INDUCTION TECHNOLOGY OPTIMIZATION CODE*

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Abstract

A code has been developed to evaluate relative costs of induction accelerator driver systems for relativistic klystrons. The code incorporates beam generation, transport and pulsed power system constraints to provide an integrated design tool. The code generates an injector/accelerator combination which satisfies the top level requirements and all system constraints once a small number of design choices have been specified (rise time of the injector voltage and aspect ratio of the ferrite induction cores, for example). The code calculates dimensions of accelerator mechanical assemblies and values of all electrical components. Cost factors for machined parts, raw materials and components are applied to yield a total system cost. These costs are then plotted as a function of the two design choices to enable selection of an optimum design based on various criteria.

Introduction

The Induction Technology Optimization Study (ITOS) was undertaken to examine viable combinations of a linear-induction accelerator and a relativistic klystron (RK) for high-power microwave production. It is proposed, that microwaves from the RK will power a high-gradient accelerator structure for linear collider development [1]. Previous work [2] indicates that the RK will require a nominal 3-MeV, 3-kA electron beam with a 100-ns flat top. The proposed accelerator-RK combination will be a high average power system capable of sustained microwave output at a 300-Hz pulse repetition frequency (prf). The ITOS code models many combinations of injector, accelerator, and pulse power designs that will supply an RK with the beam parameters described above.

Accelerator design equations are written into the ITOS code and follow a criterion that equally weights three characteristic time scales in the system: (1) Rise time of the source pulse which is determined by the inductance of the output switch, (2) Rise time of the induction module gap voltage due to cell capacitance, (3) Rise time of the A-K gap voltage due to injector stalk charging. Given initial design information, the ITOS code calculates the dimensions of all accelerator mechanical assemblies and values of all electrical components. Costs are generated from the mechanical data. These calculations are repeated by changing three design inputs over a range of interest. The resulting costs are plotted as a family of surfaces. Each cost point on the surface is a valid accelerator-RK system design for one set of input conditions. Interesting cost minimums can be selected from the cost surface and studied in greater detail.

The three input quantities which specify a given design are the risetime fraction, the aspect ratio of the ferrite core in the induction cells and the injector balance parameter.

The risetime fraction is simply an e-folding time divided by the duration of the "flattop" (100 ns). The aspect ratio of the ferrite core is the ratio of the core axial length to the difference in outer and inner radius of the core. The injector balance parameter is given by the number of induction cells on the anode stalk minus those on the cathode stalk divided by the sum of the two. An injector balance parameter of 0.0 corresponds to a balanced injector while a value of -1.0 corresponds to a cathode stalk only. The code loops through designs by varying the risetime fraction and ferrite aspect ratio for a given choice of injector balance parameter.

Injector, Accelerator and Transport Constraints

The ITOS code contains numerous constraints on various quantities. The injector cathode stalk radius is set such that the radial electric field on the surface is less than or equal to 100kV/cm in order to avoid field emission. The cathode current density is limited to 25 A/cm^2 in order to impose a minimum on the bore of the anode beam pipe.

The beam pipe radius is determined by imposing two constraints: the pipe must be larger than three times the equilibrium edge radius of the beam, and the pipe must be large enough to limit the growth of the beam breakup instability to 5 e-folds (the cavity coupling impedance is a strong function of the pipe radius) [3].

The total cyclotron phase advance (and hence the solenoidal focusing field) is constrained by requiring the corkscrew amplitude of the beam in the RK to be less than one mm. The corkscrew amplitude [4] arises from four sources of misalignment in the code: injector displacement, injector tilt angle, individual random solenoid tilts and individual random solenoid displacements. Alignment tolerances achieved in practice with the ETA-II accelerator are used. The energy variation over the "flattop" portion of the beam is assumed to be 1%.

The three characteristic times mentioned earlier are forced to equal an input parameter, the risetime fraction multiplied by the flattop width of the beam. The cell voltage rise time is given by the product of the cell capacitance and the cable impedance which is roughly equal to the cell voltage divided by the sum of the beam and ferrite leakage currents. Since the capacitance is a function of the cell dimensions (which can be related to the cell voltage) specifying the cell "RC" time determines the cell voltage.

