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A Precision Energy Calibration
for the
Cambridge Electron Accelerator

by

Herman Winick

February 1965

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CAMBRIDGE ELECTRON ACCELERATOR

HARVARD UNIVERSITY
42 OXFORD STREET
CAMBRIDGE, MASS. 02138

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Abstract

The external electron beam of the C.E.A. was focussed vertically and bent upward by a six foot deflecting magnet. The deflected and undeflected beams were allowed to drift 20 feet through a vacuum pipe producing a separation of about 32". Accurate measurements of this separation were made by surveying the spots produced by the beams on glass slides. Combining this measurement of angular deflection with a precise mapping of the field of the deflecting magnet yielded a calibration of the energy of the synchrotron at nominal energies of 1, 2, 3, 4, 5, and 6 GeV. These measurements show that the peak synchrotron energy is linear with peak synchrotron magnet current. Expressed in terms of the synchrotron magnet D.C. current (in terms of millivolts on the shunt), the result 62.73 mv per GeV was obtained. This result is accurate to better than $\pm 0.2\%$. It was found that careful control of hysteresis and eddy current effects in the deflecting magnet were essential in obtaining reproducible magnetic field plots.

Soon after the electron beam was first extracted from the synchrotron, and initial measurements showed that the emittance and energy spread were both small, (less than 1 cm-mrad horizontally and less than 0.3 cm-mrad vertically), it was suggested by G.A. Voss and others, that a precision energy measurement could be made on this beam by magnetic deflection. Such measurements have now been made at nominal energies of 1, 2, 3, 4, 5 and 6 GeV and are here reported.

Measurement Technique

The apparatus used is shown in fig. I. The emergent beam passed through quadrupole lenses Q1 and Q2, and then through the vertical deflecting magnet M, after which it drifted about 20' to a location where it produced darkened spots on 1" X 3" glass microscope slides placed in the proper position to intercept the straight-through and deflected beams. Vertical deflection was chosen because the vertical size of spots is insensitive to fluctuations in power levels of the current strip and ejection magnet which eject the beam from the synchrotron. Hence spots are defined vertically better than they are horizontally. The beam travelled in vacuum essentially all the way emerging from a thin window 5" before striking the slides. The slides were held on a 30" diameter wooden disk which was remotely rotatable from the main control room. This disk had its plane perpendicular to the undeflected beam, and its height was adjusted so that slides located at the bottom would be approximately at undeflected beam height. The location of the wheel along the beam run was so chosen that electrons

deflected by about $1/8$ radian would strike the upper slides. Thus a measurement of the deflection could be made by allowing the beam to strike the lower slide, producing a darkened spot there with the magnet off and then, without rotating the wheel, the magnet was powered (see magnet cycling procedure) to produce the nominal $1/8$ radian deflection and the upper slide was exposed and a spot was produced there. The appearance of these spots is shown diagrammatically in fig. II, for the 5 GeV case.

The shape of the deflected spot reflects the energy spread in the beam, due largely to the fact that the beam is spilled over a period of several hundred microseconds near the peak of the magnetic field. The energy of the beam varies quadratically with time measured relative to the time of peak energy, and is down by 0.9% at 0.5 milliseconds. The intrinsic energy spread due to quantum fluctuations is calculated by K. Robinson to vary linearly with energy above 3 GeV and to equal about $\pm 0.1\%$ at 6 GeV. The highest energy in the beam is quite well defined as the lowest point in the deflected spot, and its location, relative to the undeflected beam position, is used to calculate the energy corresponding to peak magnetic field.

The exposure time was judged by observing the spots darkening on closed circuit television. Typical exposure time was about 30 seconds. The location of these spots was later measured to an accuracy of ± 0.01 " using two Wild Levels and a vertical hanging precision

3' scale. The separation of these spots, d , combined with the distance between the deflecting magnet and the slides, L , permit a calculation of the bending angle. Actually, since the remanence field in the magnet was not negligible, two spots were taken with the magnet off, one with each polarity of remanence field. The center of these two spots was used as the undeflected beam position. The separation of the deflected and undeflected beams (about 32") could therefore be measured to better than ± 0.02 " which results in less than $\pm 0.06\%$ error in the calculation of bending angle. The distance L was measured to $\pm \frac{1}{16}$ " which results in less than $\pm 0.03\%$ error in the calculation of bending angle.

