Control of Energy Sweep and Transverse Beam Motion in Induction Linacs*

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Abstract

Recent interest in the electron induction accelerator has focussed on its application as a driver for high power radiation sources - free electron laser (FEL), relativistic klystron (RK) and cyclotron autoresonance maser (CARM). In the microwave regime where many successful experiments have been carried out typical beam parameters are: beam energy 1 to 10MeV, current 1 to 3kA and pulse width 50nsec. Radiation source applications impose conditions on electron beam quality, as characterized by three parameters; energy sweep, transverse beam motion and brightness. These conditions must be maintained for the full pulse duration to assure high efficiency conversion of beam power to radiation. The microwave FEL that has been analyzed in the greatest detail requires energy sweep <±1%, transverse beam motion <±1mm and brightness ~ 1 x 10^8A/m^{2}rad^2[1]. In the visible region the requirements on these parameters become roughly an order of magnitude more stringent. Recently with the ETAII accelerator at LLNL we have achieved energy sweep <±1%, transverse beam motion <±0.6mm and brightness >10^8A/m^{2}rad^2 for 40nsec flattop with 1.5kA of beam current and 2.7MeV energy. In this paper we will discuss the recent data and the advances that have made the improved beam quality possible. The most important advances are; understanding of focussing magnetic field errors and improvements in alignment of the magnetic axis, a redesign of the high voltage pulse distribution system between the magnetic compression modulators and the accelerator cells, and exploitation of a beam tuning algorithm for minimizing transverse beam motion. We will also briefly describe the prospects for increasing the pulse repetition frequency to the range of 5kHz and a delayed feedback method of regulating beam energy over very long pulse bursts, thus making average power megawatt level microwave sources at 140GHz and above a possibility.

INTRODUCTION

The kiloampere beam current of an electron induction accelerator makes it an attractive driver for high power radiation sources. The success of the ELF FEL experiments[2] producing up to 1GW at 35GHz with 40% extraction efficiency drew attention to this possibility. Electron beam quality and the extension to high pulse repetition rate or high average power are crucial for the success of future development. Electron beam quality is characterized by energy sweep, spatial sweep and brightness.

In the discussion of transverse beam motion it is useful to make some distinctions - firstly between transverse motions of the beam cross-section radius and of the beam centroid and secondly between centroid motions that are purely dynamical (beam corkscrew[3,4]) or that are instability driven (beam break-up or BBU instability[5]). The paper is organized around these distinctions.

Specific examples will be taken from recent experience with the ETAII accelerator[6]. Nominal beam parameters for ETAII are 7.5MeV beam energy, 2kA beam current, 70nsec pulse width. Up until now normal operation has been at 1Hz PRF. The magnetic modulators have the capability of running pulse bursts at 5kHz but need some additional development in timing stability.[7] ETAII drives a wiggler to produce 140GHz microwaves for use in ECRH heating the MTX tokamak plasma.[8] Initial experiments encountered difficulty producing full width microwave pulses due to transverse beam sweep entering the wiggler. The beam sweep was diagnosed as beam corkscrew motion caused by the combination of energy sweep and misalignment of the magnetic axis of the focussing solenoids.[9] At the exit of the accelerator the amplitude of the transverse sweep was typically ±10mm whereas the FEL requires an amplitude less than about ±1mm. Subsequently the accelerator (sixty cells) was disassembled and the first twenty cells put back together with a stretched wire magnetic alignment device[10] and a new pulse power distribution system to reduce the energy sweep[11]. In addition a new tuning algorithm was developed for minimizing the beam corkscrew motion. Recent operation has demonstrated good beam quality. The remaining forty cells of the accelerator are being reassembled in preparation for resuming FEL operation.

The central issues regarding energy sweep and transverse beam motion in an induction linac can be identified with reference to an induction cell shown in Fig. 1. The electron beam is focussed with solenoids in each cell surrounding the beam tube. The solenoidal field is typically 250G. With injector energy 1.0MeV and beam energy 2.7MeV at the exit of twenty cells the equilibrium rms beam radius for 1.5kA beam current is 2.4/1.6 cm at the entrance/exit of the twenty cells and the cyclotron wavelength is 120/265 cm. Accurate control of the transverse displacement and tilt of the solenoids is important for controlling the amplitude of beam corkscrew motion. A sin/cos coil pair is wrapped around each solenoid for correcting dipole errors. The cell contains a high voltage plate fed from two sides across a 0.75cm gap isolated from ground by ferrite toroids. Factors influencing beam energy sweep are the shape of the drive pulse, time dependence of the cell capacitance(120pF) charging current, ferrite leakage current[12] and beam loading current. There are some important compensation effects that help maintain constant accelerating voltage during the pulse - the rise and fall of the

