Algorithm for the Lifetime/Loss Measurement with a High Precision DC Transformer

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Abstract

In the HERA proton storage ring the DC current is measured with a high precision DC transformer. Not only does it provide the exact proton current but also a measure of the beam lifetime under very different running conditions. The lifetime might range from three seconds to many hundred hours. The short lifetimes are needed immediately. Beam lifetimes of tens of hours can only be determined by taking the measurements of many minutes back in beam history. One wants not to take more points than necessary, and never to take any points that don't belong in the series of points. Determining this by eye seems to be simple; doing it automatically requires a fairly flexible algorithm.

1. INTRODUCTION

The algorithm for the lifetime/loss measurement is designed with HERA in mind. HERA is a complex of an 820 GeV proton and a 30 GeV electron ring with two common interaction regions. The arcs of the proton ring have superconducting magnets, which have to be protected even against small particle losses. This gives an extra incentive for very sensitive lifetime measurements, which adapt quickly to changes in lifetime.

Typical currents for the proton ring are 20 to 30 mA and for the electron ring between 5 and 20 mA. The proton lifetime at full energy with electrons is of the order of a few hundred hours and without electrons approximately two orders of magnitude larger. The electron ring lifetime is typically ten hours within half an order of magnitude. During machine set-up, machine studies and machine tuning the lifetimes can be much smaller and the currents can be radically different.

The beam lifetimes are derived from very precise current measurements. The proton ring uses a DC current transformer with excellent magnetic shielding. [1] The current measurement is limited by an intrinsic noise level equivalent to typically 0.5 µA and at most 0.8 µA [2] For the electron ring with its moderate lifetimes one uses a transformer with a resolution of slightly more than a micro Ampere (1.1±0.2µA standard deviation with 30 consecutive measurements of one Hertz rate). The currents are read out at a frequency of one Hertz. Four sets of the past 300 data points, with intervals of seconds, ten seconds, minutes and ten minutes, are always available for analysis.

The lifetime/loss is a measure of how fast the current changed over the past "short" time interval relative to the total current. For very long lifetimes the currents hardly change, rendering this approach a very indirect one. Here more direct approaches are valuable. For HERA two are used: particle loss measurements directly at the collimator [3] and particle loss measurements at various places around the ring [4]. Both are very sensitive even for the highest lifetimes and even more important, both are fast. The direct particle loss measurements have different systematic errors from the one presented here. They are only able to measure local losses. In addition the calibration of the measurement is less straight forward.

2. LOSS AND LIFETIME

One wants to measure the loss/lifetime as fast as possible. This means that one has to determine how many of the past data points one wants to consider and then derive the loss/lifetime from them. So first lets assume, that we have a reasonable set of current measurements.

2.1 Determining the Loss/Lifetime from a Given Set of Data Points

The loss is the relative current drop per time. Or more formally, the loss is defined as the slope of current versus time normalised to the current. With this definition the lifetime is just the inverse of the loss. From a reasonable set of data points one determines the loss simply by fitting a line through them and then dividing the slope by the average current:

$$I_i = I(i \cdot \Delta t),\ i = 0, 1, \ldots, n-1 \quad (1)$$

$$I(t) = I(n \cdot \Delta t/2) + L \cdot t \quad (2)$$

$$\tau := 1/L \quad (3)$$

Consider the errors in the loss measurement. For our purpose only measurements of the loss with a large current, i.e. negligible $\sigma(I)/I$, are meaningful. We require $I_{min} = 100 \cdot \sigma(I) = 0.065$mA. This is also quite large relative to the zero offset and zero drifts of the current monitor at HERA. Secondly, we require a small change of current over time compared to the measured currents. This not only results in optimally fast measurements, but also permits us to ignore the nonlinearities due to an exponential decay of the beam. The consequence of the requirements is that we can determine the loss by a linear fit to the data points, and that the error in the loss is completely described by the error in the slope. The errors of the current measurements can be fairly well described as a normal distribution. So the errors in the loss will also be described by a normal distribution. If one uses n current measurements spaced Δt apart one gets for the error in the loss:

$$\sigma(L) = \frac{\sigma(I)}{I \cdot \Delta t} \cdot \sqrt{\frac{12}{(n-1) \cdot n \cdot (n+1)}} \quad (4)$$

where the $\sigma(I)/(I \cdot (n-1) \cdot \Delta t)$ dependence originates from the calculation of a line through the endpoints and the $1/n^{½}$ dependence from the increase in statistics due to the extra points. For a 20mA proton beam we would get a resolution in loss of approximately 1% / h for ten seconds and 1‰ / h for one minute of measurement time.

2.2 Loss Versus Lifetime

We have seen that it is possible to measure a loss of 1 ‰ / h with a resolution of 1 ‰ / h within one minute. Now one might naively think this means we could measure a lifetime of 1000 hours with a resolution of 1000 hours. This is certainly not the case. A one sigma positive fluctuation in loss already corresponds to an infinite lifetime. Not only the variance in terms of tau is much worse, it is also ill distributed (see figure 1). This leads to too low most probable values of lifetime, a too high average and a significant number of reversed sign lifetime measurements. Presenting this to the user obviously creates some confusion - to say the least.

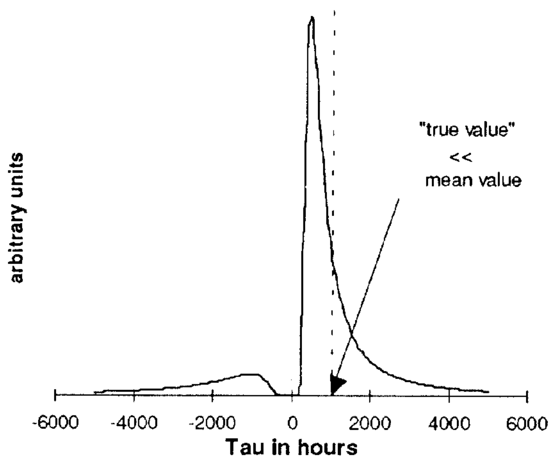

Fig. 1: Probability distribution for measuring a specific lifetime τ. Basis of this plot is a normal distributed loss of 0.001/h with a standard deviation of 0.001/h. Note the total distortion and the extra minimum at small values.

This problem only exists for the range of losses of $L=\pm10\cdot\sigma(L)$, if one is content with accuracy of the order of a few per cent. The effect is disastrous for measurements in the $L=\pm3\cdot\sigma(L)$ range. For the protons with their extremely long lifetimes, such situations are quite common. So it is much better to use the relative loss instead of the lifetime. However, the lifetime has some intuitive value in its own right. So for our lifetime display, we in fact plot the lifetime τ on a $1/\tau$ grid. This hides the fact that we have a plot linear in loss. So all values drawn have at least comparable and in space symmetrical errors. Note that a logarithmic display would be still too mild to encompass values up to and above infinity in lifetime, the logarithm of a negative lifetime isn't even defined and a cutoff in lifetime is a quite artificial an construct.

3. Selecting an Optimal Set of Points for the Loss/Lifetime Fit

The basic idea is to try to find as many consecutive points of the immediate current history as necessary for a resolution $\sigma(L)/L$ of a few percent and to try to ignore those parts of the present curve with a different loss. For example ten seconds ago there may have been an electron injection with a resulting small loss in proton current. This is usually not even noticeable in the current display itself, but for our extremely long proton lifetimes it is a big step down in current. So one only wants to use the points after the injection for the fit. But even if there is a potentially infinite pool of good consecutive measurements, one doesn't want to consider more than necessary, so as to reduce the "integration time" and hence the actuality of the result.

3.1 The Ideal Number of Points

The aim here is to try to collect points until one gets a relative resolution in loss of ca. 2 %. The algorithm should not be biased to large current difference fluctuation.