During the slide exposures, especially during the critical exposures with the deflecting magnet powered, careful record was kept of the following:

1. Synchrotron magnet current.
2. RF frequency.
3. Deflecting magnet current.
4. Timing of emergent beam relative to the magnet cycle (spill time).

The manner of measuring each of these, and the effects of variations on the synchrotron energy will now be discussed separately.

1. Synchrotron Magnet Current: The magnet current has a wave form given by:

$$\text{Eq(1)} \quad I(t) = I_{DC} - I_{AC}^{\text{peak}} \cos \omega t$$

The peak current is:

$$I_{\text{peak}} = I_{DC} + I_{AC}^{\text{peak}}$$

Until recently I_{DC} was measured on a $\pm 0.1\%$ shunt which developed 0.1 mv per amp. This shunt would have limited the precision of the present measurements, primarily because its output voltage was low - only 6.3 mv at 1 GeV level. In anticipation of the present measurements a more precise ($\pm 0.04\%$), higher signal (1 mv per amp.) Leeds and Northrup shunt was provided by the Electrical Engineering Department and installed in series with the synchrotron magnet D.C. Both this new shunt and the old shunt were read during these measurements using two Leeds and Northrop potentiometers. Shunts of this type (i.e. 1 mv per amp. $\pm 0.04\%$ precision) were used for all measurements of synchrotron magnet current and deflecting magnet current.

I_{AC}^{peak} is measured by observing the separation of pulses from an unbiased toroidal peaking strip, which surrounds a magnet current cable and produces a pulse when the current passes through zero. The current is

made to pass through zero twice on each magnet cycle by making $\frac{I_{AC}^{peak}}{I_{DC}} > 1$.

The synchrotron is usually operated with a 1 millisecond spacing between these zero current pulses. If T is the separation of the zero current pulses then $I(t) = 0$ at $t = T/2$. Substituting this in Eq(1) yields

$$\text{Eq(2)} \quad \frac{I_{AC}^{peak}}{I_{DC}} = \sec \frac{\omega T}{2}$$

For $T = 1$ millisecond $\sec \frac{\omega T}{2} = 1.017$ and

$$\text{Eq(3)} \quad I_{peak} = 2.017 I_{DC}$$

Most of the deflection measurements were made with a stable peaking strip spacing (variation of less than $\pm 30 \mu\text{sec}$). However, at the 1.0 GeV excitation the spacing varied by ± 0.1 milliseconds. An attempt was made to make a measurement at 0.5 GeV but the magnet instability there was very great, resulting in much larger beam spots. Since it was difficult to estimate the actual peak magnet current this measurement was discarded.

The effect of a variation in peaking strip spacing on the peak magnet current (and hence peak machine energy) may be obtained by differentiating Eq(2) with respect to T to yield:

$$\frac{\Delta \left[\frac{I_{AC}^{peak}}{I_{DC}} \right]}{\frac{I_{AC}^{peak}}{I_{DC}}} = \left(\frac{\omega T}{2} \right)^2 \frac{\Delta T}{T} \approx \frac{2 \Delta I_{peak}}{I_{peak}} = \frac{2 \Delta(pc)}{pc}$$

The last part of this equation is obtained by approximating Eq(3) by $I_{peak} = 2I_{DC}$, and assuming that any variations in peaking strip spacing are due to variations in either A.C. or D.C. but not both.

For $\omega = 377$ (60 C.P.S.), $T=1$ millisecc, and $\frac{\Delta T}{T} = .1$ Eq(4) yields $\frac{\Delta(pc)}{pc} = 0.18\%$, the correction applied to the 1 GeV measurements. At all other energies the peaking strip spacing was accurate and stable to better than $\pm 30 \mu\text{sec}$ which corresponds to an error in peak energy of less than $\pm 0.06\%$.

2. RF Frequency: The rf frequency was measured to a precision of $\pm 2\text{kc}$ on a frequency counter. Since the rf frequency at the peak of the magnet cycle is relevant to the peak energy, care was taken to exclude from the measurement the two millisecond interval at injection when the frequency is higher. This is most simply done by selecting a short sampling period (1 millisecond) for the frequency counter and ignoring the occasional higher frequency displayed when the sampling period happens to occur near injection time when the frequency is higher. Although the rf frequency was constant during a single energy measurement, it varied from a low 475.659 Mc to a high of 457.701 during the series of measurements.