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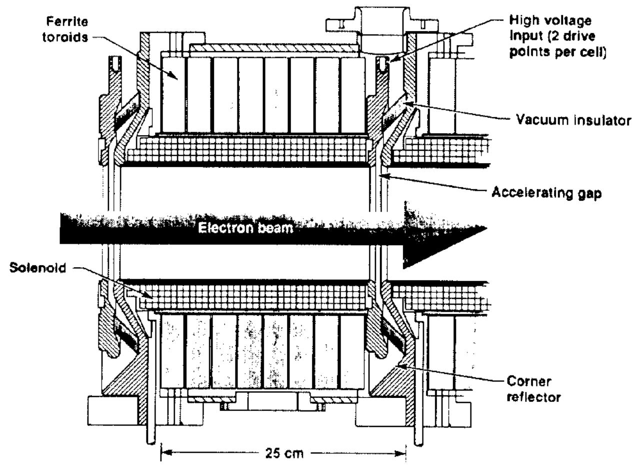

Fig. 1: Cross section of an ETAII induction cell

beam current load is partially compensated at the leading edge by the fall in capacitor charging current and on the falling edge by the rise in ferrite leakage current as the ferrite goes into saturation. The flatness of the accelerating pulse is also a sensitive function of the relative timing between the beam current pulse and the voltage pulse applied to the gap.

LOW FREQUENCY MOTION OF THE BEAM CENTROID - BEAM CORKSCREW

Definition of beam corkscrew motion

If an electron beam crosses the magnetic axis of a solenoidal focussing channel at an angle α in the x-z plane the downstream orbit is given by;

$$x(z) = (\sin(\alpha)/k_c)*\sin(k_c z) \qquad (1)$$
$$y(z) = (\sin(\alpha)/k_c)*(1 - \cos(k_c z))$$

where $k_c = eB/(m\gamma\beta c^2)$ is the cyclotron wavenumber. As long as the beam passes through the required physical apertures this motion is not too troublesome and can be removed with a pair of static steering coils if necessary. A more serious problem arises when there is an energy sweep $\Delta\gamma(t)$ during the pulse since this will give a differential phase shift $\Delta\phi(z,t)$ in the cyclotron phase advance $\phi = k_c z$ between portions of the beam having different energy ;

$$\Delta\phi(z,t) = - k_{co}z * \Delta\gamma(t)/\gamma_o \ , \qquad (2)$$

assuming β is approximately equal to unity. At a given z location the transverse beam position will acquire a time dependence given by;

$$x(z,t) = (\sin(\alpha)/k_c)*\sin(k_{co}z - k_{co}z * \Delta\gamma(t)/\gamma_o)$$
$$(3)$$
$$y(z,t) = (\sin(\alpha)/k_c)*(1 - \cos(k_{co}z - k_{co}z * \Delta\gamma(t)/\gamma_o)) \ .$$

This time dependent motion is called the beam corkscrew.[3] From eqn.(2) we see that the differential phase advance is proportional to the total phase advance and therefore increases linearly as the beam propagates causing an upshift in the frequency of the motion. If the magnitude of the differential phase shift exceeds 2π the beam will sweep out the entire cyclotron motion at a given z location.

To evaluate what happens in an actual accelerator many details need to be included - time dependence of the current, statistical misalignment of each of the focussing coils, acceleration and actual shape of the driving voltage pulse, ferrite and beam loading, realistic magnetic field profiles. This has been done for ETAII to set tolerances required to reduce the corkscrew amplitude to a tolerable level. The result was that with ±1mrad rms magnet tilts, magnet offsets measured with the stretched wire technique (<±.5mm horizontally,<±.25mm vertically) and ±1.3% energy sweep, the corkscrew motion was calculated to be less than ±.5mm at the exit of sixty acceleration cells.[13]

Magnetic alignment

The magnetic axis of ETAII was aligned with a pulsed stretched wire technique.[10] A current pulse interacts with transverse error fields to produce a wave detected at one end of the wire with a photodetector. The wave has different signatures for transverse field errors due to displacement and tilt of the focussing solenoids. Displacement data are corrected for catenary sag. The final rms displacement errors were determined to be 270/120 microns in the horizontal/vertical direction. Uncorrected magnet tilts had an rms value of 5mrad corrected to an rms accuracy of about 1mrad based on repeated measurements.[10]

