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Validation of the flux loop diagnostic for measurement of launch package motion during electromagnetic launch

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Summary

The development of diagnostics for studying the behaviour and performance of armatures and rail accelerators is one of the subjects covered by the section EML-research of the PML-Pulse Physics Laboratory. Within that framework the development of data analysis software is in progress.
This report describes a new data reduction technique to resolve armature motion from the measurement of the voltage induced in a flux loop diagnostic and the load current through the rail-armature circuit and/or its time derivative. Velocity and position of the armature as a function of time are calculated by the computer code developed. The recent improvements in data reduction are exemplified by the results of experiments performed with a 1m, 15mm square bore dipole rail accelerator. Validation of the flux loop diagnostic, in terms of accuracy, precision, range of operation, resolution, sensitivity and prospects is carried out. Suggestions to reduce the influence of the disadvantages observed are given, too.

Samenvatting

Het onderzoek naar diagnostieken voor het bestuderen van het gedrag en de prestatie van armaturen en versnellers voor het elektromagnetisch lanceren vormt een van de taken van de sectie EML-research van het Laboratorium voor Pulsfysica. Binnen dat kader vindt ook de ontwikkeling van signaalverwerkingsprogrammatuur plaats.
Dit rapport beschrijft een nieuwe techniek voor het bewerken van experimentele data verkregen met een "flux loop" diagnostiek tot een set tijdsafhankelijke grootheden die de beweging van een armatuur weergeven tijdens het versnelproces in een railversneller. Met het ontwikkelde data bewerkingsprogramma is uit de meting van de in de "flux loop" geïnduceerde spanning en de belastingsstroom door het rail-armatuur circuit en/of haar tijdsafgeleide de snelheid en positie van het armatuur als funktie van de tijd te bepalen. De recente verbeteringen in de methode van data bewerking worden verduidelijkt aan de hand van de resultaten van een aantal experimenten met een 1m railversneller.
De uitgevoerde evaluatie van de bruikbaarheid van de "flux loop" diagnostiek voor EML-research leidt tot inzicht in de mogelijkheden en beperkingen van deze diagnostiek voor wat betreft nauwkeurigheid, werkingsgebied, oplossend vermogen, gevoeligheid en verwachtingen voor de toekomst. Het rapport geeft tevens suggesties om geconstateerde nadelen te verminderen.

CONTENTS

1 INTRODUCTION

Launch package velocity is an important parameter in the assessment of the performance of the electromagnetic rail accelerator and the armature used. To calculate quantities like kinetic energy and efficiency during launch and to resolve the current density from B-dot signals by deconvolution methods, accurate velocity-time or velocity-position data are necessary. In addition, the net force balance on the armature during acceleration can only be established when the complete velocity history of the projectile is accurately known. Experimental data on the (time) evolution of the acting Lorentz force and the static and kinetic force of friction will increase insight into the physical processes that take place at the rail-armature interface. Such experimental data is also very valuable for the verification of the theoretical results of predictive computer codes.

Accurate velocity diagnostics are therefore essential for furthering EML-research.

Among the several techniques used in this field, most are discrete determinations. Average values for velocity can be obtained easily using the position-time points measured with e.g. B-dot probes and light screens.

A better approach is to use a flux loop, which provides continuous information on the in-bore launch package motion. Being a "sensor" that is based on the inductive principle, it suffers from some intrinsic difficulties in the harsh environment that is dominated by large, fast changing currents.

Two other techniques can be used to study the in-bore motion of the launch package: velocity interferometry and Doppler radar. Both have their limitations and are therefore not often applied in EML-research. The former has shown promising experimental results, the latter is not used at the Pulse Physics Laboratory.

This report highlights the application of the flux loop as a velocity diagnostic. To increase its usefulness for the rail accelerator experiments performed, the technique is examined extensively. As a result, a data reduction routine was written to improve the results obtained earlier and to reduce the time needed to analyse the flux loop data.

2 THEORY FLUX LOOP DIAGNOSTIC

A flux loop diagnostic [1] is a very simple, but elegant diagnostic to determine armature motion inside electromagnetic rail accelerators. Figure 1 shows the operating principle.

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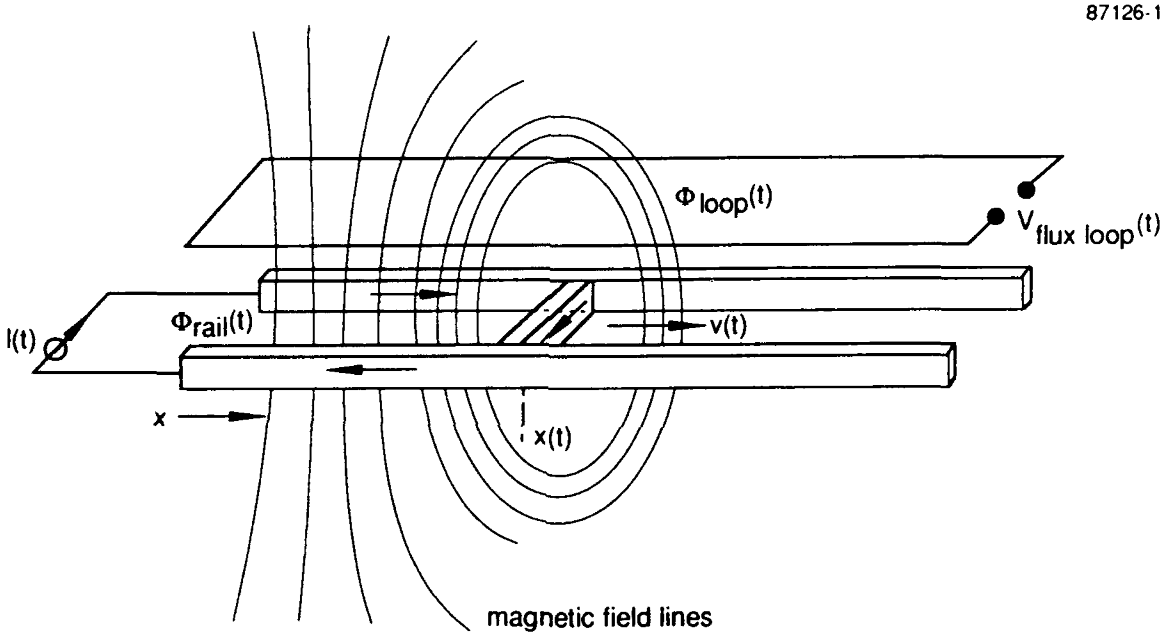

Figure 1 Operating principle of a flux loop diagnostic.

Magnetic flux created by the current through the rail-armature circuit is linked to the wire loop in close proximity to this circuit. The part of the flux that is linked is given by the constant ratio k, the coupling factor between both loops:

$$k = \frac{\Phi_{loop}}{\Phi_{rail}} \tag{1}$$

The flux created by the rails-armature circuit is the product of the current I through the circuit and the inductance L of the circuit:

$$\Phi_{rail}(t) = L(x) \cdot I(t) \tag{2}$$

The voltage that is induced in the wire loop, i.e. the electromotive force, is given by:

$$V_{ind}(t) = -\frac{d\Phi_{loop}}{dt} = -k \, . \frac{d\Phi_{rail}}{dt} = -k \, . \frac{d(L.\,I)}{dt} = -k \, . \, L \, . \frac{\partial I}{\partial t} - k \, . \frac{\partial L}{\partial t} \, . \, I(t)$$

$$= -k \, . \, L' \, . \, x(t) \, . \frac{\partial I}{\partial t} - k \, . \frac{\partial L}{\partial x} \, . \frac{\partial x}{\partial t} \, . \, I(t) = -k \, . L' \, . \, x(t) \, . \frac{\partial I}{\partial t} - k \, . \, L' \, . \, v(t) \, . \, I(t) \qquad (3)$$