A change in rf frequency, Δf , is related to an energy change $\Delta(\text{pc})$ by the relationship:

$$\text{Eq(5)} \quad \frac{\Delta(\text{pc})}{\text{pc}} = \frac{-1}{\alpha} \frac{\Delta f}{f}$$

where α is the average momentum compaction factor and has a value of 0.031. Thus the 42 kc range of frequencies encountered during the measurements corresponds to a 0.29% energy change. All results presented here are normalized to an rf frequency of 475.700 Mc. In any attempt to use these results a correction must be made for any difference in rf frequency from 475.700 Mc. using Eq(5).

3. Deflecting Magnet Current: The deflecting magnet current was measured using a Leeds and Northrop ($\pm 0.04\%$ precision) air cooled shunt in a series with the magnet. The shunt voltage was measured on a Dymec 5 digit voltmeter (Model 2401A) and a Leeds and Northrop potentiometer. The magnet current was stable to better than $\pm 0.02\%$ during an individual measurement.
4. Spill Time: The signal from a scintillation counter near the emergent beam run was displayed on an oscilloscope along with the pulse which indicates the peak of the magnetic field (B_{max}). The accelerator operator adjusted the beam bump amplitude and timing to keep the

scintillation counter signal centered on the $B_{\max}$ pulse. The spill time was stable during each measurement, and always included the time of peak magnetic field.

Magnetic Measurements.

It was desired to construct a point-by-point field map of the deflecting magnet to an accuracy of $\pm 0.1\%$ or better. A first attempt was made with Hall probes which were calibrated against a nuclear magnetic resonance device in a standard magnet. Although individual readings could be made to the required precision, the calibration often abruptly changed by as much as 0.6%. More success was had using a nuclear magnetic resonance (NMR) probe and a rotating coil. The NMR (Varian type F-8) was used to measure the uniform fields far inside the magnet and up to 2" from the magnet ends. The large gradients present close to the magnet ends, and in the fringe fields, precluded its use at these locations, so a rotating coil (Rawson type 820 0.1% differential gaussmeter) was used here. The rotating coil was calibrated before and after each set of fringe field measurements at a point 6" inside the magnet. The two calibrations agreed to $\pm 0.1\%$ or better. Since the fringe field contributes only about 1/6 of the total magnetic length this precision is quite adequate. The NMR of course is extremely precise, giving frequencies which were read on the frequency counter to better than $\pm 0.005\%$ and which repeated to better than $\pm 0.02\%$.

This instrumentation proved adequate for obtaining the high precision measurements required. However, the results were not

reproducible from day to day. It was found that the relationship between magnet excitation current and magnetic field was a function of the previous history of the magnet. The factors that were most important were:

- a. The level to which the magnet had been previously excited.
- b. The time rate of change of magnet current in arriving at the new current.

The first factor was readily controlled by establishing a pattern for cycling the magnet through full excitation in one polarity to full excitation in the opposite polarity prior to setting the current to the desired value. In effect this put the magnet on a particular hysteresis curve.

The second factor was more intractable and was overcome only after changing the regulation circuitry of the magnet power supply. Initially the regulator circuit in the power supply contained a local voltage reference battery built into the supply cabinet itself. A fraction of this voltage was selected by a motor-driven potentiometer which was powered remotely, and this voltage was fed to the current regulator circuit of the power supply. With this apparatus the manner of arriving at a given magnet current (or a given fraction of the reference voltage) was not easily controllable or reproducible. The operator would watch a meter measuring magnet current and jog the toggle switch which powered the motorized potentiometer until arriving at the desired current.

With the assistance of the Electrical Engineering Department

the problem was solved by using voltage references at the location from which the power supply was being controlled. Two Electronic Development Corporation precision D.C. voltage reference sources were connected to a selector switch through which the output of either one could be applied to the power supply current regulation circuit. The following procedure was then used to arrive at a given magnet current:

Start with the two voltage reference sources "A" and "B" set to 0 volts.

