GeV laboratory will definitely take over CERN's present role as the principal general purpose high energy laboratory in Europe.

JOHNSEN: In addition to Hine's remark, it may be noted that only little operation time of the CERN PS is required to fill the storage rings.

MCMILLAN: You mean that it will take one hour to fill the rings, and that a filling will last a day?

JOHNSEN: With the present CERN PS conditions about 1.5 hours is required to fill both storage rings. We hope that the rings should then be able to operate for twelve hours, without requiring a refilling. With an improved intensity of the CERN PS the required filling time will be proportionally reduced.

KOLOMENSKY: I have a question about one old problem. What are your final requirements to the magnetic field stability and to the momentum spread in order to decrease the dangerous moving of the working point, which in turn leads to multiple crossing of nonlinear resonances (nonlinear noise)?

JOHNSEN: We have put the requirement on field stability to 10^{-4}. There will be a sextupole component on the field to make $dQ/dp \simeq 0$, but still slightly positive to damp coherent oscillations that may be caused by resistive wall instabilities.

SOME EXPERIMENTS WITH THE CERN ELECTRON STORAGE AND ACCUMULATION RING (CESAR)

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(Presented by M. J. Pentz)

1. INTRODUCTION

The design, construction, and running-in of CESAR have been described in an earlier paper (1).

In the period since the publication of that paper, CESAR has been improved in a number of ways, a first series of beam lifetime and stacking measurements have been performed and a second series is beginning at the time of writing (August 1965). Results of the present series will be included as an Annexe to this paper if they are available in time.

The main improvements have been in the vacuum, the voltage stability of the 2 MeV Van de Graaff injector and the flexibility of the radiofrequency programme.

As reported in the earlier paper, the mean pressure in the vacuum chamber before bakeout was 2×10^{-8} torr, and beam life-time measurements were made at that pressure which did not then appear to agree very well with the theoretical values.

In 1964, a bakeout of the vacuum chamber was attempted which was only partly successful. A number of leaks (mainly in gold-wire gaskets) developed during bakeout at 300 °C, so that in the end it was necessary to reduce the bakeout temperature to 150 °C and bake only about half the vacuum chamber.

The mean pressure was nevertheless reduced to 2×10^{-9} torr, at which the measured half-life of the beam near the central orbit (where the aperture is largest) was about 1 second.

During a long shut-down earlier this year, the vacuum chamber was demounted completely all the flanges repolished, and various other minor improvements made. A bakeout at 250 °C was then carried out. In spite of a fracture in one of the stainless steel bellows during the first bakeout, which caused a leak up to atmospheric pressure, a second bakeout was effected without further trouble, and the mean pressure was reduced to 3×10^{-10} torr. Lifetime measurements at this pressure are now about to be made.

In January of this year a first series of experiments on radio-frequency stacking were performed, the results of which are summarised in this paper. They have been reported in more detail in a CERN Report (2).

Both the accuracy of these measurements and the range of parameters over which they could be made were limited by the voltage instability of the Van de Graaff injector ($\pm$ 5 kV or more). A fast stabilisation system of a rather original

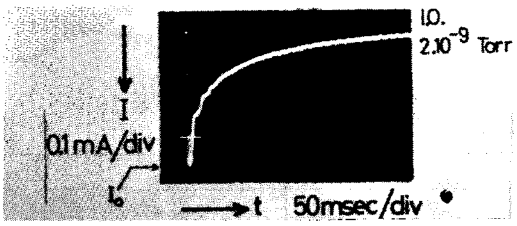


Fig. 1 - Exponential decay of single pulse due to plural scattering.

design was accordingly built into the Van de Graaff during the shut-down. The principles of this system are summarised in the present paper, and details will be available in a CERN Report now in preparation (3). With this system a stability of better than ± 200 V has been achieved, and it seems that adjustment of the system may give a further improvement of a factor of two or more.

The voltage programme of the radio-frequency acceleration system has been modified so as to permit an exponential reduction of the voltage during the acceleration cycle, and thereby to ensure that stacking can be effected with full buckets even if the trapping conditions at the beginning of the cycle are such that the buckets start off partly emply.

In view of the interest that exists in the effects on stacking efficiency of radio-frequency noise, a variety of devices have been installed which can inject different amounts and kinds of noise (random noise, line-spectrum noise, etc.) into the radio-frequency system. Experiments along these lines are planned for the immediate future.

