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A MOMENTUM CALIBRATION OF THE SPS PROTON BEAM

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ABSTRACT

The momentum of the SPS proton beam has been measured at the nominal value of the 1991 collider run. It was deduced from the measured difference in RF frequency and hence speed difference between oxygen ions and protons at constant magnetic field and radius. The resolution obtained in the experiment was $3.4\ 10^{-4}$. The momentum of the beams during the collider run of December 1991 is deduced to be $p = 270.55 \pm 0.095$ GeV/c.

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CONTENTS

1. INTRODUCTION

During the 1991 antiproton-proton collider run of the SPS, it appeared that the quality of the data taken by the UA4-2 experiment [1)] was such that the largest uncertainty on both the total cross-section and the ρ-parameter would lie in the knowledge of the beam momenta, determined earlier with a relative precision of 0.5% [2)]. A study demonstrated [3)] that an accuracy better than 0.1% is attainable by measuring the speed difference between protons at 270 GeV/c and ions at the same magnetic field and radius in the SPS as used in the collider run.

In this note, we present the result of such a measurement, done recently during a dedicated machine development session, during which both protons and oxygen ions were accelerated to 270 GeV/c.

2. PRINCIPLE OF THE MEASUREMENT

The Lorentz force is proportional to the total charge, ze, of the moving particles, e being the the electronic charge and z the number of them for a given kind of particles. At highly relativistic energies, i.e. when the relative difference of speed $\Delta\beta$ of the particles is very small, the Lorentz force per unit mass of ions ($A \approx 2z$) is halved when compared to protons ($A \approx z = 1$) at constant magnetic field. Therefore, to keep both kinds of particles on the same trajectory (same radius) at constant magnetic field, the momentum per unit mass will be halved for ions. The relative speed of the two kinds of particles will differ and consequently the time needed to make one machine turn. This will therefore result in a measurable RF frequency difference, the amount of which allows computation of the proton beam momentum.

To be quantitative, if $\beta = v/c$ is the relative velocity of the particles and f the RF frequency measured at equal radius and B field, then (the index "p" stands for proton and "i" for ion)

$$\frac{f_p}{f_i} = \frac{\beta_p}{\beta_i} \quad (1) \quad \text{in which } \beta_p{}^2 = \frac{p^2}{p^2+m_p{}^2}, \quad \beta_i{}^2 = \frac{p^2}{p^2+m_i{}^2}$$

with $m_i = M_i/z_i$. By taking the square of (1) and replacing β's by the above expressions, we get:

$$p^2 = \frac{(\frac{f_p}{f_i})^2\, m_p{}^2 - m_i{}^2}{1 - (\frac{f_p}{f_i})^2} \qquad (2)$$

For quick approximations and error calculus, simplified formulae are obtained by writing $f = f_p = f_i + \Delta f$ ($\approx f_i$ whenever appropriate), $m_i \approx 2\, m_p$ and $\Delta\beta = \beta_p - \beta_i$. Δf is the frequency difference that we are going to measure. Then from (2), we deduce:

$$p = m_p \sqrt{\frac{3}{2\,\Delta\beta}} = m_p \sqrt{\frac{3f}{2\,\Delta f}} \qquad (3)$$

and $$\frac{\sigma(p)}{p} = \frac{1}{3}\,\gamma^2\,\sigma(\Delta\beta) = \frac{1}{3}\,\gamma^2\,\frac{\sigma(\Delta f)}{f} \qquad (4)$$

The factor 1/3 in (4) is related to $\Delta\beta = \beta_p - \beta_i \approx 3\,(1 - \beta_p)$, because $p_{ion} \approx 0.5\, p_{proton}$ (per nucleon). Numerically, if $f \approx 2.10^8$ Hz, and $p = 270$ Gev/c, then by inverting (3):

$$\Delta\beta = 1.8\ 10^{-5} \quad , \quad \Delta f = 3590 \text{ Hz}$$

By inspecting (4), we see that to get $\sigma(p)/p < 10^{-3}$, then the error on Δf shall be

$$\sigma(\Delta f) < 8 \text{ Hz}$$

a condition which is discussed in the next section.