V_{ind} is regarded as the open loop voltage. It is assumed that the flux loop diagnostic is not charged by the measurement equipment and therefore the current in the wire loop can be ignored.
Rewriting equation (3) results in a first order differential equation for x, the momentary position of the armature inside the rail accelerator:

$$\frac{\partial x}{\partial t} = \frac{-V_{ind}(t) - k \, . \, L' \, . \, x(t) \, . \frac{\partial I}{\partial t}}{k \, . \, L' \, . \, I(t)} \qquad (4)$$

Therefore the first derivative of position, i.e. velocity, can be obtained if all other quantities in eq. (4) are known as a function of time. Since k and L' are fixed parameters - the former being dependent on the orientation of the flux loop with respect to the rail-armature circuit, the latter being an intrinsic rail accelerator parameter - and both constants can be measured independently using the methods described in [2], the only variables that must be measured during the acceleration process are the voltage induced in the flux loop diagnostic and the load current I(t) and/or its derivative $\frac{\partial I}{\partial t}$

3 FLUX LOOP DATA REDUCTION ROUTINE

The first results of the flux loop diagnostic at the Pulse Physics Laboratory were reported in [2,3,4], where reduction of the flux loop data was performed using a fit to the discrete time-position points obtained with B-dot probes. The results are of ample accuracy, especially in the stage of the acceleration process where the load current is constant.
Another approach is used in [5,6,7], where after the installation of a velocity interferometer, VISAR [8,10], the integrated velocity history, obtained with this instrument, is used as position data to obtain the velocity from the flux loop data. The motivation for also applying a flux loop diagnostic in the same experiment lies in the fact that plasma blowby may occur that can obscure the projectile, disturbing the VISAR measurement. A flux loop diagnostic might give better results in these cases.

Since a flux loop diagnostic is in fact a stand-alone diagnostic it will be treated as such in the remainder of this report. To resolve the armature motion from the measurement of the load current and the voltage induced in the flux loop without the à priori knowledge of armature position data x(t) as in the former approaches, the first order differential equation in x, equation (3), is solved using a fourth order Runge-Kutta method. A data reduction routine for the Pulse Physics HP-computer has been written in the C-language to perform this task.
The following functional requirements are met by the implementation of the program.
Before running the routine, the load current and flux loop data measured must be processed to obtain the proper input signals. All signals can be corrected for offset. Depending on the input signals used to calculate the armature velocity and position, the measured load current is differentiated numerically by applying a centre-type differentiation or the measured $\frac{\partial I}{\partial t}$ is integrated numerically using Simpson's rule. After differentiation, the data are smoothed using a non-causal filtering technique. A single running median of a fixed number of points (adaptable) is therefore computed.
A crucial point in the reduction of the data is the actual time-zero (t_{start}) for the analysis. Flux coupled into the wire loop before the armature starts moving, gives rise to an induction voltage and would result erroneously in the false detection of armature motion unless this voltage is compensated by the changing load current (measured $\frac{\partial I}{\partial t}$). If this compensation is, for some reason, less successful, it is important to have the time-zero as close as possible to the actual start of the armature motion.
When solving for eq. (3), the boundary values are taken to be the initial position and velocity of the armature. By choosing an appropriate t_{start}, the program sets the following variables:

$x(t_{start})$ $= x_0$ (initial position armature)

$v(t_{start})$ $= v_0$ (initial velocity armature)

Since the armature is accelerated from stand-still (chapter 5), the initial velocity is set to zero. The initial armature position is usually 30 mm.

The accuracy of the flux loop diagnostic is estimated from the following simple error analysis. The error $\Delta v(t)$ at some fixed time t is assumed to be given by:

$$\Delta^2 v(t) = \Sigma_i \left(\frac{\partial v(t)}{\partial s_i(t)}\right)^2 \Delta^2 s_i(t) \tag{5}$$

where $s_i(t)$ is the signal measured at time t and $\Delta s_i(t)$ is the associated (measurement) error. The accuracy of the instrument to measure signal $s_i(t)$ is defined as $\Delta s_i(t)/s_i(t)$. Then, the maximum error in the position x at time t is calculated as:

$$\Delta x(t) = \int_{t_o}^{t} \Delta v(t) \,.\, dt \quad (x) \tag{6}$$

Eq. (6) presents the worst case situation because $\Delta v(t)$ is defined as a positive value.

Rewriting eq. (4) gives:

$$v(t) = -\frac{V_{ind}(t)}{k \,.\, L' \,.\, I(t)} - \frac{x(t)}{I(t)} \frac{\partial I}{\partial t} \tag{7}$$

By substituting eq. (7) in eq. (5) the complete formula for the error in the calculated velocity is found:

$$\Delta^2 v(t) = \left(\frac{1}{k \cdot L' \cdot I(t)}\right)^2 \Delta^2 V_{ind}(t) + \left(\frac{V_{ind}}{k \cdot L' . I(t)}\right)^2 \Delta^2 k + \left(\frac{V_{ind}}{k \cdot L' \cdot I(t)}\right)^2 \left(\frac{\Delta L'}{L'}\right)^2 +$$

$$\left(\frac{V_{ind}}{k \cdot L' \cdot I(t)}\right)^2 \left(\frac{\Delta I(t)}{I(t)}\right)^2 + \left(\frac{\frac{\partial I}{\partial t}}{I(t)}\right)^2 \Delta^2 x(t) + \left(\frac{x}{I(t)}\right)^2 \Delta^2 \frac{\partial I}{\partial t} + \left(\frac{x \cdot \frac{\partial I}{\partial t}}{I(t)}\right)^2 \left(\frac{\Delta I(t)}{I(t)}\right)^2 \qquad (8)$$

Both errors are coupled via the flux loop differential equation as can be seen from eq.(7) and eq. (8). Because of its cumulative nature, the increase of the error in x strongly affects the accuracy of the determination of velocity. For large x the error in v is also very sensitive to a large $\frac{\partial I}{\partial t}$.
The error caused by digitizing the data is much smaller than the error that results from the accuracy of the diagnostic. The resolution of the recording equipment is 12 bit, which leads to an digitizing error of less than 0.03%, and can therefore be ignored.

Implementation of the functional requirements outlined in this chapter is described below.

4 DESCRIPTION OF THE COMPUTER PROGRAM

The flux loop data reduction routine is executed by typing "fldrr". First there will appear a question for an experiment number on the screen. Then the following input files are loaded:

measurement type	format
flux loop voltage	<Experiment number>.fl
load current	<Experiment number>.lc
$\frac{\partial I}{\partial t}$	<Experiment number>.di

Whether or not all data files are used in the analysis depends on the operator's choices. The following data reduction schemes are possible:

option 1 : data reduction using measured I and $\frac{\partial I}{\partial t}$

option 2 : data reduction using measured I and numerically differentiated $\frac{\partial I}{\partial t}$

option 3 : data reduction using measured $\frac{\partial I}{\partial t}$ and numerically integrated I

Depending on the option chosen, the flux loop voltage and the load current or its time derivative are plotted. The values of fixed parameters such as sampling rate, rail accelerator inductance gradient L' and the coupling factor k are plotted in the upper left corner.

Examining eq. (3) shows that for positive velocity and position and for an increasing current ($\frac{\partial I}{\partial t} > 0$) the sign of the voltage induced in the flux loop must be negative. Therefore the program asks whether or not the flux loop and $\frac{\partial I}{\partial t}$ signals should be inverted accordingly.

A correction procedure for offset is included in the program as an option. By using the cursor the range is selected over which the offset is calculated and the flux loop signal is corrected accordingly. The same procedure is followed for the load current, except that the range is at the end of the record.