1. With the power supply off and the selector switch put to voltage reference "B", reference "A" was set to a particular voltage (5.000v), corresponding to the maximum current that could be drawn from the power supply used (208 amps).
2. The power supply was then turned on, following which the selector switch was changed to reference "A". The power supply would then approach a current of 208 amps. This current would be stable after about two minutes.
3. The selector switch was then put to reference "B" which was still at 0 volts. The power supply would then approach a very small current (about 0.4 amps) after which the power supply was turned off and its polarity reversed.
4. After turning on the power supply the selector switch was put to "A", which was still at 5.000v. The power supply would now approach a current of 208 amps. in the reverse polarity.

5. The selector switch was then put to "B" which was still at 0 volts causing the power supply to approach 0.4 amps after which it was turned off.

The cycle (steps 1 to 5) was repeated 3 or 4 times, ending with the completion of step two on the last cycle, i.e. the magnet is left with 208 amps flowing in the normal polarity. Then a particular current, corresponding to a $1/8$ radian deflection at one of the nominal energies, would be set in two more steps.

6. Set "B" to a voltage corresponding to the current desired for the measurement.
7. Change the selector switch to "B". The magnet would now approach the desired current.

In this way the magnet could be cycled in a standard manner along a particular hysteresis loop, and any desired current could be arrived at in a manner which reproduced the ratio of magnetic field to magnet current to better than $\pm 0.02\%$. This magnet cycling and current setting procedure was used during the magnetic measurements and during the actual deflection measurements.

According to the prescription outlined above, the magnet was brought to a desired current for a measurement after it had been set to 208 amps in the normal polarity. This was arbitrary, and another prescription could have been chosen which, if followed closely, would yield equally reproducible results, but with different values of the ratio of magnetic field to magnet current. During the course of the measurements the following different prescription was once used:

The highest excitation (the 6 GeV level) was set after the normal cycling procedure. The lower excitations were set directly in sequence without going through the cycling procedure. The measurements of magnetic field made with this procedure resulted in a quite different ratio of magnetic field to magnet current from the ratio obtained with the standard procedure (see table I for the standard procedure ratios). The new ratios were higher by the following percentages:

<u>Magnet Current</u>	<u>Increase in Field to Current Ratio</u>
109.0 amps	.02%
88.4 amps	.03%
65.3 amps	.10%
42.5 amps	.20%
21.4 amps	.37%
11.6 amps	.83%

The need for a standard procedure in setting magnet currents when making precision magnetic measurements is obvious.

The NMR and rotating coil probes were used to make a set of 104 point measurements of magnetic field along the axis of the magnet at each of the seven excitations. The NMR measurements were taken at 2" intervals since the field varies slowly inside the magnet. The rotating coil measurements were taken at varying intervals down to 0.1" depending on the steepness of the gradient.

During the magnetic measurements the magnet current was monitored continuously on a 5 digit voltmeter and occasionally on a Leeds and Northrop potentiometer. The power supply (number 601, a Pacific

Electric Co. type) functioned very well. Although its current regulation rating is only $\pm 0.1\%$ it was never observed to vary by more than $\pm 0.02\%$ during the time required to make a set of measurements ($\frac{1}{2}$ hour to several hours).

The point-by-point measurements were fed into a computer which computed $\int H(x)dx$ along the centerline of the magnet.

The overall accuracy of these final results is better than $\pm 0.06\%$. The magnetic measurements were made and the computer calculation carried out, for each of the seven nominal excitations corresponding to $1/8$ radian deflection at the seven energies to be measured. The results are presented in table I and fig. III. For completeness a less precise ($\pm 0.3\%$) measurement made with a Hall probe at considerably higher excitation is included.

Four sets of measurements of the field variation transverse to the magnet axis (or electron direction) were also made at each excitation, at 36" inside the magnet, 20" inside, 6" inside, $1\frac{1}{2}$ " outside. These data were later used to correct $\int H(x)dx$ along the axis for the slightly different fields along the actual electron trajectory.

These magnetic measurements were all made with the vacuum box inside the magnet. The vacuum box has .5" thick carbon steel top and bottom plates and stainless steel side plates and effectively reduces the 3" aperture of the magnet to 2". The magnetic measurements were made at atmospheric pressure with the end plates off to allow access for probes. Since the actual deflection measurements on the electron beam were made with the box under vacuum, a check was made to determine the effect of the vacuum on the magnetic field. It was found

that under vacuum the field along the magnet centerline increased by 0.05%. A correction for this small effect was made to the final energy measurement data, but it has not been included in table I.