3. PARAMETERS AND ACCURACIES

3.1. Masses

The masses of the proton and oxygen nuclei are deduced from $^{4)}$. We used

$$m_p = .93827231 \text{ GeV}/c^2 \quad \text{and} \quad m_i = M_{Oxygen}/8 = 1.86188551 \text{ GeV}/c^2$$

The absolute accuracy of these values is better than 10^{-8} when they are expressed in GeV/c^2, and with (2), $\sigma(p)$ is approximately linearly dependent on $\sigma(m)$.

3.2. Magnetic field

During the MD calibration session, the absolute knowledge of the magnetic field is not important. The beam momentum and the B field are linearly dependent, and having the same value of B field during the RF measurement of both proton and oxygen beams is a sufficient condition. But, to extrapolate the result of the experiment to the collider run of 1991, an absolute measurement of the bending field in the magnets or of some quantity related to it is required. We discovered at the beginning of the MD session that to reproduce the B field as read by the NMR gauge installed in the reference magnet, powered in series with the bending magnets of the SPS, we needed a current of I = 3194.70 A in the main power supplies as opposed to the value of 3196.26 A measured during the collider run. The NMR gauge is a time-independent absolute reference to better than 10^{-5} 5) while the DCCT driving the power supplies is a relative reference. We relied on the NMR value, which is the most direct measurement of the B field and which was recorded both during the collider run, and during the MD session. These measurements are summarized in table 1.

The field varied by approximately 2.10^{-5} during the collider run.

An additional source of error in the knowledge of the magnetic field is due to some orbit correctors used at injection which are left under power at high energy. The amount of additional B·l around the ring was somewhat different during the collider run and during the MD. Upper bounds on the residual B·l are also given in table 1.

By combining all these sources of fluctuations, we get an overall effective field variation between the collider run and the MD $\sigma(B)/B < 3.3\ 10^{-5}$. The variation between the proton and oxygen measurement during the MD was smaller than 10^{-5}.

TABLE 1 : Magnetic field as read by the NMR gauge

Collider Run		B in Tesla	
date	2.12.1991	1.226314	Average:
	6.12.1991	1.226350	B = 1.226321 ± 0.000026
	9.12.1991	1.226300	$\delta B/B = 2.1\ 10^{-5}$
Relative residual Bl due to orbit correctors			$\delta B/B < 0.7\ 10^{-5}$
MD		B in Tesla	
date	5.05.1991, 22^{00}	1.226314	Average:
	5.05.1991, 23^{00}	1.226329	B = 1.226323 ± 0.000006
	6.05.1991, 03^{00}	1.226327	$\delta B/B = 6\ 10^{-6}$
	6.05.1991, 04^{00}	1.226323	
Relative residual Bl due to orbit correctors			$\delta B/B < 2.6\ 10^{-5}$
Overall field fluctuations during the MD :			$dB/B < 2.7\ 10^{-5}$
Overall field fluctuations , Collider + MD :			$dB/B < 3.3\ 10^{-5}$

3.3 Frequency

The RF frequency measurement is driven by a quartz which is stable to much better than 1 Hz at short term (<1 day). During the MD, the frequency was measured regularly, in batches of 20 measurements of one second, such that the sampling error was smaller than 0,1 Hz . Therefore, during the MD:

$$\sigma(f) < 0.1\text{Hz}$$

Then, using (4),

$$\frac{\sigma_f(p)}{p} < \frac{1}{3}\gamma^2 \frac{\sigma(f)}{f} = 1.4\ 10^{-5}$$

3.4 Radius of the machine and closed orbit measurement

At fixed magnetic field, the radius of the machine and the RF frequency are related by

$$df \approx -\frac{f}{R}\ dR \approx -180\ dR\ \ [\text{Hz,mm}] \qquad (5)$$

with $R = 1.1\ 10^6$ mm and $f = 2\ 10^8$ Hz (for more exact numbers, see section 6). This formula permits correction of the measured frequency for a known radius offset. But on the other hand, an uncertainty δR on the radius measurement induces an equivalent error δf following (5), which affects the momentum measurement through (4), i.e. linearly with a coefficient $\gamma^2/3$ with either δf or δR.

