we have

$$\eta = \frac{Z_m}{Z_m + R}$$

(11)

This efficiency is good provided that $Z_m$ is large compared to $R$. According to Eq. (9) one condition is to get $\mu$ as large as possible. Another condition is to improve the $r_e / r_i$ ratio, but this ratio also depends on other requirements. However the true efficiency is lower due to another resistance which is added in parallel with the cell in order to protect it against over voltages. Indeed if operational problems occur, for example if the beam gets out of step with the high voltage pulse, this additional resistance (we call it the "Ballast" resistor) prevents the gap from seeing an over voltage which could result in damaging breakdown. The actual efficiency can drop off to values under fifty percent.

2.5 High voltage generator

This aims at providing the induction cell with HV pulses having specific characteristics:

- high intensity, since $I = I_b + I_m$
- $\Delta \tau$ and $V_o$ fitted to the magnetic core characteristics. For electron induction linacs values in the range experimentally used.
- Flat-top pulse is an usual requirement in order to have a monokinetic beam accelerated. This can have important repercussions on the beam transport in the accelerator.
- High repetition rate is needed in some cases, especially when high mean power application is required.

If high repetition rate operation is not required, classical technology with charged Blumlein and spark-gap is available. As an example Fig. 7 shows the result obtained with the...
HV voltage pulse generator developed in our laboratory for the AIRIX program and designed for a 250 kV standard operation with a ± 1% flatness over 70 ns.

![Graph of experimental results of the AIRIX high-voltage pulse generator](image)

If high repetition rate operation is needed, then the use of a generator with magnetic switches instead of spark-gaps appears unavoidable. These magnetic switches are made with magnetic cores which operate as saturable materials. They again use ferrites or Metglass and present the advantage of a low jitter operation up to a few kHz. Moreover by placing several magnetic switches in series a pulse compression can be realized.

### 3. BEAM TRANSVERSE DYNAMICS IN INDUCTION LINACS

The problems arising from beam transport along the induction linac are mainly due to its specific characteristics:

- High intensity beams up to multi-kiloampere values are currently accelerated and transported. This is due to the fact that the major part of the current does not flow through the magnetic cores. The beam current which is given by the diode characteristics of the injector has, in fact, no other limitation than the power of the pulse generator.
- Acceleration of long pulses is achievable as long as the cell (magnetic cores) is fitted to the pulse generator according to Eq (3). As an example the induction cells for our AIRIX facility are designed to provide a 250 kV acceleration to an electron beam of 3.5 kA and 60 ns duration.

The phenomena which appear during the propagation can lead to a degradation of the beam quality from:

- an emittance growth due to space charge effects,
- an effective emittance growth due to transverse motions originating in chromatic effects and Beam Break-Up (BBU) instabilities.

We briefly give some results concerning these phenomena and what can be done to minimize their effects.

### 3.1 Space charge effects
These find their origin in the non-uniform radial distribution of the charges in the beam. This results in a transformation of the potential energy into transverse kinetic energy. The effect is a redistribution of the electric charges in the beam which causes an emittance growth as shown in the next equation:

$$\Delta \epsilon_n^2 \propto R^2 \frac{I}{I_o} \frac{1}{\beta \gamma} [U(z) - U(o)]$$

(12)

where $\epsilon_n$ is the normalized emittance of the beam
$R$ is the beam radius (mean quadratic radius)
$I$ is the beam current and $I_o$ is the limit current
$\beta$ and $\gamma$ are the relativistic parameters.

The quantity in square brackets represents the variation of the electrostatic energy. As the beam travels through the accelerator the beam profile has the tendency to get uniform which implies that $U(z)$ goes to zero.

In order to minimize these effects which appear mainly in the case of high currents at low energy the obvious solutions consists in:

- injecting into the linac particles with as high an energy as possible (large $\gamma$)
- transporting a small radius beam.

But in the present case it is not possible to minimize $I$ since it is a major feature of the induction linac. Another way is to consider the injection of an electron beam with a uniform radial distribution, but this is a characteristic of the injector. In practice this effect is generally important only at the entrance of the linac and compared to the following effects becomes negligible as the energy increases.