2. BEAM LIFETIME MEASUREMENTS

Method

The betatron core was used to accelerate a single injected pulse of electrons to any desired orbit, where it was allowed to circulate.

The intensity of circulating beam was displayed by a "beam transformer" with a long time constant (> 200 sec) on a memoscope, from which traces convenient for measurement were photographed. Fig. 1 shows a typical exponential decay of the beam intensity I, due to gas scattering. The half-life times $\tau_{1/2}$ for $I = I_0/2$ were measured at several orbits and as a function of the distance of a vertical target and a horizontal target coming from the outside of the aperture (Fig. 2). The target positions at whith the lifetime began to be reduced provided a measure of the effective aperture, which is determined by the vacuum chamber with all built-in obstacles and by the closed orbit distortions.

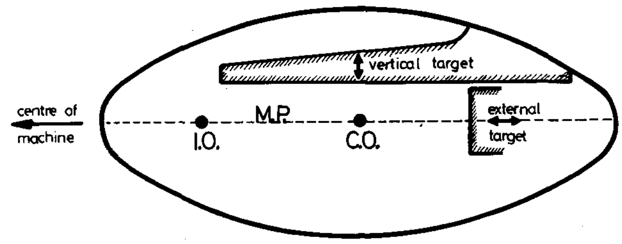


Fig. 2 - Vacuum chamber cross section — I.O.: Injection orbit; C.O.: Central orbit; M.P.: Median plane.

Results

The measured half-lifetimes near the central orbit at pressures of 2×10^{-8} torr and 2×10^{-9} torr, and the effective apertures are shown in Table I. The theoretical values were computed by a Monte Carlo method for the given effective apertures, pressures and gas composition (mainly N_2 and CO, as measured with an Omegatron). For apertures of this size, the dominant scattering process is neither single nor multiple scattering. The electrons are scattered on the average two or three times before they are lost. For this intermediate range, E. Fischer (4) has proposed the term "plural scattering".

The agreement with the theory is better than it appeared at first (1). The earlier theory contained an arithmetical error of $\sqrt{2}$ (lifetimes against single and multiple scattering quoted in (1) are for that reason too long by a factor $\sqrt{2}$). In addition, the plural scattering computations show a further reduction in lifetime.

The agreement is certainly well within the error in measuring the average residual pressure and the betatron oscillation amplitudes (from which the reduced aperture $A_{red} = \sqrt{A^2 - a^2}$, a = rms betatron amplitude, is calculated). We suspect that there is coupling in CESAR but we do not know how strong it is.

TABLE I

Beam lifetime measurements

Residual pressure torr	*Vertical aperture mm*	*Reduced aperture mm*	*Half-life*	
			Measured sec	*Theoretical sec*
2×10^{-8}	5	4.6	0.10	0.08* 0.13**
2×10^{-9}	5	4.6	1.00	0.8 * 1.3 **

* With strong coupling between horizontal and vertical betatron oscillations.
** Without horizontal-vertical coupling.

3. RADIO-FREQUENCY STACKING MEASUREMENTS

Methods

Three kinds of experiment were done:

a) stacking with full buckets,

b) stacking with partly empty buckets,

c) displacement of a previously stacked beam with completely empty buckets.

The stacking mode employed was what we call " repetitive stacking " or " stacking at the top of the stack ». In this mode, the radio-frequency cycle is reproduced exactly at each pulse, and electrons are always accelerated to the same final energy at which they are deposited when the radiofrequency voltage is abruptly turned off.

The energy width of the stacked beam, and the position of the centre and the edges of the stack (in the displacement experiment) were measured by sweeping an empty " scanning bucket " of constant area through the stack and observing the signal from an electrostatic pick-up electrode (EPU). A typical EPU signal is shown in Fig. 3. The scanning bucket used for stacking experiments had a height of 5 kV and a phase parameter $\Gamma = \sin \varphi_s = 0.13$. This is a rather wide (in phase) and slow-moving bucket, and it did not produce an observable perturbation of the stacked beam.

The theoretical area A_s of the stacking buckets could be computed from the measured values of the accelerating voltage and frequency modulation rate. According to the well-known theory (5) the energy width of an n-pulse stack should be not less than $n\, A_s/2\pi$.