The radius offset from the central orbit is measured by the average value of the 108 beam position monitors (BP's). In our measurement, we only need to measure the frequency at equal radius, or at a relative radius difference for which the frequency can be corrected with (5), avoiding the adverse effect of any systematic error (like transverse mispositioned monitors) affecting the closed orbit measurement.

But even a relative equal radius between protons and ions is delicate to obtain. The individual BP resolution is $\delta x \approx 0.05$mm (see section 5), limited by electronic random noise . The relative radius R is obtained by averaging over N ~ 100 monitors, such $\delta R \approx \delta x\ /\ \sqrt{N} \approx 0.005$ mm, such that

$$\frac{dp}{p} = \gamma^2 \frac{\delta R}{R} = \gamma^2 \frac{\delta f}{f} \approx 4\ 10^{-4}$$

The momentum p is measured by the RF frequency difference of two beams (a multiplying factor $\sqrt{2}$ on the error), and it benefits of a factor 3 in resolution (see formula 4). Therefore,

$$\frac{\sigma(p)}{p} = \frac{\sqrt{2}}{3}\frac{dp}{p} \approx 1.9\ 10^{-4}$$

The attainable resolution on the relative radius measurement is the limiting factor of the whole experiment, and much care was given to the orbit analysis, as is explained in the next section.

4. PREPARATION OF THE MACHINE

The MD was started at the the end of the S16+ heavy ion physics run on monday 4th of May at 10^{00}. It was stopped at midday for 30hours first by a 380kV power trip, and then by a vacuum leak in TT2. Sulphur was replaced by Oxygen in order to have enough intensity stored in the SPS, to allow all BP's in the ring to measure the beam position with enough accuracy. The data taking was done during the tuesday night. Normal operation for physics was restored in the morning of Wednesday 6th May. We did the Oxygen measurement first, then switched to protons.

The lepton cycles and the high energy extraction on the ion cycle were disabled and the MD cycle was set up, starting from the current ion cycle, initialised at " 273 GeV/c ", in order not to lose all the adjustment done at low energy. The main dipole field, measured in coast, was adjusted to fit the NMR gauge of the collider run (see Section 3.2).

We tried to equalize the beam intensities as best we could in the time at our disposal. The beam intensities were :

for Oxygen:	In TT10 , 1.2 10^{11} charges per SPS cycle (4 batches), In the ring, after debunching and rebunching at 200 MHz at the end of the flat the bottom and ramping there remained 5-7 10^{11} charges in 4620 bunches on the flat top.
for protons:	In TT10, a few 10^{11} protons in 1 batch. In the ring , the same procedure as above, giving 10^{11} charges in 4620 bunches on the flat top.

Oxygen or proton beams were available from CPS, whenever wanted, during the entire measurement session.

5. DATA TAKING AND CLOSED ORBIT ANALYSIS

Once the beam was in coast (oxygen, then protons), many checks were done. The stability of the NMR signal and of the main power supply were observed during half an hour. No significant changes appeared.