Experimentally the sin/cos coil currents were set to the values determined with the stretched wire and we observed a relatively large corkscrew motion that was reduced by a factor of ten by the optimization process described below. The beam optimization process minimizes corkscrew motion due to the combined effects of solenoid transverse displacements and tilts. If the cyclotron wavelength is infinitely long compared to the length of an individual solenoid then transverse displacements are not expected to contribute to corkscrew motion of the electron beam. For ETAII however the cyclotron wavelength is only a few cells long and orbit calculations indicate that the measured offsets and tilts contribute about equally to the corkscrew motion. The sin/cos coil currents measured with the stretched wire compensate the tilts only. Secondly, there are pairs of solenoids at the ends of ten cell sets that had inferior mechanical mounts. The largest discrepancies between stretched wire and beam optimized sin/cos currents were for these coils and in retrospect it seems that they were not aligned as well as was thought. These mechanical mounts have been replaced.

Energy sweep

Voltage reflections in the common bus structure that fed a set of ten acceleration cells caused distortions in the voltage pulse shape applied to the acceleration gaps and were the main problem with energy sweep prior to the results reported at this conference. This structure has been replaced by a pulse distribution network that drives each pair of cells with a pair of transit time isolating 40 Ohm cables.[11] The ±1% energy flattop has been extended from 13nsec[9] to about 40nsec[14].

Beam tuning algorithm

Because of the large number of sin/cos correction coils (56 on the 20 cell and 96 on the 60 cell accelerator) it is advantageous to have a systematic, quantitative and automated procedure for beam tuning. Until the recent set of experiments tuning the accelerator was done manually without an explicit quantitative procedure. At best this was a tedious and lengthy procedure and had two serious limitations; firstly, since the tuning procedure was not systematic and quantitative it was never clear if the best result had been obtained and secondly, except for the person doing the tuning, it was difficult to follow the progress in detail.

To develop the tuning algorithm we separate the problem of beam centroid motion (corkscrew) from beam radial motion, which is treated in a later section. To begin the solenoids are set to reproduce a calculated magnetic field profile that minimizes beam radial oscillations for the anticipated beam current, acceleration gap voltages and beam emittance. The sin/cos coils are then initialized to values that should minimize residual dipole errors due to the solenoid tilts measured with the pulsed stretched wire setup described above. In order to develop an optimization procedure for the sin/cos coil currents we turn to the model eqns.(3) above. At any axial location the beam corkscrew motion is characterized by an amplitude and a phase shift. From eqns.(3) it is apparent that the amplitude of corkscrew motion is determined by misalignments of the focussing magnetic axis while the phase shift is determined by energy sweep. Physically then the amplitude of the corkscrew motion is controlled by the variables that affect the alignment of the magnetic axis - the sin/cos coil currents - and the phase is controlled by variables affecting the energy sweep - relative timing between the beam current and voltage pulse applied to the acceleration gaps and magnitude of the gap voltage (since the waveshape from the pulse power modulators is amplitude dependent). The amplitude and phase of beam centroid motion are readily derived from beam position monitors measuring x(t) and y(t) at the exits of the injector and each set of ten acceleration cells. The instantaneous radius of curvature $\rho(t)$ is given by;

$$1/\rho = (dx/dt*d^2y/dt^2 - dy/dt*d^2x/dt^2)/((dx/dt)^2 + (dy/dt)^2)^{3/2}. \tag{4}$$

It is convenient to integrate over a time interval (t_1,t_2) to obtain an amplitude A characteristic of the entire pulse;

$$A^2 = \frac{1}{\Delta t} \int_{t_1}^{t_2} (\rho^2)\, dt \tag{5}$$

$$A^2 = \frac{1}{\Delta t} \int_{t_1}^{t_2} ((x-x_c)^2 + (y-y_c)^2)\, dt$$

where x_c and y_c are the coordinates of the instantaneous center of motion . Similarly we define a cumulative corkscrew phase between t_1 and t_2 by;

$$\Phi = \int_{t_1}^{t_2} \frac{((dx/dt)^2 + (dy/dt)^2)^{1/2}}{|\rho|}\, dt\ . \tag{6}$$

