RECONSTRUCTION OF FXR BEAM CONDITIONS*

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Abstract:

Beam-envelope radius, envelope angle, and beam emittance can be derived from measurements of beam radius for at least three different transport conditions. We have used this technique to reconstruct exit parameters from the FXR injector and accelerator. We use a diamagnetic loop (DML) to measure the magnetic moment of the high current beam. With no assumptions about radial profile, we can derive the beam mean squire radius from the moment under certain easily met conditions. Since it is this parameter which is required for the reconstruction, it is evident that the DML is the ideal diagnostic for this technique. The simplest application of this technique requires at least three shots for a reconstruction but in reality requires averaging over many more shots because of shot to shot variation. Since DML measurements do not interfere with the beam, single shot time resolved measurements of the beam parameters appear feasible if one uses an array of at least three DMLs separated by known transport conditions.

1 INTRODUCTION

A common technique for determining accelerator beam parameters, R, R', ε, requires the measurement of the beam radius for at least three different settings of the magnetic transport separating the reconstruction point and the downstream measurement location. Here R is the envelope radius, R'= dR/dz, the envelope slope and ε is the emittance. Although in theory the beam energy could also be obtained with a fourth measurement, γ is generally obtained from a separate measurement. The data can be fitted with an envelope equation to obtain the input parameters or the latter can be found using matrix transport theory. All of this is straightforward and has been done many times. The reduction of optical images of the beam interaction with a thin foil is the common method used on induction linacs for radial measurements. The interest of this report lies in the use of diamagnetic loops (DML) to measure the beam magnetic moment from which under certain easily met conditions one can derive a time resolved measurement of the mean square radius, independent of beam profile. As the discussion below shows, this is the input parameter required for beam reconstruction using matrices. This approach has a number of advantages, the most important being that it is a non-interfering, totally electrical, measurement.

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2 DML RADIUS MEASUREMENTS

The development of the DML measurement technique has been ongoing for a number of years both by the author [1] and by workers at LANL [2-4]. When a beam transported by an axially symmetric field encounters a change in axial field strength, it experiences a radial field which induces an azimuthal current component. This current, spread over a finite cross section, produces an axial magnetic moment. The change of the flux linking a beam encircling wire loop, the DML, due to the changing magnetic moment induces the DML voltage signal. The high beam current, relatively low beam energy, guide field strength and symmetry, and equilibrium beam radius of induction linacs combine to make the time resolved measurement and interpretation of this signal feasible.

The beam magnetic moment can have three components

$$M(z) = M_r(z) + M_c(z) + M_\rho(z)\,.$$

Of these components

$$M_\rho = \frac{1}{2}\frac{\rho v_\theta}{\beta c} I_z \qquad (1)$$

(where ρ= $(\langle x\rangle^2+\langle y\rangle^2)^{1/2}$) is finite if the beam centroid intercepts the plane of the DML off axis and its velocity vector is skew to the axis. The second component

$$M_c(z) = -\frac{1}{4\pi}\left(\frac{|e|}{\gamma m\beta c}\right) < \psi(0) > I_z \qquad (2)$$

is the contribution due to the total magnetic flux linking the cathode. Thus, if the cathode field is set so that the total flux linking it is minimized and the beam is steered on center in the plane of the loop, the first component,

$$M_r(z) = \frac{k_{ce}(z)}{4}\int_0^{I_z} r^2 dI_z = \frac{1}{4}\left(\frac{|e|}{\gamma m\beta c}\right) B_z(z)\, \underline{r}^2(z) I_z \qquad (3)$$

can be made dominant if the axial magnetic field at the loop per unit electron energy is strong enough. In deriving Equation (3) the common paraxial approximations and conservation of canonical angular momentum in the axial-symmetric guide field leads to a relation between the theta current component and the axial current. Note that $\underline{r}$ is the beam rms radius and Equation (3) is independent of any assumptions about the beam radial profile or azimuthal symmetry (as long as $I \ll I_{Alfven}$).

Since values of beam current and position are needed to reduce the loop data, we have combined all of these measurements into one diagnostic package. This was possible with rather simple modifications of our standard beam current and position monitor. This "beam bug" is a resistive-foil wall-return-current monitor.[5] A ferrite torus, by increasing the inductance of the parallel circuit, forces the bulk of the beam return wall current to flow through a 5μm thick Nichrome foil cylinder whose diameter matches the beam tube and whose length is ~30 mm. Beam current and centroid position are determined from the voltage drop across the foil measured at eight azimuthally symmetric locations. A cross-linked polystyrene cylinder is located between and coaxial with the foil and the ferrite core. One or two turns of 0.018" Formvar insulated copper wire are wrapped and glued in a groove centered on the cylinder. O-rings at the cylinder ends form the vacuum seal. On the time scale of the experiment flux is conserved within the beam tube consequently a loop located at the wall would not detect a signal. The ferrite cavity behind the resistive foil allows some axial flux to penetrate the foil, return external to the loop and a signal to be generated.

