LINEAR INDUCTION ACCELERATORS FOR INDUSTRIAL APPLICATIONS

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Abstract

Electron beams and x-rays have a variety of industrial and commercial applications including the sterilization of food, medical products and sludge, the detoxification of pollutant gases, the crosslinking and polymerization of plastics, the alteration of gemstone color, oil well logging, and cancer therapy. These requirements are presently met by chemical techniques, radioisotopes, electrostatic acclerators, or RF accelerators. Induction accelerators can be used in a number of these applications, with significant advantages in cost, efficiency, reliability and power handling capability.

In this paper, we will briefly discuss the principles of the induction accelerator and will describe our development program. The goals of our program are to improve system reliability and to reduce system cost. An accelerator presently under construction which embodies a number of industrial improvements will be described. Unique features are a low cost accelerator design, and an SCR switched, tubeless pulsed power system.

General Induction Accelerator Considerations

A ferromagnetic linear induction accelerator[1] in its essentials consists of a series of induction cores, as shown in Fig. 1, with the voltage applied as on a transformer with a single turn on the primary, and the particle beam acting as a secondary. An accelerating electric field is developed in the center of the toroidal core, and when appropriate electrodes are supplied, the accelerating voltage is applied between two grounded electrodes, facilitating series stacking of accelerating modules. In fact, the induction accelerator provides us with a means of stacking pulsed quasistatic voltages to arbitrarily high voltages.

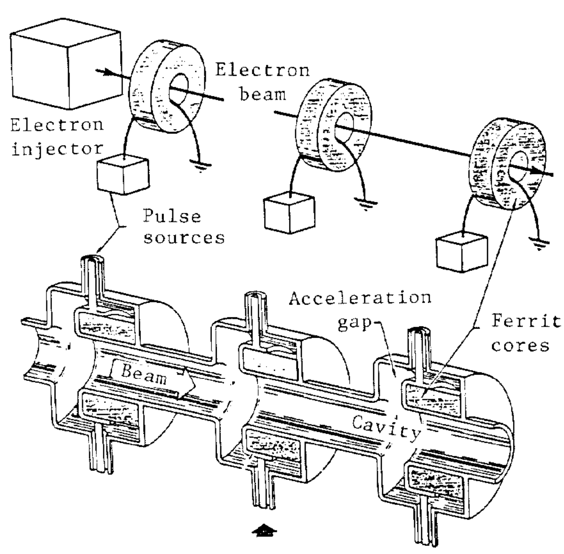

Fig. 1. The diagram above shows the induction cores with a beam linking the secondary.

Since the accelerator is effectively a transformer, the efficiency can be high (>50%). Large volumes of ferromagnetic material are required, so the accelerating gradients are relatively low (~1-5 MV/m).

In a practical system, the primary areas which distinguish accelerator designs are the type of pulsed power system chosen to supply the voltages, the type of ferromagnetic material chosen, the accelerator beam line configuration, and the beam focusing system and the beam injector system. These component designs in turn depend on the specific application, and the detailed physics and chemistry of the radiation interaction. Capital cost, maintenance cost, and reliability are the key considerations for all industrial accelerators.

PSI Induction Accelerator

Our goal in building the accelerator is to make advances in key technology areas relevant to both cost and reliability so that induction accelerator technology can be effectively implemented in an industrial environment. We have designed the accelerator to be useful for most of the applications listed above. The priorities we have chosen are:

1) Reliability
2) System cost
3) Energy efficiency

We will describe the accelerator below, with emphasis on these issues.

Accelerator System Parameters

The accelerator module parameters chosen are based on generic radiation physics--the thick target x-ray production efficiency is ~.016E where E is the electron beam energy in MeV. Thus, in x-ray production mode, energies $\geq$1 MeV are required, while undesirable photoneutron activation effects limit the energy in x-ray mode to <10 MeV. Similarly, for applications which utilize the electron beam directly, the beam range of $\ell \sim .4E/\rho$ (ρ is density in gm/cm^3) is usually required to be greater than 1 cm (1 gm/cm^2), so we have E > 2.5 MeV. An accelerator module of $\leq$1 MeV gives us the flexibility to address a variety of applications, in a multi-module system.

The energy per core and pulse length are based on the unique properties of the Mag-I type of magnetic compressor developed by LLNL[2]. This device produces ~800 J in 75 ns, 150 kV matched pulses, and is, in our opinion, ready for commercialization without further modification. Note that alternatives such as a directly driven long pulse (1 μsec) linac were considered, but rejected due to the large energy per pulse required, and the large core losses. Thus, we choose 140 kV/cell (note, we de-rate the mag performance slightly) as our operating voltage, and 6 cells per module for a total output of 840 kV/module.