Then the closed orbit (c.o.) was measured, together with the RF frequency. It became clear that some BP's were not working properly. Out of 108, 15 were rejected by the calibration program itself (too weak signals), and some others gave abnormally large positions, incompatible with expected values, extrapolated from neighbouring BP's. Furthermore, some of them were also strongly fluctuating from one measurement to the next one (~ 1-3 mm, instead of <0.1 mm). We eliminated some of these BP's in the on-line calculation of the average radius. Subsequent analysis showed that this was not enough with the result that the real average radius was quite distant from the value at which we wanted to do the RF measurement (wanted: dR = -0.9mm, the approximate offset measured during the collider period, see Section 7). We recorded the individual values of all BP's together with the frequency measurement, twice for oxygen (OXA, OXB) with a 30 minute time separation, and 10 times for protons, 9 measurements in 10 minutes (P1-9) and a single one an hour later (P10). In this way, a detailed off-line analysis of the BP values was made possible.

The acquisition of orbits P1 to P9 was done without any deliberate change of radius or RF frequency. After proton injection and coasting, we had a data acquisition problem on the Apollo side. We therefore used the NODAL system to record the data P1 to P9 but did not calibrate the BP's. While these data are very useful for analysing the response of the BP's (nine identical orbits), we cannot use them for the energy measurement (see Section 6). These data differ among themselves only by beam ripple or such effects, and fluctuations in the reading of the BP's. We identified a portion of sextant 3 as giving values with large fluctuations between BPH23609 and BPH32409. We decided to eliminate these 13 BP's, even if some of them might have been good, to avoid any useless risk of error. The number of beam positions necessary to fix the radius of the closed orbit is quite small, because in a linear optic, any transverse position along the ring is uniquely defined by any set of positions at two locations and the transfer matrices. Also to do our measurement, we only need to know the difference of radius between two orbits, such that local deformations, not contained in transfer matrices are eliminated by subtraction of the two orbits. Therefore, if many BP values are very useful for reducing the error on the average radius by increased statistics, eliminating some of them introduces no bias in the difference of two orbits, provided that one given BP is eliminated from all measurements which are compared.

We computed the r.m.s. value of every BP not eliminated by the on-line calibration program for the P1 - P9 sample. The distribution of the r.m.s. value is given in figure 1. Most of the good BP's have an r.m.s. value x <0.1 mm. Those rejected in LSS3 are often well above this value, and those below 0.1 mm are not distributed like the good ones. We did an additional cut in the distribution at x = 0.10 mm, which eliminated six additional BP's, outside sextant 3. With 15 values eliminated at data taking and 13 rejected in sextant 3, we finally used 74 BP's to compute a radius (in fact, an averaged horizontal offset to the theoretical central orbit, supposed to pass in the middle of each BP).