The absolute value of ρ is taken in the integrand of eqn.6 to avoid cancellation with reversal of the sign of the energy sweep. As the current in a sin/cos coil is varied a well defined minimum in the amplitude A calculated from a downstream beam postion monitor is expected to occur when the sin/cos coil passes through the setting that minimizes the local dipole field error. Similarly as the relative timing between the injector current and accelerator voltage waveforms or the overall magnitude of acceleration voltage are changed one expects to observe a well defined minimum in the phase Φ given by eqn.6. This type of behavior has been observed in theoretical simulations[13] and in actual experiments[15]. Operationally the accelerator is tuned iteratively, starting at the injector and sequentially adjusting the current in each sin/cos coil for a minimum in A until end of the accelerator is reached. This procedure has been included in the MAESTRO control program developed for operation and simulation of the ETAII accelerator.[16] Adjustment of timing between the injector and accelerator has so far been done manually. The process is repeated to take account of small correlations between the various correction coils. In practice the procedure converges with two passes through the accelerator and only very small changes on the second pass. Using this technique the corkscrew sweep for 40nsec has been reduced from ±3.2mm with all of the sin/cos coils turned off to ±.225mm with them set to their optimized values. Because of numerical difficulty calculating the second derivatives in eqn.4 we have so far opted to use a modified version of eqn.5. The coordinates of the instantaneous center of motion x_c, y_c have been chosen to have fixed mean values over the interval t_1 to t_2 and we have then minimized the rms displacement from the mean using the second form of eqn.5.

HIGH FREQUENCY MOTION OF THE BEAM CENTROID - BEAM BREAKUP INSTABILITY

We now turn to the beam break-up(BBU) instability.[5] The BBU mode is driven by coupling between a transverse magnetic dipole mode and the transverse motion of the beam centroid. The mode grows exponentially with beam propagation distance, with axial inverse growth length $\Gamma \sim Z_T I/B$ where Z_T is the transverse cell impedance. This mode, which has been extensively studied on ETA and ATA[3], has so far not been of central concern for ETAII. An example of BBU oscillations(f=300MHz) and corkscrew motion appearing on the beam position monitor signals at the exit of the 20 cell accelerator is shown in Fig.2 For this example the accelerator has not been tuned to minimum corkscrew and the BBU oscillations,although small, are more pronounced than normally. Near the center of the pulse the peak to peak amplitude of the transverse BBU motion is 400microns.

The ETAII cells have been modeled with the AMOS electromagnetic code[17] and the transverse cell impedance has been measured with the two wire transmission line technique at LANL[18]. The code results and experimental measurements gave a dominant TM_{110} mode with Z_T=1500 Ohms/m at f=300MHz. Because of the desire to operate at low focussing field strength to minimize corkscrew phase advance and the inverse scaling of BBU growth rate with focussing strength, it seemed advantageous to lower the cell impedance if possible. This has been done employing an idea of Craig's to insert a metal ring on the high voltage feed plate of the cell which improves mode damping by the ferrite.[19] Measurements and code simulations showed a factor of two reduction in transverse impedance for a cell fitted with the ring. The forty cells now being installed on ETAII will have these rings.

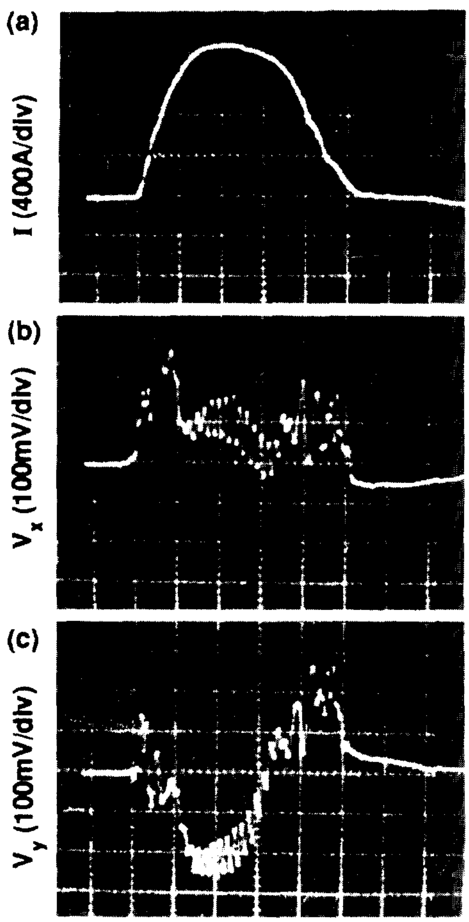

Fig. 2 (a) Beam current, (b)current weighted x and (c) y motion of the beam for a case exhibiting corkscrew and superimposed 300MHz BBU.

LOW FREQUENCY RADIAL OSCILLATIONS - THE PROBLEM OF BEAM MATCHING

Tuning the accelerator to minimize centroid oscillations is one part of the tuning process. The other part is tuning the accelerator to minimize radial oscillations of the beam cross section - mismatch oscillations. Procedurally, in the absence of a non-perturbing diagnostic of beam radius with good time resolution, we have used an axial magnetic field profile that has been calculated to have very small radial oscillations for conditions of beam current, acceleration and emittance close to those of the experiment. Nexsen has recently been developing a beam radius diagnostic with some promise.[20] An axis encircling loop is used to measure the diamagnetism of an initially field free beam injected into a solenoidal focussing channel (the cathode for ETAII is field free). Measurement of the beam diamagnetic moment gives the rms beam radius directly. In this section we indicate how such a diagnostic of beam radius could be used for matching the electron beam.