The injector charge time (which is quasi-diffusive) depends on the length of the longest stalk (and hence on the

* Work performed under the auspices of the US Department of Energy by the Lawrence Livermore National Laboratory under W-7405-ENG-48.

number of cells in the longest stalk) so that fixing this time and the injector balance parameter results in a selection of the injector voltage. The code checks that the perveance of the injector is less than or equal to 3 micropervs in order to insure sufficient beam quality.

Pulse Power Architecture

The ITOS pulse power model must generate the prescribed voltage pulse at each induction cell for every trial design. Rather than searching out a variety of pulsed circuits for every design change, the ITOS code uses a single network architecture and varies the circuit values to match the needs of each design. The network is simple and efficient, for low cost, yet robust enough to accommodate an interesting variety of accelerator shapes and sizes.

The pulsed power network for ITOS was selected with three fundamental ideas in mind:

1. The study is based on a detailed pulse-power circuit specifically derived for this one application. The network architecture is fundamentally capable of generating a reasonably flat, 100-ns pulse of the proper voltage, current, prf, and jitter specifications.

2. The pulsed-power technology selected for the study combines the best features of previous induction accelerators constructed at LLNL. This experience has helped us to select network elements that are reliable, efficient, low maintenance, and low in cost.

3. Calculations of the network component values are bounded by physical limitations, such as insulation breakdown strength, field-emission threshold, and magnetic material saturation.

The network architecture selected for ITOS is shown in Figure 1. The air-core resonant transformer (T_0) and water-filled Blumlein pulse-forming line are circuit features found in the ATA pulsed power system [5]. The single stage of magnetic pulse compression draws on our more recent experience from the ETA-II accelerator [6].

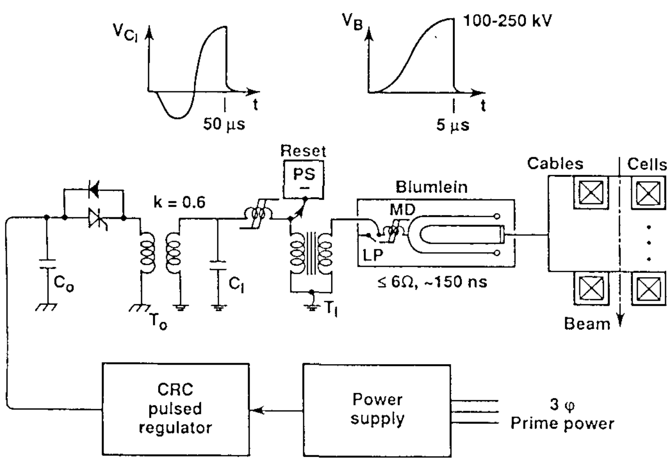

Figure 1.

Normally, the induction cell pulse is initiated by a spark gap attached to the Blumlein, but in this application high-pressure spark gaps are unsuitable due to the high prf and long service life required. For ITOS, the spark gap has been replaced by a series combination of a magnetic switch and a low-pressure gas switch. Our previous experience with low-pressure switching indicates that high prf operation can be obtained, but the amount of anode erosion is unacceptable [7]. Other researchers have shown that delaying the onset of current flow by a series magnetic switch reduces electrode erosion and increases switch efficiency [8,9]. Laboratory research is now underway to develop a magnetically-delayed low-pressure switch (MDLPS) for the ITOS network. Other commercial switches, such as the back-lighted thyratron, are also under consideration as the critical Blumlein switch.

Network Operation and Features

The network of Figure 1 begins its operation by charging C_0 from a power supply connected to a pulsed voltage regulator, depicted in the figure as a command resonant charge device (CRC). The silicon-controlled rectifier (SCR) connects C_0 to the air-core transformer, T_0, which charges C_1. In this design, the transformer has a coupling coefficient of 0.6 and the primary and secondary frequencies are the same [10]. The primary current is bidirectional, so a diode is employed to conduct the reverse current. The magnetic switch saturates when C_1 is fully charged and connects C_1 to the transformer T_1.

The power conditioning section described above has several interesting design features selected for this application:

(a). Solid-state switches were selected for long life and high prf capability. Reverse current through the diode assists the SCR's recovery.

(b). The air-core transformer does not need a reset supply. Isolation is easily obtained between the slow power-conditioning ground and the faster pulsed ground due to the low transformer coupling coefficient. Pulse transformers that also isolate compression stages help reduce instrumentation noise by avoiding large ground loops.