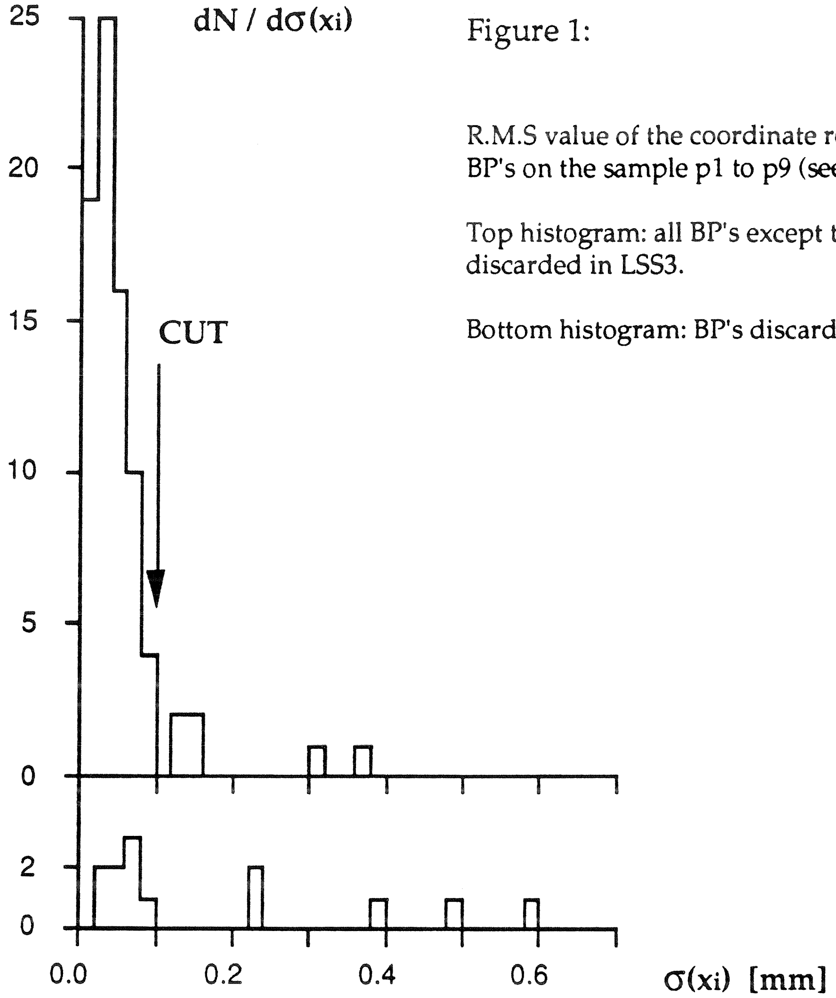

Figure 1:

R.M.S value of the coordinate read by the BP's on the sample p1 to p9 (see text).

Top histogram: all BP's except those discarded in LSS3.

Bottom histogram: BP's discarded in LSS3

6. DATA ANALYSIS

The computed average radius offset and the measured RF frequency are given in table 2. The measured radius offset dR_m is the result of a discrete sampling at the BP_i locations, where the dispersion coefficients are D_i, such that dR_m is biased by a coefficient $1/c_D = (\Sigma D_i)/D_{av}$, where D_{av} is the average dispersion seen by the beam. The effective radius offset is therefore $dR = c_D dR_m$. The corrected radius is given in Table 2. The value of c_D depends on the effective list of BP's used for the calculation. It is computed with a MAD simulation, together with D_{av}. For the MD data, $c_D = 0.7711$, and $D_{av} = 2.039$m. The two oxygen sets were averaged to simplify the statistical analysis. The frequencies are reduced to the null radius offset with the differential formula which relates f to R at fixed B field:

$$df = -\frac{\gamma^2 - \gamma_{tr}^2}{\gamma^2} \frac{f}{R} dR \qquad (6)$$

We used the proton momentum p = 271 GeV/c to compute γ for these corrections. All the parameters used are given in Table 3. An error of 10^{-3} on γ introduces a relative error of 1.3 10^{-5} on the coefficient multiplying dR in (6), while the effect of a 3% error on γ_{tr} is 4 10^{-4} , or 0.1Hz in df. Numerical values are given in Table 3. The uncertainty in R is negligible here (see section 8) , and there is none in f, because we compute the beam momentum with frequency ratios (see formula 2). The reduced frequencies are given in table 3.

The momentum of the protons during the MD is computed by using the formula 2, with $<f_i>$ as the average of the two oxygen values and $f_p = f_{10}$. The mass values are given in Table 3. The error on the momentum is computed with formula 4 :

$$\sigma(p) / p = 1.39\ 10^{-4}\ \sigma(f) \quad , \quad \text{with} \quad \sigma(f) = \sqrt{2}\ \sigma(f_p)$$

The factor $\sqrt{2}$ is to take into account the error on f_i which is equal to the one on f_p, $\sigma(f_i) = \sigma(f_p)$. The r.m.s. value of the nine P1-9 proton frequencies is 1.2Hz (see Table2) to which we added quadratically the same amount to take into account a potential calibration drift during the time spent between the calibration and the measurements. In fact, such a drift is smaller than the random fluctuations in a few hours after a calibration7) but was never quantified precisely . We conservatively assume a contribution equal to the random fluctuations. This gives $\sigma(f_p) = 1.7$ Hz. Therefore , $\sigma(f) = 2.4$ Hz and according to table 3:

$$p_{MD} = 270.66 \pm 0.091 \text{ GeV/c}$$

The resolution is $\sigma(p) / p = 3.4\ 10^{-4}$. The error is dominated by the fluctuations on the closed orbit measurement, a mixing of electronic noise and of beam position fluctuations, themselves induced by ripples on power supplies and noise in the RF system. In section 3.4, we estimated the effect of the fluctuations on the closed orbit control to be $\sigma(p) / p = 1.9\ 10^{-4}$. Corrected for the effective number of BP's used (74 vs. 100) and multiplied by $\sqrt{2}$ for the potential calibration drift introduced above, this estimated resolution becomes $\sigma(p) / p = 3.1\ 10^{-4}$, a value almost equal to the measured resolution.

This result is obtained by measuring a frequency ratio, with the requirement of equal relative radius and B field. The precision on the first of these conditions is the ultimate limitation of the measurement, while the second one is ten times more precise. The precision on the proton and oxygen ion masses is even more precisely known, so that we can consider that this result is not affected by systematic errors.

Table 2 : Frequencies and Measured Radius offset

Frequency : add high digits: 200390000 Hz. R in mm

Radius correction c = 0.77107217

	Frequency [Hz]	Radius Offset Measured [mm]	 Corrected [mm]	Frequency at null Radius [Hz]
OXA	214.8	-0.7893	-0.6086	106.7
OXB	209.3	-0.7593	-0.5855	105.4
p1	3931.5	-1.8678	-1.4402	3670.8
p2	3930.6	-1.8684	-1.4406	3669.8
p3	3930	-1.8618	-1.4356	3670.2
p4	3929.4	-1.8716	-1.4432	3668.2
p5	3929.2	-1.8625	-1.4361	3669.3
p6	3928.7	-1.8590	-1.4335	3669.2
p7	3928.6	-1.8726	-1.4439	3667.3
p8	3928.5	-1.8444	-1.4222	3671.1
p9	3927.8	-1.8508	-1.4271	3669.5
			Average p1/9	3669.5
			r.m.s p1/9	1.2
p10	3829.2	-1.3323	-1.0273	3643.3
pbar	3825		-0.9104	3660.2

Table 3 : Reduced Frequencies and Beam momentum

f offset	200390000
proton mass	0.9382723
Oxygen mass/8	1.861885513
R [mm]	1100009
momentum	271
gamma p	288.8305
gamma Ox	145.5548
gamma tr	23.22

f/R x (g2-g2tr)/g2

proton	180.9974
oxygen	177.5353

	f measured [Hz]	f at dR=0 [Hz]	Momentum
OX A+B	212.05	106.1	
p 1-9	3929.9	3669.3	(uncalibrated)
p10	3829.2	3643.2	270.66
pbar	3825	3660.2	

7. EXTRAPOLATION TO THE 1991 COLLIDER RUN

To our degree of resolution, we can consider that the B field was the same during the MD and the collider run. The average offset radius during the collider run was measured as $\Delta R_{meas} = -0.95 \pm 0.1$ mm. This error of 0.1 mm includes the radius variations along the duration of a coast, induced by a slight sensitivity of the feed-back of the RF system to the stored beam intensity. It also contains slight variations from coast to coast. Four orbits were recorded during the collider run. We compared these data to those of the MD by eliminating bad BP readings found in any set from all sets and correcting the radius accordindly (here $c_D' = 0.7706$). The measured collider radius offset is shifted by $dR = -0.148 \pm 0.009$ mm after the BP elimination.