Relationship of Magnetic Field to Current in the Synchrotron Magnets.

A study was made to determine the effect of previous magnet history on the relationship of magnetic field to current in the synchrotron magnets. The dynamic remanence field (i.e., the magnetic field at the instant at which the magnet excitation current is zero) was measured at several excitations with several different previous excitations of the magnet. For instance, the dynamic remanence field at 1 GeV level was measured after running at 6 GeV level and also at 2 GeV level. Unbiased toroidal peaking strips were used to sense the time of zero current and unbiased wire peaking strips in the magnetic field detected the time of zero magnetic field. From this data the dynamic remanence could be calculated. It was found that the dynamic remanence field was a constant at a given excitation, independent of previous excitation. The accuracy was about ± 1 gauss which is about .1% of the peak field at 1 GeV level.

Relation between momentum, magnetic field and deflection angle.

At any point s on the trajectory of a particle in a magnetic field, the field, $H(s)$ in gauss, the radius of curvature, $\rho(s)$ in cm, and the momentum of the particle, pc in GeV are related by:

$$Eq(6) \quad H(s) \rho(s) = \frac{pc}{c} \times 10^{17}$$

where c is the velocity of light in cm/sec.

For an arbitrary path defined in a rectangular coordinate system by a function $y(x)$, the radius of curvature at a point s (coordinates x, y) on the curve is given by:

$$\frac{1}{\rho(x,y)} = \frac{y''}{[1+y'^2]^{3/2}} = \frac{u'}{[1+u^2]^{3/2}} \quad \text{where } y'' = \frac{d^2 y}{dx^2} = u'$$

$$u = y' = \frac{dy}{dx}$$

Using this and equation (6) one obtains:

$$\int \frac{du}{(1+u^2)^{3/2}} = \frac{c \times 10^{-17}}{pc} \int H(s) dx$$

where the integrals are over the entire region of magnetic field. The left hand side of this equation is directly integrable yielding:

$$\text{Eq(7)} \quad \sin \theta_f - \sin \theta_i = \frac{c \times 10^{-17}}{pc} \int H(s) dx$$

$$\text{where:} \quad \theta = \tan^{-1} \left(\frac{dy}{dx} \right)$$

This very useful relation is exact and quite general. It was first pointed out to me by T. L. Collins. It may be applied to the present case by setting up a rectangular coordinate system with the x-axis in the median plane of the magnet and perpendicular to the end faces (i.e. the principle axis of the magnet). Then for a symmetric trajectory through the magnet, ($\theta_i = -\theta_f$) eq (7) reduces to:

$$\text{Eq (8)} \quad 2 \sin \frac{\theta}{2} = \frac{c \times 10^{-17}}{pc} \int H(s) dx$$

where θ is the total deflection angle. Furthermore, for this symmetric case, the intersection point of the initial and final beam directions is at a point equidistant from the end faces of the magnet, and the tangent of the total deflection angle θ is equal to the deflection, d , over the length L , measured from this intersection point to the location at which the deflection is measured. (See fig. I).

Eq (8) and the above described method of obtaining $\tan \theta$ are strictly true only for the symmetric trajectory through the magnet. A trajectory through a rectangular magnet will be symmetric if the following are satisfied:

- a. The upstream and downstream halves of the magnet must be symmetric relative to the midplane of the magnet.
- b. The principle axis of the magnet must make an angle with the incoming ray of one half the final deflection angle.

These two conditions were satisfied to a sufficient precision in the present case, as will now be shown.

- a. The magnetic measurements made on the deflecting magnet indicate that one half of the magnet, the upstream half, contributed 0.25% more to $\int H dx$ than did the other half. This small asymmetry in the magnet results in a 0.01% larger deflection 20 feet downstream of the magnet than would obtain from a perfectly symmetric magnet, hence this

asymmetry of the magnet may be ignored.

- b. During the deflection measurements the magnet was oriented within 5 milliradians of the correct angle. A change of 5 milliradians in the magnet angle results in a change of less than 0.02% in the final deflection 20 feet downstream of the magnet, hence the magnet was aligned sufficiently accurately.