In our design the loop links both the beam and the beam bug foil, consequently the signal it detects is due both to the beam and to the azimuthal currents induced in the foil by the beam. The beam moment is

$$M(t) = k[\tau_1\tau_2\frac{dV(t)}{dt} + (\tau_1+\tau_2)V(t) + \int_{-\infty} V(t')dt'] \qquad (4)$$

where $V(t)$ is the DML signal, τ_1, τ_2 are the foil and loop L/R time constants and k is the calibration constant. For calibration the beam bug was sandwiched between two lengths of stainless steel tubing which simulate the flux conserving beam tube and the loop response to a long, small diameter pulsed-solenoid of known moment, inserted along the loop axis, was measured. From simultaneous measurement of the current in the standard moment and the loop response the above relation was used to find the best values of k, τ_1, τ_2.

If the magnetic field at the DML is set to zero and the beam centroid is steered to pass through the DML center then any remaining signal will be due to a finite flux linking the cathode. This flux is that due to the injector field minus flux generated by a bucking coil. The proper setting of the bucking coil for minimum flux linkage can be determined from DML measurements.(Figure 1)

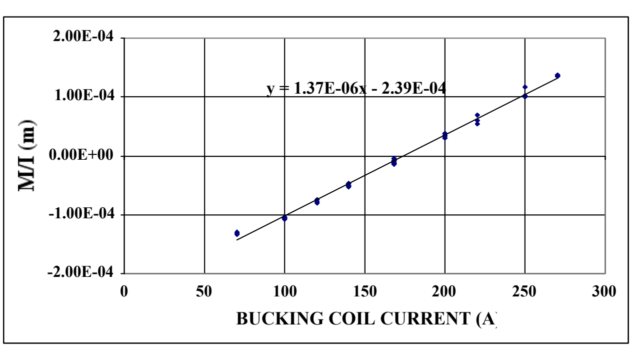

Figure 1: M_c/I_z vs. Bucking Coil Current. The DML bias field is set to zero and beam centred at DML.

Using Equation 2 we can calculate the expected value of M_c/I_z and compare with the measured values of Figure 1. We use as a model profile for the current emitted from the cathode, $J_z(r,0) = \frac{I_z}{\pi R^2(1+\nu/2)}(1+\nu\frac{r^2}{R^2})$ where ν is the shape parameter, -1≤ ν. For ν = 0, the profile is flat while if ν = -1, the profile is parabolic and for ν = 1 the profile is somewhat hollow. This distribution gives for the current weighted average of the cathode flux,

$$(\frac{M}{I})_{calc} = -\frac{1.76E07\,R(0)^2}{4(2+\nu)\gamma\beta c}[(1+\frac{2}{3}\nu)B(0,0)+(\frac{1}{3}+\frac{\nu}{4})\Delta B] \qquad (5)$$

where $R(0)$ is the cathode radius. $B(0,0)$, the field on axis at the cathode surface is known as a function of injector tune and bucking coil current, and $B(0,r) = B(0,0)(1+\Delta B(r/R(0))^2)$. For the data of Figure 1, γ=8, $R(0)$=0.054 m and ΔB= -4.5 G. In Figure 2 we plot calculated values versus measured for two values of ν.

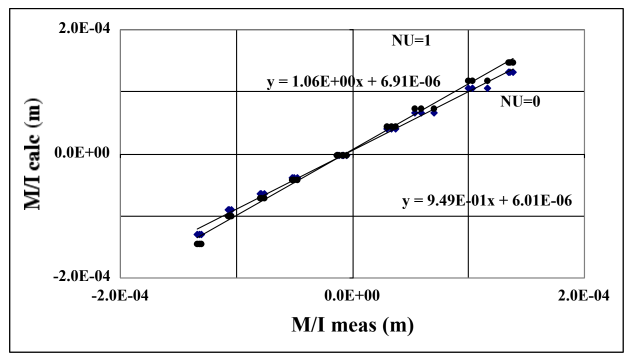

Figure 2: $(M_c/I_z)_{calc}$ vs $(M_c/I_z)_{meas}$ for the data of Figure 1 and two values of the parameter ν.

The beam profile at the cathode is expected to be somewhat hollow because of the beam potential. The good agreement between the calculated and measured values strengthens our confidence in our calibration.

A direct comparison of foil and DML measurement of beam radius at the same axial location is not feasible on FXR; the minimum separation of the two measurements is ~ 50 cm, a distance over which the radius can vary considerably. Instead one must compare the results of reconstructing the beam parameters using the two diagnostics. This test will be carried out in the near future.