Next, the flux loop voltage and $\frac{\partial I}{\partial t}$ signals are replotted and a cursor appears in the graph again. By moving the cursor with the mouse to the correct position and by clicking the left button at the appropriate time, the time is selected where the program starts analyzing the data. As a result a plot of the velocity and position of the armature inside the accelerator appears on the screen as a function of time. The selected time t_{start} is printed in the upper left corner of the screen. By choice, it is possible to show graphs of the error estimates in both velocity and position as a function of time superimposed on the velocity/position plot (expanded by a factor 10). A further option is the possibility to plot the armature velocity as function of its position inside the rail accelerator as calculated by the routine.

The program is quitted by clicking the right button.

5 RESULTS

Several experiments have been carried out with the 1m dipole rail accelerator [4,5,6], in which velocity was measured using the flux loop diagnostic. In these experiments launch packages with solid brush armatures, weighing 25 to 45 grams, were accelerated to about 700 m/s at current levels of 250 to 300 kA. In a number of experiments the transition of the armature to an anticipated hybrid form did not occur during the acceleration process. In those experiments in which a transition did occur the data reduction is more complicated. Since it involves the à priori knowledge of the current density profile $J(\eta,t)$ in the armature as a function of time, treatment is beyond the scope of this report. Nevertheless, the analysis up to the moment of transition is exactly the same as for a transition-less acceleration.

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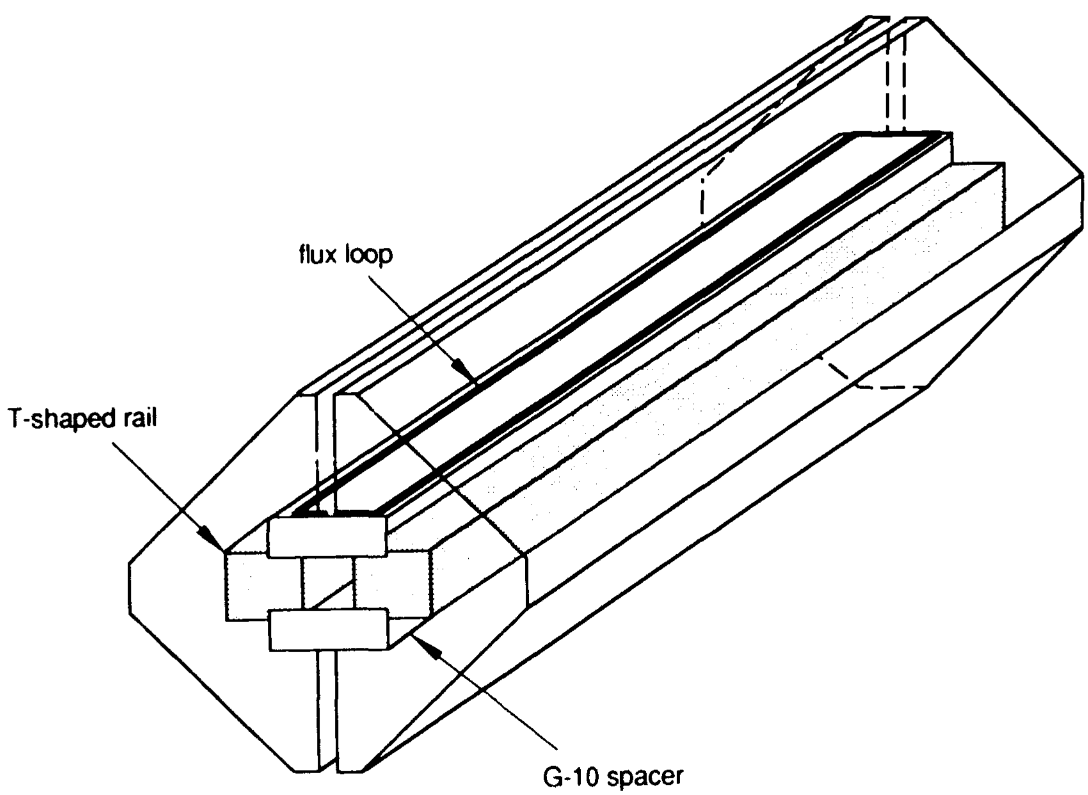

Figure 2 Flux loop diagnostic, incorporated in one of the G10 spacers that hold the T-shaped copper rails of the 1m dipole rail accelerator apart. Only the inner structure of the 1m rail accelerator is shown.

The flux loop diagnostic was incorporated in the accelerator structure as shown in figure 2. The value of the coupling factor k (0.46 ± 5%) and the rail accelerator inductance gradient (0.37 μH/m ± 5%) were obtained experimentally using the methods described in [2]. Usually the flux loop voltage is measured using a 1:100 ratio Pearson coil transducer with a 3MHz bandwidth and an estimated overall accuracy of 1%. Rogowski coils are used to measure the time rate of change of current, $\frac{\partial I}{\partial t}$. The load current is obtained by integrating electronically the output of a Rogowski coil. The accuracy of the Rogowski coils amounts to 5%.

Figure 3 shows a representative example of the load current for a 1m rail accelerator experiment. Figures 4 and 5 show the derivative of the load current as calculated by the routine and the flux loop signal measured. At the rising edge of the load current a small rise in the voltage induced (V_{ind}) is measured across the flux loop terminals that can be ascribed to the large time rate of change of the current. When the current falls, the strong coupling between the current carrying circuit and the flux loop diagnostic results in a large signal. The flux loop signal shows an almost linear decrease, proportional to the increase in flux linked by the wire loop, in the time domain of constant current, which indicates an almost constant acceleration of the armature.

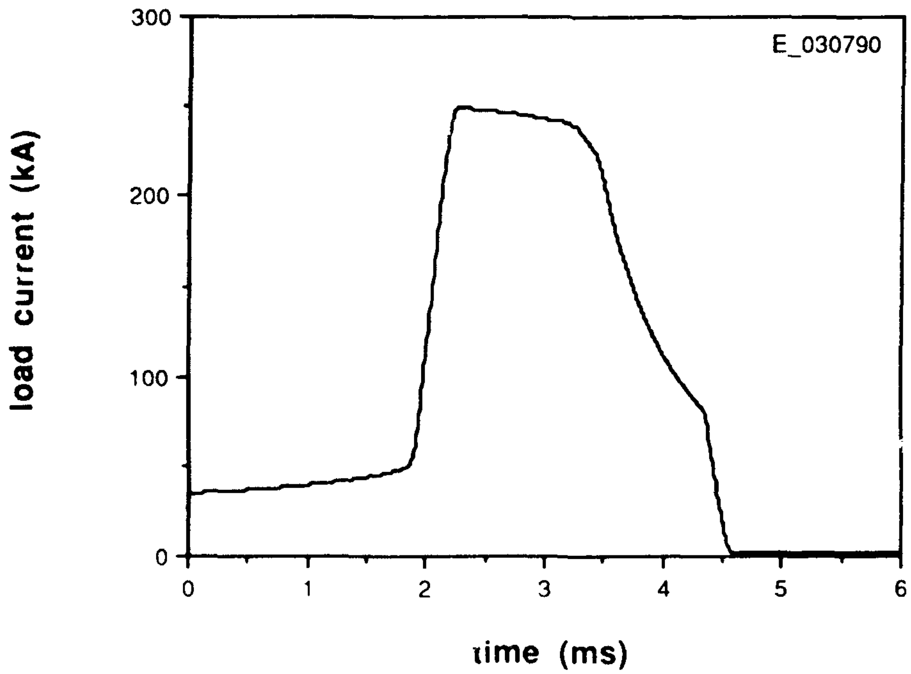

Figure 3 Load current profile during a 1m dipole rail accelerator experiment.