Thus, Eq (8) may be used directly to determine p_c . The values of $\int H(x)dx$ listed in table I were corrected to obtain $\int H(s)dx$ along a symmetric trajectory. This correction was 0.05% or less. The deflection magnet currents actually used during the deflection measurements were about 3% higher than the current settings for which the magnetic measurements were made. A computer program was written which took the basic data of the deflection measurements (deflection d , distance between magnet and glass slides L , deflection magnet current, synchrotron D.C. current, and rf frequency) and the data of the magnetic measurements (deflection magnet current and $\int Hdx$), performed the required normalizations for different deflection magnet currents and for a standard rf frequency (selected for convenience at 475.700 Mc), and used Eq (8) to compute p_c and the ratio of synchrotron D.C. current (expressed in mv on the shunt: 1 mv = 1 amp) to p_c . This ratio is the simplest way to express the results of the measurements, and the ratios are listed in table II and fig IV. A 1 msec peaking strip pulse spacing is assumed.

Table II - Results

Energy (GeV)	1	2	3	4	5	6
D.C. Millivolts per GeV at 475.700Mc and 1 msec peaking strip pulse spacing	62.74	62.63	62.78	62.78	62.77	62.61
Precision	$\pm 0.3\%$	$\pm 0.2\%$	$\pm 0.2\%$	$\pm 0.2\%$	$\pm 0.2\%$	$\pm 0.3\%$

The errors indicated are conservative estimates of the combined effects of the several contributing errors. The error is larger at 1 GeV due to the magnet instability there, and at 6 GeV due to the small and varying accelerated beam intensity which necessitated a longer exposure time.

Discussion

The final results are quite consistent with a constant ratio of D.C. millivolts per GeV for the energy range 1 to 6 GeV. The weighted average of the individual measurements gives 62.73 mv per GeV at 475.700 Mc and 1 msec peaking strip pulse spacing, a result which is accurate to $\pm 0.2\%$ or better.

In using this result it is important that a correction be made for any difference in rf frequency from 475.700Mc, using Eq (5). The frequency used must correspond to the peak of the magnet cycle, avoiding the 2 millisecond period near injection when the rf frequency is higher. Also the result applies only to the energy of the circulating beam, or any beam put on a target, or extracted from the synchrotron, by the beam bump method (i.e. a beam that is in phase synchronism with the rf). If rf turnoff is used, a correction must

be made for the energy loss of the electrons as they spiral inward to the target position. This correction is given by

$$\frac{\Delta(\text{pc})}{\text{pc}} = \frac{1}{\alpha} \frac{\Delta r}{r}$$

where α is again .031, r is the average distance from the center of the synchrotron to the orbit (1420 in), and Δr is the distance between the target to be engaged and the local equilibrium orbit (typically $\Delta r \approx 1$ in).

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TABLE I
Magnetic Measurements

<u>Nominal Energy</u>	<u>Deflecting Magnet Current</u>	<u>$\int H(x)dx$ along Centerline</u>	<u>$\int H(x)dx$ Current</u>	<u>Precision</u>
	200.2 amps	1317.3 kg-in	6.580 $\frac{\text{kg-in}}{\text{amp}}$	$\pm 0.3\%$
6 GeV	131.390	977.65	7.4408	$\pm 0.06\%$
5 GeV	109.294	820.74	7.5095	$\pm 0.06\%$
4 GeV	88.454	666.52	7.5352	$\pm 0.06\%$
3 GeV	65.316	493.15	7.5502	$\pm 0.06\%$
2 GeV	42.574	322.10	7.5657	$\pm 0.06\%$
1 GeV	21.395	162.55	7.5976	$\pm 0.06\%$
0.5 GeV	11.660	89.229	7.6526	$\pm 0.06\%$

Notes: The measurement at 200.2 amps. was made with a Hall probe. All others were made with N.M.R. and rotating coil. These measurements are at atmospheric pressure. Under vacuum the distortion at the vacuum box causes the field along the magnet centerline to increase by 0.05%.

FIG I

FIG II

FIG III

FIG IV
D.C. Millivolts per GeV
vs.
pc (GeV)

x = individual measurement
o = Average

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