Aside from a statistical improvement (large number n of measurements) the relative resolution is basically given by the difference in current between the first and last measured point ΔI. From (4) it follows for the required ΔI:

$$\Delta I = \frac{\sqrt{2}\cdot\sigma(I)}{\sigma(L)/L}\cdot\sqrt{\frac{6\cdot(n-1)}{n\cdot(n+1)}} \qquad (5)$$

This formula gives a quick estimate of at what stage it is worthwhile to stop considering more past data points. For the HERA application this formula is generalised taking into account the averaged current measurements over the different sized time intervals. The formula is only reliable for $\sigma(L)/L$ reasonably small. For HERA $\sigma(L)/L\cong2\%$ is used, allowing measurements down to $I_0=100\ \sigma(I)$ with a nonlinearity error of then a similar order of magnitude.

It is essential not to stop taking more points as soon as a fixed ΔI is reached. This would lead to biasing in favour of stopping at points with a large fluctuation in current difference, leading to systematic overestimates of the lifetime. In the algorithm presented there are fixed values for the number of collected points, n, at which the collection is stopped if condition (5) has been satisfied at least once. Each such stop point corresponds to a significant change in the $\sigma(L)$ resolution. So we try to be sensitive to a true enhancement in resolution and not so much to fluctuations.

This still is not as bias free as one would naively think. It doesn't take care of coherent fluctuations of the DC transformer with time scales of the order of the measurement times, which are known to exist.

3.2 Noticing Significant Changes in the Loss Before All Points are Collected

Now we leave simple mathematics and enter the realm of simple pattern recognition. Here one has to use the data points to estimate which data points belong to the relevant set for the loss measurement and still be relatively bias free.

The idea is the following (fig. 2): take the most recent three points and then use the first and the third point to estimate the expected current difference between any consecutive two points. Use this difference to calculate the expected value for the next most recent current. If the actual measured current differs significantly from the expected one, don't take this or any further point for the fit. Otherwise continue backward in time with this test.

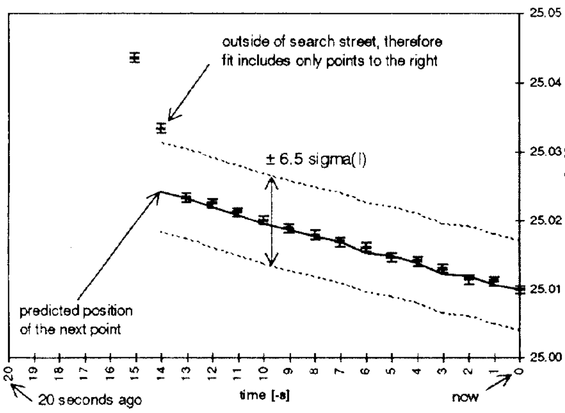

Fig. (2) Search street of 6.5 standard deviations in current resolution is used for finding the current values used for fitting. The centre line of the search street is given by the previous point corrected by the slope of the first three points.

How wide should the search street be chosen? One has to consider two points: First one doesn't want to lose more information than necessary. Second one doesn't want any wrong one. For a street width of $\pm 6.5\ \sigma(I)$ the chance of our 300 to 1200 collected values to survive this cut is in the few percent range. Note that this estimate is very sensitive to the quality of your resolution guess in the shape of the resolution distribution tail.

The sensitivity due to adiabatic changes in loss is very low though. For a current of 20 mA only a loss of more than 10% / h would fall with one standard deviation out of the street. One would get for adiabatic loss changes an averaged loss over the ideal amount of current measurements. In practice this is not the problem. Either the changes are really very slow, than the average is a good practice or they are not, than there are significant steps in current.

4. CONCLUSION

With this algorithm we then can provide stable pictures of the lifetime (fig. 3a, 3b) for the HERA control room.

Also in the case of small current losses this algorithm usually leads to better results than one would get by determining the fitting ranges by eye. Often the small steps in current, which accompany a change in loss, escape undetected.