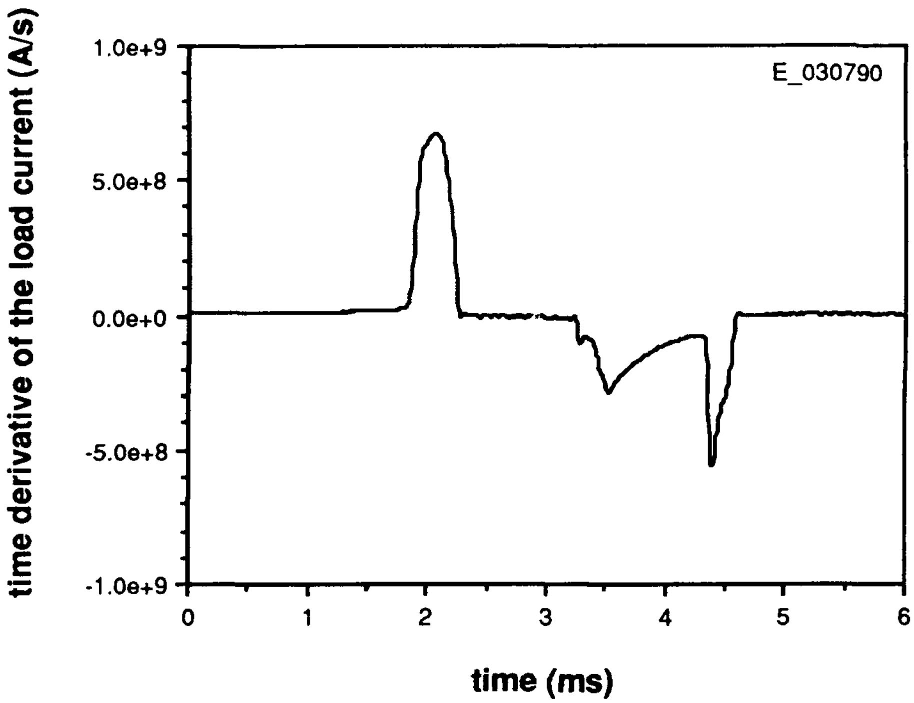

Figure 4 Derivative of the load current during a 1m dipole rail accelerator experiment.

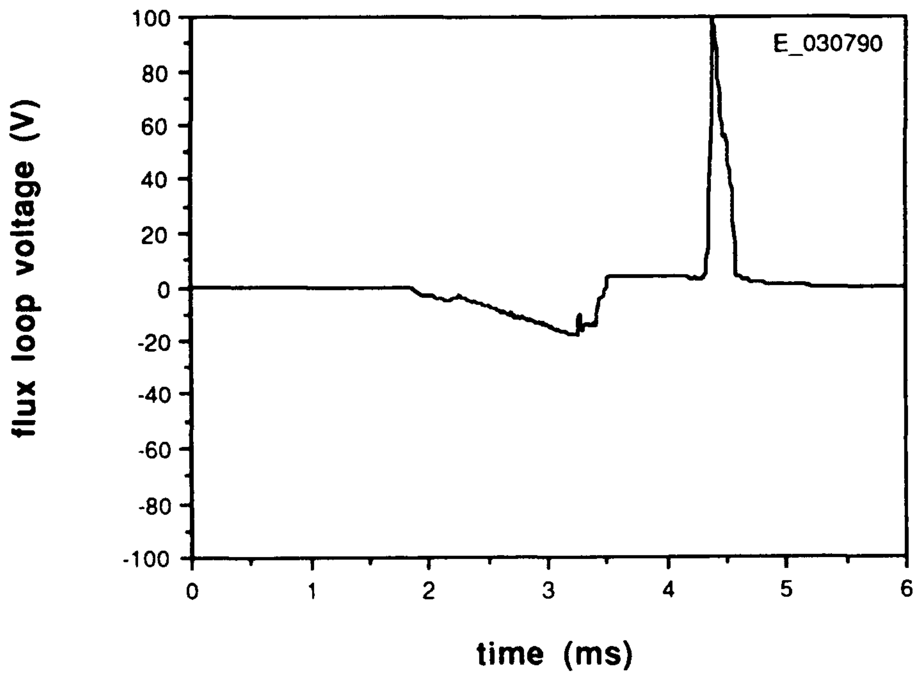

Figure 5 Flux loop signal during a 1m dipole rail accelerator experiment.

Using the signals in figure 3 through 5 as input data, and setting the time-zero to an appropriate value, the results of the flux loop data reduction routine for armature velocity and position are shown in figure 6 and 7, respectively. The velocity profile shows less accurate results in the early and final stage of the acceleration process. The armature velocity is clearly overestimated in the early and underestimated in the final stage compared to the velocity-time points obtained with the B-dot probes. The plot of the armature position as a function of time shows that the results obtained with the flux loop diagnostic and data reduction technique are in good agreement with the results obtained with the B-dot probes. The armature current type B-dot probes are assumed to give accurate time position marks. The zero-crossing of the B-dot signal indicates the moment of passage of the "centre of mass" of the armature current.

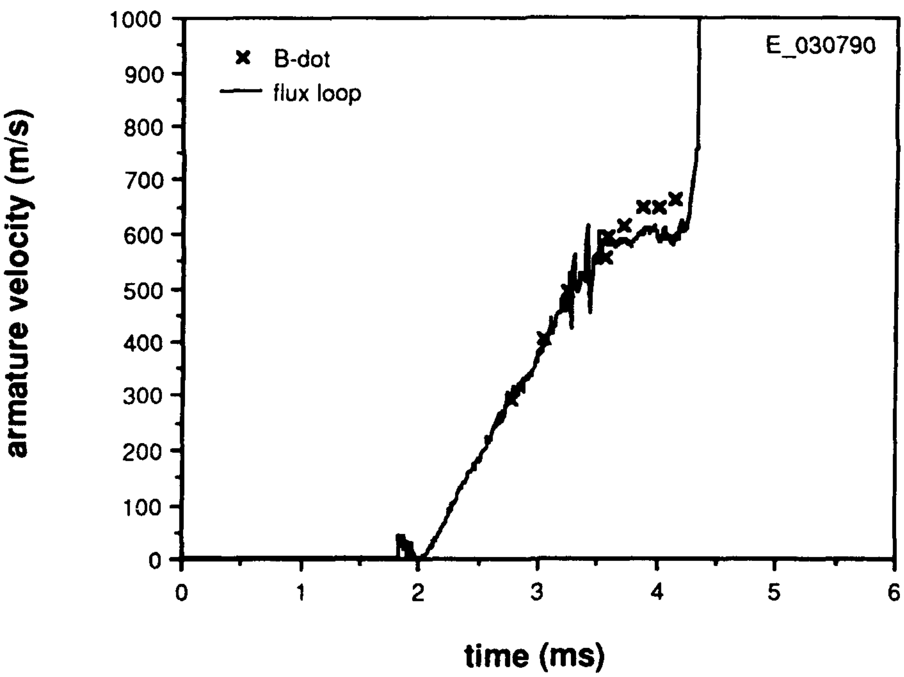

Figure 6 Velocity as a function of time obtained by applying the flux loop data reduction routine. The data are compared with average velocities determined from B-dot probe signals.