3 BEAM RECONSTRUCTION

We follow a method outlined by Paul [6] for reconstructing the beam conditions. Let $\boldsymbol{\sigma_0}$ be the matrix characterizing the phase space ellipse bounding the beam at the reconstruction point. For a round beam the non-zero elements are taken to be:

$$a \equiv (\sigma_{11})_0 = (\sigma_{33})_0$$
$$b \equiv (\sigma_{12})_0 = (\sigma_{21})_0 = (\sigma_{34})_0 = (\sigma_{43})_0$$
$$c \equiv (\sigma_{22})_0 = (\sigma_{44})_0$$

The desired exit beam parameters are found from the elements of this sigma matrix.

$$R_0 = a^{1/2}$$
$$R'_0 = dR_0/dz = b/a^{1/2} \qquad (6)$$
$$\varepsilon_x = \varepsilon_y = \varepsilon = (ac-b^2)^{1/2}$$

R is the four-dimensional transformation matrix relating the sigma matrix at this point to measurement locations downstream by $\boldsymbol{\sigma} = \mathbf{R}\boldsymbol{\sigma}_0\mathbf{R}^T$. In our approach $\mathbf{R} = \mathbf{L_2FL_1}$ where $\mathbf{L_1}$ is the transfer matrix for a drift space of length L_1 between the exit and a solenoid, described by the transfer matrix **F**, and $\mathbf{L_2}$ is the transfer matrix for a drift space of length L_2 between the solenoid and the measurement location. Three values of solenoidal field with the measurement of the resultant beam radii are needed to reconstruct the beam parameters. If r_j^2 $(j=1,2,3)$ are measured values of mean square radius for three different values of **R**

$$r_j^2 = (\sigma_{11})_j = C_{j1}\, a + C_{j2}\, b + C_{j3}\, c \qquad (7)$$

where C_{j1} , C_{j2}, C_{j3} are known combinations of the elements of the transformation matrix, **R**,

$$C_{j1} = [R_{11}^2 + R_{13}^2]_j$$
$$C_{j2} = 2[R_{11}R_{12} + R_{13}R_{14}]_j \qquad (8)$$
$$C_{j3} = [R_{12}^2 + R_{14}^2]_j$$

The coefficients of Equation (7) are obtained from **R** and Equations (7) solved for *a,b,c* and R, R' and ε obtained from Equations (6).

4. APPLICATION

We have begun the use of the DML technique on the LLNL FXR induction linac. FXR has a maximum energy ~18Mev, maximum current of ~4000 A and pulse length of~80 ns fwhm. It is used for the generation of flash X-rays, consequently the minimization of the beam spot size at the beam target is very important. Beam emittance being an important contributor to spot size, we plan to use this diagnostic to aid in tuning the accelerator for minimum emittance. Initial reconstruction of FXR beam parameters at the output of the injector and accelerator are given in Table 1.

Table 1: Reconstructed beam parameter values

	γ	R (cm)	R'(mr)	ε(cm-mr)
Injector	4.7	2.5± 0.2	-64.9±8.5	47.9±8.6
Accelerator	36	0.90±0.03	-7.1±0.3	11.1±0.5

The values of Table 1 are higher than one would expect from FXR but are consistent with recent spot size measurements.

5. DML ARRAYS

The technique described above requires at least three shots to make a reconstruction. As Paul has pointed out this technique can be very sensitive to random shot to shot errors and measurement accuracy may require averaging over many shots. This is true whether foil or DML is used for the radial measurement.

Since, unlike the foil measurement, the DML does not interfere with the beam, problems arising from shot to shot reproducibility can be avoided or at least greatly diminished with the use of an array of loops taking data simultaneously. One possible loop array for this purpose would consist of a loop located at the exit of the accelerator, a drift region of length, L_1, a second loop closely followed by a solenoid of peak field, B, and length, L_s a second drift region of length, L_2 , and a third loop. For this array, the transformation matrices are:

$$\mathbf{R_1} = \mathbf{I}$$
$$\mathbf{R_2} = \mathbf{L_1} \qquad (9)$$
$$\mathbf{R_3} = \mathbf{L_2FL_1}$$

The components of these matrices will be used in Equations (8) to generate the coefficients of Equations (7) where now the input values of the mean square radii will be those measured by the three loops. By solving the Equation (7) set for *a, b* and *c* we can obtain single shot, time resolved measurements of the beam parameters. By greatly reducing the number of shots necessary for an emittance measurement the application of the DML array will make practicable the tuning of FXR for minimum emittance.

CONCLUSIONS

We have reported the first use of DMLs for reconstructing the induction linac beam rms radius, envelope slope angle and rms emittance. We have proposed a method which, relying on the non-interference of the loop measurement, should allow the use of loop arrays to make single shot beam parameter determination and bypass the problems arising from shot to shot variation. We are now preparing such an array for FXR.

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