There was also one simultaneous radius and RF measurement during the collider run, for which $\Delta R^{RF}{}_{meas} = -0.890$mm. This radius must be shifted by the correction found above and multiplied by c_D', i.e. $\Delta R_1 = (\Delta R^{RF}{}_{meas} - .148)\ c_D' = -0.800$mm. To compare a frequency at null radius with the MD data, we must shift ΔR_1 to the value which would have been measured with the BP sampling of the MD . The offset is obtained by computing the radius difference between the MD data in the two analysis (MD and MD+collider). The resulting radius $\Delta R_2 = \Delta R_1 - 0.11 = -0.91$ mm is reported in Table 2. The collider frequency reduced to null radius differs from the proton MD value by 17 Hz. The RF can drift with time, with an approximate law $\delta_{RF}f \approx 1\text{Hz} \cdot \sqrt{N}$ days. Between December 1991 and May 1992, N day ≈ 150, such that $\delta_{RF}f = 12$ Hz, a value not much different from 17 Hz. It might also be that the calibration of the BP's , which was not done just before this measurement has slightly drifted. Indicatively, a 17 Hz difference corresponds to $\delta r = 0.095$mm, a very possible drift a month after the calibration. We can of course not deduce the collider energy with such uncontrolled fluctuations.

To compute the collider momentum, we proceed in the following way. We consider the B field to be constant (see Section 3.2). Therefore the collider energy at null radius is the one measured during the MD. It then remains to correct for the observed radius offset during the collider run. It was

$$\Delta R_{collider} = (\Delta R_{meas} - 0.148)\ c_D' = -0.80 \pm 0.2 \text{ mm}$$

In the absence of a better estimator for the error on $\Delta R_{collider}$, we add linearly to the error on ΔR_{meas} the $\delta r = 0.095$mm discussed in the previous paragraph. This additional offset is added to $\Delta R_{collider}$. Then, we use the differential relation between p and R at fixed B to compute the collider momentum offset, $\Delta p = \gamma_{tr}^2 (p/R)\ \Delta R = -0.106 \pm 0.026$ GeV/c. The collider beam momentum is then $p_{collider} = p_{MD} + \Delta p$. The error is the quadratic addition of $\sigma(p_{MD})$ and $\sigma(\Delta p)$. The result is

$$P_{collider} = 270.55 \pm 0.095 \text{ Gev/c.}$$

The resolution is $\sigma(p)/p = 3.5\ 10^{-4}$.

8. RADIUS MEASUREMENT DURING THE MD

The radius of the machine can be computed as

$$R = \frac{\beta\, c\, N_h}{2\pi\, f_{RF}}$$

in which βc is the speed of the beam, with $\beta = (1 - 1/\gamma^2)^{1/2} = 1\text{-}6.0087\ 10^{-6} \pm 4\ 10^{-9}$ and $c = 299792458$ m/s, with no error, see 6). Nh = 4620 is the SPS harmonic number. The frequency is $f_{10} = 200393643$ Hz (see Table 3). The relative error on R is given by the quadratic addition of $\sigma(\beta)/\beta$ and $\sigma(f)/f$. The error on β is here negligible. We estimate the absolute error on f_{RF} to be $\sigma(f) \approx 20$ Hz, assuming that after N day ≈ 400 (1 year), the crystal is getting quite stable. Then, $\sigma(R) = 10^6\ (20/2\ 10^8) = 0.1$mm. The result is compared to older values in table 4. We see a remarkable stability of the SPS radius, the change in radius being smaller than 0.2 mm over 10 years, a change compatible with zero if the error is considered.

Table 4: **Radius and RF with time**

Date	Radius [mm]	Frequency [Hz]
June 1982	1100009.3 ± 0.2	200393620 8)
May 1985	1100009.3 ± 0.3 9)	-
May 1992	1100009.05 ± 0.1	200393643

9. CONCLUSIONS

The momentum of the SPS proton beam was measured at the nominal value of the 1991 collider run. The momentum is deduced from the measurement by RF of the speed difference between oxygen ions and protons at constant magnetic field and radius. The resolution obtained in the experiment is $3.4\ 10^{-4}$. This result could be improved by a factor 2 in future measurements with a more precise and systematic study of the closed orbit. The momentum of the beams during the collider run of December 1991 is deduced to be $p = 270.55 \pm 0.095$ GeV/c.

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