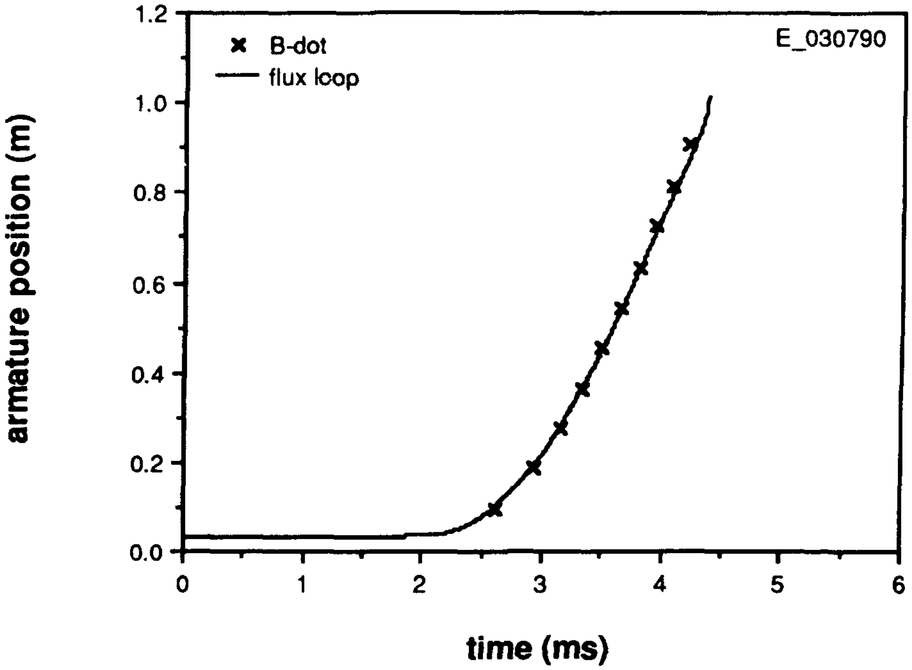

Figure 7 Armature position as a function of time obtained by applying the flux loop data reduction routine together with the position-time points obtained from B-dot probe signals.

The accuracy obtained for the determination of armature motion, as calculated from eq. (8) for velocity and eq. (7) for armature position, are plotted in figure 8 and figure 9. Three accuracy regimes can be discerned: one at the rising edge of the load current with the armature close to the breech, a second, intermediate regime with nearly constant load current and a third at the falling edge of the load current with the armature close to the muzzle, where the sensitivity of the flux loop diagnostic to a changing magnetic field is largest.

Additional smoothing of the velocity data and taking the time derivative, results in an acceleration plot (figure 10). The value for the acceleration at constant current is in good agreement with the value calculated from the acting Lorentz force. The large oscillations at the initial and final stage of the acceleration process are believed to be artificial.

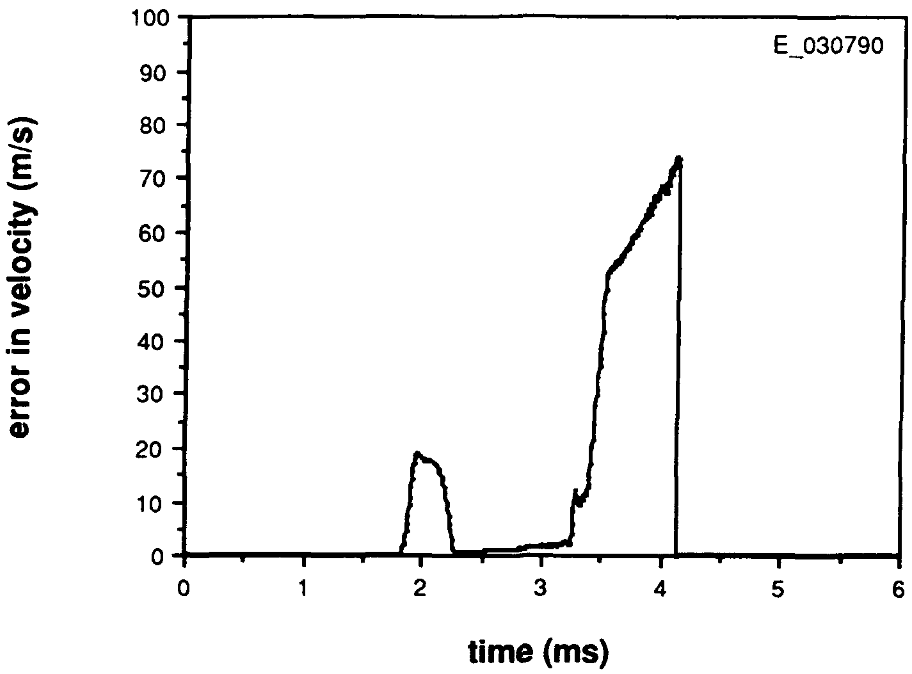

Figure 8 Estimated error in the calculated velocity for the experiment shown in figure 6.

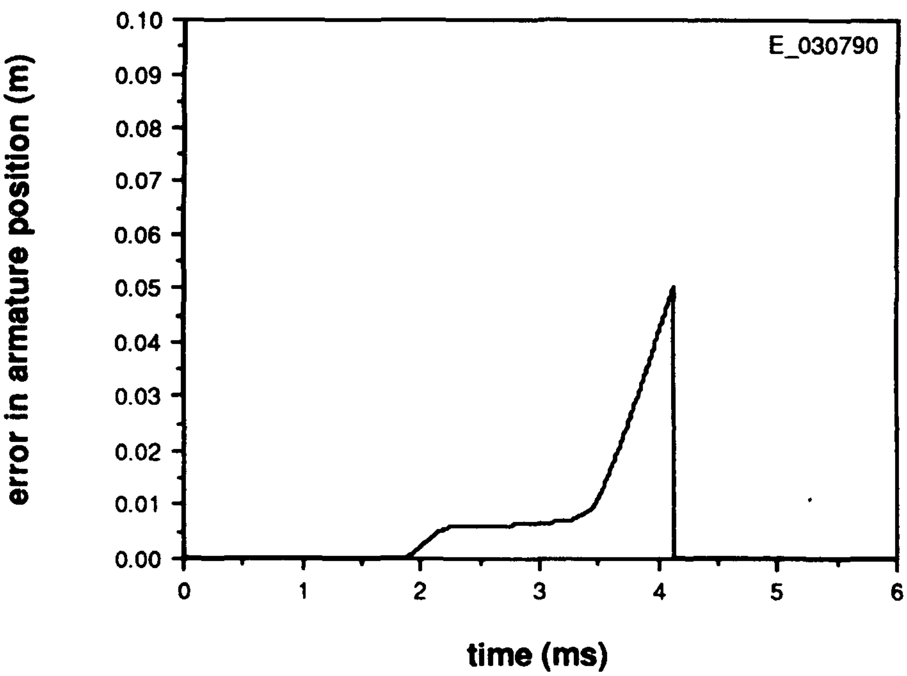

Figure 9 Estimated error in the armature position for the experiment shown in figure 7.

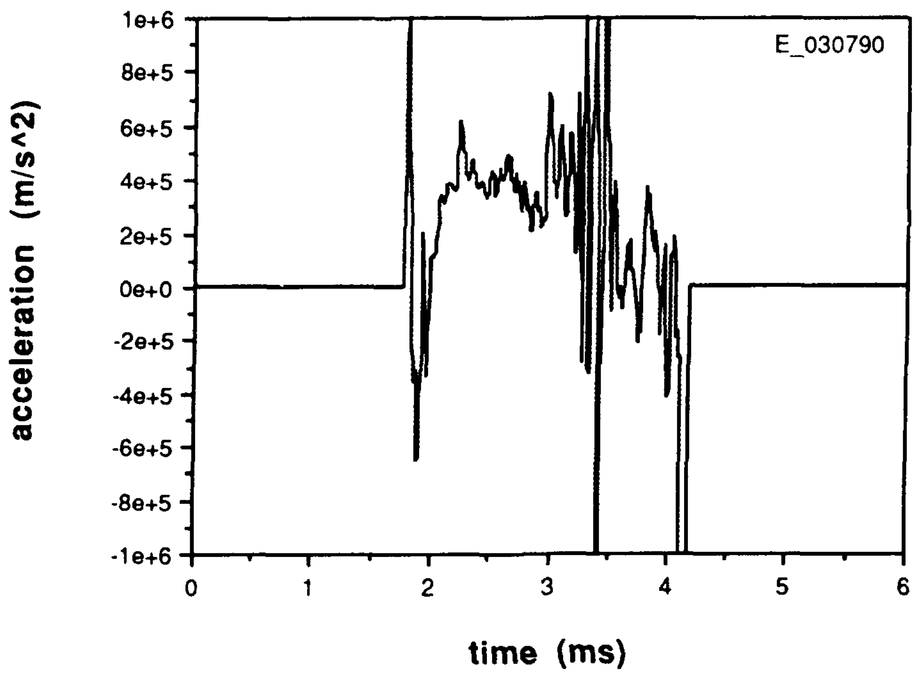

Figure 10 Acceleration obtained by differentiation of the velocity trace in figure 6.