The current per pulse is chosen by balancing considerations of core loss, focusing, and relevant

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applications. We note that for a single cell of voltage V and pulse length τ, we have a leakage current $I_\ell \cong 2\pi V\tau/\mu_p \ell \ln b/a$ where μ_p is the pulse permeability of the core material, ℓ is the core length, and b(,a) are the core outer (inner) radii. Since $V\tau \sim \Delta B \ell (b-a)$, and $\mu_p \sim \Delta B/H$, where ΔB is the material flux swing at a given magnetization H, we find

$$I_\ell \sim \frac{2\pi H(b-a)}{\ln b/a}$$

Our general desire to minimize ℓ results from the accelerator shielding, and focusing requirements, so we wish to use the largest b-a cores available. Note that for existing ferrite, cost varies as b, rather than b^2, so we suffer no economic penalty through this choice. For the chosen parameters, ferrite manufactured by TDK (PE-11B) or Stackpole (C7DC) in sizes up to 20" OD will be used. Other factors relevant to our choice of parameters are the magnetic field energy required for focusing, and the ratio of pulsed beam current I_b to leakage current. Setting aside the magnetic compressor, the energy efficiency in a cell is given by

$$\eta = \frac{I_b V\tau f}{\frac{1}{2} I_\ell V\tau f + P_m}$$

where f is the pulse repetition frequency. The magnetic field power P_m required is generally proportional to I_b through the relativistic beam equilibrium condition $I < 2.8B^2 r_b^2 E$ kA, where r_b is the beam radius in cm, and B is in kG. Due to considerations such as the beam breakup instability and the magnetic field energy requirements of the beam source, we will not assume that B can be decreased as the equilibrium condition suggests, but we will assume the E ~ 1 MeV value. We require the effective magnetic field coil radius $r_c \sim 3r_b$ due to physical constraints so that the field energy per cell (note that the overall length of a cell is ~2 ℓ) is given by $\varepsilon_m \sim I\ell/300$.

For pulsed coils with energy recovery efficiency g, and an OD/ID ratio of 1.5,

$$\eta = \frac{I_b V_b \tau}{\frac{\pi H(b-a) V_b \tau}{\ln b/a} + .065 I\ell g + I_b V_b \tau}$$

while for DC coils,

$$\eta = \frac{I_b V_b \tau}{\frac{\pi H(b-a) V_b \tau}{\ln b/a} + \frac{15\ell I_b}{f} + I_b V_b \tau}$$

Several factors are worth noting as they relate to design:

(1) The achievable efficiency is dependent on the core H.

(2) Efficiency increases with current.

(3) Efficient accelerators must be designed with $I_b > \pi H(b-a)/\ln b/a$

(4) Low power applications must run with pulsed field coils for high efficiency.

(5) Efficiency optimization depends on the trade-off between a, b, ℓ.

Most accelerator costs depend only weakly on average output power, so the induction accelerator is most attractive for high output powers, where low $/Watt are available. Similarly, there is a minimum useful energy per pulse dictated by H ~ 6)e, (at ΔB = 5.5 kG) for existing ferrites. Lower power accelerators could be built with smaller IDs.

We have chosen a pulsed magnetic field system which allows the most varied set of applications with I_b = 2 kA, and τ = 65 ns. We have decided to use a combination of a large core and a nested small core so that a ~ 5 cm, b ~ 25 cm, and we have r_b = 1 cm, and B $\gtrsim$ 1 kG.

Electron Beam Injector

A diagram of the injector is shown in Fig. 2--it is designed as a modified accelerator section at 840 kV. This total voltage is applied across the central gap between the pierce corrected gun and the drift tube anode. A type M dispenser cathode is used since this type of cathode is capable of supplying >25 A/cm . A conservative vacuum field stress level of E < 100 kV/cm is used in the design at all points. The pulsed magnetic field coils shown are independently controllable to facilitate tuning. This gun is designed in the shielded source configuration. This is simplified by the choice of pulsed magnets, since placing a conductive plate behind the cathode prevents the fields from penetrating through the cathode.

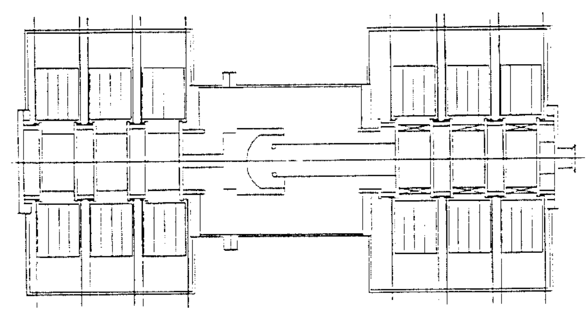

Fig. 2. Injector configuration.

As will be discussed in the accelerator section, the entire system--including cores--is placed in two oil-filled tanks with vacuum pumping in the connecting tube. The beam is compressed by the converging magnetic field in the injector, and exits with a radius of ~1.5 cm.

The injector is connected to the first accelerator section with Kwik-Flange-type connections to facilitate rapid maintenance or replacement.

