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Induction Accelerator Test Module for HIF*

Andris Faltens
Lawrence Berkeley Laboratory,
University of California
Berkeley, CA 94720

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Induction Accelerator Test Module for HIF*

Andris Faltns

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

ABSTRACT

An induction linac test module suitable for investigating the drive requirements and the longitudinal coupling impedance of a high-power ion induction linac has been constructed by the Heavy Ion Fusion (HIF) group at LBL. The induction linac heavy ion driver for inertial confinement fusion (ICF) as presently envisioned uses multiple parallel beams which are transported in separate focusing channels but accelerated together in the induction modules. The resulting induction modules consequently have large beam apertures—1-2 meters in diameter— and correspondingly large outside diameters. The module geometry is related to a low-frequency "gap capacity" and high-frequency structural resonances, which are affected by the magnetic core loading and the module pulser impedance. A description of the test module and preliminary results are presented.

1. INTRODUCTION

The induction linac heavy ion driver uses multiple parallel beams which are transported in individual focusing channels but accelerated together in common induction modules. Because the focusing and acceleration requirements change with energy, there is a slow change in the appearance of the accelerator with distance. In the low energy end the preferred scenario is a large number of electrostatically focused beams (e.g. 64) whose quadrupoles occupy most of the available axial space, and consequently the induction cores must surround the cluster of focusing elements, which has a diameter of about 1 m. As the ions gain energy, it becomes more economical to combine the beams to a smaller number of beams (e.g. 16) focused with superconducting magnetic quadrupoles. The diameter of the cluster of quads increases to about 2 m. This transition point is dictated by economics, and nominally takes place at 100 MeV. With further acceleration it becomes advantageous to change to an arrangement where the induction modules alternate with the quadrupole arrays, and the cluster of beams and the resultant module inner diameter can both be reduced back towards the 1 m diameter size. Viewed along the length of the accelerator, the inner diameter would be constant for the first few hundred meters, then bulge out to about twice its initial value, and then gradually decrease. There is a similar variation in the induction core size of the modules, dictated by economics considerations combined with other constraints. At the low energy end acceleration is limited by an assumed

velocity tilt limit, which leads to a rapidly increasing allowed acceleration rate with distance, and an increasing core size. Later in the acceleration process, the decrease of pulse duration and maximum electric field limits lead to a decrease of the required core. The resulting outer diameter of the induction cores is about 2 m at the front end, reaches a maximum of about 3 m past the electric to magnetic focusing transition point, and gradually decreases to about 2 m at the end of the accelerator.

II. MODULE CONSTRUCTION

A large induction module which is representative of the required driver modules has been constructed at LBL. The main difference from previous electron and ion induction accelerator modules is the very large central aperture. The test module was made with a 1 m diameter aperture and a 2 m outer diameter. The area which would normally be filled with ferromagnetic core is filled to only a 10% occupancy by winding the core loosely and by alternating thin spools of tape of about 1 cm radial buildup with empty regions of about 9 cm radial extent. This choice of geometry allows the high power measurements to be performed at a relatively comfortable level of 20 kV or less, and allows probing the voltages and currents within the core region, whereas a completely filled core would require up to 200 kV for the same measurements. Figure 1 is a photograph of the module near the completion of its assembly. The largest conveniently available insulator, shown in the middle of the picture, has a diameter of 0.7 m, but the other important dimensions are full size. The top surface of the module, which is not yet installed in the photograph, has an array of capacitive dividers and current loops which enable the voltage and current distributions to be measured in the "gap" region of the induction module. The bottom plate has a similar array of probes, some of which are visible in Fig. 1. The intermediate plate, 25% of which is shown in the photo, has provisions for single, two-point, and three-point drive connections at its outer radius. The spaces between spools of tape are largely filled with aluminum ducting to approximately maintain the capacitance of a solid core. The same effect could have been achieved by winding the core loosely.