3.2 Chromatic effects

These are often referred to as "corkscrew" motions especially in the North-American litterature. Their origin is double :

- The particle energy has a $\Delta E$ variation during the pulse.
- And the focusing system is not perfect (mechanical alignment, design of the focusing magnets,...).

The result is a motion of the beam centroïd. Due to the length of the particle pulse in an induction linac, it induces a global emittance growth when this effect is integrated over the whole pulse duration.

In order to minimize these effects care has to be taken of the beam quality with regard to its energy spread over the pulse duration. This is why we specify a $\Delta E \leq \pm 1\%$ for the electron beam injected in to our AIRIX induction linac.

Another consequence is the need for an excellent quality focusing system along the accelerator. As was indicated in Fig. 2 each induction cell has to be provided with a guiding magnet. An example is shown in Fig. 8 representing the focusing magnet design of the AIRIX induction cells. As can be seen in this figure soft-iron homogenizer rings mechanically concentric to the beam pipe have been introduced. The effect is to reduce the transverse component of the magnetic field inside the solenoid. Measurements have shown an improvement in the ratio of the transverse-to-axial components which reduce to values under $10^{-4}$ all over the solenoïd axis.
In the same way, the mechanical design of the cells is an important concern in that the mechanical axis has to be aligned with the magnetic axis since only the latter has an influence on the beam. Moreover all the cells must be aligned together in order to minimize the dispersion of their axes not only for off-axis displacements but also for tilt effects. These considerations of cell alignment are also concerned with beam break-up instabilities.

3.3 Beam Break-Up (BBU) Instability

This comes from the interaction of the beam with transverse electromagnetic fields in the gap cavities. The BBU mechanism can be briefly summarized as follows:

- an off-axis beam propagation in the induction cell induces the excitation of transverse electromagnetic fields in the gap cavity.
- These electromagnetic fields then react on the beam to induce transverse motions at the frequencies of the electromagnetic modes. Consequently the next cavities get excited from step to step.

BBU instability is an exponentially growing phenomenon inducing transverse displacements which can be approximated by the following equation:

\[
x = x_o \exp \left\{ \frac{I_o \omega_\perp (\gamma - \gamma_o)}{k_\beta E} \right\}
\]

(13)

where \( Z_\perp \) is the transverse impedance of the cell cavity and depends on:
- the gap geometry
- the materials used in the cavity
- \( \omega_\perp \) is the pulsation of the electromagnetic mode
- \( \delta E \) is the cell accelerating gradient
- \( k_\beta \) is the wave number of the guiding magnet.

In order to prevent the growth of BBU instabilities or to minimize their effects the following recommendations must be taken into account:

- on-axis propagation of the beam in the accelerator,
- accurate cell alignment (see § 3.2),
- reduce the transverse impedance of the cell, especially for the dominating mode. It depends on the gap geometry according to

\[ Z_\perp \propto \frac{a}{D^2} \]  

(14)

where \( a \) is the width of the gap and \( D \) is the beam pipe diameter.

This impedance depends on the dielectric constant \( \varepsilon \) of the insulator. A smaller \( \varepsilon \) leads to lower values of \( Z_\perp \). For this purpose a plastic insulator, like Rexolite (\( \varepsilon \sim 2.5 \)) must be preferred to an alumina insulator (\( \varepsilon \sim 9 \)).

- increase the cell gradient \( \varepsilon \),
- increase the \( k_B \) wave number, that is to say use a large \( B \) guiding field, but an optimization has to be found with other effects which can lead to adjusting the \( B \) values along the accelerator according to, for example:

\[ B \propto \sqrt{\gamma} \]  

(15)

The use of an electromagnetic code is necessary to calculate the transverse impedances. In Fig. 9 are shown the impedances corresponding to different designs of the gap cavity for the AIRIX program with the PALAS code. The "VACUUM" case concerns a cell in which the ferrites are under vacuum and there is no insulator, "REXOLITE" the technology designed for the use of a specific plastic insulator, and "ALUMINA" the technology when a pure alumina insulator is brazed on the body of the cell ensuring a perfect insulation between the ferrite area in oil and the beam area in vacuum. In this example we should notice that the technological characteristics (mechanical, electrical,...) have to be compared with the corresponding cell behaviours concerning the BBU instability.