If a space charge dominated electron beam is injected into a solenoidal focussing channel with rms radius $R = R_0 + dR_0$, where R_0 is the matched beam radius, the beam will undergo radial oscillations, which according to the linearized envelope equation[21] are given by;

$$R(z) = R_0 + dR_0 * \cos(k_c z/(2)^{1/2}) . \qquad (5)$$

This is reminiscent of the centroid motion in eqn.(2) with the wavenumber divided by $(2)^{1/2}$. If the beam is emittance dominated then $(2)^{1/2}$ is replaced by unity. Sticking with the space charge dominated beam for illustration, introducing an energy sweep $\Delta\gamma(t)$ causes a time dependence of beam radius at a given z location given by;

$$R(z,t)=R_0 + \Delta R_0 * \cos(k_{c0}z/(2)^{1/2} - k_{c0}z/(2)^{1/2} * \Delta\gamma(t)/\gamma_0) \qquad (6)$$

A procedure analogous to that developed for the corkscrew motion can now be developed. An amplitude function

$$B^2 = \frac{1}{\Delta t} \int_{t_1}^{t_2} (R(z,t) - R_m(z))^2 \, dt \qquad (7)$$

is minimized by sequential adjustment of the upstream focussing solenoids. R_m is a mean radius, taken for example as the mean of the extrema in R. In practice this may require iteration with the corkscrew minimization since changing the solenoid currents will also change their error fields. It seems best to start with the corkscrew amplitude minimization, do the radius and then the phase minimization and iterate until reasonable convergence is achieved.

BEAM BRIGHTNESS

The intrinsic brightness of the type of cathode used on ETAII (M-type dispenser cathode) has been measued to be $1.5 \times 10^{10} A/m^2 rad^2$[22] and we would eventually like to understand and minimize degradation of this brightness by beam extraction, acceleration and transport. A whole beam brightness of $6 \times 10^8 A/m^2 rad^2$ has been measured in the full sixty cell configuration before the improvements discussed here were put in place.[23] In the twenty cell configuration the pepper pot technique has been used to measure brightness. Preliminary results are reported in two companion papers.[24,25] Briefly, the brightness of individual beamlets is observed to lie in the range $1\text{-}3 \times 10^9 A/m^2 rad^2$ whereas brightness integrated over the entire beam falls to about $1\text{-}4 \times 10^8 A/m^2 rad^2$[24]. Non-linear phase space distortions, evident on the pepper pot images, exceed the thermal spread of the beamlet images and are responsible for the degradation of whole beam brightness from the beamlet value. The cause of these distortions is under investigation. An interesting experiment demonstrating the deleterious effects of envelope oscillations was done by deliberately detuning one of the focussing solenoids and observing a decrease in the brightness of the individual beamlets.[25]

HIGH REP RATE OPERATION

The primary issue for operation at high rep rate is pulse to pulse stability. In order to hold beam energy variation to ±1% the rms timing jitter between the injector and accelerator cell waveforms must be held to about 1nsec and the voltage waveform amplitude should be reproducible to ±1%. At present in 5kHz, 50 pulse bursts the waveform amplitude of a magnetic compression modulator has been measured to have a rms deviation of 0.7%. The statistical timing jitter has an rms value 4-5nsec, which is too large. These data and many other details that are under active investigation are presented in a companion paper.[7]

DELAYED FEEDBACK CURRENT CONTROL OF BEAM ENERGY

Due to its effect on cell loading, variation of electron beam current I_b can be exploited as a way of controlling the acceleration gap voltage. Since the injector is ordinarily operated in the space charge limited regime the beam current is related to the cathode to anode voltage V_b by the Child-Langmuir relation $I_b = A\, V_b^{3/2}/d^2$ and controlling the voltage provides the means to control I_b (relativistic corrections are not important for this discussion). A practical means of doing this using high voltage vacuum tube modulators to drive special purpose induction cells of the injector has been suggested.[26] Total injector voltages are of the order of a megavolt and triode modulator voltages of interest fall in the range 25 to 100kV. Compact high current tubes of this voltage and with band widths extending to 1GHz are readily available commercially. The scheme has not yet been used in an actual accelerator. However experiments have been done to develop a prototype vacuum triode modulator regulating voltage across an induction cell.[26]

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