Figures 3 through 10 show the results of an experiment in which nearly the full in-bore travel of the armature could be determined by application of a flux loop diagnostic and data reduction routine. Usually slightly less accurate results are obtained for 1m rail accelerator experiments. An example is given in figures 11 and 12, the former showing the load current and the latter showing a overlay plot of its time derivative and the flux loop signal. The dashed line indicates the start of the analyses. Results can be drastically incorrect if the time zero is not set properly.

Figure 13 displays the velocity as obtained with the flux loop data reduction routine. The result is compared with discrete velocity points obtained with B-dot probes and the velocity profile measured with the VISAR, which is assumed to be the more accurate diagnostic [8,10]. The velocity trace obtained with the flux loop deviates severely from the VISAR measurement in the early and final stages of the acceleration process. Figure 14 shows the position of the armature inside the rail accelerator as a function of time as obtained with the diagnostics applied. The horizontal dashed line indicates the muzzle end of the accelerator. Position and velocity data beyond this point have no meaning. Results of the position-time data calculated from the results of the flux loop diagnostic and data reduction routine are adequate, except for the final stage of the acceleration process.

A quantitative measure for the accuracy obtained in this particular experiment is shown in figure 15, where the error in both velocity and position is plotted as a function of time.

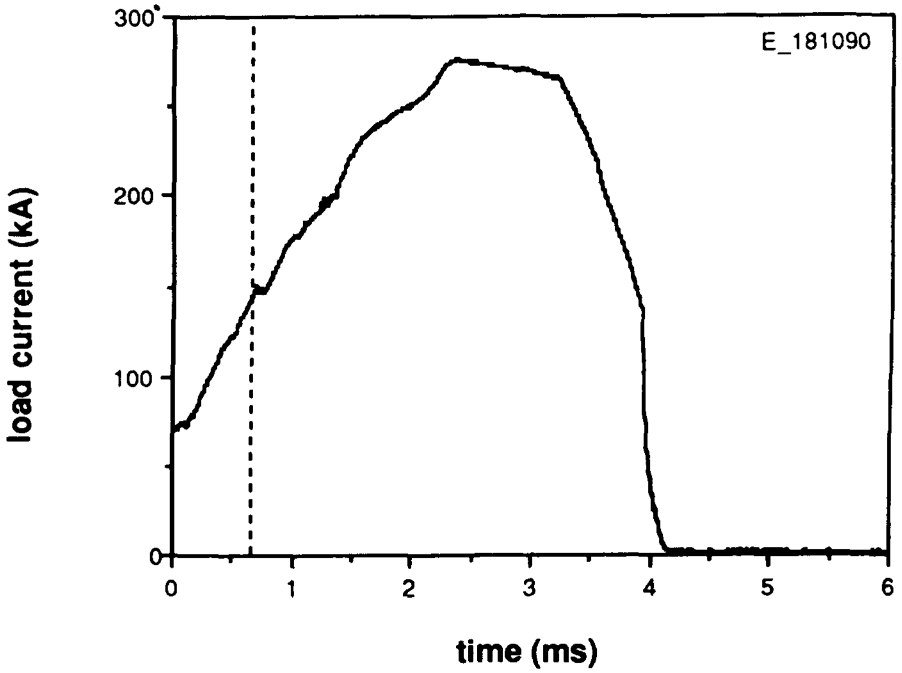

Figure 11 Load current during 1m rail accelerator experiment. The dashed line indicates the start of the analysis performed with the flux loop data reduction routine.

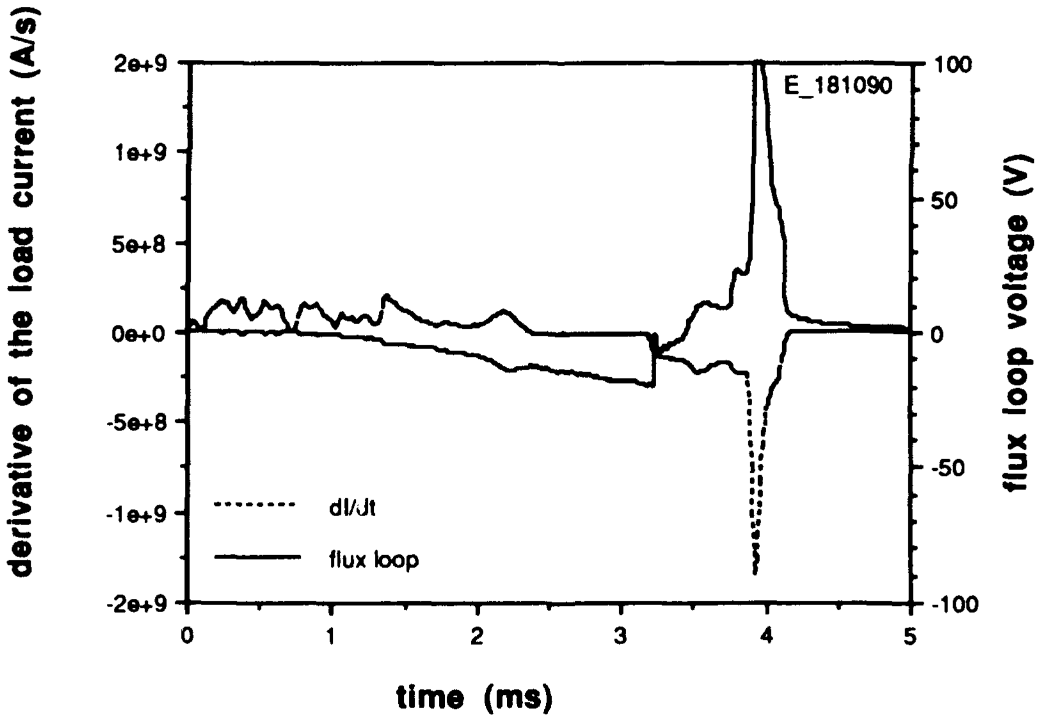

Figure 12 Derivative of the load current and flux loop voltage during the experiment shown in figure 11.

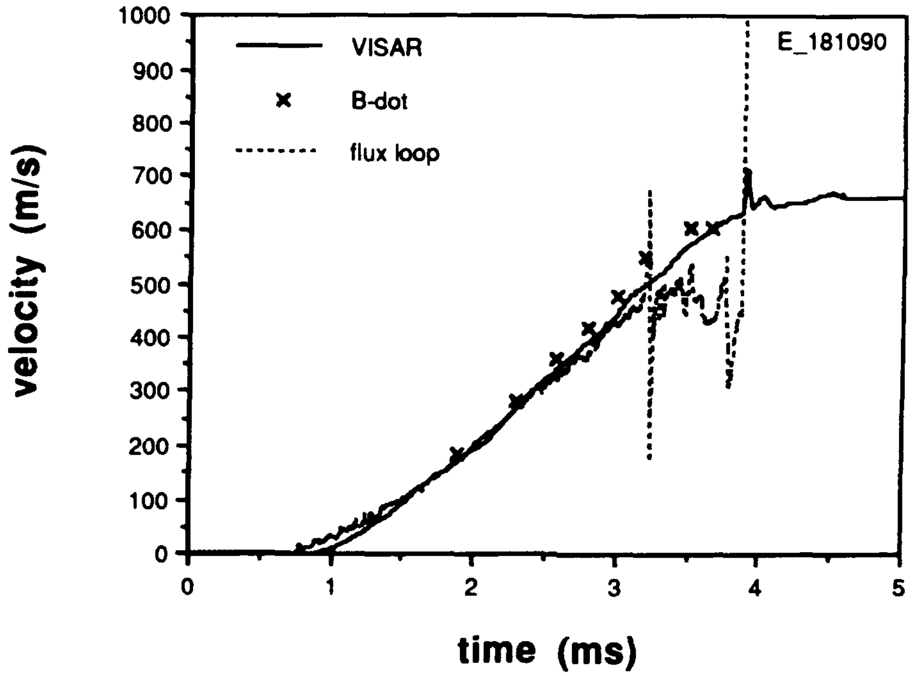

Figure 13 Armature velocity as a function of time as obtained with the flux loop diagnostic.