We define the " stacking efficiency " ε_s to be the ratio of the theoretical stack width to the measured stack width ΔE_n

$$\varepsilon_s = n\, A_s/2\pi\Delta E_n$$

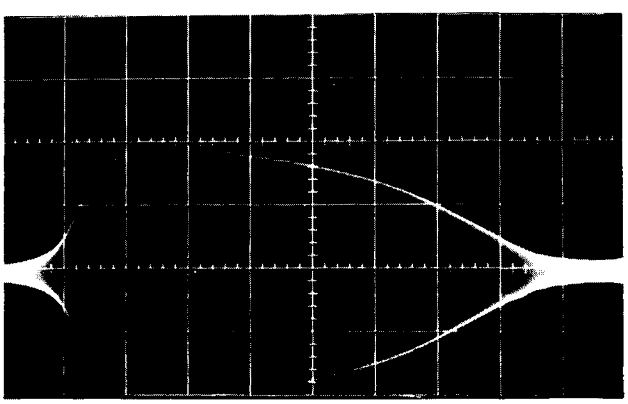


Fig. 3 - Typical signal from the electrostatic pickup electrode when a 40-pulse stack is scanned by en empty bucket. The high energy end of the stack is on the left.

Results

In the first experiment (stacking with full buckets), ε_s was measured for values of the phase parameter Γ in the range $0.2 \leqslant \Gamma \leqslant 0.8$ and for several different values of A_s for each value of Γ. The number of pulses stacked was in the range $2 < n \leq 10$. The results are plotted in Fig. 4. (The point $\varepsilon_s = 0$ at $\Gamma \geqslant 1$ is, of course, an experimental point only in the sense that we found, as expected, that one cannot stack at all with an imaginary bucket).

Fig. 5 shows the dependence of stacking efficiency on the number of pulses stacked, in the range $5 \leqslant n \leqslant 25$, with $\Gamma = 0.46$.

The results show the kind of dependence of stacking efficiency on Γ and on n that is predictable from the established bucket theory, and the magnitude of the stacking efficiency is also about what one would expect.

The stacking efficiency approaches 90% after only 25 pulses with $\Gamma = 0.46$. Even with $\Gamma = 0.8$ and after 10 pulses or so, the stacking efficiency is no lower than 25%.

These results are of some interest in relation to the design of the intersecting storage rings for the CERN Proton Synchrotron (I.S.R.), in which an overall stacking efficiency of 50% is assumed to be achievable.

This stacking efficiency is defined in terms of particle densities in the stack and at injection. What we have measured with CESAR is stacking efficiency in terms of phase space which we have « painted » (more or less uniformly) with electrons so as to see what happens to it. The overall

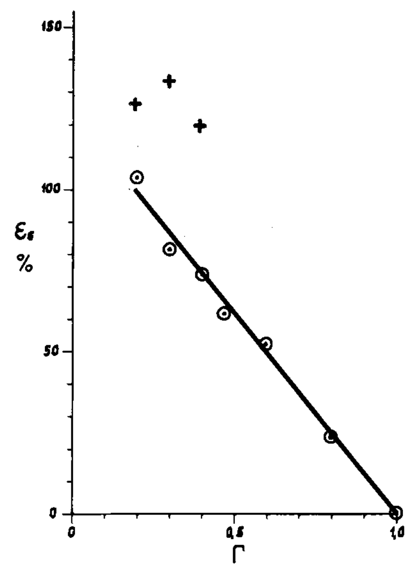


Fig. 4 - Stacking efficiency as a function of stable phase parameter $(2 < n \leq 10, n =$ number of pulses stacked). ⊙ Full buckets + Nearly empty buckets.

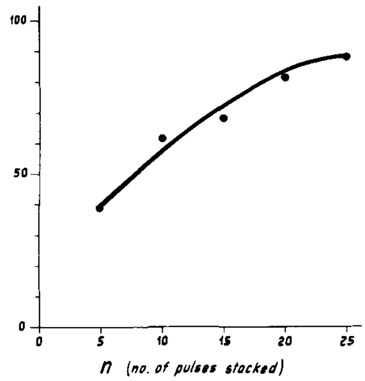


Fig. 5 - Stacking efficiency as a function of number of pulses stacked (Full buckets; $\Gamma = 0.46$).

