Induction Linac Pulsers

by

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The pulsers used in most of the induction linacs evolved from the very large body of work that was done in the U.S. and Great Britain during the development of the pulsed magnetron for radar. The center for the radar development was the M.I.T. Rad Lab, which in part was patterned after the Berkeley Rad Lab, and it included persons associated with accelerators before and after the war (Alvarez before his Manhattan Project work, Laslett, etc.). The radar modulators started at ~100 kW and reached >10 MW by 1945. A typical pulse length was 1μs at a repetition rate of 1,000 pps. A very comprehensive account of the modulator development is Pulse Generators by Lebacqz and Glasoe, one of the Radiation Laboratory Series. J.V. Lebacqz went on to work at the S.L.A.C. linac.

There are many permutations of possible modulators, two of the mail choices being tube type and line type. In earlier notes I wrote that technically the vacuum tube pulser met all of our induction linac needs, in the sense that a number of tubes, in series and parallel if required, could produce our pulses, regulate their voltage, be useable in feed-forward correctors, and provide a low source impedance. At a lower speed, an FET array is similar, and we have obtained and tested a large array capable of >10 MW switching. A modulator with an electronically controlled output only needs a capacitor for energy storage and in a switched mode can transfer the energy from the capacitor to the load at high efficiency. Driving a full size Astron induction core and a simulated resistive “beam load” we achieved >50% efficiency. These electronically controlled output pulses can produce the pulses we desire but are not used because of their high cost.

The second choice, the line type pulser, visually comprises a closing switch and a distributed or a lumped element transmission line. The typical switch cannot open or stop conducting after the desired pulse has been produced, and consequently all of the initially stored energy is dissipated. This approximately halves the efficiency, and the original cost estimating program LIACEP used this factor of two, even though our circuits are usually worse, and even though our inveterate optimists often omit it. The “missing” energy is that which is reflected back into the line from mismatches, the energy left in the accelerator module’s capacitance, the energy lost in the switch during switching and during the pulse, and the energy lost in the pulse line charging circuit. For example, a simple resistor-limited power supply dissipates as much energy as it delivers to the pulse forming line, giving a factor if two by itself, therefore efficiency requires a more complicated charging system.

The first induction linac, the Astron Injector at LLNL used high voltage coaxial cables as the pulse forming elements for 300-400 ns pulser as well a small, lumped element correction networks. The second induction linac, the Electron Ring Accelerator (ERA) injector, used coaxial 45 ns Blumlein lines, which evolved from a folded radial line accelerator for the electron ring itself. The Long Pulse Induction module at LBNL used lumped element capacitors and inductors for a 1.5 μs PFN. The subsequent ETA and ATA induction linacs at LLNL were similar to the ERA injector, but produced ~70 ns pulses at higher power levels. FXR and DARHT I are similar.

The induction linac pulsers have generally comprised a closing switch and a line type of pulse forming network. The choice of the closing switch includes magnetic modulators of several kinds, hydrogen thyratrons, ignitrons, FET's and other semiconductors, and spark gaps of various kinds. For at least 40 years there have been research efforts on many light or electron beam activated switches and amplifiers, but despite good prospects and high expectations, including modest contributions from our group, these switches are not in general use. A modest exception is the optically coupled SCR, but it is too slow for our applications.

For obtaining higher voltages, the initiating pulse generator can use the Blumlein configuration, use a "cable" or a standard output transformer, or in some cases a tapered impedance transmission line. The ERA pulse line accelerator was designed with both a Blumlein circuit and a tapered radial transmission line. Because of the unfavorable scaling of breakdown voltage, there has been little incentive to develop higher voltage modules. The Astron Injector used several parallel 50 Ω transmission lines charged to ~30 kV to produce ~15 kV pulses into smaller transmission lines (coax cables) going to each core. One hydrogen thyratron drove one ½" long core of about 30" OD, 11" ID, and altogether ~600 thyratron chasses were used. Our 2000 FET pulser provided a similar output pulse to that of one thyratron pulser and, for a developmental model, cost about 100 times more and was several times larger. The ERA Injector used 250 kV pulsers, for shorter but higher current pulses, and was switched with a spark gap. Roughly, it was equivalent to 16 thyratron pulsers.

The use of a 250 kV induction module switched by a spark gap compared to the "16" thyratron switched modules resulted in a smaller and less expensive system overall. The higher gap voltage was and still is a concern, and better insulator prototypes were made at LBL and later at LLNL, but not used. At the end of the ERA and ATA projects a few of the accelerator modules were disassembled for inspection, and a small fraction of those showed well developed discharge trees going partially through the insulator. With additional pulses these would have failed. The unused better solution was an essential part of the LIACEP insulator: subdivision of the insulator into several shorter pieces. The work on glass ceramics of a decade ago had promise of embedding the required metal subdivision rings into one insulator casting at low cost.

An important difference between the various switches is the switching speed: nanoseconds for a hard tube and a power FET, ~20 ns for the spark gaps, and ~50 ns for the thyratrons. The rise time of the voltage in the accelerator gap is substantially longer due to the "gap capacity" or the wave travel and settling times around the typically 1-2 m size modules.

Operational Experience

The radar systems mentioned earlier which were the basis for much of the pulser technology would operate for of the order of 1000 hours and got $\left(10^{3}h\right)\left(3.6x10^{3}\right)\left(10^{3}pps\right) \sim 3.6x10^{9}$ pulses.

The SLAC linac, at an earlier tally, had ~10^{11} pulses on similar modulators

The Bevatron linac, at 2 pps, had 10^{9} pulses

The Astron Injector, at 5 pps, had 10^{8} pulses

The ATA Induction linac had 10^{7} pulses, including a burst rate of 1000 pps

The ERA Injector Induction linac had $5x10^{6}$ pulses at 1/3 pps

The HIF machines, the 2 MV Cs Injector, SBTE, and MBE-4 all had ~$5x10^{5}$ pulses each, at pulse rates of <1 pps, and a few thousand pulses per day. Most of the induction linac rep rates were limited by power supplies and data taking limits.

The standard practice in accelerators is to make a repeatable beam and measure its properties such as position, profile, transverse emittance, and longitudinal emittance by scanning the beam in small steps with a pair of transverse slits, parallel and perpendicular, and a Faraday cup behind to second slit to measure current for the transverse phase space, and to vary an energy spectrometer over many pulses to measure the longitudinal phase space. Other techniques exist, but the above is typical. Starting at the source, the above set of measurements is repeated along the accelerator. During this entire measurement sequence the beam is expected to be repeatable and most or all of the equipment continue operating.

This is markedly different from “single shot” devices, where all of the information must be obtained on one pulse because the next one might be different.

The induction linacs for HIF are therefore well along towards development of a driver because the rep rates and total numbers of pulses in some cases already approach the driver requirements. The early radar experience is particularly relevant because the common radars used a PFN, a switch, and a pulse transformer, essentially the ingredients of an induction linac. The MIT Rad Lab group working on pulsers reached about 50 persons, and estimating about 10 such groups in the country, such as the Bell Labs and in many of the private companies, the total comes to a few thousand-man years of effort. Adding to this perhaps 5 people at a dozen labs for the next 60 years gives a total of perhaps five thousand man-years. Our group added to the very short pulse, short rise time, <1 ns jitter, >1 GW area of the modulator parameter space.