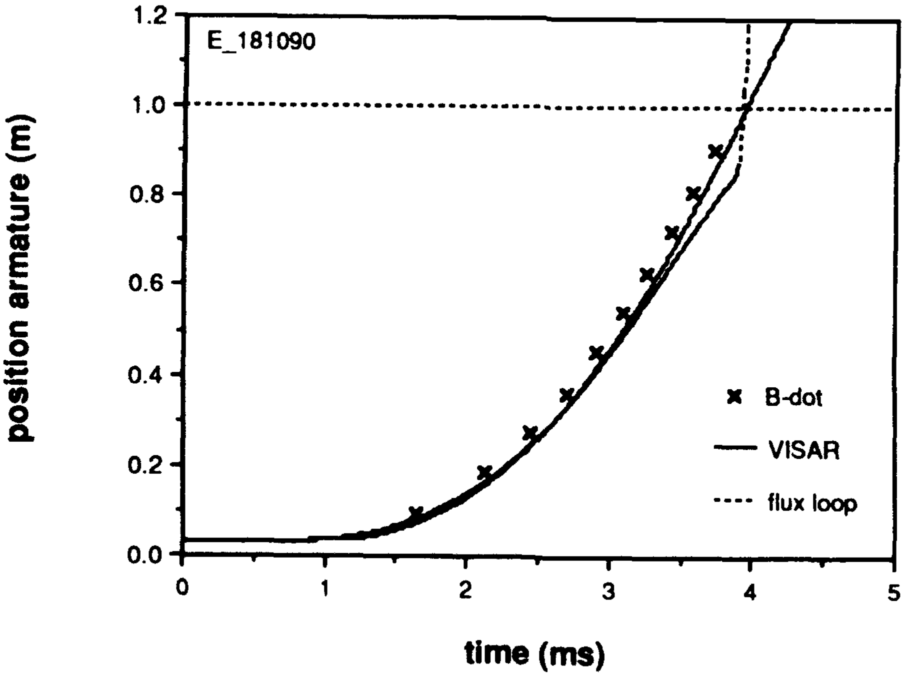

Figure 14 Position of the armature as a function of time.

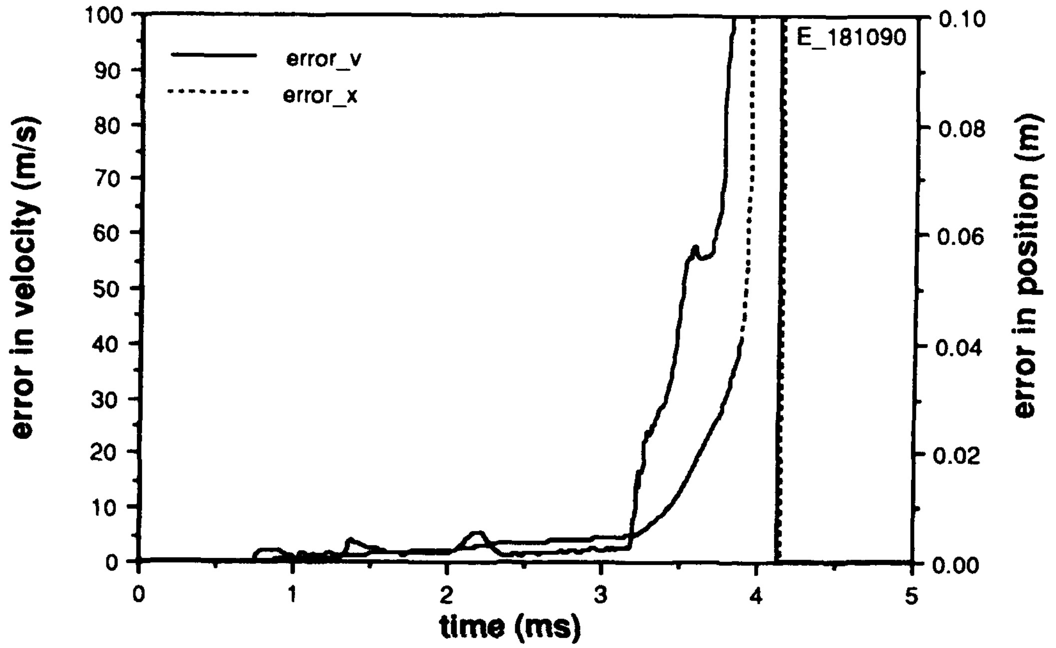

Figure 15 Plot of the associated errors in velocity and position for the experimental data used in figures 11 through 14.

6 DISCUSSION

This report shows the best results obtained thus far with a flux loop diagnostic at PML-Pulse Physics. As was outlined in chapter 5, the diagnostic suffers from some intrinsic difficulties. Being an inductive diagnostic it is sensitive to changes in flux through its sensitive area A:

$$V_{ind}(t) = -\frac{d\Phi_{loop}}{dt} = -k \cdot \frac{d\Phi_{rail}}{dt} = -k \cdot \frac{d(B.A)}{dt} = -k \cdot B \cdot \frac{\partial A}{\partial t} - k \cdot A \cdot \frac{\partial B}{\partial t} \tag{9}$$

where A is the area spanned by the current carrying circuit and B is the magnetic induction generated. First term of the right hand side of eq. (9) is the velocity dependent term of interest. The second term is the disturbance caused by the changing load current. The contribution of the second term has more significance at the time the load current is switched off, since the area A is much larger at the end of the acceleration process, when the armature is near the muzzle, than when it is at the breech. Moreover, the time rate of change of area A is much smaller than the time rate of change of magnetic induction B. Consequently, a plausible explanation for the fact that the results at the time the current is switched off are incorrect, might be that the second term of eq. (9) is not compensated by the measured $\frac{\partial I}{\partial t}$, i.e. the change in flux due to the increase in area A is much smaller than the change in flux due to the second term.

It is suggested that using a flopped flux loop [11], consisting of a number of small area cells with alternating (opposite) normal vectors, will compensate for the $\frac{\partial I}{\partial t}$ contribution in the neighbouring cells by averaging the contributions to the voltage induced of the cells passed by the armature, thus reducing the second term of eq.(9). Analysis of the signals, obtained with such an "advanced" flux loop, which includes solving eq.(3) for successive cells, will be treated in a separate report.

The reason why compensation for the $\frac{\partial I}{\partial t}$ term is not complete in the early stage of the acceleration process, despite of what one would expect from eq. (3), might also be caused by the fact that part of the flux is linked to the wire loop in front of the armature, where its relative contribution to the total flux linked to the loop, is largest. This component of the flux is constant during that part of acceleration where the current is constant, and gives therefore no changes in the voltage induced in the wire loop unless the end of the wire loop is reached and where this part of the flux is "pushed" out of the wire loop area A. Considering the rapid decrease of the magnetic induction B in front of the armature this effect would be expected to be insignificant up to a few centimetres before the end of the wire loop is reached.