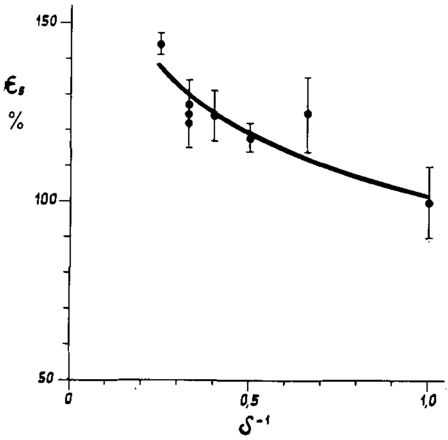


Fig. 6 - Staicking efficiency as à function of emptiness of bucket ($\Gamma = 0.2$; $5 < n \leq 10$, n = number of pulses stacked).

stacking efficiency is the product of several factors, of which we have measured only one. The others depend upon whether there are losses of particle density during trapping or due to nonadiabatic processes during acceleration and stacking. It seems reasonable to conclude from our results so far that the first component of the overall stacking efficiency should be close to 100% in the I.S.R., where several hundred pulses will be stacked, at any rate for moderate values of Γ. It should not be too difficult to keep the product of the remaining components above 50%. As for the possibility of stacking with rather high values of Γ ($\Gamma \sim 0.84$ is suggested) in order to make "repetitive stacking" possible in the I.S.R., we are not yet in a position to say whether the first component of the stacking efficiency, which is only 25% for $\Gamma = 0.8$ and $n \sim 10$, will also approach 100% for $n \sim 100$.

With the vacuum and Van de Graaff stability we now have, it should be possible to extend our results up to values of n in the range 100 to 200.

In the second experiment (stacking with partly empty buckets) the stacking efficiency was measured for several values of Γ and for $5 \leqslant n \leqslant 10$ with buckets of various degrees of emptiness. The results of one set of such measurements (for $\Gamma = 0.2$) are shown in Fig. 6, in which the parameter δ^{-1} is an approximate measure of the emptiness ($\delta^{-1} = 1$ for full buckets). Three points from these measurements are also shown in Fig. 4.

It is apparent from these results that the stacking efficiency (as defined above) can exceed 100% if the buckets are not full.

This somewhat surprising result should be considered in relation to the third experiment (displacement of a stack by empty buckets), which was performed in two different ways.

In the first, a single pulse was stacked near the centre of the energy aperture. Empty buckets were then run through the stack and turned off near the upper limit of the energy aperture. The empty bucket parameters were $\Gamma = 0.2$, $A_s/2\pi = 10.3$ keV. The height of such a bucket is about 20 keV, and it was turned off more than 100 keV above the stack.

After n traversals of the stack ($0 < n \leqslant 8$) the stack width was measured in the usual way with a separate scanning bucket and the EPU.

The results are shown in the lower curve of Fig. 7. The upper curve is derived from the results of the computation reported by Swenson (6).

At the same time the displacements of the stack edges were measured. It was found that the stack displacement per traversal by the empty bucket was 7.0 keV as against the theoretical value of 10.3 keV, i.e. about 1.5 times smaller. This figure may be compared with the " empty bucket efficiencies " plotted in Fig. 6 wich approach 1.5 for nearly empty buckets.

The relative levels of the two curves in Fig. 7 have no significance, since they depend upon an arbitrary normalization procedure, but it is of some significance that, within the accuracy of the measurrements, the measured stack width in this case does not increase with n, whereas the computed stack width does. It should, however, be noted that the low signal to noise ratio would probably conceal an actual increase in stack width. In certain cases an increase in stack width was observed, but it was always less than the theoretical value.

These results suggested that some process, not included in the Hamiltonian upon which Swenson's computations were based, may be producing, in effect, a phase-space compression. A furt ther experiment was accordingly done to check whether this was the case.