Accelerator Modules

A diagram of a single .84 MV module is shown in Fig. 3. At this point, we are fabricating the injector and one accelerating section. A 10 MeV machine would consist of 11 accelerating modules plus the injector and would be 12.5 m in length.

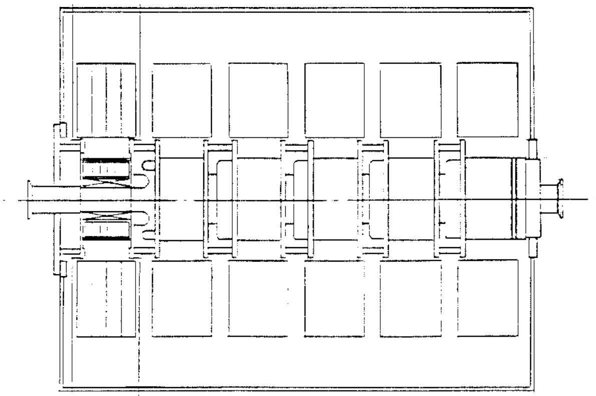

Fig. 3. Accelerator configuration.

The module is made from two separable pieces--the tank in which 6 large cores are mounted, and the removable beam line [3]. The tank is filled with transformer oil and pulse power is fed in by 6, 50 Ω, 200 kV DC high voltage cables. The cables are attached to a bus bar, which is in turn attached to rods which connect it to the beam line.

The beam line itself includes all the stainless electrodes, drift tubes, magnetic field coils, vacuum insulators, etc. required to transport the beam. It is held together with insulated bolts, and the pulse power which is brought in on rods from the bus bar is attached to 12 tabs on the beam line. Six more beam line tabs are used to provide solenoid power. Cooled oil is also brought in through fittings on the beam line. At the planned operating frequencies of ~100 Hz, the waste heat per module is estimated as ~2000 Watts, although we expect to be able to run at up to 600 Hz without excessive ferrite core heating. This type of construction has considerable advantages in cost and ease of maintenance over conventional cylindrical cavity designs.

Power System

There are two key components in the power system: the modified magnetic compressor, and the SCR modulator which is used to power it. A Mag-IC compressor furnished by LLNL has been modified since it was designed to put out a 900 J pulse and we require a nominal 280 J pulse. This difference allows us to trade energy for compression factor, so we can change the normal operating voltage from 300 kV to ~160 kV, with an increase in input pulse duration from 1 μsec to ~4 μsec. Three steps are required in order to do this: the input transformer is modified to a turns ratio of 2:11, the first stage compression reactor is rewound to have 7 turns rather than 3, and a 2:1 output stepup transformer is added to the system. These changes are straightforward, reversible and have already been made.

We regard the use of SCRs in this application as a major advance since the thyratrons previously required were subject to unscheduled failure, and replacement was expected to be a major cost over the accelerator life. An SCR modulator of the type we have demonstrated also eliminates the need for a separate 25 kV power supply and charging inductor to drive the Mag-I.

A simplified schematic of the SCR modulator is shown in Fig. 4. The power train starts at the input power line with 3 phase, 208 V power. In our prototype modulator, a 3-phase SCR bridge (SCR1) charges the capacitors C_1 to up to ±160 V. The pulse capacitors C_2 are resonantly charged to ~550 Volts after the SCR2 pulse.

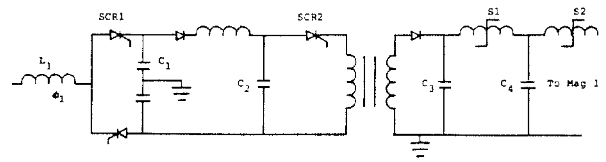

Fig. 4. SCR modulator circuit

When SCR2 is triggered (~100 Hz in the prototype) the pulse capacitors C_2 are discharged into the primary of the 50:1 stepup transformer T1. The first storage capacitor C_3 is charged to ~26 kV by the transformer. It is discharged in ~25 μsec when reactor S1 saturates after ~130 μsec. This charges C2, which is discharged through S2 in ~4 μsec into the primary of the stepup transformer in the mag. Based on our preliminary results at 30 J/pulse, we expect resistive losses of ~8%, and magnetic switch losses of ~8%, including reset. Higher efficiency is expected in a higher energy modulator. Component costs for this module, at 200 J/pulse, are ~$14,000 plus assembly labor. The final cost is expected to be less than 75% of a Thyratron/HV supply system.

Conclusions

We anticipate first operation of our accelerator in July 1987. Based on efficiencies of ~80% in the accelerator, ~84% in the SCR modulator, and 80% in the modified magnetic compressor, an overall wall plug to beam efficiency of ~55% is anticipated in the prototype. Multi-module accelerators operated at higher power are expected to achieve overall energy efficiencies of ~65%. We suggest that the SCR driven induction accelerator is the accelerator of choice for applications at energies >50 kW and modest (<20 MeV) energies. This work was supported by the U.S. Department of Energy under Contract No. DE-AC03-86ER80238.501, and by PSI internal funds.

References

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