Another effect that might not be insignificant is a change in the coupling factor k during the launch experiment, fo· which k was assumed to be constant up to now. Skin effects in the rail will cause this factor to be velocity and $\frac{\partial I}{\partial t}$ dependent. The skin depth, which is a measure for the diffusion of the magnetic field into the rails and depends on material properties and on the time since the current began to flow through a particular segment of the rails (diffusion) and on armature velocity (velocity skin effect), has a constant value when the current through the rails is constant and the armature is at stand-still [9]. When the current is commutating into the load, i.e. rails and armature, the skin depth decreases due to the increasing load current and, when the armature starts accelerating, due to the increasing velocity. In the case of the velocities obtained in the experiments described in the previous chapter it remains approximately constant up till the current is switched off [9]. The skin depth will increase again because of the large negative time-rate of change in the load current at the end of the current pulse. As a result, the coupling factor k will be a function of time during a launch experiment. The dependence of the coupling factor on the skin depth is complex and the effect on the flux loop data reduction is hard to predict. According to eq. (1) the coupling factor is defined as the ratio of flux through the rail and flux through the wire loop. The flux through the rails is proportional to the current through the circuit and its inductance, which depends on armature position and skin depth. Therefore a change in skin depth in the rails will alter the flux through the wire loop, since it changes the area A and causes a different flow of the field lines.

Effort will be undertaken to determine a $\frac{\partial I}{\partial t}$ dependent k-factor. This can be done by measuring the voltage induced in the flux loop during an experiment in which the rails are shorted at the muzzle when the current is commutated into the accelerator. When the results are successful, the so obtained $\frac{\partial I}{\partial t}$ dependent coupling factor will be incorporated in the flux loop data reduction program.

As shown in figure 16 the accuracy of the flux loop diagnostic is limited. Even in the case of perfect compensation, the two terms in eq. (9) give rise to uncertainties in the results, since two large numbers, both possessing a measurement error, are subtracted.

By using a flux loop diagnostic, accurate determination of velocity in an early stage of the acceleration process will never be possible. Muzzle velocities can at best be estimated within a 10% range. Better results can be obtained for the determination of armature position, but they must be treated with care since absolute measurements will deviate more while relative measurements seem to be better.

The usefulness of the acceleration data obtained with the flux loop data reduction routine is limited to the determination of average values. Incorrect fluctuations in the velocity data result in large erroneous fluctuations in the acceleration profile.

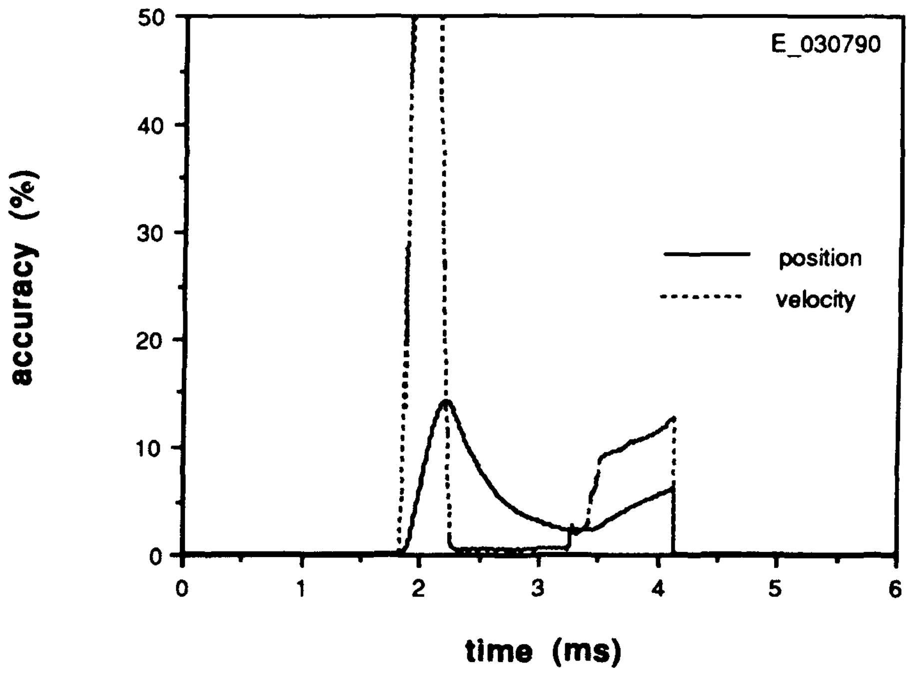

Figure 16 Accuracy of the velocity and position determination with the flux loop diagnostic.

7 CONCLUSIONS

The flux loop data reduction routine developed analyzes the measured data of the voltage induced in a flux loop as a stand alone diagnostic. Only one other set of data is required for the analysis. This can be either the load current or its time derivative as a function of time.
Results obtained for armature motion have been much improved by application of the routine compared to those obtained by the data reduction methods used before. Intrinsic difficulties of the flux loop diagnostic prevent the possibility to determine the full in-bore motion of the armature. Lack of signal amplitude in the initial stage and large changes in flux in the final stage of the acceleration process limit its range of operation to the intermediate region where the $\frac{\partial I}{\partial t}$ signal is small. A future diagnostic, the so called "advanced" or flopped flux loop, is suggested as a possible remedy to increase the range of operation.
The accuracy of the flux loop diagnostic is limited. In addition to the intrinsic difficulties the error analysis in chapter 5 explains quantitatively the poor results for the determination of velocity in the initial and final stage. The velocity resolution in the intermediate region is estimated from the accuracy of the individual recording instruments and transducers and amounts to about 1%.

The results of the flux loop diagnostic are less accurate than VISAR measurements but better than the average velocity values obtained with B-dots. The value of the flux loop diagnostic for EML-research is somewhat underestimated, since its simplicity makes it a good additional diagnostic for detecting armature motion and can be useful as an alternative diagnostic in those cases where plasma blow-by prevents the application of the more accurate VISAR.
The large amount of noise in measurements with the flux loop diagnostic do not justify the determination of armature acceleration, except for rough estimates.
The computer routine to solve the flux loop differential equation is implemented as an independent module of the Pulse Physics EML-research data analysis software.

8 AUTHENTICATION

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10 LIST OF SYMBOLS

A	area spanned by the rail armature circuit	[m^2]
B	magnetic induction	[T]
I	load current	[A]
L'	rail accelerator inductance per unit length	[H/m]
k	coupling factor between flux loop and rail armature circuit	[-]
v	velocity	[m/s]
v_0	initial velocity of the armature	[m/s]
x	position of the armature along the accelerator bore	[m]
x_0	initial position of the armature	[m]
t_{start}	time of start for analyzing flux loop data	[s]
t	time	[s]
Φ	magnetic flux	[Wb = V.s]
J	current density in the armature	[A/m]
η	internal dimension in the armature in the direction of accelerator axis	[m]

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Validation of the flux loop diagnostic for measurement of launch package motion during electromagnetic launch.
(Evaluatie van de "flux-loop" diagnostiek voor het meten van de beweging van het armatuur tijdens electromagnetische lancering.)

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14. SUPPLEMENTARY NOTES

15. ABSTRACT (MAXIMUM 200 WORDS (1044 BYTE))

The development of diagnostics for studying the behaviour and performance of armatures and rail accelerators is one of the subjects covered by the section EML-research of the PML-Pulse Physics Laboratory. Within that framework the development of data analysis software is in progress.
This report describes a new data reduction technique to resolve armature motion from the measurement of the voltage induced in a flux loop diagnostic and the load current through the rail-armature circuit and/or its time derivative. Velocity and position of the armature as a function of time are calculated by the computer code developed. The recent improvements in data reduction are exemplified by the results of experiments performed with a 1m, 15mm square bore dipole rail accelerator. Validation of the flux loop diagnostic, in terms of accuracy, precision, range of operation, resolution, sensitivity and prospects is carried out. Suggestions to reduce the influence of the disadvantages observed are given, too.

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Computer Programs	Railguns
Data Processing	Armatures
Motion	Accelerators
	Diagnostics
	Flux Loop

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