4. DIAGNOSTICS

This is not the place to deal with the accelerator diagnostics in general. But, as we have seen previously, induction linacs are characterized by very high intensity beams and long pulses. These specific features induce some problems of beam transport along the apparatus. In order to minimize the effects according to the recommendations given in the last section the accelerator designers are required to accurately measure some important parameters of the beam and namely the beam emittance, the electron energy and energy spread, the beam position and profile, and the beam current. As we have seen they also have to take care about the alignment of each component (guiding magnet and cell) and of the whole apparatus.

To give an example, the 60 cells of the AIRIX induction linac have been designed and will be built and aligned in order to allow the 60 corresponding magnetic axes to be held in a 100 \( \mu \)m radius cylinder and a 500 \( \mu \)rad half-angle cone. These specifications involve sophisticated means of machining, assembly and alignment.
An original method for checking the possible discrepancy between the mechanical and magnetic axes of a cell is the so-called stretched-wire technique. It uses a conductive thin wire perfectly aligned on the mechanical axis of the cell. A short electric pulse is injected at the input of the wire. When this pulse goes across the magnetic field area inside the cell it encounters a magnetic force which induces in the wire a small oscillation. The observation of this small displacement with an adequate motion detector at the other end of the wire gives a signature closely related to the kind of misalignment between the magnetic field lines of the solenoid and the mechanical axis of the cell. This technique is schematized in Fig. 10.

As induction linacs are often single-pulse machines, the usual scanning-wire techniques cannot be employed. A good time resolution is required to analyse the evolution of the phenomena during the pulse since high frequency modes (BBU) are likely to develop.

In fact most of the beam diagnostics consist of the optical observation of the interaction of the (electron) beam with a specific target. The definition of the interaction – and hence of the target – is related to the desired efficiency, directivity, spatial resolution, and temporal resolution of the optical phenomena which often depend on the energy and intensity of particles in the beam. Commonly used interactions are scintillation and Cerenkov radiation, but for high energy beams, that is to say $E \geq 10$ MeV, Optical Transition Radiation (OTR) presents advantages as far as time resolution and directivity are concerned. Moreover scintillation and Cerenkov radiation involve volume interaction and therefore can use beam disturbing converters while OTR is a surface phenomenon, induced by an index step, and is likely to use thin windows transparent to high-enough energy particles. But further studies have to be carried through before the use of OTR can be generalized.

At the CESTA laboratory we developed a magnetic spectrometer in order to measure accurately the time evolution of the electron beam energy for the AIRIX induction linac. In the image plane of the electromagnet the electrons undergo a Cerenkov interaction into an optical fiber sheet which leads the information to a streak camera. A first optical-fiber sheet allows the observation of a broad spectrum versus time, while another sheet of closer fibers can give a
Typical cases :

Fig. 10 The stretched-wire technique for cell alignment

high resolution ($\Delta E \sim 4$ keV) in a chosen domain of the spectrum. This zoom effect appears very useful for adjusting the flat-top part of the electron pulse injected into the AIRIX linac.

The other basic diagnostic tool for induction linac users is the emittance meter. We use the well-known pepper-pot technique with a thin (0.5 mm) Bicron scintillator as analyser and a gated camera to record the optical information as a two-dimensional image with a 5-ns resolution. At LANL, a streak camera is used giving the evolution of one spatial dimension versus time. The same technique of recording can lead to the measurement of the beam position and dimension with time resolution using Cerenkov or scintillation converters.

The beam intensity, and the position of the beam centroid, can be reached from B-loop measurements. This device uses a small loop placed on the beam pipe, perpendicular to the $\beta \theta$ field of the electron beam. By integrating the loop signals to obtain the sum or the difference of diametrically opposite loops it is possible to measure the total beam current or the beam centroid displacements (charge density center) versus time. These so-called Beam Position Monitors (BPM), can, if carefully designed and built and accurately calibrated, lead to high-resolution time measurements of the beam-centroid motions closely related with the chromatic effects or even with the high frequency modes of the BBU instabilities.

5. APPLICATIONS

The specific applications of induction linacs result from their main characteristics:

- High intensity (multi-kA) and high brightness (small emittance)
\[ B = \frac{2I}{(\pi \varepsilon_n)^2} \]  

- Long pulse (\( \geq 50 \text{ ns} \))
- Small energy variations during the pulse
- Repetition rate capability
- High peak power and high average power.