The maximum intensity in the stack (i.e. the maximum height of the EPU signal) was measured as a function of the number of empty bu-

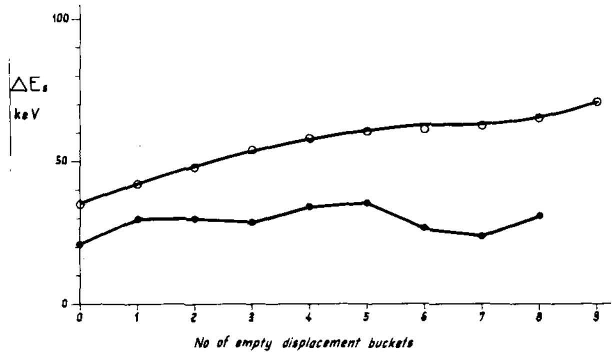


Fig. 7 - Stack width as a function of the number of empty displacement buckets passed through the stack.
-•- Experiment with $\Gamma = 0.2$
-o- Computation with $\Gamma = 0.3$

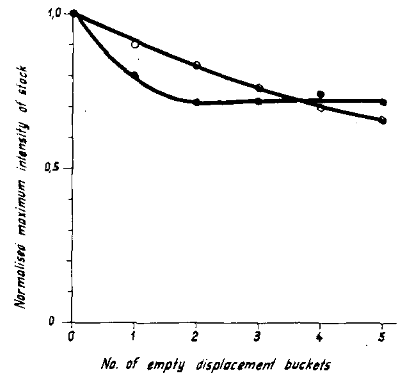


Fig. 8 - Intensity of stacked beam as a function of the number of empty displacement buckets passed through the stack.
-•- Experiment with $\Gamma = 0.2$
-o- Computation with $\Gamma = 0.3$

ckets that had been carried through the stack. At the same time, the total circulating current was measured with the beam current transformer. The former quantity was then normalized by dividing it by the latter.

The result is shown in Fig. 8, where it is compared with the result of Swenson's computation, for which the normalization factor is inherently unity (no electrons are lost in the computation).

After the first few traversals, the normalized intensity appears to remain approximately constant. Theoretically, it should go on decreasing.

This result seems to imply that an empty bucket may not only displace phase space as predicted by the usual theory, but may also redistribute it, and that the result of the two effects is that both the displacement and the energy spread of a stack traversed by empty buckets may be appreciably less than what is predictable from displacement only.

At first sight, this might appear to be in contradiction with Liouville's theorem. This need not be so. The only conclusion that can be drawn from these results (and even this with some caution, in view of their limited accuracy and range of variation of the parameters) is that the higher order time derivative terms that are dropped out of the Hamiltonian in the theory upon which Swenson's computations were based are of some importance in the experimental reality of CESAR.

One interesting candidate for inclusion in an extended theory is radiofrequency noise. It is conceivable that noise could have the effect of making the bucket separatrix permeable to particles. When the bucket is full, particles could diffuse in or out of it with equal probability. But a partly empty bucket moving through a stack could capture more particles than it loses, thereby producing a redistribution as well as a displacement of the stack. Our results show normal stacking efficiencies with full buckets and abnormally high efficiencies with empty ones.

Theoretical studies of the effect of radio-frequency noise upon stacking efficiency are in progress. As mentioned in the Introduction, we hope to study the problem experimentally in the near future.

4. FAST STABILISATION SYSTEM FOR THE VAN DE GRAAFF INJECTOR

We are only interested in stabilising the Van de Graaff voltage with respect to the mean bending field of the storage ring magnets. Our reference is accordingly the field of a thirteenth bending magnet, identical to the twelve in the ring, connected in series with them to a current stabilised power supply (stability $\pm 1 \times 10^{-4}$) and maintained at the same temperature as that of the ring magnets to ± 0.2 °C.

We use the independent second pulsed electron beam of the Van de Graaff (which has two acceleration tubes) both to monitor and to control the terminal voltage.

After collimation and deflection by the reference magnet, this beam goes down a magnetically shielded pipe 4 metres long to a pair of insulated slits 0.4 mm apart. The error signals derived from these slits control the repetition frequency of a light pulse that triggers the electron gun in the Van de Graaff. At essentially constant pulse current, the rate of discharge of the terminal by this beam is thus proportional to the repetition rate, which is variable in the range 100 kHz to 1 MHz.

Fig. 9 shows oscillograms of the terminal voltage (observed with a pick-up electrode housed in the tank liner) without and with stabilisation.