The core is wound from Metglas 2605 CO material insulated with SiO₂ microspheres and the transformer oil into which the core is immersed. This insulation combination has been satisfactory for core switching speeds of 1 μ s and above for the 5 cm wide, 25 μ m thick ribbon used. For shorter pulse durations and dense packing the preferred insulation today would be interleaved thin mylar. The tape was rewound from 0.36 m diameter spools onto 12 spools of diameters ranging from 1 - 2 meters, without subsequent annealing. The 2605 CO material was chosen because it has low sensitivity to stress on its magnetic properties. The spools of tape are arranged in 6 sections radially and 2 sections axially. The

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Fig. 1. The induction accelerator test module.

excitation winding is formed by joining the intermediate plate to the bottom plate with a copper cylinder. The external drive is applied at one or more discrete points at the outer radius.

III. MODULE ISSUES, MODELS, AND MEASUREMENTS

The issues which the test module is intended to address are the drive power requirements for the various pulse durations of interest, the drive pulse transients, the beam loading transients, and the longitudinal coupling impedance presented by the module to the ion beam. There has been an upsurge of interest in the longitudinal coupling impedance due to high-frequency cavity modes in the past year or so, and the initial measurements have consequently concentrated on this topic. The transverse coupling impedance and the beam deflections induced by the drive current are lesser concerns. A practical question is whether the module geometry needs to be modified for driver designs to reduce the Q s of higher order mode resonances, or whether the Q s are low enough without additional attention. In the present and ensuing discussion various common terms such as voltage, current, Q , and impedance are used in their customary senses even though they are applied to an intrinsically nonlinear and time-dependent induction device. Use of the familiar cavity mode designations such as TM₀₁₀, TM₁₁₀, etc., however, is inaccurate and misleading, because these usually refer to oscillations in a pillbox cavity with short-circuit boundary conditions at the outer radius, whereas the induction cavities have a complicated impedance boundary at the outer radius which is closer to an open circuit.

The uncertainties in the electrical operation of an induction module arise largely from the induction core. In the usual operating sequence, a reset pulse is used to saturate the core material in the reverse direction and then leave the core at the remanent magnetization level. In some cases the reset current flows through the core while the drive pulse is applied. In either case, the drive pulse is very much larger than the reset pulse, and depending on the desired pulse duration, drives the core close to or into complete saturation in the opposite sense on a time scale of a microsecond or so. One of the goals is to eventually determine the rf properties of the module during this

switching process. Except for the faster time scale involved, this is essentially the same process that takes place in the ferrite-tuned rf acceleration cavities used in synchrotrons. The major difference is that the rf modes of an induction cavity play no useful role in the acceleration process and are instead the analogues of parasitic resonances in a pulse transformer. In the preliminary measurements reported here, the rf and drive pulses are applied separately, but the rf can be applied at various static states of core magnetization.

Ideally, an induction module would have a core with such a high impedance that it could be replaced with an open circuit; the resulting geometry is two "washers" facing each other and connected through a pulse generator with impedance, R_g , as shown in Figure 2. This geometry is needed partly to provide an acceptable electric field distribution in the vicinity of the beams, and partly to shield the beams from possible deflections from the core drive current. At low frequencies the equivalent circuit is the generator in parallel with a capacity, the "gap capacity" formed by these washers, where it is understood that the electric fields are confined to the interior of the structure. At higher frequencies, the first important resonances are the various ring modes of the structure, which are essentially TEM-like waves running circumferentially around the structure. Their character depends on the relative magnitudes of the characteristic impedance of the stripline formed by the washers and the drive or generator impedance. If the generator impedance is low compared to the line impedance, as might be the case for a very high current accelerator, then the lowest mode is a quarter-wave oscillation, where distance is measured from the drive point to the open circuit symmetry point opposite, followed by the $3\lambda/4$, $5\lambda/4$, etc. modes. If the opposite impedance ratio holds, then the lowest mode is a half-wave oscillation, followed by the λ , $3\lambda/2$, etc. modes. The electrical length of the structure is well approximated by measuring distance at the average radius of the washers. A comparison of the calculated and measured resonant frequencies is given in Fig. 3. Relation of these resonances to a coupling impedance depends on the particle velocity, the beamlet arrangement, and the mode of oscillation among the beamlets. This will be the subject of a future publication. There is not a clear distinction between deflecting and accelerating modes as in a single beam machine with high- Q rf cavities, because what is a deflecting cavity mode for one beamlet mode of oscillation can be a longitudinal cavity mode for another beamlet mode of oscillation. Also, because these modes are incidental to the operation of the linac, the radial and