(c). The unique dual-resonant waveshape on C_1 allows the magnetic switch to always saturate at the peak charge on C_1 without regard to the absolute voltage amplitude. The combination of resonant-transformer charging and magnetic switching yield the specific benefits of low switching jitter and a self-resetting switch core. These technical details are described elsewhere [11].

(d). The step-up transformer, T_1, allows the voltage at C_1 to be within the application range of inexpensive, solid-dielectric capacitors. If the Blumlein switch fails to fire at the peak voltage on C_1, then T_1 will saturate and discharge the Blumlein safely.

The Blumlein is charged from T_1 in approximately 5 µs through the anode of the MDLPS. The charging time is selected fast enough to mildly stress the water dielectric in the Blumlein, but slow enough that charging reflections within the Blumlein have damped out before switching. Closing the MDLPS launches a pulse that is distributed by the cable system and eventually reaches the acceleration gap in each induction cell.

This pulse-forming section described above also has a few subtle design features:

(a). Charging the Blumlein from T_1 also resets the magnetic core in the MDLPS and the ferrite cores in the cells.

(b). The MDLPS is a triggered switch and thereby exercises final timing control over the acceleration pulse.

(c). The Blumlein generates an output pulse voltage that equals the charge voltage. This feature reduces the peak voltage handled by the charging network.

(d). The cables connecting the cells to the Blumlein provide transit-time isolation between cells.

The cells are designed with more ferrite than is needed to support the volt-seconds of the acceleration pulse. This was done to avoid the near-saturation behavior of the ferrite and thereby match the stabilized cell impedance to the constant cable impedance. Shunt resistors are also provided in the cell design to maintain a constant load impedance, should the beam current vary from a nominal 3 kA.

Calculational Modules

The circuit of Figure 1 is partitioned into modules and shown in Figure 2. Each box represents a set of design calculations specific to one or two elements in the circuit. The arrows indicate that the calculations proceed from the cell load to the prime power. The feedback module contains MDLPS inductance and Blumlein impedance information needed to calculate one of the three rise time conditions at the cell.

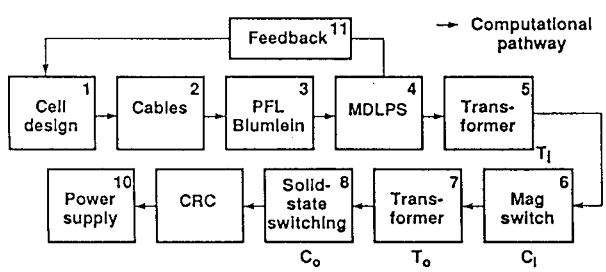

Figure 2.

Information from the previous module is processed to yield component values for the network and mechanical dimensions of the network elements. The newly calculated circuit information is passed onto the next module while mechanical dimensions are processed to obtain cost and weight of the network elements. Each module assesses an electrical efficiency and local checks of physical limits are imposed.

The results of a run over many point designs are shown in Figure 3 for an injector balance ratio of -0.2.

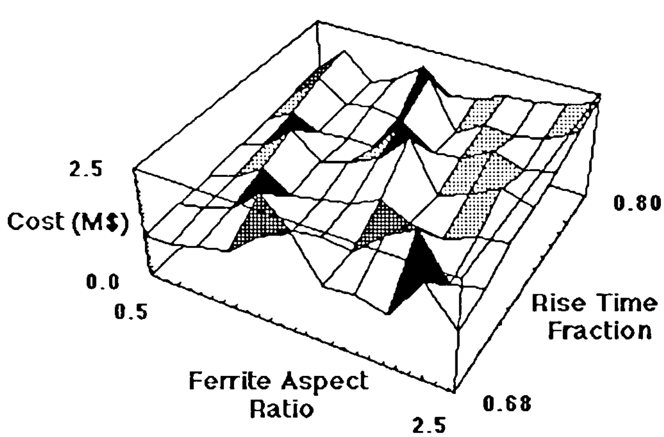

Figure 3.

Summary

The ITOS prices an injector and accelerator combination based upon a valid end-to-end design. Many design iterations are displayed as families of cost surfaces, which allows the researcher a wide selection of optimal designs ranging in cost. The ITOS combines the best pulsed power technology from past accelerators and bounds the designs by physical limits.

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