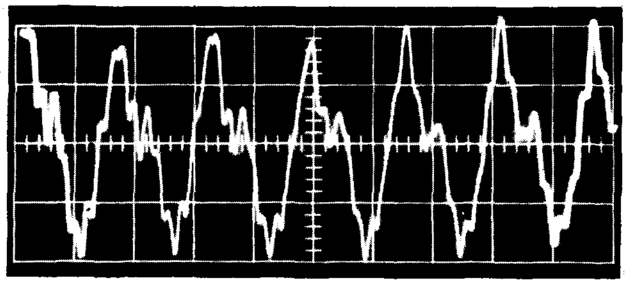
5. OBSERVATION OF A BEAM INSTABILITY DUE TO SPACE-CHARGE FORCES

A beam instability occuring in the stached been has been investigated. The effect is illustrated in Fig. 10, which shows the gas-scattering decay of a 12-pulse stached beam with and without the application of a small voltage (about 5 watts) to the clearing field electrodes. With a smaller clearing field, the instability occurs later and is less pronounced. It occurs equally wall with a stuched beam of only one or two pulses. There is a threshold current below which the instability will not occur, and this current is larger the further the operating point is away from the fourth order seem resonance

$$2\,Q_H + 2\,Q_V = 9$$

The Q-values at the position of a very narrow stuched beam of only one or two pulses can be measured by radio-frequency knock-out to a

a)



b)

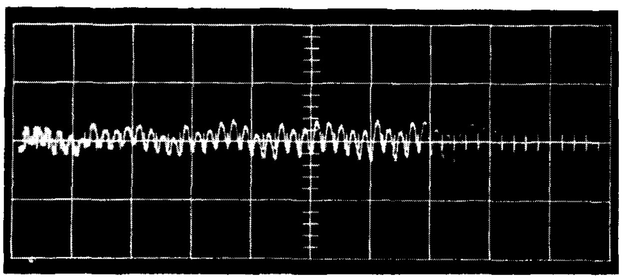


Fig. 9 - a) Van de Graaf terminal voltage ripple, without stabilisation (Sensitivity: 1 div. = 500 V; Time-base: 1 div. = 0.1 sec).
The Van de Graaff was unusually stable at the time, with only ± 1 kV of 6 cycle per secondo belt ripple.
b) Van de Graaff terminal voltage ripple with stabilisation (same conditions as in a)).
The 6 cycle component is now almost too small to measure. What remains is ± 150 V of mainly 50 cycles per second due to stray magnetic fields, Since CESAR is operated at 50 pulses per second in synchronism with the mains, voltage fluctuations of that frequency are of no significance. The relative stability is thus better than ± 5 x 10^{-5} r.m.s.

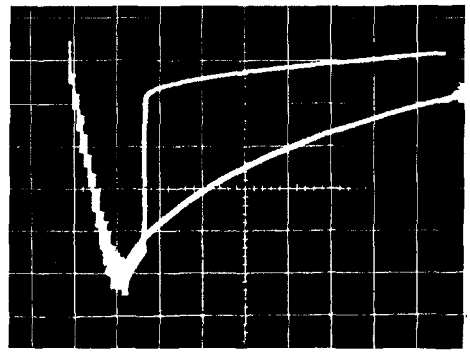


Fig. 10 - The figure shows the accumulation of 12 pulses and their subsequent decay due to gas scattering. The vertical scale in 0.4 mA per division, and the horizontal scale 0.2 sec per division. The upper trace shows the instability that occurs without clearing fields, and the lower trace the normal decay with 4 V applied to the clearing field electrodes.

precision of butter than an point in the thousand thes, for instance, we here found the threshold event to be 0.28 mA if the beam is located at the position where $2\,Q_H + 2\,Q_V = 8.998$, and 0.6 mA where $2\,Q_H + 2\,Q_V = 8.995$.

There is little doubt that this instability occurs when the space-charge neutralization of the beam has built up mangle to produce the additional magnetic focusing required to shift the Q-values in to the sum resonance.

By changing slightly the lens currents, the operating point could be moved to a point where Q_H was very slightly below 2.75. The same instability was descrived, in this case due to a shift of the horizontal Q value into the fourth order resonance.

It seems that the theoretical threshold circuits for most of the barion space-charge instabilities are quite close to the currents actually injected into CESAR. This, together with the very high stability and reproducibility that has now been achieved and the rather precise measurements that can be made indicates that CESAR should prove to be a useful instrument for the investigation of these effects.

Worth along these lines will continue in the rimediate future.

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