Fig. 2. The circuit idealization for the module.

axial transit time factors can be made very low if desired without affecting the basic acceleration mechanism. A reasonable algorithm is to average the central electric field distribution over the beamlet mode of oscillation; for example, the 0 or in-phase mode of the beams would not interact longitudinally with any of the azimuthally varying electrical modes which have an integral number of wavelengths circumferentially, but would have a transverse coupling impedance, whereas a mode of oscillation where the beams are out of phase across a diameter would have a longitudinal coupling impedance as well as a transverse impedance from the full wavelength mode. Most of these modes have the beams passing through the low-amplitude portions of their fields and therefore have low coupling impedances.

At higher frequencies, the azimuthally symmetric modes begin to appear. For a drive impedance which is high compared to the mode characteristic impedance, the lowest one of these is the analogue of a radial half-wave mode. Beginning with an open circuit at the outer radius, the mode can be computed by making an impedance transformation to an open circuit at zero radius. A conceptual simplification is to taper the radial lines slightly to counteract the impedance change with radius of the parallel plate geometry, in which case the radial extent of the plates is a free-space half-wave shortened by the index of refraction. Although tapered plates are an option for the modules because of their mechanical strength, most similar modules have been constructed in a planar geometry, as has been the test module, and this has the effect of lowering the lowest resonant frequency by about 30%. With a tapered geometry and the assumption that the drive impedance can be averaged over the outer circumference, the impedance at these resonances is the drive or generator impedance. If the geometry is not tapered, but the generator impedance is spread

over the outer circumference, then the coupling impedance rises with frequency, eventually by a factor of R_o/R_i , which is a factor of two for the test module. In the actual geometry of a discrete number of drive points, there is no easy simplification that is useful for the required impedance transformation from the drive terminals to the center of the module, but a measurement is very easy.

The presence of the induction core and the necessity to enclose it with a conductor perturbs the frequencies of the previously described simplified modes and, together with the generator impedance determines the Qs of the resonances. The core winding conductor introduces a zero in the impedance at zero frequency, followed by a pole or impedance peak at about 10 MHz, which is the lumped element parallel resonance of the gap capacity and the core inductance. The inductance and damping are expected to vary during the acceleration pulse because of the changing state of magnetization of the core material, and if it is similar to the much more familiar case of ferrite its properties will be a function of the amplitude of the rf excitation. The losses are expected to increase with amplitude. For the low frequency lumped element resonance, the beam coupling impedance is dominated by the module generator impedance and is limited to a low value. For the higher-frequency higher order modes, the damping from the core material is expected to be more important. At low amplitude and in a static magnetization condition, the Qs of the resonances are near 10, as shown in Fig. 3. Further measurements will look at the amplitude dependence of these same resonances and their dependence on the dynamic magnetization process. The apparatus for these more extensive measurements has been acquired. The measurements reported here are the first results of a more comprehensive program planned for the remainder of this year.

Fig. 3. Transmission measurements to a diametrically opposite voltage pickup, solid curve and a pickup near 90°, dashed curve, from a high impedance drive point. The first resonance, $f = 10$ MHz, $Q = 1$, is the lumped element LC parallel resonance of the module. The next set of resonances is the circumferential or ring modes, $f = 42$ MHz, 80 MHz, etc., $Q = 10$. Alternate resonances of this set have a voltage null near the 90° pickup, seen in the dashed curve, which aids in identifying these modes. The radial modes become evident beyond 140 MHz and have lower Q's. The resonant frequencies calculated for the simplified models are 42, 84, and 126 MHz for the ring modes and 142, 226 MHz for the radial modes, which are indicated by the marks on the frequency scale.