Since the first machine, built in 1964, many applications of the induction linacs have been developed. As we have seen in the first section they mainly concern the USA and the USSR but more recently important programs began in eastern Asia (China, Japan, Corea) and in Europe (France). We will not review here all the facilities and all the subjects of interest but only give an overview of the main applications and focus attention on two particular subjects (see § 5.1 and 5.2).

At LLNL first studies were carried out for the goal of beam propagation in the atmosphere (ATA) but programs rapidly turned to FEL applications.

Research on magnetic confinement fusion was concerned at the beginning with the ASTRON program and recently with the MTX experiment. At LBL an ion induction linac is being developed for inertial confinement fusion. At LLNL the FXR facility was built for high power flash-radiography application [17] and at Los Alamos the DARHT induction accelerator is designed to improve significantly the performances of FXR [18]. At CESTA, the CEA is now designing and building the new AIRIX induction linac, similar to DARHT, for flash radiography.

But potential applications of the induction linac are not so limited: New studies are going on for the injector of the future CLIC (CERN Linear Collider) where an induction linac could be used as a drive beam in a Two-Beam Accelerator (TBA) concept [19]. At the other extremity industrial applications can be developed where high brightness beams are required which cannot be reached with classical diode-type generators. They include all kinds of irradiation of materials and particularly sterilization [20].

### 5.1 Free Electron Laser (FEL) application

The induction linac is a good driver for FEL experiments where high power output radiation is required. Since the FEL wavelength depends on the electron energy and the wiggler parameters \( \gamma_w, \beta_w \) according to the equation

\[ \lambda = \frac{\lambda_w}{2 \gamma^2} \left[ 1 + \frac{1}{2} \left( \frac{e B_w \lambda_w}{2 \pi m_e} \right)^2 \right] \]  
in most cases the resulting wavelength is in the microwave or Infrared (IR) domains. In these conditions induction linac characteristics (small emittance and energy spread) can lead to a good efficiency in the FEL interaction. Moreover the high beam intensity and brightness with high repetition rate capability can lead to high peak power and high average power radiation emission.

An example of an induction linac FEL application was the MTX Tokamak experiment at LLNL. The microwave radiation at 140 GHz from the ETA II induction linac driven FEL was used to heat the plasma of the MTX Tokamak. In this experiment the ETA II accelerator has been improved (ETA III) in order to generate up to 50 pulses at a 2-kHz repetition rate. The FEL used the IMP wiggler in the amplification mode of a gyrotron source at 140 GHz. The accelerator operation was stable enough to allow 25 microwave pulses to be injected in the Tokamak with a 1-GW power.
5.2 Flash radiography with induction linacs

Electron induction linacs can generate a powerful flash of hard X-Rays in order to make high quality radiographic images of dense, rapidly-moving objects. Here the goal is to produce a large amount (dose) of X-Rays by focusing on a small spot ($\phi \sim 2$ mm) into a conversion target a high intensity electron beam of convenient duration ($\Delta t \sim 100$ ns).

The quality of the radiographic source is given by a figure of merit (FM).

$$FM \propto \frac{D}{\phi^2}$$  \hspace{1cm} (18)

where $D$ is the dose of X-Rays and $\phi$ the diameter of the X-Ray source.

As the dose is proportional to the beam intensity, multi-kiloampere induction linacs can be used where other accelerators cannot produce a good quality beam with a sharp focusing ability. For Bremsstrahlung radiation from a target of $Z$ atomic number the dose is approximated by

$$D \propto ZV^{2.8} \Delta t$$  \hspace{1cm} (19)

where $V$ is the electron energy on the target and which has to be high enough to produce the desired dose of X-Rays on the object.

Small emittance is needed to achieve a good quality beam. We have seen that, in order to limit the emittance growth along the accelerator care has to be taken to reduce the chromatic effects and the BBU instabilities. The pulse duration is a compromise between dose and blurring due to the object velocity. Two new accelerator projects for this purpose are now in progress: DARHT at Los Alamos USA, and AIRIX at CESTA near Bordeaux, France.
REFERENCES