The major improvements that could still be done for the lifetime measurements are in the improvement of the absolute current measurements. One could take the magnet currents of the proton and electron ring into account (100 GeV of proton ramp fakes 0.001 mA of current, the electron magnet cycle fakes a current range of 0.0036 mA). Second it would be worthwhile to study the effect of the toroid temperature on the current readings.

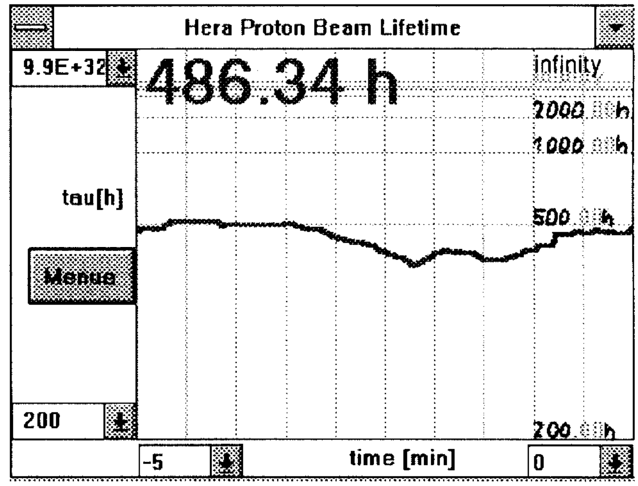

Fig. 3a Plot of the lifetime of the past 5 Minutes.

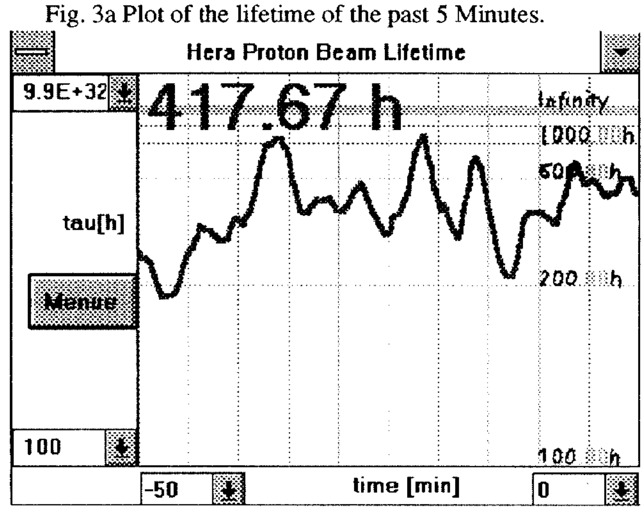

Fig. 3b Plot of the lifetime of the past 50 Minutes.

Fig 3 Both 3a and 3b were taken on a typical day with luminosity, where I just needed the plot, at the same time. Plotted is the lifetime τ on a $1/\tau$ (i.e. linear in loss) display. The vertical scale shows the lifetime from 200 (a) / 100 (b) hours to past infinity. Typical measurement times for each point were a few hundred seconds[1]. I_p=25 mA, I_e=9 mA

4. REFERENCES

[1] W. Schütte, "Mechanical Design of the Beam Current Transformers for the HERA Proton Ring", in Proc. of the Particle Accelerator Conference San Francisco, 1991, p. 1219-1221.

[2] W. Schütte and K. B. Unser, "Beam Current and Beam Lifetime Measurements at the HERA Proton Storage Ring", DESY HERA 93-03 and in Proc. of the Accelerator Instrumentation Workshop, Berkeley, CA, 1992.

[3] M. Seidel, "The Proton Collimator System of HERA", University of Hamburg, Germany, Dr. rer. nat. Dissertation, 1994

[4] K. Wittenburg, "Preservation of Beam Loss Induced Quenches, Beam Lifetime and Beam Loss Measurements with the HERAp Beam-Loss-Monitor System", DESY 94-003, 1994.

[1] So the wavy structure just shows fluctuations in the current passed slowly through the fitting window.